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Scientific Program and Abstracts

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September 12-14, 1
Sheraton Palace Hotel
San Francisco, California

CO - CHAIRMAN : RICHARD J. BRIGGS
CO - CHAIRMAN : ALAN J. TOEPFER

BEAMS '83

FIFTH INTERNATIONAL CONFERENCE ON HIGH-POWER PARTICLE BEAMS

FIFTH INTERNATIONAL CONFERENCE ON HIGH-POWER PARTICLE BEAMS

"BEAMS '83"

PROGRAM

The Fifth International Conference on High-Power Particle Beams will be held at the Sheraton-Palace Hotel in San Francisco, California, on September 12-14, 1983. The meeting is organized jointly by the Lawrence Livermore National Laboratory and Physics International Company.

As in the previous conferences in this series, the program will include the following topics:

1. High-power, electron- and ion-beam acceleration and transport.

2. Diode physics.

3. High-power particle beam interaction with plasmas and dense targets.

4. Particle beam fusion (inertial confinement).

5. Collective ion acceleration.

6. Particle beam heating of magnetically confined plasmas.

7. Generation of microwaves/free-electron lasers.

The Conference will cover three full days from Monday, September 12 through Wednesday, September 14, 1983. The Conference will include both oral sessions and poster sessions and will have no simultaneous activities. Each morning and afternoon is scheduled with an oral session and a poster session on a related topic.

PREPARATION OF PAPERS

Paper blanks and instructions for manuscript preparation have been provided to the authors. Manuscripts must be submitted at the time of the Conference to be included in the Conference Proceedings. Authors should leave their manuscripts with the Conference Proceedings Editor, Carol Gerich, at the Editor's desk in the Regency Room.

AUDIOVISUAL

An overhead projector for transparencies, a 35 mm slide projector, and a 16 mm movie projector will be available. If you have a special request for equipment, please see the Session Chairman.

LABORATORY VISITS

There will be no scheduled visits to laboratories in the area during the Conference. Participants are invited to prearrange, by mail, directly with the laboratory contact for visits at the following laboratories.

Physics International Company - James Benford
Lawrence Berkeley Laboratory - Denis Keefe
Lawrence Livermore National Laboratory - William A. Barletta

ACCOMPANYING PERSONS PROGRAM

Accompanying person are invited to register at the registration table. A welcome coffee will be held in the Regency Room of the Sheraton Palace, Monday morning, September 12 at 9:30 a.m. Information on shopping and sightseeing in the San Francisco Bay area will be available.

RECEPTION

All participants and accompanying persons are invited to a reception party at 6:30 p.m., Monday, September 12, at the Exploratorium. Bus transportation between the Exploratorium and the Sheraton Palace Hotel will be provided. The first bus will depart at 6:00 p.m.

BANQUET

The conference banquet will be held on the evening of Tuesday, September 13 in the Garden Court of the hotel. There will be no host cocktails at 6:30 p.m., and the dinner will begin at 7:45 p.m. Banquet tickets may be purchased by participants, guests, and accompanying persons at the Conference Office in the Regency Room until Tuesday, 9:00 a.m. The banquet fee ($24.00) is not included in the Registration fee.

REGISTRATION

The Registration Desk for the Conference will be open from 6:00 to 8:00 p.m., on Sunday evening, September 11 and on Monday morning, September 12, between 8:00 and 9:00 a.m. for late registration.

The Conference fee covers:

- Registration and conference material
- Breakfast each morning of the conference
- Refreshment breaks
- Reception
- One copy of the Conference Proceedings

AIRPORT TRANSPORTATION

Buses depart from San Francisco International Airport every 15 minutes between 5:30 a.m. and 9:35 p.m. for Airporter's downtown terminal, Taylor and Ellis Streets. Direct service is also provided from the airline terminals to many San Francisco Hotels, including the Sheraton Palace. Travel time is 30 minutes, Adult, one-way fare is $4.00. Call 673-2432.

SCIENTIFIC PROGRAM

Conference Opening and Welcome 8:45-9:00 a.m.

A - ORAL SESSION A MONDAY MORNING 9:00-11:00 a.m.

Inertial Confinement Fusion, Targets (Chmn: Dr. K. W. Billman)

ICF Programs

9:00 A1 Progress in Light Ion Beam Fusion
J. P. VanDevender

9:30 A2 Status of the Angara V ICF Program
L. I. Rudakov

10:00 A3 Particle Beam ICF Research at ILE Osaka
S. Nakai, K. Imasaki, S. Miyamoto, S. Higaki, T. Ozaki, A. Yoshinouchi, T. Yabe, K. Nishihara, K. Mima, C. Yamanaka

10:15 A4 Recent Progress in Beam-Fusion Studies of the ETIGO Project at Nagaoka
K. Yatsui, Y. Araki, K. Masugata, M. Ito, M. Matsui

Deposition

10:30 A5 The Interaction of Fast Charged Particles with Plasma Targets
E. Nardi, Z. Zinamon

10:45 A6 Beam Target Interaction of Intense Ion Beams: Theory and Experiment
T. A. Mehlhorn, J. M. Peek, J. N. Olsen, E. J. McGuire, A. V. Farnsworth

11:00 Poster Session 1P Monday Morning 11:30 - 1:00 p.m.

1P1 A Proposal to Fusion Scheme by Light Ion Beam
K. Niu, S. Kawata, T. Okada, H. Murakami, M. Tamba

1P2 Progress in Intense Ion Beam Research for Inertial Confinement Fusion at Cornell University
D. A. Hammer, B. R. Kusse, J. Maenchen, A. Mankofsky, J. Neri, T. J. Renk, R. N. Sudan

1P15 Optical Emission From High Energy Proton Beam Propagation Through Air and Through Aluminum Samples
S. N. Stone, R. R. Karl, D. D. Cobb

1P16 Alternative Implosion Concepts by Particle Beams and Lasers
S. Higaki, S. Miyamoto, K. Imasaki, S. Nakai, C. Yamanaka

1P17 Electrostatic Fields and Double Layers at High Power Particle Beam Interaction with Dense Plasmas
H. Hora, P. Lalousis

1P18 Interaction of Light Ion Beams with Matter at the 0.5×10^{11} W/cm^2 Level
J. C. Arnoud, R. Bailly-Salins, A. Bernard, C. Bourgeois, N. Chevallier, C. G'Agostini, B. Duborgel, E. Pasini, N. Camarcat

1P19 Theoretical Interpretations of Proto-I Ion Beam Target Experiments
A. V. Farnsworth, Jr., E. J. T. Burns, D. J. Johnson, R. J. Leeper, M. M. Widner, J. Chang

1P20 Effect of Nonuniformity on Target Implosion
S. Kawata, K. Niu

1P21 Ion Stopping in Heated Targets
J. N. Olsen, T. A. Mehlhorn, D. J. Johnson, P. L. Dreike

B - ORAL SESSION B MONDAY AFTERNOON 1:30-3:40 p.m.

Diode Physics (Chmn: Prof. Dr. W. Schmidt)

Diodes

1:30 B1 Recent Advances in the Development of Large Area Explosive Emission Cathodes
G. A. Mesyats

2:00 B2 Overview of Ion Diode Research
P. A. Miller

2:30 B3 Intense Electron and Ion Diode Research at NRL
G. Cooperstein, et al.

2:45 B4 Studies of Conditions in Detail in Magnetically Insulated Intense Ion Beam Diodes
Y. Maron, D. A. Hammer, R. Pal, R. N. Sudan

3:00 B5 Intermediate Weight and Light Ion Beam Research with Pulsed Power Generators
J. C. Arnoud, R. Bailly-Salins, A. Bernard, C. Bourgeois, N. Camarcat, J. Chevallier, G. D'agostini, A. Devin, E. Pasini, C. Patou, C. Peugnet

3:20 B6 Blackjack 5' Annular Electron Beam Experiments
J. Shannon, W. Clark, M. Gersten, A. Kolb, J. Pearlman, J. Rauch, R. Richardson, J. Riordan, D. Tanimoto, M. Wilkinson

Poster Session 2P Monday Afternoon 4:00-5:30 p.m.

2P1 Efficient Low-Impedance High Power Electron Beam Diode
C. R. McClenahan, R. C. Backstrom, J. P. Quintenz, T. P. Wright, P. W. Spence

2P2 Light Ion Beam Productions by Applied Br Magnetically Insulated Annular Diodes
J. Mizui, K. Masugata, Y. Nakagawa, K. Yatsui, H. Yonezu, T. Tazima

2P3 High Brightness Point-Like Source for Intense Ion Beam
Y. Matsukawa, Y. Nakagawa

2P4 Performance of a Self-Magnetically B_θ-Insulated Ion Diode
K. W. Zieher, D. O. Stoltz

2P5 Investigation of an Annular Magnetically Insulated Ion Diode Operated in Long Pulse Mode
Y. Nakagawa, Y. Matsukawa

2P6 Performance Tests of Extraction Diodes with Cryogenic Anode
K. Horioka, A. Urai, T. Takahashi, H. Yoneda, K. Kasuya

2P7 Intense Pulsed Ion Source with Cryogenically Refrigerated Anode Cooled by Liquid Helium
T. Takahashi, K. Horioka, H. Yoneda, K. Kasuya

2P20 Production of Intense Beams of Spin-Polarized Nuclei
J. Katzenstein, N. Rostoker

2P21 Ampfion Hybrid Diodes on Hydramite and PBFA I
C. W. Mendel, Jr., J. P. Quintenz, P. A. Miller, R. J. Anderson, J. T. Crow, L. P. Mix, S. E. Rosenthal, M. M. Widner, J. P. VanDevender

2P22 Hybrid Ion Diode Theory and Computations
J. P. Quintenz, C. W. Mendel, Jr., P. A. Miller, J. T. Crow, L. P. Mix, S. E. Rosenthal

C - ORAL SESSION C TUESDAY MORNING 8:30-10:20 a.m.

Modeling/Plasma Loads (Chmn: Dr. D. Mosher)

Codes

8:30 C1 Numerical Simulation of Charged Particle Beams
A. Mankofsky, L. Seftor, A. T. Drobot

9:00 C2 Numerical Simulations of High Power Diodes
J. P. Quintenz, J. W. Poukey, D. B. Seidel, C. W. Mendel, Jr.

Gas Puffs, Pinches

9:15 C3 Imploding Plasma Pinches Driven by High Power Generators
W. Clark, M. Gersten, A. Kolb, J. Pearlman, J. Rauch, R. Richardson, J. Riordan, D. Tanimoto, M. Wilkinson

9:35 C4 The "Needle Plasma", A Soft X-Rays Initiated, Gas Embedded Z-Pinch Computational and Experimental Approaches
H. J. Doucet, B. Etlicher, J. P. Furtlehner, M. Gazaix

9:50 C5 Gas Puff Implosion Experiments on PROTO-II
R. B. Spielman, J. P. Anthes, D. L. Hanson, M. A. Palmer

10:05 C6 Studies of an Imploding Plasma X-Ray Laser
R. J. Dukart, S. L. Wong, D. Dietrich, R. Fortner, R. Stewart

Poster Session 3P Tuesday Morning 10:30-12:00 a.m.

3P1 IBEX - A Pulsed Power Accelerator That Generates No Prepulse
J. J. Ramirez, J. P. Corley, M. G. Mazarakis

3P2 A Compact 100 kV E-Beam Generator
C. Goldstein, P. Bahat, J. Shiloh, S. Eckhouse

3P3 Proto-II Magnetic Flashover Inhibition Experiments
R. E. Mattis, R. W. Stinnett

3P4 Electrode Plasma Formation in MITL's
R. W. Stinnett, G. R. Allen, M. A. Palmer, G. J. Lockwood

3P5 Intense Energetic Ion Beams for Injection into Magnetic Confinement Geometries
J. Katzenstein, S. Robertson, N. Rostoker

3P6 The Limit of Power Flow Along a High Power MITL,
P. Sincerny, M. Di Capua, R. Stringfield, S. Wong, C. Gilman, S. Ashby, T. Sheridan

3P7 Numerical Simulation of Erosion Switch Performance on a Multi-Terrawatt Pulsed Power Generator
R. Kares

3P8 Experimental Investigations of the Plasma Erosion Switch on the PITHON Accelerator
R. Stringfield, P. Sincerny, S. Wong, T. Peters, T. Sheridan, C. Gilman

3P9 Large Ferrite Core Tests Using a 50 ns Pulse
L. Chengjun, D. Guangsen, C. Nianan, P. Wucheng

3P10 Applications of Dense Plasma Pinches
J. Pearlman, W. Clark, M. Gersten, A. Kolb, J. Rauch, R. Richardson, J. Riordan, D. Tanimoto, M. Wilkinson

3P11 Enhancing the Radiographic Capabilities of the GREC Accelerator Using Plasma Erosion Switches and a Two-M, 150-Ohm MITL
J. Buchet, R. Guix, G. Vernier, H. Biro, R. D. Genuario, P. D'A. Champney, P. W. Spence, W. Weseloh, C. Eichenberger, R. Altes

3P12 X-Ray Emission Efficiency of Imploding Aluminum Wire Plasmas
C. Bruno, J. Chevallier, J. Delvaux, J. Barbaro, A. Bernard, G. Wolff, J. David

3P13 Magnetic Trapping of Intense Ion Beams
T. P. Wright, W. Beezhold, T. A. Mehlhorn, T. W. L. Sanford

3P14 Simulation of Dense Ion Ring Formation
R. J. Faehl, G. Gisler, W. Peter

3P15 Experimental Research on Ion Rings for Magnetic Fusion
J. B. Greenly, D. A. Hammer, P. M. Lyster, P. D. Pedrow, E. Schamiloglu, R. N. Sudan

3P16 Radiofrequency Sustainment of Current Drive by Relativistic Electron Beams
I. Fidone, M. Fichet, G. Giruzzi, G. Granata, R. L. Meyer

3P17 Hose and Hollowing - Competing High Pressure Propagation Instabilities
B. Sabol, G. F. Kiuttu, R. J. Adler

3P18

3P19 Energetic Plasma Beam Propagation in Weak and Strong Magnetic Fields
W. R. Shanahan, R. J. Faehl, A. Kadish, B. Newberger

3P20 Power-Amplification of a Heavy Ion Beam in an Induction Linac
A. Faltens, D. Keefe

D - ORAL SESSION D TUESDAY AFTERNOON 1:00-3:00 p.m.

Opening Switches, MFE and Beam Transport (Chmn: Dr. K. Niu)

Opening Switches

1:00 D1 The Reflex Switch: An Opening Switch for Terawatt-Level Power Amplification in Vacuum
L. Demeter, E. Ecker, H. Helava, G. Proulx, J. Creedon

1:15 D2 The NRL Plasma Erosion Opening Switch Research Program
R. A. Meger, J. R. Boller, R. J. Commisso, G. Cooperstein, S. A. Goldstein, R. Kulsrud, J. M. Neri, F. Oliphant, P. F. Ottinger, T. J. Renk, J. D. Shipman, Jr., S. J. Stephanakis, B. V. Weber, F. C. Young

1:30 D3 Plasma Erosion Swiches for Large Pulsed Power Generators
R. Richardson, E. Brown, W. Clark, J. Pearlman, J. Shannon

MFE Applications

1:45 D4 Recent Results on Plasma Heating by a Relativistic Electron Beam (REB) in a Solenoid
E. P. Kruglyakov

2:10 D5 Intense Ion Beam Research for Magnetic Fusion
J. B. Greenly, D. A. Hammer, P. M. Lyster, P. D. Pedrow, E. Schamiloglu, R. N. Sudan

Beam Transport

2:30 D6 Resistive Instabilities of Propagating Electron Beams
M. Lampe, G. Joyce, R. F. Hubbard

Poster Session 4P Tuesday Afternoon 3:30-5:00 p.m.

4P1 Grad-B Drift Transport of High Current Electron Beams
J. R. Lee, R. C. Backstrom, J. A. Halbleib, T. P. Wright

4P2 IBEX - Annular Beam Propagation Experiments
M. G. Mazarakis, R. B. Miller, S. L. Shope, J. W. Poukey, J. J. Ramirez, C. A. Ekdahl, R. J. Adler

4P3 Damping Beam Displacements Through Phase Mixing - An Illustrative Model
W. A. Barletta, R. J. Briggs

4P4 Space and Time-Dependent Return Current in Secondary Plasma Created in Atmosphere by a Short Pulse Ultra-Relativistic High Power Electron Beam
J.-M. Dolique, A. Piquemal, J.-R. Roche, P. Sortais

E - ORAL SESSION E WEDNESDAY MORNING 8:00-10:20 a.m.

Accelerators (Chmn: Dr. R. O. Bangerter)

Conventional Accelerators

8:00 E1 Beam Dynamics in the Advanced Test Accelerator (ATA)
G. J. Caporaso, W. A. Barletta, D. L. Birx, R. J. Briggs, Y. P. Chong, A. G. Cole, T. J. Fessenden, R. E. Hester, E. J. Lauer, V. K. Neil, A. C. Paul, D. S. Prono, K. W. Struve

8:20 E2 "Conventional" and "Modified" Betatrons
D. W. Kerst

8:40 E3 High Current Betatron Experiments and Theory
N. Rostoker

9:00 E4 Progress in the Development of the Modified Betatron
C. A. Kapetanakos, et al.

9:20 E5 The Stellatron Accelerator
A. Mondelli, D. Chernin, C. W. Roberson

Collective Acceleration

9:40 E6 Electron Beam Wave Accelerators
John Nation

10:00 E7 Collective Accelerator Injector for Heavy Ion Accelerator
V. P. Sarantsev

Poster Session 5P Wednesday Morning 10:30-12:00 a.m.

5P1

5P2 Strong-Focusing Hollow Beam Transport
P. Krejcik

5P3 New Methods for RF Acceleration of Intense Electron Beams
Stanley Humphries, Jr., Chang-Sing Hwang

5P4 Simulation Studies on a Novel Betatron Injection Scheme
W. Peter, R. J. Faehl, F. Mako

5P17 A Study on Collective Acceleration of Barium Ions
M. Masuzaki, S. Watanabe, K. Kamada, I. Nakashima,
S. Kawasaki, T. Nakanishi

5P18 Tomography, A New High Speed REB Diagnostic
J. Chang, L. D. Kissel

5P19 Direct Measurement of the Energy Spectrum of an Intense Proton Beam
R. J. Leeper, J. R. Lee, D. J. Johnson,
W. A. Stygar, D. E. Hebron, L. D. Roose

5P20 Energy and Velocity Diagnostics for Intense Relativistic Electron Beams
D. A. Kirkpatrick, R. E. Shefer, Y. Z. Yin,
G. Bekefi

5P21 Diagnosing the Ion Beam on the Applied-B Diode
E. J. T. Burns, P. L. Dreike, D. J. Johnson,
R. J. Leeper, L. P. Mix, F. C. Perry, S. A. Slutz,
W. A. Stygar, J. C. Chang

5P22 Using Inner Shell X-Rays as an Ion Beam Diagnostic
G. R. Montry, E. J. McGuire, E. J. T. Burns

5P23 Determination of Intense Relativistic Beam Quality by Thomson Scattering
L. Vallier, J.-M. Buzzi

F - ORAL SESSION F WEDNESDAY AFTERNOON 1:00-2:40 p.m.

Accelerators, Microwaves (Chmn: Dr. L. I. Rudakov)

Collective Accelerators

1:00 F1 Generation and Acceleration of Multicharge Positive Ions and Negative Ions in High Current Diodes by Means of Collective Effects
A. A. Kolomensky

Microwaves

1:20 F2 Free Electron Laser Theory and Experiments
D. Prosnitz

1:40 F3 Intense Electromagnetic Pulsed Radiation from Relativistic Electron Beam-Research Program at the Ecole Polytechnique
J. M. Buzzi, H. J. Doucet, M. Gazaix, B. Etlicher,
J. P. Furtlehner, H. Lamain, C. Rouille, L. Vallier

2:00 F4 A Review of High Pulsed Power Microwave and Millimeter Wave Generation
V. L. Granatstein

2:20 F5 Relativistic Plasma Microwave Generator
M. V. Kuzelev, F. Kh. Mukhametzyanov, M. S. Rabinovich, A. A. Rukhadze, P. S. Strelkov, A. G. Shkvarunets

Poster Session Wednesday Afternoon 3:00-5:00 p.m.

6P1 Quantum Coherence in Electron Beams
H. Hora, P. Attard, A. K. Ghatak

6P2 A High Frequency Vircator Microwave Generator, I: Theory
D. J. Sullivan, E. A. Coutsias

6P3 Microwave Generators: Oscillating Virtual Cathodes and Reflexing Electrons
T. J. T. Kwan, L. E. Thode

6P4 Kinetic and Magnetic Effects in Virtual Cathode Oscillations
A. Kadish

6P5 Pulsed Power Diode Generation of Highpower Microwaves
A. L. Peratt, M. A. Mostrom, T. J. T. Kwan, L. E. Thode

6P6 Cyclic Beam Bunchers and Wave Amplifiers
F. S. Felber, T. Tajima, J. Vomvoridis

6P7 Generation of High Frequency Radiation by a Quasi-Optical Gyrotron at Harmonics of the Cyclotron Frequency
W. Manhiemer, B. Levush

6P8 Microwave Generation by REB in Lowbitron Geometry as FEL
S. Kawasaki, K. Kamada, M. Masuzaki

6P9 Investigation of Microwave Generation by Intense Relativistic E-Beams
I. Shraga, Y, Goren, H. Leibovitz, S. Eckhouse, A. Gover

ICF PROGRAMS

PROGRESS IN LIGHT ION BEAM FUSION*

J. Pace VanDevender, D. B. Seidel, P. A. Miller, and G. R. Fawkes**

Sandia National Laboratories

Albuquerque, New Mexico 87185

*This work was supported by the U.S. Department of Energy

**PEGASUS, Falls Church, VA 22043

STATUS OF THE ANGARA V ICF PROGRAM

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PARTICLE BEAM ICF RESEARCH AT ILE OSAKA

S. Nakai, K. Imasaki, S. Miyamoto, S. Higaki, T. Ozaki,
A. Yoshinouchi, T. Yabe, K. Nishihara, K. Mima and C. Yamanaka
Institute of Laser Engineering, Osaka University
Suita, Osaka 565, Japan

The major efforts for particle beam driven fusion at ILE Osaka are as follows ; A development of pulsed power technology and to construct a reliable and compact module for breakeven system. A generation of high bright ion beam and its focusing and transport. An investigation of beam target interaction and design studies of targets for efficient implosion by pulsed power and also by hybrid drivers with laser and particle beams.

Reiden IV, 1 TW and 1 to 3 MV machine is the test bed for the technology developments water switches of pulse power system and also used for the beam experiments. An inverse pinch diode was developed to improve the diode brightness. Ion beam was generated by pinch reflex diode for the investigations of beam focusing, transport and interaction.

Simulational experiments of beam transport through the multi plasma channel in a reactor system were performed. The effect of channel overlap to the beam divergence was investigated.

Investigation for more efficient exsotic implosion schemes is underway. Using hydrodynamic codes Himico (1D), Izanami and Hisho (2D), new targets for hybrid driver were designed. Foundamental research for these processes was partially performed in Reiden III.

RECENT PROGRESS IN BEAM-FUSION STUDIES OF THE ETIGO PROJECT AT NAGAOKA

K. Yatsui, Y. Araki, K. Masugata, M. Ito and M. Matsui
Laboratory of Beam-Fusion Technology, The Technological University of Nagaoka, Nagaoka, Niigata 949-54, Japan

Systematic studies have been carried out of R & D on ion-beam fusion at Tech. Univ. of Nagaoka, called ETIGO Project. It consists of several sub programs associated with generation, focusing, transport, post-acceleration, bunching, target irradiation, and so on. Their progresses will be reviewed.

I) Focusing: Using a spherically-shaped, magnetically insulated diode, we have studied the detailed focusing properties of proton beam. An annular distribution of ion-current density observed experimentally has been found to be due to space-charge effect by ion-trajectory calculations. The space-charge neutralization factor is evaluated to be more than 99.9 %. Besides the proton beam, we have also produced boron, nitrogen, carbon, and deuteron beams, the dynamics of which have been studied in detail. Basic physics of MID and B_r diodes are examined by use of an image converter camera.

II) Transport: Proton-beam (800-keV of energy) transport has been studied in a wall-confined, z-discharge plasma channel (1-m long). Good transport efficiency (∿80 %) has been obtained. Under certain conditions, however, the beam ceases to be transported due to some plasma instabilities. Using image converter camera, we have obtained clear evidences of sausage instability, being reasonable agreement between the experiment and the theory.

III) Post-Acceleration: An induction acclerator (420-kV, 6-kA, 50-ns) has been constructed to study post-acceleration of a medium-atom ion beam (MIB). The transport of MIB is being studied without using a conventional z-discharged channel. An estimate is given to use 166-MeV, 30-kA, B^+ for MIB-ICF.

DEPOSITION

BEAM-TARGET INTERACTION OF INTENSE ION BEAMS: THEORY AND EXPERIMENT

T. A. Mehlhorn, J. M. Peek, J. N. Olsen, E. J. McGuire, A. V. Farnsworth
Sandia National Laboratories
Albuquerque, New Mexico 87185
F. C. Young
Naval Research Laboratory
Washington, D. C.

Work has continued toward the goal of developing and experimentally verifying a numerical model that can accurately predict the stopping power of any ion in any target material at any density, temperature, and degree of ionization. We will review our most recent theoretical work to compute the stopping power of low-Z ions in partially ionized material. We are presently attempting to develop an accurate description of the atomic electron contribution to the stopping power, especially around the maximum of the curve. Our atomic electron stopping power models (e.g. the Local Oscillator Model, the Generalized Oscillator Strength Model, etc.) use realistic descriptions of atomic and solid-state charge densities and energy levels. Such modeling was successfully used in coupled deposition-hydrodynamic simulations of the NRL enhanced stopping power experiments that were performed last year. These experiments provided the first verification of ion stopping power enhancement in partially ionized targets and this was also the first definitive test of our stopping power models. Further stopping power experiments are in progress on Sandia's PROTO-I accelerator and they are producing the first time-dependent measurements of the energy loss of intense ion beams via Rutherford scattering into a Thomson Parabola analyzer. We will also discuss the role of enhanced ion stopping power in the interpretation of beam intensity diagnostics. Finally, the effects of enhanced stopping power on the design of PROTO-I and PBFA-I target experiments will be summarized.

*This work was supported by the Department of Energy.

THE INTERACTION OF FAST CHARGED PARTICLES WITH PLASMA TARGETS

E. Nardi and Z. Zinamon
Weizmann Institute of Science, Rehovot Israel

The processes governing the interaction of fast charged particles with plasmas are discussed. The charge state of fast ions as they are slowed down in plasma targets is calculated, considering the processes of ionization and electron capture. The projectile ionization processes are collisions with free electrons and target ions. The capture processes are the three body, radiative and dielectronic recombination for free electrons, and interacctions with bound electrons in the plasma ions. the resulting deposition profiles are described and shown to be quite different from those expected in cold targets. the specific example of Cu ions in carbon plasma is discussed.

Methods of calculating energy deposition by charged particles in plasma targets are discussed, considering the contributions of free and bound electrons. In particular, models for calculating the effective ionization potentials in the plasma ions are presented.

Features in target hydrodynamics which are due to the high intensity of the incident beam are discussed.

INERTIAL CONFINEMENT FUSION, TARGETS

A PROPOSAL TO FUSION SCHEME BY LIGHT ION BEAM

K. Niu, S. Kawata, T. Okada*, H. Murakami** and M. Tamba***
Tokyo Institute of Technology, Midori-ku, Yokohama 227
*Tokyo University of Agriculture and Technology, Koganei, Tokyo 184
**Metropolitan College of Technology, Hino, Tokyo 191
***The Institute of Physical and Chemical Research, Wako, Saitama 351

Twelve Marx generators, whose total stored energy is 24MJ and diode voltage is 10MV, supply the energy to diodes to extract proton beams. The diode with 11.4cm radius of insulated by the radial magnetic field of 4.8T extracts the rotating beam whose energy is 0.5MJ, pulse width is 25ns, propagation energy is 5MeV, mean rotation energy is 5MeV and electric current along the propagation direction is 1MA. The neon gas filling the reactor cavity with the number density of $10^{22}/m^3$ neutralizes the charge of proton beam during 1ns, but does not neutralize the current of the beam because the mean Larmor radius of electrons in the neon gas is shorter than the electron mean free path. The proton beam pinches to the radius of 3.5mm by the action of self-induced magnetic field in the azimuthal direction and its propagation is stabilized by the action of self-induced magnetic field in the propagation direction. The cryogenic hollow shell target of 4mm radius consists of three layers of Pb, Al and DT fuel. The inhomogeneity of the irradiation on the target surface by 12 beams is 9% at the maximum points and less than 5% on the average. The fuel implodes with the velocity of 2.29×10^5m/s after the deposition of beam energy of 6MJ. The ion temperature and R of the fuel reaches 3.69keV and $5.41g/cm^2$. Thus we have the output energy of 2400MJ from a target. When the reactor is operated with the operation rate of 1Hz, the reactor supplies the electric output power of 800MW.

PROGRESS IN INTENSE ION BEAM RESEARCH FOR INERTIAL CONFINEMENT FUSION AT CORNELL UNIVERSITY*

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Recent studies of time integrated and time dependent ion beam divergence using two magnetically insulated diodes at 10^{10}-10^{11} W show a directionality which is apparently a result of electron dynamics in the diodes. Beam uniformity, divergence and "aiming error" are dependent upon the detailed diode structure and operating conditions. Experiments performed on the 10^{12} W LION acceleration show a reasonable power coupling from the magnetically insulated transmission line to an annular magnetically insulated diode, with $>10^9$ W/cm^2 beams at ~1.5 MV being generated. This diode utilizes an applied radial magnetic field and the self-field of the ion current to provide the total magnetic field needed to cut off the electron flow across the accelerating gap. Power flow into the diode and diode operating characteristics will be discussed. Computer simulations of the propagation of 3-7 MeV, 1-2 MA proton beams in a 0.6 cm radius plasma channel have been performed using the 2-1/2 D hybrid CIDER code. Results suggest that 75% of the beam energy can be transported in a 4 m long channel.

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AN 80 GW INTENSE ELECTRON BEAM ACCELERATOR

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An 80 GW intense electron beam accelerator is designed and built at the Institute of Atomic Energy of The People's Republic of China for fundamental research in pulse power technology and particle beam inertial confinement fusion. Its pulse parameters are 80 GW, 5.6 kJ, 1 MV, 80 kA, 70 ns. The system consists of oil-immersed Marx generator, Blumlein transmission line which is filled by deionized water and field emission vacuum diode.

The Marx generator is composed of 20 stages of 0.7 μF, 100 kV capacitors. Maximum charge voltage of 70 kV has been applied to the capacitors. At this time the bank store an energy of 34.3 kJ. Total system inductance is 15 μH. The energy from the Marx generator is transferred to the Blumlein in 0.9 μs. All gaps are triggered. The generator can be triggered down to nearly 50 percent of the self-breakdown voltage (V_B) of the spark gap.

The electrical potential distribution of the Blumlein transmission line was calculated carefully by electrical computer.

The different types of cathode had been studied. Experimental results demonstrated, that the amplitude of the prepulse voltage affects the behavior of the diode.

The diameter of the focusing electron beam, which is impinged on the anode, is 2.5 mm. The pinhole camera is used for this measurement.

MICROINSTABILITIES OF LIGHT ION BEAMS IN FUSION TARGET CHAMBERS

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In the investigation of inertial confinement fusion by a light ion beam (LIB), it is the most important problem to propagate the LIB stably through the chamber to the target. Mainly this concept is being carried with the method by use of plasma channels theoretically and experimentally for propagation of LIB in a reactor. In our previous theoretical investigations, it has appeared that the microinstabilities are the most deleterious instabilities for LIB propagation in the plasma channel. Especially, in the parameter region of inertial confinement fusion, LIB can not propagate through a target chamber without triggering the instabilities or with sufficiently slow instability growth. In order to restrain the instabilities, we have proposed the method of rotating ion layer as a possible driver for inertial confinement fusion. The equilibrium and microinstabilities of the rotating ion layer were investigated by the basis of the Vlasov-Maxwell equations. Consequently, it was clarified that the most dangerous instabilities for the problem of the propagation of LIB could be stabilized by the magnetic fields due to the rotation of the ion beam.

STABILIZATION OF PROPAGATING LIGHT ION BEAM BY ITS ROTATING MOTION

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The stability of propagating proton beam with rotation around the propagation axis is examined here numerically. If the electron number density of the background gas in the reactor is chosen to be so small that the electron mean free path is longer than the mean electron Larmor radius but the number density is high enough to satisfy that the plasma frequency of the background gas is larger than 10^{10} rad/s, then the charge of the ion beam is neutralized within 1 ns but the current of the ion beam is not neutralized. Thus the Lorentz force by the self-induced magnetic field in the azimuthal direction confines the propagating ion beam in a small radius. The macroinstability of mixed type of the Kelvin-Helmholtz, tearing and sausage modes can be supressed by the action of the self-induced magnetic field in the propagation direction. The solution of the propagating ion beam with rather high rotating velocity is obtained first in the steady state in equilibrium. Then the dispersion relation is derived through the linearized system of equations for perturbed quantities. The velocity ratio of the mean rotating velocity to the propagating one in order to stabilize the macroinstability can be described for the given steady state solution of the propagating ion beam.

LASER-INITIATED DISCHARGE CHANNELS IN SODIUM VAPOR

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We have produced discharge channels for the propagation of ion beams in the vapor of alkaline metal by means of laser beam.

Electrical discharges in sodium vapor were initiated by laser beams which had a resonance line (λ=589 nm) with the sodium atom. The heated discharge chamber (inner diameter of 50 mm) was filled with the sodium vapor and the air. The total pressure of the gas was about 0.15 Torr, and the maximum temperature of the chamber was 320 °C. The temperature corresponded to the sodium vapor pressure of 0.03 Torr. The discharge channel of 30 cm in length was initiated by the laser beam with the spectral power density of 14 kW $cm^{-2}nm^{-1}$, under the applied electrode voltage of half the self-breakdown voltage (0.7 kV). The breakdown voltage with the laser-initiation decreased with the increase of the spectral power density. The starting processes of the discharge channels were also observed with a streak camera. The self-break discharge channel spread all over the chamber from the beginning, while the laser-initiated discharge channel in the early stage could be produced only near to and along the path of the laser beam.

Now, we are proceeding experiments of the discharge channels initiated by laser beams having a resonance line (λ=769.8 nm) with the potassium atom , or ultraviolet-laser beams ionizing cesium atoms by a single photon.

TOROIDAL MAGNETIC LENS SYSTEMS FOR INTENSE ION BEAM FOCUSING

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Numerical calculations were performed to elucidate the focusing property of annular cylindrical high intensity proton beams in toroidal magnetic lens systems. The ion beams were assumed to be emitted uniformly from the annular anode at the diode voltage in a toroidal-magnetically insulated diode and to be force-free except for the deflecting forces due to the magnetic fields in the lens system. A single toroidal field coil could be used as a diverging(D) lens or a focusing(F) lens corresponding to the two magnetic field directions. The beam focusing characteristics were compared for three kinds of lens system: the single lens, double lens and triple lens, changing the beam particle energies and lens parameters such as the thickness, major radius, magnetic field strength of each coil, and its field direction and the distances between coils. Variations in focal length and focal spot size caused from the change of beam particle energy and spread of proton velocity direction at the anode were found to be minimized for the D-F-D triple lens system. From our experiments on toroidal-magnetically insulated ion diodes, we observed the beam orbit which was consistent with the path deflected only by the toroidal magnetic field. Concerning the mechanism of magnetic field deflection for plasma-like ion beams, shorting effects of polarized electric field induced in the magnetic field are now under examination.

LIGHT ION BEAM TRANSPORT IN A MULTI-PLASMA CHANNEL SYSTEM

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In a light ion beam driven fusion, transportation and overlapping of several beams through current-carrying plasma channels are proposed to overcome low intensity of the beam. In the channel overlap region around fuel pellet, the individial channel magnetic fields might be canceled out each other. The ballistic or inertial motion of the beam particles must be examined for efficient transport onto the target. Triple wire-exploding channels (Ni-50μm) were generated as a simulational model of reactor channel system. Each channels have a length of 10∿40cm, a current of 10∿40kA and a risetime of several μs in 1∿50Torr air. Proton beam with several tens kA/cm^2 and injection angle of 10°, generated from a pinch-reflex ion diode mounted on Reiden IV, was injected to the center one. The trajectories of post-transported beam particles were observed by a pinhole shadow box as a function of the particle energy. Beam expansion and beam deflection in the channel overlap region were investigated by comparing the experimental results with the case of single channel. Variations of overlap gain and implosion efficiency due to the enlarged beam injection angle to the pellet are to be discussed.

SAUSAGE INSTABILITY IN A PROTON-BEAM TRANSPORT THROUGH WALL CONFINED PLASMA CHANNEL AT NAGAOKA

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Transport of an intense pulsed proton beam with an energy of 800-keV has been studied through a wall-confined, z-discharged plasma channel (1-m long) in the Nagaoka ETIGO-I. The transport efficiency increases with increasing channel current or decreasing channel pressure. Reasonable agreement is obtained between the experiment and the existing theories. Changing the timing between the channel current and the beam injection, we have found that there exists a relevant timing for the beam injection. In some cases, the beam ceases to be transported through the channel probably due to the presence of plasma instabilities. The non-transport region has been clarified in a parameter space.

Using an image converter camera, we have studied the macroscopic behavior of the channel. In the non-transport region, clear evidences of the sausage instability have been obtained from the streak and framing photographs. As the instability grows with time, the wavelength tends to be elongated. The pinch velocity of the channel has also been measured in a parameter space, which gives reasonable agreement with a hydrodynamic theory.

In addition, we have also studied the detailed dynamics of the post-transport proton beam, e.g., maximum emission angle, beam expansion angle, etc. The detailed comparison is made between the experiment and the theoretical consideration.

INTENSE PROTON BEAM PLASMA INTERACTIONS*

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A study has been initiated to investigate interactions between an intense proton beam and a background hydrogen plasma. The magnetic and electric neutralization of the ion beam by the plasma as well as collective interactions between the beam and the plasma are objects of this study. The plasma is produced by a conical theta-pinch gun and injected into a 5 kG solenoidal guide field. Plasma densities in the neighborhood of 10^{13} cm^{-3} and electron temperatures of 1-10 eV are observed. The plasma column is 1 meter long and 7 cm in diameter. The 5 kA proton beam is emitted from a magnetically insulated diode at 500 keV. This paper presents an outline of the theory of the interactions and some initial experimental results.

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PROTO-I AXIAL FOCUSING EXPERIMENTS*

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The time-integrated axial (z) focus of the 4.5-cm-radius Proto I (1.5 MV, 500 kA) radial proton diode is presently limited to ∿ 3 mm FWHM. This result is obtained with current neutralized beam transport in a gas cell with 6 Torr argon. If the vertical local divergence is the same (1° or less) as the horizontal divergence, the local divergence alone would produce a 1.5 mm FWHM focus. The axial focal size is evidently limited by time-dependent effects: 1) self-magnetic field bending, 2) movement of the electric equipotential surfaces during the pulse due to diamagnetic electron flow or electron pile-up, and 3) self-magnetic-field-induced astigmatism associated with non-uniform ion emission across the face of the anode. These effects are studied by observing the beam incident upon various targets with two time-resolved pinhole cameras. The first camera observes Rutherford-scattered protons from gold targets with an array of 13 silicon PIN detectors. The second camera observes K_{α}-florescence from aluminum targets with 5 independently-gated channel-electron-multiplier arrays.

Data indicate significant distortion of the electric equipotential surfaces with respect to the B_{app}-field lines during the pulse. The implications of these results with respect to lower impedance ion diodes will be discussed.

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THEORETICAL TREATMENT OF THE CURRENT NEUTRALIZATION OF

HIGH INTENSITY PROTON BEAMS IN ARGON*

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Current neutralization of intense ion beams by an argon background gas has been demonstrated experimentally and calculated theoretically for proton beam current densities approaching 100 kA/cm^2 and energies in the range of 1-2 MeV. Current densities as high as 1 MA/cm^2 have actually been observed in target experiments at Sandia National Laboratories. In order to treat these higher current densities, an earlier theoretical model due to Slutz has been extended. This model treats both the resistive and inductive effects in the plasma created from the gas; neutral and singly ionized argon species were considered. Extensions to this model have included an expanded treatment of the argon chemistry which considers a higher degree of ionization in the background gas and a generalized treatment of the current and voltage waveforms. The implications for focusing extremely high intensity proton beams will be discussed.

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TRANSPORT AND FOCUSING CONSIDERATIONS FOR LIGHT ION ICF*

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Channel transport of intense light ion beams will be required for standoff in a survivable diode ICF system. The standoff distance will also allow for time-of-flight beam bunching. Beam focusing both at the diode and after exiting the transport channel into a final focusing cell is also required to reduce the radius of the beams to pellet size. Efficient use of the available beam energy is achieved by maintaining beam brightness as well as possible during transport and focusing. Aside from beam bunching, all other beam phenomena which occur between the diode and the target tend to degrade the beam brightness introduced at the source. Beam-plasma stability, radial channel expansion and beam energy losses during transport must also be considered in order to choose the proper channel plasma parameters for good beam transport. For a multimodule system packing constraints are also important. Consideration of all these factors in designing the optimum transport and focusing system have been studied in detail and results will be presented which show the role that each factor plays in the design.

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OPTIMIZATION OF TARGET IRRADIATED BY LIGHT ION BEAM

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A proposal is given here for a method to optimize the cryogenic hollow shell target which consists of the three layers of Pb, Al and DT fuel. The target is named as "Niu target" and does a cannon ball type of implosion.

By using a model that the ion beam deposits its energy instantaneously in the Al pusher in the target and the pusher expands adiabatically and homogeneously, the final implosion velocity U_{DT} of the fuel can be obtained as a function of the beam energy E_b, the target radius r_{Al}, the fuel radius r_{DT}, the thickness $_{Pb}$ of the Pb layer, the thickness $_{Al}$ of the Al layer and the rate C_{Al} of beam energy deposition in the Al layer. Through the empirical laws obtained by simulations, the ion temperature T_i and the fusion parameter R of the fuel after the fuel collision at the target center can be derived as functions of the preheat temperature T_o of the fuel, the effective mass M of the imploding materials (the fuel mass added by the pusher mass), the fuel mass M_{DT} and U_{DT}. Through T_i and R, the averaged reaction rate Y of the fuel is estimated. Thus the output thermal energy E_f can be obtained as functions of the particle energy e_b (hence $_{Pb}$ and $_{Al}$), E_b, r_{Al}, r_{DT} T_o and C_{Al}. The pellet radius must be decided by considering the instabilities in the pellet and is chosen as r_{Al}=4mm. Now we choose E_b=4MJ, T_o=100K and let us optimize E_f with respect to r_{DT}, e_b and C_{Al}. At last we have r_{DT}=2.5 mm (M_{DT}=1.19x10^{-5} kg) e_b=5 MeV ($_{Al}$=96.1 m and $_{Pb}$=16.7 m) and C_{Al}=89% as optimum values.

OPTICAL EMISSION FROM HIGH ENERGY PROTON BEAM PROPAGATION THROUGH AIR AND THROUGH ALUMINUM SAMPLES*

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Photographic radiance and spectroradiometric measurements were made of light emitted from the passage of an 800 MeV proton beam through air of about 600 torr pressure and through thin aluminum samples. A two-cm-diam proton beam from the LAMPF accelerator was used with average currents of 1 to 100 nanoamps. Photographic observations were made with a standard film camera and with an intensified camera. Low dispersion spectra - 30 nm/mm in first order and about 2 nm resolution - were obtained with an objective grating spectrograph. Exposure durations for the intensified camera ranged from 0.125 to 32 seconds, and for the standard film camera, from 1 minute to 3 hours. Analysis of the air emission spectra showed N_2^+ (First Negative) and N_2 (Second Positive) molecular fluorescence radiated in discrete spectral bands. The spectra from the aluminum samples, on the other hand, were continuous and exhibited no apparent discrete structure. Candidate mechanisms for the light production will be discussed.

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ALTERNATIVE IMPLOSION CONCEPTS BY PARTICLE BEAMS AND LASERS

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For particle beam fusion, the power concentration is one of the most important and difficult technical problems. Two physical concepts of the design of the target structure to increase the power density on the target have been investigated experimentally appling a focused REB generated by REIDEN III.

A high velocity plasma jet formation was observed experimentally when a cylindrical Au target was irradiated by REB. The areal energy density of the jet was 6 times higher than that of the accelerated foil of plane geometry and the plasma jet was strongly collimated, which is favorable characteristics for the application to ICF.

The experimental and computational study on the velocity multiplication in a double foil acceleration have been conducted to clarify the condition for the elastic collision. It was indicated that the key point of the velocity multiplication is the inhibition of shock heating of the foils at collision.

A LIB and laser hybrid implosion have been also studied computationally. The LIB or liner compress a hollow shell. In the cavity of the shell a fuel pellet are mounted and the laser is already injected. This concepts permit the efficient conversion of the pulse power energy into the fuel pellet.

ELECTROSTATIC FIELDS AND DOUBLE LAYERS AT HIGH POWER PARTICLE BEAM INTERACTION WITH DENSE PLASMAS

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A basically new result was derived numerically which may change the scenario of the study of plasma properties for inertial confinement fusion or similar interaction conditions. A genuine two fluid plasma code without any approximation or simplification with time steps much less than the plasma oscillation period (on 7600 and Cray) permits for the first time the study of the bahaviour of inhomogeneous, irradiated, freely expanding, dense plasmas and overcomes the well known difficulties in the coupling by the Poisson equation. Remarkable damping mechanisms by coupling to ion oscillations have been observed. During this dynamical process with inhomogeneities in densities and temperatures of the two fluids, large electrostatic fields and double layers are generated sustaining for much longer times than the usually known decay of fields in conducting plasmas if densities and temperatures are spatially constant (homogeneous).

Related to the well known electrostatic effects at the periphery of a pellet plasma when expanding against vacuum[1,2,3], the strong reduction of the thermal conduction within the areas of high fields suppresses the energy transport in the fusion pellets. We report on first results about disadvantages in gain computation during the last years and about advantages for ion beam fusion where the suppression of electron precursor waves permits an interpenetration heating.

The results support the new concept of Alfven[4] for double layers in expanding plasmas against the Cowling concept where the simplification to homogeneous conditions would not permit the electrostatic fields we derived.

[1] H. Hora, Laser Plasmas and Nuclear Energy, Plenum, New York 1975.
[2] C. W. Mendel and J. N. Ohlsen, Phys. Rev. Letters 34, 859 (1975).
[3] S. Eliezer et al, Monterey Workshop 25-29 Oct. 1982 (in print).
[4] H. Alfven, Cosmic Plasmas (Reidel, Dordrecht, (1981).

INTERACTION OF LIGHT ION BEAMS WITH MATTER
AT THE 0.5 x 10^{11} W/cm^2 LEVEL

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The Sidonix II generator fired in positive polarity in the long pulse (100 ns FWHM), 0.7 TW mode has been used to accelerate 100-200 kA ion beams and focus the beam in a 1 Torr air cell downstream the cathode. For low total D^+ and P^+ current (100 kA) but reproducible beams, it has been possible to perform neutron diagnostics yielding 2-3 x 10^{10} neutrons on a 30 mm diameter CD_2 target. D^+ energies have been measured by activation of B_4C targets in good agreement with the accelerating voltage corrected for energy loss in the 3.5 µm thick air cell boundary. The motion of subrange (5 µm) and overange (10 µm) Al foils on focus has been visualized with a streak camera. With front face velocities of 3 x 10^6 cm/s we estimate a focused power level of a few 10^{10} W/cm^2. A machine upgrade is underway to double the power up to 1.4 TW, yielding an expected total ion current of 300-400 kA. Then it is expected that the focused power level will reach over 10^{11} W/cm^2

+ Centre d'Etudes de Limeil, France

THEORETICAL INTERPRETATIONS OF PROTO I ION BEAM TARGET EXPERIMENTS*

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The focal properties of intense light ion beams, as well as other important beam characteristics, are largely inferred from time integrated and time resolved target response measurements. A number of recent target experiments on the Proto I accelerator, employing a variety of diagnostics, have been compared with computer simulations to determine beam parameters. The radiation emitted from conical targets that are thinner than the ion range, and the hydrodynamic response of thick cylindrical targets have been examined, comparing calculated with experimental XRD, PIN, and FXR data, to infer beam intensities exceeding 1 Tw/cm^2. From observed radiation data, ion spectrometer data, and nuclear reaction data we have inferred that the proton pulse length is significantly shorter than the total electrical current pulse as measured by machine B-dot monitors. The conclusions drawn from target response calculations are sensitive to the physics models used in the radiation-hydrodynamics code, e.g. the ion energy deposition model. These experiments indicate what improvements in the theoretical models are required and are used to normalize codes for target calculations.

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EFFECT OF NONUNIFORMITY ON TARGET IMPLOSION

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In inertial confinement fusion (ICF), one of the most crucial problem is the effect of the inhomogeneity on a target implosion. The inhomogineities are originated from the inhomogeneous deposition of the driver energy, the inhomogeneity of the target itself and the instabilities. To investigate the effect of inhomogeneity on a target implosion, 2- or 3-dimensional computer simulation code is required. In a real case of a target implosion, 3-dimensional effect is considred to be important. Therefore a three dimensional simulation code for the implosion study is developed by the PIC method. The PIC method is recently advanced and becomes attractive for such numerical simulation. By the simulation code, the inhomogeneity effect on a target implosion is investigated for many cases. The detail results will be presented in the conference.

ION STOPPING IN HEATED TARGETS*

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Range shortening occurs in high temperature ion targets as the target atoms become ionized. Although the energy loss to the free electrons is easily calculated, the interaction with the remaining bound electrons has been the subject of much recent theoretical work. In this experiment the 1 TW/cm^2 applied field ion diode on Proto I has been used to study ion stopping in a 30 eV target. We use a time-resolved Thomson parabola analyzer to measure the proton beam particle energies before and after passing through a subrange target foil. Recent experimental results will be compared to the ion-target interaction model.

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DIODES

RECENT ADVANCES IN THE DEVELOPMENT OF LARGE AREA EXPLOSIVE EMISSION CATHODES

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Large area cathodes are widely used in accelerators applicable for technology. In many cases for this purpose the cathodes are employed in which a great number of explosively emitting sites are created by some way, e.g. due to the explosion of protrusions on the metal or graphite surfaces or by some special systems of plasma ignition. The paper deals with the development of the cathodes with an area in the range $10^2 \div 10^4$ cm^2 operating at currents of $10 \div 10^4$ A with pulse lengths of $10^{-8} \div 10^{-3}$ s. The operation of such cathodes in electron accelerators is analyzed for the conditions of periodical pulsing with a repetition rate up to 200 Hz at an accelerator power up to 20 kW and higher. The safe operation of the accelerators applied for technology is achieved for more than 10^8 pulses. The physical processes on the cathode and anode that affect the parameters of the electron beams extracted from an accelerator were elucidated, e.g. a "screaning" effect, an effect of "touches", stimulation of new emitting sites by cathode flare plasma, electron desorption of molecules from the anode, etc.

OVERVIEW OF ION DIODE RESEARCH*

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Research into generation of intense proton beams has been conducted using Applied-B, Hybrid, and Pinch Reflex ion diodes. This work has been carried out in close collaboration with Cornell University and the Naval Research Laboratory. The goal of this work is to determine the ion diode configuration which maximizes the probability of achieving target ignition on PBFA II, which is to be operational at Sandia in 1986. A diode selection process has been established in order to narrow options and concentrate limited resources on a single diode type for development until mid-84, when the PBFA-II diode hardware design must be initiated. Diodes of all three types have been tested and compared on PBFA I and elsewhere, and scaling calculations have been carried out. Data have been obtained about diode efficiency, impedance behavior, microscopic and global divergence, ion transport and neutralization, and MITL-diode coupling, and novel diagnostic techniques have been developed. Results of diode comparisons and an overview of the diode research will be presented, with detailed treatments being presented in subsequent papers.

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INTENSE ELECTRON AND ION DIODE RESEARCH AT NRL†

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The pinched beam diode has been studied at NRL as both an electron beam source for x-ray bremsstrahlung production as well as a light ion source for ICF. For both applications new geometries have been tested which have demonstrated currents approaching twice the conventional diode critical current. Experiments have been performed on two pinched electron beam diodes connected in series and on a "Magnetically Isolated Splitter" diode where post hole convolutes are used to convert a coaxial generator output to a triaxial output to drive a ring diode. A new barrel-shaped ion diode geometry called the "Equatorial Pinch Reflex Diode" has been studied. Ion diode studies have emphasized the limitations on ion beam power brightness. Recent developments in plasma erosion opening switch technology have allowed testing pinched beam ion diodes with fast risetime, short pulses on Gamble II. Preliminary results from these experiments show fast turn on, efficient ion production and smaller ion divergence.

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†Work supported by the Department of Energy and the Defense Nuclear Agency.
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STUDIES OF CONDITIONS IN DETAIL IN MAGNETICALLY INSULATED INTENSE ION BEAM DIODES*

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In order to better understand the operation of magnetically insulated diodes, we have performed and are performing detailed studies of conditions within these diodes. Electron and ion flow and their correlation have been studied locally in the LONGSHOT diode ($\lesssim$ 100 kV, 700 ns). The observed correlations made it possible to differentiate among three classes of ion deflections. Results imply the presence of transverse electric fields in the diode caused by changes in the anode plasma shape (two classes) or by cathode plasma processes (the third class). In experiments on a 50 ns, 400 kV diode generating ~125 A/cm^2 ion current density from a surface flashover anode, an average electron density of ~10^{15}/cm^3 in the anode plasma was inferred from Stark (density) broadening of the hydrogen H_β line. Preliminary measurements of ion transverse velocities in a 250 kV, 300 ns ion diode obtained from the Doppler Broadening of optical emission from Ba^+ ions have indicated a mean transverse energy of ~1/2 keV. Moreover, the Stark shift of the emission line due to the applied electric field is seen. It is proposed to measure the local electric field with precision using two-photon Doppler-free spectroscopy of tunable dye laser light.

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INTERMEDIATE WEIGHT AND LIGHT ION BEAM RESEARCH WITH PULSED POWER GENERATORS

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We endeavour to accelerate a C^{4+} beam by heating the anode of a pinch reflex diode with a CO_2 laser. At the time of the writing of this abstract, we encounter difficulties to synchronize the laser and the 0.1 TW generator driving the diode. Still, we hope to focus a 40 J - 40 ns laser pulse on a 1 cm^2 area. The objective of this proof-of-principle experiment is to demonstrate the possibility of heating the anode sufficently to obtain C^{4+} ions but not too much to avoid gap closure by thermal expansion.

We also intend to report on our more classical light ion beam work performed on the Sidonix II generator operating at 0.7 and 1.4 TW in > Ø polarity. Optical, nuclear and electrical beam diagnostics give consistent determinations of ion energy on target. Streak camera pictures of 5 and 10 μm Al foils when the beam is focussed in a 1 Torr air cell yield front face velocities of 3 x 10^6 cm/s. The focused power density is estimated to be in the range 10^{10} - 10^{11} W/cm^2.

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BLACKJACK 5' ANNULAR ELECTRON BEAM EXPERIMENTS*

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The 0.6 Ω, 10 TW BLACKJACK 5 machine has been modified to reduce its output impedance to 0.3 Ω. The new machine, BLACKJACK 5', achieves this result via a triaxial output section. In order to couple the output power to an electron beam for production of bremsstrahlung X-rays, a dual electron beam diode has been developed. The diode consists of two vacuum transmission line feeds and a 12 site magnetically isolated splitter (MIS) post-hole convolute, feeding a 25 cm ring cathode. The MIS diode and the stability and characteristics of the electron beam at high power levels will be discussed.

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*This work was supported by the Defense Nuclear Agency.

DIODE PHYSICS

EFFICIENT LOW-IMPEDANCE HIGH POWER

ELECTRON-BEAM DIODE*

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A new relativistic electron-beam diode configuration (the TRIAX diode) is proposed. Electrons emitted from the inner and outer sides of an annular cathode shank flow in two coaxial magnetically insulated radial gaps and are combined with electrons emitted from the planar cathode face. The return current is split between an axial rod and an outer cylindrical conductor. Ion emission is restricted to the planar gap, resulting in low ion current. This mechanism can produce an efficient high power (5.0 TW), low impedance (0.8 ohm) electron diode. Analytical modelling, numerical simulation and diode experiments have been performed to investigate this diode concept. The experiments were performed on a 4.8 Ohm accelerator with peak voltages between 1.3 and 1.8 MeV. The beam at the anode was annular and about the same size as the cathode cross section. Carbon activation analysis indicated that the proton current was less than 1 percent of the total diode current. These results agree with numerical simulations which show that ion current would cause the beam to pinch on the inner anode.

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Light Ion Beam Productions by Applied Br Magnetically Insulated Annular Diodes

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We tested Br magnetically insulated annular diodes for light ion beam productions with high efficiency because of the long residence time of electrons in the gap. It is because that electrons drift in the combination of the gap electric and radial magnetic field is in the azimuthal direction, and electron orbits can be stable and self-conneted. The plasma anode was a 2 mm -thick annular plastic flashboard (80 cm^2) with copper pins (1.2 mm diam, and 2.5 mm pitch). The diode voltage of 200 kV was supplied by a 3 Ω, 70 nsec LIMAY-I pulse generator through a 1 m vacuum pulse transmission line. The diode current was 50 kA in the case of a 7 mm A-K gap at the critical insulation magnetic field, which was provided by a 3 kV, 400 μF capacitor bank. The ion current density of about 170 A/cm^2 at the distance of 3 cm from the anode was measured by a small charge collector. The significant enhancement of the proton current density above the child-Langmuir limit of 10 A/cm^2 was observed although the damage pattern of the anode was not uniform. More detail experiments on ion energy detections are under way using a Thomson parabola ion analysor and activation methods. For the next step we are planning to test a focused ion diode with the Br magnetic insulation field.

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HIGH BRIGHTNESS POINT-LIKE SOURCE FOR INTENSE ION BEAM

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By a pinched electron beam diode having electrodes in a conical shape, high brightness point-like ion beam source was obtained.

The anode of a conical diode consists of plastic insulator (delrin) and the diameter of the cathode is 8cm. The apex angle of the anode and the cathode are 56^0 and 40^0 respectively. The applied high voltage is 200$\sim$250kV with $\sim$150 nsec duration and the diode current is 30$\sim$35kA. During 70nsec ion (proton) beam with energy of $\sim$200keV is emitted. The mean ion current density within 16mm around the axis is about three times that from an usual flat parallel diode with the same dimension and impedance. It was seen by a shadow box that the ion beam is emitted from a small region ($\sim$6mmϕ) at the apex of the conical anode.

For the measurement of the ion beam current a biased ion collector was used. By changing several window plates with different distribution of pinholes (0.3mmϕ) the radial distribution of the ion beam current density at 12cm from the anode apex $J_i(r)$ was measured. On the assumption that the distribution is Gaussian, $J_i(r)$ is expressed by $587\exp(r^2/0.88^2)$A/cm^2. This means that the e-folding divergence angle at the origin θ_σ is 0.073rad=4.2^0, the ion current within this angle is 900A and the current density is 3.2kA/cm^2. From these values the brightness and the power brightness is estimated at $B=J_i/\pi\beta^2\gamma^2\theta_\sigma{}^2=447$ MA/cm^{2}sr and $\mathcal{B}=J_iV/\theta_\sigma{}^2=1.19\times10^{11}$W/cm^{2}sr. These are fairly high values among the brightness of ion beam sources at low voltage operation previousely published and can be raised to large values at high voltage operation.

PERFORMANCE OF A SELF-MAGNETICALLY B_θ-INSULATED ION DIODE

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Experimental results on the performance of a self-magnetically B_θ-insulated ion diode are presented. At a diode voltage of 450 keV and a diode impedance of 3 Ω an ion current of 15 kA has been observed. Measurements of the beam geometry at low ion efficiency show that the ion deflection in the insulating magnetic field is nearly independent of diode voltage due to the feedback mechanisme of the self-magnetic insulation. Effects of material erosion on the anode support structure are interpreted as material disintegration by pressure waves due to leakage electrons.

2P4

INVESTIGATION OF AN ANNULAR MAGNETICALLY INSULATED ION DIODE OPERATED IN LONG PULSE MODE

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Electron motion in the gap and mechanism of anode plasma formation were investigated in an annular magnetically insulated diode operated by low impedance($\sim 3\Omega$) Marx generator(200kVmax., stored energy;10kJ). Total ion current is about 2.5kA which is measured by the biased ion collector with multi-holes. It is increased by factor 2 when 12 radial cathode vanes are used in addition to the usual azimuthal cathode. Ion current density surpassing the Child-Langmuir current by 30 is also achieved. To investigate the electron motion in the gap, X-rays which are due to electron bombardment on anode from one radial cathode vane are measured by a detector consisted of plastic scintillater, photomultiplier. Distribution of X-ray intensity along the azimuthal direction of the annular anode indicates that electrons drift to E×B direction and average length of electron motion is about 30mm at B_r=3000 gauss and $V_{max.}$ =120kV. Photographs of X-ray from anode by X-ray pinhole camera and of anode plasma also indicate the electron motion in the same length. Based on fundamental theory, the ion production efficiency is estimated by this length consistently with the experimental value(20%). Magnitude of E×B current evaluated from this length is enough to modify the insulation magnetic field which is predicted by the theory describing enhanced ion production. Using Ti-H anode, we ascertained that not only surface flashover but also electron bombardment makes sufficient anode plasma and ions in this long pulse diode.

PERFORMANCE TESTS OF EXTRACTION DIODES WITH CRYOGENIC ANODE

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Performances of magnetically insulated diodes with the externally applied Br radial magnetic field were tested experimentally.

Beam generation and propagation have been studied in detail as a function of the insulating magnetic field, the structure of anode surface and the cathode geometry. It was clarified that the axial component of the insulating field Bz in the diode gap degraded the diode efficiency and the return field in the beam drift region was not preferable for the neutralization. Making use of longer cathodes in order to minimize the effects of the return field the characteristics of the beam propagation were improved.

Various types of flashover anodes were tested. By the use of cryogenic anode, proton beams in excess of $20A/cm^2$ with their energy of 130keV have been produced with good reproducibility from H_2O ice. These values were three times of the Child-Langmuir value and not at all inferior to the ones extracted from conventional anodes. The effects of detailed anode geometry to the beam qualities were also examined.

INTENSE PULSED ION SOURCE
WITH CRYOGENICALLY REFRIGERATED ANODE COOLED BY LIQUID HELIUM

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We proposed a new type of pulsed ion source with a cryogenically refrigerated anode (Cryo-Anode) in the lastest beam conference of this series (June-July, 1981 in palaisean). At that time the new concept was applied to the ion sources of magnetically insulated diodes. The anode metal base was cooled by liquid nitrogen, and H_2O or D_2O ice was frozen on the metal base. Proton or deuteron beams, without carbon or other harmful ingredients, was extracted from the source with good reproducibility and a reasonable repetition rate.

With this new type of ion source, various kinds of ion beams are expected to be produced according to the anode temperature. If the metal base is near the helium temperature, hydrogen isotopes are extracted without any impurity. Xe, Kr, Ar, O, N, and Ne beams are generated within the temperature range from 60K to 20K. These clean beam source refrigerated by liquid helium is the most hopeful candidate driver for ICF and another applications.

A new Cryo-Anode with a helium-coolant system came into operation recently. Xe, Kr, Ar, O_2, or N_2 gas was supplied through an injection nozzle, and was frozen on the anode base. The type of diode adopted in our experiment was a B_r-magnetically insulated diode. The diode was fed by a pulsed power machine, which consisted of a 5KJ-500KV marx generator and a 5Ω-70nsec blumline line. We clarified the characteristics of the diode and also the extracted beams. Details will be shown in the conference.

CHARACTERISTICS OF INVERSE PINCH ION DIODE

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The developments of the ion diode with high brightness and low divergence is one of the most important items for inertial confinement fusion by the light ion beam.

In inverse pinch ion diode, an anode stalk pass through the hollow cathode and electrons flow outward from the cathode due to the E X B drift. There is no electron pinch region where the ion beam divergence is large.

The inverse pinch ion diode experiments were performed using a 12 cm diameter hollow cathode and a 20 cm diameter anode on Reiden IV, 1 TW pulse power machine. Ion beam divergence was measured by shadow box with filtered CR-39 particle track detector and aluminum damage plate. Ion current density was measured by a neuclear activation method and biased charge collectors. The measured ion beam divergence were 3° for the inner anode region (near the cathode) and < 1° for outer anode region. Ion current density at anode was several handred A/cm^2.

The simulations analysis of the ion extraction experiments are being performed.

DYNAMICS OF MAGNETICALLY-INSULATED DIODES IN THE NAGAOKA ETIGO-I

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Detailed studies are being carried out on the dynamics of magnetically-insulated diodes (MID) in the Nagaoka ETIGO-I. First, focusing properties have been evaluated by use of a spherically-shaped MID's. Local divergence is found to have less effect on the focusing than a deviation of ion trajectories from the ideal ones (aberration), which strongly affects the focusing. Taking care of electrodes so as to make accelerating direction directed toward the geometric focusing point, we have succeeded in the reduction of the aberration angle. An annular distribution of an ion-current density observed experimentally is found by ion-trajectory calculations to be a space-charge effect. The space-charge neutralization factor is evaluated to be more than 99.9 %. The current-neutralization factor, which is low in the diode region, is found to increase with the distance, reaching 100 % at around the geometric focusing point. Reasonable agreement of the ion-current density is obtained between the experiment and the theory.

Using an image converter camera, we have studied the temporal evolution of the beam trajectories extracted, and found that beam qualities in the cencer and the periphery change both in time and space.

Besides the proton beam, we have also produced boron, nitrogen, carbon, and deuteron beams, the energy distribution of which have been evaluated by a very sensitive Thomson parabola constructed.

New attempts are being carried out to develop more efficient MID's with a flashboard anode preionized by an external power supply.

ABLATIVE CLOSURE IN DIODES*

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We review the advances made in the past two years on the phenomenon of ablative closure in pulsed power vacuum diodes. Included among these are the theoretical and experimental demonstration that hydrogenic material is present on the surfaces of such diodes and is responsible for rapid expansion whenever the magnetic field is small. Another is the realization that with imploding wire pinches, UV radiation is created early in the pulse, possibly by a surface plasma layer. The third is the demonstration that in some pulsed power machines the prepulse can be sufficient to give rise to UV radiation which causes substantial closure of the diode long before peak power is delivered to the diode. We discuss how these three effects influence the design of pulsed power machines and in the manner in which they are used with plasma loads.

*This work supported by Defense Nuclear Agency, Washington, D.C.

LOW INDUCTANCE, DUAL-FEED DIODE DEVELOPMENT*

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We have tested three low inductance, sub-ohm impedance diode configurations on the SNLA SPEED pulse generator at power levels above 1 TW. SPEED is a single module, ≃ 20 nsec FWHM accelerator with a .4 ohm triaxial power flow transmission line in the water section and a double-sided vacuum-water insulator at a radius of 53 cm. In these experiments, the dual feed was continued with a triplate disk arrangement to a diode radius of 4 cm, resulting in a load inductance of 5 nH. The diodes were configured to operate in a Langmuir-Childe's bipolar mode, a paravector potential mode, and a double pinched beam mode. We observed pulses with V = 900 kV, I = 1.5 MA, and pulse width = 19 nsec FWHM at the diode. Diode impedance was governed by plasma gap closure; closure velocities of ≅ 7 cm/μsec can be inferred from the data. In addition, a 4 nsec difference in the arrival time of the waves at the diode from the two feed lines was found to significantly perturb the expected diode performance. Diode performance improved markedly when the two feed lines were isolated from each other.

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STABILITY THEORY OF MAGNETICALLY INSULATED ELECTRON FLOW*

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The general theory for the stability properties of relativistic Brillouin flow was developed by Swegle and Ott within the context of planar geometry and cross field propagation of the waves parallel to the equilibrium electron flow. In this paper, we extend the previous theory by including two important features in the analytical model. They are (1) resistive plasma layers formed in the vicinity of the diode surfaces, and (2) ambient ion flow across the diode gap. In addition, we formulate our problem to allow waves propagating at arbitrary angles relative to the electron flow. Therefore, the effect of oblique propagation can be studied. Numerical simulations have also been performed to make valid comparison with the theory. The resulting theory conforms more closely to realistic diode configurations and indicates that the choice of specific diode parameters has a profound influence on stability.

*This work was supported by Lawrence Livermore National Laboratory and in part by Sandia National Laboratory.

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ELECTRON SHEATH DYNAMICS IN MAGNETICALLY INSULATED DIODES*

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The two-dimensional flow of electrons in magnetically insulated diodes has been investigated through numerical simulation with the MASK code and kinetic theory modeling. We have studied the dynamics of electron sheaths in the presence of gap discontinuitites using MASK, a 2 1/2-dimensional electromagnetic, and relativistic particle simulation code. The discontinuity is represented by a step in the anode or cathode surface or the localized emission of ions. In the case of a step in the anode surface, a simple kinetic theory description is consistent with numerical simulations. The critical applied magnetic field necessary for magnetic insulation depends heavily on the nature of the discontinuity and is observed to be a function of the size of the discontinuity, the direction of flow, relative to the discontinuity, and the usual diode parameters. The objective of this study is to determine the conditions for magnetic insulation and unsteady flow and the influence of electron flow irregularities on diode performance and beam divergence.

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*Work is partially supported by Sandia National Laboratories and Lawrence Livermore Laboratory.

MODELLING OF DIODE EMISSION PROCESSES*

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Detailed knowledge of the physics and chemistry of early time cathode and anode surface emissions is necessary to accurately predict the resulting electron or ion beam generation performance of high power diodes. The presence of adsorbed gases and metallic oxides in conjunction with surface irregularities and whisker sites greatly influences diode initiation phenomena such as the creation and propagation of the cathode space charge limited layer and any subsequent anode ion emission. The development of solutions in the near-cathode and near-anode regions, together with consideration of a global diode model, is given. The emphasis of the work is the determination of mechanisms responsible for the intrinsic beam emittance generated in the diode gap. Localized whisker erosion, coupled with production of a multi-component partially ionized flare region, is treated in detail.

Recent experimental observations indicate temporally uniform optical radiation emission, at the anode, after a sub-nsec voltage rise time. As a possible diagnostic of early time behavior the observed optical emission may be interpreted as transition radiation. Calculations of the radiation lobe intensities at the anode surface are made.

*This work has been supported by the Office of Naval Research, Sandia National Laboratory, and Lawrence Livermore National Laboratory.

APPLIED-B ION DIODE EXPERIMENTS ON PBFA I*

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The applied-B diode has produced the highest brightness proton beam of any ion diode at the 1 TW and 3 TW power levels on the Proto I and Proto II accelerators. An experiment has begun on PBFA I to study the diode's electrical coupling to the accelerator, ion conversion efficiency, and focusability of the proton component of the beam. The particular diode is a slightly larger version of a diode used successfully on Proto II. The diode radius has been increased from 14 cm to 15 cm, and the height from 5 cm to 6 cm, increasing the anode area from 440 cm^2 to 560 cm^2 to accommodate PBFA-I's lower output impedance. Current neutralized beam propagation is provided by injecting the beam into a gas cell with a 2 μm mylar window a few mm from the AK gap, typically filled with 5 torr argon. We will discuss the status of these experiments.

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2P16

ANALYSIS OF MECHANISMS FOR ANODE PLASMA FORMATION IN ION DIODES*

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The method by which anode plasma is formed in intense pulsed-power ion diodes by breakdown is of much interest. Formation of a passive "flashover" anode plasma source may involve one or more of the following: polarization of the anode dielectric, direct leakage electron bombardment, UV-stimulated desorption of excited gas in the gap or on the anode surface, ionization of desorbed neutrals in a surface plasma by electron return currents associated with ion extraction, or bombardment by low energy electrons or negative ions. At Sandia National Laboratories experiments have been done on Nereus, the PI 110A, Proto I, Proto II, and HydraMITE using anodes that contain dielectric-filled surfaces. The experiments represent a variety of anode turn-on delays (2 to 15 ns), magnetic field strengths (7 to 30 kG), voltages (300 keV to 2 MeV), and anode configurations (photo-etched copper screen laminated to a dielectric surface, dielectric-filled grooves machined into the anode surface, and holes drilled through a dielectric surface that coats the anode). Data include ion beam current from Faraday cups, holographic observation of plasma motion, the spatial and temporal character of visible light emitted from the plasma, and optical metallographic examination of the dielectric surface.

The experimental data are assessed in an attempt to determine what mechanism or mechanisms contribute to formation of a surface flashover plasma source. If these mechanisms can be understood, anode design might be improved by producing a more uniform plasma that turns on earlier.

*This work supported by the U. S. Department of Energy.

DEVELOPMENT OF A GAS FILLED ION DIODE *)

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On the basis of the Pseudo-Spark, a special low pressure gas discharge that produces ion an electron beams of high density (10^{16}/cm^{-3}) and low divergence, an ion-diode was developed. Experiments were carried out at the 3Ω , 100 GW pulse power line "Pollux" in the Kernforschungszentrum Karlsruhe.

The divergence of the beam depends on power and geometry. Best results are up to now 10^{-2} radian. The energy of the protons is in agreement with the acceleration voltage.

*) This work is supported by the Kernforschungszentrum Karlsruhe, Germany

DEBRIS SHIELDS FOR HIGH POWER DIODES*

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High power electron beam diodes are used in a number of applications including the generation of bremsstrahlung radiation. The high energy densities in the anode region cause material erosion and result in large quantities of debris. We have conducted an evaluation of candidate materials for debris shields using the 1 TW BLACKJACK 3 pulse generator. Experiments with aluminum plates were performed to characterize the impulse conditions. Then the candidate material responses were measured. The result of these measurements will be presented along with impulse scaling relations.

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*This work was supported by the Defense Nuclear Agency.

PRODUCTION OF INTENSE BEAMS OF SPIN-POLARIZED NUCLEI*

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The dependence on relative spin orientation of thermonuclear reaction cross-sections as well as other elementary processes make the production of highly polarized intense beams of nuclei desirable. High degrees of nuclear polarization in the solid state can be achieved by use of a dilution refrigerator in combination with a high-field superconductive magnet. For hydrogen isotopes the relaxation times of spin orientation can be controlled by the ortho-para conversion process so that the polarized samples can be transferred to an atmospheric pressure helium cryostat without appreciable loss of polarization. The magnetically insulated ion diode obtains the ions to be accelerated by rapid ablation of the anode by an electric discharge. Hence if this anode consists of highly polarized solid hydrogen isotope samples produced by the above method the resulting ion beam should retain this polarization as the ablation process is too rapid to permit nuclear depolarization. The resulting polarized intense ion beam could thus be used for injection into a thermonuclear reactor or into a particle accelerator for high-energy physics experiments.

* This work was supported by the Department of Energy.

AMPFION HYBRID DIODES ON HYDRAMITE AND PBFA I*

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The Ampfion diodes are designed to have uniform behavior over the entire anode, and to generate ions efficiently by providing an insulating magnetic field from a series magnetic field coil. In the Hybrid versions of this diode the ions are supplied by surface-dielectric anodes like those used in other diodes.

In this presentation, three diodes will be discussed; a 20 cm focal length polar or extraction diode for the 0.8 TW Hydramite pulser, and 25 cm and 15 cm focal length equatorial diodes for the PBFA-I pulser (6 to 15 TW at the diode terminals). The Hydramite work will include both proton and lithium beam experiments.

The presentation will show progress toward the ultimate goals of high efficiency and small focus. More importantly, data will be presented which leads us to conclude that the diode is reasonably well understood. This includes data on the uniformity of the diode output, data showing the interaction of the relativistic electron cloud with the field coil, data showing the accuracy of focusing predictions, and other comparisions between data and theoretical modeling. One critical and poorly understood part of the diode is the anode. Anode turn-on delay will be discussed, along with the limitations it implies for our present technology.

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HYBRID ION DIODE THEORY AND COMPUTATIONS*

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Intense ion beams for inertial confinement fusion research are produced by diodes in which electron current is inhibited by strong magnetic fields. The insulating magnetic field in these diodes can be produced by the particle currents themselves or by an external field coil. The Hybrid ion diode incorporates a series field coil and a grooved, epoxy-filled anode to produce the pulsed ion beam. An extensive theory has been developed for this diode. This theory has been applied in the design of three Hybrid diodes for use on the Hydramite and PBFA-I pulsers at Sandia National Laboratories. Both polar and equatorial versions of this diode concept have been tested. The design of these diodes will be discussed, including the description of various computer codes used in this process. The confirmation of various aspects of the theory for Hybrid diode operation will be discussed. The sensitivity of Hybrid diode performance in accelerator voltage and current variations will be examined, and a method for optimizing the diode focus will be detailed. A ray trace code has been written to investigate the focal properties of beams from these diodes and results will be given. Some particle-in-cell computations for specific diode designs will also be presented and compared with experimentally measured quantities.

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CODES

NUMERICAL SIMULATION OF CHARGED PARTICLE BEAMS*

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Problems involving the physics of intense charged particle beams are often characterized by complicated geometries and strong inhomogeneities. Electromagnetic effects, particle flows, atomic physics and radiation may also be present, thereby making analytic approaches extremely difficult. Numerical simulation is frequently the most attractive alternative. Simulations may be used for a number of purposes: to aid in the interpretation of experimental data, to design the experiments themselves, or simply to improve one's understanding of the physics of the problem. In this paper, we discuss simulation techniques applicable to studying particle beams, and present several examples of these techniques as applied to problems of current interest. Among those configurations we consider are pulsed-power diodes for beam production, microwave devices, and transport and propagation of intense beams.

*Work supported by Sandia National Laboratories and Lawrence Livermore National Laboratory.

NUMERICAL SIMULATIONS OF HIGH POWER DIODES*

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The numerical simulation of intense electron and ion beam diodes can be an important tool in the understanding of these devices. Two types of two-dimensional particle-in-cell diode simulation codes have been used at Sandia National Laboratories to study high power diodes: an electrostatic-magnetostatic code and a fully electromagnetic code. In a steady-state simulation, the voltage across the anode and cathode electrodes is held fixed at some value (peak voltage for example) and the simulation is continued until the gross diode features such as total current or potential distribution undergo acceptably small fluctuations about a steady state. These codes have been very useful in understanding the effect of various parameter variations on diode performance. As the general understanding of these diodes has improved, more detailed time dependent information has been required. Fully electromagnetic codes have been developed and applied to diode simulations to investigate inductive effects and answer questions concerning electromagnetic stability. For example, MAGIC (an electromagnetic code written by B. Goplen of Mission Research Corporation) has been used to address issues such as stability and efficiency in pinched electron beam and applied-B field ion diodes. Some examples of steady-state and electromagnetic simulations will be presented. The particular example of the Hybrid ion diode will be discussed.

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GAS PUFFS, PINCHES

IMPLODING PLASMA PINCHES DRIVEN BY HIGH POWER GENERATORS

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Moderately high Z imploding plasma pinches with temperatures in the kilovolt range have been produced in discharges with currents up to 5 MA. Streak and framing photography and laser shadowgraphy show the behavior of the plasmas during the implosion phase. At the end of the implosion phase, a Z-pinch is formed with electron densities up to $\sim 10^{21}$ cm^{-3}. These Z-pinches produce copious X-ray radiation. The X-ray emission above 1 keV is composed primarily of lines from atomic transitions in fully to partially stripped ions. The intensity of the K-shell X-ray emission decreases strongly as the atomic number of the plasma increases. Neon (Z = 10), plasma implosions driven by the BLACKJACK 5' pulse generator, for example, produce $\sim$55 kJ of K-line X-rays at $h\nu$ $\sim$1 keV, while titanium (Z = 22) plasmas driven by the same generator produce only $\sim$2.1 kJ K-line emission at $h\nu$ $\sim$5 keV. Measurements of the X-ray emission and characteristics of these plasmas at current levels between 500 kA and 5 MA suggest a number of possible applications, including X-ray laser research and X-ray lithography.

THE "NEEDLE PLASMA", A SOFT X RAYS-INITIATED, GAS EMBEDDED Z-PINCH COMPUTATIONNAL AND EXPERIMENTAL APPROACHES.

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Achieving temperature in the keV range by Joule heating seems possible for a needle plasma characterized by long lenght (1-10 cm) and minute diameter (10-100µm). Preliminary analyses show that temperature evolution is thigtly related to the plasma diameter. Therefore our approach considers ionization in a very small diameter using soft X-Rays.

A simple zero-dimensional computer model is used for solving a set of coupled differential equation describing the macroscopic plasma evolution. In contrast with previously others models, we do not assume that a Bennett equilibrium is reached from the early beginning. The model describes kinetic and magnetic pressures and time variation of the gas ionization. Energy balance includes Joule heating, free-free bremsstrahlung and expansion cooling. Current variations are introduced by coupling the plasma with a high voltage coaxial line. The results of this simple model, giving ion and electron temperatures, plasma radius, current and electron density variations versus time, help us to design an experimental setup made of a 0.5 Ω coaxial line delivering a 40ns and 130kV pulse in a pressurized discharge chamber filled with 1-10 atm of hydrogen or noble gas. The ionization of the gas is made by a tiny beam of soft X-Rays (8-13 nm) produced by a 1J Ruby laser focussed under vacuum on a thick target.

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GAS PUFF IMPLOSION EXPERIMENTS ON PROTO-II

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We have successfully imploded annular-argon gas puffs on Proto-II (a 10 TW, .125Ω accelerator with a 40 ns FWHM voltage pulse). This set of experiments (named NARYA) utilized a 38 cm diameter single-disk diode fed by sixteen 2Ω-triplate water lines in parallel. The NARYA diode, with a total inductance of 10 nH, delivered 4 MA to the gas puff load. Time-resolved Ni bolometers have measured isotropic x-ray yields of 25 kJ with Argon puffs. (These bolometers have a flat spectral response to 2.5 keV.) A significant fraction of the x-rays had energies greater than 1 keV. Time-integrated pinhole pictures (at 2 keV) have shown pinch diameters of 0.5 mm. PIN diodes looking in the spectral region 1-5 keV yielded signals with 10-12 ns FWHM. Data taken with XRD's and a KAP time-integrated spectrograph will be presented. We will describe the results of Neon and Krypton, as well as Argon, gas puff implosion experiments.

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STUDIES OF AN IMPLODING PLASMA X-RAY LASER*

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Water pulse line driven gas puff implosions have been used to create high temperature (∿1 keV), high density (10^{20}-10^{21} cm^3) plasmas as intense sources of XUV and x-ray radiation. This technology is currently being used to form Ne-like krypton plasmas and test theoretical predictions of a collisionally pumped XUV (∿100 eV) laser. An advantage of pulse line driven plasmas over laser produced plasmas is the large physical extent (∿4 cm length) produced by the former. The x-ray laser pumping mechanism will be described. Results from the first year of this work will be presented. They include improvements in plasma uniformity and simultaneity of implosion, identification of XUV krypton lines in the 15-to 250-Å region, and measurements of plasma temperature and density.

*This work was supported by the Department of Energy Division of Advanced Energy Projects.

MODELING/PLASMA LOADS

IBEX - A PULSED POWER ACCELERATOR THAT GENERATES NO PREPULSE*

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Intense relativistic electron beams are produced in vacuum diodes driven by pulsed power accelerators. For pulse widths ~100 nsec, pulse forming lines (PFL) are used to generate the accelerating voltage pulse. This pulse is produced by sequential switching of stored energy through two or more stages. Capacitance and/or inductive coupling usually results in the generation of a low level prepulse voltage some time during the switching sequence. This prepulse is known to have a substantial effect on the performance of the vacuum diode during the main accelerating pulse. Most accelerators use various schemes for reducing this prepulse to acceptable levels. The Isolated Blumlein PFL concept was developed at Sandia to allow for the generation of the main accelerating pulse without generating a prepulse voltage. This concept was implemented into the IBEX accelerator which generates a 4 MV, 100 kA, 20 nsec output pulse. Design and performance data are presented.

*This work was supported by the United States Department of Energy under Contract DE-AC04-76-DP00789.

A COMPACT 100KV E-BEAM GENERATOR

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A 100 KV, 1 KA, 40 ns E- Beam generator was designed and built using a 3μF/ 4 KV capacitor, a transformer and a 50Ω coaxil line. The generator is simple to build and operate as well as being inexpensive. It occupies a small volume (~40 cm x 40 cm x 40 cm) and can operate in a single-pulse mode or repetitively. It is very simple to handle because of the low D.C. voltages involved. The capacitor is discharged through a spark gap into an aircore autotransformer with a 1:45 turn ratio. The transformer charges a 4 meter long, 50Ω coaxial cable which in turn is connected to a field emission diode through a self breakdown pressurized spark gap switch. The use of a transformer instead of a marx generator has proven to be an advantage for a small E- Beam generator. Operational characteristics for different transformer designs, diode configurations and varions voltage current parameters will be presented.

PROTO II MAGNETIC FLASHOVER INHIBITION EXPERIMENTS

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The limiting component in the power flow chain of high power pulsed accelerators is typically the vacuum-insulator interface. The low electric field stress at which interface flashover occurs constrains the size, design and inductance of the accelerator load. Previous theoretical and experimental studies have indicated that applied and self-generated magnetic fields can be used to delay or prevent the electrical breakdown processes. Earlier experiments showed that Magnetic Flashover Inhibition (MFI) was effective for $\vec{E} \times \vec{B}$ away from the insulator and that the onset of MFI occurs at a critical value of E/B. In these experiments, power densities of up to $100 TW/m^2$ were passed through acrylic-vacuum interfaces. Recent experiments on the Proto II accelerator attempted to further utilize MFI to pass power densities of $300 TW/m^2$ through a 3cm high, 15cm radius acrylic insulator to low inductive loads (3-10nh). Results indicate that geometric considerations and field uniformity play an intimate role in establishing MFI. The experimental data and accelerator design considerations made to utilize MFI will be discussed.

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ELECTRODE PLASMA FORMATION IN MITL'S

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Factors which may influence electrode plasma formation and expansion across magnetically insulated transmission lines (MITL) include electrode surface topography, surface contaminants, electron and photon stimulated desorption of neutrals, and turbulence in the cathode plasma. We have studied electrode plasma formation in MITL's using time resolved spectroscopy, holography, and visible photography to determine plasma parameters and how they vary with different electrode surface conditions. This determination of plasma parameters also allows us to estimate criteria for the turn on of turbulence in the plasma.

Electron and photon stimulated desorption may also play an important role in gap closure. Measurements of electron intensity incident on the anode during the establishment of magnetically insulated flow together with estimates of neutral desorption efficiency indicate that a neutral cloud may be formed near the anode due to desorption processes. Neutral desorption may also be important in cathode plasma formation.

* This work was supported by the U.S. Department of Energy under contract DE-AC04-76DP00789.

INTENSE ENERGETIC ION BEAMS FOR INJECTION INTO MAGNETIC CONFINEMENT GEOMETRIES*

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The intense energetic ion beams produced by magnetically insulated diodes are competitive with conventional methods of neutral injection used for injection into magnetic confinement geometries in both particle energy, particle density, and cost. We have demonstrated that such intense ion beams in the energy range of 50 to 150 keV can be injected and trapped in a tokamak. The potential advantages and limitations of these sources will be discussed.

* This work was supported by the Department of Energy.

THE LIMIT OF POWER FLOW ALONG A HIGH-POWER MITL*

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The minimum electrode spacing of the magnetically insulated transmission line (MITL) on the PITHON generator (peak current 4 MA with a 200 ns base to base pulse length) is experimentally observed to be limited to 8.0 mm due to current losses occuring after peak current. These current losses limit the minimum inductance, and thus the maximum possible current produced. The scaling of these losses to higher power generators may require an even larger electrode spacing and resultant inductance. To study this limitation an array of Faraday collectors has been used to measure the loss current density ($A\ cm^{-2}$) as a function of the local linear current density ($A\ cm^{-1}$) at several locations along the radially converging PITHON MITL. Results were obtained with both imploding plasma and fixed inductance loads to determine the effect of V-UV and x-ray on these losses. A comparison of the results from filtered and unfiltered Faraday collectors show that with a 4 mm electrode spacing a significant fraction of the loss current is carried by negative ions.

* This work supported by the Defense Nuclear Agency.

NUMERICAL SIMULATION OF EROSION SWITCH PERFORMANCE ON A MULTITERAWATT PULSED POWER GENERATOR

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A model for the operation of a plasma erosion switch on the PITHON generator is presented. The switch region of the PITHON vacuum feed is modeled as a lossy transmission line whose shunt conductance corresponds to space charge limited, bipolar flow across a cathode sheath transitioning smoothly to single species ion flow after the onset of magnetic insulation. Model calculations are shown to be in good agreement with results of recent erosion switch experiments on PITHON. Model predictions for the scaling of opening time and switched charge with plasma density and other switch parameters are discussed.

*This work supported by the Defense Nuclear Agency.

EXPERIMENTAL INVESTIGATIONS OF THE PLASMA EROSION SWITCH ON THE PITHON ACCELERATOR*

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Experiments on the behavior or plasma erosion switches on the PITHON accelerator have been performed at larger current levels than has been reported previously (1.0 MA). Currents as great as 1.5 MA have passed through the switch at the time of switch opening. The total charge through the switch prior to opening has been increased to 50 mC. The factors responsible for these increases are a ∿ 50 percent increase in switch area and a doubling of plasma density over previously reported values. Scaling of switch voltage, current, and power with downstream inductance suggest that the opening mechanism is dominated by magnetic cut-off of electron flow. The general agreement of the experimental switch behavior with magnetic insulation theory suggests that numerical modeling of the switch can be performed.

*Work supported by the Defense Nuclear Agency.

LARGE FERRITE CORE TESTS USING A 50 ns PULSE

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During an investigation of the pulsed properties of large ferrite cores, a pulser capable of 300 kV maximum peak voltage with 50 ns pulse width and 7 ns risetime was built. Various ferrite cores with 50 cm O.D., 20 cm I.D., and 2.5 cm thick were tested. The oscillograms of the voltage and excitation current and some typical plots of ΔB vs. ΔH are shown. The pulsed properties of a flux swing $\Delta B \geq 0.5$ T and an incremental permeability $\mu\Delta \geq 400$ with a peak self-reset equivalent to 4 Oe are obtained.

APPLICATIONS OF DENSE PLASMA PINCHES

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Dense plasmas can be created by imploding gas annuli with the current from high power generators. Of particular interest for this paper are the applications of these dense plasma sources. These applications cover a broad range of fields from atomic physics to biology. In this paper, three subjects will be examined in detail: X-ray lasers, materials evaluation, and X-ray microscopy. The characteristics of these plasmas have been studied to maximize their suitability for each application. Experimental results in each of these areas will be reviewed. Finally, future applications of pulsed power in these areas will be discussed along with the projected next generation power conditioning requirements.

ENHANCING THE RADIOGRAPHIC CAPABILITIES OF THE GREC ACCELERATOR USING PLASMA EROSION SWITCHES AND A TWO-M, 150-OHM MITL

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Recently we performed experiments to enhance the radiographic capabilities of the GREC Accelerator. Routine operation using a 2-m, 56 ohm MITL achieved dose levels of ∿250 R at a distance of 1-m from the source. By employing a higher impedance MITL (free space impedance ∿150 ohm), plasma erosion switches to eliminate prepulse and increase the rate of rise of the input current, shaped cathodes to improve pinch quality, and a thin aluminum foil over the tantalum converter, output dose levels of 550 ± 50 R were routinely obtained. Using stainless steel current shunts at the input and output of the 2-m MITL, we measured excellent current transport to the diode. Using plasma erosion switches, an average increase of 2.5 in the rate of rise of the input current was observed. Spot size measurements and the successful mechanical approach to cantelivering the small diameter 5-m inner conductor are discussed.

X-RAY EMISSION EFFICIENCY OF IMPLODING ALUMINIUM WIRE PLASMAS

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X-Rays plasmas have been created by imploding wire arrays. They were driven by SIDONIX I prime pulse generator (peak power 0.5 TW , transmission line impedance 0.75 Ω, diode inductance 25 nH). Photon pulses were observed using XRD diodes, PIN diodes, bolometer, X-Ray pinhole camera and convex curved crystal spectrograph. Emission efficiency and spectroscopic results are presented (electron temperature on the order of 0.5 keV with electron density in the 10^{20} cm^{-3} range in the hotest regions have been registered).

Attractive results were obtained by means of a 1 D MHD code. These results have induced preliminary study of the implosion behaviour when a thin glass tube is introduced on the array's axis. Pinhole photographs show intense external and internal emitting regions.

MAGNETIC TRAPPING OF INTENSE ION BEAMS*

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Intense light-ion beam sources are being developed for the inertial confinement fusion program. It is possible to trap converging ion beams from such sources by imposition of a strong local mirror magnetic field in the target region and by using a thin stripping foil to suddenly increase the ionic charge. One application of this concept would be to generate compact hot ion rings for MFE studies. Another application is in the heating of thin foils. The trapped ions can reflex through the foil several times, leading to enhanced deposition and heating. We report on one aspect of the problem: the stripping, trapping and energy deposition of a 1.5 MeV Lithium beam. We assume that the Lithium ions are initially singly ionized and that they are ballistically focused onto the target foil. Results are obtained using a 3-D particle trajectory code with magnetic fields, charge exchange and ion deposition physics.

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SIMULATION OF DENSE ION RING FORMATION*

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Two dimensional PIC simulations have been employed to study the formation of dense ion rings when full electron dynamics are included. Formation by cusp injection into a weak background plasma has been simulated previously. We compare our present results with previous ones to ascertain the role of electrons. Various resistive wall configurations are also investigated. Properties of the trapped ion rings are compared with simple model characteristics. The degree of stochasticity is estimated.

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3P14

EXPERIMENTAL RESEARCH ON ION RINGS FOR MAGNETIC FUSION

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3P15

RADIOFREQUENCY SUSTAINMENT OF CURRENT DRIVE BY RELATIVISTIC ELECTRON BEAMS

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ABSTRACT

Current drive by relativistic electrons sustained by radiofrequency is investigated. The deformation and slow down of an initial beam is numerically investigated using the one-dimensional quasi-linear kinetic equation with and without the high-phase-velocity wave-packet. It is found that for acceptable wave power, the electron beam can be maintained in steady-state with little modification from the initial distribution. The effect of unstable plasma waves destabilized by the positive slope of the beam distribution function in the low velocity side is also investigated.

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3P16

HOSE AND HOLLOWING - COMPETING HIGH PRESSURE PROPAGATION INSTABILITIES*

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Recent experiments on the VISHNU accelerator (1 MV) in high pressure air (1-620 Torr) have resulted in hose stable propagation at low current (4 kA). It was found that, at this current, the onset of unstable growth can be directly related to the beam transverse noise level upon injection. Hose growth is slower than Nordsieck expansion at 620 Torr. Severe hollowing of the beam is observed below 50 Torr in air. These competing instabilities are studied by changing the state of the beam on injection through current, emittance, and transverse perturbation amplitude variations. The evolution of the frequency spectrum of transverse motion of the magnetic axis is being monitored by a system of position monitors while beam current, profile, and transverse displacement are monitored on a multipurpose collector probe.

*Work supported by the Air Force Office of Scientific Research.

ENERGETIC PLASMA BEAM PROPAGATION IN WEAK AND STRONG MAGNETIC FIELDS*

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The conventional view of plasma beam propagation across a magnetic field is that such propagation occurs by initial beam polarization followed by E × B drifting. Such a view implicitly assumes an ambient field strength and beam single particle energy that yield a Larmor radius small compared to the beam radius. In this paper, we present an analytic and numerical study of plasma beam propagation for a somewhat wider parameter regime. For initially weak magnetic fields wave generation, anomalous electron heating and gradual plasmoid dispersal are the dominant features, while for strong fields interaction of the external field with induced currents plays an important role. Two- and three-dimensional particle-in-cell simulations of the relevant phenomena are presented. By transforming to the plasmoid frame of reference, we examine the effect of large-scale magnetic field gradients on the dynamics of propagation.

*This work was supported by the U.S. Department of Energy.

POWER-AMPLIFICATION OF A HEAVY-ION BEAM IN AN INDUCTION LINAC*

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In contrast to an rf linac - a constant-current device is which the beam power is increased solely by the addition of kinetic energy, qV, - the induction linac, made up of many independently pulsed modules, can amplify the beam power at a much more rapid rate. Proper programming of the switching of the modules and the shape of their voltage waveforms, in the early stages of acceleration, can result in a beam current that rises at a rate between $V^{1/2}$ and V and, consequently, a beam power that varies in the range $V^{3/2}$ to V^2. The current amplification ratio is limited by the transport lens system, which must always be able to overcome the beam defocussing force due to space charge.

Performance of a prototype induction accelerating unit made up of 12 independent modules, suitable for the front end of a heavy ion induction linac, is described. This unit has accelerated a $^{133}Cs^{+1}$ ion beam. Features of its ability to provide appropriate pulse shapes are demonstrated.

*This work was supported by the Assistant Secretary for Defense Programs, Office of Inertial Fusion, Laser Fusion Division, U.S. Department of Energy, under Contract No. DE-AC03-76SF00098.

OPENING SWITCHES

THE REFLEX SWITCH: AN OPENING SWITCH FOR TERAWATT-LEVEL POWER AMPLIFICATION IN VACUUM*

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Pulsed power systems based on power amplification of magnetic energy in vacuum offer dramatic advantages in compactness, power scaling and cost over present-day technology. We report the successful operation of a vacuum inductive storage system which uses the "reflex switch," a fast-opening, high-current switch, to produce pulsed compression in vacuum. In our best results to date, a compact vacuum magnetic store (1 m long, 15 cm diameter) produced a 1.8-MV, 10-ns risetime, 20-ns FWHM inductive voltage pulse after being charged to 160 kA over 50 ns, with the reflex switch "closed." Then the switch was "opened" in 10 ns, giving more than an order-of-magnitude increase of impedance at a rate of over 1.0 ohm/ns, choking the inductor current and producing the power-amplifying voltage pulse, which we used to generate an intense REB. Energy transfer from the magnetic store to the REB was highly efficient. Switch opening is controllable and is based on a transition from the reflex triode mode to the bipolar Langmuir diode mode of particle flow.

*Work supported by the United States Defense Nuclear Agency.

THE NRL PLASMA EROSION OPENING SWITCH RESEARCH PROGRAM*

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Existing technology places limits on power concentration and delivery in conventional pulsed power systems. The use of inductive storage systems with fast opening switches offers the possibility of increased energy density and higher power output. The key element in such a system is a final vacuum opening switch which must be able to conduct megampere-level currents, open in $\lesssim$ 10ns, and withstand megavolt-level voltages when open. The Plasma Erosion Opening Switch meets these requirements. Experiments using this switch in conjunction with a vacuum inductive store have been performed on the Gamble I and Gamble II generators at the Naval Research Laboratory (NRL). Pulse compression and power multiplication have been demonstrated, and some scaling experiments have been performed. Similar switches have been used previously at Sandia National Laboratory, NRL, and other laboratories for prepulse suppression and risetime sharpening.

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*Work supported by U.S. Department of Energy, Sandia National Laboratory, Defense Nuclear Agency, and Office of Naval Research.

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PLASMA EROSION SWITCHES FOR LARGE PULSED POWER GENERATORS*

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The addition of plasma erosion switches (PES) to large pulsed power generator diodes has the potential for increasing the current rise time and eliminating undesired prepulse conditions. Development of an effective PES was initiated several years ago by C. Mendell at Sandia National Laboratories. More recently, we have performed a parametric study leading to the optimization of the switches for operation at very high current levels. This is particularly important for high current machines where the number of switches required could become unwieldy. In this paper, the results of experiments will be reviewed in which switches operate at higher currents than previously reported. In addition, alternative PES concepts will be discussed.

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*This work was supported by the Defense Nuclear Agency.

MFE APPLICATIONS

RECENT RESULTS ON PLASMA HEATING BY A RELATIVISTIC ELECTRON BEAM (R E B) IN A SOLENOID

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The results on REB-plasma interaction obtained at the Institute of Nuclear Physics (Novosibirsk) are reviewed.

The experiments on the INAR device with a beam having small angular spread have shown that non-maxwellian distribution of plasma electrons is formed at energies from tens eV to tens keV.

In the GOL-1 device operating with a scattered beam a small group of plasma electrons is heated up to tens keV. The density of these electrons decreases and their energy increases with increasing the beam angular spread.

A theoretical model of beam excited turbulence is developed which describes the saturation of two-stream instability and the absorbtion of Langmuir waves by hot electrons.

First experimental data from the microsecond REB accelerator U-1 are obtained. This accelerator is a modulus of the beam source for the multimirror machine GOL-3 which is now being constructed.

INTENSE ION BEAM RESEARCH FOR MAGNETIC FUSION*

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The application of intense pulsed ion beams to magnetic fusion requires (1) the development of multikilojoule sources of 100-500 keV ions, (2) an understanding of the physics of intense ion beam propagation transverse to magnetic fields, and (3) the ability to inject and merge these beams with an existing plasma, such as a Spheromak or Field Reversed Configuration. The achievement of 1.5 kJ per pulse is the design goal of LONGSHOT II, scaled-up from the $\lesssim$ 100 kV, 800 nsec annular magnetically insulated LONGSHOT diode which produces $\lesssim$ 1/2 kJ of ions per pulse. Initial LONGSHOT II results will be reported. The transport of ion beams across magnetic fields is being addressed by two experiments, IREX and LONGSHOT. In IREX, a 30-50 kA ion beam is injected through a cusp-shaped magnetic field region filled with ~30 mTorr gas by a fast puff valve. Beam transport results will be compared with those obtained in a static gas fill and with a gun-injected $\lesssim 10^{12}/cm^3$ plasma. In LONGSHOT, improvements in ion beam transport have been effected by changes in the magnetic configuration which minimize the propagation distance in transverse fields. Studies of the merging of an ion ring with a compact toroid plasma are being initiated with the 2-1/2 D hybrid simulation code CIDER and preliminary results will be discussed.

*Research supported by DOE Contract DE-AC02-77ET53005.

BEAM TRANSPORT

RESISTIVE INSTABILITIES OF PROPAGATING ELECTRON BEAMS*

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In recent years there has been substantial progress in understanding the resistive instabilities of a self-pinched relativistic beam. We will discuss the properties of the hose and axisymmetric instabilities under a wide variety of realistic conditions, including the effects of: (1) plasma return current or parallel-flowing current (as might be provided by an external discharge), (2) self-consistent evolution of the plasma conductivity, (3) variation of beam parameters (radius, current, energy, etc.) during the pulse, (4) rapid erosion of the beam nose, and (5) Nordsieck expansion of the beam. Mathematical tools used include analytic techniques [dispersion relations that include effects (1-2)], particle simulations (treating axisymmetric dynamics exactly and hose perturbations linearly), and various macroscopic simulation models. The results will be compared with available experimental data.

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* Supported by DARPA.

** JAYCOR, Alexandria, VA 22304

OPENING SWITCHES, MFE
AND BEAM TRANSPORT

GRAD-B DRIFT TRANSPORT OF HIGH CURRENT ELECTRON BEAMS*

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Grad-B transport, bunching and focusing of relativistic electron beams has been proposed as a method of increasing the power delivered to an ICF target by an order of magnitude. Recent experiments have demonstrated the efficient transport of high current electron beams over 1.0 m distances in the 1/r azimuthal magnetic field of a current-carrying wire. The electron drift velocity was measured as a function of wire current and found to be in good agreement with theory. Measurements of x-ray production in a tantalum target were used as a diagnostic tool to study transport efficiency. A theoretical model of the experiment was developed to calculate bremsstrahlung production in the target, assuming 100 percent transport efficiency. This model predicted radial x-ray dose profiles in the experimental converter assembly which were in good agreement with the measurements.

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IBEX - ANNULAR BEAM PROPAGATION EXPERIMENTS*

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IBEX is a 4 MV, 100 kA, 20 ns cylindrical isolated Blumlein accelerator recently conceived and constructed by Sandia National Laboratories. The mechanism of pulse generation is inductive and completely eliminates any voltage prepulse. Reproducibility of the machine parameters is excellent and it can operate at 4 MV with up to 12 shots per day. In the experiments reported here, the accelerator is fitted with a specially designed foilless diode which is completely immersed in a uniform magnetic field. Several diode geometries have been studied as a function of magnetic field strength. The beam propagates a distance of about 50 cm ($\sim$ 4 cyclotron wavelengths) before striking a witness target. Rogowski current monitors, diamagnetic loops and position monitors are placed along the beam path in order to follow the beam current, temperature, and possible envelope oscillations in a nondestructive manner. The objectives of this experiment are to establish the proper parameters for the most quiescent 4 MV, 30 kA annular beam, and to compare the results with available numerical code simulations.

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*This work was supported by the U.S. Department of Energy under Contract No. DE-AC04-76-DP00789 and the U.S. Air Force Project Order AFWL-PO-82-113.

DAMPING BEAM DISPLACEMENTS THROUGH
PHASE MIXING - AN ILLUSTRATIVE MODEL*

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We develcpe a simple model of a beam transported in a hard wall channel (an idealized very high order magnetic multipole channel). The extremely anharmonic nature of the potential leads to damping of coherent transverse displacements of the beam via phase mixing. For the case of small uniform displacements of the beam we can write down by inspection the analytical form of the motion of the beam centroid. The same technique allows us to evaluate the effects of focussing and scattering elements in the transport channel upon the damping of the transverse motion of the beam.

* Performed jointly under the auspices of the U. S. DOE by LLNL under W-7405-ENG-48 and for the DoD under DARPA, ARPA Order No. 4395, monitored by NSWC.

Prepared for submittal to the Fifth International Topical Conference on High-Power Electron and Ion-Beam Research and Technology, September 12-14, 1983, San Francisco, California.

SPACE AND TIME-DEPENDENT RETURN CURRENT IN SECONDARY PLASMA CREATED IN ATMOSPHERE BY A SHORT PULSE ULTRARELATIVISTIC HIGH POWER ELECTRON BEAM*

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Possibilities provided to energy propagation in atmosphere by short pulse high power electron beams, in the ns range, are presently being actively explored. Among the physical variables which condition dynamical beam equilibrium as well as stability, a prime place is held by secondary plasma current neutralization factor $f_m = \|\vec{J}plasma\| / \|\vec{J}beam\|$. Theoretical models have until now included this quantity in the form of a given space and time constant, considered as some kind of average.

Actually, as it has recently been pointed out, the radial dependence of f_m plays a decisive role in beam equilibrium. As for axial dependence it seems clear that for short pulses ($\tau \not\gg \tau_d$ magnetic dipole decay time) the assumption of axial constancy has no physical grounding.

To gain information on $\vec{J}plasma(r,z,t)$, we have used the PEGASE code working in nitrogen at variable pressure, with a 1 to 10 ns ultrarelativistic, 0.5 GeV, 10 kA, electron beam.

PEGASE is an axisymmetric 2 D multifluide code (e, N_2^+, N^+, N,..) based on macroscopic equations of continuity - including a detailed nitrogen chemistry -, motion and energy, coupled with the full set of Maxwell equations.

Results concerning $\vec{J}plasma(r,z,t)$, which show a strong space and time dependence - both in intensity and in angle - are presented in the form of 2 and 3 D maps, and discussed.

*This work was supported by the DRET. France

DETAILED THEORETICAL CALCULATION OF THE TIME DEPENDENT VISIBLE FLUORESCENCE SPECTRUM EXCITED IN NITROGEN BY A HIGH POWER ELECTRON BEAM. EXPERIMENTAL CHECK AT 1.7 MeV

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Visible fluorescence spectrum excited in air or nitrogen, at various pressures, by a relativistic high power electron beam, has been the subject of various experimental studies. As for theoretical interpretation, it has been generally limited to steady state conditions and to a rather crude description of the pumping terms by phenomenological fluorescence efficiencies.

The present approach aims at a more sytematic description.

Firstly, excitation of electronic and vibrational levels of N_2 and N_2^+ was deduced from the inelastic differential cross sections, themselves computed within the framework of the relativistic BETHE theory.

Then, restricting the study, for the present, to the visible part of the fluorescence spectrum, we followed the time dependent population of the 4 N_2 triplet states, and of the 4 N_2^+ doublet states, by resolution of the corresponding 0 D continuity equations.

From the densities $n_{N_2^*j}(t)$, $n_{N_2^{+*}k}(t)$, the 1 P, 2 P, 1 N line intensities were deduced, as function of time.

They were compared to experimental results, concerning both time-resolved and time integrated spectra, obtained with a prism spectograph and photomultipliers on the EUPHROSYNE facility, at the CEA-DAM Valduc Research Center, with a 1.7 MeV, 40 kA, 2.5 cm diameter, 75 ns, electron beam, propagating in nitrogen at a variable pressure.

PARTIAL EXPERIMENTAL CHECKING OF THEORETICAL PREDICTIONS ON TIME DEPENDENT ELECTRICAL CONDUCTIVITY OF THE SECONDARY PLASMA CREATED IN ATMOSPHERE BY A HIGH POWER ELECTRON BEAM

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The key role played by secondary plasma electrical conductivity in stability of a high power electron beam propagating in gaseous atmosphere, is well known. For a long time, in theoretical models, this parameter has been considered as a given space and time constant or, at best, as a time constant possessing a radial dependence :$\sigma(r)$. Recent calculations have shown the very important stabilizing effect of the rapid time variation of σ, as the secondary plasma is progressively created, cooled or heated. The theoretical and numerical model PEGASE gives access to $\sigma(r,z,t)$. It is a 2 D, axisymetric, multifluid (e, N_2^+, N^+, N, N^*,..)model based on macroscopic equations of continuity - including a detailed air chemistry -, motion and energy, closed by the full set of Maxwell equations.

A partial experimental check has been performed at the C.E.A.-D.A.M. Valduc Research Center, on the EUPHROSYNE facility, with a 1.7 MeV, 40 kA, 2.5 cm diameter, 75 ns electron beam, propagating in nitrogen at a variable pressure. The measured net current has been compared to predictions of a circuit model including the time dependent electrical resistance of the secondary plasma column. The agreement is highly satisfactory.

THOMSON SCATTERING MEASUREMENTS OF ELECTRON TEMPERATURE AND DENSITY IN A PLASMA CHANNEL CREATED BY A RELATIVISTIC ELECTRON BEAM*

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The electron density (n_e) and temperature (T_e) of the plasma channel created by the propagation of a relativistic electron beam in air have been measured by a ruby laser Thomson scattering diagnostic. The measurements were made at the MIMI electron beam accelerator (1.6 MV, 20 kA, 70 ns) at various times during the plasma channel development, with 25 ns temporal resolution and 2 mm radial resolution. For example, in 5 Torr air, at the time of maximum electron beam current, the results are $n_e = 1.56 \times 10^{15}$ cm^{-3} (±13%), $T_e = 3.87$ eV (±18%). These results, as well as those with other timing, are in good agreement with the theoretical results of the Air Propagation Code: $n_e = 1.65 \times 10^{15}$ cm^{-3}, $T_e = 2.59$ eV. Signal-to-noise is very good (10:1), limited by x-ray fluorescence of the fiber optics at the spectrometer. In fielding the diagnostic on higher energy accelerators, however, the dominant noise is expected to be the background light from the plasma and hot gas, or the fluorescence of the collecting optics. Improvements to the diagnostic to address these issues, as well as additional results from a planned experiment in 80 Torr of air, at 4 MV, 50 kA will be presented.

*This work was supported by Defense Advanced Research Projects Agency, Air Force Weapons Laboratory, and Department of Energy.

HIGH PRESSURE ELECTRON BEAM TRANSPORT EXPERIMENTS*

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We have conducted a comprehensive set of experiments on intense electron beam transport in the VISHNU accelerator. The 1.1 MeV, 3.5 kA beam has been characterized after propagation in a narrow (4.5 cm ID) drift tube. Measurements include beam profile, transverse noise, plasma decay time, resistive hose instability growth, nose erosion, velocity, radiation length and radial particle emission in the 1-620 Torr pressure regime. The most important phenomenon in this regime is the resistive hose instability. Due to the low measured beam front velocity (~.6 c) the instability is found to grow in the beam front frame early in the pulse. Later in the pulse, the hose frequency is observed to be comparable to the predictions of the spread mass model. At high pressures, the beam propagates stably for 2 Nordsieck lengths. Correlations between instability measurements and plasma decay time measurements will be examined.

*Work supported by the Air Force Office of Scientific Research.

4P8

STABILITY OF RELATIVISTIC ELECTRON BEAMS IN DENSITY CHANNELS I*

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NRL has recently performed a set of experiments on propagation of intense relativistic electron beams in laser-produced density channels in NH_3 gas at 40 torr. We have conducted a theoretical and computational analysis of beam stability in such density channels, with emphasis on the effect of varying the form of the channel radial density profile. The influence of the density profile on the beam is primarily through the dependence of the avalanche breakdown rate on radial location; this dependence is very strong if the peak electric field is in the range $E/P \sim 10^2$ kV/cm-atm. If the channel density has an on-axis minimum (solid channel), avalanche ionization enhances the return current flow inside the beam and strongly enhances both the resistive hose instability and the axisymmetric hollowing instability. However, if the channel is hollow (minimum density in an annulus off-axis), avalanche localizes much of the return current outside the beam, thus improving stability and guiding the beam. Model calculations for both types of channels will be compared with the experimental results.

* Supported by DARPA.
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RELATIVISTIC ELECTRON BEAM EQUILIBRIUM IN THE PRESENCE OF A GAS CHANNEL OR AN EXTERNAL FIELD*

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A pre-formed density channel or weak conductivity channel can modify the equilibrium of a propagating beam in a non-trivial way, since electrostatic image forces dominate the beam-channel interaction at the beam head, while magnetic image forces dominate further back. Similarly, the effect of a transverse external electric or magnetic field on the beam orbit is not readily apparent when the relativistic factor γ varies from the head to the tail of the beam. To study questions such as these, we have developed a code called DYNASTY that solves the field equations fully implicitly, in three dimensions without linearizing about cylindrical symmetry. The code uses fast Fourier transform in the azimuthal dimensional and finite differences with nonuniform mesh in the radial direction. In the presence of a channel we have found two distinct types of equilibria, with the beam either on-axis or displaced from the axis by a prescribed amount. A variety of other results will be discussed as well.

*Supported by DARPA

THEORY OF BEAM CHANNEL HYDRODYNAMICS*

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We report on recent theoretical studies of hot beam-produced channels. The results are compared with NRL experiments involving channels produced by electric discharges and/or laser pulses in air or nitrogen. Schlieren photographs clearly show fully developed turbulence and rapid channel expansion due to the entrainment of cooler ambient air, leading to an effective thermal diffusivity for early time channel cooling that is three to four orders of magnetude faster than for classical thermal conduction. We explain these phenomena on the basis of vorticity generation due to asymmetries between pressure and density gradients as the hot channel expands to pressure equilibrium. This will occur whenever a beam pulse deviates from cylindrical symmetry. We derive a theory describing the residual vortex strength and mixing time scale for the fundamental classes of asymmetry and compare the results to experimental data and to two and three dimensional fluid simulations. We find nonuniformities in the interior of a beam pulse to be the strongest source of channel turbulence.

* Supported by ONR and DARPA.
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AXISYMMETRIC INSTABILITIES OF
PROPAGATING RELATIVISTIC ELECTRON BEAMS*

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We have used a particle simulation code SIMMO to study the axisymmetric resistive macro-instabilities of an intense pinched electron beam propagating in a plasma of high density but low initial coductivity. The (m = 0, n = 1) sausage mode is found to be stable as predicted by theory, but the (m = 0, n = 2) hollowing mode is violently unstable under certain conditions, namely when there is strong avalanche ionization near the beam head and the avalanche coefficient (as a function of r) is strongly peaked on axis. The instability grows quickly into the nonlinear regime and disrupts the beam. We present results of a wide-ranging simulation study which elucidates the instability mechanism and specifies the unstable parameter range in uniform density gas.

* Supported by DARPA.
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ELECTRON BEAM GENERATED CONDUCTIVITY IN N_2 AND AIR*

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A plasma channel, with a low degree of ionization, can be generated by an electron beam propagating in a gaseous medium. The time evolution of the channel conductivity plays a key role in beam propagation, and also in regard to applications of such channels, to switching for example. The conductivity, in turn, depends on a large number of atomic and molecular processes which in general comprise the channel chemistry.

These basic processes affecting the conductivity will be discussed in detail. In addition, chemistry models and computer results will be presented for the conductivity generated in N_2 and air by intense high energy electron beams.

*Supported by DARPA

STABILITY OF RELATIVISTIC ELECTRON BEAMS IN DENSITY CHANNELS - II*

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In a series of experiments we have observed the interaction of an intense relativistic electron beam with reduced density channels. The time history of the REB pulse approximated a half-sine wave with amplitude ~9kA and half-period ~ 40ns. The energy of the REB was ~1MeV and the radius at injection into the channel was 1cm. Interaction experiments took place in a large chamber filled with ammonia gas to a pressure of 40 Torr. Channels were formed in the ammonia by absorption of the high energy beam (≤ 400J) from a pulsed CO_2 laser. To create solid channels (on axis density minimum) the laser beam was passed through a simple aperture with radius 1cm. To create annular channels (density minimum in an annulus off-axis) the laser beam was passed through an annular aperture with inner radius 1cm and outer radius 2cm. In both cases the minimum density in the channel was approximately half the chamber filling density. The REB was injected into these channels coaxially, concentrically but at an angle to the channel axis, and off-axis. In all cases the presence of the channel caused dramatic changes to the propagation of the REB compared to that in the absence of the channel.

* Supported by DARPA

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RELATIVISTIC FLUID MODEL TREATMENT OF CHARGED PARTICLE BEAMS

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A relativistic fluid model is developed to study the dynamic evolution and stability of the relativistic electron beam. Starting with the relativistic Vlasov equation, a consistent, closed set of moment equations are generated employing the paraxial assumption and an ordering scheme based on velocity correlation functions. The resulting fluid model is applied to the problem of beam evolution and stability in a beam-generated plasma.

CONSEQUENCES OF NON-OHMIC CURRENTS AND NON-LOCAL ENERGY DEPOSITION FOR ELECTRON BEAM PROPAGATION IN REDUCED-DENSITY AIR

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The velocity distribution of electrons produced near the head of an electron beam propagating in low density air is far from Maxwellian. The complexity of calculations based on the Boltzman equation precludes the routine usage of this approach in conjunction with equally complex beam propagation calculations. A simplified model has been developed to account for non-ohmic, non-local effects. We present some results obtained by incorporating this model into a comprehensive air chemistry code and some propagation codes.

ELECTRON BEAM GENERATED PLASMA CHANNEL AT LOW PRESSURES

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The evolution of an electron beam generated plasma channel is sensitive to the pressure of the background gas. An adequate understanding of low density conductivity generation is important to the propagation of intense relativistic electron beams through gases. A multi-group treatment of the electron distribution function is used to model electron dynamics at low pressures, P $\lesssim$ 100 Torr. Important inertia, non-ohmic, and non-local effects are calculated self-consistently from Maxwell's equations and the plasma currents. Comparisons will be made to existing theoretical models and experiments.

TIME RESOLVED BEAM PROFILE MEASUREMENTS ON THE EXPERIMENTAL TEST ACCELERATOR (ETA)*

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Examples are given of time resolved beam profiles measured on ETA using several techniques. One method uses a Faraday cup that is remotely moveable in two-transverse dimensions (x,y). The beam electrons passing through a small-diameter hole are collected on the center conductor of an electrically open 50 ohm coaxial transmission line. The collector is in vacuum and gas is excluded by a thin foil. In another method a small diameter wire or pellet target is moved across the beam and the bremstrahlung x ray intensity is plotted. The data for these methods is recorded using a Tektronix 7912 digitizer at 16 equally spaced times during 50 ns. These methods require moving nearly identical beam pulses. Three other methods use a time gated (4 ns) microchannel plate television camera to record a two-dimensional image of the beam intensity on a single pulse. The light sources used for imaging are: Cerenkov light from a Kapton foil, prompt visible light from a titanium foil and radiated light from gas molecules excited by the beam. The time histories of these optical emissions are measured using microchannel plate detectors having time resolution < 1 ns. We are also testing an x ray pin-hole camera using K_α x rays from tungsten.

*Performed jointly under the auspices of the U.S. DOE by LLNL under W-7405-ENG-48 and for the DOD under DARPA, ARPA Order No. 4395, monitored by NSWC.

ELECTRON BEAM PROPAGATION IN THE ION FOCUSED REGIME (IFR) WITH THE EXPERIMENTAL TEST ACCELERATOR (ETA).*

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The IFR is a well known stable, low pressure (.010 to .120 Torr in air) propagation window. Secondary electrons created by collisions of beam electrons with gas atoms are rapidly expelled by the strong radial electric field due to the beam charge. The ions that remain inside the beam partially neutralize the electric field, allowing magnetic pinch forces to focus the beam. Experiments with the ETA beam have re-verified this stable window and will be reported. Image forces from a close wall IFR propagation tank are also both computationally and experimentally shown to center the beam and damp transverse oscillations. Results of experiments using 5 and 15 cm diameter beam tubes will be reported. For $p\tau > 2$ Torr-ns (gas pressure x time into pulse), the beam charge becomes completely neutralized by the ions, allowing a build up of plasma and resultant beam-plasma instabilities. The onset of these instabilities has been measured using rf pickup loops (0-2 GHz) and microwave detectors (6-40 GHz), and will also be reported.

*Performed jointly under the auspices of the U.S. DOE by LLNL under W-7405-ENG-48 and for the DOD under DARPA, ARPA order No. 4395, monitored by NSWC.

OBSERVED CURRENT ENHANCEMENT WITH PROPAGATION OF THE EXPERIMENTAL TEST ACCELERATOR (ETA) ELECTRON BEAM IN AIR*

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It is observed with the ETA electron beam propagating in air that the net current is greater than the beam current for pressures between 50 and 100 Torr. Microwave measurements indicate that this current enhancement is distinctly different than that associated with the two-stream instability at low pressure. Detailed measurements of its dependence on pressure, current, beam size, and propagation distance are given. Measurements of radial profile of the net current, and energy content of the forward current are also presented. A theory is proposed that energetic secondary electrons are pushed forward by the beam self-magnetic field. Detailed comparison of measurements with the results of a BOLTZMANN code are made.

*Performed jointly under the auspices of the U.S. DOE by LLNL under W-7405-ENG-48 and for the DOD under DARPA, ARPA order No. 4395, monitored by NSWC.

NUMERICAL COMPARISON OF HYDRODYNAMIC BEAM MODELS WITH KINETIC TREATMENTS*

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Hydrodynamic models have been derived by Mark and Yu and by others to describe energetic self-pinched beams, such as those used in ion-beam fusion. The closure of these models is obtained with adiabatic assumptions mathematically analogous to those of Chew, Goldberger, and Low for MHD. The hydrodynamic beam models are compared with particle simulations by investigating axisymmetric beam dynamics including phase-mix damping and the resistive sausage instability. Also, a linearized dispersion relation for the resistive hose instability is obtained from the fluid equations and compared with the results of a Vlasov hose model.

*Performed jointly under the auspices of the U. S. DOE by LLNL under W-7405-ENG-48 and for the DOD under DARPA, ARPA Order No. 4395, monitored by NSWC.

SIMULATION OF ELECTRON BEAM TRANSPORT IN PIPES*

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Electron beams can be transported in pipes using vacuum transport or gas focusing. Vacuum transport uses guide magnetic fields or an on axis wire. Gas focusing occurs in the sub torr pressure range where a beam generated ion channel focuses the beam. These mechanisms are used to transport beams to experiments while centering the beam in the pipe and damping transverse motions.

To study these transport mechanisms we have developed the CENTRING particle simulation code. The beam is represented as particles; particle effects such as scrapeoff, foil scattering, and phase mix damping are thus properly described. Fields are represented with parameterized descriptions appropriate for each force mechanism. The CENTRING code typically takes 10-20 seconds of CRAY computer time for a full propagation run.

We will present the models employed in the CENTRING code for particle dynamics and force calculation. Detailed comparisons with transport results for the Experimental Test Accelerator (ETA) will be discussed.

*Performed jointly under the auspices of the U. S. DOE by LLNL under W-7405-ENG-48 and for the DOD under DARPA, ARPA Order No. 4395, monitored by NSWC.

Theory of time-dependent injection of an electron beam into a finite drift space

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The time dependent treatment of monoenergetic electron-beam injection into a 1D half space by Poukey and Rostoker /1/ and the further investigation of their model by Hantzsche /2/ served as a useful tool in estimating important injection characteristics such as penetration depth and minimum potential. It is shown here that injection into a finite 1D-drift space is also tractable analytically - at least in the non-relativistic case, where a linear partial integrodifferential equation is solved in terms of a power series. The simple theory is restricted in time by the smaller of the mixing time (divergence of density) and the time of flight through the drift space (particle loss at end plate). The quantities of interest are calculated for various drift-space lengths and time dependences of the injected current.

/1/ Poukey J.W., Rosto-ker N.: Plasma Phys. 13 (1971) 897
/2/ Hantzsche E.: Beitr.Plasmaphys. 15 (1975) 157, 17 (1977) 253

SCATTERING LOSSES OF A CHARGED PARTICLE BEAN FROM A PREFORMED CHANNEL*

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In charged particle beam-pellet fusion an intense charged particle beam passes through a gaseous atmosphere on its way to the target creating a hot ionized channel along its path. The interaction of the beam with such a channel determines the efficiency with which energy is delivered to the target and such phenomena as beam expansion, scattering losses and stability play an important role in this regard. In this paper we examine the scattering losses of a charged particle beam as it traverses a preformed fully on partially ionized channel.

A Monte Carlo code that allows for Coulomb and neutral scattering is utilized to determine the losses from an intense electron beam moving in a cylindrical channel. Neglecting relativistic effects and self fields it is shown that a one-cm radius, 90 keV beam propagating in a hydrogen channel of the same radius traverses a 1/2 meter channel whose density and temperature are $10^{14}cm^{-3}$ and 1/2 eV effectively without losses. Complete losses take place when the same beam propagates in the same channel but at 20% ionization. The axial and angular distribution of scattered beam particles as well as the threshold for the generation of delta rays will be presented and discussed.

*Work supported by U.S. AFOSR

CONVENTIONAL ACCELERATORS

BEAM DYNAMICS IN THE ADVANCED TEST ACCELERATOR (ATA)*

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T. J. Fessenden, R. E. Hester, E. J. Lauer,
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We will review the performance of the Advanced Test Accelerator, a 50 MeV, 10 kA induction linac. The discussion will cover the operation of the plasma cathode electron source, beam transport throughout the accelerator, and transverse instabilities. Particular emphasis will be placed on the beam breakup instability and on methods used to minimize it. These include a program of design changes that lead to an order of magnitude reduction in the Q of the accelerator cavity modes and optimization of the transport tune.

*Performed jointly under the auspices of the U. S. DOE by LLNL under W-7405-ENG-48 and for the DOD under DARPA, ARPA Order No. 4395, monitored by NSWC.

"CONVENTIONAL" AND "MODIFIED" BETATRONS

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In early conventional betatrons the beam current, though small, did assist capture of a high emittance injected beam because of the self-flux, the space charge, space charge loss, and particularly wall IR drop. Self-generated radio frequency fields observed within accelerating chambers also influence trapping and stability. All of these influences should be much stronger in high current and in modified betatrons having a toroidal magnetic field. In both conventional or modified high current betatrons primary winding beam load, wall images of beam current and of charge must be arranged to provide properly shaped self-fields.

A new feature produced by the toroidal field modification is the F (focus-self forces) X B (toroidal)/B^2 drift, or bounce, which coherently takes the whole beam out of or around the vessel. This influences the injection strategy to be used. This drift has been predicted as dangerous at currents well below the currents which the toroidal field can hold together. The addition of strong focusing with a stellarator-like focusing field provides further possibilities for stably holding high currents by raising the focus force term.

HIGH CURRENT BETATRON EXPERIMENTS AND THEORY*

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A conventional Betatron has been modified by introducing a toroidal magnetic field to control space charge. Electrons are injected continuously from a thermionic emitter while both toroidal and Betatron fields are rising. Electrons have been contained and accelerated for about 3000 turns to about 600 keV. The beam current is 150 A. The usual theory of Betatrons based on the paraxial approximation is not applicable. A new theory based on adiabatic particle dynamics has been developed which is consistent with the experimental results to date. In a second Betatron experiment the current is increased by elongation with no toroidal magnetic field. It is a small Astron with Larmor radius 6 cm and mirror spacing 80 cm. Rapid data acquisition is facilitated by a 1 Hz repetition rate. The purpose of the experiment is basic studies of injection, trapping and extraction. The injection is nearly tangential compared to inductive charging and it is expected that this will result in a lower emittance beam. Multi-turn injection has been demonstrated with electrostatic and magnetic inflectors. The trapped charge limit is about 10 nC which is contained for about 10 μ s. Comparisons will be made with theoretical expectations.

* This work was supported by Office of Naval Research and Department of Energy.

PROGRESS IN THE DEVELOPMENT OF THE MODIFIED BETATRON

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This paper will report on the progress recently achieved in the development of the NRL modified betatron. Particular emphasis will be given to the scaling laws that govern the modified betatron concept. These scaling laws cover all major areas of the high current accelerator including injection, equilibrium, stability and field errors. It has been found that the accessible parameter space, determined from the scaling laws, is sensitive to the energy, current and emittance of the injected beam.

In addition, we will report on the design of a proof of principle modified betatron accelerator. This multikiloampere, compact device has been designed to accelerate the electron beam up to 50 MeV in approximately 3 msec.

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THE STELLATRON ACCELERATOR*

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A stellatron is a high current accelerator concept which combines the magnetic field configuration of a stellarator and a betatron. Such a configuration can be designed by adding a $\ell=2$ stellarator winding to a betatron accelerator. The stellarator field provides a twisted quadrupole configuration which is analagous to an alternate-gradient, strong-focusing system. This configuration can easily tolerate a mismatch between the average particle energy and the vertical magnetic field of 50% at injection, with multi-kiloamp electron beams. The allowed energy mismatch of a conventional or modified-betatron is typically 2 to 3%. There is a family of potentially-interesting high current accelerators which consist of a betatron augmented by stellarator fields of various ℓ-number. We will present a comparison of energy bandwidth for various ℓ-number stellatron configurations.

* This work was supported by the Naval Research Laboratory

COLLECTIVE ACCELERATION

ELECTRON BEAM WAVE ACCELERATORS*

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An account will be presented describing the present status of electron beam supported wave accelerator research. We shall review the various approaches to collective acceleration using waves on an electron beam, and then focus attention on ion acceleration in space charge waves.

We shall describe the results of experiments on non-linear wave propagation in inhomogeneous guides, and an attempt will be made, using these results, to define the possible limits of applicability of the converging guide to ion acceleration. Results will also be presented reviewing work on the use of beat waves on electron beams for collective acceleration. In both cases we shall summarize the status of theoretical studies of these acceleration techniques and will indicate directions for future research.

*Research supported by DOE Contract DE-AC02-80-ER10569 and, in [illegible], by AFOSR Contract AFOSR-80-0087C.

COLLECTIVE ACCELERATOR INJECTOR FOR HEAVY ION ACCELERATOR

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ACCELERATORS

STRONG-FOCUSING HOLLOW BEAM TRANSPORT

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A coaxial transport structure for hollow beams, proposed at the last conference in this series as a means of producing intense particle beams, has been built at GSI, Darmstadt. Beams of heavy ions are produced from the GSI high-current ion source CORDIS which are then expanded into a 12cm diameter hollow beam. At the end of a coaxial beam transport line the space-charge limited current and beam emittance behaviour are measured for various focusing conditions.

A unique feature of the hollow beam structures reported here is that they provide strong, alternating-gradient focusing over a large annular aperture thus enabling larger currents to be transported when space charge is the limiting factor. For this reason the structures have been studied as injector accelerators for high-energy machines in both heavy ion fusion and a future intense neutron source.

The results from the static hollow beam transport experiment described here form the basis for a design study of a new linear accelerator. This rf coaxial accelerator is a continuous focusing accelerating structure which can capture and bunch a dc beam, thus serving as a high-power injector for hollow beams.

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*In collaboration with the Gesellschaft für Schwerionenforschung (GSI), Darmstadt, Fed. Rep. Germany.

NEW METHODS FOR RF ACCELERATION OF INTENSE ELECTRON BEAMS

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Most work in the field of intense electron beam acceleration has concentrated on induction accelerators. Radio-frequency (RF) accelerators do not require ferro-magnetic isolation cores or high power switches; thus, they may have significant advantages in terms of voltage gradients, reliability, net pulse length and duty cycle. We will describe two accelerator concepts that may allow the generation of high energy electron beams for long macropulses (10 μs) at currents in the range from 1 to >10 kA.

The first involves the excitation of RF cavities by direct injection of driving beams, modulated in either density or position. We will discuss cavity dynamics, methods of modulating the driving beam, and defocusing effects of RF fields on the driving beam. The second concept is based on RF cavities filled with purified water (except for the beam transport region on axis). We will demonstrate that accelerators can be configured so that the properties of RF cavities present no limitation on beam current. We will discuss resistive and dielectric losses in water, methods to maintain cavity tune, available voltage gradients, optimization of insulators, and beam loading. We will present a conceptual design for a 10 kA, 500 MeV RF accelerator.

SIMULATION STUDIES ON A NOVEL BETATRON INJECTION SCHEME*

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Simulations of a newly proposed scheme [F. Mako, W. M. Manheimer, D. Chernin, J. Golden, and C. A. Kapetanakos, to be published] for relativistic electron beam injection into crossed Betatron fields will be presented. Our results will be directly applicable to the modified Betatron experiment currently underway at NRL. A current channel created by the electrical breakdown of a gas is used to focus a 10 kA electron beam across transverse fields $B_x = 0.7$ kG and $B_z = 2$ kG. By tapering B_x and the B_θ self-field of the current channel, it may be possible to transport a low-emittance beam effectively into a modified Betatron. Of particular interest to us is the possibility that in the absence of the B_x field, bunching of the electron beam may provide a mechanism for an extremely phase-coherent microwave generation scheme. Tunability of this microwave source may have distinct advantages over other conventional sources.

*This work was supported by the U.S. Department of Energy.

RING ACCELERATORS*

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We present two-dimensional simulations in (r-z) and (r -θ) cylindrical geometries of imploding-liner-driven accelerators of rings of charged particles. We address issues of azimuthal an longitudinal stability of the rings. We discuss self-trapping designs, and designs in which beam injection and extraction is aided by means of external cusp fields. Our simulations are done with the 2½D particle-in-cell plasma simulation code CLINER, which combines collisionless, electromagnetic PIC capabilities with a quasi MHD finite element package

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* This work was supported by the U.S. Department of Energy.

LINEAR AND NONLINEAR DEVELOPMENT OF THE NEGATIVE INSTABILITY IN A MODIFIED TOROIDAL BETATRON ACCELERATOR*

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The modified betatron is a toroidal device designed to inductively accelerate a high-current electron pulse confined by both toroidal and vertical magnetic fields. Linear dispersion relations show that this device may be susceptible to a "negative mass" instability that leads to bunching and kinking of the beam. A comparison will be made between analytic growth estimates and numerical results from the 3-D particle-in-cell electromagnetic code, IVORY. Nonlinear growth of the instability over many toroidal periods and effects of beam temperature on saturation amplitude will be explored. Analysis of the effects of gaps or ports in the accelerator wall on linear instability growth will also be presented.

*Work supported by the Office of Naval Research.

ANALYSIS OF A MODIFIED BETATRON WITH ADIABATIC PARTICLE DYNAMICS*

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The usual analysis of the Betatron and other accelerators is based on the paraxial approximation in which the velocity in the toroidal direction is assumed to be large compared to velocities in orthogonal directions. The particle orbits are not assumed to be adiabatic; in fact they are far from adiabatic in a conventional Betatron. Consequently the Fermi drift in a modified Betatron treated with the paraxial approximation is a small non-linear correction to the equations of motion that can usually be neglected. For low energy injection as in the method of inductive charging, the paraxial approximation is not valid. For this case we have developed a new description based on adiabatic particle dynamics which can be justified for a modified Betatron. The particle dynamics is more like a tokamak than a conventional accelerator. A particle to first approximation follows the field lines. The combination of toroidal and Betatron fields would lead a particle to the wall if it were not for the Fermi drift which cancels the motion towards the wall. Orbits in which a particle does not go around the torus must be considered which are absent in the paraxial theory. Appropriate averages over particle orbits must be defined to describe a beam. The theoretical description based on adiabatic particle dynamics will be compared with recent experimental results of the UCI tokamak. The particular features of interest are that equilibrium is maintained without satisfying the Betatron condition $\bar{B}=2B_o$ and that the beam drifts into the wall after accelerating over 10^3-10^4 turns around the torus. * Supported by ONR.

A STRETCHED BETATRON*

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and

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A Betatron of novel geometry is under development at UCI. Electrons are injected into an elongated magnetic mirror. The Larmor radius is 6 cm. The distance between mirrors is 80 cm. We seek to show that the total charge capacity of such a mirror trap is simply proportional to its length. The electron trajectories are helical with an axial period of 40 ns and an azimuthal period of 3. ns. The 40 ns axial period simplifies the use of both electrostatic and magnetic inflectors. A field emission injector (50 kV, 1 amp, 150 ns) allowed us to trap about 10 nC and contain it for about 10 μsec. A 15-fold increase in the injected current led to radial loss of electrons in about 100 nS with no significant increase in the amount of charge trapped. Diagnostic methods are varied. A directional X-ray detector permits localization of beam spill. Electrostatic antennas detect radiation associated with collective motion of the electrons. A gate coil allows controlled opening of the magnetic trap. As the electrons are gated out they are collected to yield a direct measurement of trapped charge. Present work seeks to establish the mechanism of electron loss and to study the effect of asymmetries in fields and conducting boundaries.

* This work is supported by the United States Department of Energy.

** On leave from Weizmann Institute, Rehovot, Israel.

BEHAVIOR OF ELECTRON BEAM IN A HIGH CURRENT BETATRON*

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The UCI High Current Betatron has a uniform toroidal magnetic field in addition to the betatron field. Electrons are injected continuously from a thermionic emitter while both the toroidal and the betatron fields are rising. Electron capture takes place when more than 3 A is emitted from the injector either tangentially or non-directionally. Acceleration continues under a condition that the ratio between the average betatron field inside the orbit and the betatron field at the orbit is in the range of 1.2 - 3. At the initial phase of acceleration, the beam current increases rapidly with time. Then the beam suffers a gradual loss. Finally the whole beam disrupts and generates a burst of X-rays. If the injection is stopped in the middle of the course of the acceleration, the disruption of the beam happens at that moment.

Influence of the space charge on the beam behavior is evident. The life of the beam becomes shorter as the injection current is reduced down to the threshold. The final electron momentum p inferred from X-ray measurement is related to the betatron field B and the major radius R by $p \approx 0.5$ eBR, instead of p = eBR. The beam current and electron energy increase with the increase of the injection voltage. Beam current of 150 A and electron energy of 500 keV are obtained at an injection voltage of 30 kV.

* This work was supported by the Office of Naval Research.

BEAM CURRENT LIMITATION DUE TO INSTABILITIES IN THE MODIFIED AND CONVENTIONAL BETATRON

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A dispersion relationship for both the longitudinal and transverse modes in a modified betatron field configuration has been derived. The modified betatron field configuration consists of a strong toroidal field superimposed on a conventional betatron focusing field. Included in the derivation are: beam self field effects, induced field effects arising from image wall charges and currents as well as finite chamber wall conductivity effects. Toroidal effects associated with the beam self fields and chamber wall image fields have been neglected. The longitudinal and tranverse impedances, which characterize the beam environment, are incorporated in a phenomenological way in the short wavelength limit. The dispersion relation, therefore, treats both long and short wavelength disturbances, i.e., wavelengths much longer or shorter than the chamber minor radius. The short wavelength model for the impedances contain effects associated with chamber resonances, pick-up electrodes, bellows and effects due to other structures contained within an actual vacuum chamber. With the inclusion of the short wavelength contributions to the impedances, estimates for the current limitations due to the various instabilities are obtained. The stability current limitations are obtained for both the modified and conventional betatron.

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EMMITTANCE GROWTH IN A MODIFIED BETATRON CROSSING THE ORBITAL-TURNING-POINT TRANSITION

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Higher equilibrium current densities are possible in a modified betatron accelerator because of the focusing provided by addition of the azimuthal magnetic field. If the current density at injection exceeds the limiting value for a conventional betatron, a transition in the form of the equilibrium occurs during acceleration as the vertical-field focusing by itself becomes sufficient to overcome the beam space charge. During this transition equilibrium is transiently lost until the beam reestablishes a new equilibrium at a lower current density.

The parametric dependence of the growth in beam radius on external field index, beam emittance, and longitudinal velocity spread is discussed. Simulations are presented to illustrate the dynamics of the beam as the transition is crossed.

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SELF CONSISTENT MODIFIED BETATRON EQUILIBRIUM
AND THEIR ADIABATIC EVOLUTION*

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An analytic and numerical scheme is developed to determine self consistent equilibria in modified betatrons. As the beam accelerates over a time scale of many poloidal drift times, the equilibrium develops by passing through a sequences of time dependent equilibria. At any time, the equilibria is characterized by number of particles in a drift (P_θ) surface, and toroidal flux through a P_θ surface. One can follow the equilibria as the beam accelerates. At some energy, the beam begins to make a transition from diamagnetic to paramagnetic poloidal drift. This transition is characterized by a change in topology of the P_θ surfaces. Depending on the change in shape at transition, the new P_θ surface can either be confined in the liner, or run into the liner. Conditions for confined orbits at the transition will be given for parameters of the NRL modified betatron experiment.

* Work supported by ONR.
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5P12

LONG PULSE ION INDUCTION LINEAR ACCELERATOR

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A prototype of proton induction linac was developed to study the beam dynamics and the operational characters in the accelerator of this type, which may have a potential feasibility as an accelerator of intense light and heavy ion beams. The model was successfully operated to produce about 100 mA of the protons accelerated up to 120 keV. The device consists of 5 similar modules of the accelerating unit, each of which has tree magnetic toroidal cores made of laminated silicon iron foil of 0.1 mm thick. The accelerating field of 25 kV/module is induced by driving a simple LC discharge circuit linked with the cores. The pulse duration of the extracted ion beam was typically 2 μ sec. A compact ion source of an electron beam discharge type forms hydrogen plasma, from which the beam is extracted into the accelerating unit directly by the inductive field. For the time being the source and the focusing elements limit the intensity of the accelerated beam which can be transported to the end of the device without particle loss. An array of permanent magnets made in toroidal shape and placed inside the vacuum wall coaxially along the particle orbit would have supplied the beam with the required focusing and stability. The magnet in present use has no intense field enough to get the satisfactory beam transport. Detailed analysis of the beam parameters such as energy spectrum is being carried out.

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GENERATION AND CONTROL OF CHARGED PARTICLE BEAMS
USING INDUCTION ACCELERATORS*

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Investigations have been carried out into the use of Induction Linacs for the acceleration of proton beams. A 1.5 MeV, 2 kA, 50 nsec beam has been generated using an inductively fed magnetically insulated diode. Results will be presented describing beam generation and propagation. A comparison will be made of propagation with and without collective focusing of the beam.

A program to study autoacceleration techniques for the production and time compression of high energy beams has been started recently. A ferrite loaded cavity was used to couple energy from the beam to a 70 ohm transmission line and, after a predetermined delay, back to the beam. Initial experimental results demonstrating particle acceleration and pulse compression will be presented.

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A NEW DIAGNOSTIC METHOD FOR INVESTIGATING THE MECHANISM OF COLLECTIVE ION ACCELERATION BY REB DIODES

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Collective ion acceleration has been observed in several laboratories in a great variety of experimental configurations. The common basis to at least part of the models explaining the mechanisms of ion acceleration is the formation of a potential well by the intense electron beam entering the drift tube region. In our work the existance and the characteristics of that potential well are investigated using an externally generated ion beam as a probe.

The measurements were performed on a 450 kV, 80 nsec FWHM electron beam accelerator, with a 3Ω pinching diode, giving rise to an approximately 40 nsec duration, 5 kA/cm^2, collectively accelerated ion current propagating in an evacuated metallic drift tube. The probe beam, (mainly 180 keV protons, 50÷100 mA/cm^2), was injected at various distances from the anode plane, perpendicularly to the drift tube axis. The probe particles,after traversing the potential well, struck a fast scintillator, which was viewed by a fast converter camera. The potential well created by the REB emerging through a thin metallic anode deflected the probe particles. This deflection was observed as a function of time by means of the scintillator-camera system. It is hoped that probing the potential well by varying the injection point both along the drift tube axis and in a direction perpendicular to it will give insight into the temporal and spatial behaviour of the electron cloud responsible for the collective acceleration of ions. Ways to improve the signal to noise ratio and to achieve better spatial and temporal resolution will be discussed. Typical results showing deflection of the probe beam will be presented and the potential scope of this probing method and its limitations will be reviewed.

THEORY OF COLLECTIVE ION ACCELERATION IN THE LUCE DIODE*

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The most successful collective ion acceleration to date has been observed when a relativistic electron beam has been discharged in the Luce diode (dielectric anode) geometry. In these experiments, the ratio of peak ion energy to beam kinetic energy has been as high as 30. The ion source is a plasma formed on the anode surface by electron impact ionization of the dielectric material. The diode physics, which couples the electron beam generation to the number of ions extracted from the plasma, is an essential feature of the acceleration mechanism in the Luce diode.

Two dimensional electromagnetic particle-in-cell simulations which are based on the Cornell University Luce diode experiments have been carried out. The simulations include an exact model of the electron beam generator's diode and the drift space where the collective ion acceleration takes place. Ion acceleration is clearly due to trapping in a train of traveling waves. The source of the waves appears to be an ion-electron two stream instability. The instability growth rate, saturation length and coincident microwave production are consistent with experimental results.

*Work supported by the Air Force Office of Scientific Research.

A STUDY ON COLLECTIVE ACCELERATION OF BARIUM IONS

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Barium ions were collectively accelerated to a peak energy on order of GeV using an intense relativistic electron beam (IREB). The IREB generator used was a Physics International Pulserad 110A which produces a 1.5 MV, 27 kA, 30 ns pulse in a conventional diode configuration. Two rail-type plasma guns with barium electrodes produced a barium plasma in a partitioned space (the anode space), which was used as a plasma anode and as an ion source. The density and the electron temperature of the plasma were about 10^{13} cm^{-3} and 10 eV, respectively. Electrons field-emitted from a 3-mm-diam tungsten cathode was injected into vacuum through this plasma. Without this preformed barium plasma, an IREB could hardly propagate in a drift tube (30 cm long and 16 cm in diameter). At the best timing of firing, the peak kinetic energy of beam-electrons and the peak beam current at 20 cm from the cathode were 1.3 MeV and 16 kA respectively. Ion energies were measured using a time-of-flight method and stacked foil-SSNTD (solid state nuclear track detector) combinations. From the time-of-flight, the maximum ion energy was 7.4 MeV/amu which corresponds to 1.0 GeV for barium ions. Ions with energy above 1.8 GeV were detected using a stacked aluminum foil-SSNTD combination.

TOMOGRAPHY, A NEW HIGH SPEED REB DIAGNOSTIC

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In REB propagation experiments, characteristic distance and time of interest are extremely short. This is especially true for the first 10 cm of the beam front. In order to study beam stability, observation techniques must have a subnanosecond temporal resolution.

We have developed a tomographic imaging technique that could make subnanosecond measurements of the REB beam cross-section. It consists of a multi-channel (200) fiber optic input array, a high speed (2 ps) streak camera, and a computer supported digital readout system. The fiber input array could be used to observe visible light as well as x-ray signals from the beam channel. A computer tomographic technique is used to reconstruct the 2-D beam cross-section as a function of time.

The system, its applications, and proof-of-principle experimental results will be presented.

* This work was supported by the U. S. Department of Energy.

DIRECT MEASUREMENT OF THE ENERGY SPECTRUM OF AN INTENSE PROTON BEAM

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A time resolved magnetic spectrometer employing a gold Rutherford scattering foil has been successfully employed to measure for the first time the energy spectrum of an intense high current density (500 kA/cm^2 to 1 MA/cm^2) proton beam. The spectrometer consists of a 6.6 K Gauss 12.7 cm diameter samarium-cobalt permanent magnet with a collimator consisting of two 1 mm diameter input apertures separated by 12.3 cm. The spectrometer operates by allowing a direct high brightness proton beam to Rutherford scatter through 90° from a thin gold foil (2500 Å) into the spectrometer. In this way, a high current density proton beam can be reduced in intensity to a level suitable for magnetic analysis. In order to provide time integrated and time resolved records, the magnetically deflected protons are recorded on CR-39 and eight 1 mm^2 by 35 μm thick PIN diodes simultaneously. A Monte Carlo code has been written which simulates proton trajectories through the spectrometer and enables a complete determination of the spectrometer's resolution and sensitivity. Data from runs on Proto I will be presented.

* This work was supported by the U. S. Department of Energy.

ENERGY AND VELOCITY DIAGNOSTICS FOR INTENSE RELATIVISTIC ELECTRON BEAMS*

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Three diagnostics for measuring electron energy and velocity in an REB are being tested on the MIT Pulserad 110A electron beam facility (1.5MV, 20kA, 30ns). The first of these is a magnetic spectrometer built to measure the energy distribution function $f(\gamma)$ in the beam. The spectrometer is of the Browne-Buechner type and is capable of a resolution in $\Delta\gamma/\gamma$ of $\lesssim 0.1\%$. This instrument is used to diagnose the beam from a multistage electron gun designed to produce a high quality beam for an intense beam free electron laser experiment.

A second diagnostic involves a simultaneous measurement of the beam current and radial electrostatic potential. Beam current is measured with a Rogowski coil and the potential is determined from the voltage across a cylindrical capacitor coaxial with the beam. This technique allows one to determine the spatially averaged axial streaming velocity in the beam.

The third diagnostic measures the electron cyclotron wavelength in a beam propagating in a uniform guiding magnetic field. This is accomplished by placing a small pinhole aperture in the path of the beam and a moveable collector of comparable diameter downstream of the pinhole. The observed periodicity of the downstream current modulation allows one to calculate the product $\gamma v_{\parallel}$ in the beam.

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DIAGNOSING THE ION BEAM ON THE APPLIED-B DIODE*

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Diagnosing the ion beam on the applied magnetic field ion diode includes measuring the particle energy, ion current and beam focus as a function of space and time. We will discuss our recent efforts in each of these areas. An array of particle energy spectrometers has been used to measure the diode voltage as well as the particle energy distributions in the region between the anode and target. These time-resolved spectrometers include Thomson-parabola analyzers, arrays of filtered Faraday cups, and a magnetic spectrometer with fast detectors. Proton currents are measured by nuclear activation and inner-shell radiation, in addition to dB/dt monitors. Prompt-γ radiation from the $^{19}F(p,\alpha\gamma)^{16}O$ and $^{7}Li(p,\gamma)^{8}Be$ reactions are measured by shielded, scintillator-photomultiplier detectors to determine the time-resolved proton current. The time-integrated proton charge is measured by the $^{63}Cu(\gamma,n)^{62}Cu$ reaction using the gamma radiation from the lithium reaction. Proton current as a function of time can also be measured from inner-shell x-rays emitted from aluminum and gold targets. The time-resolved proton focus can be measured by imaging these x-rays on open or sealed microchannel plates. Other focused beam diagnostics utilize the target response to the beam. For example, velocity measurements from exploding pusher and ablative targets have been obtained using flash radiography and holography. Similar information is provided by the radiation temperature of a target, as inferred from total radiation measurements using XRDs. Representative results of these diagnostics on the Applied-B diode on the Proto-I and PBFA-I accelerators will be presenced.

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5P21

USING INNER SHELL X-RAYS AS AN ION BEAM DIAGNOSTIC*

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A beam of protons impinging on a metal foil will ionize inner shell electrons, leaving an atom in an excited state. The atom will then decay via a cascade of Auger or radiative transitions. An analysis has been done of the various radiative transitions resulting from the ionization of M-shell electrons in gold foils. The results of the analysis have been combined with a 1-D hydrodynamic code in order to predict the time dependent x-ray signals emitted from a target irradiated by proton beams. A comparison of the theoretical and measured signals shows that inner shell x-rays can be used as a viable ion beam diagnostic. In particular, gold M-shell radiation has been used to infer the proton current as a function of time with the applied-B diode On the PROTO I accelerator.

*This work supported by the U.S. Department of Energy.

DETERMINATION OF INTENSE RELATIVISTIC BEAM QUALITY BY THOMSON SCATTERING

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Beam quality is critical for electromagnetic wave generation experiments using IREB, particularly Free Electron Laser experiments. Preliminary experimental results concerning a Thomson scattering experiment on a 1 MeV, 1 kA and 20 nS duration electron beam will be presented in order to determine space averaged (1 cm^{-3}) but time resolved electron distribution functions.

The experiment use a 3 J, 3 nS neodynium laser shooting at 150° with respect to the beam direction of propagation. The scattered light is observed in the forward beam direction, i.e. 0°, in order to detect in the visible part of the spectrum. This angle of detection maximizes both the energy resolution and the number of scattered photons. The scattering is limited to a one cm^{-3} region of the beam and permits some spatial resolution in the direction of the beam propagation. The spectrum of the scattered light is time resolved.

Results concerning the triggering, by a fraction of the probe laser beam, of the Blumlein master switch of a Physics International Co. 110A machine, will be also presented.

COLLECTIVE ACCELERATORS

GENERATION AND ACCELERATION OF MULTICHARGE POSITIVE IONS AND NEGATIVE IONS IN HIGH CURRENT DIODES BY MEANS OF COLLECTIVE EFFECTS

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MICROWAVES

FREE ELECTRON LASER THEORY AND EXPERIMENTS*

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A review of the major Free Electron Laser (FEL) experiments will be presented. These experiments are designed to produce radiation from the far infrared to the ultraviolet. Different categories of FELs, Compton, Raman, optical klystron, two stage, etc., as well as the suitability of various types of electron accelerators to power FELs will also be discussed. Potential applications of the FEL will be summarized.

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* Performed jointly under the auspices of the U. S. DOE by LLNL under W-7405-ENG-48 and for the DoD under DARPA, ARPA Order No. 4856, Program Code No. 3B10.

INTENSE ELECTROMAGNETIC PULSED RADIATION FROM RELATIVISTIC ELECTRON BEAM.
-RESEARCH PROGRAMM AT THE ECOLE POLYTECHNIQUE-

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Our REB programm is presently oriented towards the production of intense electromagnetic pulses in millimeter and submillimiter wavelenghts by Free Electron Laser and in soft X-Rays by hot and dense plasmas.

On Free Electron Laser, our present effort is mainly devoted to the determination of the relativistic electron beam quality by Thomson scattering of a short pulse neodynium laser. The Nd laser is shooting with an angle of 150^0 with respect to the beam direction of propagation, and the scattered visible light is observed in the e-beam direction. This diagnostic is space averaged in a volume of about 1 cm^{-3}, and is time resolved.

Two different devices are under studies for Soft X-Rays production:

- The fast compression (50ns) of a hollow cylinder of supersonic jet of Aluminium plasma produced by a exploding thin foil expanding through a circular slit. This prevents the presence of gas inside of the hollow cylinder ,increasing the compression efficiency, and produces quite a uniform plasma, limiting the development of instabilities.

- A "needle plasma", very dense gas imbedded Z-Pinch at a few atmospheres, ionized inside a very thin diameter using soft X-Rays produced by a Ruby laser focussed on a lead target, and heated by Joule effect.

* Also with C.E.A., CEN de Saclay, 91191 Gif-sur-Yvette Cedex (France).

A REVIEW OF HIGH PULSED POWER MICROWAVE AND MILLIMETER WAVE GENERATION

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Intense relativistic electron beams have been used to generate microwave pulses with peak power 100 MW $\lesssim$ P $\lesssim$ 10 GW and frequency 1 GHz $\lesssim$ f $\lesssim$ 800 GHz. This review will survey the different wave generation mechanisms used including magnetron, BWO, reflex triode/virtual cathode oscillator and gyrotron. The best mechanism for the various frequency ranges will be suggested. Perceived limitations in risetime, peak power, coherence and pulse duration will be discussed for each type of microwave generator. The relationship of electron beam impedance to the efficiency of wave generation will be considered. Finally, a number of new wave generation experiments will be described and evaluated.

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RELATIVISTIC PLASMA MICROWAVE GENERATOR

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The first experiments on plasma-REB microwave generator are described. The conditions for optimal generation in the centimeter range are determined. The microwave power is equal to 35 MW, the efficiency ~7%, the width of frequency is less than 20%. One mode is emitted. The variation of plasma density allows to change the wavelength from 2.8cm up to 1.8cm. The experimental results are in agreement with the theoretical ones obtained for a model with an infinite magnetic field.

ACCELERATORS, MICROWAVES

QUANTUM COHERENCE IN ELECTRON BEAMS

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Following the experimental results on the interaction of electron beams with solids and molecules, the properties of the electron beam after the interaction with discrete changes of the energy have been studied; such studies are important for beam modulation or for free electron lasers. The quantum mechanical description of the electron beam results in a coherence property which is basically different from optical beams. The earlier discussion of coherence of electron beams was correct only in first order to be analogous to the optical beam (correlation coherence). The quantum coherence of the electron beam includes the complete temporal expansion of a wave packet - though well known - had not yet been evaluated for the problems of coherence. The essential properties found for electron beams are the different components depending on amplitudes with and without modulation to interpret the preceding experiments of beam-matter interaction

Working with electrons of an energy E_0 and a Gaussian energy distribution of a width ΔE_0, the quantum coherence is expressed by a spatial limitation to times t below t_0

$$t < t_0 = \frac{m\sigma^2}{h} \approx \frac{h}{2E_0}\left(\frac{E_0}{\Delta E_0}\right)^2$$

with a maximum quantum coherence length $\Lambda_{qc} = t_0 v$, using the mean electron velocity v (= $[2E_0/m]^{\frac{1}{2}}$), σ representing the spatial extent of the beam.

A HIGH FREQUENCY VIRCATOR MICROWAVE GENERATOR

I: THEORY*

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The virtual cathode oscillator (vircator) has the potential for producing very high power microwave pulses in the centimeter and millimeter wavelength regimes. In a foilless diode configuration it is tunable by adjusting the imposed axial magnetic field. This permits high frequency operation. In a foil diode or reflex triode tuning is accomplished by changing the A-K gap spacing. The microwave generation will be coherent and efficient, if electron reflexing into the diode region is prevented. Gigawatt power levels have already been produced in the centimeter regime.

For an injected current a factor of three greater than the limiting current, $f_{osc} \sim \omega_p^{rel}/\sqrt{2\pi}$. Because the oscillating beam is equivalent to a deformable dipole, the preferred waveguide mode for an axisymmetric beam in a straight-walled cylindrical guide is TM_{0n} where $n = D/\lambda_0$, D is the waveguide diameter and λ_0 is the free space wavelength. Thus, D/λ_0 should be chosen to be close to an integer value. Note that both the limiting current and the cutoff wavelength depend on the guide dimensions and geometry. Both must be considered in choosing an experimental configuration. Our experimental results with a millimeter wave vircator are presented in the accompanying paper.

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*Work supported by the Air Force Office of Scientific Research.

MICROWAVE GENERATORS: OSCILLATING VIRTUAL CATHODES AND REFLEXING ELECTRONS*

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We have demonstrated via PIC simulations that efficient production of high-power microwave by oscillating virtual cathodes and the associated reflexing electrons can be achieved in pulsed-power electron beam facilities. It has been shown in our simulations that virtual cathode formation is only possible if the current carried by the reflected electrons can be partially drained away. In foil diodes, this condition can always be satisfied; however, in foilless diodes, the condition becomes critically dependent upon the diode geometry. We have simulated the operation of electron beam diodes and the subsequent formation of virtual cathodes in cylindrical waveguides. The formation of the virtual cathode resulted in a potential well between the real and the virtual cathode that trapped the electrons reflected by the oscillating virtual cathode. The trapped electrons phase-bunched coherently in the potential well so that a substantial amount of microwave was generated. Strong excitation of electromagnetic waves at 10.65 GHz and 25.74 GHz were observed in one of our simulations, and they were determined to be due to the reflexing electrons and the oscillating virtual cathode, respectively. The approximated microwave power output was 21 GW and the estimated efficiency of microwave production was 10.5%.

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*This work was supported by the U.S. Department of Energy.

KINETIC AND MAGNETIC EFFECTS IN VIRTUAL CATHODE OSCILLATIONS*

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Results of simulations of particle bunching and virtual cathode oscillations employing a macroscopic, cold plasma, electrodynamic model will be presented. The model identifies particle bunching and virtual cathode oscillations as electrodynamic shock phenomena. Comparison of fully kinetic electromagnetic simulations with the electrodynamic approximation allows the isolation and identification of kinetic and magnetic effects in more complete investigations. These will be discussed.

*This work was supported by the U.S. Department of Energy.

PULSED-POWER DIODE GENERATION OF HIGHPOWER MICROWAVES*

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The generation of microwave radiation at gigahertz frequencies in high-voltage pulsed power diodes has been treated analytically and with electromagnetic particle simulations. Pulsed power in the form of a 0.5 - 1.0 MV, TEM wave is fed to the diode via a 5 cm diameter cylindrical stalk onto which a 30 cm diameter cathode has been mounted. Located some 3-5 cm in front of the cathode is a foil anode grid.

As the TEM wave propagates between the stalk and an outer cylindrical cage (70 cm diameter) a stream of electrons are emitted off the stalk when the local electric field exceeds 200 kV/cm. This flow is then magnetically insulated and confined by the induced B_θ fields resulting from the 25-50 kA current flow within the stalk. Convex shaping of the cathode surface allows the emitted electrons to form a virtual cathode beyond the grid, then phase bunch to produce high-Q 1GHz microwaves over an area equal to that of the cathode. Radiation patterns from the dipole-like electron motions centered on the grid, that follow closely the classical Barkhausen - Kurz description, are presented.

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CYCLIC BEAM BUNCHERS AND WAVE AMPLIFIERS*

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An rf wave circulating in a toroidal or cylindrical cavity in a TE mode with a superimposed magnetostatic betatron field is capable of producing deep density modulations on an intense relativistic electron beam when the phase velocity of the wave is matched to the beam cyclotron frequency. The rf wave can transfer energy from some electrons to others and produce beam bunching at the rf wavelength by the negative mass effect. Alternatively, the phase velocity of an rf wave or a microwave can be chosen to extract energy from the beam and amplify the wave. The effect of an inductive toroidal electric field is to replenish the electron beam energy for quasi-dc operation of the cyclic wave amplifier. Examples of operation of cyclic devices in both the beam bunching mode and wave amplifying mode are presented.

*This work was supported in part by the Office of Naval Research.

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GENERATION OF HIGH FREQUENCY RADIATION BY A QUASI-OPTICAL GYROTRON AT HARMONICS OF THE CYCLOTRON FREQUENCY*

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A quasi-optical gyrotron can work, in principle, at harmonics of the electron cyclotron frequency, as well as at the fundamental. In addition to demonstrating the mechanism at a harmonic, one must also suppress the fundamental and lower harmonics, since in a quasi-optical cavity, all harmonics are simultaneously present. Also the device must work at sufficiently low electric fields to be physically realizable. Design parameters are presented which achieve this at the second and third harmonics.

*Work supported by Department of Energy.
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MICROWAVE GENERATION BY REB IN LOWBITRON GEOMETRY AS FEL

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The interaction of a REB (0.6 MV, 10 kA and 10 ns from PI 105 model) and the londitudinal wiggler in the uniform guide field is investigated in a coaxial geometry in detail experimentally. An annular cross sectional beam of REB is injected into a longitudinal wiggler having the period of 2 cm and the modulation intensity of 5 % of the uniform field (1.2 T max.). Strong bursts of the microwave in X and Ku bands were observed. The radiation spectrum and intensity were analysed with a long (100 m) dispersive line. The parameters of the wiggler and uniform magnetic fields can be controlled independently. This facilitates the discrimination between possible various modes of the radiation mechanisms. The intensities of the observed microwaves are the order of a few MW at their maximum. In the X band, it is found that the most dominant mechanism is identified to be the electron cyclotron maser instability, which is consistent with the results of the experiments carried out in other laboratories. We also found intense bursts of very narrow frequency width in both bands, which could be attributed to the lowbitron-longitudinal wiggler beam interaction. The effect of the beam spiraling is testd and the result supports this conclusion. In the framework of the linear analysis the dispersion equations are solved numerically and compared with the experiment. The analysis of the non-linear effects is being planned.

INVESTIGATION OF MICROWAVE GENERATION BY INTENSE RELTIVISTIC E- BEAMS.

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Microwave emission from a relativistic electron beam propagating in uniform and rippled magnetic fields has been investigated in a wide frequency range (12 GHZ - 110 GHZ). The electron beam generator is connected to a foilless diode immeresed in a uniform magnetic field. The beam (V=750 KV and I= 5-10 KA) is propagated in a stainless steel drift tube perallel to an external magnetic field of up to 40 K gauss. Different foilless diode configurations and drift tube diameters were investigated. The properties of the beam have been measured using Faraday cups, damage plates, calorimeters and x-ray monitors. Results of microwave generation in uniform and rippled magnetic fields using different diodes and different beam parameters will be presented and disscused. Also, the influence of the strength and the period of the rippled magnetic field on the radiated power will be analysed. Computer Simulations of the beam behavior were carried out for the different cathode-drift tube configurations. The computer results will be compared to the measured beam properties.

A SLOW WAVE ECM WITH AXIAL INJECTION

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A continuous electron beam injected axially into a slow wave structure containing a circularly polarized TE wave and a longitudinal magnetostatic field will produce microwaves by maser action. The slow wave structure allows energy to be coupled out of an electron beam with no initial transverse momentum. A narrower spread of energy about the ECM resonance and more efficient high power operation is possible with axial injection. A nonlinear (strong field) analysis of energy coupling of electrons to a slow wave in an electron cyclotron maser is presented. Magnetostatic field tapering, finite emittance, finite gyroradius effects, and other design considerations are used in a conceptual design of a slow wave ECM microwave amplifier.

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A K_a-BAND UBITRON*

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In this paper we present theoretical results and design parameters of a K_a-band ubitron (a low voltage free-electron laser) under construction at the Naval Research Laboratory. The objective of this experiment is to demonstrate high gain and efficiency in a ubitron amplifier configuration. As an aid in selecting the experimental parameters a fully self-consistent 3-dimensional theory of the ubitron interaction has been derived. This analysis includes the transverse variations in the helical wiggler field, finite waveguide geometry, and space charge effects. The source current and charge density for the Maxwell-Poisson equations are found by perturbation about the steady-state trajectories in the combined axial and helical magnetic fields. With the assumption of a thin, monoenergetic beam, a dispersion equation is obtained and solved numerically to give the linear gain as a function of signal frequency. A confined-flow Pierce gun is being designed for the experiment. The gun will operate at 250 kV and approximately 100 amperes. The electrostatic and magnetic profiles are being adjusted to achieve a high beam quality. The wiggler magnetic field will be produced by a bifilar helix electromagnet and the guide field by solenoidal windings. The RF interaction will take place with the TE_{11} fundamental circular waveguide mode. Design details and test results will be presented along with the theoretical calculations of performance.

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*Work supported by the Naval Electronic Systems Command
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EXPERIMENTAL AND THEORETICAL RESULTS FROM A RIPPLED FIELD MAGNETRON (CROSS-FIELD FEL)*

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We report measurements and theory of millimeter wave emission from a rippled field magnetron (cross-field FEL). In this device the electrons move under the combined action of a radial electric field, a uniform axial magnetic field and an azimuthally periodic wiggler magnetic field.

The device comprises a smooth cylindrical field emission cathode enclosing a smooth cylindrical anode. A Physics International Pulserad 110A (0.7-1.4MV) accelerator supplies a radial electric field across the anode-cathode gap. The wiggler magnetic field (~2kG, periodicity 2.53cm) is produced by a periodic assembly of samarium-cobalt bar magnets positioned behind the smooth stainless steel electrodes. Microwave power of ~300kW is observed in a narrow spectral line whose frequency can be varied continuously from 32-45GHz by varying the axial magnetic field.

A theoretical study has been carried out for the case of the planar version of the rippled field magnetron, with allowance made for the presence of the Brillouin space-charge cloud. The computations show an unstable mode due to the coupling of the slow (negative energy) Doppler shifted cyclotron wave with the superluminous TE waveguide mode. Numerical simulations will also be presented.

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NUMERICAL RESULTS OF 2-D PULSE PROPAGATION IN THE FREE ELECTRON LASER OSCILLATOR WITH A TAPERED WIGGLER*

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Numerical results of the radiation pulse evolution in the free electron laser (FEL) oscillator using a semi-analytical formulation are presented. The radiation pulse is analyzed in both the radial and axial directions as a function of time. The radial variation of the radiation pulse is obtained analytically while the axial variation is obtained numerically. By decomposing the radiation pulse into transverse resonator modes, the two-dimensional formulation reduces to an effective one-dimensional formulation. All the radial dependences are analytically combined into spatially varying complex filling factors. We will present results using the Stanford FEL oscillator parameters as well as the LANL FEL oscillator parameters.

*This work is supported by DARPA.

SIMULATION OF A HIGH GAIN, TAPERED WIGGLER FREE-ELECTRON LASER*

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We present results from a numerical model of a high-gain (electron-beam power $>$ input laser beam power) FEL amplifier. The model is radially resolved and includes the effects of diffraction, electron and laser beam profiles, and wiggler field variations. The laser beam is propagated under the paraxial approximation with FEL source terms. The electron beam is represented by $\approx$ 128 macroparticles at each radial position whose energy and relative phase are followed by the usual equations of motion. The wiggler field is chosen so that synchronism can be maintained at a single, arbitrary radial position.

We discuss the dependence of amplifier gain upon electron and laser beam profiles, laser beam quality, and energy spread. We also show where two-dimensional considerations strongly affect the design of an optimal experiment.

*Performed jointly under the auspices of the U. S. DOE by LLNL under W-7405-ENG-48 and for the DOD under DARPA, ARPA Order No. 4395, monitored by NSWC.

DETAILED SPECTRA OF HIGH POWER BROADBAND MICROWAVE RADIATION FROM INTERACTIONS OF RELATIVISTIC ELECTRON BEAMS WITH WEAKLY MAGNETIZED PLASMAS*

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We observe prodigious quantities of microwave energy uniformly across a wide frequency band when a relativistic electron beam penetrates a plasma. Typically we measure 20 MW total for $\Delta\nu \simeq 40$ GHz with preliminary observations of bandwidths as large as 100 GHz. We fire an intense annular pulsed REB ($I \simeq 128$ kA; $r \simeq 3$ cm; $\Delta r \simeq 1$ cm; 50 ns FWHM; $\gamma \simeq 3$) through an unmagnetized or weakly magnetized plasma column ($n_p \sim 10^{13}$ cm^{-3}). We use $0.01 \leq n_b/n_p \leq 2$, the higher values of this range being an unconsidered region for most previous theoretical and experimental efforts. For these high n_b/n_p values, the observed emission with $\omega >> \omega_p$ and weak harmonic structure is wholly anticipated from Langmuir scattering or soliton collapse models. A model of Compton-like boosting of ambient plasma waves by the beam electrons, with collateral emission of high frequency photons, qualitatively explains our spectra. Frequencies up to $\sim \gamma^2\theta^2 \omega_p$ should be emitted with substantial power, where θ is the angle between beam electrons and plasma waves. For our experiment, $\theta \geq 0.5$ radians. Power emerges largely in an angle $\sim 1/\gamma$, as required by Compton mechanisms. As n_b/n_p falls, we observe ω_p - $2\omega_p$ structure and harmonic power ratios consistent with soliton collapse theories. With further reduction of n_b/n_p only the ω_p line persists. Thus we have observed a transition in spectral behavior from the weak to strong turbulence theories advocated for Type III solar burst radiation, and further into a regime we characterize as super-strong REB-plasma interactions.

*Work supported by AFOSR Grant #82-0233

MICROWAVE EMISSION FROM A REB PROPAGATING IN AIR

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We introduced a high-current (100 kA), relativistic ($\gamma = 2.75$), annular electron beam of ~ 100 ns duration into an air-filled drift chamber, 10 cm radius, a meter long. Microwave emissions from the excited gas were analyzed by an array of spectrometers spanning 7 - 40 GHz. We examined the data for instantaneous power, integrated band-energies and time-evolution. Our power-vs.-pressure curves for each microwave band illustrate a transition between

(a) high power, ~ MW reflexing radiation of the beam at low chamber pressures (< 0.02 Torr) and

(b) gas breakdown, oscillation processes at higher pressures, followed by plasma (0.02 Torr < p < 2 Torr).

In all regimes the microwave peak power spectra decline with increasing frequency. Microwave pulse duration scales inversely with pressure. Significant radiation seems to persist for times exceeding the beam pulse. The beam radiates a few ergs. We observe no emission above 2 Torr., presumably due to electron-neutral collisions which inhibit beam-plasma instabilities. Magnetic fields ~ 800 G generally inhibit emission at all pressures.

Propagation at full atmospheric pressure is possible using an initial low-pressure chamber to prepare a stable, self-pinched beam. Some emission appears, directed narrowly along the beam, at full atmospheric pressure.

We discuss correlations with theory of beam transport processes and calorimetric observations of energy transport.

*Work supported by AFOSR Grant #82-0233.

ENERGY TRANSFER FROM AN ULTRA-BRIGHT INTENSE RELATIVISTIC ELECTRON BEAM TO DENSE PLASMA*

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We report on an ongoing experimental program to study the feasibility of heating a small volume ($\sim 1\ cm^3$) of dense plasma ($N_e \sim 10^{17}/cm^3$) with an Ultra-Bright ($\sim 300\ MA/Cm^2/Sr$) electron beam by means of the relativistic two stream instability. Using a 2 Torr H_2 target, 5% of the beam energy is transferred to a 6 cm long region. Theoretical modeling predicts a stronger interaction with 20-30% of the beam energy being deposited in less than a 1 cm long volume. From a variety of measurements and from theoretical considerations, it is likely that energy transfer is inhibited by plasma density gradients resulting from the beam induced ionization process. Accordingly, a Z-discharge preionizer is being developed to generate a fully ionized homogeneous target plasma. Initial coupling measurements will be presented. Also, the progress of Raman scattering experiments in which CO_2 laser radiation is scattered from beam induced plasma waves to measure the wave frequency and wave number will be discussed.

*Performed under the auspices of US DoE

FILAMENTATION INSTABILITY OF ION ACOUSTIC WAVES DRIVEN BY A SCATTERED RELATIVISTIC ELECTRON BEAM*

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In beam-plasma interaction, the two-stream instability in general has a larger growth rate than the Weibel instability. The high-frequency two-stream instability heats the plasma electrons while leaving the ions relatively unperturbed. As the electron temperature far exceeds the ion temperature, ion-acoustic waves can be excited by the beam directly, in addition to the usual Buneman instability driven by the return current. Since the speed of a relativistic beam is much greater than the sound speed in the plasma, this instability exists only for wave vectors nearly perpendicular to the beam. In certain parameter regimes, this instability can grow faster than the Weibel instability. Just like the two-stream instability, beam temperature tends to stablize the short wavelength region of this one also. We have investigated this instability for a scattered relativistic beam propagating in a plasma where the electrons are much hotter than the ions. Details of the linear dispersion analysis and particle-in-cell simulation results will be presented.

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6P18

THE SPACE TIME EVOLUTION OF THE NONLINEAR TWO-STREAM INSTABILITY*

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A cold electron beam penetrating a cold plasma is electostatically unstable. The instability produces a growing field which saturates when the beam electrons are suddenly trapped by a single wave. During trapping a significant amount of energy is transferred from the beam to the field and utimately the plasma. At Los Alamos experiments are being performed which demonstrate this anamolous beam driven plasma heating.

The heating efficiency and energy deposition lengths are functions of the growth rate and phase velocity of the trapping wave. According to our generalization of a calculation first done by R. Briggs, the instability is absolute and its wave form evolves in both space and time. Modifying the sudden trapping theory to account for the space and time evolution of the two stream instability, we find that the heating efficiency should grow and the deposition length shorten in time. These predictions are in agreement with one and two dimensional PIC simulations.

*This work was supported by the U.S. Department of Energy.

SIMULATIONS OF THE EFFECTS OF MOBILE IONS ON THE RELATIVISTIC BEAM-PLASMA INSTABILITY FOR INTENSE BEAMS*

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The concept of using intense relativistic electron beams to heat high density plasmas for inertial fusion is currently being investigated. The heated plasma surrounding the fusion pellet provides an efficient transfer of energy from the beam to the pellet and avoids the preheat problem associated with high voltage beams. In order for this concept to be a viable inertial fusion driver, the beam must couple efficiently to the plasma. Previous studies have shown efficient energy coupling is possible via the relativistic beam-plasma or two-stream instability. This instability operates at the plasma frequency and most of the energy transfer is to the plasma electrons. Furthermore, it has been found that plasma density gradients along the beam direction can degrade the interaction. The heating of the plasma electrons raises the sound speed and allows the ions to move forming density gradients. This phenomenon has been studied using the particle-in-cell simulation code CCUBE. It has been found that heat flow out of the plasma limits the gradient forming process, thus offering promise of avoiding severe interaction degradation resulting from self-consistent gradient formation.

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*This work was supported by the U.S. Department of Energy.

GAIN, BANDWIDTH, AND TUNABILITY OF A HIGH POWER MILLIMETER-WAVE FREE-ELECTRON LASER

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Initial spectral measurements on a high-power superradiant millimeter-wave free-electron laser experiment have produced emission spectra that agree well with theoretical predictions. Moderate linewidths in the range of 6% to 15% have been measured, demonstrating the broad gain bandwidth of the interaction. Additionally, this experiment has observed for the first time the predicted simple broadband tuning of the FEL interaction, with tuning demonstrated over a 50% range of frequencies through variation of the axial electron velocity by means of changing the strength of the wiggler field. Direct gain measurements have demonstrated a single-frequency gain of ~0.5 dB/cm, through variation in the interaction length for the superradiant emission. Additionally, a frequency shift, accompanied in some cases by a large increase in total power and efficiency has been observed through shortening the region of uniform axial field and tapering the strength of the axial magnetic field at the end of the uniform wiggler region. The highest power produced in this way is estimated to be $\gtrsim$ 70 MW at ~5% efficiency.

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DEMONSTRATION OF A TWO-STAGE BACKWARD-WAVE OSCILLATOR/FREE-ELECTRON-LASER

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An experimental study of a two-stage millimeter wave source has been carried out. The same intense relativistic electron beam first produces powerful (500 MW) radiation at 12.5 GHz via a corrugated-wall BWO mechanism, and then uses that radiation as a "pump" for a Free Electron Laser (FEL) interaction at frequency f > 140 GHz. Implication for two-stage FEL experiments with reduced electron energy requirements will be discussed.

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6P22