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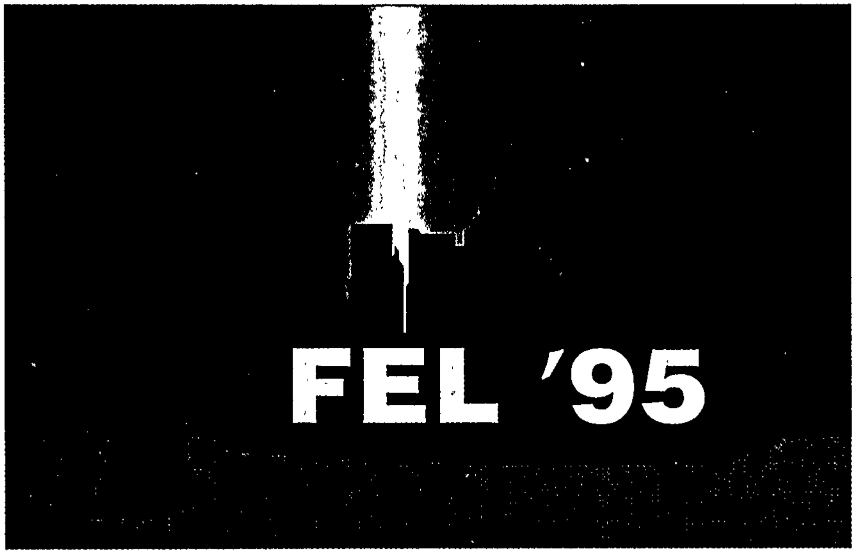
PROGRAM AND ABSTRACTS

17TH INTERNATIONAL FREE ELECTRON LASER CONFERENCE
AND
2ND INTERNATIONAL FEL USERS' WORKSHOP



NEW YORK MARRIOTT MARQUIS
NEW YORK, NEW YORK
AUGUST 21–25, 1995

HOSTED BY
BROOKHAVEN NATIONAL LABORATORY

BNL 61982

17th International Free Electron Laser Conference
and
2nd International FEL Users' Workshop

Hosted by
Brookhaven National Laboratory

August 21 - 25, 1995

PREFACE

Welcome to the 17th International Free-Electron Laser Conference and 2nd International FEL Users Workshop. This year the conference and workshop (FEL'95) are hosted by Brookhaven National Laboratory. We have decided to hold the conference and workshop at the same location and time but in parallel sessions in order to enhance the interaction between FEL builders and users. We hope and trust that this interaction will lead to better FELs for the users, promote new ideas and strengthen our community.

Together with the International Program Committee of the FEL Conference, we have selected topics of current interest in FEL research as the basis for the oral sessions in the FEL'95 program. The choice of these subjects was influenced by the response cards that were distributed in the First Announcement of the conference. The chairs of the sessions were invited to participate in the meeting of the Program Committee on April 30 in Dallas. The Chairs, together with the Program Committee helped us develop a strong program that highlights the current research activities in our field. The program for the User's Workshop was developed in a similar manner. The breadth of science represented in the program is indicative of the expanding role of FEL facilities as a tool for research. The response to the call for papers has been gratifying as you may judge for yourself by looking at the program and abstracts. We wish to thank all those who have worked together to develop the program and make this conference possible.

We have selected the beautiful Marriott Marquis hotel at the heart of New York City to be the site of these events. We hope that in addition to having an exciting time scientifically at FEL'95, that you will also have an opportunity to enjoy the many cultural and social activities available in New York City.

Ilan Ben-Zvi　　Samuel Krinsky
Conference Co-Chairs

Glenn Edwards　　Erik Johnson
Workshop Co-Chairs

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The organizers of FEL'95 would like to thank the following sponsors for the important support that they have provided.

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----------	----------	---------- 11:00 a.m. *Storage Ring Based FELs* J. Madey, Chair Session Mo2 Broadway Ballroom North	---------- 10:35 a.m. *High Power FELs* G. Neil, Chair Session Tu2 Broadway Ballroom North	---------- 10:00 a.m. Users' Talks *Biomedical* K.D. Straub, Chair Session We3 Broadway Ballroom North Conference Posters Session We1 continued	---------- 10:30 a.m. *New Directions* C. Pellegrini, Chair Session Th2 Broadway Ballroom North Users' Posters Session Th4 continued	---------- 10:30 a.m. *FEL Facility Challenges* J. Allen, Chair Session Fr2 Broadway Ballroom North **Joint Session**
Afternoon		2:20 p.m. *Electron Beam Physics and Technology* I. Lehrman, Chair Session Mo3 Broadway Ballroom North	Conference Posters Session Tu3 Broadway Ballroom South	*TRIP TO BNL* (Includes lunch and dinner). Buses leave Marriott at 11:30 a.m. and return approx. 10:30 p.m. *Vendor Exhibition till Friday*: Majestic/Music Box Room -MKS Instruments -Northrop-Grumman -Titan Beta -VAT, Inc. - Hamamatsu Corp.	Conference Posters (Session Th3) Broadway Ballroom South 1:30 p.m. Users' Talks *Materials II* A. Schwettman, Chair Session Th5 Broadway Ballroom South	
----------	----------	---------- 4:15 p.m. *Long Wavelength FELs* G. Bekefi, Chair Session Mo4 Broadway Ballroom North	---------- Conference Posters Session Tu3 continued Broadway Ballroom South		---------- Conference Posters Session Th3 continued 3:30 p.m. Users' Talks *Biophysics* A. Doukas, Chair Session Th6	
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FEL'95 Program

Monday, August 21, 1995

FEL Prize/New Lasing

8:30 - 8:45	MoI	**Welcome**
8:45 - 8:50	MoI	**Introductory Remarks - Session Chair** Kulipanov, G.
8:50 - 9:40	MoI - 1	**FEL Prize Talk - Dynamical Aspects on FEL Interaction in Single Passage and Storage Ring Devices** Dattoli, G., Renieri, A.
9:40 - 9:50	MoI - 2	**First Lasing, Capabilities, and Flexibility of FIREFLY** Berryman, K.W., Smith, T.I.
9:50 - 10:00	MoI - 3	**Optical Properties of Infrared FELs from the FELI Facility II** Saeki, K., Okuma, S., Oshita, E., Wakita, K., Kobayashi, A., Suzuki, T., Yasumoto, M., Tomimasu, T.
10:00 - 10:10	MoI - 4	**First Lasing of the KAERI Millimeter-Wave Free Electron Laser** Lee, B.C., Jeong, Y.U., Cho, S.O., Kim, S.K., Lee, J.
10:10 - 10:20	MoI - 5	**Report on First Masing and Single Mode Locking in a Prebunched Beam FEM Oscillator** Cohen, M., Eichenbaum, A., Kleinman, H., Arbel, M., Yakover, I.M., Gover, A.
10:30 - 11:00	*Coffee Break*	

Storage Ring Based FELs

11:00 - 11:10	Mo2	**Introductory Remarks - Session Chair** J. Madey
11:10 - 11:35	Mo2 - 1	**Microscopic Study on Lasing Characteristics of the UVSOR Storage Ring Free Electron Laser** Hama, H., Kimura, K., Yamazaki, J., Takano, S., Kinoshita, T., Couprie, M-E.
11:35 - 12:00	Mo2 - 2	**Lasing at 300 nm and Below: Optical Challenges and Perspectives** Garzella, D., Couprie, M.E., Billardon, M.
12:00 - 12:25	Mo2 - 3	**Duke Storage Ring UV/VUV FEL: Status and Prospects** Litvinenko, V.N., Burnham, B., Madey, J.M.J., Park, S.H., Wu, Y.
12:25 - 12:50	Mo2 - 4	**Present Status of the NIJI-IV Storage-Ring Free-Electron Lasers** Yamazaki, T., Yamada, K., Sei, N., Kawai, M., Yokoyama, M., Hamada, S., Ohgaki, H., Sugiyama, S., Mikado, T., Suzuki, R., Noguchi, T., Chiwaki, M., Ohdaira, T.
12:50 - 2:20	*Lunch*	

Monday, August 21, 1995 (continued)

Electron Beam Physics and Technology

2:20 - 2:30	Mo3	**Introductory Remarks - Session Chair** I. Lehrman
2:30 - 2:45	Mo3 - 1	**Kinetic Theory of Free Electron Lasers** Hafizi, B., Roberson, C.W.
2:45 - 3:00	Mo3 - 2	**Experimental Characterization of High-Brightness Beam at the Brookhaven Accelerator Test Facility** Wang, X.J., Srinivasan, T., Batchelor, K., Babzien, M., Ben-Zvi, I., Malone, R., Pogorelsky, I., Qui, X., Skaritka, J., Sheehan, J.
3:00 - 3:15	Mo3 - 3	**Determination of Electron Bunch Shape Using Transition Radiation and Phase-Energy Measurements** Crosson, E.R., Berryman, K.W., Richman, B.A., Smith, T.I., Swent, R.L.
3:15 - 3:30	Mo3 - 4	**Design and Characterization of the DC Acceleration and Transport System Required for the FOM 1 MW Free Electron Maser Experiment** Caplan, M., Urbanus, W.H., van der Geer, C., Valentini, M.
3:30 - 3:45	Mo3 - 5	**Electron Bunch Length Measurement at the Vanderbilt FEL** Amirmadhi, F., Brau, C.A., Mendenhall, M., Engholm, J.R., Happek, U.
3:45 - 4:15	*Coffee Break*	

Long Wavelength FELs

4:15 - 4:25	Mo4	**Introductory Remarks - Session Chair** G. Bekefi
4:25 - 4:50	Mo4 - 1	**Generation of Frequency-Chirped Optical Pulses with FELIX** Knippels, G.M.H., van der Meer, A.F.G., Mols, R.F.X.A.M., Oepts, D., van Amersfoort, P.W.
4:50 - 5:05	Mo4 - 2	**Theoretical Analysis of Saturation and Limit Cycles to Short Pulse FEL Oscillators** Piovella, N., Chaix, P., Shvets, G., Jaroszynski, D.
5:05 - 5:20	Mo4 - 3	**Experimental Results of a Sheet-Beam, High Power, FEL Amplifier with Application to Magnetic Fusion Research** Cheng, S., Destler, W.W., Granatstein, V.L., Levush, B., Rodgers, J., Antonsen, A.
5:20 - 5:35	Mo4 - 4	**High-Efficiency CARM** Bratman, V.L., Kol'chugin, B.D., Samsonov, S.V., Volkov, A.B.
5:35 - 5:50	Mo4 - 5	**Measurements of the Temporal and Spatial Phase Variations of a 33 GHz Pulsed Free Electron Laser Amplifier and Application to High Gradient rf Acceleration** Volfbeyn, P., Bekefi, G.

Tuesday, August 22, 1995

Short Wavelength FELs

8:30 - 8:40	Tu1	**Introductory Remarks - Session Chair** L.H. Yu
8:40 - 9:05	Tu1 - 1	**Multisegment Wigglers for Short Wavelength FEL** Vinokorov, N.A.
9:05 - 9:20	Tu1 - 2	**Studies on a VUV Free Electron Laser at the Tesla Test Facility at DESY** Rossbach, J., et al.
9:20 - 9:35	Tu1 - 3	**Exact and Variational Calculations of Eigenmodes for Three-Dimensional Free Electron Laser Interaction with a Warm Electron Beam** Xie, M.
9:35 - 9:50	Tu1 - 4	**Research and Development Toward a 4.5 - 1.5 Å Linac Coherent Light Source (LCLS) at SLAC** Tatchyn, R., Arthur, J., Baltay, M., Bane, K., Boyce, R., Cornacchia, M., Fisher, A., Hahn, S.J., Hernandez, M., Loew, G., Miller, R., Nuhn, H.D., Palmer, D., Paterson, J., Raubenheimer, T., Weaver, J., Wiedemann, H., Winick, H., Pellegrini, C., Rosenzweig, J., Travish, G., Caspi, S., Fawley, W., Halbach, K., Kim, K.J., Schlueter, R., Xie, M., Bamber, C., Melissinos, A., Meyerhofer, D., Bonifacio, R., DeSalvo, L.
9:50 - 10:05	Tu1 - 5	**Nonlinear Analysis of Wiggler Imperfections in Free-Electron Lasers** Freund, H.P., Yu, L.H.
10:05 - 10:35	*Coffee Break*	

Tuesday, August 22, 1995 (continued)

High Power FELs

10:35 - 10:45	Tu2	**Introductory Remarks - Session Chair** G. Neil
10:45 - 11:00	Tu2 - 1	**High-Power FEL Design Issues - A Critical Review** Litvinenko, V.N., Madey, J.M.J., O'Shea, P.G.
11:00 - 11:15	Tu2 - 2	**Status of the Project of Novosibirsk High Power FEL** Pinayev, I.V., Erg, G.I., Gavrilov, N.G., Gorniker, E.I., Kulipanov, G.N., Kuptsov, I.V., Kurkin, G.Ya., Oreshkov, A.D., Petrov. V.M., Popik, V.M., Salikova, T.V., Sedlyarov, I.K., Shaftan, T.V., Skrinsky, A.N., Sokolov, A.S., Vesherevich, V.G., Vinokurov, N.A., Vobly, P.D.
11:15 - 11:30	Tu2 - 3	**Status Report on the Development of a High Power UV IR FEL at CEBAF** Benson, S., Bohn, C., Dylla, H.F., Fugitt, J., Jordan, K., Kehne, D., Liu, H., Merminga, L., Neil, G., Neuffer, D., Shinn, M., Wiseman, M., Goldstein, J., Colson, W., Wong, R., Li, Z.
11:30 - 11:45	Tu2 - 4	**A Proposed Visible FEL Facility at Boeing** Dowell, D.H., Adamski, J.L., Hayward, T.D., Parazzoli, C.G., Vetter, A.M.
11:45 - 12:00	Tu2 - 5	**Experimental Study of High-Current FEM with Broadband Microwave System** Denisov, G.G., Bratman, V.L., Ginzburg, N.S., Kol'chugin, B.D., Peskov, N.Yu., Samsonov, S.V., Volkov, A.B.
12:00 - 12:15	Tu2 - 6	**Design of a High Average Power FEL Driven by an Existing 20 MV Electrostatic- Accelerator** Kimel, I., Elias, L.R.
12:15 - 2:00	*Lunch*	

Tuesday, August 22, 1995
Poster Session
2:00 - 5:00 p.m.

Tu3-1 **Wiggler Magnet for FEL Low Voltage Operation**
Al-Shamma'a, A., Stuart, R.A., Lucas, J.

Tu3-2 **Combined Electromagnetic and Permanent Magnet Undulator to Achieve Higher Field and Easier Field Variation Without Mechanical Movement**
Bogachenkov, V.A., Papadichev, V.A.

Tu3-3 **Initial Studies of Bremsstrahlung Energy Deposition in Small-Bore Superconducting Undulator Structures in Linac Environments**
Cremer, T., Tatchyn, R.

Tu3-4 **FEL Undulators with the Hollow-Ring Electron Beam**
Epp, V., Bordovitsyn, V., Kozhevnikov, A., Zalmezh, V.

Tu3-5 **Hybrid Undulator Numerical Optimization**
Hairetdinov, A.H., Zukov, A.A.

Tu3-6 **Advanced Optimization of Permanent Magnet Wigglers Using a Genetic Algorithm**
Hajima, R.

Tu3-7 **A Helical Optical Klystron for Circular Polarized UV-FEL Project at the UVSOR**
Hama, H.

Tu3-8 **A New Undulator for the Extension of the Spectral Range of the CLIO FEL**
Marcouille, O., Berset, J.M., Glotin, F., Jarozinsky, D., Prazeres, R., Ortega, J.M.

Tu3-9 **Performance of an Undulator for Visible and UV FELs at FELI**
Miyauchi, Y., Zako, A., Koga, A., Suzuki, T., Tomimasu, T.

Tu3-10 **Coherent Harmonic Production Using a Two-Section Undulator FEL**
Jaroszynski, D.A., Prazerse, R., Glotin, F., Marcouillet, O., Ortega, J.M., Oepts, D., van der Meer, A.F.G., Knippels, G., van Amersfoort, P.W.

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Tu3-57 **A Table-Top X-Ray FEL Based on Laser Wakefield Accelerator-Undulator System**
Nakajima, K., Kawakubo, T., Nakanishi, H., Ogata, A.

Tu3-58 **About the Scheme of the Infrared FEL System for the Accelerator Based on HF Wells**
Kabanov, V.S., Dzergach, A.I.

Tu3-59 **Nonlinear Resonances in a Multi-Stage Free-Electron Laser Amplifier**
Hashimoto, S., Takayama, K.

Tu3-60 **Picosecond Pulses of Coherent MM-Wave Radiation in a Photoinjector-driven Waveguide Free-Electron Laser**
Fochs, S.N., LeSage, G.P., Feng, H.X.C., Laurent, L.Rosenau, S., Umstattd, R., Hartemann, F.V., Heritage, J.P., Luhmann, N.C.

Tu3-61 **Broadband Short Pulse Measurement by Autocorrelation with a Sum-Frequency Generation Set-Up**
Glotin, F., Jaroszynski, D., Marcouille, O., Ortega, J.M., Peremans, A., Prazeres, R.

Tu3-62 **Three-Dimensional Study of the Multi-Cavity FEL**
Krishnagopal, S., Kumar, V.

Tu3-63 **A Compact FEL Upconverter of Coherent Radiation**
Liu, Y., Marshall, T.C.

Tu3-64 **Wavelength Switching in an Optical Klystron**
Berryman, K.W., Smith, T.I.

Tu3-65 **Coherent Undulator Radiation of Electron Beam, Microbunched for the FEL Power Outcoupling**
Kulipanov, G.N., Sokolov, A.S., Vinokurov, N.A.

Tu3-66 **New Method of Beam Bunching in Free-Ion Lasers**
Bessonov, E.G.

Tu3-67 **Superradiance of Short Electron Pulses in Regular and Corrugated Waveguides**
Ginzburg, N.S., Konoplev, I.V., Shpak, V.G., Shunailov, S.A., Sergeev, A.S., Yalandin, M.I., Zotova, I.V.

Tu3-68 **The Role of Radiation Reaction in Lienard-Wiechert Description of FEL Interaction**
Kimel, I., Elias, L.R.

Tu3-69 **Application of the Green Function Formalism to Nonlinear Evolution of the Low Gain FEL Oscillator**
Shvets, G., Wurtele, J.S., Gardent, D., Ishii, S.

Tu3-70 **"Optical Guiding" Limits on Extraction Efficiences of Single-Pass, Tapered Wiggler Amplifiers**
Fawley, W.M.

Tu3-71 **High-Gain Optical Cherenkov Oscillator Driven by Low-Voltage Electron Beam**
Smetanin, I.V., Oraevsky, A.N.

Tu3-72 **Compact FELs Based on Slow Wave Wigglers**
Riyopoulos, S.

Tu3-73 **Resonance Hard Radiation in a Gas-Loaded FEL**
Gevorgian, L.A.

Tu3-74 **Z-Discharge Free Electron Laser**
Schep, T.J., Bazylov, V.A., Tulupov, A.V.

Tu3-75 **On the Origin of the Coherent X-Ray Radiation from Plasma Focus**
Zhevago, N.K., Glebov, V.I.

Tu3-76 **Gain Enhancement of Plasma-Loaded FEL in the Presence of Beat Waves**
Shamamian, A.H., Gevorgian, L.A.

Tu3-77 **Acoustic Analog of a Free-Electron Laser**
Zavtrak, S.T.

Tu3-78 **On Use of Time-Dependent Microwave Fields to Increase an FEL Oscillator Efficiency**
Saldin, E.L., Schneidmiller, E.A., Yurkov, M.V.

Tu3-79 **Coherent Sase with Electron Beams Prebunched in a Masked Chicane**
Nguyen, D.C., Carlsten, B.E.

Tu3-80 **Measurements and Simulation of the Radiation Build-up Process in a Prebunched Maser Oscillator**
Gilutin, L., Pinhasi, Y., Cohen, M., Yakover, I.M., Eichenbaum, A., Gover, A., Levush, B., Antonsen, T.M., Granatstein, V.L.

Tu3-81 **Experience on the Operation of the 2-in-1 Electromagnetic Undulator of FELICITA I**
Geisler, A., Nolle, D., Ridder, M., Schmidt, T.

Tu3-82 **Optical Aspects for Lasing in the Visible and UV with FELICITA I**
Schmidt, T., Geisler, A., Nolle, D., Ridder, M.

Tu3-83 **Picosecond Pump Probe Using an FEL and a Synchrotron Source**
Denbeaux, G., Straub, K.D., Madey, J.M.J., O'Shea, P.G., Litvinenko, V., Szarmes, E., Barnette, G.

Wednesday, August 23, 1995
Poster Session
8:00 - 12:00 noon

Wel-1 **Source Challenges Resulting of the First Applications of a UV Storage Ring FEL on Super-ACO**
Couprie, M.E., Bakker, R., Delboulbé, A., Garzella, D., Nahon, L., Marsi, M., Merola, F., Hara, T., Billardon, M.

Wel-2 **Plans for a Far-Infrared Free-Electron Laser in India**
Krishnagopal, S., Kumar, V., Ramamurthi, S.S.

Wel-3 **Construction and Development of a UV Free Electron Laser Under the Cooperation of Nihon U, KEK, PNC, ETL and Tohaku U.**
Hayakawa, K., Tanaka, T., Torizuka, Y., Sato, K., Matsubara, Y., Kawakami, I., Sato, I., Fukuda, S., Kurihara, T., Kamitani, T., Ohsawa, S., Enomoto, A., Toyama, S., Nomura, M., Yamazaki, Y., Yamazaki, T., Yamada, K., Ikezawa, M., Sibata, Y., Oyamada, M.

Wel-4 **Optical Wavelength Modulation in Free Electron Lasers**
Mabe, R.M., Wong, R.K., Colson, W.B.

Wel-5 **Vibrational Spectroscopy at Interfaces by IR-VIS Sum-Frequency Generation Using CLIO FEL**
Peremans, A., Tadjeddine, A., WanQuan, Z., Guyot-Sionnest, P., Buck, M., Remy, P., Ryschenkow, G., Caudano, Y., Li-Ming, Y., Thiry, P., Dumas, P., Bourguignon, B., Dubost, H., Draggnea, B., Carrez, S.

Wel-6 **FEL Beam Sharing Systems for Eight User's Stations of the FELI**
Okuma, S., Saeki, K., Kobayashi, A., Oshita, E., Wakita, K., Yasumoto, M., Tomimasu, T.

Wel-7 **Temporal and Spectral Evolution of a Storage Ring FEL Source: Experimental Results on Super-ACO and New Theoretical Approach**
Hara, T., Couprie, M.E., Billardon, M.

Wel-8 **Compton Backscattering of Intracavity Storage Ring Free-Electron Laser Radiation**
Dattoli, G., Giannessi, L., Torre, A., Altobelli, G., Gallardo, J.

Wel-9 **Gain Narrowing of Temporal and Spectral Widths in the UVSOR-FEL**
Kimura, K., Yamazaki, J., Takano, S., Kinoshita, T., Hama, H.

Wel-10 **Resonant Condition for Storage Ring Short Wavelength FEL with Power Exceeding Renieri Limit**
Litvinenko, V.N., Burnham, B., Wu, Y.

Wel-11 **On the Spectrum of Optical Klystron in the Oscillations Mode**
Kayran, D.A., Vinokurov, N.A.

Wel-12 Withdrawn

Wel-13 **Magnetic Beam Position Monitor**
Varfolomeev, A.A., Ivanchenkov, S.N., Khlebnikov, A.S., Osmanov, .S., Tolmachev, S.V.

Wel-14 **The Primary Test of Measuremental System for the Actual Emittance of Relativistic Electron Beams**
Fu, L., Du-T-b., Chen, X., Liu, N-q.

Wel-15 **Beam Extraction Experiment with Field-Emission Arrays**
Ishizuka, H., Watanabe, A., Shiho, M., Kawasaki, S., Itoh, J., Yokoo, K.

Wel-16 **A Method of Forming a High-Quality Electron Beam for Free Electron Masers**
Samsonov, S.V., Bratman, V.L., Manuilov, V.N.

Wel-17 **A New Beam Source for Free Electron Lasers**
Wang, M.C., Wang, Z.J., Zhu, J.B., Zhang, L.F., Huang, Y., Lee, J.K.

Wel-18 **High-Power, High-Brightness Pseudospark-Produced Electron Beam Driven by Improved Pulse Line Accelerator**
Zhu, J., Wang, M., Wang, Z., Zhang, L.

Wel-19 **Carbon-Fiber Low-Voltage Electron Guns**
Drori, R., Jerby, E.

Wel-20 **Strategies for Minimizing Emittance Growth in High Charge CW FEL Injectors**
Liu, H.

Wel-21 **A Photocathode RF Gun for X-Ray FEL**
Wang, X.J., Palmer, D.T., Batchelor, K., Ben-Zvi, I., Miller, R., Winick, H., Woodle, M.H.

Wel-22 **Next Linear Collider Test Accelerator Injector Upgrade**
Yeremian, A.D., Miller, R.H.

Wel-23 **An Experimental Study on Microwave Electron Gun**
Wang, G., Tang, C., Wu, Y., Wang, Y., Xie, J.

Wel-24 **Progress in the Injector for FEL at CIAE**
Yang, T., Zhou, W., Fu, S., Shi, X., Ma, Y., Shi, Y., Liu, W.

Wel-25 **Beam Transport for an SRF Recirculating-Linac FEL**
Neuffer, D., Douglas, D., Li, Z., Cornacchia, M., Garren, A.

Wel-26 **Current Status of the Superconducting RF Linac Driver for the JAERI Free Electron Laser Facility**
Minehara, E.J.,Sugimoto, M., Sawamura, M., Nagai, R., Kikuzawa, N.

Wel-27 **Sensitivity and Alternative Operating Point Studies on a High Charge CW FEL Injector Test Stand at CEBAF**
Liu, H., Kehne, D., Benson, S., Merminga, L., Neil, G., Neuffer, D., Sinclair, C.

Wel-28 **The Mark III IR FEL: Improvements in Performance and Operation**
Barnett, G.A., Madey, J.M.J., Straub, K.D., Szarmes, E.B.

Wel-29 **SSRL Photocathode RF Gun Test Stand**
Hernandez, M., Baltay, M., Bamber, C., Boyce, R., Fisher, A., Melissinos, A., Meyerhofer, D., Miller, R., Palmer, D., Weaver, J., Wiedemann, H., Winick, H.

Wel-30 **High Power Testing of a 17 GHz Photocathode RF Gun**
Chen, S.C., Danly, B.G., Gonichon, J., Lin, C.L., Temkin, R.J., Trotz, S., Wurtele, J.S.

Wel-31 **A Compact High-Gradient 25 MeV 17 GHz RF Linac for Free-Electron Laser Research**
Danly, B.G., Chen, S.C., Kreischer, K.E., Temkin, R.J., Trotz, S., Haimson, J., Mecklenburg, B.

Wel-32 **E-Beam Dynamics Calculations and Comparison with Measurements for a High Duty Accelerator at Boeing**
Parazzoli, C.G., Dowell, D.H.

Wel-33 **The Boeing Photocathode Accelerator Magnetic Pulse Compression and Energy Recovery Experiment**
Dowell, D.H., Adamski, J.L., Hayward, T.D., Vetter, A.M.

Wel-34 **Longitudinal Phase Space Experiments on the ELSA Photoinjector**
Dowell, D.H., Joly, S., deBrion, J.P., Haouat, G., Loulergue, A.

Wel-35 **GHz Repetition Rate Tabletop X-Band Photoinjector for Free-Electron Laser Applications**
LeSage, G.P., Fochs, S.N., Feng, H.X.C., Laurent, L., Rosenau, S., Umstattd, R., Hartemann, F.V., Heritage, J.P., Luhmann, N.C.

Wel-36 **The Spartial Distribution of the Particles of the Beam Interacting with an Inhomogenous Electromagnetic Wave**
Serov, A.V.

Wel-37 **The Spectral-Angular and Polarization Characteristics of Radiation from an Electron Beam Traversing an Inhomogeneous Electromagnetic Wave**
Koltsov, A.V., Serov, A.V.

Wel-38 **Lattice Design of a Quasi-Isochronous Ring for a Storage Ring FEL**
Ohgaki, H., Robin, D., Yamazaki, T.

Wel-39 **The Performance of the Duke FEL Storage Ring**
We, Y., Burnham, B., Litvinenko, V.N., Madey, J.M.J., O'Shea, P.G., Park, S.

Wel-40 **A Study of Influence of Stohastic Process on the Synchrotron Oscillations of a Single Electron Circulated in VEPP-3 Storage Ring**
Pinayev, I.V., Popik, V.M., Salikova, T.V., Shaftan, T.V., Sokolov, A.S., Vinokurov, N.A., Vorobyov, P.V.

Wel-41 **Improvement of Current Limitation in the Storage Ring NIJI-IV**
Yokoyama, M., Kawai, M., Mikado, T., Yamada, K., Sei, N., Hamada, S., Sugiyama, S., Ohgaki, H., Noguchi, T., Suzuki, R., Ohdaira, T., Chiwaki, M., Yamazaki, T.

Wel-42 Withdrawn

Wel-43 **A 3 GHz Photoelectron Gun for High Beam Intensity**
Bossart, R., Braun, H., Dehler, M., Godot, J-C.

Wel-44 **Cyclotron Resonance Cooling by Strong Laser Field**
Taguchi, T., Mima, K.

Wel-45 **Diagnostics and Electron-Optics of a High Current Beam in the TANDEM Free Electron Laser - Status Report**
Arensburg, A., Avramovich, A., Chairman, D., Cohen, M., Draznin, M., Gover, A., Kleinman, H., Pinhasi, Y., Sokolowski, J.S., Shterngartz, V., Yakover, I.M., Levin, L.A., Shahal, O., Rosenberg, A., Shiloh, J., Schnitzer, I.

Wel-46 **Diffraction and Pulse Slippage in the Boeing 1 KW FEL Oscillator**
Blau, J., Wong, R.K., Colson, W.B.

Wel-47 **The Trapped-Particle Instability in the Boeing 1 KW FEL Oscillator**
Ramos, L., Blau, J., Colson, W.B.

Wel-48 **Energy Stability in a High Average Power FEL**
Merminga, L., Bisognano, J., Delayen, J.

Wel-49 **Electron Beam Effects in a UV FEL**
Wong, R.K., Blau, J., Colson, W.B.

Wel-50 **Multi-Stage FEL Amplifier with Diaphragm Focusing Line as Direct Energy Driver for Inertial Confinement Fusion**
Saldin, E.L., Sarantsev, V.P., Schneidmiller, E.A. Ulyanov, Yu.N., Yurkov, M.V.

Wel-51 **Analysis of the Eigenvalue Equation of the FEL Amplifier with Axisymmetric Electron Beam and Diaphragm Focusing Line**
Saldin, E.L., Schneidmiller, E.A., Ulyanov, Yu.N., Yurkov, M.V.

Wel-52 **Structure of the Spontaneous Emission Spectra of a High-γ Free Electron Lasers as Measured at the Darmstadt (S-DALINAC) FEL**
Renz, G., Spindler, G., Schlott, V., Hahn, R.

Wel-53 **On a Theory of an FEL Oscillator with Multicomponent Undulator**
Saldin, E.L., Schneidmiller, E.A., Yurkov, M.V.

Wel-54 **Some Novel Features of an FEL Oscillator with Tapered Undulator**
Saldin, E.L., Schneidmiller, E.A., Yurkov, M.V.

Wel-55 **Nonlinear Theory of a Plasma Cherenkov Maser**
Choi, J.-S., Heo, E.-G., Hong, B.-H., Choi, D.-I.

Wel-56 **Nonlinear Saturation Characteristics of a Dielectric Cherenkov Maser**
Choi, J.-S., Heo, E.-G., Hong, B.-H., Choi, D.-I.

Wel-57 **The Magnetoresonance Operation of Microwiggler on the Piezoelectrics with a Strong Magnetic Guide Field**
Choi, J.-S., So, C.-H., Moon, J.-D., Chung, H.-T., Heo, E.-G.

Wel-58 **Design of a Demonstration Experiment on the Wide-Bandwidth High-Power Dielectric Cherenkov Maser Amplifier**
Harin, V., Melnikov, G., Shlapakovskii, A.

Wel-59 **Mode Competition and Mode Control in Free Electron Lasers with One and Two Dimensional Bragg Resonators**
Peskov, N.Yu., Ginzburg, N.S., Phelps, A.D.R., Robb, G.R.M., Sergeev, A.S.

Wel-60 **Development of a High Average Power, CW, MM-Wave FEL**
Ramian, G.

Wel-61 **Lightning Control System Using High Power Microwave FEL**
Shiho, M., Watanabe, A., Kawasaki, S., Ishizuka, H., Fujioka, T.

Wel-62 **Construction and Testing of the 1 MW, 130-260 GHz Fusion FEM**
Urbanus, W.H., Bongers, W.A., van Dijk, G., van der Geer, C.A.J., van Honk, A.G.R.J.E., Manintveld, P., Sterk, A.B., Valentini, M., Verhoeven, A.G.A., Weijman, R.M.M., van der Wiel, M.J., Varfolomeev, A.A., Ivanchenkov, S.N., Khlebnikov, A.S., Bratman, V.L., Denisov, G.G., Caplan, M.

Wel-63 **First Operation of a Dielectric Loaded Double-Stripline Free Electron Maser Experiment**
Einat, M., Jerby, E., Shahadi, A.

Wel-64 **Beam Quality and Wavelength Limitation in Visible and UV FEL Oscillations**
Tomimasu, T.

Wel-65 **Optical Properties of Mid-Infrared FELs from the FELI Facility I**
Kobayashi, A., Okuma, S., Oshita, E., Wakita, K., Saeki, K., Suzuki, T., Yasumoto, M., Tomimasu, T.

Wel-66 **"Hot"-Electron Laser Using a Bragg Reflection of Electrons**
Malov, Yu.A., Babazhan, E.I.

Wel-67 **New Results of the "CLIO" Infrared FEL Using the New Undulator "OMIR" and a Hole Coupling Extraction**
Prazeres, R., Berset, J.M., Glotin, F., Jaroszynski, D., Marcouillé, O., Ortega, J.M.

Wel-68 **Report on First Masing and Single Mode Locking in a Prebunched Beam FEM Oscillator Operating in the Collective Regime**
Cohen, M., Eichenbaum, A., Kleinman, H., Arbel, M., Yakover, I.M., Gover, A.

Wel-69 **Optical Properties of Infrared FELs from the FELI Facility II**
Saeki, K., Okuma, S., Oshita, E., Wakita, K., Kobayashi, A., Suzuki, T., Yasumoto, M., Tomimasu, T.

Wel-70 **First Lasing, Capabilities and Flexibility of FIREFLY**
Berryman, K.W., Smith, T.I.

Wel-71 **First Lasing of the KAERI MM-Wave Free Electron Laser**
Lee, B.C., Joung, Y.U., Cho, S.O., Kim, S.K., Lee, J.

Wel-72 **Progress of the Commissioning of the Delta Storage Ring FEL Facility**
Nolle, D., Geisler, A., Ridder, M., Schmidt, T.

Wel-73 **Non-Destructive Diagnosis of Relativistic Electron Beams Using a Short Undulator**
Ponds, M.L., Feng, Y., Madey, J.M.J., O'Shea, P.G.

Thursday, August 24, 1995

FEL Technology

8:30 - 8:40	Th1	**Introductory Remarks - Session Chair** M.E. Couprie
8:40 - 8:55	Th1 - 1	**Advances in Undulator Technology at STI Optronics** Robinson, K.E., Gottschalk, S.C., Quimby, D.C., Shemwell, D.M.
8:55 - 9:10	Th1 - 2	**Characteristics of the MIT Microwiggler for Free Electron Laser Applications** Catravas, P., Stoner, R., Bekefi, G.
9:10 - 9:25	Th1 - 3	**Multi-Order Harmonic Lasing with a Modified Wiggler** Asakawa, M., Nakao, N., Ishida, T., Watanabe, T., Yasuda, E., Fujita, M., Chen, J., Moon, A., Roy, P.K., Kuruma, S., Imasaki, K., Mima, K., Ohigashi, N., Tsunawaki, Y., Nakai, S., Yamanaka, C.
9:25 - 9:40	Th1 - 4	**Optical Alignment and Diagnostics for the ATF Microundulator FEL Oscillator** Babzien, M., Ben-Zvi, I., Catravas, P., Fang, J.-M., Fisher, A., Graves, W.S., Qiu, X., Segalov, Z., Wang, X.J.
9:40 - 9:55	Th1 - 5	**The ENEA F-Cube Facility: Trends in RF Driven Compact FELs and Related Diagnostics** Doria, A., Gallerano, G.P., Giovenale, E., Kimmitt, M.F., Messina, G.
9:55 - 10:30	*Coffee Break*	

Thursday, August 24, 1995 (continued)

New Directions

10:30 - 10:40	Th2	**Introductory Remarks - Session Chair** C. Pellegrini
10:40 - 10:55	Th2 - 1	**Observation of Enhanced Compton Scattering in a Supercavity** Fujita, M., Moon, A., Asakuma, T., Minamiguchi, T., Asakawa, M., Chen, J., Imasaki, K., Yamanaka, C., Roy, P.K., Mima, K., Nakai, S., Nakao, N., Ishida, T., Yasuda, E., Watanabe, T., Ohigashi, N., Tsunawaki, Y., Yamazaki, Y., Sakuma, M.
10:55 - 11:10	Th2 - 2	**Inverse Compton Gamma-Ray Source for Nuclear Physics and Related Applications** O'Shea, P.G., Litvinenko, V.N., Madey, J.M.J., Roberson, N.R., Schreiber, E.C., Straub, K.D., Weller, H.R., Wu, Y.
11:10 - 11:25	Th2 - 3	**An FEL Design for Gamma-Gamma Colliders Based on Chirped Pulse Amplification Techniques** Kim, K.-J., Xie, M., Sessler, A.M.
11:25 - 11:40	Th2 - 4	**Coherent Spontaneous Radiation From Highly Bunched Electron Beams** Berryman, K.W., Crosson, E.R., Ricci, K.N., Smith, T.I.
11:40 - 11:55	Th2 - 5	**Stimulated Coherent Emission From Short Electron Bunches in Free Space** Robb, G.R.M., Ginzburg, N.S., Phelps, A.D.R., Sergeev, A.S
11:55 - 12:10	Th2 - 6	**Sideband Elimination and High Efficiencies in a Strongly Tapered FEL Amplifier** Bhattacharjee, A., Chen, J.
12:10 - 12:25	Th2 - 7	**High-Gradient Acceleration of Electrons in a Plasma Loaded Wiggler** Maroli, C., Petrillo, V.
12:25 - 2:00	*Lunch*	

Thursday, August 24, 1995
Poster Session
2:00 - 5:00 p.m.

Th3-1 **Saturation and Pulsed FEL Dynamics**
Giannessi, L., Mezi, L.

Th3-2 **Theoretical Analysis of Advanced Schemes for Free Electron Laser with a Large μ_c**
Zhulin, V.I., Zanadvorov, N.P.

Th3-3 **Deliberate Misalignment in Free Electron Lasers with a Hole Coupling**
Zhulin, V.I.

Th3-4 **Evolution of Transverse Modes in FELIX Macropulses**
Weits, H.H., Lin, L.Y., van Werkhoven, G.H.C., Oepts, D., van Amersfoort, P.W.

Th3-5 **Measurement of Characteristics of an Infrared Free-Electron Laser with the L-Band Linac at Osaka University**
Okuda, S., Ishida, S., Honda, Y., Kato, R., Isoyama, G.

Th3-6 **Design Study of a Longer Wavelength FEL for FELIX**
Lin, L., Oepts, D., van der Meer, A.F.G., van Amersfoort, P.W.

Th3-7 **Design of a Far-Infrared CHI Wiggler Free-Electron Laser**
Jackson, R.H.Blank, M.Freund, H.P.Pershing, D.E.Taccetti, J.M.

Th3-8 **Shaping Pulses Using Frequency Conversion with a Modulated Picosecond Free Electron Laser**
Hooper, B.A., Madey, J.M.J.

Th3-9 **On a Theory of an FEL Amplifier with Circular Waveguide and Guiding Magnetic Field**
Saldin, E.L., Schneidmiller, E.A., Yurkov, M.V.

Th3-10 **Efficiency Optimization in a FEL with Fields Nonadiabatic Tapering**
Goncharov, I.A., Belyavskiy, E.D., Silivra, A.A.

Th3-11 **High-Efficiency FEL Oscillator with Bragg Resonator Operated in Reversed Guide Field Regime**
Kaminsky, A.K., Bogachenkov, V.A., Ginzburg, N.S., Kaminsky, A.A., Peskov, N.Yu., Sarantsev, V.P., Sedykh, S.N., Sergeyev, A.P., Sergeyev, A.S.

Th3-12 **Velocity Distributions Produced by a Thermionic Electron Gun and the Effect on the Performance of a Cerenkov FEL**
Van der Slot, P.J.M., Voronin, V.S.

Th3-13 **Simulations of the Performance of the Fusion-FEM, for an Increased e-Beam Emittance**
Tulupov, A.V., Urbanus, W.H., Caplan, M.

Th3-14 **Orbital Motion in Generalized Static Fields of FELs Accounting for Axial Magnetic Field, Beam Forces, Undulator and External Focusing**
Papadichev, V.A.

Th3-15 **Distorted Orbit Due to Field Errors and Particle Trajectories in Combined Undulator and Axial Magnetic Field**
Papadichev, V.A.

Th3-16 **A Comparison of Various Schemes of Beam Conditioning for FEL**
Papadichev, V.A.

Th3-17 **Vortices in the Electron Beams in the Inhomogeneous Undulator Magnetic Field**
Golub, Y., Rozanov, N.E.

Th3-18 **Investigation of Electron Beam Transport in a Helical Undulator**
Jeong, Y.U., Lee, B.C., Kim, S.K., Cho, S.O., Lee J.

Th3-19 **Microwave Axial Free-Electron Laser with Enhanced Phase Stability**
Carlsten, B., Fazio, M., Haynes, W., May, L., Potter, J.

Th3-20 **JINR Test Facility for Studies FEL Bunching Technique for CLIC Driving Beam**
Dolbilov, G.V., Delahaye, J.P., Fateev, A.A., Ivanov, I.N., Johnson, C.D., Kaminskky, A.A., Daminskky, A.K., Lebedev, N.I., Petrov, V.A., Sedykh, S.N., Sergeev, A.P., Yurkov, M.V.

Th3-21 **Self Fields in Free Electron Lasers**
Roberson, C.W., Hafizi, B.

Th3-22 **Influence of Static Electron Beam's Self-Fields on the Cyclotron-Undulator Resonance**
Rozanov, N.E., Golub, Y.Y.

Th3-23 **Spectral Dynamics of a Collective Free Electron Maser**
Eecen, P.J., Schep, T.J., Tulupov, A.V.

Th3-24 **Space Charge Field in a FEL with Axially Symmetric Electron Beam**
Goncharov, I.A., Belyavskiy, E.D.

Th3-25 **Design of a 'Slow Wave' Ubitron**
Pershing, D.W., Jackson, R.H., Freund, H.P., Blank, M., Taccetti, J.M.

Th3-26 **Theory of Spontaneous and Stimulated Radiation from Electrons in a Helical Wiggler with a Guiding Magnetic Field**
Zhevago, N.K., Glebov, V.I.

Th3-27 **2-D Simulation of a Waveguide Free Electron Laser Having a Helical Undulator**
Kim, S.K., Lee, B.C., Jeong, Y.U., Cho, S.O., Lee, J.

Th3-28 **Theory of Low Voltage Annular Beam Free-Electron Lasers**
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Drori, R., Jerby, E., Shahadi, A., Sheinin, M.

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Yakover, I.M., Pinhasi, Y., Gover, A.

Th3-44 **Study of the Smith-Purcell Effect in the Relativistic Regime**
Doucas, G., Dumitru, M., Kimmitt, M.F., Korschinck, G., Stan-Sion, C., Goldstein, M., Woods, K.J., Wash, J.E.

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Woods, K.J., Walsh, J.E.

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Goldstein, M., Walsh, J.E.

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Walsh, J.E., Woods, K.J., Kirk, H.G., Fernow, R.C.

Th3-48 **Van der Pol Model of a Cerenkov Maser**
Kleckner, M., Ron, A., Botton, M.

Th3-49 **Harmonic Generation in VUV/X-Ray Range at the Duke Storage Ring FEL Using Electron Beam Outcoupling**
Litvinenko, V.N., Burnham, B., Madey, J.M.J., Park, S.H., Wu, Y.

Th3-50 **Predicted Performance of a Multi-Section VUV FEL with the Amsterdam Pulse Stretcher and Storage Ring Amps**
Bazylev, V.A., Pitatelev, M.I., Tulupov, A.V., Luijckx, G., Maas, R., van Amersfoort, P.W.

Th3-51 **Parameter Study of the VUV-FEL at the Tesla Test Facility**
Brefeld, W., Faatz, B., Pierini, P., Saldin, E.L., Schneidmiller, E.A., Yurkov, M.V.

Th3-52 **Parametric X-Ray FEL Operating with External Bragg Reflectors**
Baryshevsky, V.G., Batrakov, K.G., Dubovskaya, I., Ya.

Th3-53 **Limiting Parameters of the X-Ray Lasers**
Bessonov, E.G.

Th3-54 **Optical Cavity and Electron Beam Requirements for the Operation of a 1.5 Å LCLS in a Regenerative Amplifier Mode**
Tatchyn, R.

Th3-55 **Non-Wiggler Averaged Theory of Short Wavelength Free-Electron Lasers**
Freund, H.P.

Th3-56 **Effects of Undulator Interruptions on the Performance of High-Gain FEL Amplifiers**
Kim, K.J., Xie, M., Pelligrini, C.

Th3-57 **Numerical Simulations of X-Ray Generation in Multisectional FELs**
Pitatelev, M.M.

Th3-58 **Strong Focusing Influence on High Gain FEL Characteristics**
Smirnov, A., Varfolomeev, A.

Th3-59 **Radiation from Relativistic Electron Beams in Periodic Structures**
Babzien, M., Batchelor, K., Ben-Zvi, I., Bekefi, G., Blastos, J., Catravas, P., Fang, J., Fisher, A., Graves, W., Marshall, T., Segalov, Z., Sisson, D., Stoner, R., Qin, X.Z., Wang, X.J.

Th3-60 **FEL Gain as a Function of Phase Displacements Induced by Undulator Intersection Gaps**
Varfolomeev, A.A.

Th3-61 **Scaling Formulae for FEL Operating in Linear and Non Linear Regime**
Dattoli, G., Mezi, L., Segreto, A., Torre, A

Th3-62 **Longitudinal and Transverse Mode Evolution in Free Electron Laser**
Dattoli, G., Giannessi, L., Georgii, R., Torre, A., Segreto, A.

Th3-63 **Simulation of the Short Pulse Effects in the Start-Up From Noise in High-Gain FELs**
Hahn, S.J., Kim, K.J.

Th3-64 **Shot Noise Startup of the 6 nm SASE FEL at the TESLA Test Facility**
Pierini, P., Fawley, W.M.

Th3-65 **Self-Consistent Analysis of Radiation and Relativistic Electron Beam Dynamics in a Helical Wiggler Using Lienard-Wiechert Fields**
Tecimer, M., Elias, L.R.

Th3-66 **Criterion of Transverse Coherence of Self-Amplified Spontaneous Emission in High Gain Free Electron Laser Amplifiers**
Xie, M., Kim, K.J.

Th3-67 **Transverse Effects in UV FELs**
Small, D.W., Wong, R.K., Colson, W.B.

Th3-68 **Ultrahigh Harmonics Generation in a FEL with a Seed Laser**
Goloviznin, V.V., van Amersfoort, P.W.

Th3-69 **Small-Signal Gain in a Gas-Loaded FEL**
Goloviznin, V.V., van Amersfoort, P.W.

Th3-70 **Design Optimization and Transverse Coherence Analysis for an X-Ray Free Electron Laser Driven by SLAC Linac**
Xie, M.

Th3-71 **Step-Tapered Operation of the FEL: Efficiency Enhancement and Two-Colour Operation**
Jaroszynski, D.A., Prazeres, R., Glotin, F., Marcouillet, O., Ortega, J.M., Oepts, D., van der Meer, A.F.G., Knippels, G., van Amersfoort, P.W.

Th3-72 **Half-Period Optical Pulse Generation Using a Free-Electron Laser**
Jaroszynski, D.A., Chaix, P., Piovella, N.

Friday, August 25, 1995

Challenging Research at FELs
Session Chair: G.S. Edwards

8:30 - 9:00	Fr1-1	**Terahertz Quantum Transport in Semiconductor Nanostructures with the UCSB Free Electron Lasers** Allen, J.
9:00 - 9:30	Fr1-2	**Title to be Announced** B. Noordam
9:30 - 10:00	Fr1-3	**Energy Transfer at the Active Sites of Heme Proteins** Dlott, D.D., Hill, J.R.
10:00 - 10:30	*Coffee Break*	

Friday, August 25, 1995 (continued)

FEL Facility Challenges

10:30 - 10:40	Fr2	**Introductory Remarks - Session Chair** Allen, J.
10:40 - 11:05	Fr2 - 1	**Challenges at FEL Facilities: The Stanford Picosecond FEL Center** Schwettman, H.A..
11:05 - 11:30	Fr2 - 2	**Activities of the CLIO Infrared Facility** Ortega, J.M., Berset, J.M., Chaput, R., Glotin, F., Humbert, G., Jaroszynski, D., Joly, P., Kergosien, B., Lesrel, J., Marcouille, O., Peremans, A., Prazeres, R., Taddjedine, A.
11:30 - 11:55	Fr2 - 3	**Commissioning the FELI Linac and UV-FEL Facility** Tomimasu, T., Saeki, K., Miyauchi, Y., Suzuki, T., Oshita, E., Okuma, S., Wakita, K., Kobayashi, A., Zako, A., Nishihara, S., Koga, A., Ogino, S., Nishimura, E., Mitsuyu, T., Wakisaka, K., Tongu, E., Nagai, A., Yasumoto, M.
11:55 - 12:20	Fr2 - 4	**The Research Facilities of the Duke FEL Laboratory - Uniqueness and Challenges** Madey, J.M.J., Barnett, G., Burnham, B., Litvinenko, V.N., O'Shea, P.G., Straub, K.D., Szarmes, E., Wu, Y.
12:20 - 12:30		Closing Remarks

DYNAMICAL ASPECTS ON FEL INTERACTION IN SINGLE PASSAGE AND STORAGE RING DEVICES

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The dynamical behaviour of the free-electron lasers is investigated using appropriate scaling relations valid for devices operating in the low and high gain regimes, including saturation. The analysis is applied to both single passage and storage ring configurations. In the latter case the interplay between the interaction of the electron beam with the laser field and with the accelerator environment is investigated. In particular we discuss the effect of FEL interaction on the microwave instability.

FIRST LASING, CAPABILITIES, AND FLEXIBILITY OF FIREFLY[1]

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FIREFLY is a free electron laser that was designed to produce picosecond pulses of light in the range between 15 and 100 microns. It uses an inexpensive electromagnetic wiggler and variable outcoupling to provide maximum flexibility for user experiments. FIREFLY first lased on November 23, 1994, and has now operated from 15 to 65 microns. It has lased in both a traditional undulator configuration and as an optical klystron, and has also lased on the third harmonic between 9 and 11 microns. We present measurements of optical spectral width and pulse width at a range of wavelengths in both configurations. We also compare direct measurements of electron beam extraction efficiency with observed optical power for fundamental, third harmonic, and optical klystron operation. We discuss wavelength switching between adjacent peaks in the gain spectrum of an optical klystron, observed for the first time in FIREFLY.[1] Finally, we focus on issues relevant to experimentation with FIREFLY, including continuously variable outcoupling, optical mode quality, and beam handling in the far-infrared.

[1] K.W. Berryman and T.I. Smith, "Wavelength Switching in an Optical Klystron," these proceedings.

[1] Work supported in part by the Office of Naval Research, Grant No. N00014-94-1-1024.

OPTICAL PROPERTIES OF INFRARED FELs FROM THE FELI FACILITY II

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The FELI Facility II has succeeded in infrared FEL oscillation at 1.91 μm using a 68-MeV, 40-A electron beam from the FELI S-band linac in Feb. 27, 1995. The FELI Facility II is composed of a 3-m vertical type undulator (λ_u=3.8cm, N=78, K_{max}=1.4, gap length≧20mm) and a 6.72-m optical cavity. It can cover the wavelength range of 1-5 μm. The FELs can be delivered from the optical cavity to the diagnostics room through a 40-m evacuated optical pipeline. Wavelength and cavity length dependences of optical properties such as peak power, average power, spectrum width, FEL macropulse, FEL transverse profile are reported.

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FIRST LASING OF THE KAERI MILLIMETER-WAVE FREE ELECTRON LASER

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The millimeter-wave FEL program at KAERI aims at the generation of high-power CW laser beam with high efficiency at the wavelength of 3~10 mm for the application in plasma heating and in power beaming. In the first oscillation experiment, the FEL has lased at the wavelength of 10 mm with the pulsewidth of 10~30 μs. The peak power is about 1 kW. The FEL is driven by a recirculating electrostatic accelerator having tandem geometry[1]. The energy and the current of the electron beam are 400 keV and 2 A, respectively. The FEL resonator is located in the high-voltage terminal and is composed of a helical undulator, two mesh mirrors, and a cylindrical waveguide. The parameters of the permanent-magnet helical undulator are : period = 32 mm, number of periods = 20, magnetic field = 1.3 kG. At present, with no axial guiding magnetic field, only 15 % of the injected beam pass through the undulator. Transport ratio of the electron beam through the undulator is very sensitive to the injection parameters such as the diameter and the divergence of the electron beam. Simulations show that, with improved injection condition, the FEL can generate more than 50 kW of average power in CW operation. Details of the experiments, including the spectrum measurement and the recirculation of electron beam, are presented.

1. Sung Oh Cho *et al.*, Nucl. Instr. and Meth. A 341 (1994) ABS 55.

REPORT ON FIRST MASING AND SINGLE MODE LOCKING IN A PREBUNCHED BEAM FEM OSCILLATOR

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Radiation characteristics of a table-top free electron maser (FEM) are described in this paper. The FEM employs a prebunched electron beam and is operated as an oscillator in the low-gain collective (Raman) regime. Using electron beam prebunching single mode locking at any one of the possible oscillation modes was obtained.

The electron beam is prebunched by a microwave tube section before it is injected into the wiggler. By tuning the electron beam bunching frequency, the FEM oscillation frequency can be locked to any eigen frequency of the resonant waveguide cavity which is within the frequency band of net gain of the FEM. The oscillation build up process is sped up, when the FEM operates with a prebunched electron beam, and the build-up time of radiation is shortened significantly. First measurements of masing with and without prebunching and characterization of the emitted radiation are reported.

MICROSCOPIC STUDY ON LASING CHARACTERISTICS OF THE UVSOR STORAGE RING FREE ELECTRON LASER

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Characteristics of storage ring free electron laser (SRFEL) at a short wavelength region (UV and visible) has been studied at the UVSOR facility, Institute for Molecular Science. We have measured the laser power evolution by using a biplanar photodiode, and the micro-macro temporal structure of both the laser and the electron bunch with a dual-sweep streak camera.

The saturated energy of the laser micropulse in the gain-switching (Q-switching) mode has been measured as a function of the ring current. We have not observed a limitation of the output power yet within the beam current can be stored. We have analyzed the saturated micropulse energy based on a model of gain reduction due to the bunch-heating. The bunch-heating process seems to be very complicate. We derived time dependent gain variations from the shape of macropulse and the bunch length. Those two gain variations are almost consistent with each other but slightly different in detail. The gain may be not only simply reduced by the energy spread but also affected by the phase space rotation due to synchrotron oscillation of the electron bunch.

As reported in previous issue, the lasing macropulse consists of a couple of micropulses that are simultaneously evolved. From high resolution two-dimensional spectra taken by the dual-sweep streak camera, we noticed considerable internal substructures of the laser micropulse in both the time distribution and the spectral shape. There are a couple of peaks separated with almost same distance in a optical bunch. Such substructure does not seem to result from statistical fluctuations of laser seeds. Although the origin of the substructure of macropulse is not clear at the present, we are going to discuss about SRFEL properties.

Lasing at 300 nm and below: Optical challenges and perspectives

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The FEL experiment in the visible and near UV on the Super ACO storage ring has given, since 1989, important informations on the SRFEL dynamics and, furthermore, a very good beam stability has been achieved. In addition, the operation at 350 nm with this good stability and a long beam lifetime allowed us to perform the first user experiment in biology and to start with a campaign for using the laser as photons source for experiments in other domains, coupling FEL light and the Synchrotron Radiation. For this, FEL starts to be very competitive with respect to the other conventional laser sources, provided that it could oscillate further in the UV, say at 300 nm and below. So, the real challenge is now given by the lasing at shorter wavelengths and, for this, by the optical technology existing nowaday. Since 1992 the efforts have been concentrating to look for every kind of solution allowing us to overcome the problem of having a very low gain. From an optical point of view, in the range of wavelengths explored, there is a lack of transparents dielectric materials for substrates and coatings. Substrates are required at the same time to be relatively not absorbing (a few tens 10^{-6}), to have a very good surface quality (RMS roughness below 10 Å) because of scattering losses dramatically increasing in this spectral range and, due to the thermal load of the undulator emission, to have adequate thermal characteristics. In order to fulfill all these requirements, a good characterisation and modelisation of the substrates is needed, especially to correlate thermal loading and mechanical deformations from one hand, and roughness and scattering losses from the other hand.

Coatings must be not absorbing too and, above all, the most amorphous as possible (this could be obtained with IBS deposition technique), in order to insure a good reproduction of the substrate roughness at the interfaces and on the top layer and an higher resistance to the XUV photons load. Moreover, the high degree of amorphism of the coating could prevent occasional but severe effects of birefringence, which modelisation in correlation with some results will be exposed.

In the actual experiment, the presence of the critical enviroment given by the ultrahigh vacuum operation and by the presence of the broad spectrum and powerful undulator emission reveals a relatively fast degradation of the initial losses of the optical cavity. Some previous works investigated the degradation and losses recovery separately by means of optical and non optical characterisation. Here we try to give a correlation between all the parameters concurring at this degradation process.

The results of this work show that the search for new solutions and technologies for the optical cavities is one of the main challenges for the future of storage ring based FEL experiments, no matter of the amount of gain, in order to have more powerful and flexible (tunability and intracavity devices) laser sources.

DUKE STORAGE RING UV/VUV FEL: STATUS AND PROSPECTS*

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The 1 GeV Duke storage ring was successfully commissioned with parameters exceeding initial specification[1]. The OK-4 FEL has arrived at the Duke FEL laboratory from the Novosibirsk Institute of Nuclear Physics. The OK-4 installation and commissioning is in progress.

In this paper we describe the up-to-date status of the Duke storage ring and the OK-4 FEL. The projected performance of the OK-4 UV/VUV FEL is presented based on the electron beam parameters achieved.

Initial plans to operate the OK-4 UV/VUV FEL at the Duke 1 GeV storage ring are outlined. Future plans and prospects of both the OK-4 FEL and the Duke storage ring are discussed.

*This work supported by ONR grant #N00014-94-1-0818

[1]V. N. Litvinenko, B. Burnham, J. M. J. Madey, Y. Wu, "Commissioning of the Duke Storage Ring", Proc. of the 1995 Particle Accelerator Conference, May 1-5, 1995, Dallas, Texas, USA

PRESENT STATUS OF THE NIJI-IV STORAGE-RING FREE-ELECTRON LASERS

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The tunable region of the free-electron-laser (FEL) wavelength with the NIJI-IV system is now 348~595 nm. After the lasing at 352 nm in 1994, the quality of the electron beam stored in the ring has been improved further, and the highest peak intensity of the laser obtained so far is more than 300 times as high as that of the resonated spontaneous emission. The macro-temporal structure of the lasing has been greatly improved.

Recently, a single-bunch injection system was completed, and the system has been installed in the injector linac, which is expected to increase the peak stored-beam current. The commissioning and the test of the new system is under way. The beam transprting system from the linac to the ring is also being modified by increasing the number of quadrupole magnets. The experiments related to the FEL in the ultraviolet wavelength region will be begun in this coming May.

The results and the status of the FEL experiments will be presented at the Conference.

KINETIC THEORY OF FREE ELECTRON LASERS*

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We have developed a relativistic kinetic theory of free electron lasers (FELs)[1]. The growth rate, efficiency, filling factor and radius of curvature of the radiation wave fronts are determined. We have used the theory to examine the effects of beam compression on growth rate[2]. The theory has been extended to include self field effects on FEL operation. These effects are particularly important in compact, low voltage FELs[3]. The surprising result is that the self field contribution to the beam quality is opposite to the emittance contribution. Hence self fields can improve beam quality, particularly in compact, low voltage FELs.

*Work supported by ONR
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[1] B. Hafizi and C. W. Roberson, Phys. Rev. Lett. **68**, 3539 (1992)
[2] C. W. Roberson and B. Hafizi, Phys. Rev. Lett. **72**, 1654 (1994)
[3] C. W. Roberson and B. Hafizi, IEEE J. Quantum Electron. QE-**27**, 2508 (1991)

EXPERIMENTAL CHARACTERIZATION OF HIGH-BRIGHTNESS BEAM AT THE BROOKHAVEN ACCELERATOR TEST FACILITY

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The high-brightness electron beam produced by the Brookhaven Accelerator Test Facility (ATF) in-line photocathode RF gun was measured. The photocathode RF gun operated reliably at 100 MV/m peak acceleration field, the highest acceleration field achieved is 130 MV/m. The quantum efficiency of the copper cathode was optimized using both laser polarization and Schottky effect, measured quantum efficiency is 4×10^{-4}. The electron beam bunchlength was measured to be less than 11 ps(100%), and the normalize 100% emittance for 0.2 nC charge was measured to be 4.7 mm-mrad. This is the first experimental demonstration of emittance compensation for high gradient photocathode RF gun.

Determination of Electron Bunch Shape using Transition Radiation and Phase-Energy Measurements [1]

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We present data comparing microbunch temporal information obtained from electron beam phase-energy measurements with that obtained from transition radiation auto-correlation measurements[2]. The data was taken to resolve some of the ambiguities in previous transition radiation results. By measuring the energy spectrum of the electron beam as a function of its phase relative to the accelerating field, phase-energy information was extracted. This data was analyzed using tomographic techniques to reconstruct the phase-space distribution assuming an electron energy dependence of $E(\varphi) = E_o + E_{acc}\cos(\varphi)$, where E_o is the energy of an electron entering the field, E_{acc} is the peak energy gain, and φ is the phase between the crest of the RF wave and an electron. Temporal information about the beam was obtained from the phase space distribution by taking the one dimensional projection along the time axis. We discuss the use of this technique to verify other transition radiation analysis methods.

1 Work supported in part by the Office of Naval Research, Grant No. N00014-94-1-1024.

2 E. R. Crosson, *et al.*, Nucl. Instr. Meth. **A358** (1995) 216.

DESIGN AND CHARACTERIZATION OF THE DC ACCELERATION AND TRANSPORT SYSTEM REQUIRED FOR THE FOM 1 MW FREE ELECTRON MASER EXPERIMENT

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A Free Electron Maser (FEM) has been constructed and is soon to be tested at the FOM Institute (Rijnhuizen) Netherlands with the goal of producing 1 MW long pulse to CW microwave output in the range 130 GHz to 250 GHz. The design uses a DC beam system in a depressed collector configuration in order to make the overall wall plug efficiency 50%. The high voltage (~ 2 MeV) power supply provides only the body interception current (~ 30 mA) while the 12 amp beam current is supplied by the 100-200 keV collector supplies. Some of the design features to ensure low interception current, which is critical to long pulse (CW) operation are:

(1) DC beam in-line transport and acceleration system
(2) emittance conserving solenoid focusing system
(3) halo suppression techniques at cathode edge
(4) very low beam fill factor ($\leq$20%)

A relativistic version of the Herman Optical theory developed for microwave tubes is used to determine current distribution functions everywhere along the beam from the electron gun, through the DC accelerator and transport system to the wiggler. This theory takes into account thermals far out on the gaussian tail which translates into beam current far outside the ideal beam edge. This theory is applied to the FOM beam line design to predict a series of beam envelope contours containing various percentages of total beam current up to 99.9%. Predictions of body interception current due to finite emittance (effective temperature) are presented and compared with measured experimental results.

*This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract No. W-7405-Eng-48.

ELECTRON BUNCH LENGTH MEASUREMENT AT THE VANDERBILT FEL

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During the past few years, a number of experiments have been performed to demonstrate the possibility to extract the longitudinal charge distribution from spectroscopic measurements of the coherent far-infrared radiation emitted as transition radiation or synchrotron radiation. Coherent emission occurs in a spectral region where the wavelength is comparable to or longer than the bunch length, leading to an enhancement of the radiation intensity that is on the order of the number of particles per bunch, as compared to incoherent radiation.

This technique is particularly useful in the region of mm and sub-mm bunch lengths, a range where streak-cameras cannot be used for beam diagnostics due to their limited time resolution.

Here we report on experiments that go beyond the proof of principle of this technique by applying it to the study and optimization of FEL performance. We investigated the longitudinal bunch length of the Vanderbilt FEL by analyzing the spectrum of coherent transition radiation emitted by the electron bunches.

By monitoring the bunch length while applying a bunch-compression technique, the amount of the compression could be easily observed. This enabled us to perform a systematic study of the FEL performance, especially gain and optical pulse width, as a function of the longitudinal electron distribution in the bunch. The results of this study will be presented and discussed.

This work was supported by a grant of The Office of Naval Research.

GENERATION OF FREQUENCY-CHIRPED OPTICAL PULSES WITH FELIX

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Frequency-chirped optical pulses have been produced in the picosecond regime by varying the energy of the electron beam on a *micro*second time scale. These pulses were then compressed close to their bandwidth limit by an external pulse compressor. The amount of chirp can be controlled by varying the sweep rate on the electron beam energy and by cavity desynchronisation. To examine the generated chirp we used the following diagnostics: a pulse compressor, a crossed-beam autocorrelator, a multichannel electron spectrometer and a multichannel optical spectrometer. The compressor is build entirely using reflective optics to permit broad band operation. The autocorrelator is currently operating from 6 μm to 30 μm with one single crystal. It has been used to measure pulses as short as 500 fs. All diagnostics are evacuated to prevent pulse shape distortion or pulse lengthening caused by absorption in ambient water vapour.

Pulse length measurements and optical spectra will be presented for different electron beam sweep rates, showing the presence of a frequency chirp. Results on the compression of the optical pulses to their bandwidth limit are given for different electron sweep rates. More experimental results showing the dependence of the amount of chirp on cavity desynchronisation will be presented.

THEORETICAL ANALYSIS OF SATURATION AND LIMIT CYCLES IN SHORT PULSE FEL OSCILLATORS.

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We derive a model for the non linear evolution of a short pulse oscillator from low signal up to saturation in the small gain regime. This system is controlled by only two independent parameters: cavity detuning and losses. Using a closure relation, this model reduces to a closed set of 5 non linear partial differential equations for the EM field and moments of the electron distribution. An analysis of the linearised system allows to define and calculate the eigenmodes characterising the small signal regime. An arbitrary solution of the complete nonlinear system can then be expanded in terms of these eigenmodes. This allows interpreting various observed nonlinear behaviours, including steady state saturation, limit cycles, and transition to chaos. The single mode approximation reduces to a Landau-Ginzburg equation. It allows to obtain gain, nonlinear frequency shift, and efficiency as functions of cavity detuning and cavity losses. A generalisation to two modes allows to obtain a simple description of the limit cycle behaviour, as a competition between these two modes. An analysis of the transitions to more complex dynamics is also given. Finally, the analytical results are compared to the experimental data from the FELIX experiment.

EXPERIMENTAL RESULTS OF A SHEET-BEAM, HIGH POWER, FEL AMPLIFIER WITH APPLICATION TO MAGNETIC FUSION RESEARCH*

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The experimental study of sheet-beam FELs as candidate millimeter-wave sources for heating magnetic fusion plasmas has achieved a major milestone. In a proof-of-principle, pulsed experiment, saturated FEL amplifier operation was achieved with 250 kW of output power at 86 GHz. Input microwave power was 1 kW, beam voltage was 450 kV and beam current was 17 A. The planar wiggler had a peak value of 3.8 kG, a period of 0.96 cm and was 71 cm long. The linear gain of 30 dB, saturated gain of 24 dB and saturated efficiency of 3% all are in good agreement with theoretical prediction. Follow-on work would include development of a thermionic sheet-beam electron-gun compatible with CW FEL operation, adding a section of tapered wiggler to increase the output power to levels in excess of 1 megawatt, and increasing the FEL frequency.

*Work supported by the US Department of Energy.

HIGH-EFFICIENCY CARM

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The Cyclotron Autoresonance Maser (CARM) is a well-known variety of FEMs. Unlike the ubitron in which electrons move in a periodical undulator field, in the CARM the particles move along helical trajectories in a uniform magnetic field. Since it is much simpler to generate strong homogeneous magnetic fields than periodical ones for a relatively low electron energy ($\mathcal{E}\leq$1-3 MeV) the period of particles' trajectories in the CARM can be sufficiently smaller than in the undulator in which, moreover, the field decreases rapidly in the transverse direction. In spite of this evident advantage, the number of papers on CARM is an order less than on ubitron, which is apparently caused by the low (not more than 10 % [1]) CARM efficiency in experiments. At the same time, ubitrons operating in two rather complicated regimes - trapping and adiabatic deceleration of particles [2] and combined undulator and reversed guiding fields [3] - yielded efficiencies of 34 % and 27 %, respectively. The aim of this work is to demonstrate that high efficiency can be reached even for a simplest version of the CARM.

In order to reduce sensitivity to an axial velocity spread of particles, a short interaction length where electrons underwent only 4-5 cyclotron oscillations was used in this work. Like experiments [3,4], a narrow anode outlet of a field-emission electron gun cut out the "most rectilinear" near-axis part of the electron beam. Additionally, magnetic field of a small correcting coil compensated spurious electron oscillations pumped by the anode aperture. A kicker in the form of a sloping to the axis frame with current provided a control value of rotary velocity at a small additional velocity spread. A simple cavity consisting of a cylindrical waveguide section restricted by a cut-off waveguide on the cathode side and by a Bragg reflector on the collector side was used as the CARM-oscillator microwave system. The rotating $H_{1,1}$ mode under the grazing condition between the dispersion characteristics of the beam and the wave was chosen as the operating mode.

In experiment on the CARM with a 500-keV, 100-A electron beam at an optimal rotary velocity $v_{\perp}/c$=0.55 and guiding field B_0=12.4 kG generation of the $H_{1,1}$ mode with the wavelength of 7.9±0.1 mm and output power of about 13 MW was obtained. The corresponding electronic efficiency amounted to 25±5 %.

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MEASUREMENTS OF THE TEMPORAL AND SPATIAL PHASE VARIATIONS OF A 33 GHz PULSED FREE ELECTRON LASER AMPLIFIER AND APPLICATION TO HIGH GRADIENT RF ACCELERATION

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We report the results of temporal and spatial measurements of phase of a pulsed free electron laser amplifier (FEL) operating in combined wiggler and axial guide magnetic fields. The 33 GHz FEL is driven by a mildly relativistic electron beam (750 kV, 90-300 A, 30 ns) and generates 61 MW of radiation with a high power magnetron as the input source. The phase is measured by an interferometric technique from which frequency shifting is determined. The results are simulated with a computer code.

Experimental studies on a CERN-CLIC 32.98 GHz 26-cell high gradient accelerating section (HGA) were carried out for input powers from 0.1 MW to 35 MW. The FEL served as the r.f. power source for the HGA. The maximum power in the transmitted pulse was measured to be 15 MW for an input pulse of 35 MW. The theoretically calculated shunt impedance of 116 $M\Omega/m$ predicts a field gradient of 65 MeV/m inside the HGA. For power levels >3MW the pulse transmitted through the HGA was observed to be shorter than the input pulse and pulse shortening became more serious with increasing power input. At the highest power levels the output pulse length (about 5 nsec) was about one quarter of the input pulse length. Various tests suggest that these undesirable effects occur in the input coupler to the HGA. Light and X-ray production inside the HGA have been observed.

STUDIES ON A VUV FREE ELECTRON LASER AT THE TESLA TEST FACILITY AT DESY

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The TESLA Test Facility (TTF) currently under construction at DESY is a test-bed for acceleration sections of a high-gradient, high efficiency superconducting linear collider. Due to ist unrivaled ability to sustain high beam quality during acceleration, a superconducting rf linac is considered the optimum choice to drive a Free Electron Laser (FEL). We aim at a photon wavelength of $\lambda = 6$ nanometer utilizing the TTF after is has been extended to 1 GeV beam energy. Due to lack of mirrors and seed-lasers in this wavelength regime, a single pass FEL and Self-Amplified-Spontaneous-Emission (SASE) is considered. A first test is foreseen at a larger photon wavelength. The overall design as well as both electron and photon beam properties will be discussed.
To reach the desired photon wavelength, the main components that have to be added to theTTF are:
a) a low emittance rf gun including space charge compensation
b) a two stage bunch compressor increasing the peak bunch current from 100 A up to 2500 A
c) four more accelerating modules to achieve 1 GeV beam energy
d) a 25 m long undulator (period length 27 mm, peak field 0.5 T)
The average brillance will be larger than $1 \cdot 10^{22}$ photons/s/mm^2/mrad^2/0.1%. Each 800 μs long pulse will contain up to 7200 equidistant bunches. The repetition frequency of the linac is 10 Hz.

EXACT AND VARIATIONAL CALCULATIONS OF EIGENMODES FOR THREE-DIMENSIONAL FREE ELECTRON LASER INTERACTION WITH A WARM ELECTRON BEAM*

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I present an exact calculation of free-electron-laser (FEL) eigenmodes (fundamental as well as higher order modes) in the exponential-gain regime. These eigenmodes specify transverse profiles and exponential growth rates of the laser field, and they are self-consistent solutions of the coupled Maxwell-Vlasov equations describing the FEL interaction taking into account the effects due to energy spread, emittance and betatron oscillations of the electron beam, and diffraction and guiding of the laser field. The unperturbed electron distribution is assumed to be of Gaussian shape in four dimensional transverse phase space and in the energy variable, but uniform in longitudinal coordinate. The focusing of the electron beam is assumed to be matched to the natural wiggler focusing in both transverse planes. With these assumptions the eigenvalue problem can be reduced to a numerically manageable integral equation and solved exactly with a kernel iteration method. An approximate, but more efficient solution of the integral equation is also obtained for the fundamental mode by a variational technique, which is shown to agree well with the exact results. Furthermore, I present a handy formula, obtained from interpolating the numerical results, for a quick calculation of FEL exponential growth rate. Comparisons with simulation code TDA will also be presented. Application of these solutions to the design and multi-dimensional parameter space optimization for an X-ray free electron laser driven by SLAC linac will be demonstrated. In addition, a rigorous analysis of transverse mode degeneracy and hence the transverse coherence of the X-ray FEL will be presented based on the exact solutions of the higher order guided modes.

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RESEARCH AND DEVELOPMENT TOWARD A 4.5-1.5Å LINAC COHERENT LIGHT SOURCE (LCLS) AT SLAC[1]

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In recent years significant studies have been initiated on the theoretical and technical feasibility of utilizing a portion of the 3km S-band accelerator at the Stanford Linear Accelerator Center (SLAC) to drive a short wavelength (4.5-1.5Å) Linac Coherent Light Source (LCLS), a Free-Electron Laser (FEL) operating in the Self-Amplified Spontaneous Emission (SASE) regime[2]. Electron beam requirements for single-pass saturation include: 1) a peak current in the 3-7 kA range, 2) a relative energy spread of <0.05%, and 3) a transverse emittance, ε[r-m], approximating the diffraction-limit condition $\varepsilon \leq \lambda/4\pi$, where λ[m] is the output wavelength. Requirements on the insertion device include field error levels of 0.1-0.2% for keeping the electron bunch centered on and in phase with the amplified photons, and a focusing beta of 4-8 m for inhibiting the dilution of its transverse density. Although much progress has been made in developing individual components and beam-processing techniques necessary for LCLS operation down to ~20 Å, a substantial amount of research and development is still required in a number of theoretical and experimental areas leading to the construction and operation of a 4.5-1.5 Å LCLS. In this paper we report on a research and development program underway and in planning at SLAC for addressing critical questions in these areas. These include the construction and operation of a linac test stand for developing laser-driven photocathode rf guns with normalized emittances approaching 1 mm-mr; development of advanced beam compression, stability, and emittance control techniques at multi-GeV energies; the construction and operation of a FEL Amplifier Test Experiment (FATE) for theoretical and experimental studies of SASE at IR wavelengths; an undulator development program to investigate superconducting, hybrid/permanent magnet (hybrid/PM), and pulsed-Cu technologies; theoretical and computational studies of high-gain FEL physics and LCLS component designs; development of x-ray optics and instrumentation for extracting, modulating, and delivering photons to experimental users; and the study and development of scientific experiments made possible by the source properties of the LCLS.

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[1] Work supported in part by the Department of Energy Offices of Basic Energy Sciences and High Energy and Nuclear Physics and Department of Energy Contract DE-AC03-76SF0015.
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NONLINEAR ANALYSIS OF WIGGLER IMPERFECTIONS IN FREE-ELECTRON LASERS

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We present an analysis of the effect of wiggler imperfections in FELs using a variety of techniques. Our basic intention is to compare wiggler-averaged and non-wiggler-averaged nonlinear simulations to determine the effect of various approximations on the estimates of gain degradation due to wiggler imperfections. The fundamental assumption in the wiggler-averaged formulations is that the electrons are described by a random walk model, and an analytic representation of the orbits is made. This is fundamentally different from the approach taken for the non-wiggler-averaged formulation in which the wiggler imperfections are specified at the outset, and the orbits are integrated using a field model that is consistent with the Maxwell equations. It has been conjectured on the basis of prior studies using the non-wiggler-averaged formalism that electrons follow a "meander line" through the wiggler governed by the specific imperfections; hence, the electrons behave more as a ball-in-groove than as a random walk. This conjecture is tested by comparison of the wiggler-averaged and non-wiggler-averaged simulations. In addition, two different wiggler models are employed in the non-wiggler-averaged simulation: one based upon a parabolic pole face wiggler which is not curl and divergence free in the presence of wiggler imperfections, and a second model in which the divergence and z-component of the curl vanish identically. This will gauge the effect of inconsistencies in the wiggler model on the estimation of the effect of the imperfections. Preliminary results indicate that the inconsistency introduced by the non-vanishing curl and divergence result in an overestimation of the effect of wiggler imperfections on the orbit. The wiggler-averaged simulation is based upon the TDA code, and the non-wiggler-averaged simulation is a variant of the ARACHNE and WIGGLIN codes called MEDUSA developed to treat short-wavelength Gauss-Hermite modes. We study an example using a 30 MeV/110 A electron beam to generate radiation near 3.5 microns. A series of calculations will be carried out to test whether the output power is more directly related to the averaged trajectory deviation from the axes than to the pole-to-pole peak field errors.

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HIGH-POWER FEL DESIGN ISSUES - A CRITICAL REVIEW*

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The high-average power capability of FELs has been much advertised but little realized. In this paper we provide a critical analysis of the technological and economic issues associated with high-average power FEL operation from the UV to near IR.

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STATUS OF THE PROJECT OF NOVOSIBIRSK HIGH POWER FEL

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The project of IR FEL for the Siberian Center of photochemical researches is described. The distinguished features of this project are the use of the race-track microtron-recuperator and the "electron output of radiation". The building for the machine is under reconstruction now. About half of hardware has been manufactured. The assembly of installation began.

STATUS REPORT ON THE DEVELOPMENT OF A HIGH-POWER UV/IR FEL AT CEBAF*

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Last year we presented a design for a kilowatt industrial UV FEL based on a superconducting RF accelerator delivering 5 mA of electron-beam current at 200 MeV with energy recovery to enhance efficiency.[1] Since then, we have progressed toward resolving several issues associated with that design. More exact simulations of the injector have resulted in a more accurate estimate of the injector performance. A new injection method has reduced the longitudinal and transverse emittance at the linac entrance. A more compact lattice has been designed for the UV FEL, and a new recirculation scheme has been identified which greatly increases the threshold for longitudinal instabilities. We decided to use a wiggler from the Advanced Photon Source which leads to a robust high-gain FEL. Analysis of the stability of an RF control system based on CEBAF control modules indicates that only minor modifications will be needed to apply them to this FEL. Detailed magnet specifications, vacuum-chamber beam apertures, and diagnostic specifications have been developed for the recirculation arcs. The design of the optical cavity has been conceptualized, and control systems have been devised to regulate mirror distortion. A half-scale model of one of the end-corner cubes has been built and tested. Finally, three-dimensional simulations have been carried out which indicate that the FEL should exceed its minimum design goals with adequate performance margin.

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A PROPOSED VISIBLE FEL FACILITY AT BOEING*

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A 1-kW average power, visible wavelength FEL is described, based on a 120-MeV, 0.1-A macropulse average current linac operating at a duty factor of 0.6% and having average beam power of 70 kW. The accelerator will employ a demonstrated photoinjector,[1] 18-MeV, 433-MHz linac[2] as an injector, followed by a 1300-MHz longitudinal phase space "linearizer,"[3] a magnetic buncher chicane, and seven 1300-MHz, pulsed traveling wave linac sections.[4] The magnets used to transport the beam from the linac to the FEL centerline, the 5-m THUNDER wiggler, and the optical resonator will be reclaimed from previous FEL demonstration experiments.[5] We expect to attain pulse lengths of 7 ps for 3.5 nC, with minimal distortion of the pulse profile and normalized rms emittance of $7.5 \pm 2.5\ \pi$ mm-mr. FELEX projects a laser conversion efficiency of 4.3 %, yielding average output of 3 kW.

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EXPERIMENTAL STUDY OF A HIGH-CURRENT FEM WITH A BROADBAND MICROWAVE SYSTEM

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One of the main features of FELs and FEMs is the possibility of fast and wide-band tuning of the resonant frequency of active media, which can be provided by changing the particle energy. For a frequency adjustable FEM-oscillator, a broadband microwave system, which is simply combined with an electron-optical FEM system and consists of an oversized waveguide and reflectors based on the microwave beams multiplication effect has been proposed and studied successfully in "cold" measurements [1]. Here, the operating ability of a cavity, that includes some key elements of the broadband microwave system, was tested in the presence of an electron beam. To provide large particle oscillation velocities in a moderate undulator field and the presence of a guide magnetic field, the FEM operating regime of double resonance was chosen. In this regime the cyclotron as well as undulator resonance conditions were satisfied [2].

The FEM-oscillator was investigated experimentally on a high-current accelerator "Sinus-6" that forms an electron beam with particle energy 500keV and pulse duration 25ns. The aperture with a diameter 2.5mm at the center of the anode allows to pass through only the central fraction of the electron beam with a current about 100A and a small spread of longitudinal velocities of the particles. Operating transverse velocity was pumped into the electron beam in the pulse plane undulator of a 2.4cm period.

The cavity with a frequency near 45GHz consists of a square waveguide and two reflectors. The broadband up-stream reflector based on the multiplication effect had the power reflectivity coefficient more than 90% in the frequency band 10% for the H_{10} wave of the square waveguide with the maximum about 100% at a frequency 45GHz. The down-stream narrow-band Bragg reflector had the power reflection coefficient approximately 80% in the frequency band of 4% near 45GHz for the operating mode.

In the "hot" experiment, radiation at the designed frequency and mode with a power about 6MW and efficiency about 12% was measured. The maximum radiation power was reached at 8kOe of the guide magnetic field and about 0.5kOe of the undulator field.

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DESIGN OF A HIGH AVERAGE-POWER FEL DRIVEN BY AN EXISTING 20 MV ELECTROSTATIC-ACCELERATOR

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There are some important applications where high average-power radiation is required. Two examples are industrial machining and space power-beaming. Unfortunately, up to date no FEL has been able to show more than 10 Watts of average power. To remedy this situation we started a program geared towards the development of high average-power FELs.
As a first step we are building in our CREOL laboratory, a compact FEL which will generate close to 1 kW in CW operation. As the next step we are also engaged in the design of a much higher average-power system based on a 20 MV electrostatic accelerator. This FEL will be capable of operating CW with a power output of 60 kW. The idea is to perform a high power demonstration using the existing 20 MV electrostatic accelerator at the Tandar facility in Buenos Aires. This machine has been dedicated to accelerate heavy ions for experiments and applications in nuclear and atomic physics. The necessary adaptations required to utilize the machine to accelerate electrons will be described.
An important aspect of the design of the 20 MV system, is the electron beam optics through almost 30 meters of accelerating and decelerating tubes as well as the undulator. Of equal importance is a careful design of the long resonator with mirrors able to withstand high power loading with proper heat dissipation features.

A WIGGLER MAGNET FOR FEL LOW VOLTAGE OPERATION

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In low voltage FELs (ie, 200kV), operation is necessarily in the microwave frequency range for wiggler periods of the order of cms., so that a waveguide system is mandatory. Also, because of the relatively low velocity of the electron beam, the wiggle amplitude of the electron beam can be much larger than is normal for highly relativistic FELs. Both these factors mean that the electron trajectory must be carefully controlled to avoid beam collision with the waveguide walls. A wiggler system with half poles at entrance and exit is not an acceptable solution because of the offset it gives rise to the electron trajectory. Consequently, we have designed and constructed a wiggler magnet with exponential entrance and exit tapers for a minimal deflection and displacement of the electron beam. Simulations and experimental measurements showed that an on axis trajectory is easily obtainable.

COMBINED ELECTROMAGNETIC AND PERMANENT MAGNET UNDULATOR TO ACHIEVE HIGHER FIELD AND EASIER FIELD VARIATION WITHOUT MECHANICAL MOVEMENT

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Hybrid or pure permanent magnet undulators (PMU) are widely used because they have high field quality, allow easy field correction and do not consume power. Their main drawback is the necessity of moving one half of the magnet relative to the other to change field value, which requires a high precision, remotely controlled (and thus costly) driving system. On the other hand, electromagnetic undulators (EMU) have no problem with field variation, but consume too much power (100 - 400 kW) for high fields. Adding permanent magnets to EMU results in a considerable decrease of power consumption, while retaining the advantage of easily changing field level. A model of a CW combined EM+PM plane undulator having a 4.8 cm period and 8 periods long is described. It is simple in design and cheap in manufacturing: magnet yokes are made of soft steel rings in which 1.6 cm air gaps were cut to form pole faces. Odd yokes are placed to one side of the undulator axis and even yokes to the other with the air gaps on the axis. Each set of yokes is excited by its own separate winding of simple racetrack shape. Undulator deflection parameter K = 1.1 (B = 2.4 kG) can be reached at a 0.78-kW power level, i.e., less than 100 W per period, while without PM only a maximum K = 0.8 can be obtained and requires 4 kW power. No water cooling is needed, which greatly simplifies undulator design. The undulator was not optimized relative to the axial-air-gap to ring-width ratio: one might expect some increase in field level for thinner rings. Field amplitude depends also on relative transverse position of odd and even pole faces (perpendicular to undulator axis and magnetic field). These dependences for both cases, with and without PM, are presented. Quadrupole focusing along the transverse direction perpendicular to undulator field was introduced by slightly increasing pole width with radius of steel ring.

INITIAL STUDIES OF BREMSSTRAHLUNG ENERGY DEPOSITION IN SMALL-BORE SUPERCONDUCTING UNDULATOR STRUCTURES IN LINAC ENVIRONMENTS[1]

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One of the more promising technologies for developing minimal-length insertion devices for linac-driven, single-pass Free Electron Lasers (FELs) operating in the x-ray range is based on the use of superconducting (SC) materials[2,3,4]. In recent FEL simulations, for example, a bifilar helical SC device with a 2 cm period and 1.8 T field was found to require a 30 m saturation length for operation at 1.5Å on a 15 GeV linac, more than 40% shorter than an alternative hybrid/permanent magnet (hybrid/PM) undulator[5] . At the same time, however, SC technology is known to present characteristic difficulties for insertion device design, both in engineering detail and in operation[6]. Perhaps the most critical problem, as observed, e.g., by Madey and co-workers in their initial FEL experiments[7,8], was the frequent quenching induced by scattered electrons upstream of their (bifilar) device. Postulating that this quenching was precipitated by directly-scattered or bremsstrahlung-induced particle energy deposited into the SC material or into material contiguous with it, the importance of numerical and experimental characterizations of this phenomenon for linac-based, user-facility SC undulator design becomes evident. In this paper we discuss selected prior experimental results and report on initial EGS4 code[9] studies of scattered and bremsstrahlung-induced particle energy deposition into SC structures with geometries comparable to a small-bore bifilar helical undulator.

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[1]Work supported in part by the Department of Energy Offices of Basic Energy Sciences and High Energy and Nuclear Physics and Department of Energy Contract DE-AC03-76SF0015.

[2]Ben-Zvi, I., et al, Nucl. Instrum. Meth. A318, 781(1992).

[3]Schlueter, R., "Undulators for Short Wavelength FEL Amplifiers," Proc. 16th Int'l. FEL Conference, Stanford University, August 21-26, 1994, to appear in Nucl. Instrum. Meth., 1995.

[4]Caspi, S., "A Superconducting Helical Undulator for Short Wavelength FELs," LBID-2052, SC-MAG-475, September 1994.

[5]Xie, M., SLAC LCLS Research Group Minutes, 3/95.

[6]Caspi, S., Shlueter, R., Tatchyn, R., "High Field Strong-Focusing Undulator Designs for X-Ray Linac Coherent Light Source (LCLS) Applications," presented at the PAC95 Conference, - ms. FAQ23.

[7]Elias, L.R., and Madey, J. M., Rev. Sci. Instrum. 50(11), 1335(1979).

[8]Todd Smith, private communication.

[9]Ralph Nelson, W. R., Hirayama, H., and Rogers, W, O., "The EGS4 Code System," SLAC-Report-265, December 1985.

FEL UNDULATORS WITH THE HOLLOW-RING ELECTRON BEAM

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A conceptual design of undulators with a modulated longitudinal magnetic field is proposed. The magnetic field is created by use of a solenoid with axis coincident with the electron beam axis. In order to modulate the magnetic field we propose an insertion of a row of alternating ferromagnetic and superconducting diaphragms in line with electron beam.

The simulation of two-dimensional distribution of the magnetic field in the plane containing undulator axis was made using the computer code "Mermaid". The magnetic field was analysed as a function of the system geometry. The dependence on the spacing l between superconducting diaphragms, inner a and outer b radii of the last ones is investigated. Two versions of the device are considered: with ferromagnetic rings made of magnetically soft material placed between the superconducting diaphragms and without them. It is shown that the field modulation depth increases with ratio of b/l and can exceed 50% in case of the ferromagnetic insertions.

An approximate analytical calculation of the magnetic field distribution is performed as follows. The axial-symmetrical magnetic field can be defined by the vector potential with only one nonzero component $A(r,\phi)$ where r and ϕ are the cylindrical coordinates. The solution of the Laplace's equation is found under the assumption that the magnetic field is infinitely extended and periodic along the z-axis. The boundary conditions are defined by the undulator design.

The result is used for the calculation of the particle dynamics and for the investigations of the trajectory stability. The spectral and angular distribution of the radiation emitted from the described systems is found. The estimations show that the proposed design allows to create relatively high magnitude of the magnetic field (up to 1 T) with a short period about 1 cm or less.

HYBRID UNDULATOR NUMERICAL OPTIMIZATION

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3D properties of the hybrid undulator scheme are studied numerically using PANDIRA code. It is shown that there exist two well defined sets of undulator parameters which provide either maximum on-axis field amplitude or minimal higher harmonics amplitude of the basic undulator field. Thus the alternative between higher field amplitude or pure sinusoidal field exists. The behavior of the undulator field amplitude and harmonics structure for a large set of (undulator gap)/(undulator wavelength) values is demonstrated.

ADVANCED OPTIMIZATION OF PERMANENT MAGNET WIGGLERS USING A GENETIC ALGORITHM

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In permanent magnet wigglers, magnetic imperfection of each magnet piece causes field error. This field error can be reduced or compensated by sorting magnet pieces in proper order. We showed a genetic algorithm has good property for this sorting scheme.[1]

In this paper, this optimization scheme is applied to the case of permanent magnets which have errors in the direction of field. The result shows the genetic algorithm is superior to other algorithms.

[1] R.Hajima et al., Nuclear Instruments and Methods A318 (1992) 822-824

A HELICAL OPTICAL KLYSTRON FOR CIRCULAR POLARIZED UV-FEL PROJECT AT THE UVSOR

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Most of existing storage ring free electron lasers (SRFEL) are restricted those performances by degradation of mirrors in optical cavities. In general, the SRFEL gain at the short wavelength region with high energy electrons is quite low, and the high reflectivity mirrors such as dielectric multilayer mirrors are therefore required. The mirror degradation is considered as a result of irradiation of higher harmonic photons that are simultaneously emitted from planar optical klystron (OK) type undulators, which are commonly used in SRFEL. This problem is getting severer as the lasing wavelength becomes shorter.

The UVSOR-FEL had been originally scheduled to be *shutdown* by 1996 because another undulator project for spectroscopic studies with circular polarized photon would take the FEL's place. According to suggestion of the insertion device group of the SPring-8[1], we have designed a helical undulator that is able to vary degree and direction of the polarization easily. In addition, the undulator can be converted into a helical OK by replacing magnets at the center part of undulator in order to coexist with further FEL experiments.

Using a calculated magnetic field for magnet configurations of the OK mode, the radiation spectrum at wide wavelength range was simulated by a Fourier transform of Lienard-Wiechert potentials. As a matter of course, some higher harmonics are radiated on the off-axis angle. However it was found out that the higher harmonics is almost negligible as far as inside a solid angle of the Gaussian laser mode. Moreover the gain at the UV region of 250 nm is expected to be much higher than our present FEL because of high brilliant fundamental radiation. The calculated spatial distribution of higher harmonics and the estimated instantaneous gain is presented. Advantages of the helical OK for SRFEL will be discussed in view of our experience, and a possibility of application two-color experiment with SR will be also mentioned.

1. Hideo Kitamura, private communication.

A NEW UNDULATOR FOR THE EXTENSION OF THE SPECTRAL RANGE OF THE CLIO FEL

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Summary :

We built a new undulator in order to extend the lasing range of the CLIO infrared FEL.

Presently, CLIO operates in the wavelength range 2 - 17 µm. Beyond 14 µm, the power decreases rapidly, because of the diffraction losses of the vacuum chamber (7 mm height and 2 m long). Thus, lasing at higher wavelengths implies installing a chamber with a heigth approximately twice. Then the minimum gap is increased and the maximum deflection parameter, K, is reduced from 2 to 1 : the laser tunability is greatly reduced. This is why a new undulator has been built. The main characteristics are summarized below.

permanent magnets	$SmCO_5$
undulator period	50.4 mm
number of periods	38
undulator length	96 cm +96 cm (independantly ajustable)
lasing range	3 - 40 µm

Hall probe magnetic measurements of the undulator have been performed both in a magnetic measurement room and on-site : we have shown that the ambiant remanent field has to be taken into account in order to adjust the end magnet of each undulator.

Lasing has been obtained successfully between 3 and 16 µm. Diffraction losses disappeared (the cut-off wavelength shifted from 11 µm to 14 µm), but the power is still limited by the ZnSe extraction plate which becomes less and less transparent above 15 µm.

To reach the full wavelength range requires extracting laser beam by hole coupling (see companion paper by R. Prazeres et all) and changing the RF coupler in order to improve the quality of the electron bunching at low energy.

PERFORMANCE OF AN UNDULATOR FOR VISIBLE AND UV FELs AT FELI

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Two infrared free electron lasers (FELs) of the FELI project are now operating in the wavelength range of 1–20μm. A 2.68–m undulator has been constructed for visible and UV FELs covering the wavelength of 1–0.2μm for 100–165 MeV electron beams. It generates alternating, horizontal magnetic field, and wiggles electron beam on a vertical plane.
The undulator length and period are 2.68m and 40mm, respectively. The gap of undulator magnets can be changed remotely by using servomotors with an accuracy of 1μm from the control room. The maximum K–value and related magnetic field strength are 1.9 and 0.5T, respectively, when its gap is set to the minimum value of 16mm.
In order to minimize magnetic field reduction due to radiation damage, Sm–Co permanent magnet was adopted. Its structure and the results of magnetic field measurement will be reported.

COHERENT HARMONIC PRODUCTION USING A TWO-SECTION UNDULATOR FEL

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We present measurements and a theoretical analysis of a new methgod of generating harmonic radiation in a free-electron laser oscillator with a two section undulator inn a single optical cavity. To produce coherent harmonic radiation the undulator is arranged so that the downstream undulator section resonance frequency matches a harmonic of the upstream undulator. Both the fundamental and the harmonic optical fields evolve in the same optical cavity and are coupled out with different extraction fractions using a hole in one of the cavity mirrors. We present measurements that show that the optical power at the second and third harmonic can be enhanced by more than an order of magnitude in this fundamental/harmonic configuration. We compare the production of harmonic radiation of a two sectioned fundamental/harmonic undulator with that produced from a FEL operating at its highest efficiency with a step-tapered undulator, where the bunching at the end of the first section is very large. We examine the dependence of the harmonic power on the intracavity power by adjusting the optical cavity desynchronism, δL. We also examine the evolution of the fundamental and harmonic powers as a function of cavity roundtrip number to evaluate the importance of the small signal gain at the harmonic. We compare our measurements with predictions of a multi-electron nyumerical model that follows the evolution of fundamental and harmonic power to saturation.
This fundamental/harmonic mode of operation of the FEL may have useful applications in the production of coherent X-ray and VUV radiation, a spectral range where high reflectivity optical cavity mirrors are difficult or impossible to manufacture.

A CHI WIGGLER UBITRON AMPLIFIER EXPERIMENT: WIGGLER CHARACTERIZATION*

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A 35 GHz CHI (Coaxial Hybrid Iron) wiggler [1] ubitron amplifier experiment is under construction at the Naval Research Laboratory. The CHI wiggler configuration has the potential of generating high wiggler magnetic fields at short periods with excellent beam focusing and transport properties. This makes it a desirable configuration for the generation of high power coherent radiation in relatively compact systems. The CHI wiggler consists of alternating rings of magnetic and non-magnetic materials concentric with a central rod of similar alternating design but shifted along the axis by half a period. Once inserted in a solenoidal magnetic field, the CHI structure deforms the axial field to create a radial field oscillating with the same periodicity as the rings. An annular electron beam is propagated through the coaxial gap where the oscillating radial field imparts an azimuthal wiggle motion. The principal goals of the experiment are to investigate the performance tradeoffs involved in the CHI configuration for high frequency amplifiers operating at low voltages with small wiggler periods. The nominal design parameters are a center frequency of 35 GHz, wiggler period of 0.75 cm, and beam voltage of approximately 150 kV. Calculations have shown an intrinsic (untapered) efficiency of ≈ 7% when operating at 6.3 kG axial field (wiggler field, $B_w \approx 1270$ G). The calculated gain was 36 dB, saturating at a distance of 46 cm. These parameters yield an instantaneous amplifier bandwidth of ≈ 25%. There appears to be room for further improvement in efficiency, a matter which will be scrutinized more closely in the final design. A prototype CHI wiggler is presently being fabricated for use in conjunction with an existing 30 kG superconducting solenoid. The performance properties of the prototype will be characterized and compared with linear and non-linear calculations. An electron gun is being designed to generate a 150 kV, 35 A annular electron beam. It will use components from a SLAC klystron gun with modified cathode and anode structures. Results to date will be presented.

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[1] R.H. Jackson, H.P. Freund, D.E. Pershing and J.M. Taccetti, Nucl. Instr. and Meth. A341 (1994) 454.

IMAGE TUNING TECHNIQUES FOR ENHANCING THE PERFORMANCE OF PURE PERMANENT MAGNET UNDULATORS WITH SMALL GAP/PERIOD RATIOS [1]

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The on-axis field of a small-gap undulator constructed out of pure permanent magnet (PM) blocks arranged in an alternating-dipole (i.e., 2 dipoles/period) array can be substantially varied by positioning monolithic permeable plates above and below the undulator jaws[2]. This simple technique, which can be used to control the 1st harmonic energy in conventional synchrotron radiation (SR) or Free Electron Laser (FEL) applications requiring sub-octave tuning, can also be shown to suppress magnetic inhomogeneities that can contribute to the undulator's on-axis field errors. If a standard 4 block/period Halbach undulator, composed of PM blocks with square cross sections, is rearranged into an alternating-dipole array with the same period, the peak field that can be generated with superimposed image plates can substantially exceed that of the pure-PM Halbach array. This design technique, which can be viewed as intermediate between the "pure-PM" and standard "hybrid/PM" configurations, provides a potentially cost-effective method of enhancing the performance of small-gap, pure-PM insertion devices. In this paper we report on the analysis and recent characterization of pure-PM undulator structures with superimposed image plates, and discuss possible applications to FEL research.

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[1]Work supported in part by the Department of Energy Offices of Basic Energy Sciences and High Energy and Nuclear Physics and Department of Energy Contract DE-AC03-76SF0015.
[2]Tatchyn, R., "Permanent Magnet Edge-Field Quadrupoles As Compact Focussing Elements for Single Pass Particle Accelerators," SLAC-PUB-6058, February 1993.

FINAL CONSTRUCTION OF THE C.R.E.O.L. 8 MILLIMETER PERIOD HYBRID UNDULATOR

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The construction of an 8 millimeter period hybrid undulator for the C.R.E.O.L. high power far-infrared free electron laser has just been completed. This FEL is expected to come on-line in the fall of 1995 and produce close to a kilowatt of continuous power at wavelengths of 225 - 800 microns. The undulator has extremely precise mechanical tolerances and high field uniformity allowing for high electron beam recovery rates. Almost complete beam recovery is required for DC operation at high currents. A novel method for measuring the magnetic properties of individual magnets and sorting the magnets to reduce magnetic field errors will be reported. The peak field and phase errors of the undulator without the pole pieces are reduced through a magnet ordering procedure. These errors are further reduced by inserting and tuning adjustable pole pieces. The reduction of field errors through these two techniques will be presented. An analysis of the final undulator errors and the results of measurements of the mechanical tolerances will be presented.

HIGH HARMONICS FOCUSING UNDULATOR

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It was shown in our previous work[1] that there exist a possibility to enhance significantly the 'natural' focusing properties of the hybrid undulator. Here we analyze the actual undulator configurations which could provide such field structure. Numerical simulations using 2D code PANDIRA were carried out and the enhanced focusing properties of the undulator were demonstrated. The obtained results provide the solution for the beam transport in a very long (short wavelength) undulator schemes.

[1] A.A.Varfolomeev, A.Hairetdinov 'Focusing properties of the undulator with anharmonic magnetic field' FEL'94 Proceedings

KIAE-1.5-3 UNDULATOR PERFORMANCE

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Hybrid type undulator with 60 periods of λ_w=1.5 cm and tunable gap in wide range has been designed and manufactured. Additional side magnet arrays provide high magnetic field (near Halbach limit) along with transverse field profiles for e.b. focusing.

TUNING AND CHARACTERIZATION OF THE 'TEUFEL'-UNDULATOR

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Three important criteria are used to tune the undulator are: reduce longitudinal phase errors, have approximately equal two plane focusing and have a good overlap between the electron beam and the optical beam. Although these criteria are the main design goals it is hard to meet them directly from the assembling. Small errors inevitably appear during the assembly, even when care is taken to keep the tolerances as tight as possible. The magnetic field was constantly monitored during construction using the pulsed wire method. However some kind of tuning mechanism is always needed to improve the performance of the undulator.

The undulator we designed and build is of the Hybrid type, i.e. permanent magnets and high permeable poles. The well known method of using small permanent magnets to correct the field errors is nearly impossible due to the presence of iron poles. Hence, as a logical step, we decided to try to correct the various errors with shims in the form of small iron plates. The shims were put on the pole face at the edge of the poles. Different configurations were used to correct the different kind of errors. In the presentation an overview of the various shim configurations will be discussed. Steering errors are quite easy to correct, since only dipole fields are involved. We did put quite some effort in correcting the quadrupole errors. Gradients dBy/dx and dBx/dy were easy to correct with two shims on one side. The other gradients, on the other hand needed extensive shimming to be corrected. The error correction is limited by the presence of sextupole errors. We even found by experience that sextupole errors increased with the number of shims used.

The ratio of the focusing strength of the undulator is measured to be 3/2, being slightly stronger in the direction of the wiggle motion.

Longitudinal phase errors are introduced by amplitude and wavelength deviations in the undulator. A Fourier transform of the measured magnetic field was taken to check this characteristic. The height and width of the central frequency peak of the measured data was indistinguishable from a pure sine field. From this we concluded that longitudinal phase errors are of no significance in this undulator.

A HYBRID TYPE UNDULATOR FOR FAR-INFRARED FELs AT FELI

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Two FEL facilities of the FELI are now operating in the wavelength range of 1–20 μm. A 3.2–m hybrid type undulator (λ_u=80mm, N=40) has been designed for far–infrared FELs and will be installed in December. It can cover the wavelength of 20–60 μm by changing K–value from 1 to 2.7 for a 28.0–MeV electron beam.

It is composed of ferrite magnetic poles and Sm–Co permanent magnets. Commonly wound coils induce alternating magnetic field in ferrite poles. Combination of the induced field and the permanent magnet field can controlls the magnetic field between the undulator gap.

SUPPRESSION AND CONTROL OF LEAKAGE FIELD IN ELECTROMAGNETIC HELICAL MICROWIGGLER

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Shortening the period of electromagnetic wiggler introduces both the radical increase of the leakage field and the decrease of the field in the gap region. The leakage field is severer problem in planar electromagnetic wiggler than in helical wiggler. Hence, in order to develop a short period electromgnetic wiggler, we have adopted "three poles per period" type electromagnetic helical microwiggler[1].

In this work, we inserted the permanent magnet (PM) blocks with specific magnetized directions in the space between magnetic poles, for suppressing the leakage field flowing out from a pole face to the neighboring pole face. These PM-blocks must have higher intrinsic coersive force than saturation field of pole material. The gap field due to each pole is adjustable by controling the leakage fields, that is, controling the position of each iron screw set in each retainer fixing the PM-blocks.

At present time, a test wiggler with period 7.8mm, periodical number 10 and gap length 4.6mm has been manufactured. Because the ratio of PM-block aperture to gap length is important parameter to suppress the leakage field, the parameter has been surveyed experimentaly for PM-blocks with several dimensions of aperture. The field strength of 3-5kG (K=0.2-0.4) would be expected in the wiggler.

[1] N. Ohigashi, et al., Nucl. Instr. and Meth.A, A431(1994)426.

COMPARISON OF DIFFERENT UNDULATOR SCHEMES WITH SUPERIMPOSED ALTERNATING GRADIENTS FOR THE VUV-FEL AT THE TESLA TEST FACILITY

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For the VUV-FEL at the TESLA Test Facility an undulator with a total length of 30 m is needed. In this study three different approaches to realize an undulator with a sinusoidal plus a superimposed quadrupolar field were studied with the 3D code MAFIA.

The results are presented and discussed.

GAIN LENGTH DEPENDENCE ON PHASE SHAKE IN THE VUV-FEL AT THE TESLA TEST FACILITY

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The TTF VUV FEL, which is in its design stage at DESY, consists of a 30 m long SASE FEL which will radiate around 6 nm, driven by a superconducting linac with final energy of 1 GeV. One of the important issues in its design is the undulator performance, which is studied in this paper. The present setup, including FODO lattice, is discussed in this paper. Results of simulations, including the realistic wiggler field errors and beam stearing, are presented. Dependence of the performance, in particular the gain and saturation length as well as the saturation peak power, on the wiggler field errors is discussed.

FEL GAIN OPTIMISATION AND SPONTANEOUS RADIATION

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Colson et al.[1] have evaluated FEL gains for small deviations from perfect electron beam injection, with radiation of the same polarisation as that of the wiggler fields. We find that for optimum gain the polarisation of the optical field should be the same as that of the spontaneous emission under these conditions.

With a helical wiggler the axial oscillations resulting from small departures from perfect electron beam injection lead to injection dependent unequal amplitudes and phases of the spontaneous radiation in the two transverse directions. Viewed along the axis therefore the spontaneous emission is elliptically polarised. The azimuth of the ellipse varies with the difference of phase of the two transverse components of spontaneous emission but the eccentricity remains the same.

With planar wigglers the spontaneous emission viewed in the axial direction is linearly polarised, again with an injection dependent azimuth.

For optimum coherent gain of a radiation field its polarisation characterstics must be the same as those of the spontaneous radiation with both types of wiggler. Thus, with a helical wiggler and the data[1] reported earlier, an increase of 10% in the FEL gain at the fundamental frequency and of 11% at the fifth harmonic has been calculated in the small gain per pass limit. Larger enhancements in gain may result from more favourable values of input parameters.

1. W.B. Colson, G. Dattoli and F. Ciocci: Phys. Rev. A 31 p.828 (1985)

A BROADLY TUNABLE AUTOCORRELATOR FOR ULTRA-SHORT, ULTRA-HIGH POWER INFRARED OPTICAL PULSES

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ABSTRACT

We describe the design of a crossed-beam, optical autocorrelator that uses an uncoated, birefringent beamsplitter to split a linearly polarized incident pulse into two orthogonally polarized pulses, and a Type II, SHG crystal to generate the intensity autocorrelation function. The uncoated beamsplitter accommodates extremely broad tunability while precluding any temporal distortion of ultrashort optical pulses at the dielectric interface, and the specific design provides efficient operation between 1 μm and 4 μm. Furthermore, the use of Type II SHG completely eliminates any single-beam doubling, so the autocorrelator can be operated at very shallow crossed-beam angles without generating a background pedestal. The autocorrelator has been constructed and installed in the Mark III laboratory at Duke University as a broadband diagnostic for ongoing compression experiments on the chirped-pulse FEL.

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NEW AUTOCORRELATION TECHNIQUE FOR THE IR FEL OPTICAL PULSE WIDTH MEASUREMENTS

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We have developed a new technique for the autocorrelation measurement of optical pulse width at the Vanderbilt University FEL center. This method is based on nonlinear absorption and transmission characteristics of semiconductors such as Ge, Te and InAs suitable for the wavelength range from 2 to over 6 microns. This approach, aside being simple and low cost, removes the phase matching condition that is generally required for the standard frequency doubling technique and covers a greater wavelength range per nonlinear material. In this paper we will describe the apparatus, explain the principal mechanism involved and compare data which have been acquired with both frequency doubling and two-photon absorption.

NONLINEAR ABSORPTION AND TRANSMISION PROPERTIES OF Ge, Te AND InAs USING TUNEABLE IR FEL

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Nonlinear absorption properties of Ge, Te and InAs are being investigated using the transmission of FEL optical pulses through these semiconductors (z-scan method). Wavelength, intensity and macropulse dependence are used to differentiate between two-photon and free-carrier absorption properties of these materials. Macropulse dependence is resolved by using a Pockles Cell to chop the 4-μs macropulse down to 100 ns. Results of these experiments will be presented and discussed.

TEMPORAL CHARACTERIZATION OF FEL MICROPULSES AS FUNCTION OF CAVITY LENGTH DETUNING USING FREQUENCY-RESOLVED OPTICAL GATING[1]

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Results of frequency resolved optical gating (FROG) measurements on the Stanford mid-IR FEL system show the effect of FEL cavity length detuning on the micropulse temporal structure. The FROG technique enables the acquisition of complete and uniquely invertible amplitude and phase temporal dependence of optical pulses. Unambiguous phase and amplitude profiles are recovered from the data. The optical pulses are nearly transform limited, and the pulse length increases with cavity length detuning.

1 Work supported in part by the Office of Naval Research, Contract #N00014-91-C-0170

POTENTIAL APPLICATIONS OF A DUAL-SWEEP STREAK CAMERA SYSTEM FOR CHARACTERIZING PARTICLE AND PHOTON BEAMS OF VUV, XUV, AND X-RAY FELS*

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The success of time-resolved imaging techniques in the characterization of particle beams and photon beams of the recent generation of L-band linac-driven or storage ring FELs in the infrared, visible, and ultraviolet wavelength regions[1,2] can be extended to the VUV, XUV, and x-ray FELs. Tests and initial data have been obtained with the Hamamatsu C5680 dual-sweep streak camera system which includes a demountable photocathode (thin Au) assembly and a flange that allows windowless operation with the transport vacuum system. This system can be employed at wavelengths shorter than 100 nm and down to 1 Å.

First tests on such a system at 248-nm wavelengths have been performed on the Argonne Wakefield Accelerator (AWA) drive laser source. A quartz window was used at the tube entrance aperture. A preliminary test using a Be window mounted on a different front flange of the streak tube to look at an x-ray bremsstrahlung source at the AWA was limited by photon statistics. This system's limiting resolution of $\sigma \sim 1.1$ ps observed at 248 nm would increase with higher incoming photon energies to the photocathode. This effect is related to the fundamental spread in energies of the photoelectrons released from the photocathodes. Possible uses of the synchrotron radiation sources at the Advanced Photon Source and emerging short wavelength FELs to test the system will be presented.

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*Work supported by the U.S. Department of Energy, Office of Basic Energy Sciences, under Contract No. W-31-109-ENG-38.

COMPARISON OF OPTICAL AND ELECTRON SPECTRA IN AN INFRA-RED FREE ELECTRON LASER

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Time-resolved electron and optical spectra recently acquired at the FELIX facility are presented, showing the evolution of the respective macropulses. A comparison is made between the optical power output during the macropulse and the measured power extracted from the electron beam using a simple model of the cavity losses. Data are available for a wide range of operating conditions: the wavelength range is from 9 μm to 28 μm and detunings are between ¼λ and 2λ.

The effect of rapid electron beam energy changes on the optical and electron spectra will also be discussed.

REAL TIME DIAGNOSTIC FOR OPERATION AT A CW LOW VOLTAGE FEL

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At Liverpool University, a system for single user control of an FEL has been designed to satisfy the low voltage FEL (ie 200kV) operational requirements. This system incorporates many aspects of computer automation for beam diagnostics, radiation detection and vacuum system management. In this paper the results of the development of safety critical control systems are reported.

VUV OPTICAL RING RESONATOR FOR DUKE STORAGE RING FREE ELECTRON LASER

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The conceptual design of the multifaceted-mirror ring resonator for Duke storage ring VUV FEL is presented.
The expected performance of the OK-4 FEL with ring resonator is described.
We discuss in this paper our plans to study reflectivity of VUV mirrors and their resistivity to soft X-ray spontaneous radiation from OK-4 undulator.

* Work supported by Office of Naval Research Contract #N0014-94-1-0818.

ON THE FUNDAMENTAL MODE OF THE OPTICAL RESONATOR WITH TOROIDAL MIRRORS.

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The fundamental mode of the optical resonator with the toroidal mirrors is investigated. The losses in such resonator with the on-axis holes are low in compare with the case of spherical mirrors. The use of this type of optical resonator is briefly discussed.

CAVITY-MIRROR DEGRADATION IN THE DEEP-UV FEL

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It is known that the degradation of dielectric multilayer mirrors used in short wavelength free-electron lasers (FELs) is caused by the carbon contamination on the mirror surface and the defects inside the dielectrics. We reported last year that the degraded dielectric multilayer mirrors can be repaired with both surface treatment by RF-induced oxygen plasma and thermal annealing. However, such a mirror degradation is still one of the most critical issues in the deep ultraviolet (UV) FELs, because the fundamental undulator radiation resonating in the laser cavity, the intensity of which is much higher than that of higher harmonics, can be sufficiently energetic to cause the mirror degradation through photochemical reactions. We are investigating the mirror degradation mainly in the deep UV region down to 240 nm. The experimental results will be shown. The mirror degradation mechanism will be discussed.

ELECTRON ORBITS IN THE MICROWAVE INVERSE FEL ACCELERATOR (MIFELA)[1]

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The MIFELA is a new device based on stimulated absorption of microwaves by electrons moving along an undulator.[2] An intense microwave field is used ($a_s = eE_s / k_s mc^2 = 0.2$) as well as a large undulator field ($a_w/\gamma = eB_\perp/\gamma k_w mc^2 = 1/2$) to accelerate electrons emitted at 6MeV from a rf gun to 20MeV in 1.5m. The spiral radius of the electrons in the undulator is 8mm, in a waveguide of diameter 34mm, with undulator period about 10cm. There is a small guiding field, and the electrons move in type I orbits. We describe three problems connected with the orbital motion of the electrons in this structure: (i) injecting the electrons in an increasing undulator field prior to entering the MIFELA; (ii) orbital motion and stability inside the MIFELA; (iii) extraction of electrons from the spiral orbit in the accelerator into an axially-propagating beam, obtaining $\beta_\perp < 0.02$. These studies have application to a MIFELA which is under construction at Yale University by Omega-P.

(1) Research supported by the Department of Energy and Omega-P.
(2) T.B. Zhang and T.C. Marshall, Physical Review E 50, 1491 (1994)

A 300-nm Compact mm-Wave Linac FEL Design*

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Microfabrication technology offers an alternative method for fabricating precision, miniature-size components suitable for use in accelerator physics and commercial applications. The original R&D work at Argonne, in collaboration with the University of Illinois at Chicago, has produced encouraging results in the area of rf accelerating structure design, optical and x-ray masks production, deep x-ray lithography (LIGA exposures), and precision structural alignments [1]. In this paper we will present a design study for a compact single pass mm-linac FEL to produce short wavelength radiation. This system will consists of a photocathode rf gun operated at 30 GHz, a 50-MeV superconducting constant gradient structure operated at 60 GHz, and a microundulator with 1-mm period. Initial experimental results on a scale model rf gun and microundulator will be presented.

* Work supported by the U.S. Department of Energy, Office of Basic Science, under Contract no. W-31-109-ENG-38.

[1] A. Nassiri, R. L. Kustom, F. E. Mills, Y. W. Kang, A.D. Feinerman, H. Henke, P. J. Mattews, T. L. Willke, D. Grudzien, J. Song, and D. Horan, "A 50 MeV mm-Wave Electron Linear Accelerator System for Production of Tunable Short Wavelength Synchrotron Radiation," IEEE International Electron Device Meeting, Washington DC, December, 1993, pp 111-120.

CONCEPTUAL DESIGN OF INDUSTRIAL FREE ELECTRON LASER USING SUPERCONDUCTING ACCELERATOR

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Paper presents conceptual design of free electron laser (FEL) complex for industrial applications. The FEL complex consists of three FEL oscillators with the optical output spanning the infrared (IR) and ultraviolet (UV) wavelengths ($\lambda = 0.3 \ldots 20$ μm) and with the average output power 10 – 20 kW. The driving beam for the FELs is produced by a superconducting accelerator. The electron beam is transported to the FELs via three beam lines (125 MeV and 2×250 MeV). Peculiar feature of the proposed complex is a high efficiency of the FEL oscillators, up to 20 %. This becomes possible due to the use of quasi-continuous electron beam and the use of the time-dependent undulator tapering.

APPLICATION OF FEL TECHNIQUE FOR CONSTRUCTING HIGH-INTENSITY, MONOCHROMATIC, POLARIZED GAMMA-SOURCES AT STORAGE RINGS

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A possibility to construct high-intensity tunable monochromatic γ-source at high energy storage rings is discussed. It is proposed to produce γ-quanta by means of Compton backscattering of laser photons on electrons circulating in the storage. The laser light wavelength is chosen in such a way that after the scattering, the electron does not leave the separatrix. So as the probability of the scattering is rather small, energy oscillations are damped prior the next scattering. As a result, the proposed source can operate in "parasitic" mode not interfering with the main mode of the storage ring operation.

Analysis of parameters of existent storage rings (PETRA, ESRF, Spring-8, etc) shows that the laser light wavelength should be in infrared, $\lambda \sim 10 - -400$ μm, wavelength band. Installation at storage rings of tunable free-electron lasers with the peak and average output power $\sim$ 10 MW and $\sim$ 1 kW, respectively, will result in the intensity of the γ-source up to $\sim 10^{14} s^{-1}$ with tunable γ-quanta energy from several MeV up to several hundreds MeV. Such a γ-source will reveal unique possibilities for precision investigations in nuclear physics.

EXTENSION OF THE SPECTRAL RANGE OF OF THE CLIO FEL

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Summary :

The CLIO FEL has been designed to lase between 2 and 20 µm.The electrons are produced by a 32/50 MeV RF linear accelerator. The injector is a 100 keV thermoionic gun, followed by a subharmonic prebuncher at 0.5 GHz and a buncher at 3 GHz. The electron beam is then accelerated in a 4.5 m long travelling wave accelerating section, to the nominal energy. The undulator consisted of 48 periods of 40 mm and the optical cavity is 4.8 m long which corresponds to a 1.2 m Rayleigh length. The peak power extracted by a ZnSe Brewster plate is 10 MW at 10 µm. But, beyond 11µm, the laser power decreases rapidely and no laser oscillation appears above 17 µm. In order to lase at farther wavelengths, few changes have been made:

- First of all, the power limit is due to the diffraction losses of the undulator vaccuum chamber (7 mm height and 2 m long). Numerical calculations have been made and show that cavity losses reach 55 % at 15 µm whereas the measured gain is 60 %. Consequently, the undulator vaccuum chamber have been replaced by a approximately twice bigger one. Then, the minimum gap is increased and the maximum deflection parameter K is reduced by a factor 2: laser tunability is greatly reduced. This why a new undulator has been built. The main characteristics are summarized below:

permanent magnets	SmCO5
undulator period	50.4 mm
number of periods	38
undulator length	96 cm + 96 cm (independently ajustable)
lasing range	3 - 40 µm

Hall probe measurements of the undulator have been performed both in the magnetic measurements room and on site: we have noticed that the ambiant remanent field has to be taken into account in order to adjust the end magnets of each undulator.

STATUS OF THE NORTHROP GRUMMAN COMPACT INFRARED FREE-ELECTRON LASER

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The Compact Infrared Free Electron Laser (CIRFEL) was built as part of a joint collaboration between the Northrop Grumman Corporation and Princeton University to develop FEL's for use by researchers in the materials, medical and physical sciences. The CIRFEL was designed to lase in the Mid-IR and Far-IR regimes with picosecond pulses, megawatt level peak powers and an average power of a few watts. The micropulse separation is 7 nsec which allows a number of relaxation phenomenon to be observed. The CIRFEL utilizes an RF photocathode gun to produce high-brightness time synchronized electron bunches. The operational status and experimental results of the CIRFEL will be presented.

This work is supported by the Northrop Grumman Corporation and Princeton University.

POLARIZATION IN FREE ELECTRON LASERS

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Polarization of electromagnetic radiation is required very often in numerous scientific and industrial applications: studying of crystals, molecules and intermolecular interaction, high-temperature superconductivity, semi-conductors and their transitions, polymers and liquid crystals. Using polarized radiation allows to obtain important data (otherwise inaccessible) in astrophysics, meteorology and oceanology. It is promising in chemistry and biology for selective influence on definite parts of molecules in chain synthesis reactions, precise control of various processes at cell and subcell levels, genetic engineering etc. Though polarization methods are well elaborated in optics, they can fail in far-infrared, vacuum-ultraviolet and X-ray regions because of lack of suitable non-absorbing materials and damaging of optical elements at high specific power levels. Therefore, it is of some interest to analyse polarization of untreated FEL radiation obtained with various types of undulators, with and without axial magnetic field. The polarization is studied using solutions for electron orbits in various cases: plane or helical undulator with or without axial magnetic field, two plane undulators, a combination of right- and left-handed helical undulators with equal periods, but different field amplitudes. Some examples of how a desired polarization (elliptical, circular or linear) can be obtained or changed quickly, which is necessary in many experiments, are given.

TWO FEL'S IN ONE

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A new scheme for a FEL operation is proposed. The conventional principle of FEL operationis means that the electron bunch passes through the interaction area of FEL only in one direction.

We suggest another possible layout which implies that the electron bunch makes a turn after leaving the wiggler and entries the wiggler at the same end. Actually the wiggler is a kind of a bridge between two storage rings. The electron bunches on the orbit are expected to be adjusted in the way that after one of them leaves the wiggler, another one enters in the opposite direction and in the proper phase with the wave pulse emitted by the previous bunch. So the electron bunch comes in interaction with the amplified electromagnetic wave in both directions i.e. twice per period. It is especially important for the short wavelength FELs, because each reflection from the mirror causes a significant losses of the wave magnitude. The proposed design gives one interaction per each reflection instead of one interaction per two reflections in the traditional scheme.

Another way to realize the suggested principle of operating is to insert the wiggler in the electron-positron storage ring. But this layout can be less efficient because of low intensity of the positron beam.

The comparison study of radiation from different types of described double wigglers is fulfilled. The synchronization problems are discussed in this paper.

ANALYSIS OF THE 3D MAGNETIC FIELD AND ITS ERRORS FOR UNDULATORS WITH IRON POLES

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The attainable field strength and field quality, such as the optical phase error, the electron beam displacement within the undulator and higher order multipoles of the magnetic field, are discussed. These issues are critical to the design and construction of short period undulators for use in short wavelength FEL or for operation in third generation light sources. We discuss two approaches: (i) For superferric undulators the construction of a full length device would rely on the optimum sorting of precision machined undulator segments. Magnetic data on segments with 20 periods (period length 8.80mm) will be presented. (ii) For hybrid undulators the sorting has to be done on individual poles and magnets. For this approach typical error sources such as machining tolerances, magnetization errors of the permanent magnet material and assembly errors are modeled in 3D and compared to induced errors on an existing hybrid undulator segment. In case of undulators having a full length of hundred periods at least five times as many individual parts have to be characterized. This should be done automatically where both the mechanical and magnetic data before and after the assembly of the magnetic structure are recorded in one step. A CNC programmable measuring device suitable for this task will shortly be presented.

THEORETICAL ANALYSIS OF PLANAR PULSE MICROWIGGLER

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The Magnetic field distributions of a planar pulse microwiggler are studied analytically and numerically. Exact solutions of two-dimensional magnetic fields are derived, which show that along the electron axis the fields have a variation close enough to a sine wave. We also investigate wiggler field errors due to machining tolerance and effects of the field errors on trajectories of electron with the help numerical simulations. The results are critical for successful operation of CAEP compact free-electron laser experiment under preparation.

DESIGN OF BROADLY TUNED FIR FEL BASED ON A VARIABLE-PERIOD MICROWIGGLER

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A varible-period microwiggler is proposed and investigated. The fundamental period of the microwiggler is designed as λ_o=2mm, and the period of the microwiggler can be tuned from λ_o to $n\lambda_o$ (n=1, 2, 3, ...) The wiggler fields with the period $3\lambda_o$, $4\lambda_o$, and $5\lambda_o$ are measured and compared with the theoretical results. Finally, a broadly tuned FIR FEL is designed based on the performance of the variable-period microwiggler.

INTENSE INVERSE COMPTON γ-RAY SOURCE FROM DUKE STORAGE RING FEL*.

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We suggest using FEL intracavity power in the Duke storage ring for γ-rays production via Inverse Compton Backscattering (ICB). The OK-4 FEL driven by the Duke storage ring will tens of watts of average lasing power in the UV/VUV range. Average intracavity power will be in kilowatt range and can be used to pump ICB source. The γ-rays with maximum energy from 40 MeV to 200 MeV with intensity of 0.1 - 5 10^{10} γ per second can be generated.

In this paper we present expected parameters of γ-ray beam parameters including its intensity and distribution. We discuss influence of e-beam parameters on collimated γ-rays spectrum and optimization of photon-electron interaction point.

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An Experimental Superconducting Helical Undulator[1]

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Improvements in the technology of superconducting magnets for high energy physics and recent advancements in SC materials with the artificial pinning centers (APC)[2], have made a bifilar helical SC device an attractive candidate for a single-pass free electron laser (FEL)[3]. Initial studies have suggested that a 6.5 mm inner diameter helical device, with a 27 mm period, can generate a central field of 2-2.5 Tesla. Additional studies have also suggested that with a stored energy of 300 J/m, such a device can be made self-protecting in the event of a quench. However, since the most critical area associated with high current density SC magnets is connected with quenching and training, a short experimental device will have to be built and tested. In this paper we discuss technical issues relevant to the construction of such a device, including a conceptual design, fields, and forces.

[1] This work was supported by the Director, Office of High Energy Research, High Energy Physics Division, U.S. Department of Energy under Contract DE-AC03-76SF00098.

[2]Scanlan , R. M. et.al., "Evaluation of APC NbTi Superconductor in a Model Dipole Magnet". IEEE Transactions in Magnetics Vol. 30, No. 4, July 1994.

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BEAM DIAGNOSTICS IN THE CIRFEL*

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The CIRFEL system has been operating with electron energies in the range of 11 to 12 MeV and RF pulse length of 3 to 4 μsecs. The electrons produced by a Magnesium photocathode illuminated by a 261nm mode locked laser are accelerated in the RF gun, and further boosted in energy by a booster section downstream of the RF gun. The electrons are energy selected in the bending section before insertion into a permanent magnet wiggler. We describe several recent diagnostic measurements carried out on the CIRFEL system: emittance measurements in two different sections of the beam line, energy and energy spread measurements, and jitter characteristics of the photo cathode drive laser as well as the electron beam energy.

* This research is supported by the Northrop Grumman Corporation

FEED FORWARD CONTROL: AN IMPLEMENTATION AT CIRFEL

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An integral part of the Compact InfraRed Free Electron LASER (CIRFEL) is control of the phase and amplitude stability in the RF power system. We have implemented such a Feed Forward[1] system using the LabView software package, by National Instruments. We will discuss implementation and performance data of the Feed Forward control of the RF power system at CIRFEL. We will also briefly discuss some conditions under which the problem is ill-conditioned, and what idealizations can be made to remedy these ill-conditioned systems.

Using an arbitrary function generator, we generate a driving signal for a voltage-controlled attenuator at the input side of the RF system, and we monitor the RF voltage in cell 1 of the photocathode gun using a digital storage oscilliscope in averaging mode. The system is stable enough to use data from one shot to modify the inputs for future shots. After downloading the averaged data to a personal computer via a GPIB (IEEE 488) bus, we use a simple linear transformation on the difference waveform between the current shot and the target to produce a correction signal. This signal is added to the driving signal in the arbitrary function generator, and the process is repeated until we get the flatness we need in the output signals from cell 1. The system for phase control is similar, with a voltage-controlled phase shifter replacing the attenuator, and monitoring of the RF phase in cell 1 replacing the monitoring of RF voltage.

By repeatedly alternating between correcting the RF voltage (equivalent to correcting the RF power) and RF phase in cell 1, we are able to acheive simultaneous phase variations of $<\pm 1°$ and amplitude variations of $<\pm 0.1\%$ over a 3μsec pulse.

1 I. Ben-Zvi, J. Xie, and R. Zhang, "Feed Forward RF Control System of the Accelerator Test Facility", (1991).

DOUBLE-CONFOCAL RESONATOR FOR X-RAY GENERATION VIA INTRACAVITY THOMSON SCATTERING*

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There has been a growing interest in developing compact X-ray sources through Thomson scattering of a laser beam by a relativistic electron beam. For higher X-ray flux it is desirable to have the scattering to occur inside an optical resonator where the laser power is higher. In this paper I propose a double-confocal resonator design optimized for head-on Thomson scattering inside an FEL oscillator and analyze its performance taking into account the diffraction and FEL gain. A double confocal resonator is equivalent to two confocal resonators in series. Such a resonator has several advantages: it couples electron beam through and X-ray out of the cavity with holes on cavity mirrors, thus allowing the system to be compact; it supports the FEL mode with minimal diffraction loss through the holes; it provides a laser focus in the forward direction for a better mode overlap with the electron beam; and it provides a focus at the same location in the backward direction for higher Thomson scattering efficiency; in addition, the mode size at the focal point and hence the Rayleigh range can be adjusted simply through intracavity apertures; furthermore, it gives a large mode size at the mirrors to reduce power loading. Simulations as well as analytical results will be presented. Also other configurations of intracavity Thomson scattering where the double-confocal resonator could be useful will be discussed.

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Demonstration Experiment of A Laser Synchrotron Source for Tunable, Monochromatic X-rays at 500 eV *

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Abstract

A Laser Synchrotron Source (LSS) [J. Appl. Phys. 72, 5032 (1992)] was proposed to generate short-pulsed, tunable x-rays by Thomson scattering of laser photons from a relativistic electron beam. A proof-of-principle experiment was performed to generate x-ray photons of 20 eV [J. Appl. Phys., July 1, 1995]. A demonstration experiment is being planned and constructed to generate x-ray photons in the range of ~500 eV. Laser photons of λ=1.06 μm are Thomson backscattered by a 4.5 MeV electron beam which is produced by an S-band RF electron gun. The laser photons are derived from either i) a 15 Joules, 3 nsec Nd:glass laser, ii) the uncompressed nsec pulse of the NRL table-top terawatt (T^3) laser, or iii) the compressed sub-picosec pulse of the T^3 laser. The RF electron gun is being constructed with initial operation using a thermionic cathode. It will be upgraded to a photocathode to produce high quality electron beams with high current and low emittance. The x-ray pulse structure consists of micropulses of ~10 psec within an envelope of a macropulse whose length depends on the laser used. The estimated x-ray photon flux is ~10^{18} photons/sec, and the number of photons per macropulse is ~10^8. Design parameters and progress of the experiment will be presented.

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MAGNETIC MEASUREMENTS OF MODULATOR AND DISPERSION SECTIONS FOR THE BNL HGFEL

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The Harmonic Generation Free Electron Laser is a high-gain amplifier FEL configured as an optical klystron. It is presently under construction at Brookhaven National Lab. Each of the three superconducting magnet sections (modulator, buncher, radiator) has been built and the magnetic fields have been measured. This paper reports the measurement results and compares them with three-dimensional simulations.

POLARIZED GAMMA-RAYS WITH LASER-COMPTON BACKSCATTERING

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Polarized gamma-rays were generated through laser-Compton backscattering (LCS) of a conventional Nd:YAG laser with electrons circulating in the electron storage ring TERAS at Electrotechnical Laboratory. We measured the energy, the energy spread, and the yield of the gamma-rays to characterize our gamma-ray source. The gamma-ray energy can be varied by changing the energy of the electrons circulating the storage ring. In our case, the energy of electrons in the storage ring were varied its energy from 200 to 750 MeV. Consequently, we observed gamma-ray energies of 1 to 10 MeV with 1064 nm laser photons. Furthermore, the gamma-ray energy was extended to 20 MeV by using the 2nd harmonic of the Nd:YAG laser. This shows a good agreement with theoretical calculation. The gamma-ray energy spread was also measured to be 1% FWHM for 1 MeV gamma-rays and to be 4% FWHM for 10 MeV gamma-rays with a narrow collimator that defined the scattering cone. The gamma-ray yield was 47.2 photons/mA/W/s. This value is consistent with a rough estimation of 59.5 photons/mA/W/s derived from theory[1].

Furthermore, we tried to use these gamma-rays for a nuclear fluorescence experiment. If we use a polarized laser beam, we can easily obtain polarized gamma-rays. Elastically scattered photons from ^{208}Pb were clearly measured with the linearly polarized gamma-rays, and we could assign the parity of J=1 states in the nucleus[2]. We should emphasize that the polarized gamma-ray from LCS is quit useful in this field, because we can use highly, almost completely, polarized gamma-rays. We also use the LCS gamma-rays to measure the photon absorption coefficients. In near future, we will try to generate a circular polarized gamma-ray. We also have a plan to use an FEL, because it can produce intense laser photons in the same geometric configuration as the LCS facility.

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LASER SYNCHROTRON RADIATION AND BEAM COOLING†

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The interaction of intense ($\gtrsim 10^{18}$ W/cm^2), short pulse ($\lesssim 1$ ps) lasers with electron beams and plasmas can lead to the generation of harmonic radiation by several mechanisms.[1-6] Laser synchrotron radiation may provide a practical method for generating tunable, near monochromatic, well collimated, short pulse x-rays in a compact, relatively inexpensive source.[3-6] The mechanism for the generation of laser synchrotron radiation is nonlinear Thomson scattering. Short wavelengths can be generated via Thomson scattering by two methods, (i) backscattering from relativistic electron beams, in which the radiation frequency is upshifted by the relativistic factor $4\gamma^2$, and (ii) harmonic scattering, in which a multitude of harmonics are generated with harmonic numbers extending out to the critical harmonic number $n_c \simeq a_0^3 \gg 1$, where $a_0 \simeq 10^{-9}\lambda I^{1/2}$, λ is the laser wavelength in μm and I is the laser intensity in W/cm^2. Laser synchrotron sources are capable of generating short ($\lesssim 1$ ps) x-ray pulses with high peak flux ($\gtrsim 10^{21}$ photons/s) and brightness ($\gtrsim 10^{19}$ photons/s-mm^2-mrad^2 0.1%BW). As the electron beam radiates via Thomson scattering, it can subsequently be cooled, i.e., the beam emittance and energy spread can be reduced.[1] This cooling can occur on rapid ($\sim$ ps) time scales. In addition, electron distributions with sufficiently small axial energy spreads can be used to generate coherent XUV radiation via a laser-pumped FEL mechanism.[2]

†Supported by the Office of Naval Research and the Medical FEL Program.

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A PRACTICAL METHOD TO GENERATE BRILLIANT HARD X-RAYS WITH A TABLETOP ELECTRON STORAGE RING

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With electron storage rings not only synchrotron radiation(SR) but also bremsstrahlung(BS) from a thin target placed in the electron orbit are mechanisms to generate brilliant x-ray beams. The calculated brilliance of BS with a 50 MeV storage ring, which is nearly 10^{13} photons/s, mrad^2, mm^2, 0.1% band width for 100 keV x-rays, exceeds that of SR from a 1 GeV storage ring.[1] This photon energy spectrum is almost constant and extend up to the electron energy. The reasons for this high brilliance with this new radiation scheme is that the electron beams penetrating the thin target are utilized repeatedly, the narrow angular divergence of BS is determined by the kinematics of relativistic electron as same as SR, and the x-ray source size of the order of 1 µm is determined by the size of thin target instead of electron beam sizes. Continuos injection of electron beam to the storage ring at full energy is the way to keep high and constant beam current. Peak current and repetition rate determine x-ray out put power. Note that the power of x-ray beam is also provided from a RF cavity of the storage ring.

In this paper we will report some experimental results and discuss further application on a coherent bremsstrahlung generated from a set of stacked foils placed in the electron orbit of the ring. Resulting from these investigations the photon storage ring[2] which is based on a 50 MeV exact circular electron storage ring could provide wide range of coherent and incoherent radiations from far infrared to hard x-ray in a practical amount of radiation power.

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X-RAY FEL BASED ON HARMONICS GENERATION AND ELECTRON BEAM OUTCOUPLING*

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Electron beam outcoupling was suggested by N. A. Vinokurov[1] as a method of optics independent outcoupling for high power FELs. The bunching of the electron beam is provided in a master oscillator. The prebunched electron beam then radiates coherently into an additional wiggler called the radiator. The electron beam is turned by an achromatic bend into this wiggler and its radiation propagates with a small angle with respect to the OK-4 optical axis. Thus, the radiation will pass around the mirror of the master oscillator optical cavity and can then be utilized.

This scheme is perfectly suited for harmonic generation if the radiator wiggler is tuned on one of the master oscillator wavelength harmonics. This system is reminiscent of a klystron operating on a harmonic of the reference frequency.

In this paper we present the theory of this device, its spectral and spatial characteristics of radiation, the optimization of the master oscillator, the achromatic bend and bunching for harmonic generation, and influence of beam parameters (energy spread, emittance, etc.) on generated power. Examples of possible storage ring and linac driven systems are discussed.

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VUV FREE ELECTRON LASER WITH A DISTRIBUTED FEEDBACK CAVITY

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Development of FEL to the VUV/x-ray regime is looked as one of the possible directions to its success. For eliminating the need for optical cavities, difficult to be built at that regime, we propose a VUV (50nm) SASE FEL. According to Pellegrini's scaling law, for a 290MeV/200A e-beam passing through a 10.8m long and 2cm period wiggler, a high peak power 85.5MW and a high average brightness $2.44 \times 10^{+21}$ (photons/ [mm^2.$mrad^2$.bw]) can be obtained. However, it requires ε n=2.3mm.mrad and $\Delta \gamma / \gamma = 0.15\%$ about one order above the practical parameters we can realize. For enhancing the efficiency and decreasing the requirements on the e-beam quality and the wiggler length, we put forward a concept of VUV FEL with a distributed feedback cavity. In x-ray region, the natural periodicity of crystals provides strong Bragg coupling and it has been demonstrated as the parametric radiation. In vuv region, current intense research on superlattice can provide a periodical structure with a short period in 250 Å order. High-performance vuv multilayer coatings on the inner-wall of the waveguide are used to guide the spontaneous emission and decrease the x-ray ohmic losses on the roundtrip passes. By this DFB cavity structure, it is expected to realize the lasing in a smaller size. Other practical methods such as the optical klystron for shortening the wiggler length and the tapper wiggler for enhancing the saturation power are also considered. The analytical considerations are based on the 1-D FEL equations and 1-D perturbation theory of dielectric waveguide.

SPONTANEOUS EMISSION EFFECTS IN OPTICALLY PUMPED X-RAY FEL

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An effect of spontaneous emission in both quantum and classical regimes of the optically pumped X-ray free electron laser (FEL) is investigated.

The quantum properties of an FEL are determined by the ratio of the separation $\hbar\omega$ between the absorption and emission lines (i.e. the quanta emitted) and their effective width $\Delta\varepsilon$ $\eta = \hbar\omega/\Delta\varepsilon$. In the conventional classical regime $\eta \ll 1$ an electron emits and absorbs a great number of shortwavelength photons over the interaction region, the gain in FEL being the result of these competitive processes. In the quantum limit $\eta \gg 1$ the emission and absorption lines are completely separated and thus the FEL becomes a two-level quantum oscillator with a completely inverted active medium [1].

Spontaneous emission causes the electron to leave the range of energies where resonant interaction with the laser field occurs, thus effectively reducing the number of particles that take part in generating the induced X-ray signal. This effect is found to be crucial for lasing in optically pumped X-ray FEL. The characteristic relaxation times are calculated for both classical and quantum FEL regimes. It is shown that spontaneous emission results in FEL electron beam threshold current, which is of rather high value. An optimal range of pumping laser intensities is determined.

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A MICROWAVE INVERSE CERENKOV ACCELERATOR ("MICA")[1]

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By "inverting" the stimulated Cerenkov effect[2] to stimulated Cerenkov absorption, it is possible to build an electron accelerator device driven by high power microwaves that propagate in a a slow-wave TM mode (axial E-field). An experiment now running at Brookhaven[3] uses a powerful CO_2 laser and a 50MeV electron beam moving in a gas-loaded cell. Our approach is to use the 15MW available at 2.865GHz from a SLAC klystron to accelerate an electron beam provided from an rf gun (~6MeV, few psec pulses) to energy ~20MeV. The use of microwaves permits a well defined group of electrons to be accelerated in a narrow window of phase. The waveguide is a cylinder, radius = 1.59cm, which contains an annular tube of alumina ($\varepsilon = 9.4$) having a hole about 1cm diameter; we show this will slow the waves to 0.9943c and permit electrons to be accelerated by a co-propagating field. This results in a relatively compact structure that has the advantage of a smooth-bore design and no need of magnetic focussing. We have solved for the wave dispersion in the structure, found the fields, and then used the Lorentz force equations to obtain the motion of a group of electrons distributed in radius and along the axis. We find the radial forces are focussing. Electrons in a well-defined filament ($r < 0.5$mm) remain collimated and do not strike the dielectric. Techniques for improving the dielectric breakdown of the surface should permit axial fields in the range of 100-200 kV/cm.

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A TABLE-TOP X-RAY FEL BASED ON A LASER WAKEFIELD ACCELERATOR-UNDULATOR SYSTEM

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Ultrahigh-gradient electron acceleration has been confirmed owing to the laser wakefield acceleration mechanism driven by an intense short laser pulse in an underdense plasma.[1] The laser wakefield acceleratoion makes it possible to build a compact electron linac capable of producing an ultra-short bunched electron beam. While the accelerator is attributed to longitudinal wakefields, transverse wakefields simultaneously generated by a short laser pulse can serve as a plasma undulator [2] with a very short wavelength equal to a half of the plasma wavelength. We propose a new FEL concept for X-rays based on a laser wakefield accelerator-undulator system driven by intense short laser pulses delivered from table-top terawatt lasers. The system is composed of the accelerator stage and the undulator stage in a table-top size. A low energy electron beam is accelerated and bunched into microbunches due to laser wakefields in the accelerator stage. A micro-bunched beam travelling to the opposite direction of driving laser pulses produces coherent X-ray radiation in the undulator stage. A practical configuration and its analyses are presented.

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ABOUT THE SCHEME OF THE INFRARED FEL SYSTEM FOR THE ACCELERATOR BASED ON HF WELLS.

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Accelerators, based on localization of plasmoids in the HF wells (RF traps) of the axially-symmetric electromagnetic field E_{omn} in an oversized *(m,n>>1)* resonant system, can give accelerating gradients ~100 kV/λ, *e.g.* 10 GV/m if λ=10 μm. One of possible variants of HF feeding for these accelerators is based on using the powerful infrared FEL system with 2 frequencies. The corresponding FEL's may be similar to the Los Alamos compact Advanced FEL ($\lambda_{1,2}$~10 μm, e-beam energy ~15 MeV, e-beam current ~100 A). Their power is defined mainly by the HF losses in the resonant system of the supposed accelerator.

NONLINEAR RESONANCES IN A MULTI-STAGE FREE-ELECTRON LASER AMPLIFIER

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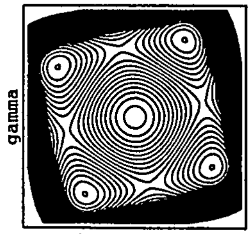
A two-beam accelerator (TBA) is a possible candidate of future linear colliders, in which the demanded rf power is provided by a multi-stage free-electron laser (MFEL). After rf amplification in each stage, a driving beam is re-accelerated by an induction unit and propagates into the next stage.

Rcently it has been recognized that the multi-stage character of the MFEL causes resonances between its periodicity and the synchrotron motion in an rf bucket.[1,2] Since the synchrotron oscillation is strongly modulated by the resonance and at the worst a large fraction of particles is trapped in the resonance islands, the nonlinear resonances in the FEL longitudinal beam dynamics can lead to notable degradation of the MFEL performance, such as output fluctuation and phase modulation which have been big concerns in the accelerator society. The overall efficiency of the MFEL and the quality of the amplified microwave power are key issues for realizing the TBA/FEL. Particularly the rf phase and amplitude errors must be maintained within tolerance. One of significant obstacles is an amplification of undesired modes. If a small-size waveguide is employed, the FEL resonance energies for undesired higher order modes shift very far from that for a fundamental mode; so it is possible to prevent higher order modes from evolving. Such a small-size waveguide, however, gives a high power density in the FEL. Simulation results have demonstrated that the nonlinear resonances occur in the FEL longitudinal motion when the power density exceeds some threshold.[2]

An analytical method for studying the nonlinear resonance in the TBA/FEL is developed based on the macroparticle model[3] which can describe analytically the drastic behaviors in the evolutions of the phase and amplitude. In the theory the basic 1D-FEL equations are reduced to a nonlinear pendulum equation with respect to the ponderomotive phase. The numerical calculation of the nonlinear pendulum equation shows that the third and fourth integer resonances occur for a typical set of TBA/FEL parameters. Furthermore, the size and position of the resonance islands are evaluated using the perturbation theory. These results are confirmed by 1D multi-particle simulations. As a result, the resonance structure is proved to significantly depend on the power density. Last, the power density threshold for the resonance is also estimated. The theory will serve as a guideline in designing the TBA/FEL.



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PICOSECOND PULSES OF COHERENT MM-WAVE RADIATION IN A PHOTOINJECTOR-DRIVEN WAVEGUIDE FREE-ELECTRON LASER*

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A 5 MeV, high repetition rate (2.142 GHz in burst mode), high brightness, tabletop photoinjector is currently under construction at the UC Davis Department of Applied Science, on the LLNL site. Ultrashort pulses of coherent synchrotron radiation can be generated by transversally accelerating the electron beam with a wiggler in either metallic or dielectric-loaded waveguide FEL structures. This interaction is investigated theoretically and experimentally. Subpicosecond photoelectron bunches will be produced in the photoinjector by irradiating a high quantum efficiency Cs_2Te (Cesium Telluride) photocathode with a train of 100 UV (210 nm), ultra-short (250 fs) laser pulses. These bunches will be accelerated in a 1-1/2 cell π-mode X-band RFgun e energized by a 20 MW, 8.568 GHz SLAC klystron. The peak current is 0.25 kA (0.25 nC, 1 ps), with a normalized beam emittance $\varepsilon_n < 2.5\ \pi$ mm-mrad. This prebunched electron beam is then transversally accelerated in a cylindrical waveguide by a 30-mm period, 10 period long helical wiggler. The peak wiggler field is adjusted to 8.5 kG, so that the group velocity of the radiated electromagnetic waves matches the axial velocity of the electron bunch (grazing condition, zero slippage). Chirped output pulses in excess of 2 MW power are predicted, with an instantaneous bandwidth extending from 125 GHz to 225 GHz and a pulse duration of 15 ps (HWHM). To produce even shorter pulses, a dielectric-loaded waveguide can be used. The dispersion relation of this waveguide structure has an inflection point (zero group velocity dispersion). If the grazing condition is satisfied at this point, the final output pulse duration is no longer determined by slippage, or by group velocity dispersion and bandwidth, but by higher-order dispersive effects yielding transform-limited pulses.

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BROADBAND SHORT PULSE MEASUREMENT BY AUTOCORRELATION WITH A SUM-FREQUENCY GENERATION SET-UP

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Previous spectral and laser pulse length measurements carried out on the CLIO FEL at wavelength $\lambda \approx 8.5$ µm suggested that very short light pulses could be generated, about 500 fs wide (FWHM). For these measurements a Michelson interferometer with a Te crystal, as a non-linear detector, was used as a second order autocorrelation device. More recent measurements in similar conditions have confirmed that the laser pulses observed are indeed single: they are not followed by other pulses distant by the slippage length $N\lambda$.

As the single micropulse length is likely to depend on the slippage, more measurements at different wavelengths would be useful. This is not directly possible with our actual interferometer set-up, based on a phase-matched non-linear crystal. However, we can use the broadband non-linear medium provided by one of our users' experiments: Sum-Frequency Generation over surfaces [see Peremans et al., User Workshop]. With such autocorrelation set-up, interference fringes are no more visible, but this is largely compensated by the frequency range provided. First tests at 8 µm have already been performed to validate the technic, leading to results similar to those obtained with our previous Michelson set-up.

THREE-DIMENSIONAL STUDY OF THE MULTI-CAVITY FEL

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The Multi-Cavity Free-Electron Laser has been proposed earlier[1], as a new configuration to obtain short, intense pulses of radiation, the key idea being to pre-bunch the electron beam in a number of very short cavities. Those studies were one-dimensional. Here we use three-dimensional simulations to study the viability of this concept when three-dimensional effects are included, particularly with regard to the transverse modes of the optical beam.

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A COMPACT FEL UPCONVERTER OF COHERENT RADIATION[1]

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The objective is to generate a powerful millimeter-wave FEL signal in a single pass, using a coherent microwave source (24GHz) to prebunch the electron beam for a harmonically-related wave (72GHz). We use the Columbia FEL facility, operating the electron beam at 600kV, 100A; undulator period = 1.85cm and 250G (K = 0.25); electron beam diameter =3mm inside a 8.5 mm ID drift tube; guiding field of 8800G. Under these conditions, both the microwave signal (5kW input) and the millimeter signal will show travelling-wave gain in the TE11 mode. We report initial experimental results for the millimeter wave spectrum and find an overall power gain of ~20 for the 24GHz input wave. Also presented will be numerical solutions of the wave growth using the FEL equations with slippage.[2] This device has the advantage of producing a high-power FEL output in a single-pass travelling-wave configuration, obtaining a millimeter wave which is phase-referenced to a coherent laboratory source.

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WAVELENGTH SWITCHING IN AN OPTICAL KLYSTRON[1]

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A symmetric optical klystron consists of two identical undulator sections separated a dispersive section. For a device of a given length, an optical klystron is capable of producing much more bunching, and therefore more gain, than a traditional undulator. Another consequence of introducing dispersion between two undulator sections is that the overall spontaneous radiation pattern results from the interference between the two undulator sections, and as such resembles a standard undulator radiation pattern modulated by a sinusoidal interference term. The presence of several wavelength peaks in the spontaneous lineshape implies an equal number of peaks in the gain spectrum. If the strength of the dispersion section is adjusted to provide nearly equal gain on the two largest of these peaks, then they will compete, and the FEL may switch wavelengths based on noise, cavity length, or other perturbations. We provide the first observations of this behavior, using the FIREFLY system at the Stanford Picosecond FEL Center. In FIREFLY, relative wavelength switching by more than 3%--more than twice the laser linewidth--has been observed by varying dispersion section strength, while at intermediate points stable switching has also been observed as a function of cavity length.

[1] Work supported in part by the Office of Naval Research, Grant No. N00014-94-1-1024.

COHERENT UNDULATOR RADIATION OF ELECTRON BEAM, MICROBUNCHED FOR THE FEL POWER OUTCOUPLING

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The spectral intensity of the coherent undulator radiation of electron beam, preliminarily microbunched by the FEL oscillator for the FEL power outcoupling, is approximately calculated by simple analytic considerations, taking into account the transverse emittances and the energy spread of the microbunched electron beam.

NEW METHOD OF BEAM BUNCHING IN FREE-ION LASERS

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An effective ion beam bunching method is suggested. This method is based on a selective interaction of line spectrum laser light (e.g. axial mode structure light) with non-fully stripped ion beam cooled in a storage rings, arranging the ion beam in layers in radial direction of an energy-longitudinal coordinate plane and following rotation of the beam at the right angle after switching on the RF cavity or undulator grouper/buncher. Laser cooling of the ion beam can be used at this position after switching off the resonator to decrease the energy spread caused by accelerating field of the resonator. A relativistic multilayer ion mirror will be produced this way. Both monochromatic laser beams and intermediate monochromaticity and band-width light sources of spontaneous incoherent radiation can be used for production of hard and high power electromagnetic radiation by reflection from this mirror. The reflectivity of the mirror is rather high because of the cross-section of the backward Rayleigh scattering of photon light by non-fully stripped relativistic ions ($\sim \lambda^2$) is much greater ($\sim 10 \div 15$ orders) then Thompson one ($\sim r_e^2$). This position is valid even in the case of non-monochromatic laser light ($\Delta\omega/\omega \sim 10^{-4}$). Ion cooling both in longitudinal plane and three-dimensional radiation ion cooling had been proposed based on this observation [1]. The using of these cooling techniques will permit to store high current and low emittance relativistic ion beams in storage rings. The bunched ion beam can be used in ordinary Free-Ion Lasers as well [2]. After bunching the ion beam can be extracted from the storage ring in this case. Storage rings with zero momentum compaction function will permit to keep bunching of the ion beam for a long time.

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SUPERRADIANCE OF SHORT ELECTRON PULSES IN REGULAR AND CORRUGATED WAVEGUIDES

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The report is devoted to theoretical and experimental study of superradiance of short electron pulses moving through waveguide systems. It is suggested that electrons oscillate or in undulator field (undulator SR) or in homogeneous magnetic field (cyclotron SR). We studied specific regimes of SR which may occur due to peculiarities of waveguide dispersion. Among them there are regimes of radiation near cut-off frequency as well as regimes of group synchronism. At the last operating regimes an electron bunch longitudinal velocity coincide with group velocity of e.m. wave. It is found the increasing of the SR instability grows rate and energy extraction efficiency in such regimes. It is also possible to observe the same enhancement using external feedback in periodically corrugated waveguide when Bragg resonance condition with forward propagated e.m. wave is fulfill.

For experimental observation of cyclotron SR we intend to use compact subnanosecond accelerator RADAN 303B on the base of the high voltage generator with special subnansecond transformer. Accelerator generates short 0.3ns electron pulses with current about 1kA and particles energy 200keV. Design of magnetic confound system provide possibility to install an active kicker to impose to electrons cyclotron rotation with pitch-factor about 1-1.5. According to numerical simulation at the mm and submm wavebands it is possible to achieve radiation pick power about 5-10MW with pulse duration less than 1ns.

THE ROLE OF RADIATION REACTION IN LIENARD-WIECHERT DESCRIPTION OF FEL INTERACTION

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The most common theoretical analysis of the FEL interaction is based on the set of equations consisting of Lorentz and wave equations. This approach explains most of FEL features and, in particular, works well to describe operation in the amplifier mode. In that approach however, there are some difficulties in describing operation in oscillator mode, as well as self amplified spontaneous emission. In particular, it is not possible to describe the start up stage since there is no wave to start with. It is clear that a different approach is required in such situations. That is why we have pursued the study of the FEL interaction in the framework of Lorentz plus Lienard-Wiechert equations.

The Lienard-Wiechert Lorentz equation approach however, presents its own set of problems. Variation in energy of the electrons is given exclusively by the Lorentz equation. Thus, the energy lost due to the radiation process is not properly taken into account. This, of course, is a long standing problem in classical electrodynamics. In order to restore energy conservation radiation reaction has to be incorporated into the framework. The first question in that regard has to do with which form of the radiation reaction equations is the most convenient for computations in the FEL process. This has to do with the fact that historically, radiation reaction has been added in an ad hoc manner instead of being derived from the fundamental equations.

Another problem discussed is how to take into account the radiation reaction in a collective manner in the interaction among electrons. Also discussed is the radiation reaction vis a vi the coherence properties of the FEL process.

APPLICATION OF THE GREEN FUNCTION FORMALISM TO NONLINEAR EVOLUTION OF THE LOW GAIN FEL OSCILLATOR

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A matrix formalism for the optical pulse evolution in the frequency domain, is applied to the nonlinear regime of operation. The formalism was previously developed for studies of the linear evolution of the low-gain FEL oscillator with an arbitrary shape of the electron beam[1]. By varying experimentally controllable parameters, such as cavity detunning and cavity losses, different regimes of operation of the FEL oscillator, such as a steady state saturation and limit cycle saturation, are studied numerically. It is demonstrated that the linear supermodes, numerically obtained from the matrix formalism, provide an appropriate framework for analyzing the periodic change in the output power in the limit cycle regime. The frequency of this oscillation is related to the frequencies of the lowest-order linear supermodes. The response of the output radiation to periodic variation of the electron energy is studied. It is found that the response is enhanced when the frequency of the energy variation corresponds to the difference of per-pass phase advances of the lowest linear supermodes. Finally, various nonlinear models are tested to capture the steady state saturation and limit cycle variation of the EM field in the oscillator cavity.

[1]S. Ishii, G. Shvets, and J. S. Wurtele, "Computationally Efficient Spectral Analysis of an FEL Oscillator Using a Green Function Analysis", Proceedings of the 16th International Free Electron Conference, to be published in the Nucl. Inst. and Meth. of Phys. Res., 1995

"OPTICAL GUIDING" LIMITS ON EXTRACTION EFFICIENCIES OF SINGLE-PASS, TAPERED WIGGLER AMPLIFIERS*

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Single-pass, tapered wiggler amplifiers have an attractive feature of being able, in theory at least, of extracting a large portion of the electron beam energy into light. In circumstances where an optical FEL's wiggler length is significantly longer than the Rayleigh length Z_R corresponding to the electron beam radius, diffraction losses must be controlled via the phenomenon of "optical guiding". Since the strength of the guiding depends upon the effective refractive index η_r exceeding one, and since (η_r-1) is inversely proportional to the optical electric field, there is a natural "limiting" mechanism to the on-axis field strength and thus the rate at which energy may be extracted from the electron beam. In particular, the extraction efficiency for a prebunched beam asymptotically grows linearly with z rather than quadratically. We present analytical and numerical simulation results concerning this behavior and discuss its applicability to various FEL designs including oscillator/amplifier-radiator configurations.

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HIGH-GAIN OPTICAL CHERENKOV OSCILLATOR DRIVEN BY LOW-VOLTAGE ELECTRON BEAM

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A novel scheme of high-gain optical (from IR up to UV) Cherenkov-type oscillator driven by low-voltage high-current electron beam is proposed in the present report.

In the scheme discussed the magnetized electron beam propagates above the surface of absorbing medium of complex dielectric susceptibility $\varepsilon(\omega) = \varepsilon_1(\omega) + i\varepsilon_2(\omega)$, $\varepsilon_2 > 0$. We have found that at frequencies ω that $\beta^2 > 2\varepsilon_1/ \mid \varepsilon \mid^2$ ($\beta = v/c$, v is the electron velocity), an amplification of co-propagating slow surface electromagnetic wave is possible. In contrast to the conventional Cherenkov oscillators, the absorption condition $\varepsilon_2 > 0$ is crucial for the gain, which is absent for transparent medium. The physics of this amplification effect is analogous to that of electron beam dissipative instability.

The wavelength generated is determined here by dielectic properties of the surface, and does not depend strongly on electron energy. Thus it is possible to use rather compact low-voltage ($\leq$ 1MeV) high-current accelerators as drivers.

Optimum oscillation conditions are found to be at frequencies near the resonance absorption lines of surface material (i.e. from IR up to UV). The gain up to $\sim$ 0.5cm^{-1} in the near IR ($\sim$ 10THz, SrF_2 absorption line) is possible for 250keV high current (density $\sim 10^{12}$cm^{-3}) electron beam.

This research is supported by Russian Basic Research Foundation (Grants N 93-02-14271 and 94-02-06072-a) and by ISF (Grant N9T000).

COMPACT FEL's BASED ON SLOW WAVE WIGGLERS

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Slow waves excited in magnetron-type cavities are attractive canditates as wigglers for compact Free Electron Lasers. Because of group velocities much below the speed of light, slow waves offer an order of magnitude increase in FEL gain under given circulating power in the wiggler resonator, compared to fast wave wigglers of similar period. In addition, they offer the versatillity of operation either at modest beam energy via upshifing of the fundamental wavelength, or at low beam energy benefiting from the submillimeter wiggler harmonics. Because the main electron undulation is in the transverse direction for all spatial harmonics, the radiated power is increased by a factor γ^2 relative to the Smith-Purcell approach that relies on axial electron undulation. Technical advantages offered by magnetron-type wiggles are: the generation of the wiggler microwaves and the FEL interaction take place inside the same cavity, avoiding the issue of high power coupling bewteen cavities; the excitation of wiggler microwaves relies on distributed electron emission from the cavity wall and does not require separate beam injection.

RESONANCE HARD RADIATION IN A GAS-LOADED FEL

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The process of induced radiation under the condition when the relativistic beam oscillation frequency coincides with the plasma frequency of the FEL filling gas, is investigated. Such a resonance results in a giant enhancement of interaction between electrons and photons providing high gain in the hard FEL frequency region. Meanwhile the spectral width of the spontaneous radiation is broadened significantly. A method is proposed for maintaining the synchronism between the electron oscillation frequency and the medium plasma frequency, enabling to transform the electron energy into hard radiation with high efficiency.

Z-DISCHARGE FREE ELECTRON LASER

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A new kind of plasma based free-electron laser is proposed. An electromagnetic wave is generated by a relativistic electron beam moving along a stabilised z-discharge. The radiation wavelength is determined by the discharge current and the relativistic factor of the beam. It is shown that the interaction is based on two bunching mechanisms. One is due to the dependency of the longitudinal beam velocity on the energy of the electrons (inertial bunching). The second mechanism leads to azimuthal bunching and is related to the energy dependence of the oscillation frequency of electrons in the magnetic field of the discharge.

At certain conditions both bunching mechanisms tend to compensate their mutual action and the system has an autoresonance. Near these conditions a high efficiency and, therefore, a high output power can be reached.

ON THE ORIGIN OF THE COHERENT X-RAY RADIATION FROM PLASMA FOCUS

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In the experiments with plasma focus [1] a highly monochromatic radiation at $\lambda \approx 13\text{Å}$ was observed at a small angle to the direction of the plasma discharge. This radiation was attributed to the following features [2]. Firstly, during the development of a plasma focus the short-period ($T \lesssim 1\mu m$) modulation of the plasma density due to the increasing instabilities takes place along the discharge over many periods. Secondly, a definite part of electrons is accelerated up to MeV energies due the cyclotron instability and the increasing diffusion of the magnetic field in the pinch region. In the present report in order to explain the experimental results, we discuss possible mechanisms of coherent X-ray radiation in plasma focus, including the transition radiation from relativistic electrons in the medium with periodically modulated dielectric permittivity, undulator radiation in periodic electric field in the medium, and Cherenkov radiation from plasma in the presence of a strong magnetic field. The calculations of the spectral and angular distributions of X-rays are presented for the various types of radiation under discussion and estimates of the radiation power are made. We also discuss the possibility of the stimulated radiation from plasma focus.

[1] G.Herziger et al. Phys.Lett. **64A**(1978)390.
[2] W.Neff et al. Nucl.Instr.Meth. **A285**(1989)253.

GAIN ENHANCEMENTOF PLASMA-LOADED FEL IN THE PRESENCE OF BEAT WAVES

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An expression for the dielectric permittivity of underdense plasma interacting with laser beat waves is derived. It is shown that the presence of beat waves in plasma results in an effective growth of the plasma frequency. The FEL Gain is investigated in the case when the frequency of soft photons weakly depending on the electron beam energy and the synchronism condition is maintained.It is shown that the plasma beat waves lead to the essential increase in FEL gain.

Session: 1.New lasing

Acoustic analog of a free-electron laser

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As well known, at the present time there are many types of laser the operation of which is based on the stimulated emission of light by an active medium. Lasers are generators of coherent electromagnetic waves in the range from ultraviolet to submillimeters. But acoustic analogs of such devices have not been created up to now in spite of the progress in laser technology.

Meanwhile, an acoustic laser could have a lot of interesting applications such as, for example, the directed underwater communication, the impact influence at underwater objects, the impact influence at armed forces on the ground (an analog of the shockwave from the supersonic aeroplane at the low height), the medical applications (destruction of stones in the kidney) etc.

Recently a theoretical scheme for an acoustic laser was proposed by the present author in Refs.[1,2]. A liquid dielectric with dispersed particles was considered as an active medium. The pumping was created by an oscillating electric field deforming dispersed particle volumes. Different types of oils or distilled water can serve as a liquid dielectric with gas bubbles as dispersed particles. Gas bubbles in water can be created by an electrolysis. The phase bunching of the initially incoherent emitters (gas bubbles) was realized by acoustic radiation forces. This scheme is an analog of the free-electron laser (FEL). Generation condition for this acoustic laser were calculated in Ref. [2]. It was shown that two types of losses must be overcome for the beginning of a generation. The first type results from the energy dissipation in the active medium and the second one is caused by radiation losses at the boundaries of the resonator.

The purposes of this report are:

- to discuss the analogies between the acoustic laser and FEL;
- to propose an effective scheme of an acoustic laser with a mechanical pumping (by a piezoelectric emitter of the piston type);
- to consider the schemes of acoustic lasers with the different types of the resonators (rectangular and cylindrical);
- to discuss the possibility of the creation of an impact acoustic laser;
- to discuss the experimental works which are planned to be carried out in cooperation with prof. L.A.Crum (Appl. Phys. Lab., University of Washington).

References

[1] S.T.Zavtrak, "Acoustic laser with dispersed particles as an analog of a free-electron laser", Phys. Rev. E 51, 2480 (1995)

[2] S.T.Zavtrak, "Generation conditions for an acoustic laser", Phys. Rev. E 51 (in press)

ON USE OF TIME-DEPENDENT MICROWAVE FIELDS TO INCREASE AN FEL OSCILLATOR EFFICIENCY

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Various schemes of a high efficiency FEL oscillator with time-dependent accelerating (or decelerating) microwave field in interaction region are proposed. All the schemes are based on standard accelerating structure and undulator technology. Feasibility of the proposed schemes is confirmed by results of numerical simulations. Realistic examples of FEL oscillators of infrared and visible wavelength ranges with efficiency about 20 % are presented.

COHERENT SASE FEL WITH ELECTRON BEAMS PREBUNCHED IN A MASKED CHICANE[a]

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We present a new FEL concept based on coherent, self-amplified spontaneous emission of electron beams that are prebunched in a chicane buncher. In this scheme, a chirped electron bunch is focused in the middle of the magnetic chicane where a transmission mask consisting of a series of slits modulates the transmitted beam current. With the appropriate slit spacing, the output of the chicane is a compressed pulse whose density is modulated at the resonant wavelength. It is then injected into a short, untapered wiggler with periods $2\gamma^2(1 + a_w^2)^{-1}$ times the beam modulation wavelength. Due to prebunched nature of the beam, the emitted radiation exhibits coherent amplification analogous to the mutual coherency of radiation emitted in multiple undulators.[1] In addition, because the bunch has a chirp, the interaction is similar to that in a tapered wiggler. The new scheme is also applicable to coherent x-ray production via Compton backscattering.

[1] N. G. Gavrilov et al., Nucl. Instr. Meth. A304 (1991) 63

[a] Supported by the Los Alamos Laboratory Directed Research and Development Initiatives under the auspices of the U. S. Department of Energy.

Measurements and simulation of the radiation build-up process in a prebunched free-electron maser oscillator

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Abstract

Numerical studies of the radiation build-up process in a prebunched free-electron maser oscillator (FEM), were carried out at Tel-Aviv University (TAU) and at the University of Maryland (UMD), and compared to the experimental measurements taken on the prebunched beam FEM experiments in TAU.

We present measurements of the temporal evolution of radiation excited from noise until a steady-state operation is established. The evolution of the spectral characteristics of the radiation was investigated using the data collected by a fast digitizing scope, which recorded the IF signal obtained from heterodyning the laser radiation with a stable local oscillator. The mode competition process was observed.

The experimental results were compared to analytical calculations of the spontaneous emission power and small-signal gain. Nonlinear 'amplifier' simulation codes were employed for calculation of the extraction efficiency and saturation power. Multi-frequency simulations of the mode competition process were carried out using simulation (MALT 1D) code, which is based on a space-time one-dimensional model of a free-electron laser oscillator. Conditions for establishment of single- (longitudinal) mode operation were identified and compared to the experimental measurements.

Prebunching of the e-beam current permits external interference in the mode competition and coherence build-up process. We found experimentally and confirmed numerically that prebunching can determine the frequency of oscillation if the e-beam is injected with a sufficient bunching power, and shortens the oscillation buildup and coherence establishment time.

EXPERIENCE ON THE OPERATION OF THE 2-IN-1 ELECTROMAGNETIC UNDULATOR OF FELICITA I

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The 5m-Undulator of FELICITA I has been installed at the final position in the storage ring DELTA in spring '95. Detailed magnetic measurements have been performed in place to get a complete characterization of this device in both possible modes, pure undulator and optical klystron mode, respectively.

The undulator consists of 38 identic poles. Four power supplies are connected to the main coils. Three of them drive the central six poles to get the dispersive section with its matching to the outer undulator sections. This setup allows a change between the optical klystron and the pure undulator mode without changing the hardware.

For measuring the magnetic field components a hall-probe was used. It was found that correction coils for compensating peak field variations were not necessary, because of errors less then 0.2 %. Only for the purpose of steering correction coils had to be used.

The field integrals were also measured with the pulsed-wire technique. For fast response concerning the matching, in particular of the dispersive section this technique was found to be very useful. Because of the large period length of 25 cm the wire sag in the rather long undulator could be neglected.

OPTICAL ASPECTS FOR LASING IN THE VISIBLE AND UV WITH FELICITA I

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In this contribution some topics of the optical cavity of the SRFEL are discussed. As rather high peak currents of the DELTA storage ring are expected, the radius of the mirrors is not optimized for maximum gain but is determined by a compromise between stability of the optical cavity and gain.

For short wavelength operation of FELs the microroughness as well as the planity of the mirror substrates are more important. Substrates with different specifications for their microroughness are compared.

FELICITA I should be able to lase down 200 nm. Therefore the ion beam sputter technique for the dielectric coatings should be used at wavelength below 300 nm with new materials for the multilayers.

PICOSECOND PUMP-PROBE USING AN FEL AND A SYNCHROTRON SOURCE*

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Two color pump-probe experiments using both the Duke Storage Ring as a synchrotron light source for visible light and the Mark III FEL as a tunable, high peak power IR source are possible. The visible synchrotron source can be used as a probe of vibrational excitation from the FEL in an experiment using vibrationally-assisted fluorescence as an indicator of overlap of the IR and the visible pulses. An optical delay line in the FEL beam will allow adjustment of the arrival time of the IR pulse relative to the visible probe. The storage ring RF booster and the Mark III FEL RF sources will be both driven by the same master oscillator with a timing jitter between sources of less than 20 psec. Exploration of coupling between electronic excitation and lifetimes of vibrational excitation of fluorescent compounds in solution can be carried out with this configuration.

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SOURCE CHALLENGES RESULTING OF THE FIRST APPLICATIONS OF A UV STORAGE RING FEL ON SUPER-ACO

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Since 1992, significant progresses were achieved on the Super-ACO (S-ACO) storage ring Free Electron Laser (FEL) in the UV. The operation at the nominal energy 800 MeV has several consequences : higher average power in the UV (25 mW at 60 mA and more recently 100 mW at 100 mA available for the users), 10 hours of lasing for the same injection of positrons, providing enough time for performing an user experiment, compatibility with the users of synchrotron radiation (SR) in the temporal structure mode for 120 mA, with the possibility of closing the four insertion devices of S-ACO. The main difficulties to extend the FEL optical performances come from the small gain (2%), limiting a rapid extention of the spectral range (either in the laser mode or by coherent harmonic generation from the FEL itself in the undulator) or linewidth narrowing. The installation of a 500 MHz harmonic cavity for bunch length reduction and gain increase is under consideration...

The stability of the FEL temporal and spectral was systematically followed versus time, for various scales (from ns to half an hour) with different detectors (dissector and streak camera for the micropulse temporal evolution, a scanning Fabry-Perot for spectral features). The stability of the laser source has been significantly improved with a longitudinal feedback system allowing the jitter of the 25 ps RMS laser micropulse to be reduced from 150-200 ps down to 10-20 ps, the intensity fluctuations to be damped down 1% and the spectral drift to be smaller than the resolution of the scanning Fabry-Perot (0.01Å) at perfect synchronism. The laser can work during more than 3 consecutive hours without readjustments. In addition, according to the ring current, the positron beam is submitted to coherent modes of synchrotron oscillations. Right now, a Pedersen type longitudinal feedback damps the dipolar modes of such oscillation. The quadrupolar modes (in the 120-60 mA range) leading to a rather unstable FEL are on the way to be damped with an additional feedback. The transverse stability is also an important issue, now under more precise study.

The feasibility of use of the S-ACO FEL in the UV has been demonstrated with the measurement of time-resolved polarized fluorescence decays of the reduced nicotinamide adenine dinucleotide coenzyme in aqueous solution, leading to high quality data collection and original results. Whereas applications are commonly developed on linac driven infra-red FELs, this first use of a UV storage ring FEL opens wide perspectives for the UV and VUV region; particularly for pump-probe experiments coupling SR and FEL. Such a combination presents various advantages : pulse to pulse natural synchronisation at a high repetition rate, access to the temporal decay of the excited state by varying the SR to FEL delay (1-120 ns on S-ACO), tunability, polarization and high brilliance of both sources. First results were obtained on the study of the surface photovoltage effect on semi-conductors/metal interfaces: the FEL pumps a few pairs of carriers, and the resulting modification of the band bending is probed by time-resolved high resolution photoemission on the VUV undulator beamline SU3. Other two-color experiments are planned in the near future : photoionisation of excited helium, FEL excitation of photocarriers and production of photofragments probed in infra-red.. It shows the real potentialities offered by an FEL source coupled to SR, in various scientific fields. The new storage ring FEL user facilities under development or project should also satisfy such strict stability requirements.

PLANS FOR A FAR-INFRARED FREE-ELECTRON LASER IN INDIA

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The Centre for Advanced Technology is building the INDUS complex of synchrotron radiation sources. As part of this programme it is also proposed to build a far-infrared free-electron laser oscillator. This will use a microtron injector and a 40 period undulator made of NdFeB permanent magnets, and is designed to lase around 200 microns. We discuss details of the FEL design and the present status of experimental activities on this front.

CONSTRUCTION AND DEVELOPMENT OF A UV FREE ELECTRON LASER UNDER THE COOPERATION OF NIHON U, KEK, PNC, ETL AND TOHOKU U

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The construction and the development of a UV free electron laser have been started under the cooperation of Nihon U, KEK[1], PNC[2], ETL[3] and Tohoku U.. The project requires a 100MeV S-band electron linear accelerator to expand the oscillation of FEL using fundamental mode to the UV region. The injection system consists of a thermionic RF-gun with a LaB_6 cathode and an α magnet for magnetic bunching. We are studying to reduce the back-bombardment electrons to realize the macropulse length of 20μsec. Electron beams, up to the energy of 100MeV, are injected into the optical oscillators. Changing the accelerating energy and/or undulator parameters, this system will cover the range from infrared to ultraviolet for the applications in various fields.

[1]National Laboratory for High Energy Physics

[2]Power Reactor and Nuclear Fuel Development Corporation

[3]Electrotechnical Laboratory

OPTICAL WAVELENGTH MODULATION IN FREE ELECTRON LASERS

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ABSTRACT

An attribute of the free electron laser (FEL) is the continuous tunability of the optical wavelength by modulation of the electron beam energy. The variation of the wavelength and power of the optical beam is studied as a function of FEL operating parameters. These results will be applied to the Stanford SCA FEL and Boeing FEL.

VIBRATIONAL SPECTROSCOPY AT INTERFACES BY IR-VIS SUM-FREQUENCY GENERATION USING CLIO FEL.

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IR-vis sum-frequency generation (SFG) has developed into a versatile technique for probing the vibrational structure of interfaces. To overcome the limited spectral range accessible by benchtop IR lasers, we have developed an SFG spectrometer that makes use of the broad band tuneable infrared beam provided by the CLIO-FEL. We will evaluate the gain in sensitivity of the FEL-SFG spectrometer in comparison to that of benchtop lasers, taking account of the surface damage by laser heating. Thereafter, we review the different research projects undertaken using this facility:

1) The interface selectivity of SFG makes it particularly suitable for probing buried liquid/solid interface. We took advantage of the spectrometer sensitivity to monitor the electrochemical deposition of hydrogen on platinum single crystals at under- and overpotential.

2) Because of its sensitivity to the molecular symmetry, SFG allows probing the conformation of self assembled monolayers deposited on metals. We discuss SFG spectra of ω-(4-nitroanilino)-dodecane adsorbed on polycrystalline gold and silver films in the 1550 - 900 cm^{-1} spectral range.

3) We have undertaken a spectroscopic approach for the investigation of polymer films adhesion on glass. Polyurethane/glass interface is investigated in the 2200 - 1600 cm^{-1} spectral region.

4) The use of the CLIO FEL allows probing of the vibrational dynamics of the prominent IR active vibrations between 1500 and 500 cm^{-1} of fullerene epitaxial films. These modes are modified upon charge transfer from the substrate to the C_{60} molecules. Preliminary SFG spectra of C_{60}/Ag interface are presented.

5) Site specific detection of CO adsorption and CO + O coadsorption on Pd(111) are studied.

FEL BEAM SHARING SYSTEMS FOR EIGHT USER'S STATIONS OF THE FELI

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Two infrared free electron lasers(FELs) of the FELI are now operating in the wavelength range of 1–20 μm. Two kinds of FEL beam are sent from the exits of the optical cavities to the diagnostics room through the evacuated optical pipelines whose inner diameter is about 150 mm. From the diagnostic room to user's stations, FEL beams are delivered through FEL beam sharing systems. Au–coated mirrors with fan–shaped holes are used instead of half mirrors such as ZnSe to share FEL beams to the diagnostics room and the following user's stations, since maximum diameter of FEL beams is 50 mm in the wavelength range of 1–20 μm and an opening angle of the fan–shaped holes can change a sharing ratio of delivering FEL average power for user's stations; for instance, 10% to the diagnostics room and 90% to eight user's stations. Each system enables us to use the same FEL beam simultaneously at the user's stations. The two beam sharing systems will be installed in the user's facility early in August.

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TEMPORAL AND SPECTRAL EVOLUTION OF A STORAGE RING FEL SOURCE: EXPERIMENTAL RESULTS ON SUPER-ACO AND NEW THEORETICAL APPROACH

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The Super-ACO FEL source in UV is now used for applications like a time-resolved fluorescence in biology and two colors experiments coupling FEL and Synchrotron Radiation, which are naturally synchronized. The stability of the FEL is then a critical issue for the users.

Detailed experimental studies conducted on the temporal characteristics of the laser micropulse showed various phenomena, such as a longitudinal micropulse jitter and a deformation of a longitudinal micropulse distribution.

A similar analysis has been performed on the laser spectral evolution with a scanning Fabry-Perot interferometer, showing a spectrum narrowing, and a wavelength drift.

A longitudinal feedback system developed after the first user experiment, allowed to reduce significantly the longitudinal jitter, the intensity fluctuation and the spectral drift.

Nevertheless, the stability of the FEL is very dependant on any perturbation, and the observed phenomena can not be described by former models like super-mode assuming a stationary regime. A new theoretical model has then been developed, in order to simulate dynamic behaviors.

A simple iterative method is employed to obtain the laser spectrum. The access to the temporal distribution requires additional complexity, because the Fourier transformation has to be performed for each pass.

The comparison between the experimental data and the simulation results will be given.

COMPTON BACKSCATTERING OF INTRACAVITY STORAGE RING FREE-ELECTRON LASER RADIATION

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We discuss the γ- ray production by Compton backscattering of intracavity storage ring Free-Electron Laser radiation. We use a semi-analytical model which provides the build up of the signal combined with the storage ring damping mechanism and derive simple relations yielding the connection between backscattered photons brightness and the intercavity laser equilibrium intensity.

GAIN NARROWING OF TEMPORAL AND SPECTRAL WIDTHS IN THE UVSOR-FEL

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Storage ring free electron laser (SR-FEL) dynamics on the UVSOR-FEL in the visible region has been studied with measurements of the temporal and the spectral widths of the laser micropulse. The micro- and the macro-temporal structures were measured using a dual sweep streak camera. We have also investigated spectral evolution of the laser with a Fabry-Perot etalon. Only a slow sweep function of the streak camera has been used for a fringe pattern formed by the air gap etalon to derive time-dependent variations of the spectral shape.

We have measured the time-averaged pulsewidths and linewidths as a function of the ring current. We observed that every macropulse contains internal substructures in both the temporal and the spectral distributions. The internal substructure, however, disappeared when the spectra of more than fifty macropulses were superimposed, and the envelope of the distribution became close to a Gaussian. We have found that the pulsewidth and the linewidth become narrower as the ring current decays. In the *gain-switching* mode, the micropulse duration and the linewidth at the maximum ring current were 80 ps(FWHM) and 0.3 nm(FWHM), respectively, and decreased down to 20 ps and 0.1 nm just above the threshold current.

The temporal and the spectral widths seem to follow the gain behavior. Assuming that the pulsewidth and the linewidth depend on the laser gain, the bandwidth in weakly saturated situation such as SR-FEL is determined by the gain narrowing of the laser amplifier. Because the gain evolution is able to be deduced from the macropulse shape, we can obtain the relation between the bandwidth and an effective gain above the mirror loss. The temporal and the spectral evolutions of the UVSOR-FEL were well explained by the gain narrowing related to a gain integrated from the oscillation build-up to the gain saturation. Detail of the experiment and the analysis will be presented.

RESONANT CONDITION FOR STORAGE RING SHORT WAVELENGTH FEL WITH POWER EXCEEDING RENIERI LIMIT.

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In this paper we discuss the possibility of operating a storage ring FEL with resonant conditions providing for preservation of electron beam structure on an optical wave scale. We suggest tuning the storage ring betatron and synchrotron tunes on one of the high (N-th) order resonances to compensate dynamic diffusion of optical phase. This mode of operation does not require isochronicity of the ring lattice.

In these conditions optical phase will be restored after N turns around the ring and stochastic conditions used in the derivation of Renieri limit are no longer applicable.

We discuss the influence of high order terms in electron motion, RF frequency stability, and synchrotron radiation effects on preservation of optical phase.

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ON THE SPECTRUM OF OPTICAL KLYSTRON IN THE OSCILLATION MODE

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The simple model of multimode oscillation in the optical klystron is discussed. The results of computer simulations (in particular, the spectra) are described.

MAGNETIC BEAM POSITION MONITOR

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Many nondestructive beam position monitors are known. However, these devices can not be used for DC particle beam diagnostics (see, for example, FOM-FEM project [1]). We investigated a method of beam diagnostics applicable for the operative control of DC high power e-beam inside closed waveguide.

A design of the detector for determination of 'center of mass' position of DC particle beam was developed. It was shown that the monitor can be used as a nondestructive method for the beam position control in resonators.

Magnetic field of the particle beam outside a resonator is used. The detector consists of the steel yokes and magnetic field sensors. The sensors measure magnetic fluxes in the steel yokes fixed outside the resonator. When the particle beam changes its position, these magnetic fluxes also change. Beam displacement sensitivity of the monitor depends on the steel yoke dimensions. The detector sensitivity is equal to 1 Gauss/mm for the conditions adequate to the FOM-FEM project.

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THE PRIMARY TEST OF MEASUREMENTAL SYSTEM FOR THE ACTUL EMITTANCE OF RELATIVISTIC ELECTRON BEAMS

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ABSTRACT

Recent, a new measuremental system has been established basically in Tsinghua University PRA. This system is able to measure the lower emittance of the electron beams from the RF accelerators for the FEL. It consists of a scanning magnetic field, a slit, a fluoresent screen, and a TV camera, an image processing system, a CAD 386 computer. Using it, an actual phase diagram is obtained for 4-10 Mev electron beams. The principle and structure of the facility were reported in the Proceeding of the 15th FEL Conference.

This paper describes the performance of the main components and the results of first measurement for the electron gun and 4Mev standing wave LINAC. Some new suggests are related too.

BEAM EXTRACTION EXPERIMENT WITH FIELD-EMISSION ARRAYS

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An experimental project aimed to develop FEL drivers using a field-emission array is under way. The subject covers design and fabrication of novel micro-emitters, operation of FEAs, beam formation and emittance diagnostics.

So far the generation of a focused beam has been demonstrated with an array of double-gated microemitters.[1] Active control of FEAs has greatly improved the stability of the emission current.[2] Large FEAs with an emitting area of up to 2 x 2 cm^2 have been fabricated for the production of high-current beams.

Dc beams (1 - 5 keV, < 100 μA) extracted from Spindt cathodes were propagated over 1 m and projected on a fluorescent screen. Separate images of FEA tips were observed and emittance measurement has been carried out. The cathode is going to be replaced by a double-gated FEA to improve the beam quality. Pulsed extraction of high currents will also be tested, employing a non-gated FEA as the cathode of a 1 MV induction linac. Results of these experiments will be presented and perspectives concerning the FEA gun will be discussed.

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A METHOD OF FORMING A HIGH-QUALITY ELECTRON BEAM FOR FREE ELECTRON MASERS

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A large number of electron microwave devices require initially rectilinear high-quality electron beams for effective operation. In FEMs such beams are pumped up to sufficiently high operating-oscillation velocity and small initial particle oscillations (cyclotron oscillations if the beam is focused by an axial magnetic field) can lead to a rather large transverse velocity spread and, correspondingly, axial velocity spread. Thus, an acute problem for these devices (essentially more important than for Cherenkov-type devices) is the formation of a beam in which electrons initially move along the axis with minimum oscillations. A new method to form such a beam by a two-electrode axially-symmetrical gun of simple configuration immersed in a uniform axial magnetic field is discussed in this paper. This method allows to improve the quality of an electron beam passing through a narrow anode outlet. It is well-known that the anode aperture acts as an electrostatic lens and disperses the electron beam. In the presence of an axial magnetic field this unwanted dispersing action can be compensated simultaneously for all electrons of the paraxial electron beam by means of a magnetic field generated by a small additional coil placed down-stream from the anode aperture [1,2]. If the coil length is equal to half the electron Larmor step, then the action of the border coil fields comes to two kicks which, being correctly phased, compensate the spurious rotary electron velocities. Computer simulations using the EPOSR-code [3] intended for the calculation of electron guns both for the temperature- and space-charge-limited regimes prove the effectiveness of this method. In particular, for a version of field-emission gun the correcting coil reduces about five times the maximum transverse velocity in the beam. Positive effect from applying this method was proved at a realization of a high-efficiency CARM-oscillator [4].

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A NEW BEAM SOURCE FOR FREE ELECTRON LASERS*

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A high power, high current density and high voltage electron beam was generated with the pseudospark discharge(PS)[1], this is a new beam source for free electron lasers. The design and construction of the pseudospark discharge was described[2], the device has low cost and is easy to fabricate. The experiments are presented, the configuration parameters of the modified pulse line accelerator(PLA) are as follows. The PS hollow cavity has a 3 cm diameter and 4.1 cm long. The discharge chamber consists of planar cathode with hollow cavity, sets of intermediate electrodes and insulators with a common channel, and a planar anode. The electrodes are made of brass and the insulators are made of Plexiglas. The diameter of the channel is 3.2 mm. The anode-cathode gap distance is varied in 10-100 mm. The electron beams have voltage of 200 KeV, current of 2 KA and beam diameter of 1mm. The beam penetrated a 0.3 mm hole on a copper foil of 0.05 mm thick at the distance of 5 cm from the anode and penetrated a 0.6 mm hole on an acid-sensitive film at the distance of 15 cm. A compact free electron laser with a table size is discussed.

* Work supported by the National Natural Science Foundation of China

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HIGH-POWER,HIGH-BRIGHTNESS PSEUDOSPARK-PRODUCED ELECTRON BEAM DRIVEN BY IMPROVED PULSE LINE ACCELERATOR

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A high power(200KV), intense current density,low emittance(71mm mrad), high brightness (8×10^{10}A/(m rad)^2 electron beam was generated in the 10cm long, high-voltage-resistive multi-gap hollow cathode pseudospark chamber filled with 15pa nitrogen and driven by an improved pulse line accelerator. The beam was ejected with the 1mm diameter, the 2.2KA beam current, and the 400ns pulse length, and could propagated 20cm in the drift tube. At a distance of 5cm from the anode it penetrated consecutively an acid-sensitive discoloring film and a 0.05mm-thick copper foil both stuck closely, left 0.6mm and 0.3mm holes on them, respectively. That 10 shots on an acid-sensitive film produced a hole of 1.6mm at 7cm downstream of anode showed its good repeatability.

After 60 shots the pseudospark discharge chamber was disassembled and observed that almost no destructive damage traces left on the surfaces of its various electrodes and insulators. But on almost all the surfaces of changeable central hole parts installed on intermediate electrodes there are traces of electron emission from the sides facing the anode and of bombardment on the sides facing the cathode, in contrast with which on the front- and back-surfaces of hollow cathode no visible traces of electron emission from them was observed. In addition, there were different tints, strip-like regions on the side of anode facing the cathode.

Another interesting phenomenon was that there were a set of concentric circular or elliptical ring pattern on the acid-sensitive discoloring film got at 5cm from the anode and observed under a metallograph. It seems that the pseudospark electron beam is Laminar beam i.e, being possessed of a multi-layer structure, at least in the case of multi-gap pseudospark discharge chamber.It was found experimentally that the quality of pseudospark electron beam is much better than that of the cold-cathode electron beam.

This high-quality pseudospark electron beam will be used to improve the efficiency of our Raman FEL and for soft X-ray laser research.

CARBON-FIBER LOW-VOLTAGE ELECTRON GUNS

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Carbon-fiber cathodes are used in cold electron-guns in our laboratory. They operate in low-voltage (< 10 kV) free-electron maser and cyclotron-resonance maser experiments. The paper presents $I - V$ characteristics of various carbon-fiber electron-guns and show results of the corresponding maser experiments.

STRATEGIES FOR MINIMIZING EMITTANCE GROWTH IN HIGH CHARGE CW FEL INJECTORS*

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This paper is concerned with the best strategies for designing low emittance, high charge CW FEL injectors. This issue has become more and more critical as today's interest in FELs is toward UV wavelength high average power operation. The challenge of obtaining the smallest possible emittance is discussed from both the practical point of view and the beam physics point of view. Various mechanisms responsible for beam emittance growth are addressed in detail. Finally, the design of a high charge injector test stand at CEBAF is chosen to help illustrate the design strategies and emittance growth mechanisms discussed in this paper.

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A PHOTOCATHODE RF GUN FOR X-RAY FEL

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A 1.6 cell photocathode RF gun was developed by a BNL/SLAC/UCLA collaboration for X-ray FEL and other applications. The objective of the collaboration is to develop a cost effective and more reliable photocathode RF gun based on the operational experience of the original BNL gun. The new photocathode RF gun is cable of producing 1 mm-mrad normalized rms emittance photocurrent with a peak current of 100 A. The half-cell length of the new RF gun was lengthened to reduce the peak field on the cavity surface, the side-coupled scheme for cavity and waveguide coupling was replaced by a symmetrized coupling to the full-cell. The cavity aperture was increased to improve the coupling between two cells and for flat beam application. The experimental results of cold testing the RF gun will be presented. We will also present an injector design based on the new photocathode RF gun and emittance compensation technique.

NEXT LINEAR COLLIDER TEST ACCELERATOR INJECTOR UPGRADE*

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The Next Linear Collider Test Accelerator (NLCTA) is being constructed at SLAC to demonstrate multibunch beam loading compensation, suppression of higher order deflecting modes and measure transverse components of the accelerating fields in X-band accelerating structures. Currently a simple injector which provides the average current necessary for the beam loading compensations studies is under construction. An injector upgrade is planned to produce bunch trains similar to that of the NLC with microbunch intensity, separation and energy spread, identical to that of NLC. We discuss the design of the NLCTA injector upgrade.

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AN EXPERIMENTAL STUDY ON MICROWAVE ELECTRON GUN

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We report both the simulation and experimental results of using a ring cathode instead of the solid cathode to reduce the back bombardment effect of a thermionic cathode microwave electron gun. The result shows that the back bombardment power is decreased about 2/3 without changing the beam quality apparently which allows operation at higher repetition rate. Experimental results are compared with the simulation with good agreement.

PROGRESS IN THE INJECTOR FOR FEL AT CIAE

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An intense current RF-linac for the far-infrared FEL is now under construction at CIAE. The normalized brightness of 3.4×10^9 A/(m-rad)^2 was obtained from the injector of the linac. An acceleration section with 9 cells will be connected with the injector to provide an electron beam for the 200 μm FEL oscillator. In this paper, the late results from the injector beam test will be reported. The physical design and research progress in the acceleration section, beam transport, undulator as well as optical cavity will be introduced respectively.

BEAM TRANSPORT FOR AN SRF RECIRCULATING-LINAC FEL*

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The beam transport system for the CEBAF UV Demo FEL includes a two-pass transport of the beam with acceleration from injector to wiggler, followed by energy recovery transport from wiggler to dump. From that context, we discuss the general problem of multi-pass energy-recovery beam transport for FELs. Tuneable, nearly-isochronous, large-momentum-acceptance transport systems are required. The entire transport must preserve beam quality, particularly in the acceleration transport to the wiggler, and have low losses throughout the entire system. Issues such as injection and final energies, number of passes, linac focusing effects, beam separation, chronicity management, and stability constraints are critical. Various possible designs are discussed. Particle tracking results exploring the design options are also reported.

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CURRENT STATUS OF THE SUPERCONDUCTING RF LINAC DRIVER FOR THE JAERI FREE ELECTRON LASER FACILITY

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The commissioning of the superconducting rf linac driver for the JAERI free electron laser facility has been successfully performed at 10~20 MeV before the end of the1994 Japanese fiscal year. The performances obtained during the commissioning and current status of the JAERI FEL program at Tokai will be reported in detail.

SENSITIVITY AND ALTERNATIVE OPERATING POINT STUDIES ON A HIGH CHARGE CW FEL INJECTOR TEST STAND AT CEBAF*

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A high charge CW FEL injector test stand is being built at CEBAF based on a 500 kV DC laser gun, a 1500 MHz room-temperature buncher, and a high-gradient (~10 MV/m) CEBAF cryounit containing two 1500 MHz CEBAF SRF cavities. Space-charge-dominated beam dynamics simulations show that this injector should be an excellent high-brightness electron beam source for CW UV FELs if the nominal parameters assigned to each component of the system are experimentally achieved. Extensive sensitivity and alternative operating point studies have been conducted numerically to establish tolerances on the parameters of various injector system components. The consequences of degraded injector performance, due to failure to establish and/or maintain the nominal system design parameters, on the performance of the main accelerator and the FEL itself are discussed.

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THE MARK III IR FEL: IMPROVEMENTS IN PERFORMANCE AND OPERATION*

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The Mark III IR FEL has been upgraded by the installation of a new thermionic microwave gun. The new gun yields a reduced emittance and allows operation at a higher repetition rate and an increased electron macropulse length. The RF system of the Mark III has also been phase-locked to the RF system of the adjacent storage ring driver for the laboratory's short-wavelength FEL sources, making possible two-color UV-IR pump probe experiments. In this paper, the design and performance of the new gun are presented and the implications of the improvements investigated.

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SSRL PHOTOCATHODE RF GUN TEST STAND

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A photocathode RF gun test stand designed for the production and study of high brightness electron beams will be constructed at SSRL. The beam will be generated from a laser driven third generation photocathode RF gun being developed in collaboration with BNL, LBL and UCLA. The 3-5 [MeV] beam from the gun will be accelerated using a SLAC three meter S-band accelerator section. In order to achieve the desired low emittance beam, emittance compensation with solenoidal focusing will be employed. The test stand will allow the study of emittance compensation and emittance measurement through the use of quadrupole scans with phosphor screens and wire scanners, and also pepper-pots. The bunch length measurements will be derived from a streak camera and autocorrelation of measurements of coherent transition radiation. Also photocathode materials studies may be performed. Initially, a Nd:YLF drive laser may be used and the final drive laser is to be a Ti:Sapp. The design goals of the photocathode RF test stand are a normalized emittance of 1-3 [mm-mrad], longitudinal bunch duration of the order of 3 [ps] and approximately 10^{-9} [C/bunch]. A primary motivation for this test stand is to develop the high brightness photoinjector system for the Linac Coherent Light Source (LCLS) project at SLAC.

HIGH POWER TESTING OF A 17 GHz PHOTOCATHODE RF GUN*

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The physics and technological issues involved in high gradient particle acceleration at high microwave (RF) frequencies are under study at MIT. The 17 GHz photocathode RF gun has a 1½ cell (π mode) room temperature copper cavity. High power tests have been conducted at 5-10 MW levels with 100 ns pulses. A maximum surface electric field of 250 MV/m was achieved. This corresponds to an average on-axis gradient of 150 MeV/m. The gradient was also verified by a preliminary electron beam energy measurement. Even higher gradients are expected in our next cavity design. More than 80,000 pulses were accumulated in the RF conditioning process. The anticipated beam parameters, when operating with a photoemission cathode, are: energy 2 MeV, normalized emittance 0.43 π mm-mrad, energy spread 0.18, bunch charge 0.1 nC, and bunch length 0.39 ps. Status of the laser system and the integration with the RF gun system will be described. In addition to advancing the knowledge of particle acceleration at high field gradients, the research may lead to the generation of high quality electron beams suitable for applications in next generation linear colliders and free electron lasers.

* This research is supported by DOE under grant DE-FG02-91-ER40648

A COMPACT HIGH-GRADIENT 25 MeV 17 GHz RF LINAC FOR FREE-ELECTRON LASER RESEARCH

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A new compact high-gradient (60 MeV/m) high-frequency (17.136 GHz) RF linac is presently under construction by Haimson Research Corp. (HRC) for installation at the MIT Plasma Fusion Center in the High-Gradient Accelerator and High Power Microwave Laboratory. This accelerator will utilize an existing traveling-wave relativistic klystron (TWRK) which is now operating at MIT with 25 MW power, 67 dB gain, and 52% efficiency at 17.136 GHz. The new accelerator will have two options for an injector: a 17 GHz photocathode RF Gun being developed at MIT and a separate high-performance injector being designed and fabricated by HRC under the auspices of the DOE SBIR program. The projected accelerator performance with the HRC injector is for 1 μs macropulses of 250 mA, with micropulse spacing of 58.4 ps and approximately 100 A peak current using sub-picosecond electron bunches. This system will provide a state-of-the-art accelerator for the development of a high-performance FEL for a variety of basic research and medical applications.

E-BEAM DYNAMICS CALCULATIONS AND COMPARISON WITH MEASUREMENTS OF A HIGH DUTY ACCELERATOR AT BOEING*

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The electron dynamics in the photoinjector cavities and through the beamline for a high duty factor electron accelerator[1] are computed. The "particle in a cell" code ARGUS[2], is first used in the low energy (<2 MeV) region of the photoinjector, then the ARGUS-generated phase space at the photoinjector exit is used as input in the standard "particle pusher" code PARMELA[3], and the electron beam properties at the end of the beamline computed. Comparisons between the calculated and measured electron beam radial profiles and emittances are presented for different values of the electron pulse charge. A discussion of the methodology used and on the accuracy of PARMELA in the low energy region of the photoinjector is given.

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THE BOEING PHOTOCATHODE ACCELERATOR MAGNETIC PULSE COMPRESSION AND ENERGY RECOVERY EXPERIMENT*

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An 18 MeV, photocathode accelerator operating at 433 MHz is being commissioned for FEL applications. The accelerator consists of a two-cell RF photocathode injector[1] followed by four new multicell cavities[2]. The two cell injector has previously been operated at a micropulse repetition frequency of 27 MHz, a micropulse charge of 5 nC and 25% duty factor[3]. In the present experiment[4], the inclusion of a third harmonic RF linearizer (operating at 1300 MHz) allows the tailoring of flat-topped micropulse shapes with high peak current[5]. This pulse shaping leads to optimal FEL efficiency as discussed in reference 6. The 1300 MHz linearizer can also be used in a simple experiment to investigate energy recovery for high power and efficient FEL's. In this test, proper RF phasing of the drive laser micropulses allows the 1300 MHz accelerator section to simultaneously accelerate and decelerate every other micropulse. The physics and technical details of preparing the longitudinal phase space for pulse compression and energy recovery in an RF linac will be discussed.

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LONGITUDINAL PHASE SPACE EXPERIMENTS ON THE ELSA PHOTOINJECTOR

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The excellent beam quality produced by RF photocathode injectors is well-established, and has been verified by numerous measurements of the transverse emittance. However, there are few experimental determinations of the longitudinal phase space. This paper reports on experiments performed at the ELSA FEL facility to measure the longitudinal phase space distribution at the exit of the 144 MHz photoinjector cavity. Phase spaces were determined by the analysis of beam energy spectra and pulse shapes at 17.5 MeV for micropulse charges between 0.5 and 5 nC. Additional data has been obtained at lower beam charges but with higher peak current densities at the photocathode. A simple ray tracing model[1] was used to transform the injector phase space through the accelerator and around a 180 degree, three dipole, non-isochronous bend. The phase space parameters at the injector exit are varied to fit the data at 17.5 MeV. The data analysis shows the energy spread of the beam at the injector exit increases for the peak current densities from 100 to 400 A/cm^2, while the pulse length remains essentially unchanged. The increased energy spread is explained by additional acceleration produced by the space charge electric field. At 600 to 1000 A/cm^2, the pulse dissociates into multiple pulses separated by 40 to 90 ps. The paper argues the multiple pulses result from a combination of pulse length elongation and the formation of a "virtual cathode"[2]. This is the first observation of these effects in an RF photoinjector, and their importance relative to using pulse compression to achieve high peak current is discussed[3].

1. S. Joly et al., "Brightness Measurements of the ELSA Electron Beam", Contribution to the 1994 Linear Accelerator Conference, Tsukuba, Japan.
2. R.B. Miller, "An Introduction to the Physics of Intense Charged Particle Beams", Plenum Press, 1982, pages 97-105 and references contained therein.
3. D.H. Dowell et al., "Magnetic Pulse Compression Using a Third Harmonic RF Linearizer", Contribution to the 1995 Particle Accelerator Conference, Dallas, TX.

GHz REPETITION RATE TABLETOP X-BAND PHOTOINJECTOR FOR FREE-ELECTRON LASER APPLICATIONS*

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A 1-1/2 cell π-mode X-band (8.568 GHz) photoinjector system capable of producing trains of up to one hundred, 1 nC, 1ps, 5 MeV, $\varepsilon_n < 2.5\ \pi$ mm-mrad photoelectron bunches, at a micropulse repetition rate of 2.142 GHz (one bunch every fourth rf period), and a macropulse repetition rate of 1-10 Hz, is currently under development at LLNL, in the UC Davis DAS coherent millimeter-wave group. The system is powered by a 20 MW, 8.568 GHz SLAC development klystron. The system also uses a Cs_2Te (Cesium Telluride) photocathode which has a quantum efficiency > 5% in the UV (210 nm). The compact UV laser system is composed of a synchronously modelocked AlGaAs semiconductor laser oscillator which produces pulses with a duration of 250 fs and 100 pJ energy at 830nm, at a repetition rate of 2.142 GHz with less 400 fs jitter, a 5 GHz bandwidth Lithium Niobate Mach-Zender fiber modulator, an 8-pass, 10^6 gain, $Ti{:}Al_2O_3$ (Titanium:Sapphire) chirped pulse amplifier, and 2 BBO frequency doublers in series to quadruple the laser frequency into the UV (207 nm). The applications of this photoinjector range from the generation of picosecond pulses of coherent synchrotron radiation in a waveguide free-electron laser (chirped pulse FEL) to laser-based electron acceleration. In addition, to further increase the compactness, efficiency and reliability of the photoinjector facility, we are currently investigating the feasibility of upgrading the klystron-powered room-temperature linac to a very compact, magnetron-driven, cryogenic photoinjector, and to use diode-pumped LiSAF for the UV laser system. The combination of both upgrades will yield a relatively inexpensive breakthrough technology to build truly "tabletop", laser-synchronized, sources of ultrashort relativistic electron bunches that could be used by universities for research.

*This work is supported in part by AFOSR (ATRI) under Grant No. F30602-94-2-0001, in part by ARO under Grant No. DAAHO4-93-0084, and in part by LLNL/LDRD Contract No. W-7405-ENG-48.

THE SPARTIAL DISTRIBUTION OF THE PARTICLES OF THE BEAM INTERACTING WITH AN INHOMOGENEOUS ELECTROMAGNETIC WAVE

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The time variation of the spartial distribution of an electron beam reflected by an inhomogeneous wave or traverse the wave was investigated. The injected beam is perpendicular to the direction of propogation of the wave. The interaction between an electron beam and an electromagnetic wave not only produces electron oscillation but also substantially changes the electron phase and energy distribution. It is shown that under specific conditions one part of particles are reflected by an electromagnetic wave and other part of particles traverse the wave.

THE SPECTRAL-ANGULAR AND POLARIZATION CHARACTERISTICS OF RADIATION FROM AN ELECTRON BEAM TRAVERSING AN INHOMOGENEOUS ELECTROMAGNETIC WAVE

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The generation of frequency harmonics of a radiation when the electron beam traverse the inhomogeneous electromagnetic wave was investigated. The electromagnetic wave are linearly polarized. The plane beam of particles enters the wave at right angle with respect to the direction of propogation of the wave and the vector E of the wave. The spartial distribution of radiation from the higher harmonics and the power density contours are caculated.

LATTICE DESIGN OF A QUASI-ISOCHRONOUS RING FOR A STORAGE-RING FEL*

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Design work for a Quasi-Isochronous Ring (QI-Ring) dedicated to Storage-Ring FELs in Electrotechnical Laboratory has been completed. The motivation for this work is to shorten the electron bunch length in order to get a high peak current in a compact Storage-Ring (SR). By placing an inverted dipole field in a location where the energy dispersion function is relatively large, one can reduce the momentum compaction factor (α) and shorten a bunch length in a SR. The main requirements for the QI-Ring are: 1.5GeV maximum beam energy; 80m circumference; two 10m-long dispersion free straight sections for insertion devices; a few meters dispersion free straight sections for RF cavities and injection bumpers; and a wide tune ability in betatron functions and momentum compaction factor (α). As shown in figure 1, the lattice includes two 49 degree, 3 T superconducting bending magnets to reduce the circumference of the ring, a -8 degree normal inverted dipole magnet (ID), 4 families quadrupole magnets (QF, QD, QFA, QDA), and 3 families sextupole magnets. Each quadrupole family has a specific function: QF & QD control the betatron tunes, and QFA & QDA control the α and suppress the energy dispersion in a straight section. In this type of ring it is important to compensate the second order momentum compaction factor (α_2), so at least three families of sextupoles are required. The main machine parameters are summaries as:

Momentum Compaction α	variable
(1×10^{-3} to negative value),	
Maximum Energy	1.5 GeV ,
Natural Emittance	0.66 μm-rad
(at 1.5 GeV),	
Natural Bunch Length	51 μm
(at $\alpha = 2\times10^{-7}$, variable),	
Circumference	82.36 m.

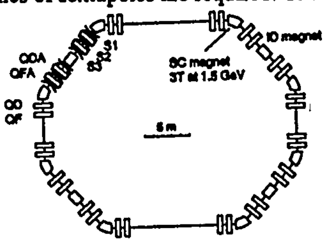

Fig.1 Schematic view of QI-Ring

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THE PERFORMANCE OF THE DUKE FEL STORAGE RING*

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The commissioning of the Duke FEL storage ring has been completed. During commissioning, we have conducted a series of performance measurements on the storage ring lattice and the electron beam parameters. In this paper, we will discuss the techniques used in the measurements, present measurement results, and compare the measured parameters with the design specifications. In addition, we will present the expected OK-4 FEL performance based on the measured beam parameters.

* Work Supported by Office of Naval Research Grant #N00014-94-1-0818.

A STUDY OF INFLUENCE OF STOHASTIC PROCESS ON THE SYNCHROTRON OSCILLATIONS OF A SINGLE ELECTRON CIRCULATED IN VEPP-3 STORAGE RING.

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Last year measurements of the single electron longitudinal motion were performed. The pictures of the synchrotron oscillations for long time were obtained and handled. The results of experiments are demonstrate the character of the diffusion on the phase space, caused by quantum fluctuations of synchrotron radiation.

IMPROVEMENT OF CURRENT LIMITATION IN THE STORAGE RING NIJI-IV

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The storage ring NIJI-IV dedicated to free-electron lasers was completed in December 1990. Lasing at 595-352 nm by using the NIJI-IV was accomplished by April 1994.

The NIJI-IV has 16 rf-buckets. The electron bunch contributed to FEL gain of the NIJI-IV is only one of 16. In order to get the redundant bunch, make beam quality better, and make the FEL operation easier, a single bunch injection(SBI) system by using a short pulse beam from an electron gun was prepared. The quality of the beam accelerated and bunched by a buncher section has already been investigated. It was convinced that the accelerated short pulse beam satisfies the performance required on the SBI of the NIJI-IV.

At present, the operation of the SBI system is being tested. Storage efficiency(the ratio of storage current to injection current) and limitation of storage current by using the SBI system will be reported in this conference. We expect lasing at below 352nm by the SBI.

A 3 GHz PHOTOELECTRON GUN FOR HIGH BEAM INTENSITY

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The CLIC Test Facility (CTF) for new accelerator structures of the proposed Compact Linear Collider (CLIC) is to be equipped with a new RF gun containing a laser driven photocathode. The new 3 GHz gun with photocathode shall produce a bunch train of 48 electron bunches of 25 nC charge each with a bunch length of 8 - 15 ps fwhm. The new RF gun consists of $2^1/_2$ cells and accelerates the beam to an energy of 7 MeV with a peak field gradient Ez = 100 MV/m. The strong space charge forces at low beam energy caused by the high charge density of the electron bunches must be contained by radial and longitudinal RF focusing in the RF gun. Radial RF focusing is applied by a conical backplane around the photocathode in the first cell where the electrons have a low energy. Longitudinal RF focusing is obtained by varying the length of each of the three cells of the gun.The total electric charge of the bunch train exceeds 1 μC and causes strong beam loading to the RF structures so that the stored energy is reduced to half of the unloaded RF energy. The RF gun under construction is being optimized by MAFIA beam simulations for an injector assembly comprising a second accelerating RF structure of 4 cells and an intermediate solenoid magnet correcting the beam divergence of the $2^1/_2$ cell gun. The scheme with two accelerating RF sections will provide a linear energy increase along the bunch suitable for further compression of the bunch length in a magnetic chicane.

CYCLOTRON RESONANCE COOLING BY STRONG LASER FIELD

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Abstract

Reduction of energy spread of electron beam is very important to increase a total output radiation power in free electron lasers. Although several cooling systems of particle beams such as a stochastic cooling are successfully operated in the accelerator physics, these cooling mechanisms are very slow and they are only applicable to high energy charged particle beams of ring accelerators.

We propose here a new concept of laser cooling system by means of cyclotron resonance. Electrons being in cyclotron motion under a strong magnetic field can resonate with circular polarized electromagnetic field, and the resonance take place selectively depending on the velocity of the electrons. If cyclotron frequency of electrons is equal to the frequency of the electromagnetic field, they absorb the electromagnetic field energy strongly, but the other electrons remain unchanged. The absorbed energy will be converted to transverse kinetic energy, and the energy will be dumped into the radiation energy through bremsstrahlung.

To build a cooling system, we must use two laser beams, where one of them is counter-propagating and the other is co-propagating with electron beam. When the frequency of the counter-propagating laser is tuned with the cyclotron frequency of fast electrons and the co-propagating laser is tuned with the cyclotron frequency of slow electrons, the energy of two groups will approach and the cooling will be achieved.

We solve relativistic motions of electrons with relativistic radiation dumping force, and estimate the cooling rate of this mechanism. We will report optimum parameters for the electron beam cooling system for free electron lasers.

Diagnostics and Electron-Optics of a High Current Electron Beam in the TANDEM Free Electron Laser - Status Report

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abstract

In the construction of the Israeli TANDEM FEL the major task is to develop a high quality electron optic system. The goal is to focus the e-beam to a minimal radius (1mm) in the interaction region (the wiggler). Furthermore, good focusing throughout the accelerator is essential in order to achieve high transport efficiency avoiding discharge and voltage drop of the high voltage terminal.

We have completed the electron optical design and component procurement, including 8 quadrupole lenses 4 steering coils and an electrostatic control system. All are being assembled into the high voltage terminal and controlled by a fiber optic link. Diagnostic means based on fluorescent screens and compact CCD camera cards placed at the HV terminal and at the end of the e-gun injector have been developed. We report first measurements of the beam emittance at the entrance to the Tandem accelerator tube using the "pepper pot" technique. The experiment consists of passing the 0.5 Amp. beam through a thin plate which is perforated with an array of 0.5 mm holes. The spots produced on a fluorescent screen placed 90 cm from the pepper pot were recorded with a CCD camera and a frame grabber. The measured normalized emittance is lower than 10π mm·mR which is quite close to the technical limit of dispenser cathode e-guns of the kind we have.

Recent results of the measured transport efficiency and the diagnostics of the high current (1A, 1.5MV) electron-optical system will be reported.

DIFFRACTION AND PULSE SLIPPAGE IN THE BOEING 1 kW FEL OSCILLATOR

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ABSTRACT

A four-dimensional simulation in x, y, z, and t, including betatron motion of the electrons, is used to study the combined effects of diffraction, pulse slippage and desynchronism in the Boeing 1 kW FEL oscillator.

THE TRAPPED-PARTICLE INSTABILITY IN THE BOEING 1kW FEL OSCILLATOR

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ABSTRACT

The new design for the Boeing High Average Power Free Electron Laser will operate at 1 KW average power (0.63 μm) with a peak current of 132A. Simulations are used to investigate the trapped-particle instability and diffraction effects. Incorporating large desynchronism may prove to be a useful method of controlling the trapped-particle instability.

ENERGY STABILITY IN A HIGH AVERAGE POWER FEL*

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Recirculating, energy-recovering linacs can be used as driver accelerators for high power FELs. Instabilities which arise from fluctuations of the cavity fields or beam current are investigated. Energy changes can cause beam loss on apertures, or, when coupled to M_{56}, phase oscillations. Both effects change the beam induced voltage in the cavities and can lead to unstable variations of the accelerating field. Stability analysis for small perturbations from equilibrium is performed and threshold currents are determined. Furthermore, the analytical model is extended to include feedback. Comparison with simulation results derived from direct integration of the equations of motion is presented. Design strategies to increase the instability threshold are discussed and the UV Demo FEL, proposed for construction at CEBAF, and the INP Recuperatron at Novosibirsk are used as examples.

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ELECTRON BEAM EFFECTS IN A UV FEL

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ABSTRACT

At the Continuous Electron Beam Accelerator Facility (CEBAF), a free electron laser (FEL) is designed to produce ultraviolet (UV) light. A four-dimensional FEL simulation studies the effects of betatron oscillations, external focusing, and longitudinal pulse compression of the electron beam on the FEL performance.

MULTI-STAGE FEL AMPLIFIER WITH DIAPHRAGM FOCUSING LINE AS DIRECT ENERGY DRIVER FOR INERTIAL CONFINEMENT FUSION

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An FEL based energy driver for Inertial Confinement Fusion (ICF) is proposed. The key element of the scheme is free electron laser system. Novel technical solutions, namely, using of multi-channel, multi-stage FEL amplifier with diaphragm focusing line, reveal a possibility to construct the FEL system operating at radiation wavelength $\lambda = 0.5\ \mu$m and providing flush energy $E = 1$ MJ and brightness 4×10^{22} W cm^{-2} sr^{-1} within steering pulse duration $\tau \sim 0.1 - 2$ ns. Total energy efficiency of the proposed ICF energy driver is about of 11% and repetition rate is 40 Hz. It is shown that the FEL based ICF energy driver may be constructed at the present level of accelerator technique R&D.

ANALYSIS OF THE EIGENVALUE EQUATION OF THE FEL AMPLIFIER WITH AXISYMMETRIC ELECTRON BEAM AND DIAPHRAGM FOCUSING LINE

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The paper presents analysis of the eigenvalue problem of the FEL amplifier with axisymmetric electron beam and diaphragm focusing line. An FEL model is discussed wherein diffraction effects, space charge fields and energy spread of electrons in the beam are taken into account. To take into account diffraction effects at the diaphragms we apply the rigorous impedance boundary conditions proposed by Veinstein. The rigorous solutions of the eigenvalue problem have been found for the stepped and bounded parabolic electron beam profiles. Analytical expressions for eigenfunctions of active open waveguide and formulae of their expansion in eigenfunctions of passive open waveguide, are derived, too. Asymptotic behaviour of the obtained solutions is studied in details. The multilayer approximation method has been used to solve the eigenvalue problem for the beams with an arbitrary gradient profile of current density.

This novel type of an FEL amplifier has perspective to be used for applications where high average and peak radiation power is required.

STRUCTURE OF THE SPONTANEOUS EMISSION SPECTRA OF HIGH-γ FREE ELECTRON LASERS AS MEASURED AT THE DARMSTADT (S-DALINAC) FEL[1]

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Recent spontaneous emission measurements at the Darmstadt infrared FEL indicate a relatively broad (down-shifted) spectrum with several intensity maxima. The typical features of the measured spectrum can be well reproduced by a numerical simulation comprising the 3-d electron dynamics in a realizable planar wiggler field, the spontaneous radiation according to the well-known Jackson formula, as well as the detection of the radiation with a finite aperture detector. An analytical consideration attributes the observed down-shift to the reduced Doppler up-shift of the radiation as observed under a finite angle with respect to the axis. The intensity peaks appear as a consequence of a modulation of the transverse velocity amplitudes of the electrons due to the betatron oscillation. The spectral spacing of these "sidebands" are roughly given by the Doppler up-shifted betatron frequency. Consequences for very high energy FELs will be discussed.

[1]Supported by the BMFT contract number 05 345 EAI and the European Network contract number SC1-0471(CA)

ON A THEORY OF AN FEL OSCILLATOR WITH MULTICOMPONENT UNDULATOR

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Some novel results of a theory of an FEL oscillator with multicomponent undulator are presented. Two popular FEL oscillator configuration are under consideration: optical klystron and FEL oscillator with a prebuncher and tapered main undulator. Using similarity techniques, universal formulae and plots are obtained which allow one to calculate the FEL oscillator lasing conditions and output parameters at saturation.

SOME NOVEL FEATURES OF AN FEL OSCILLATOR WITH TAPERED UNDULATOR

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A one-dimensional analysis of an FEL oscillator with a linear undulator tapering is presented. Some principally novel results have been obtained. The origin of these results is in principal difference between the FEL oscillator and an FEL amplifier. In the case of the FEL amplifier the frequency of the amplified wave and all the other parameters are defined by an experimenter. Contrary to this, the case of the FEL oscillator with tapered undulator is more complicated. The lasing frequency is defined by the maximum of the small-signal gain and depends on the tapering depth in some complex way. In particular, at smooth increasing of the tapering depth, the lasing frequency may change by a leap and lasing occurs at another local maximum of the gain curve. This effect influences significantly on the FEL oscillator operation at saturation. As a result, generally accepted method of undulator tapering (for instance, by decreasing undulator field at fixed period) provides an efficiency increase only in a narrow range of the parameters of tapering. We show that in some cases, so called "negative tapering" (for instance, by increasing undulator field at fixed period) has a benefit against traditional tapering method. Ignoring of these basic features of the FEL oscillator with the tapered undulator have led many FEL research groups to nonoptimal design of the FEL experiments and incorrect interpretation of the obtained results.

NONLINEAR THEORY OF A PLASMA CHERENKOV MASER

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The nonlinear saturation state in a plasma Cherenkov maser(PCM), propagating the intense relativistic electron beam through a circular waveguide partially filled with a dense annular plasma, is analyzed from the nonlinear formulation[1] based on the cold fluid-Maxwell equations. We obtain the nonlinear efficiency and the final operation frequency under consideration of the effects of the beam current, the beam energy and the slow wave structure. We show that the saturation mechanism of a PCM instablity is a close correspondence in that of the relativistic two stream instability[2] by the coherent trapping of electrons in a single most-ustable wave. And the optimal conditions in PCM operation are also obtained from performing our nonliear analysis together with computer simulations.

[1] B.-H. Hong, S.-K. Kim, J.-S. Choi and D.-I. Choi, Nucl. Instr. & Meth. **A341**, ABS105 (1994).
[2] Martin Lampe and P. Sprangle, Phys. Fluids **18**, 475 (1975).

NONLINEAR SATURATION CHARACTERISTICS OF A DIELECTRIC CHERENKOV MASER

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The nonlinear saturation state in a dielectric Cherenkov maser (DCM) with the TM mode and the intense relativistic electron beam is analyzed from the nonlinear formulation[1] based on the cold fluid-Maxwell equations. We obtain the nonlinear efficiency and the final operation frequency under consideration of the effects of the beam current, the beam energy and the dielectric materials and show that the characteristics of a DCM instablity has a strong resemblance to that of the relativistic two stream instability by the coherent trapping of electrons in a single most-ustable wave. Finally, the nonlinear analysis shows that the Cherenkov maser operation with a lower-energy beam can be more efficient in the higher frequency regime for the case of the high power DCM with a high current.

[1] B.-H. Hong, S.-K. Kim, J.-S. Choi and D.-I. Choi, Nucl. Instr. & Meth. **A341**, ABS105 (1994).

THE MAGNETORESONANCE OPERATION OF MICROWIGGLER ON THE PIEZOELECTRICS WITH A STRONG MAGNETIC GUIDE FIELD

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We proposed that a new type of the electrostatic microwiggler[1] with a wiggler period ($0.1\text{mm} \leq l_w \leq 1\text{mm}$) and the wiggler field strength ($E_w \leq 100$ kV/m) can be produced on the surface of a PZT when a high power and high frequency ultrasonic wave travels through a PZT bar. Numerical simulations in the linear and nonlinear gain regime show that a weak microwiggler ($E_w \approx 100$ kV/m, $\lambda_w \approx 1$mm, 100 periods), operating in magnetoresonance[2] with a strong guide field ($B_0 \approx 3.6$T), can generate millimeter and submillimeter radiations with medium electronic efficiency of few percents. It is shown that the maximum output power of the compact FEL using the wiggler system generated on the surface of the piezoelectric material may be upto a few Watts with a relatively low energy and low current electron beam ($E_w \approx 100$ keV and $I_b \approx 1$mA).

[1] J.- S. Choi, C.-H. So, J.-D. Moon, D.-R. Kim, Y.-H. Ko, H.-T. Chung, J. Kor. Phys. Soc. **28**, 32 (1995).

[2] G. Spindler and G. Renz, Phys. Plasma **1**, 398 (1994).

DESIGN OF A DEMONSTRATION EXPERIMENT ON THE WIDE-BANDWIDTH HIGH-POWER DIELECTRIC CHERENKOV MASER AMPLIFIER

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Hardware is being developed for an experiment that will demonstrate the -3 dB instantaneous bandwidth of 40-50% for the X-band dielectric Cherenkov maser amplifier driven by a high-current electron beam. Bandwidth dependences on the parameters of an electron beam and dielectric-lined waveguide have been calculated from the system dispersion relation, and the optimal set of parameters yielding large value of the bandwidth has been chosen. One-dimensional nonlinear simulations have been carried out. The output power of 50 MW at the peak gain of 27 dB is planned to be achieved. The wide-bandwidth input coupler has been constructed, and the results of microwave transmission measurements through the no-beam system are presented.

MODE COMPETITION AND MODE CONTROL IN FREE ELECTRON LASERS WITH ONE AND TWO DIMENSIONAL BRAGG RESONATORS

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In the report we present a time domain approach to the theory of FELs with one[1] and two[2] dimensional Bragg resonators. It is demonstrated that traditional 1-D Bragg resonators provide possibilities for effective longitudinal mode control. In particular, simulation of the FEL realized in the joint experiment of JINR (Dybna) and IAP (N.Novgord) confirms achievement of the single mode operating regime with high efficiency of about 20 %. However, 1-D Bragg resonators lose their selectivity as the transverse size of the system is increased. We simulate mode competition in FELs with coaxial 1-D Bragg resonators and observe a progressively more complicated azimuthal mode competition pattern as the perimeter of the resonator is increased. At the same time, using 2-D Bragg resonators for the same electron beam and microwave system perimeter gives very fast establishment of the single frequency regime with an azimuthally symmetric operating mode. Therefore, FELs utilising 2-D Bragg resonators with coaxial and planar geometry may be considered as attractive sources of high power spatially coherent radiation in the mm and sub-mm wave bands.

References

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DEVELOPMENT OF A HIGH AVERAGE POWER, CW, MM-WAVE FEL†

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Important operational attributes of FELs remain to be demonstrated including high average power and single-frequency, extremely narrow-linewidth lasing. An FEL specifically designed to achieve these goals for scientific research applications is currently under construction. Its most salient feature is operation in a continuous-wave (CW) mode with an electrostatically generated, high-current, recirculating, DC electron beam. Parameters are:

λ	1.0 mm
P_{out}	3 KW - ave.
E	2.0 MeV
I_b	2.0 A - DC
I_{loss}	< 1.6 mA
r_{rec}	≥ 99.92 %

The undulator will use a 16 period permanent magnet helical design. The resonator will use a TE_{11} circular waveguide mode, terminated by Bragg reflectors. This results in a short straight beam path with minimal loss.

CW operation implies only one startup, and thus obviates the stochastically generated broad average linewidth. Investigation into and development of line narrowing phenomena will be carried out and are expected to result in extremely narrow linewidth lasing.

CW operation requires highly efficient beam recirculation and high charging current. New charging system technology is being applied to a total of eight charging chains, making available as much as 2 mA of current. Still, many challenges exist and will be addressed in the course of development.

One of the most important aspects of this project is the demonstration of a number of "next generation" concepts for electrostatic accelerator based FELs. These concepts represent an evolutionary path toward practical, compact FELs of the future.

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LIGHTNING CONTROL SYSTEM USING HIGH POWER MICROWAVE FEL

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A research project for developing a thunder lightning control system using an induction linac based high power microwave free electron laser (FEL) started at JAERI. The system will produce weakly ionized plasma rod in the atmosphere by high power microwaves and control a lightning path, away from , e.g., nuclear power stations and rocket launchers.

It has been known that about MW/cm^2 power density is enough for the atmospheric breakdown in the microwave region, and which means high power microwave FEL with GW level output power is feasible for atmospheric breakdown, and accordingly is feasible for thunder lightning control tool with making a conductive plasma channel in the atmosphere. From the microwave attenuation consideration in the atmosphere, FEL of 35GHz(0.13dB/km), 90GHz(0.35dB/km), 140GHz(1.7dB/km), and of 270 GHz(4.5dB/km) are the best candidates for the system. Comparing with other proposed lightning control system using visible or ultraviolet laser, the system using microwave has an advantage that microwave suffers smaller attenuation by rain or snow which always exist in the real atmospheric circumstances when lightning occurs.

Detailed description and feasibility study of the system will be described.

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CONSTRUCTION, TESTING OF THE 1 MW, 130-260 GHz FUSION-FEM

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During the previous 9 months the major part of the Fusion-FEM[1] has been constructed. The 2 MV Insulated Core Transformer, the electron gun, the accelerator, the focusing lenses and the undulator have been tested on-site.

In the present - temporary - set-up, the electron beam line consists of a 12 A, 80 keV thermionic electron gun, a 2 MeV dc accelerator, beam transport optics, the undulator and a collector. The gun is mounted in the high voltage terminal, which is now at -2 MV, and the undulator and mm-wave system are at ground potential outside the SF_6-filled pressure tank. This so-called inverse set-up allows easy access to the larger part of the beam line, the undulator and the mm-wave system, which is important in the conditioning phase. The decelerator and depressed collector are not yet installed.

The design of the electron beam line has been optimised using the GPS particle-tracking code and the TOSCA code. The TOSCA code is used for accurate field calculations of the magnetic lenses. The results are used in the GPS code. The combination of these two codes allows optimization of the lens designs with respect to aberrations, such as to avoid emittance growth.

The mm-wave beam line has been designed, including a Boron-Nitride, Brewster angle, high power, broadband window. The window is designed for transmitting 1 MW of mm-wave power in the frequency range 130 - 260 GHz. Loss power is of the order of a percent.

The first major goal is the transport of the electron beam through the undulator with only a small loss current. We report the final design of the electron beam line, the design of the mm-wave beam line, and the status of construction and testing of the Fusion-FEM.

1. W.H. Urbanus, et al, 16th Int. FEL Conference, Stanford, Aug. 21-26, 1994.

FIRST OPERATION OF A DIELECTRIC-LOADED DOUBLE-STRIPLINE FREE-ELECTRON MASER EXPERIMENT

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A table-top free-electron maser (FEM) experiment based on a dielectric-loaded double-stripline waveguide is presented. It employs a low-energy (8 keV, 0.5 A) electron beam and a folded-foil wiggler ($\lambda_W = 2$ cm). Metal striplines protects the dielectric slabs from the electron beam and support quasi-TEM modes in the waveguide. Radiation output is observed at $f = 3.5$ GHz, in agreement with the dielectric-loaded FEM tuning relation

$$f = \frac{\beta_z}{1 - \beta_z\sqrt{\epsilon_{eff}}}\frac{c}{\lambda_W}.$$

The effective dielectric constant of the stripline waveguide is found in cold measurements as $\epsilon_{eff} \cong 6$. Experimental results of the FEM oscillator are presented and compared with theory.

BEAM QUALITY AND WAVELENGTH LIMITATION IN VISIBLE AND UV FEL OSCILLATIONS

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The FELI linac beam has succeeded in visible-FEL oscillation on the third harmonics at 0.64 μm using a 3-m undulator and a 6.72-m optical cavity with two Au-coated mirrors in Feb. 28, 1995. The beam is a 68-MeV, 40-A electron beam with a normalized emittance of 26π mm•mrad and a relative energy spread of 1%. The electron gun of the FELI linac is a 150-kV thermionic triode gun triggered by a 22.3125-MHz, 500-ps pulser. In 1993, an ultraviolet (UV) FEL oscillation was already achieved on the third harmonics at 0.37 μm using a 46-MeV, 130-A electron beam with a normalized emittance of 3π mm•mrad and a relative energy spread of 0.24% from the APEX L-band linac with an rf photocathode electron gun. However, we are now trying to achieve an FEL oscillation in the UV range using the FELI linac with the thermionic gun because of long-life, easy-operation, and low-cost of the thermionic gun, as the FELI ring with 9.8-m long straight sections capable of storing a long lived 1-A beam is in the design stage[1].

Recent experimental and theoretical results on relations between beam quality and short wavelength FEL oscillations have been also reviewed and wavelength limitations due to normalized emittance and relative energy spread are discussed.

[1] T. Tomimasu, et al.: Proc. HEACC '92 (Hamburg, July 20-24, 1992) p.1133

OPTICAL PROPERTIES OF MID-INFRARED FELs FROM THE FELI FACILITY I

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The FELI Facility I has succeeded in mid-infrared FEL oscillation at 6 μm using a 30-MeV, 42-A electron beam from the FELI S-band linac in Oct. 31, 1994. The FELI Facility I is composed of a 2-m vertical type undulator (λ_u=3.4cm, N=58, K_{max}=1.55, gap length≧14mm) and a 6.72-m optical cavity. It can cover the wavelength range of 5-20 μm. The FELs can be delivered from the optical cavity to the diagnostics room through a 50-m evacuated optical pipeline. Wavelength and cavity length dependences of optical properties such as peak power, average power, spectrum width, subpulses in FEL macropulse, FEL transverse profile are reported.

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"HOT" - ELECTRON LASER USING A BRAGG REFLECTION OF ELECTRONS.

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Authors of paper (1) have suggested developing FEL which uses hot ballistic electrons in a superlattices under the assumption that the superlattices is short, equivalently, one would be dealing with the motion of electrons within a single band. The single-band model is valid if the reflection coefficient of the superlattices less unit. In the present paper analyze a "hot"-ballistic-electron laser under the condition that there is a Bragg reflection of electrons from the superlattices or, equivalently, under the condition that the energy of a hot electron is close to the bottom of one of the quasibands of the superlattices. In this case the interaction of the electron with the superlattices is not weak and the reflection coefficient is approximately unit. If the photon energy is greater than the width of the quasigap "vertical" transitions can occur between the edges of neighboring quasibands, corresponding to a stimulated emission. If the lower quasiband is not filled, there would be essentially no absorption. The IR gain in the area 0.1- 0.4 eV is approximately 100 %. The possibility of experimentally observing the effect is discussed for realistic values of the parameters of the superlattices and of the injected electron beam.

1.Yu.A. Malov, D.F. Zaretsky, Abstracts 16th Laser Conference. International Free Electron.

NEW RESULTS OF THE "CLIO" INFRARED FEL USING THE NEW UNDULATOR "OMIR" AND A HOLE COUPLING EXTRACTION

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In order to extend the "CLIO" laser spectral range toward larger wavelength, the previous undulator "POPOO" has been replaced by a new one called "OMIR" (see compagnion paper[1] by O.Marcouillé et al). The new undulator has now N=38 periods of λ_0=5.04cm, instead of N=48 and λ_0=4cm. Lasing toward larger wavelength needs also a new larger undulator vacuum chamber to avoid laser diffraction. The ZnSe Brewster plate, which was initially used for laser extraction, has been replaced by a hole coupling extraction in order to allow lasing above 17µm. This paper summarizes the general performances of CLIO with this new configuration, and makes a comparison with the previous results. The laser power has been increased for the users, and the wavelength range has been extended. Two colours operating mode has also been observed with hole coupling (see compagnion paper[2] by D.Jaroszynski et al).

1. "A new undulator for the extension of the spectral range of the CLIO FEL" : O.Marcouillé, et al.
2. "Step tappered operation of the FEL : efficiency enhancement and two colour operation" : D.Jaroszynski, et al.

REPORT ON FIRST MASING AND SINGLE MODE LOCKING IN A PREBUNCHED BEAM FEM OSCILLATOR

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Radiation characteristics of a table-top free electron maser (FEM) are described in this paper. The FEM employs a prebunched electron beam and is operated as an oscillator in the low-gain collective (Raman) regime. Using electron beam prebunching single mode locking at any one of the possible oscillation modes was obtained.

The electron beam is prebunched by a microwave tube section before it is injected into the wiggler. By tuning the electron beam bunching frequency, the FEM oscillation frequency can be locked to any eigen frequency of the resonant waveguide cavity which is within the frequency band of net gain of the FEM. The oscillation build up process is sped up, when the FEM operates with a prebunched electron beam, and the build-up time of radiation is shortened significantly. First measurements of masing with and without prebunching and characterization of the emitted radiation are reported.

OPTICAL PROPERTIES OF INFRARED FELs FROM THE FELI FACILITY II

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The FELI Facility II has succeeded in infrared FEL oscillation at 1.91 μm using a 68−MeV, 40−A electron beam from the FELI S−band linac in Feb. 27, 1995. The FELI Facility II is composed of a 3−m vertical type undulator (λ_u=3.8cm, N=78, K_{max}=1.4, gap length≧20mm) and a 6.72−m optical cavity. It can cover the wavelength range of 1−5 μm.
The FELs can be delivered from the optical cavity to the diagnostics room through a 40−m evacuated optical pipeline. Wavelength and cavity length dependences of optical properties such as peak power, average power, spectrum width, FEL macropulse, FEL transverse profile are reported.

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FIRST LASING, CAPABILITIES, AND FLEXIBILITY OF FIREFLY[1]

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FIREFLY is a free electron laser that was designed to produce picosecond pulses of light in the range between 15 and 100 microns. It uses an inexpensive electromagnetic wiggler and variable outcoupling to provide maximum flexibility for user experiments. FIREFLY first lased on November 23, 1994, and has now operated from 15 to 65 microns. It has lased in both a traditional undulator configuration and as an optical klystron, and has also lased on the third harmonic between 9 and 11 microns. We present measurements of optical spectral width and pulse width at a range of wavelengths in both configurations. We also compare direct measurements of electron beam extraction efficiency with observed optical power for fundamental, third harmonic, and optical klystron operation. We discuss wavelength switching between adjacent peaks in the gain spectrum of an optical klystron, observed for the first time in FIREFLY.[1] Finally, we focus on issues relevant to experimentation with FIREFLY, including continuously variable outcoupling, optical mode quality, and beam handling in the far-infrared.

[1] K.W. Berryman and T.I. Smith, "Wavelength Switching in an Optical Klystron," these proceedings.

[1] Work supported in part by the Office of Naval Research, Grant No. N00014-94-1-1024.

FIRST LASING OF THE KAERI MILLIMETER-WAVE FREE ELECTRON LASER

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The millimeter-wave FEL program at KAERI aims at the generation of high-power CW laser beam with high efficiency at the wavelength of 3~10 mm for the application in plasma heating and in power beaming. In the first oscillation experiment, the FEL has lased at the wavelength of 10 mm with the pulsewidth of 10~30 μs. The peak power is about 1 kW. The FEL is driven by a recirculating electrostatic accelerator having tandem geometry[1]. The energy and the current of the electron beam are 400 keV and 2 A, respectively. The FEL resonator is located in the high-voltage terminal and is composed of a helical undulator, two mesh mirrors, and a cylindrical waveguide. The parameters of the permanent-magnet helical undulator are : period = 32 mm, number of periods = 20, magnetic field = 1.3 kG. At present, with no axial guiding magnetic field, only 15 % of the injected beam pass through the undulator. Transport ratio of the electron beam through the undulator is very sensitive to the injection parameters such as the diameter and the divergence of the electron beam. Simulations show that, with improved injection condition, the FEL can generate more than 50 kW of average power in CW operation. Details of the experiments, including the spectrum measurement and the recirculation of electron beam, are presented.

1. Sung Oh Cho *et al.*, Nucl. Instr. and Meth. A 341 (1994) ABS 55.

PROGRESS OF THE COMMISSIONING OF THE DELTA STORAGE RING FEL FACILITY

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This paper will present the status of the ongoing commissioning of the DELTA storage-ring FEL facility. The commissioning of the LINAC started in autumn '94. The operation of the booster started in spring'95, the first stored beam was achieved end of march'95. During the summer of '95 the commissioning of the main storage ring will be started.

Simultaneously, the first FEL FELICTA I was built. All FEL hardware is in house, the undulator is already mounted in the storage-ring. Thus first operation of the undulator with electron beam, will take place immediately after the first stored beam in DELTA. Therefore, first spontanous photons are to be expected in late summer '95.

As soon as DELTA provides stable and rather reliable operation the experiments on FELICITA I will start. 16 mA total average current in DELTA at 500 MeV should be sufficient to reach the laser threshold in the FEL mode of FELICITA I. Operating the device as an optical klystron should result in lasing at substantial less currents.

NON-DESTRUCTIVE DIAGNOSIS OF RELATIVISTIC ELECTRON BEAMS USING A SHORT UNDULATOR+

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The performance of an FEL depends critically on the characteristics of the electron beam used to drive it. In the past it has been very difficult to measure the details of the transverse and longitudinal phase-space distributions of high-energy electron beams with the precision required to predict FEL performance. Furthermore, the available diagnostics were generally perturbative, and could not be used simultaneously with lasing. We investigate the potential use of a short undulator insertion device for non-destructive diagnosis of relativistic electron beams. Incoherent visible to near-infrared synchrotron radiation from a single magnet in the diagnostic undulator will be used to obtain information on beam position and transverse phase-space. Coherent off-axis undulator radiation in the millimeter to sub-millimeter range will be used to measure longitudinal phase-space characteristics of the beam. These two types of radiation can be analyzed simultaneously, while the FEL is lasing; thus giving a complete picture of relevant electron beam characteristics. In this paper we analyze the theoretical and practical design issues associated with such a diagnostic undulator.

+ *Work supported by ONR MFEL Program grant #N00014-94-1-0818.*

ADVANCES IN UNDULATOR TECHNOLOGY AT STI OPTRONICS

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Eighteen undulators and wigglers have been designed and built by STI Optronics since 1980 for FEL and synchrotron radiation applications. Design concepts for producing higher magnetic field strength with improved field quality will be reviewed. Shim tuning methods have permitted magnetic field tolerances, including pole-to-pole field uniformity, trajectory straightness, and higher order moments, to be controlled to low levels as needed for various applications. A key figure of merit is the optical phase error, which determines the coherence of the light generated in the device. Coherence is a strict requirement for maximizing gain in FELs and is highly desirable for maintaining spectral intensity in synchrotron radiation sources with low emittance.

The measurement capability necessary to certify coherence over extended undulator lengths has been developed. Example results obtained on undulators delivered to the Advanced Photon Source (APS) will be presented. STI is currently under contract for delivery of nineteen APS Undulator-A devices. These are 2.4 m long, wedged-pole hybrid undulators with on-axis peak field in excess of 0.75 tesla at a gap of 11.5 mm and a period of 33 mm. The optical phase error is nominally controlled to 3° over the undulator length, thereby maintaining the spectral intensity of the third harmonic synchrotron radiation to better than 90% of the ideal value. The first five of these devices have been delivered as of early 1995 and the remainder are under construction. Experience gained applicable to free-electron lasers will be emphasized.

CHARACTERISTICS OF THE MIT MICROWIGGLER FOR FREE ELECTRON LASER APPLICATIONS

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We report work on the development of microwiggler technology for free electron laser research. The MIT microwiggler is a pulsed electromagnet with 70 periods of 8.8 mm each which generates a peak on-axis field of 4.2 kG. The wiggler is characterized by extensive tunability. We developed a novel tuning regimen to control 140 degrees of freedom afforded by the individually tunable half periods and achieved an rms spread in the peak amplitudes of 0.08%. This is the lowest attained to date in any sub-cm period wiggler. The microwiggler design and comprehensive measurements of its characteristics will be described.

Multi-order harmonic lasing with a modified wiggler

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A novel wiggler for multi-order harmonic lasing has been developed at ILT/ILE. This wiggler, called modified wiggler, produces a composite magnetic field that is expanded as a sum of harmonics of a fundamental field component:

$$B(z) = B_1 \sin(k_1 z) + B_3 \sin(3k_1 z) + B_5 \sin(5k_1 z) + \cdots,$$

where k_1 is the wavenumber of the fundamental field component and B_n is the magnetic flux of nth order field component. Analytical work predicted the improvement of the gain on FEL harmonics with the modified wiggler. This effect on the gain is remarkable for the higher order harmonics, so that fifth or higher order harmonic lasing will be possible.

We constructed a modified wiggler by arranging high-permeability shims inside the gap of a conventional wiggler of 20 mm period. This modified wiggler has a ratio of the third-harmonic flux to the fundamental, B_3/B_1, of 10 %, which is enough to increase the gain on the FEL harmonics.

The harmonic lasing experiment is now under way using a 9 MeV S-band photo-injector at ILT/ILE. Then the wavelength is 15 μm at third-harmonic and 10 μm at fifth-harmonic. The gain on the third-harmonic is calculated to be 27%, which is 1.5 times greater than that of non-modified wiggler. The fifth-harmonic lasing is seeded by a CO_2 laser. We will discuss about the gain enhancement as a function of modification ratio.

OPTICAL ALIGNMENT AND DIAGNOSTICS FOR THE ATF MICROUNDULATOR FEL OSCILLATOR

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The microundulator FEL oscillator has a wiggler period of 8.8 mm, and is designed for initial lasing at 0.5 microns with a 50 MeV electron beam. The design and performance of the optical diagnostics and alignment are discussed.

A HeNe coalignment laser is mode-matched to the resonator cavity for transverse alignment. Interference fringes are observed in the cavity with a pellicle, allowing an alignment tolerance of +/- 10 micro-radians. The same pellicle is used to produce transition radiation by the electron beam. This enables precise transverse alignment of the electron beam to the resonator axis. The HeNe laser is also used to align the wiggler by backlighting its bore. This method aligns the wiggler to the optic axis to a tolerance of +/- 50 microns. A frequency-doubled,pulsed Nd:YAG laser that produces the electron bunch train is also mode-matched to the FEL cavity. The cavity length is adjusted to resonate with this pulse train.

Light from the FEL is transported to the diagnostic room using two separate paths: one for the single pass spontaneous emission, and the second for the multipass cavity output. Several diagnostics (CCD camera, photodiode, photomultiplier tube, joulemeter, spectrometer, and streak camera) are used to characterize the light. These instruments measure light energy per micropulse ranging from 10 femto-Joules to 10 micro-Joules.

THE ENEA F-CUBE FACILITY: TRENDS IN R.F. DRIVEN COMPACT FELs AND RELATED DIAGNOSTICS

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The Frascati FEL Facility F-CUBE (FEL-Compact for User Basic Experiment) currently operates in the mm-wave region providing about 600 hrs of beam time per year to users.

This FEL is a low cost compact device intended to be the first step in making the FEL a laboratory tool. It exploits some unique features like short pulses with coherent emission seeding and the dispersion properties of a waveguide resonator at "zero slippage" to provide wide band tunability.

The system is presently being upgraded to extend these characteristics into the far infrared. A new NdFeB permanent magnet undulator has been built and magnetic measurements have been performed. FEL tunability in the interval from 400 to 800 μm will be provided by the variation of the undulator gap and of the gap of the planar waveguide in the resonator.

Due to the short electron bunch duration coherent spontaneous emission is expected also in this wavelength range. Its effect on the FEL performance will be discussed together with a comparison of different coherent emission mechanisms, like coherent transition radiation (CTR), which can be used as a diagnostic tool.

OBSERVATION OF ENHANCED COMPTON SCATTERING IN A SUPERCAVITY

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The enhanced Compton scattering in a supercavity has been observed experimentally. The supercavity with ~99.99% reflectivity mirrors was used to confine the LD-pumped Nd:YAG laser light ($\lambda \sim 1.06\mu$m, CW power ~500mW, bandwidth <5kHz). The confined photons were scattered by 100kV electron beams generated from the laser-heated CW electrostatic accelerator. In this experiment, the scattered photon wavelength was in a visible range (<380nm). In order to increase the beam current and the system efficiency, the design of a beam recovery system is also in progress.

As an alternative way to confine the laser power, a novel multi-pass optical resonator is being designed. 9MeV electron bunch from the rf linac with photoinjector will be used to interact with MW~TW high peak power laser pulse in the resonator. In this experiment, the scattered photon energy is in a x-ray regime.

These experimental data is used to design the monochromatic γ-ray sources for annihilation of the radioactive nuclear waste.

INVERSE COMPTON GAMMA-RAY SOURCE FOR NUCLEAR PHYSICS AND RELATED APPLICATIONS AT THE DUKE FEL*

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In recent years the development of intense, short-wavelength FEL light sources has opened opportunities for the development new applications of high-energy Compton-backscattered photons. These applications range from medical imaging with X-ray photons to high-energy physics with $\gamma\gamma$ colliders. In this paper we discuss the possibilities for nuclear physics studies using polarized Compton backscattered γ-rays from the Duke storage-ring-driven UV-FEL.
There are currently a number of projects that produce polarized γ-rays for nuclear physics studies. All of these facilities operate by scattering conventional laser-light against electrons circulating in a storage ring. In our scheme, intra-cavity scattering of the UV-FEL light will produce a γ-flux enhancement of approximately 10^3 over existing sources. The Duke ring can operate at energies up to 1.2 GeV and can produce FEL photons up to 12.5 eV. We plan to generate γ-rays up to 200 MeV in energy with an average flux in excess of 10^7 /s/MeV, using a modest scattering beam of 10-mA average stored current. The γ-ray energy may be tuned by varying the FEL wavelength or by adjusting the stored electron beam energy. Because of the intense flux, we can eliminate the need for photon energy tagging by collimating of the γ-ray beam. We will discuss the characteristics of the device and its research opportunities.

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AN FEL DESIGN FOR GAMMA-GAMMA COLLIDERS BASED ON CHIRPED PULSE AMPLIFICATION TECHNIQUES*

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A next generation e^+-e^- linear collider in the TeV range can be converted into a γ-γ collider by converting it to e^--e^- operation and then generating γ-rays via Compton backscattering with optical beams. This provides unique access to some areas of fundamental physics as well as highly desirable redundancy to the e^+-e^- collisions [1]. The required optical beam (with a wavelength of about 1 micron) must have very high peak power, (about 1 TW) as well as average power (about 10 kW). To achieve a 1 : 1 conversion from an electron to γ-quantum, each micropulse must contain about one Joule and must be about one picosecond long, the micropulse peak power being about one Terawatt. To match the electron beam pulse structure, a macropulse consists of a sequence of about one hundred micropulses separated by about one nanosecond, and the macropulses are repeated at a rate of about 100 Hz. Thus, the time average power is about 10 kW. We propose and analyze a promising scheme to produce the required optical beam based on the chirped pulse amplification technique [2]. In this scheme, a low power optical beam of the same time structure required for the γ-γ collider is passed through a grating pair to stretch and chirp the picosecond micropulses to about one nanosecond, so that each macropulse will be an almost continuous, 100 nanosecond long pulse, but with chirps (from red to blue) within each nanosecond. The optical beam is then amplified in an FEL, driven by an intense electron beam from an induction linac. The amplified beam is then passed through another grating pair to compress the micropulses, thus recovering the original time structure, but containing about one Joule per micropulse. The requirements for electron beams, about 100 MeV energy, 1 kA current, 50 mm-mrad rms emittance, 10^{-3} energy spread, are consistent with the state-of-the-art induction linac technology. We analyze the requirement on the chirping accuracy and possible degradation of the pulse compression performance due to the electron beam fluctuation, and find that the effects are small.

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COHERENT SPONTANEOUS RADIATION FROM HIGHLY BUNCHED ELECTRON BEAMS[1]

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Coherent spontaneous radiation has now been observed in several FELs, and is a subject of great importance to the design of self-amplified spontaneous emission (SASE) devices. We report observations of coherent spontaneous radiation in both FIREFLY and the mid-infrared FEL at the Stanford Picosecond FEL Center. Coherent emission has been observed at wavelengths as short as 5 microns, and enhancement over incoherent levels by as much as a factor of 4×10^4 has been observed at longer wavelengths. The latter behavior was observed at 45 microns in FIREFLY with short bunches produced by off-peak acceleration and dispersive compression. We present temporal measurements of the highly bunched electron distributions responsible for the large enhancments, using both transition radiation and energy-phase techniques.

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STIMULATED COHERENT EMISSION FROM SHORT ELECTRON BUNCHES IN FREE SPACE

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In previous papers [1-6] stimulated coherent emission of short electron bunches (superradiance-SR) was considered in the frame of 1-D models. In the present work we study superradiance of an electron bunch which has a finite transverse size in the frame of a 2-D model. This model include effects of optical guiding as well as transverse electromagnetic energy escaping and diffraction. Using a nonstationary parabolic equation we described SR of a sheet shaped electron bunch in free space. It is shown that the radiation is composed of a sequence of e.m. pulses which are diffracted after escaping from the channel formed by the electron beam. This process is accompanied by a progressive increase of the electron efficiency. This enhancement is caused by the phenomenon of permanent self supporting resonance due to the variation of the radiation angle and frequency.

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SIDEBAND ELIMINATION AND HIGH EFFICIENCIES IN A STRONGLY TAPERED FEL AMPLIFIER

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Recently, an analytical theory[1] has shown that sideband instabilities can be eliminated in a strongly tapered FEL amplifier, leading to high efficiencies. It is found that a drastic suppression of the sideband spectrum occurs due to a continuous detuning effect which causes the real frequency of the most unstable sideband mode to vary continuously along the wiggler axis in the presence of a strong taper, with the consequence that no sideband can grow significantly before it is tuned away. Assuming extremely strongly pre-bunched beams with zero thermal spread, ideal efficiencies exceeding 60% were predicted by the theory with sideband intensities suppressed by nearly eight orders of magnitude with respect to the intensity of the primary signal.

The theoretical predictions have been tested and verified by a one-dimensional numerical simulation. The numerical simulations permit us to go beyond the scope of the analytical model and allow us to examine (i) if optimization of strongly tapered wiggler configurations can allow us to achieve the desired high efficiencies within acceptable length constraints, and (ii) whether the high ideal efficiencies predicted by theory survive in the presence of partial pre-bunching and finite thermal spread of electron beams. By experimenting with different tapering schemes, we have found interesting strongly tapered configurations in which the accessible electron phase-space area remains nearly constant, with realistic assumptions on pre-bunching and thermal spread of the electron beam. In particular, for parameters representative of the Livermore experiment,[2] we obtain efficiencies in the rage 40-50% with thermal spreads in the range 0.5-1% and pre-bunched electron phases in the range $2\pi/3-\pi$ using a wiggler 5 meters long. The optical quality of the radiation produced is free of parasitic sideband instabilities which do not grow beyond noise levels. These studies suggest that FEL amplifiers using strongly tapered wigglers of moderate length can achieve simultaneously the goals of strong sideband suppression and high efficiencies. These conclusions are not altered by the inclusion of two-dimensional effects.

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High-gradient acceleration of electrons in a plasma loaded wiggler

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The interaction of an electron beam with a transverse electromagnetic field and an electrostatic wave in a plasma laoded wiggler is described by means of a system of self-consistent nonlinear equations. We demonstrate that the system is able to sustain resonantly high-amplitude electrostatic waves with phase velocity c, which give rise to high gradient acceleration of the electron beam Both gradient and saturation value of the average gamma factor of the beam increase considerably with increasing magnetic field of the wiggler and plasma density.

Th2 - 7

SATURATION AND PULSED FEL DYNAMICS

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The behavior of a FEL operating in the saturated pulsed regime, may be reproduced by the linear FEL integral equation, suitably modified to include saturation effects through a gain depression coefficient depending on the laser intensity. This simple method allows to evaluate several FEL parameters like gain, efficiency, bandwidth and optical pulse duration as functions of the optical cavity length, only with a numerical integration. The predictions have been compared with available experimental and numerical data, and the method has been applied to estimate the operating characteristics of some planned FEL experiments.

THEORETICAL ANALYSIS OF ADVANCED SCHEMES FOR FREE ELECTRON LASER WITH A LARGE μ_c

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The possibility to operate with a short pulse FEL (electron pulse length $\sigma \simeq 1mm$) in far infrared region (with the radiation wavelength $10\mu m \leq \lambda \leq 300\mu m$) gives rise to many new applications. The parameter $\mu_c = N\lambda/\sigma$, which characterises the interaction time between the electron and radiation pulses in the undulator with N periods, becomes rather large ($\mu_c \sim 10$) even for $\lambda \sim 100\mu m$[1]. An increase in λ leads to the reduction in output power owing to an increase in both the diffraction losses and μ_c. We consider two options capable to improve the situation in the FEL with planar undulator geometry:

I. Reduction of the diffraction losses by use of circular or rectangular hollow waveguides in the cavity.

II. Effective reduction of μ_c factor by increasing the FEL-interaction time by means of the optical klystron[2] undulator scheme.

We demonstrate that:
I. Introduction of a waveguide into the cavity causes additional difficulties. In both circular and rectangular cases the waveguide dispersion leads to the undesirable variation of radiation pulse shape.

For the circular case the effect of depolarization becomes important and leads to the additional losses (up to 30%) due to the violation of the axial symmetry and linear polarization.

II. The optical klystron scheme consisting of several separated undulators, can indeed increase the FEL-interaction time. The right choice of electron bunch delay between these undulators gives the possibility to couple several successive electron pulses with one radiation pulse during one passage through the cavity. This results in considerable increase in FEL-interaction time and corresponding increase in gain.

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DELIBERATE MISALIGNMENT IN FREE ELECTRON LASERS WITH A HOLE COUPLING

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In a conventional laser operation misalignment of resonator mirrors leads usually to undesirable effects and has to be avoided. But in some certain types of cavity configurations deliberate introduction of misalignment makes it possible to improve considerably the characteristics of output radiation. The example of such configurations is an optical scheme with hole coupling. Two options are considered:

- the free electron laser (FEL) with the radiation output through the on-axis hole at the exit mirror[1];
- the external resonator (used for pulse stacking) where the exit FEL radiation enters this resonator through the on-axis hole at the input mirror[2].

These configurations are investigated with the continuous wave 3-D code [3].

It is shown that in a FEL with a hole coupling the transverse distribution of intracavity mode is characterised under certain conditions by a on-axis dip. The introduction of deliberate misalignment, characterised by a mirror tilt angle θ, leads to a shift and variation of the spacial structure. It is shown that due to the complicated structure of intracavity field, the dependences of the output power P on θ become nonmonotonic. For optimal value of $\theta = \theta_{opt}$ the output power could be much bigger than for the case $\theta = 0$. Moreover, the introduction of deliberate misalignment into optical cavity provides an opportunity not only to increase the output power but also to smooth the dependences of the output characteristics on the radiation wavelength.

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EVOLUTION OF TRANSVERSE MODES IN FELIX MACROPULSES

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We present ringdown measurements of both the intracavity beam, using a low reflection beamsplitter, as well as the hole-outcoupled beam of FELIX, the intracavity measurements being taken at various sets of transverse coordinates. Recent measurements show a significant difference in the decay of the signals at different radial positions, suggesting the presence of higher order transverse modes.

The formation of transverse modes depends on the properties of the cold cavity and its losses (i.e. resonator parameters, diffraction and outcoupling at the hole, absorption and edge losses on the mirrors, waveguide clipping), as well as on the gain mechanism. Both simulations with the axisymmetric ELIXER code and previous hole-outcoupled measurements indicated a substantial energy content of the 2nd or 4th Gauss-Laguerre (GL) mode for the 20-30 μm regime of FELIX. Moreover, as FELIX has a phase degenerate cavity, the fundamental and higher order transverse modes can interplay to create a reduced outcoupling efficiency at the hole.

For example, in contrast to the decay rate of 13% per roundtrip that we would expect for a pure gaussian beam when we include a loss of 6% for the reflection at the intracavity beamsplitter, recent simulations indicate a decay rate as high as 23% of the hole-outcoupled signal. In this case the 2nd order GL mode contains 30% of the total intracavity power.

The effect of transverse modes on subpulses in the limit cycle regime is an interesting aspect. As soon as a subpulse is losing contact with the electrons, its transverse pattern will exhibit an on-axis hole after a few roundtrips, according to the simulations. This process could mean that the subpulses are less pronounced in the hole-outcoupled signal of FELIX 1.

MEASUREMENT OF CHARACTERISTICS OF AN INFRARED FREE-ELECTRON LASER WITH THE L-BAND LINAC AT OSAKA UNIVERSITY

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Free-electron laser (FEL) experiments have been conducted with the 38-MeV L-band electron linac at the Institute of Scientific and Industrial Research, Osaka University. It is a 1.3 GHz RF linac with a thermoionic gun, and equipped with two 12th and one 6th sub-harmonic prebunchers for producing the high-intensity single-bunch beam with a charge up to 67 nC/bunch. For oscillation experiments of FEL, the gun is replaced with that with a smaller cathode area in order to reduce the emittance of the beam. The normalized emittance has been measured to be 200 π mm·mrad. The linac is operated in the long-pulse mode and one of the 12th sub-harmonic bunchers and the 6th sub-harmonic buncher are operated, so that the time duration of the macropulse is 4 μs and the spacing between micropulses is 9.2 ns. The length of the micropulse is 30-40 ps and the charge in each micropulse is 2 nC. The electron beam from the linac is transported to a wiggler which has the period length of 6 cm and the number of periods of 32. The first half of the macropulse is lost in the transport line because the energy of electrons in that part gradually changes and there is a momentum slit in the transport line. An optical resonator is 5.53 m long and the round-trip time of light in it is 37 ns, which is precisely four times as long as the spacing of micropulses. Since the time duration of the macropulse passing through the wiggler is 1.8 μs, the number of amplifications of light in the cavity is 49.

The first lasing was achieved in 1994 at wavelengths between 32 and 40 μm and preliminary results were reported at the 16th FEL Conference last year. The laser light was detected with a Ge:Be detector which has the time resolution of 3 μs. Since the time duration of the macropulse of the laser light is estimated to be less than 2 μs, we could measure only the total energy in a macropulse of the output light.

In order to measure the time structure of the FEL light, a new Ge:Be infrared detector with a better time resolution has been employed. The time response of the detector was measured to be 170 ns (FWHM) with self-amplified spontaneous emission (SASE) at the wavelength of 40 μm emitted by the intense single-bunch beam passing through the wiggler. The time duration of the SASE light is estimated to be less than 30 ps, and is negligibly short compared with that of the FEL macropulse. The output light of the FEL has been measured with the detector. The rise time and the fall time of the macropulse are approximately 300 ns and 1 μs, respectively, and there is no flat top. Because the number of amplifications is small, saturation of the intensity has not been obtained. The loss of the optical resonator derived from the decay time of the laser light is 6 % in the roundtrip. The FEL gain has been determined from the rise time and the loss to be 57 %. The highest energy so far obtained in the experiments is 75 μJ in a micropulse of the output light.

DESIGN STUDY OF A LONGER WAVELENGTH FEL FOR FELIX

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We present a design study of FEL3, which will extend the FELIX spectral range towards a few hundred microns. A rectangular waveguide will be used to reduce diffraction losses. Calculations show that with a waveguide gap of 1 cm, only one sinusoidal mode along the guided direction can exist within the FEL gain bandwidth, thus excluding group velocity dispersion and lengthening of short radiation pulses. To incorporate FEL3 in the existing FELIX facility, two options are being considered: to combine FEL3 with FEL1 by insertion of a waveguide into FEL1, and to build a dedicated third beam line for FEL3 after the two linacs. Expected FEL performance: gain, spectrum, power, pulse shape, etc., will be presented based on numerical simulations.

DESIGN OF A FAR-INFRARED CHI WIGGLER FREE-ELECTRON LASER*

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The preliminary design of a far-infrared free-electron laser with a Coaxial Hybrid Iron (CHI) wiggler is presented. The CHI wiggler consists of a central rod and outer ring of alternating ferrite and dielectric spacers.[1] A periodic wiggler field is produced when the CHI structure is immersed in an axial magnetic field. The design under investigation makes use of 1A, 1 MV annular electron beam interacting with the TE_{01} coaxial waveguide mode at approximately 1 THz (λ = 300 μm). The nominal wiggler period is 0.5 cm and the inner and outer waveguide radii are 0.4 and 0.8 cm, respectively. An axial guide field of 5-10 kG is used. The device performance is modeled with slow-time-scale non-linear code. Self fields and axial velocity spread are included in the model. Theoretical results will be presented.

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SHAPING PULSES USING FREQUENCY CONVERSION WITH A MODULATED PICOSECOND FREE ELECTRON LASER*

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Computer simulations and experiments indicate that we can shape the infrared picosecond pulses of the Mark III FEL in amplitude, frequency, and phase. Strongly modulated fundamental and second harmonic pulses have been generated by operating the Mark III FEL in the regime of strong sideband growth. In this paper, we present the results of simulations and experiments for second harmonic generation with fundamental inputs from 2 to 3 μm.

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ON A THEORY OF AN FEL AMPLIFIER WITH CIRCULAR WAVEGUIDE AND GUIDING MAGNETIC FIELD

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We consider an FEL amplifier with an axisymmetric electron beam, circular waveguide, helical undulator and guiding magnetic field. The presented nonlinear theory of the FEL amplifier is based on Hamiltonian description of particle motion and radiation field representation with Green function method. The space charge fields, energy spread and diffraction effects are taken into consideration.

Such an FEL amplifier configuration possesses some peculiarities when it operates in a regime with the negative longitudinal mass (i.e. when $\mu^{-1} \propto dv_z/d\mathcal{E} < 0$). It is shown that in the presence of strong space charge fields, the so-called "negative mass" instability may influence significantly on the FEL amplifier operation resulting in a significant increase in the FEL amplifier efficiency.

It is proposed in the presented paper to use the effect of the "negative mass instability" to achieve an effective bunching of the CERN Linear Collider (CLIC) driving beam.

EFFICIENCY OPTIMIZATION IN A FEL WITH FIELDS' NONADIABATIC TAPERING

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Amplification of an electromagnetic wave in free electron lasers with a reversed guide field and right-hand polarized wiggler field is investigated both analytically and numerically. An effect of electron bunch trapping by the high frequency electromagnetic field is used for efficiency optimization. On the basis of motion stability criteria a possibility of bunches trapping by FEL parameters nonadiabatic (experimentally realizable) tapering is shown. The stability analysis of electron motion is based on Lyapunov theory for autonomy systems.

A particle simulation is carried out for FEL parameters close to the experimental ones (relativistic factor $\gamma=4.75$, wiggler field strength $B_w = 2.8$ kG, guide field strength $B_0 = -1.4$ kG, operation wavelength $\lambda=6.2$ mm) for the case of wiggler field tapering. Theoretically predicted rule of wiggler field tapering corresponding to FEL efficiency of 55% is approximated by stepped functions. For the experimentally realizable tapering it is found that FEL efficiency can be over 40%.

HIGH-EFFICIENCY FEL-OSCILLATOR WITH BRAGG RESONATOR OPERATED IN REVERSED GUIDE FIELD REGIME

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The aim of the present work was to develop a narrow-band FEL-oscillator working in millimeter wavelength with high efficiency. It looked promising to combine the high selective property of Bragg resonator[1] with high efficiency and other advantages of FEL operation in the reversed guide-field regime[2,3].

An experimental study of the FEL was performed using linac LIU-3000 (JINR, Dubna) with the electron energy of 1 MeV, beam current up to 200 A and pulse duration of 200 ns. The beam was injected into the interaction region with guide magnetic field of 2.9 kGs. Transverse oscillations of electrons were pumped by the helical wiggler with the period length of 6 cm and the field slowly up-tapering over the initial 6 periods.

The FEL electrodynamic system consisted of a circular waveguide with diameter 20 mm and two Bragg reflectors. The H_{11} wave of the circular waveguide was chosen for operation. Two effective feedback waves were observed in "cold" electrodynamic measurements in correspondence with calculations: the E_{11} wave near the frequency of 31.5 GHz and the E_{12} wave - 37.5 GHz. The width of the both reflection resonances was about 2%.

In "hot" experiments the radiation on the designed H_{11} wave and frequencies corresponding to the both feedback waves was registered separately. Selection of the frequency was realized by varying of the wiggler field strength. The spectrum was measured with a set of the cut-off waveguide filters with inaccuracy less than 2%. Calibrated semiconductor detectors were used to measure the radiation power. The radiation with the frequencies of 37.5 and 31.5 GHz was observed in vicinity of the wiggler field amplitude of 2.5 kGs. The measured spectrum width of the output FEL-oscillator radiation did not exceed the width of the Bragg reflector resonances for the both feedback waves. The maximal radiated power was about 5 MW with efficiency of (4±1)% at frequency of 37.5 GHz and about 20 MW with efficiency of (15±3)% at frequency of 31.5 GHz.

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VELOCITY DISTRIBUTIONS PRODUCED BY A THERMIONIC ELECTRON GUN AND THE EFFECT ON THE PERFORMANCE OF A CERENKOV FEL

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For a normal thermionic electron gun, with a limited emission current density of the order of 10 A/cm^2, (magnetic) beam compression is required to obtain an electron beam with a current of up to 100 A with a small diameter. This method is used in an electron gun for a Cerenkov FEL (CFEL).

When the electron beam is compressed from its initial dimensions at the cathode to its final dimensions in the interaction region of the CFEL, the electrons obtain a small transverse momentum and perform a Larmor motion around a centre given by the magnetic field lines. The amount of transverse momentum obtained depends on the field at the cathode B_c and the field B_o at the final compressed beam. By using a so called bump coil it becomes possible to tune the magnetic field to obtain zero transverse momentum for electrons emitted at a certain radius r_z at the cathode. However it is not possible to have zero transverse momentum over the complete cathode surface since it is not possible to vary the magnetic field over the beam dimensions.

Computation of single particle trajectories in the given electrostatic accelerating and magnetostatic compression fields show that the transverse momentum in the interaction region is nearly linear with the displacement from r_z where the proportionality constant k_p is a constant which depends on B_c and B_o but is almost independent of r_z when the bump coil position and field strength are optimised for each value of r_z. One thus finds that the longitudinal velocity distribution as a function of radial position is parabolic of shape and that the position of the maximum is determined by the position of r_z.

Using these type of velocity distributions nonlinear simulations of the CFEL have been performend. It is found that an increase in k_p has several effects. First a stronger dependency of output power on r_z is found. This is a result of a larger variation of $\langle\beta_z\rangle$ with r_z and an increased spread $\delta\beta_z$. So for a fixed frequency one expects a change in gain if $\langle\beta_z\rangle$ varies as a function of r_z. Second the optimal value of r_z, i.e. for maximum output power, shifts towards the centre of the beam. This has to be attributed to the radial dependence of the longitudinal electric field component of the amplified TM_{01} mode which falls of exponentially with the distance towards the dielectric liner. For equal spreads one expect an increased gain for r_z approaching the outer beam diameter. However this will be accompanied by an increase in spread which will counteract the increase in gain.

SIMULATIONS OF THE PERFORMANCE OF THE Fusion-FEM, FOR AN INCREASED e-BEAM EMITTANCE

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The original design of the Fusion-FEM, which is under construction at the FOM-Institute for Plasma Physics, was based on an electron beam emittance of 50 π mm mrad[1,2]. Recent measurements of the emittance of the beam emitted by the electron gun showed that the actual emittance is 80 π mm mrad. This results in a 2.5 times lower beam current density inside the undulator. As a result it changes the linear gain, the start-up time, the saturation level and the frequency spectrum.

The main goal of the FEM project is to demonstrate a stable microwave output power of at least 1 MW. The decrease of the electron beam current density has to be compensated by variations of the other FEM parameters, such as the reflection (feedback) coefficient of the microwave cavity and the length of the drift gap between the two sections of the step-tapered undulator.

All basic dependencies of the linear and nonlinear gain, and of the output power on the main FEM parameters have been simulated numerically with the CRMFEL code. Regimes of stable operation of the FEM with the increased emittance have been found. These regimes could be found because of the original flexibility of the FEM design.

1. W.H. Urbanus, et al, 16th Int. FEL Conf., Stanford, Aug. 21-26, 1994.
2. A.V. Tulupov, et al, Nucl. Instrum. Meth. in Phys.Res., A341, 305, 1994.

ORBITAL MOTION IN GENERALIZED STATIC FIELDS OF FELs ACCOUNTING FOR AXIAL MAGNETIC FIELD, BEAM FORCES, UNDULATOR AND EXTERNAL FOCUSING

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Various types of undulators with or without axial magnetic field are used in FELs. Supplementary beam focusing can be applied by wedging, inclining or profiling pole faces of plane undulators or superposing external focusing magnetic fields in addition to undulator own focusing. Space-charge forces influence significantly particle motion in high-current, low-energy electron beams. Finally, one can use simultaneously two or more different undulators for some specific purpose: more efficient and selective higher harmonics generation, changing polarization types and direction, gain enhancement in double-period undulator etc. All these cases can be treated by solving the generalized equations of transverse orbital motion in a linear approximation, which is widely used for orbit calculation, gives sufficient accuracy for practical purposes and allows to consider many variants and optimize the chosen one. The undulator field is described as a field of two plane undulators with mutually orthogonal fields and an arbitrary axial (phase) shift between them. Various values of the phase shift correspond to right- or left-handed helical undulators, plane undulator of different polarization etc. The general formulae are reduced to forms that allow easier examination of particular cases: planar or helical undulator combined with axial magnetic field or without it, gyroresonance, limiting beam current, polarization etc.

DISTORTED ORBIT DUE TO FIELD ERRORS AND PARTICLE TRAJECTORIES IN COMBINED UNDULATOR AND AXIAL MAGNETIC FIELD

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Undulator and solenoid field errors cause electron trajectory deviation from the ideal orbit. Even small errors can result in a large lower frequency excursion from the undulator axis of a distorted orbit, and of betatron oscillations performed now around it, especially near resonant conditions. Numerical calculation of a trajectory step by step requires large computing time and treats only particular cases, thus lacking generality. Theoretical treatment is traditionally based on random distribution of field errors, which allows a rather general approach, but is not convenient for practical purposes. In contrast, analytical treatment shows explicitly how distorted orbit and betatron oscillation amplitude depend on field parameters and errors and indicates how to eliminate these distortions. An analytical solution of the equations of motion can be found by expanding field errors and distorted orbit in Fourier series as was done earlier for the simplest case of a plane undulator without axial magnetic field [1]. The same method is applied now to the more general case of combined generalized undulator and axial magnetic fields. The undulator field is a superposition of the fields of two plane undulators with mutually orthogonal fields and an arbitrary axial shift of the second undulator relative to the first. Beam space-charge forces and external linear focusing are taken into account. The particle trajectory is a superposition of ideal and distorted orbits with cyclotron gyration and slow drift gyration in the axial magnetic field caused by a balance of focusing and defocusing forces (or betatron oscillations, if axial magnetic field is zero). The amplitudes of these gyrations depend on transverse coordinate and velocity at injection and can nearly double the total deviation of an electron from the undulator axis even after an adiabatic undulator entry. If the wavenumber of any Fourier harmonic is close to the wavenumbers of cyclotron or drift gyrations, a resonant increase of orbit distortion occurs. Some examples of distorted orbit and electron trajectories are given.

1. V.A. Papadichev. Proc. 16th Int. FEL Conf., Palo Alto, 21 - 26 Aug. 1994, USA. To be published in Nucl. Instr. & Meth. in 1995.

A COMPARISON OF VARIOUS SCHEMES OF BEAM CONDITIONING FOR FEL

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In the first proposal on electron beam conditioning [1], a plane undulator with parabolic pole faces was used to elaborate the scheme. It has indisputable advantages as well as some limitations Therefore, it is of some interest to look for alternative schemes and devices. It is proposed in this report to employ another device, i.e , a combination of two identical plane undulators with the second shifted a quarter-period along the common axis and rotated 90 degrees around the axis relative to the first. Betatron oscillation wavenumbers along both transverse directions are the same as for a plane undulator, which facilitates constant longitudinal velocity (averaged over the undulator period) during betatron oscillation and allows to compensate the influence of transverse magnetic field inhomogeneity and finite beam emittance. The possibility of using a helical undulator in conditioning schemes is analysed when excessive undulator focusing is diminished by electron beam or background negative-ion space-charge or when employing external axially symmetric defocusing. Increasing electron energy and lowering undulator deflection parameter are also beneficial. An earlier proposed scheme using a helical undulator combined with uniform magnetic field [2] is analysed. It is impossible to eliminate the influence of finite beam emittance in a straightforward way. But it is possible to decrease angular divergence (transverse velocities in the beam) by increasing beam radius and have a net gain over the effect of lower beam current density (especially for Raman FELs). The method of exciting the necessary profile of transverse cyclotron velocity in the beam is analysed in more detail than previously [2] One can also increase useful beam diameter and current for FEL by employing beams with larger radius, but the same angular divergence

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2. V A. Papadichev "A new mehtod of equalizing longitudinal velocity (conditioning) in an electron beam propagating in a longitudinal magnetic field". Proc. of 16th Int FEL Conf., Stanford University, Stanford, California, USA, August 21-26, 1994. To be published in Nucl. Instrum. & Meth in 1995.

VORTICES IN THE ELECTRON BEAMS IN THE INHOMOGENEOUS UNDULATOR MAGNETIC FIELD

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In this paper we analyze the influence of the inhomogeneouty of undulator and longitudinal magnetic fields, in which cylindrical electron beam with nonuniform profiles of density and velocity propagates, on the conditions of the existence and the characteristics of two-dimensional vortices. These vortices are nonlinear, stationary, localized in perpendicular to direction of the beam propagation plane waves of a density, running along the axis of the beam and rotating around it and, in general case, having spiral structure. It has been shown that these two-dimensional vortices, which are localized in perpendicular plane, can exist not only in electron beams with inhomogeneous profiles of density and velocity[1], but in beams with uniform density and velocity, if they propagate in inhomogeneous external magnetic field.

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INVESTIGATION OF ELECTRON BEAM TRANSPORT IN A HELICAL UNDULATOR

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Lossless transport of electrons through the undulator is essential for CW operation of the FELs driven by recirculating electrostatic accelerators. We calculate the transport ratio of an electron beam in a helical undulator by using a 3-D simulation code and compare the results with the experimental results. The energy and the current of the electron beam are 400 keV and 2 A, respectively. The 3-D distribution of the magnetic field of a practical permanent-magnet helical undulator is measured and is used in the calculations. The major parameters of the undulator are : period = 32 mm, number of periods = 20, number of periods in adiabatic region = 3.5, magnetic field strength = 1.3 kG. The transport ratio is very sensitive to the injection condition of the electron beam such as the emittance, the diameter, the divergence, *etc.*. The injection condition is varied in the experiments by changing the e-gun voltage or the field strength of the focusing magnet located at the entrance of the undulator. It is confirmed experimentally and with simulations that most of the beam loss occurs at the adiabatic region of the undulator regardless of the length of the adiabatic region. The effect of axial guiding magnetic field on the beam transport is investigated. According to the simulations, the increase of the strength of axial magnetic field from 0 to 1 kG results in the increase of the transport ratio from 15 % to 95 %.

MICROWAVE AXIAL FREE-ELECTRON LASER WITH ENHANCED PHASE STABILITY

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Free-electron laser (FEL) amplifiers have demonstrated high efficiencies and high output power at microwave wavelengths. However, measurements and simulations have indicated that the present level of phase stability for these devices is not sufficient for driving linear accelerators. Fluctuations in the diode voltage, which is needed to accelerate the electron beam, are the largest cause of the shifts in the phase of the output power. Pulse-power technology cannot keep the voltage fluctuations less than 1/4%. However, we have found a scheme that will make the output phase much less sensitive to these fluctuations by exploiting the traveling-wave nature of the FEL interaction. In this paper we study the phase stability issue by analyzing the dispersion relation for an axial FEL, in which the rf field is transversely wiggled and the electron trajectories are purely longitudinal. The advantage of using the axial FEL interaction instead of the common transverse FEL interaction is that (1) the dispersion relation is not additionally complicated by how the transverse electron motion depends on the diode voltage and (2) such a device is simpler and less expensive to construct than a transverse-coupling FEL because there is no wiggler. The axial FEL interaction is with a fast wave and does involve axial bunching of the electron beam, so the results found for this device also apply to transverse-coupling FELs. By examination of the dispersion relation it is found that the effect of the phase dependency on the beam's velocity can be cancelled by the effect of the phase dependency on the beam's plasma wave, for an annular electron beam. By changing the annulus radius, exact cancellation can be found for a variety of beam voltages and currents in the ranges of 0.5-1.0 MV and 1-5 kA. This cancellation leads to first-order phase stability, which is not possible for standing-wave devices, such as klystrons. Particle-in-cell simulations of an axial FEL showing this phase stability scheme are presented. Progress in our experiment demonstrating these effects is reviewed.

JINR TEST FACILITY FOR STUDIES FEL BUNCHING TECHNIQUE FOR CLIC DRIVING BEAM

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SILUND-21 linear induction accelerator (energy up to 10 MeV, peak current about of 1 kA, pulse duration 50 – 70 ns) is constructed at JINR in the framework of experimental program to study free electron laser physics, a problem of two-beam acceleration and microwave electronics. In this paper we present project of an experiment to adopt the FEL bunching technique for generation of the CLIC driving beam.

SELF-FIELDS IN FREE-ELECTRON LASERS*

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We have analyzed the free-electron laser (FEL) interaction in the high gain Compton regime.[1] The theory has been extended to include self field effects on FEL operation. These effects are particularly important in compact, low voltage FELs[2]. The theory applies to the case where the optical beam is guided by the electron beam by gain focusing and maintains a constant profile through the wiggler. The finite-emittance electron beam, in turn, is matched to the wiggler. The betatron motion of the electrons is determined by i) the focusing force due to wiggler gradients and, ii) the repulsive force due to self-fields. Based on the single-electron equations, it can be shown that self-field forces tend to increase the period of transverse oscillations of electrons in the wiggler. In the limit, the flow of electrons is purely laminar, with a uniform axial velocity along and across the wiggler resulting in an improved beam quality. We shall also discuss the effects of beam compression on growth rate[3].

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[2] C. W. Roberson and B. Hafizi, IEEE J. Quantum Electron. QE-**27**, 2508 (1991)
[3] C. W. Roberson and B. Hafizi, Phys. Rev. Lett. **72**, 1654 (1994)

INFLUENCE OF STATIC ELECTRON BEAM'S SELF-FIELDS ON THE CYCLOTRON-UNDULATOR RESONANCE

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When undulators with a leading magnetic field B are used, the regime of double resonance is possible in which an undulator period is equal to an electron cyclotron wavelength. In the vicinity of this resonance an amplitude of particle oscillations in the undulator strongly depends[1] on a difference between B and a resonant value of the leading magnetic field. Consequently, it is important to investigate a role of self-fields of the electron beam, in particular, due to its influence on the electron cyclotron wavelength. At the paper analytically and by numerical simulation the influence of the static fields of the annular electron beam on its dynamics in the axisymmetrical magnetic undulator with the leading magnetic field in the vicinity of the cyclotron-undulator resonance is investigated. It is shown that the value of the resonant magnetic field is changed with the rise of beam's current. A shift of the resonant magnetic field may be both to larger values of B and to smaller ones, when different values of beam and waveguide radii, beam energy and undulator period are considered. A width of the resonance (on B - scale) is increased with the beam current.

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SPECTRAL DYNAMICS OF A COLLECTIVE FREE ELECTRON MASER

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A theoretical and numerical study of the nonlinear spectral dynamics of a Free Electron Maser (FEM) is reported. The electron beam is modulated by a step-tapered undulator consisting of two sections with different strengths and lengths. The sections have equal periodicity and are separated by a field-free gap. The millimeter wave beam is guided through a rectangular corrugated waveguide. The electron energy is rather low and the current density is large, therefore, the FEM operates in the collective (Raman) regime.

Results of a computational study on the spectral dynamics of the FEM are presented. The numerical code is based on a multifrequency model in the continuous beam limit with a 3D description of the electron beam. Space-charge forces are included by a Fourier expansion. These forces strongly influence the behaviour of the generated spectrum of the FEM. The linear gain of the FEM is high, therefore, the system quickly reaches the nonlinear regime. In saturation the gain is still relatively high and the spectral signal at the resonant frequency of the second undulator is suppressed.

The behaviour of the sidebands is analysed and their dependence on mirror reflectivity and undulator parameters will be discussed.

SPACE CHARGE FIELD IN A FEL WITH AXIALLY SYMMETRIC ELECTRON BEAM

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Nonlinear two-dimensional theory of the space charge of an axially symmetric electron beam propagating in combined right-hand polarized wiggler and uniform axial guide fields in a presence of high-frequency electromagnetic wave is presented. The well-known TE_{01} mode in a cylindrical waveguide for the model of radiation fields and paraxial approximation for the wiggler field are used.

Space charge field components are written in the Lagrange coordinates by the twice averaged Green's functions of two equally charged infinitely thin discs. For that "compensating charges" method is applied in which an electron ring model is substituted by one with two different radii and signs discs. On this approach the initial Green's functions peculiarities are eliminated and all calculations are considerably simplified. Coefficients of a twice averaged Green's function expansion into a Fourier series are obtained by use of corresponding expansion coefficients of longitudinal Green's functions of equal radii discs and identical rings known from the one-dimensional theory of super HF devices taking into account electron bunches periodicity. This approach permit the space charge field components for an arbitrary stratified stream to be expressed in a simple and strict enough form.

The expressions obtained can be employed in a nonlinear two-dimensional FEL theory in order to investigate beam dynamical defocusing and electrons falling on the waveguide walls in the high gain regime. This is especially important for FEL operation in mm and submm.

DESIGN OF A 'SLOW-WAVE' UBITRON*

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The NRL fundamental TE_{11} mode ubitron has been successful in demonstrating high gain (29 dB large signal), broad instantaneous bandwidth (>20 %), high power (>4 MW), and efficient (18%) amplification in K_u band with a 245 kV, 94 A beam [1]. For a second generation ubitron amplifier design, it is desired to operate at higher frequencies and lower voltages, while preserving the gain, power, and bandwidth characteristics measured with the K_u band amplifier.

A K_a band ubitron amplifier is currently under development utilizing the basic design concepts of the K_u band amplifier: grazing intersection for wide instantaneous bandwidth, circularly polarized wiggler and microwave fields for high gain and power, and a high quality Pierce gun generating a cylindrical, uniform density electron beam for high efficiency. As has been previously demonstrated [2], the dispersion characteristics of a periodic waveguide can be exploited for low voltage FEL operation. This is the major point of departure from the K_u band design; operation in the HE_{11} mode of corrugated cylindrical waveguide which permits broader bandwidth amplification at lower voltages than is possible with smooth waveguide. Preliminary calculations indicate that 30 % bandwidth operation in K_a band is possible at voltages less than 150 kV with a 8-9 mm period wiggler. Design details and performance calculations will be presented.

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THEORY OF SPONTANEOUS AND STIMULATED RADIATION FROM ELECTRONS IN A HELICAL WIGGLER WITH A GUIDING MAGNETIC FIELD *

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Neglecting the dependence of a wiggler field on the transverse coordinates and assuming the transverse velocity of electrons to be small compared to the longitudinal velocity, we have found the solution of the motion equations in an analytical form. From the analysis of the electron trajectories it follows that the transverse motion may be considered as the radial oscillations with the frequency $\omega_\rho = \omega_w + \omega_H$ (where ω_w is the wiggler frequency and ω_H is the relativistic cyclotron frequency chosen to be positive for the reversed field configuration and negative for the conventional one) and the precession around the definite center with the precession frequency $\omega_{pr} = -\omega_H$. We have found out that the longitudinal oscillations of electrons are excited with a frequency equal to ω_ρ and an amplitude depending on the wiggler parameter p and the ratio $q = \omega_H/\omega_w$. Using the general approach which had been developed previously in [1] to calculate the radiation spectrum from electrons precessing in the transverse plane, we obtained rather simple expressions for the frequency and angular distribution of the spontaneous radiation. Particulaly, the radiation spectrum at an angle $\theta \ll 1$ from electrons with the Lorentz factor $\gamma \gg 1$ is determined by the following frequencies $\omega_{nn'} = 2(n\omega_w + n'\omega_H)/[\theta^2 + \gamma^{-2}(1 + p^2(1+q^2)/(1+q)^2)]$ where n, n' are the harmonic numbers which besides positive may have zero or negative value. In the frame of the small-signal approximation we derived the expressions for the gain and come to conclusion that the gain coefficient G_{10}, corresponding to the wiggler harmonic ($n = 1$, $n' = 0$), as a function of q has two relatively broad maxima below the antiresonance point $q = 1$ and above it. These maxima are, generally speaking, separated by a dip near $q = 1$. We investigated the character of the gain dependance on the electron energy E and found out that there is no a significant broadening of the resonance for a reversed field ($q > 0$), but such a broadening exists at $q < 0$. Therefor, the substantial efficiency enhancement may take place rather for the conventional direction of the guiding field than for the reversed one, at least if the nonlinear effects are not taken into account.

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*Work supported by the Russian Foundation for Fundamental Research.

2-D SIMULATION OF A WAVEGUIDE FREE ELECTRON LASER HAVING A HELICAL UNDULATOR

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We have developed a 2-D simulation code for the calculation of output power from an FEL oscillator having a helical undulator and a cylindrical waveguide. In the simulation, the current and the energy of the electron beam is 2 A and 400 keV, respectively. The parameters of the permanent-magnet helical undulator are : period = 32 mm, number of periods = 20, magnetic field = 1.3 kG. The gain per pass is 10 and the output power is calculated to be higher than 10 kW. The results of the 2-D simulation are compared with those of 1-D simulation.

THEORY OF LOW VOLTAGE ANNULAR BEAM FREE-ELECTRON LASERS*

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An nonlinear analysis of an annular beam propagating through a cylindrical waveguide in the presence of a helical wiggler and an axial guide field is presented. The analysis is based upon the ARACHNE simulation[1,2] which is a non-wiggler-averaged slow-time-scale simulation code in which the electromagnetic field is represented as a superposition of the TE and TM modes in a vacuum waveguide, and the beam space-charge waves are represented as a superposition of Gould-Trivelpiece modes. The DC self-electric and self-magnetic fields are also included in the model. ARACHNE has been extensively benchmarked against experiments at MIT and NRL in the past with good agreement, but all of these experiments have dealt with solid electron beams and beam voltages in excess of 200 kV. In seeking to reduce the beam voltage requirements we now consider the effect of operation with an annular beam. One advantage to be obtained by using an annular beam is that, for a fixed beam current, the effect of the DC self-fields (i.e., the space-charge depression in beam voltage) will be reduced relative to that of a solid beam. This facilitates beam transport in short period wigglers in which the transverse dimensions are also small. A specific example is under study which makes use of 55 kV/5A electron beam with inner and outer radii of 0.27 cm and 0.33 cm respectively. The wiggler amplitude is 250 G with a period of 0.9 cm, and guide fields up to 3 kG corresponding to Group I trajectories. The waveguide radius is chosen to correspond to grazing incidence for the fundamental mode in Ku-Band (12-18 GHz). Preliminary results indicate that efficiencies upwards of 10% are possible with no wiggler taper. In addition, the energy spread must be held below 0.1%, and the instantaneous bandwidth is found to be greater than 20%.

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NORMAL AND ANOMALOUS DOPPLER EFFECTS IN PERIODIC WAVEGUIDE CYCLOTRON MASER

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A linear analysis of the periodic-waveguide cyclotron (PWC) maser [1] shows that the PWC interaction with fast-waves possesses properties of the known anomalous Doppler resonance interaction [2] if the wave impedance of the resonant spatial harmonic, Z_n, is much smaller than the free space impedance, i.e. if $Z_n \ll Z_0$. The feasibility of a fast-wave PWC interaction in a low impedance waveguide is examined theoretically in this paper. A practical scheme of a slotted-waveguide PWC operating in the fundamental harmonic near cutoff is proposed for a future experiment. The possible advantages of the quasi-anomalous Doppler effect in the fast-wave-PWC operating regime are the alleviation of the initial electron rotation and a high-efficiency operation.

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FREE ELECTRON MASER EXPERIMENTS IN THE LOW-FREQUENCY LIMIT

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Table-top free-electron maser (FEM) experiments operating in the low-frequency (< 1 GHz) low-energy ($\sim$ 1 keV) limit are reported. These FEM devices employ parallel-stripline non-dispersive waveguides (which support TEM-modes), and planar folded-foil wigglers. Thermionic cathodes and carbon-fiber cold-cathodes are used in these experiments. Results of oscillator and amplifier experiments are presented and compared with theory.

FREE-ELECTRON LASER CHALLENGES IN THE LOW-VOLTAGE LIMIT

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Based on the experimental results of our low-voltage (1-10 kV) free-electron- and cyclotron-resonance-maser experiments, we present in this talk several goals for our future studies. These include new compact schemes of low-voltage high-power masers, and of two-stage maser-laser devices.

FEL ON SLOW CYCLOTRON WAVE

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A physical mechanism of interaction of fast electromagnetic wave with slow cyclotron wave of relativistic electron beam in a FEL with helical wiggler field is described. It is shown that:

- interaction is possible for both group of steady state electron trajectories
- positive gain is achieved within certain interval of guide field strength
- operation wavelength for group 1 trajectories ($\Omega_0/\gamma < k_w v_{\parallel}$) is shorter than for the conventional FEL synchronism

A nonlinear analysis shows that efficiency of slow cyclotron FEL is restricted mainly by a breakdown of a single electron synchronism due to dependance of (modified) electron cyclotron frequency on an energy of electron. Nevertheless, as numerical simulation shows, typical efficiency of 15 % order is achieved in millimeter wavelength band for the midrelativistic ($\gamma = 3 \div 4$) slow cyclotron wave FEL. Tapering of magnetic field results in a substantial increase of efficiency.

EVOLUTION OF LONGITUDINAL MODES IN LOW VOLTAGE FEL

Stuart,R.A. ,Al-Shamma'a,A. ,Shaw,A. ,Balfour,C. ,Lucas,J.

A low voltage FEL operating at 130 kV which can be run cw with a continuous electron beam current level up to 12 mA has been constructed for the X-Band microwave range (8-12 GHz). In this poster, we will report on the dependence on time, after the electron beam is switched on, of the growth and competition of those longitudinal modes in the cavity having nett gain.

GAIN RESULTS FOR LOW VOLTAGE FEL

Shaw,A. ,Stuart, R.A., Al-Shamma'a,A. ,Balfour,C. ,Lucas,J.

We have designed and constructed a low voltage (130 kV) FEL system capable of operating in the microwave frequency range for which the electron beam current is cw (rather than pulsed) in time at a level of ~ 12 mA. The gain of this system has been measured as a function of the electron beam accelerating voltage and current level, and the input microwave frequency (8-10 GHz). The results are compared with the predictions of a simple theoretical model.

X-BAND PREBUNCHED FEL AMPLIFIER

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Abstract

Following the successful results of the ion-channel-guiding FEL experiments, we began a new experiment "prebunched FEL". It is an FEL driven by prebunched beams, whose configuration is a normal FEL system with a prebuncher like the bunching section of a klystron. There are two purposes in this prebunched FEL system ;

(1) Demonstration of a compact / efficient FEL.
Attaining the saturation power level with a short wiggler length (compact wiggler) and enhancing the power through the remaning wiggler length by wiggler tapering (high efficiency FEL).

(2) Experimental simulation of multi-stage FELs in the FEL-TBA [1].
Examination of FEL interactions with prebunched injection beams, especially, about the controllability of the output RF phase by changing the RF phase of the input seed power to the wiggler.

Recent experimental results show;

(1) The saturation power of 120MW has been attained at the wiggler length of 1.1m by 1.5MeV prebunched beams with a 45%-modulated 750A current. However, enhanced power has not been observed yet by wiggler tapering.

(2) The current modulation of the injection beam (1.5MeV-500A) becoming higher than 30%, the adjustable range of the output RF phase was limitted less than 40 degrees by the input power of 60kW only.

Detail explanations of design concept, theoretical and experimental results will be presented at the conference.

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SPONTANEOUS EMISSION MEASUREMENTS FROM A LOW VOLTAGE PRE-BUNCHED ELECTRON BEAM

Dearden,G. ,Mayhew,S.E. , Lucas,J. ,Stuart, R.A.

Recently we have carried out measurements on the spontaneous microwave (8.2 GHz) emission which results when a low-voltage (55kV) pre-punched electron beam is passed through a waveguide in a wiggler magnetic field. The variation of the spontaneous emission output power level with the average electron beam current and energy are reported and compared with the theory presented by Doria et al. [1]*. The effect of the degree of bunching of the electron beam has also been observed and compared with theory.

*[1] A. Doria, R. Bartolini, J. Feinstein, G.P. Gallerano and R.H. Pentell IEEE J. of Quantum Electronics, Vol.29, No.5, pp.1428-1435, 1993.

GAIN MEASUREMENTS ON A WAVEGUIDE FEL AMPLIFIER WITH PRE-PUNCHED ELECTRON BEAM

Dearden,G. ,Mayhew,S.E. , Lucas,J. ,Stuart, R.A.

A theory proposed by Doria et al. [1]* suggests that a synchronous pre-bunched electron beam should amplify radiation with a power gain which is inversely proportional to the square root of the input power. We have measured the power gain experimentally for a waveguide FEL system using a low-voltage (55kV) pre-bunched electron beam produced by a waveguide cavity buncher. The gain has been observed as a function of the electron beam current and energy; the results are compared with theory.

*[1] A. Doria, R. Bartolini, J. Feinstein, G.P. Gallerano and R.H. Pentell IEEE J. of Quantum Electronics, Vol.29, No.5, pp.1428-1435, 1993.

Transverse mode coupling and supermode establishment in a free-electron laser oscillator

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Abstract

A three-dimensional study of transverse mode evolution in a free-electron laser (FEL) oscillator is presented. The total electromagnetic field circulating in the resonator is represented as a superposition of transverse modes of the cavity. Coupled -mode theory is employed to derive a generalized 3-D steady-state oscillation criterion, from which the *oscillator supermode* is found analytically.

The oscillator supermode keeps its transverse features after each round-trip, and it is the eigenmode solution of the oscillator at steady-state. Relations between the *oscillator supermode* and the *amplifier supermode* are discussed. It is shown that they are identical only when the feedback process is entirely non-disperssive and non-discriminating.

We employ a 3-D, non-linear simulation code to demonstrate the evolvement of transverse modes in the oscillator towards formation of a supermode. The simulation shows that the resulted supermode is identical to that predicted by the analytical approach.

THE DYNAMICS OF RADIATION FORMATION IN A FEL

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The dynamics of stimulated radiation formation from spontaneous emission of the relativistic electrons moving in a magnetic helical undulator is investigated theoretically. The total radiation field of the electron beam has been calculated by summating the spontaneous undulator radiation fields of its individual electrons. The nonlinear dynamics of pointed electrons motion in the total radiation field and the self-amplification of this radiation are considered for the finite length of the electron beam. We analyzed the linear and nonlinear regimes for the one-dimensional model. In the linear regime, the longitudinal displacements of electrons relative to their equilibrium trajectories in the undulator have been obtained analytically as functions of entry time, the beam length and axial position of electrons in the undulator. The dependence of the efficiency on the beam length is established . We determined the mechanisms of axial beam bunching in the case of the intense electron beam, where the average distance between electrons in the beam reference frame is smaller than the undulator radiation wavelength, and in the limit case of ultra-short wavelength radiation, where the number of particles over the wavelength is not very large. The one-dimensional numerical simulation of nonlinear dynamics of the beam electron motion in the undulator magnetic field and the total radiation field is carried out for the finite beam length. The expression obtained by the analytical methods well agrees with the numerical simulation.

SIMULATION OF WAVEGUIDE FEL OSCILLATOR USING RF LINAC

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One dimensional multifrequency simulation code for waveguide mode FEL has been developed. Using this simulation code, we analyzed the spontaneous emission from electron micropulse from RF Linac. It is found that some parameters both high and low frequency waveguide modes are growing simultaneously, so the two radiation pulses are generated and amplified. And the experimental data for cavity length detuning of the radiation power are analyzed.

THE FERMI FEL PROJECT AT TRIESTE

Walker R.P.[1], Bulfone D.[1], Cargnello F.[1], Castellano M.[3], Cevenini F.[4], Ciocci F.[2], Cutolo A.[5], D'Auria G.[1], Daclon F.[1], Dattoli G.[2], De Angelis A.[2¶], Dipace A.[2], Doria A.[2], Ferianis M.[1], Gallerano G.P.[2], Garosi F.[2], Giannessi L.[2], Giannini M.[1], Giovenale E.[2], Margaritondo G.[1§], Massarotti A.[1], Mezi L.[2], Ottaviani P.L.[2], Patteri P.[3], Renieri A.[2], Rindi A.[1], Rosei R.[1], Rubbia C.[1¥], Sabia E.[2], Segreto A.[2‡], Tazzari S.[3], Tazzioli F.[3], Torre A.[2], Visintini R.[1], Wrulich A.[1], Zangrando D.[1],

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¶ guest; ‡ study grant holder

The goal of the FERMI project - Free Electron Radiation and Matching Instrumentation - is to construct a new user facility for FEL radiation beams covering a broad spectral range (2-250 μm) to complement the high brightness VUV/Soft-Xray radiation available from the ELETTRA synchrotron radiation facility at Trieste. A unique feature of the project will be the possibility of carrying out "pump-probe" experiments using synchronized radiation beams from FERMI and ELETTRA on the same sample. The project was launched at a meeting with Italian FEL experts held in Trieste on the 18th November 1994, chaired by C. Rubbia, as a collaboration between Sincrotrone Trieste, ENEA (Frascati), INFN (Frascati) and the University of Naples (Department of Electronic Engineering).

The facility will make use of an existing linac, that forms part of the ELETTRA injection system, and a hall into which the beam can be extracted. In addition, for the first phase of the project equipment will be used from the suspended INFN/ENEA "SURF" FEL experiment, including the undulator, beam transport magnets and optical cavity.

In this first International FEL Conference report on the project, we summarize the main features of the project, concentrating in particular on the most recent activities, including : results of measurements of the linac beam in the FEL mode of operation, further studies of the electron beam transport system including possibilities for bunch length manipulations, and further numerical calculations of the FEL performance.

Integrated Computer Simulation on FIR FEL Dynamics

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An integrated computer simulation code has been developed to analyze the RF-Linac FEL dynamics. First, the simulation code on the electron beam acceleration and transport processes in RF-Linac (LUNA) has been developed to analyze the characteristics of the electron beam in RF-Linac and to optimize the parameters of RF-Linac. Second, a space-time dependent 3D FEL simulation code (Shipout) has been developed [1]. The RF-Linac FEL total simulations have been performed by using the electron beam data from LUNA in Shipout. The number of particles using in a RF-Linac FEL total simulation is approximately 1000. The CPU time for the simulation of 1 round trip is about 1.5 minutes.

At ILT/ILE, Osaka, a 8.5MeV RF-Linac with a photo-cathode RF-gun is used for FEL oscillation experiments. By using 2 cm wiggler, the FEL oscillation in the wavelength approximately 46 μm are investigated. By the simulations using LUNA with the parameters of an ILT/ILE experiment, the pulse shape and the energy spectra of the electron beam at the end of the linac are estimated. The pulse shape of the electron beam at the end of the linac has sharp rise-up and it slowly decays as a function of time. By the RF-Linac FEL total simulations with the parameters of an ILT/ILE experiment, the dependencies of the start up of the FEL oscillations on the pulse shape of the electron beam at the end of the linac are estimated. The coherent spontaneous emission effects and the quick start up of FEL oscillations have been observed by the RF-Linac FEL total simulations.

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STUDY OF WAVEGUIDE RESONATORS FOR FEL OPERATING AT SUBMILLIMETER WAVELENGTHS

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This paper presents theoretical results of waveguide resonator study for FEL operating at the submillimeter wavelength region. Because of increased ohmic losses it is harder to obtain high Q waveguide cavities at these wavelengths.

The following unconventional multimode waveguides: metal-dielectric, corrugated and curved parallel plates, were considered. The type and structure of the operating modes were determined and their attenuation constant, effective mode area and wave impedance were calculated. On the basis of this analysis small-signal gain simulations were made.

We have performed a parametric study of the various FEL oscillator cavity designs based on the parameters of the Israeli Tandem FEL experiment. It was found that an FEL utilizing unconventional waveguides has much better performance in comparison to an FEL based on conventional multimode rectangular and circular waveguides. In particular, promising design parameters for a sub-mm wavelength FEL utilizing a metal-dielectric waveguide were identified: gain of 45%/Amp and ohmic losses of 2% at frequency 300 GHz, and gain of 20%/Amp and ohmic losses 1% at frequency 675 GHz.

STUDY OF THE SMITH-PURCELL EFFECT IN THE RELATIVISTIC REGIME

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We propose to investigate the spontaneous emission of radiation arising out of the interaction of a relativistic electron beam with a metallic grating (the Smith-Purcell effect). The work will concentrate, primarily, in the 50–120 μm part of the infrared spectrum and will be an extension of the work begun by the Oxford-Dartmouth-Essex collaboration;[1,2] one of the early objectives of the project will be to develop a quantitative understanding of the power spectrum of the emitted radiation over a wide range of emission angles. In particular, the limits of relativistic peaking of forward directed emission will be investigated.

The electron beam will be produced by laser irradiation of a metallic cathode in the terminal of a small Van de Graff accelerator located in the Technische Universität, München. Beam energies will be in the range of 2 - 4 MeV. Initial tests on photoproduction of electrons have yielded 10 mA pulses with a width of about 20 ns. The electron pulse length is long enough to not only produce easily observed levels of spontaneous emission, but in principle gain due to stimulated emission should also be observable. Observation of gain is a second goal of the project. The manufacture of the grating chamber and the voltage tests on the accelerator will progress in parallel.

This is a 3-year project and is supported, in part, by the British-German Academic Research Collaboration (ARC) program.

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SMITH-PURCELL FREE-ELECTRON LASER*

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The term Smith-Purcell free electron laser can be employed generally to describe any coherent radiation source in which a diffraction grating is used to couple an electron beam with the electromagnetic field. To date, most practical developments of this concept have focused on devices which operate in the millimeter spectral regime. In this paper construction of a Smith-Purcell free-electron laser operating in the far-infrared (FIR) region using a novel resonator cavity design and the electron beam from a low energy (0.5-5 MeV) radio-frequency accelerator will be discussed. A tunable source in this region would have many applications and since the beam energy is low, the small size and low overall cost of such a device would make it a laboratory instrument.

Current projects which are progressing towards developing a FIR source are the programs at Stanford [1] and CREOL [2]. Both of these projects are using permanent magnet undulators to couple the electron beam with the electromagnetic field. An alternative approach is to use an electron beam passing over a diffraction grating as the radiating mechanism. This phenomenon is known as Smith-Purcell radiation [3] and was first demonstrated for incoherent emission at visible wavelengths. The addition of feedback enhances the stimulated component of the emission which leads to the growth of coherence. Recent calculations for spontaneous emission have shown that the wiggler parameter and the grating efficiency are analogous. This result has important implications for the development of a Smith-Purcell FEL because a grating based free-electron laser would offer a greater range of tunability at a lower cost than its wiggler based counterpart.

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HIGH FREQUENCY LIMIT OF A VACUUM MICROELECTRONIC GRATING FREE-ELECTRON LASER.

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The dependencies that limit high frequency operation of a vacuum microelectronic grating free-electron laser are examined. The important parameters are identified as the electron beam energy, emittance, and generalized perveance. The scaling of power with emittance and frequency is studied in the far-infrared spectral range using a modified scanning electron microscope (SEM) and submillimeter diffraction gratings. The SEM is suited to the task of generating and positioning a low emittance ($10^{-2}\,\pi$-mm-mrad), low current (100 μA), but high current density (50-500 A cm^{-2}) electron beam. It has been used to demonstrate the spontaneous emission process[1] known as the Smith-Purcell effect[2]. A vacuum microelectronic grating free-electron laser has the potential of generating radiation throughout the entire far-infrared spectral range which extends from approximately 10 to 10^3 μm. An introduction to the theory, initial results, and details of the experiment are reported.

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SMITH-PURCELL RADIATION IN THE HIGHLY RELATIVISTIC REGIME

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An electron moving over the surface of a diffraction grating will transfer a part of its kinetic energy to radiation *via* a velocity synchronous coupling with a slow space harmonic component of the field. Since the phase velocity of a slow space harmonic is less than the speed of light, the slow components decay exponentially, or evanesce, with distance above the grating and the evanescence scale is determined by the product of the relative velocity, β, the relative energy, γ, and the wavelength λ. Thus, in the relativistic regime, good electron - grating coupling can be maintained at beam heights that are greater than the emitted wavelength. In order to explore this regime a series of experiments have been carried out with moderately energetic beams[1,2] and an experiment with the 70-MeV beam at the Accelerator Test Facility is in the planning stage. The work has two basic goals: the first is to explore the characteristics of the spontaneous emission produced by the beam as it moves over the grating, and the second is to evaluate the potential of grating-coupled or Smith-Purcell free-electron lasers. The spontaneous emission is of direct interest. It appears on the basis of work to date that the broad spectral distribution produced by a relativistic electron beam moving over a grating is potentially an alternative source for experiments of the type now carried out on synchrotron infrared beam lines. The grating, or a system of gratings, are also a potential alternative to the magnetic undulator and thus another basic approach to free-electron laser design.

The presentation will include a summary of the design of the experiment which is to be carried out on the 70-MeV A.T.F. beam line and a review of the theory of Smith-Purcell radiation in the high energy limit. Gain calculations and the role of beam quality in establishing performance limits will be discussed.

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VAN DER POL MODEL OF A CERENKOV MASER

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Abstract

A non-linear analysis of a Cerenkov maser is presented. The system consists of a ring configuration of a cylindrical waveguide filled with a dielectric material. A single transverse-magnetic mode is assumed to propagate in the system. A low-density pencil electron beam travels in part of the ring, confined by a strong axial magnetic field.

Using the single-particle description for the beam and the wave equation for the field, we obtain a set of two coupled non-linear differential equations describing the slowly varying amplitude and phase of the electromagnetic mode. The gain per path is assumed to be small and the spatial growth of the field is neglected. The resulting time dependent amplitude includes the exponential gain of the linear stage and the saturation to its maximum value. The time dependent frequency is also calculated. The two equations are combined to a single Van Der Pol equation with a non-linear restoring force. This description demonstrates the similarities and differences between the Cerenkov maser and other lasing systems.

HARMONIC GENERATION IN VUV/X-RAY RANGE AT THE DUKE STORAGE RING FEL USING ELECTRON BEAM OUTCOUPLING*

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We suggest using the OK-4 FEL operating in giant pulse mode to generate intracavity optical power at a level of hundreds of megawatts. These levels of power are sufficient to generate harmonics in the electron beam density. The prebunched electron beam then radiates coherently in an additional wiggler which is tuned on a harmonic of the OK-4 wavelength. The electron beam is turned by an achromatic bend into this wiggler, and harmonic radiation propagates with a small angle with respect to the OK-4 optical axis. This radiation will pass around the mirror of the OK-4 optical cavity and can then be utilized.

This electron outcoupling scheme was suggested by N. A. Vinokurov[1] as a method of optics independent outcoupling for high power FELs where electron beam bunching is provided in the master oscillator. This scheme is perfectly suited for optics independent harmonic generation.

We suggest to operate the OK-4 FEL as a master oscillator in the UV range of 100 to 250 nm where conventional optics are available. This harmonic generation scheme would allow us to cover the VUV and soft X-Ray range with tunable coherent radiation.

In this paper we present the possible layout of this system at the Duke storage ring and its expected operating parameters.

*This work supported by ONR grant #N00014-94-1-0818

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PREDICTED PERFORMANCE OF A MULTI-SECTION VUV FEL WITH THE AMSTERDAM PULSE STRETCHER AND STORAGE RING AmPS

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A design is proposed to realize a VUV FEL with the Amsterdam Pulse Stretcher and Storage Ring (AmPS). The FEL is based on 4 identical undulator sections and 3 dispersive sections. The total magnetic system has a lenghth of 12 m. 3 D simulations with the actual electron beam parameters of AmPS have been done with a version of TDA code modified for multi-sectional FELs. The spectral range between 50 and 100 nm has been considered. The simulations show that an amplification as large as 1*E5 - 1*E7 can be achieved. The amplification can be enhanced by a further optimisation procedure.

PARAMETER STUDY OF THE VUV-FEL AT THE TESLA TEST FACILITY

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Abstract

In this contribution we present a detailed study of the influence of the electron beam and machine parameters on the performance of the TTF VUV FEL, which is in its design stage at DESY. The TTF FEL will be a 6 nm SASE device operating with the beam provided by the Tesla Test Facility superconducting linac, driven by an rf photcathode gun.

The FEL output power and saturation length have been assessed with the use of different 2D-3D steady state simulation codes. The parameter range over which the FEL would reach saturation within the specified undulator length of 25 to 30 m have been determined and checked against semi-analytical expressions.

PARAMETRIC X-RAY FEL OPERATING WITH EXTERNAL BRAGG REFLECTORS

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In [1-3] the crystal X-ray FELs using channeling and parametric quasi-Cherenkov mechanisms of spontaneous radiation were considered as versions of FEL allowing, in principle, to obtain coherent X-ray source. In this case a crystal is both radiator and resonator for X-rays emitted by a particle beam passing through crystal. However, it is well-known that a beam current density required for lasing is extremely high in X-ray spectral range for any radiation mechanisms and it is very important to find a way to lower its magnitude.The application of three-dimensional distributed feedback formed by dynamical diffraction of emitted photons permitted to reduce starting beam current density 10^2 - 10^4 times up to 10^8 A/cm^2 [1]. One of ways to lower the starting current is the formation of multi-wave distributed feedback [1] the another one is the application of external reflectors.

The thing is that lasing regime was shown to be produced at frequencies in the vicinity of degeneration point for roots of dispersion equation describing radiation modes excited in an active medium (crystal plus particle beam). Unfortunately, in case of parametric quasi-Cherenkov FEL this region coincides with the region of strong self-absorption of radiation inside a crystal. That fact, obviously, increases the starting beam current. In this report we have shown that the application of external Bragg reflectors gives the possibility to lower radiation self-absorption inside a crystal by modifying radiation modes excited in the active medium under consideration. The corresponding dispersion equation and the expression for excited modes are derived. The generation equation determining starting conditions for lasing is obtained. Using these expressions we have shown that the application of external Bragg reflectors permits to reduce starting beam current density more than 10 times.

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LIMITING PARAMETERS OF THE X-RAY LASERS

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Recent progress in free-electron lasers is do to such advantages as tunability, ability to operate at high power or to extend into X-ray regions. The scaling of fre-electron and free-ion lasers down to X-ray regime is analyzed theoretically. A production of a relativistic multilayer ion mirror [1] and hard and high power electromagnetic radiation by reflection from this mirror are discussed. The reflectivity of the mirror is rather high because of the cross-section of the backward Rayleigh scattering of photon light by non-fully stripped relativistic ions ($\sim \lambda^2$) is much greater ($\sim 10 \div 15$ orders) then Thompson one ($\sim r_e^2$). This position is valid even in the case of non-monochromatic laser light ($\Delta\omega/\omega \sim 10^{-4}$). Ion cooling both in longitudinal plane and three-dimensional radiation ion cooling had been proposed based on this observation [2]. The using of these cooling techniques will permit to store high current and low emittance relativistic ion beams in storage rings. The bunched ion beam can be used in ordinary Free-Ion Lasers as well [3]. After bunching the ion beam can be extracted from the storage ring in this case.

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OPTICAL CAVITY AND ELECTRON BEAM REQUIREMENTS FOR THE OPERATION OF A 1.5 Å LCLS IN A REGENERATIVE AMPLIFIER MODE[1]

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Current conceptual designs for Linac Coherent Light Sources (LCLSs) in the 100-1 Å wavelength range are based on Free Electron Lasers (FELs) that are designed to saturate in a single pass of the electron beam through the undulator[2]. This, in practice, leads to insertion devices several tens of meters in length, which greatly dominates the component costs of the overall LCLS system. Although it is well known that amplification within a cavity would enable much shorter and more economical undulators to be employed, two major practical problems are currently adduced to discount the use of such configurations in the sub-100 Å wavelength regime: 1) the temporal jitter of the (sub-picosecond) electron bunches required for such FELs can be comparable to or larger that the durations of the bunches themselves, rendering reliable synchronization extremely difficult, and 2) the lack of optical elements of sufficient reflectivity and bandwidth out of which adequately efficient optical cavities can be constructed. In this paper we re-assess the requirements associated with these two aspects of x-ray FEL technology, and consider the use of diffractive and capillary x-ray optics as a possible approach to resolving or making more tractable the resolution of some of the basic problems involved.

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NON-WIGGLER-AVERAGED THEORY OF SHORT WAVELENGTH FREE-ELECTRON LASERS

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A three-dimensional nonlinear analysis of the interaction in short wavelength free-electron lasers is presented using a non-wiggler-averaged formulation for the electron trajectories. The analysis and simulation code (which is referred to as MEDUSA for convenience) is based upon a slow-time-scale amplifier model in which it is assumed that the interaction is with a single frequency wave, and Maxwell's equations are averaged over a wave period. This eliminates the fast time scale from the analysis. Note that although Maxwell's equations are averaged over the wave period, no average is imposed on the Lorentz force equations. The electromagnetic field is represented as a superposition of Gaussian optical modes. The wiggler model used is that of a three-dimensional planar wiggler which dictates the choice of a Gauss-Hermite mode decomposition. These fields are substituted into Maxwell's equations and, after averaging over the wave period and integration over the transverse coordinates, yields nonlinear differential equations for the evolution of the amplitude and phase of each mode. These equations are integrated (for each mode) simultaneously with the three-dimensional Lorentz force equations for an ensemble of electrons. Advantages which are derived from the non-wiggler-averaged orbit treatment are: (1) the adiabatic injection of the beam into the wiggler can be modeled, (2) effects due to the transverse wiggler inhomogeniety such as betatron oscillations and synchrotron-betatron coupling are implicitly included in the treatment, (3) wiggler imperfections can be included in the analysis by the relatively simple expedient of allowing the wiggler amplitude to vary with axial position, and (4) harmonic interactions are implicitly included. The first two advantages relate to the self-consistent treatment of emittance growth due to the injection process and the transverse wiggler inhomogenieties. It should also be noted that MEDUSA is also capable of analyzing the effect of the measured imperfections of a specific wiggler magnet to be used in an experiment. An example corresponding to the specific parameters of the proposed Linear Coherent Light Source (LCLS) at SLAC will be discussed. This is a 4 nm SASE experiment using a 7 GeV/2.5 kA electron beam with a planar wiggler with a 7.7 kG amplitude and a 8.3 cm period.

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EFFECTS OF UNDULATOR INTERRUPTIONS ON THE PERFORMANCE OF HIGH-GAIN FEL AMPLIFIERS

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The high-gain amplifiers for short wavelength free-electron lasers (FELs) such as the LCLS project require a long undulator. The construction of the undulator as well as the FEL operation would become easier if the undulator could be interrupted with drift sections every few gain lengths. We have investigated the influence of such interruption on the FEL performances. Three effects are considered: (i) the diffraction loss, (ii) the phase mismatch and, (iii) the phase smearing due to velocity spread and to dispersion errors. The effect (i) is the loss during the process in which the optical mode in a section of the undulator leaves the undulator, propagates through the free space and then re-enters and re-adjusts in the next section. The effect (ii) is the fact that the phase of the optical beam is displaced with respect to the electrons' density modulation for optical FEL interaction due to the slippage of the electron beam in the interruption region. The effect (iii) is the fact that electrons' velocity spread, emittance, and dispersion due to misalignment of the quadrupoles used for additional focusing lead to a reduction of the bunching factor. We present an approximate analysis of these effects. When applied to the LCLS parameters, we find that the effect (i) is negligible, the effect (ii) gives a condition on the length of the drift section, and the effects (iii) are small, but could be non-negligible if there are sufficient number of interruptions.

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NUMERICAL SIMULATIONS OF X-RAY GENERATION IN MILTISECTIONAL FELs

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The process of x-ray generation in milticomponent FELs with alternate undulator and dispersion sections [1] is investigate. The coptuter simulation was fulfilled for the ultrarelativistic electron beams [2,3]. It was shown that the use of much number of dispersion sections allows to increase the gain considerably and to use more short magnetic systems.

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STRONG FOCUSING INFLUENCE ON HIGH GAIN FEL CHARACTERISTICS

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The use of intrinsic alternating focusing in a linac-driven FEL with planar undulator is considered numerically. The analysis is done on the basis of TDA code[1] for soft X-ray FEL with FD lattice implementing focusing of quadrupole and periodic sextupole type. The influence of the focusing (type and phase advance) on FEL performance and the reasons of difference in FEL performance for focusing of two kinds are analyzed. A possibility of some kind of beam conditioning for intrinsic[2] focusing is discussed.

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RADIATION FROM RELATIVISTIC ELECTRON BEAMS IN PERIODIC STRUCTURES

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We present an experimental study of emission of radiation from relativistic electrons in a novel periodic structure. The MIT microwiggler is a pulsed ferromagnetic-core electromagnet consisting of 70 periods of 8.8 mm periodicity, generating an on-axis peak magnetic field of 4.2 kG. Each field peak in independently tunable. We employed a novel tuning scheme to reduce the RMS spread in the peak amplitudes to 0.08%, the lowest ever attained in a sub-cm magnetic field.

A high brightness, 40 MeV pulsed electron beam produced by the LINAC at the Accelerator Test Facility at Brookhaven National Laboratory was injected into the short-period wiggler and visible spontaneous emission was produced. Spectral density profiles were measured and the measured peak wavelength was shown to vary appropriately with beam energy. It is shown that the principal spectral broadening mechanisms are longitudinal energy spread in the electron beam and off-axis emission. Further work is planned at 50 MeV.

FEL GAIN AS A FUNCTION OF PHACE DISPLACEMENTS INDUCED BY UNDULATOR INTERSECTION GAPS

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Gain characteristics are analitically considered for FEL based on a multisection undulator with short intersection gaps. It is shown that small phase displacements between laser beam and electron beam respectively caused by the above intersection gaps can seriously change the gain resonance frequancy as well as gain curve shape. This effect is different from that of OK and can be used for fast undulator tuning or for its tapering.

SCALING FORMULAE FOR FEL OPERATING IN LINEAR AND NON LINEAR REGIME

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Scaling relations for the FEL gain, including the e-beam quality effects, have been usefully exploited to design FEL devices.
We propose further extension of the above formulae including high gain, inhomogeneous broadening and saturation effects. A crucial role to get these relations is the use of approximant methods generalizing the Padé procedure.
We derive gain equations containing the corrections due to energy spread, emittances and field intensity. It is shown that these equations can be exploited to "simulate" the FEL evolution with an almost negligible computational effort.
Comments on the role of the saturation intensity and its dependence on the e-beam quality, high gain corrections etc. are also presented.

LONGITUDINAL AND TRANSVERSE MODE EVOLUTION IN FREE ELECTRON LASER

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We use the method of Padé approximants and Fourier transform techniques to treat analytically the problem of transverse and longitudinal mode evolution in FELs. We obtain simple relations providing a transparent understanding of the dynamic of pulse propagation effects and of transverse mode guiding. We discuss the interplay with inhomogeneous broadening effects and derive gain formulae including longitudinal and transverse mode couplings.

SIMULATION OF THE SHORT PULSE EFFECTS IN THE START-UP FROM NOISE IN HIGH-GAIN FELS

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The spatio-temporal evolution of high-gain free electron lasers from noise is investigated by 1-D simulation calculation. To understand the discrepancy between the experimental result and theoretical prediction of the self-amplified spontaneous emission(SASE),[1] the strong slippage effect in the short pulse electron beam and the coherent bunched beam effect are considered.[2] When the length over which the electron density varies significantly is comparable or smaller than the FEL wavelength, the initial noise level would be increased due to the enhanced coherence between electrons. With a proper computer modeling of the start-up from noise including the energy spread, the overall performance and characteristics of SASE are studied. This work will be helpful to increase the credibility of the simulation calculation to predict the SASE performance in all wave-length regions.

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SHOT NOISE STARTUP OF THE 6 NM SASE FEL AT THE TESLA TEST FACILITY

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Abstract

We present here an analysis of the shot noise startup of the 6 nm SASE FEL proposal at the TESLA Test Facility in DESY.
The statistical fluctuations of the saturation length and output power due to the intrinsic randomness of the noise startup are investigated with the use of the 2D time dependent code GINGER, that takes into account propagation effects and models shot noise. We then provide estimates for the spectral contents and linewidth of the emitted radiation and describe its spiking characteristics. The output radiation will develop superradiant spikes seeded by the shot noise in the electron beam, which can enhance the average emitted power at the expense of some spectral broadening.

SELF-CONSISTENT ANALYSIS OF RADIATION AND RELATIVISTIC ELECTRON BEAM DYNAMICS IN A HELICAL WIGGLER USING LIENARD-WIECHERT FIELDS

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Lienard-Wiechert (LW) fields, which are exact solutions of the Wave Equation for a point charge in free space, are employed to formulate a self-consistent treatment of the electron beam dynamics and the evolution of the generated radiation in long undulators. In a relativistic electron beam the internal forces leading to the interaction of the electrons with each other can be computed by means of retarded LW fields. The resulting electron beam dynamics enables us to obtain three dimensional radiation fields starting from an initial incoherent spontaneous emission, without introducing a seed wave at start-up. Based on the formalism employed here, both the evolution of the multi-bucket electron phase space dynamics in the beam body as well as edges and the relative slippage of the radiation with respect to the electrons in the considered short bunch are naturally embedded into the simulation model.

In this paper, we present electromagnetic radiation studies, including multi-bucket electron phase dynamics and angular distribution of radiation in the time and frequency domain produced by a relativistic short electron beam bunch interacting with a circularly polarized magnetic undulator.

CRITERION OF TRANSVERSE COHERENCE OF SELF-AMPLIFIED SPONTANEOUS EMISSION IN HIGH GAIN FREE ELECTRON LASER AMPLIFIERS*

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In a high gain free electron laser amplifier based on Self-Amplified Spontaneous Emission (SASE) the spontaneous radiation generated by an electron beam near the undulator entrance is amplified many orders of magnitude along the undulator. The transverse coherence properties of the amplified radiation depends on both the amplification process and the coherence of the seed radiation (the undulator radiation generated in the first gain length or so). The evolution of the transverse coherence in the amplification process is studied based on the solution of the coupled Maxwell-Vlasov equations including higher order transverse modes. The coherence of the seed radiation is determined by the number of coherent modes in the phase space area of the undulator radiation. We discuss the criterion of transverse coherence and identify governing parameters over a broad range of parameters. In particular we re-examine the well known emittance criterion for the undulator radiation, which states that full transverse coherence is guaranteed if the rms emittance is smaller than the wavelength divided by 4π. It is found that this criterion is modified for SASE because of the different optimization conditions required for the electron beam. Our analysis is a generalization of the previous study by Yu and Krinsky [1] for the case of vanishing emittance with parallel electron beam. Understanding the transverse coherence of SASE is important for the X-ray free electron laser projects now under consideration at SLAC and DESY.

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TRANSVERSE EFFECTS IN UV FELs

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ABSTRACT

In an ultraviolet Free Electron Laser (UV FEL), the electron beam size can be approximately the same as the optical mode size. The performance of a UV FEL is studied including the effect of emittance, betatron focusing, and external focusing of the electron beam on the transverse optical mode. The results are applied to the Industrial Laser Consortium's UV FEL.

ULTRAHIGH HARMONICS GENERATION IN A FEL WITH A SEED LASER

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One of the most challenging problems in modern FEL technology is to operate in the X-ray region, especially in the "water window". Because of the absence of optical resonators in this range of wavelengths, only a single-pass device may be suitable for this task. The Self-Amplified Spontaneous Emission (SASE) mechanism is now under active discussion as a realistic way to provide high-power coherent emission in the X-ray range. Both the undulator parameters and the electron beam parameters required for the lasing are achieveable at today's technological level. On the other hand, the SASE approach implies a very long and expensive periodic magnetic structure, typically several tens of meters long. This is mainly because of the rather long build-up time necessary to establish a coherent mode from incoherent noise. A mechanism of shortening this time would be therefore highly desirable.

In the present paper we consider a scheme using two undulators and a seed-laser to produce coherent X-ray emission. The first undulator and the seed-laser provide a pre-modulation of the beam while the second undulator serves as a source of coherent spontaneous radiation at a very high harmonic of the seed-laser frequency; the whole scheme may then be considered to be an FEL-based frequency upconvertor. The total length of the periodic magnetic structure is shown to be of the order of several meters, nearly an order of magnitude shorter than in the SASE case. For the same beam quality as in the SASE scheme and with realistic seed-laser parameters, the efficiency of the beam pre-modulation at the 50-th (!) harmonic is shown to be as high as 15%. The output radiation is tunable between discrete harmonics of the seed-frequency.

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SMALL-SIGNAL GAIN IN A GAS-LOADED FEL

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At present, existing FEL facilities operate in the infrared and visible ranges of wavelengths. Generation of shorter waves (in the VUV and X-ray region) is of great scientific interest, but this would require a very expensive accelerator which could provide a high-current electron beam in the GeV-range of energies. A promising way to relax requirements on electron energy by introduction of a gas into the optical cavity was proposed nearly ten years ago. For small deviations from the vacuum wavelenght, the idea was confirmed in experiments performed in Stanford; however, a detailed theory of such a device is still not developed.

We present an analysis of the small-signal gain in a gas-loaded free-electron laser. Multiple scattering of electrons by the atoms of the gas inside the optical cavity is shown to lead to two additional effects, as compared to the case of a vacuum FEL: a loss of coherence between different parts of the electron trajectory and an enhancement of the phase "jitter". Both effects become increasingly important at short wavelengths and significantly reduce the small-signal gain per pass. In 1D approximation analytical expressions are obtained and numerical calculations are made to estimate beam and undulator parameters necessary for lasing in the vacuum ultraviolet.

Hydrogen-filled FELs are shown to have good prospects for this at today's technological level. To operate in the range of wavelengths 125–140 nm, an electron beam should have an energy above 50 MeV and a good quality: a normalised emittance of the order of 5π mm·mrad and an energy spread below 10^{-3}. All these parameters are achieveable with modern linacs and photoinjectors.

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DESIGN OPTIMIZATION AND TRANSVERSE COHERENCE ANALYSIS FOR AN X-RAY FREE ELECTRON LASER DRIVEN BY SLAC LINAC*

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I present a design study for an X-ray Free Electron Laser driven by the SLAC linac, the Linac Coherent Light Source (LCLS). The study assumes the LCLS is based on Self-Amplified Spontaneous Emission (SASE). Following a brief review of the fundamentals of SASE, I will provide without derivation a collection of formulas relating SASE performance to the system parameters. These formulas allow quick evaluation of FEL designs and provide powerful tools for optimization in multi-dimensional parameter space. Optimization is carried out for the LCLS over all independent system parameters modeled, subjected to a number of practical constraints.

In addition to the optimizations concerning gain and power, another important consideration for a single pass FEL starting from noise is the transverse coherence property of the amplified radiation, especially at short wavelength. A widely used emittance criteria for FELs requires that the emittance is smaller than the radiation wavelength divided by 4π. For the LCLS the criteria is violated by a factor of 5, at a normalized emittance of 1.5 mm-mrad, wavelength of 1.5 Å, and beam energy of 15 GeV. Thus it is important to check quantitatively the emittance effect on the transverse coherence. I will examine the emittance effect on transverse coherence by analyzing different transverse modes and show that full transverse coherence can be obtained even at the LCLS parameter regime.

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STEP-TAPERED OPERATION OF THE FEL : EFFICIENCY ENHANCEMENT AND TWO-COLOUR OPERATION

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We present new measurements of the temporal and spectral properties of radiation produced from two step-tapered undulator free-electron lasers (FEL), CLIO in France and FELIX in the Netherlands. Using a two section undulator with independently adjustable deflection parameters (K) the FEL will operate either with enhanced efficiency and improved spectral properties (with a small positive ΔK step) or will operate simultaneously at two frequencies (for large ΔK). The first experiments demonstrating two-colour operation were restricted to a maximum wavelength difference, $\delta\lambda/\lambda < 0.15$ because of the influence of optical dispersion in the cavity introduced by a dielectric outputcoupling plate. Using a dispersion-free hole output coupler the maximum $\delta\lambda/\lambda$ has been extended to more than 0.6. We present these new dispersionless two-colour operation results and show that quenching of one of the wavelength occurs due to electron heating arising from laser operation at the other wavelength unless the optical cavity is detuned significantly so that the FEL operates with reduced efficiency and lower intracavity power. To overcome this problem a larger fraction of the radiation will need to be coupled in the future to limit the intracavity power. To determine the temporal distribution of the optical radiation at the two wavelengths we have carried out second order autocorrelation measurements using a nonlinear crystal and established that the optical pulses are very short, a few hundreds of femtoseconds long, and overlapping. To establish how the two colours build up in the cavity we have also measured the spectral and temporal evolution of the macropulse. To establish the efficiency over a wide range of ΔK values we have measured the electron spectra of the electrons leaving the undulator and find that the efficiency is enhanced significantly over normal undulator operation. We also present new measurements that show that the FEL will produce significant amounts of coherent spontaneous radiation simultaneously at two wavelengths when the wavelength is long and the electron bunch is short. Finally, we show that when ΔK is small the optical pulse duration can be adjusted by a factor of two or more by adjusting ΔK in the range $|\Delta K| < 0.05$. We also observe that sidebands due to synchrotron oscillations are suppressed for some ΔK values.

HALF-PERIOD OPTICAL PULSE GENERATION USING A FREE-ELECTRON LASER

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Recently there has been a growth in interest in non-equilibrium interaction of half-period long optical pulses with matter. To date the optical pulses have been produced by chopping out a half-period long segment from a longer pulse using a semiconductor switch driven by a femtosecond laser. In this paper we present new methods for producing tunable ultra-short optical pulses as short as half an optical period using a free-electron laser driven by electron bunches with a duration a fraction of an optical period. Two different methods relying on the production of coherent spontaneous emission will be described.
In the first method we show that when a train of ultra-short electron bunches pass through an undulator in an optical cavity then interference between adjacent optical pulses can result in ultra-short optical pulses as short as one half period. We present calculations which show that the small signal gain is unimportant in the early stages of radiation build up in the cavity when the startup process is dominated by coherent spontaneous emission. To support our proposed method we present encouraging experimental results from the FELIX experiment in the Netherlands which show that interference effects between the coherent spontaneous optical pulses at start-up are very important.
The second proposed method relies on the fact that coherent spontaneous emission mimics the undulations of electrons as they pass through the undulator. We show that ultra-short optical pulses are produced by coherent spontaneous emission when ultra-short electron bunches pass through an ultra-short undulator. We discuss the interesting case of such undulator radiation in the presence of an optical cavity and show that the optical pulse can be "taylored" by simply adjusting the optical cavity desynchronism.
The proposed methods may be realisable using existing rf driven FELs in the far-infrared.

THE STANFORD PICOSECOND FEL CENTER[1]

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In the past year there have been significant increases in the quantity and quality of FEL beam available at the Stanford Picosecond FEL Center. The new mid-IR FEL has been brought into full operation from 3 to 12 microns and has produced substantially higher peak and average power than was available in the past. The far-IR FEL has operated from 15 to 65 microns and will soon be ready for routine user operation. The number of hours of experimenter's beam time has increased to over 2000 hours per year, and the macropulse repetition rate has routinely been 20 Hz instead of the 10 Hz of previous years, allowing more data collection in each hour of beam time.

Several of the experimental areas have undergone extensive modifications. Some of these changes are to improve operation in spectral regions where the atmosphere is highly absorbing. Also, the Ti:sapphire laser which is synchronized to the FEL on a picosecond level has been outfitted with an amplifier which produces 150 μJ pulses for use in two-color pump-probe experiments. In addition, a new room has been built for experiments which use the far-IR FEL.

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ACTIVITIES OF THE CLIO INFRARED FACILITY

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The CLIO infrared FEL is operated since 1992. It is based on a 3 GHz RF linac. The laser beam time was about 2400 h in 1994, 1600 for users and 800 for FEL physics and machine optimisation. The beam time is limited mainly by user ability to work during nights.

The CLIO specific features are the following :

- Large spectral range : 2 to 16 μm, that is being extended to about 40 μm (see FEL conf. papers by O. Marcouillé et al. & R. Prazeres et al.)
- Full user control of the machine, allowing night shifts without the presence of operators
- Wavelength stabilisation by an RF high voltage feedback.
- Adjustable delay between the micropulses from 4 to 32 ns. It allows to synchronize CLIO with external lasers and to vary the average power, at constant peak power. In present SFG conditions, up to 500 mW average power is available on the user table at 25 Hz (macropulse) and 16 ns delay between micropulses (i.e. 40 μJ/pulse and 10 MW peak).
- Electron pulse length rather long for this type of machine : typically 8 ps. This allow the production of a relatively small linewidth (0.2 to 0.4 %) with only a small loss in average power (10 to 20 %) compared with its maximum. We are also able to produce short optical pulses, by adjusting the cavity, down to 350 fs (see FEL conf. paper by F. Glotin et al.).
- We have demonstrated 2-colors FEL simultaneous operation, that enhances its application capabilities (see FEL conf. paper by D. Jaroszynski et al.)
- We have successfully developed a "sum frequency generation" (SFG) set-up, open to users (see companion paper by A. Peremans et al.)
- We are developing optical parametric oscillators ("OPOs") synchronized with CLIO in the near infrared (λ < 4 - 5 μm). This permits several users to be served simultaneously (CLIO being reserved for longer wavelength or higher power), in particular to increase the "duty cycle" of the SFG experiment and to perform pump probe experiment with CLIO in mid-infrared (in 2-colors FEL operation both are in mid-infrared).
- Electrochemical cells are available for use in the SFG experiment.
- UHV chambers including surface diagnostics have been specially built for SFG use.
- Various pieces of equipments are available : cryostats, monochromators, detectors...etc

The CLIO application experiments in 1994 have been :

- Surfaces studies by SFG :
  - Various problems in electrochemistry : studies of the evolution of molecules adsorbed at the electrodes interface (LURE)
  - Polymers on glass surfaces (St Gobain - CNRS)
  - Fullerenes epitaxial films (University of Namur)
  - Studies in ultrahigh vacuum : molecular dynamics (LURE & LPPM - Orsay)

The SFG technique is very efficient and will represent about half of our activity in 1995.

- Semiconductors
  - Non-linear processes (Heriot-Watt)
  - Quantum wells (" ")
  - Quantum well detectors (Thomson)
- Molecules in rare gas matrices
  - isomerisation (University of Marseille)
  - " (University of Paris VI)
  - Pump-probe experiments (LPPM - Orsay)
- Near field infrared microscopy (CNRS - St Gobain & CNET)
- Surface photo-emission (CEA & Budapest University)

COMMISSIONING THE FELI LINAC AND UV-FEL FACILITY

Tomimasu, T., Saeki, K.[†1]*, Miyauchi, Y., Suzuki, T., Oshita, E., Okuma, S., Wakita, K., Kobayashi, A.*[†2]*, Zako, A., Nishihara, S., Koga, A., Ogino, S., Nishimura, E., Mitsuyu, T., Wakisaka K., Tongu, E., Nagai, A. and Yasumoto, M.*[*]

Free Electron Laser Research Institute, Inc. (FELI)
4547-44, Tsuda, Hirakata, Osaka 573-01, Japan
** Osaka National Research Institute*
1-8-31, Midorigaoka, Ikeda City, Osaka 563, Japan

The FELI 165-MeV linac and UV-FEL facility are in the commissioning stage. A thermionic triode gun of the 6-MeV injector emits 500-ps pulses of 2.3A at 22.3125MHz. These pulses are compressed to 60A× 7ps by a 714-MHz prebuncher and a 2856-MHz buncher and seven ETL type accelerating waveguides with a length of 2.93m. The length of the linac including bending sections of two S-type BT systems for two undulators used for IR-FEL oscillations is 46m. The buncher and these accelerating waveguides are powered by two klystrons (E3729, 2856MHz, totla 48MW, 24-μs flat top long pulses). The flatness of our klystron modulator pulses is 0.067% at 24-μs duration. An rf-ageing for new four accelerating waveguides will be started in May.

An S-type BT line for 165-MeV beam from the linac will be installed in the end of April. A 2.68-m undulator (λ_u=4.0cm, N=67, K_{max}=1.9, gap length≧16mm) and an optical cavity (L_c=6.72m) will be installed early in July. The beam conditionings for UV-FEL experiments will be started in July.

Present address: † 1 *Matsushita Electric Industrial Co., Ltd.*
2-7, Matsuba-cho, Kadoma City, Osaka 571, Japan

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The Research Facilities of the Duke FEL Laboratory - Uniqueness and Challenges*

J. M. J. Madey, G. Barnett, B. Burnham, V. N. Litvinenko, P. G. O'Shea, K. D. Straub, E. Szarmes and Y. Wu

FEL light sources offer unique promise as broadly tuneable, high brightness sources of radiation throughout the electromagnetic spectrum. But the effective utilization of these new light sources also raises a series of unprecedented issues and challenges arising, in general, from the limited number of beamlines which can be supported by a single source. The cost effective utilization of this technology therefore requires emphasis on (1) the realization of one or more truly unique research capabilities, (2) the optimization of access to the research beamlines which are available, and (3) the management and support services required by users to maximize their productivity. The experience we have acquired in the development and operation of the facilities of the Duke FEL Lab provide a point of reference which may prove useful to other research-oriented FEL facilities.

* Work supported in part by the Office of Naval Research under Grant Number N00014-94-1-0818

FEL'95 Schedule

	Sunday 8/20	Monday 8/21	Tuesday 8/22	Wednesday 8/23	Thursday 8/24	Friday 8/25
Morning ----------	 ----------	8:30 a.m. *FEL Prize/ New Lasing* G. Kulipanov, Chair Session Mo1 Broadway Ballroom North ---------- 11:00 a.m. *Storage Ring Based FELs* J. Madey, Chair Session Mo2 Broadway Ballroom North	8:30 a.m. *Short Wavelength FELs* L.H. Yu, Chair Session Tu1 Broadway Ballroom North ---------- 10:35 a.m. *High Power FELs* G. Neil, Chair Session Tu2 Broadway Ballroom North	Conference Posters (Session We1) Broadway Ballroom South 8:15 a.m. *Users' Opening Session/Materials I* E. Johnson, Chair Session We2 ---------- 10:00 a.m. Users' Talks *Biomedical* K.D. Straub, Chair Session We3 Broadway Ballroom North Conference Posters Session We1 continued	8:30 a.m. *FEL Technology* M.E. Couprie, Chair Session Th1 Broadway Ballroom North Users' Posters Session Th4 Broadway Ballroom South ---------- 10:30 a.m. *New Directions* C. Pellegrini, Chair Session Th2 Broadway Ballroom North Users' Posters Session Th4 continued	8:30 a.m. *Challenging Research at FELs* G.S. Edwards, Chair Session Fr1 Broadway Ballroom North ---------- 10:30 a.m. *FEL Facility Challenges* J. Allen, Chair Session Fr2 Broadway Ballroom North **Joint Session**
Afternoon ----------	 ----------	2:20 p.m. *Electron Beam Physics and Technology* I. Lehrman, Chair Session Mo3 Broadway Ballroom North ---------- 4:15 p.m. *Long Wavelength FELs* G. Bekefi, Chair Session Mo4 Broadway Ballroom North	Conference Posters Session Tu3 Broadway Ballroom South ---------- Conference Posters Session Tu3 continued Broadway Ballroom South	*TRIP TO BNL* (Includes lunch and dinner). Buses leave Marriott at 11:30 a.m. and return approx. 10:30 p.m. *Vendor Exhibition till Friday*: Majestic/Music Box Room -MKS Instruments -Northrop-Grumman -Titan Beta -VAT, Inc. - Hamamatsu Corp.	Conference Posters (Session Th3) Broadway Ballroom South 1:30 p.m. Users' Talks *Materials II* A. Schwettman, Chair Session Th5 Broadway Ballroom South ---------- Conference Posters Session Th3 continued 3:30 p.m. Users' Talks *Biophysics* A. Doukas, Chair Session Th6	
Evening	5:00 - 7:00 p.m. FEL Conference Registration and Reception THE VIEW		6:00 - 9:00 p.m. Users' Registration and Reception SKY LOBBY		6:00 - 9:00 p.m. Banquet ASTOR BALLROOM 9:00 - 12:00 p.m. Users' Wenckebach Forum SKY LOBBY	

Users' Workshop Program

Wednesday, August 23, 1995

Materials I

8:15 - 8:30	We2	**Introductory Remarks/Welcome** - Session Chair - E. Johnson
8:30 - 9:00	We2-1	**Time Dependence of FEL-Induced Surface Photovoltage on Semiconductor Interfaces Measured with Synchrotron Radiation Photoemission Spectroscopy** Marsi, M., Bakker, R., Couprie, M.E., Delboulbe, A., Garella, D., Hara, T., Indlekofer, G., Nahon, L., Taleb-Ibrahimi, A., Billardon, M.
9:00 - 9:30	We2-2	**Vibrational Relaxation Dynamics of SD Molecules in As_2S_3: Observation of an Anomalous Isotope Effect** Engholm, J.R., Happek, U., Rella, C.W., Schwettman, H.A.
9:30 - 10:00	*Coffee Break*	

Wednesday, August 23, 1995 (continued)

Biomedical
Session Chair - K. Dave Straub

10:00 - 10:30	We3-1	**Photoablation in Dental Hard Substances and Atheromatous Plaques - The Efficiency and Selectivity Criteria for Surgery** Jean, B.
10:30 - 11:00	We3-2	To be announced

Thursday, August 24, 1995
Posters
8:30 - 12:00

Th4-1 **Experiments on Ocular Tissue Ablation at 5.3 and 6.0 µm with the Los Alamos Advanced FEL**
Nguyen, D.C., Ren, Q., Hill, R., Liaw, L., Keates, R.H., Berns, M.

Th4-2 **Matrix-Assisted Laser-Desorption-Ionization Mass Spectrometry of Proteins Using a Free-Electron Laser**
Cramer, R., Haglund, R., Hillenkamp, F.

Th4-3 **Sum-Frequency Generation From Molecular Monolayers Using 14 µm Radiation from the FELIX Free-Electron Laser**
Van der Ham, E.W.M., Vrehem, Q.H.F., Eliel, E.R., 't Hooft, G.W., Auerhammer, J.M., Van der Meer, A.F.G.

Th4-4 **Time-Resolved Protein Dynamics Using a Synchronized Ti:Sapphire Regenerative Amplifier/Infrared FEL**
Stanley, R.J., Haar, P., Boxer, S.G.

Th4-5 **Biological Effects of Laser-Induced Stress Waves**
Doukas, A., Lee, S., McAuliffe, D., Zhang, H., Lamb, D., Flotte, T.

Th4-6 **Temperature Dependence of the Two Photon Absorption in Indium Arsenide**
Berryman, K.W., Rella, C.W.

Th4-7 **Reflection and Transmission Measurements on High-Tc Superconducting Films in the mm-Wave Region**
Gallerano, G.P., Boffa, V., Dore, P., Doria, A., Giovenale, E., Kimmitt, M.F.

Th4-8 **Photo-Induced Reflectivity in the Mid and Far Infrared**
Haar, P., Harrington, K.J., Schwettman, H.A.

Th4-9 **Heterostructures as a Quantum Optical Klistron**
Malov, Y.A.

Th4-10 **Many-Body Dynamics and Energy Relaxation Times in a Wide Semiconductor Quantum Well as Probed by Nonlinear Far-Infrared Absorption**
Sherwin, M.S., Craig, K., Unterrainer, K., Williams, J.B.

Th4-11 **The Photon Drag Effect: A Fast FIR Detector**
Sigg, H.C., van Son, P.C., Wenckebach, W.Th.

Th4-12 **Users Program for Storage-Ring Based FEL and Synchrotron Sources of the Duke FEL Laboratory**
Straub, K.D., Barnett, G., Burnham, B., Litvinenko, V.N., O'Shea, P.G., Madey, J.M.J., Szarmes, E., Wu, Y.

Th4-13 **Microglial Responses to Free Electron Laser Incisions in Rat Brain**
Zhang, M.Z., Edwards, G.S., Reinisch, L., Casagrande, V.A., McKanna, J.A.

Th4-14 **The User Facility FELIX: Past, Present and Future**
van der Meer, A.F.G., van Amersfoort, P.W.

Th4-15 **Development of a Scanning Near-Field Infrared Microscope Based on a Free Electron Laser**
Hong, M.K., Erramilli, S., Jeung, A.

Th4-16 **Excitation and Deexcitation of the Si-H Stretching Mode in a Si:H with Picosecond Free Electron Laser Pulses**
Xu, Z., Fauchet, P.M., Rella, C.W., Schwettman, H.A., Tsai, C.C.

Th4-17 **Picosecond Intersubband Hole Relaxation in p-type Quantum Wells**
Xu, ZZ., Fauchet, P.M., Rella, C.W., Schwettman, H.A., Wicks, G.W.

Th4-18 **Electronic Properties of Superconductors Studied Using Photo Induced Activation of Microwave Absorption (PIAMA)**
Feenstra, B.J., Schoonveld, W.A., Bos, C., Barber, Z., Matijasevic, V., van der Marel, D.

Th4-19 **Quantum Well Intersubband Lifetimes Measured by Mid-IR Pump-Probe Experiments**
Woods, G.L., Sung, B., Proctor, M., Ebert, C.B., Milo, R., Harris Jr., J.S., Fejer, M.M., Rella, C.W., Schwettman, H.A.

Th4-20 **Vibrational Relaxation of a Triatomic Molecular Impurity: D_2O in Vitreous As_2S_3**
Rella, C.W., Schwettman, H.A., Engholm, J.R., Happek, U.

Th4-21 **Influence of Phonon Emission on Intersubband Lifetimes in Wide GaAs/AlGaAs and Si/SiGe Quantum Wells**
Murdin, B.N., Pidgeon, C.R., Lee, S.C., Galbraith, I., Langerak, C.J.G.M., Heiss, W., Hertle, H., Unterrainer, K., Gornik, E., Helm, M.

Th4-22 **Wavelength Dependent Delay in the Onset of FEL Tissue Ablation**
Tribble, J.A., Lamb, J.A., Reinisch, L., Edwards, G.S.

Th4-23 **Mode Pumping Experiments on Biomolecules**
Austin, R.H., Erramilli, S., Xie, A., Schramm, A.

Th4-24 **Medical and Molecular Biological Application in the FELI**
Nishimura, E., Yasumoto, M., Ogino, S., Saeki, K., Miyauchi, Y., Suzuki, T., Oshita, E., Okuma, S., Wakita, K., Kobayashi, A., Zako, A., Nishihara, S., Koga, A., Mitsuyu, T., Wakisaka, K., Tongu, E., Nagai, A., Tomimasu, T.

Th4-25 **Time Dependent Weak Localization of a 2DEG in the Presence of Andreev Reflections**
Drexler, H., Harris, J., Yuh, E.L., Gwinn, B., Allen, S.J., Wong, K., Kroemer, H.

Th4-26 **Studies of Fullerene Absorption and Production Using an Infrared Free Electron Laser**
Affatigato, M., Ying, Z.C., Compton, R.N., Haglund, R.F.

Th4-27 **Dynamic Localization and Negative Absolute Conductance in Terahertz Driven Semiconductor Superlattices**
Keay, B.J., Allen, S.J., Campman, K.L., Maranowski, K.D., Gossard, A.C., Bhattacharya, U., Rodwell, M.J.M.

Th4-28 **Picosecond Response of a Photon Drag Detector**
Kimmitt, M.F.

Th4-29 **Vibrational Population Dynamics in Liquids and Glasses: IR Pump-Probe Experiments from 10K to 300 K**
Kwok, A.S., Francis, R.S., Rector, K.D., Ferrante, C., Taiti, C., Tokmakoff, A., Fayer, M.D.

Th4-30 **Electrostatic-Accelerator Free-Electron Lasers for Power Beaming**
Pinhasi, Y., Yakover, I.M., Gover, A.

Thursday, August 24, 1995

Materials II
Session Chair - H.A. Schwettman

1:30 - 2:00	Th5-1	**Measurement of the Resonant Polaron Effect in the Restrahlen Band of GaAs:Si Using Far-Infrared Two-Photon Excitation** Wenckebach, W.,Th., Planken, P.C.M., van Son, P.C., Hovenier, J.N., Klassen, T.O., Barmby, P.W., Dunn, P.W., Bates, J.L., Foxon, C.A., Langerak, C.J.G.M.
2:00 - 2:30	Th5-2	**Inverse Bloch-Oscillator: Strong THZ-Photocurrent Resonances at the Bloch Frequency** Unterrainer, K., Keay, B.J., Wanke, M.C., Allen, S.J., Leonard, D., Medeiros-Ribeiro, G., Bhattacharya, U., Rodwell, M.
2:30 - 3:00	Th5-3	**Coherent Transient Grating Effects and Auger Inhibition in InAsSb Systems** Murdin, B.N., Pidgeon, C.R., Ciesla, C.M., Hughes, S., Jaroszynski, D., Prazeres, R., Langerak, C.J.G.M., Phillips, C.C., Stradling, R.A.
3:00 - 3:30	*Coffee Break*	

Thursday, August 24, 1995 (continued)

Biophysics

Session Chair: A. Doukas

3:30 - 4:00	Th6-1	**Vibrational Lifetimes of Protein Amide Modes** Peterson, K.A., Rella, C.A.
4:00 - 4:30	Th6-2	**IR-UV Photochemistry of Protein-Nucleic Acid Systems** Kozub, J., Edwards, G.
4:30 - 5:00	Th6-3	To be announced

Friday, August 25, 1995

Challenging Research at FELs
Session Chair: G.S. Edwards

8:30 - 9:00	Fr1-1	**Terahertz Quantum Transport in Semiconductor Nanostructures with the UCSB Free Electron Lasers** Allen, S.J.
9:00 - 9:30	Fr1-2	**To be Announced**
9:30 - 10:00	Fr1-3	**Energy Transfer at the Active Sites of Heme Proteins** Dlott, D.D., Hill, J.R.
10:00 - 10:30	*Coffee Break*	

Friday, August 25, 1995 (continued)

FEL Facility Challenges

10:30 - 10:40	Fr2	**Introductory Remarks - Session Chair** Allen, J.
10:40 - 11:05	Fr2 - 1	**Challenges at FEL Facilities: The Stanford Picosecond FEL Center** Schwettman, H.A., Smith, T.I., Swent, R.L.
11:05 - 11:30	Fr2 - 2	**Activities of the CLIO Infrared Facility** Ortega, J.M., Berset, J.M., Chaput, R., Glotin, F., Humbert, G., Jaroszynski, D., Joly, P., Kergosien, B., Lesrel, J., Marcouille, O., Peremans, A., Prazeres, R., Taddjedine, A.
11:30 - 11:55	Fr2 - 3	**Commissioning the FELI Linac and UV-FEL Facility** Tomimasu, T., Saeki, K., Miyauchi, Y., Suzuki, T., Oshita, E., Okuma, S., Wakita, K., Kobayashi, A., Zako, A., Nishihara, S., Koga, A., Ogino, S., Nishimura, E., Mitsuyu, T., Wakisaka, K., Tongu, E., Nagai, A., Yasumoto, M.
11:55 - 12:20	Fr2 - 4	**The Research Facilities of the Duke FEL Laboratory - Uniqueness and Challenges** Madey, J.M.J., Barnett, G., Burnham, B., Litvinenko, V.N., O'Shea, P.G., Straub, K.D., Szarmes, E., Wu, Y.
12:20 - 12:30		Closing Remarks

TIME DEPENDENCE OF FEL-INDUCED SURFACE PHOTOVOLTAGE ON SEMICONDUCTOR INTERFACES MEASURED WITH SYNCHROTRON RADIATION PHOTOEMISSION SPECTROSCOPY

M. Marsi*, R. Bakker°†, M.E. Couprie°†, A. Delboulbé°, D. Garzella°, T. Hara°†, G. Indlekofer°, L. Nahon°†, A. Taleb-Ibrahimi° and M. Billardon°**
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During the last year, the first surface science experiments simultaneously using a Free Electron Laser (FEL) and Synchrotron Radiation (SR) have been performed on SuperACO at LURE (Orsay, France).

These "two color" experiments studied the surface photovoltage (SPV) induced on semiconductor surfaces and interfaces by the SuperACO FEL, a storage ring FEL delivering 350 nm photons which are naturally synchronized with the SR; the SPV was measured by synchrotron radiation core-level photoemission spectroscopy on the high-resolution SU3 undulator beamline.

We will describe the experimental setup, which allowed us to convey the FEL light onto the samples sitting in the SU3 experimental station by means of a series of mirrors, and show the results we obtained for prototypical systems such as Ag/GaAs(110) and Si(111)2×1. The dependence of the SPV was studied in function of various parameters, changing sample doping and photon flux; but our efforts were mainly devoted to studying its dependence on the time delay between the FEL pump and the SR probe. On SuperACO, such delay can be varied between 1 and 120 ns, the limits being given by the time duration of a SR pulse and by the interval between two consecutive positron bunches, respectively.

The results show a clear temporal dependence of the amount of SPV on cleaved Si surfaces, where as the Ag/GaAs(110) does not show any difference on the ns time scale. We will discuss these results in terms of the role of surface recombination in the dynamics of the photoinduced electron-hole pairs.

These studies follow the evolution of the density of electrostatic charge at surfaces and interfaces on a nanosecond time scale, and might pave the way for a new series of experiments: for example, one might explore what are the physical mechanisms limiting the time response of Schottky diodes. The opportunity of operating an FEL synchronized to SR made it possible to extend the well established capabilities of core-level photoemission spectroscopy to the study of systems out of electrostatic equilibrium.

VIBRATIONAL RELAXATION DYNAMICS OF SD MOLECULES IN As_2S_3: OBSERVATION OF AN ANOMALOUS ISOTOPE EFFECT

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It is generally assumed that the vibrational relaxation of molecular impurities in crystals and glasses mainly depends on the order of the decay process, with lower order processes leading to more rapid relaxation (a behavior that is known under the term "gap-law"). Here we present measurements that contradict this assumption. Using high intensity psec pulses of the Stanford FEL we measured the relaxation rate of the SD vibrational stretch mode (at a frequency of 1800 cm^{-1}) by applying a pump-probe technique. We find relaxation rates on the order of 2×10^{9} sec^{-1}, which are a factor of 2 <u>lower</u> than those found for the isotope molecule SH (at a frequency of about 2500 cm^{-1}) in the same host[1]. We recall that the relaxation of the SD vibrational stretch mode is controlled by a lower order process as compared to the SH molecule, which is due to the smaller number of host vibrational quanta to match the energy of the stretch mode; a fact we have confirmed experimentally by temperature dependent relaxation measurements.
Thus our results are in marked contrast to the so-called "Gap-Law" and emphasize the importance of the molecule - host coupling in the relaxation dynamics..

The work was supported in part by the Office of Naval Research, Grant No. N00014-94-1-1024.

1. U. Happek, J.R. Engholm, and A.J.Sievers, Chem.Phys.Lett. 221 (1994) 279

Photoabalation in Dental Hard Substances and Atheromatous Plaques - The Efficiency and Selectivity Criteria for Surgery

Benedikt Jean, MD PhD
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The basic principals of IR photoabalation are relatively easy to understand as long as water is the predominant absorber in the target tissue (e.g. brain tissue, cornea).

Dental hard substances are typical target materials for the study of biological materials with low water content (30%) Its main constituent is hydroxyapatit (50%) with maximal absorption at 9.5 μm wavelength. The photoablation efficiency, the collateral thermal damage and the resultant formation of thermally induced surface cracks were investigated. Unlike the 2.95 μm of the Er:YAG, already in use, the 9.5 μm radiation minimizes the penetration depth; as a consequence, the volume of heated material per pulse is minimal too and thus thermal cracks - a potential source of caries are avoided. Furthermore at 9.5 μm, the ablation threshold requires a minimal fluence; this is an element of selectivity, limiting photoablation to dentin and enamel, while neighboring gingiva cannot be ablated accidentally.

Removal of atherosclerotic plaques for recanalization of obliterated cardiac vessels (laser angioplasty) is a minimally invasive surgical procedure of highest socio-economic relevance. The rather inhomogeneous composition of apatit and colesterol (both absorbing at 9.5 μm) make plaques a particularly complex target material; while the ablation efficiency has to be high, the related shock wave should be minimal. The "selectivity" criterion of the ablation process must avoid accidental perforation of the underlying vessel walls (composed of connective tissue with high water content), a deadly complication! Experimental results with FELIX will be demonstrated.

Photoacoustic spectroscopy in a recently developed non contact mode has been proved to provide various informations (on line) about the IR-photoablation process. As the absorption coefficient of the target material is related to the amplitude of the resultant signal, the method allows the discrimination of target materials for every volume of tissue removed; this is an important option for future "smart" laser control. FEL experiments have proved the feasibility of the concept.

Acknowledgment: This work as received support from US-ONR (0014-91-0109) and the European Union ERB 4050 PL 940877.

EXPERIMENTS ON OCULAR TISSUE ABLATION AT 5.3 AND 6.0 μm WITH THE LOS ALAMOS ADVANCED FEL[1]

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We investigated the ablation characteristics of a picosecond free-electron laser and compared its ablation effects on ocular tissues at 5.3 μm and 6.0 μm. The Advanced FEL at Los Alamos, operating in the wavelength range 4–6 μm, was used for this study. The 10-μs macropulse consisted of ~1000 micropulses, each approximately 15 ps in length and separated from one another by 9.2 ns. The FEL beam was passed through a series of attenuator and focused to a 200-μm spot in the sample with a 150-mm f.l. CaF_2 lens. The energy in each macropulse ranged from 5 to 120 mJ. Five transplantable corneal-scleral buttons preserved in corneal storage media were used for this study. The tissue sample was positioned at the focused FEL beam for the ablation, and then fixed for histologic study. Corneal cuts made at 6.0 μm revealed a well-defined ablation boundary. The measured lateral zone of the tissue damage was 11 ± 2 μm. The integrity of the adjacent tissue was well maintained. By contrast, the ablation boundary of the corneal cuts made at 5.3 μm appeared to be very disruptive. The collagen fiber near the ablation was thermally denatured and lost its organized structure. The lateral dimension of such effect extended out to 220 μm beyond the intended cut into the surrounding tissues. We concluded that a short-pulsed laser operating at 6 μm may be a potentially effective tool for cutting ocular tissues.

[1] Supported by the Los Alamos Laboratory Directed Research and Development Initiatives under the auspices of the U. S. Department of Energy.

MATRIX-ASSISTED LASER-DESORPTION-IONIZATION MASS SPECTROMETRY OF PROTEINS USING A FREE-ELECTRON LASER[1]

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Matrix-assisted laser desorption-ionization (MALDI) mass spectrometry (MS) is one of the most promising techniques for spectral fingerprinting large molecules, such as proteins, oligonucleotides and carbohydrates. In the usual implementation of this technique, the analyte molecule is dissolved in an aromatic liquid matrix material which resonantly absorbs ultraviolet laser light. Resonant absorption by π-π^* transitions volatilizes the matrix and initiates subsequent charge transfer to the analyte molecules,[2] which are detected by time-of-flight mass spectrometry.

Recent MALDI-MS studies with Er:YAG[3] (2.94 μm) and CO_2[4] (9.4-10.6 μm) lasers suggest that there is significant unexplored potential for mass spectrometry of macromolecules, including oligonucleotides,[5] in the mid-infrared. Preliminary experiments show that it is possible to capitalize on the rich rovibronic absorption spectrum of virtually all organics to initiate resonant desorption in matrix material over the entire range of *pH* values. However, the mechanism of charge transfer is particularly problematic for infrared MALDI because of the low photon energy.

In this paper, we report the results of MALDI-MS studies on small proteins using the Vanderbilt FEL and several matrix materials. Proteins with masses up to roughly 6,000 amu were detected with high resolution in a linear time-of-flight mass spectrometer. By varying the pulse duration using a broadband Pockels cell, we have been able to compare the results of relatively long (5 μs) and short (0.1 μs) irradiation on the desorption and ionization processes. Compared to uv-MALDI spectra of identical analytes obtained with a nitrogen laser (337 nm) in the same time-of-flight spectrometer, the infrared results appear to show that the desorption and ionization process goes on over a somewhat longer time scale.

We have also varied the FEL wavelength to determine the effects of resonant *vs* nonresonant absorption on desorption and ionization efficiency.

1. Supported by the Office of Naval Research, Contract N000014-94-C-0109.
2. K. Tang, R. F. Haglund, Jr. and C. H. Chen, submitted to Chem. Phys. Lett.
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SUM-FREQUENCY GENERATION FROM MOLECULAR MONOLAYERS USING 14 μm RADIATION FROM THE FELIX FREE-ELECTRON LASER

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Sum-frequency generation (SFG) has developed into a widely applied tool for study of surfaces and interfaces where molecules are present. It combines the surface specificity of a second-order nonlinear optical technique with the power of a spectroscopic method, and it can be used under widely varying experimental conditions ranging from UHV to electrochemical cells. The important characteristic of SFG is that it allows one to study the average spatial orientation of a molecular bond in a monolayer of molecules at an interface.

Until recently SFG measurements were confined to the frequency interval $\nu > 1700$ cm^{-1} because of a lack of suitable laser sources at wavelengths $\lambda > 6$ μm. So for most molecules only a few vibrational modes and thus intramolecular bonds can be studied. We have developed a universal sum-frequency spectrometer around the FELIX free-electron laser that covers the complete molecular fingerprint since we can generate any IR wavelength between 2.75 and 110 μm at the FELIX facility[1,2].

We have used this setup for a series of exploratory SFG experiments in a frequency range that was hitherto unexplored in the study of molecular monolayers. We have studied thiol monolayers chemisorbed on a variety of noble metals (Au, Ag, Pt) where we focussed on the C-S stretch vibration at $\nu = 702$ cm^{-1} ($\lambda = 14.3$ μm). We have found spectroscopic features revealing the presence of both the *trans* and *gauche* conformers of the adsorbed molecules. The present measurements open a whole new wavelength range for nonlinear optical studies of interfaces.

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Time-Resolved Protein Dynamics using a Synchronized Ti.Sapphire Regenerative Amplifier/Infrared FEL[1]

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ABSTRACT

We have synchronized a femtosecond 5 kHz Ti Sapphire regenerative amplifier (regen) to the Stanford Superconducting Accelerator/Free Electron Laser (SCA/FEL) to within 2 picoseconds time jitter. We are using this capability to measure the time-resolved spectral evolution of the radical cation band of the initial electron donor from bacterial reaction centers (*Rb. sphaeroides*) after the initiation of electron transfer using a ~120 fs NIR pulse from the regen. The FEL is used to probe for the appearance of the radical cation band at ~ 4 μm.

[1]Work supported in part by the Office of Naval Research, Grant No. N00014-94-1-1024

BIOLOGICAL EFFECTS OF LASER-INDUCED STRESS WAVES

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Laser-induced stress waves can be generated by one of the following mechanisms: Optical breakdown, ablation or rapid heating of an absorbing medium. These three modes of laser interaction with matter allow the investigation of cellular and tissue responses to stress waves with different characteristics and under different conditions. The most widely studied phenomena are those of the collateral damage seen in photodisruption in the eye and in 193 nm ablation of cornea and skin. On the other hand, the therapeutic application of laser-induced stress waves has been limited to the disruption of noncellular material such as renal stones, atheromatous plaque and vitreous strands.

The effects of stress waves to cells and tissues can be quite disparate. Stress waves can fracture tissue, damage cells, and increase the permeability of the plasma membrane. The viability of cell cultures exposed to stress waves increases with the peak stress and the number of pulses applied. The rise time of the stress wave also influences the degree of cell injury. In fact, cell viability, as measured by thymidine incorporation, correlates better with the stress gradient than peak stress. Recent studies have also established that stress waves induce a transient increase of the permeability of the plasma membrane *in vitro*. In addition, if the stress gradient is below the damage threshhold, the cells remain viable. Thus, stress waves can be useful as a means of drug delivery, increasing the intracellular drug concentration and allowing the use of drugs which are impermeable to the cell membrane. The present studies show that it is important to create controllable stress waves. The wavelength tunability and the micropulse structure of the free electron laser is ideal for generating stress waves with independently adjustable parameters, such as rise time, duration and peak stress.

TEMPERATURE DEPENDENCE OF THE TWO PHOTON ABSORPTION IN INDIUM ARSENIDE[1]

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Nonlinear optical processes in semiconductors have long been a source of interesting physics. Two photon absorption (TPA) is one such process, in which two photons provide the energy for the creation of an electron-hole pair. Researchers at other FEL centers have studied room temperature TPA in InSb, InAs, and HgCdTe.[1-3] Working at the Stanford Picosecond FEL Center, we have extended and refined this work by measuring the temperature dependence of the TPA coefficient in InAs over the range from 80 to 350 K at four wavelengths: 4.5, 5.06, 6.01, and 6.3 microns. The measurements validate the functional dependence of recent band structure calculations[4] with enough precision to discriminate parabolic from non-parabolic models, and to begin to observe smaller effects, such as contributions due to the split-off band. These experiments therefore serve as a strong independent test of the Kane band theory, as well as providing a starting point for detailed observations of other nonlinear absorption mechanisms.

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[1] Work supported in part by the Office of Naval Research, Grant No. N00014-94-1-1024.

REFLECTION AND TRANSMISSION MEASUREMENTS ON HIGH-Tc SUPERCONDUCTING FILMS IN THE MM-WAVE REGION

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The characterization of high-Tc superconducting films is in progress at the Frascati FEL Facility, F-CUBE. The experiment is aimed at obtaining the complex conductivity of YBCO films deposited on a $LaAlO_3$ substrate by measuring the reflection and transmission coefficients. Similar experiments have been performed by other groups at far infrared wavelengths. The continuos tunability and the high peak power, up to 10 kW, of F-CUBE make this experiment possible also at millimeter wavelengths even in very lossy samples with transmission of less than 1%.

Such an experiment is important for the study of high-Tc superconductors, because it provides additional spectral information and a better comprehension of the internal structure of these materials.

The experimental technique utilized will be discussed together with the issues related to the detection process and to the stability of the FEL source. Results in the spectral range between 2 and 3.5 mm will be presented and compared with the characteristics at shorter wavelengths.

PHOTO-INDUCED REFLECTIVITY IN THE MID AND FAR INFRARED[1]

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Interest in switching FEL beams[2,3] has motivated studies of photo-induced reflectivity in the mid and far infrared. We are particularly interested in Ge[4], GaAs, and Si[5], materials that can be pumped with a visible or near-IR conventional laser and which together cover the wavelengths from 3-100μm. We have made quantitative measurements to determine the induced reflectivity, carrier lifetime, and transient absorption of these materials at several wavelengths across this range using a variety of pump laser wavelengths and pulse lengths. These measurements allow us to determine the feasibility of single pulse selection and cavity dumping with our FELs at high repetition rates.

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HETEROSTRUCTURES AS A QUANTUM OPTICAL KLISTRON.

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THE beam of "hot" ballistic electrons which were first obtained experimentally in (1) is considered when passing through the heterostructures consisting of two potential barriers in barriers in the presence of FEL tuning in infra-red region.In the presence of the first barrier the electron beam in the FEL electromagnetic field can either absorb or emit the field quanta. The initial electron beam may split into states n=1 (absorption of one quantum), n=0 (the beam energy unchanged), and n=-1 (emission of one quantum). The interference of the states with n=0, n=1 and n=0, n=-1 results in the initiation of two traveling modulation waves at electromagnetic frequency w.

Beats between these waves in the region of the of their overlapping lead to a periodic dependence of the modulation from w.

It has been found that the spontaneous coherent radiation (SCR) intensity oscillates with the period depending on FEL frequency w. It is possible to increase or to decrease the spectral intensity of SCR varying w. The suggested idea of modulation on the first barrier of heterostructures and the radiation of modulated electron beam on the second barrier is a scheme of an quantum optical klistron in infra-red region.

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MANY-BODY DYNAMICS AND ENERGY RELAXATION TIMES IN A WIDE SEMICONDUCTOR QUANTUM WELL AS PROBED BY NONLINEAR FAR-INFRARED ABSORPTION[1]

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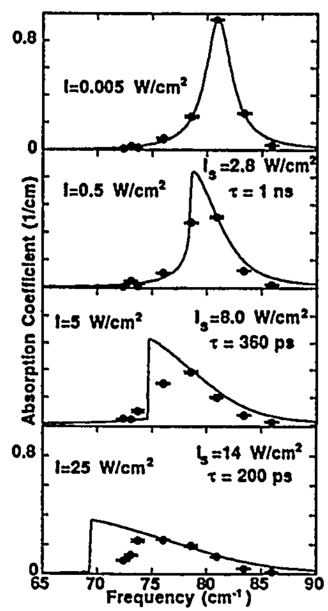
In quantum wells, absorption between the quantized subbands of the conduction band does not take place at the difference of the subband energies; the interactions of the electrons shift the intersubband absorption to higher frequency; this is called the depolarization shift. This shift can be thought of as a dynamic screening effect, and depends upon the difference in population between the subbands of interest. These are the first group of measurements of the dynamics of the depolarization shift, and they offer the possibility of both increased understanding of many-body interactions in real systems, and the possibility of novel quasi-optical devices operating in the far-infrared (FIR).

We have performed measurements of intersubband absorption of a modulation-doped 400Å GaAs/AlGaAs quantum well at 10K using the UCSB Free-Electron Laser as a source of intense tunable FIR. We use direct FIR transmission to measure the absorption of the well as a function of both frequency and intensity. These measurements allow us to directly probe the dynamics of the depolarization shift, as well as investigate the energy relaxation processes in our well. Our preliminary results are shown to the left; the dots are experimentally measured intersubband absorption strength as a function of frequency; the different plots show several intensities. (Note that this is very preliminary data with a large uncertainty in intensity and therefore relaxation time.) In general, we find reasonably good agreement with a theory by Zaluzny[2], as shown with the solid curves.



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THE PHOTON DRAG EFFECT: A FAST FIR DETECTOR

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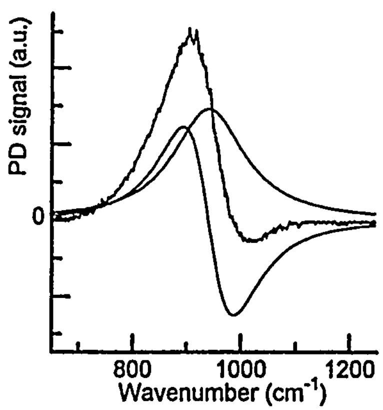
The photon drag (PD) effect in solids is the electrical current generated along the path of the absorbed photons. It is a very direct transducer which is also very fast because the momentum relaxation times of the electrons are involved. We studied the PD effect in the 2D electron gas (2DEG) of a GaAs/AlGaAs multi-quantum well system using the free-electron laser source FELIX (Nieuwegein, The Netherlands). The temporal response on a ps timescale has been observed, and the continuous spectral response through the intersubband resonance (ISR) is investigated. For high excitation intensities we observe saturation of both the PD effect and the ISR absorption.
The experiments are performed on an MBE grown GaAs/AlGaAs sample with 30 8-nm-wide quantum wells, each containing 0.8 10^{12} electrons/cm^2. The light is coupled to the 2DEG through a single-pass internal reflection in a Ge prism pressed onto the sample surface, and the electrical signal is capacitively coupled out to a microstrip line. The measured temporal response to the 2-ps-long infrared micropulses is limited by the 34 GHz bandwidth of the sampling oscilloscope. The spectral response (ISR at 120 meV) and the saturation of the PD effect and of the optical absorption are measured real-time on the timescale of the FELIX macropulse (typically 2 μs).



Two contributions to the PD signal can be distinguished in the spectral response: One is proportional to the absorption and the other is proportional to its derivative with respect to frequency. The relative strength of the contributions is related to the momentum relaxation times of the electrons in the lowest and first excited subbands. At high excitation intensities, the relative strength of the two contributions stays surprisingly constant, despite the strongly increased ISR linewidth and the saturation of the signal. This indicates that the limiting relaxation time relevant for the saturation of the PD effect is longer than the sub-picosecond momentum relaxation times. However this observation does not exclude a sub-picosecond electrical response of the photon drag detector.

USERS PROGRAM FOR STORAGE-RING BASED FEL AND SYNCHROTRON SOURCES OF THE DUKE FEL LABORATORY*

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The storage ring at the Duke FEL Laboratory was first operated with a stored e-beam in November, 1994. It has nowachieved operation energies in excess 1 GeV with more than 100 mA current at 280 MeV. The ring has several ports for FEL and synchrotron light source research. The circulating ring current can be synchronized with the seperate Mark III FEL operating in the 2-9.5 µm IR region. This allows low optical jitter (10-20 ps) between the two sources and thus pump-probe operation. The ring has been configured to drive a number of light sources including the OK-4 FEL system capable of FEL operation between 400 and 65 nm, an inverse Compton scattering source using this undulator which will yield 4-200 MeV gammas, an undulator source at approximately 40 Å (not an FEL), a mm FEL with inverse compton scattering providing 1-100 keV x-rays and two synchrotron ports from the bend magnets for which the λ_c = 11-12 Å for 1 GeV. The broadly tunable FEL sources and their associated inverse compton scattering are extremely bright. The initial research proposals, submitted to the Laboratory emphasizes photoelectron spectroscopy, PEEM, high resolution vacuum UV of gases, solid spectroscopy and photochemistry in the UV, X-ray microprobe studies, X-ray microscopy, X-ray holography, X-ray crystallography, Mossbauer spectroscopy, nuclear spectroscopy, neutron production, photon activation therapy and broadband synchrotron as a probe of fast reaction in the IR and near IR.

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MICROGLIAL RESPONSES TO FREE-ELECTRON LASER INCISIONS IN RAT BRAIN.

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In the CNS, two distinct populations of ramified glia, microglia and astrocytes, are identified by two Ca^{++}-binding proteins, lipocortin 1 (LC1) and S100-β, respectively. In some forms of CNS trauma, the responses of these two populations are quite different (*J Neurosci Res* 36:491-500). The present study sought to characterize and compare the responses of microglia and astrocytes to cortical incisions made with the free-electron laser (FEL, 6.45 and 4.0 μm wavelength) and with a scalpel.

After 3 and 6 days recovery, rats were perfused with acidified glutaraldehyde; the activated glia were identified using immunohistochemistry and quantified using BIOQUANT.

In a 200 μm thick zone of gliosis located beneath the damaged necrotic tissue, similar response patterns were observed for both incision types. At either time point, S100-β-positive glia showed only minor shape changes and slight increases relative to astrocytes in control regions. Conversely, the population density of microglia in the reaction zone increased approximately 2- and 3-fold at days 3 and 6, respectively. Mitotic figures are detected among the LC1-positive glia at day 3, indicating that the activated phagocytes arise from proliferating resident microglia rather than from hematogenous invaders.

Thus, in this system, the glial response to CNS damage comprises primarily microglia rather than astrocytes. The data also suggest that the anti-inflammatory and immuno-suppressive properties of LC1 may play important roles in recovery from CNS trauma and disease.

Preliminary experiment show subdued glial responses to incisions made with FEL at 6.45 versus. 4.0 μm wavelengths, suggesting that tissue damage is wavelength dependent.

Supported by DOD Medical FEL program.

THE USER FACILITY FELIX : PAST, PRESENT AND FUTURE

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The performance over the past year and the current user-relevant characteristics of the User Facility FELIX will be discussed. Also the existing plans for improving and extending the capabilities and provisions will be presented.

Development of a Scanning Near-Field Infrared Microscope Based on a Free Electron Laser

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Infrared spectroscopy is one of the most sensitive technique available for identifying and characterizing organic materials. Most molecules exhibit a large number of well-resolved strongly absorbing spectral lines in the mid-IR region of the spectrum. In addition to our own efforts described last year, Creuzet et al have also been working on combining infrared spectroscopy with sub-micron spatial resolution imaging (Creuzet et al, *FEL 94*). Scanning Near Field Infrared Microscopy (SNIM) when combined with high brightness tunable FEL radiation, provides a powerful new research tool. We have developed two new probes for use in SNIM. The first are chalcogenide fibers capable of transmitting images in the 2-12 μ range. At the Stanford picosecond Free Electron Laser, we have successfully obtained images of metal surfaces and of collagen fibers on diamond at a wavelength of 5.01 μ, with a nominal spatial resolution of 0.5 μ, demonstrating that near field imaging can be obtained on biological samples. At a wavelength of 6.3 μ, we found that the chalcogenide fibers are limited in their ability to withstand high powers, most likely because of the presence of absorption bands in the polyimide coating used to sheath the brittle fibers. In collaboration with Prof. J. Harrington (Rutgers University), we have also developed hollow glass capillaries with metal coated on the inside. These probes are able to withstand significantly higher powers, and can function to longer wavelengths, out into the Far IR region.

: Support from a grant from the National Science Foundation, and the Office of Naval Research is gratefully acknowledged.

Excitation and Deexcitation of the Si-H Stretching Mode in a-Si:H with Picosecond Free Electron Laser Pulses

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Hydrogen in amorphous and crystalline silicon has been the topic of intense theoretical and experimental investigations for more than one decade. To better understand how the Si-H bonds interact with the Si matrix and how they can be broken, it would be useful to excite selectively these bonds and monitor the energy flow from the Si-H bonds into the bulk Si modes. One attractive way of exciting the Si-H modes selectively is with an infrared laser tuned to a Si-H vibrational mode. Unfortunately, up to now, this type of experiment had not been possible because of the lack of a laser producing intense, ultrashort pulses that are tunable in the mid infrared. In this presentation, we report the first measurement where a 1 picosecond long laser pulse was used to excite the Si-H stretching modes near 2000 cm^{-1} and another identical laser pulse was used to measure the deexcitation from that specific vibrational mode. The laser was the Stanford free electron laser generating ~ 1 ps-long pulses, tunable in the 5 µm region and focussed to an intensity of ~ 1 GW/cm^2. The pump-probe measurements were performed in transmission at room temperature on several 2 µm thick a-Si:H films deposited on c-Si. Samples with predominant $Si\text{-}H_1$ modes, predominant $Si\text{-}H_{n>1}$ modes and with a mixture of modes were prepared. The laser was tuned on resonance with either of these modes.

Immediately after excitation, we observe a bleaching of the infrared absorption, which can be attributed to excitation of the Si-H mode. Beaching is expected since, as a result of anharmonicity, the detuning between the $(E_3 - E_2)$ resonance and the $(E_2 - E_1)$ resonance is larger than the laser bandwidth. Note that despite the anharmonicity, it should be possible to climb the vibrational ladder due to power broadening. The vibrational deexcitation of the Si-H stretching mode is biexponential and occurs with two characteristic time constants: a short time constant between 10 and 40 picoseconds and a long time constant that is approximately 5 times longer. The decay times vary depending on the type of $Si\text{-}H_n$ bond.

In a typical crystalline semiconductor, the decay time for an optical phonon is of the order of 1 picosecond. The long time constant observed here suggests that the Si-H stretching mode is weakly coupled to the Si matrix and thus that significant energy can be deposited in this mode in a very localized fashion. These results will be compared to simulations that take into account the different vibrational modes present in a-Si:H and to experimental results obtained on ideal Si surfaces that are terminated by hydrogen.

We acknowledge support from the US Office of Naval Research through contracts N00014-92-J-4063 and N00014-94-1-1024.

Picosecond Intersubband Hole Relaxation in p-type Quantum Wells

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We report the first direct measurement of the relaxation time of holes in p-type quantum wells using tunable, subpicosecond mid-infrared laser pulses in a pump-probe arrangement. The QW layers consisted of 50 $In_{0.5}Ga_{0.5}As/Al_{0.5}Ga_{0.5}As$ periods. The $In_{0.5}Ga_{0.5}As$ well was 4 nm wide and the $Al_{0.5}Ga_{0.5}As$ barrier was 8 nm wide. The dopant concentration was 10^{19} cm^{-3} which corresponds to a sheet density of 1.2×10^{13} cm^{-2}. The room temperature IR spectrum showed a 50 meV wide absorption peak at 5.25 µm (220 meV). This energy agrees with the calculated n=1 heavy hole to n=1 light hole transition energy of 240 meV (150 meV for strain and 90 meV for confinement). The large absorption width results from hole-hole scattering and the difference in dispersion relations between the two subbands. The equal-wavelength pump-probe transmission measurements were performed using the Stanford free electron laser (FEL). The FEL pulses were tuned between 4 and 6 µm and their duration was less than 1 ps. The measurements were performed as a function of temperature, pump wavelength and intensity (from 0.3 to 10 GW/cm^2).

In all our experiments, we find an increase of transmission (decrease of absorption or bleaching) following photopumping, which recovers as a single exponential with a time constant (relaxation time) of the order of 1 picosecond. The maximum change in transmission is linear with pump intensity below 1 GW/cm^2 and saturates to ~3% with a saturation intensity I_{sat} of 3 GW/cm^2. As the saturation regime is entered, the relaxation time increases from 0.8 ps to 1.8 ps. This relaxation time depends on the temperature T: it increases from 0.8 ps to 1.3 ps as T decreases from 300 K to 77 K. Finally, when we tune the laser through the absorption band, the magnitude of the signal changes but its temporal behavior does not change, within the accuracy of the measurements.

We have been able to fit the data very well with a simple two-level system model, in which the relaxation time corresponds to carriers leaving the excited state. In p-type QWs, I_{sat} is much higher than n-type QWs in large part because the absorption cross-section is one order of magnitude lower in p-type QWs. The wavelength independence of the relaxation time is consistent with the assumption of a homogeneously broadened two-level system. The most important question is whether our relaxation time is the dwell time (i.e., the time it takes for an energy-nonconserving scattering event to empty the excited state) or the cooling time (here, the excited carriers form a distribution on a time scale faster than the pulse duration). Within the second model, the increase in relaxation time with intensity might be atributed to hot phonons. However, the increase of the relaxation time with decreasing temperature is fitted very well assuming that the total scattering rate is due to the sum of phonon absorption and phonon emission by the photoexcited holes. Thus, we conclude that at low intensity, we measure the dwell time. Detailed calculations of the intersubband scattering rate yield a dwell time of 0.66 ps in agreement with the experimental data. In our model, the ground state is assumed to be replenished instantly by the cold hole reservoir in the heavy hole subband and the increase of the relaxation time in the saturation regime is thus due to a strong depletion of the heavy hole subband, which reduces the rate at which the ground state is replenished. Since the bleaching is caused by the sum of the excited state occupation and ground state depletion dynamics, the measured relaxation time is expected to increase in saturation.

In conclusion, we have measured and modelled the relaxation of hot holes excited by intersubband pumping with a mid-IR short pulse laser. We acknowledge support from the US Office of Naval Research through contracts N00014-92-J-4063 and N00014-94-1-1024.

ELECTRONIC PROPERTIES OF SUPERCONDUCTORS STUDIED USING PHOTO INDUCED ACTIVATION OF MICROWAVE ABSORPTION (PIAMA).

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Electronic properties of superconductors are contemporarily being studied using many different experimental techniques, among which infrared spectrometry, photoelectron spectroscopy and microwave cavity techniques play an important role. The data analysis, however, is complicated by the fact that in these materials the phonon-frequency range overlaps with the one in which the energy gap is expected.

This problem can be circumvented by making use of two different sources, one to induce the excitations (the Free Electron Laser in Nieuwegein, The Netherlands, FELIX), and one to study the behavior of these excitations (i.e. quasiparticles). In our case the latter source is monochromatic microwave radiation, transmitted through a thin superconducting film.

We measured both a conventional superconductor (NbN, $T_c = 17$ K) and a high T_c superconductor ($SmBa_2Cu_3O_{7-\delta}$, $T_c = 92$ K). For NbN we observed a positive change in transmission, followed by a relaxation to a transmission smaller than the original value, after which the starting situation was restored within ~ 100 µs. In case of $SmBa_2Cu_3O_{7-\delta}$, the changes persisted above T_c. At very low temperatures we observed slow oscillations ($\sim$ 4kHz) in the induced signal, which were absent in NbN.

The long time scales can possibly be explained by the so-called bottleneck, i.e. quasiparticles excited with a lot of excess energy lose part of their energy by exciting other quasiparticles. In this case the quasiparticle lifetime is enhanced considerably. The oscillations point towards an intrinsic difference of the low energy excitations, i.e. the symmetry of the pairing.

QUANTUM WELL INTERSUBBAND LIFETIMES MEASURED BY MID-IR PUMP-PROBE EXPERIMENTS

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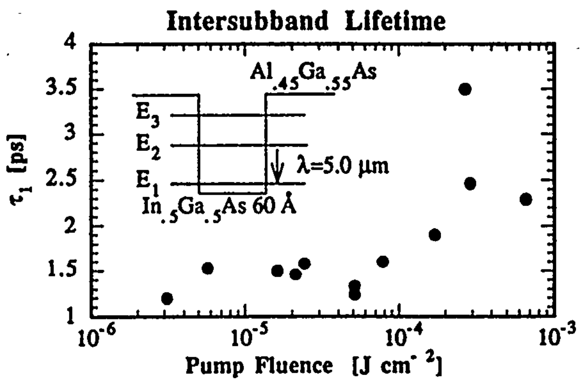
Semiconductor quantum wells exhibit quantum-confined electronic energy levels, or subbands, that are similar to one-dimensional "particle in a box" wavefunctions. The light effective mass of electrons allows large spatial extents of the wavefunctions and concomitantly large dipole overlaps between states. These large dipoles have been exploited in a variety of experiments including nonlinear frequency conversion[1], infrared photodetection[2], and lasing[3].

A key parameter for many devices is the upper state lifetime. The decay of carriers in the upper state is believed to be dominated by optical phonon scattering, and lifetimes on the order of 1ps are expected[4]. While Raman[5] and saturation[6] measurements have shown good agreement with theory, direct pump-probe measurements have reported longer lifetimes, partially due to carrier heating[7]. In this paper, we discuss our mid-IR (5μm) pump-probe measurements of intersubband lifetimes, performed at the Stanford Picosecond Free Electron Laser Center. At low excitation densities we observe lifetimes of about 1.5 ps, in good agreement with phonon theory. At high excitation densities the lifetime increases to 3.5 ps, demonstrating the transition from the low- to high-excitation regime.



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VIBRATIONAL RELAXATION OF A TRIATOMIC MOLECULAR IMPURITY: D_2O IN VITREOUS As_2S_3

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Measurements of the relaxation of the D_2O stretch mode in vitreous As_2S_3 are presented. Because the bending mode of the molecule offers an intra-molecular decay channel for the stretch mode, the decay scheme of the D_2O molecule is more complex than that of diatomic molecules. The asymmetric stretch mode of D_2O has a frequency of 2680 cm^{-1}. To study the relaxation of this mode we applied a pump-probe technique, using intense psec pulses of the Stanford Free Electron Laser. Due to the small cross-section of the vibrational mode, successful efforts were made to improve the signal to noise ratio by using a laser stabilization system and a tightly focused beam to increase the intensity, by averaging the signal with a kHz repetition rate and by using samples with an optimized D_2O concentration. A rapid relaxation rate on the order of 5×10^9 sec^{-1} at low temperature is found that increases with temperature. Recalling that the bending mode of the D_2O molecule has a frequency of 1170 cm^{-1}, one would expect a decay in a third order process, involving two quanta of the bending mode plus a vibrational host quanta with a frequency of 340 cm^{-1}, which coincides with a fundamental frequency of the pyramidal building blocks of the glassy As_2S_3 host. Instead, we find from the temperature dependence of the relaxation rate that the D_2O stretching mode relaxes in a higher order process. This indicates that the relaxation dynamics of small molecules is more complex than generally assumed.

The work was supported in part by the Office of Naval Research, Grant No. N00014-94-1-1024.

INFLUENCE OF PHONON EMISSION ON INTERSUBBAND LIFETIMES IN WIDE GaAs/AlGaAs AND Si/SiGe QUANTUM WELLS.

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We have previously used the picosecond, far-infrared free electron laser FELIX, at Rijnhuizen, to make the first direct excite-probe determination of the intersubband relaxation rate in wide GaAs/AlGaAs quantum wells with the subband separation smaller than the optical phonon energy[1]. This measurement yielded short (40ps) lifetimes while acoustic phonon emission occurs on a 200ps scale[2]. This is also in contrast with, among others, saturation measurements of swide wells with the UCSB FEL[3] which gave lifetimes of 600ps. We discuss here the interpretation of the range of published results by calculation of the LO-phonon scattering rate, including the effects of finite electron temperature, T_e. We have shown that relaxation can be dominated by LO-phonon emission even in wide wells, through the high energy tail of the distribution. The rate is very sensitive to T_e between 30-70K, and also to carrier concentration, making it possible to account for the wide variety of published results with a single mechanism. We have extended our measurements to wide Si/SiGe quantum wells, and find similarly short times (20-30ps). However, in non-polar materials such as SiGe the deformation potential scattering is much weaker and acoustic phonon emission (order 10ps in n-silicon[4]) is expected to dominate.

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WAVELENGTH DEPENDENT DELAY IN THE ONSET OF FEL TISSUE ABLATION

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We are investigating the wavelength dependence of the onset of laser tissue ablation in the IR, Visible and UV ranges. Toward this end, we have made simultaneous measurements of the ejected material (using a HeNe probe beam tangential to the front surface) and the residual stress transient in the tissue (using traditional piezoelectric detection behind the thin samples). For the IR studies we have used the Vanderbilt FEL and for the UV and Vis range we have used a Q-switched ND:Yag with frequency doubling and quadrupling. To satisfy the conditions of the near field limit for the detection of the stress transient, the duration of the IR FEL macropulse must be as short as possible. We have obtained macropulses as short as 100 ns using Pockels Cell technology. The recording of the signals from both the photodiode monitoring the HeNe probe beam and the acoustic detector are synchronized with the arrival of the 100 ns macropulse. With subablative intensities, the resulting stress transient is bipolar with its positive peak separated from its negative peak by 100 ns in agreement with theory. Of particular interest is the comparison of ablative results using 3 μm and 6.45 μm pulses. Both the stress transient and the ejection of material suffer a greater delay (with respect to the arrival of the 100 ns pulse) when the FEL is tuned to 3 μm as compared to 6.45 μm. A comparison of IR, Vis and UV data will be discussed in terms of microscopic mechanisms governing the laser ablation process.

MODE PUMPING EXPERIMENTS ON BIOMOLECULES

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We will explore several aspects of protein dynamics and energy transfer that can be explored by using the intense, picosecond, tunable mid-IR output of the FEL. In order of appearance they are:

(1) Saturation recovery and inter-level coupling of the low temperature amide-I band in acetanilide. This is a continuation of earlier experiments to test soliton models in crystalline hydrogen bonded solids. In this experiment we utilize the sub-picosecond time resolution and low repetition rate of the Stanford SCLA FEL to do both T_1 and T_2 relaxation measurements at 1650 cm^{-1}.

(2) Probing the influence of collective dynamics in sensory rhodopsin. In this experiment we use the FIR output of the Stanford FIREFLY FEL to determine the lifetime of collective modes in the photo-active protein sensory rhodopsin, and begin experiments on the influence of collective modes on retinal reaction dynamics.

(3) Probing the transition states of enzymes. This experiment, in the initial stages, attempts to use the intense IR output of the FEL to probe ȧd influence the reaction path of a transition state analog for the protein nucleoside hydrolase. The transition state of the inosine substrate is believed to have critical modes softened by the protein so that bond-breaking paths show absorption at approximately 800 cm^{-1}. A form of action spectrum using FEL excitation will be used to probe this state.

MEDICAL AND MOLECULAR BIOLOGICAL APPLICATION IN THE FELI

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Some of the user's rooms of the FELI have been equipped for medical and molecular biological research. Main subjects are immunological reaction and cell fusion induced by IR FEL.

We are beginning to do the preliminary irradiation experiments.

The cultured T lymphocytes (Molt-4, human) are irradiated to FEL at wavelength 6.3μm with the power density approximate 500mW/mm² for 10 minutes, in the culture media (RPMI-1640) including 10% fetal bovine serum.

Swelling and consequent collapse of the cells can be observed, probably due to abrasion of the cell membranes.

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TIME DEPENDENT WEAK LOCALIZATION OF A 2DEG IN THE PRESENCE OF ANDREEV REFLECTIONS

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Experiments on superconducting-normal-superconducting, SNS, junctions, comprised of Nb- 2D InAs - Nb, exhibit AC currents at $\nu = 4eV/h$, twice the Josephson frequency. These currents can be ascribed to time dependent weak localization in the 2D InAs electron gas modulated by the presence of superconducting electrodes.

The change of the current-voltage characteristic of a SNS structure under far-infrared (FIR) illumination (180GHz, 300GHz) has been investigated as a function of temperature, FIR power and magnetic field. The sample is an InAs/AlSb quantum well with a 1μm-period Nb grating contacting the InAs. In the experiments a series connection of $N = 300$ junctions is measured. The differential resistance of the sample shows a very clear subharmonic gap structure, indicating multiple Andreev reflections between the SN-interfaces. Below a temperature of about $T = 5K$ the sample is superconductive.

At sufficiently high temperatures ($T > 6K$) the photoresponse of the sample under FIR illumination exhibits only a single resonance. This resonance is at $V = Nh\nu/4e$, that is half the voltage at which the first step of the AC Josephson effect would occur. B.Z. Spivak and D.E. Khmel'nitskii[1] predicted this effect which arises from the quantum correction of the conductivity of a normal state electron gas due to Andreev reflections. Electrons and holes that are Andreev reflected at the superconductor interface acquire a phase shift that is determined by the phase Φ of the superconductor. Interference terms of time reversed paths that include Andreev reflections on adjacent superconductor stripes oscillate with $2(\Phi_2-\Phi_1) = 4eVt/\hbar$ and therefore lead to a time-dependent conductivity. The manifestation of the oscillating conductivity in the experiments is similar to the Shapiro steps of the AC Josephson effect but with twice the frequency.

The experiments show that this effect is very sensitive to an applied magnetic field. The resonance vanishes at magnetic fields of about $B = 100\mu T$. This is expected since a magnetic field leads to a phase change that depends on the length of the paths and therefore averages out the fixed phase shifts due to the Andreev reflections.

This work is supported by ONR (N00014-92-J-1452) and NSF Science and Technology Center for Quantized Electronic Structures (DMR 91-20007).

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STUDIES OF FULLERENE ABSORPTION AND PRODUCTION USING AN INFRARED FREE-ELECTRON LASER[1]

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Tunable photon sources such as free-electron lasers are potentially valuable tools in spectroscopic studies of fullerenes, a new class of carbon materials with unique cage structures. We have used the infrared free-electron-laser facility at Vanderbilt University to study the infrared absorption of gas-phase fullerene molecules and also to investigate the effects of an infrared laser in the synthesis and crystallization of fullerene materials.

In one experiment, fullerene vapor was created in a heat pipe through which the FEL beam was passed; the transmission of the FEL beam relative to a reference detector was measured as a function of wavelength. A large (>10%) absorption of the IR laser was observed when it passed through C_{60} vapor at ~800°C. Due to the broad spectral width of the FEL as well as spectral congestion, no spectral peaks were seen when the laser wavelength was tuned across a T_{1u} C_{60} IR mode near 7.0 µm. However, it is expected that the vibrational features can be resolved experimentally by passing the transmitted beam through a monochromator.

In a separate experiment, the FEL beam was focused onto a surface of graphite or graphite/metal mixture target. Various fullerene molecules, including endohedral types, were produced when the soot was recovered from the ablation chamber. The yield of the products was measured to be ~0.4 g/J of the incident laser energy. However, both the yield and the product distribution are virtually, the same as those in experiments using a nanosecond Nd:YAG laser. This suggests that the laser wavelength is not a crucial parameter in making fullerenes by laser ablation. Even when the laser is at resonance with one of the vibrational modes of C_{60}, the fullerene production is neither substantially enhanced nor suppressed.

We are currently modifying the absorption experiment to achieve higher spectral resolution, and plan to measure electron emission and ion time-of-flight spectra in laser ablation to clarify the results of these initial experiments.

[1] Research at Vanderbilt University is supported by the Medical Free-Electron Laser Program of the Office of Naval Research under contract N00014-91-C-0109. Work by Compton and Ying was supported by the Director's Research and Development Program, Oak Ridge National Laboratory, supported by the United States Department of Energy under contract DE-AC05-84OR21400 with Martin-Marietta Energy Systems..

DYNAMIC LOCALIZATION AND NEGATIVE ABSOLUTE CONDUCTANCE IN TERAHERTZ DRIVEN SEMICONDUCTOR SUPERLATTICES

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We report the first observation of Negative Absolute Conductance (NAC), dynamic localization and multiphoton stimulated emission assisted tunneling in terahertz driven semiconductor superlattices.

Theories predicting NAC in semiconductor superlattices subjected to AC electric fields have existed for twenty years[1], but have never been verified experimentally. Most theories are based upon semiclassical arguments and are only valid for superlattices in the miniband or coherent tunneling regime. We are not aware of models predicting NAC in superlattices in the sequential tunneling regime, although there has been recent theoretical work on double-barrier structures [2].

Perhaps the most remarkable result is found in the power dependence of the current-voltage (I-V) characteristics near zero DC bias. As the laser power is increased the current decreases towards zero and then becomes negative. This result implies that the electrons are absorbing energy from the laser field, producing a net current in the direction opposite to the applied voltage.

NAC around zero DC bias is a particularly surprising observation considering photon-assisted tunneling is not expected to be observable between the ground states of neighboring quantum wells in a semiconductor superlattice[3]. Contrary to this believe our results are most readily attributable to photon absorption and multiphoton emission between ground states of neighboring wells.

The I-V characteristics measured in the presence of terahertz radiation at low DC bias also contain steps and plateaus analogous to photon-assisted steps observed in superconducting junctions. As many as three steps have been clearly resolved corresponding to stimulated emission into the terahertz field by a three-photon process.

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PICOSECOND RESPONSE OF A PHOTON DRAG DETECTOR

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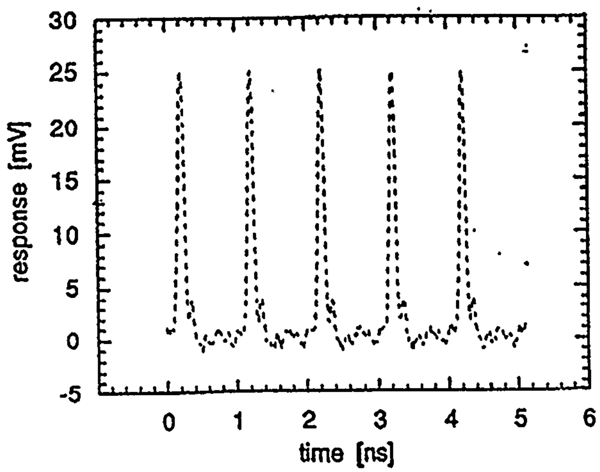
The primary use of photon drag detectors has been with CO_2 lasers at 10μm. Commercially-available devices are limited to response times of 0.5-1ns and voltage responsivities of <0.5μV W^{-1}. This poster paper will describe the first photon drag detector specifically designed for very fast response. Using the free-electron laser FELIX at the FOM Institute in the Netherlands, a rise time of <50ps has been demonstrated, using a 5mm^2 area detector with a responsivity of >1μV W^{-1} over the wavelength range 10-25μm. The figure shows the clear resolution of the micropulse structure of the laser. The actual width of each pulse is a few picoseconds, with a micropulse spacing of 1ns. The advantages of photon drag detectors are room-temperature operation, linear response to intensities greater than 10^6MW cm^{-2} and very high damage threshold. These detectors are cheap to manufacture and, using different semiconductors, can be designed for any wavelength from 1μm-5mm.



Detector Response at 15μm

VIBRATIONAL POPULATION DYNAMICS IN LIQUIDS AND GLASSES: IR PUMP-PROBE EXPERIMENTS FROM 10 K TO 300 K

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The temperature dependent vibrational relaxation of the CO stretching mode of Rhodium dicarbonyl acetylacetonate ($Rh(CO)_2(acac)$) and tungsten hexacarbonyl ($W(CO)_6$) in dibutylphthalate (DBP) and 2-methylpentane (2-MP) were measured with IR pump and probe (P-P) experiments. The experiments were performed with ~1.5 ps pulses generated by the Stanford superconducting accelerator pumped free electron laser (FEL) [1]. Measurements were performed on the $Rh(CO)_2(acac)$ CO asymmetric stretching mode at $\lambda = 4.98$ μm from 10 K to 300 K. Both the parallel and magic angle probe polarizations decay curves are bi-exponential over the entire temperature range. The slow component (ranging from 40 ps at 300 K to 55 ps at 10K) is attributed to the population relaxation[2]. For the fast component (ranging from 4-5 ps at 300 K to 13-15 ps at 10K), we propose a mechanism of spectral diffusion, in contrast to the previously proposed mechanism[2] of scattering between closely spaced vibrational levels. Support for this assignment is given by the lack of a steep temperature dependence consistent with the Boltzmann factor for the separation of the levels and the detection of spectral diffusion using multi-bandwidth P-P measurements and associated vibrational photon echo experiments done on $W(CO)_6$ in 2 MP by Tokmakoff and co-workers [1,3]. For the $W(CO)_6$ in DBP, preliminary data were taken at $\lambda = 5.06$ μm in the temperature range 75-300 K. The data are again bi-exponential both with parallel and magic angle probing. The decay time of the slow component increases as the temperature increase: going from 55 ps at 75 K to 70-80 ps at room temperature. For the fast component, instead, the decay time decreases with increasing temperature, changing form 15 ps at 75 K to 5 ps at 300 K in a manner very similar to that observed for $Rh(CO)_2(acac)$.

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ELECTROSTATIC-ACCELERATOR FREE-ELECTRON LASERS FOR POWER BEAMING

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Novel concepts of electrostatic-accelerator free-electron lasers (EA-FELs) for energy transfer through the atmosphere are presented. The high average power attained from an EA-FEL makes it an efficient source of mm-wave for power beaming from a ground stations.

General aspects of operating the FEL as a high power oscillator (like acceleration voltage, e-beam current, gain and efficiency) are studied and design considerations are described. The study takes into account requirements of power beaming application such as characteristic dips in the atmospheric absorption spectrum, sizes of transmitting and receiving antennas and meteorological conditions.

We present a conceptual design of a moderate voltage (.5-3 MeV) high current (1-10 Amp) EA-FEL operating at mm-wavelength bands, where the atmospheric attenuation allows efficient power beaming to space. The FEL parameters were calculated, employing analytical and numerical models. The performance parameters of the FEL (power, energy conversion efficiency, average power) will be discussed in connection to the proposed application.

MEASUREMENT OF THE RESONANT POLARON EFFECT IN THE RESTSTRAHLEN BAND OF GaAs:Si USING FAR-INFRARED TWO-PHOTON EXCITATION

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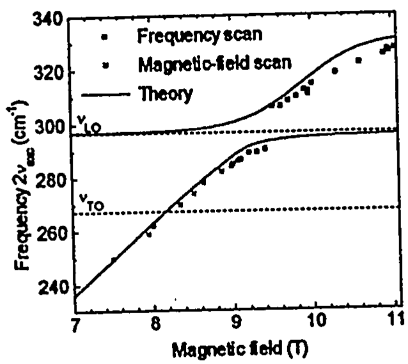
We present the results of photoconductivity measurements of the resonant electron-phonon interaction *in the middle of the Reststrahlen band* using *two-photon excitation* with intense picosecond pulses with frequency around 143 cm^{-1} (70 μm). We use two photons rather than a single photon for the excitation of the resonant-polaron to avoid the problems of strong reflection and dielectric artifacts encountered in direct single-photon excitation in the Reststrahlen band. The sample is a 10 μm thick Si-doped GaAs epitaxial layer on a 400 μm semi-insulating GaAs substrate. The electronic levels of the Si shallow donor can be tuned by the application of a magnetic field. Intense tunable picosecond pulses with a frequency of around 143 cm^{-1} from the Dutch free-electron laser FELIX are weakly focussed onto the sample, which is kept at 8 K. Electrons excited to the $3d^{+2}$ state via the electric-dipole allowed two-photon transition out of the $1s_0$-ground state, decay to the conduction band and give rise to an increase in the photoconductivity. The figure shows the energy-peak position of the $3d^{+2}$ transition thus obtained as a function of the magnetic-field strength. The figure clearly shows the avoided crossing around the LO-phonon energy where the coupling between the $3d^{+2}$ state and the LO phonon is strongest. Note that the data between 267 cm^{-1} and 296 cm^{-1} are extremely difficult to obtain with single-photon excitation because of their position in the middle of the Reststrahlen band.



INVERSE BLOCH-OSCILLATOR: STRONG THZ-PHOTOCURRENT RESONANCES AT THE BLOCH FREQUENCY

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We have observed resonant changes in the current-voltage characteristics of miniband semiconductor superlattices when the Bloch frequency is resonant with a terahertz field and its harmonics: the inverse Bloch oscillator effect. The resonant feature consists of a peak in the current which grows with increasing laser intensity accompanied by a decrease of the current at the low bias side. The peak position moves linearly with the laser frequency. When the intensity is increased further the first peak starts to decrease and a second peak at about twice the voltage of the first peak is observed due to a two photon resonance. At the highest intensities we observe up to a four photon resonance.

A superlattice is expected to show negative differential conductance (NDC) due to the strong nonparabolicity of the miniband. In this situation the carriers should undergo Bloch oscillations with a frequency $\omega_B = eEd/\hbar$. Transient Bloch oscillations of photo excited carriers have been observed in time resolved Thz emission measurements /1/. However, the possibility of Thz generation form a DC voltage biased superlattice is still under discussion.

We have approached this problem by exploring the inverse Bloch oscillator effect in a superlattice excited by the Thz radiation form the UCSB FEL. The superlattice consists of 40 periods of 80Å GaAs wells and 20Å $Al_{0.3}Ga_{0.7}As$ barriers (miniband width is 20meV). To couple the electric field of the Terahertz radiation parallel to the growth direction a coplanar bowtie antenna has been employed.

Our results show clearly that the external radiation couples to Bloch oscillations in contrary to theoretical suggestions that Thz radiation would not couple to a uniform Wannier Stark ladder. We conclude that this result is intimately related to dissipation and line broadening of the otherwise identical states in the ladder: absorption appears above the Wannier Stark splitting ($\omega_B < \omega$) and gain below ($\omega_B > \omega$).

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COHERENT TRANSIENT GRATING EFFECTS AND AUGER INHIBITION IN InAsSb SYSTEMS.

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Pump-probe measurements of interband recombination lifetimes have been performed with the Free Electron Laser (CLIO) at room temperature undoped bulk InSb. Significant bleaching near and below the fundamental absorption edge at 7μm was seen near the excitation frequency, with recovery times in the range 0.2-5 ns which were found to be strongly dependent on the pump photon energy. The scattering is dominated by Auger processes, which have rates following quadratic or linear carrier density dependence in low excitation and highly degenerate regimes respectively. The coefficients for Auger recombination in InSb at room temperature were found to be $1.1\pm0.5\times10^{-26}$ cm^6s^{-1} and $4.0\pm0.5\times10^{-9}$ cm^3s^{-1} in these two regimes.

These experiments also reveal associated coherent transient grating effects for the first time in these systems. A parametric scattering of the pump pulse into the probe beam is observed at delay times smaller than the coherence length of the FEL which allows us to determine the third-order non-linear susceptibility and the coherence length of the laser system.

A preliminary bleaching experiment on an undoped strained layer superlattice (SLS) sample of $InAs/InAs_{0.61}Sb_{0.39}$ is also reported. It is well known that the narrower the bandgap in HgCdTe alloys the easier energy and momentum conservation becomes. This SLS structure (band edge 11μm) shows strong inhibition of the Auger recombination process with lifetimes up to 30 times longer than even the bulk InSb sample (7μm). This opens the possibility of a major leap into the IR for III-V semiconductor light-emitting and detection device applications.

VIBRATIONAL LIFETIMES OF PROTEIN AMIDE MODES

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Measurement of the lifetimes of vibrational modes in proteins has been achieved with a single frequency infrared pump-probe technique using the Stanford Picosecond Free-electron Laser. These are the first direct measurements of vibrational dynamics in the polyamide structure of proteins. In this study, modes associated with the protein backbone are investigated. Results for the amide I bahd, which consists mainly of the stretching motion of the carbonyl unit of the amide linkage, show that relaxation from the first vibrational excited level (v=1) to the vibrational ground state (v=0) occurs within 1.5 picoseconds with apparent first order kinetics. Comparison of lifetimes for myoglobin and azurin, which have differing secondary structures, show a small but significant difference. The lifetime for the amide I band of myoglobin is 300 femtoseconds shorter than for azurin. Further measurements are in progress on other backbone vibrational modes and on the temperature dependence of the lifetimes.

Comparison of vibrational dynamics for proteins with differing secondary structure and for different vibrational modes within a protein will lead to a greater understanding of energy transfer and dissipation in biological systems. In addition, these results have relevance to tissue ablation studies which have been conducted with pulsed infrared lasers. Vibrational lifetimes are necessary for calculating the rate at which the energy from absorbed infrared photons is converted to equilibrium thermal energy within the irradiated volume. The very fast vibrational lifetimes measured here indicate that mechanisms which involve direct vibrational up-pumping of the amide modes with consecutive laser pulses, leading to bond breakage or weakening, are not valid.

IR-UV PHOTOCHEMISTRY OF PROTEIN-NUCLEIC ACID SYSTEMS

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UV light has often been used to induce the formation of covalent bonds between DNA (or RNA) and tightly-bound protein molecules. However, the internal photoreactions of nucleic acids and proteins limit the yield and complicate the analysis of intermolecular crosslinks. In an ongoing search for improved reaction specificity or new photoreactions in these systems, we have employed UV photons from a Nd:YAG-pumped dye laser and mid-IR photons from the Vanderbilt FEL. Having crosslinked several protein-nucleic acid systems with nanosecond UV laser pulses, we are currently studying the effect of various IR wavelengths on a model system (gene 32 protein and poly[dT]). We have found that irradiation with sufficiently intense FEL macropulses creates an altered form of gene 32 protein which was not observed with UV-only irradiation. The electrophoretic mobility of the product is consistent with the formation of a specific protein-protein crosslink. No evidence of the non-specific protein damage typically induced by UV light is found. The yield of the new photoproduct is apparently enhanced by exposure to FEL macropulses which are synchronized with UV laser pulses. With ideal exposure parameters, the two-color reaction effectively competes with UV-only reactions. Experiments designed to determine the reaction mechanism and to demonstrate FEL-induced reactions in other protein-nucleic acid systems are currently underway.

Terahertz quantum transport in semiconductor nanostructures with the UCSB Free Electron Lasers

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Quantum transport in semiconductor nanostructures takes on new dimensions in the presence of intense terahertz electric fields. Terahertz frequencies lift us into the regime where the scattering and relaxation is not so important and strong terahertz electric fields provided by the UCSB FEL's explore non-linear dynamics far fro the perturbative limit. New quantum transport channels that are assisted by the absorption or emission of a photon appear in current voltage characteristics. We will describe some of these experiments, the new phenomena they expose and the potential impact on future terahertz semiconductor electronics.

ENERGY TRANSFER AT THE ACTIVE SITES OF HEME PROTEINS

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Experiments using a picosecond pump-probe apparatus at the Picosecond Free-electron Laser Center at Stanford University, were performed to investigate the relaxation of carbon monoxide bound to the active sites of heme proteins. The significance of these experiments is two-fold: (1) they provide detailed information about molecular dynamics occurring at the active sites of proteins; and (2) they provide insight into the nature of vibrational relaxation processes in condensed matter.

Molecular engineering is used to construct various molecular systems which are studied with the FEL. We have studied native proteins, mainly myoglobin obtained from different species, mutant proteins produced by genetic engineering using recombinant DNA techniques, and a variety of model systems which mimic the structures of the active sites of native proteins, which are produced using molecular synthesis. Use of these different systems permits us to investigate how specific molecular structural changes affect dynamical processes occurring at the active sites. This research provides insight into the problems of how different species needs are fulfilled by heme proteins which have greatly different functionality, which is induced by rather small structural changes.

This research is the result of a collaborative effort between groups at the University of Illinois (Dlott, Dana D.; Hill, Jeffrey R.; Suslick, Kenneth; Rosenblatt, Michael; Zieglar, Christopher), New Mexico State University (Peterson, Kristen A.), and Stanford University (Fayer, Michael D.; Boxer, Steven; Decatur, Sean; Rella, Christopher). Work performed by the Dlott group is supported by the MFEL program, administered by the Office of Naval Research (Biology Division), through contract N00014-95-1-0259.

Challenges at FEL Facilities: The Stanford Picosecond FEL Center*

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In the past two years, FELs have decisively passed the threshold of scientific productivity. There are now six FEL facilities in the United States and Europe, each delivering more than 2000 hours of FEL beam time per year. At the present time approximately 100 papers are published each year in refereed journals describing optics experiments performed with FELs.

Despite the recent success there are important challenges that FEL facilities must address. At Stanford these challenges include:

1) Providing sufficient experimental time at reasonable cost: At Stanford we provide 2000 hours of experimental time per year at a cost of approximately $500 per hour: We are now studying options for markedly increasing experimental time and decreasing cost per hour.

2) Competing effectively with conventional lasers in the mid-IR: Despite the NRC report we do not intend to concede the mid-IR to conventional lasers. FELs are capable of providing optical beams of exceptional quality and stability, and they can also be remarkably flexible devices. Improvements in our superconducting linac driver and our optical beam conditioning systems will dramatically enhance our FEL experimental capabilities.

3) Making the transition from first generation to second generation experiments: Important pump-probe and photon echo experiments have been performed at Stanford and others are feasible using present capabilities. None-the-less we are now investing substantial experimental time to improving signal-to-noise and developing other optical capabilities.

4) Extending operation to the far-infrared where the FEL is unique in its capabilities: "FIREFLY" will extend our FEL capabilities to 100 microns. We are now seeking funds for optical instrumentation.

5) Creating and maintaining a good environment for graduate students.

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ACTIVITIES OF THE CLIO INFRARED FACILITY

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The CLIO infrared FEL is operated since 1992. It is based on a 3 GHz RF linac. The laser beam time was about 2400 h in 1994, 1600 for users and 800 for FEL physics and machine optimisation. The beam time is limited mainly by user ability to work during nights.

The CLIO specific features are the following :

- Large spectral range : 2 to 16 µm, that is being extended to about 40 µm (see FEL conf. papers by O. Marcouillé et al. & R. Prazeres et al.)
- Full user control of the machine, allowing night shifts without the presence of operators
- Wavelength stabilisation by an RF high voltage feedback.
- Adjustable delay between the micropulses from 4 to 32 ns. It allows to synchronize CLIO with external lasers and to vary the average power, at constant peak power. In present SFG conditions, up to 500 mW average power is available on the user table at 25 Hz (macropulse) and 16 ns delay between micropulses (i.e. 40 µJ/pulse and 10 MW peak).
- Electron pulse length rather long for this type of machine : typically 8 ps. This allow the production of a relatively small linewidth (0.2 to 0.4 %) with only a small loss in average power (10 to 20 %) compared with its maximum. We are also able to produce short optical pulses, by adjusting the cavity, down to 350 fs (see FEL conf. paper by F. Glotin et al.).
- We have demonstrated 2-colors FEL simultaneous operation, that enhances its application capabilities (see FEL conf. paper by D. Jaroszynski et al.)
- We have successfully developed a "sum frequency generation" (SFG) set-up, open to users (see companion paper by A. Peremans et al.)
- We are developing optical parametric oscillators ("OPOs") synchronized with CLIO in the near infrared ($\lambda < 4$ - 5 µm). This permits several users to be served simultaneously (CLIO being reserved for longer wavelength or higher power), in particular to increase the "duty cycle" of the SFG experiment and to perform pump probe experiment with CLIO in mid-infrared (in 2-colors FEL operation both are in mid-infrared).
- Electrochemical cells are available for use in the SFG experiment.
- UHV chambers including surface diagnostics have been specially built for SFG use.
- Various pieces of equipments are available : cryostats, monochromators, detectors...etc

The CLIO application experiments in 1994 have been :

- Surfaces studies by SFG :
  - Various problems in electrochemistry : studies of the evolution of molecules adsorbed at the electrodes interface (LURE)
  - Polymers on glass surfaces (St Gobain - CNRS)
  - Fullerenes epitaxial films (University of Namur)
  - Studies in ultrahigh vacuum : molecular dynamics (LURE & LPPM - Orsay)

The SFG technique is very efficient and will represent about half of our activity in 1995.

- Semiconductors
  - Non-linear processes (Heriot-Watt)
  - Quantum wells (" ")
  - Quantum well detectors (Thomson)
- Molecules in rare gas matrices
  - isomerisation (University of Marseille)
  - " (University of Paris VI)
  - Pump-probe experiments (LPPM - Orsay)
- Near field infrared microscopy (CNRS - St Gobain & CNET)
- Surface photo-emission (CEA & Budapest University)

COMMISSIONING THE FELI LINAC AND UV-FEL FACILITY

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The FELI 165-MeV linac and UV-FEL facility are in the commissioning stage. A thermionic triode gun of the 6-MeV injector emits 500-ps pulses of 2.3A at 22.3125MHz. These pulses are compressed to 60A × 7ps by a 714-MHz prebuncher and a 2856-MHz buncher and seven ETL type accelerating waveguides with a length of 2.93m. The length of the linac including bending sections of two S-type BT systems for two undulators used for IR-FEL oscillations is 46m. The buncher and these accelerating waveguides are powered by two klystrons (E3729, 2856MHz, totla 48MW, 24-μs flat top long pulses). The flatness of our klystron modulator pulses is 0.067% at 24-μs duration. An rf-ageing for new four accelerating waveguides will be started in May.

An S-type BT line for 165-MeV beam from the linac will be installed in the end of April. A 2.68-m undulator (λ_u=4.0cm, N=67, K_{max}=1.9, gap length≧16mm) and an optical cavity (L_c=6.72m) will be installed early in July. The beam conditionings for UV-FEL experiments will be started in July.

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The Research Facilities of the Duke FEL Laboratory - Uniqueness and Challenges*

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FEL light sources offer unique promise as broadly tuneable, high brightness sources of radiation throughout the electromagnetic spectrum. But the effective utilization of these new light sources also raises a series of unprecedented issues and challenges arising, in general, from the limited number of beamlines which can be supported by a single source. The cost effective utilization of this technology therefore requires emphasis on (1) the realization of one or more truly unique research capabilities, (2) the optimization of access to the research beamlines which are available, and (3) the management and support services required by users to maximize their productivity. The experience we have acquired in the development and operation of the facilities of the Duke FEL Lab provide a point of reference which may prove useful to other research-oriented FEL facilities.

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AUTHOR/ABSTRACT LIST