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US Activities in the Development of Plasma-Based X-ray Lasers

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Plasma-based X-ray Lasers:Status and Prospects
Prague, Czech Republic
September 1, 2005 through September 2, 2005

US Activities in the Development of Plasma-Based X-ray Lasers

James Dunn

Lawrence Livermore National Laboratory

Presented at the:
"Plasma-Based X-ray Lasers: Status and Prospects" Workshop
Prague, Czech Republic 1 - 2 September, 2005

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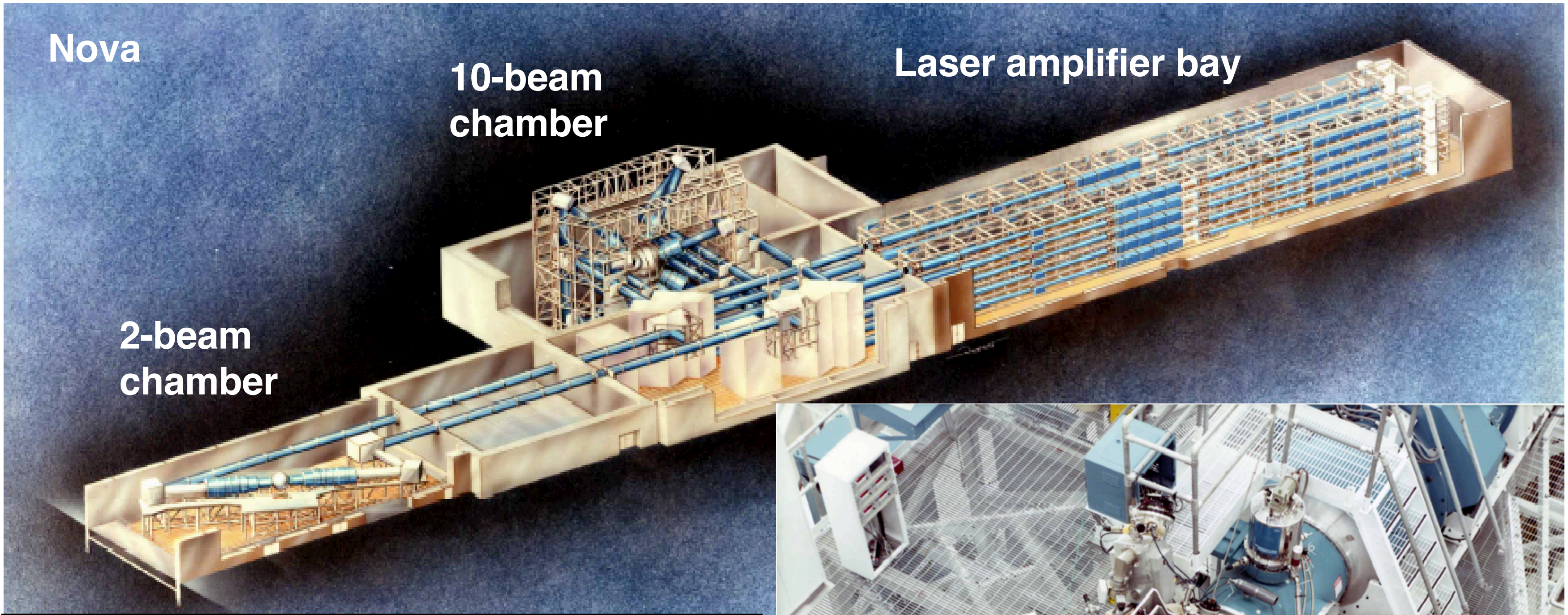
Outline:

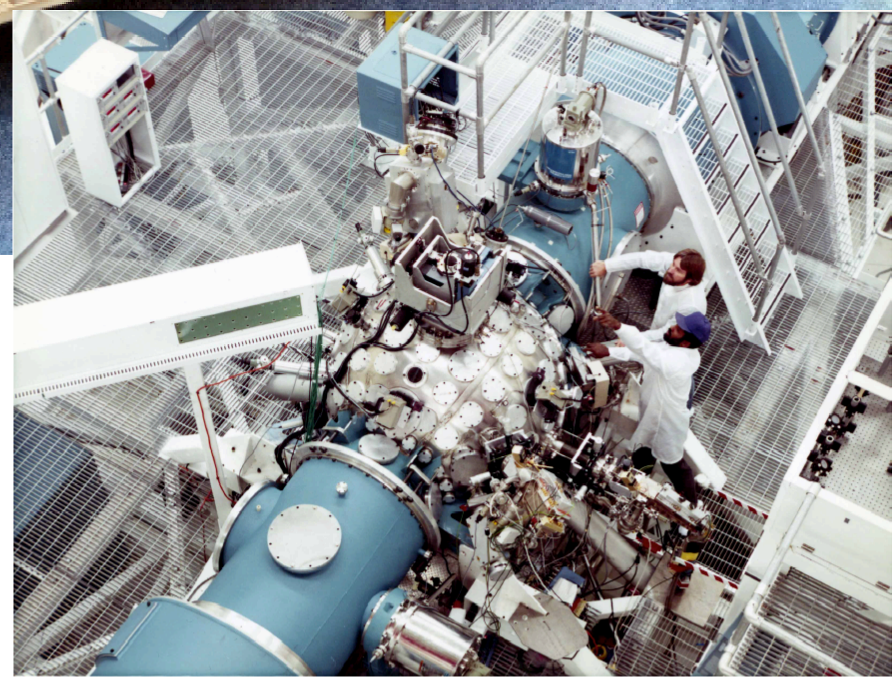
- **Historical Perspective for US X-ray Laser Effort**
  - **- Nova X-ray laser effort (1984 - 1996)**
  - **- Achievements and applications**
  - **- Recombination scheme at Princeton University**
- **Developments in various US laboratories and schemes (- 1999)**
- **Review of present US status (2000 - 2005)**
  - **- Source development**
  - **- Characterization**
- **X-ray Laser Applications (Round Table discussion 9/2/05)**
- **Future trends: Laser drivers for x-ray lasers**
  - **- High Energy, High Peak Power, High Repetition Rate**
  - **- High Peak Power: Titan at LLNL**
  - **- High Repetition Rate: Mercury DPSSL**

Historical Perspective:

- Nova X-ray laser effort (1984 - 1996)
- Achievements and applications
- Recombination scheme at Princeton University

Early effort 1984 - 1996 on x-ray lasers was performed on the Nova laser: collisional excitation scheme was developed



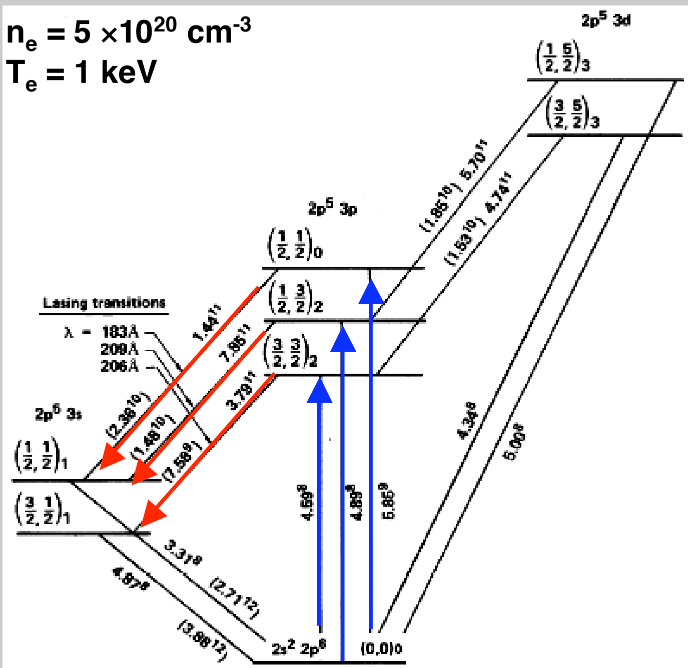


- Substantial infrastructure investment
- 2-beam target chamber was designed for x-ray laser research activities
- Soft x-ray diagnostics, optics, materials and instrumentation were developed

Large scale Inertial Confinement Fusion driver used for first experiments: Main laser amplifier bay

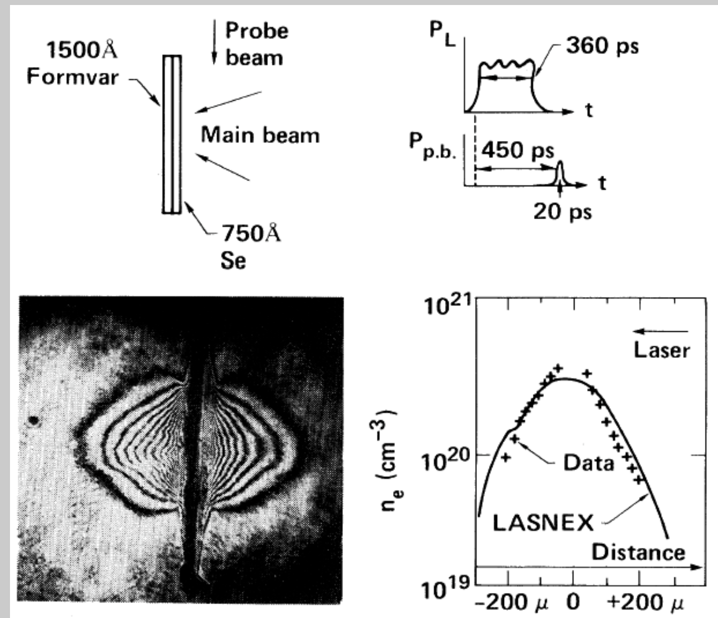
Exploding foil target and x-ray laser was designed after substantial modeling and experimental characterization effort

Ne-like Se Simplified Level Diagram



- 2-D LASNEX hydro simulations combined with XRASER atomic kinetics code (100s of levels included)
- Gain on following lines: 18.3, 20.6, 20.9 nm

Density Profile Measurements

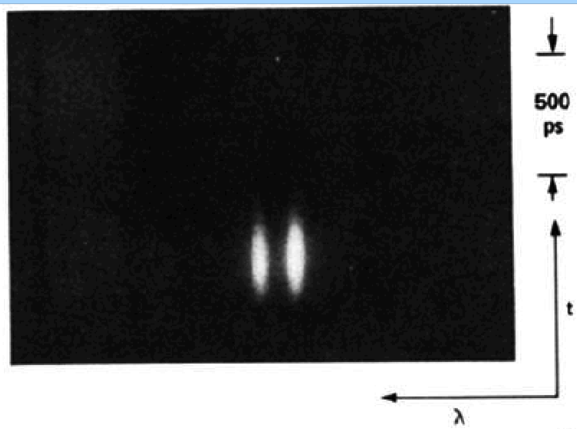


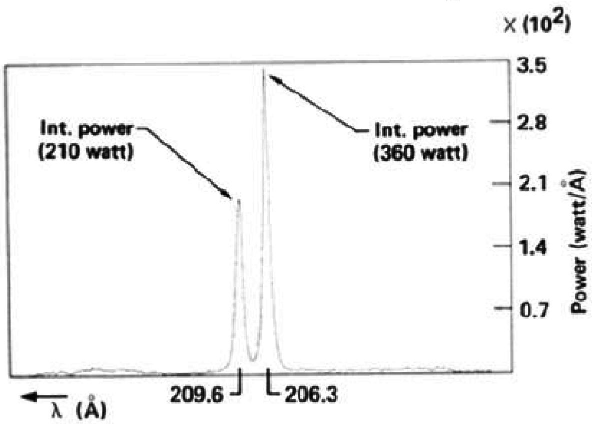
- Exploding Se foil compared with 2-D LASNEX simulations for laser irradiation conditions (n_e density profile)
- T_e ionization conditions measured

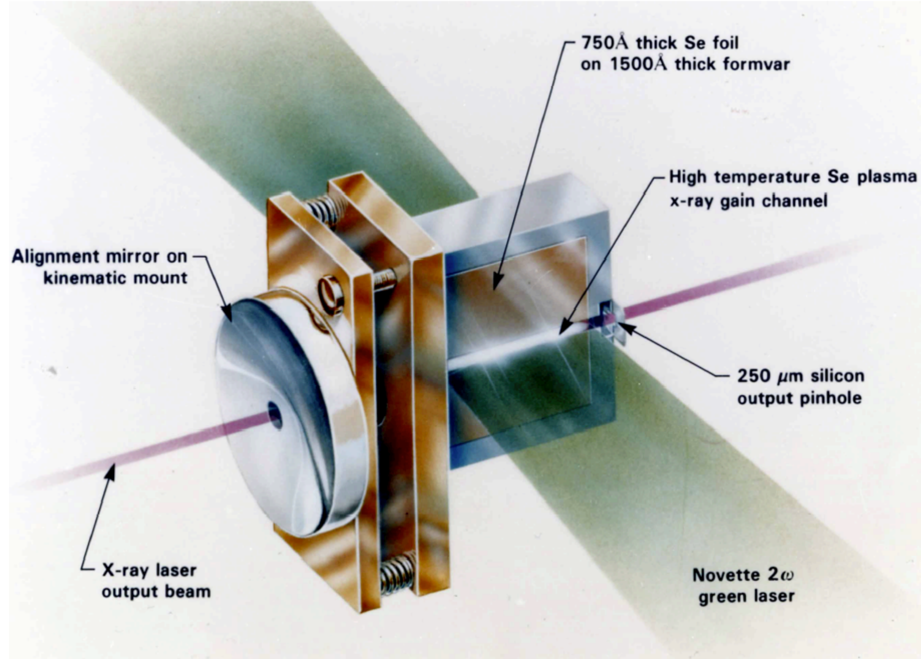
M. D. Rosen, P. L. Hagelstein, et al, PRL 54, 106 (1985)

Ne-like Se laser at ~20 nm was first demonstration of collisional excitation x-ray laser in 1984 on Novette

- Exploding foil Se target
- 1 kJ, 450 ps 2ω each side
- Line focus 200 μm ×1.1 cm, 2.2 cm
- Double and single-sided irradiation







- Lasing observed on Ne-like Y transitions
- Lasing observed on Ne-like 3p - 3s J = 2 - 1 lines at 20.63 and 20.96 nm
- g ~ 5 cm^{-1}, gL = 6.5
- No lasing observed on 18.3 nm J= 0 -1 line

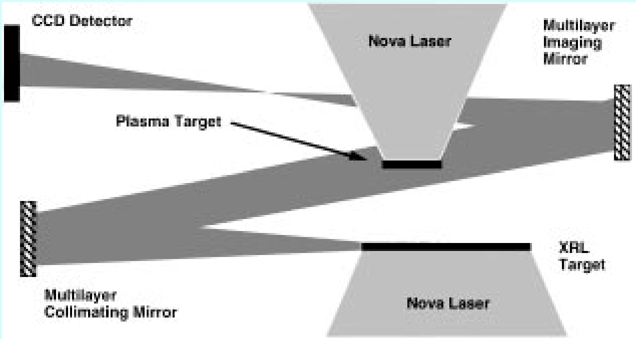
D.L. Matthews et al, PRL 54, 110 (1985)

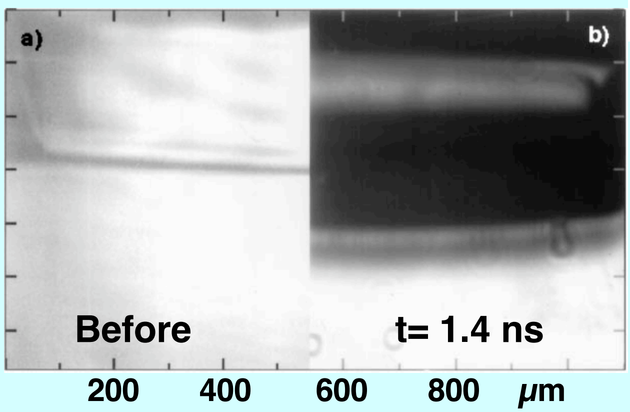
Further achievements with Nova x-ray laser:

- Wavelength scaling for Ne-like ion x-ray lasers to 10 nm (Fields 1992)
- Demonstration of Ni-like ion XRLs Eu 6.6, 7.1 nm (MacGowan 1987)
- Double-pass XRL amplifiers using multilayer optics (Ceglio 1988)
- X-ray laser holography demonstration (Trebes 1988)
- X-ray laser coherence measurements (Trebes)
- Shortest wavelength XRL Ni-like Au 3.5 nm (MacGowan 1990)
- High peak power measurements (Da Silva et al 1993)
- Line width measurements (Koch 1992)
- Hyperfine splitting Ne-like Nb 14.59 nm (Nilsen 1993)
- Use of pre-pulse to improve XRL generation (Nilsen 1993)

Applications using the Nova-driven x-ray laser:

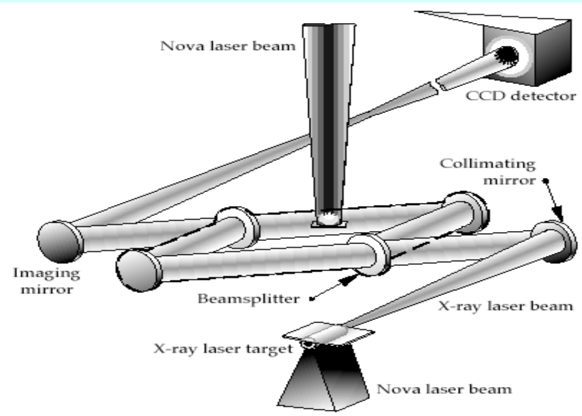
XRL Radiography Imaging of laser-heated Al Foil

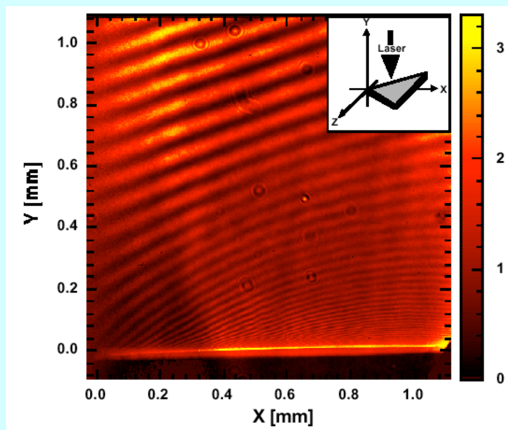




R. Cauble et al, PRL 74, 3816 (1995)

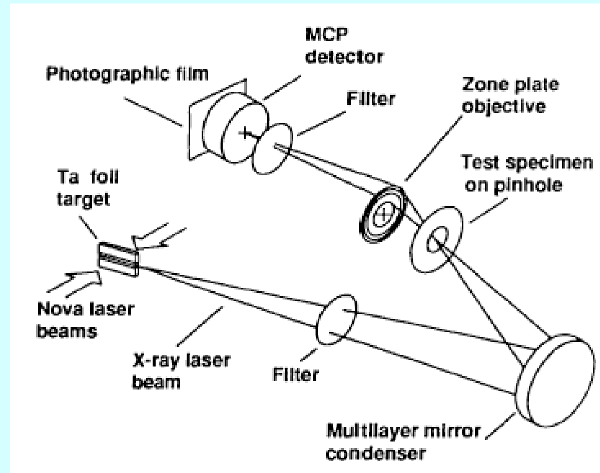
XRL Interferometry of Laser Plasmas

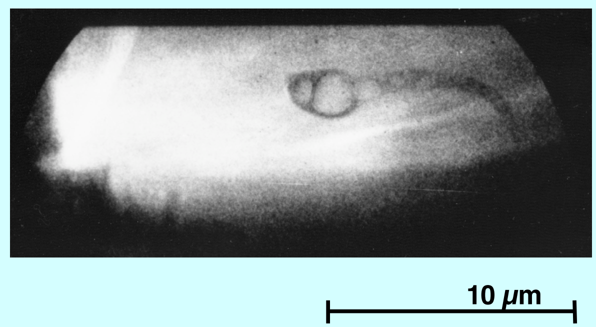




Da Silva *et al*, PRL 74, 3991 (1995).

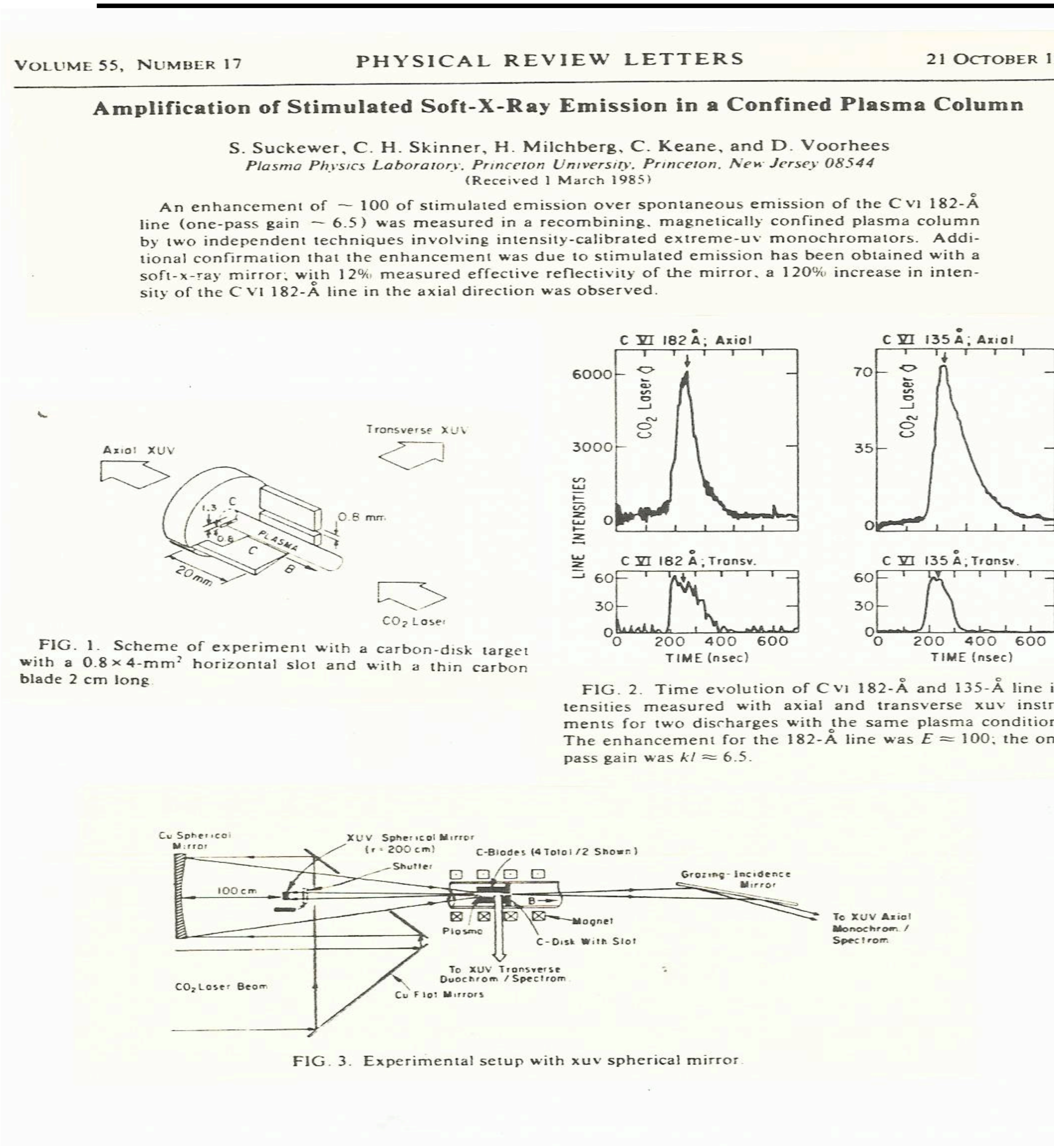
X-ray Laser Microscopy of Biological Cells at 4.5 nm





L. Da Silva *et al.*,
Science 258, 269 (1992)

Recombination Carbon 18.2 nm laser at Princeton based on a magnetically confined plasma column 1984 - 1985



VOLUME 55, NUMBER 17 PHYSICAL REVIEW LETTERS 21 OCTOBER 1985

Amplification of Stimulated Soft-X-Ray Emission in a Confined Plasma Column

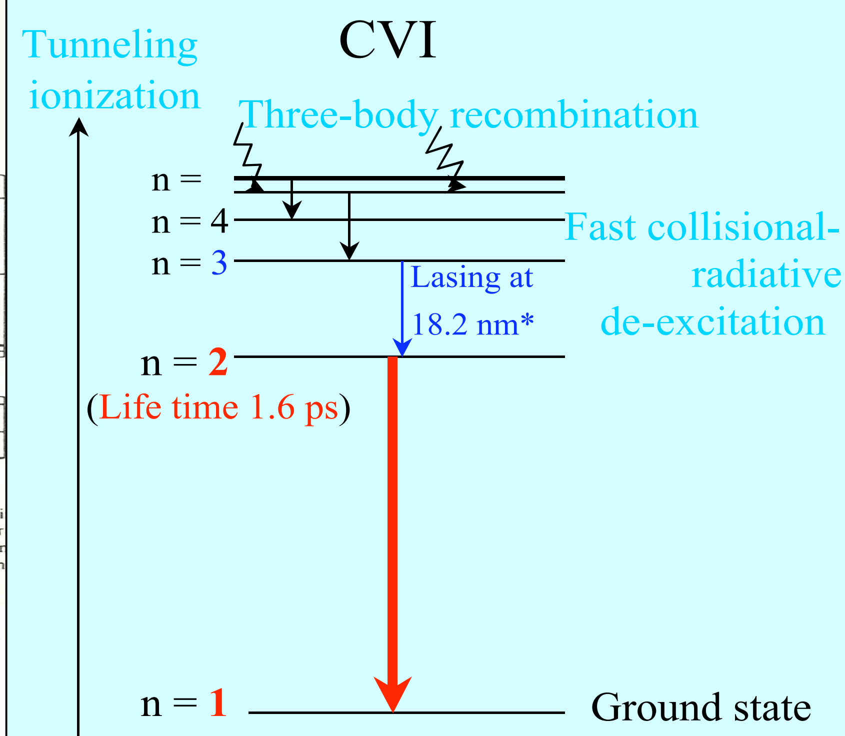
S. Suckewer, C. H. Skinner, H. Milchberg, C. Keane, and D. Voorhees
Plasma Physics Laboratory, Princeton University, Princeton, New Jersey 08544
(Received 1 March 1985)

An enhancement of ~ 100 of stimulated emission over spontaneous emission of the C VI 182-Å line (one-pass gain ~ 6.5) was measured in a recombining, magnetically confined plasma column by two independent techniques involving intensity-calibrated extreme-uv monochromators. Additional confirmation that the enhancement was due to stimulated emission has been obtained with a soft-x-ray mirror; with 12% measured effective reflectivity of the mirror, a 120% increase in intensity of the C VI 182-Å line in the axial direction was observed.

FIG. 1. Scheme of experiment with a carbon-disk target with a 0.8 × 4-mm² horizontal slot and with a thin carbon blade 2 cm long.

FIG. 2. Time evolution of C VI 182-Å and 135-Å line i[ntensities] measured with axial and transverse xuv instr[uments] for two discharges with the same plasma condition[s]. The enhancement for the 182-Å line was $E \approx 100$; the on[e-]pass gain was $kl \approx 6.5$.

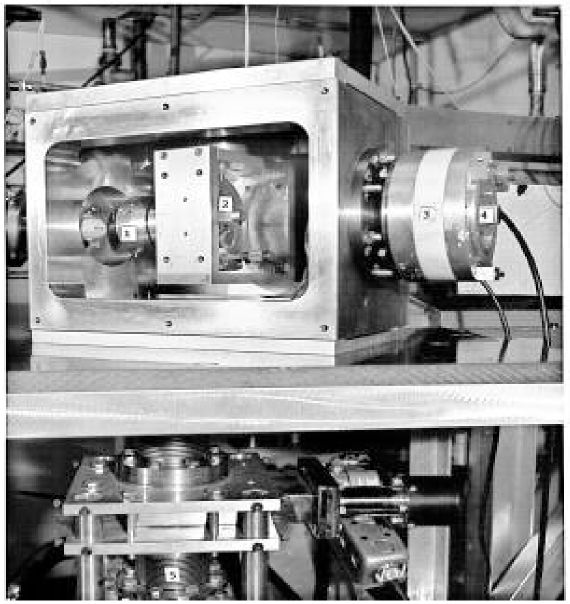
FIG. 3. Experimental setup with xuv spherical mirror.



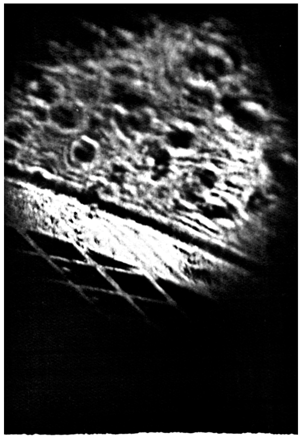
Pumped with 0.3 kJ, 80 ns CO_2 laser
gL ~ 8 for 18.2 nm n = 3 - 2 H-like C

S. Suckewer et al, PRL 55, 1753 (1985)

Recombination carbon x-ray laser applications: 18.2 nm soft x-ray reflection microscopy of biological cells (1992 - 1995)

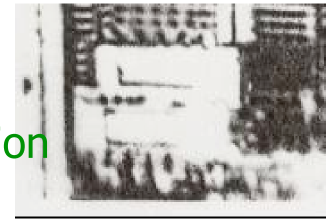


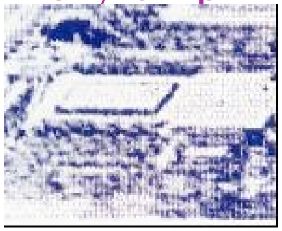
Biological Cells



High density memory chip

SXL Reflection microscope





Optical microscope

Dicicco et al, Opt. Lett. 17, 157 (1992)

Other US X-ray Laser Research in 1980s and 1990s

- Summary of activities in different US laboratories
- X-ray laser schemes
- Highlights of x-ray laser research

Other laboratories in 1980s and 1990s:

- **Collisional Excitation:**

  Using smaller lasers, 1ω, slab targets:

  - 200 J, ~1 - 2 ns class lasers

  - Naval Research Lab. (Elton, McLean): Ne-like Cu - Se - 1992

  - NRC Canada (Baldis, Enright): Ne-like Ge, Ni-like Sn 1989 - 1992

  - Tabletop 100 ps lasers

  - MIT (Hagelstein): Ni-like Nb 1988 - 1990s

  - Capillary Discharge - Colorado State University (Rocca) ~1992 -

  - Utah (Knight)

  - Tabletop 1 ps lasers LLNL (Dunn, Nilsen, Osterheld, Shlyaptsev) 1997-

- **Recombination Laser-driven:**

  - U. Maryland (Griem, Moreno) Al, Mg

  - LLNL Nova Al 20 ps drive

  - U. Rochester (Richardson)

  - Colorado State University (Rocca) C, F, O - 1992

Other laboratories and x-ray laser schemes

- Resonant Photo-pumping: Not demonstrated
  - NRL (Apruzese, Davis) 1985 Z-pinch Na X - Ne IX
  - LLNL (Nilsen) many schemes proposed
  - U. Rochester (Boehly) Ne-like Ti
  - Sandia Nat. Lab. (Matzen, Porter) Z-pinch Na X - Ne IX
  - U. Cornell (Hammer) Z-pinch

- Innershell: Some earlier work in UV by Silfast (1983), Kapteyn (1980s)
  - U. San Diego (Barty, Kim, Toth) electron pumped various XRLs
  - LLNL (Eder, Moon, Weber, Celliers) photo-ionized C K-α 4.5 nm

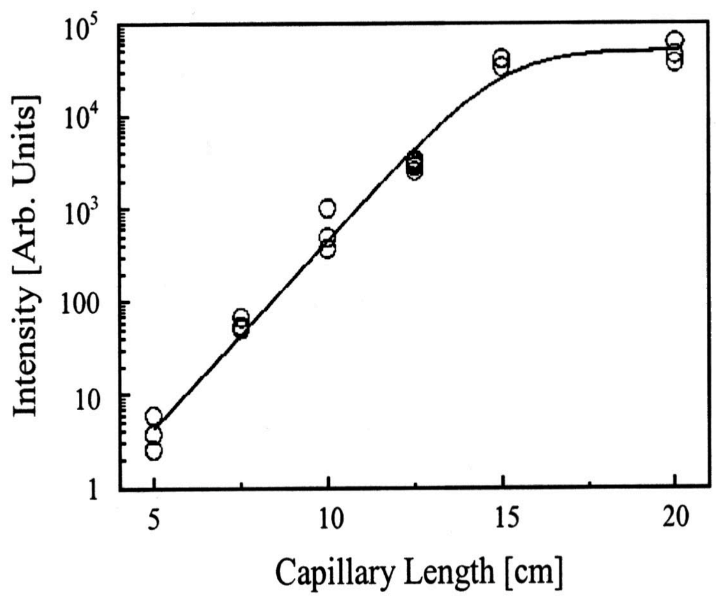
- Optical Field Ionization (OFI):

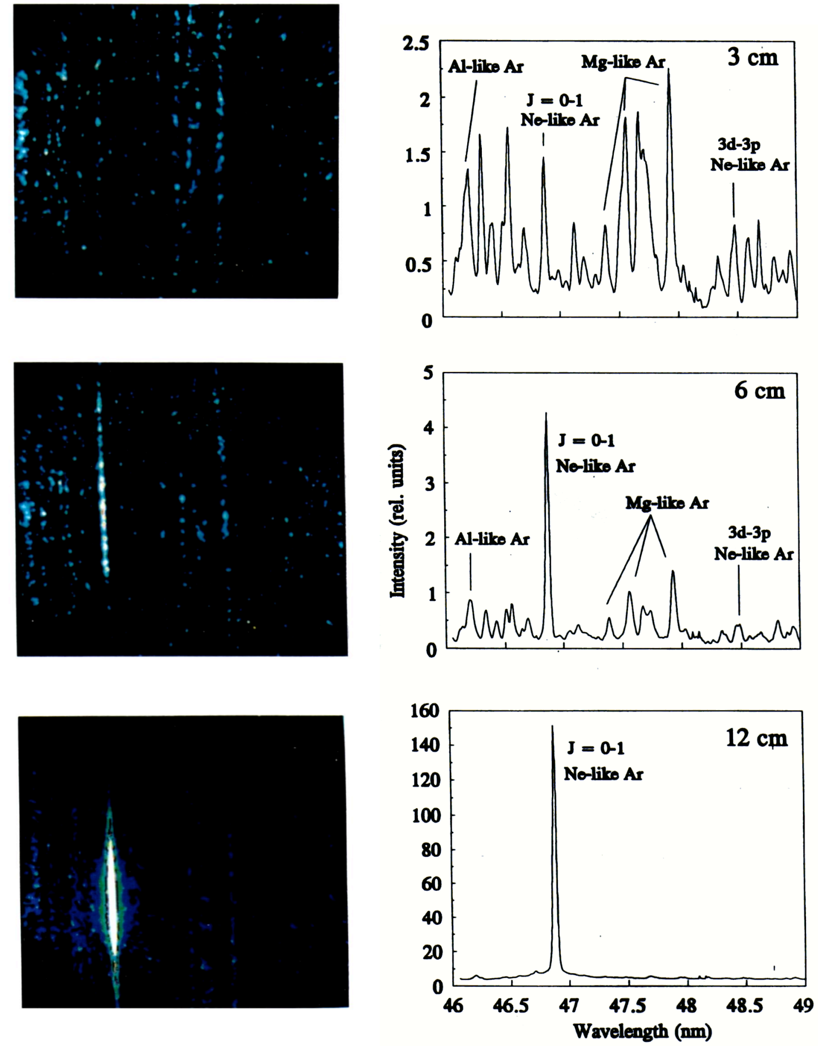
  Collisional Excitation
  - U. Stanford (Lemoff, Barty, Harris) Pd-like Xe 41.8 nm 1995

  Recombination
  - Princeton (Korobkin, Suckewer) Li Ly-α 13.5 nm 1996

Capillary Discharge: Amplification in Ne-like Argon at 46.9 nm

- Exponential amplification of the $3p^1S_0 - 3s^1P_1$ line creates a bright single line laser source at 46.9nm
- Gain saturation achieved for 15cm plasma column lengths





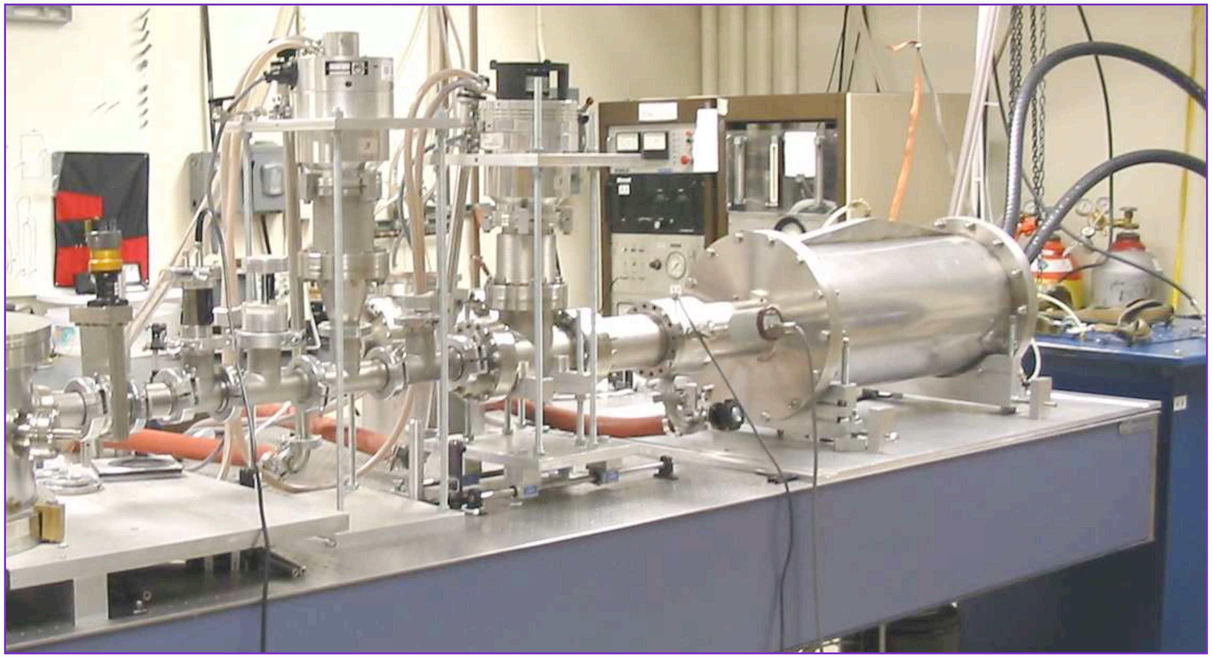
J. J. Rocca et al., PRL 73, 2192 (1994); PRL 77, 1476 (1996).

Tabletop capillary discharge laser produces similar coherent average power at λ=46.9 nm as synchrotron

Capillary discharge 46.9 nm laser

- **High average power:** 1-3 mW
- **High pulse energy:** 0.1 mJ – 0.8mJ @4 Hz
- **Narrow spectral bandwidth:** $\Delta\lambda/\lambda = 10^{-4}$
- **Beam directionality:** θ = ~5 mrad

Highest average power compact coherent SXR light source available

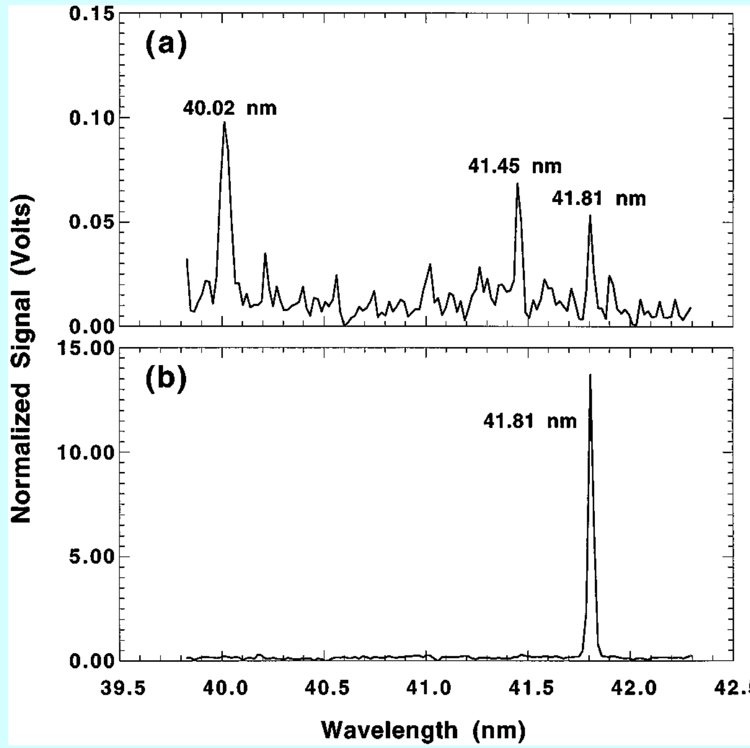


B. Benware et al., PRL 81, 5804 (1998): C.D. Macchietto et al., Opt. Lett. 24, 1115 (1999).

Optical Field Ionization process was demonstrated for collisional x-ray lasers using inert gas medium at Stanford

- OFI/collisional scheme proposed by Burnett and Corkum 1989.
- Gas is stripped by tunneling ionization by laser electric field to create desired ion state
- Energetic electrons collisionally pump ground state to create inversion
- 40 fs, 70 mJ, 10 Hz, 3×10^{16} W cm^{-2}
- Xe gas cell, longitudinally pumped
- g ~ 13 cm^{-1}, gL = 11, Pd-like Xe
- OFI collisional x-ray lasers have been driven into gain saturation regime recently by LOA group for Xe and Kr

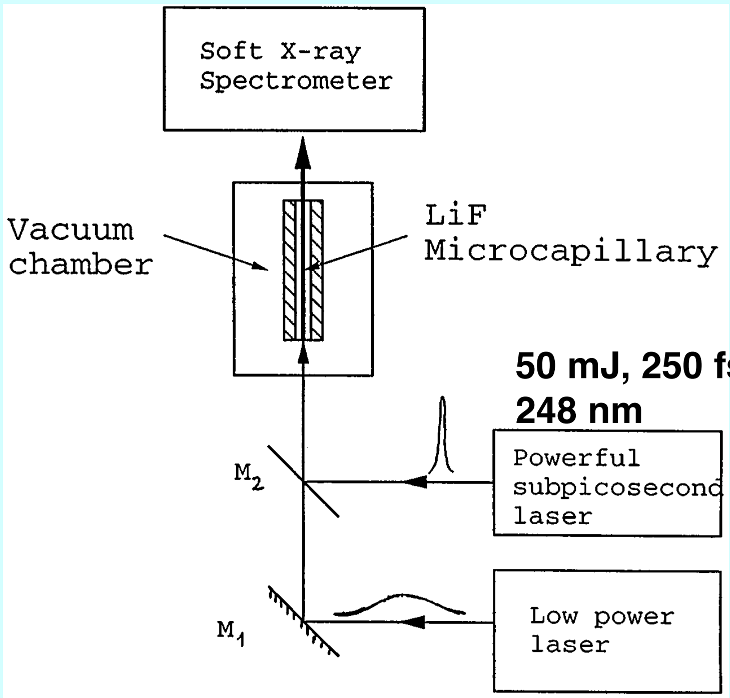
Pd-like Xe 5d - 5p x-ray laser at 41.8 nm wavelength



B.E. Lemoff et al, PRL 74, 1574 (1995)

Optical Field Ionization was also demonstrated for recombination Li III 2 - 1 13.5 nm x-ray laser at Princeton

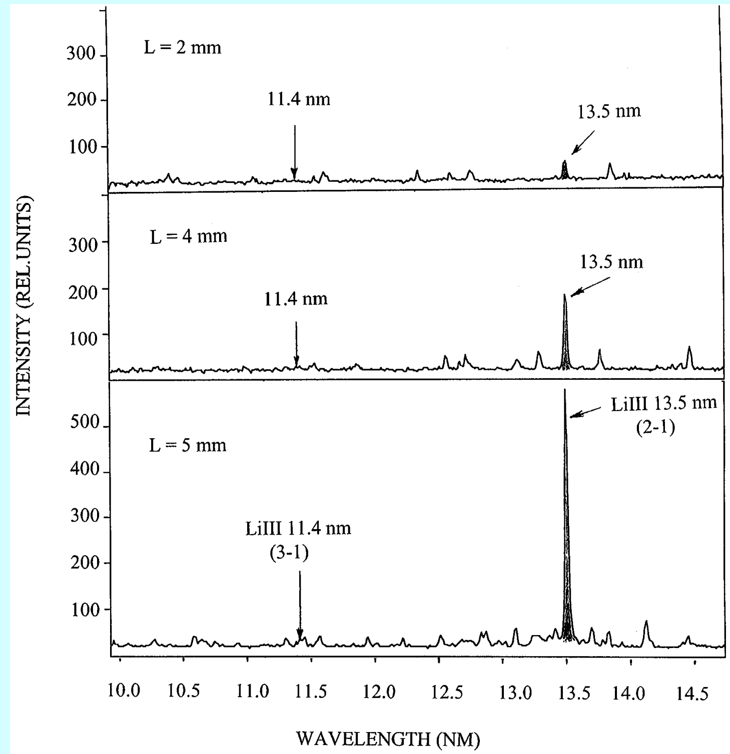
Experimental Geometry



50 mJ, 250 fs, 248 nm

100 mJ, 5ns, 1 μm

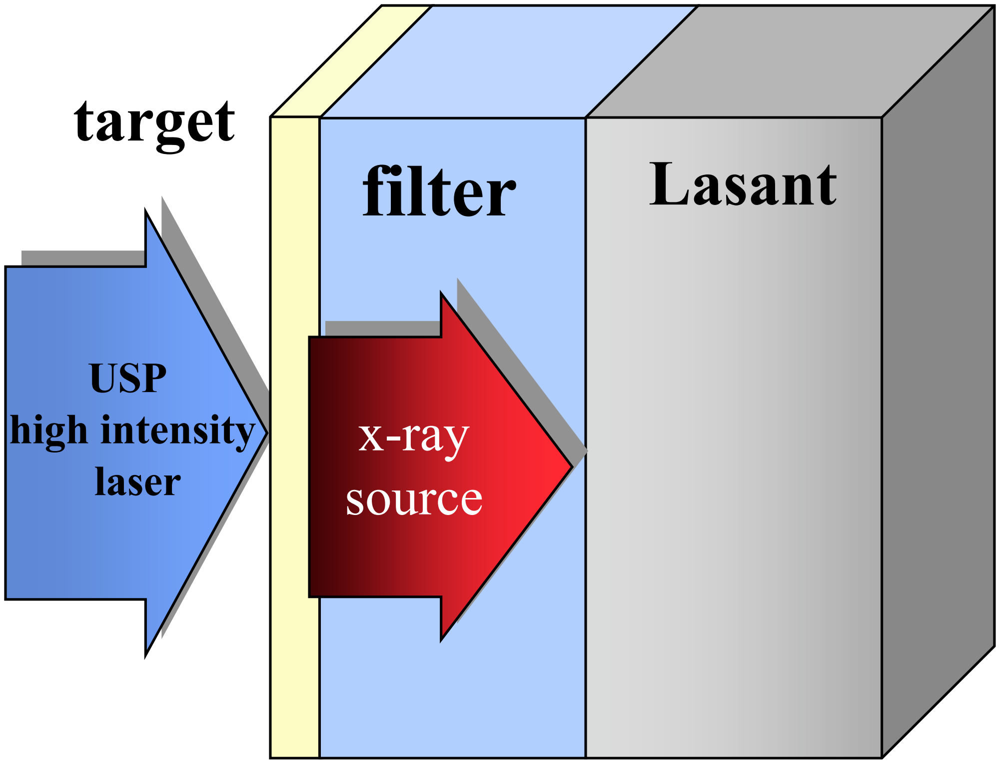
H-like Li Ly-α 13.5 nm x-ray laser



Korobkin et al, PRL 77, 5206 (1996)

- g ~ 11 cm^{-1}, gL = 5.5
- Experiment repeated at NRL using capillary discharge

Basics of Inner-shell Photo-ionized x-ray laser:



USPL (< 50 fs FWHM) @ > 1 J produces a hot plasma at line focus.

Plasma generates a broad-band x-ray spectrum with a rapid rise time.

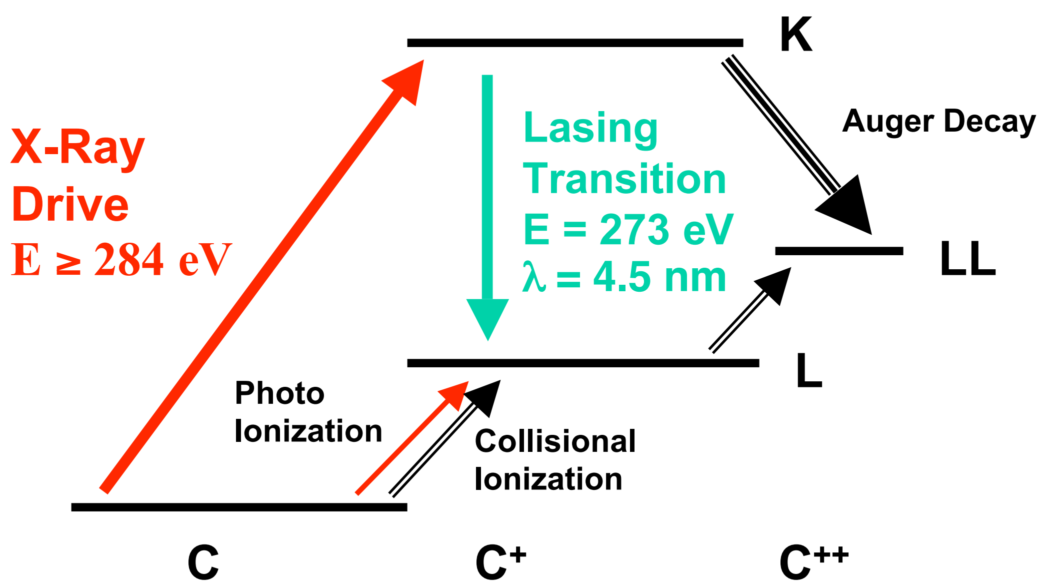
A high-pass filter rejects a majority of low energy x-rays that can populate the lower state.

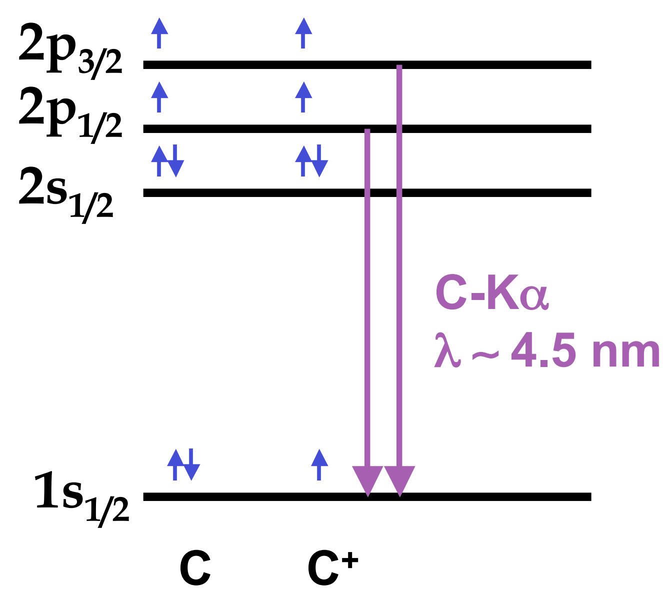
Remaining harder x-rays primarily photo-ionize inner-shell of lasant atoms.

- **Proposed by Duguay and Rentzepis (1967)**
- **Modeling for C by (Eder, Moon), experimental activities by Weber and Celliers**

F. Weber

Competing Basic Atomic Processes Provide Challenge for ISPI Lasing In Carbon

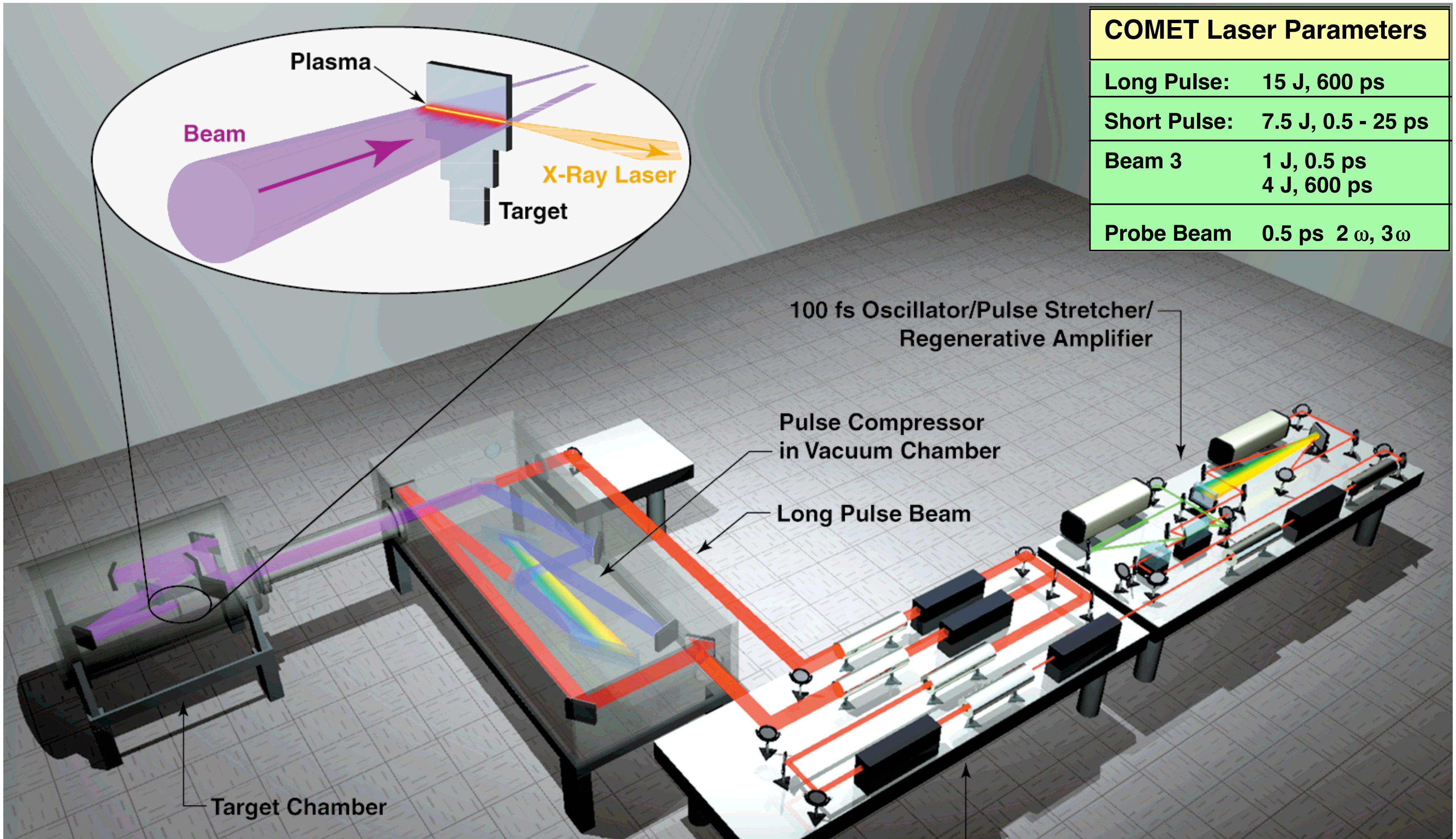




- The filtered pump produces a population inversion, and resulting positive gain for an allowed 2p-1s radiative transition in the singly charged ion.
- Rapid Auger decay of the 1s hole state competes with the lasing transition and produces a large number of energetic electrons into the lasant material.
- Electron induced ionization to the lower laser state ($1s^2 2s^2 2p^1$) limits the magnitude and duration of positive gain.
- Ultra-short pulse x-ray lasing is inherent in this scheme.

F. Weber

Tabletop Transient 1 ps x-ray laser work at LLNL started in 1997 - motivated by Ne-like Ti results at MBI group in Berlin



COMET Laser Parameters	
Long Pulse:	15 J, 600 ps
Short Pulse:	7.5 J, 0.5 - 25 ps
Beam 3	1 J, 0.5 ps 4 J, 600 ps
Probe Beam	0.5 ps 2 ω, 3ω

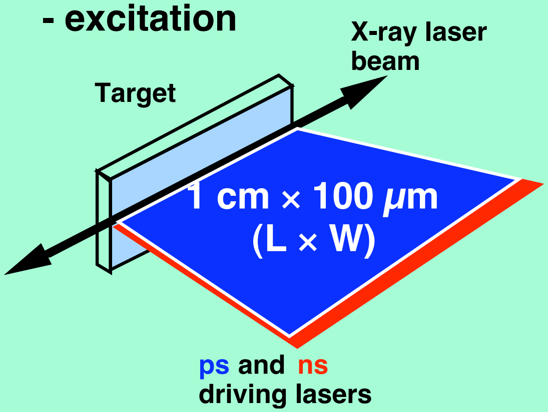
Compact Multipulse Terawatt (COMET) laser has 4 beams of 0.5 - 600 ps pulse duration available simultaneously for experiments

Transient scheme uses 1 ps, 5 - 10 TW laser pulse to optimize excitation - Tabletop X-ray Laser

Two Stage Process

Long laser pulse: 1 - 5 J
- plasma formation
- ionization
- delay for relaxation of density gradients

Short laser pulse: 2 - 7 J
- excitation



Tabletop

Laser Driver

Optimize Excitation

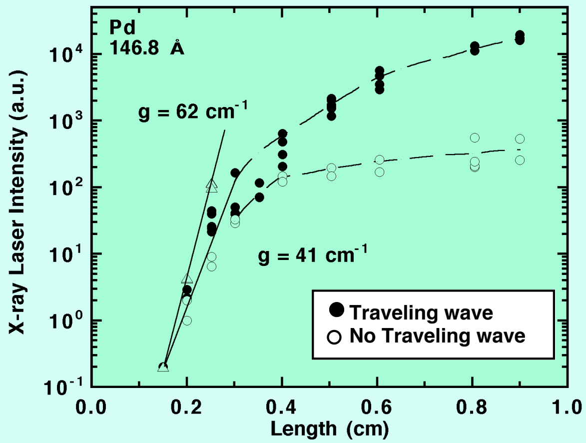
- Pump energy: <10 J, ~2 - 7 J
- High gain: 25 - 65 cm^{-1}
- Target length: ~ 1 cm
- Wavelength: 119 Å (104 eV)
- High shot rate: 1 shot/4 min. 50-100 shots/day
- XRL duration: 3 - 7 ps
- Inexpensive slab targets

P.V. Nickles *et al*, PRL 78, 2748 (1997)
Yu. V. Afanasiev and V.N. Shlyaptsev, Sov. J. Quant. Electron. 19, 1606 (1989).

10 - 1000x reduction in laser energy for transient scheme compared to Nova x-ray laser

Traveling wave drives Ni-like Pd at 14.7 nm into gain saturation regime with 5 - 7 J energy in line focus

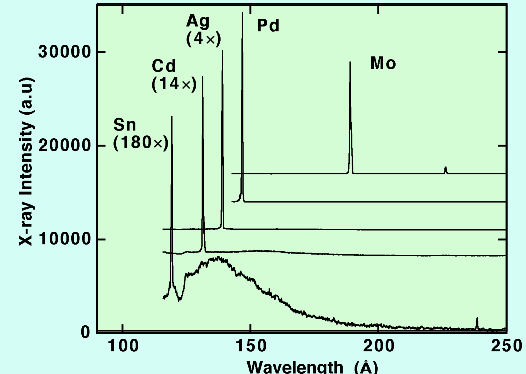
Ni-like Pd gain with traveling wave

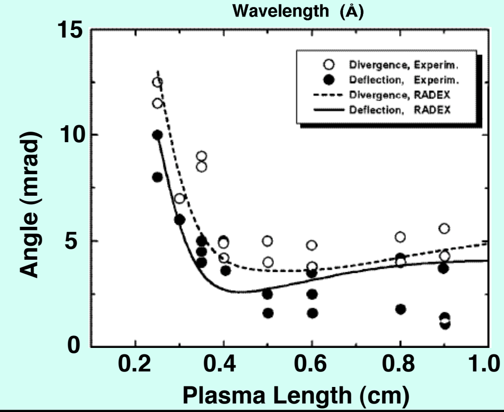


J. Dunn, Y. Li, A.L. Osterheld, J. Nilsen, J.R. Hunter, V.N. Shlyaptsev,Phys. Rev. Lett 84, 4834 (2000)

- Small signal gain of 41 - 62 cm^{-1}
- 100x enhancement with TW
- gL = 18, output energy ~ 12 μJ
- 0.5 - 1.5 J, 600 ps , 4.5 - 5.5 J, 1.3 ps

Ni-like x-ray lasers and Pd angular pointing





- Radex simulations indicate maximum deflection angle $(n_e/n_c)^{0.5}$ reveals optimal amplification at n_e ~0.9 x 10^{20} cm^{-3}

Higher efficiency of Ni-like XRL well matched to small driver

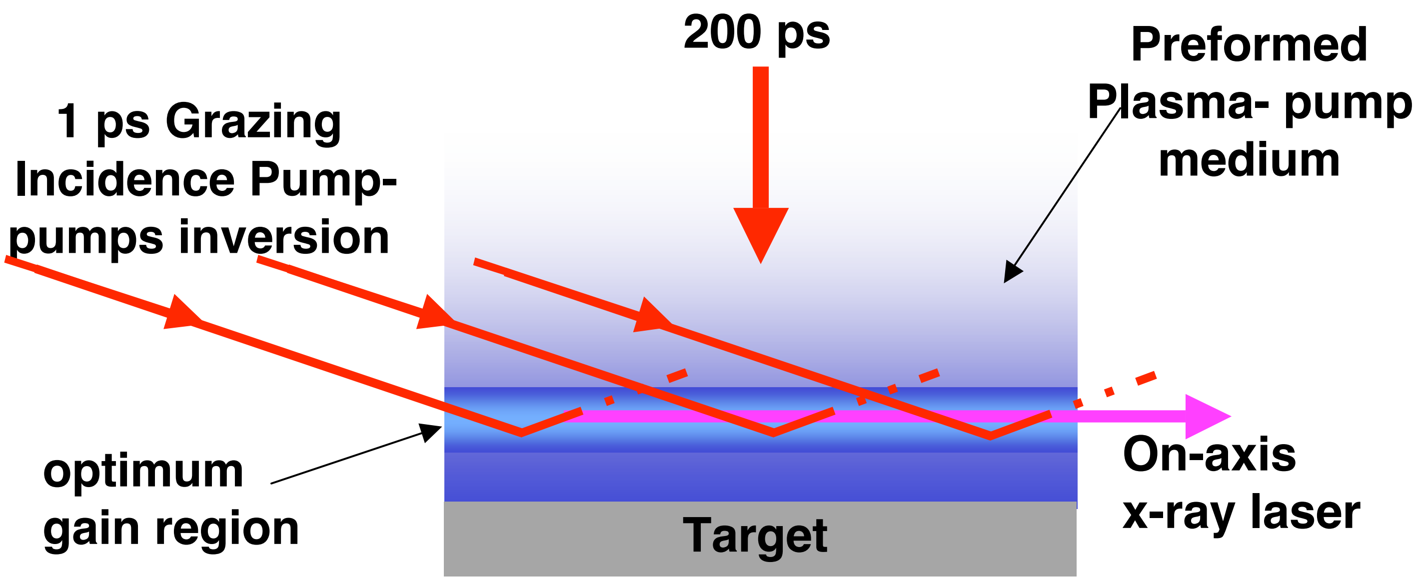
Output still increasing with length - extract more XRL energy

Physics & Advanced Technologies

Recent highlights of present US status (2000 - 2005)

- Grazing Incidence Pumping
- Source development capillary discharge

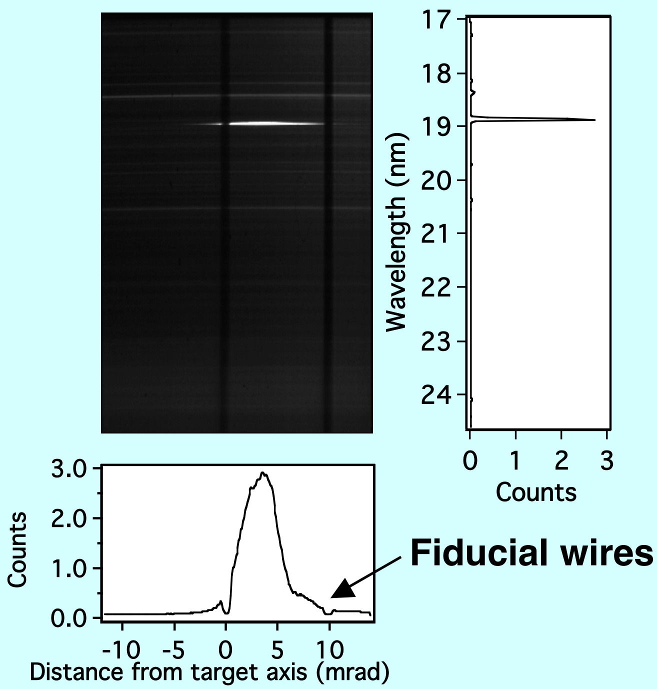
Grazing Incidence Pumping (GRIP): Novel method for efficient x-ray lasers uses controlled refraction of pump



- **Two stage pumping process to generate x-ray laser**
- **Short pulse propagates in plasma up to a specific electron density and selectively pumps the active volume for the gain region**
- **Short pulse is then refracted back into gain region**
- **Short pulse angle given by** $\theta = \sqrt{n_{e0} / n_{ec}}$ **where** n_{e0}**= density at turning point**
- **Traveling wave pump inherent and no restriction on target length**
- **Absorption efficiency of 5-8% for transverse increases to 50-70% for GRIP**

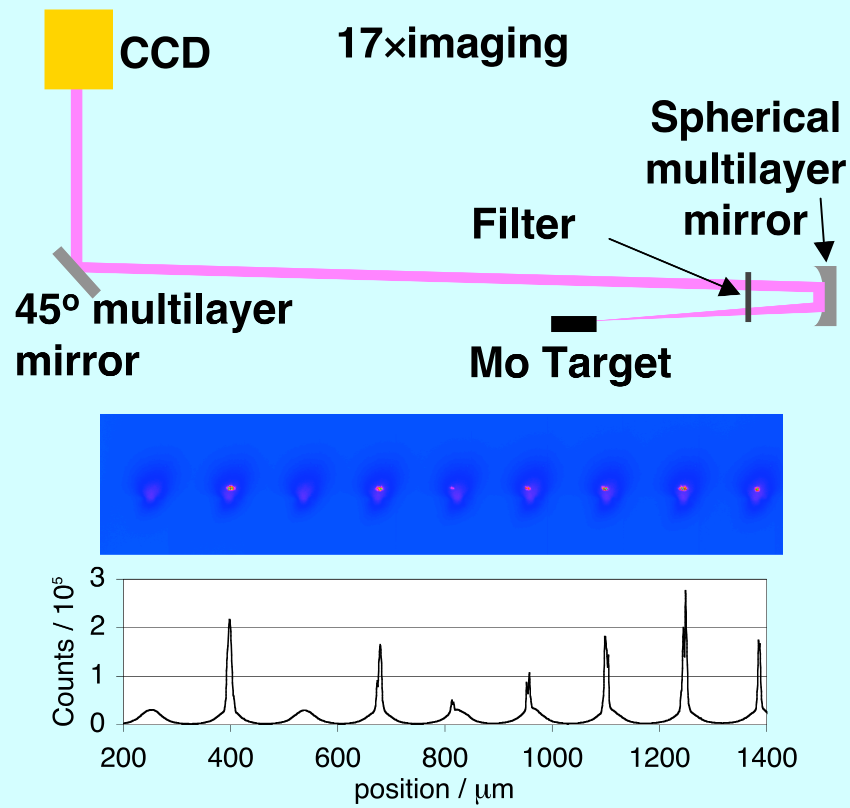
Ni-like Mo 18.9 nm, 10 Hz x-ray laser demonstrated using 150 mJ of 800 nm laser energy

Spectrometer: Wavelength, Refraction and Divergence Angle



4.5 mrad deflection angle
3 mrad (FWHM) beam divergence

Imaging XRL with multilayer optics: exit size, beam line reproducibility

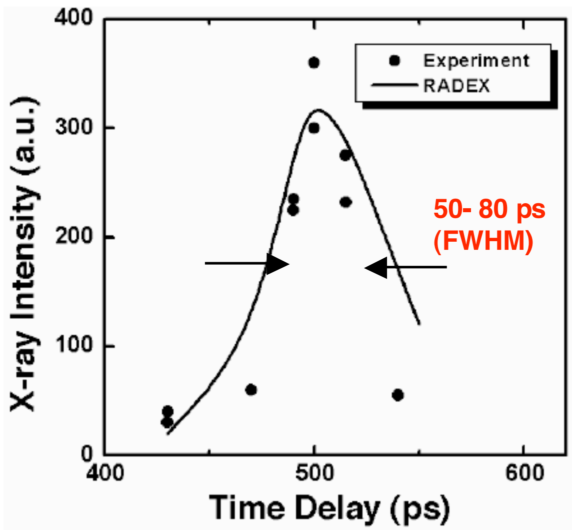


Mo:Si multilayers courtesy of J. Nilsen, T.W. Barbee, Jr.

XRL has good characteristics but sensitive to pump laser overlap

Pumping conditions optimized to maximize Ni-like Mo 18.9 nm x-ray laser output

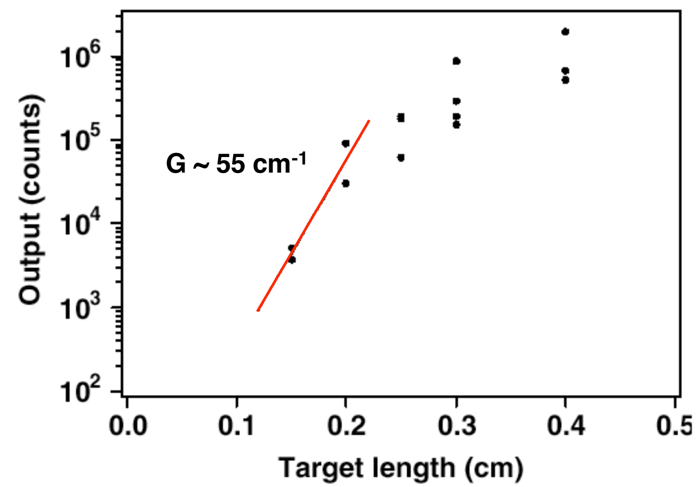
Delay between laser pulses with modeling



Plasma produced by narrow 15 μm LP line focus strongly affects window for optimized lasing

XRL output shows saturation-like behavior at 4 mm

SP = 1.5 ps, Δt = 500 ps



R. Keenan et al, Phys. Rev. Lett. 94, 103901 (March 2005)

gl~14 operating close to saturation

Estimated XRL output of >10 nJ

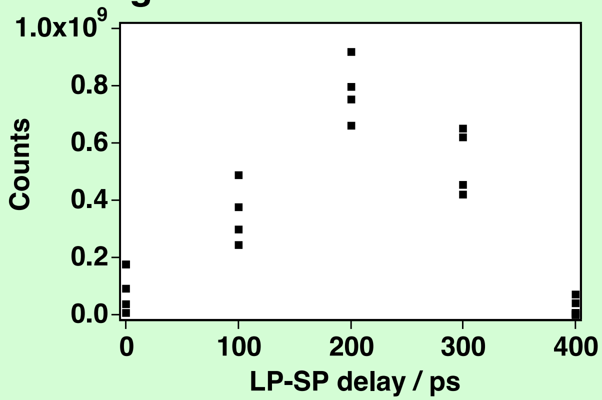
High XRL gain observed for very small laser energy pump and experimental delay between pulses in agreement with simulations

Physics & Advanced Technologies

GRIP scheme transferred to COMET for x-ray laser wavelength scaling with ~1 - 2J laser drive

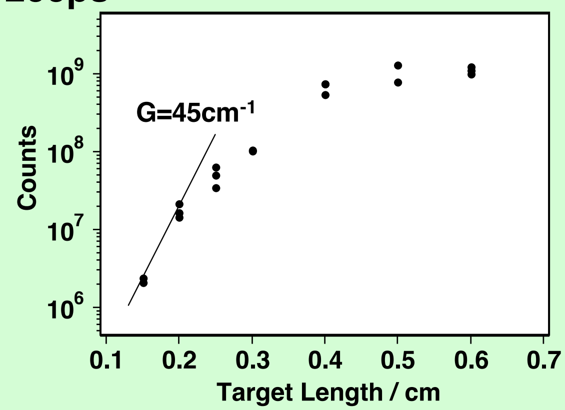
Ni-like Pd 14.7 nm output vs LP-SP delay

Pd 4 mm target



XRL output vs length

Δt=200ps



XRL spectrum and pump conditions

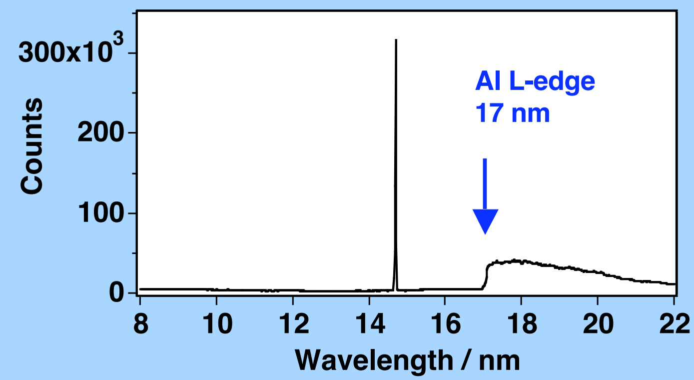
Laser Pump Conditions

LP (1ω): 1.2 J, 1054 nm, 600 ps

SP (2ω): 1.3 J, 527 nm, 1.5 ps

θ: 10° $n_e \sim 1.2 \times 10^{20}$ cm^{-3}

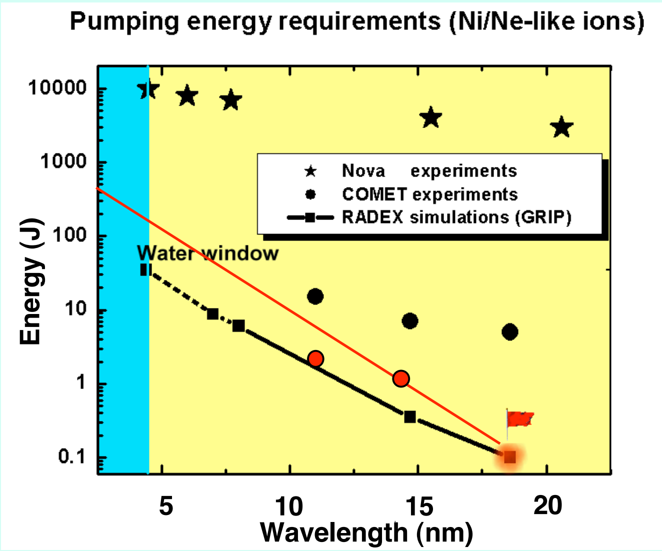
X-ray Filter: 2000Å Al



- GRIP x-ray laser works well for different Z, laser pump conditions
- 10x more pump energy gives >100x more output

Scaling x-ray laser to short wavelengths requires higher power laser pump, $P \sim \lambda_{XRL}^{-(4-6)}$

RADEX Predicted Parameters for GRIP X-ray Laser



Z	λ_{XRL} (nm)	λ_{pump} (nm)	E_{pump} (J)	n_e (10^{20} cm^{-3})	Status
Mo	18.9	800	0.15	1	✓
Pd	14.7	527	0.4 - 3	1 - 2	✓
Nd	8.0	527	9 - 12	5	Laser time?
Ta	4.5	?	50?	>5?	Laser*

X-ray Laser Wavelength

Laser Pump Wavelength

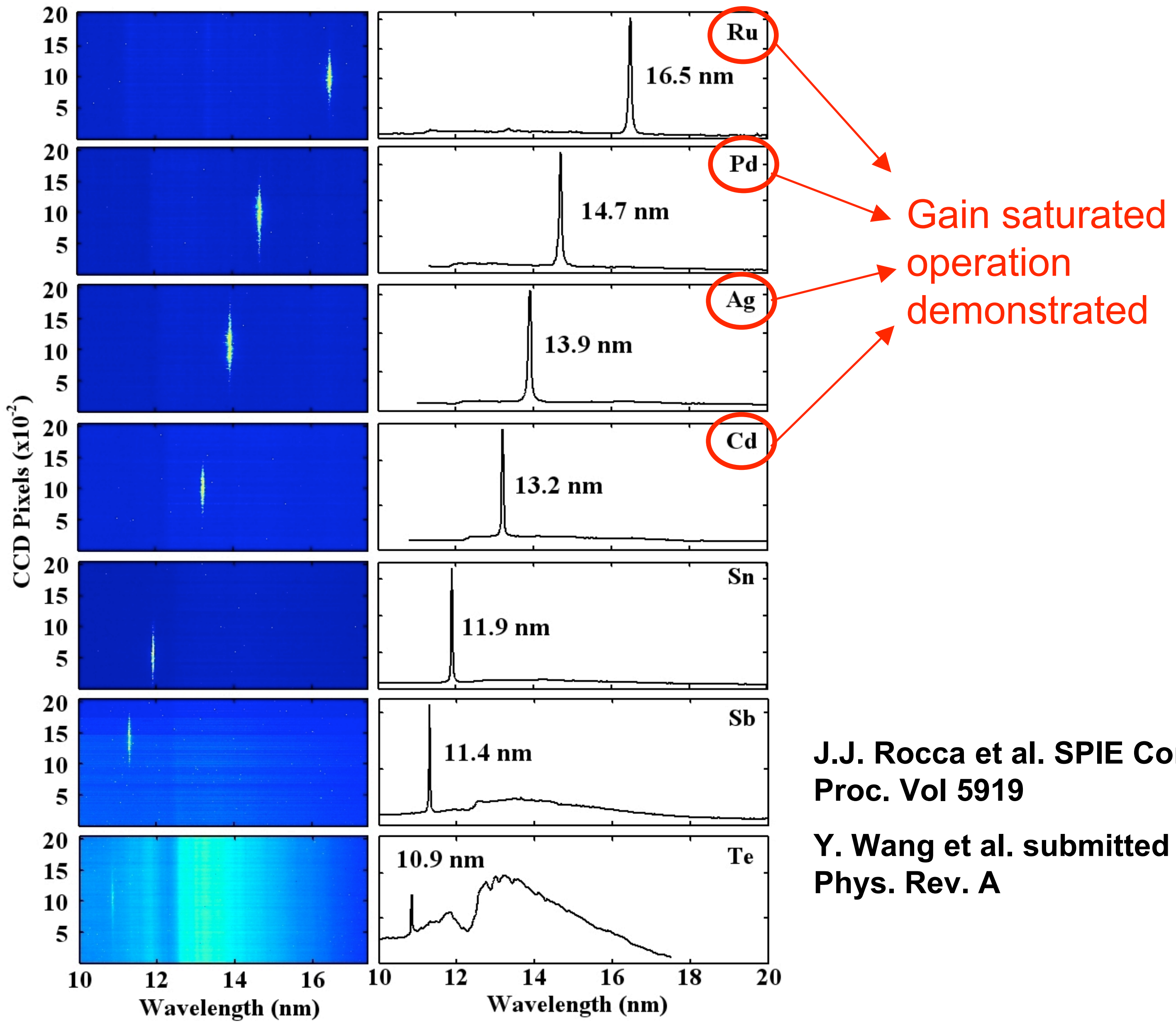
- GRIP pumping will reduce laser pump energy requirements by orders of magnitude to generate efficient x-ray laser
- Tentative extrapolation into water-window

Laser* depends on Titan ~2005

Plan to continue to study intermediate sub-10 nm XRLs

Physics & Advanced Technologies

Lasing observed at wavelengths as short as 10.9 nm

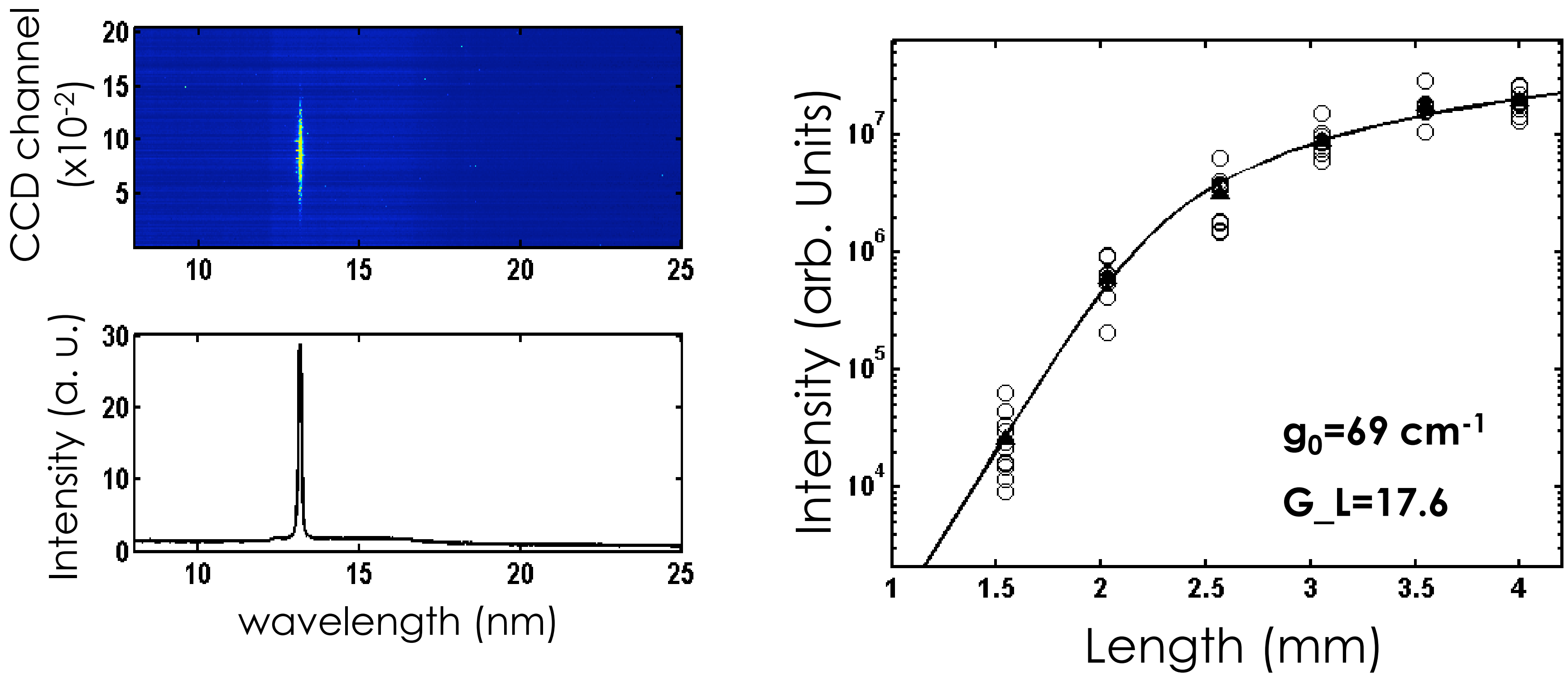


J.J. Rocca et al. SPIE Conf. Proc. Vol 5919

Y. Wang et al. submitted Phys. Rev. A

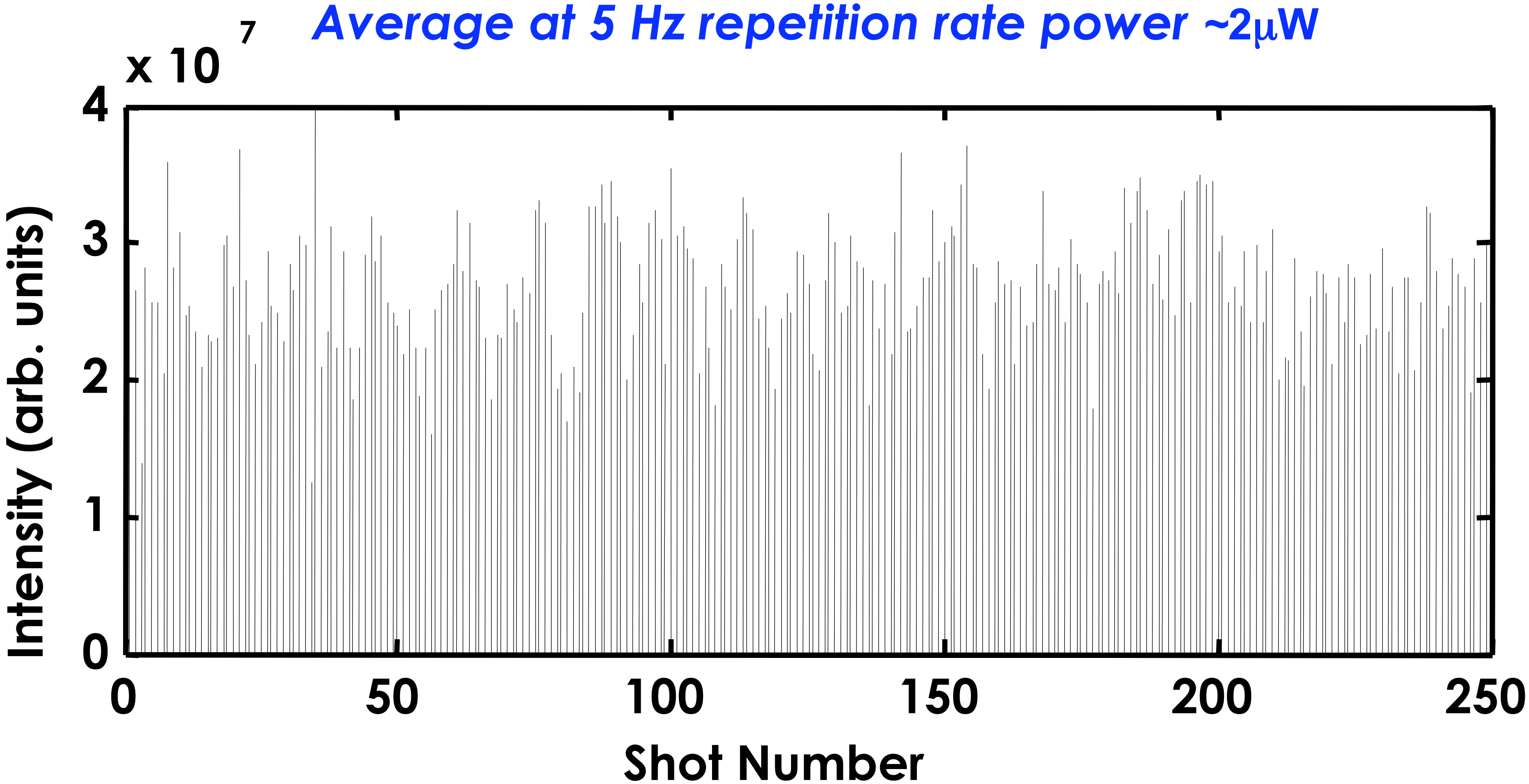
Gain-saturated Ni-like 13.2 nm Ni-like Cd laser

1 J short pulse – 23 degrees grazing incidence angle



High repetition rate operation of 13.9 nm Ni-like Ag laser

Average at 5 Hz repetition rate power ~2μW



Similar performance also obtained for Ni-like Cd @ 13.2 nm, > 1 μW average power

09-01-05-XRL-JD-33

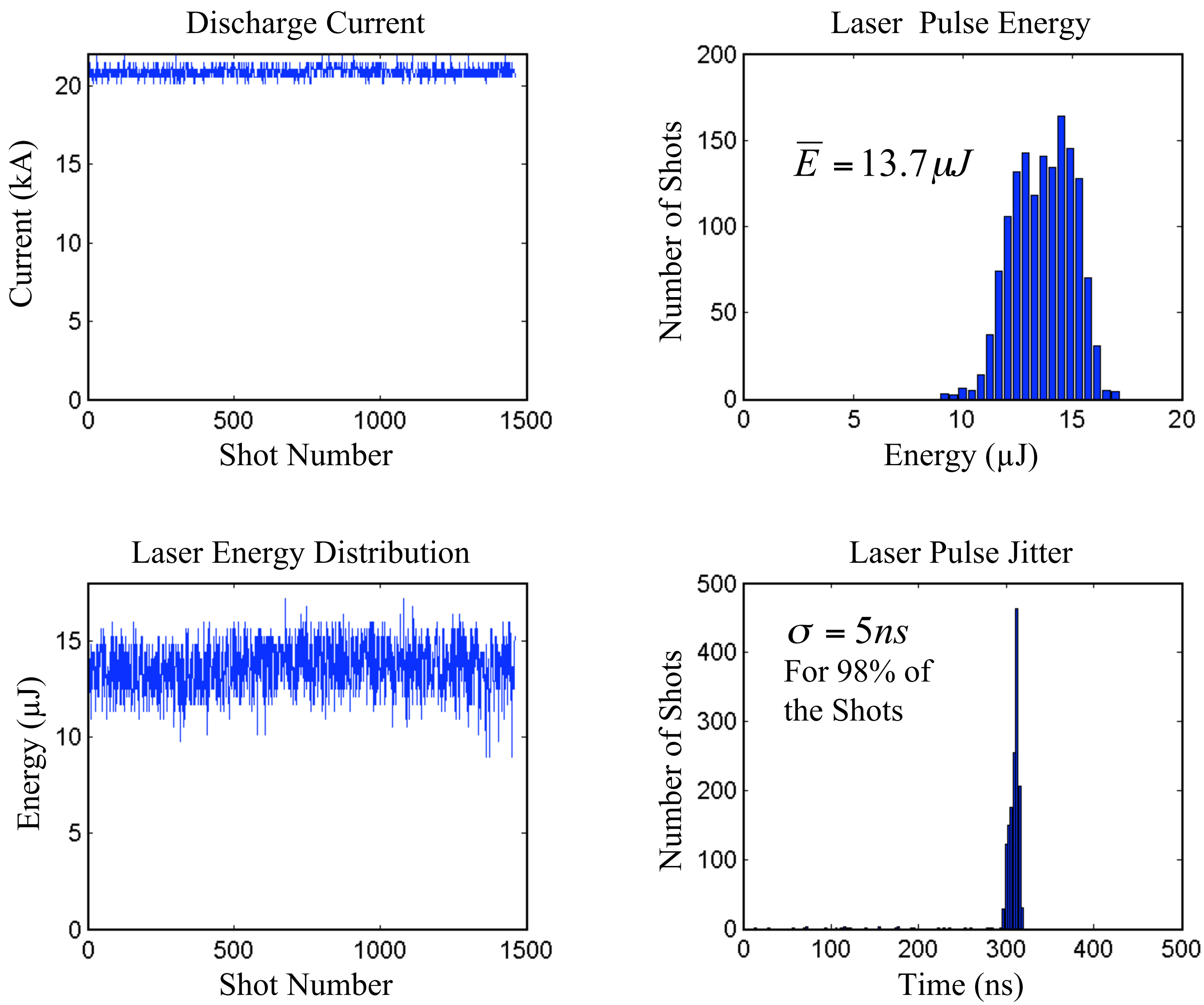
High repetition rate desk-top EUV laser

The laser occupies a table surface area of 0.4 m^2

S. Heinbuch et al., Optics Express, **13**, 4050, (2005).

09-01-05-XRL-JD-34

Desk-top 46.9 nm laser output pulse statistics
1500 shots at 12 Hz repetition rate



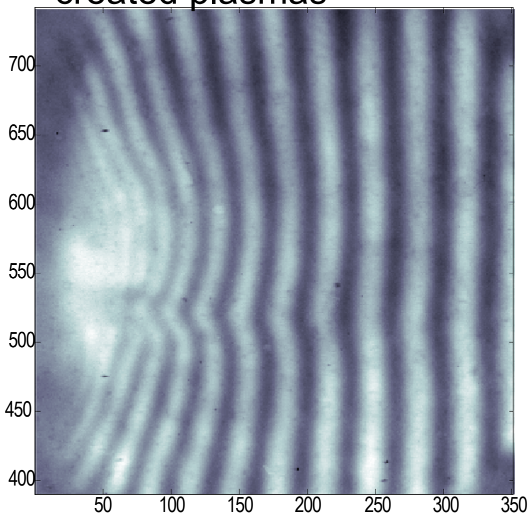
09-01-05-XRL-JD-35

X-ray Laser Applications

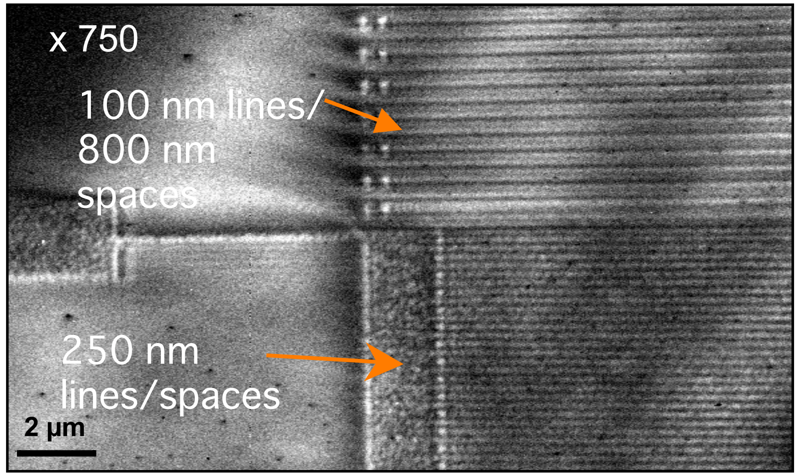
- Capillary Discharge - Various Applications
- Picosecond Transient - Photoelectron spectroscopy
- Plasma characterization - 14.7 nm interferometry
- Biological Imaging

Table-top capillary discharge Soft X-ray lasers have been used in numerous applications

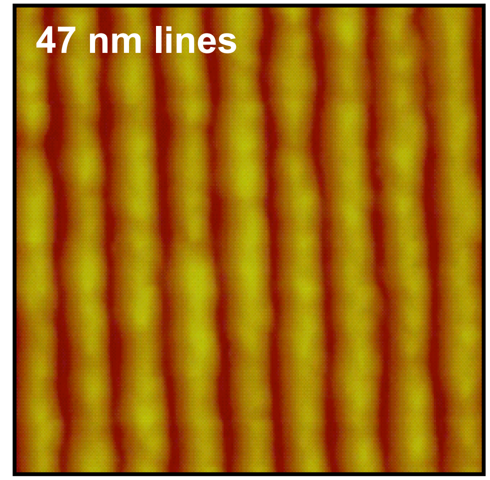
1. Interferometry of laser-created plasmas



2. EUV microscopy

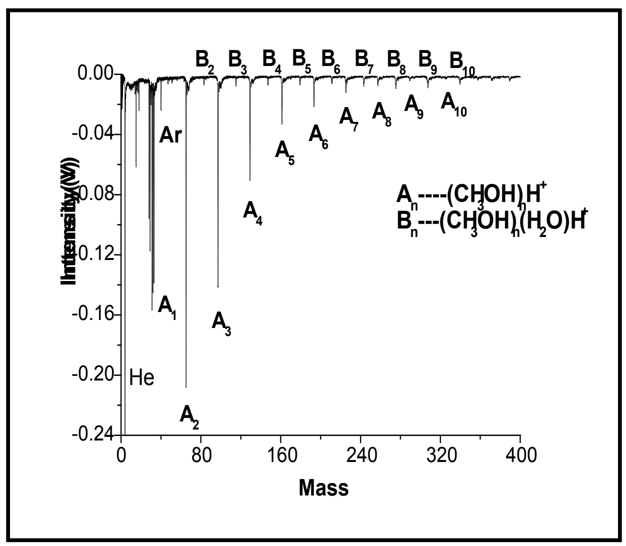


3. Nanopatterning



4. Laser Ablation

5. Nanocluster Spectroscopy

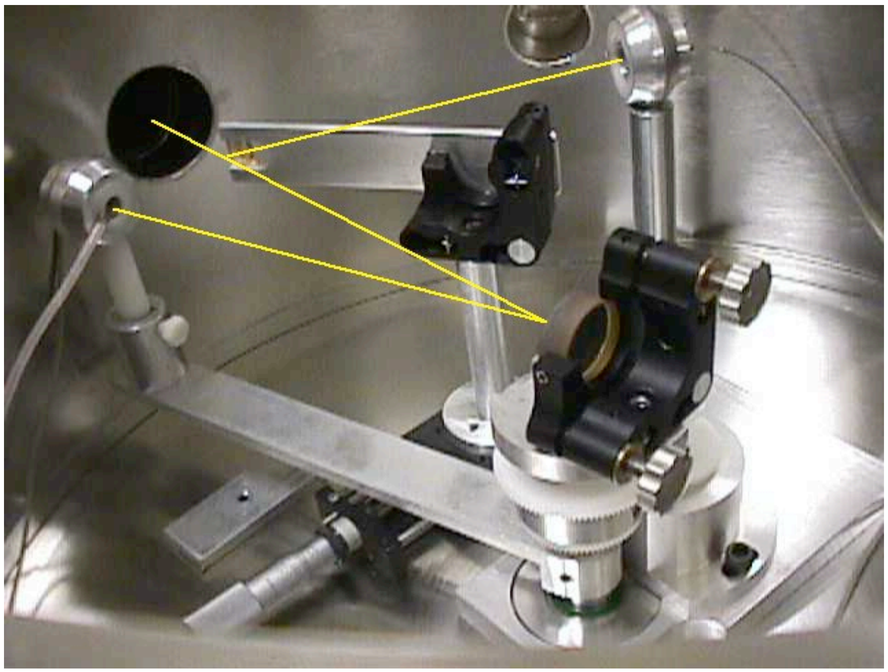


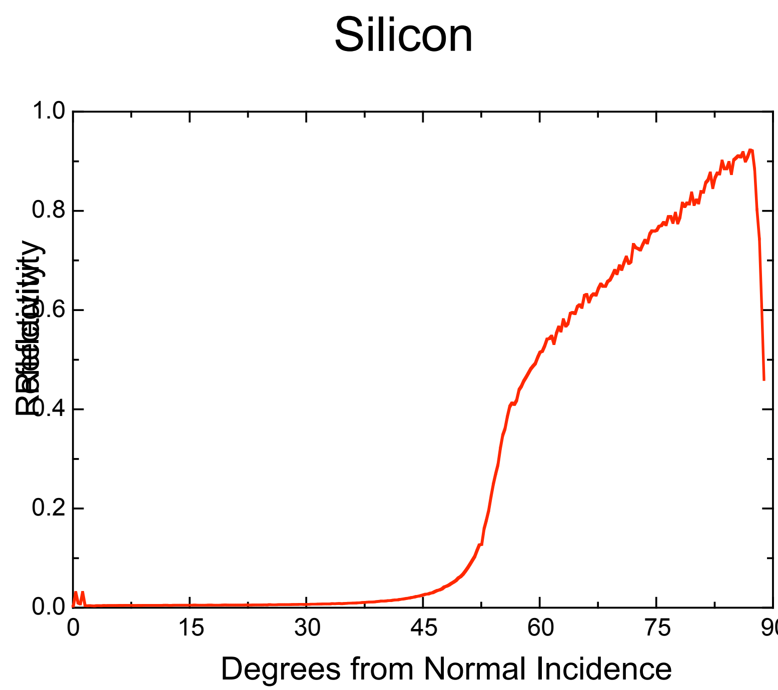
1. **J.J. Rocca et al, Phys. Of Plasmas, 10, 2031 (2003).**
2. **F. Brizuela et al, Optics Express, 13, 3983, (2005)**
3. **M.G. Capeluto et al, IEEE Transactions on Nanotechnology, (in press),**
4. **J. Juha et al, Appl. Phys. Lett. 86, 034109 (2005).- M. Grisham et al, Optics Letters, 29, 620 (2004).**

09-01-05-XRL-JD-36A-2

Determination of EUV optical constants by reflectometry

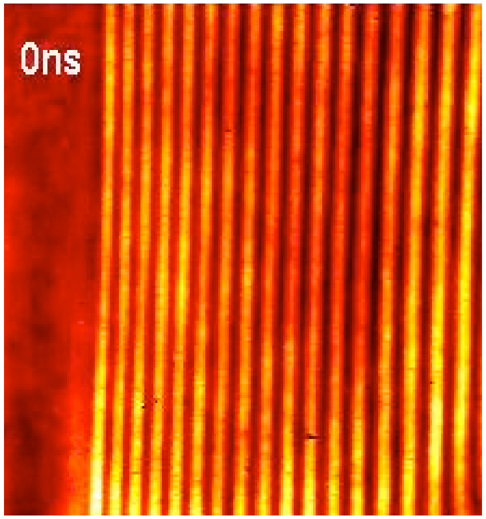
Applications of capillary discharge soft x-ray lasers





I.A. Artioukov et al., IEEE J. Selected Topics in Quantum Electron. ***30****, 328 (2000).*

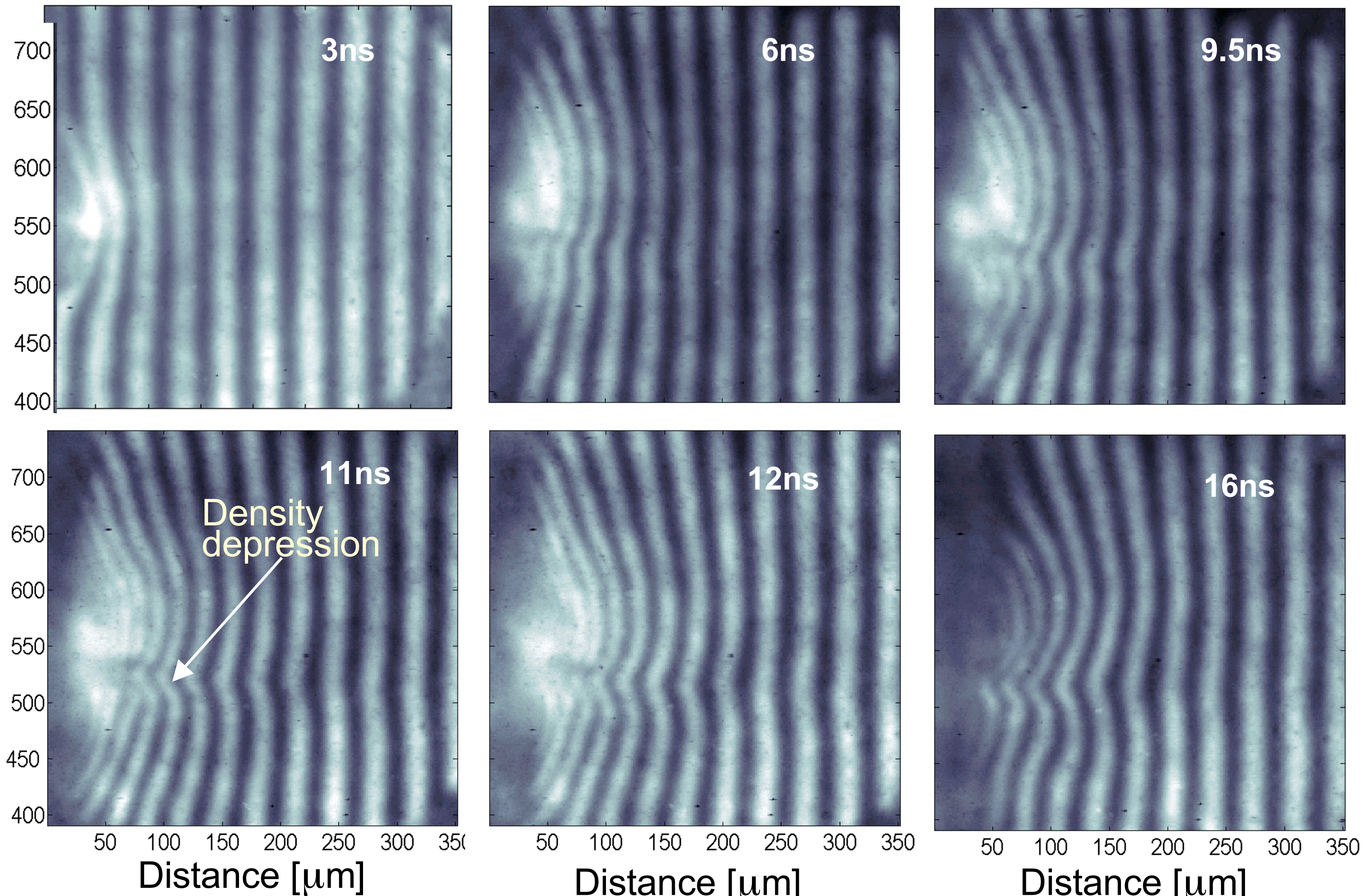
Soft x-ray interferometry laser interferomety



Soft x-ray laser interferometry of laser-created plasmas maps two-dimensional dynamics that differs from classical expansion

Line-focus plasma 1.8 mm long *(J. Filevich et al. Phys. Rev E, 67, (2003))*

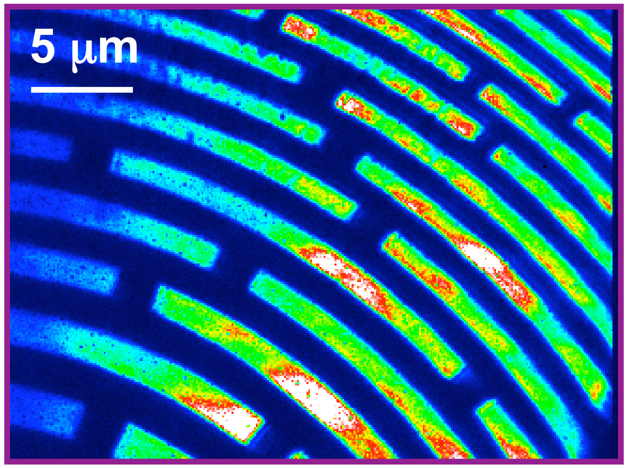
Magnification 25 x, I = 0.1 TW/cm^2, l = 1.06 mm , 13 ns FWHM pulse width

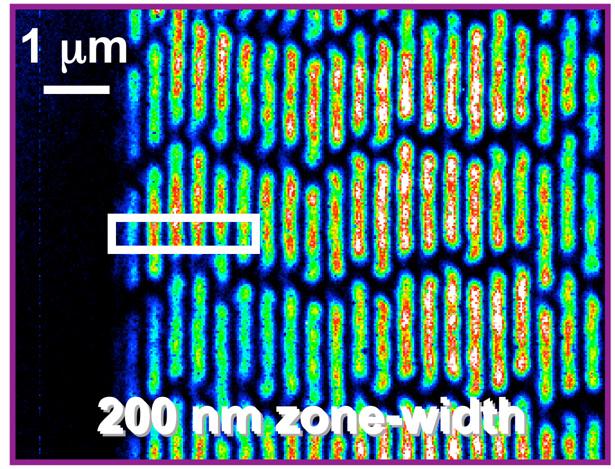


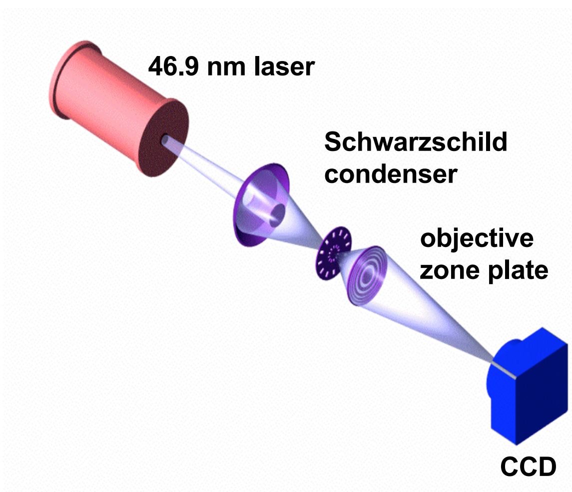
09-01-05-XRL-JD-36A-5

High resolution imaging with 46.9 nm capillary discharge laser: 120-140 nm Resolution

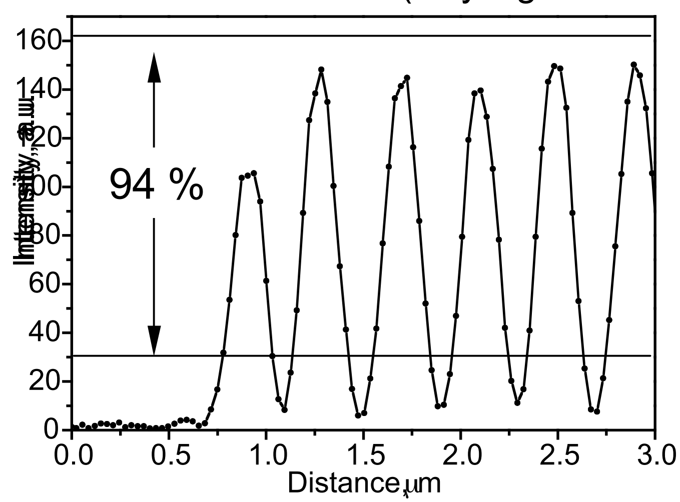
Images of a zone plate







~ 94 % modulation >> 26.5 % (Rayleigh-like modulation)



09-01-05-XRL-JD-36A-6

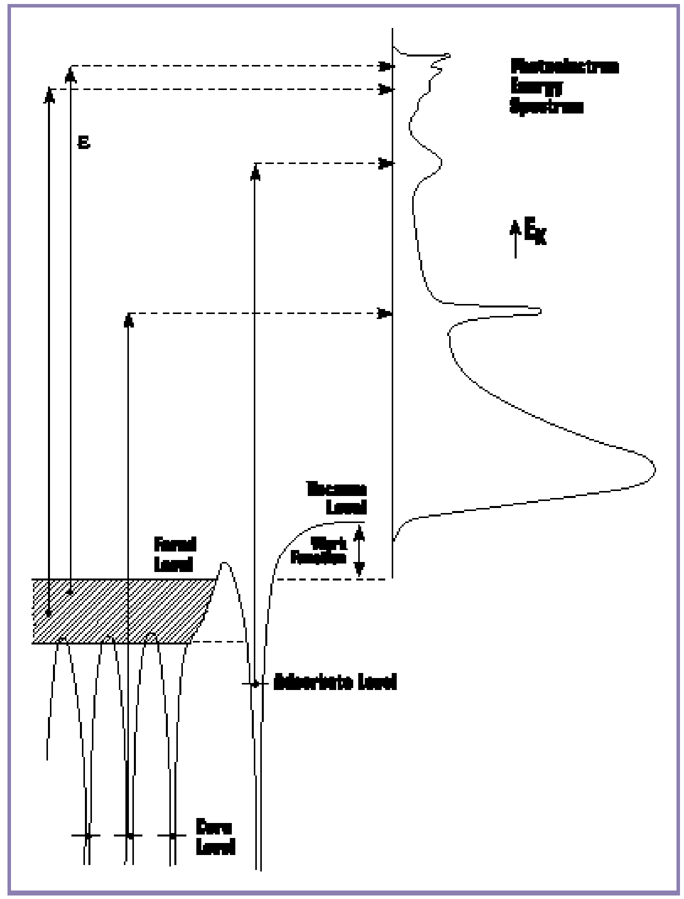
G. Vaschenko et al., Opt. Lett., in press (2005)

Time-of-Flight Photoelectron Spectroscopy requires picosecond pulsed source (84.5 eV x-ray laser photons)

Measure electron kinetic energy by time-of-flight technique

KE = hv - BE - ϕ_s, Binding energy BE, work function ϕ_s

- **COMET Ni-like Pd X-ray laser photoionizes surface atoms**
- **Extracted shallow core-level and VB photoelectrons have velocity distribution (kinetic energy distribution ≤ 84.5 eV)**
- **Time-of-flight (ToF) spectrometer used to energy analyze photoelectrons**
- **Electrons travel through drift tube detected by micro-channel plate (MCP) and fast digitizer**
- **Capable of high energy resolution with high throughput**

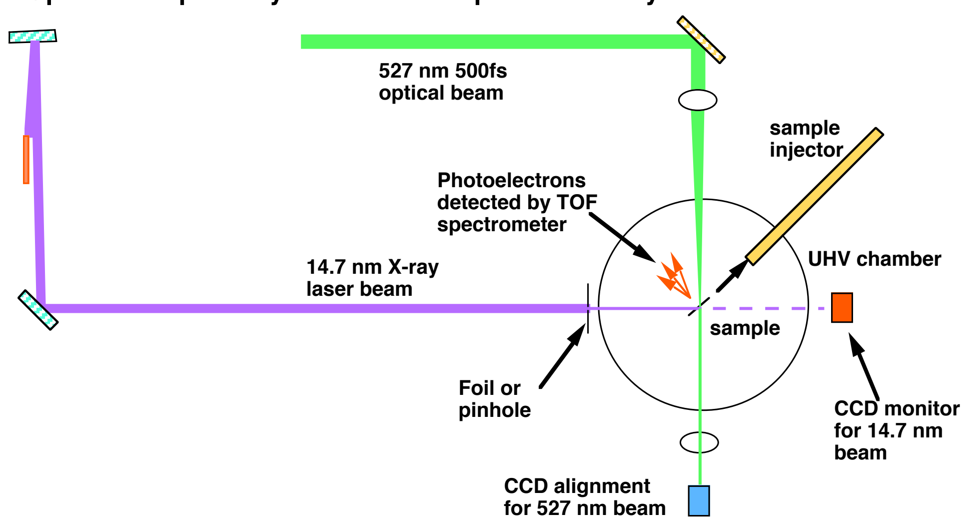


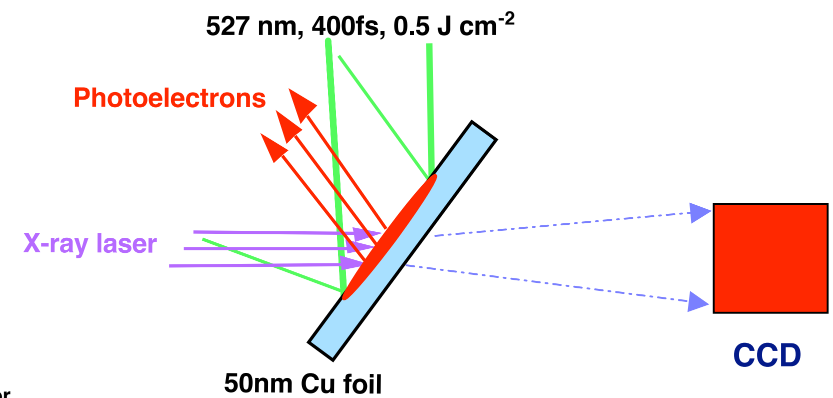
We probe changes in electronic structure during the dynamic processes of melting

COMET pump-probe experiment with e-ToF PES and soft x-ray radiography

An optical pump melts the material, and the electronic structure is probed after a time Δt by X-ray laser induced photoelectron spectroscopy

Optical Pump - X-ray laser Probe Experimental Layout





1. Foil or pinhole isolates x-ray laser beam line vacuum from UHV chamber

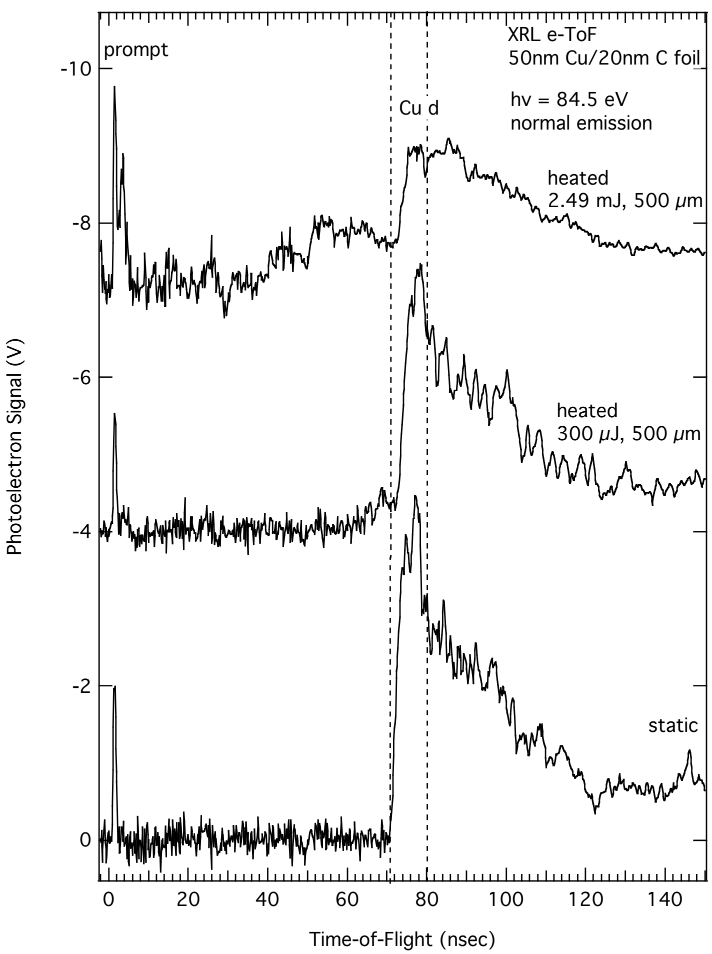
2. Optical beam fluence of ~500 mJ/cm^2 will produce melt - 5 - 50 mJ in 1 mm spot

Dynamic x-ray laser photoelectron spectroscopy of the valence band electronic structure of heated materials has been demonstrated

Physics & Advanced Technologies

Simultaneous measurement of the electronic structure and opacity of 50 nm Cu foils

- Pump 527 nm, 400 fs laser, 0.1 – 2.5 mJ energy in 500 x 700 μm^2 (FWHM) spot.
- Heating with 0.07 – 1.8 x 10^{12} W cm^{-2} intensity
- Cu *d* band emission evident in valence band



Single-shot e-ToF normal emission spectra of static and laser heated ultrathin Cu foil

decreasing Cu 3*d* peak intensity due to depopulation of the *d*-band as the electron temperature T_e increases

creates vacancies in the CB – interband absorption below the edge 3*d*-4*p* transitions

Cu 3*d* peak shifts towards lower kinetic energy (higher binding energy) – band is ‘sinking’.

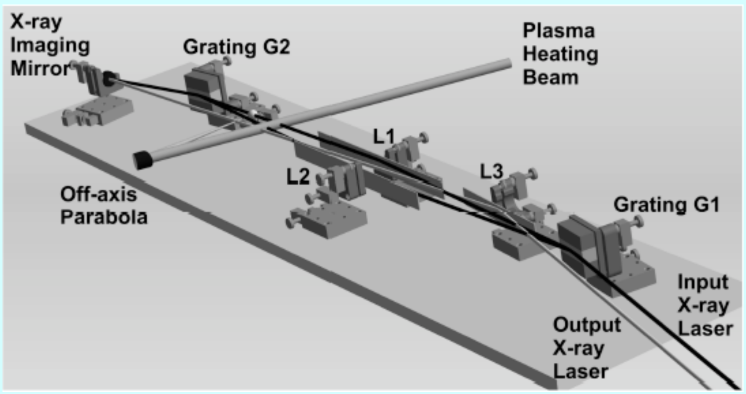
no broadening of the Cu 3*d* upon heating – nonequilibrium distribution of occupied states

A.J. Nelson et al, submitted to Appl. Phys. Lett (2005)

Physics & Advanced Technologies

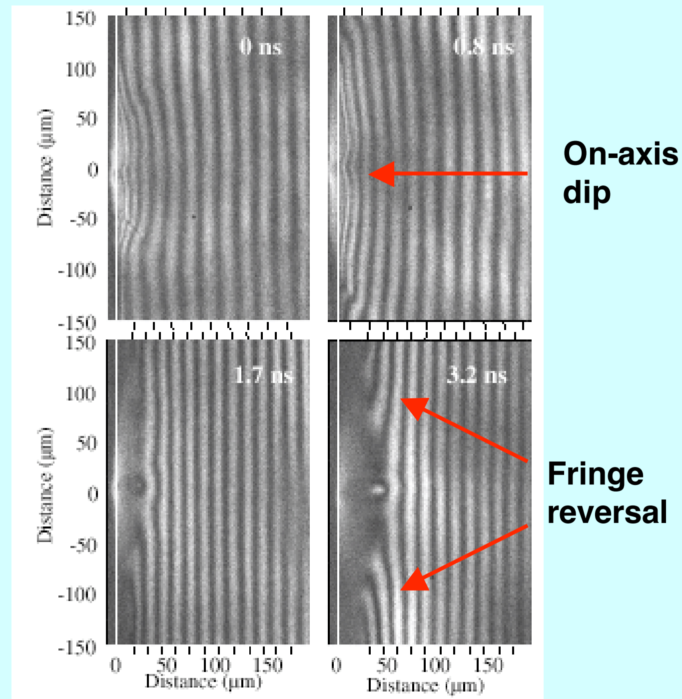
14.7 nm, ps duration soft x-ray laser interferometry at LLNL used to probe hot dense laser-produced plasmas

14.7 nm Diffraction Grating Interferometer



- X-ray laser interferometry of laser produced plasma shows interesting phenomena - formation of on-axis dip
- Fringe reversal observed at late time produced by Al^{1+} - Al^{5+} bound electrons effect on plasma refractive index

Al plasma heated at 10^{13} W cm^{-2} probed at various times



22x magnification images
~4.5 ps snapshot

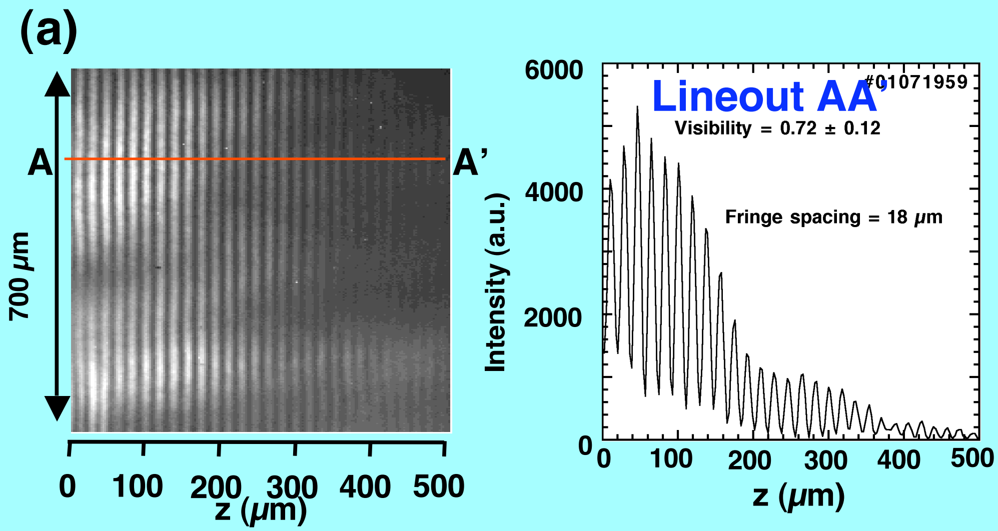
In collaboration with
Jorge Rocca, CSU

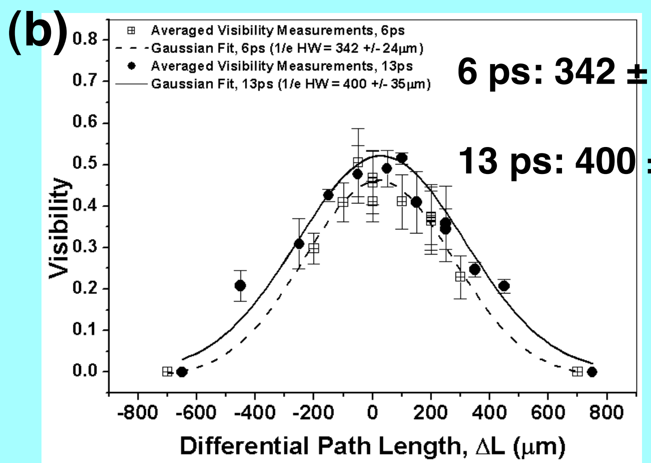
J. Filevich, J.J. Rocca, et al., "Observation of a multiply ionized plasma with index of refraction greater than one", Phys. Rev. Lett., 94, 035005 (2005)

Physics & Advanced Technologies

X-ray laser beam is characterized for interferometry: coherence and fringe visibility with 4 - 6 ps duration

XRL Coherence and Fringe Visibility



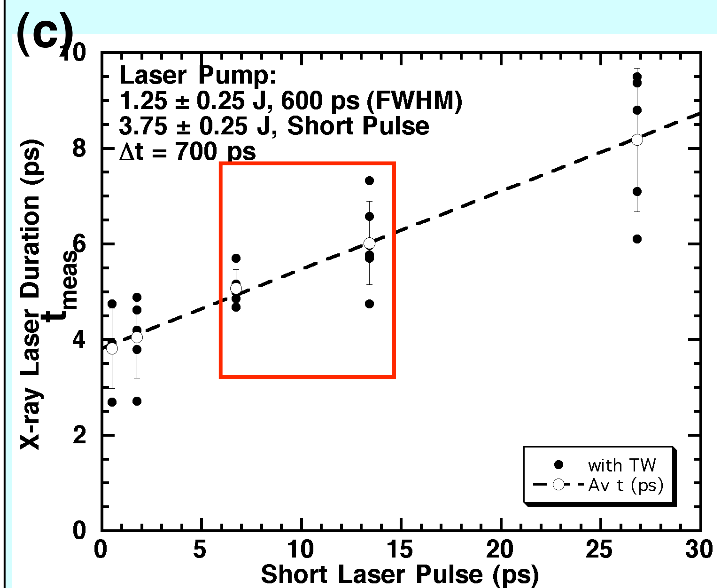


6 ps: 342 ± 24 μm 1/e HW

13 ps: 400 ± 35 μm 1/e HW

R. F. Smith *et al.*, Opt. Lett. 28, 2261 (2003).

XRL Pulse vs SP duration



With R. Shepherd, R. Booth

(a) Excellent spatial coherence - high fringe visibility 0.72 ± 0.12

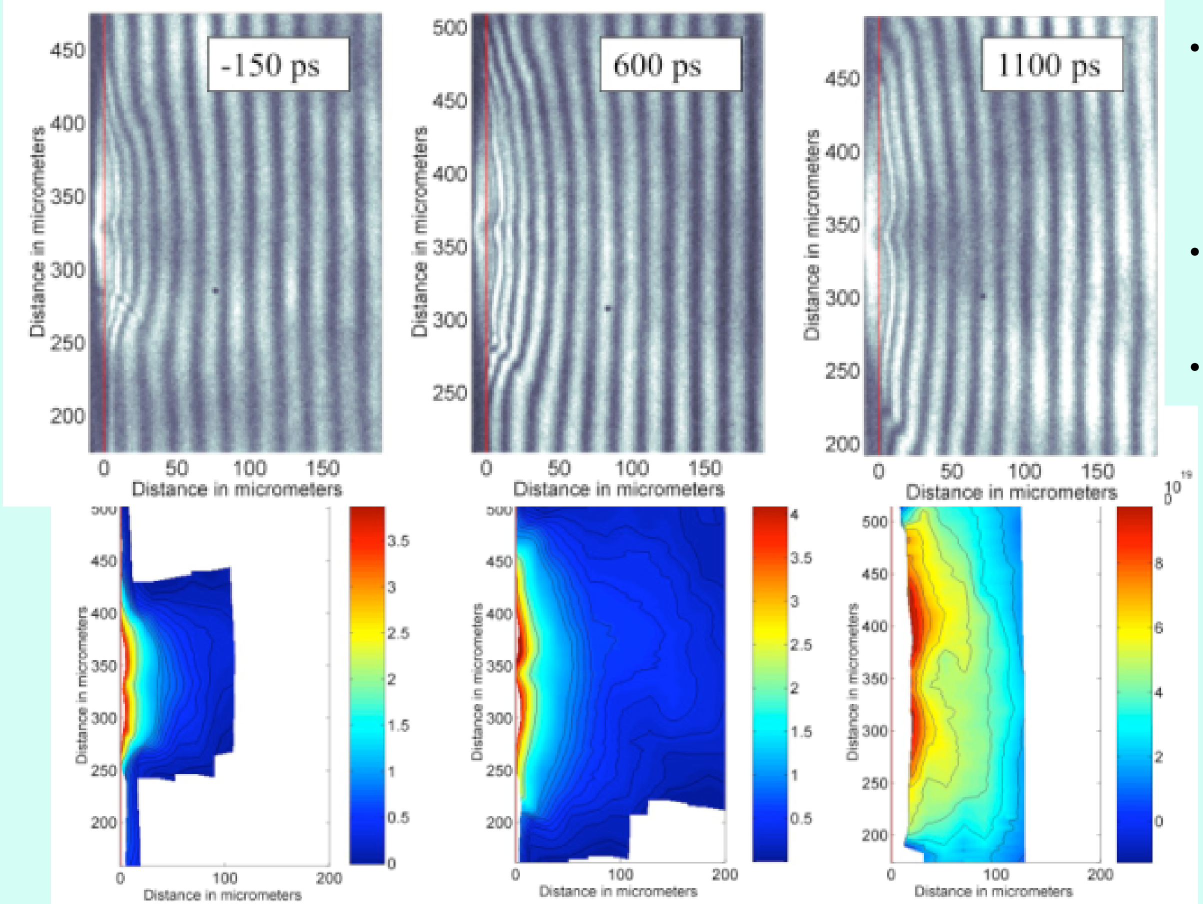
(b) Excellent longitudinal coherence - Michelson interferometry (With P. Zeitoun, S. Hubert et al LIXAM/CEA)

(c) X-ray laser pulse duration 4 - 6 ps (FWHM) for interferometry

Physics & Advanced Technologies

XRL interferometry shows features close to target surface: density dip on-axis observed n_e

Al targets heated by 3 J, 12 μm wide, 600 ps pulse at $>10^{13}$ W cm^{-2}



- Previously, flat targets irradiated at below 10^{12} W cm^{-2} have low n_e due to strong 2-D effects
- Observe $n_e > 4 \times 10^{20}$ cm^{-3} at +0.6 ns for flat target
- Plasma pressure gradients, radiative heating and thermal conduction produces dense plasma in side lobes

* Long 12 ns heating expt.

J. Filevich, J. J. Rocca *et al*, "Two dimensional effects in laser-created plasmas measured with soft-x-ray laser interferometry", Phys. Rev. E 67, 056409 (2003).

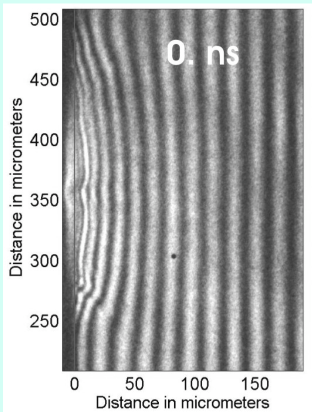
On axis dip, formation of side lobes also observed recently*

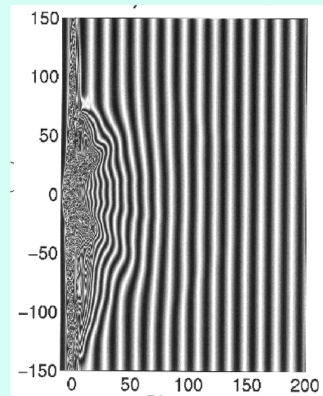
S. Moon et al, submitted to Phys. Rev. E (2005)

Experimental interferograms used for comparison with 2-D LASNEX simulations

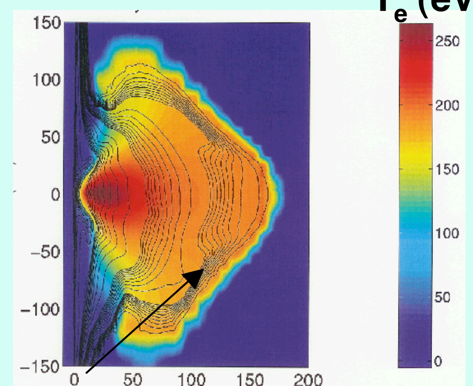
14.7 nm Interferogram | **Simulated Interferogram** | **LASNEX 2-D T_e, n_e Plot**

0 ns



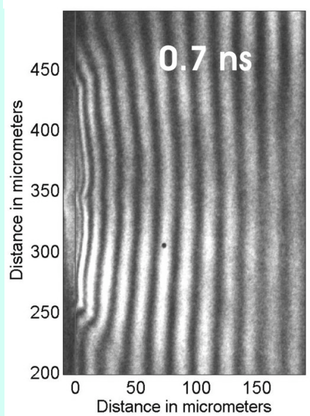


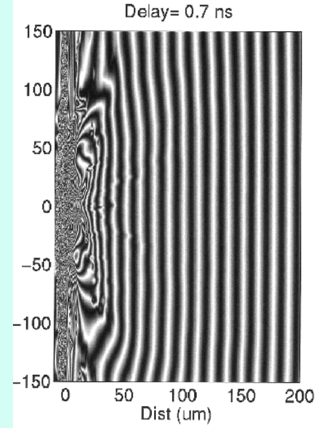
T_e (eV)



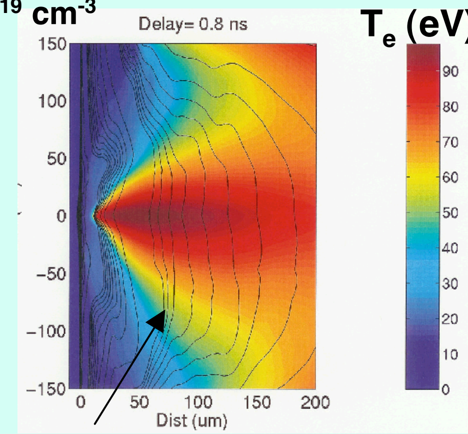
$n_e = 10^{19}$ cm^{-3}

0.7 ns





T_e (eV)



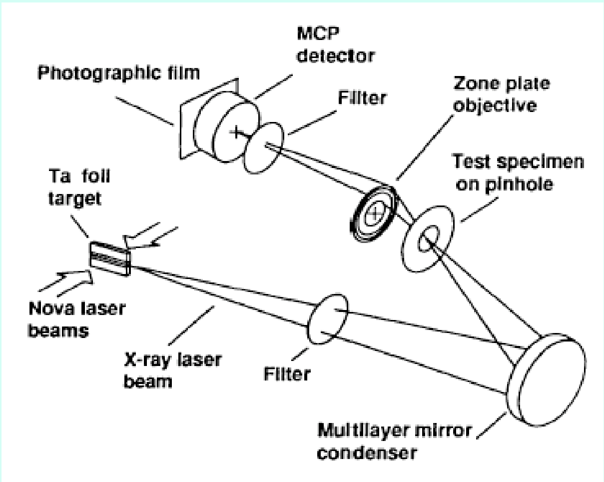
$n_e = 10^{20}$ cm^{-3}

Al targets heated by 3 J, 12 μm wide, 600 ps pulse at >10^{13} W cm^{-2}

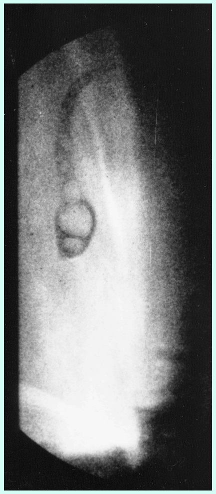
Further investigation of this phenomena is in process

Re-visit 4.5 nm x-ray laser biological imaging conducted on Nova in 1992 with smaller drive

Biological Imaging Setup Using Zone Plate Objective and Image



L. Da Silva *et al.*, Science 258, 269 (1992)



10 μm

Image of rat sperm, partially hydrated, stained with anti-protamine 2 antibodies and labeled with 40-nm gold microspheres.

Fine details observed in inner wall with ~50 nm scale

Promise of wet-cell imaging - no perturbation

High contrast possible in different cell structure (DNA, protein)

Constraints:
1. Big laser 3 - 10 kJ required for Ni-like Ta x-ray laser e.g. Nova or Gekko XII
2. Repetition rate was low - limited shots
3. Source development to improve output and repeatability
4. Expensive - e.g. present day NIF $200k/shot

Primary goal is to develop a new high efficiency E_{pump} < 200 J laser-pumped, sub-ps x-ray laser that will work in the water-window

In collaboration with UC Davis Center for Biophotonics, Science and Technology

Future trends: Laser drivers for x-ray lasers

- High Energy, High Peak Power, High Repetition Rate
- High Peak Power: Titan at LLNL
- High Repetition Rate: Mercury DPSSL

Laser Drivers: High Energy, High Power and High Repetition Rate, Ultrafast lasers have different applications for XRLs

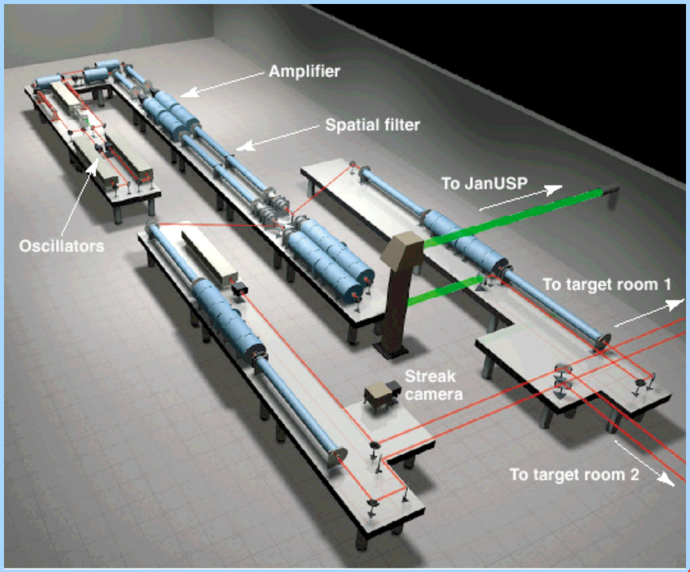
- High Energy
  - NIF (LLNL) 1.8 MJ, 192 beams under construction
  - OMEGA (LLE - U. Rochester) 40 kJ, 60 beams
  - Z-Beamlet (SNL) 0.5 kJ 2ω, 250 ps
  - Janus (LLNL) 1 kJ, 1ω, 3 ns
  - Trident (LANL) 50 - 250 J 2ω, 100ps - 3 ns, 2 beams, + 20 - 40 TW SP

- High Power
  - OMEGA EP (LLE - U. Rochester) 2.6 PW, 2.6 kJ, 1 ps under construction
  - Titan (LLNL) ~1 PW, 350 J, 0.4 ps
  - U. Texas Petawatt 1.3 PW, 200 J, 150 fs, under construction
  - Z-Beamlet Petawatt (SNL) 1 PW, 500 J, 0.5 ps under construction
  - Hercules (U. Michigan, CUOS) 45 TW, 27 fs
  - XRL — COMET (LLNL) 15 TW, 7.5 J, 0.5 ps, 5 J, 600 ps
  - ALLS (Quebec, Canada) 20 TW, 100 TW, U. Nevada, Reno, U. Ohio, ...

- High Repetition Rate (mainly Ti:Sapphire)
  - XRL — Callisto (LLNL) 0.15 J, 130 fs, 10 Hz GRIP
  - UC Berkeley (Leemans) 4 J, 30 fs, 10 Hz
  - XRL — CSU (Rocca) 1 J, 2 ps, 10 Hz
  - Falcon (LLNL) 0.5 J, 30 fs, 2 Hz
  - Mercury (LLNL) DPSSL 55 - 100 J, 10 Hz, 10 ns (short pulse being considered)
  - U. Colorado, 1.1 mJ, 28 fs, 10 kHz, U. Princeton ....

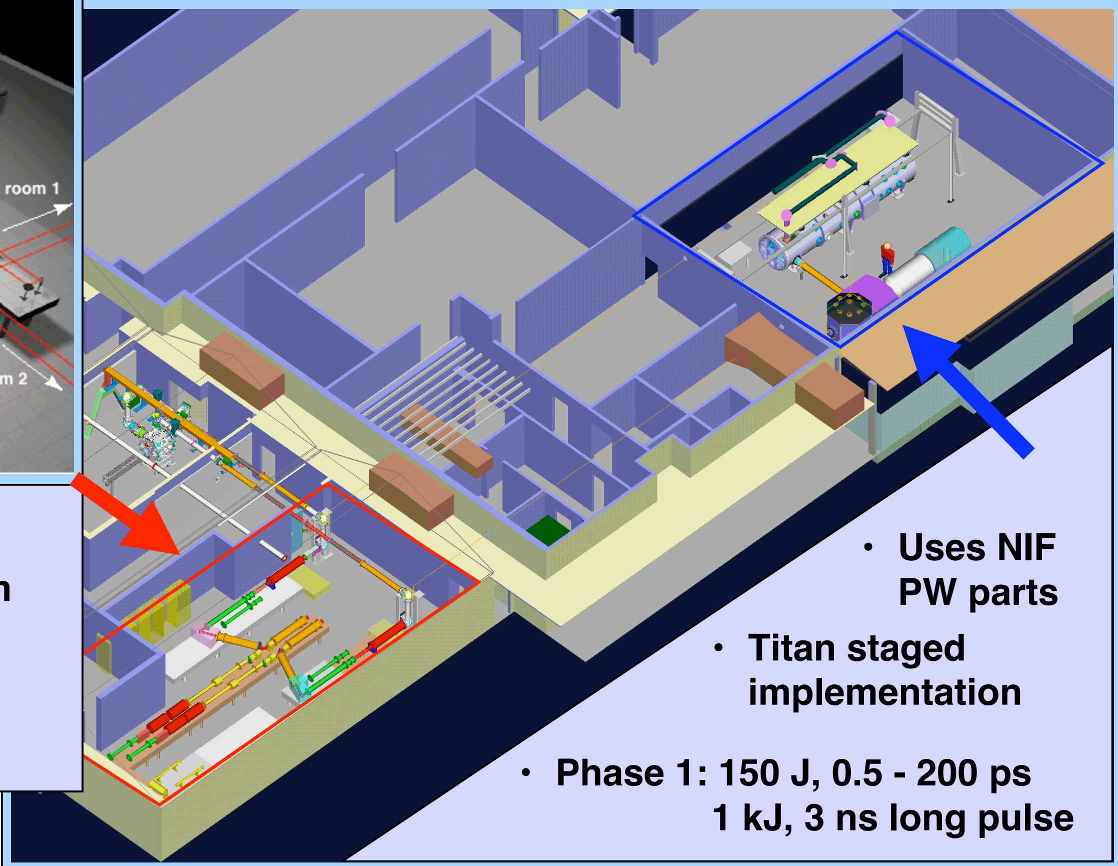
JANUS Laser system recently upgraded to 1kJ/beam
CPA Titan upgrade to install short pulse arm in 2005

JANUS Upgrade Laser 2003/4



- Uses NIF type oscillators
- Maximum energy 1 kJ, 1054 nm in 15 cm beam 3 ns
- 100 J, 527 nm, 6 ns used to pump Callisto 200 TW, 80 fs

CPA TITAN 2005



- Uses NIF PW parts
- Titan staged implementation
- Phase 1: 150 J, 0.5 - 200 ps
  1 kJ, 3 ns long pulse

LLNL Titan Laser Specification

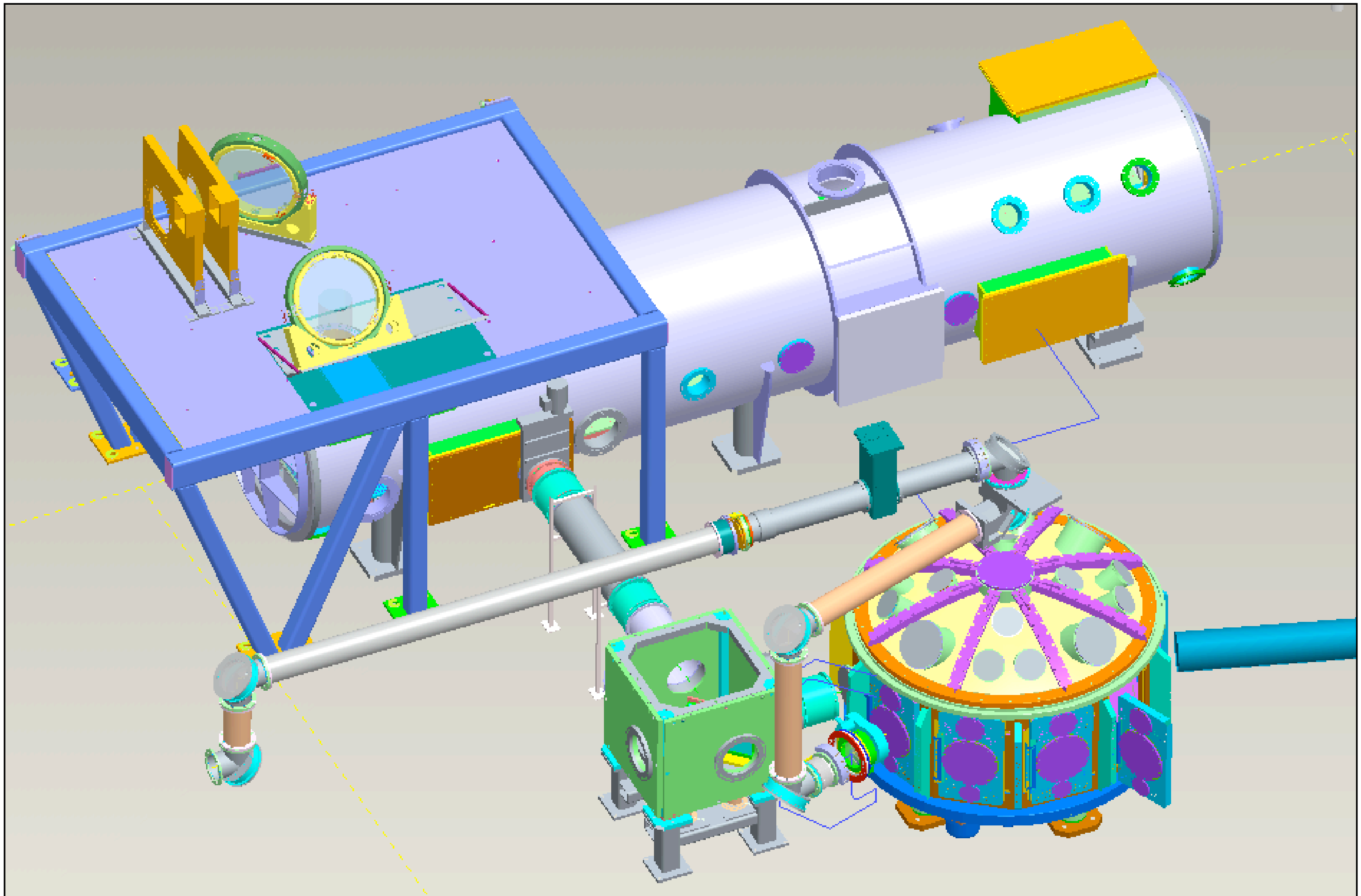
Current Upgrade:

- 1 short-pulse, 25 cm dia, 350J in 400 fs, 1 shot/30 min.
- 1 long-pulse, 14 cm dia, 1 kJ @1ω, or 600 J @2ω, 3ns
  NIF pulse-shaping capability

Not to Preclude:

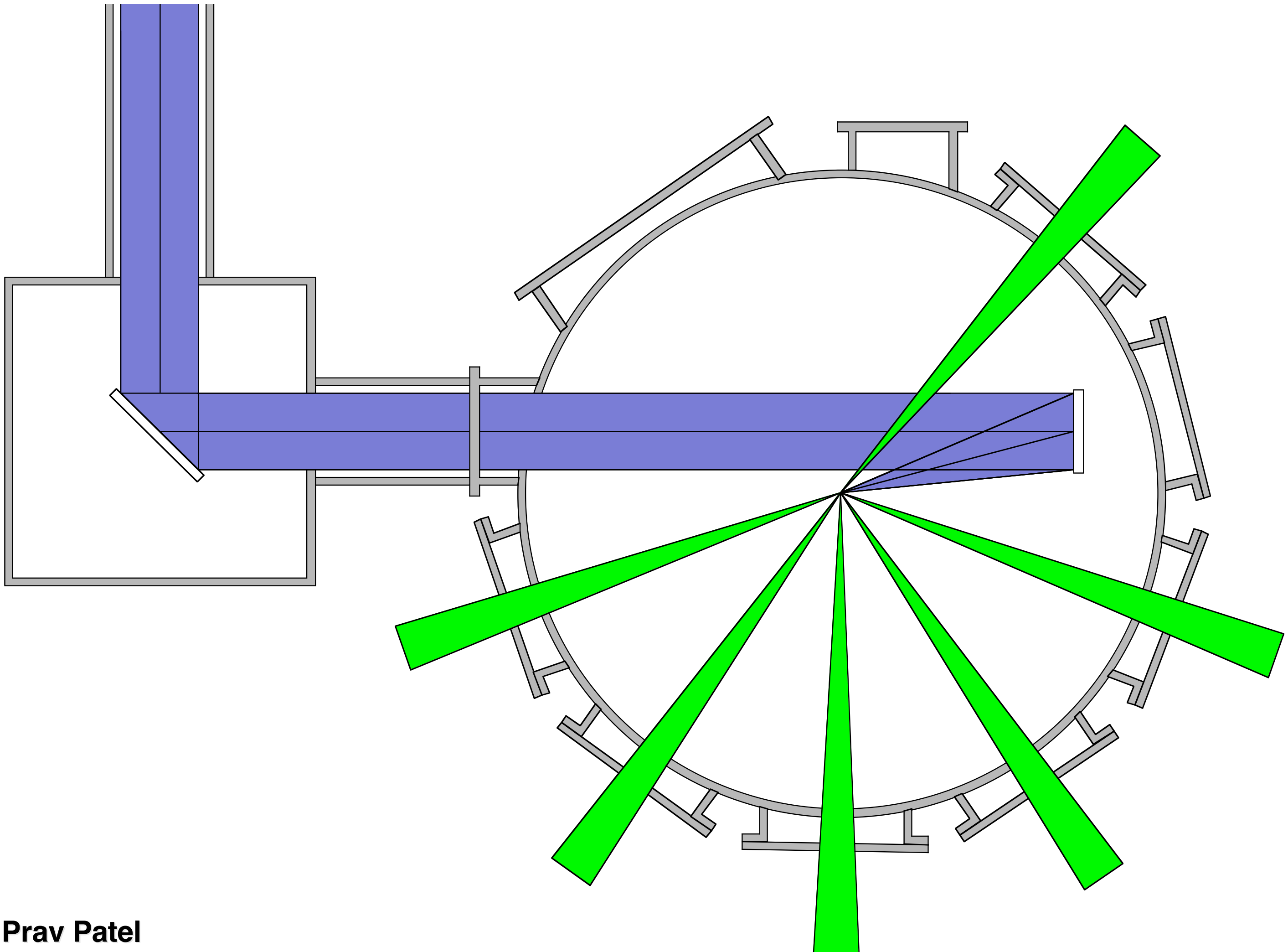
- Install 2nd CPA arm in compressor
- Independent ps probe beam ~ 100 mJ @2ω or 3ω
- Adaptive Optics
- Frequency doubling

Titan Laser Target Area: Vacuum Compressor Box and Target Chamber



From Prav Patel

Titan Target Chamber: First experiments configured for short pulse only - many options for long pulse beam

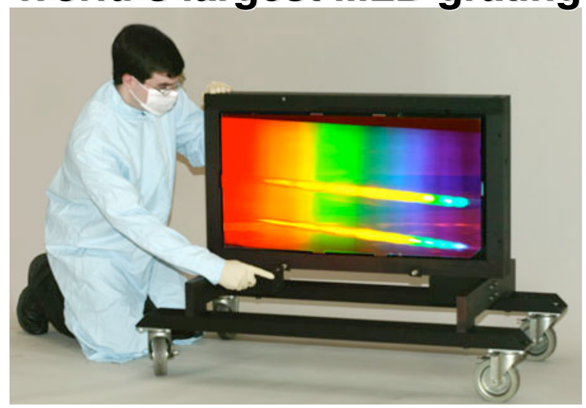


From Prav Patel

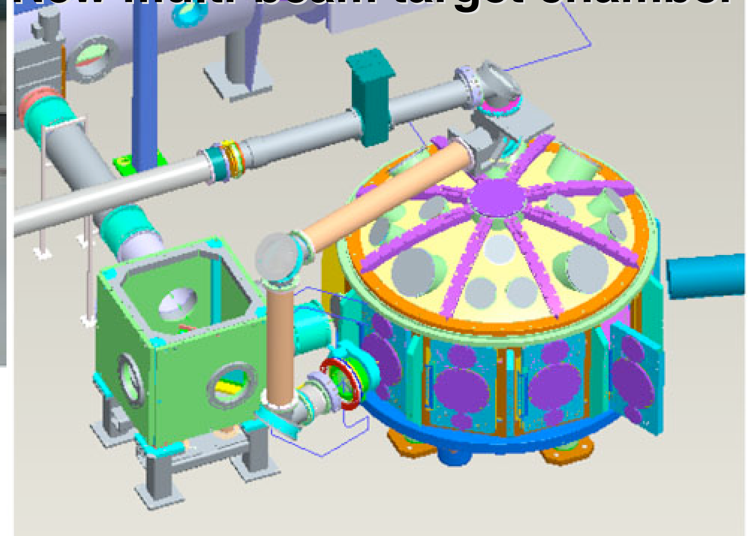
Titan first-light was June 2005 (50 J in 0.5 ps) - First experiment will be begin in September 2005

Compressor & Optics Installation

World's largest MLD gratings



New multi-beam target chamber



The Mercury Laser is the first step toward building a MW, 10 Hz class of IFE lasers - Diode Pumped Solid State Laser (DPSSL)

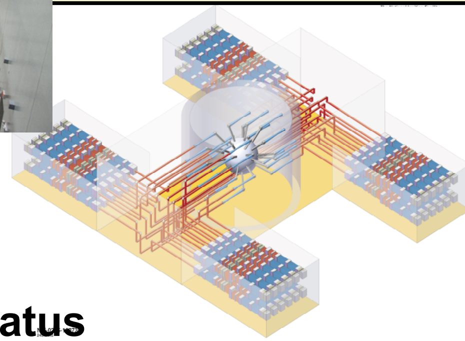
Mercury

100J IR

IRE (NIF bundle)

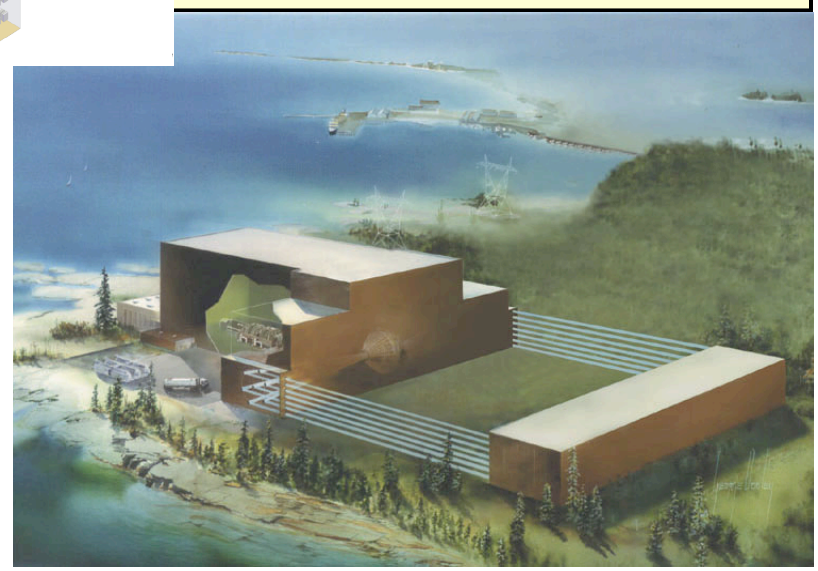
20kJ UV

ETF



2MJ UV

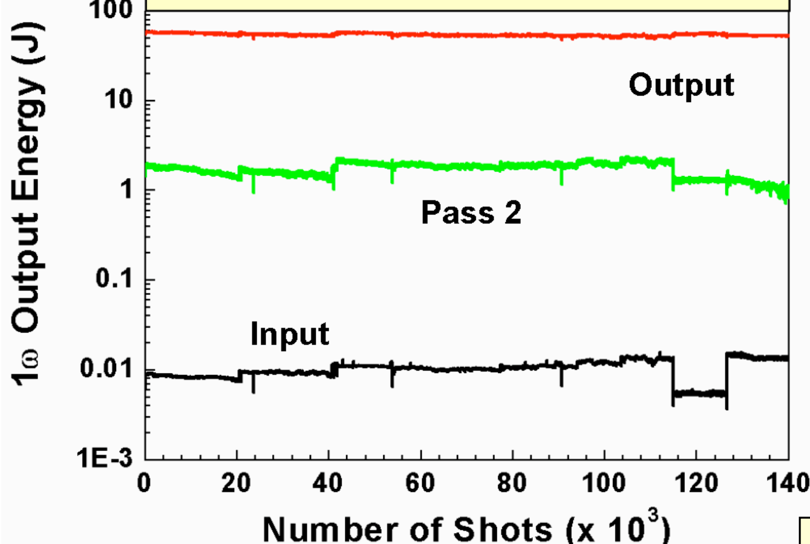
IFE

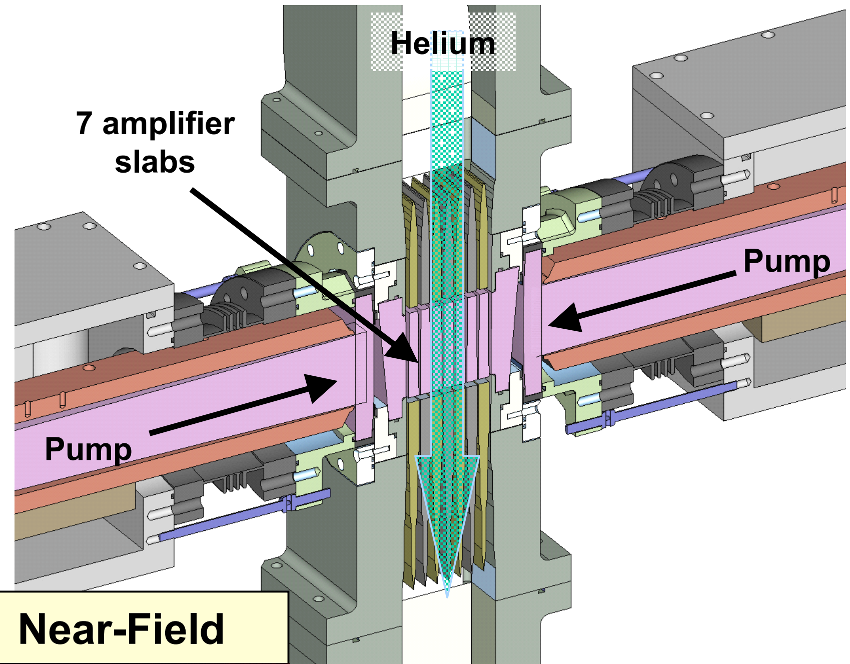


	Mercury Goals	Status
Energy	100 J, 1ω	55 J, 1ω
Efficiency	10 %	4.5 %
Repetition rate	10 Hz	10 Hz
Pulse length	3-10 ns	3-15 ns
Wavelength	0.53/0.35 μm	0.53 um
Bandwidth	>150 GHz 1ω	–
Beam quality	5 xDL	6 xDL

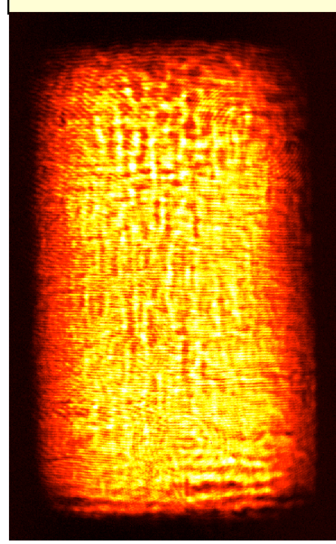
Mercury was operated for 55 J at 10 Hz for > 10^5 shots with both amplifiers deployed - use He gas cooling

Average power histogram

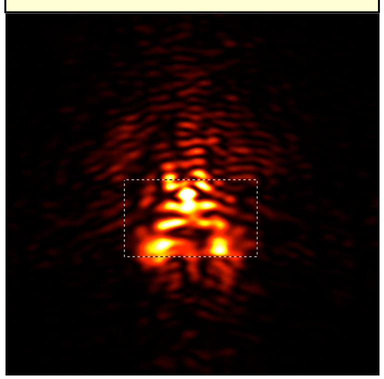




Near-Field



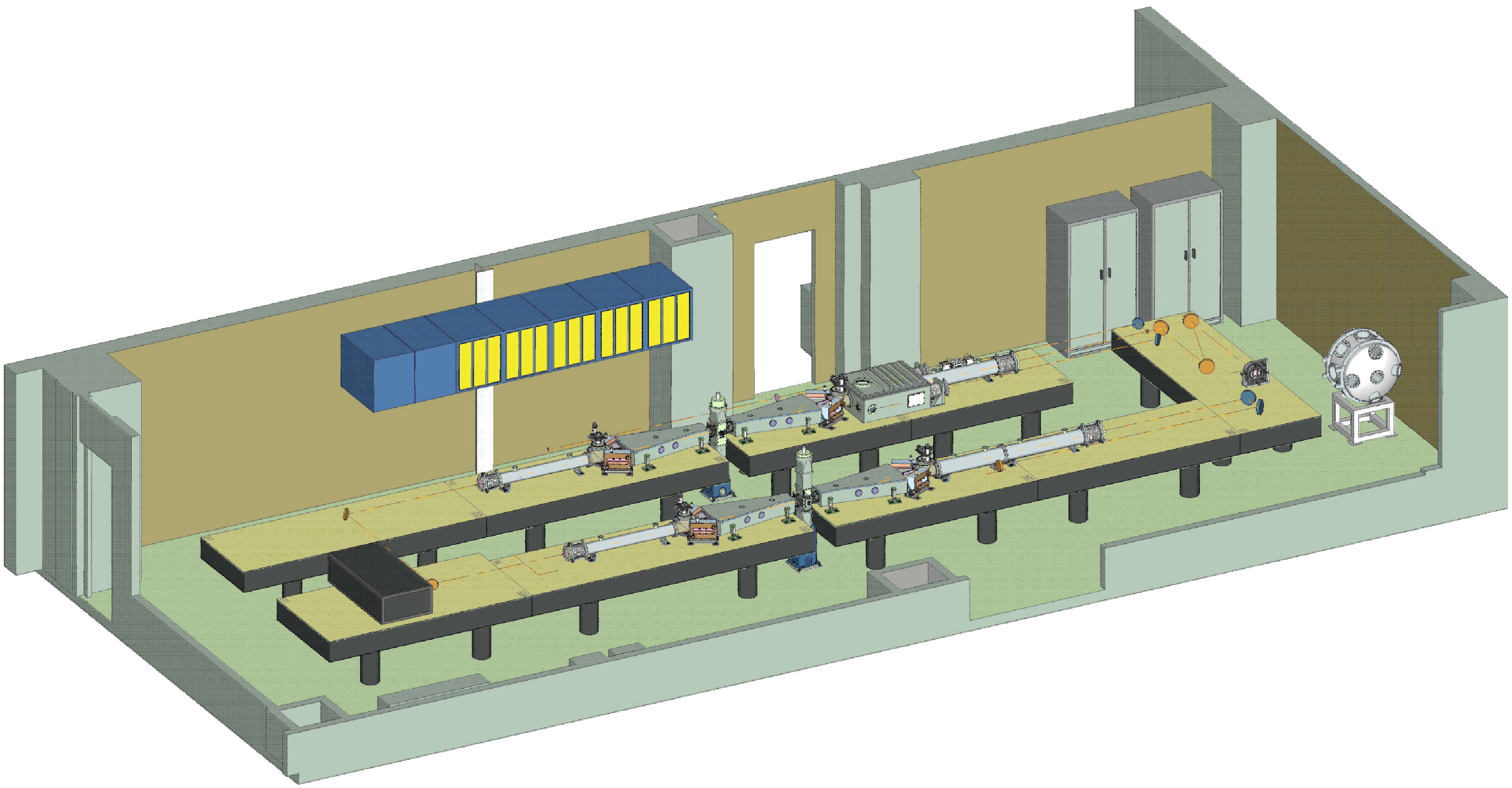
Output Far-Field



λ= 1047 nm
4.2 x 7.2 cm^2 beam
2ω operation 22 J, 10 Hz

Physics & Advanced Technologies

Mercury currently being considered for long pulse experiments in next 6 - 9 months



Short pulse architecture and capability being considered now - x-ray laser source applications would be a good match

Summary:

- Nova X-ray laser effort initiated 20 years ago
- Smaller facilities over the years have improved collisional excitation lasers at lower cost
- Potential for re-investigating some x-ray lasers OFI/Recombination, ISPI schemes using ultrafast, high peak power lasers
- Development of x-ray laser applications highly dependent on robust output with careful characterization and optimization
- Future Laser drivers for x-ray lasers will combine properties of
  - High Peak Power, High Repetition Rate
- Still a niche for bigger single shot facilities where total x-ray laser photon number is important.