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Characterization and Applications of Laser-Driven X-ray Lasers

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October 11, 2005

Atomic Spectroscopy in High Fields
Piaski, Poland
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Disclaimer

Characterization and Applications of Laser-Driven X-ray Lasers

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UCRL-CONF-216064

Acknowledgments to contributions and collaborations with numerous people:

LLNL:

Roisin Keenan	GRIP X-ray lasers, x-ray laser interferometry
Steve Moon	2-D LASNEX hydrodynamic simulations
Art Nelson	Photoelectron spectroscopy
Joe Nilsen	X-ray laser design, LASNEX and Cretin simulations
Ronnie Shepherd	X-ray laser temporal measurements
Ray Smith	X-ray laser interferometry, temporal measurements, coherence measurements

Colorado State University:

Jorge Rocca	X-ray laser interferometry
Jorge Filevich	X-ray laser interferometry

UC Davis:

Slava Shlyaptsev	X-ray laser design and RADEX simulations

LOA:

Philippe Zeitoun	X-ray laser coherence measurements

Outline:

- **Brief description of collisional excitation soft x-ray lasers:**
  $\lambda \sim 3.5$ nm - 60 nm (E ~ 400 eV - 20 eV)

- **Characterization experiments for Ps-driven x-ray lasers:**

	Ps-Driven X-ray Lasers	PALS
- gain saturation	(10 μJ output, 10^{12} photons/pulse)	10^{15} ph./pulse
- beam divergence	(~2 mrad FWHM)	
- x-ray laser duration	(2 - 8 ps FWHM)	100ps
- longitudinal coherence	(~400 μm 1/e)	
- Line width	$\lambda/\Delta\lambda$ = 50,000	
- Brightness	10^{25} ph. mm^{-2} mrad^{-2} s^{-1} [0.1% BW]$^{-1}$	10^{27}

- **Optical pump-x-ray laser probe photo-electron spectroscopy experiments: picosecond soft x-ray surface analysis tool**

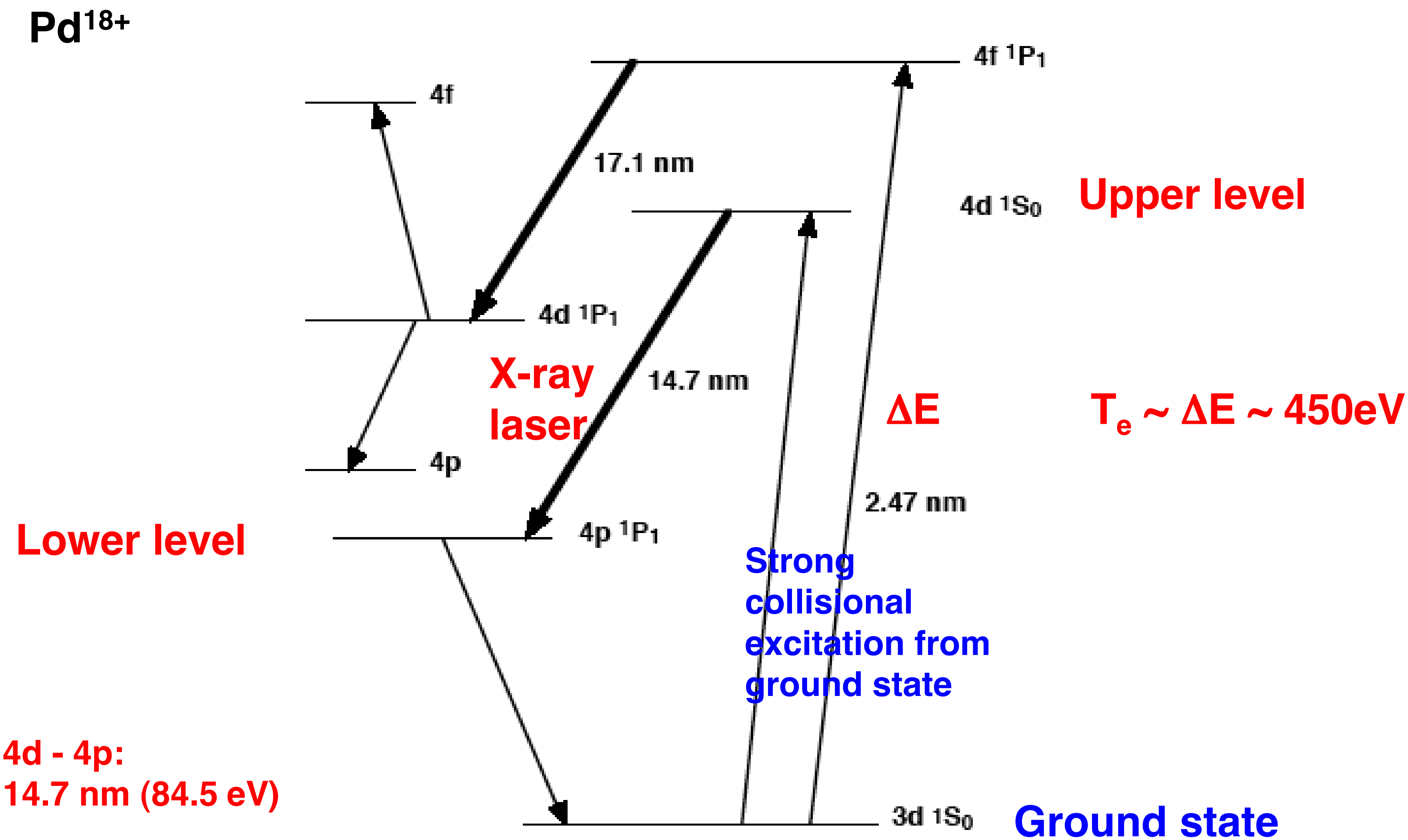
- **X-ray laser interferometry of High Energy Density (HED) plasmas**

- **X-ray laser probes of heavy ion beams (Th. Kuehl, GSI)**

- **Concluding remarks and Summary**

Physics & Advanced Technologies

Soft x-ray laser requires creating plasma column with Ni-like ion fraction and collisionally pumping 4d upper level



4d - 4p:
14.7 nm (84.5 eV)

Piaski, 09-08-05-XRL-JD-4

Physics & Advanced Technologies

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 $4d\,^1S_0\rightarrow 4p\,^1P_1$ 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)	
49	124.0		

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

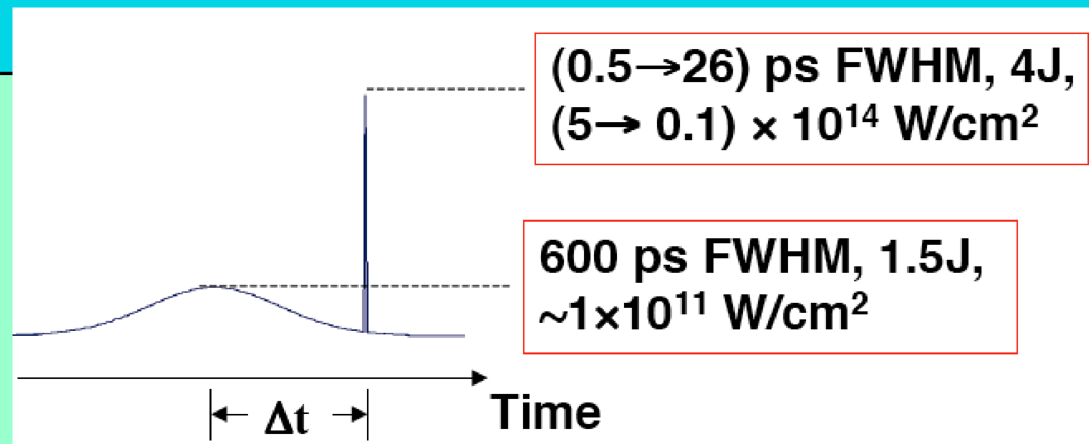
Wavelength (Å)	Reference
138.92(15)	This work
143	[13]
139.95(15)	[35]
138.9(1)	[36]
⟨138.6⟩	This work
⟨139.92⟩	[25]
⟨137.76⟩	[10]

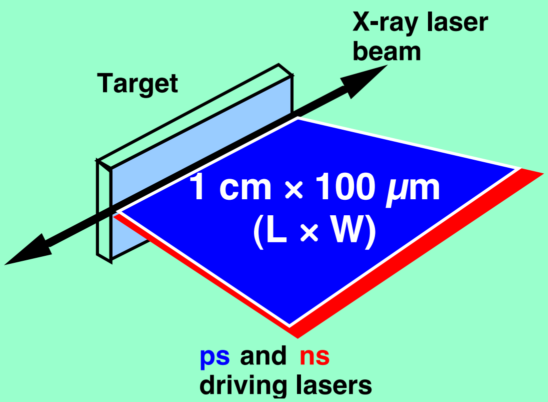
Transient scheme uses 1 ps, 5 - 10 TW laser pulse to optimize excitation - Tabletop X-ray Laser

Two Stage Process

Long laser pulse: 1 - 2 J
- plasma formation
- ionization
- delay for relaxation of density gradients

Short laser pulse: 2 - 5 J
- excitation



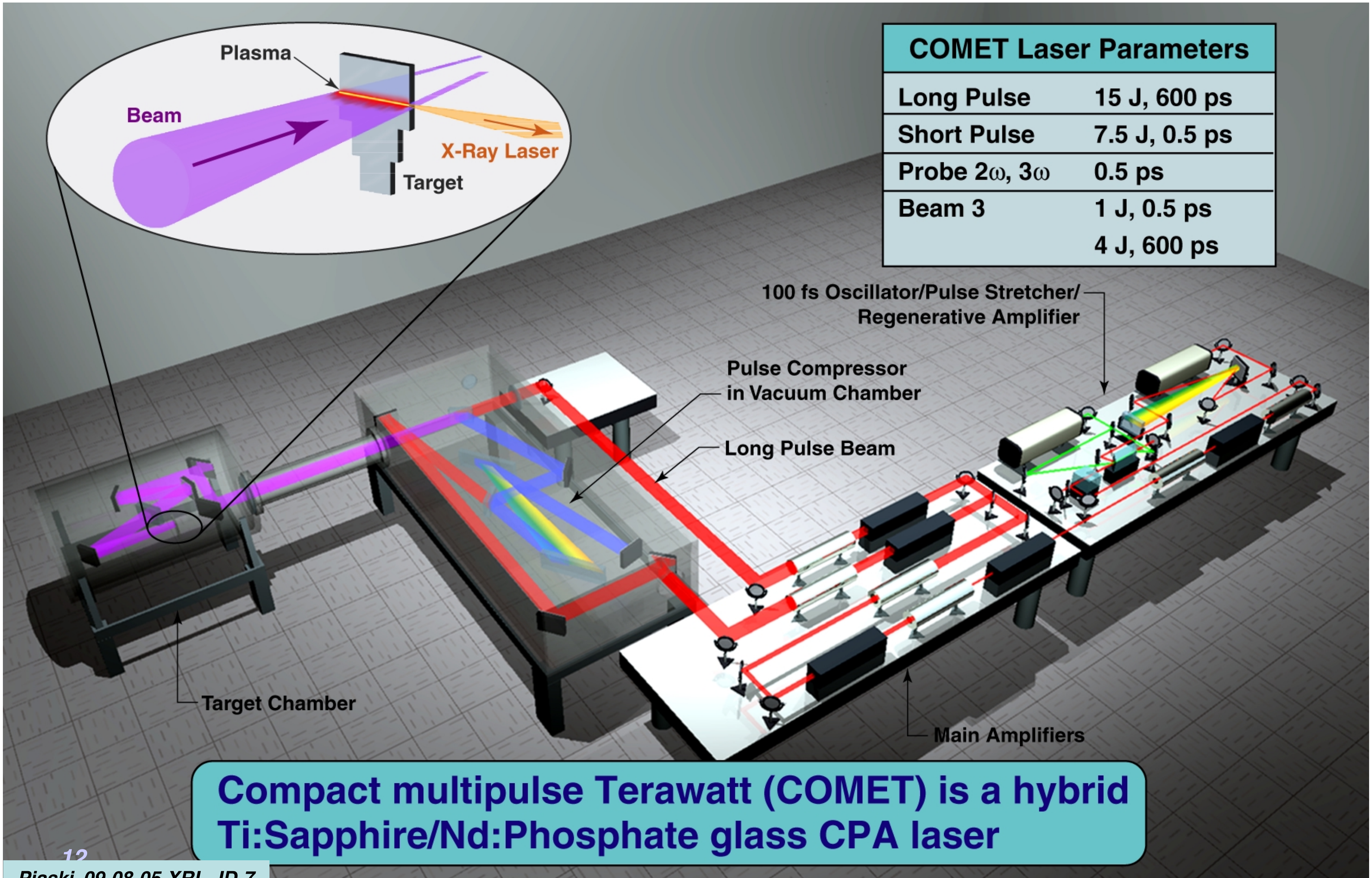


Tabletop Laser Driver

- **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).

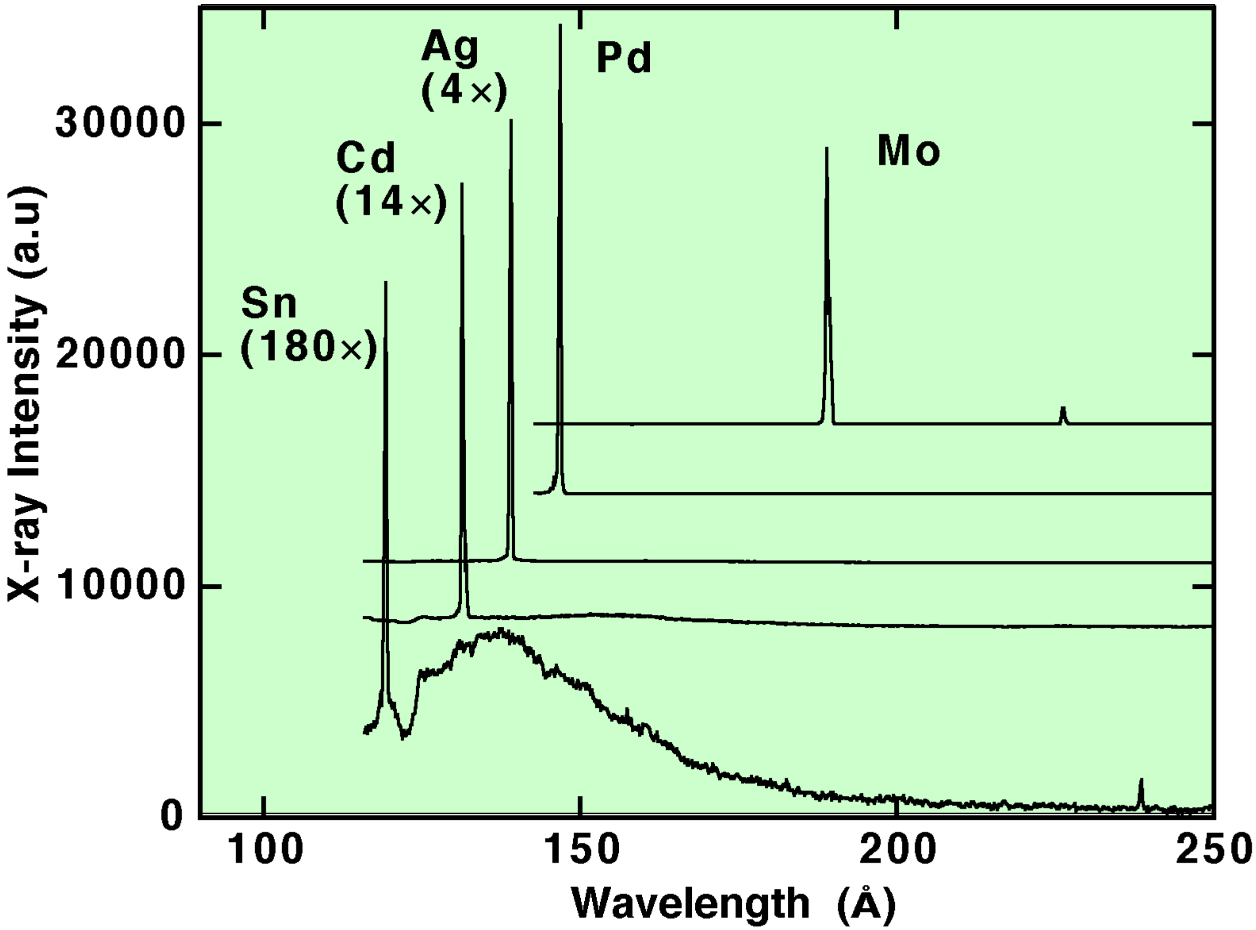
LLNL COMET tabletop, laser-driven facility produced pulsed ps duration x-ray laser at 1 shot/4 minutes



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

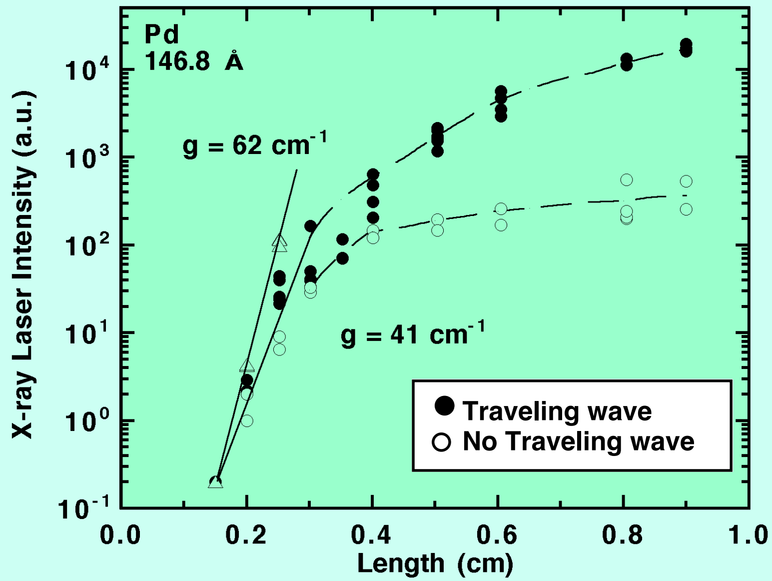
Strong lasing can be generated on 4d - 4p line of various of Ni-like soft x-ray laser lines



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

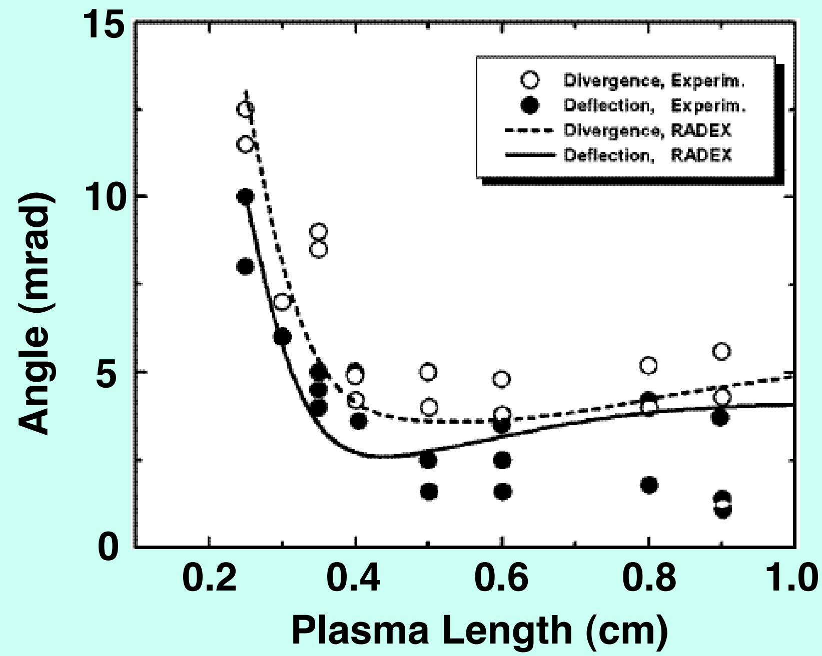
Traveling wave drives Ni-like Pd at 14.7 nm into gain saturation regime with 5 - 7 J energy in line focus

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



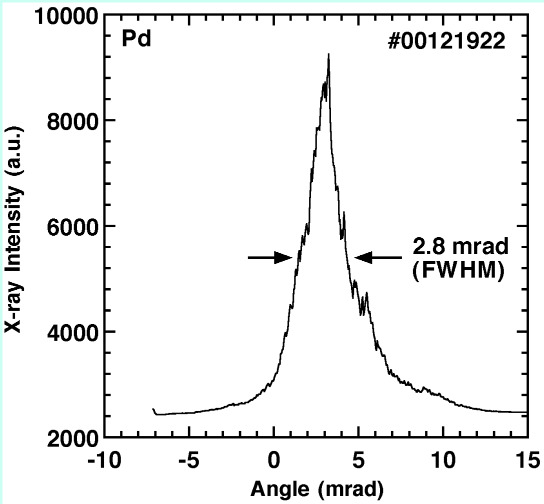
- Radex simulations indicate maximum deflection angle $(n_e/n_c)^{0.5}$ reveals optimal amplification at n_e ~0.9×10^{20} cm^{-3}

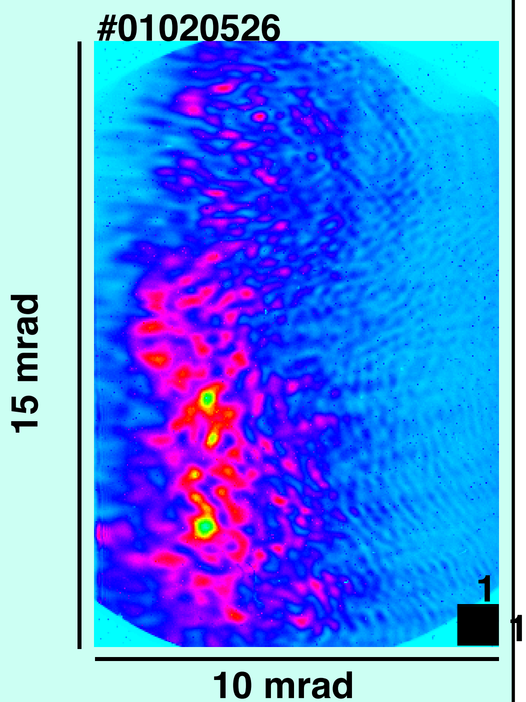
Higher efficiency of Ni-like XRL well matched to small driver

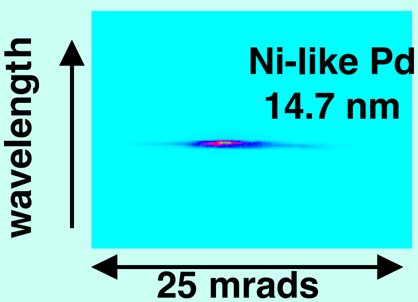
Output still increasing with length - extract more XRL energy

Characteristics of 14.7 nm x-ray laser profile

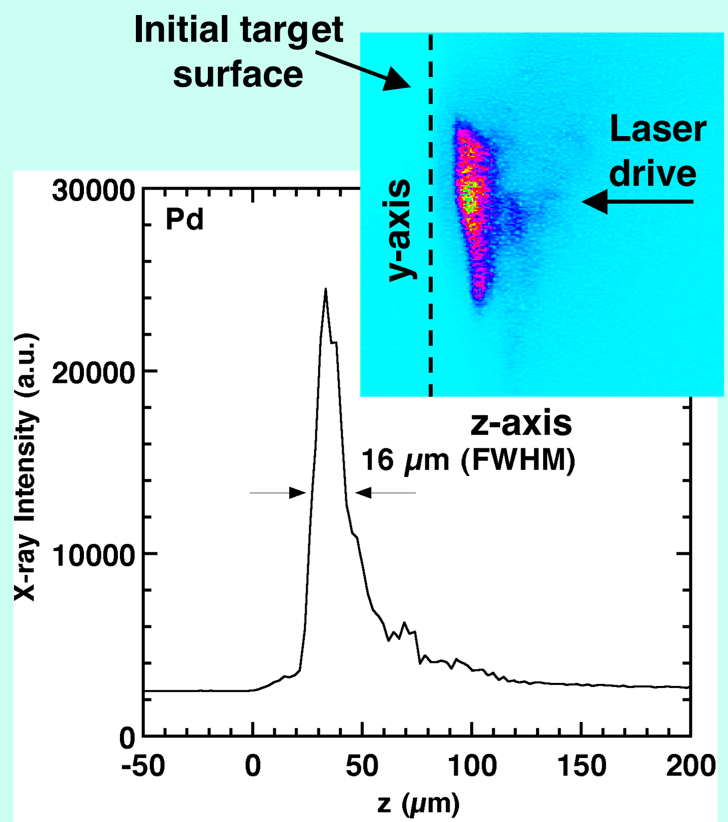
Ni-like Pd 14.7 nm Horizontal Beam Divergence and Far-Field Pattern







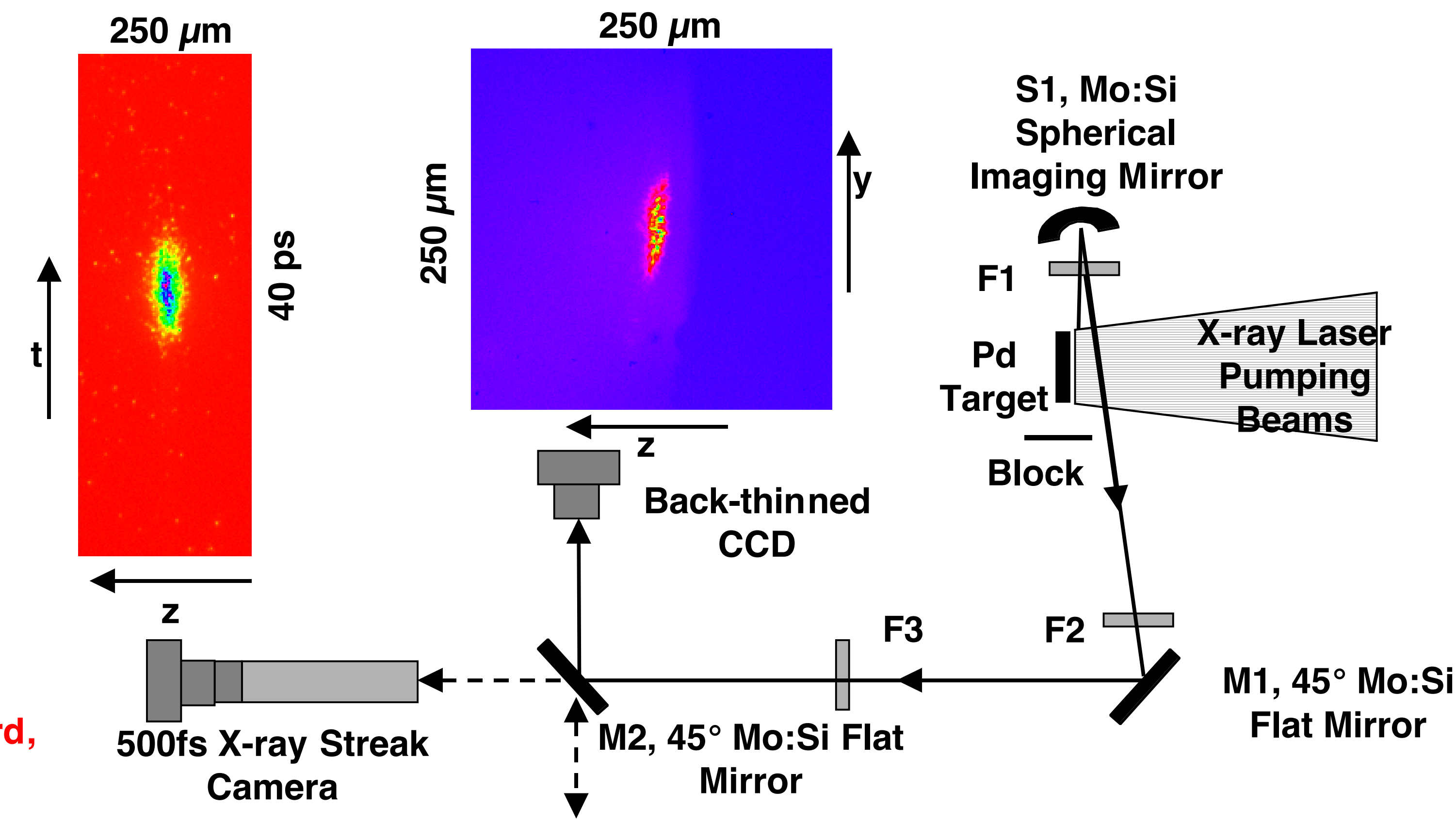
Ni-like Pd Near-Field Pattern 16 x 80 μm^2



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

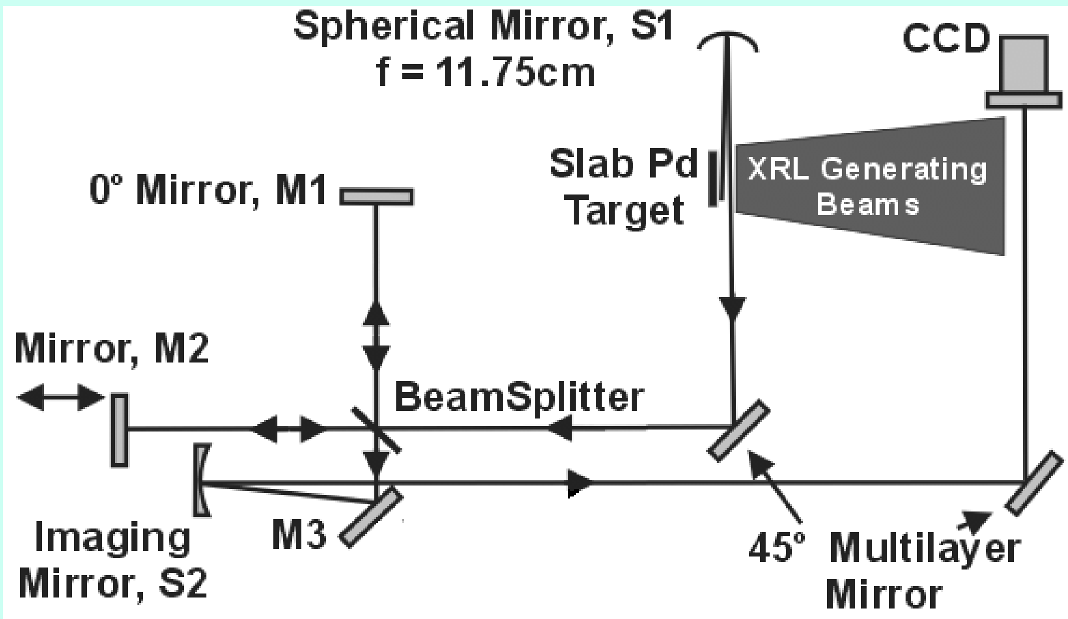
Experimental Criteria:
- Spatially resolve x-ray laser emission, localize continuum emission
- Minimize instrumental broadening effects (no chirp from spectrometer grating)
- Geometry should be similar to applications
- Control x-ray laser intensity (F1, F2, F3), repeatability, many shots



R. Shepherd,
R. Booth
(LLNL)

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

Michelson Interferometer experimental setup used to measure longitudinal coherence of 14.7 nm x-ray laser



Laser Parameters:

LP: 600 ps, 1054 nm (2 J, 2×10^{11} W cm^{-2})

SP: 13 ps, 1054 nm (5 J, 3×10^{13} W cm^{-2})

SP: 6ps (5 J, 6×10^{13} W cm^{-2})

Instrument Parameters

Multi-layer thin-foil beam splitters:

89 nm Si_3N_4 substrate with 4.5 bi-layers of Mo:Si on each side.

Reflectivity: 14%
Transmission: 15%

Arm length 34 cm

Estimated Throughput: 0.007/arm

Imaging Mirror S2, f= 50 cm

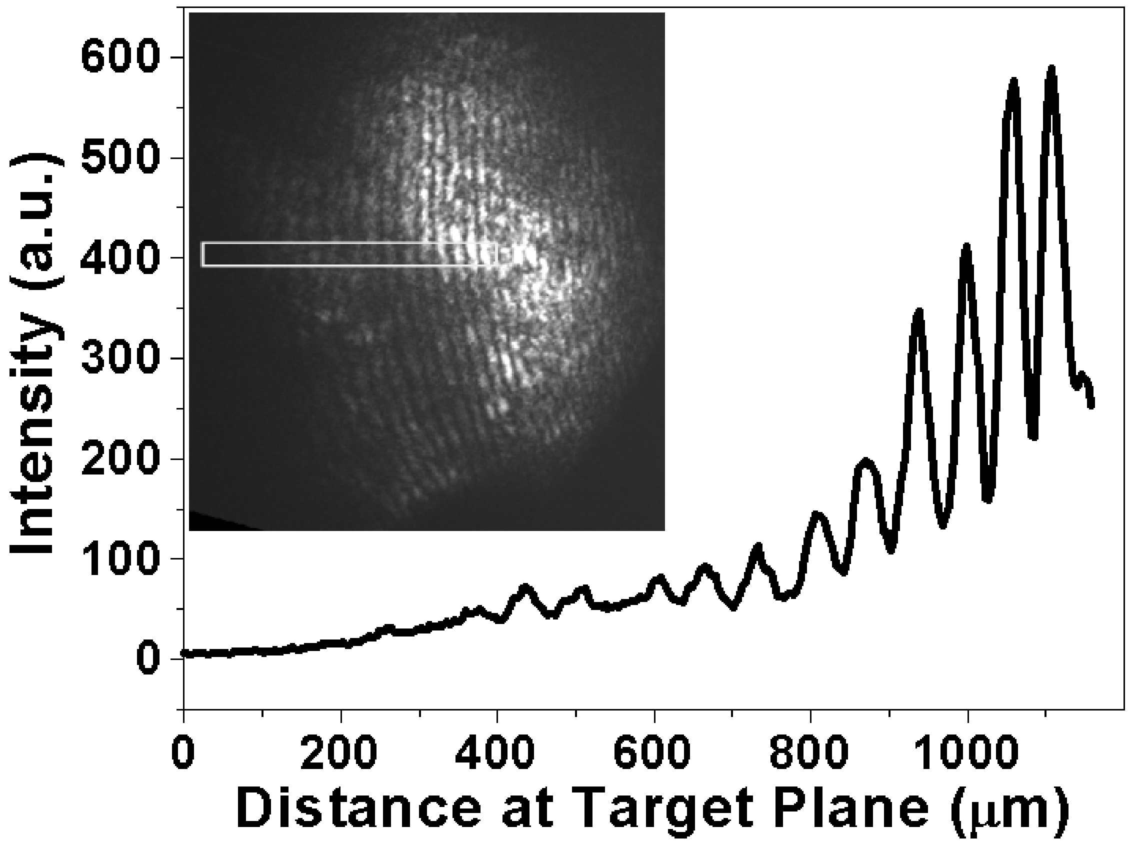
Magnification: 7x

Beam-splitters and instrument multilayers fabricated at l'Institut d'Optique, Université Paris-Sud

Michelson mirror M2 motorized to align instrument and adjust fringes

Interferogram measured for 6 ps pumping pulse and Michelson interferometer optimized

Michelson interferometer uses amplitude division technique, interference fringes generated when:
(1) Phase fronts of two arms are spatially overlapped, co-propagated
(2) Arm lengths are equalized to accuracy better than source coherence length, L_c



CCD covers 1700 x 1700 μm^2 region

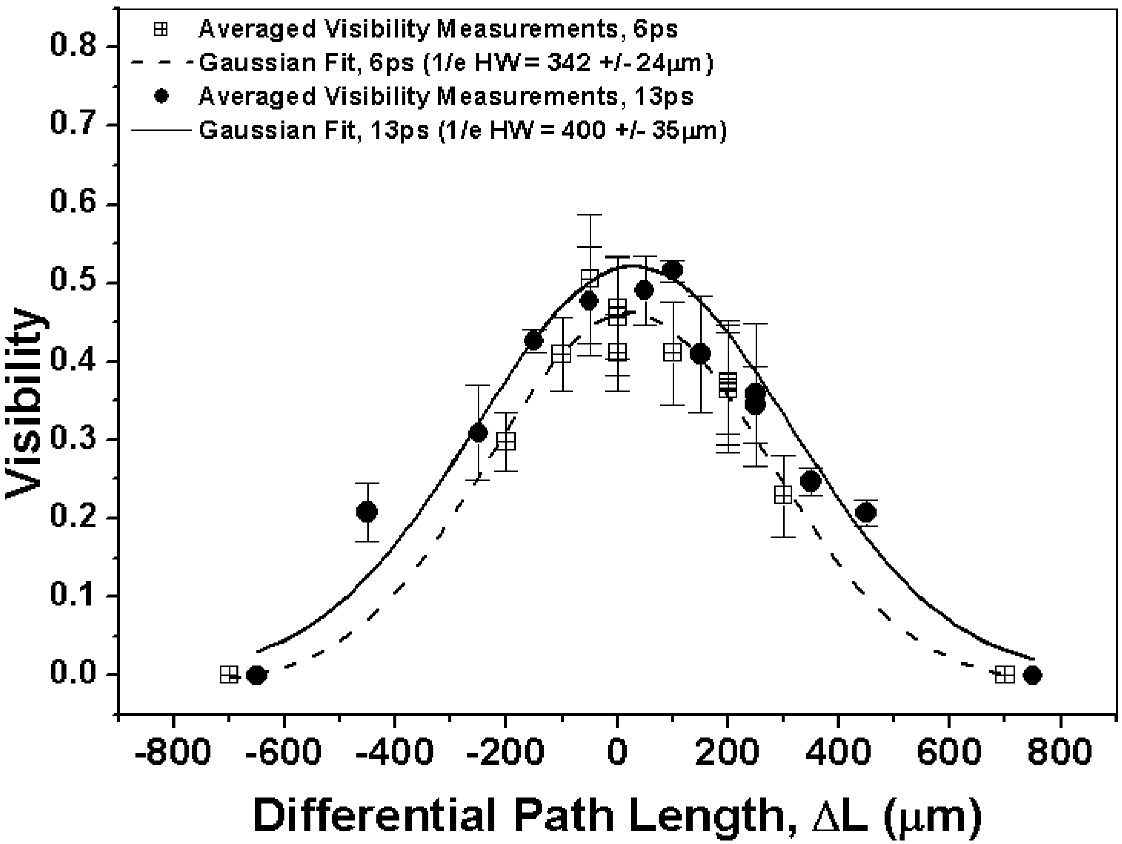
Good fringe visibility up to 70%, $V = (I_{max} - I_{min})/(I_{max} + I_{min})$ measured across intensity

Observe most of the x-ray laser beam profile

Variation in output across beam

Observe repeatable structure from shot-to-shot

Fringe visibility vs path difference for two pumping pulses 6 ps and 13 ps yields coherence length - spectral line width from FT



Fringe visibility vs path difference

Fringe visibility measured in same three positions of interferogram from shot-to-shot to improve statistics

50% visibility results from unequal throughput in two arms

Gaussian fit to data

6ps data: 342 ± 24 μm 1/e half-width

13ps data: 400 ± 35 μm 1/e half-width

Equivalent Gaussian spectral FWHM of 0.34 pm and 0.29 pm for 6 ps and 13 ps

($\lambda/\Delta\lambda$ = 43000 and 50600 for 14.7 nm)

Measured time response of 4.5 ps saturated x-ray laser indicates 4x transform limit - 2x for unsaturated output

Piaski, 09-08-05-XRL-JD-15

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

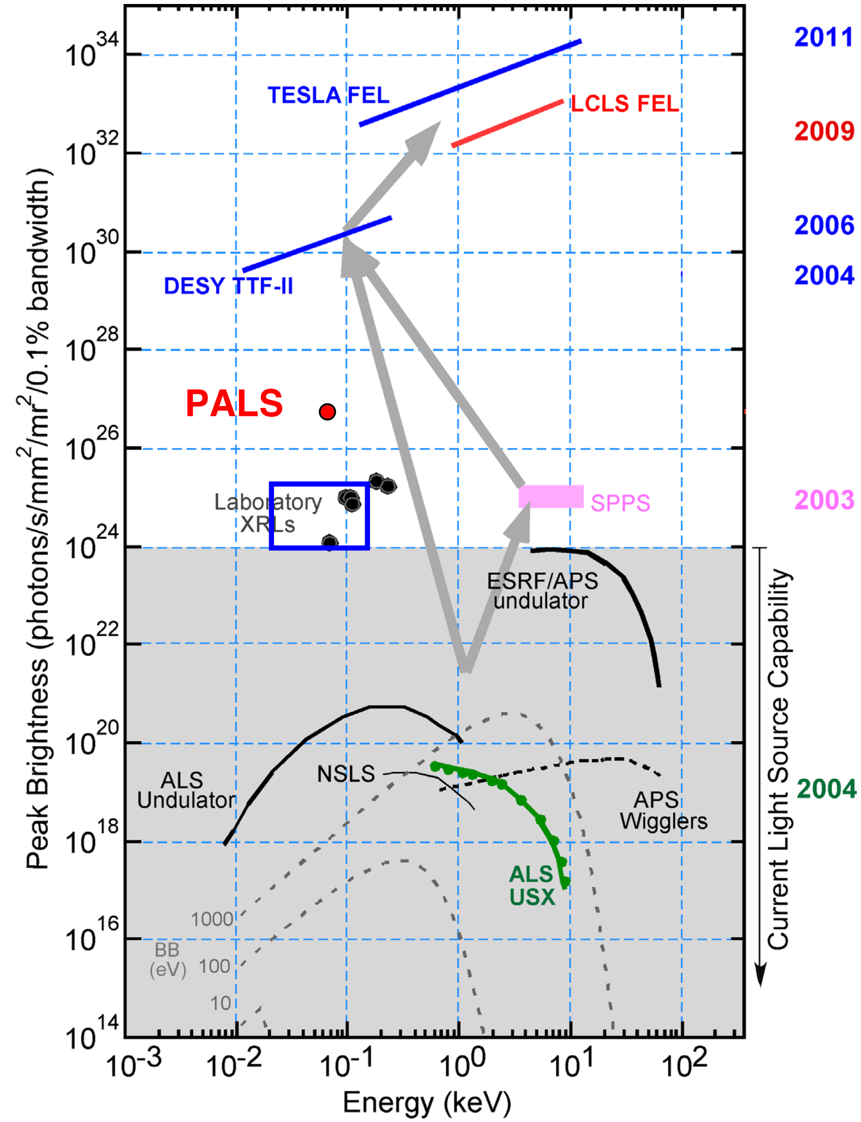
Physics & Advanced Technologies

Tabletop x-ray lasers are extremely bright, inexpensive compact sources that complement future FELs

Parameters for collisional X-ray Laser

Parameters	GRIP XRL	COMET XRL
Pump (J):	150 mJ	5 J
XRL (J):	10 nJ	>10 μJ
Photons:	10^9	10^{12}
Rate (Hz):	10	0.004
λ (nm):	18.9	12 - 47
Source (μm^2):	9 × 20	25 × 100
Div. ($mrad^2$):	3 × 5	2.5 × 6
Pulse (ps):	2	2 - 8
Peak B*:	2.0×10^{23}	1.6×10^{25}
Average B*‡:	3.7×10^{12}	1.3×10^{11}

* [Ph. mm^{-2} $mrad^{-2}$ s^{-1} (0.1% BW) $^{-1}$]
‡ For 10 Hz operation



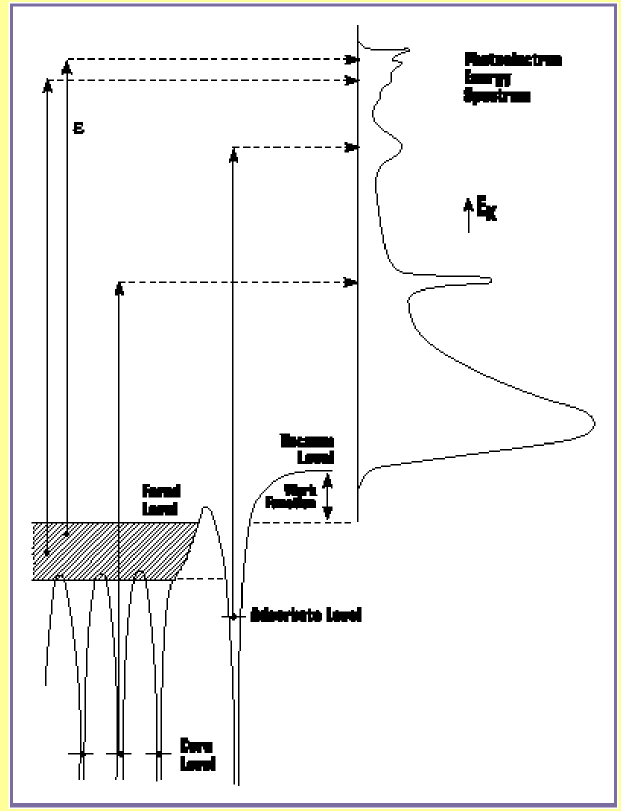
Time-of-Flight Photoelectron Spectroscopy requires pulsed source (84.5 eV x-ray laser photons)

Measure electron kinetic energy by time-of-flight technique

- 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

Binding energy BE, work function ϕ_s
Kinetic energy of emitted electrons:

KE = hv - BE - ϕ_s



COMET 85 eV x-ray laser has advantages over other laser sources for fast probing of shallow *d* states

Ge: $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 3d^{10}\ 4s^2\ 4p^2$

39.3 eV binding energy

$\sigma = 7 \times 10^{-18}$ cm^2 for 80 eV x-ray

Yeh and Lindau, At. Dat. Nuc. Tabl. 32, 1 (1985)

Photoelectron Yield Estimate at TOF MCP Detector, N_p:

$$N_p = F\, \sigma\, n\, \lambda_c\, T$$

where:

- F - X-ray fluence on sample after filter and mirror losses, 10^{11} photons/shot
- n - Ge number density, 4.4×10^{22} cm^{-3}
- σ - Photoionization crosssection, 7×10^{-18} cm^2
- λ_c - Photoelectron escape depth, 50×10^{-8} cm
- T - angular collection efficiency of MCP, $\sim 2.5 \times 10^{-4}$

$N_p = 4 \times 10^6$ photoelectrons detected/shot

Source Comparison for X-ray Photoelectron Spectroscopy (XPS):

Source	XRL	LPX[1]	LPX[2]
E, (eV)	85	276	255
$\Delta E/E$,	10^{-4}	2×10^{-2}	$>10^{-3}$
F, (ph/shot)	10^{11}	2×10^{8}	7×10^{8}
t, (psec)	5	2500	2500
N_p, /shot	4×10^{6}	190	80

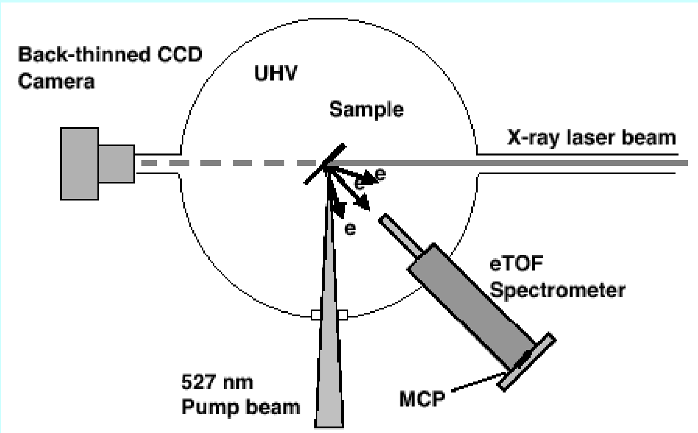
LPX[1] - Kondo *et al* (1996) for Si 2p XPS.
LPX[2] - Kondo *et al* (1998) for Si 2p XPS.

X-ray laser has orders of magnitude better energy resolution, higher x-ray fluence and picosecond pulse duration than LPX source for single-shot experiemnts

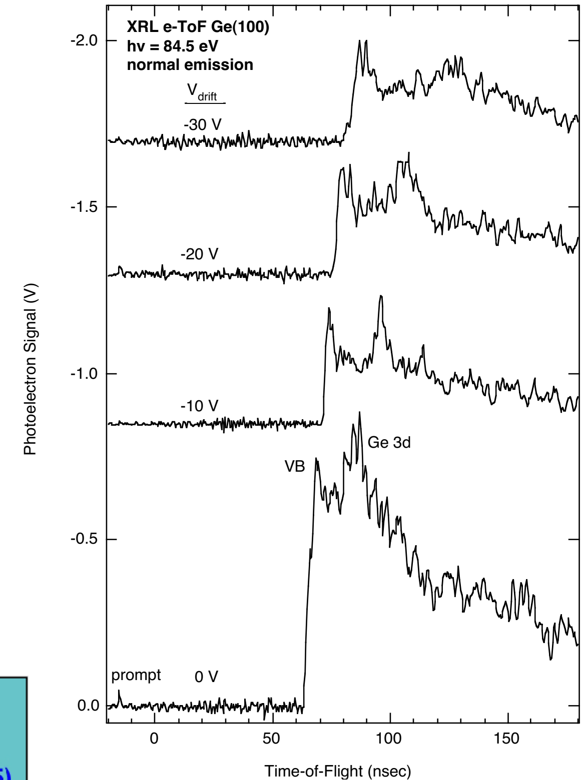
P01621-ajn-u-010

Pulsed 84.5 eV soft x-rays probe material surfaces, producing photoelectrons: Electron Time-of-Flight results for bulk Ge

Experimental Setup for X-ray Laser induced Photoelectron Spectroscopy



In collaboration with Art Nelson C&MS, LLNL



Ge: $1s^2\ 2s^2\ 2p^6\ 3s^2\ 3p^6\ 3d^{10}\ 4s^2\ 4p^2$ 39.3 eV binding energy
$\sigma = 7 \times 10^{-18}\ cm^2$ for 80 eV x-ray
Yeh and Lindau, At. Dat. Nuc. Tabl. 32, 1 (1985)

Observe Valence Band (VB) and shallow core 3d photoelectron features using e-TOF spectrometer: better energy resolution is observed by applying bias to drift tube

Apply technique to dynamic optical pump - x-ray laser probe experiments

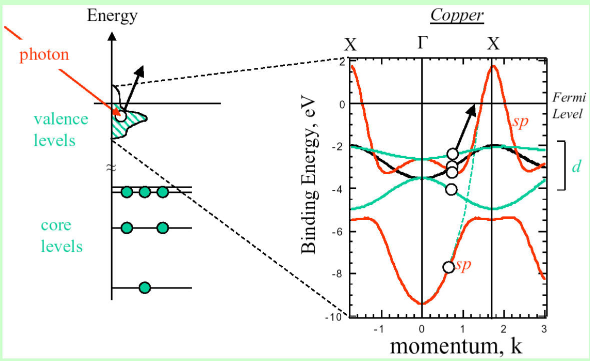
In collaboration with Art Nelson, C&MS (LLNL)

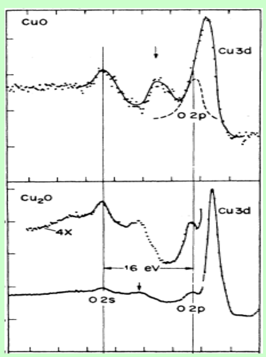
A. J. Nelson, J. Dunn, T. van Buuren, and J. Hunter, "X-ray laser-induced photoelectron spectroscopy for single-state measurements", Appl. Phys. Lett. 85, 6290 (2004).

Pump-Probe: Single shot e-ToF data from static and laser-heated ultrathin foils (50 nm Cu/20nm C)

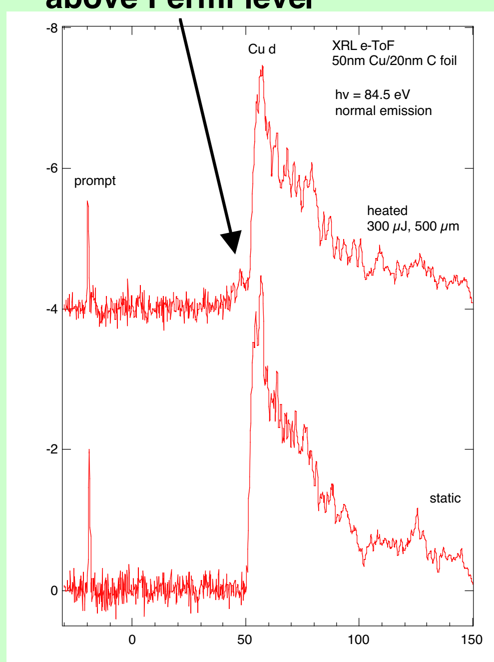
- **Pump 527 nm, 400 fs laser, 0.1 – 2.5 mJ energy in 500 x 700 μm^2 (FWHM) spot.**
- **Intensity conditions of 0.07 – 1.8 x 10^{12} W cm^{-2} intensity.**
- **Cu *d* band emission evident in valence band**

Cu Energy Levels	**Pump 300 μJ**	**Pump 2.5 mJ**

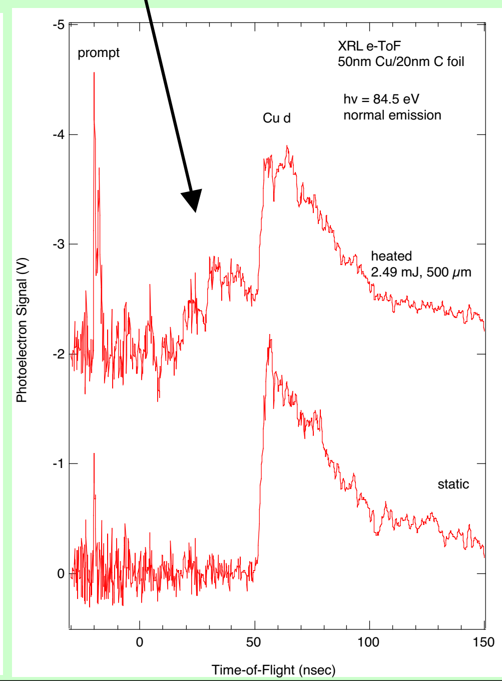




Bound electrons above Fermi level



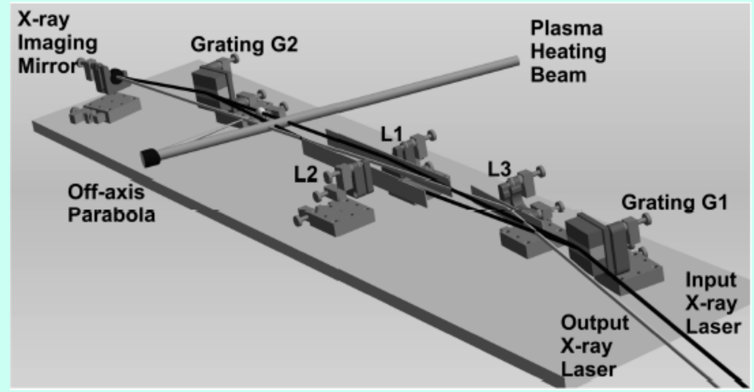
Free electrons

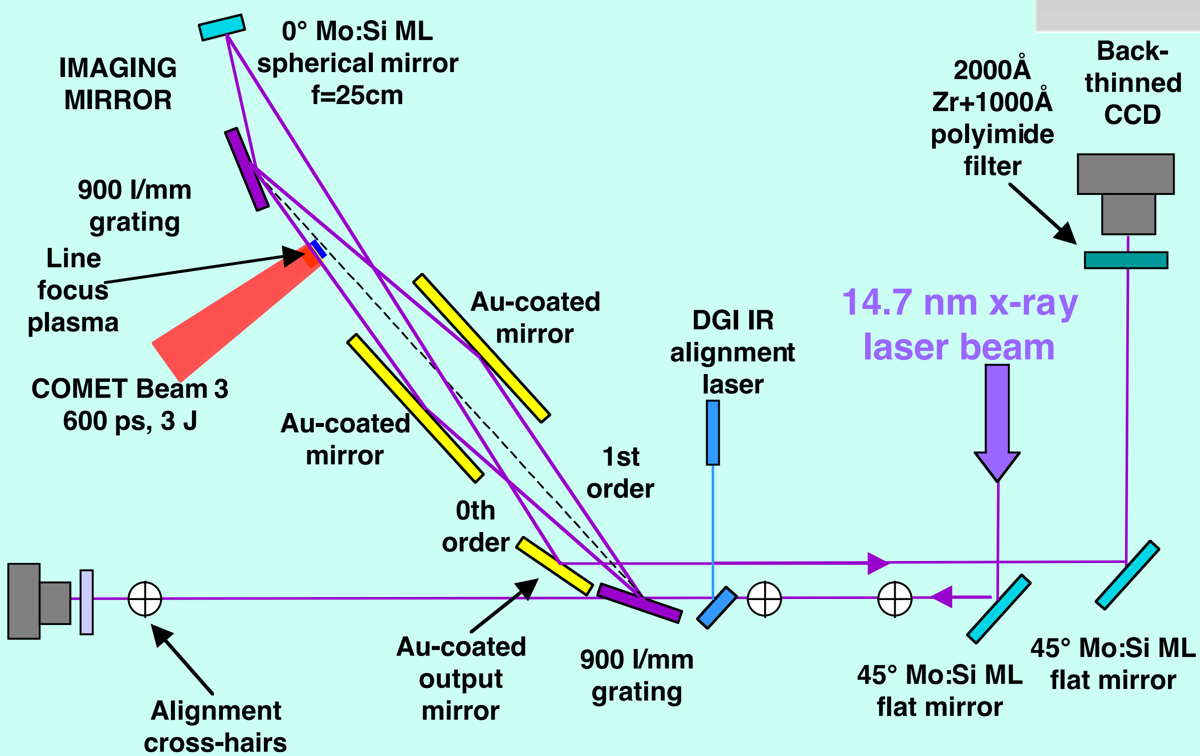


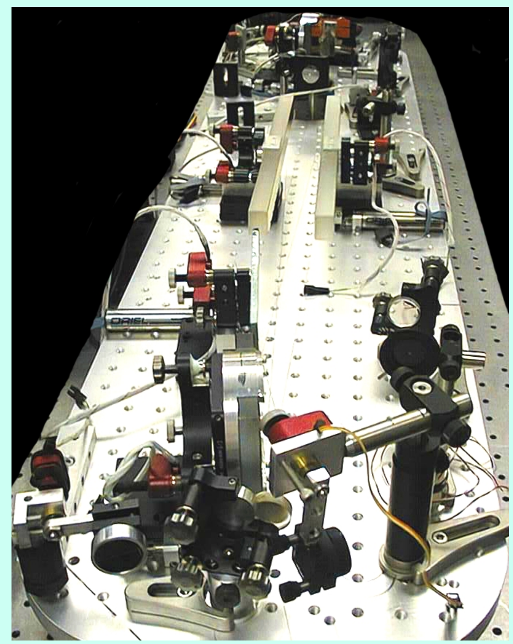
A.J. Nelson *et al.*, submitted to Appl. Phys. Lett. (2005)

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



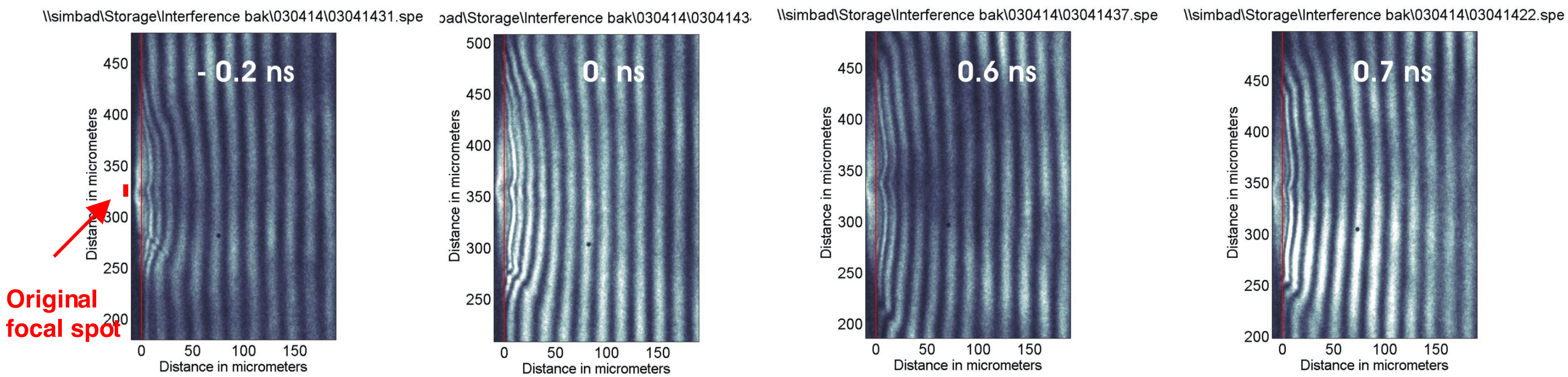




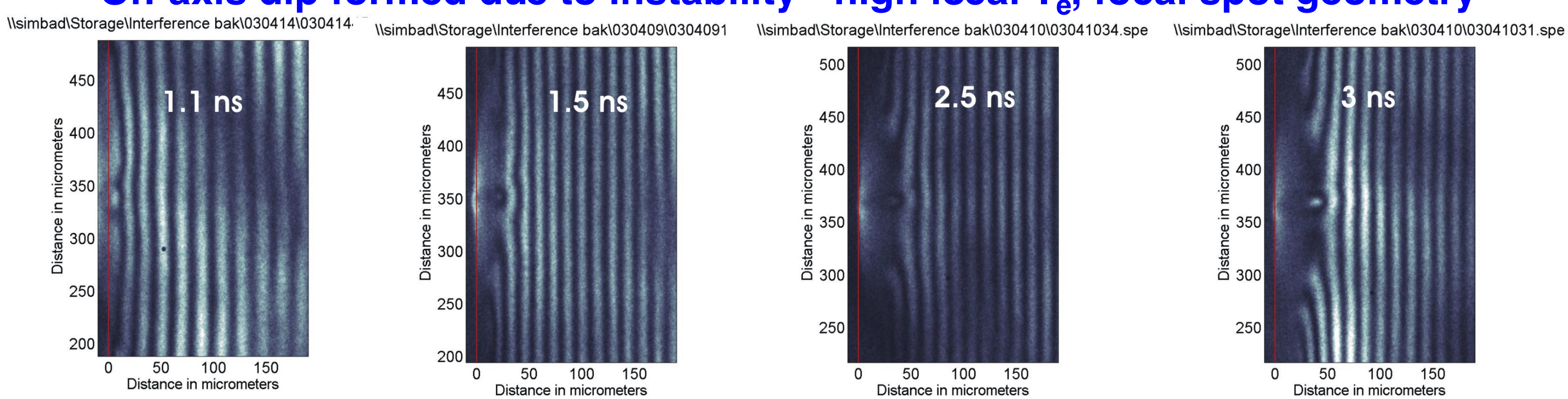
J. Rocca and J. Filevich (CSU)

Sequence of ps interferograms shows formation of remarkable dynamic plasma features at all times

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



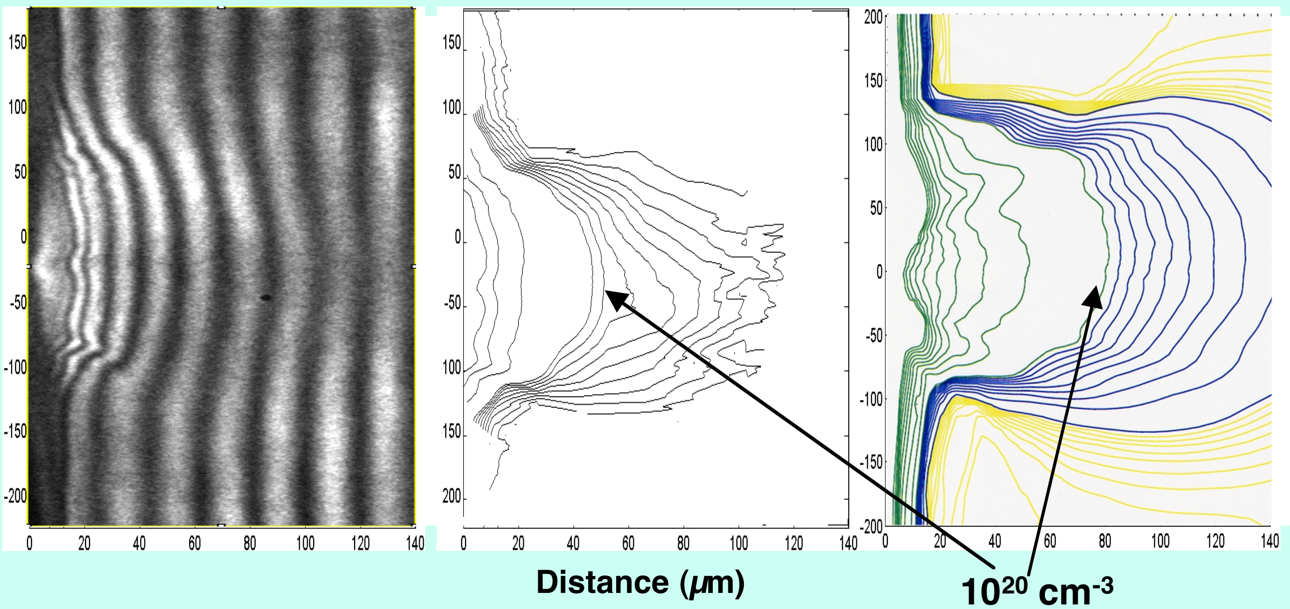
- 2-D lateral expansion observed early on - plasma pressure gradients
- On-axis dip formed due to instability - high local T_e, focal spot geometry



- Fringe reversal at late time due to bound electrons in Al - Al^{3+} ions

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}

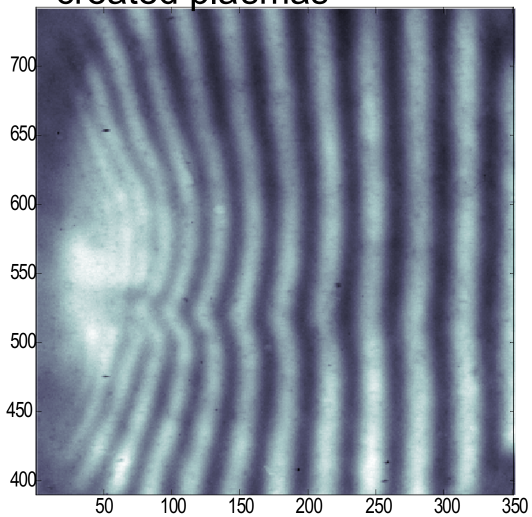
- Small 12 μm width results in substantial 2D plasma expansion - reduced on-axis density
- 1D and 1.5D LASNEX simulations do not accurately model plasma conditions
- 2D simulations use experimental focal spot and temporal pulse shape
- Plasma pressure gradients, radiative heating and thermal conduction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

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

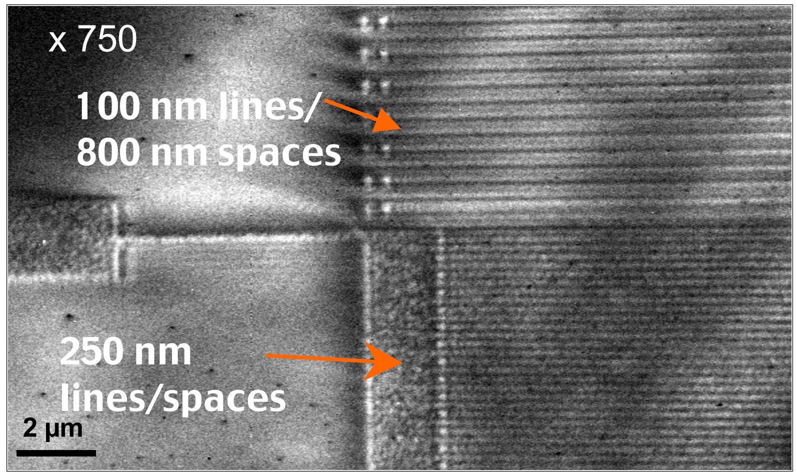
Physics & Advanced Technologies

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

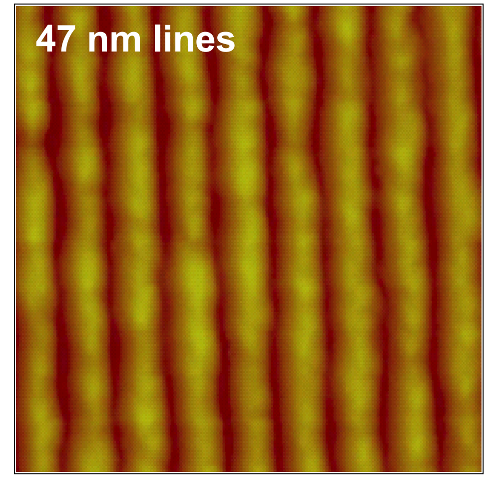
1. Interferometry of laser-created plasmas



2. EUV microscopy

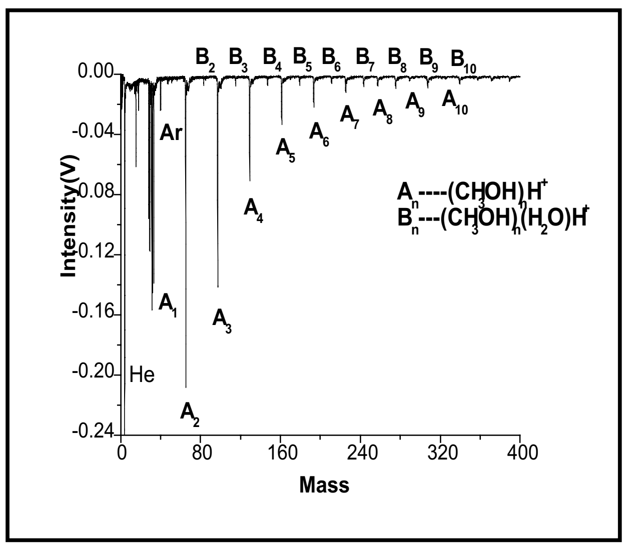


3. Nanopatterning



4. Laser Ablation

5. Nanocluster Spectroscopy



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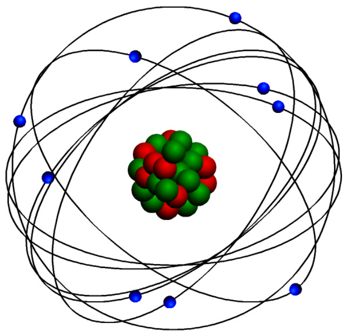
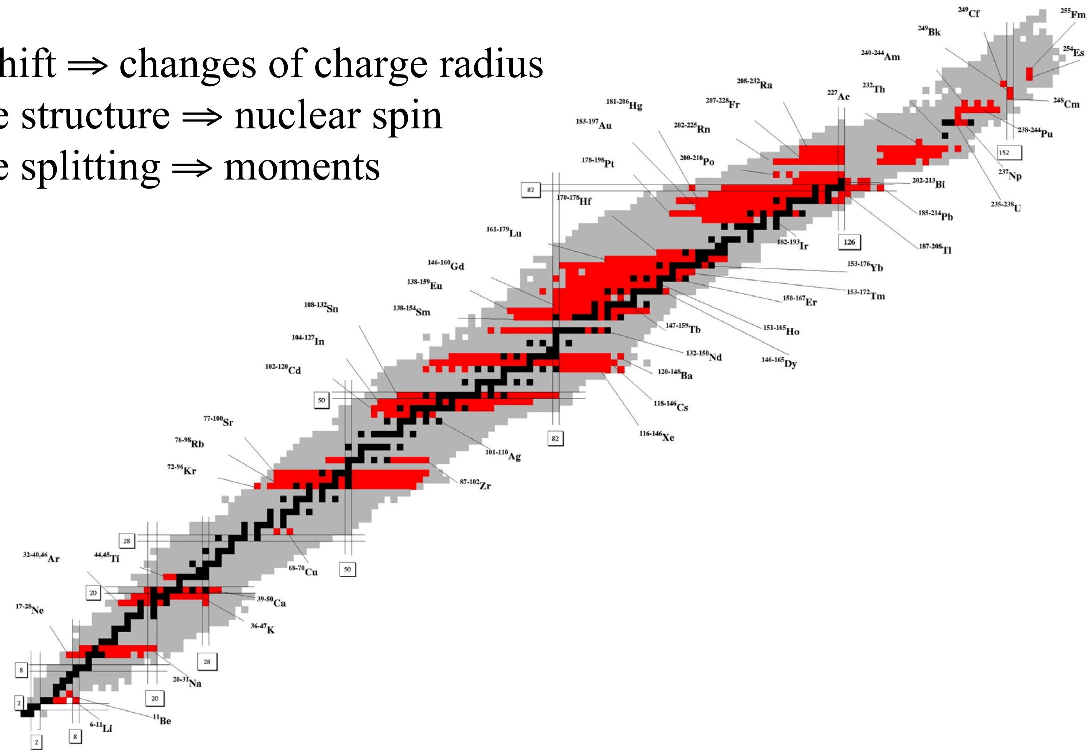
Laser spectroscopy to measure nuclear properties …



isotope shift ⇒ changes of charge radius
hyperfine structure ⇒ nuclear spin
hyperfine splitting ⇒ moments



Problem: too many electrons

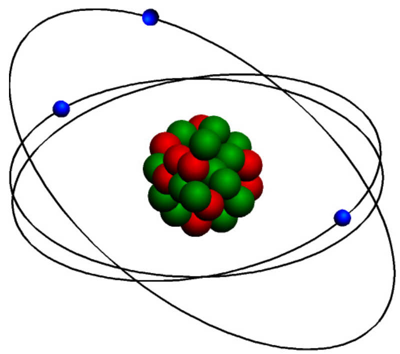
go to few-electron systems:
• H-like: very simple, but excitation energies too high, nuclear size effect small
• He-like: same

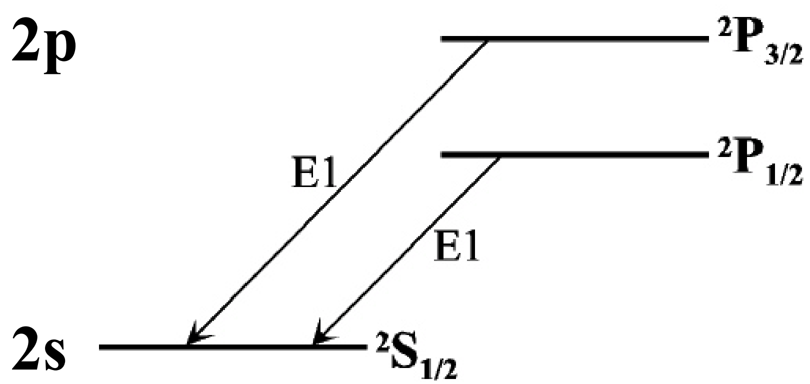
⇒ how about **Li-like** ??

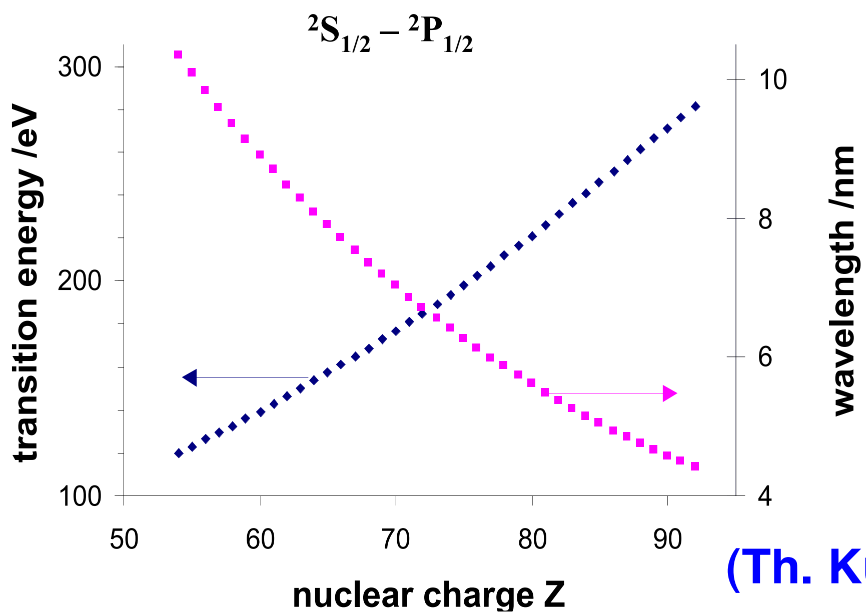
(Th. Kuehl, GSI)

… on Lithium-like Ions

calculations are getting very precise !

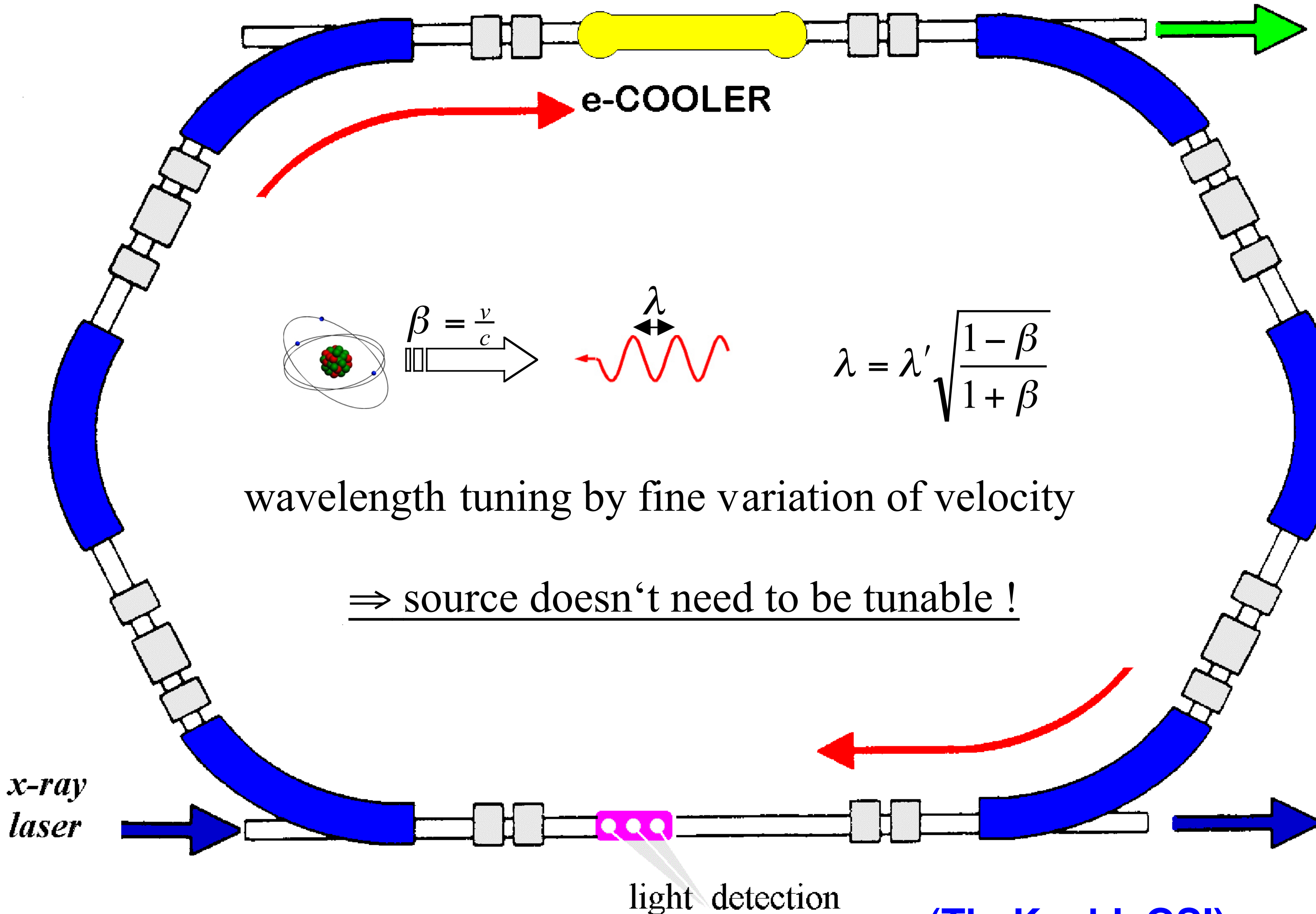






(Th. Kuehl, GSI)

… using the Doppler-shift



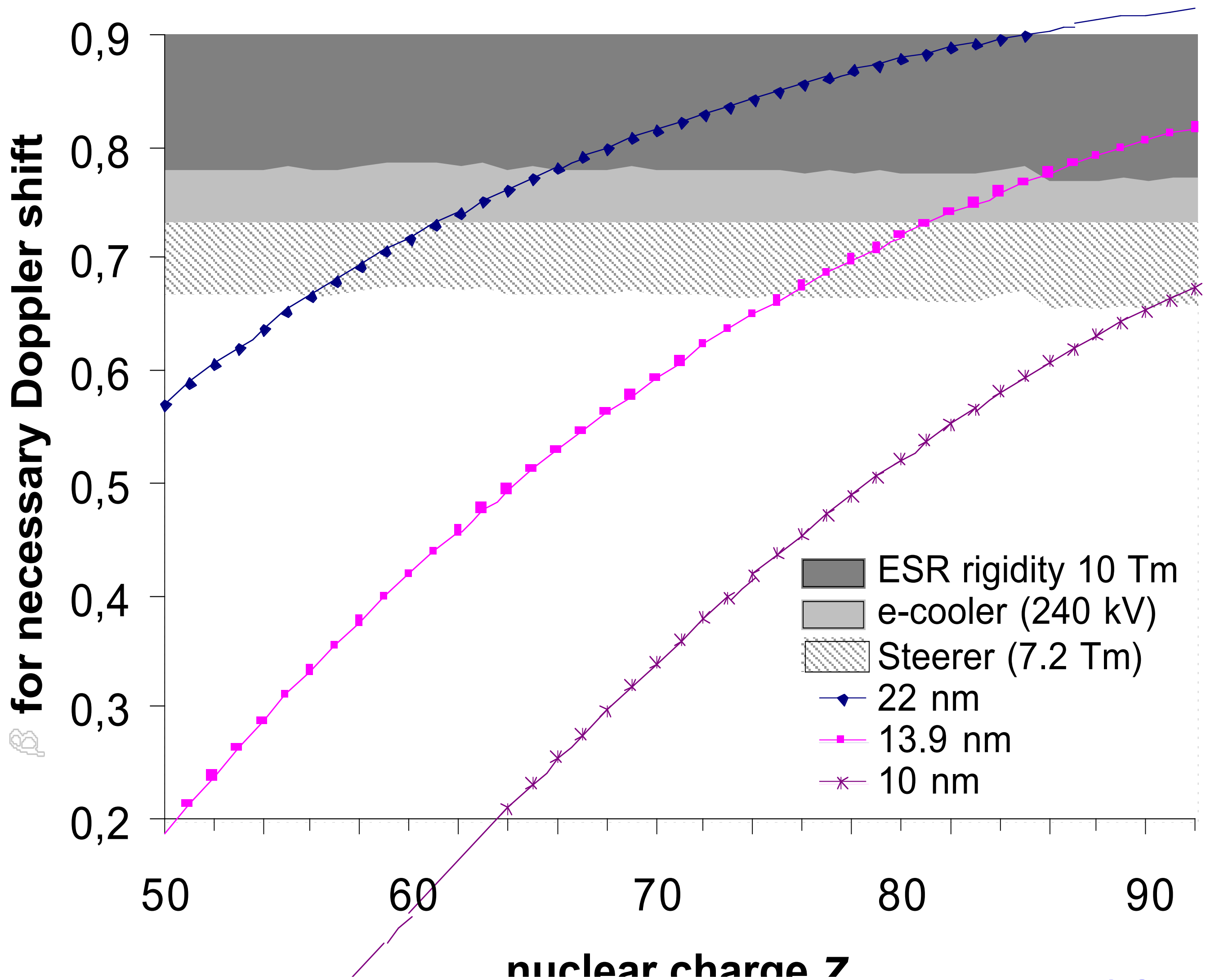
$$\lambda = \lambda' \sqrt{\frac{1-\beta}{1+\beta}}$$

wavelength tuning by fine variation of velocity

$\Rightarrow$ source doesn‘t need to be tunable !

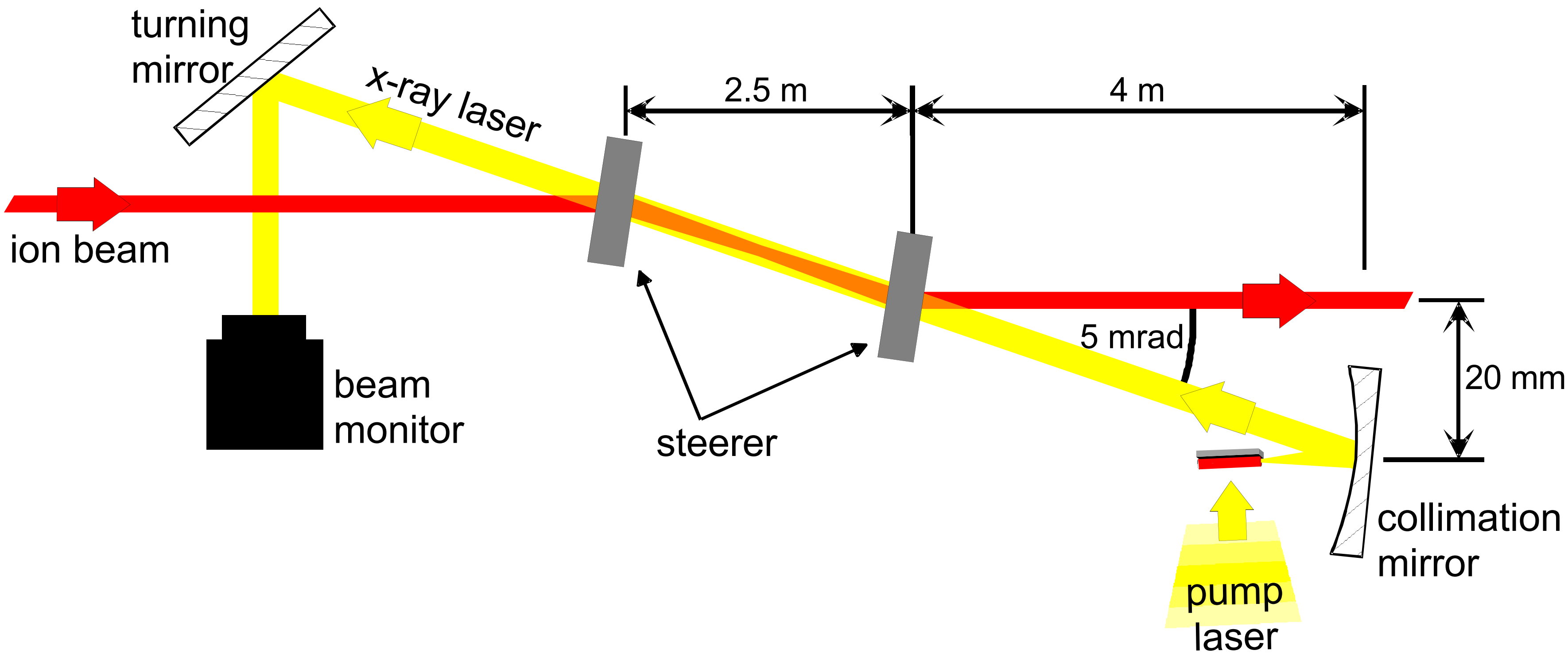
(Th. Kuehl, GSI)

many possible candidates



(Th. Kuehl, GSI)

Overlap of beams



(Th. Kuehl, GSI)

We have recently demonstrated 10 Hz, 18.9 nm x-ray laser using grazing incidence pumping (GRIP) using 150 mJ laser

PRL 94, 103901 (2005) PHYSICAL REVIEW LETTERS week ending 18 MARCH 2005

High-Repetition-Rate Grazing-Incidence Pumped X-Ray Laser Operating at 18.9 nm

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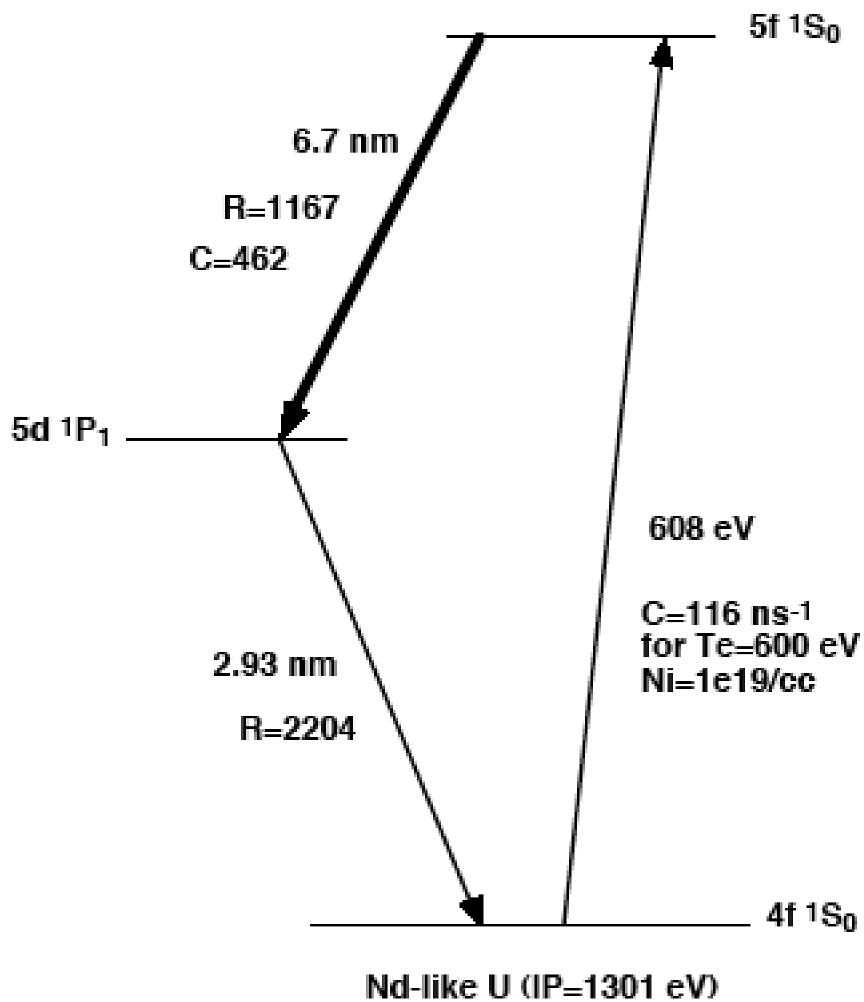
(Received 11 May 2004; published 16 March 2005)

We have demonstrated a 10 Hz Ni-like Mo x-ray laser operating at 18.9 nm with 150 mJ total pump energy by employing a novel pumping scheme. The grazing-incidence scheme is described, where a picosecond pulse is incident at a grazing angle to a Mo plasma column produced by a slab target irradiated by a 200 ps laser pulse. This scheme uses refraction of the short pulse at a predetermined electron density to increase absorption to pump a specific gain region. The higher coupling efficiency inherent to this scheme allows a reduction in the pump energy where 70 mJ long pulse energy and 80 mJ short pulse energy are sufficient to produce lasing at a 10 Hz repetition rate. Under these conditions and by optimizing the delay between the pulses, we achieve strong amplification and close to saturation for 4 mm long targets.

DOI: 10.1103/PhysRevLett.94.103901 PACS numbers: 42.55.Vc, 32.30.Rj, 42.60.By, 52.50.Jm

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

Summary:

- Continue to develop soft x-ray lasers and applications at LLNL as compact ultra bright x-ray source
  - ps duration
  - high peak brightness
  - short wavelength
  - coherence
  - highly monochromatic

- Optical pump-x-ray laser probe photo-electron spectroscopy experiments: picosecond soft x-ray surface analysis tool

- X-ray laser interferometry of HED plasmas

- X-ray laser probes of heavy ion beams