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High Brightness Plasma-Based Soft X-ray Lasers and Applications

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High Brightness Plasma-Based Soft X-ray Lasers and Applications

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LLNL-CONF-422049

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X-ray Laser Interferometry

V. Shlyaptsev, H. Baldis (UC Davis)
Simulations and new pumping geometry, Thomson Scattering

B. Rus, T. Mocek, … (Inst. Of Physics, Czech Republic)
X-ray Thomson Scattering

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S. Sebban, P. Zeitoun(LOA, France) Higher order Harmonic (HOH) seeding

J. Rocca, C. Menoni, M. Marconi (CSU, USA) HOH seeding XRLs and applications

Overview:

- History, introduction and description of plasma-based soft x-ray lasers
- Characteristics
- Recent developments in source generation: Smaller pump energy, higher repetition rate, improved beam qualities
- Examples of applications: Interferometry, microscopy, ablation studies, imaging, probing matter
- Summary

Notes:

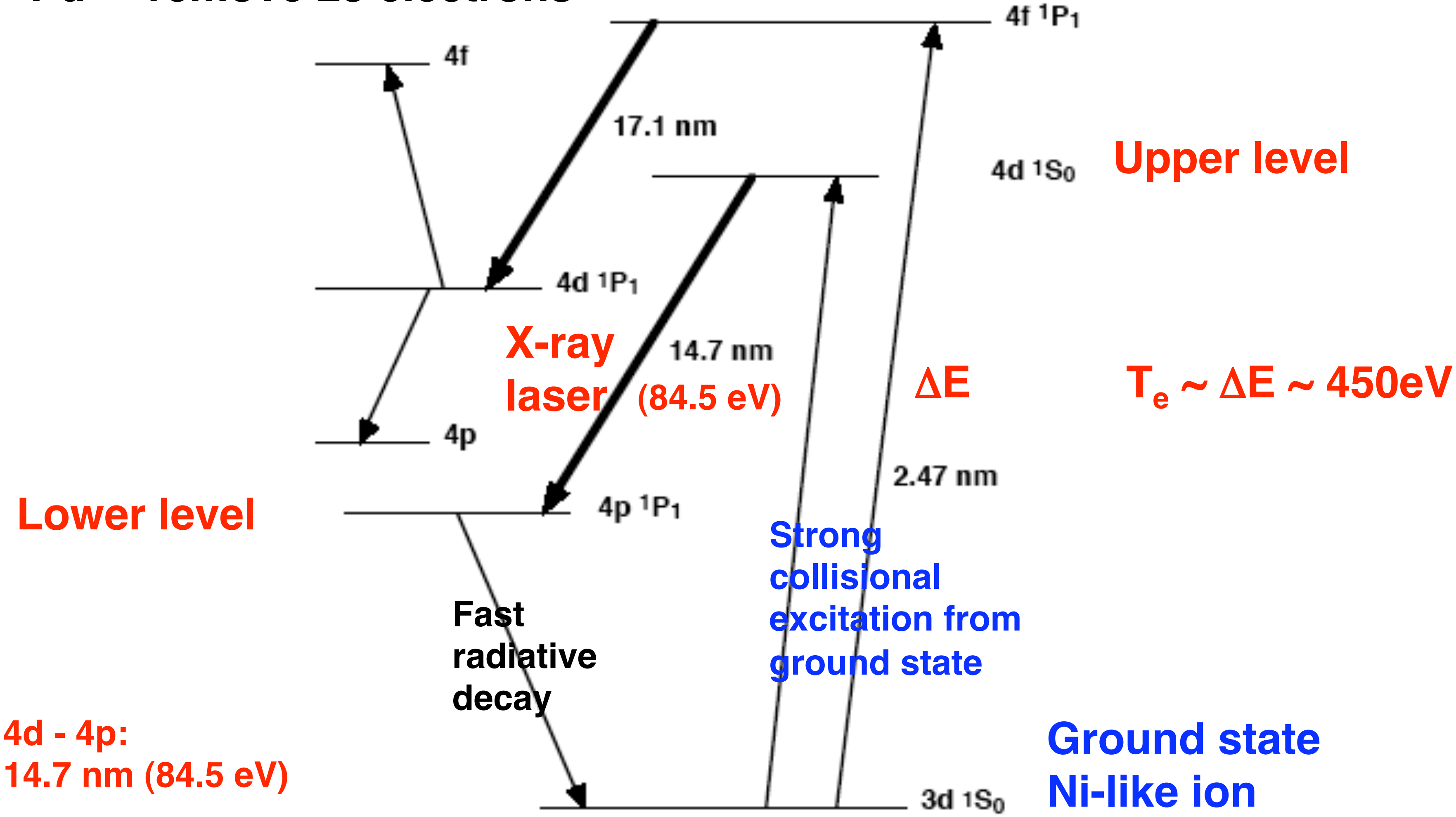
- Soft x-ray lasers are ultra-bright 10^{24} - 10^{27} ph. mm^{-2} mrad^{-2} s^{-1} [0.1% BW]$^{-1}$
- Latest generation are very compact (table top), inexpensive compared to synchrotrons, and are compatible with small group and university research
- Complement 3rd and 4th generation synchrotron sources for wavelength range, applications and regimes of interest

Brief History: Laboratory X-ray Laser is 25 years old

- Plasma-based x-ray lasers description
- Novette and Nova Laser X-ray Laser Program at LLNL

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

Pd^{18+} remove 28 electrons

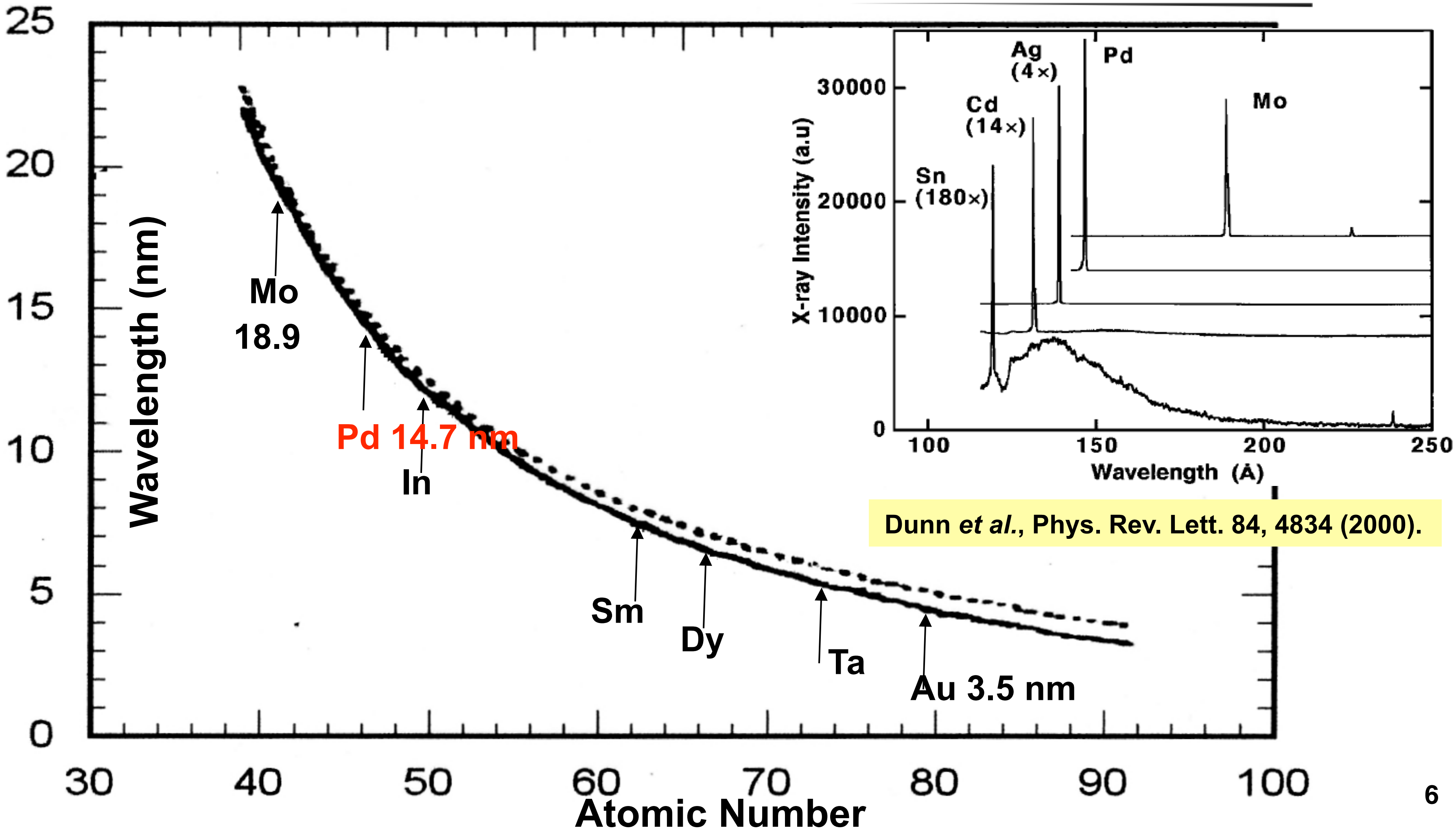


Ni-like ion (gain medium) has a closed shell configuration remains stable over a range of plasma conditions.

X-ray laser photon energy is fixed (discrete) - dependent on energy level structure of excited states of highly-charged ions

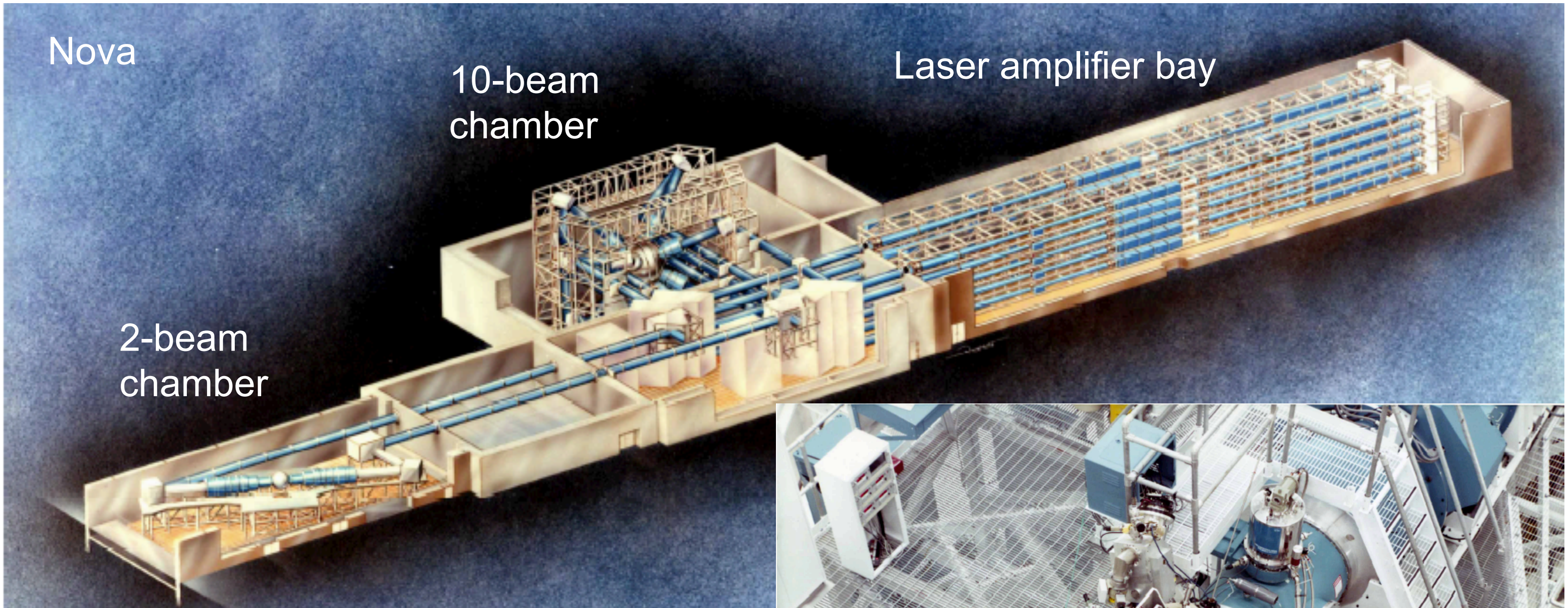
Wavelength of 4d→4p lasing transition scales as $\lambda \sim 1/Z^3$ for the Ni-like schemes

Power to pump XRL scales as $P \sim 1/\lambda^{4-6}$

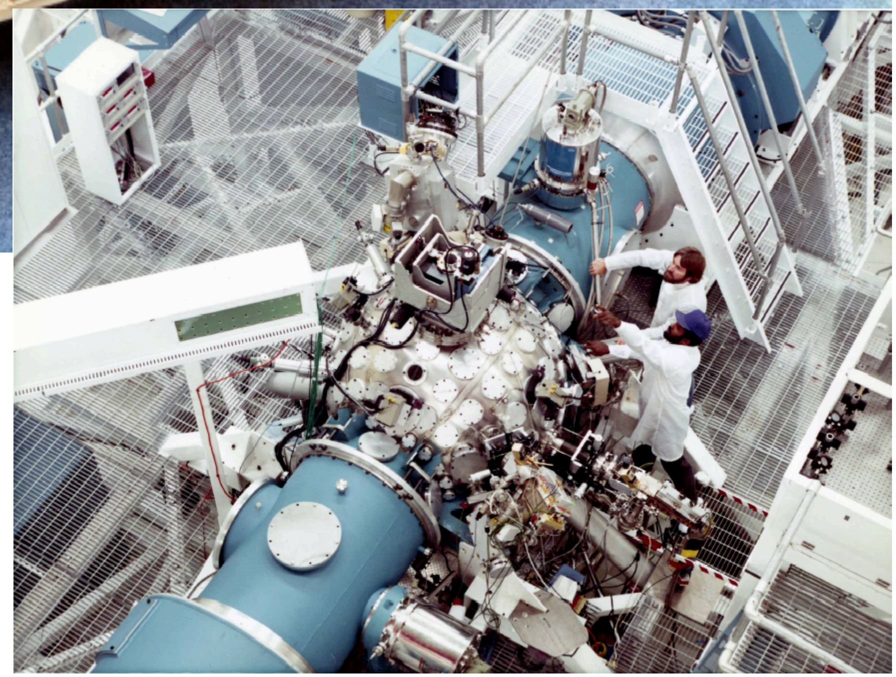


Dunn *et al.*, Phys. Rev. Lett. 84, 4834 (2000).

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

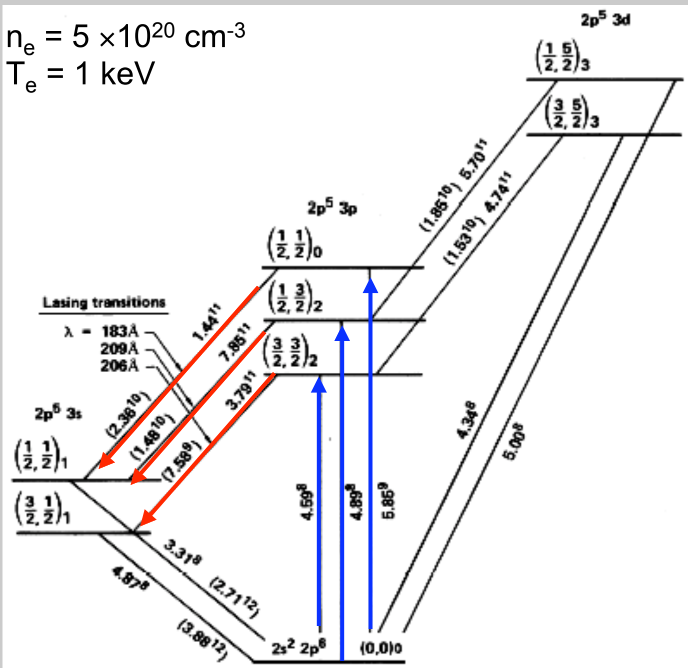


- **Substantial infrastructure investment**
- **2-beam target chamber was designed for x-ray laser research activities**
- **Soft x-ray diagnostics, optics, materials and instrumentation were developed**
- **Fostered research in many laboratories**



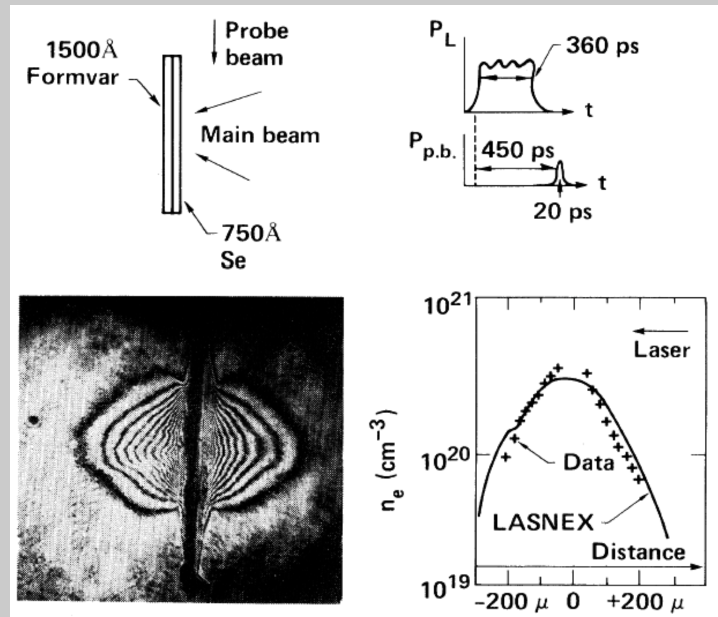
Exploding foil target and x-ray laser was designed after substantial modeling and experimental characterization effort

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

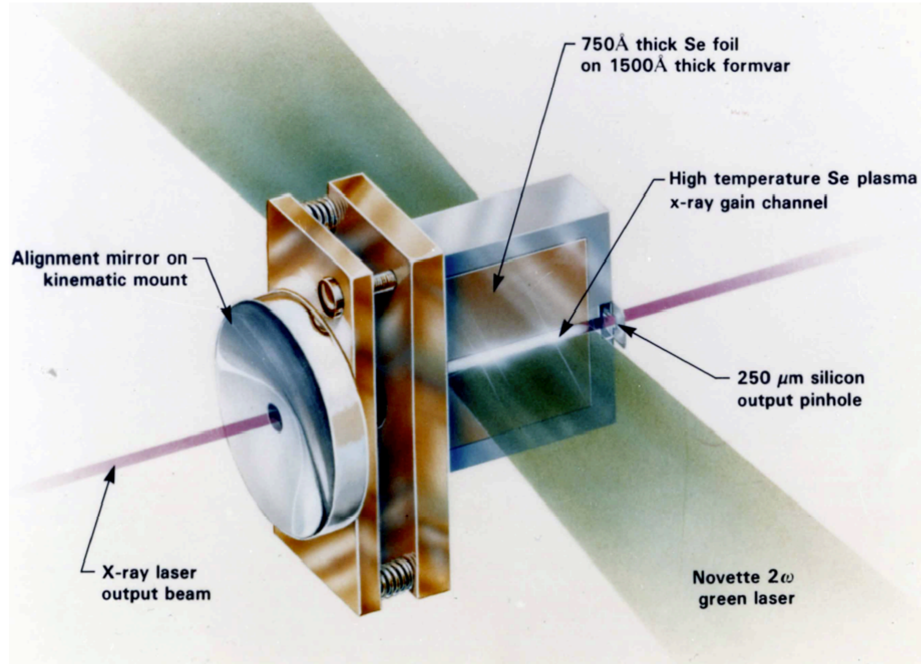


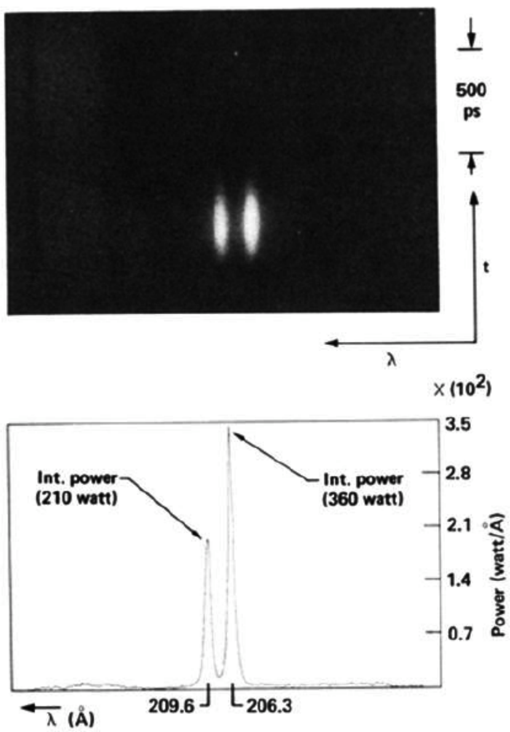
- Exploding Se foil compared with 2-D LASNEX simulations for laser irradiation conditions (n_e density profile)
- T_e ionization conditions measured

M. D. Rosen 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)

Recent developments in X-ray Laser Sources

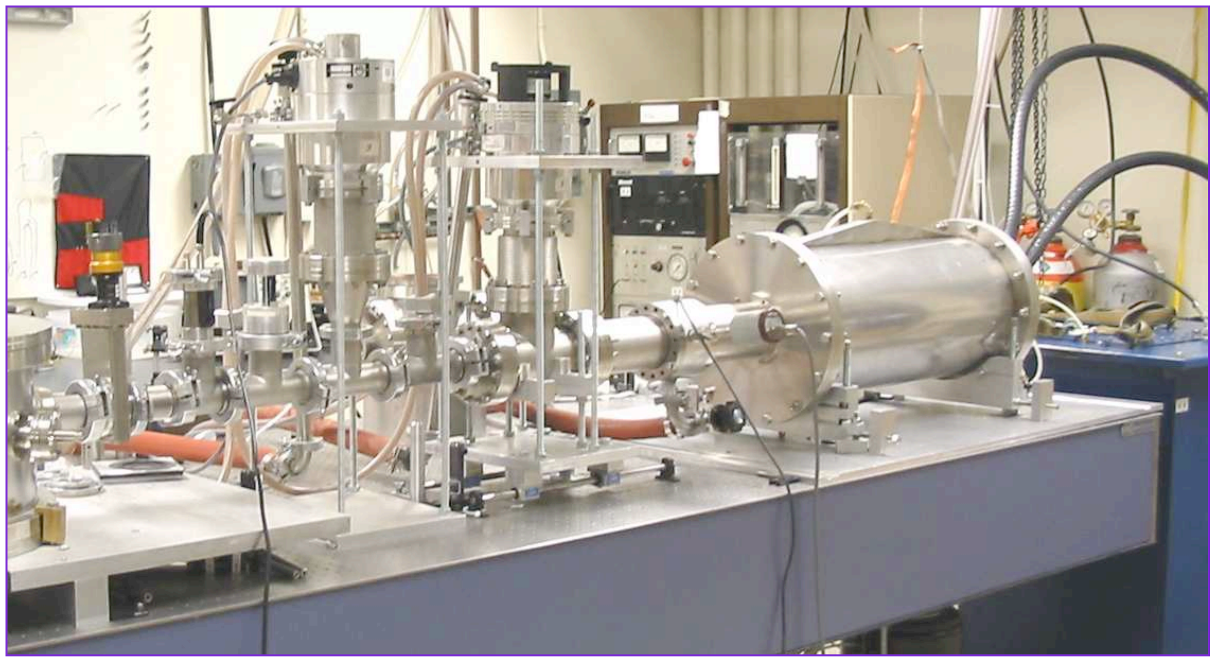
- Tabletop Capillary Discharge
- Tabletop Laser-pumped Transient scheme
- X-ray Laser characteristics

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).

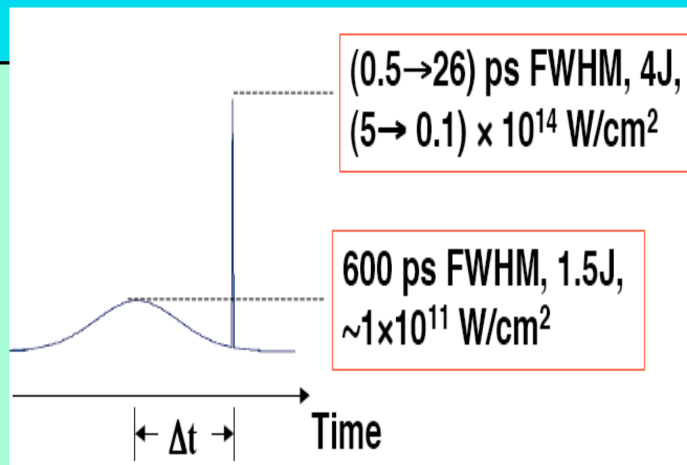
J. Rocca (CSU)

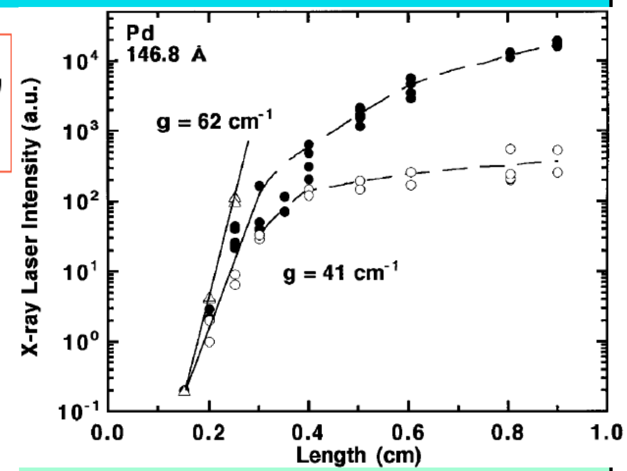
Major breakthrough: Transient scheme 1 ps, 5 - 10 TW laser pulse to optimize excitation - Tabletop X-ray Laser

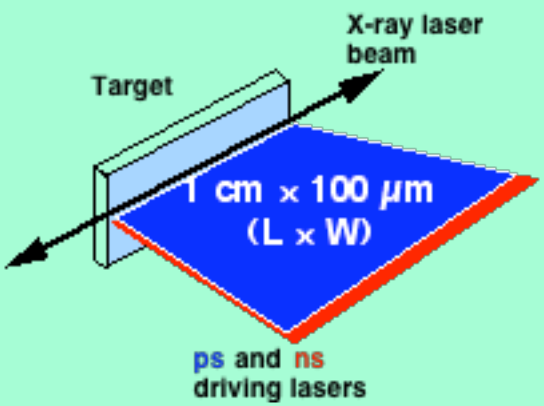
Two Stage Process

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

Short laser pulse: 2 - 5 J
- excitation







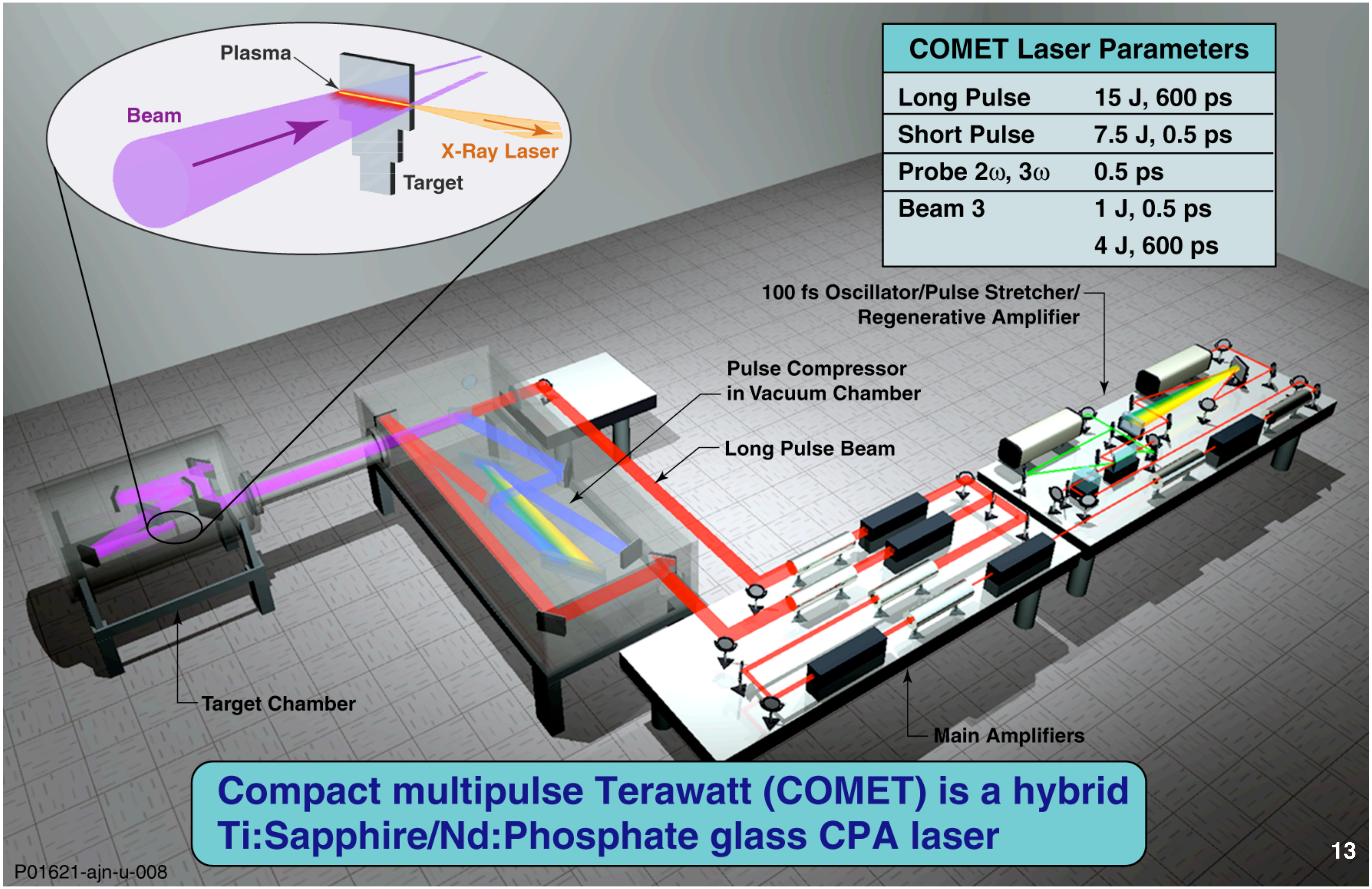
Tabletop Laser Driver

- **Pump energy:** <10 J, ~2 - 7 J
- **High gain:** 25 - 65 cm^{-1}
- **Target length:** ~ 1 cm
- **Wavelength:** 11.9 nm (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 (*vs* Nova)

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

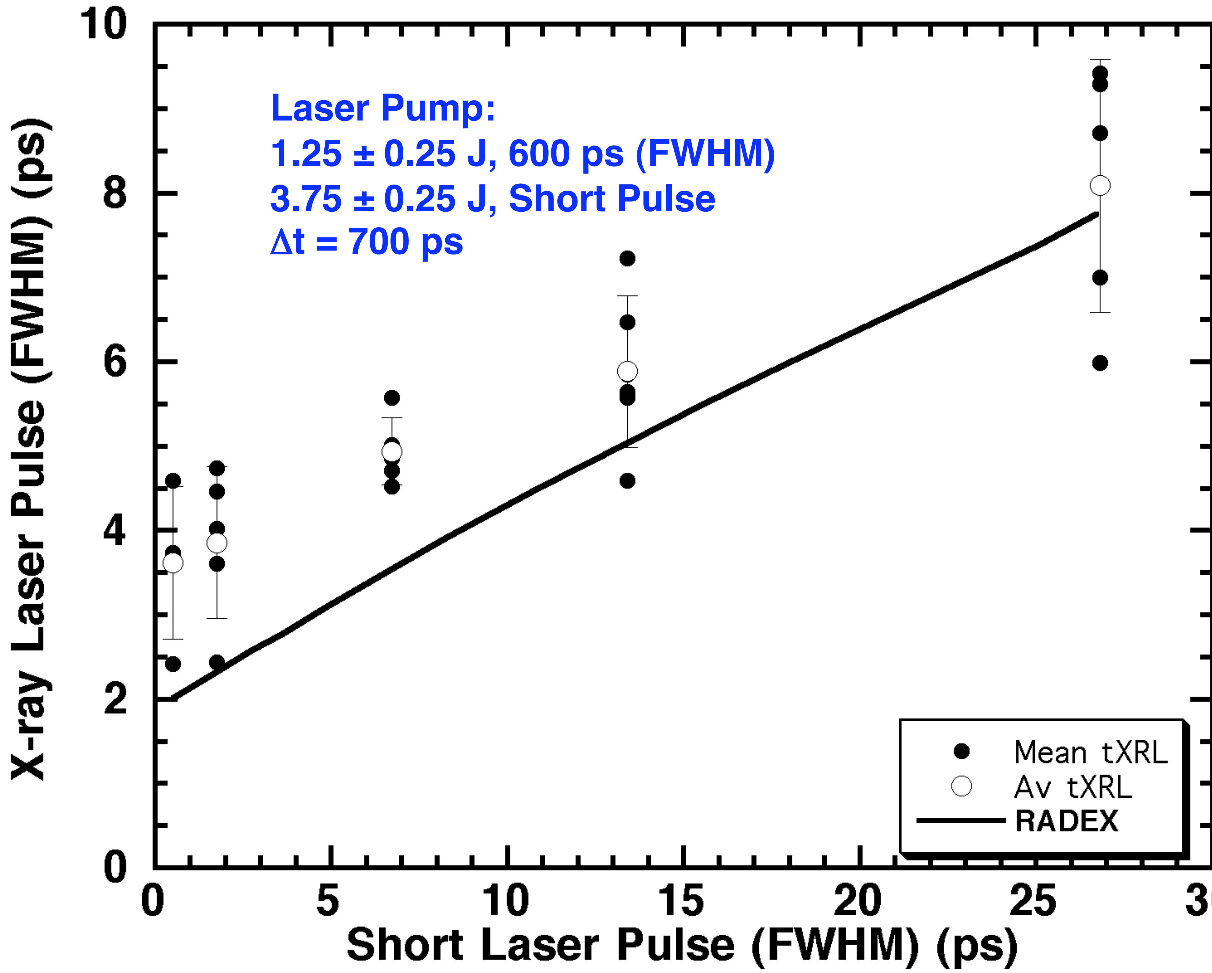


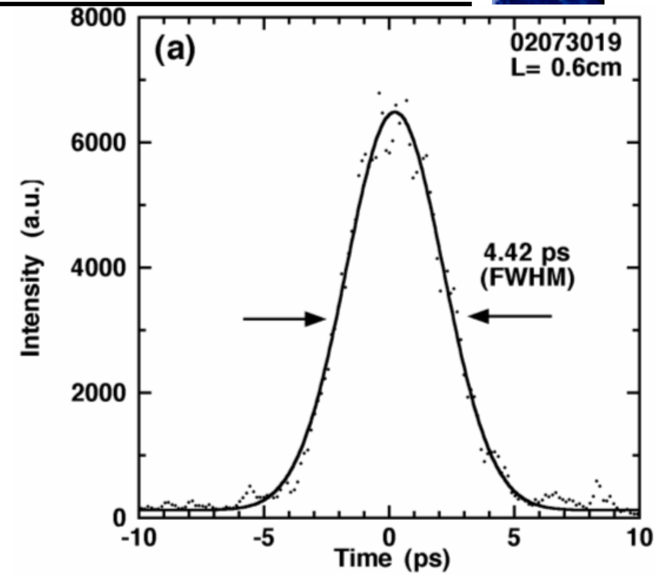
COMET Laser Parameters	
Long Pulse	15 J, 600 ps
Short Pulse	7.5 J, 0.5 ps
Probe 2ω, 3ω	0.5 ps
Beam 3	1 J, 0.5 ps
	4 J, 600 ps

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

P01621-ajn-u-008

Transient scheme produces pulsed ps duration x-ray laser - determined by gain lifetime in plasma



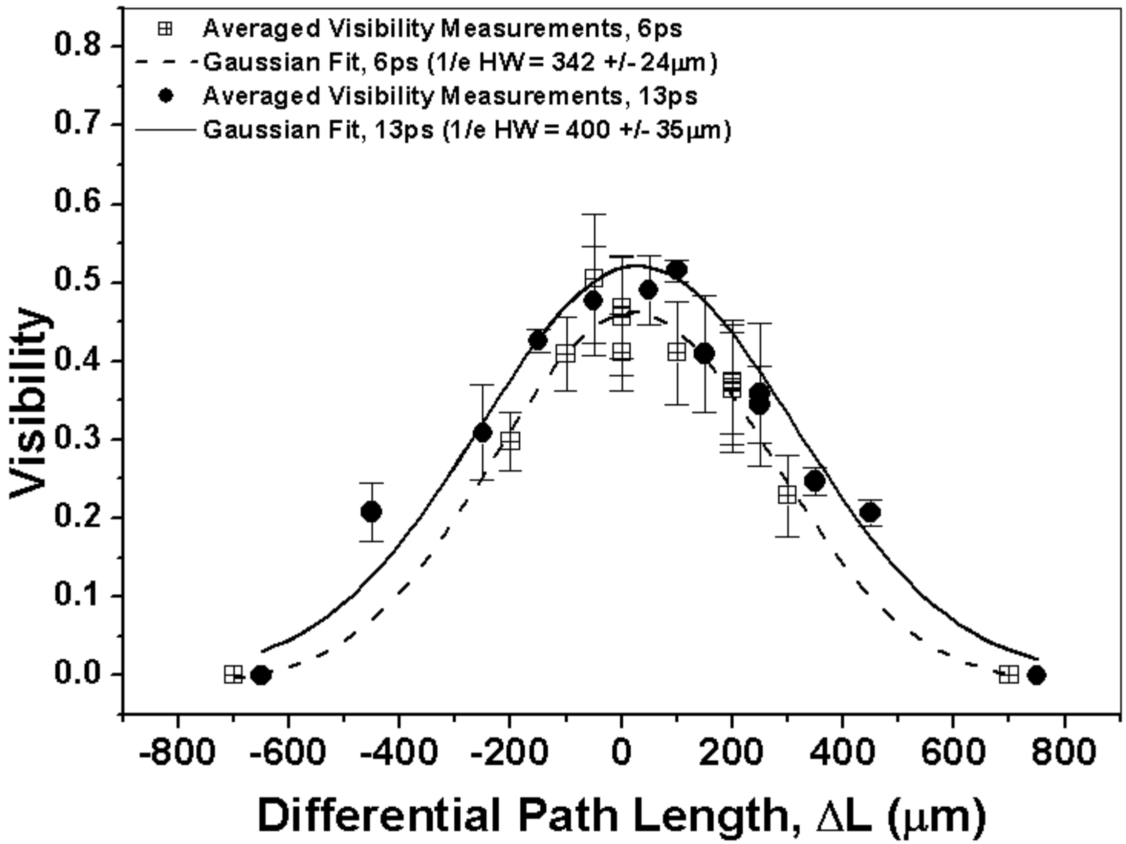


Laser Pump (ps)	t_{meas} (ps)	t_{XRL} (ps)
0.495	3.8 ± 0.8	3.62 ± 0.9
1.75	4.0 ± 0.8	3.86 ± 0.9
6.7	5.0 ± 0.4	4.94 ± 0.4
13.4	6.0 ± 0.9	5.89 ± 0.9
26.8	8.2 ± 1.5	8.09 ± 1.5

Dunn *et al.*, SPIE Soft X-ray Lasers and Applications 2003.

- t_{XRL} varies by 2.2×for 50×variation in short pulse
- Shortest observed t_{XRL} 2.4 ± 0.1 ps (FWHM) for <1.75 ps short pulse

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



In collaboration with P. Zeitoun

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

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

Summary of Present Soft X-ray (EUV) Laser Characteristics:

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

- **Characteristics:**

	Fs- Ps-Driven X-ray Lasers	PALS
- Gain saturation	10 μJ output, 10^{12} photons/pulse	10^{15} ph.
- High gain	30 - 80 cm^{-1} (small signal gain)	
- Repetition rate	1 - 10 Hz (100 Hz DPSSL proposed by MBI, Berlin, CSU)	
- Average Power	~20μW @ 13.9, 13.2 nm @ 10 Hz, 1mW @46.9 nm	
- Peak Power	1 - 10 MW	50 - 100 MW
- Beam divergence	~0.5 - 2 mrad (FWHM)	
- X-ray laser duration	1 - 8 ps (FWHM)	100ps
- Longitudinal coherence	~400 μm (1/e width)	
- Spatial coherence	~3% for ASE amp. - full coherence for seeded	
- Wave front	λ/17 @ 32.5 nm	
- Line width	$\lambda/\Delta\lambda$ = 50,000	
- Brightness	10^{25} - 10^{26} ph. mm^{-2} $mrad^{-2}$ s^{-1} $[0.1\% \, BW]^{-1}$	10^{27}

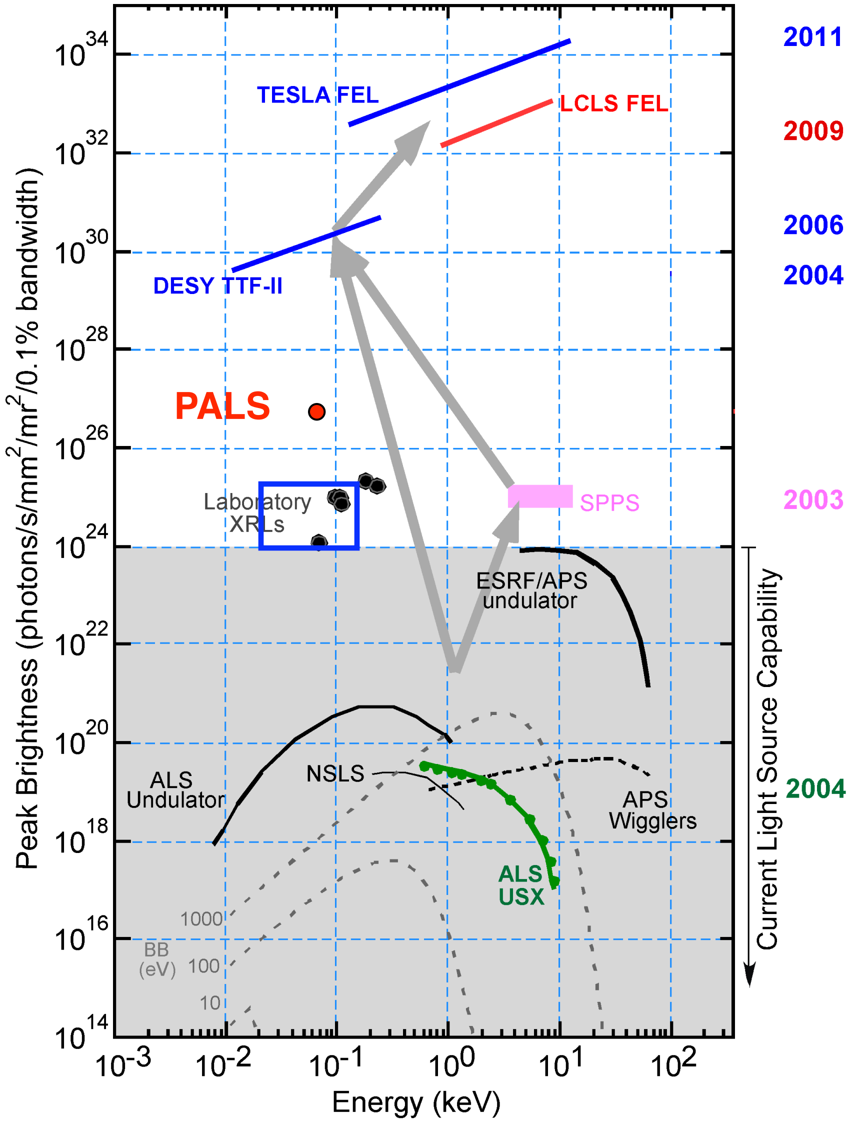
- **Close to transform limited $\Delta E . \Delta t$ operation demonstrated**

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 (μm²):	9 ×20	25 ×100
Div. (mrad²):	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}

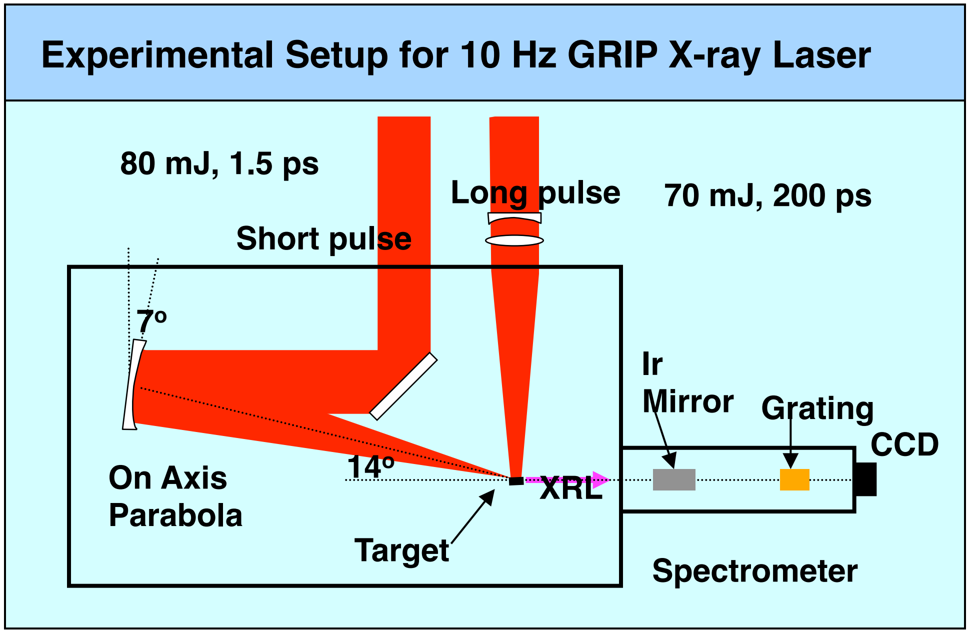
* [Ph. mm^{-2} mrad^{-2} s^{-1} (0.1% BW)$^{-1}$]
‡ For 10 Hz operation

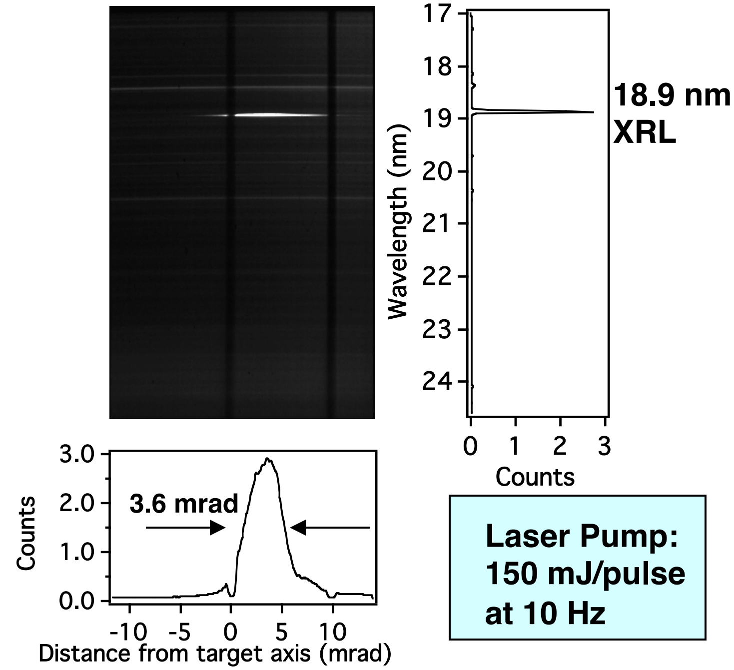


Recent developments in X-ray Laser Sources

- Grazing Incidence Pumping (GRIP)
- Higher Order Harmonic Seeding into OFI amplifier
- Higher Order Harmonic Seeding into GRIP plasma amplifier

Grazing Incidence Pumping (GRIP) x-ray laser produced by absorbing pump energy efficiently in gain region: 10 Hz XRL





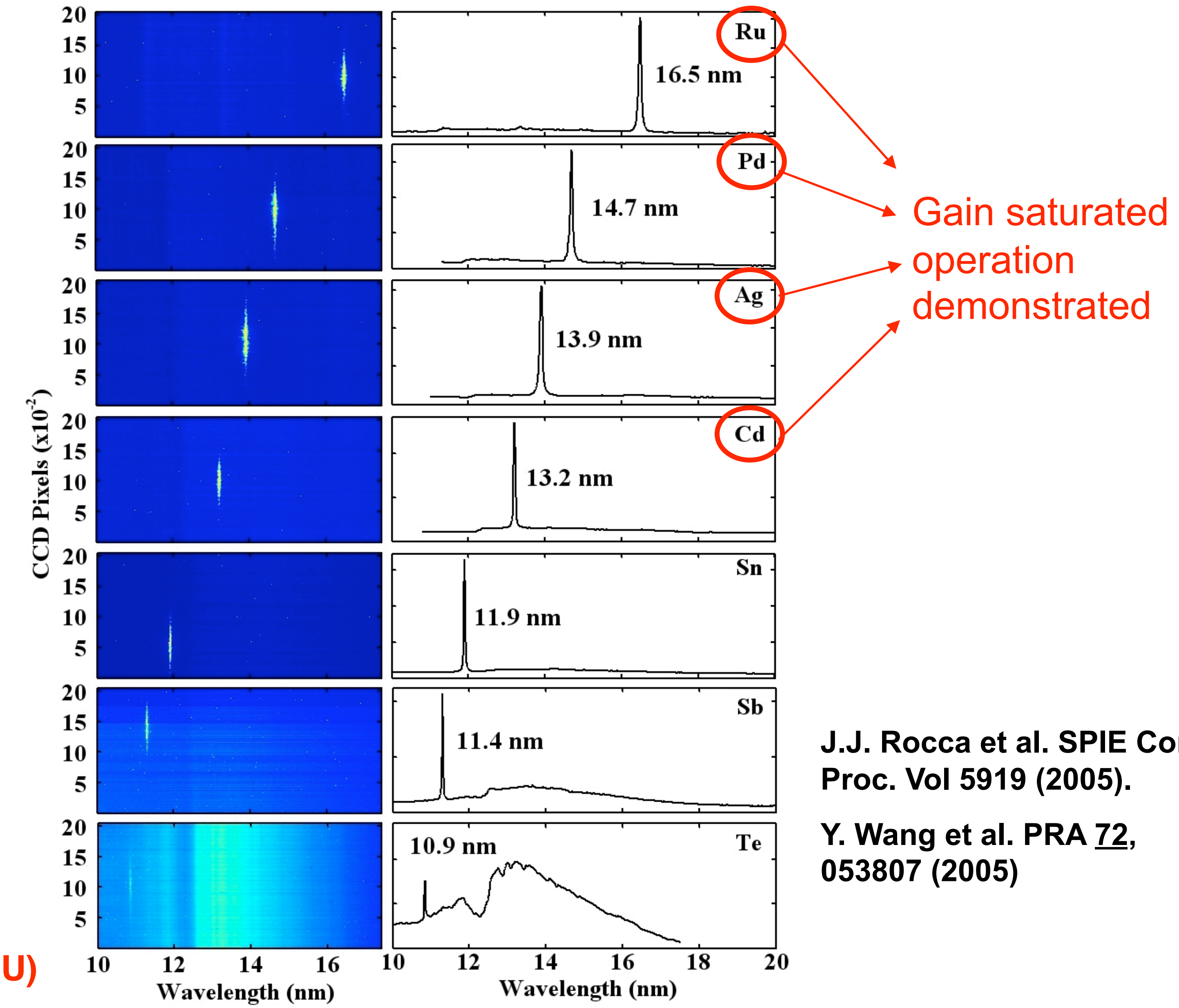
Laser Pump:
150 mJ/pulse
at 10 Hz

- Short pulse propagates in plasma up to a specific electron density
- 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 in gain region increases to 50% for GRIP

In collaboration with Slava Shlyaptsev, UC Davis

R. Keenan, J. Dunn, P.K. Patel, D.F. Price, R.F. Smith, and V.N. Shlyaptsev, “High Repetition Rate Grazing Incidence Pumped X-ray Laser Operating at 18.9 nm”, Phys. Rev. Lett., 94, 103901-1 (2005).

Lasing observed at wavelengths as short as 10.9 nm



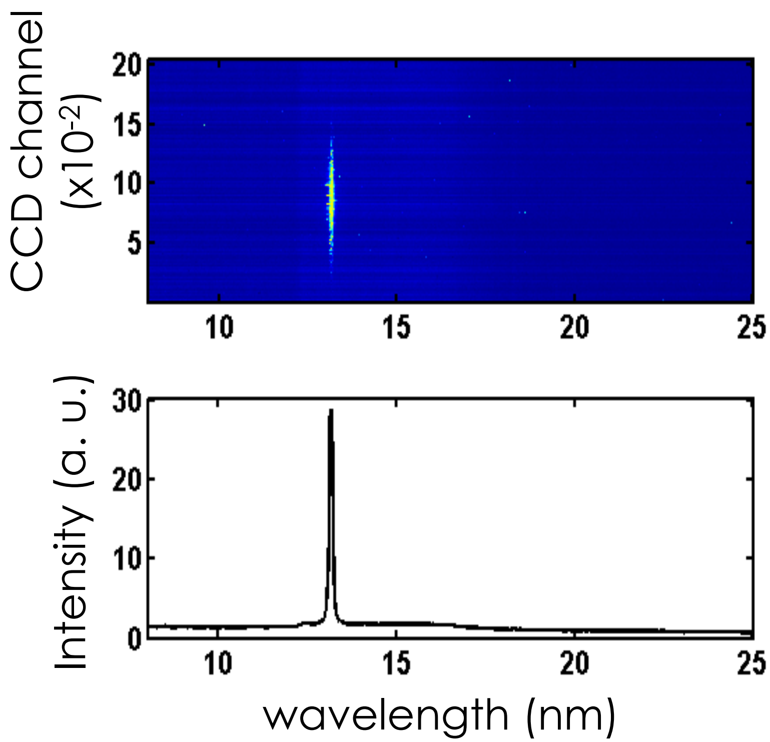
J.J. Rocca et al. SPIE Conf. Proc. Vol 5919 (2005).

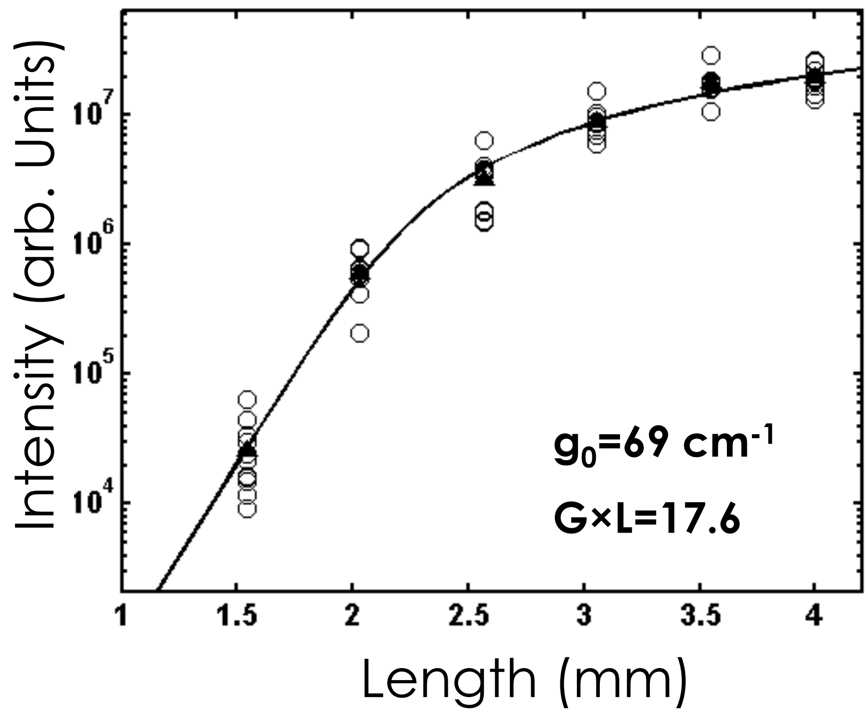
Y. Wang et al. PRA 72, 053807 (2005)

J. Rocca (CSU)

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

1 J short pulse – 23 degrees grazing incidence angle

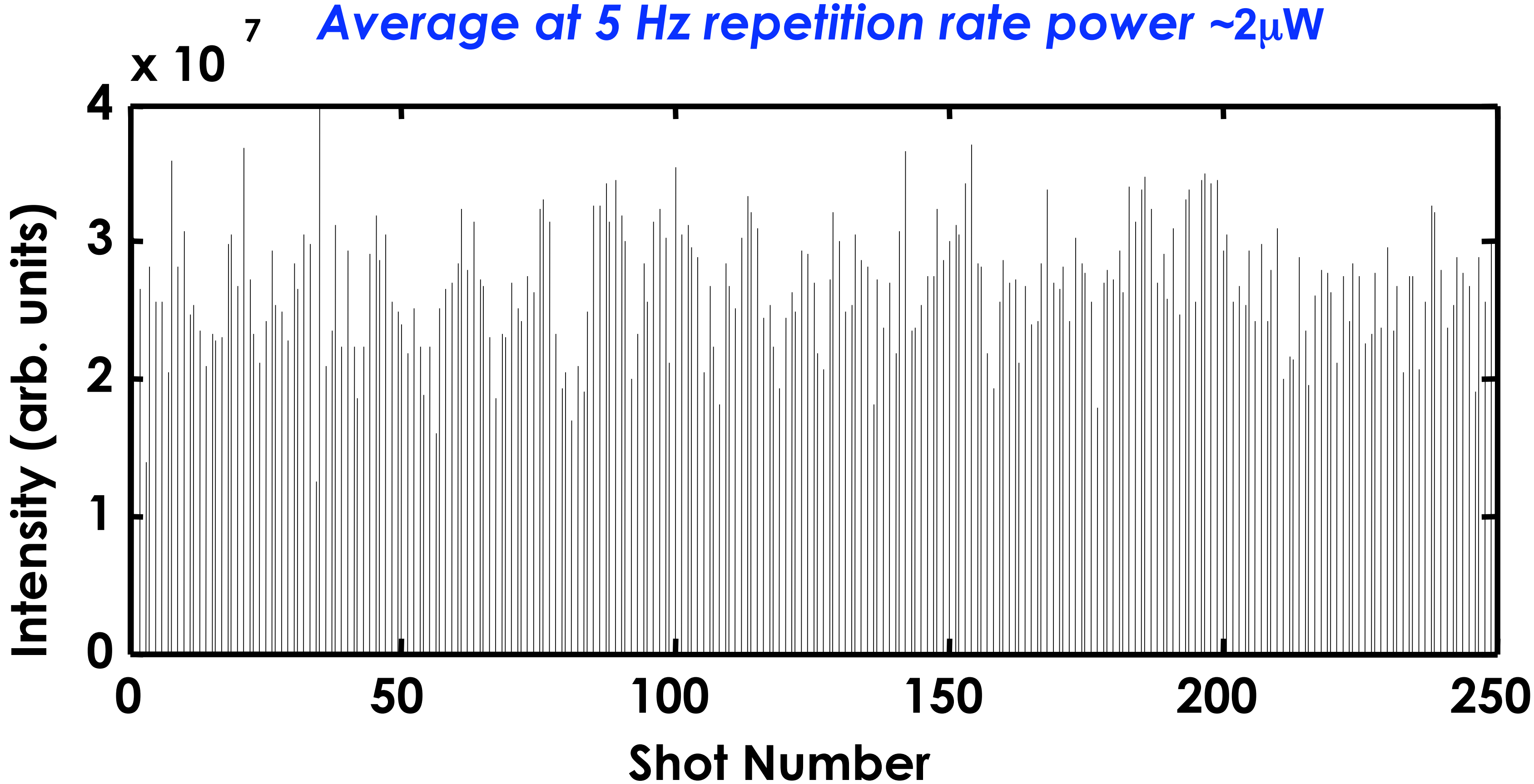




J.J. Rocca, Opt. Lett. 30, 2851 (2005).

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

Average at 5 Hz repetition rate power ~2μW

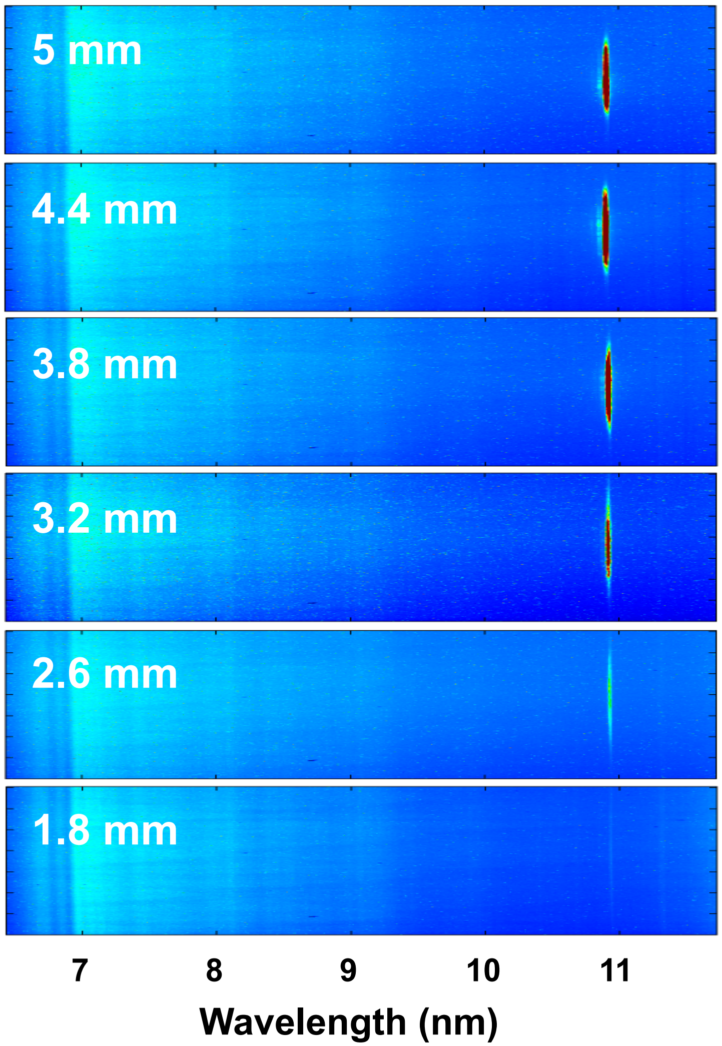


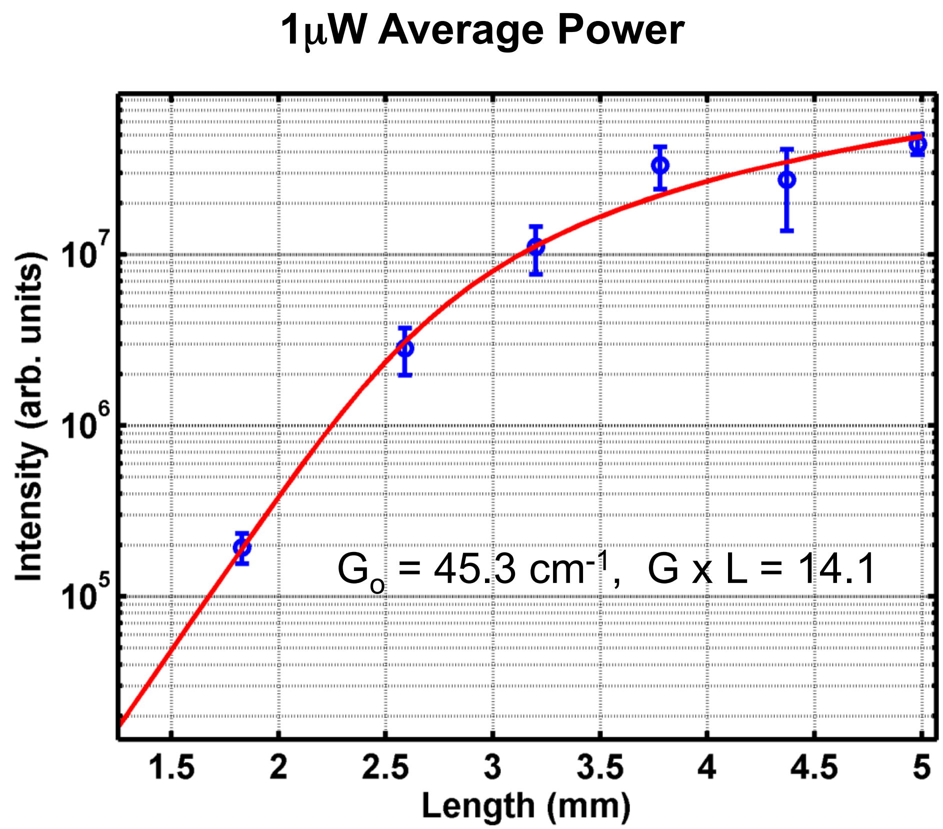
Similar performance also obtained for Ni-like Cd @ 13.2 nm, > 1 μW average power

J. Rocca (CSU)

Gain-Saturated output of table-top Laser extended to 10.9 nm at 1 Hz rep. rate

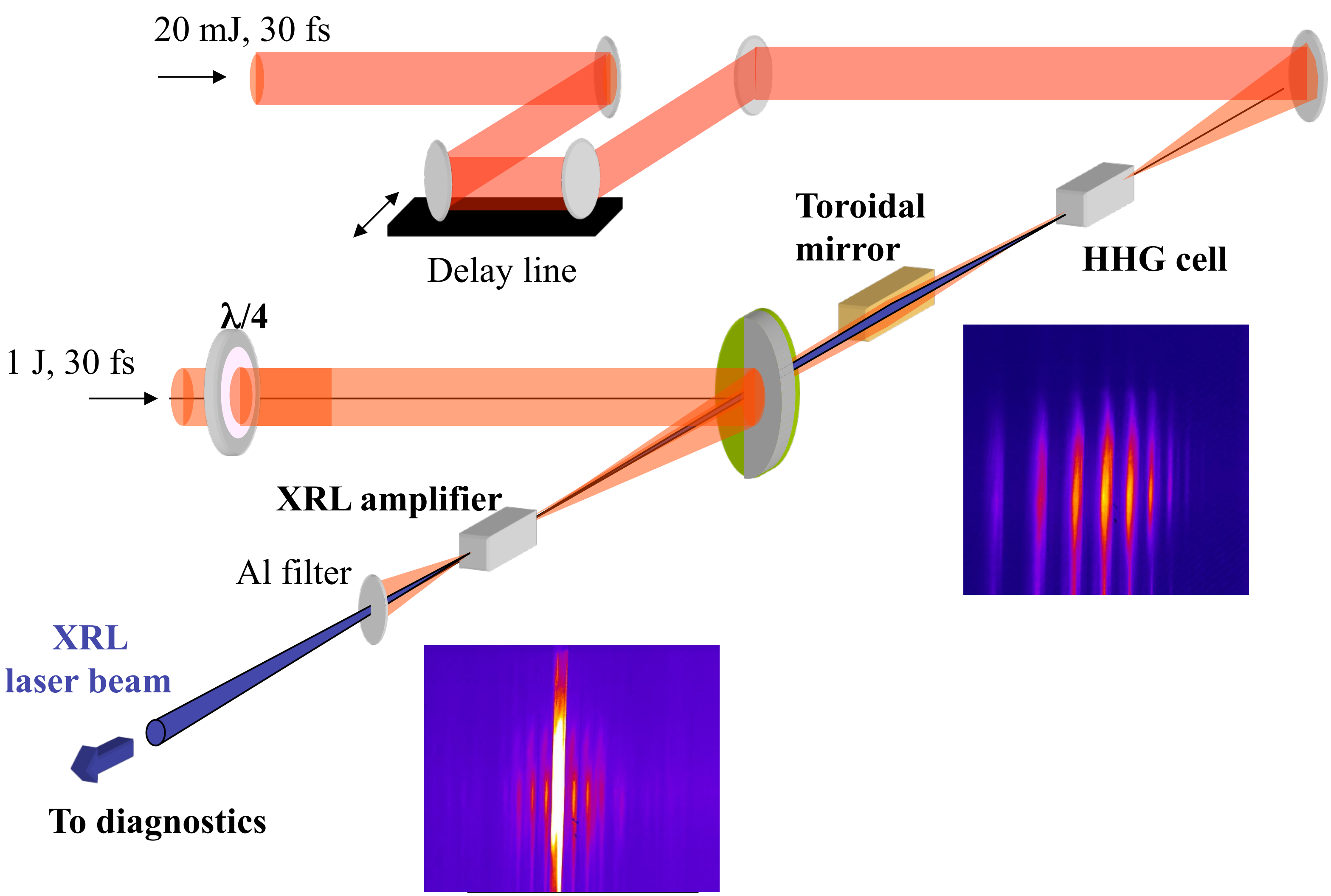
Nickel-like Tellurium





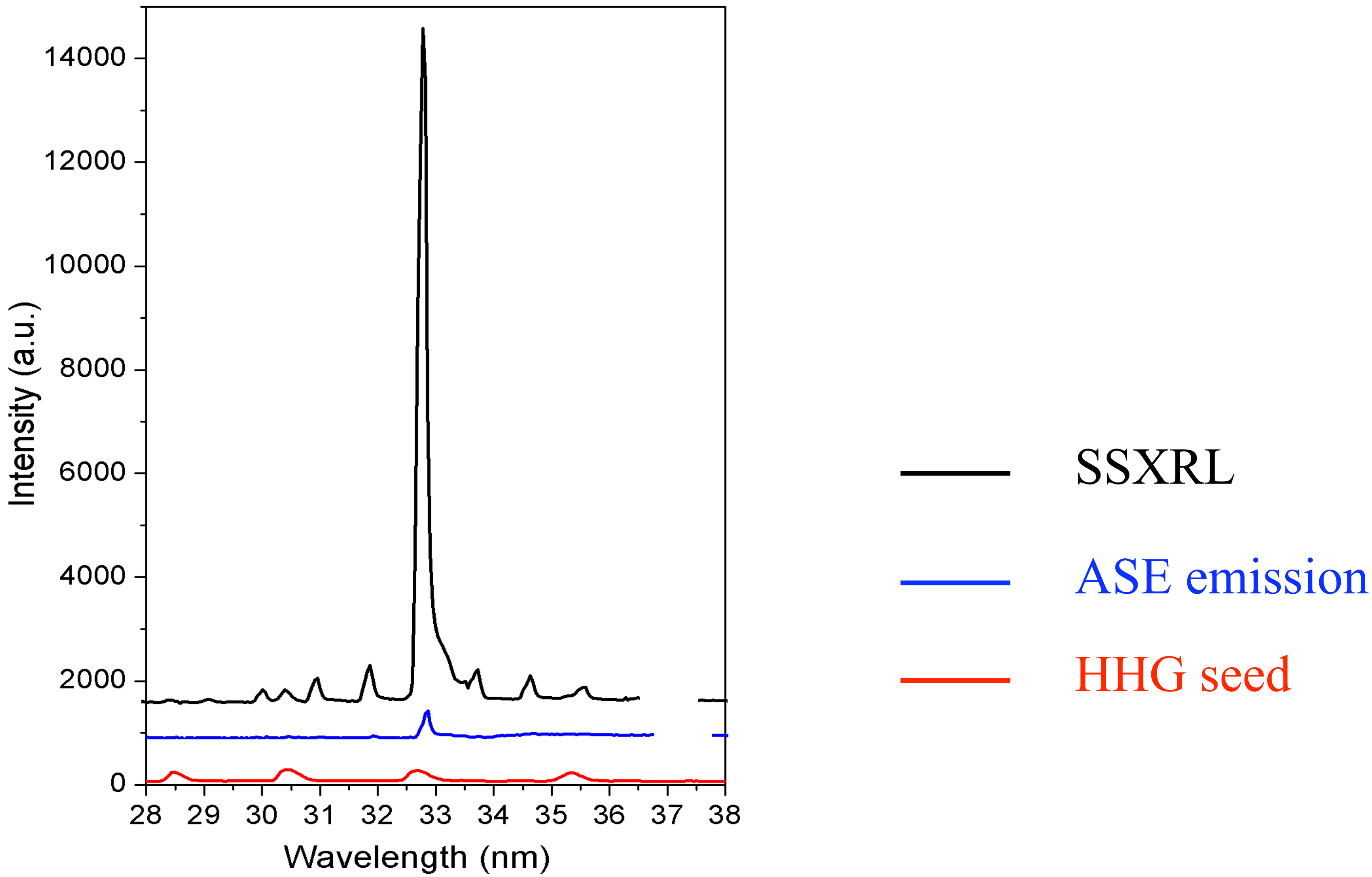
J. Rocca (CSU)

Coupling one harmonic to an XRL amplifier : set up



S. Sebban (LOA)

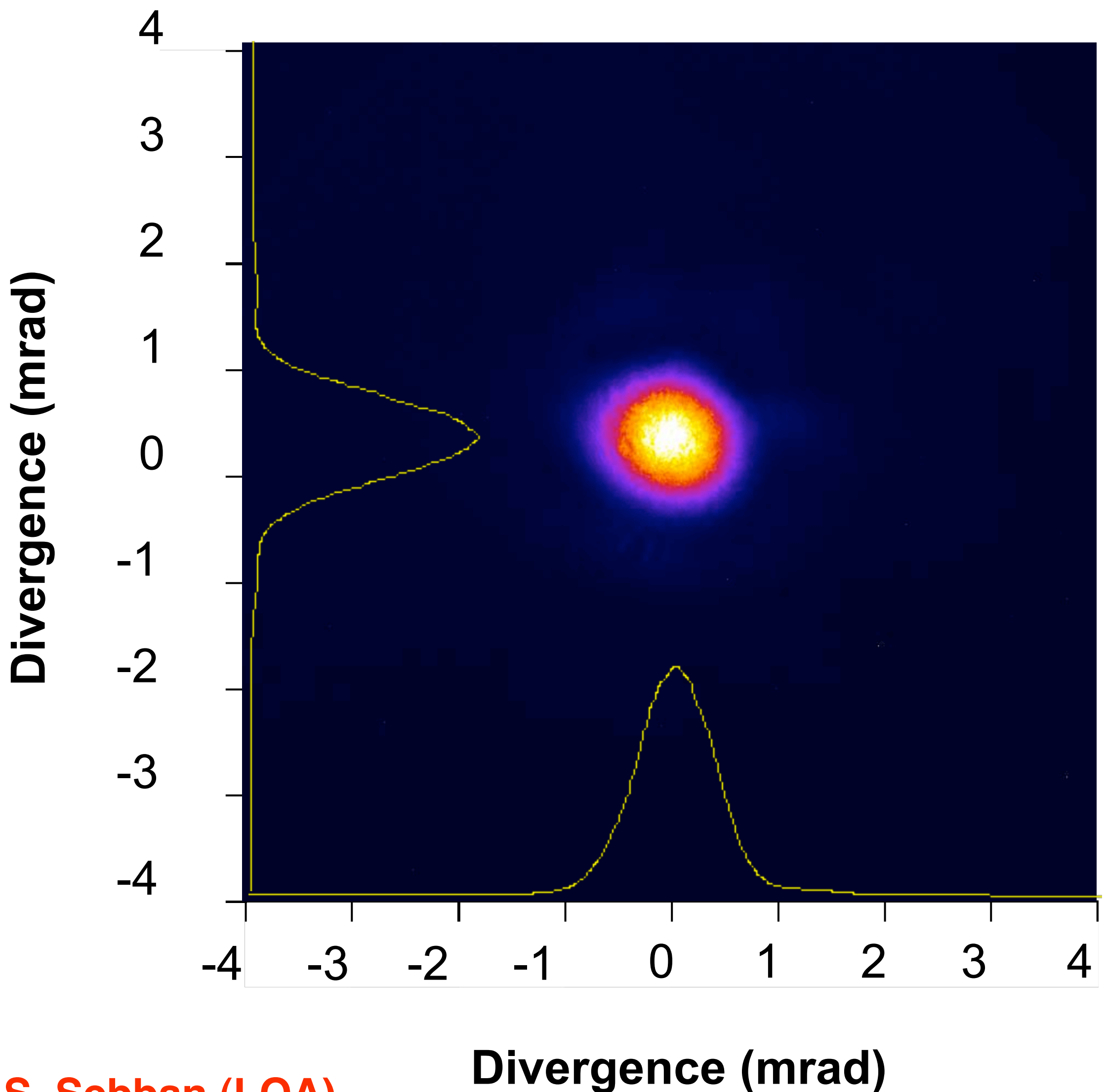
Evidence of amplification of the 32.8 nm Kr IX laser



S. Sebban (LOA)

Ph. Zeitoun at al. Nature, Vol 431, 09/2004, pp. 466

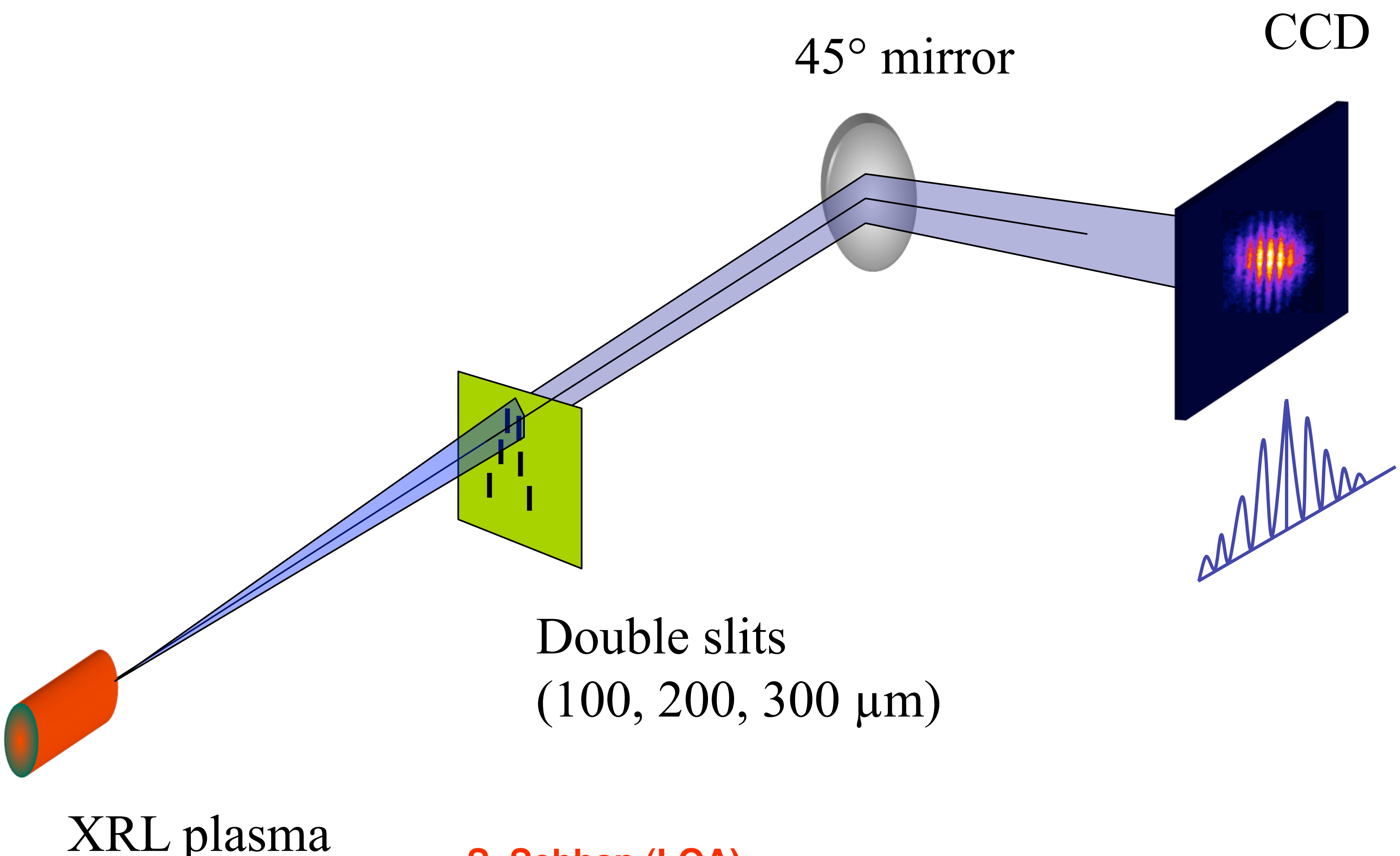
Far field pattern of the 32.8 nm seeded x-ray laser



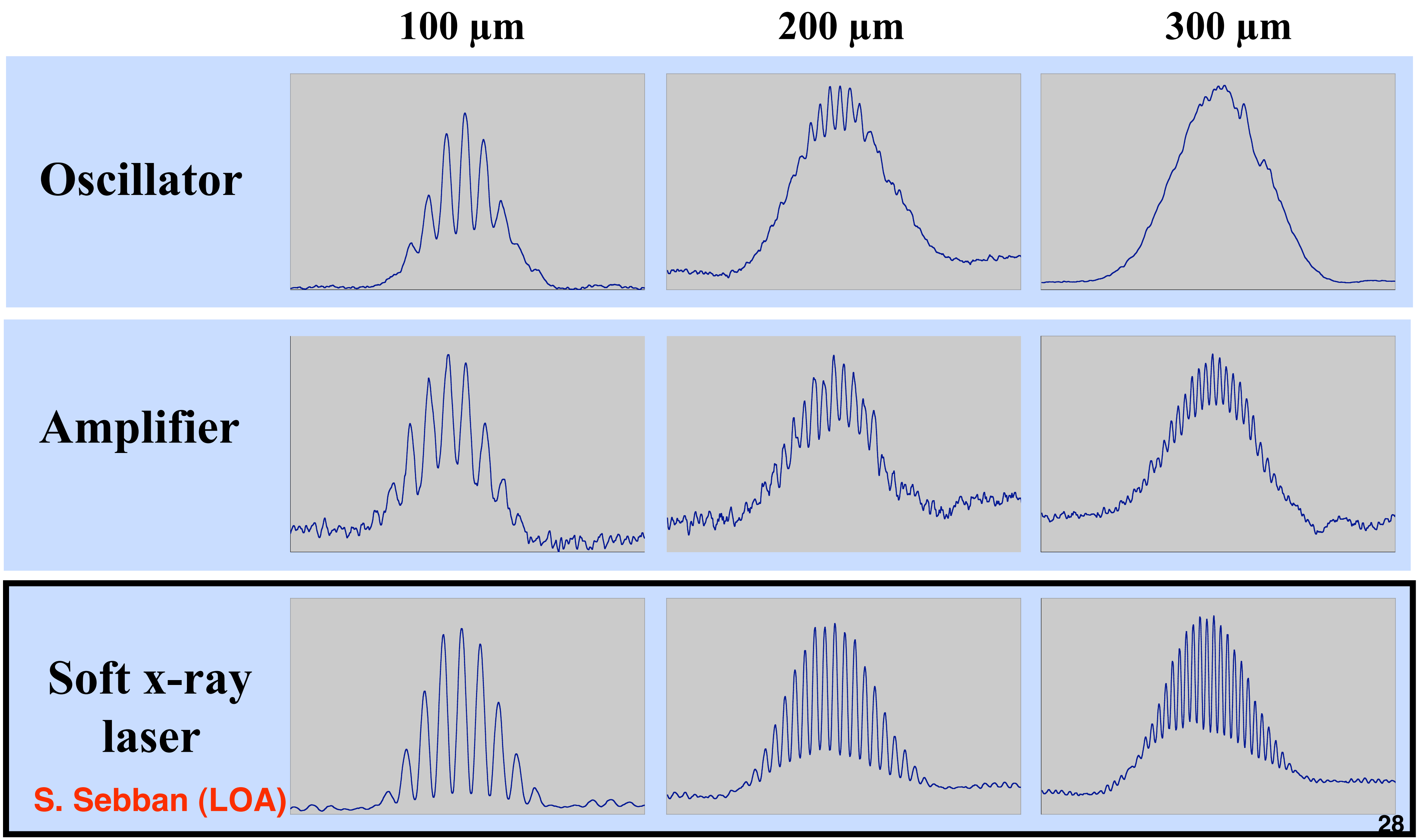
E=0.7 μJ per shot
Divergence : 0.7 mrad

S. Sebban (LOA)

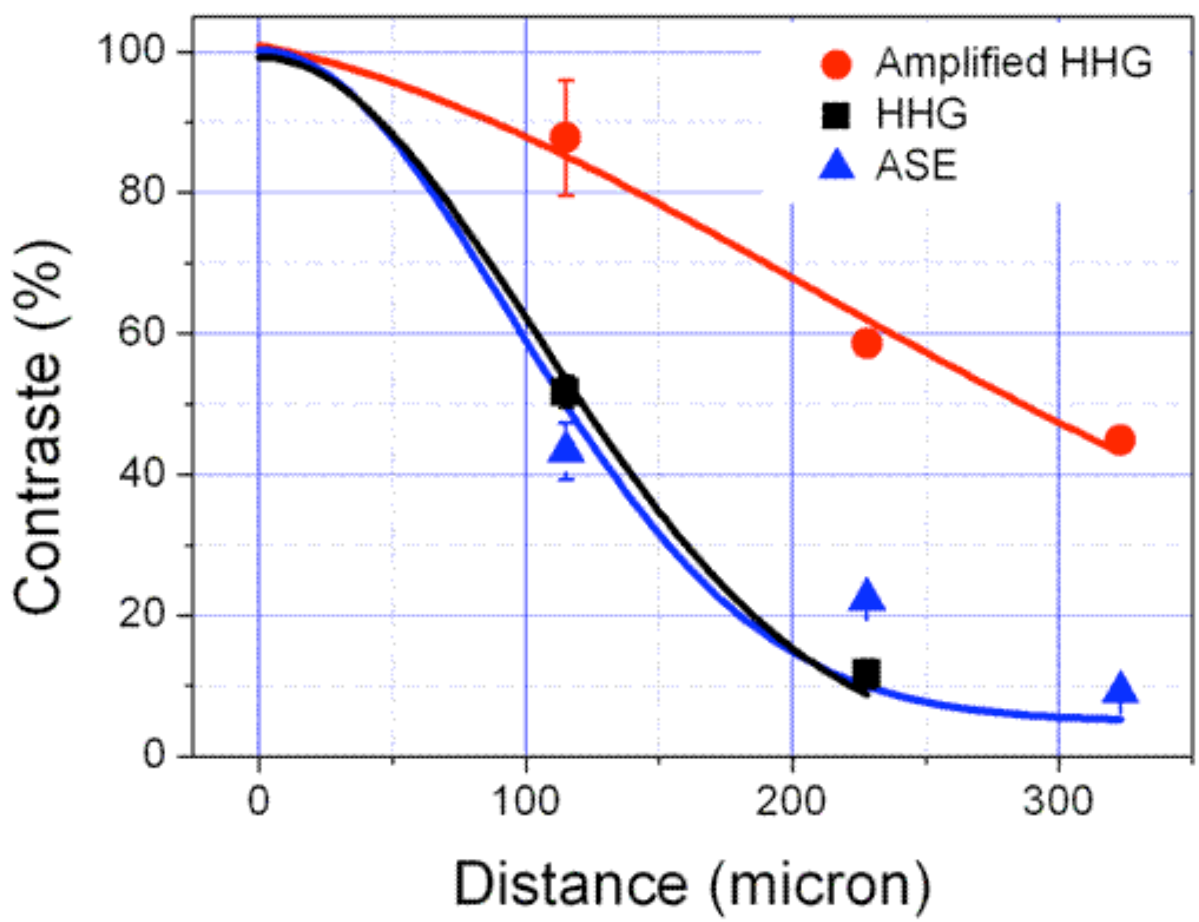
Transverse coherence : Young's double slit experiment



High spatial coherence of the seeded soft XRL (Young' slit experiment)



Contrast of the fringes pattern (Young' slit experiment)



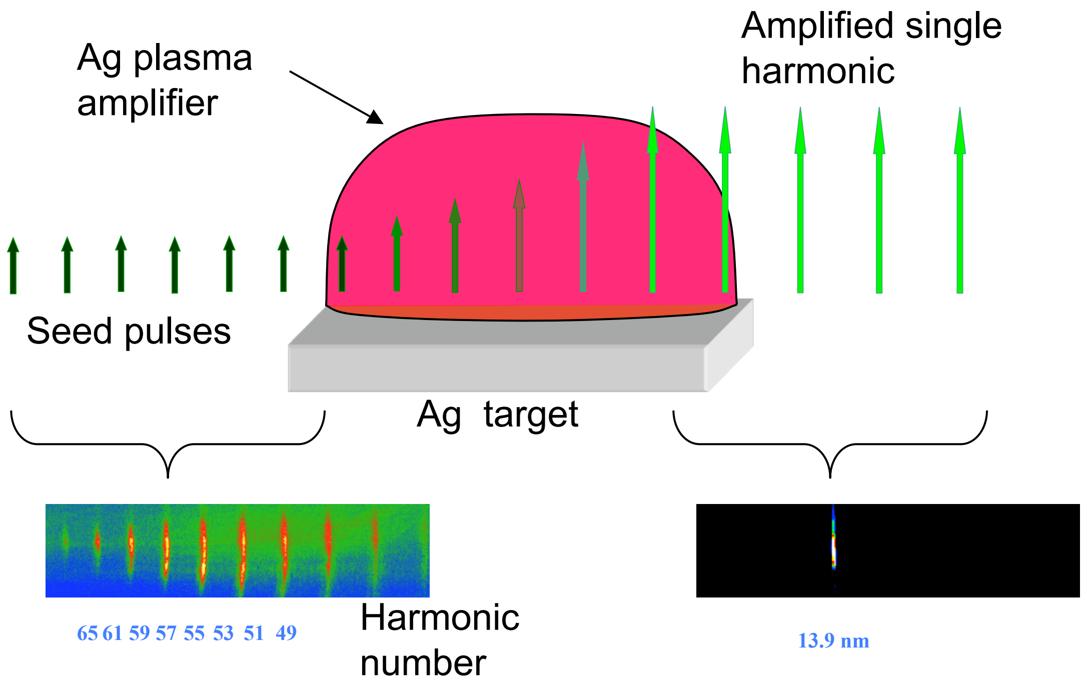
Rc= 232 μm

60% of the beam

J. Ph. Goddet et al., Opt. Lett., 32, 1498 (2007)

Seeding with high harmonic pulse can greatly increase coherence and beam brightness

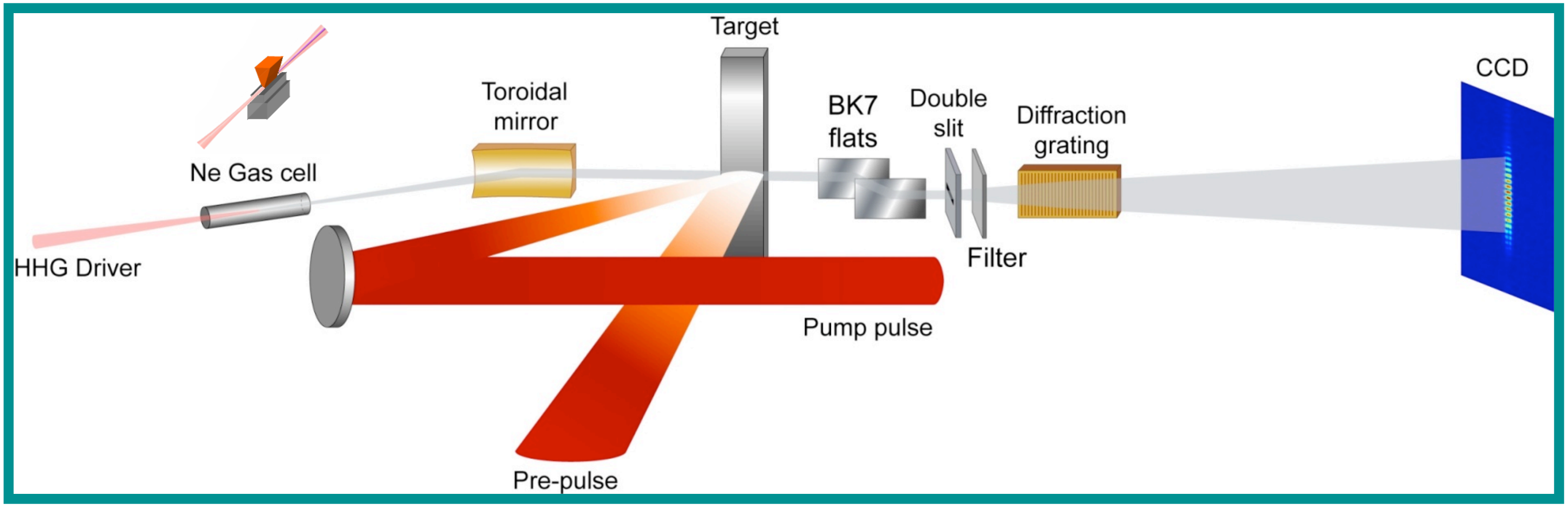
- Decreased divergence
- Shorter pulsewidth
- Defined polarization
- Higher brightness

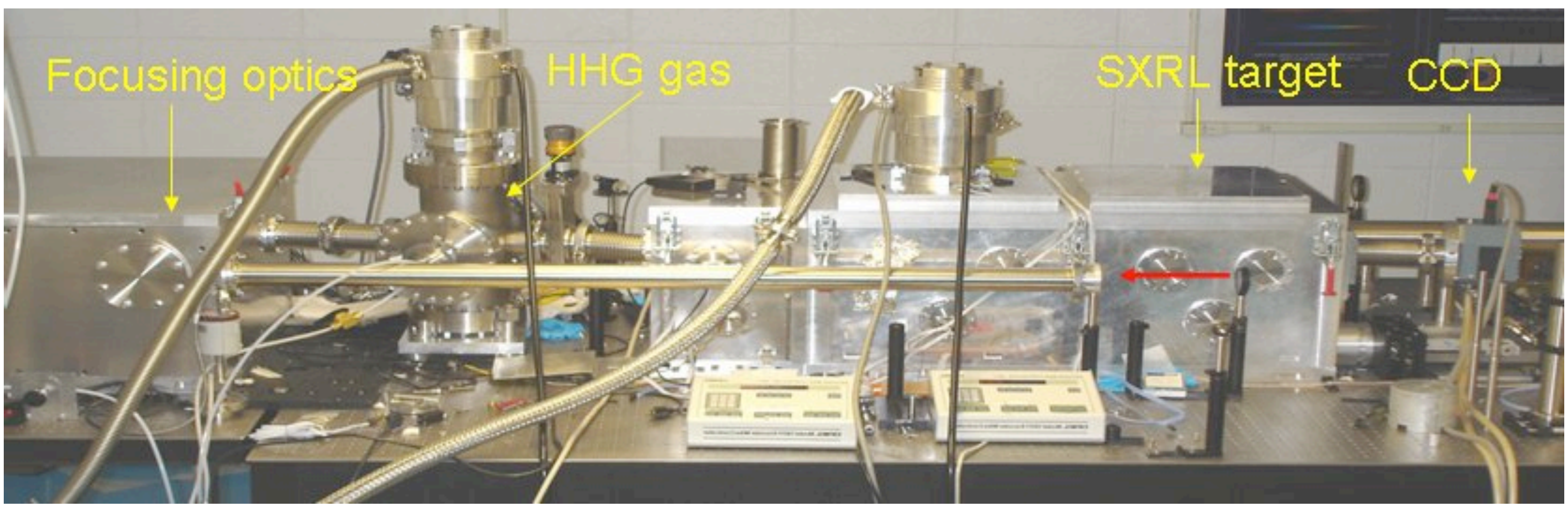


- **Proof of principle experiment**: T. Ditmire et al. Phys. Rev. A. 51, R 4337, (1995): Amplification of HHG by ~ 3 X in the λ= 25.1 nm line of a Gallium laser amplifier
- **HHG seeding of OFI amplifier:** P. Zeitoun, G. Faivre, S. Sebban, T. Mocek *et al*, Nature , **431**, 426, (2004).
- **Injection- seeded soft x-ray laser using solid target plasmas:** Y.Wang, E.Granados, M. Larotonda, M. Berrill, B.Luther, D. Patel, C.S. Menoni and J.J. Rocca, Phys..Rev.Lett, **97**,123901 (2006)

J. Rocca (CSU)

Demonstration of injection-seeded EUV laser in dense amplifier created by irradiation of solid target

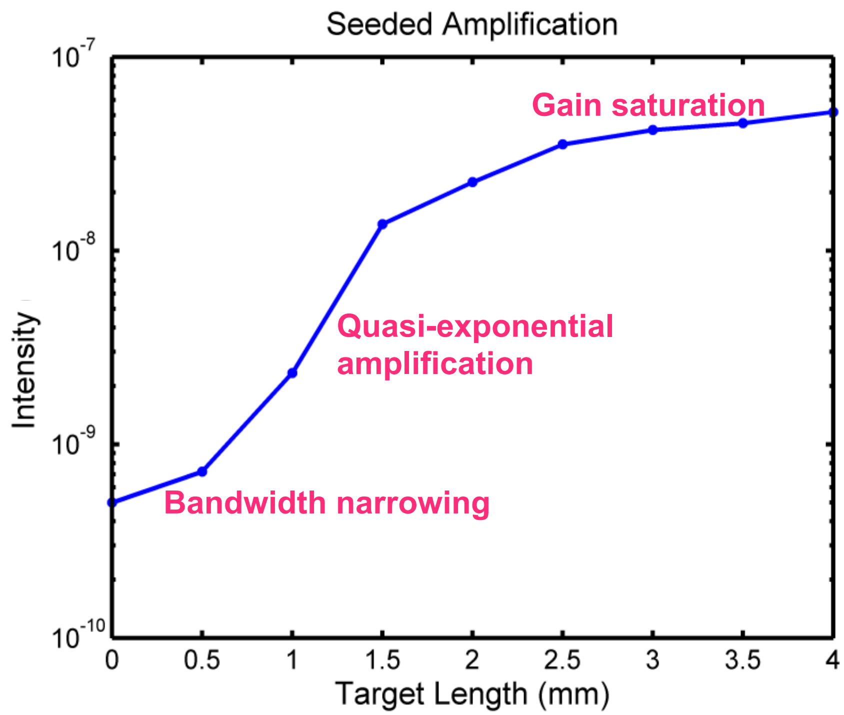




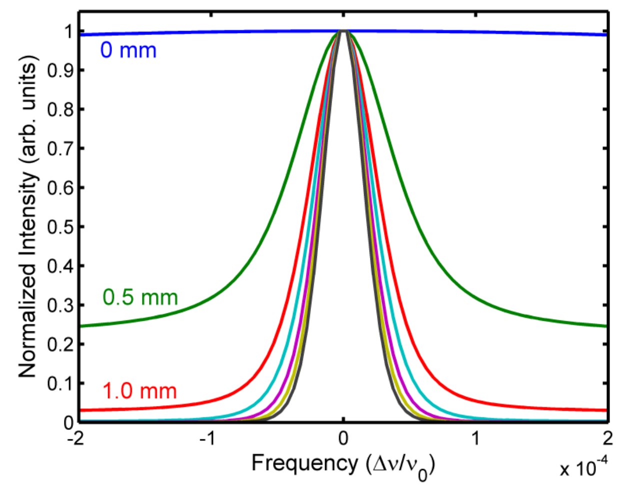
J. Rocca (CSU)

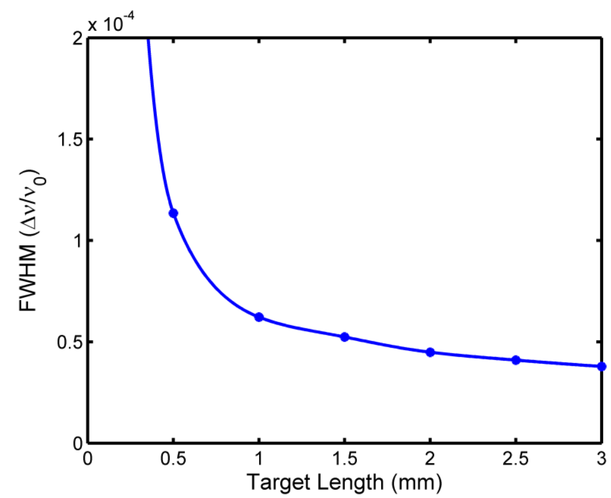
Simulation of High Harmonic seeded 32.6 nm Ne-like Ti amplifier

32.6 nm Ne-like Ti amplifier seeded by 25th harmonic of Ti:Sapphire laser



Bandwidth narrowing of amplified seed pulse



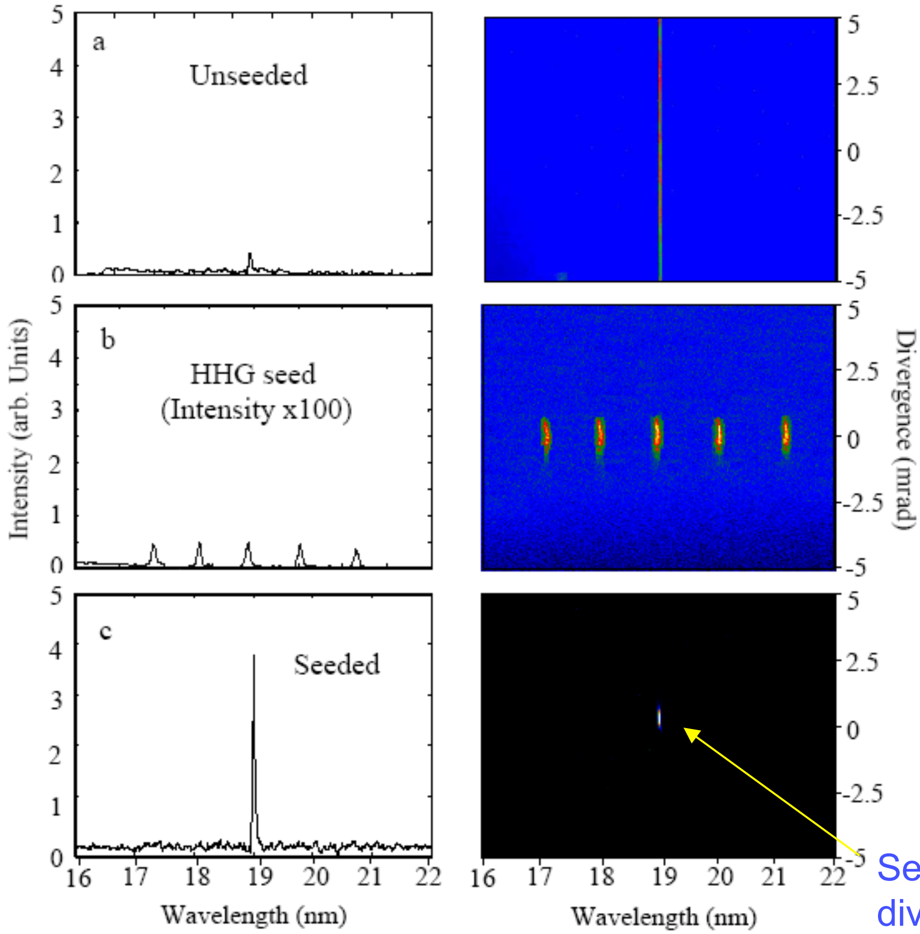


Y. Wang et al. Phys. Rev. Letters, 97, 123901, (2006)

J. Rocca (CSU)

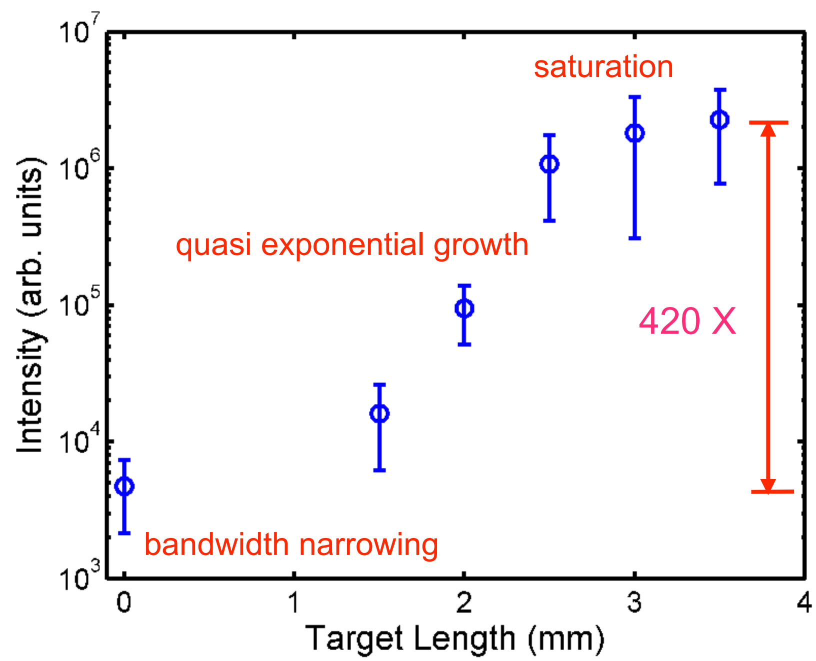
Saturated Injection Seeded 18.9 nm Ni-like Mo amplifier

2.5 mm long amplifier



Seeded laser beam divergence ~ 0.7 mrad

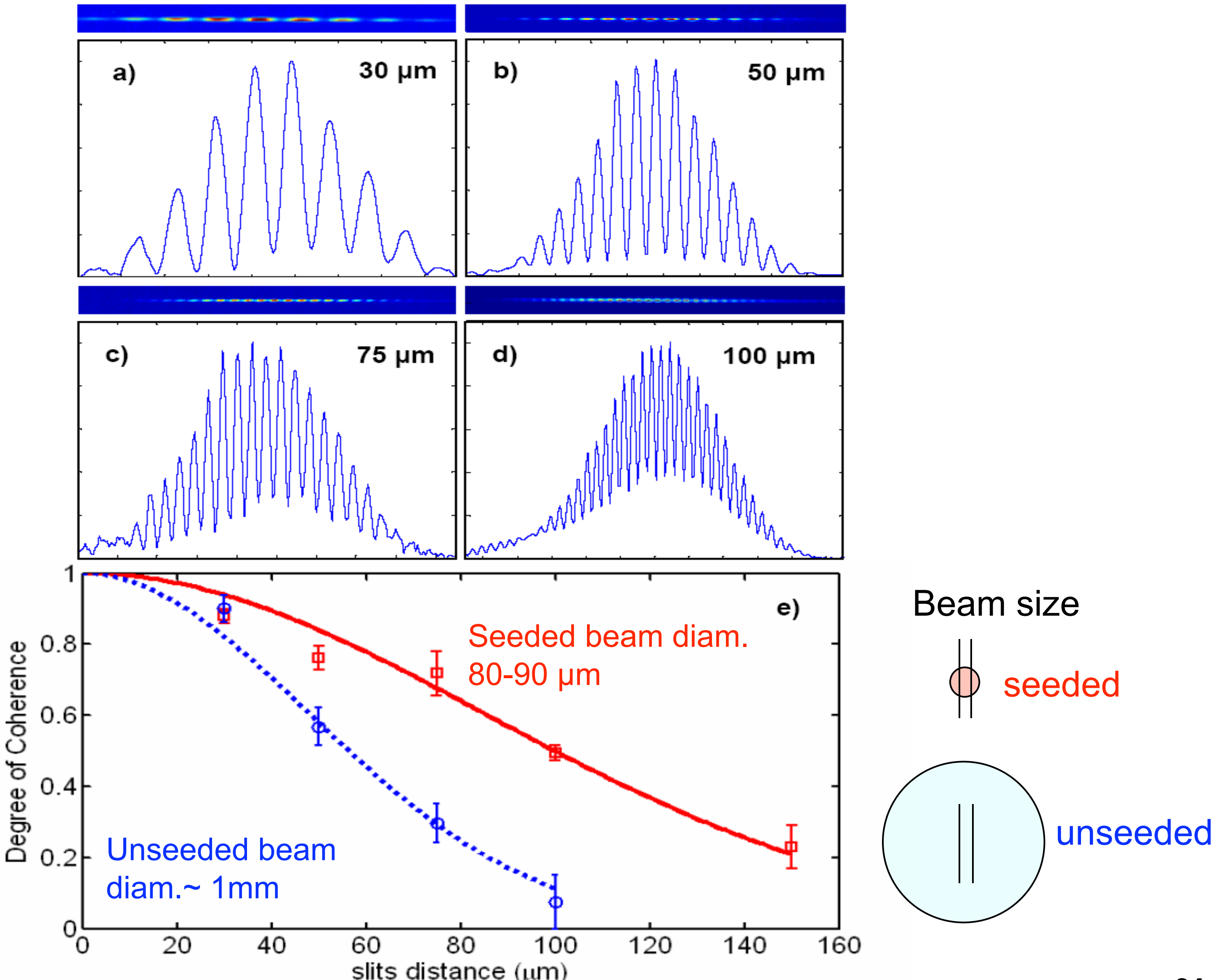
Seed is amplified more than two orders of magnitude into a narrow bandwidth low divergence beam



Y. Wang et al. Nature Photonics, 2, 94, (2008)

J. Rocca (CSU)

Essentially fully coherent output Ni-like Mo 18.9 nm

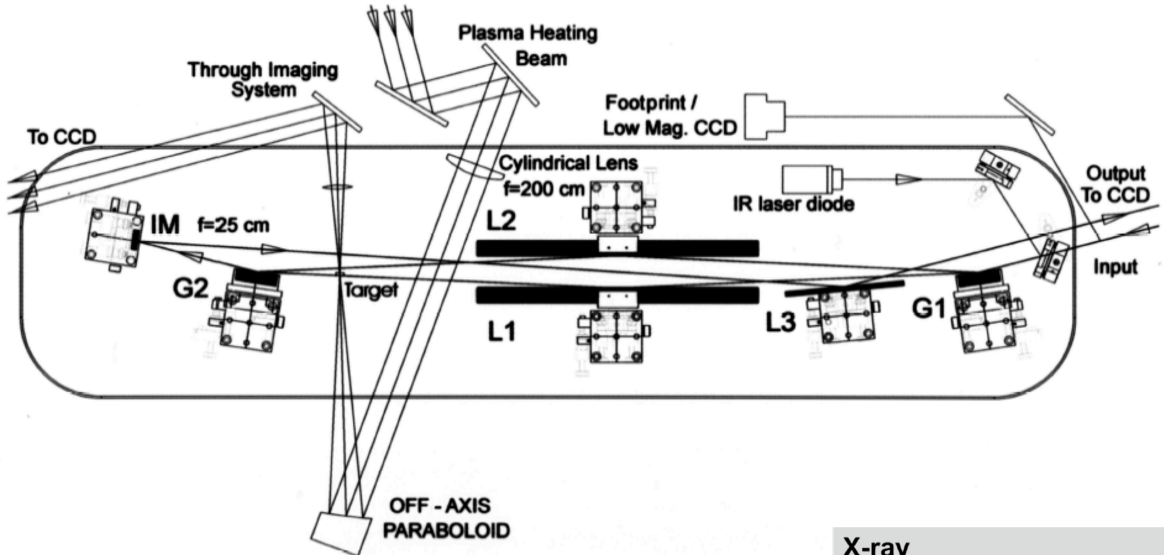


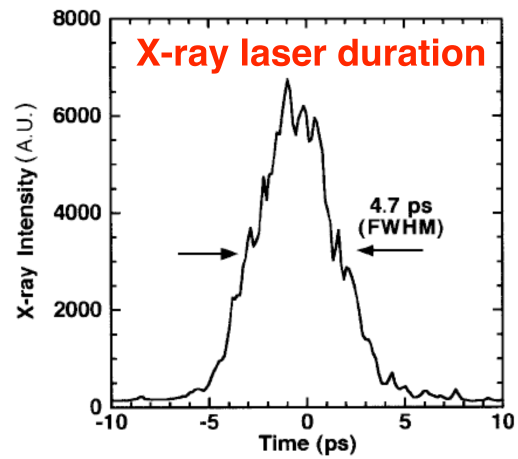
J. Rocca (CSU)

X-ray Laser Applications

- X-ray Laser Interferometry

X-ray Laser Interferometry with grating beam splitters first demonstrated at 46.9 nm at CSU, extended to 14.7 nm





Notes:

Amplitude division interferometer based on skewed Mach-Zehnder geometry

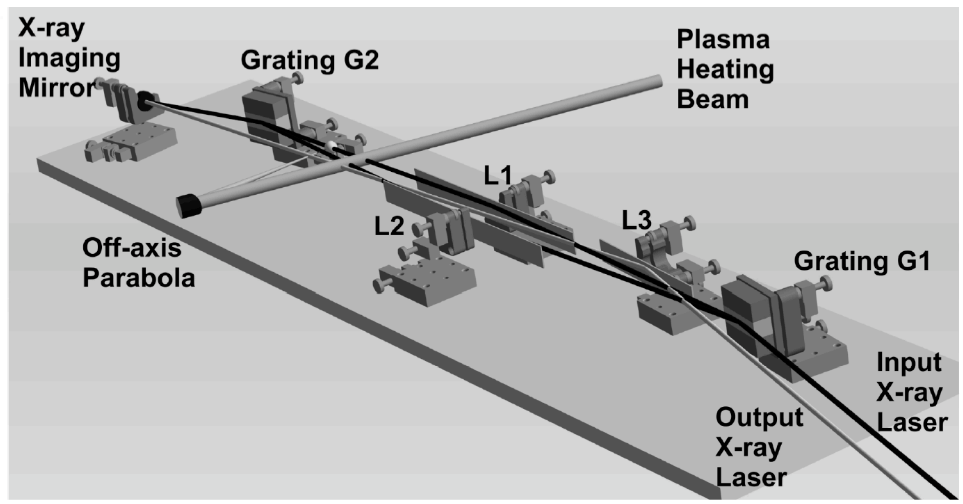
Interferometer uses 0^{th} and 1^{st} orders

G1, G2 beam splitters: 900 l/mm

X-ray Imaging optic: Mo:Si coated *f* = 25 cm spherical mirror

Magnification: 22 x

Back-thinned CCD detector: 0.5 μm spatial resolution

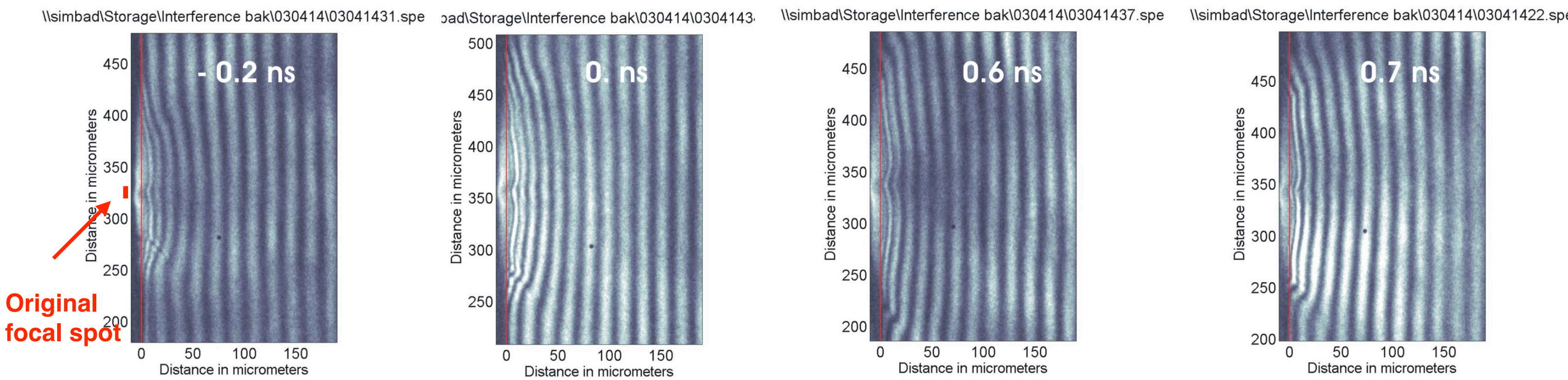


J. Filevich, K. Kanizay, M. C. Marconi, J. L. A. Chilla, and J. J. Rocca, Optics Letters 25, 356 (2000).

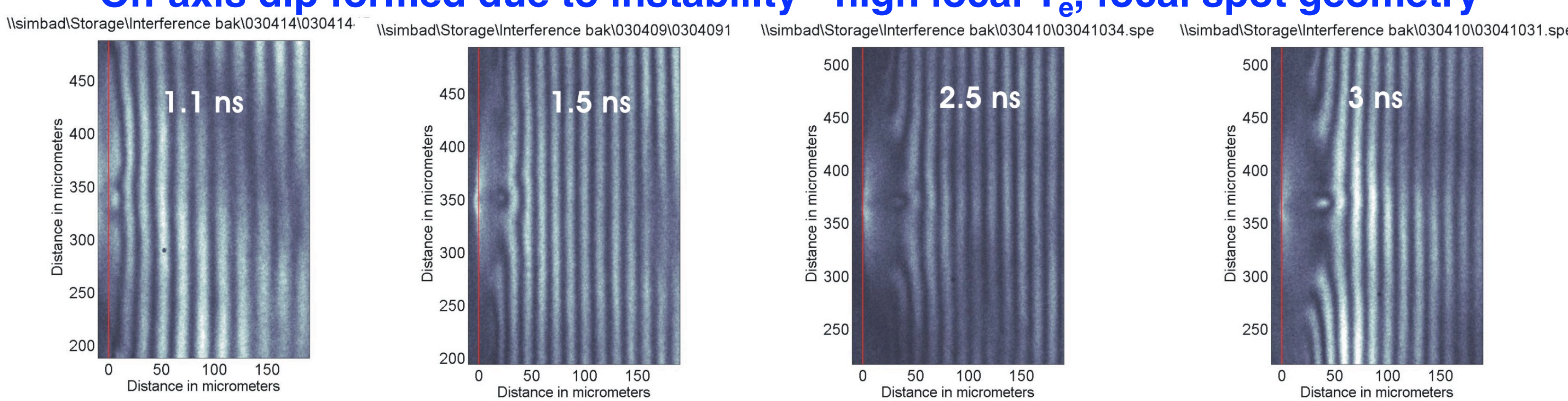
J. Filevich *et al*., Appl Opt. 43, 3938 (2004).

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}



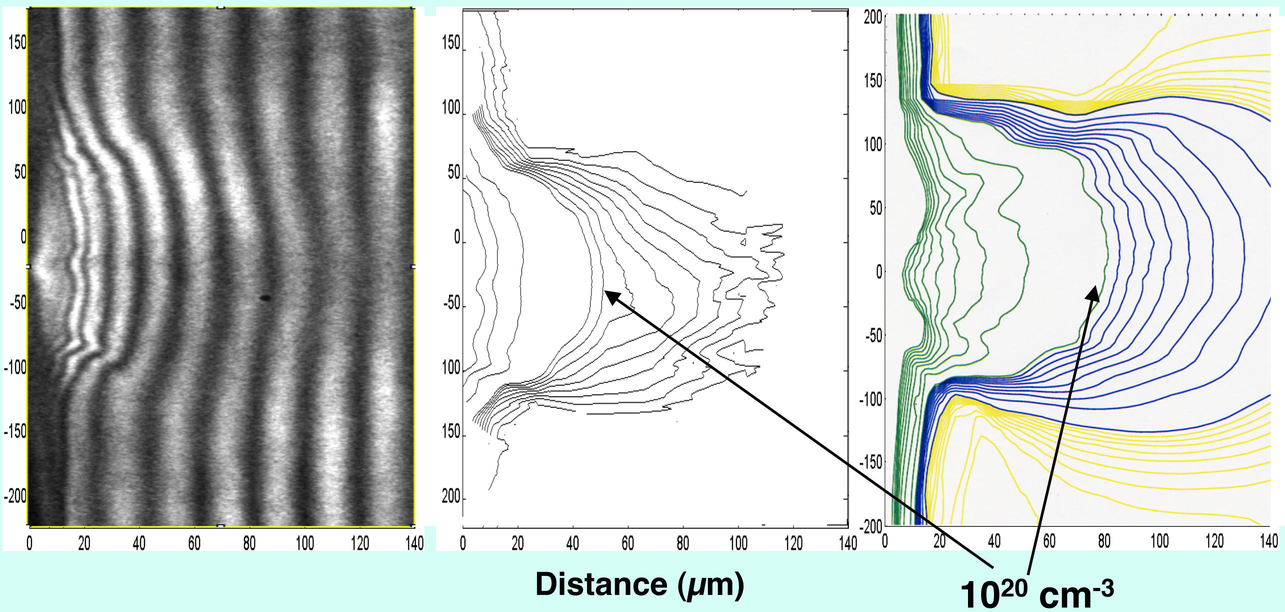
- 2-D lateral expansion observed early on - plasma pressure gradients
- On-axis dip formed due to instability - high local T_e, focal spot geometry



- 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}

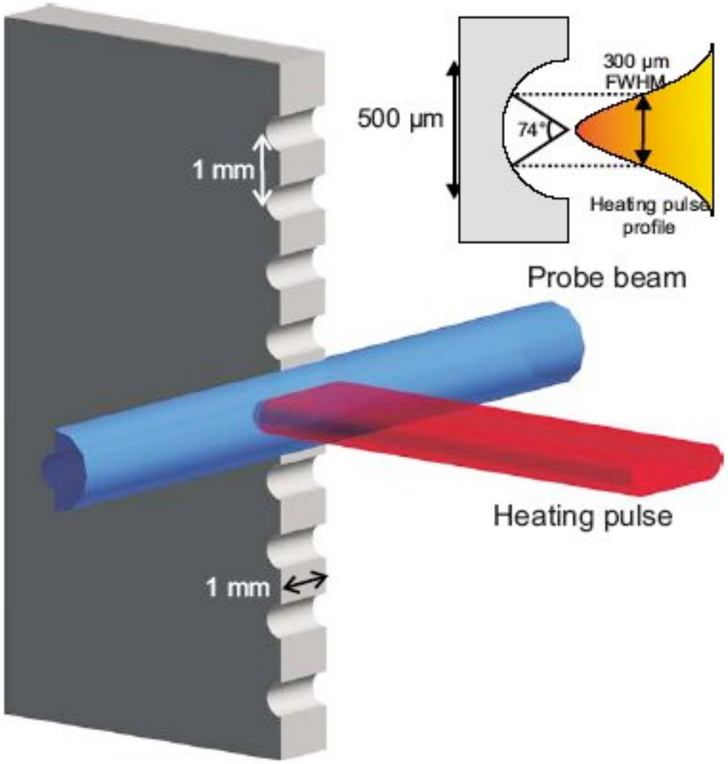
- **Small 12 μm width results in substantial 2D plasma expansion - reduced on-axis density**
- **1D and 1.5D LASNEX simulations do not accurately model plasma conditions**
- **2D simulations use experimental focal spot and temporal pulse shape**
- **Plasma pressure gradients, radiative heating and thermal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

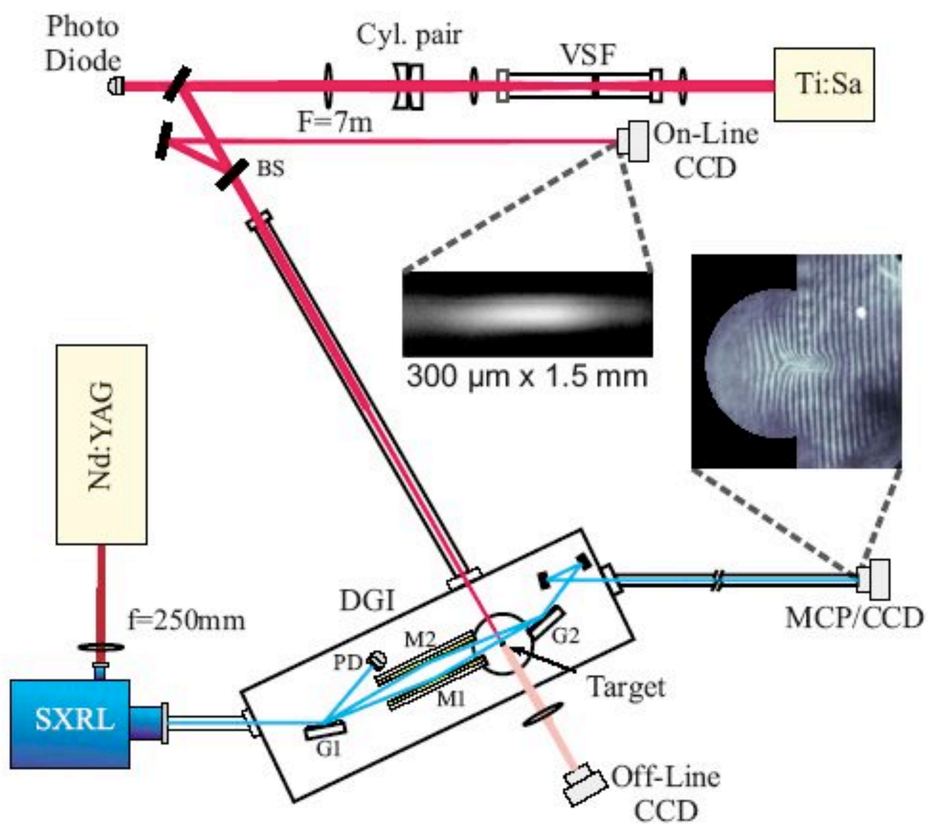
Short wavelength, ~ 1 μm spatial and ps time resolution essential

IV. Semi-cylindrical target: Experimental setup at CSU for probing laser-heated half-hohlraum type geometry

Laser Irradiation conditions:

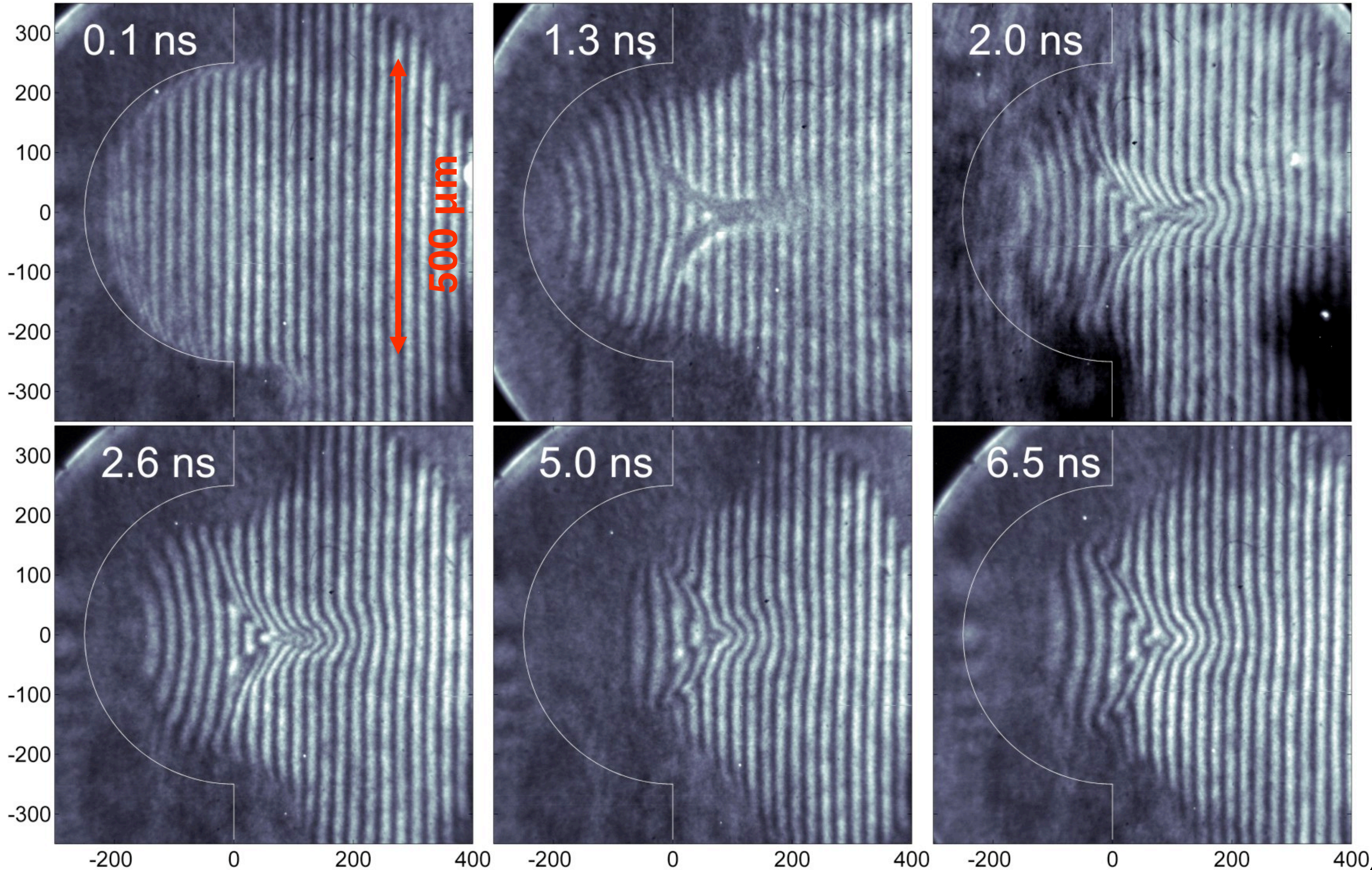
- 10^{12} Wcm^{-2} , 600 mJ at 800 nm wavelength, 120 ps (FWHM)
- Laser focus: 300μm × 1.5mm line





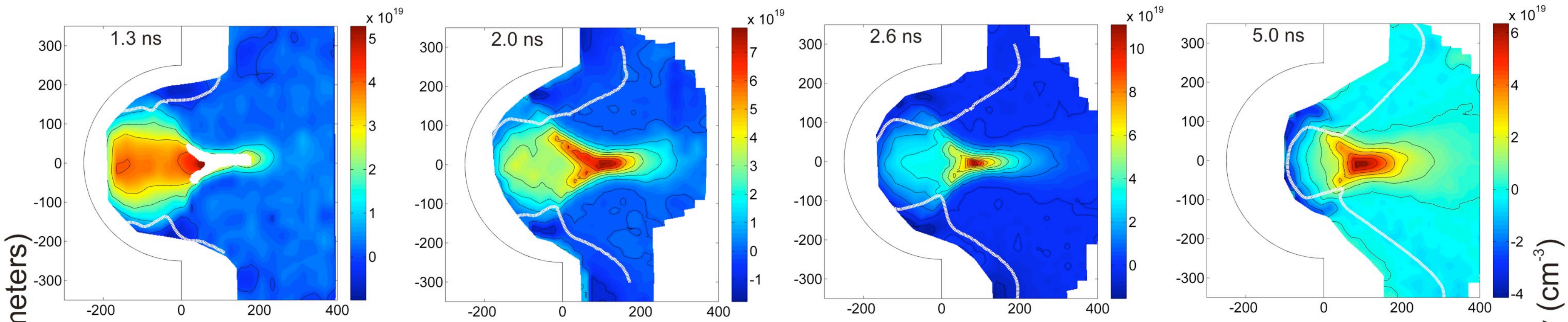
M. Purvis, J. Grava, J. Filevich, M. C. Marconi, J. J. Rocca, J. Dunn, S. J. Moon, V. N. Shyaptsev, E. Jankowska", Phys. Rev. E 76, 046402 (2007)

Carbon plasma converging plasma forms early ~1 ns and is still visible at late times ~17 ns

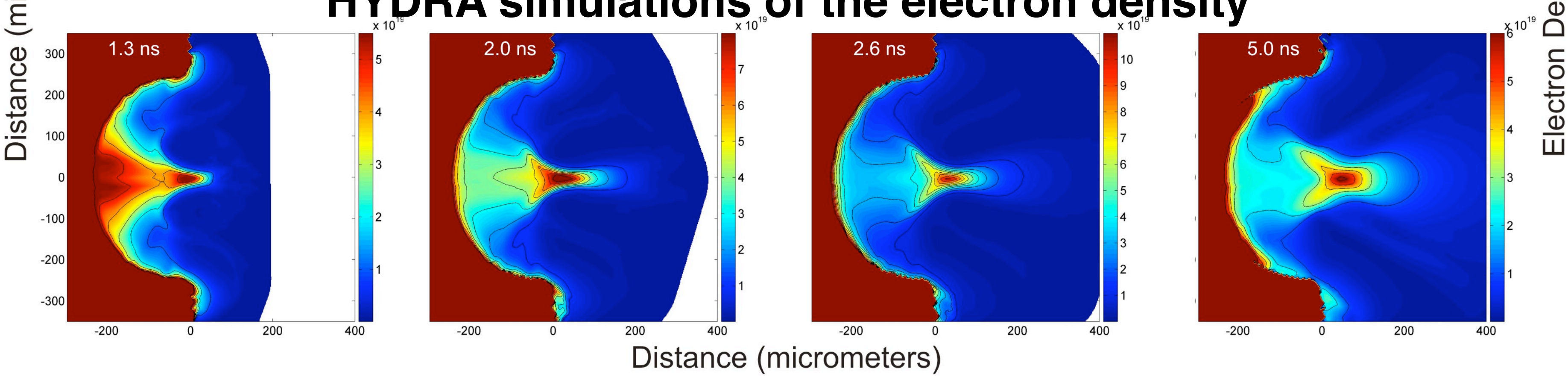


Comparison with HYDRA show excellent agreement in area where free electron contribution to fringes dominates

Electron density maps obtained with the SXR interferometry



HYDRA simulations of the electron density



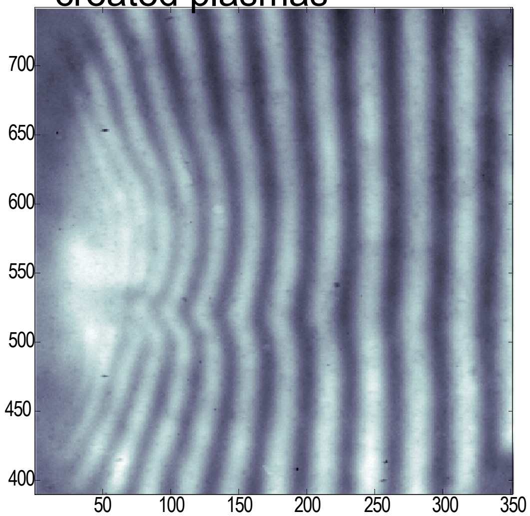
J. Filevich, J.J. Rocca, M.C. Marconi, S.J. Moon, J. Nilsen, J.H. Scofield, J. Dunn, R.F. Smith, R. Keenan, J.R. Hunter,V.N. Shlyaptsev, “Observation of a multiply ionized plasma with index of refraction greater than one”, Phys. Rev. Lett. 94, 035005, (2005).

X-ray Laser Applications

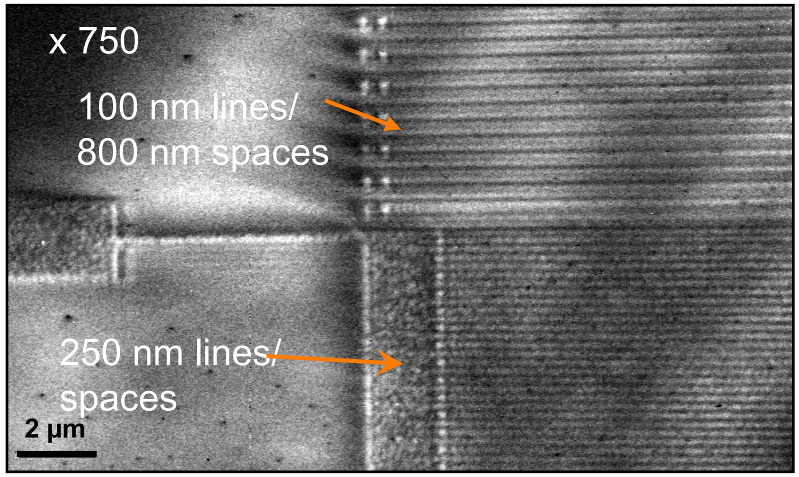
- X-ray imaging and microscopy
- Material studies, ablation, nano-patterning

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

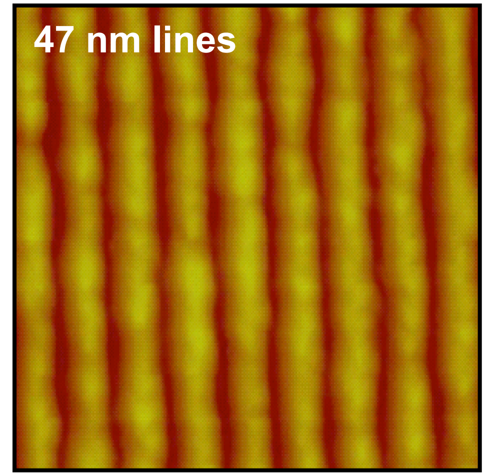
1. Interferometry of laser-created plasmas



2. EUV microscopy

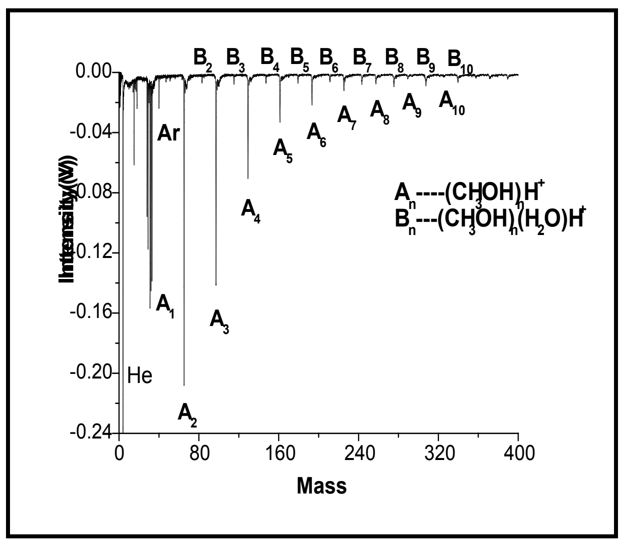


3. Nanopatterning



4. Laser Ablation

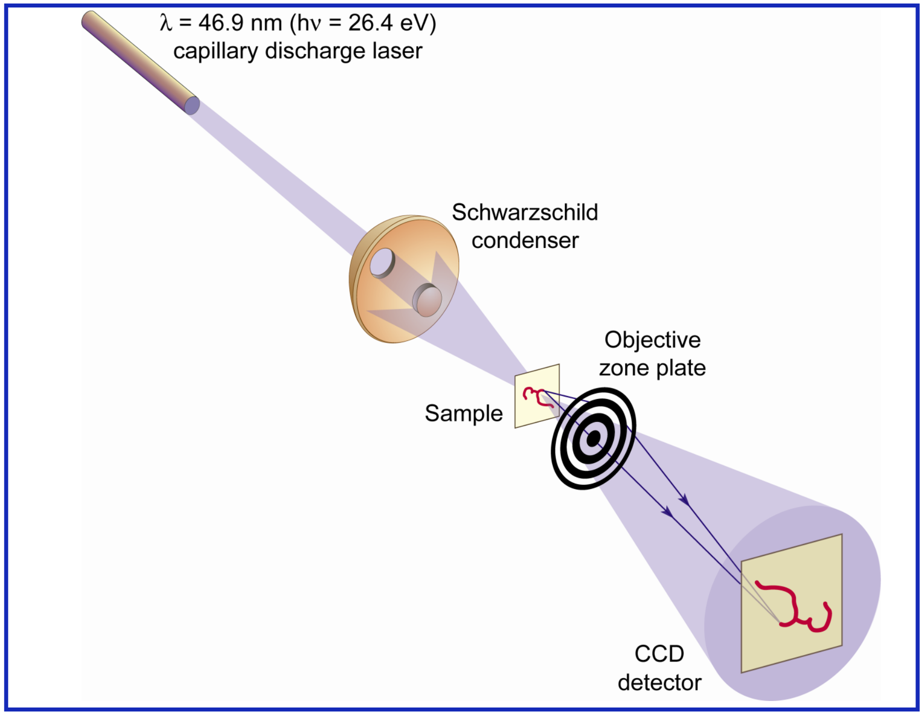
5. Nanocluster Spectroscopy

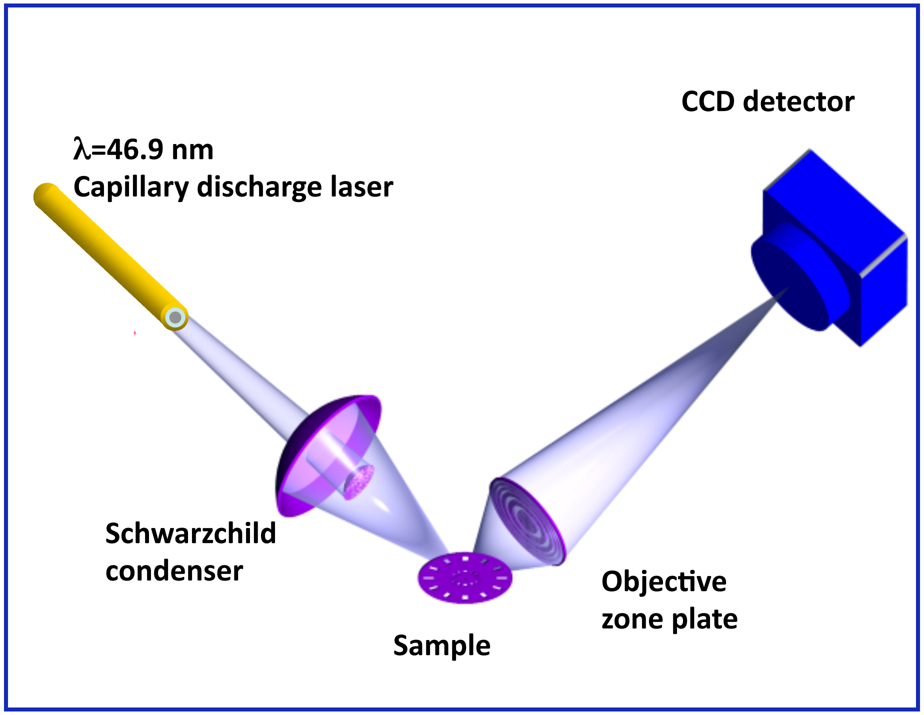


1. J.J. Rocca et al, Phys. Of Plasmas, 10, 2031 (2003).
2. F. Brizuela et al, Optics Express, 13, 3983, (2005)
3. M.G. Capeluto et al, IEEE Transactions on Nanotechnology, (in press),
4. J. Juha et al, Appl. Phys. Lett. 86, 034109 (2005).- M. Grisham et al, Optics Letters, 29, 620 (2004).

λ= 46.9 nm full field microscope operates in transmission and reflection configurations

TRANSMISSION CONFIGURATION	REFLECTION CONFIGURATION





Spatial resolution: 50 nm

Image capture time: single laser shot

Spatial resolution: 80 nm

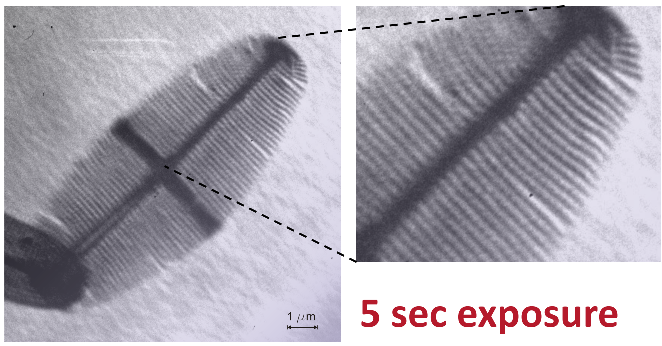
Image capture time: 5-20 sec

C. Menoni, J. Rocca (CSU), D. Attwood (LBL)

46.9 nm microscope captures images of nanostructures with near-wavelength resolution

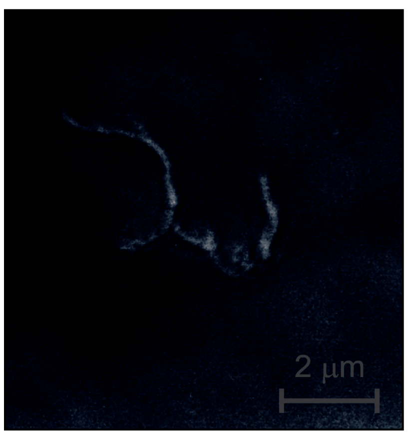
TRANSMISSION
NA=0.32 (M~1000)

200 nm half period diatom



5 sec exposure

50 nm carbon nanotube



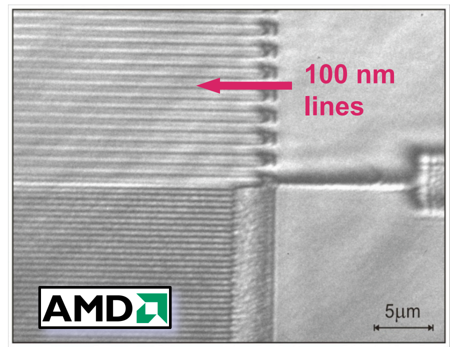
Single shot, exposure

54 nm resolution

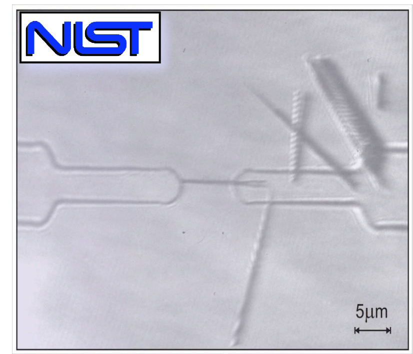
C. Brewer, et al, Opt. Lett. 33, 518 (2008)

REFLECTION
NA=0.12 and 0.19 (M~250)
5-20 sec exposures

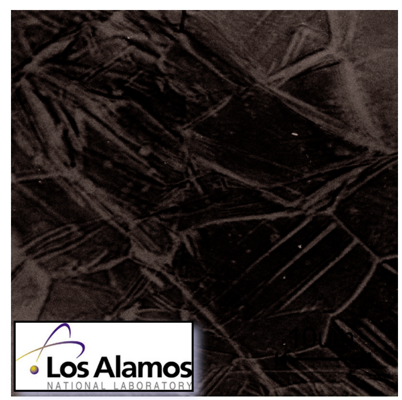
Partially Processed semiconductor chip



100nm thick GaN nanowire between Al contacts

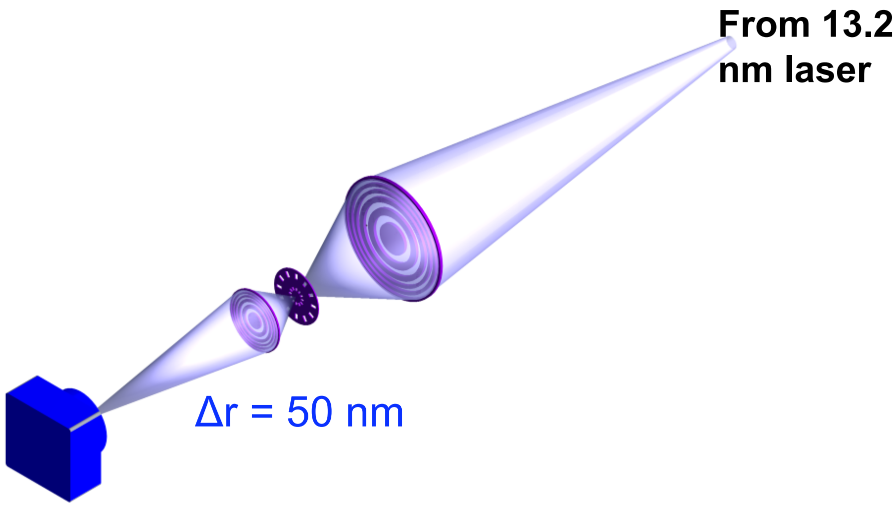


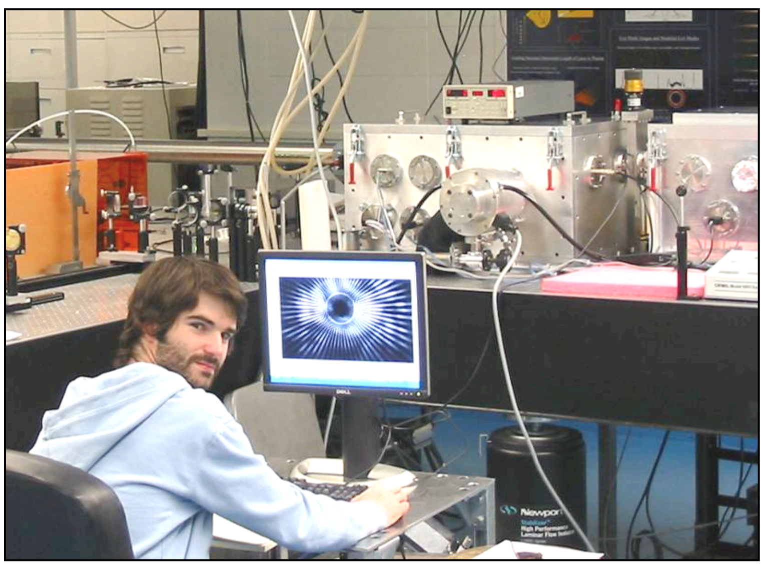
Zirconium surface

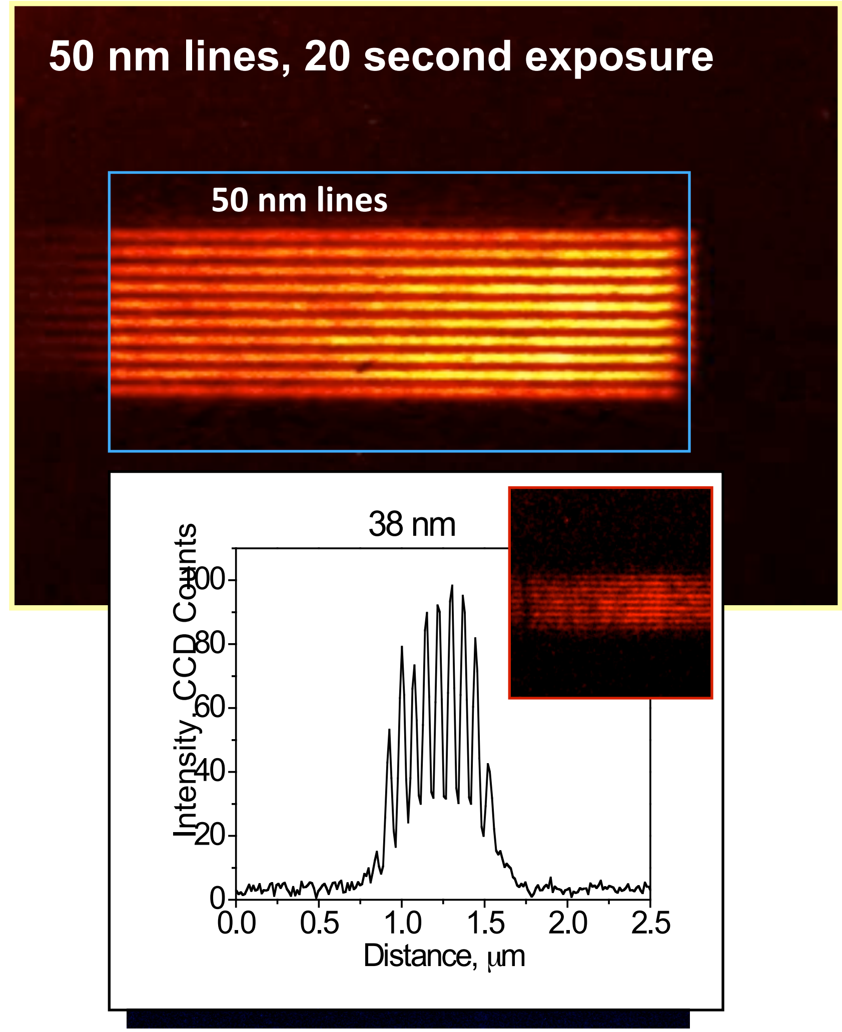


C. Menoni, J. Rocca (CSU), D. Attwood (LBL)

Table-top microscopy with resolution better than 38nm







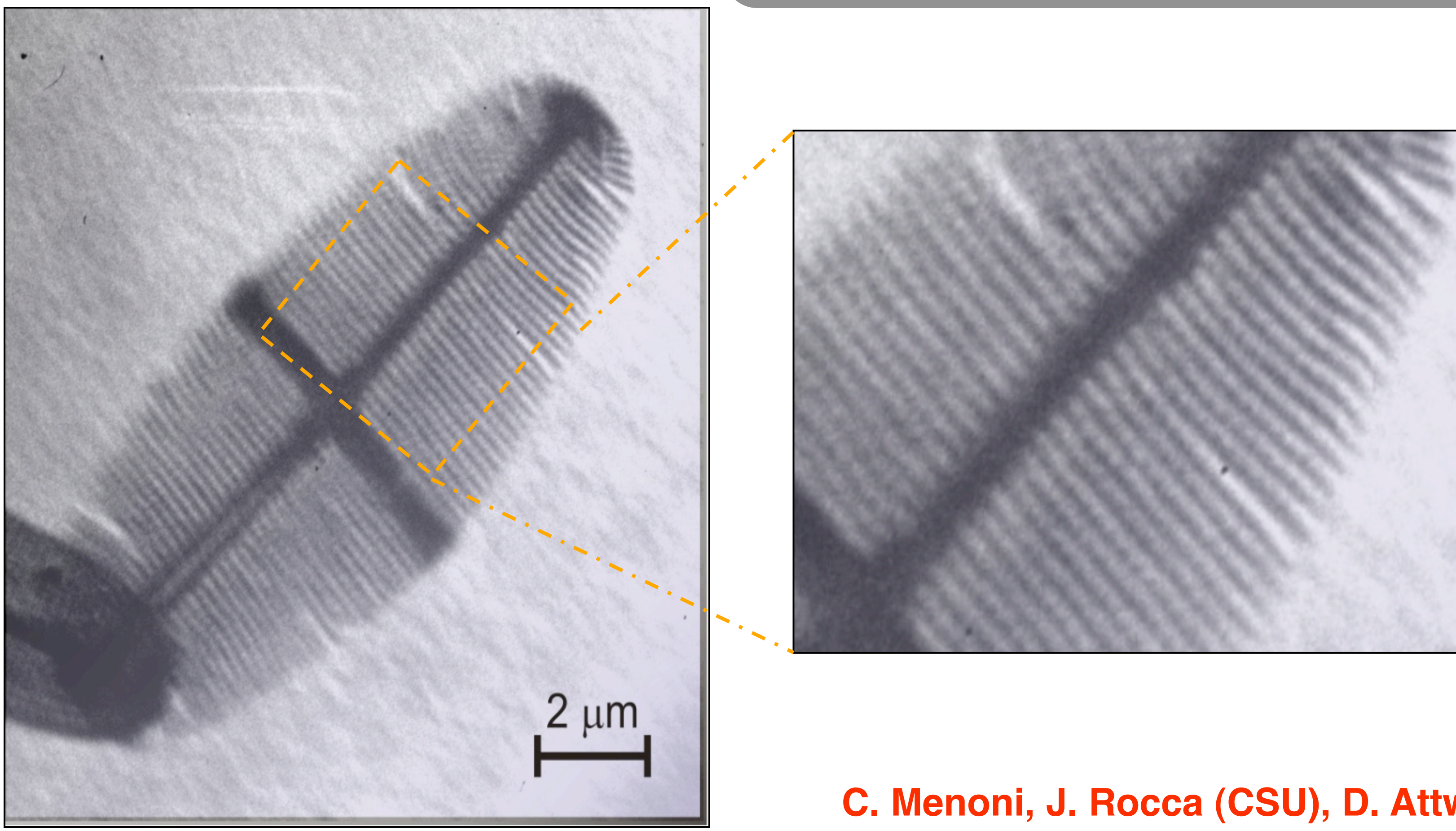
G. Vaschenko et al. Optics Lett, **32**, 1214, (2006), F. Brizuela et al, Optics Lett,**34**,271 (2009)

C. Menoni, J. Rocca (CSU), D. Attwood (LBL)

Images of nanostructures with very high resolution

200 nm half period diatom

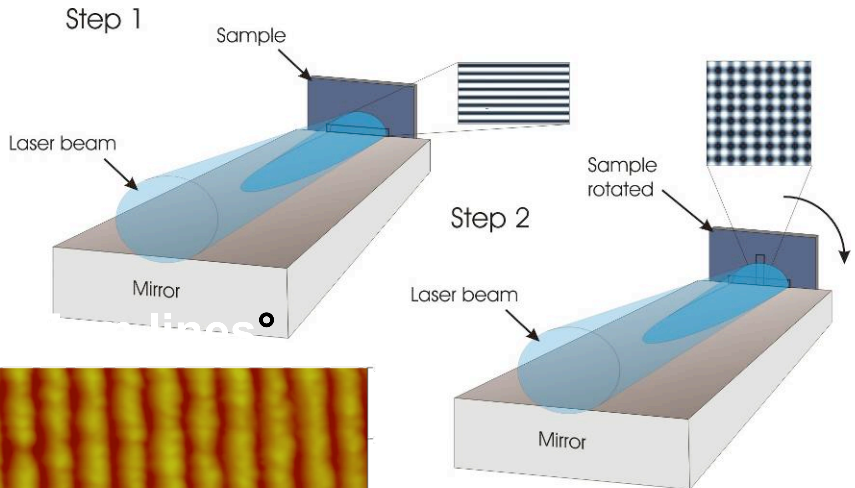
- NA = 0.32
- 20 second exposure
- M ~1080 x (image element pixel size = 12.5 nm)

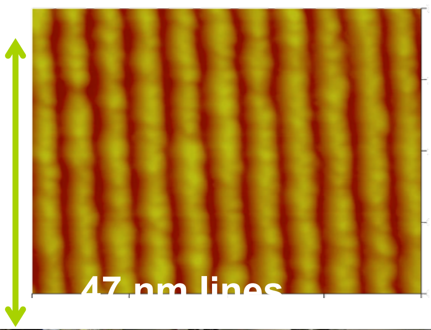


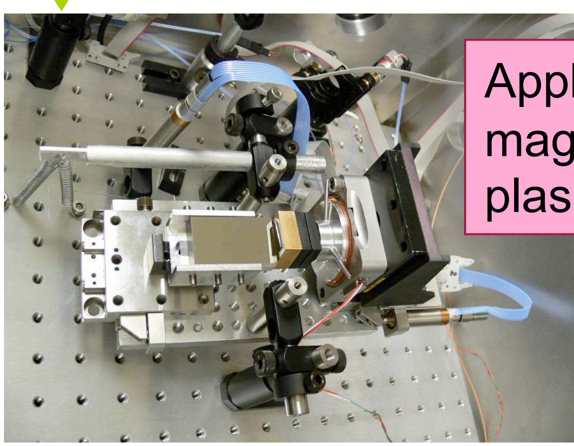
C. Menoni, J. Rocca (CSU), D. Attwood (LBL)

Nanopatterning by interferometric lithography

Lloyd's mirror interferometer





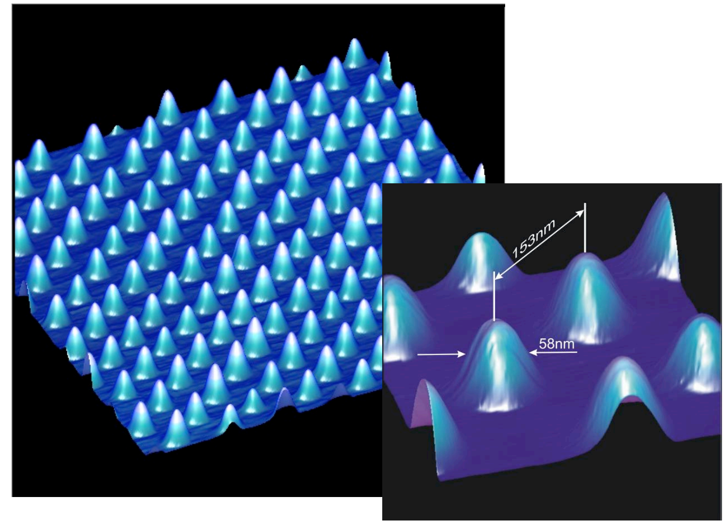


Applications: nanoscale magnetic structures, plasmonics,…....

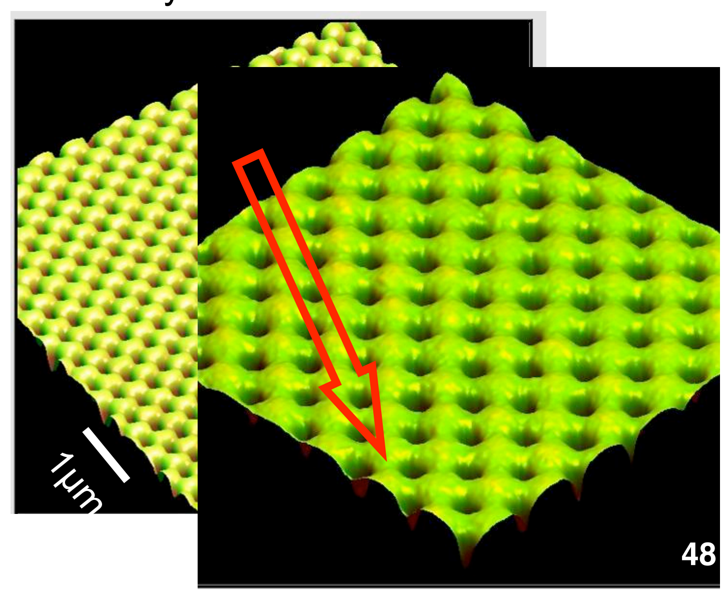
M. Marconi (CSU),

P. Wachulak et al, Optics Express 15, 3465, (2007)

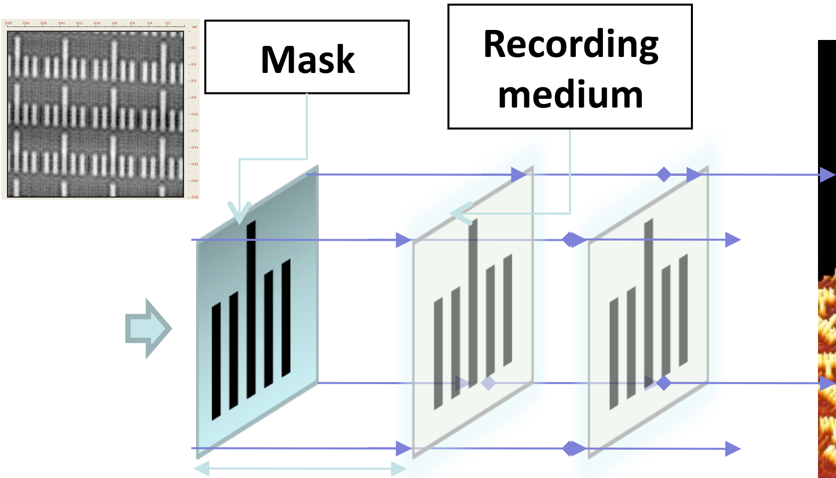
Array of 58 nm cones



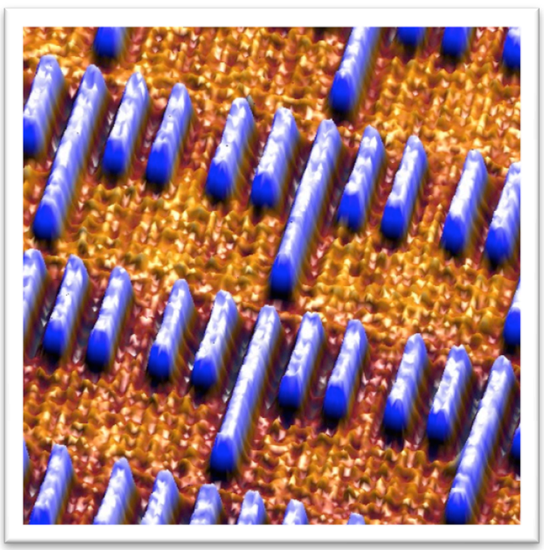
Array of 130 nm holes



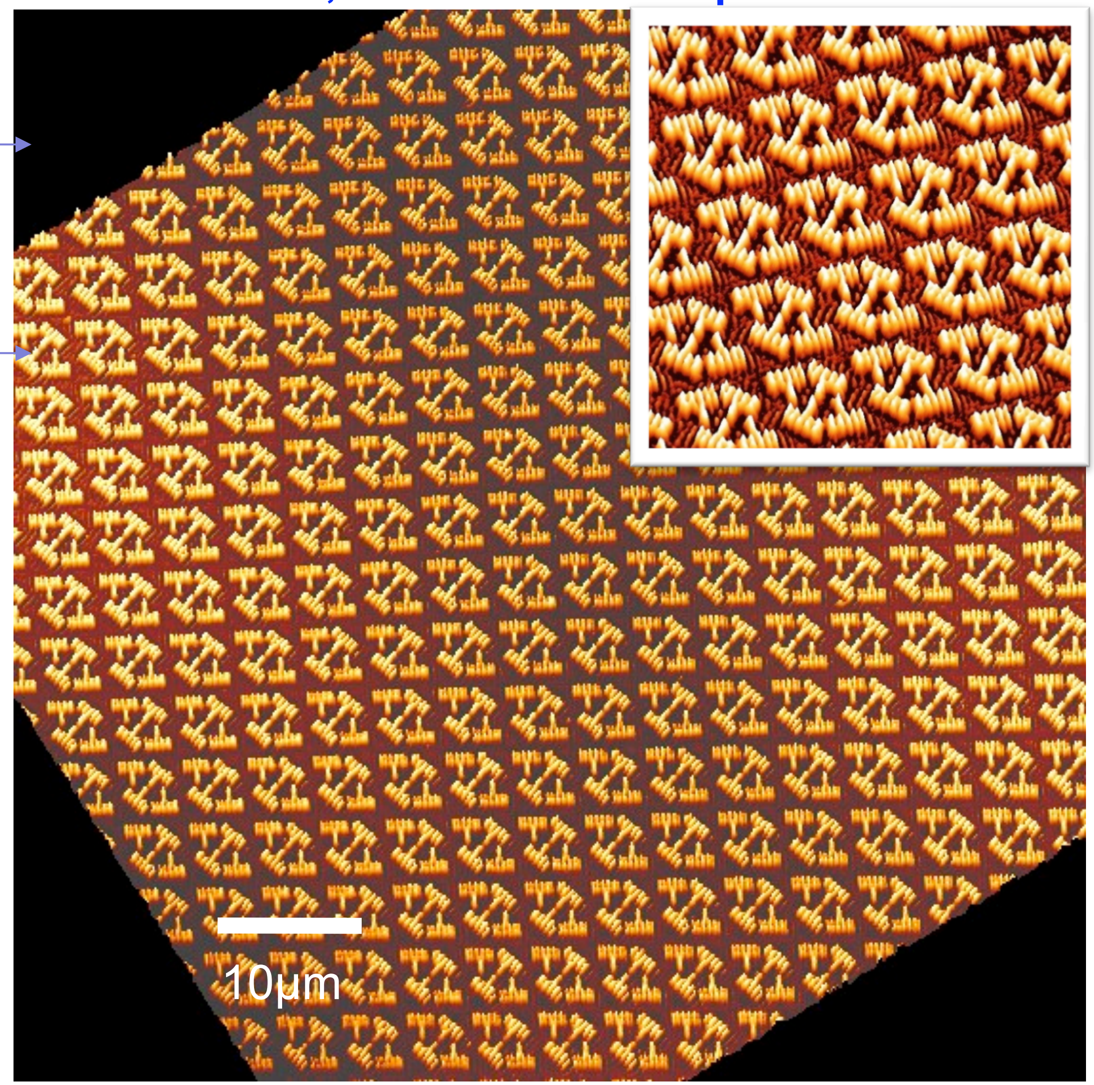
Talbot lithography: proof-of–principle experiment achieved 120 nm resolution using 650x 650 μm ^{2} mask.



Talbot distance $D = \dfrac{2 \cdot (Period)^2}{\lambda}$



M. Marconi, F. Cerrina et al. in press JVST B



M. Marconi (CSU),

Summary of Present Soft X-ray (EUV) Laser Characteristics:

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

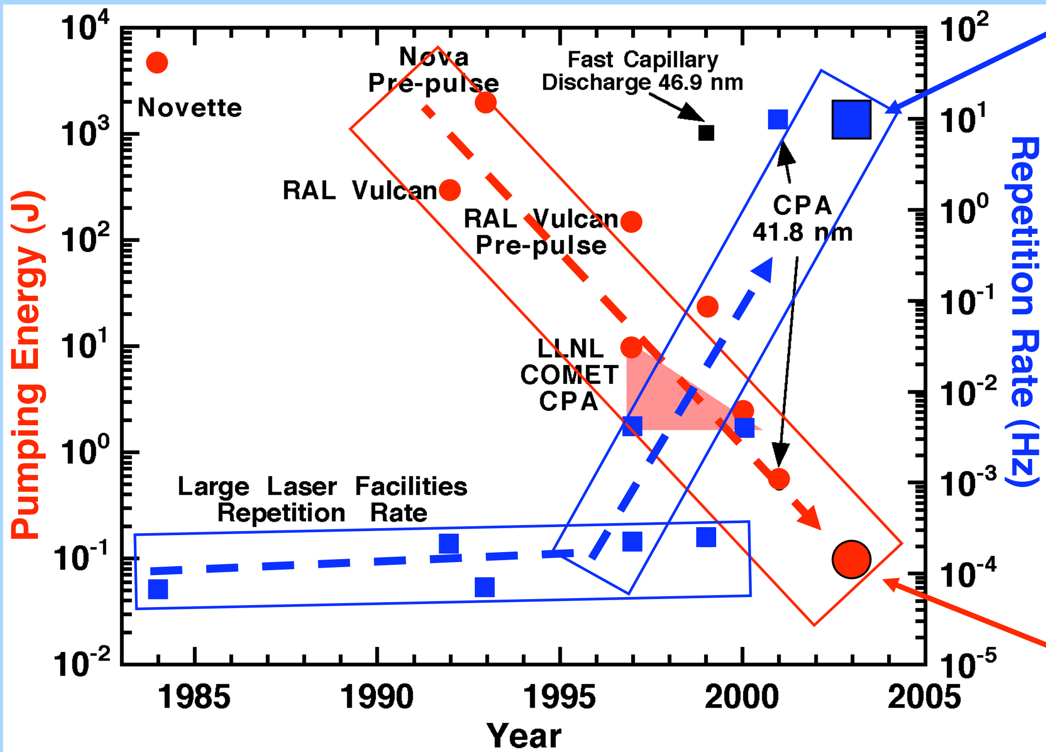
- **Characteristics:**

	Fs- Ps-Driven X-ray Lasers	PALS
- Gain saturation	10 μJ output, 10^{12} photons/pulse	10^{15} ph.
- High gain	30 - 80 cm^{-1} (small signal gain)	
- Repetition rate	1 - 10 Hz (100 Hz DPSSL proposed by MBI, Berlin, CSU)	
- Average Power	~20μW @ 13.9, 13.2 nm @ 10 Hz, 1mW @46.9 nm	
- Peak Power	1 - 10 MW	50 - 100 MW
- Beam divergence	~0.5 - 2 mrad (FWHM)	
- X-ray laser duration	1 - 8 ps (FWHM)	100ps
- Longitudinal coherence	~400 μm (1/e width)	
- Spatial coherence	~3% for ASE amp. - full coherence for seeded	
- Wave front	λ/17 @ 32.5 nm	
- Line width	$\lambda/\Delta\lambda$ = 50,000	
- Brightness	10^{25} - 10^{26} ph. mm^{-2} $mrad^{-2}$ s^{-1} [0.1% BW]$^{-1}$	10^{27}

- **Close to transform limited $\Delta E.\Delta t$ operation demonstrated**

Goal has been more efficient XRLs with lower drive energy and higher repetition rate: sub-20 nm required

Timeline for X-ray Laser Pump Energy and Repetition Rate



Matthews	5 kJ	1984
Nilsen	1 kJ	1993
Zhang (RAL)	150 J	1997
Nickles	10 J	1997
Dunn (LLNL)	5 - 10 J	1998
Tommassini	30 J	1999
Li	0.15 J	2000
Sebban	0.5 J	2001
Ozaki	0.15 J	2002
Keenan (LLNL)	0.15 J	2003

Keenan et al SPIE Vol 5197, 213 (2003)

Achieved lasing with ~10^5 less energy compared to Nova

Many scientific applications require high repetition x-ray sources

Conclusions and Future Outlook

- Description and summary of plasma-based soft x-ray lasers (laser pumped)
- Recent developments in source generation: Smaller pump energy, higher repetition rate, improved beam qualities
- Examples of applications: Interferometry, ablation studies, probing matter
- Seeded Tabletop soft x-ray Lasers are direction of future
- Soft x-ray lasers are ultra-bright 10^{24} - 10^{27} ph. mm^{-2} mrad^{-2} s^{-1} [0.1% BW]$^{-1}$
- Latest generation are very compact (table top), inexpensive compared to synchrotrons, and are compatible with small research groups and universities
- Complement 3rd and 4th generation synchrotron sources for wavelength range, applications and regimes of interest:
  - 100x narrower bandwidth than FELs coming online
  - Full wavefront (spatial) coherence
  - Potential for significantly higher output and brightness (stages)