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Overview of Tabletop X-ray Laser Development at the Lawrence Livermore National Laboratory

J. Dunn, V. N. Shlyaptsev, J. Nilsen, R. F. Smith, R. Keenan, S. J. Moon, A. J. Nelson, J. R. Hunter, Y. L. Li, A. L. Osterheld, R. Shepherd, J. Filevich, J. J. Rocca, M. C. Marconi, H. Fiedorowicz, A. Bartnik, A. Ya. Faenov, T. A. Pikuz, P. Zeitoun, M. Fajardo, S. Hubert

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Berlin, Germany
August 21, 2006 through August 25, 2006

Disclaimer

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James Dunn

Lawrence Livermore National Laboratory

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Acknowledgment to contributions from many different researchers who participated in experiments:

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A. Ya. Faenov, T.A. Pikuz	***Multicharged Ions Spectra Data Center of VNIIFTRI***
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S. Hubert	***Commissariat á l'Énergie Atomique***

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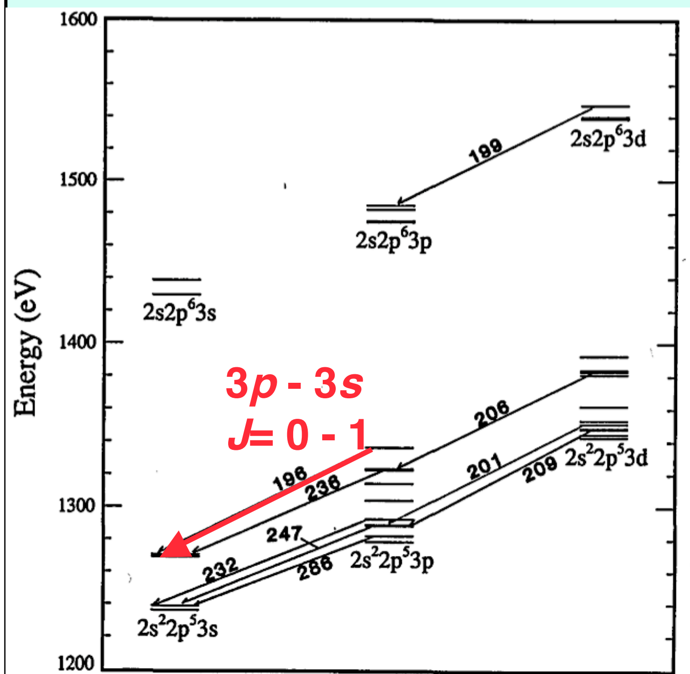
Overview and Summary:

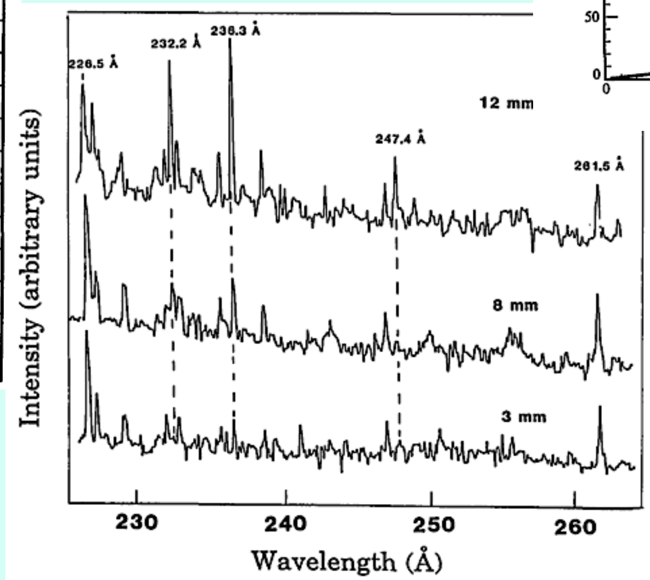
Give highlights of 10 years (1997 - 2006) of research in Tabletop X-ray Lasers at LLNL

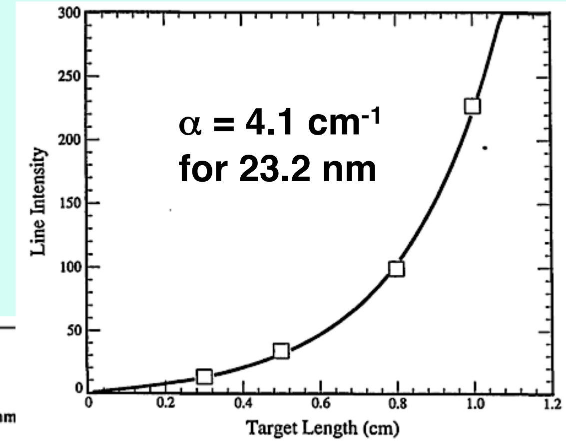
- **Initial motivation and background**
- **Development of laser system**
- **First Ne-like and Ni-like x-ray laser results**
- **Generation of saturated output**
- **Characterization of x-ray laser source**
- **Description of applications at COMET**
- **Future directions and comments**

X-ray laser experiments circa 1990 with 150 J, 1.5 ns were more challenging, gains were low and required detailed studies

Ne-like Ge Energy Level Diagram	Ge Spectrum	$3p$ - $3s$ J = 2 - 1 Intensity vs L







$$I = \frac{\epsilon}{\alpha} \frac{(e^{\alpha L} - 1)^{3/2}}{(\alpha L e^{\alpha L})^{1/2}}$$

G. Enright et al,. JOSAB 8, 2047 (1991)

- Before pre-pulse technique developed
- Multiple x-ray lines observed including 3d - 3p line at 19.9 nm

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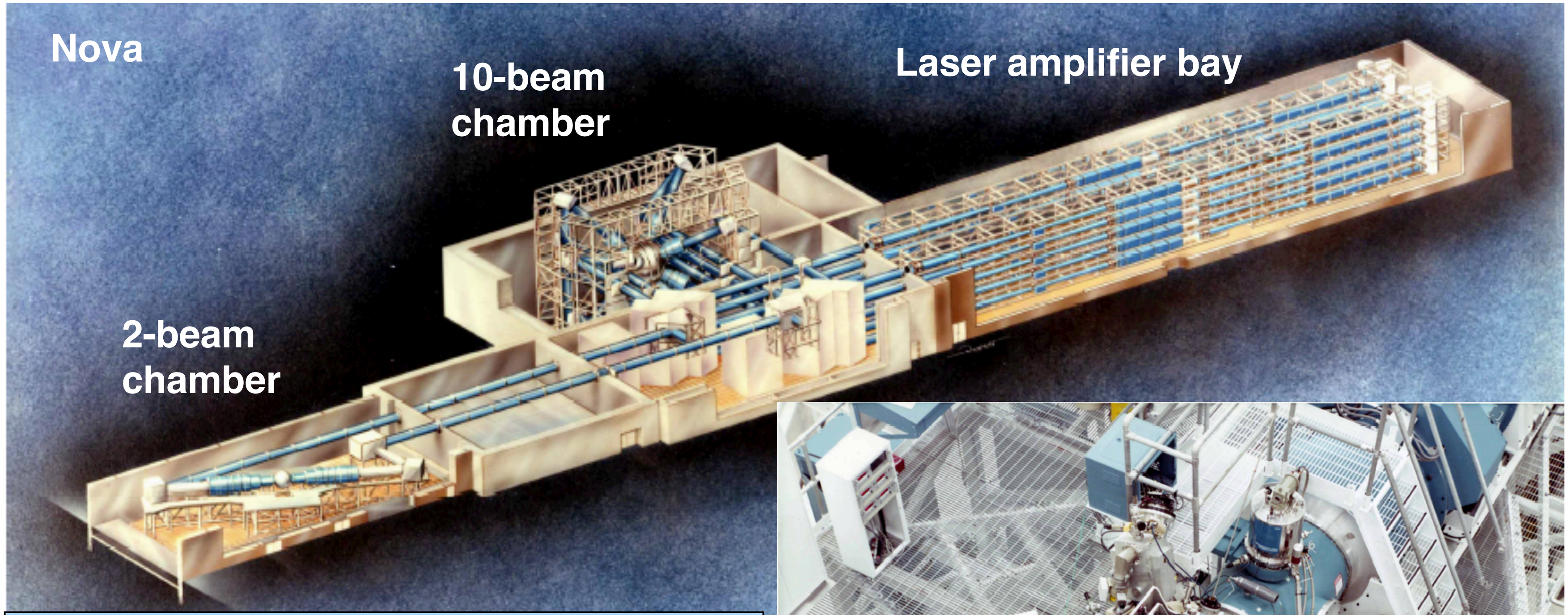
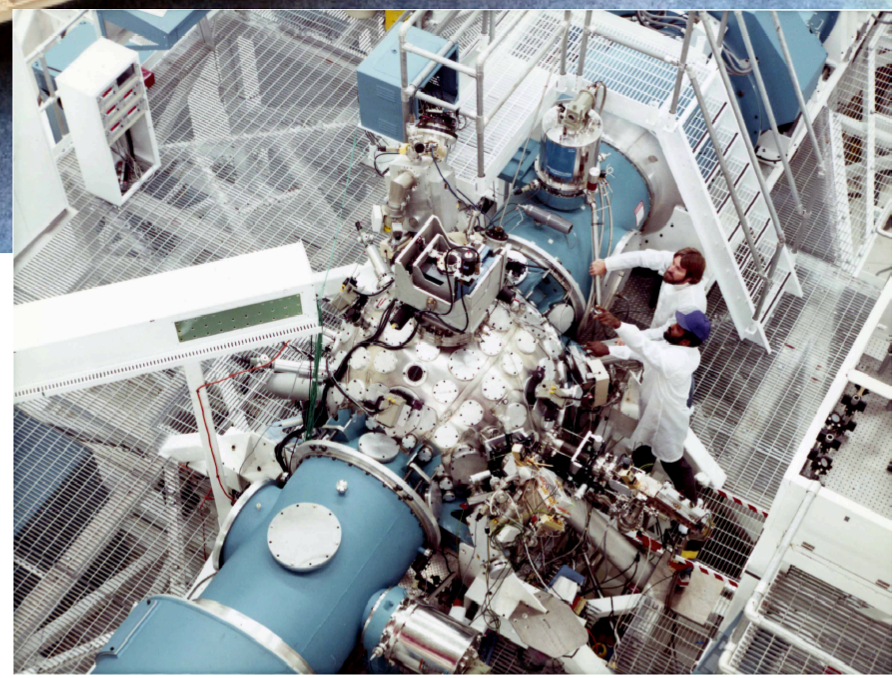
Early effort 1984 - 1996 on x-ray lasers was performed on Nova laser at LLNL: collisional excitation scheme was developed





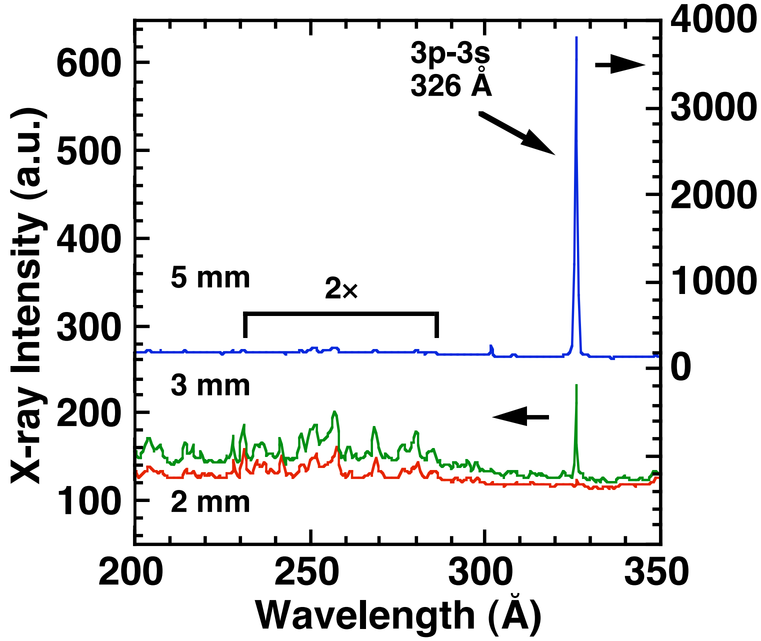
- **Substantial infrastructure investment**
- **2-beam target chamber was designed for x-ray laser research activities**
- **Soft x-ray diagnostics, optics, materials and instrumentation were developed**

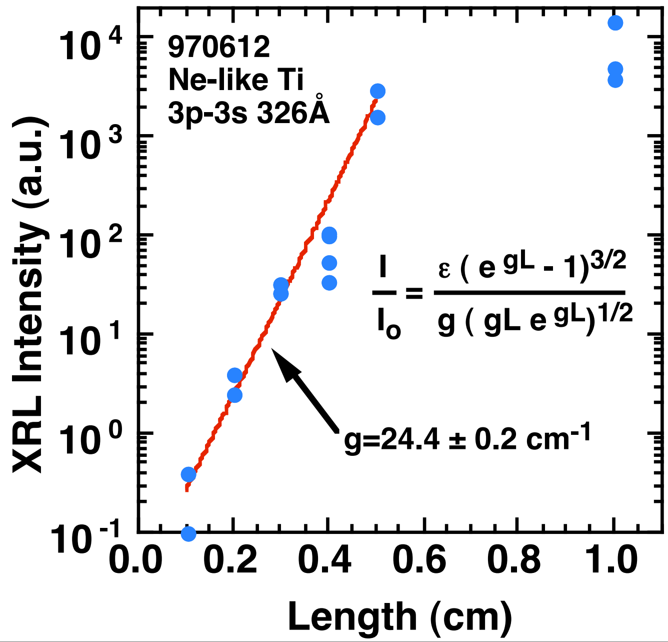
First lasing observed on tabletop system at LLNL for Ne-like Ti line at 32.5 nm on 5 June 1997:

- Exponential growth of g = 24.4 cm^{-1} inferred from Linford formula for unsaturated gain for L = 1 - 5 mm target lengths
- XRL output rises rapidly for L ≥ 1 mm
- Estimate gL product ~ 15 for 10 mm target

Laser Parameters

Shot #97061206
Ti slab, L=10mm
Line Focus 40 μm x 12.5 mm
Long Pulse: 5.5 J, 800ps (FWHM)
Short Pulse: 5.0 J, 1.5 ps (FWHM)
Laser repetition rate: 1shot/ 3 min.





Energy requirements are modest:
2 - 3 J in each beam sufficient to observe XRL

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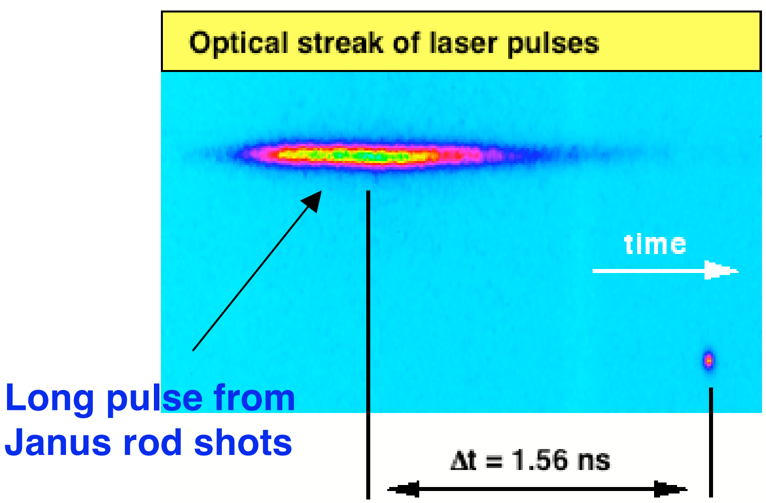
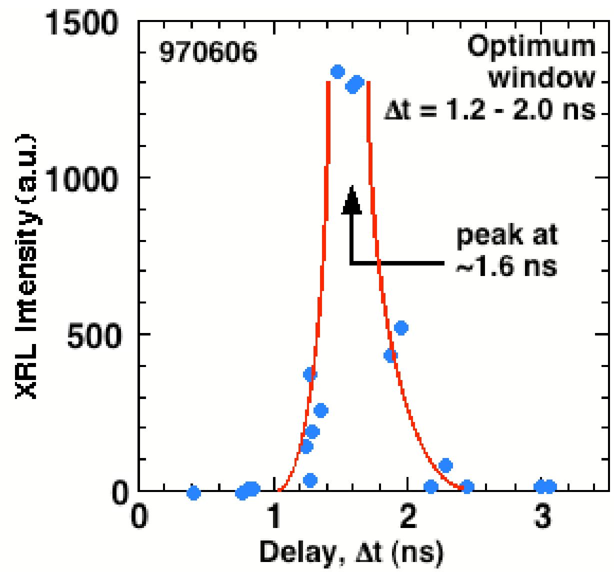
Ne-like Ti 3p-3s 326 Å x-ray laser line intensity is strongly dependent on short pulse delay

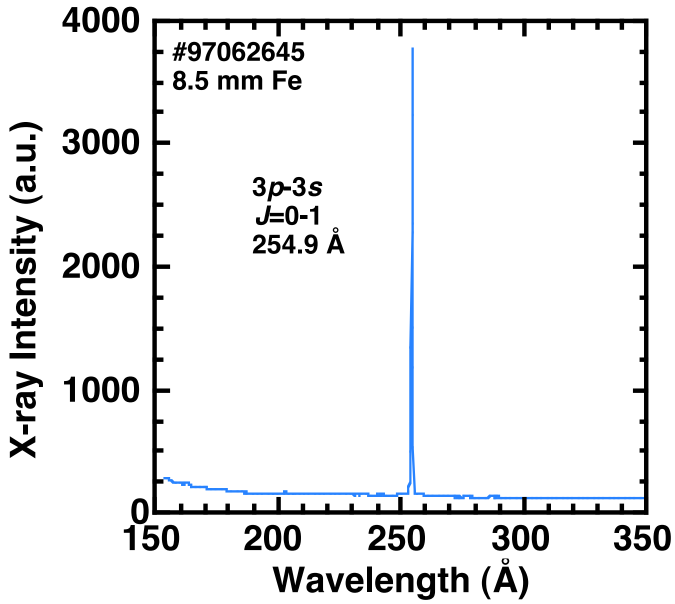
- The arrival of short pulse is delayed relative to the peak of the long pulse to investigate effect on XRL output:
- Observe no XRL line for $\Delta t \leq +800$ps and very weak for $\Delta t > 2.2$ ns
- Output rises rapidly for delay in window 1.2 ns < Δt < 2.0 ns with strong peak at ~1.6 ns

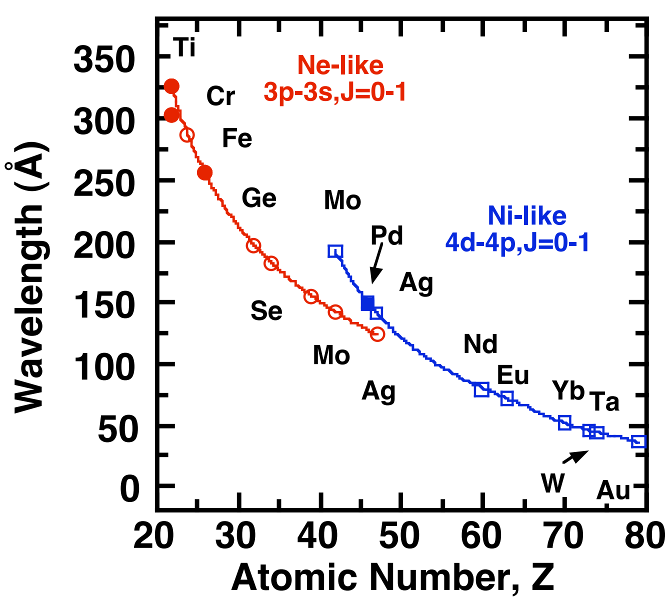




Extrapolate below 150 Å using transient XRL scheme by studying more efficient Ni-like ion sequence

- Extend XRL to shorter wavelengths from Ti 326 Å on 3*p*-3*s* *J*=0-1 using higher *Z* material e.g. Ne-like Fe readily lases at 254.9 Å
- Pump intensity requirements[1] $I \sim E_{XRL}^{3.5}$ - long pulse laser driver energies ~30x to ionize Ag to Ne-like for 123 Å XRL.
- Need Ni-like 4*d*-4*p* *J*=0-1 scheme to reach ~100 Å and shorter





[1]B. MacGowan *et al*, Phys. Fluids B 4(7), 2326 (1992)

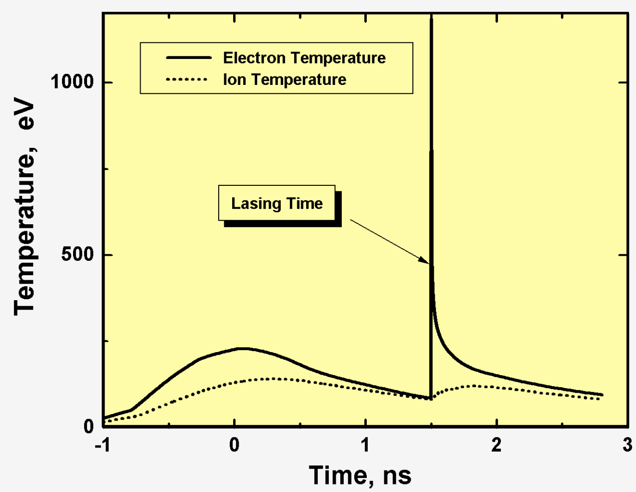
RADEX simulations indicate high transient gain during and after short pulse for Ni-like Pd 14.7 nm line

Experimental conditions simulated:

4.2 J, 850 ps pulse,
1.4 ns delay peak-to-peak
5.2 J, 1.2 ps pulse
80 μm × 1 cm line focus

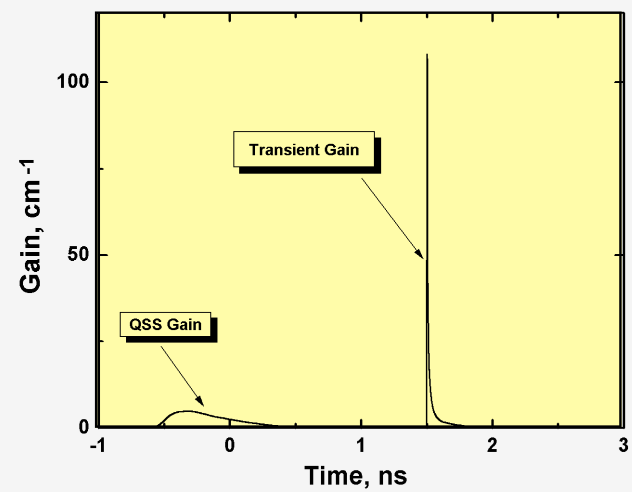
Dunn *et al*, PRL 80, 2825 (1998)

RADEX: Maximum Temperature for Ni-like Pd (Z=46)



- Plasma cools to 80 eV before arrival of picosecond pulse

RADEX: Maximum Gain for Ni-like Pd (Z=46)



- QSS gain from first pulse can be observed for longer targets

- **High gain observed when two laser pulses fired**
- **Reducing long pulse energy, requires shorter delay**

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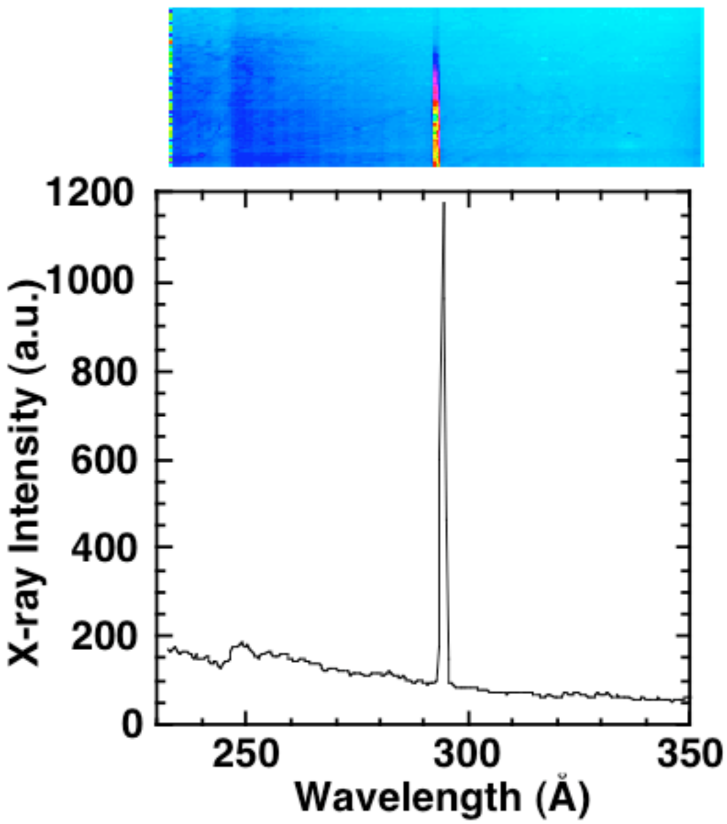
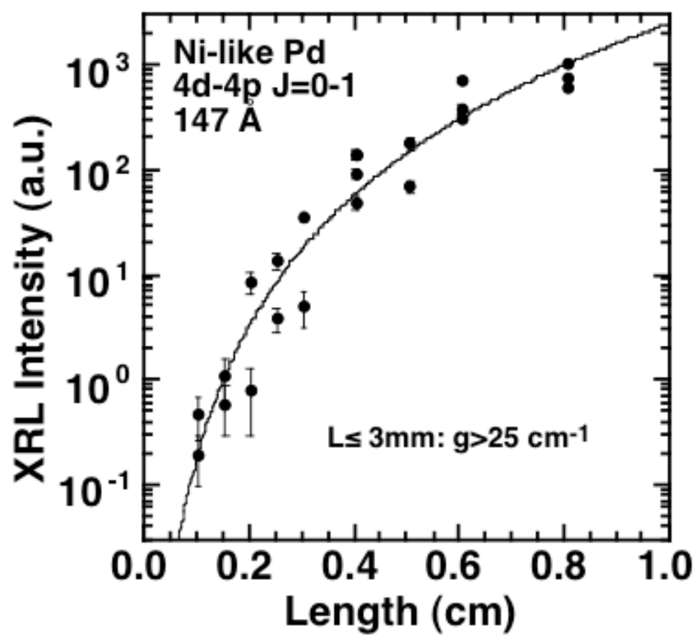
Moved onto Ni-like Pd 14.7 nm demonstration: X-ray laser exhibits high output for long targets but lower than Ti laser

- Gain measurements made in 2nd order - reduced gain for longer lengths from finite transit for XRL along plasma column
- High gain $g>25 cm^{-1}$ for L=3mm, overall gL ~ 13





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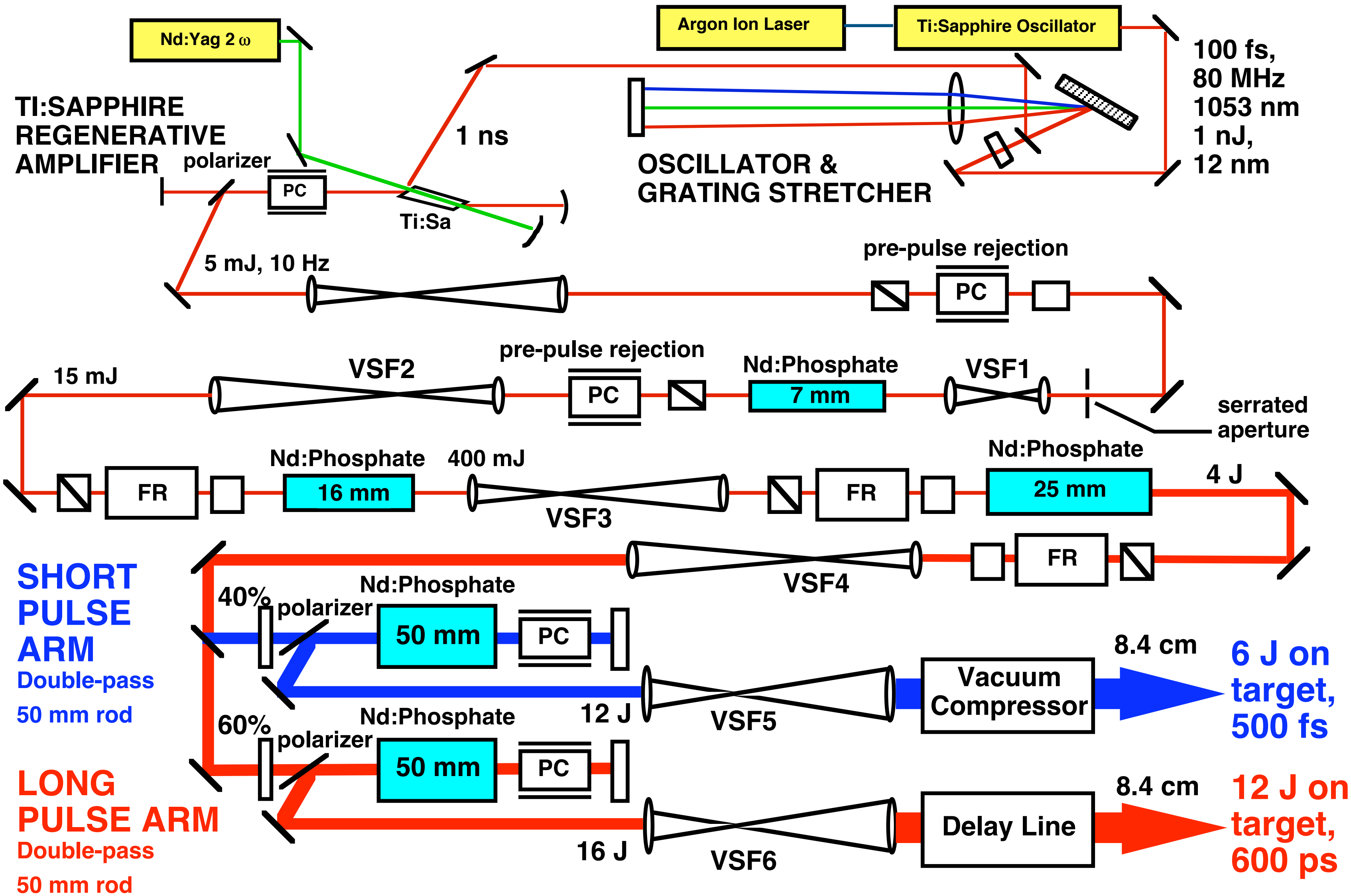
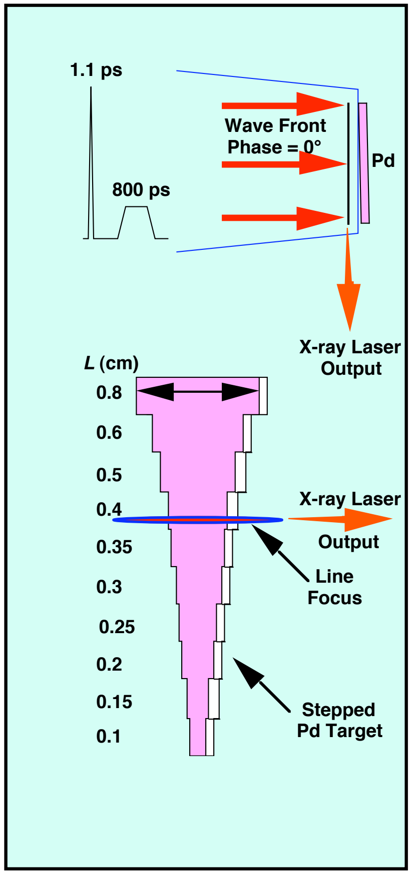
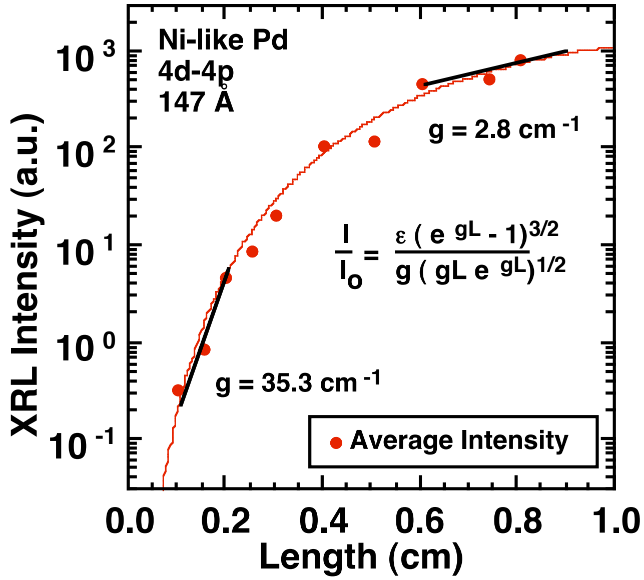
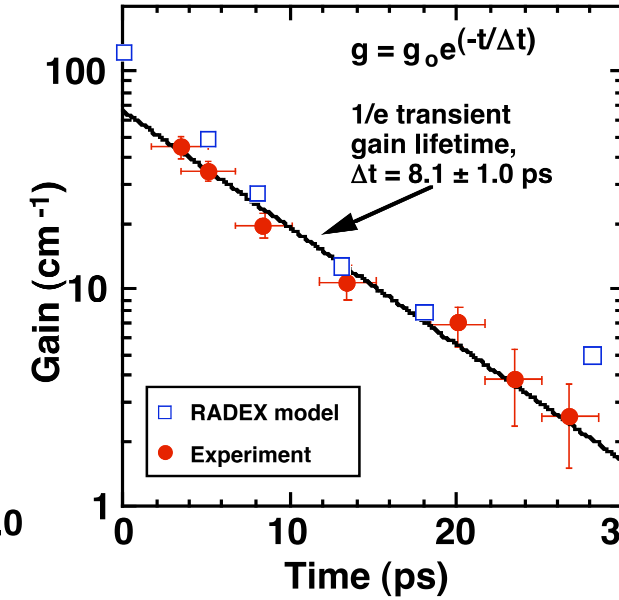
Early 1998: LLNL Table-Top X-ray Laser Facility showing Laser System Schematic



Without traveling wave gain lifetime for Pd follows close to exponential decay with time constant of 8 ps







- No travelling wave - use L/c to probe transient gain conditions
- Measured gain decays from 35 cm^{-1} (L=1.5 mm) to 2.8 cm^{-1} (L=8 mm) - approaching QSS conditions after 25 ps
- Experimental gain decay has exponential shape with 1/e ~ 8 ps (=2.4 mm) - good agreement with RADEX for 5 - 25 ps

Requirement for atomic spectroscopy to determine Ni-like ion x-ray laser lines accurately

PHYSICAL REVIEW A VOLUME 58, NUMBER 4 OCTOBER 1998

Wavelengths of the Ni-like $4d\ ^1S_0-4p\ ^1P_1$ x-ray laser line

PRA 58, R2668 (1998)

Yuelin Li, Joseph Nilsen, James Dunn, and Albert L. Osterheld
Lawrence Livermore National Laboratory, Livermore, California 94550

Alexander Ryabtsev and Sergey Churilov
Institute of Spectroscopy, Troitsk, Moscow Region 142092, Russia

(Received 11 June 1998)

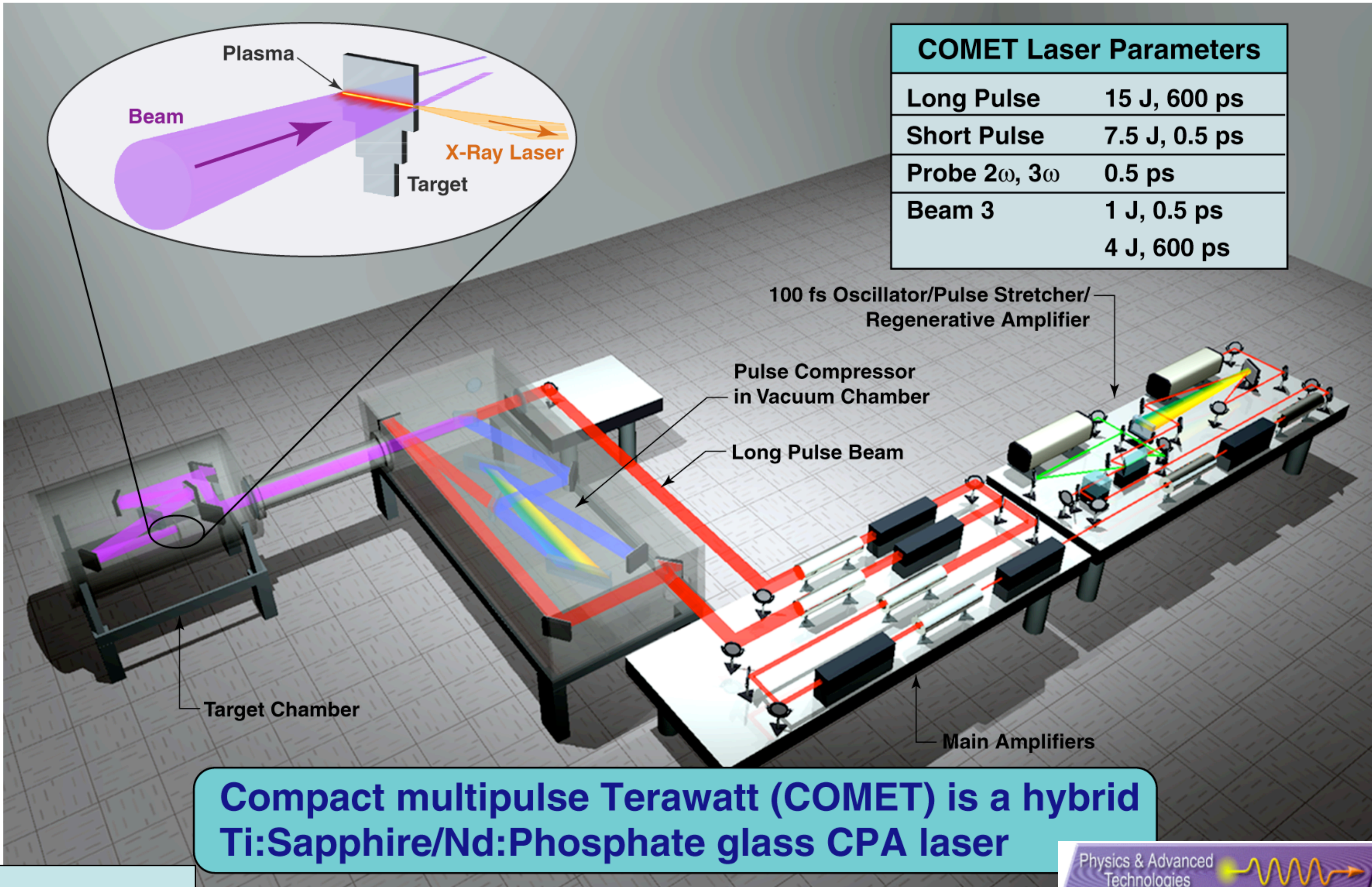
TABLE I. Wavelengths (in Å) of the $4d\,^1S_0\rightarrow4p\,^1P_1$ transition in Ni-like ions with $Z=31-60$. The uncertainties in the last digits are given in parentheses.

Z	OL prediction	Laser measurement	Nonlaser measurement
31			840.950(5)[a]
32			642.974(5)[a]
33			519.437(5)
34			435.1(4)[b]
35			374.174(5)
36			328.35(20)[b]
37			292.490(5)
38			263.71(15)[b]
39	240.2	240.11(30)	240.135(15)
40	220.0	220.20(30)	220.290(15)
41	202.9	203.34(30)	203.480(15)
42	188.3	188.95(30)	188.930(15)
43	175.5		
44	165.2		
45	155.3		
46	146.5	146.79(15)	
47	138.6	138.92(15)	
48	131.4	131.66(15)	

TABLE II. Comparison of calculated and measured wavelengths of the $4d\,^1S_0\rightarrow4p\,^1P_1$ transition for Ni-like Ag; wavelengths in angular brackets are predicted. The uncertainties in the last digits are given in parentheses.

Wavelength (Å)	Reference
138.92(15)	This work
143	[13]
139.95(15)	[35]
138.9(1)	[36]
⟨138.6⟩	This work
⟨139.92⟩	[25]
⟨137.76⟩	[10]

In 1998, established LLNL COMET tabletop, laser-driven facility producing pulsed ps duration x-ray laser at 1 shot/4 minutes



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

Compact multipulse Terawatt (COMET) is a hybrid Ti:Sapphire/Nd:Phosphate glass CPA laser

08-21-06-XRL-JD-11

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A reflection echelon was used to generate traveling wave line focus in series of steps

- Streak measurements show effectively no partial traveling wave
- Techniques e.g. tilting compressor gratings[1] or adding additional grating[2, 3] have been successfully utilized

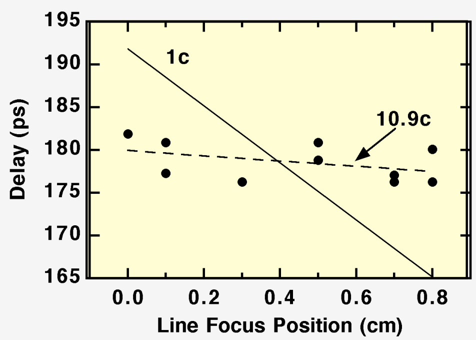
[1] J.-C. Chanteloup *et al*, *X-ray Lasers 1998*, IOP Ser. No 159, 653 (1999).

[2] J.L. Collier *et al*, *X-ray Lasers 1998*, IOP Ser. No 159, 649 (1999).

[3] A Klisnick *et al*, JOSA B 17, 1093 (2000)

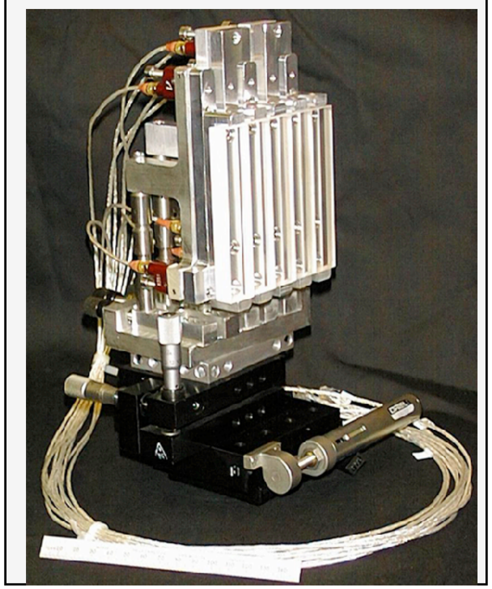
- Use reflection echelon technique Crespo López-Urrutia and Fill, SPIE 2012, 258 (1993).

Optical streak measurements along line focus - without TW

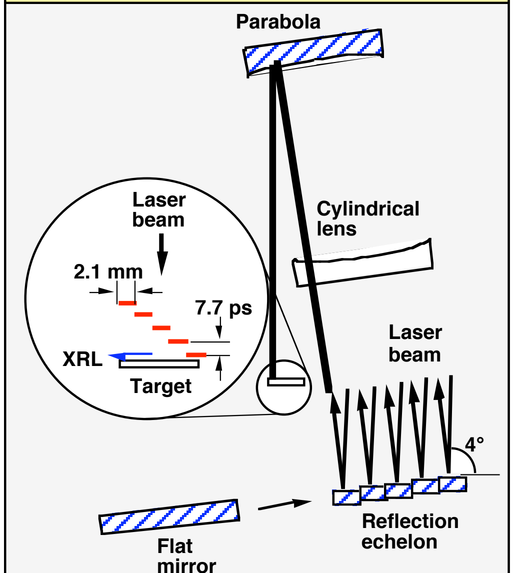


- Lower limit of ~11 c partial traveling wave

5-segment Reflection Echelon

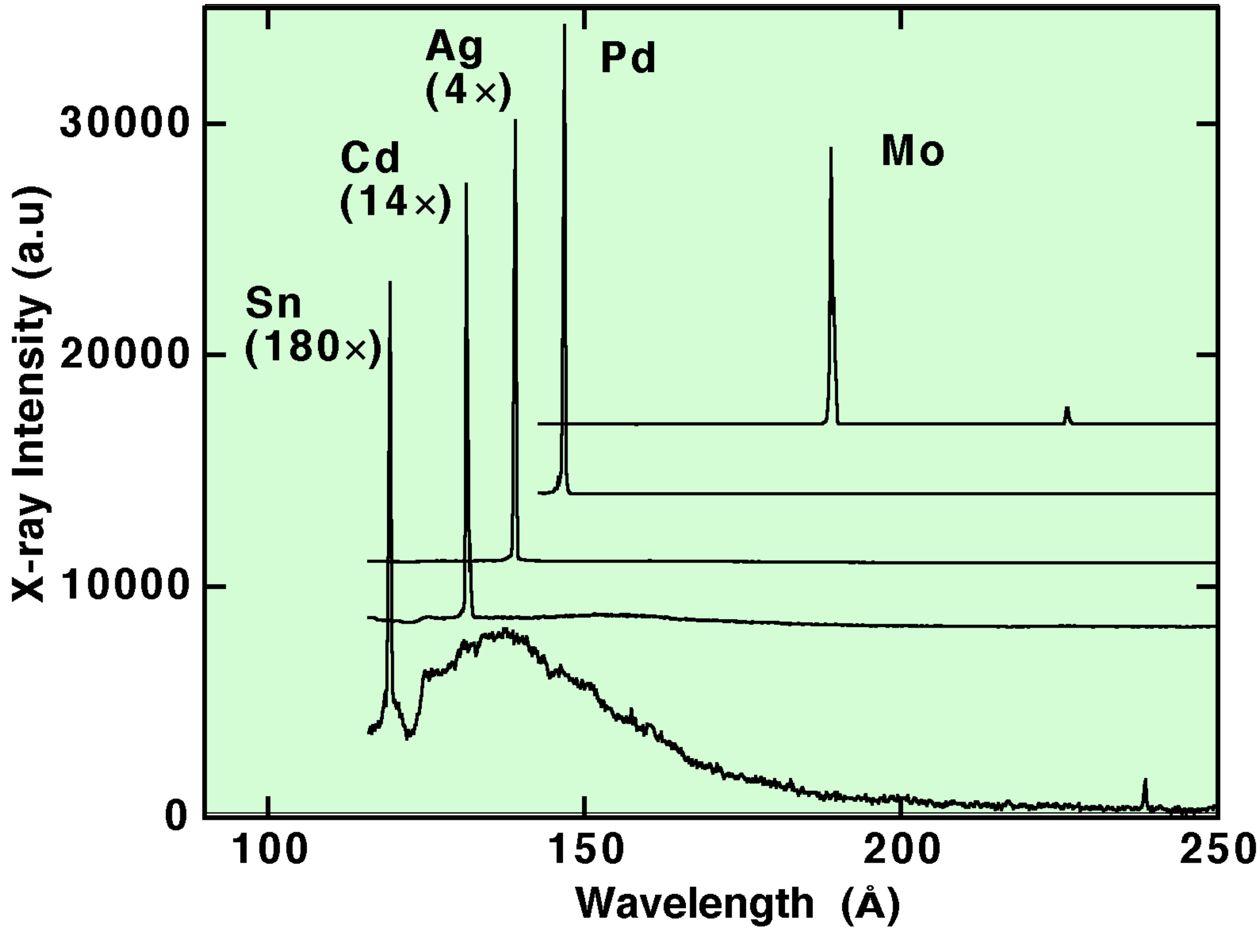


Focusing Geometry



Advantage: simple, effective technique, no energy loss and maintains integrity of 1 ps pulse along line focus

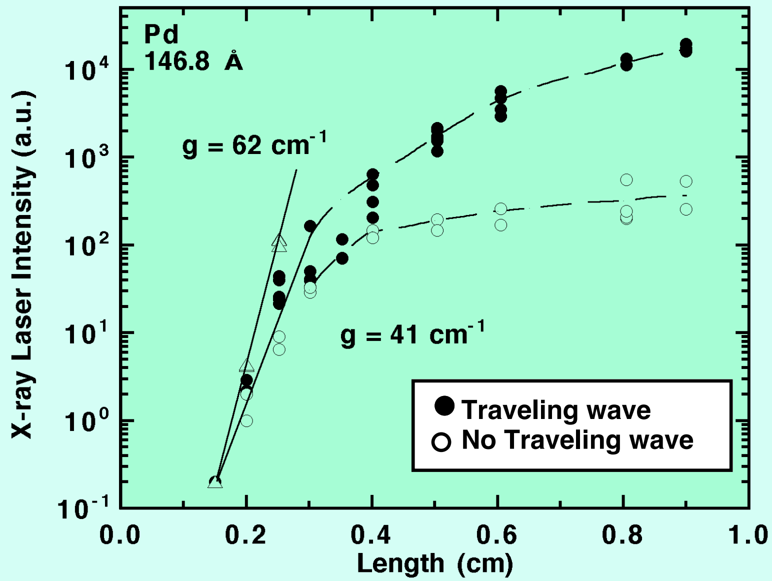
Strong lasing can be generated on 4d - 4p line of various of Ni-like soft x-ray laser lines



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

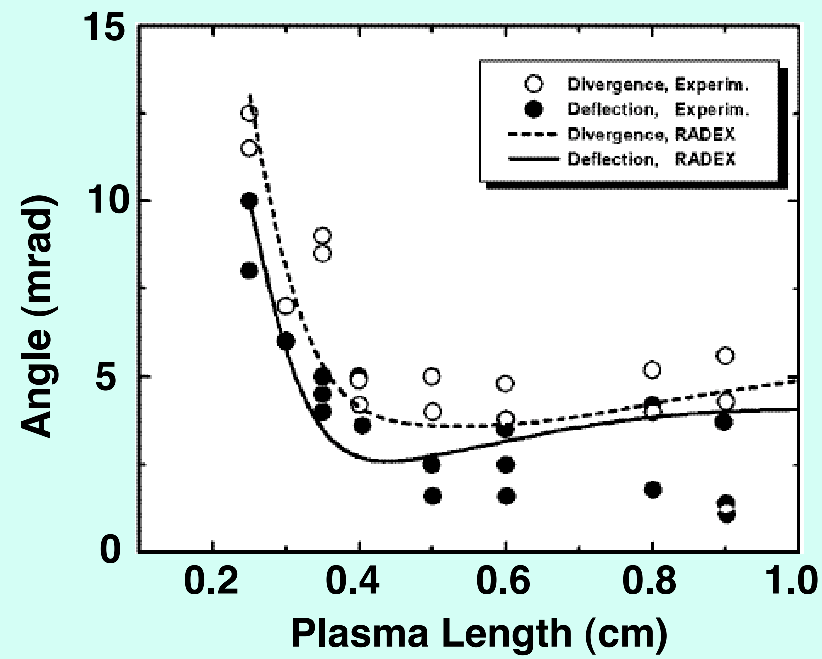
Traveling wave drives Ni-like Pd at 14.7 nm into gain saturation regime with 5 - 7 J energy in line focus

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

Pd angular pointing and divergence under amplification



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

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

Output still increasing with length - extract more XRL energy

Motivation for Gas Puff X-ray lasers: Demonstrate efficient lasing using tabletop picosecond laser drivers

Gas puffs are appealing as a laser-driven medium and have a number of substantial differences and advantages to solid targets:

- **Can create large plasma medium through choice of nozzle dimensions**
- **Can control initial gas density using backing pressure, delay**
  - closer to desired conditions for lasing
- **Density gradients within plasma are lower**
  - better amplification and propagation since refraction of XRL is lower
- **No debris generated**
  - operate at high repetition rates (>10 Hz)

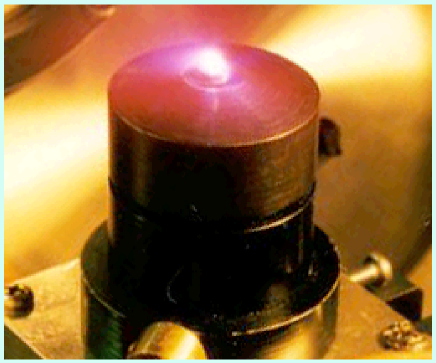
Concerns:

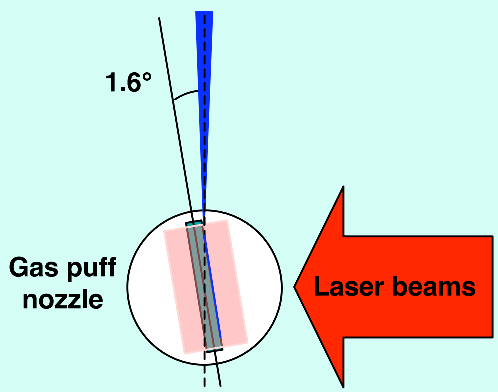
- **Very high absorption of XRL beam from cold gas at ends of column**
- **Laser drive coupling and ionization processes in gas puff plasma are less well understood**

H. Fiedorowicz, A. Bartnik

Picosecond laser driven gas puff x-ray laser setup

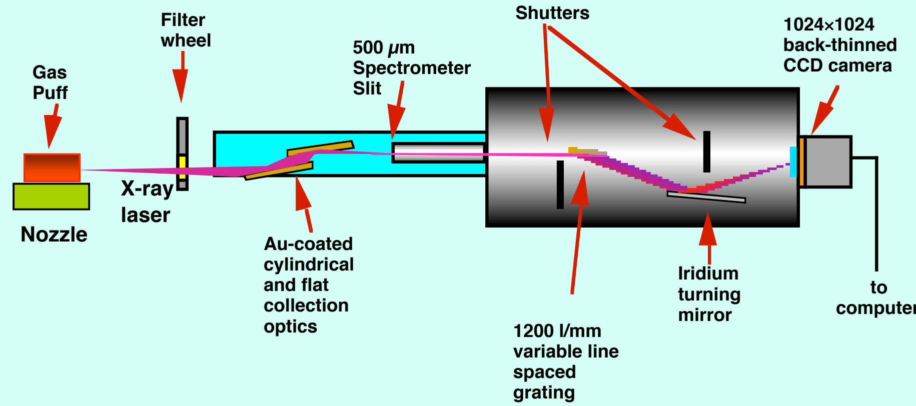
Gas puff target irradiated transversely by two laser pulses



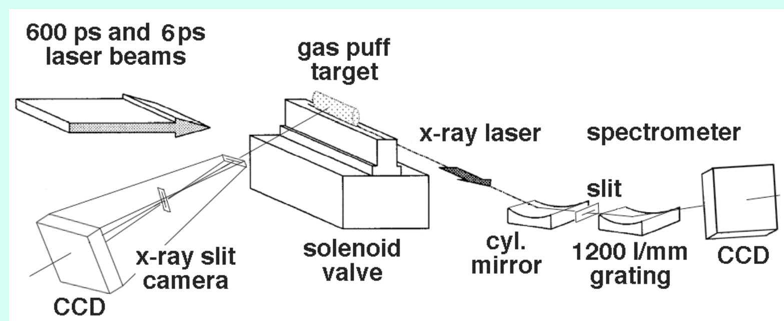


Gas puff nozzle dimensions 500 μm x 0.9 cm

On-axis Ar spectrum measured with 1200 l/mm variable line spaced flat-field spectrometer



Spectrometer wavelength range adjusted with Irridium turning mirror



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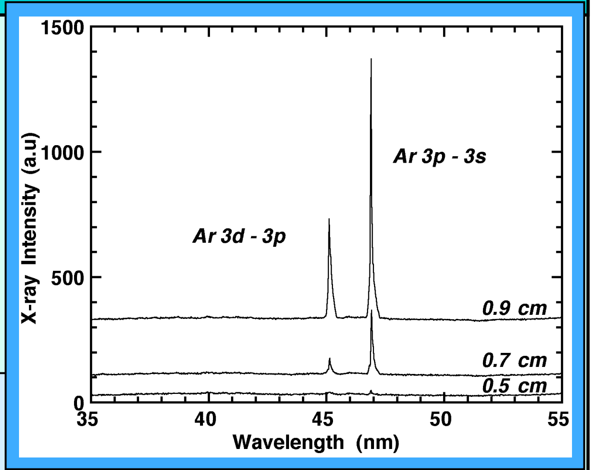
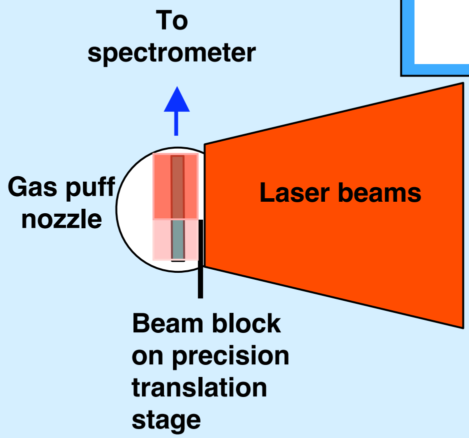
X-ray laser output for 45.1 and 46.9 nm line determined as a function of plasma column length

Ne-like Ar on-axis spectra for 0.5, 0.7 and 0.9 cm lengths

Laser energy:
4 ± 0.1 J, 600 ps
6.6 ± 0.2 J, 6 ps

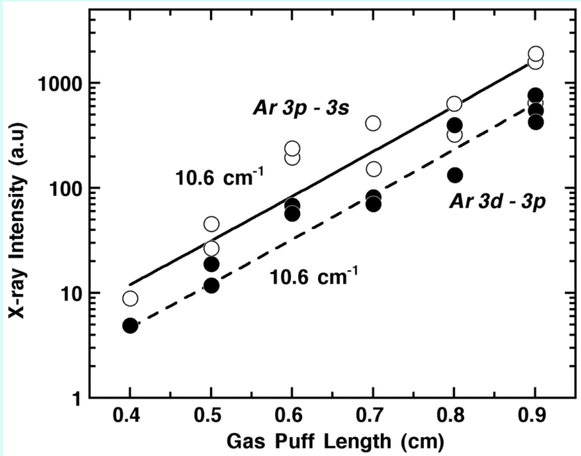
Intense lasing observed for both lines





Part of gas puff column is blocked using encoded translation stage for intensity vs length scan

Ar x-ray laser intensity vs length



Pressure:	**7 bars**
Δt Laser:	**1.0 ns**
Valve delay:	**400 - 500 μs**

G.J. Linford, E.R. Peressini, W.R. Sooy, and M.L. Spaeth, "Very long lasers", Appl. Opt. 13(2), 379-390 (1974).

Both lines have similar small signal gain 10.6 ± 1 cm^{-1} giving gL product of 9.5

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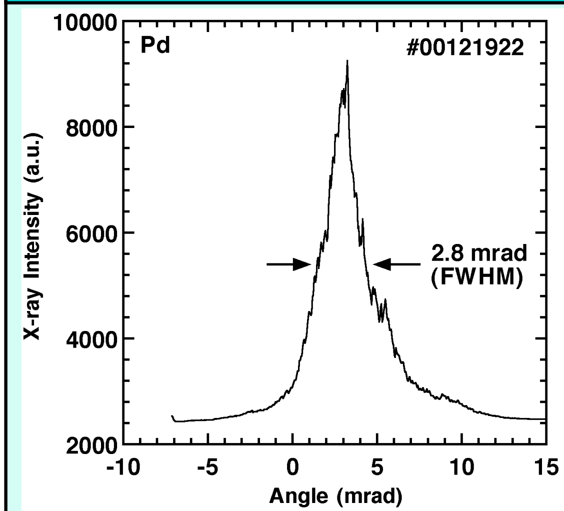
Characterization of x-ray source to improve x-ray laser parameters as a pre-cursor to application development

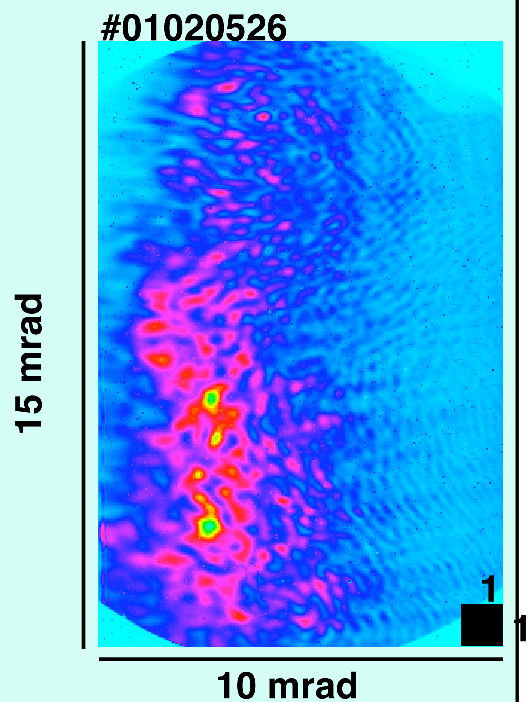
- Near- and far-field characterization
- Temporal pulse measurements
- Longitudinal coherence - spectral line width measurement
- Spatial coherence

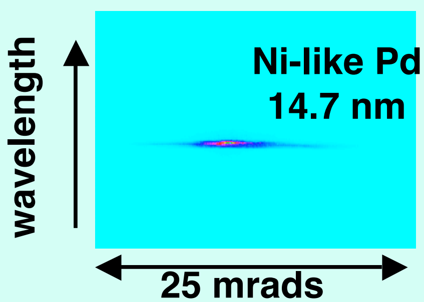
- X-ray laser-based applications
  - Interferometry of laser-produced plasmas
  - Photo-electron spectroscopy

Characteristics of 14.7 nm x-ray laser profile

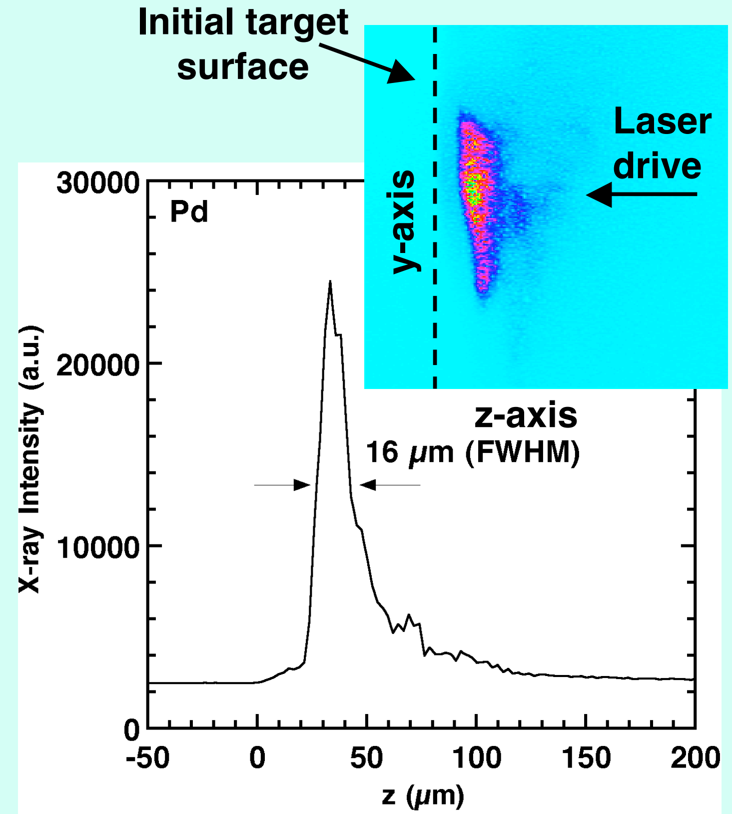
Ni-like Pd 14.7 nm Horizontal Beam Divergence and Far-Field Pattern







Ni-like Pd Near-Field Pattern 16 x 80 μm^2

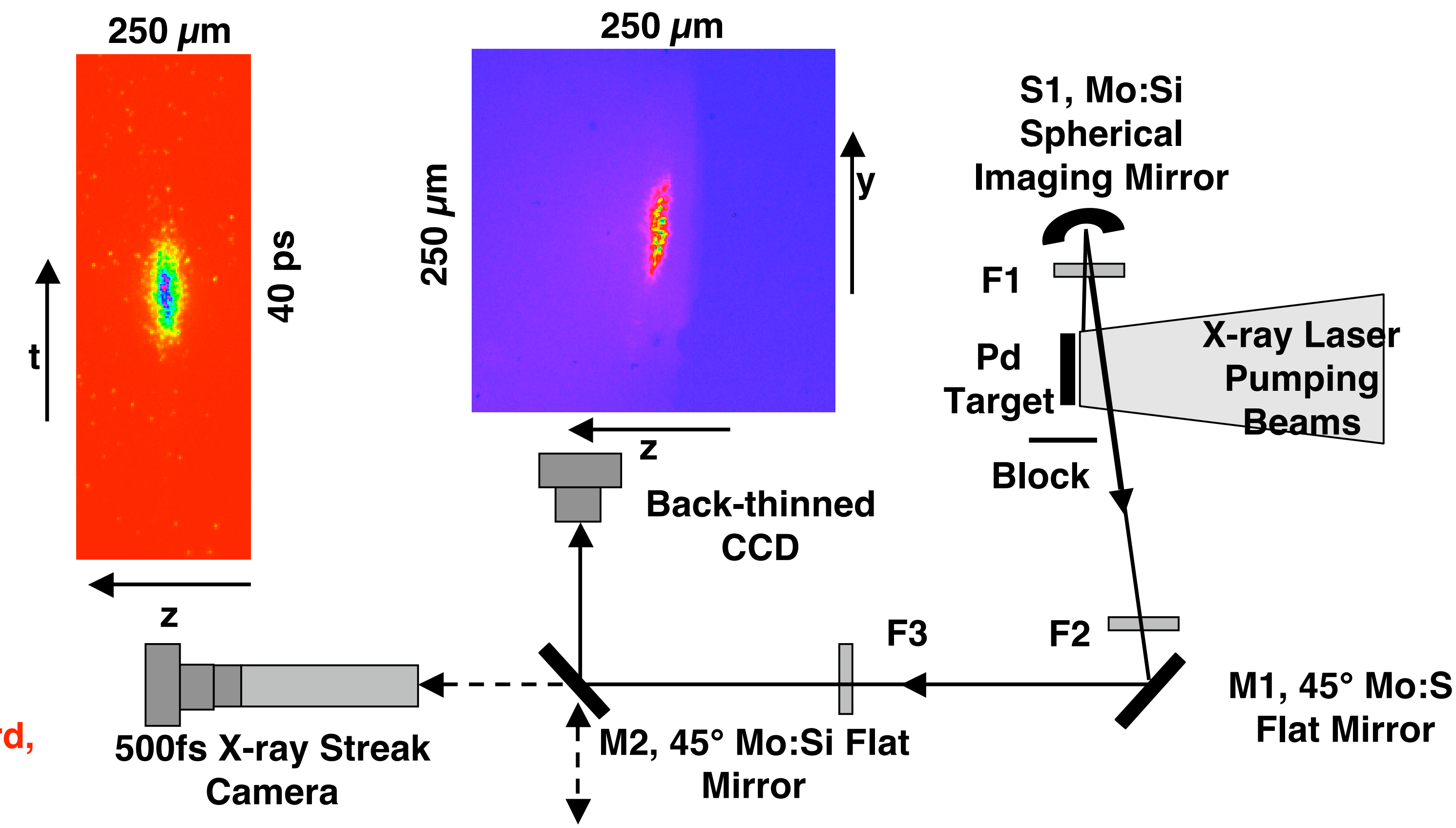


Narrow horizontal beam divergence 2.8 mrad (FWHM) but beam has multi-mode structure - observe some interference in far-field from multiple coherent sources

500 fs x-ray streak camera used to measure temporal duration of x-ray laser in 2-D near-field imaging setup

Experimental Criteria:

- Spatially resolve x-ray laser emission, localize continuum emission
- Minimize instrumental broadening effects (no chirp from spectrometer grating)
- Geometry should be similar to applications
- Control x-ray laser intensity (F1, F2, F3), repeatability, many shots



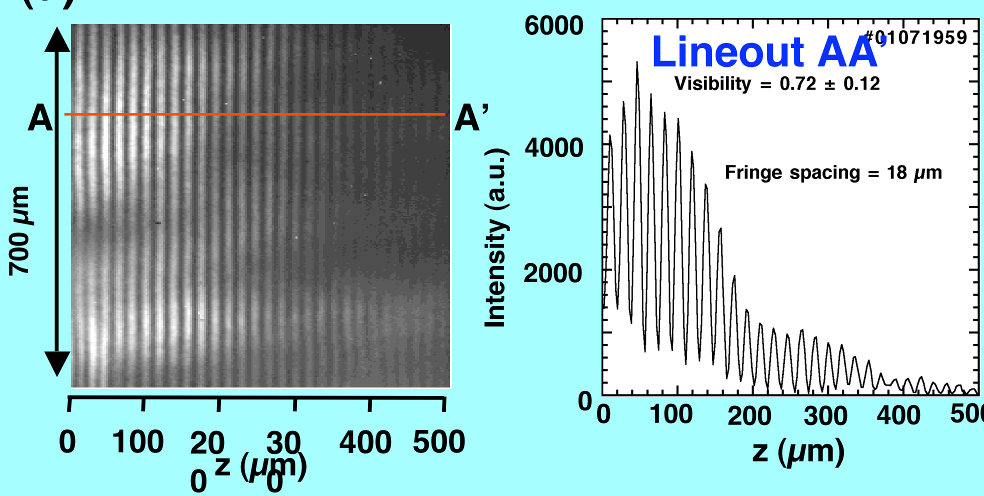
R. Shepherd,
R. Booth
(LLNL)

J. Dunn et al, submitted to Phys. Rev. A (2005).

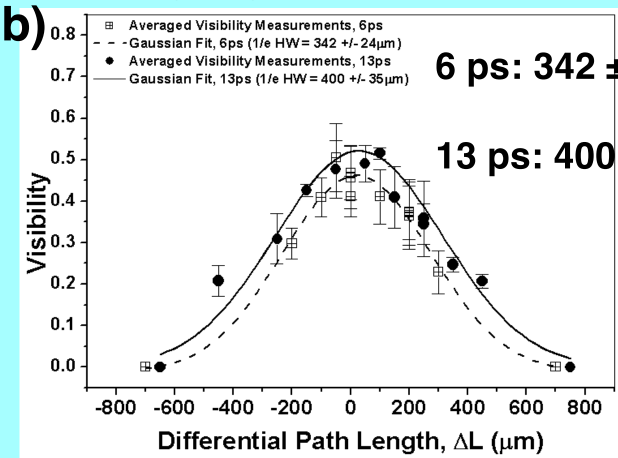
X-ray laser beam is characterized for interferometry: coherence and fringe visibility with 4 - 6 ps duration

XRL Coherence and Fringe Visibility

(a)



(b)



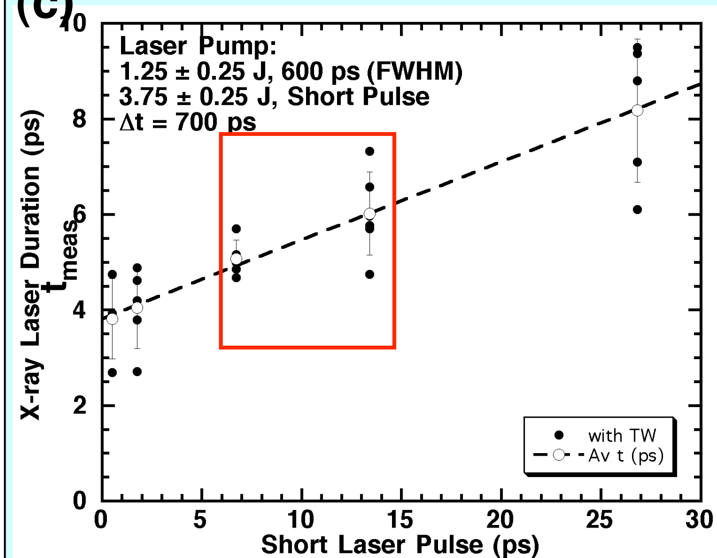
6 ps: 342 ± 24 μm 1/e HW

13 ps: 400 ± 35 μm 1/e HW

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

XRL Pulse vs SP duration

(c)



With R. Shepherd, R. Booth

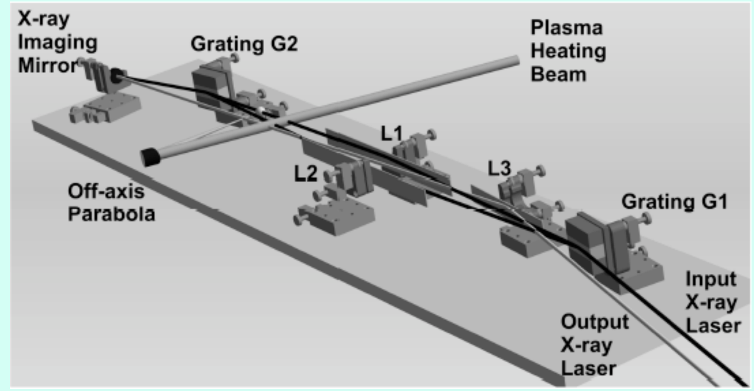
(a) Excellent spatial coherence - high fringe visibility 0.72 ± 0.12

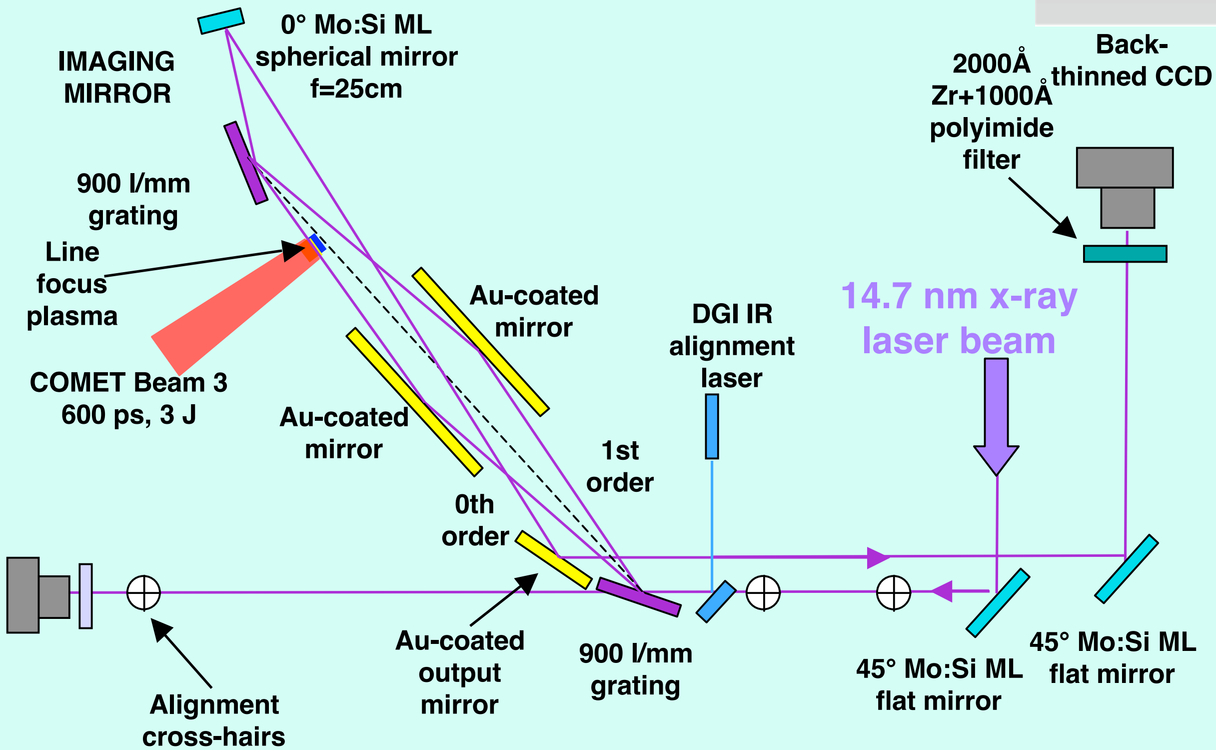
(b) Excellent longitudinal coherence - Michelson interferometry (With P. Zeitoun, S. Hubert et al LIXAM/CEA)

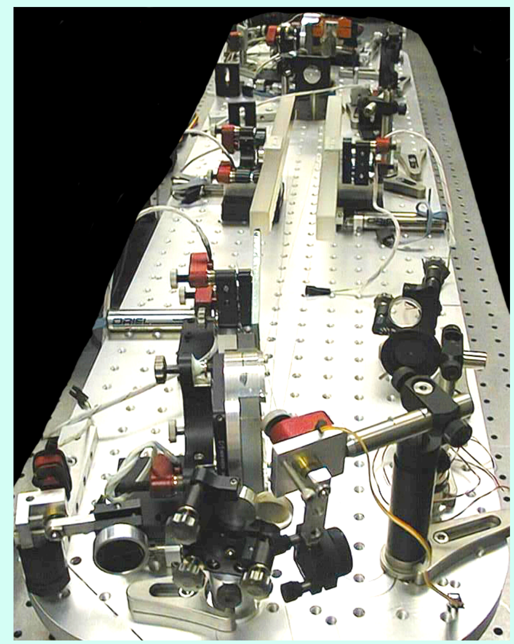
(c) X-ray laser pulse duration 4 - 6 ps (FWHM) for interferometry

Diffraction Grating X-ray Laser Interferometer Layout: Mach-Zehnder configuration for 14.7 nm Ni-like Pd x-ray laser

Detector spatial resolution ~0.5 μm
Magnification 22x setup
Gratings are beam splitters







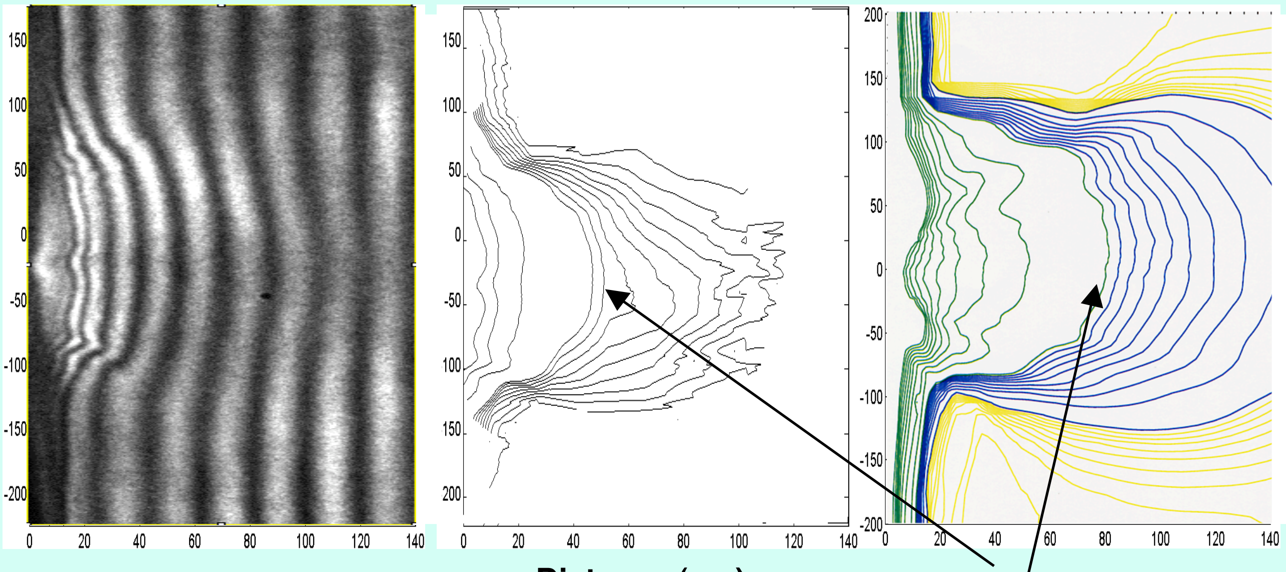
08-21-06-XRL-JD-23

J. Rocca and J. Filevich (CSU)

Physics & Advanced Technologies

Experiments used to benchmark 2-D LASNEX for high energy density laser-produced plasmas - real tool

Interferogram | **Expt. Density Profile** | **2-D LASNEX at t = +0.26 ns**



1mm Al targets
3 J, 600 ps pulse
12 μm x 3.1 mm
I ~10^{13} W cm^{-2}

Observe n_e > 4×10^{20} cm^{-3}

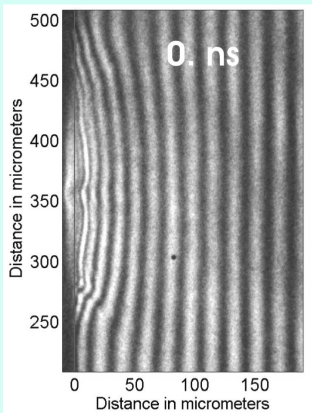
- **Small 12 μm width results in substantial 2D plasma expansion - reduced on-axis density**
- **1D and 1.5D LASNEX simulations do not accurately model plasma conditions**
- **2D simulations use experimental focal spot and temporal pulse shape**
- **Plasma pressure gradients, radiative heating and thermal conduction produces side lobes**

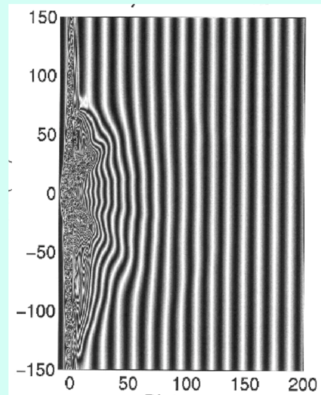
Short wavelength, ~ 1 μm spatial and ps time resolution essential

Experimental interferograms used for comparison with 2-D LASNEX simulations

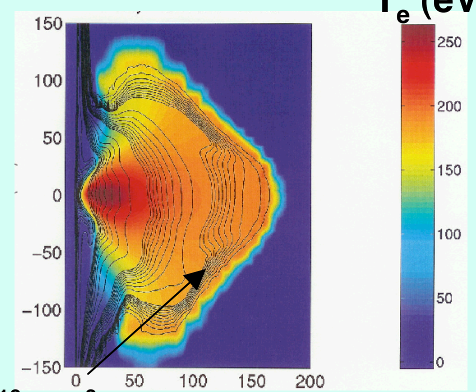
14.7 nm Interferogram	Simulated Interferogram	LASNEX 2-D T_e, n_e Plot

0 ns



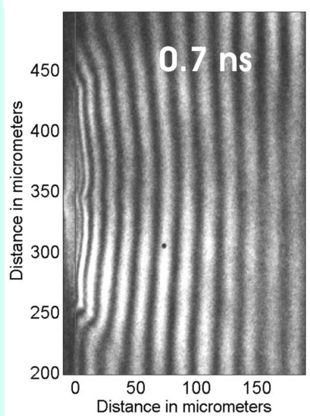


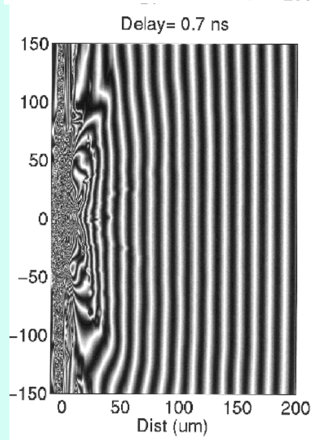
T_e (eV)



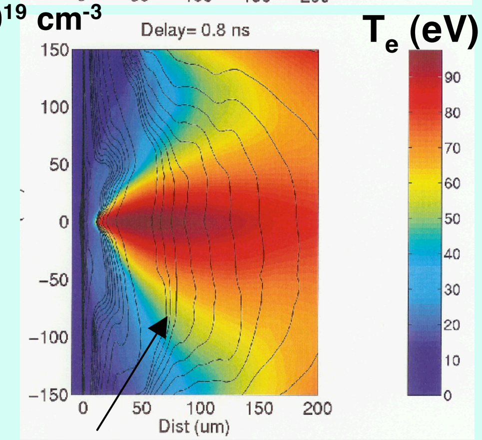
$n_e = 10^{19}$ cm^{-3}

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}

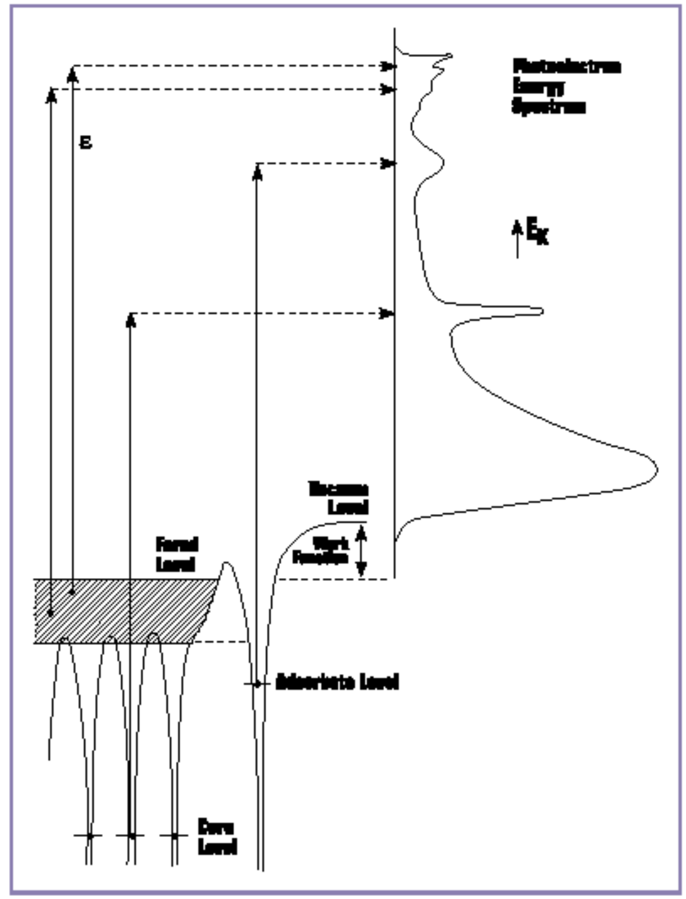
See Poster session for further discussion of LPP phenomena

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 = hν - 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**

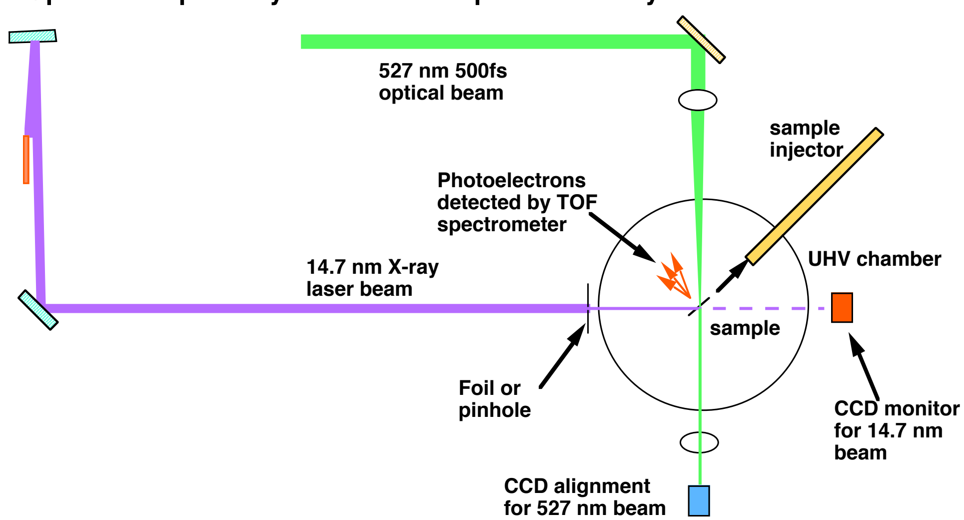


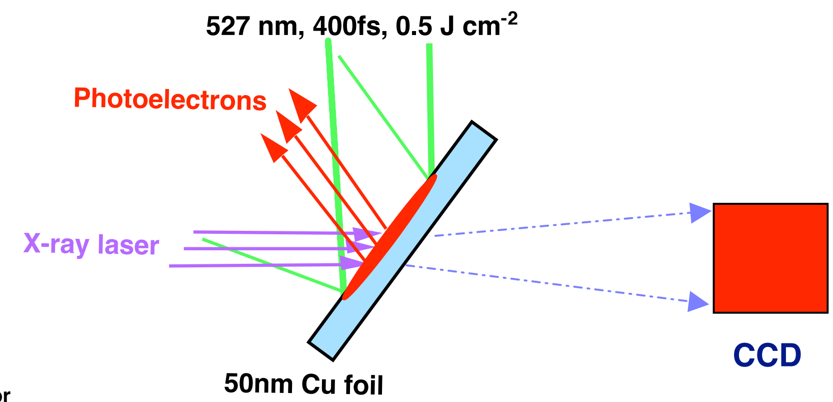
We probe changes in electronic structure during the dynamic processes of melting

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





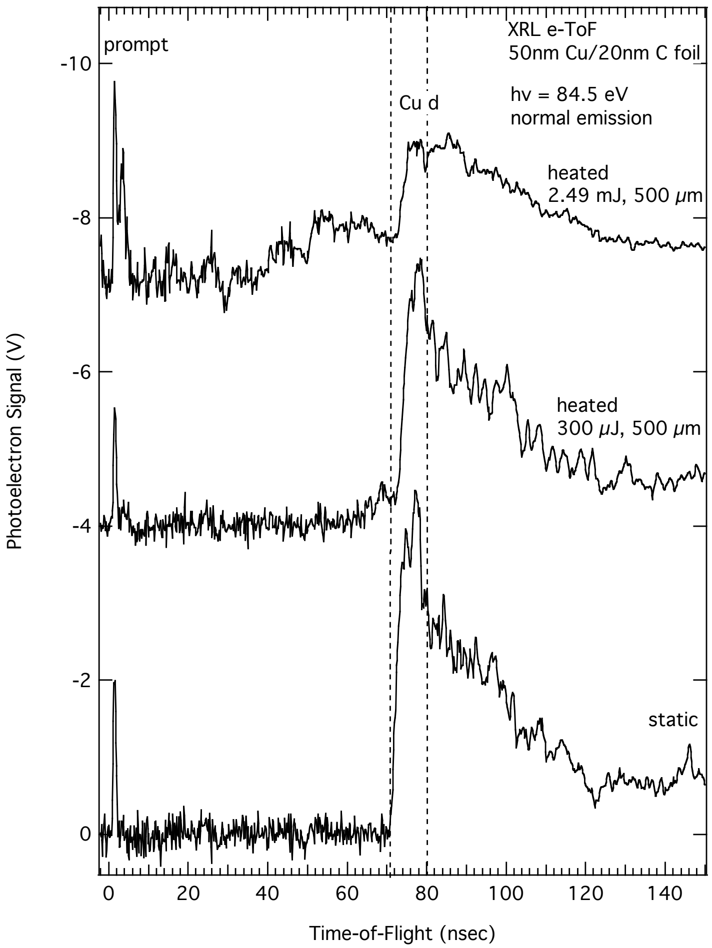
1. Foil or pinhole isolates x-ray laser beam line vacuum from UHV chamber

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

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

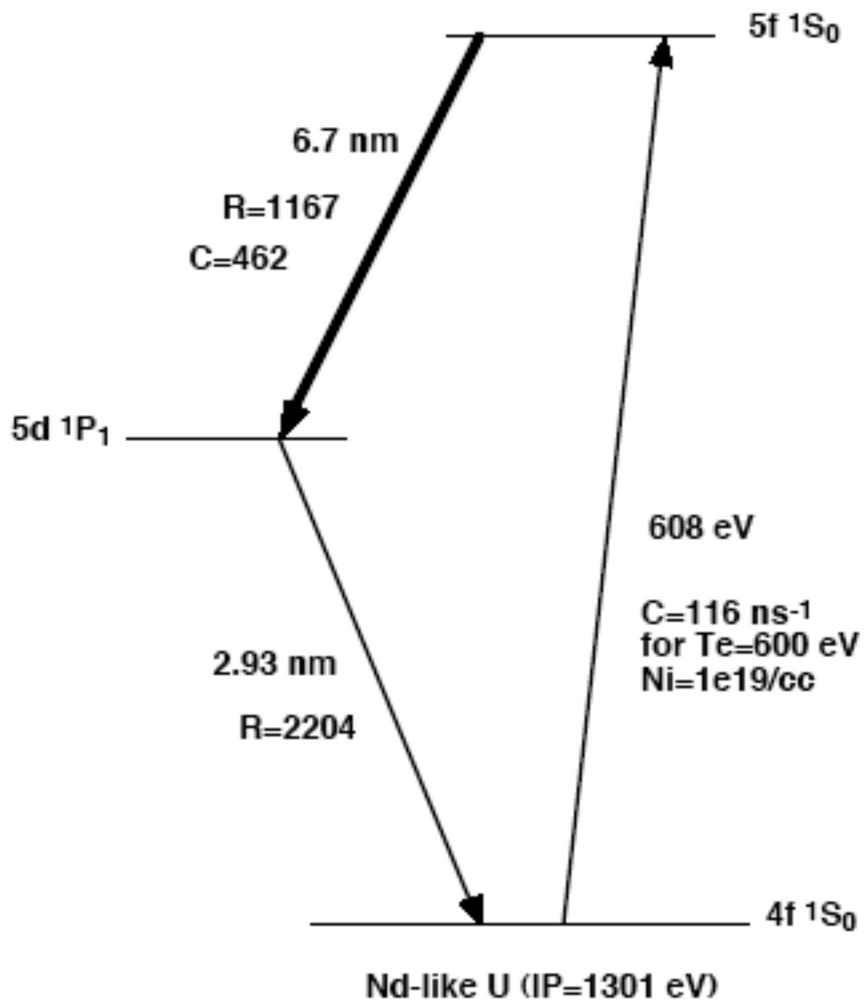
Cu 3*d* peak shifts towards lower kinetic energy (higher binding energy) – band is 'sinking'.

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

A.J. Nelson et al, published in Appl. Phys. Lett (2005)

Physics & Advanced Technologies

Other x-ray laser schemes proposed but not yet observed: Energy level diagram for Nd-like U 5f - 5d transition at 6.7 nm



Joe Nilsen, LLNL

Piaski, 09-08-05-XRL-JD-28

Overview and Summary:

Give highlights of 10 years (1997 - 2006) of research in Tabletop X-ray Lasers at LLNL

- **Initial motivation and background**
- **Development of laser system**
- **First Ne-like and Ni-like x-ray laser results**
- **Generation of saturated output**
- **Characterization of x-ray laser source**
- **Description of applications at COMET**
- **Future directions and comments**