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

J. Dunn

October 13, 2005

Plasma-based X-ray Lasers: Status and Prospects
Prague, Czech Republic
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US Activities in the Development of Plasma-Based X-ray Lasers

James Dunn

Lawrence Livermore National Laboratory

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Acknowledgments to contributions, information and discussions with numerous people:

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<th>Affiliation</th>
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<tr>
<td>Camille Bibeau</td>
<td>(LLNL)</td>
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<td>John Caird</td>
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<td>Jorge Filevich</td>
<td>(Colorado State University)</td>
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<td>Roisin Keenan</td>
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<td>Rich London</td>
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<td>Steve Moon</td>
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<td>Art Nelson</td>
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<td>Joe Nilsen</td>
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<tr>
<td>Szymon Suckewer</td>
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<td>Franz Weber</td>
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<td>Philippe Zeitoun</td>
<td>(LOA)</td>
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Outline:

• Historical Perspective for US X-ray Laser Effort
  - Achievements and applications
  - Recombination scheme at Princeton University

• Developments in various US laboratories and schemes ( - 1999)

  - 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:

- 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**

- \( n_e = 5 \times 10^{20} \text{ cm}^{-3} \)
- \( T_e = 1 \text{ keV} \)

- 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 \( (n_e \text{ density profile}) \)
- \( T_e \) ionization conditions measured

09-01-05-XRL-JD-7  
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 $2\omega$ each side
- Line focus 200 $\mu$m x1.1 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
- $g \sim 5$ 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
- XRL Interferometry of Laser Plasmas
- X-ray Laser Microscopy of Biological Cells at 4.5 nm

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


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

An enhancement of ~100 of stimulated emission over spontaneous emission of the C VI 182-Å line (tone-pass gain ~6.5) was measured in a recombining, magnetically confined plasma column by two independent techniques involving intensity-calibrated extreme-ultraviolet 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.

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 1983)

An enhancement of ~100 of stimulated emission over spontaneous emission of the C VI 182-Å line (tone-pass gain ~6.5) was measured in a recombining, magnetically confined plasma column by two independent techniques involving intensity-calibrated extreme-ultraviolet 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.

Ground state

Tunneling ionization

CVI

Three-body recombination

n = 1

Lasing at 18.2 nm*

Fast collisional-radiative de-excitation

n = 2

(Life time 1.6 ps)

n = 3

n = 4

Pumped with 0.3 kJ, 80 ns CO2 laser
gL ~ 8 for 18.2 nm n = 3 - 2 H-like C

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

Biological Cells

High density memory chip

SXL Reflection microscope

Optical microscope

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, $1\omega$, slab targets:
  - 200 J, ~1 - 2 ns class lasers
    - 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 (Aruzese, 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

Tabletop capillary discharge laser produces similar coherent average power at $\lambda = 46.9$ nm as synchrotron

Capillary discharge 46.9 nm laser

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

Highest average power compact coherent SXR light source available


09-01-05-XRL-JD-17
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, $3 \times 10^{16}$ W cm$^{-2}$
- Xe gas cell, longitudinally pumped
- $g \sim 13$ 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

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

<table>
<thead>
<tr>
<th>Experimental Geometry</th>
<th>H-like Li Ly-α 13.5 nm x-ray laser</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="" /></td>
<td>![image2.png]</td>
</tr>
<tr>
<td>50 mJ, 250 fs, 248 nm</td>
<td>![graph1.png]</td>
</tr>
<tr>
<td>100 mJ, 5ns, 1 µm</td>
<td>![graph2.png]</td>
</tr>
</tbody>
</table>

- \( g \sim 11 \text{ cm}^{-1}, \ gL = 5.5 \)
- Experiment repeated at NRL using capillary discharge

Korobkin et al, PRL 77, 5206 (1996)
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
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 \((1s^22s^22p^1)\) limits the magnitude and duration of positive gain.
- Ultra-short pulse x-ray lasing is inherent in this scheme.
Tabletop Transient 1 ps x-ray laser work at LLNL started in 1997 - motivated by Ne-like Ti results at MBI group in Berlin

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

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

Two Stage Process

- Long laser pulse: \(1 - 5 \text{ J}\)
  - plasma formation
  - ionization
  - delay for relaxation of density gradients
- Short laser pulse: \(2 - 7 \text{ J}\)
  - excitation

Tabletop Laser Driver

- Inexpensive slab targets

Ps and ns driving lasers

P.V. Nickles et al, PRL 78, 2748 (1997)

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

- 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 \(n_e \sim 0.9 \times 10^{20} \text{ cm}^{-3}\)

Higher efficiency of Ni-like XRL well matched to small driver
Output still increasing with length - extract more XRL energy
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 $\theta = \sqrt{n_{e0}/n_{ce}}$ 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

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

**Fiducial wires**

4.5 mrad deflection angle
3 mrad (FWHM) beam divergence

XRL has good characteristics but sensitive to pump laser overlap

Mo:Si multilayers courtesy of J. Nilsen, T.W. Barbee, Jr.
Pumping conditions optimized to maximize Ni-like Mo 18.9 nm x-ray laser output

Delay between laser pulses with modeling

XRL output shows saturation-like behavior at 4 mm

SP = 1.5 ps, Δt = 500 ps

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

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

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

Counts

LP-SP delay / ps

XRL output vs length

Δt=200ps

Counts

Target Length / cm

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 ~ 1.2 x 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

<table>
<thead>
<tr>
<th>Z</th>
<th>$\lambda_{XRL}$ (nm)</th>
<th>$\lambda_{pump}$ (nm)</th>
<th>$E_{pump}$ (J)</th>
<th>$n_e$ ($10^{20}$ cm$^{-3}$)</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mo</td>
<td>18.9</td>
<td>800</td>
<td>0.15</td>
<td>1</td>
<td>✔</td>
</tr>
<tr>
<td>Pd</td>
<td>14.7</td>
<td>527</td>
<td>0.4 - 3</td>
<td>1 - 2</td>
<td>✔</td>
</tr>
<tr>
<td>Nd</td>
<td>8.0</td>
<td>527</td>
<td>9 - 12</td>
<td>5</td>
<td>Laser time?</td>
</tr>
<tr>
<td>Ta</td>
<td>4.5</td>
<td>?</td>
<td>50?</td>
<td>&gt;5?</td>
<td>Laser*</td>
</tr>
</tbody>
</table>

- 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
Lasing observed at wavelengths as short as 10.9 nm

Gain saturated operation demonstrated

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

\[ g_0 = 69 \text{ cm}^{-1} \]
\[ G_L = 17.6 \]
High repetition rate operation of 13.9 nm Ni-like Ag laser

Average at 5 Hz repetition rate power $\sim 2\mu W$

Similar performance also obtained for Ni-like Cd @ 13.2 nm, $>1\mu W$ average power
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).
Desk-top 46.9 nm laser output pulse statistics
1500 shots at 12 Hz repetition rate

Discharge Current

Laser Pulse Energy

Energy (µJ)

Number of Shots

Laser Energy Distribution

Laser Pulse Jitter

Energy (µJ)

Number of Shots

Time (ns)

For 98% of the Shots

\( \sigma = 5\text{ ns} \)
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

2. F. Brizuela et al, Optics Express, 13, 3983, (2005)
Applications of capillary discharge soft x-ray lasers

Soft x-ray interferometry laser interferometry

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

Soft x-ray laser interferometry of laser-created plasmas maps two-dimensional dynamics that differs from classical expansion
High resolution imaging with 46.9 nm capillary discharge laser: 120-140 nm Resolution

Images of a zone plate

\[ \text{Intensity, a.u.} \]
\[ \text{Distance, \( \mu \text{m} \)} \]

\( \sim 94 \% \) modulation >> 26.5 \% (Rayleigh-like modulation)

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

\[ KE = h \nu - BE - \phi_s \]

Binding energy \( BE \), work function \( \phi_s \)

- COMET Ni-like Pd X-ray laser photoionizes surface atoms
- Extracted shallow core-level and VB photoelectrons have velocity distribution (kinetic energy distribution \( \leq 84.5 \) 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 $\Delta t$ by X-ray laser induced photoelectron spectroscopy.

Dynamic x-ray laser photoelectron spectroscopy of the valence band electronic structure of heated materials has been demonstrated.
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 µm² (FWHM) spot.
- Heating with 0.07 – 1.8 x 10¹² 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 3d 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 3d-4p transitions

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

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

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

- 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

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

<table>
<thead>
<tr>
<th>XRL Coherence and Fringe Visibility</th>
<th>XRL Pulse vs SP duration</th>
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<tbody>
<tr>
<td>(a) Excellent spatial coherence - high fringe visibility 0.72 ± 0.12</td>
<td></td>
</tr>
<tr>
<td>(b) Excellent longitudinal coherence - Michelson interferometry (With P. Zeitoun, S. Hubert et al LIXAM/CEA)</td>
<td></td>
</tr>
<tr>
<td>(c) X-ray laser pulse duration 4 - 6 ps (FWHM) for interferometry</td>
<td></td>
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</table>

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

Al targets heated by 3 J, 12 $\mu$m 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.


On axis dip, formation of side lobes also observed recently*
Experimental interferograms used for comparison with 2-D LASNEX simulations

<table>
<thead>
<tr>
<th>14.7 nm Interferogram</th>
<th>Simulated Interferogram</th>
<th>LASNEX 2-D $T_e$, $n_e$ Plot</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1" alt="0 ns interferogram" /></td>
<td><img src="image2" alt="0.7 ns interferogram" /></td>
<td><img src="image3" alt="LASNEX plot" /></td>
</tr>
<tr>
<td><img src="image4" alt="0 ns interferogram" /></td>
<td><img src="image5" alt="0.7 ns interferogram" /></td>
<td></td>
</tr>
</tbody>
</table>

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

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

**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

**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)

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 $2\omega$, 250 ps
  - Janus (LLNL) 1 kJ, $1\omega$, 3 ns
  - Trident (LANL) 50 - 250 J $2\omega$, 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
  - 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)**
  - Callisto (LLNL) 0.15 J, 130 fs, 10 Hz GRIP
  - UC Berkeley (Leemans) 4 J, 30 fs, 10 Hz
  - 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
Current Upgrade:

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

Not to Preclude:

- Install 2\(^{nd}\) CPA arm in compressor
- Independent ps probe beam ~ 100 mJ @2\(\omega\) or 3\(\omega\)
- 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

09-01-05-XRL-JD-42
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 Goals**

<table>
<thead>
<tr>
<th>Energy</th>
<th>100 J, 1ω</th>
<th>55 J, 1ω</th>
</tr>
</thead>
<tbody>
<tr>
<td>Efficiency</td>
<td>10 %</td>
<td>4.5 %</td>
</tr>
<tr>
<td>Repetition rate</td>
<td>10 Hz</td>
<td>10 Hz</td>
</tr>
<tr>
<td>Pulse length</td>
<td>3-10 ns</td>
<td>3-15 ns</td>
</tr>
<tr>
<td>Wavelength</td>
<td>0.53/0.35 μm</td>
<td>0.53 μm</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>&gt;150 GHz 1ω</td>
<td>–</td>
</tr>
<tr>
<td>Beam quality</td>
<td>5 xDL</td>
<td>6 xDL</td>
</tr>
</tbody>
</table>

**Status**

- IRE (NIF bundle)
- ETF
- 2MJ UV

09-01-05-XRL-JD-44
Mercury was operated for 55 J at 10 Hz for > $10^5$ shots with both amplifiers deployed - use He gas cooling.

**Average power histogram**

$\lambda = 1047$ nm

4.2 x 7.2 cm$^2$ beam

$2\omega$ operation 22 J, 10 Hz
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.