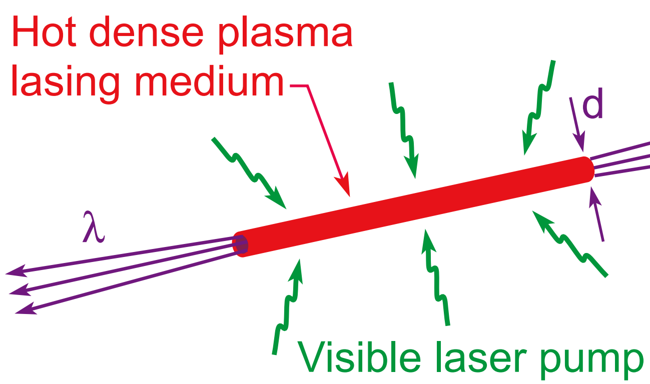
Chapter 7

EXTREME ULTRAVIOLET AND SOFT X-RAY LASERS



$$\frac{I}{I_0} = e^{GL} \tag{7.2}$$

$$G = n_u \sigma_{\text{stim}} F \tag{7.4}$$

$$\sigma_{\text{stim}} = \frac{\pi \lambda r_e}{(\Delta\lambda/\lambda)} \left(\frac{g_l}{g_u}\right) f_{lu} \tag{7.18}$$

$$\frac{P}{A} = \frac{16\pi^2 c^2 \hbar (\Delta\lambda/\lambda) GL}{\lambda^4} \tag{7.22}$$

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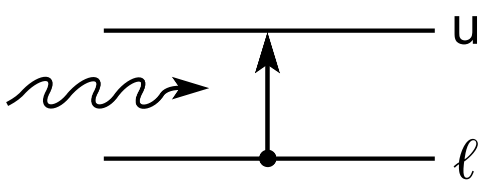
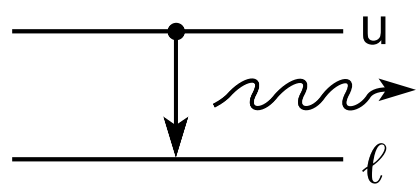
The Processes of Absorption, Spontaneous Emission, and Stimulated Emission

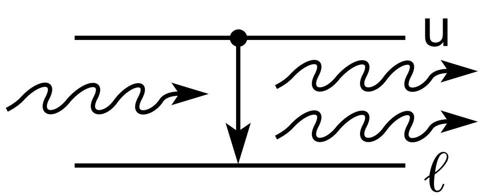
Absorption



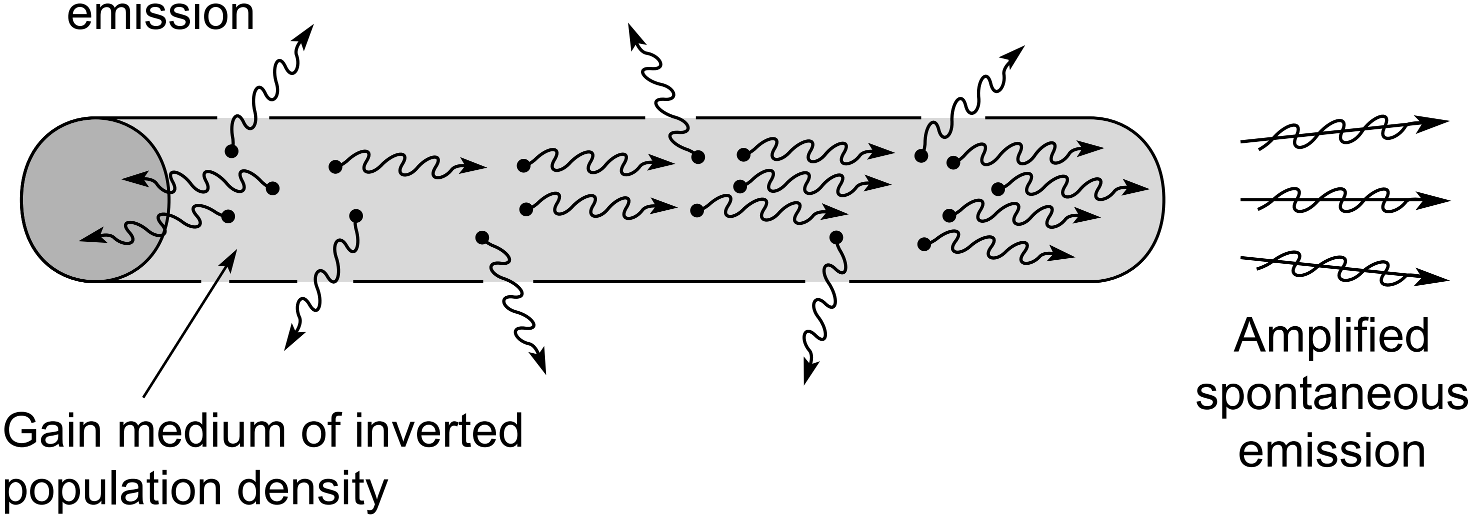
Spontaneous emission



Stimulated emission



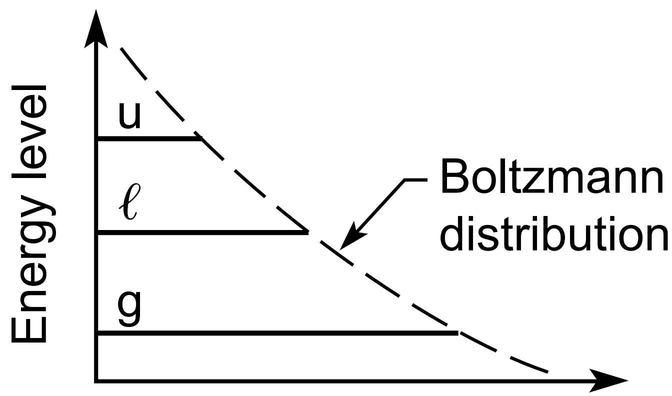
The Lasing Process Begins with Amplified Spontaneous Emission (ASE)



- both directions equally likely

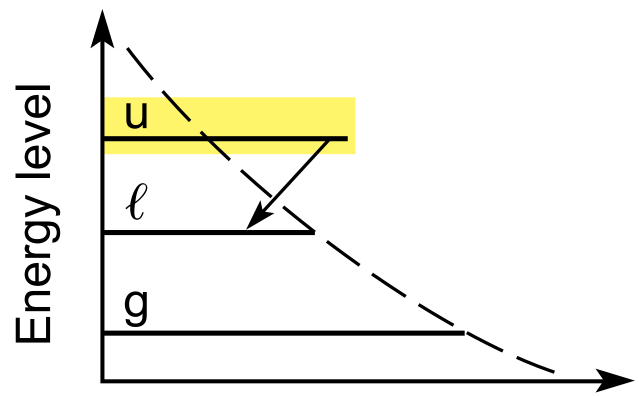
Equilibrium and Non-Equilibrium Energy Distribution

Equilibrium energy distribution



Population density

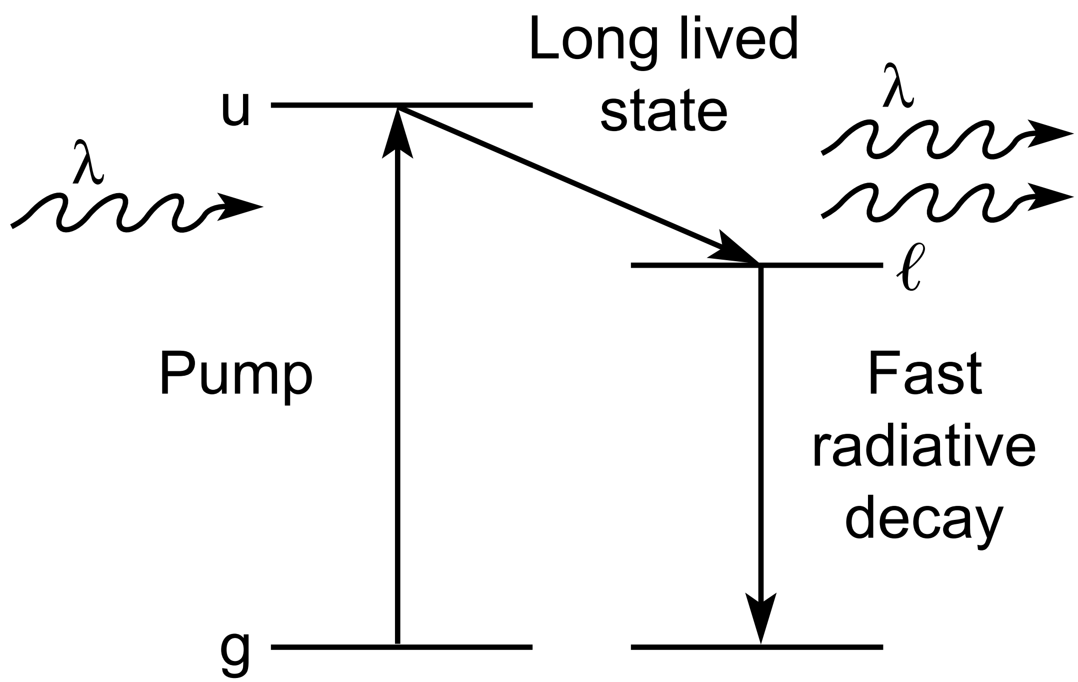
Non-equilibrium inverted energy distribution



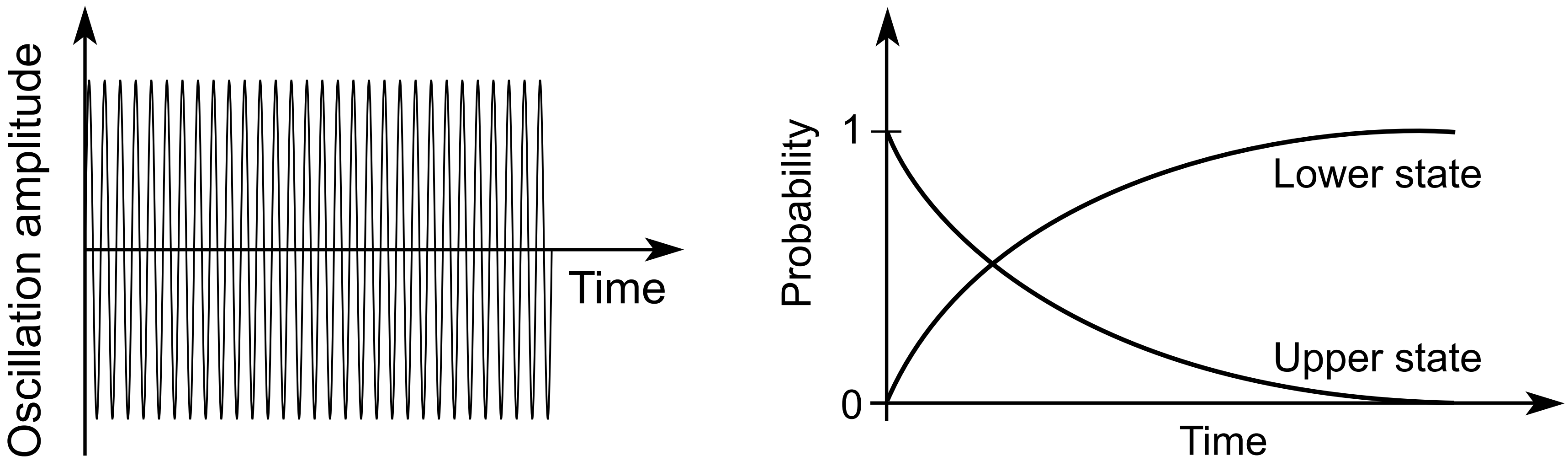
Population density

Lasing requires an inverted population density (more atoms in the upper state than in the lower state.

Three-level Lasing Between an Upper State u and a Lower State ℓ



Radiative Decay Involves An Atom Oscillating Between Two Stationary States at the Frequency $\omega_{if} = (E_i - E_f) / \hbar$



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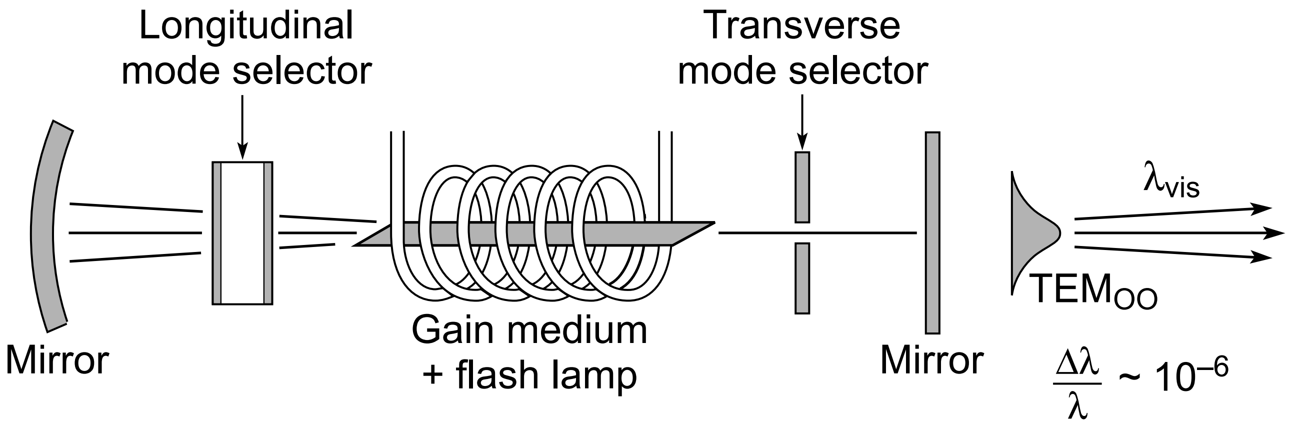
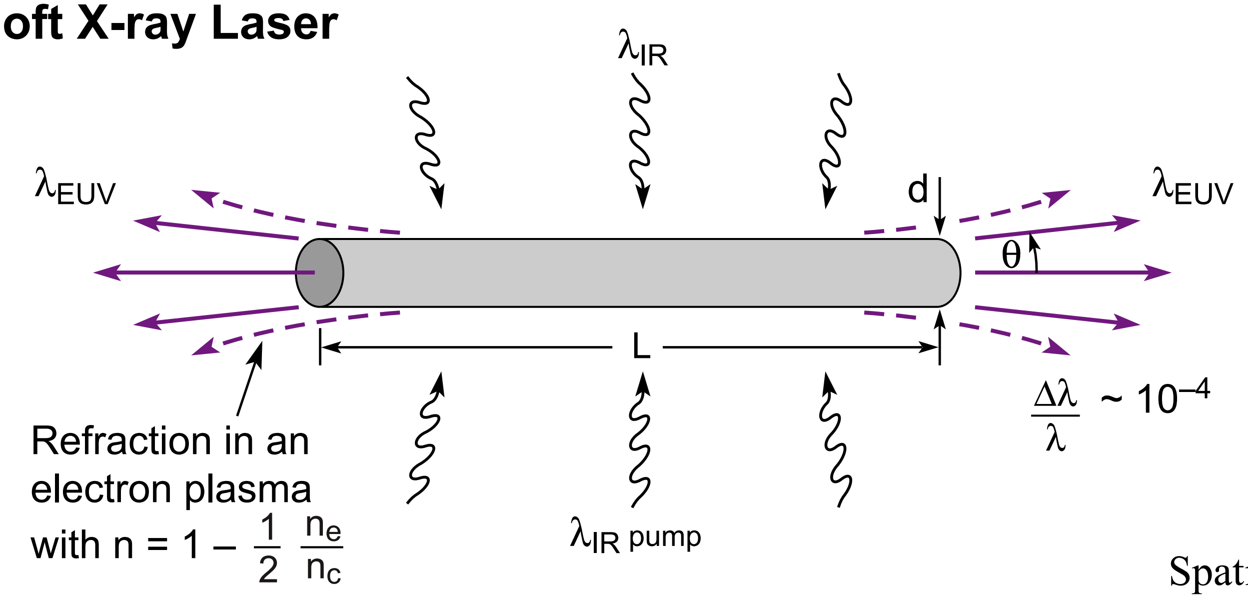
EUV/SXR Lasers are High Gain With Minimal Cavity Optics

Visible Light Laser



EUV/Soft X-ray Laser



Spatial and temporal coherence addressed in chapter 8.

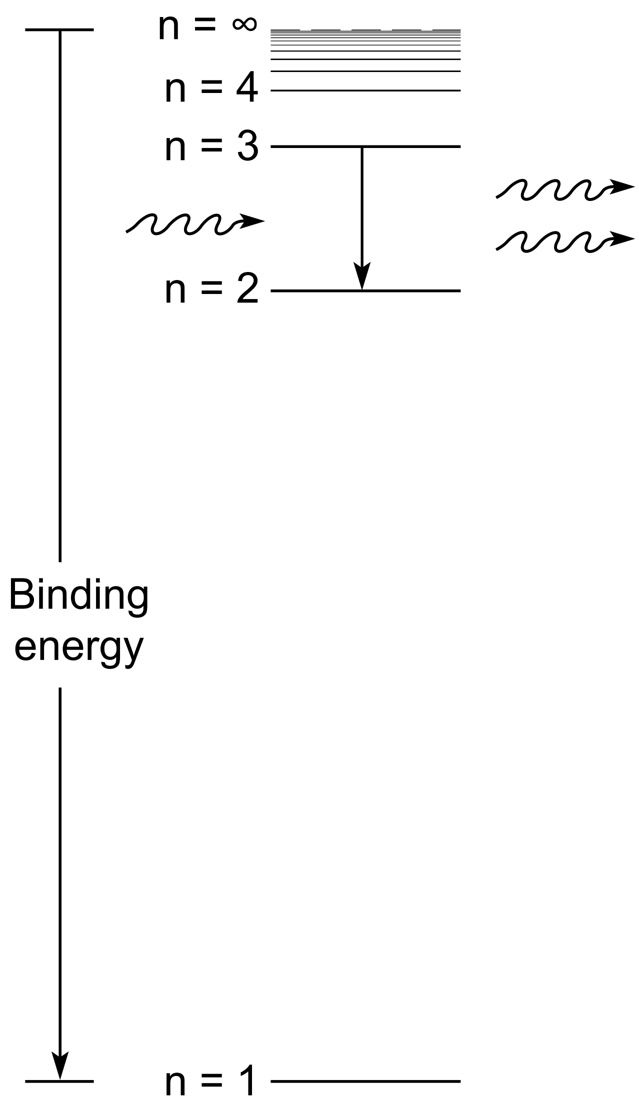
Early Successes With Lasing in the 4-46 nm Wavelength Region

- **Recombination lasing in rapidly cooled H-like carbon**
- **Collisionally pumped lasing in Ne-like Se**
- **Extension to shorter wavelengths with collisionally pumped Ni-like Ta, W, . . .**
- **Saturation of Ni-like Ag, In, Sn, Sm, . . . with refraction compensated plasmas**

More recently:

- **Table-top lasing in the EUV with high spatial coherence and mW average power**
- **Compact lasing with f_{sec} transient gain techniques**

Stimulated n = 3 to n = 2 Emission for a Hydrogen-Like Ion



$$\hbar\omega = (13.606\ \text{eV})\, Z^2 \left(\frac{1}{n_f^2} - \frac{1}{n_i^2} \right) \qquad (7.1)$$

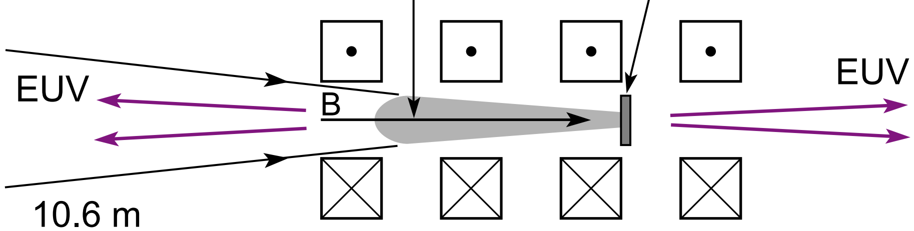
Transitions in Single Electron, Hydrogen-Like Carbon Ions (Z = 6)

$$\hbar\omega = (13.606 \text{ eV})\, Z^2 \left(\frac{1}{n_f^2} - \frac{1}{n_i^2} \right) \quad (7.1)$$

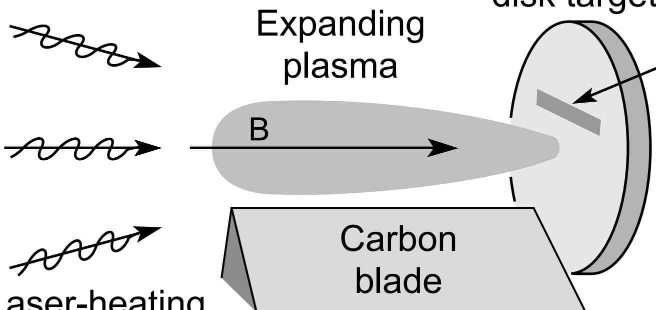
Transition u–l	Photon energy $\hbar\omega$(eV)	Wavelength λ (nm)	Oscillator strength[a] f_{lu}	Lifetime $\tau = 1/A_{ul}$ (ps)
2p–1s	367.0	3.378	0.4162	1.2
3p–1s	435.0	3.350	0.0791	
4p–1s	458.7	2.703	0.0290	
3p–2s	68.03	18.22	0.435	4.1
3s–2p	68.03	18.22	0.0136	
3d–2p	68.03	18.22	0.696	12.0
4p–2s	91.84	13.50	0.103	
4s–2p	91.84	13.50	0.0030	
4d–2p	91.84	13.50	0.122	
4p–3s	23.81	52.07	0.485	

- $\hbar\omega \propto Z^2$
- $\tau \propto \tau_H/Z^4$

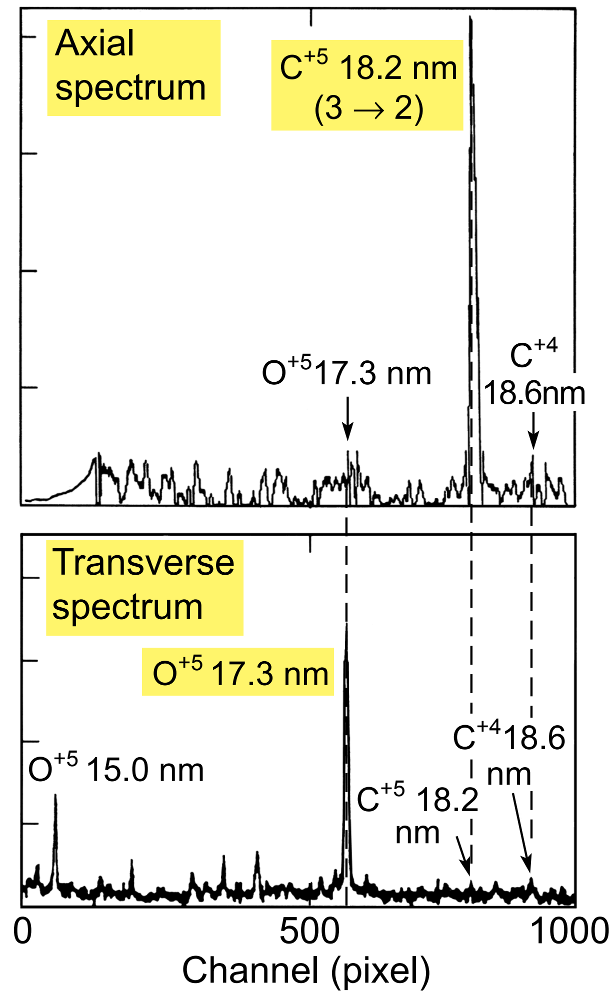
Recombination Lasing With H-like Carbon Ions



CO_2 laser: 10.6 µm, 5×10^{12} W/cm^2, 70 ns
Ionization of C^{+5} = 490 eV
Plasma: κT = 100-200 eV, 5×10^{18} e/cm^3



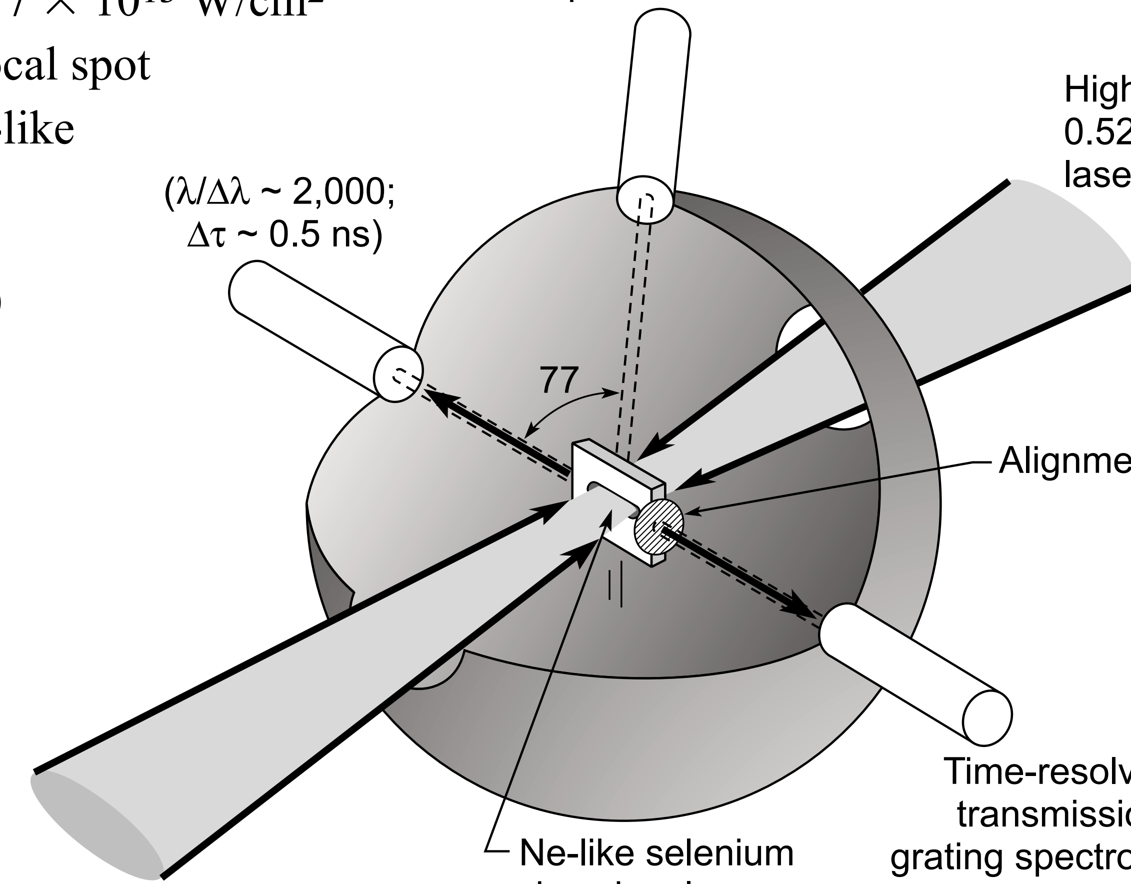
Recombination of C^{+6} and e^- cascading down excitation states (n)



Courtesy of S. Suckewer et al. (1985) Princeton University

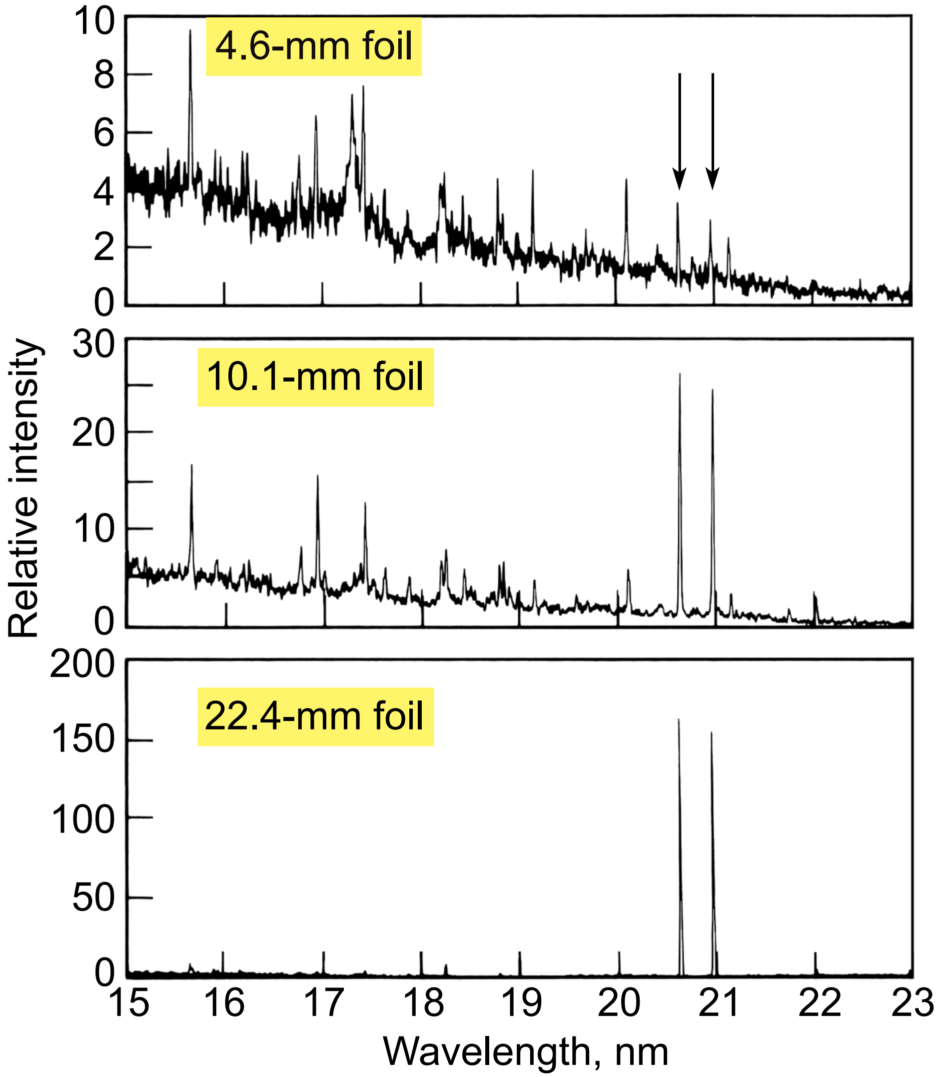
Laser Produced Plasma for Ne-like Lasing in Selenium (Z = 34)

- Double-sided irradiation of a thin Se foil
- 2.4 TW, 2ω, 450 ps, 7×10^{13} W/cm^2
- 200 μm × 1.1 cm focal spot
- About 20% ions Ne-like
- Ionization of Fl-like Se^{+23} is 1036 eV (Ne-like is 2540 eV)

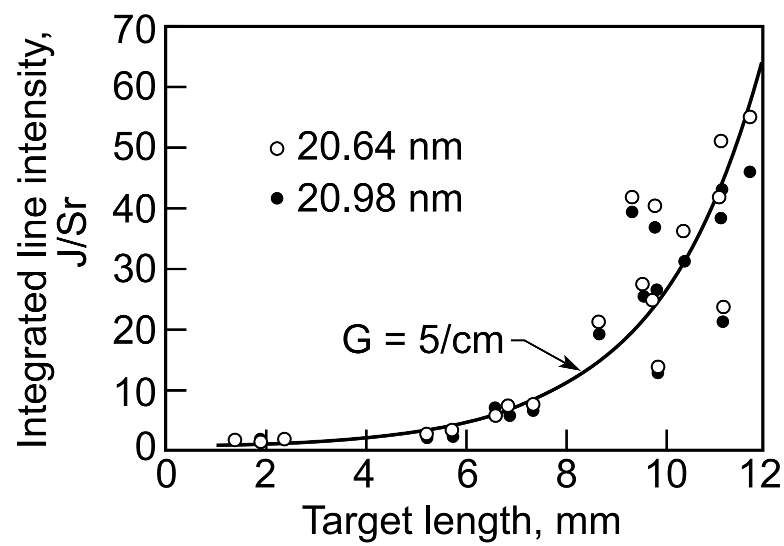


Courtesy of D. Matthews et al. (1985)
Lawrence Livermore National Laboratory

Exponential Gain Observed With Increasing Plasma Length

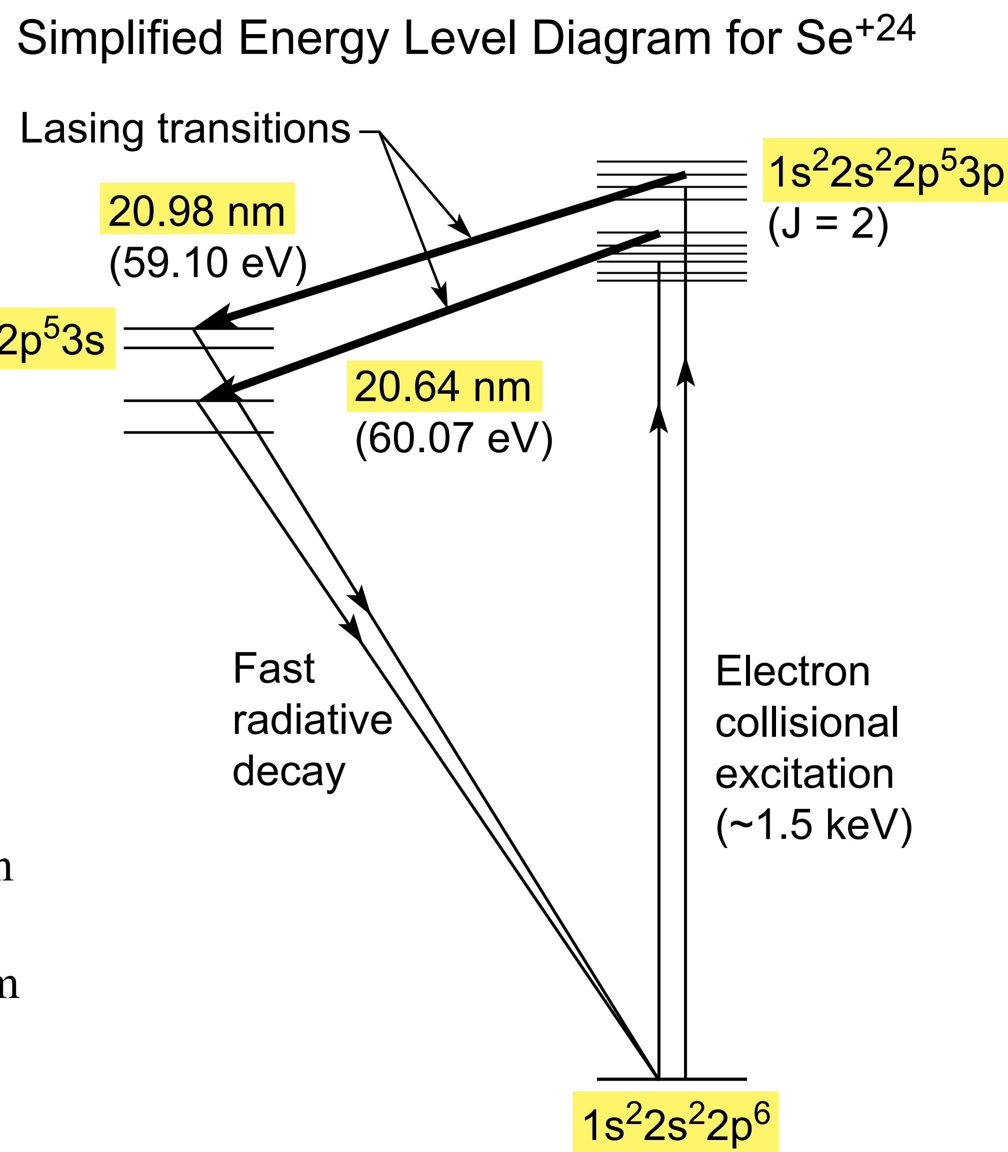


- Gain in axial direction only
- Use of on and off-axis time gated spectrometers
- 3p → 3s lasing at 20.64 nm and 20.98 nm in Ne-like Se^{+24}



Courtesy of D. Matthews et al. (LLNL)

Population Inversion in Neon-like Selenium

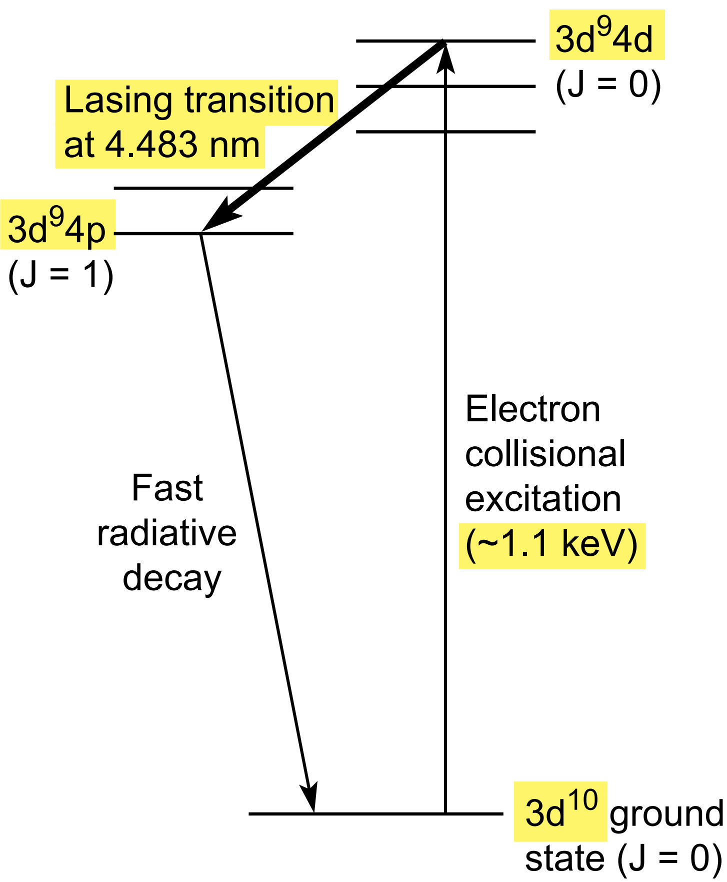


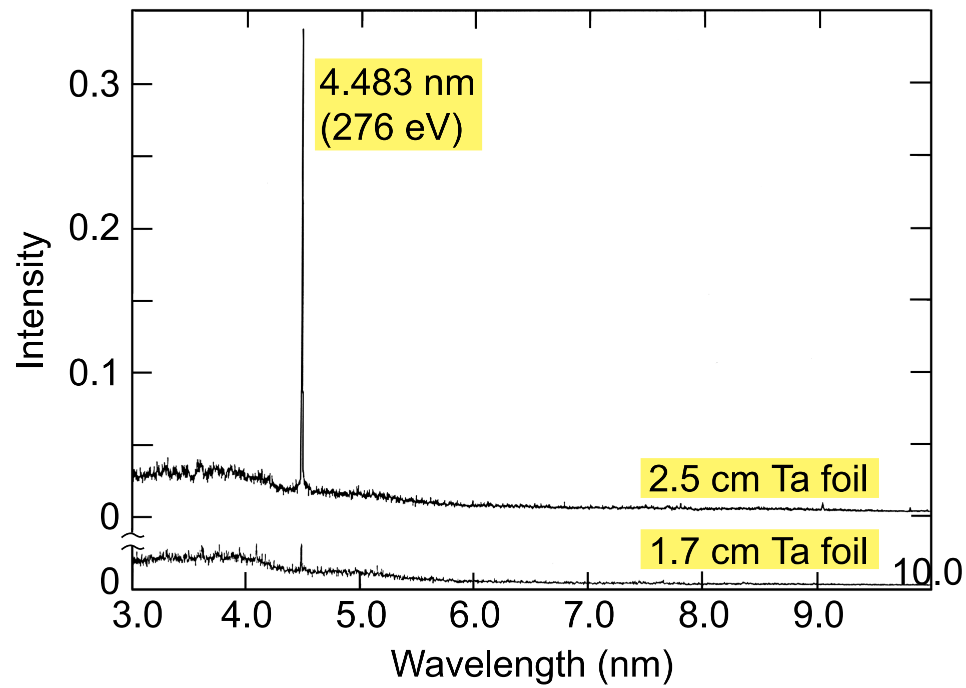
- Laser produced plasma conditions optimized for dominant Ne-like ionization stage
- Collisionally pumped to a 3p excited state
- Fast radiative depopulation of the lower 3s state
- 3p → 3s lasing at 20.64 nm and 20.98 nm based on selective depopulation

Courtesy of M. Rosen et al. (1985), LLNL.

Extension to Nickel-like Ions Permits Lasing at Shorter Wavelengths Without the Need for Higher Electron Temperature

Lasing in Ni-like Ta^{+45}

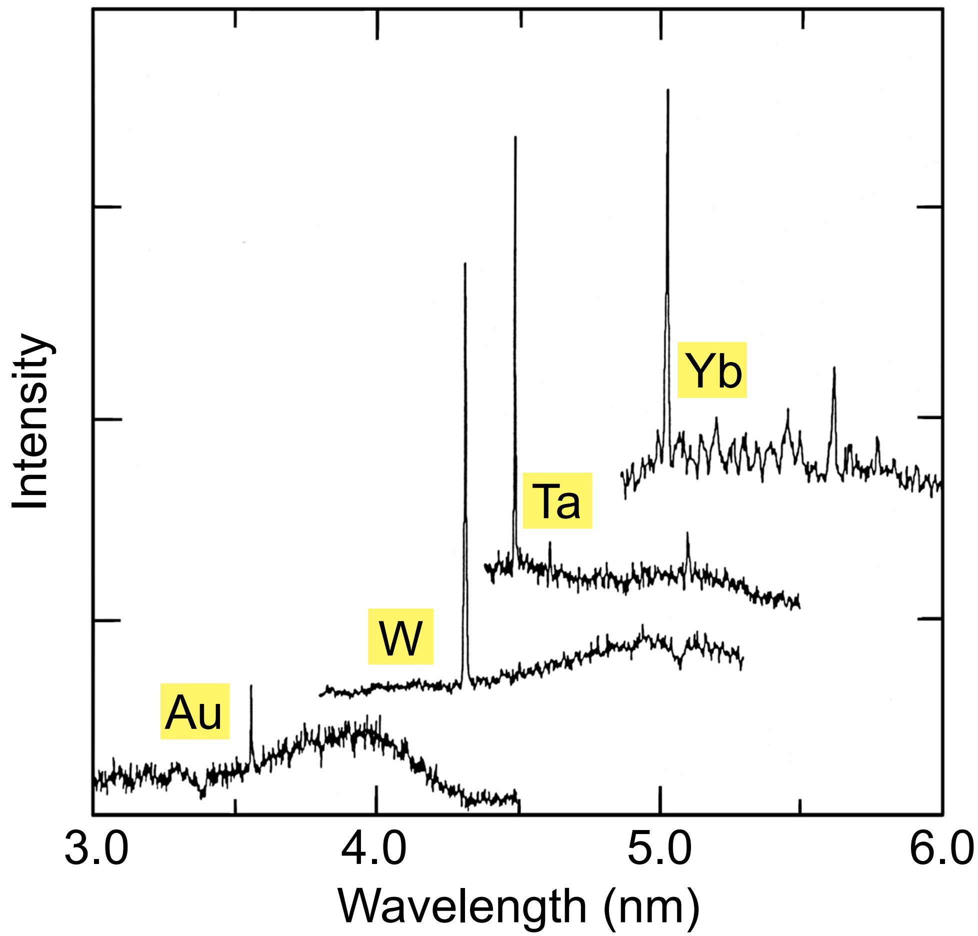




Courtesy of B. MacGowen et al. (1987), LLNL.

- Ni-like Ta ($Z = 73$, 28 e^-, +45)
- $1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10}$ ground state (28 e^-)

Nickel-like Lasing Across the K-edge of Neutral Carbon



Courtesy of B. MacGowen et al. (1987), LLNL.

4d → 4p lasing

- W at 4.318 nm
- Ta at 4.483 nm
- C-K at 4.36 nm

The water window is defined by the K-absorption edges of neutral carbon and oxygen.

Refractive Index of a Plasma

For $\omega > \omega_p$ there is a real propagating wave with phase velocity

$$\mathrm{v}_\phi = \frac{\omega}{k} = \frac{c}{\sqrt{1 - \omega_p^2/\omega^2}} = \frac{c}{\sqrt{1 - n_e/n_c}} \qquad (6.113a)$$

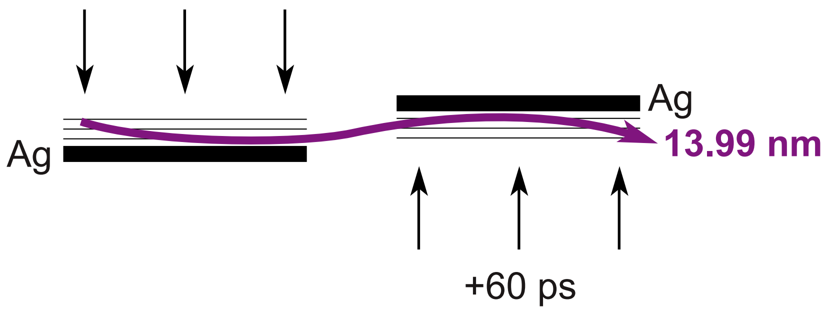
The refractive index of the plasma is

$$n = \sqrt{1 - \frac{\omega_p^2}{\omega^2}} \qquad (6.114a)$$

or equivalently

$$n = \sqrt{1 - \frac{n_e}{n_c}} \qquad (6.114b)$$

Refraction Compensating Double-Targets Used to Achieve Saturation of Lasing at 13.99 nm in Ni-like Ag



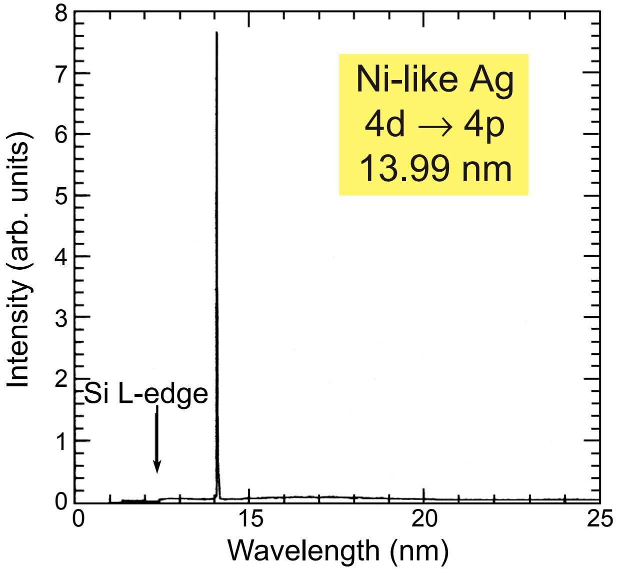
Nd laser: 1.05 μm, 2×10^{13} W/cm^2, 75 ps
Target: Ag stripes, 200 μm × 25 mm
Plasma: 700 eV, 6×10^{20} e/cm^3
43 × 57 μm, 1.5 × 3.5 mr

Courtesy of J. Zhang et al. (1997)
Rutherford Appleton Laboratory

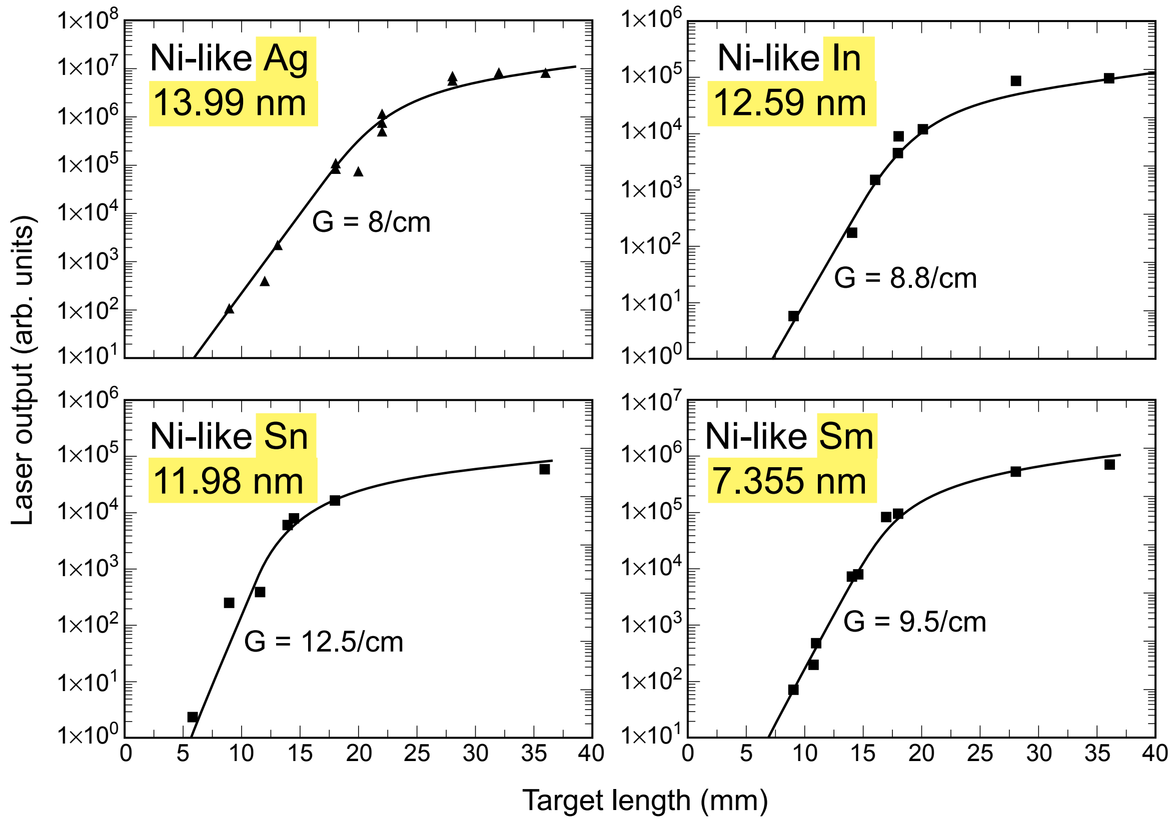
- Prepulse allows plasma expansion, decreases transverse electron density gradients and increases plasma volume
- Double targets permit refraction compensation (opposite turning angles) and double the gain length.
- Time delay of one target irradiation enhances gain in one direction
- Saturated 4d → 4p lasing at 13.99 nm in Ni-like Ag^{+19} (Z = 47, 28e$^-$)

Saturation of Nickel-like Lasing in Ag, In, Sn, and Sm

Refraction compensating double targets



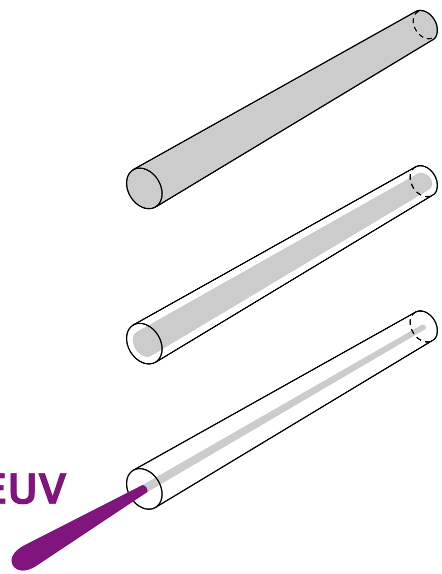
Courtesy of J. Zhang et al. (1977)
Appleton Rutherford Laboratory



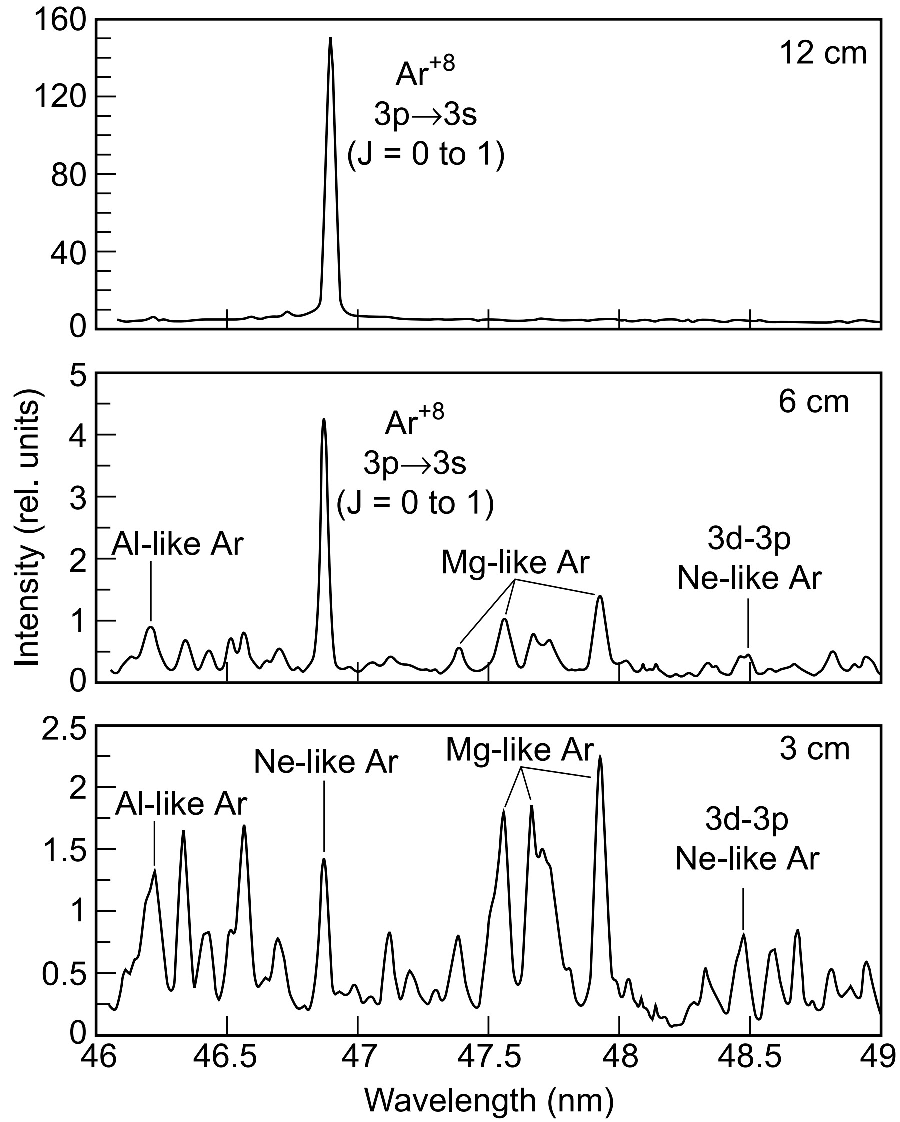
Courtesy of J.Y. Lin et al. (1999)
Appleton Rutherford Laboratory

Note: Wavelengths quoted are calculated by J. Scofield and B. MacGowan

High Average Power, High Spatial Coherence Table-Top Laser at 46.86 nm

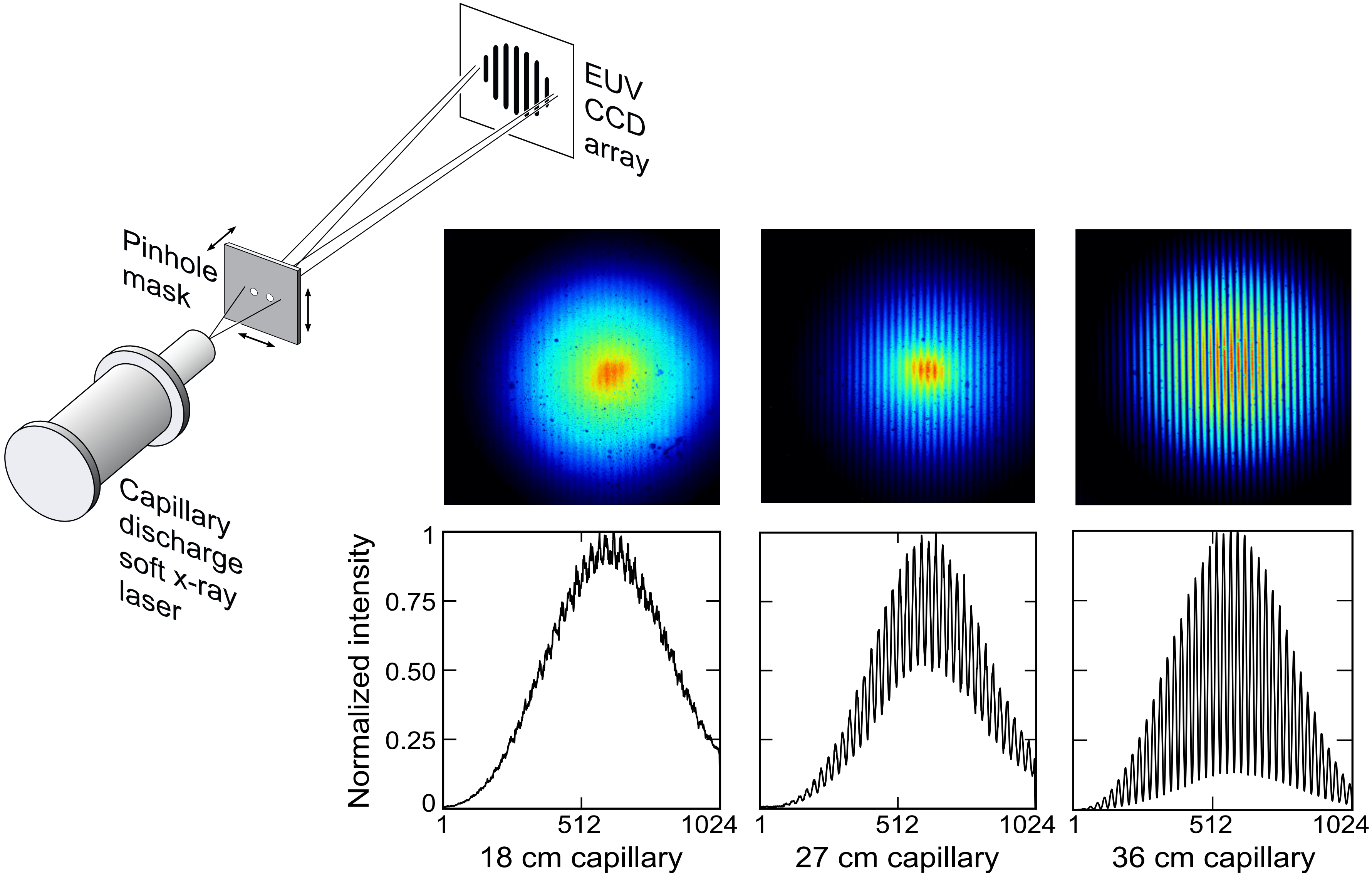


- Discharge plasma
- Fast, high current pulse compresses (**J** × **B**) and heats plasma
- 70 eV, 5×10^{18} e/cm^3
  300 µm^D × 36 cm long (1:1000)
- Ne-like Ar^{+8}, 3p → 3s at 46.86 nm
- $\overline{P}$ = 3.5 mW, spatially coherent



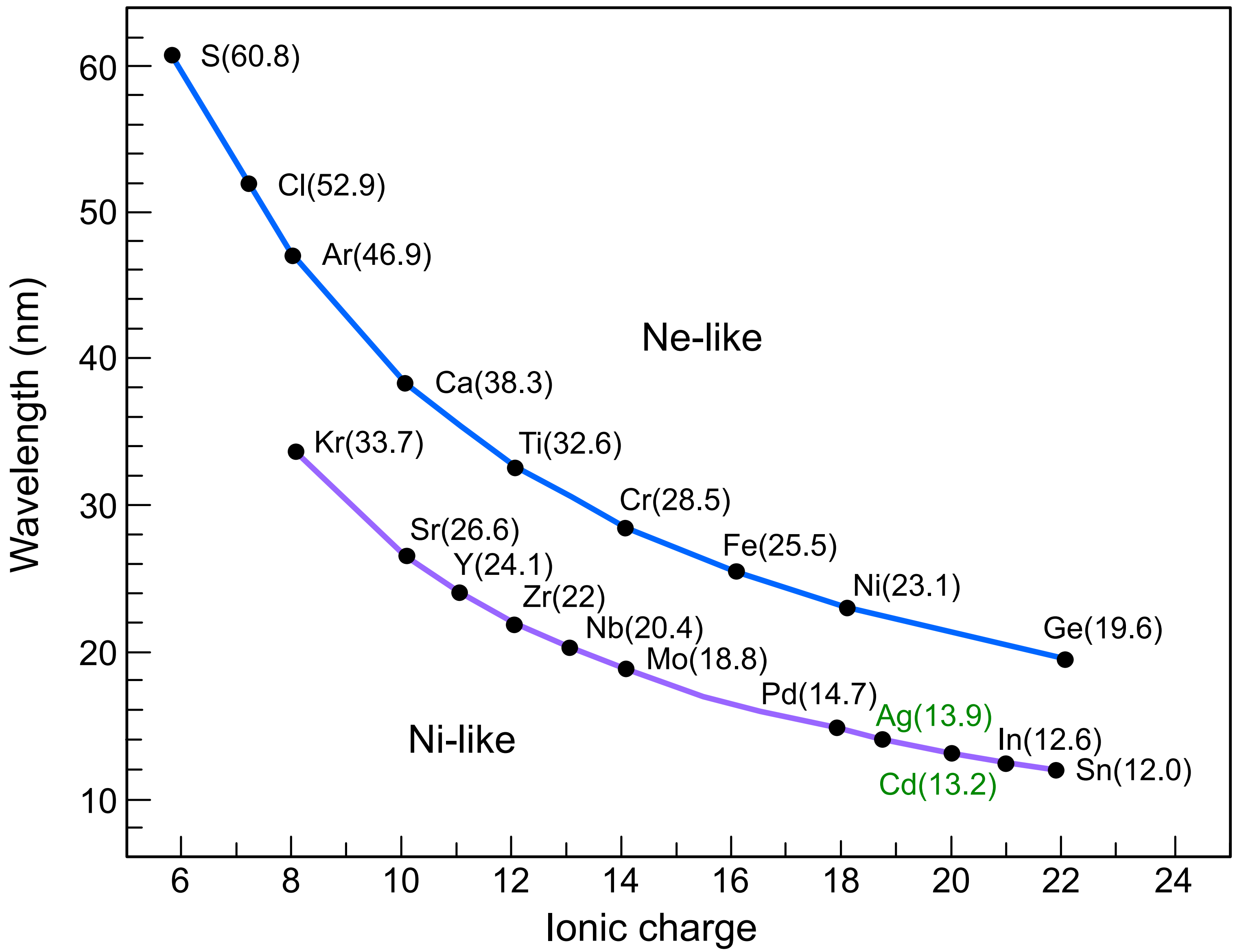
Courtesy of J. Rocca (1995), Colorado State University

Spatial Coherence of 46.86 nm Laser

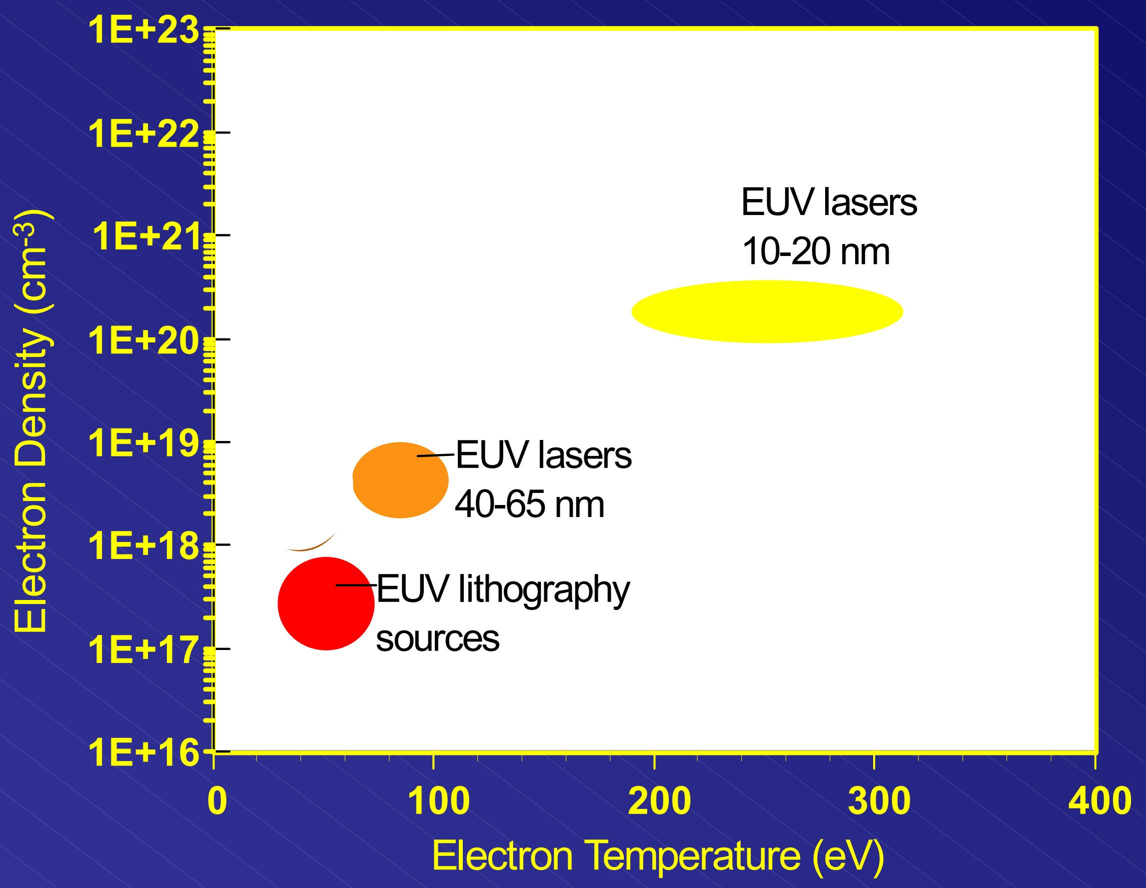


Courtesy of Y. Liu, UC Berkeley, and J. Rocca, Colorado State University (2001)

Scaling to 13 nm Requires Excitation of Ni-Like Cd Ions (Cd + 20)

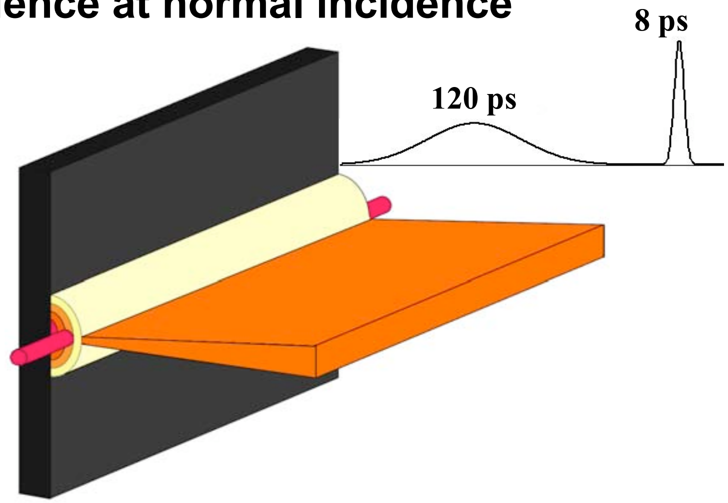


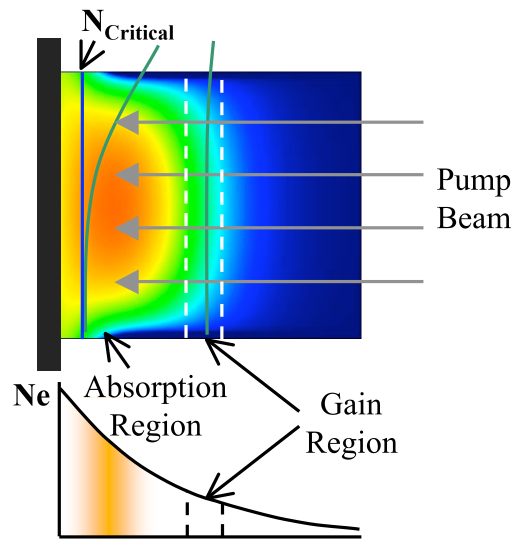
Generation of laser radiation at 13 nm requires significantly hotter and denser plasma columns



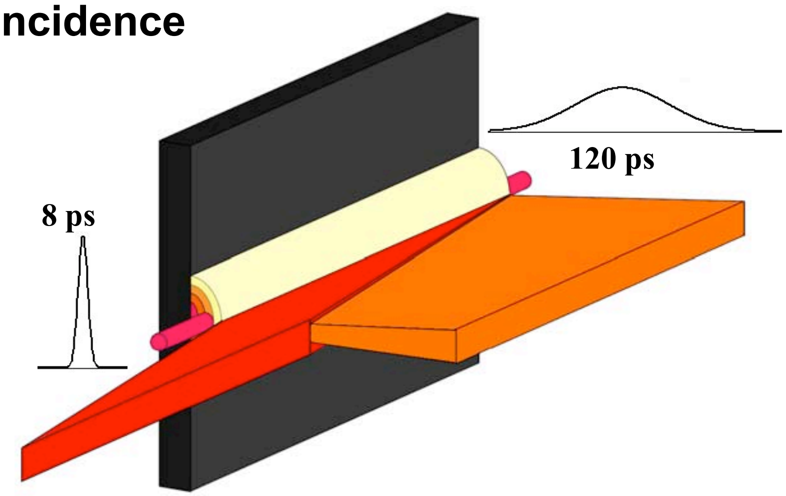
Pumping configurations for collisional EUV lasers in laser-created plasmas: Grazing incidence increases energy deposition efficiency*

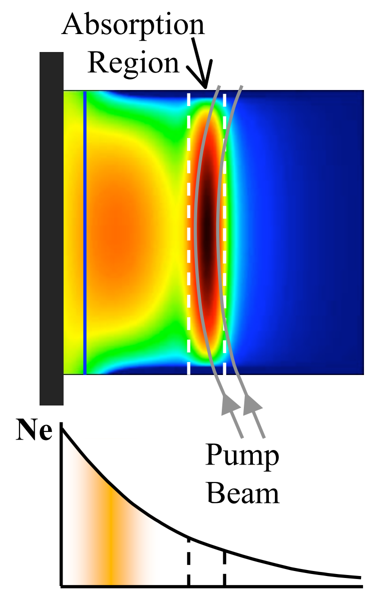
- Two pulse sequence at normal incidence





- Grazing incidence



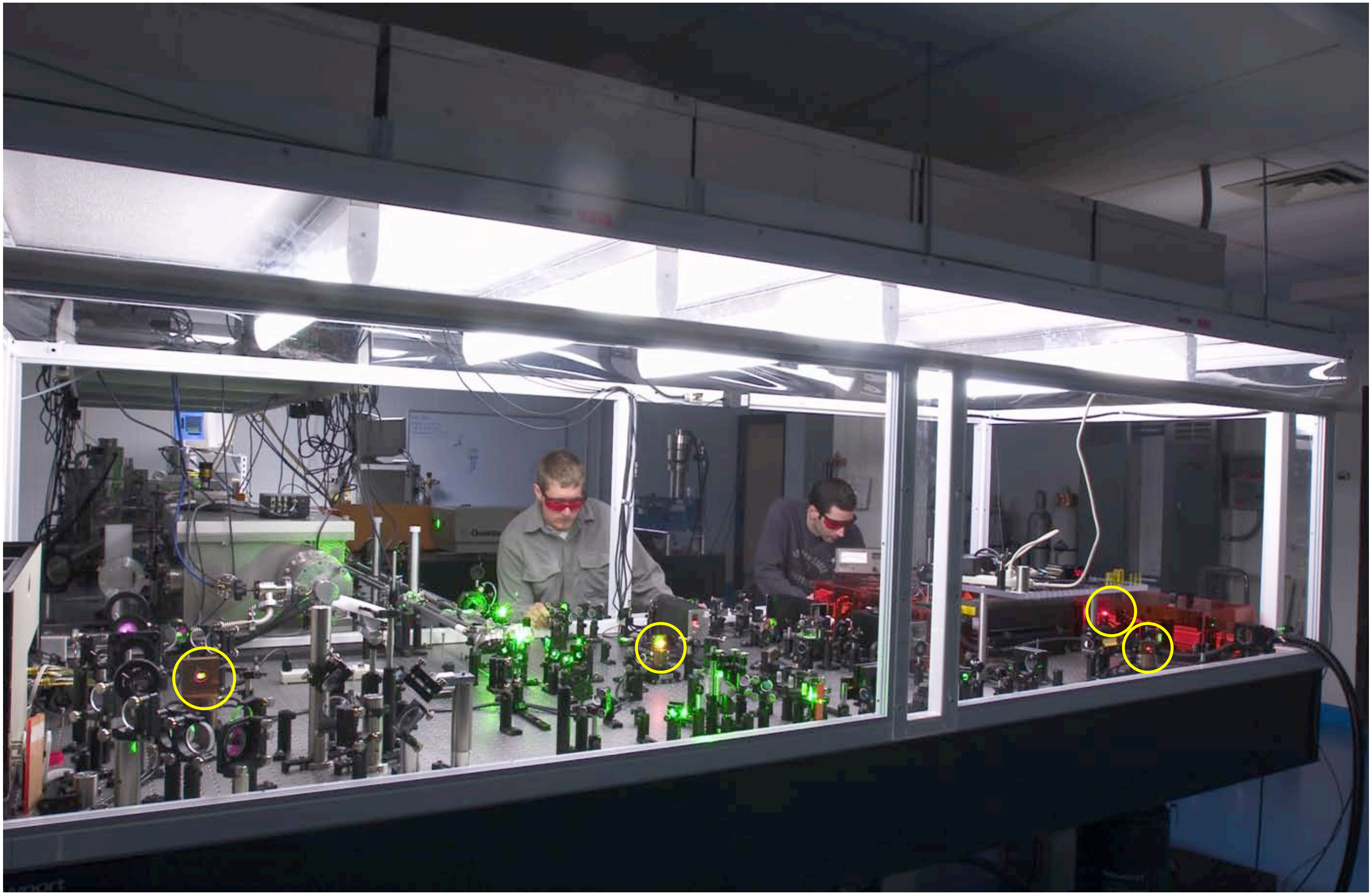


$$\theta = \sqrt{\frac{N_e}{N_c}}$$

Courtesy of J. Rocca
Colo. State U.

* R. Keenan, et al. Phys. Rev. Lett , 94, 103901 (2005).
B.M. Luther et al. Optics Lett, 30, 165 (2005)

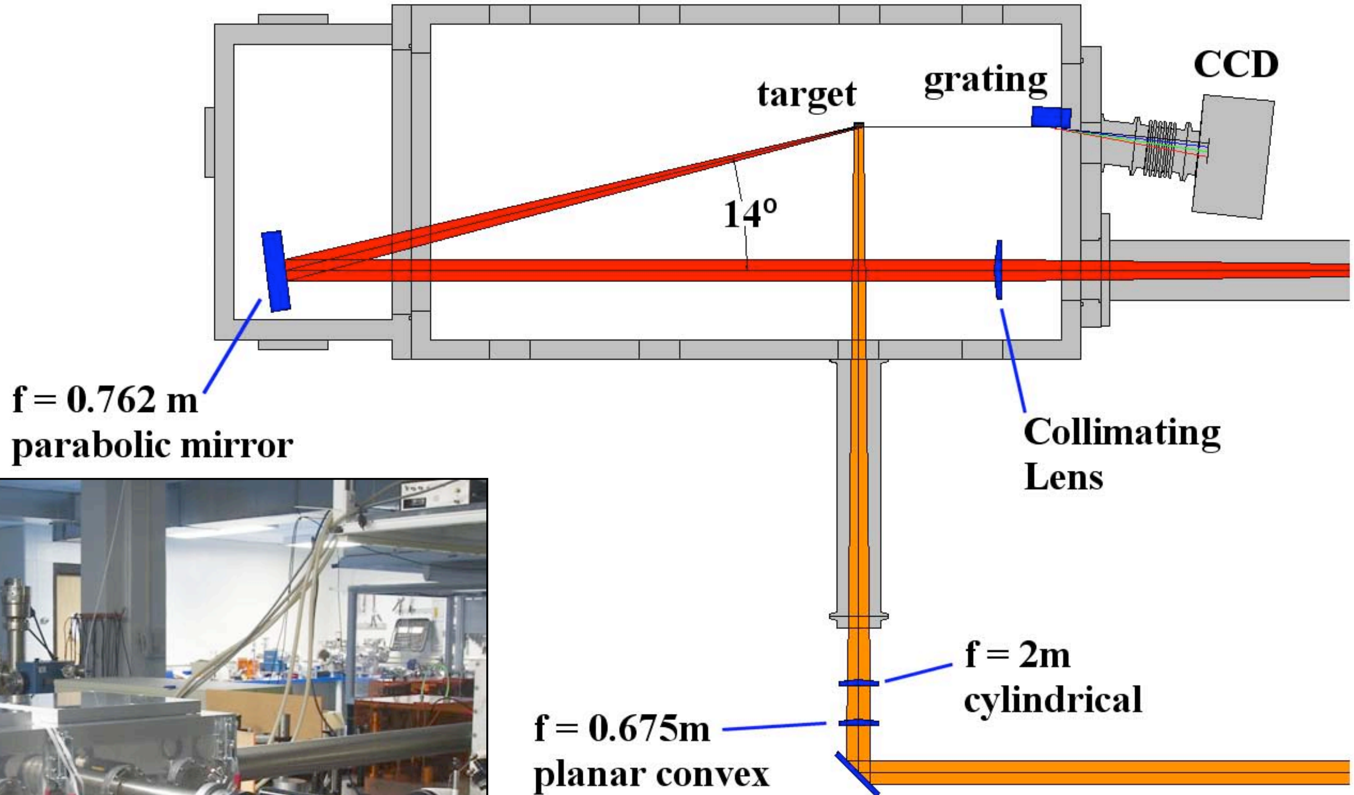
5-10 Hz Pump laser: 1 J Short Pulse Table-top Ti: Sapphire System

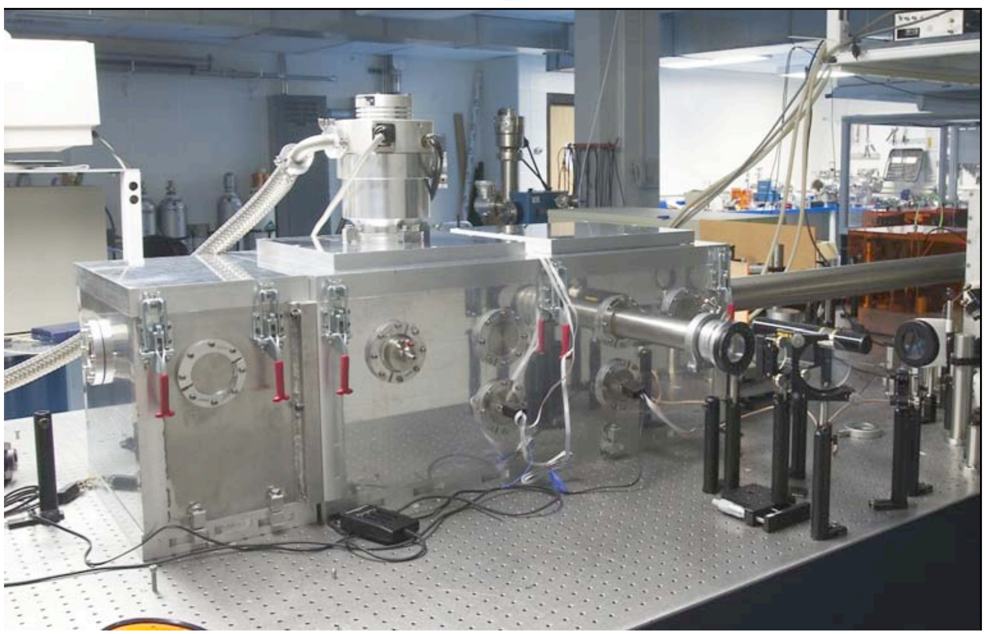


Courtesy of J. Rocca, Colo. State U.

Configuration for 30 µm wide short pulse line focus at 14 to 26 degrees grazing incidence

Line Focus
- Pre-pulse: 30µm FWHM,
- Short-pulse: 30µm FWHM,

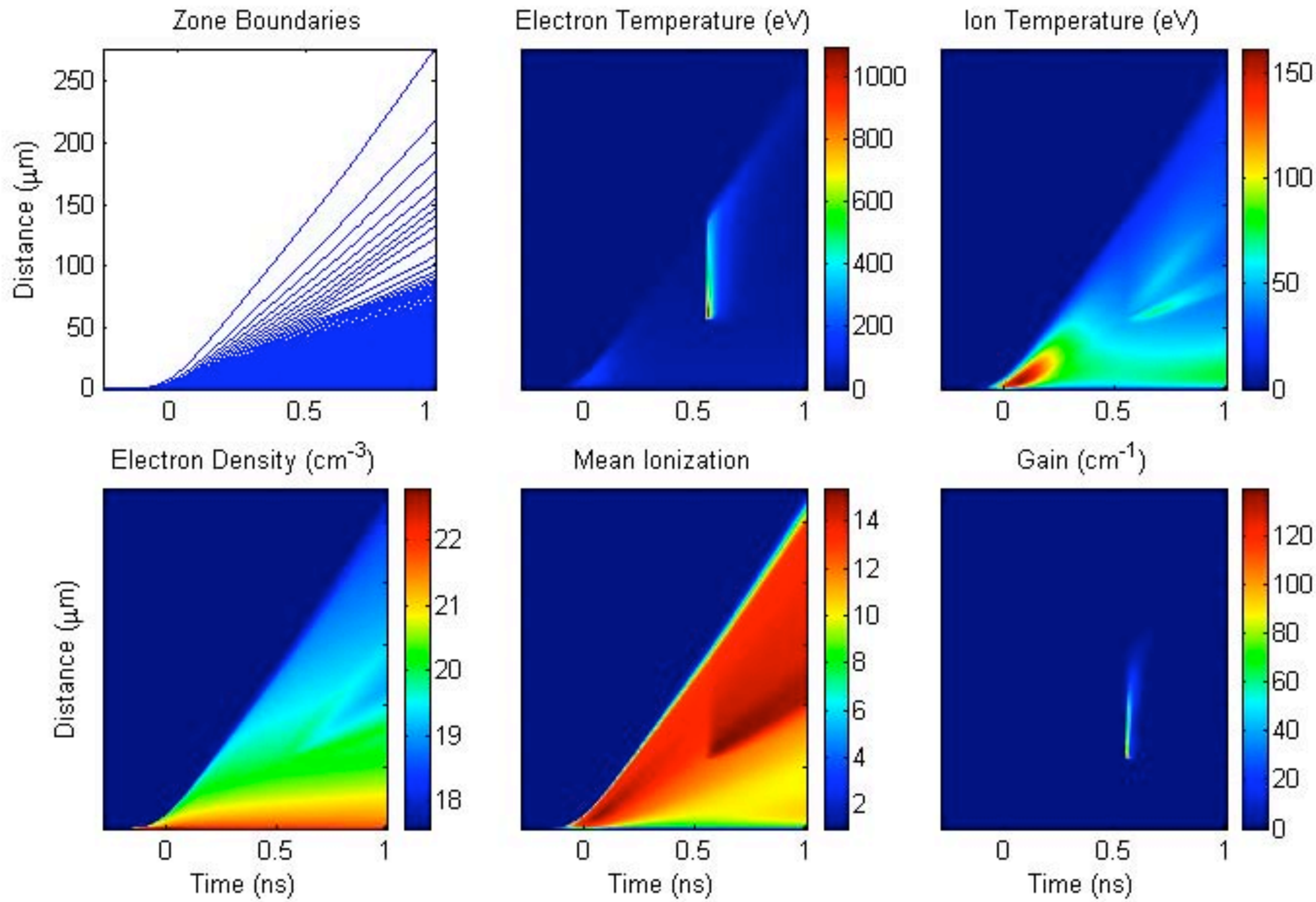




Courtesy of J. Rocca, Colo. State U.

Simulation predicts high gain at 18.9 nm in Ni-like Mo, g ~100 cm^{-1} (Mark Berrill, CSU)

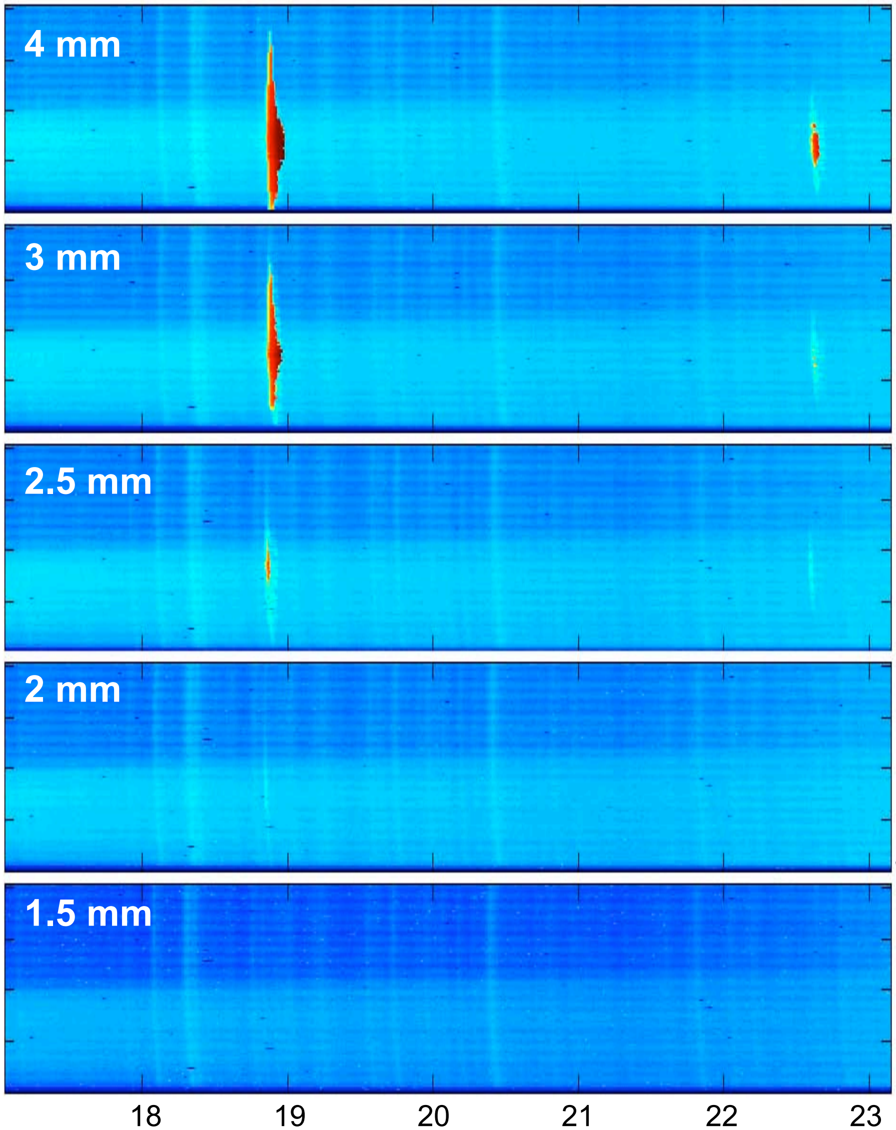
Pre-pulse: 330 mJ, 120 ps   Heating pulse: 800 mJ, 8 ps heating pulse

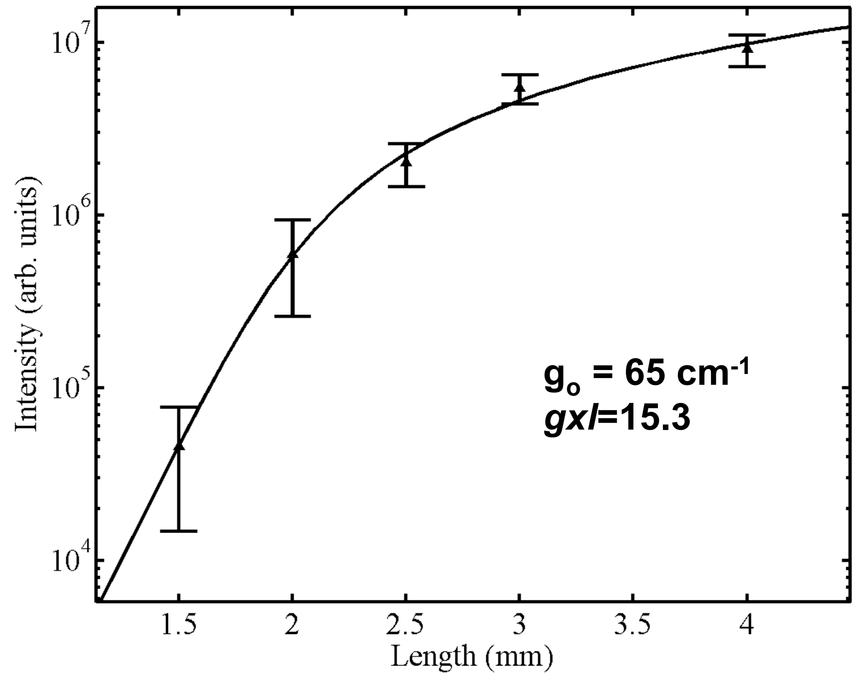


Courtesy of J. Rocca, Colo. State U.

Saturated 18.9 nm Ni-like Molybdenum Laser

Long pulse: 340 mJ - Short pulse: 1 J





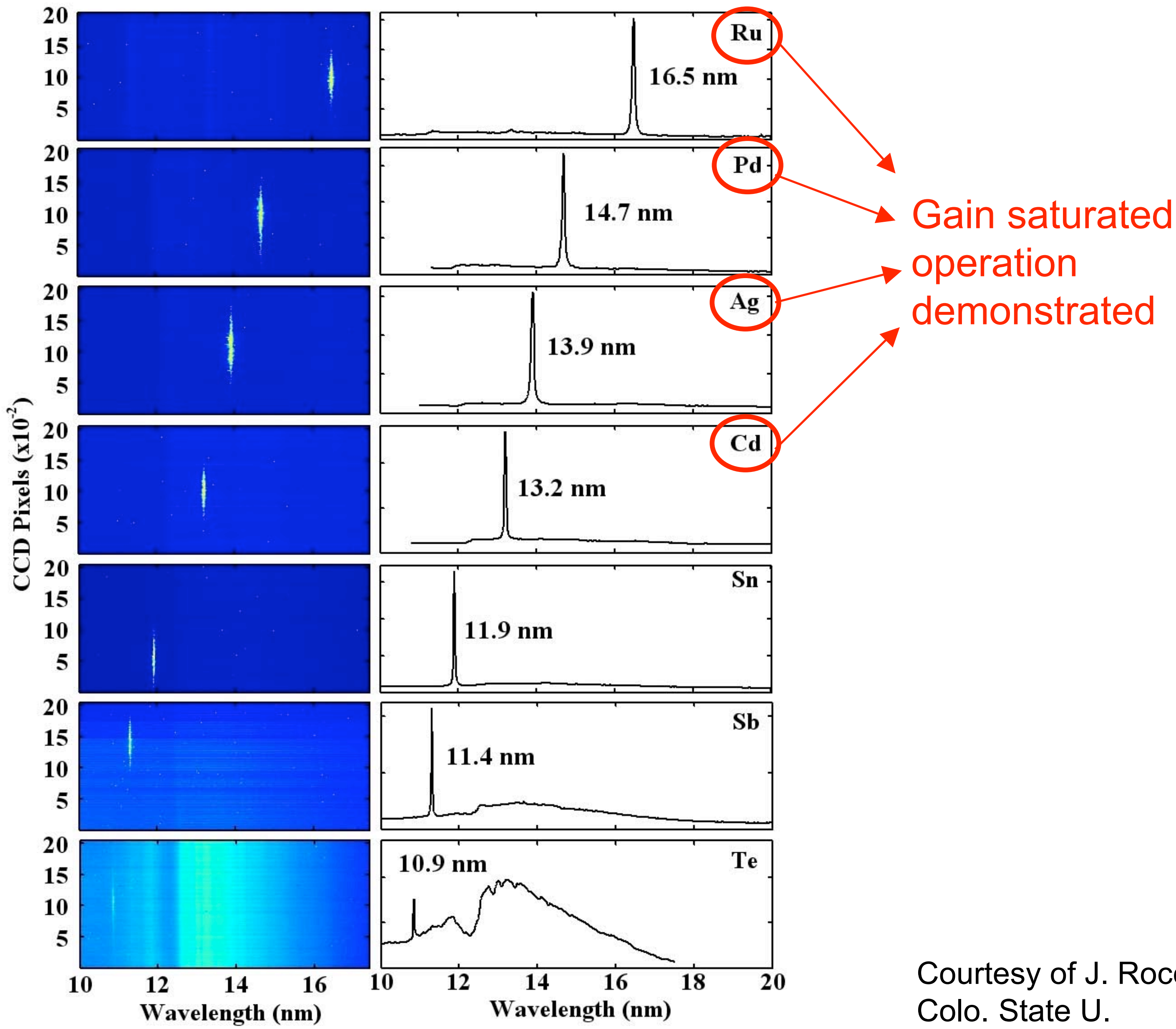
Fit with the expression from Tallents et. al. 8th Int. Conf. XRL, AIP Vol. 641, 2002.

$$GL + 2\frac{I_{av}}{I_s} = g_0 L$$

$$I_{av} = I_0 \frac{\left[\exp(GL) - 1\right]^{3/2}}{\left[GL\exp(GL)\right]^{1/2}}$$

Courtesy of J. Rocca, Colo. State U.

Lasing observed at wavelengths as short as 10.9 nm

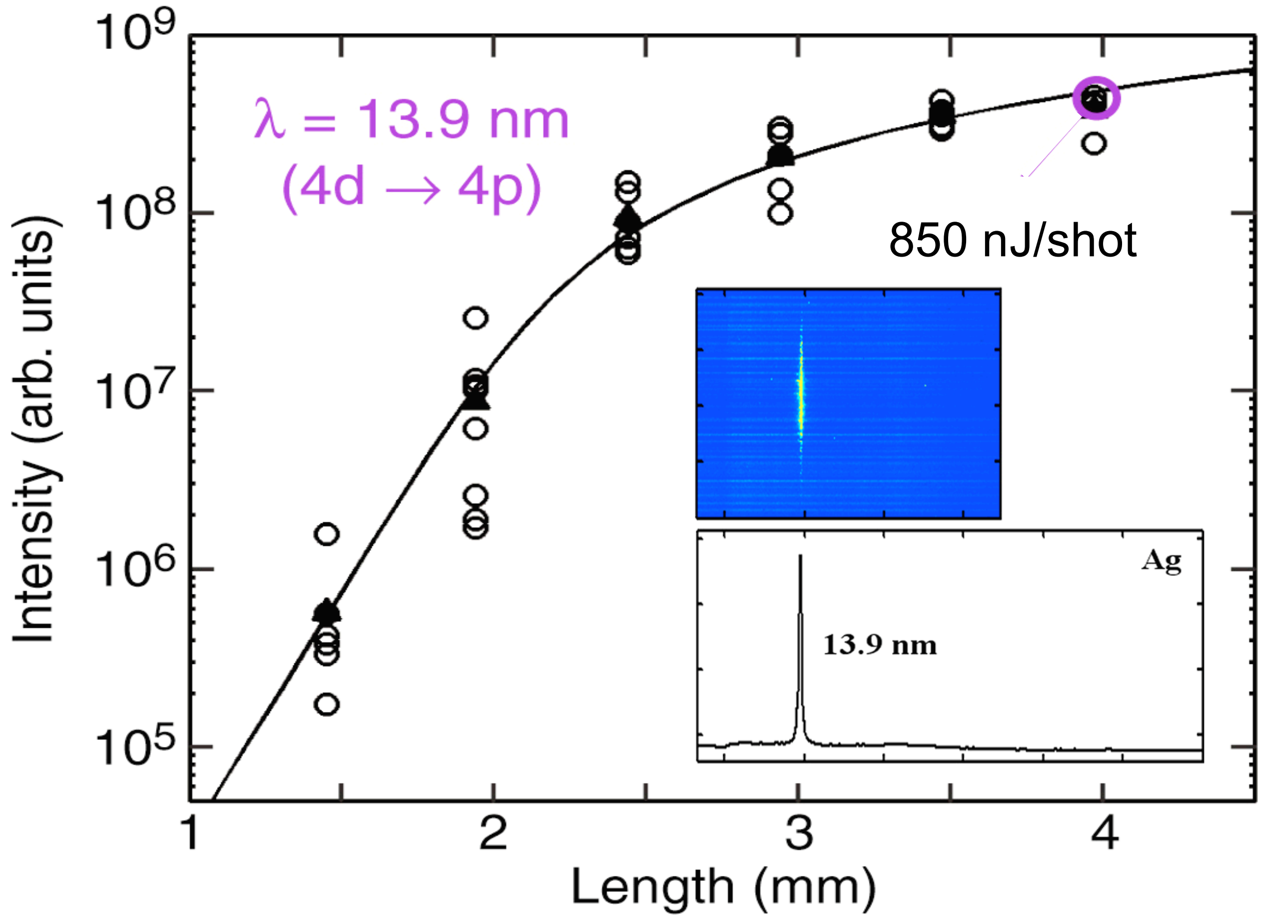


Courtesy of J. Rocca
Colo. State U.

Saturated laser operation at 13.9 nm in Nickel-like Ag

1 J short (8 ps) pulse excitation

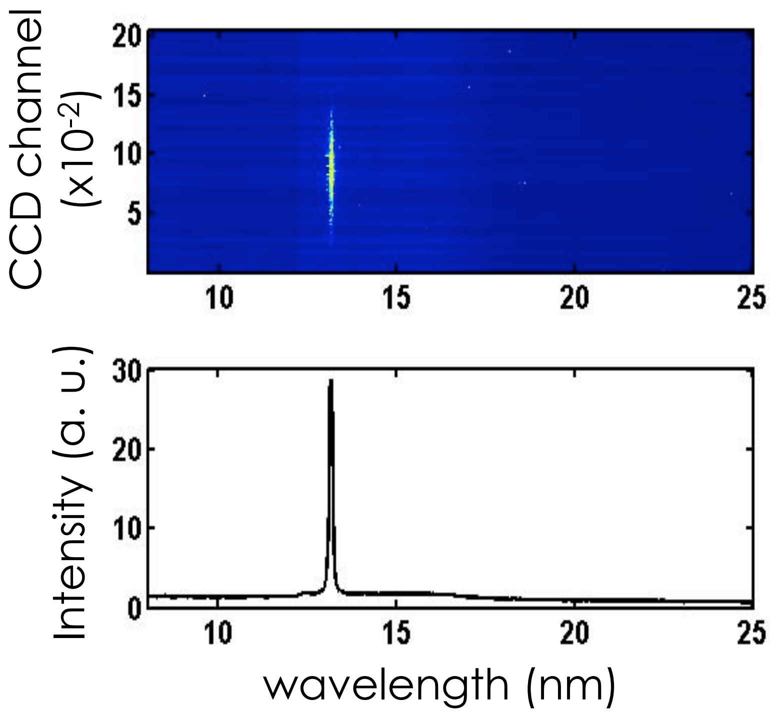
g_0=67 cm^{-1} ; gxl= 16.8

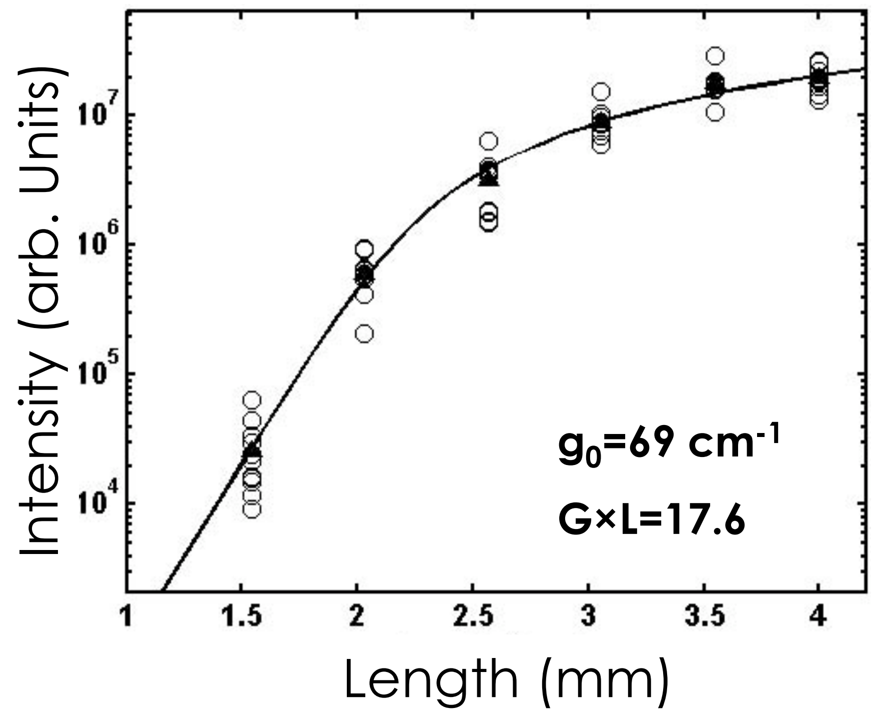


Courtesy of J. Rocca, Colo. State U.

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

1 J short pulse – 23 degrees grazing incidence angle

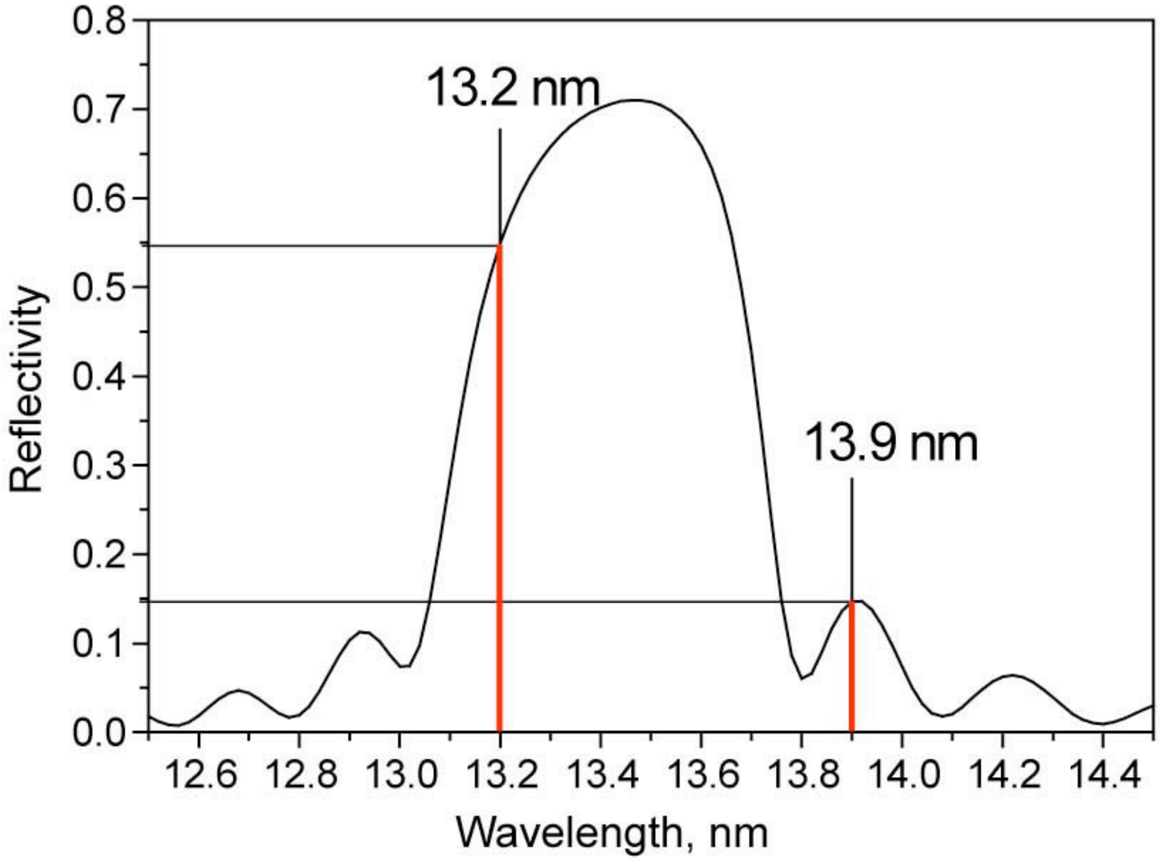




Courtesy of J. Rocca, Colo. State U.

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

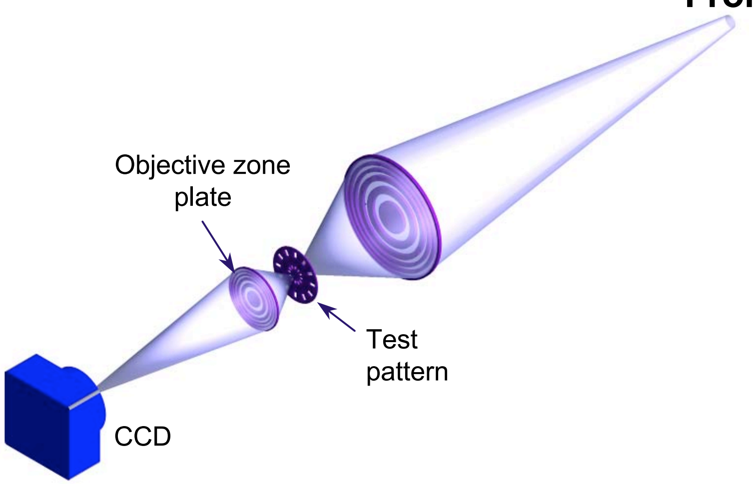
At the wavelength of the Ni-like Cd laser the reflectivity of Mo-Si mirrors centered at λ=13.5 nm is ~ 55%

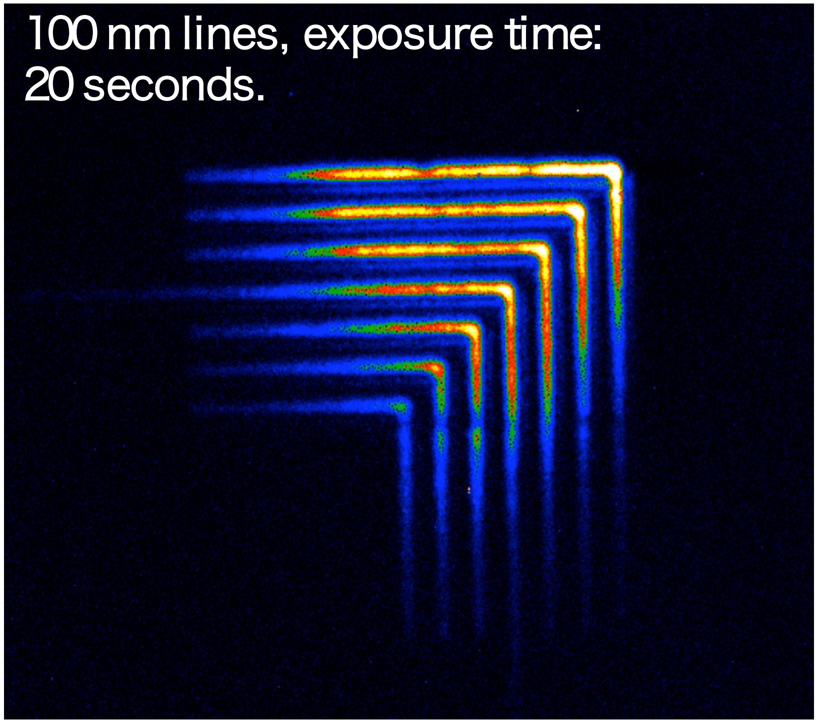


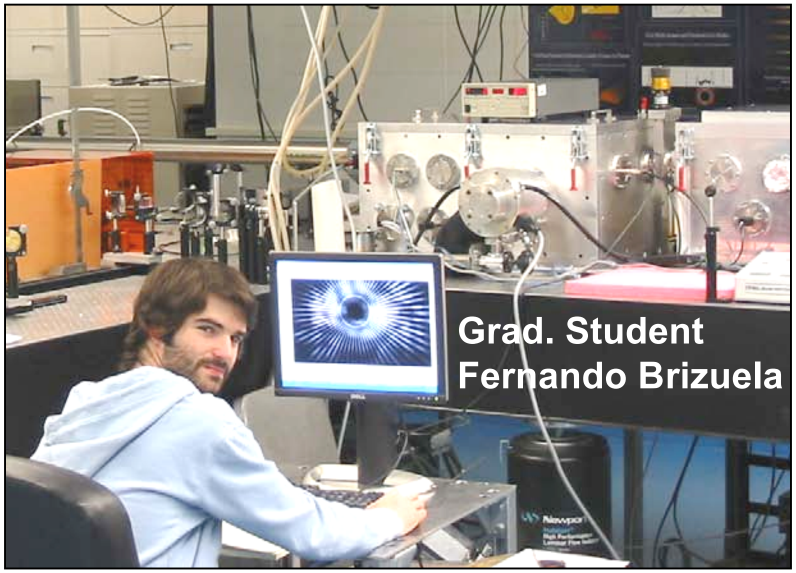
Courtesy of J. Rocca, Colo. State U.

The new compact EUV lasers are enabling application testbeds

Example: 13.9 nm Table-top EUV microscope with resolution better than 50 nm







Courtesy of J. Rocca, Colo. State U.