Table-Top EUV Lasers for Metrology

J.J. Rocca*, Y. Wang, M. A. Larotonda, B. M. Luther , D. Alessi, M. Berrill, S. Heinbuch, M.C. Marconi, G. Vaschenko, V.N Shlyaptsev[1], C.S. Menoni, Y. Liu[2], W. Chao[2], E. Andersen[2] and D. Attwood[2]

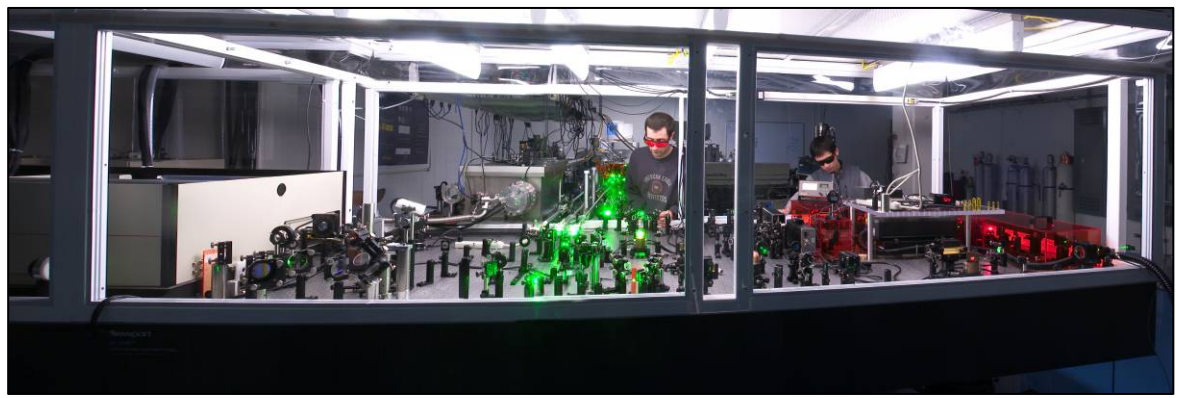
NSF ERC for Extreme Ultraviolet Science and Technology

Colorado State University

1 U. Cal. Davis

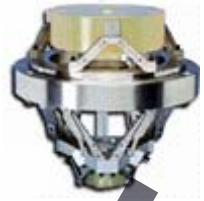
2. Lawrence Berkeley National Laboratory

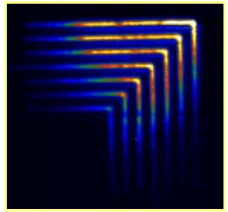
** rocca@engr.colostate.edu*

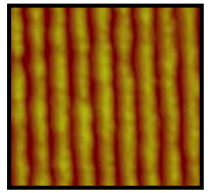


Work supported by the NSF Engineering Research Center Program under NSF award Number EEC-0310717

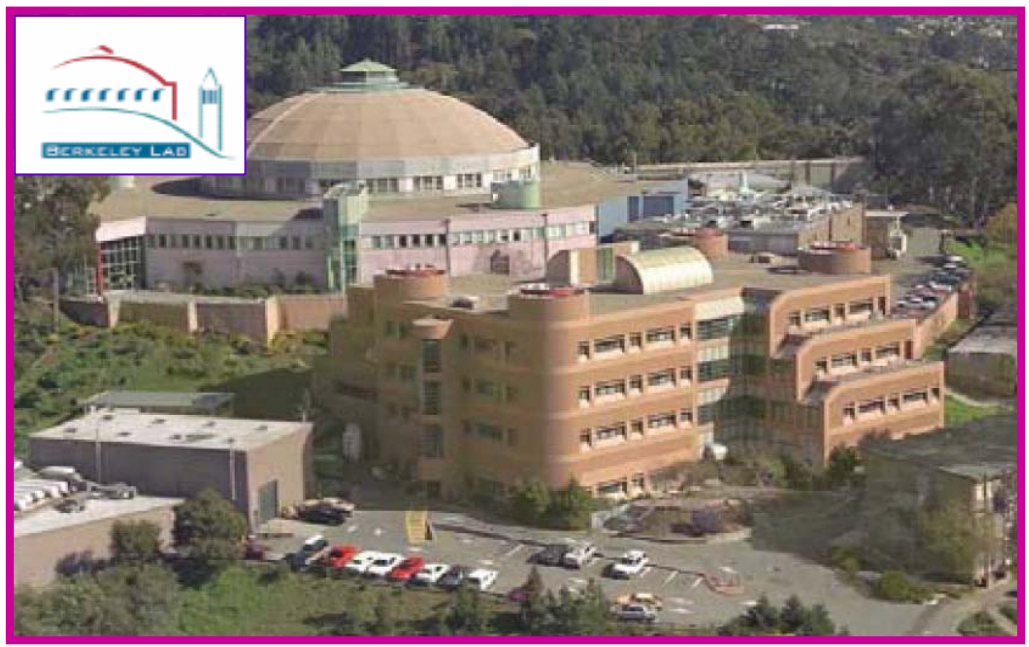
Synchrotron "light factories" allow for at-wavelength EUV metrology



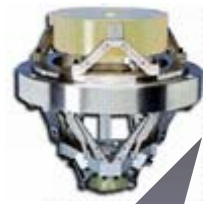


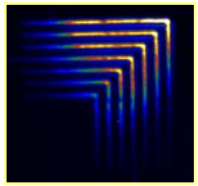


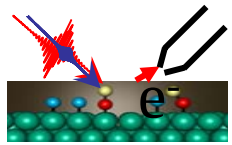
Synchrotron Light Source



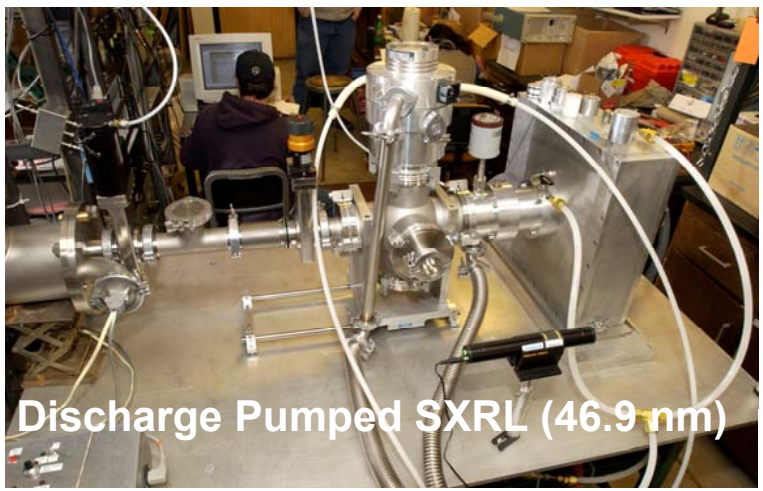
Progress in compact EUV lasers will allow EUV metrology on a table-top

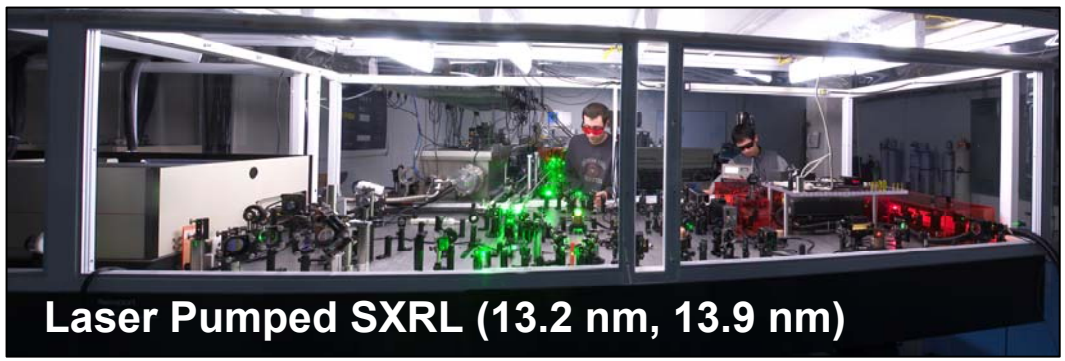






- Very high monochromaticity ($\Delta/\Delta\lambda < 10^{-4}$)
- High peak spectral brightness

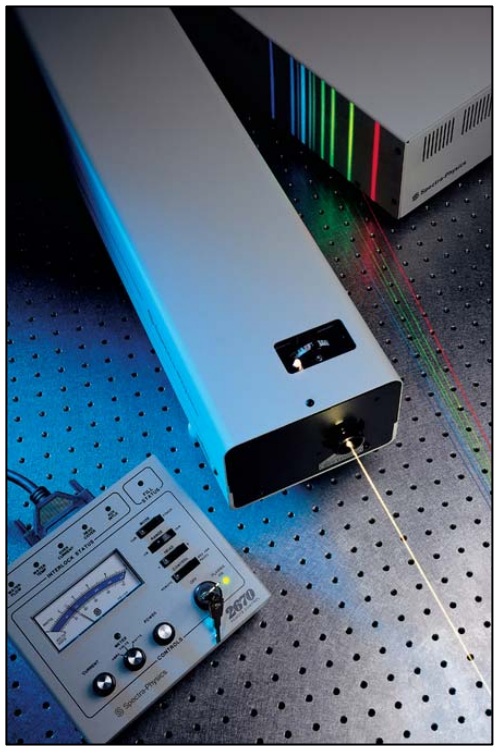


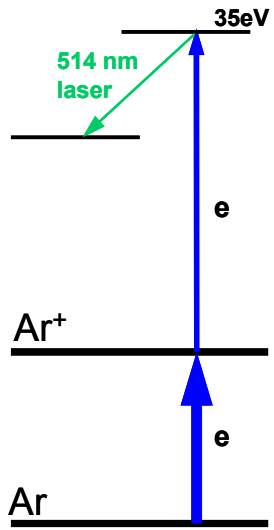


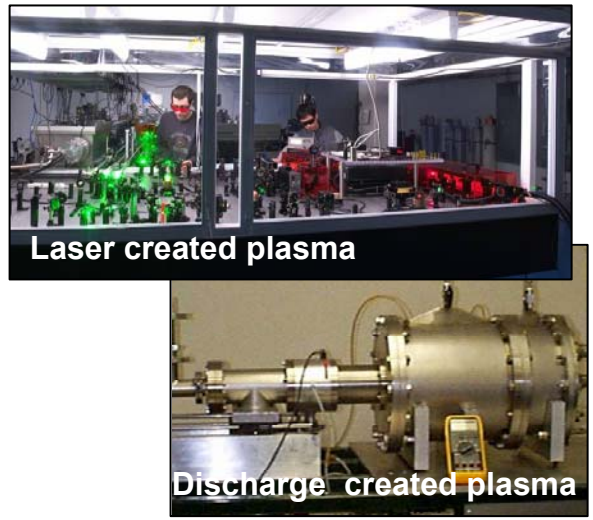
EUV lasers beams can be created by electron impact excitation of highly ionized atoms in dense plasmas

Singly ionized Ar ion, Kr ions for visible light

Highly ionized (20 times) for generation of 13 nm light



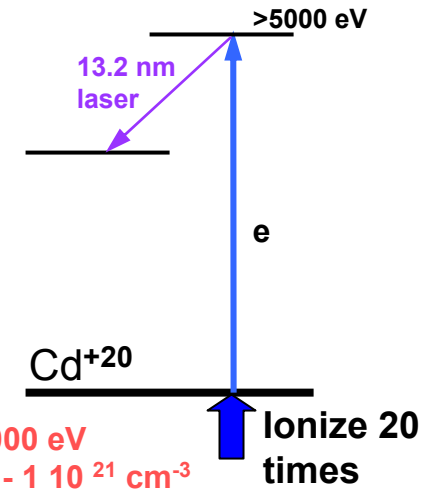




$$h\nu = \Delta E \propto Z^2$$

Plasma requirements:
Te ~ 5 eV
Ne ~ 1 10 ^{14} cm^{-3}

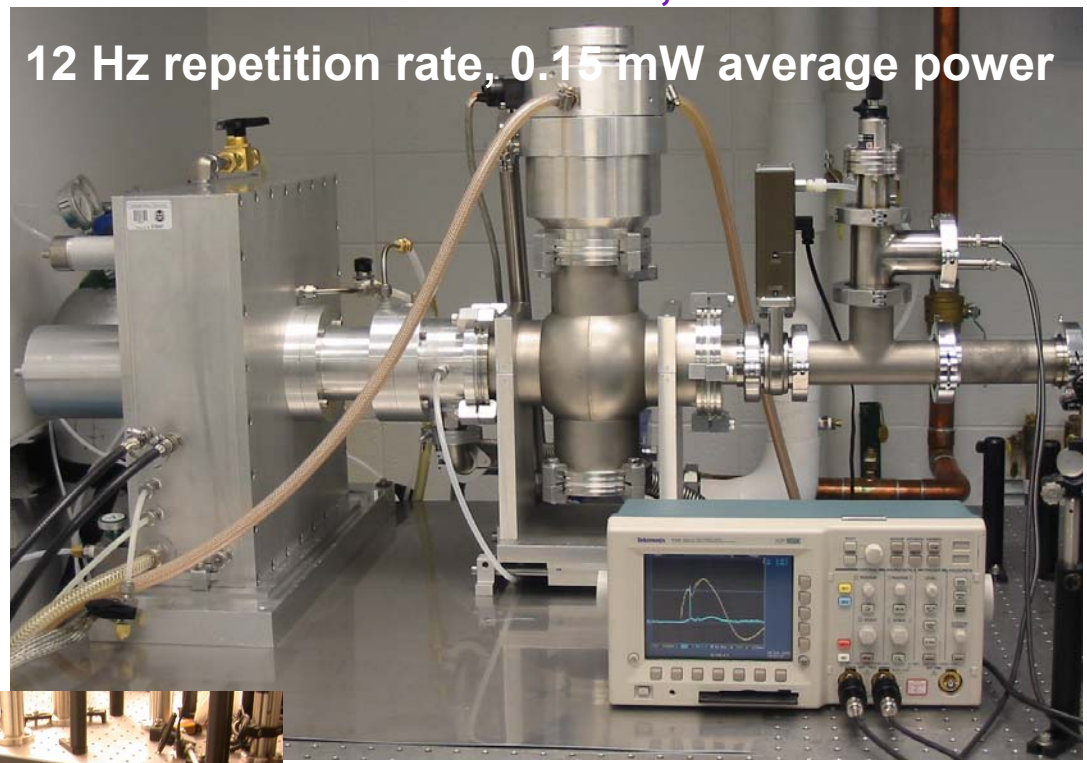
NexTe increases by 10^7-10^{10}



Te ~ 100- 1000 eV
Ne ~ 1 10 ^{19} - 1 10 ^{21} cm^{-3}

I. Recent research has shrunk capillary discharge EUV lasers (λ = 46.9 nm) to desk-top size

Smallest SXRL laser , λ=46.9 nm



- 10 microjoule /pulse
- 0.15 mW average power
- 1-12 Hz repetition rate
- Pulse duration ~1.5 ns
- $\Delta\lambda/\lambda < 1 \times 10^{-4}$

S. Heinbuch, M. Grisham, D. Martz, J.J. Rocca
Optics Express, **30**,2095, (2005)

Development of very compact reflection mode microscope with 50 nm resolution using 46.9 nm light

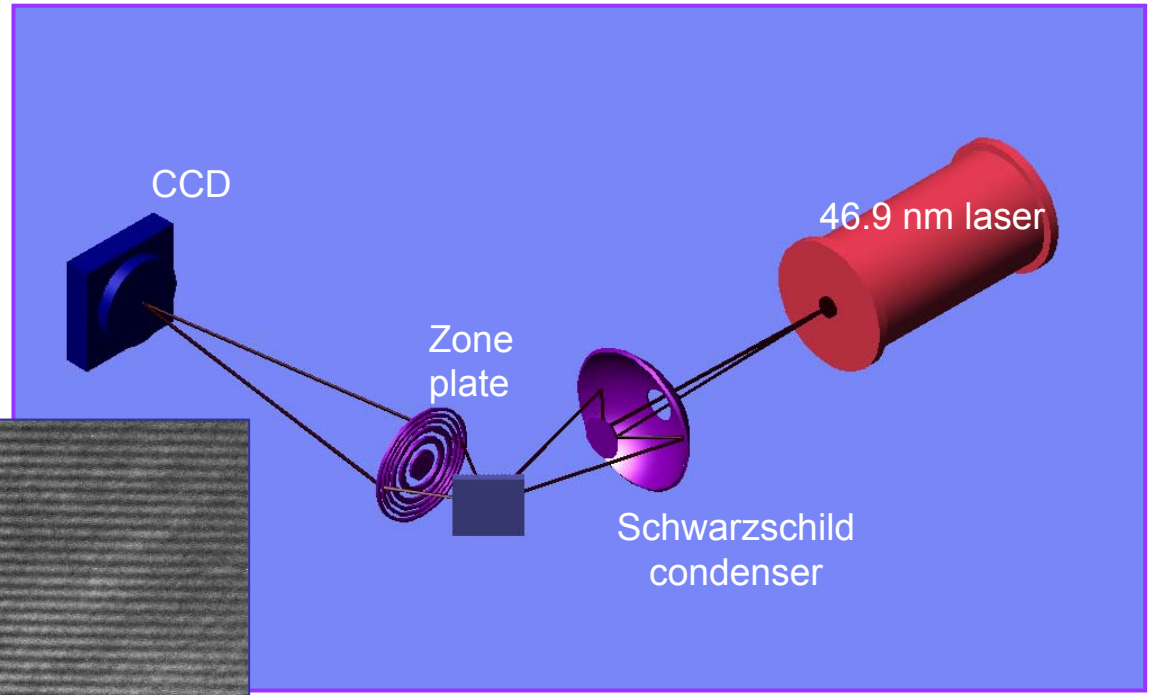
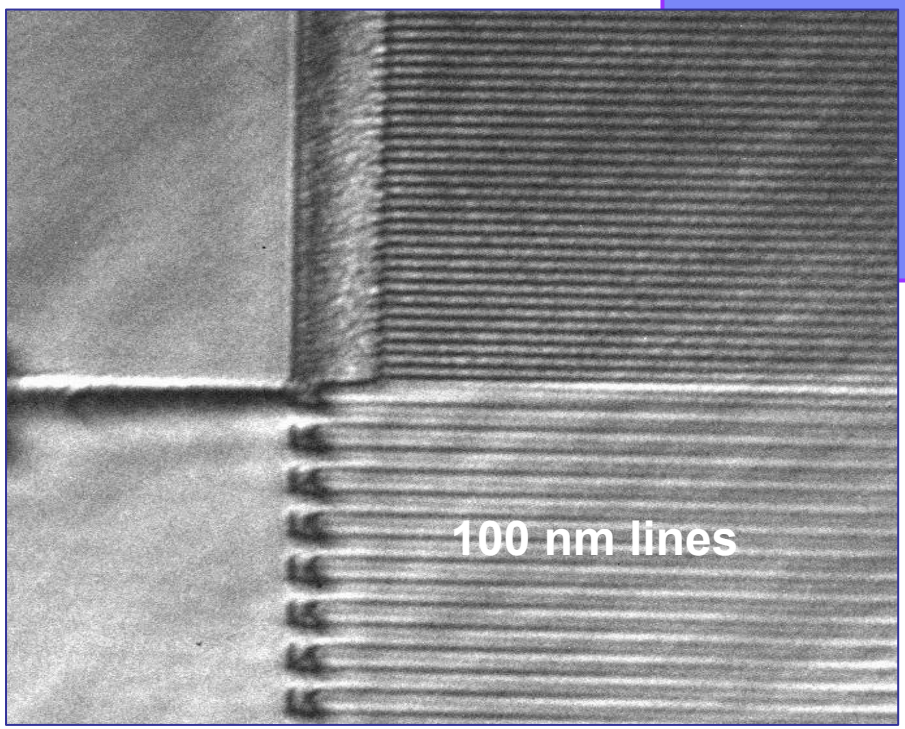


Image of wafer with: polysilicon lines on silicon



- **120 nm resolution demonstrated with Δr= 200 nm zone plate***
- **50-70 nm resolution expected with Δr= 70 nm zone plate**

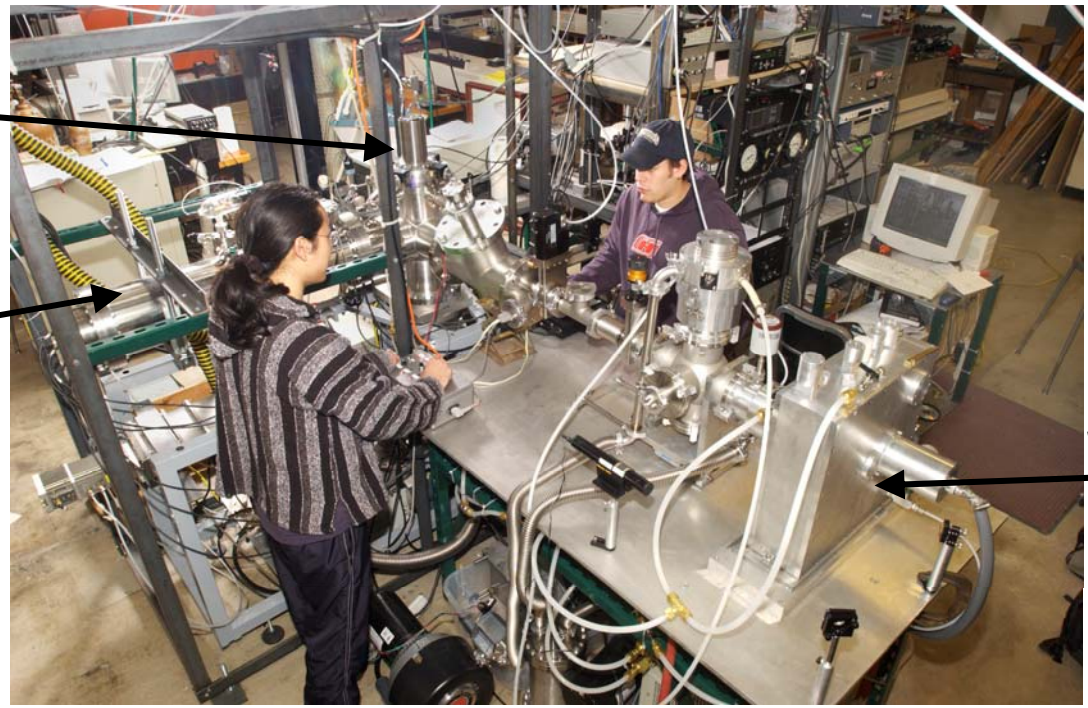
*F. Brizuela et al., Opt. Express 13, 3983 (2005)

Sample courtesy of AMD

Single photon ionization mass spectrometry study of metal-oxide nanoclusters

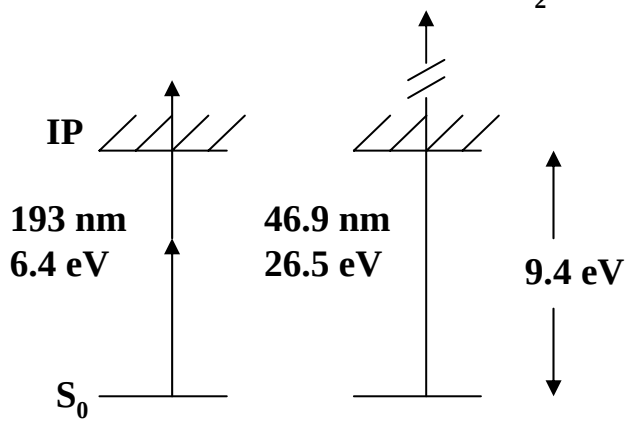
Gas Nozzle

Mass Spectrometer



Desk-top Soft x-ray Laser

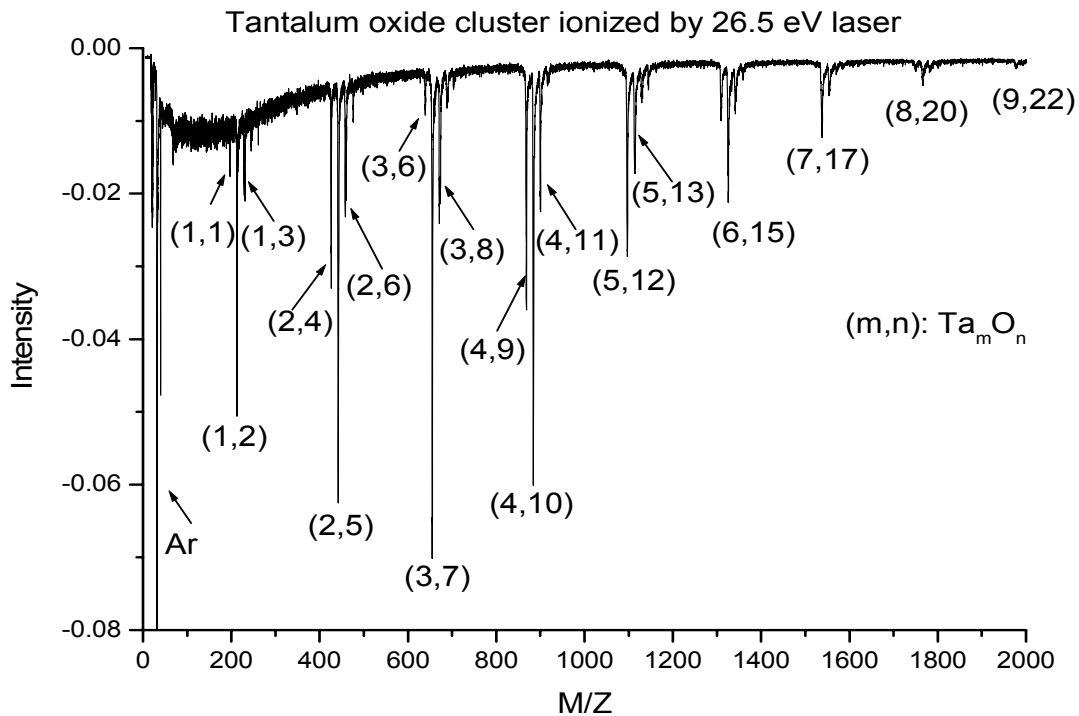
Ionization Potential of ZrO_2

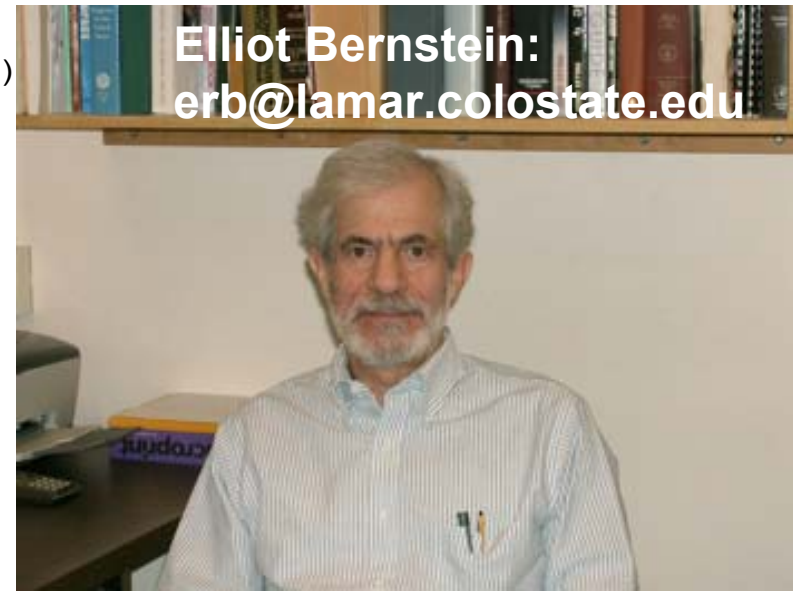


F. Dong et al. Journal of Chemical Physics, in press, (2006).

Study of the catalytic properties of titanium oxide can provide key to the design of carbophobic coatings

Tantalum Oxide spectra obtained with EUV laser ionization shows: <u>all Clusters Detected</u> , no Fragmentation

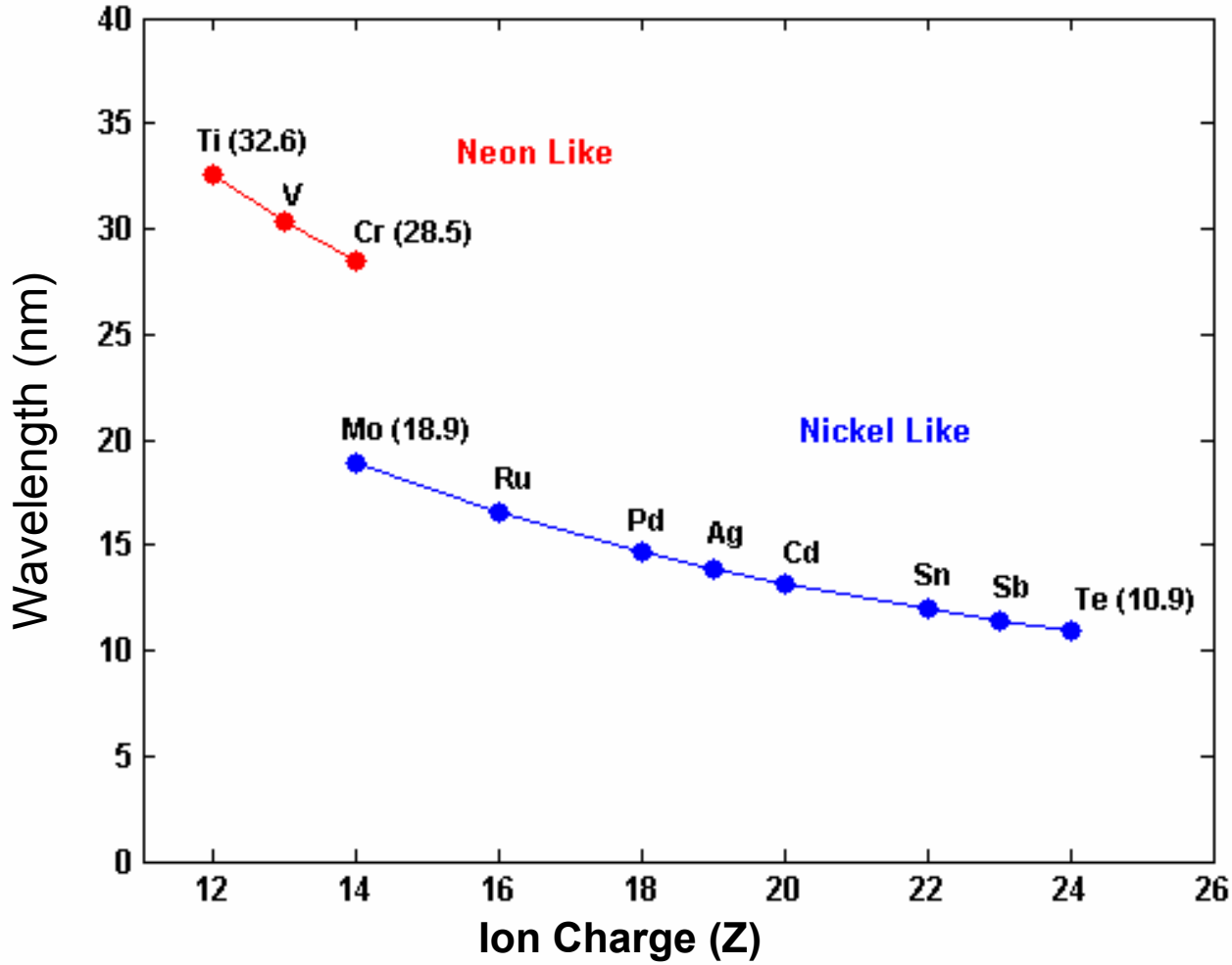




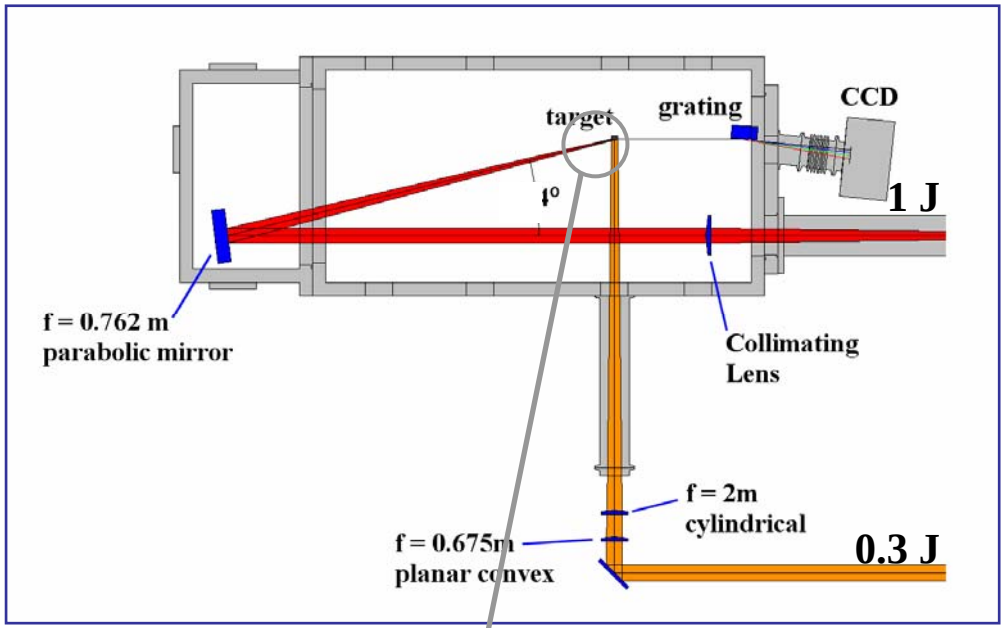
- **Tantalum oxide cluster distribution has been determined**
- **Study of reactivity of each individual cluster is now possible**

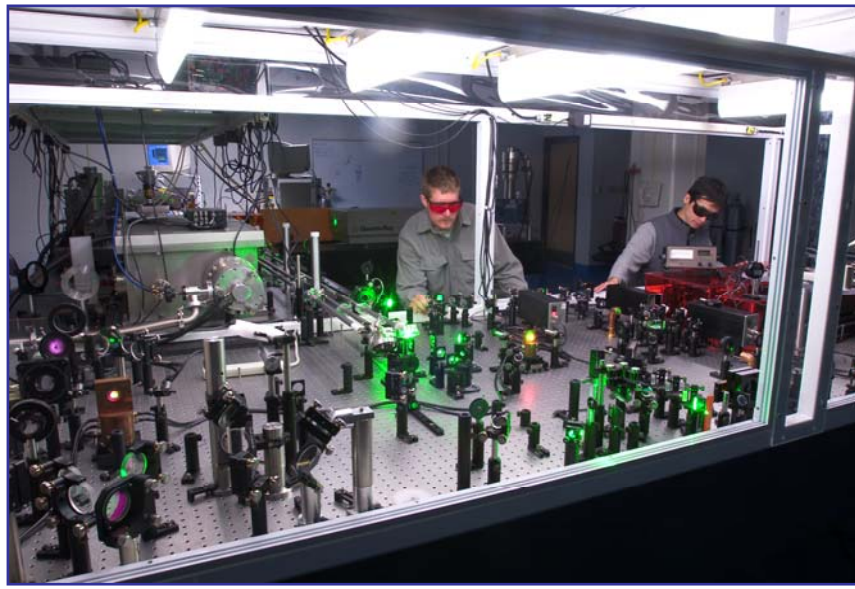
Lasers with λ~13.5 nm requires the use of very highly Ionized atoms

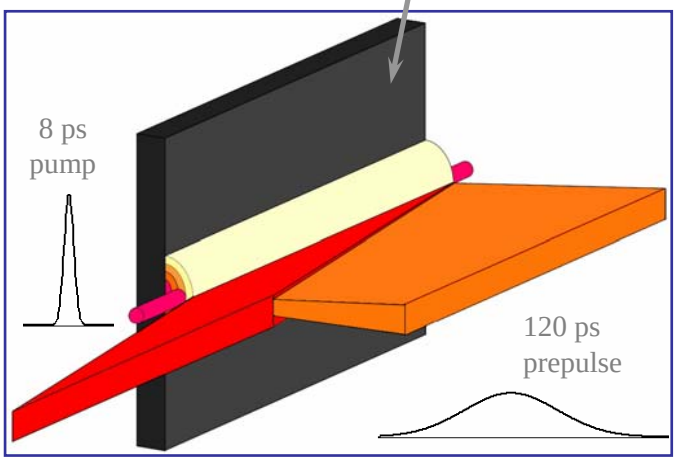
Pump power required scales as λ^{-4}- λ^{-5}



Pump laser: 5-10 Hz, 1 J Short Pulse Table-top Ti:Sa Laser System with Three Stages of Amplification



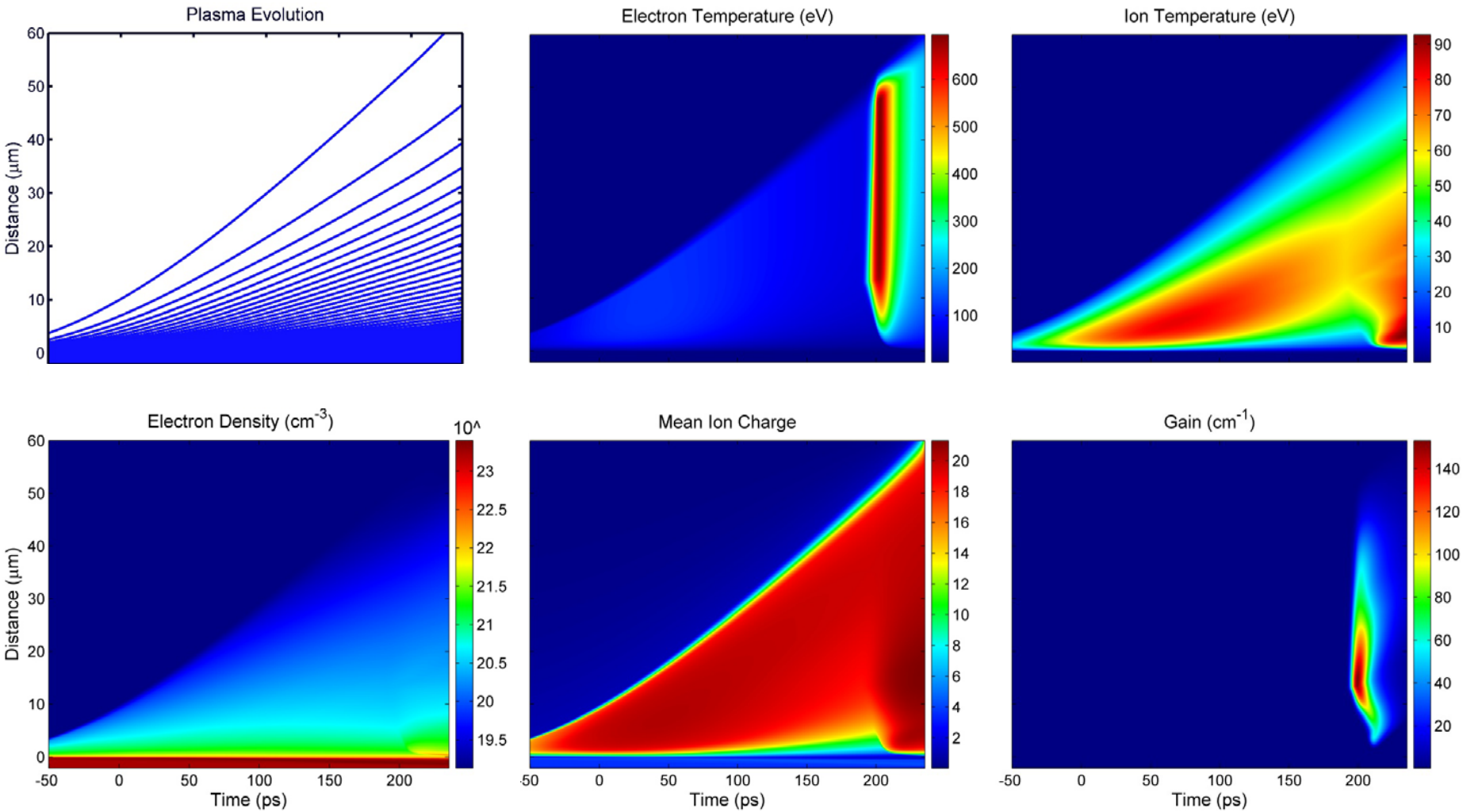




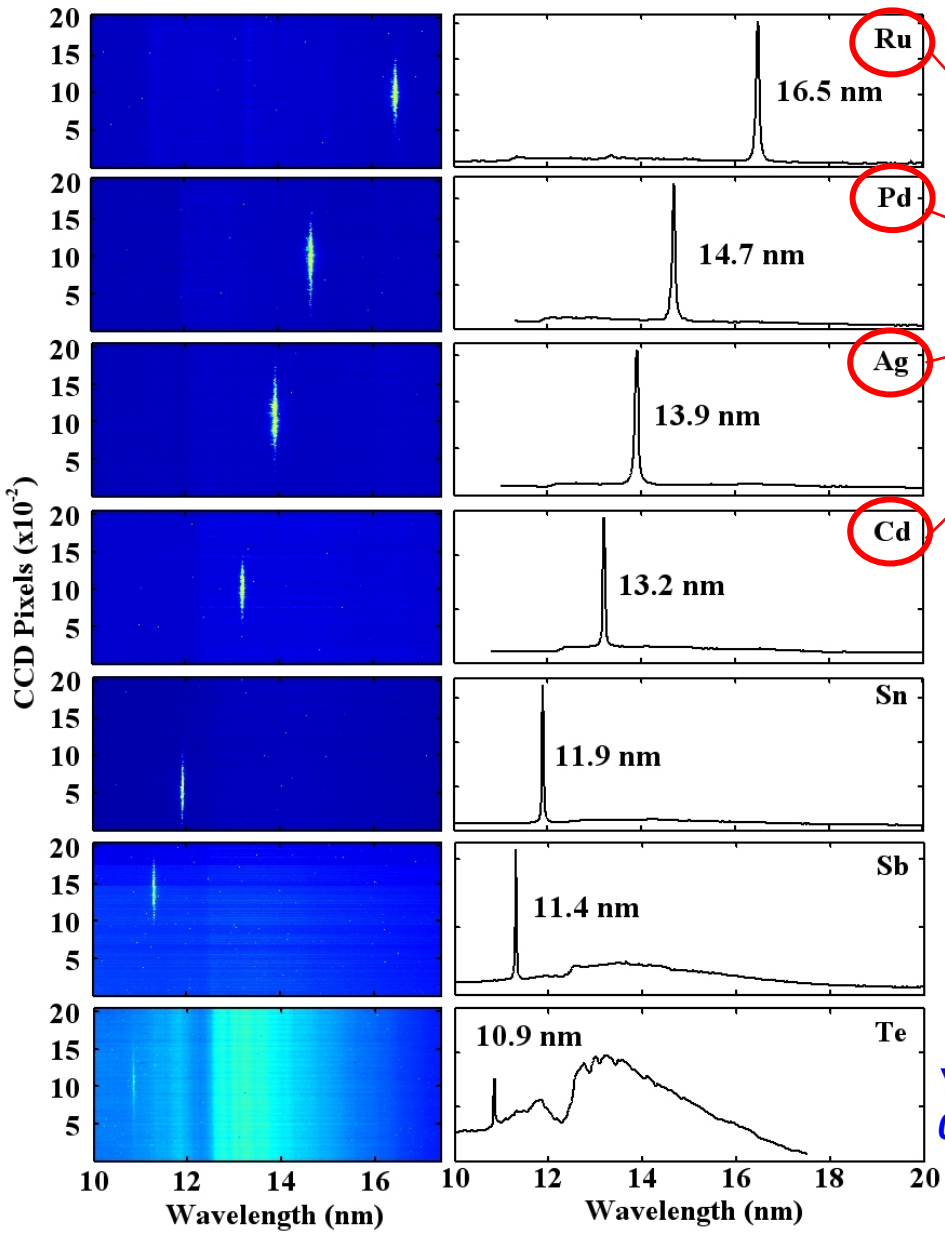
- 0.3 J, 120 ps pulses createa plasma from solid target
- The plasma is allowed to expand to reduce density gradients
- ~ 1 J , 6-8 ps pulses from amplified Ti:Sapphire laser are focused to heat the plasma at grazing incidence

Simulation predicts high gain at 13.2 nm in Ni-like Cd, g ~140 cm^{-1}

Pre-pulse: 200 mJ, 120 ps Heating pulse: 1 J, 8 ps heating pulse



High repetition rate table-top lasers extended to 13 nm spectral region and below



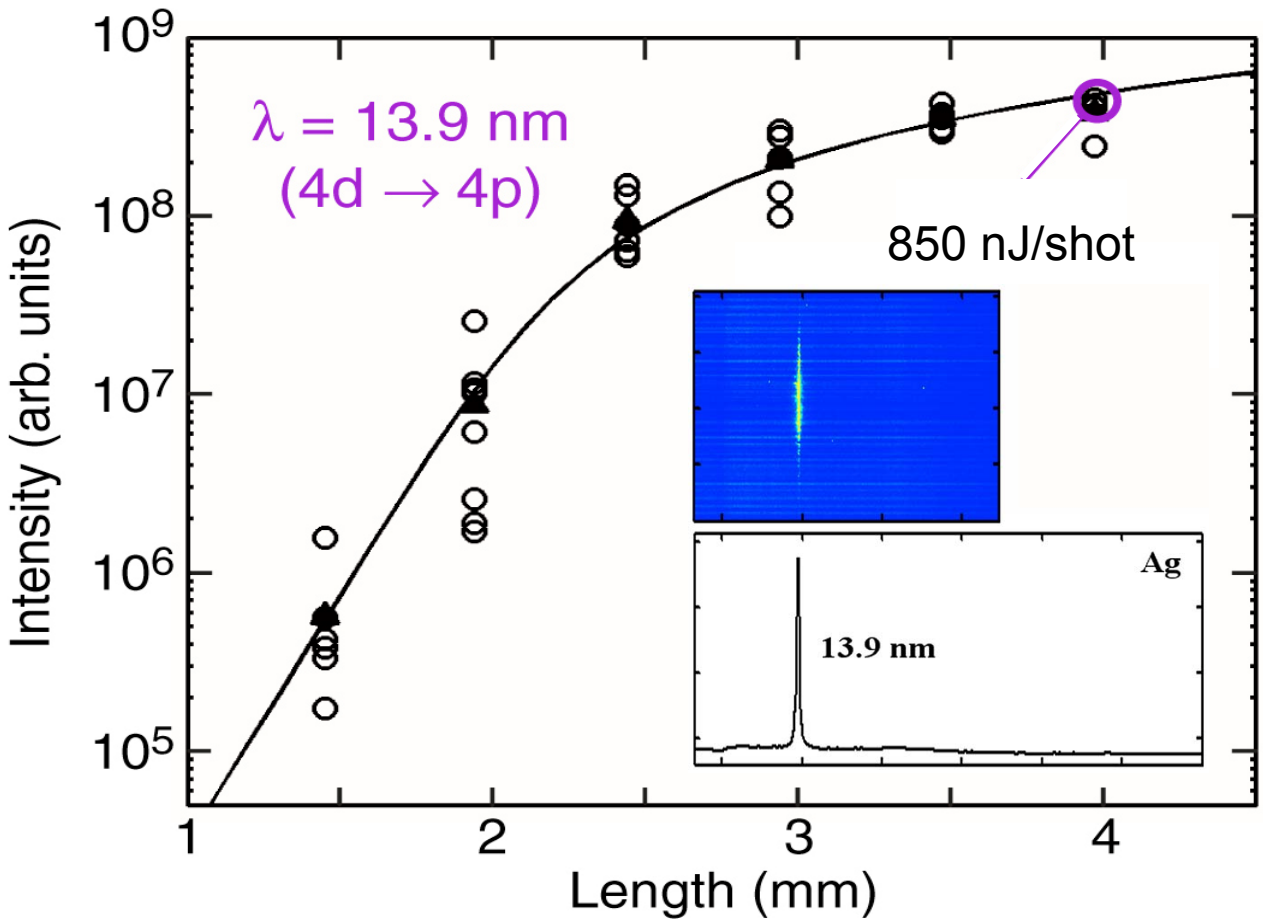
Gain saturated operation demonstrated

Y. Wang et al, Phys. Rev. A 72, 053807 (2005)

Saturated laser operation at 13.9 nm in Nickel-like Ag

1 J short (8 ps) pulse excitation

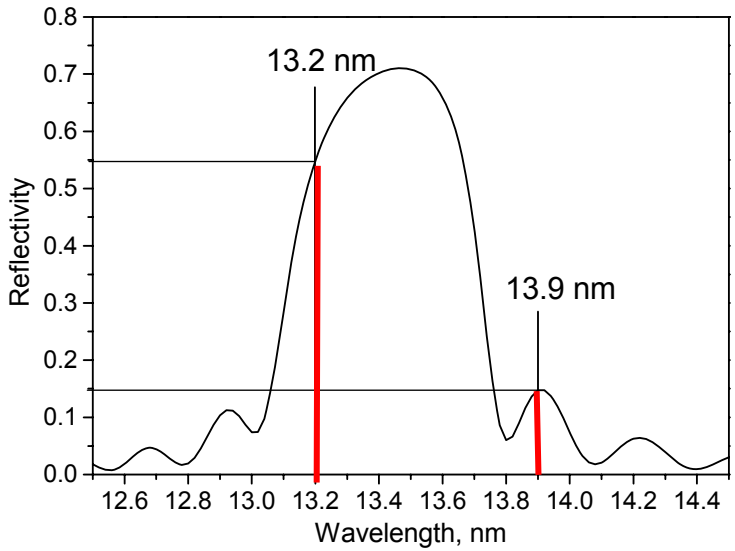
g_0=67 cm^{-1} ; gxl= 16.8

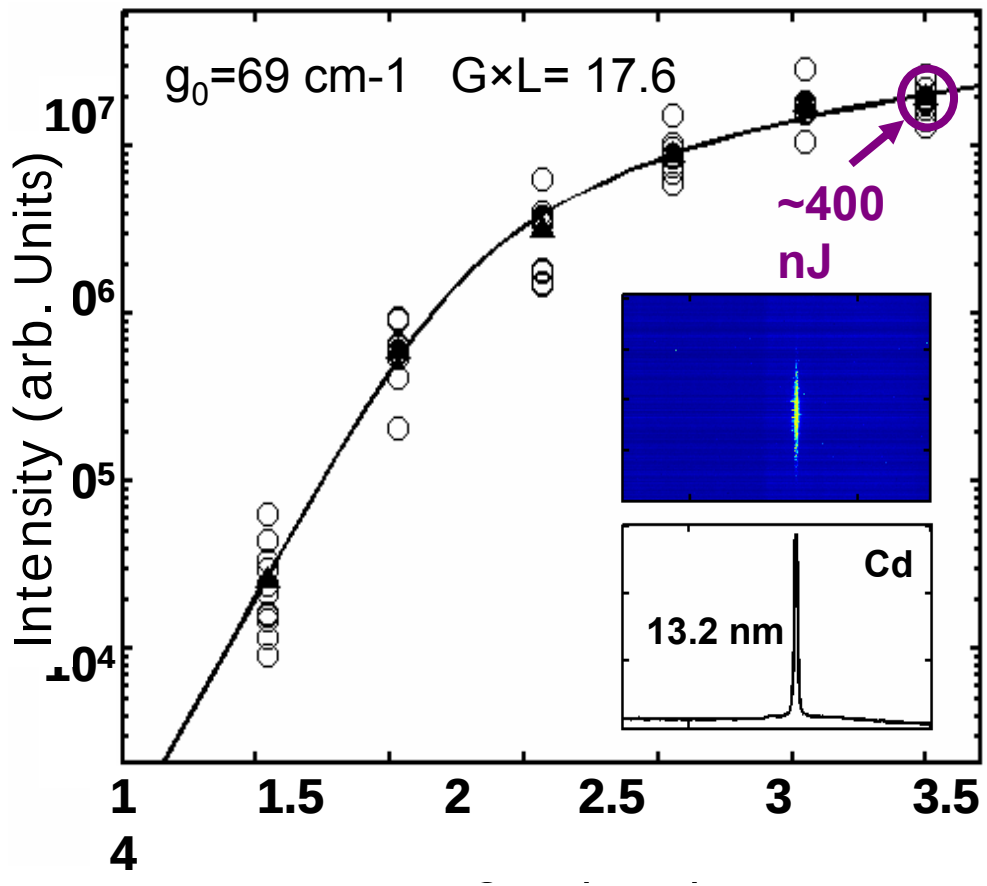


Wang et al, Phys. Rev. A 72, 053807 (2005)

Saturated Ni-like Cd laser at 13.2 nm provides a closer laser wavelength match to Mo/Si lithography mirrors

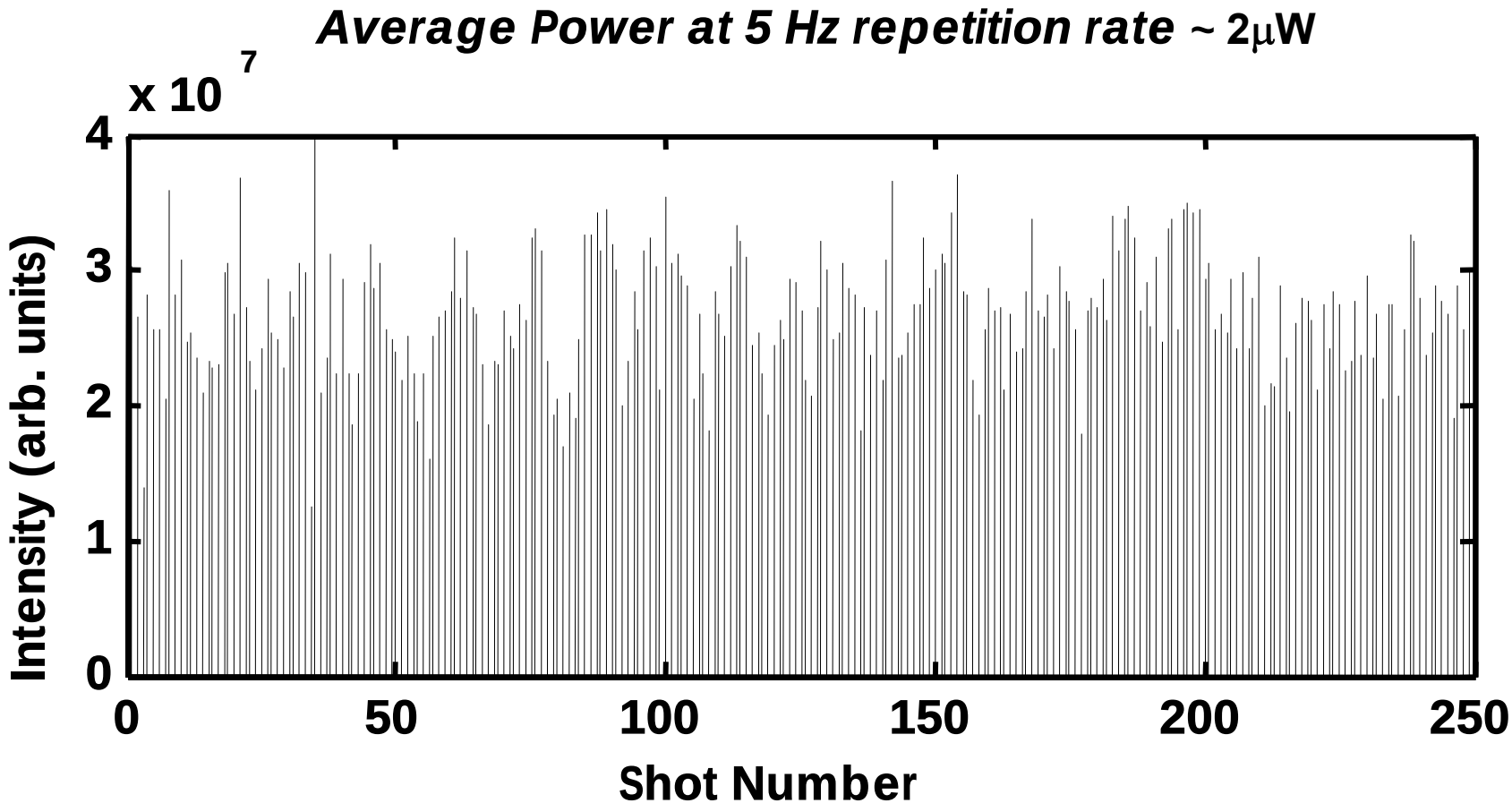
At the wavelength of the Ni-like Cd laser the reflectivity of Mo-Si mirrors centered at λ =13.5 nm is ~ 55%





J.J. Rocca et al, Opt. Lett. 30, 2581-2583 (2005)

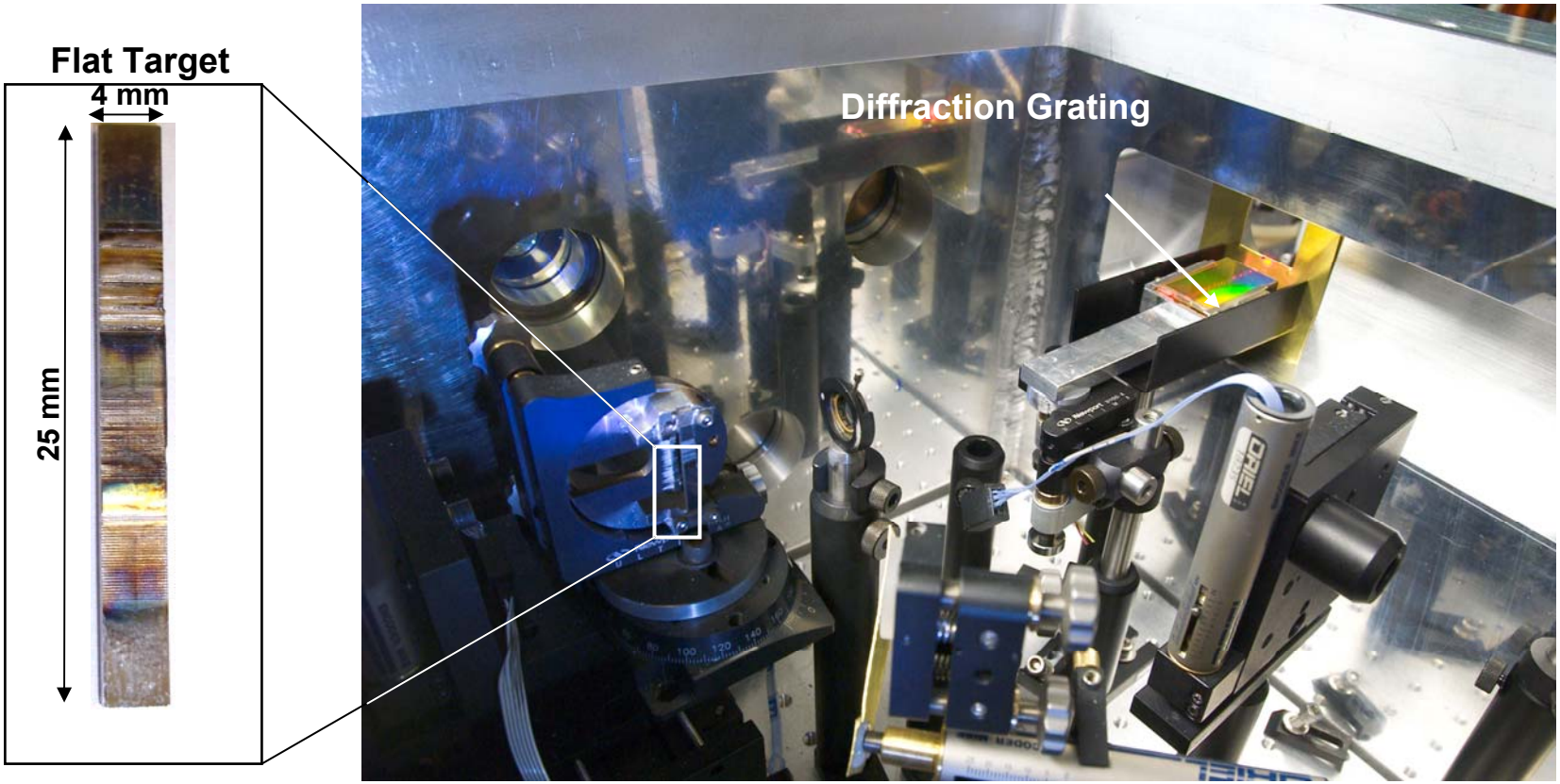
High repetition rate operation of 13.9 nm Ni-like Ag laser



Wang et al, Phys. Rev. A 72, 053807 (2005)

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

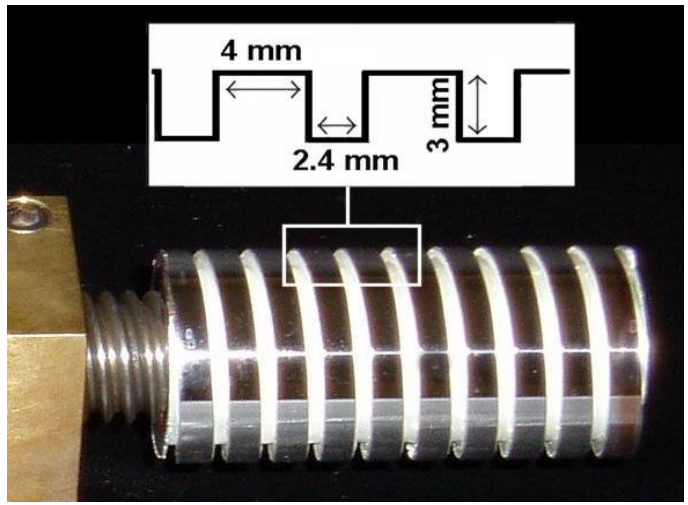
Strip target used in initial demonstration limits high repetition rate laser operation to periods of several minutes

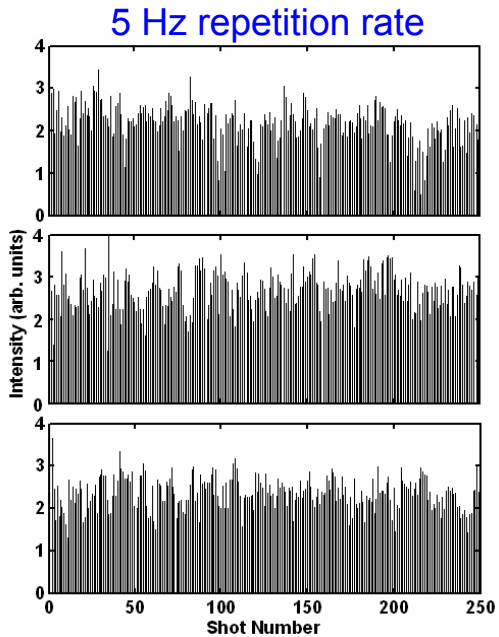


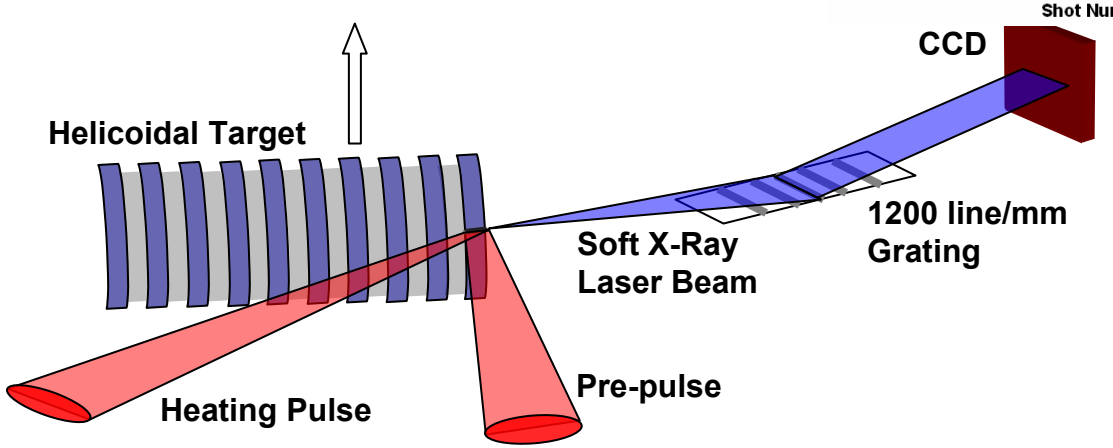
Rotating helicoidal target for extended high repetition rate operation

Hours of continuous high repetition rate laser operation will be possible

Abbey Weith et al. Optics Letters, 31, 1994, (2006)



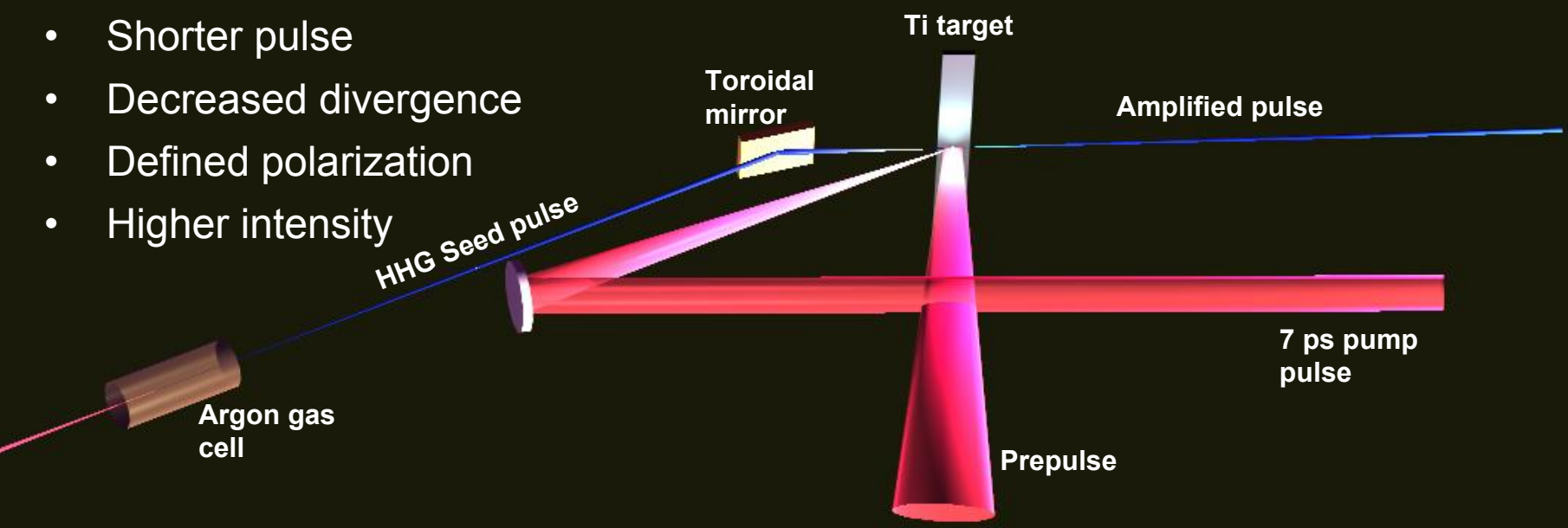




Seeding with high harmonic pulse can greatly increase spatial coherence and beam brightness

High harmonic seeding of solid target soft x-ray laser amplifier

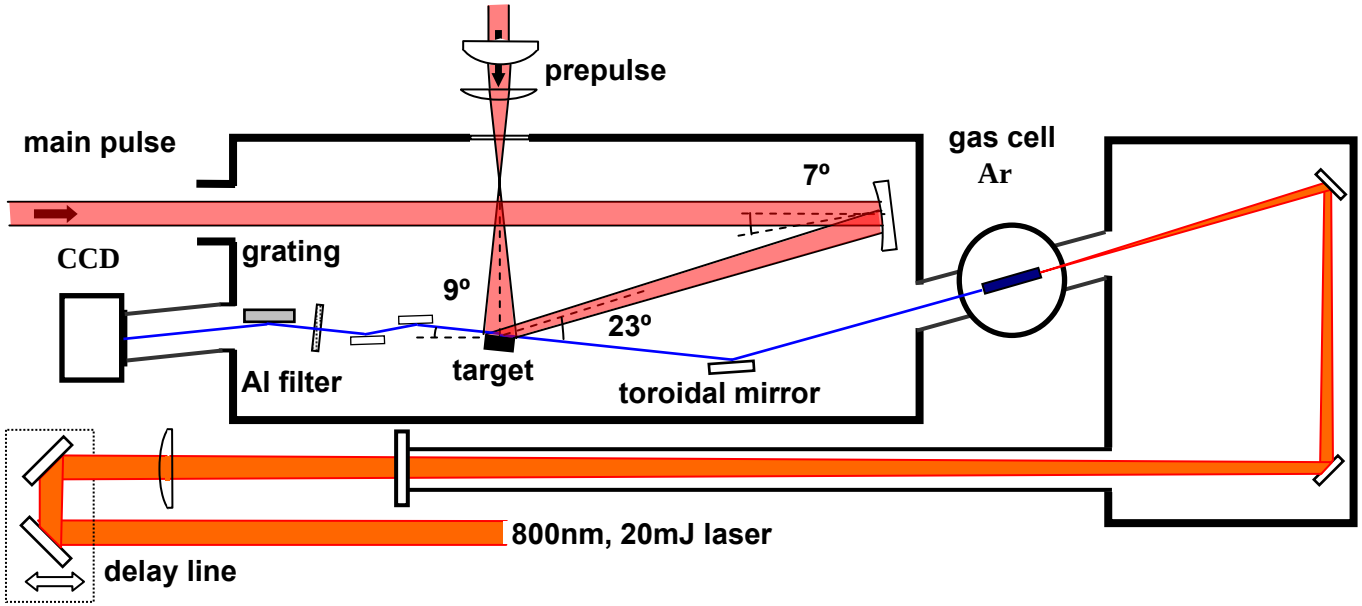
- Shorter pulse
- Decreased divergence
- Defined polarization
- Higher intensity

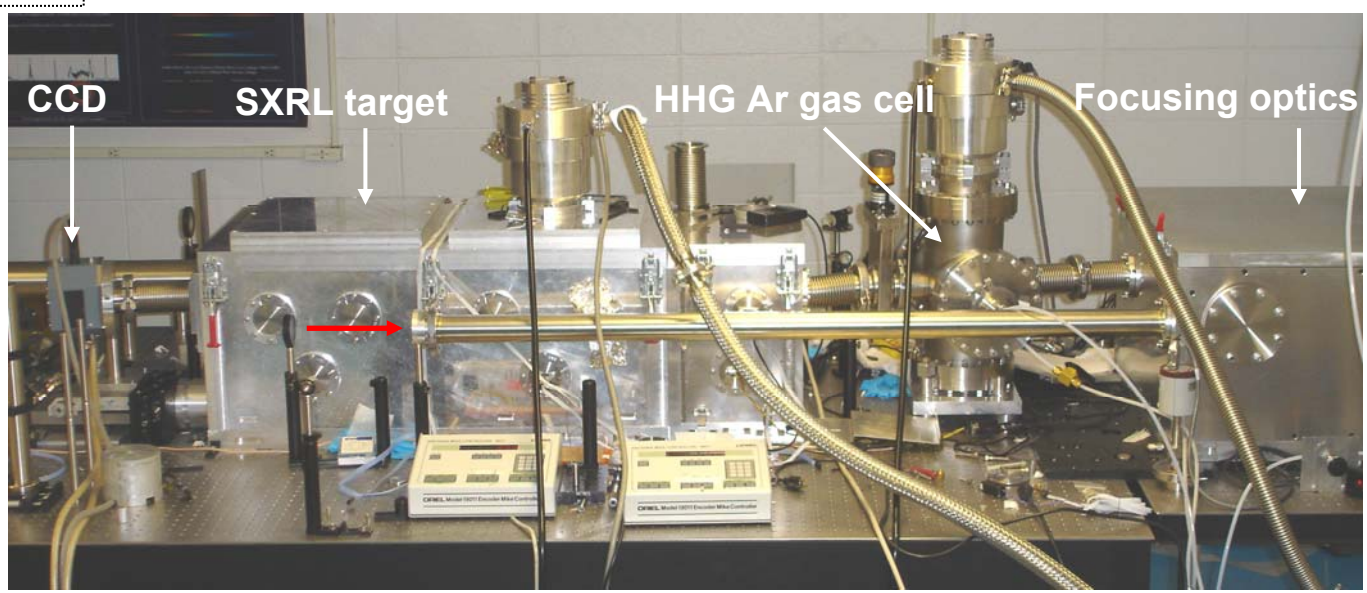


- **Proof of principle experiment**: T. Ditmire et al. Phys. Rev. A. 51, R 4337, (1995): Amplification of HHG by ~ 3 X in the λ= 25.1 nm line of a Gallium laser amplifier

- **HHG seeding of OFI amplifier:** P. Zeitoun, G. Faivre, S. Sebban, T. Mocek *et al*, Nature ,**431**, 426, (2004).

High harmonic seeding of grazing incidence amplifier

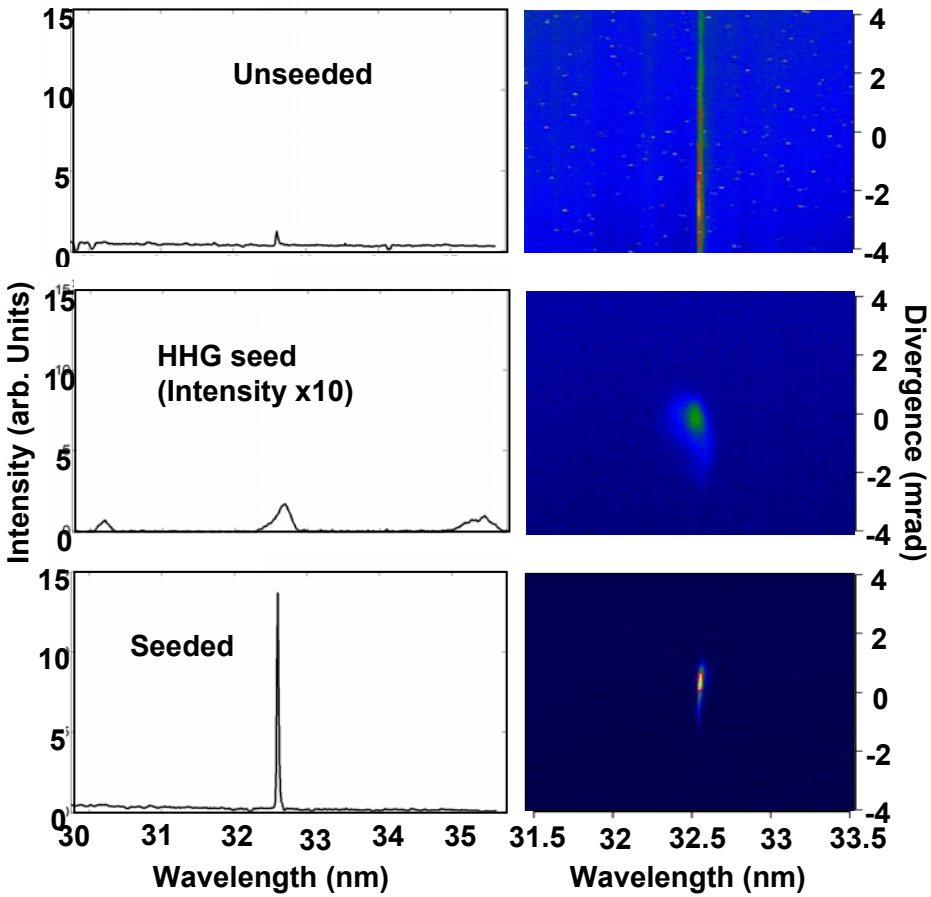


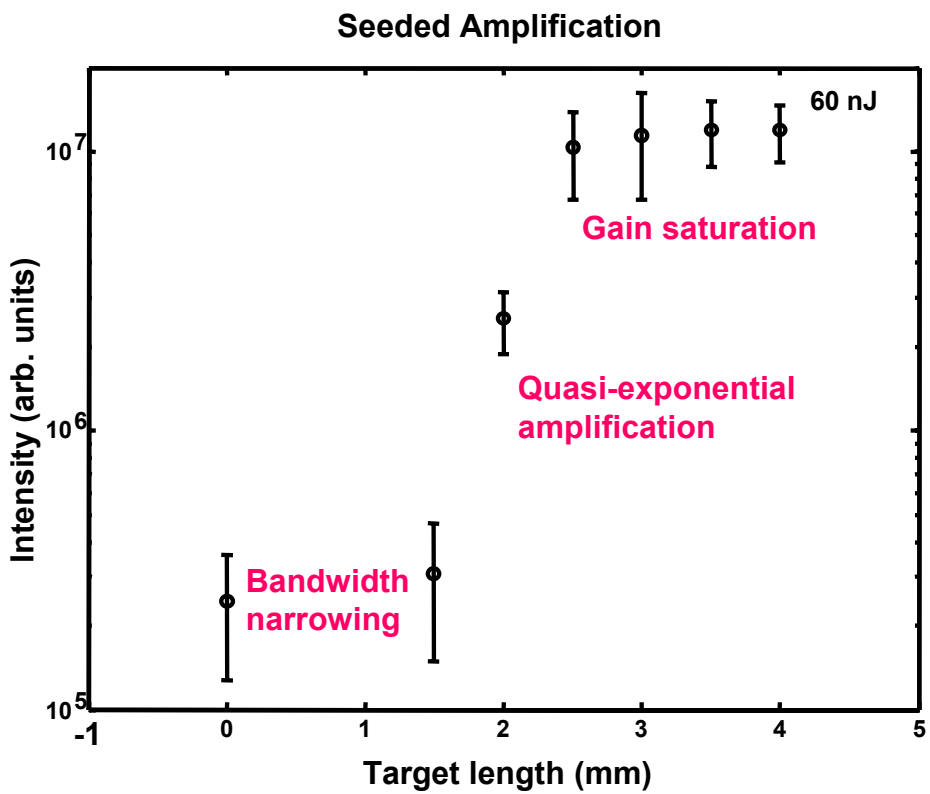


Seed is amplified nearly two orders of magnitude creating bright narrow bandwidth low divergence beam

λ = 32.6 nm Ni- like Ti amplifier – 25th harmonic of Ti:Sa

2.5 mm long plasma amplifier

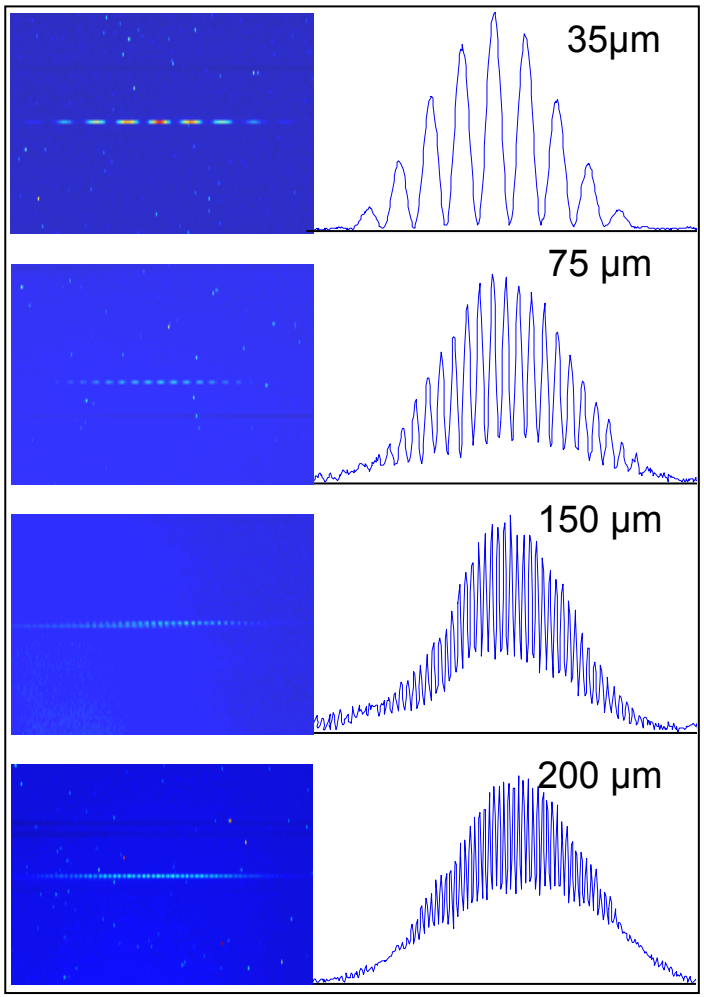


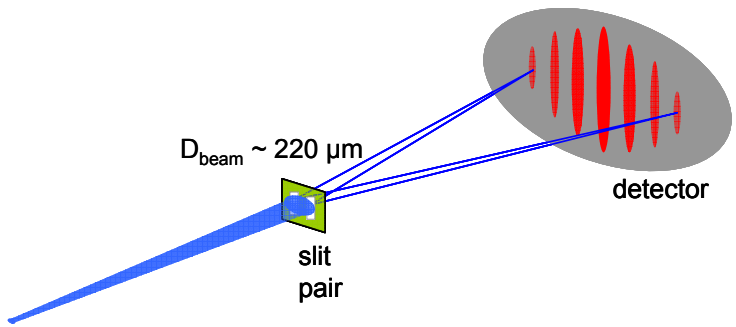


Y. Wang et al. Phys. Rev. Letters, **97,** 12390,1, (2006).

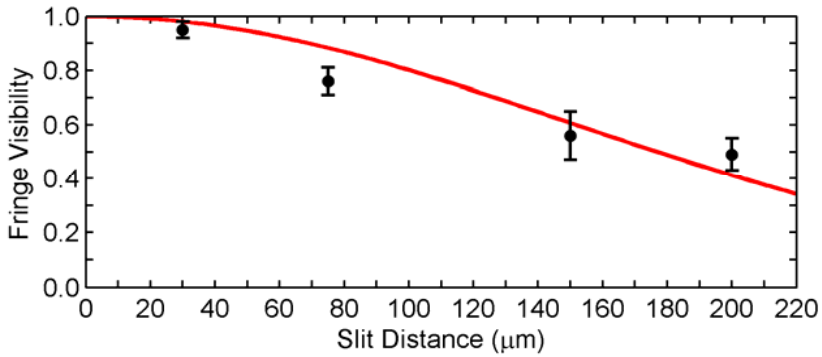
Amplified beam is measured to have essentially full spatial coherence

Measurements at 10 cm from source





Coherence length L_c ~180 μm
Beam radius of ~ 220 μm



Y. Wang et al. Phys. Rev. Letters, **97,** 12390,1, (2006).

Λ =13.2nm laser microscope for sub-40 nm resolution imaging on a table-top

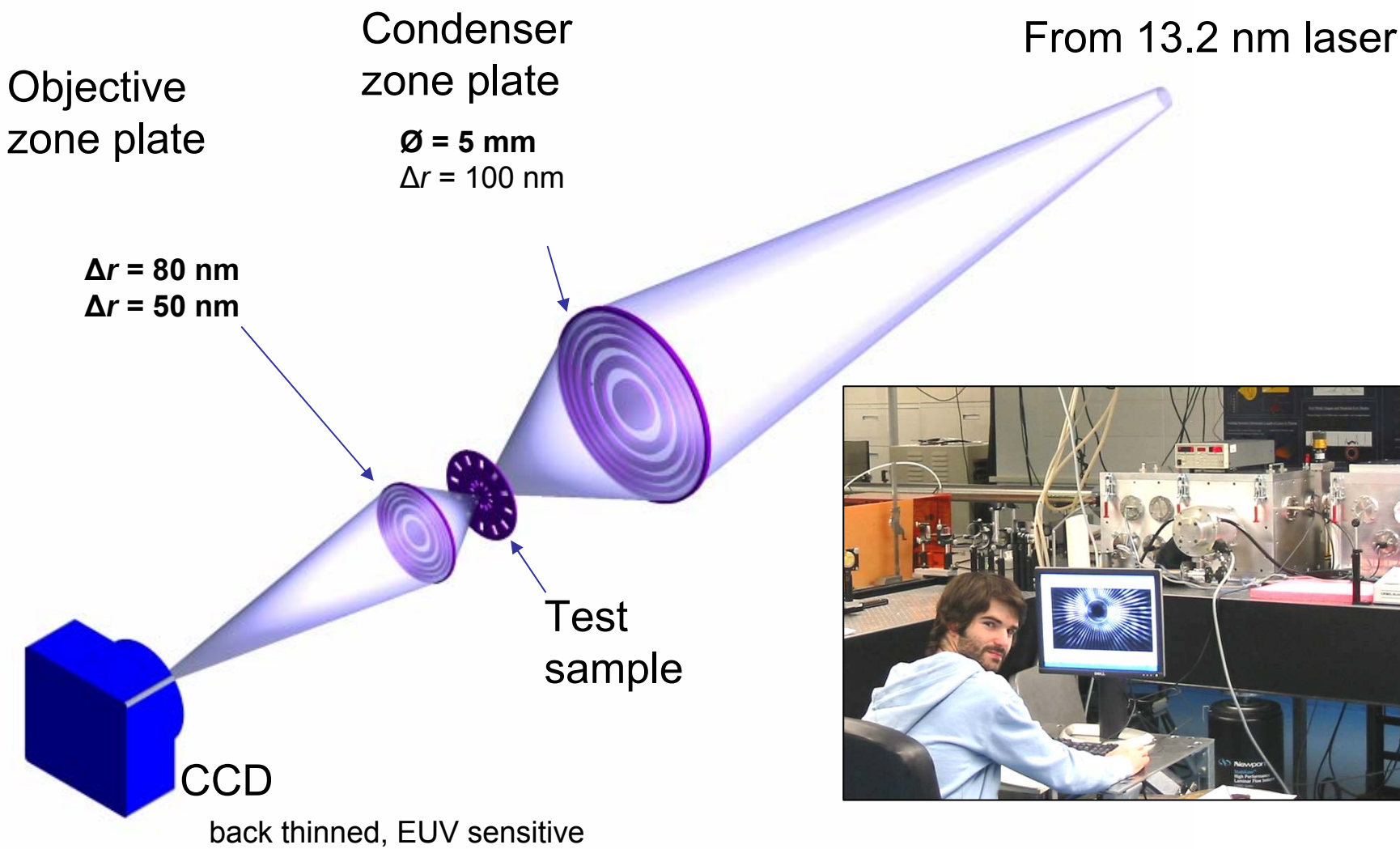
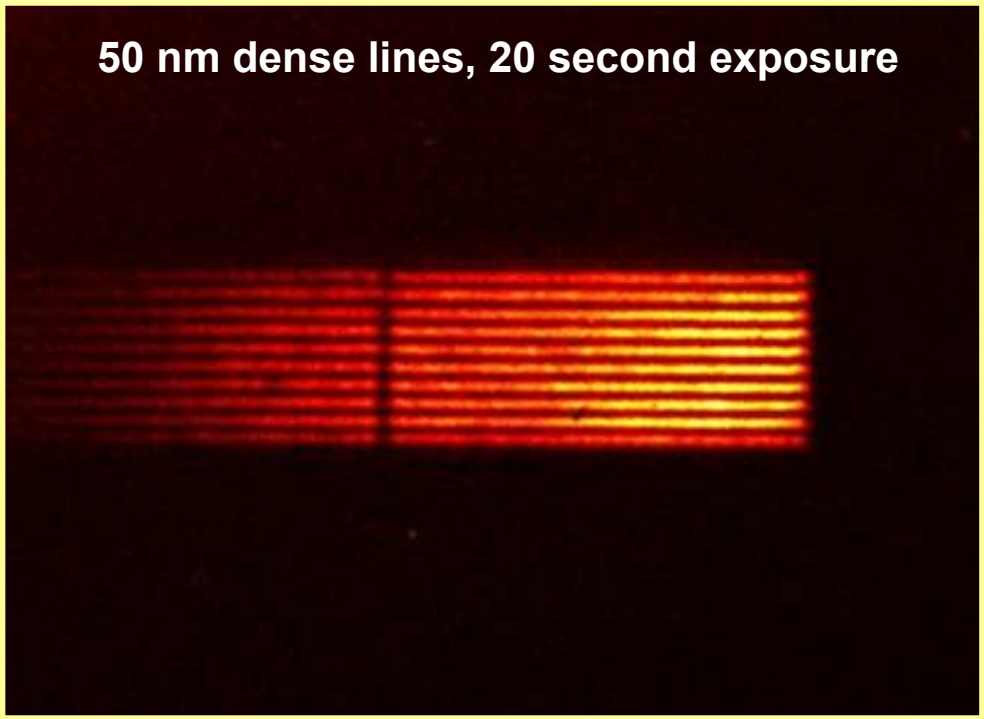
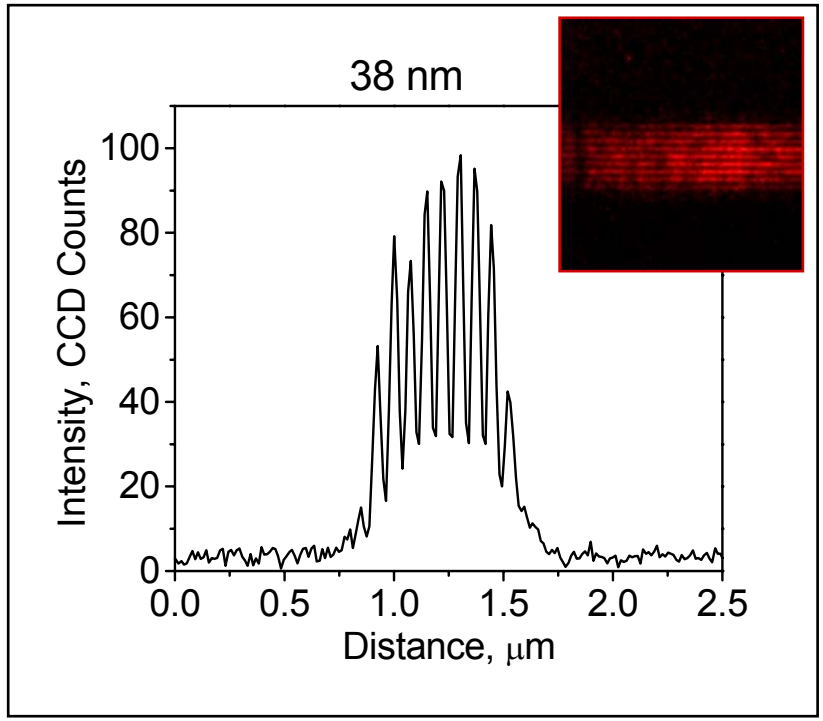


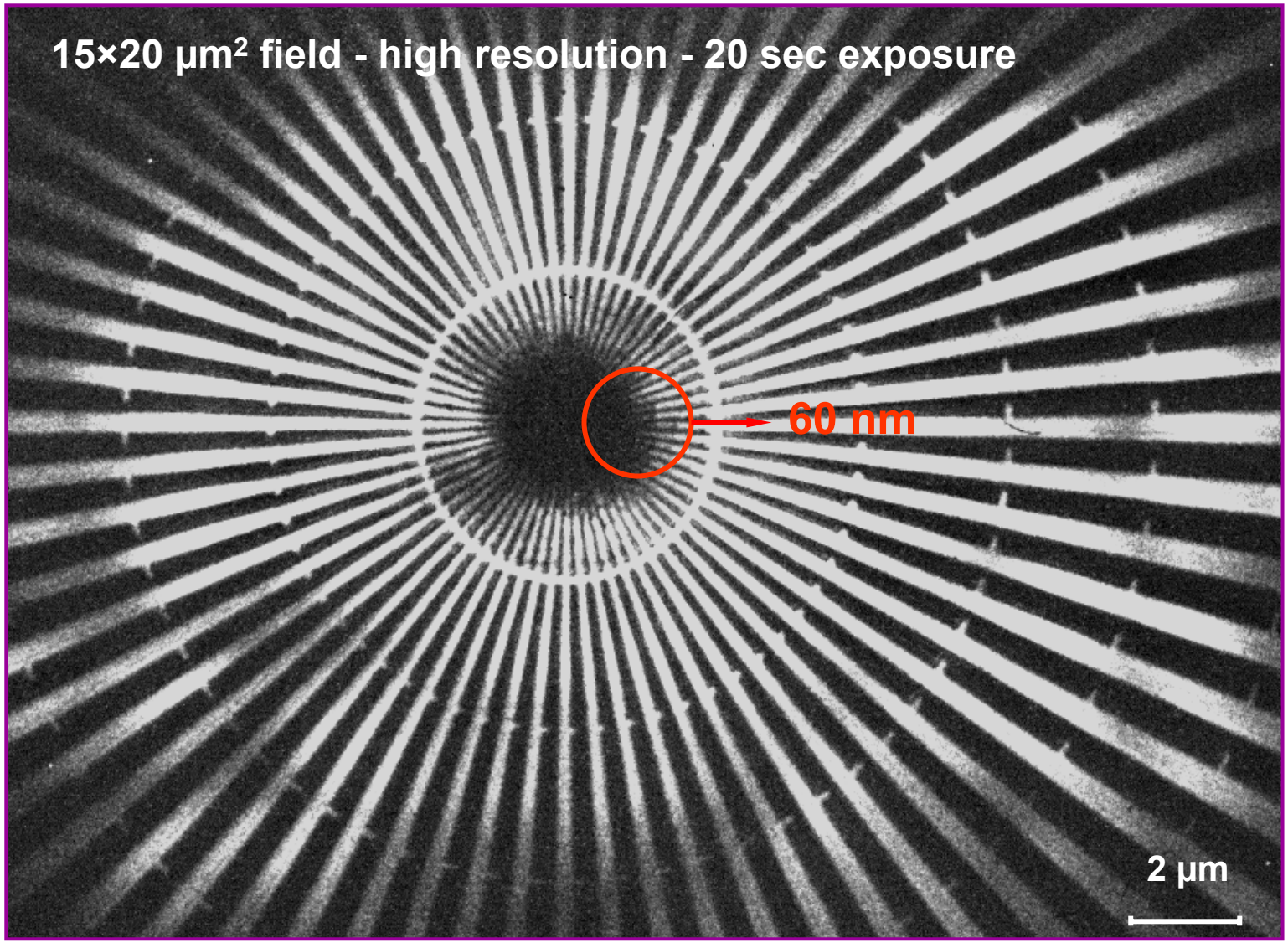
Table-top microscope with λ= 13.2 nm laser reaches sub-38 nm resolution



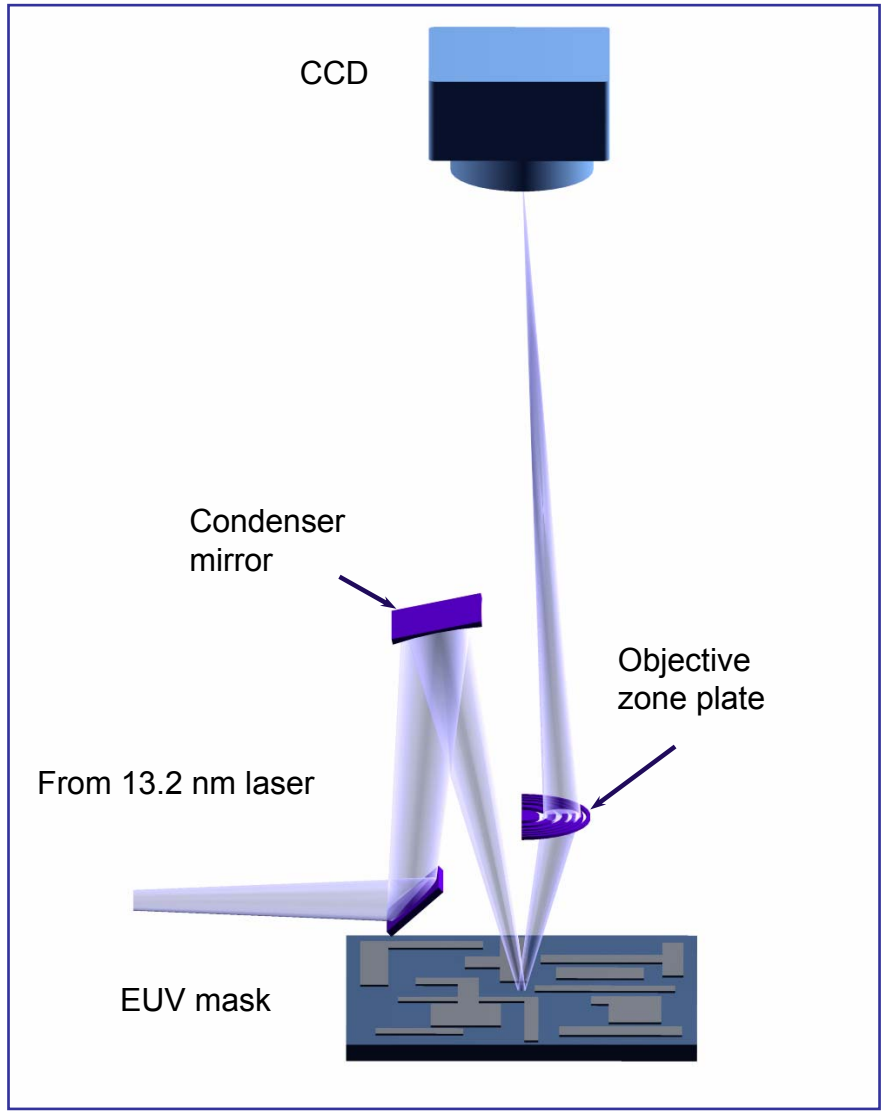


G. Vaschenko et al. Optics Lett, 32, 1214, (2006)

High resolution broad area imaging



Reflection mode microscope at 13.2 nm with sub- 50 nm resolution

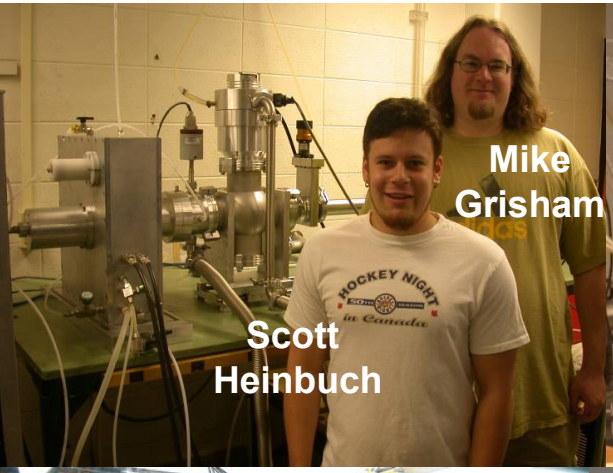
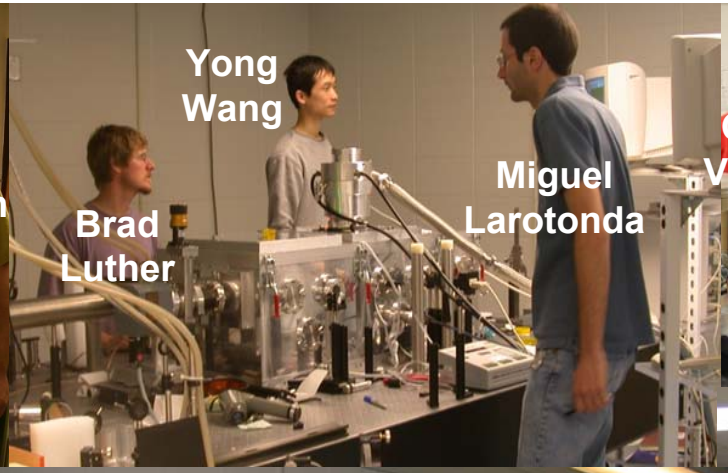
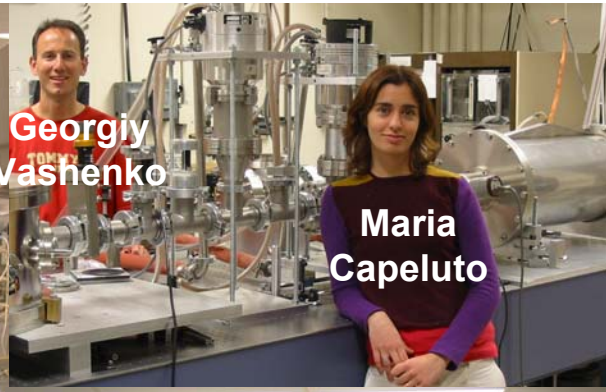
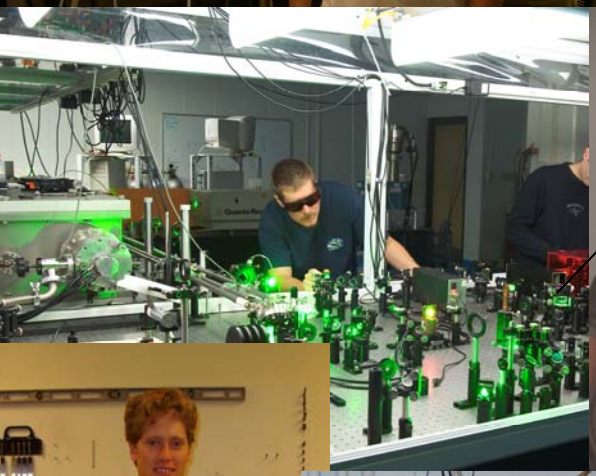
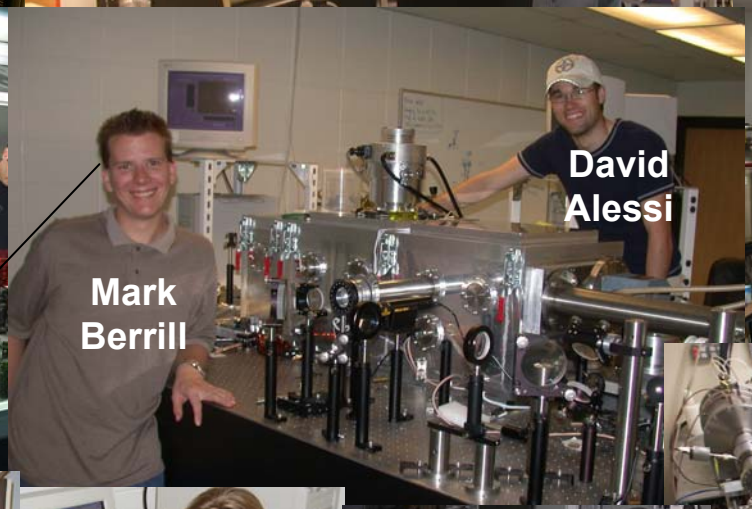
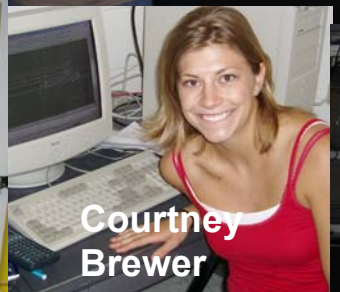


Summary

Table-Top EUV Lasers for Metrology

- 13.2 nm and 13.9 nm table-top lasers have been demonstrated
- 1-2 microwatt average power
- Demonstrated their use in high resolution imaging: resolution better than 38 nm

Future Work

- Increase average power
- Improve spatial coherence

Acknowledgements