X-ray Lasers: The evolution from Star Wars to the table-top

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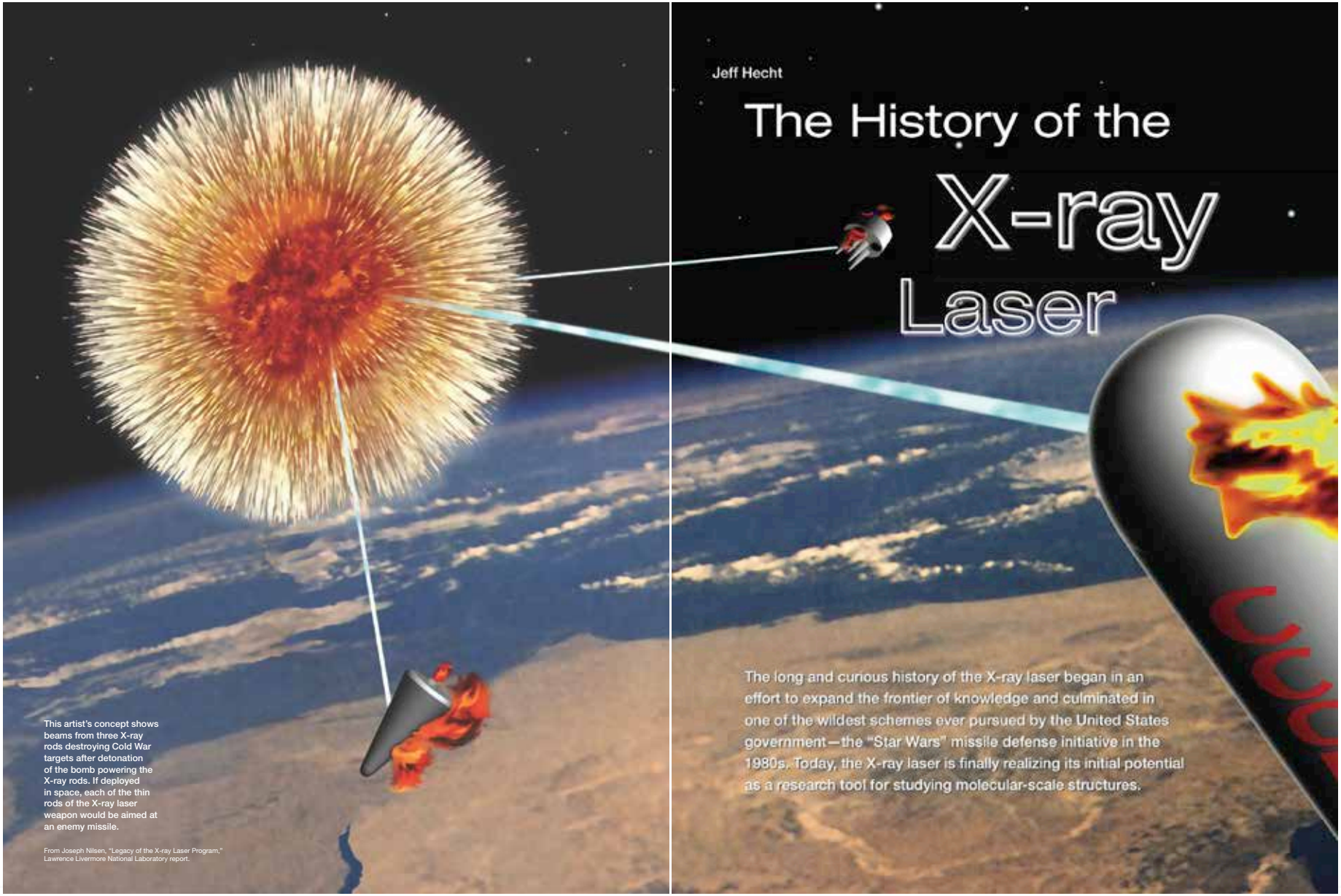
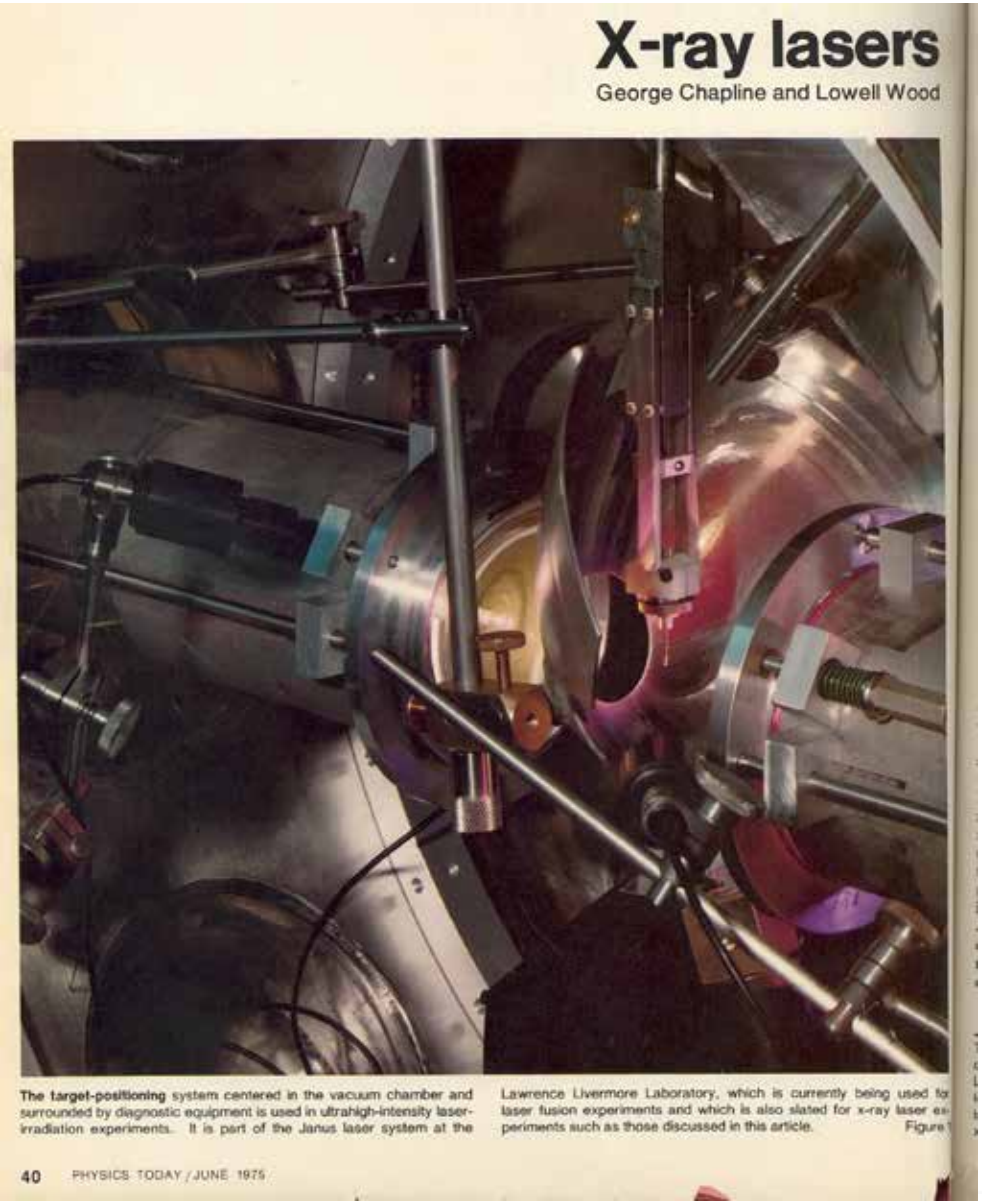
Jeff Hecht wrote a history of the X-ray laser for Optics and Photonics News in 2008 that begins with Star Wars



X-ray lasers have evolved from a Star Wars missile defense system to a table-top research tool

- LLNL proposes X-ray laser schemes in the 1970's
- First X-ray lasers demonstrated in early 1980's were nuclear pumped
- Demonstrated the world's shortest wavelength, highest energy laser
- First laboratory X-ray laser demonstrated on Novette in 1984
- A decade of progress using the Nova laser (5 kJ) from 1985 to 1996
- X-ray lasers produced at the COMET table-top facility (<10 J) since 1997
- X-ray lasers used for plasma interferometry and other applications
- 10 Hz X-ray laser at 18.9 nm demonstrated in 2004 using 0.15 J drive
- 100 Hz X-ray laser at 13.9 nm produces 1 μJ of saturated output using 0.9 J drive from diode-pumped optical laser in 2014

LLNL scientists propose X-ray laser schemes in 1975 Physics Today article using Janus and Cyclops laser to make 0.5 nm laser in H-like Kr

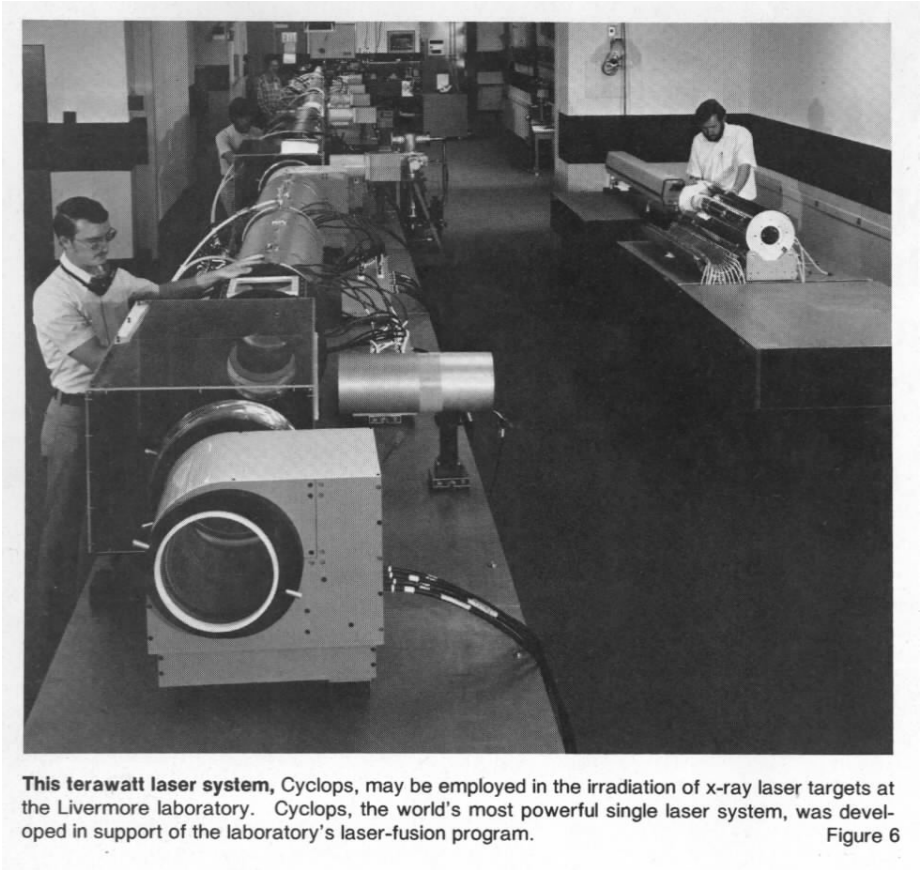


X-ray lasers

George Chapline and Lowell Wood

The target-positioning system centered in the vacuum chamber and surrounded by diagnostic equipment is used in ultrahigh-intensity laser-irradiation experiments. It is part of the Janus laser system at the Lawrence Livermore Laboratory, which is currently being used for laser fusion experiments and which is also slated for x-ray laser experiments such as those discussed in this article. Figure

40 PHYSICS TODAY / JUNE 1975



This terawatt laser system, Cyclops, may be employed in the irradiation of x-ray laser targets at the Livermore laboratory. Cyclops, the world's most powerful single laser system, was developed in support of the laboratory's laser-fusion program. Figure 6

LLNL demonstrated a nuclear pumped X-ray laser in the early 1980's prior to the laboratory X-ray laser

Soviets demonstrated a nuclear pumped X-ray laser

Laser and Particle Beams (1997), *vol.* 15, *no.* 1, *pp.* 3–15
Printed in the United States of America

Review of theoretical works on X-ray laser research performed at RFNC—VNIITF

By E.N. AVRORIN, V.A. LYKOV, P.A. LOBODA, AND V.YU. POLITOV
Russian Federal Nuclear Center—All-Russian Institute of Technical Physics, P.O. Box 245, Snezhinsk (Chelyabinsk-70), Chelyabinsk region, 456770, Russia

(Received 23 June 1996; Accepted 25 August 1996)

Research works on nonequilibrium plasma physics had a significant place in fundamental studies pursued at RFNC—VNIITF in 1980s with underground nuclear explosions. These works got under way after the XRL radiation with the wavelength $\lambda \approx 14$ Å and laser beam energy of about 100 kJ had been registered at an underground nuclear explosion (*Aviation Week and Space Technology* 1981). The goal of investigations conducted at VNIITF at that period was to verify the basic physical principles of XRL operation and evaluate the feasibility of attaining the reported parameters of XRL radiation (Aviation Week and Space Technology 1981).

Theoretical and experimental works on XRL problems resulted in the full-scale VNIITF experiment carried out in 1987. In this experiment X-ray pumping spectra and XRL radiation with the parameters close to calculated values were registered. Laser radiation energy measurements gave $E \approx 10$–20 kJ at $\lambda \approx 39$ Å and $E \approx 100$ kJ at $\lambda \approx 28$ Å.

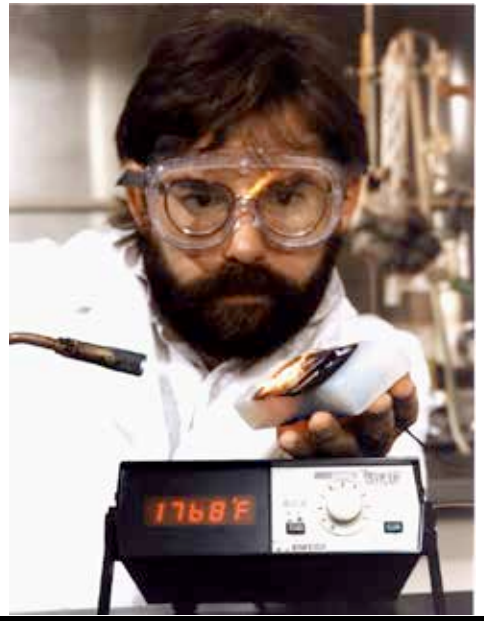
The experiment confirmed the validity of theoretical concepts on various XRL schemes and demonstrated experimentally the fundamental feasibility of creating such lasers using the energy of nuclear explosion.

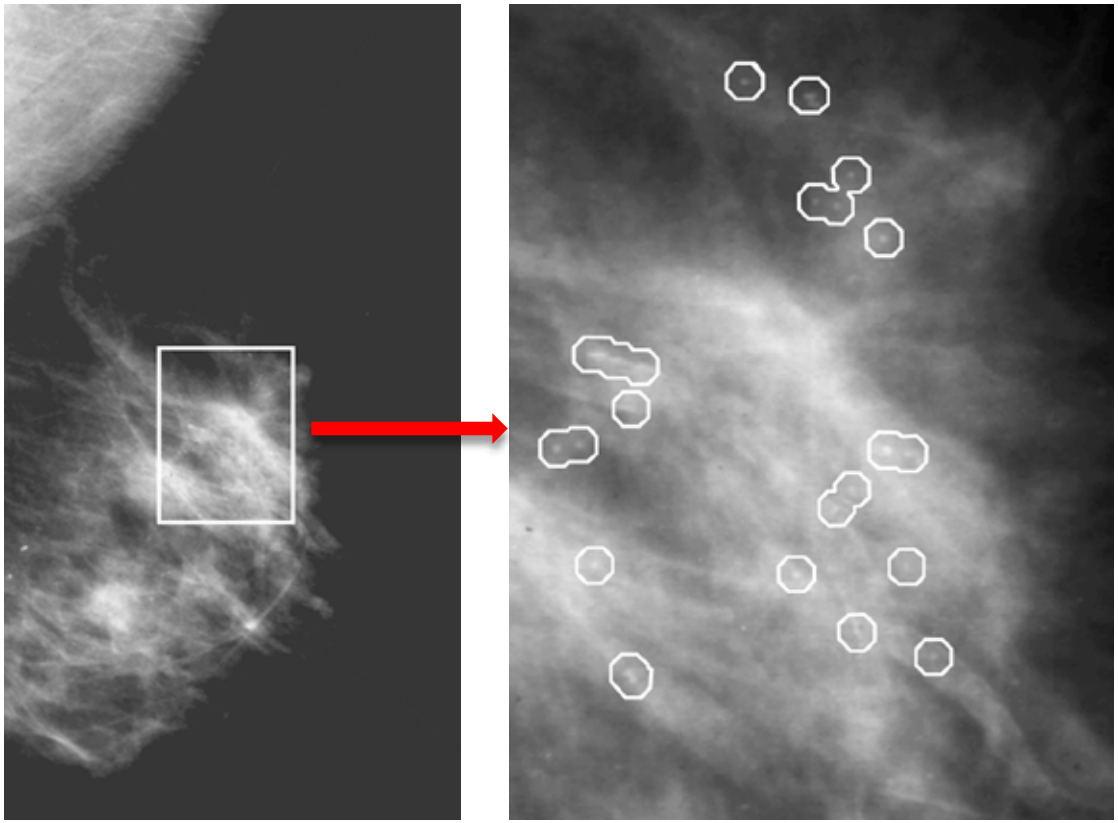
Some highlights of early LLNL X-ray laser program

First laboratory X-ray laser
Super light aerogels and other low density foams
Plasma kinetics and atomic physics codes
Greatly improved diagnostics -
- Fast x-ray detectors
- Transmission crystal spectrometers
- High-precision spatially resolved x-ray spectrometer

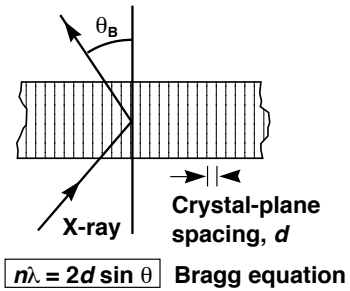
Electron-Beam Ion Trap (EBIT)
Digital mammograms
X-ray microscope using zone plates
Multilayer x-ray optics
The World's Shortest Wavelength,
- Highest Energy Experimentally Demonstrated Laser

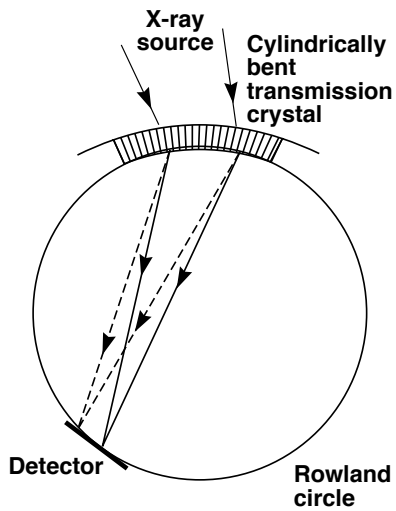
Very light aerogels and digital mammograms that identify suspicious micro-calcifications were developed as part of the X-ray laser program

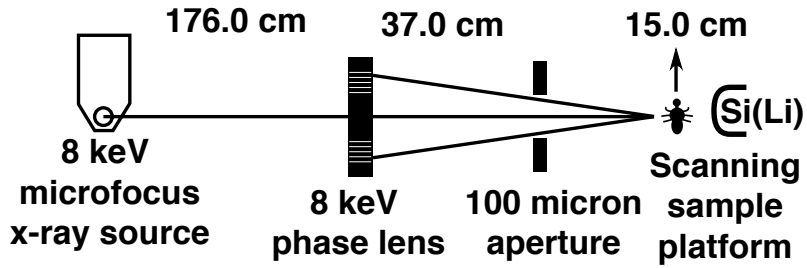


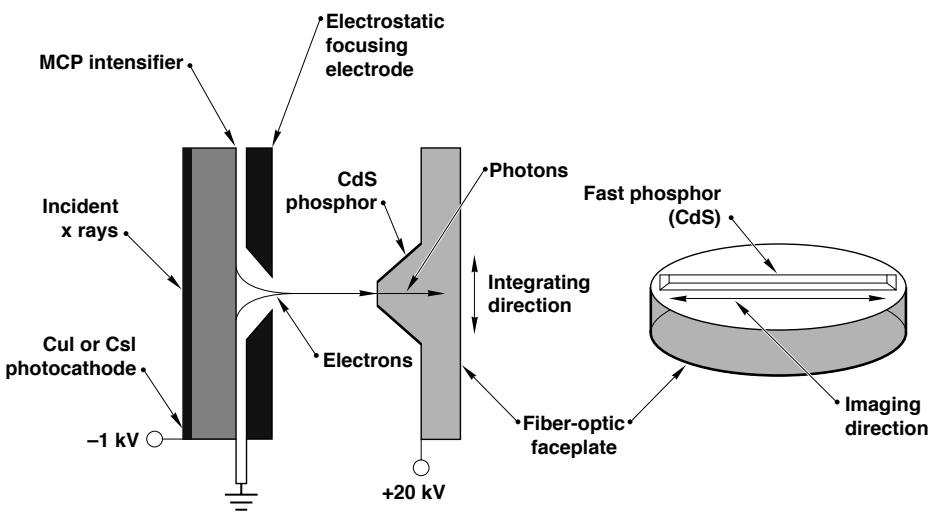


Transmission crystal spectrometer for measuring hard X-rays underground, time-resolving intensified detectors for low-level X-ray detection, and 8 keV scanning X-ray microscope are all legacies of the X-ray Laser program









LLNL demonstrated first laboratory X-ray laser in 1984 using Novette laser to drive Ne-like Se: Celebrated 30th anniversary at LLNL with symposium on May 5, 2015

VOLUME 54, NUMBER 2 PHYSICAL REVIEW LETTERS 14 JANUARY 1985

Demonstration of a Soft X-Ray Amplifier

D. L. Matthews, P. L. Hagelstein, M. D. Rosen, M. J. Eckart, N. M. Ceglio, A. U. Hazi, H. Medecki, B. J. MacGowan,[a] J. E. Trebes, B. L. Whitten, E. M. Campbell, C. W. Hatcher, A. M. Hawryluk, R. L. Kauffman, L. D. Pleasance, G. Rambach, J. H. Scofield, G. Stone, and T. A. Weaver
Lawrence Livermore National Laboratory, University of California, Livermore, California 94550
(Received 26 October 1984)

We report observations of amplified spontaneous emission at soft x-ray wavelengths. An optical laser ionized thin foils of selenium to produce a population inversion of the $2p^5 3p$ and $2p^5 3s$ levels of the neonlike ion. Using three time-resolved, spectroscopic measurements we demonstrated gain-length products up to 6.5 and gain coefficients of 5.5 ± 1.0 cm^{-1} for the $J=2$ to 1 lines at 206.3 and 209.6 Å. We also observed considerable amplification for the same transitions in yttrium at 155.0 and 157.1 Å.

VOLUME 54, NUMBER 2 PHYSICAL REVIEW LETTERS 14 JANUARY 1985

Exploding-Foil Technique for Achieving a Soft X-Ray Laser

M. D. Rosen, P. L. Hagelstein, D. L. Matthews, E. M. Campbell, A. U. Hazi, B. L. Whitten, B. MacGowan,[a] R. E. Turner, and R. W. Lee
Lawrence Livermore National Laboratory, University of California, Livermore, California 94550

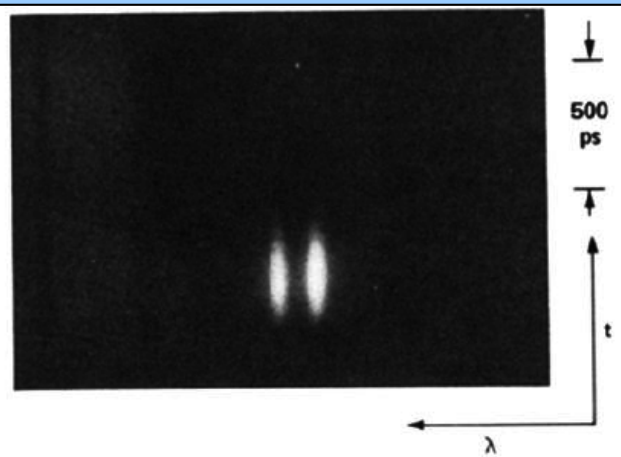
and

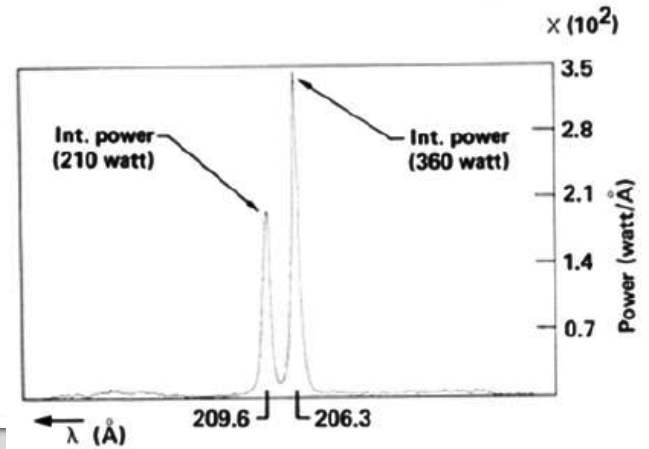
G. Charatis, Gar. E. Busch, C. L. Shepard, and P. D. Rockett
KMS Fusion, Inc., Ann Arbor, Michigan 48106
(Received 26 October 1984)

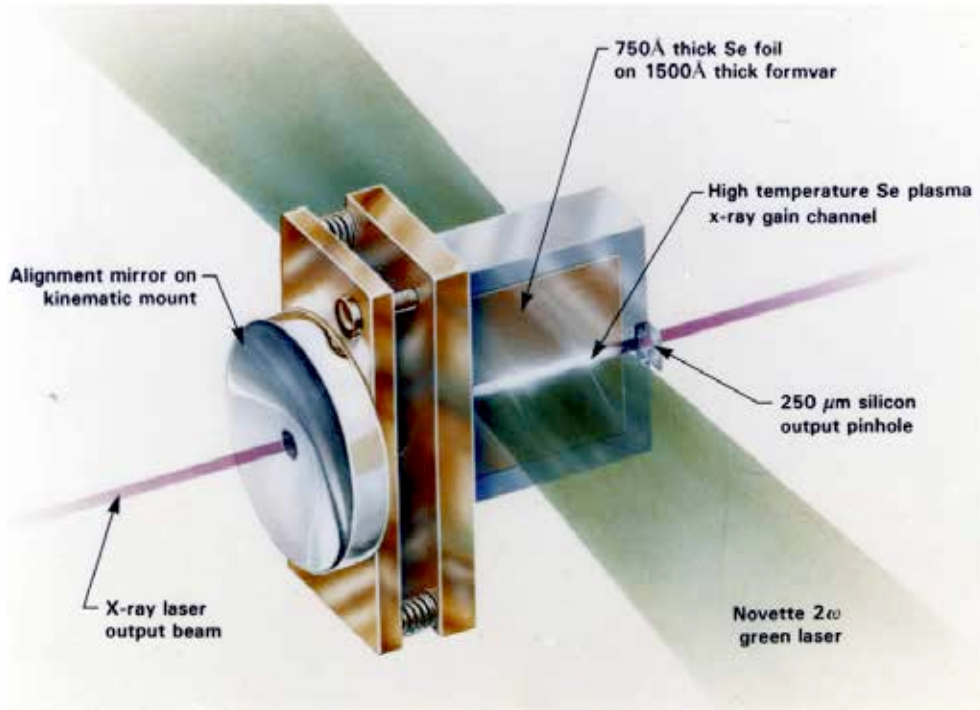
We describe a design for producing a soft x-ray laser via $3p$-$3s$ transitions in Ne-like selenium (wavelength of about 200 Å). A 0.53-μm laser, focused in a 1.2×0.02-cm spot to $\sim 5 \times 10^{13}$ W/cm^2, heats and burns through a thin foil of Se. Besides ionizing the Se to a Ne-like state, the laser explodes the foil, creating a region of uniform electron density. This allows propagation of the x rays down the 1-cm-long gain direction without debilitating refraction. Gains of 4 to 10 cm^{-1} are predicted for various transitions.

Ne-like Se laser at 20.6 and 20.9 nm was first demonstration of laboratory X-ray laser in 1984 on Novette

- Exploding foil Se target
- Double and single-sided irradiation
- 1 kJ, 450 ps 2ω pulse each side
- Line focus 200 μm × 1.1 cm, 2.2 cm



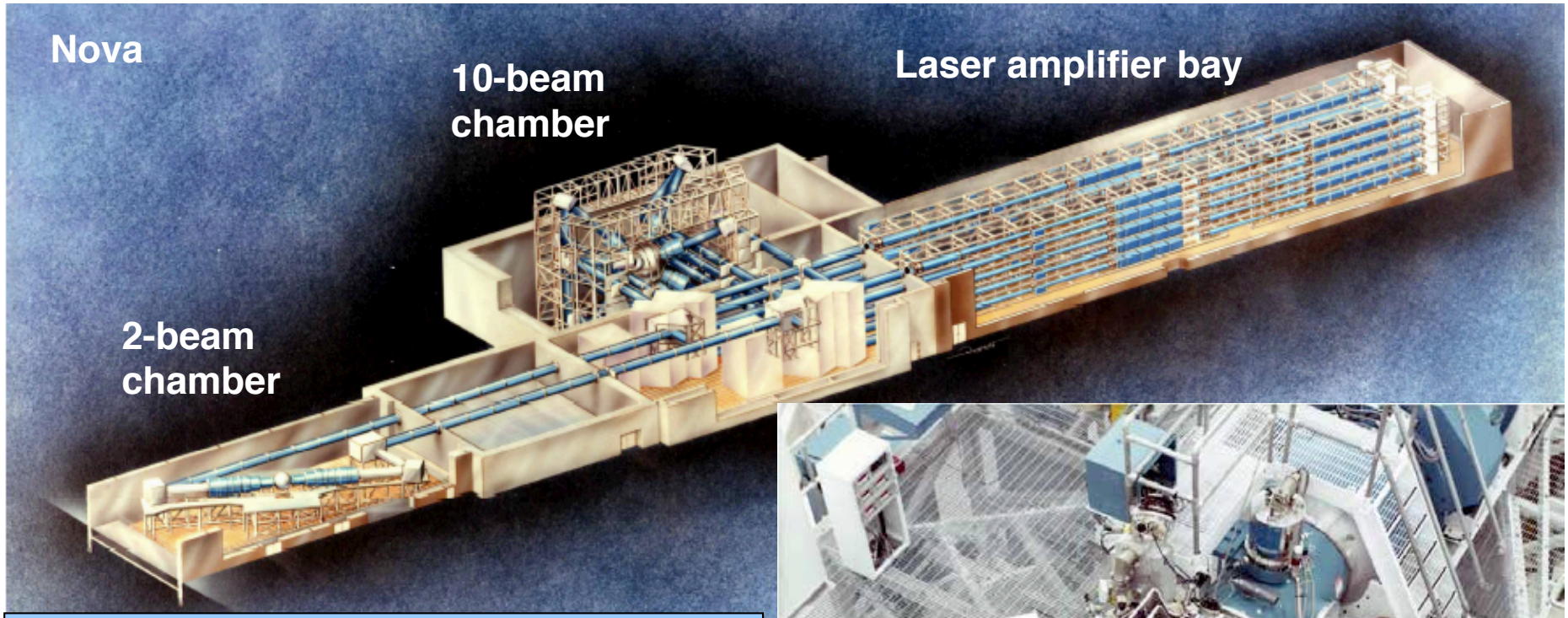




- Lasing observed on Ne-like Se 3p - 3s (J = 2 - 1) lines at 20.63 and 20.96 nm
- g ~ 5 cm^{-1}, gL = 6.5
- No lasing observed on 18.3 nm J= 0 - 1 line
- Lasing observed on Ne-like Y transitions

D.L. Matthews et al, PRL 54, 110 (1985)

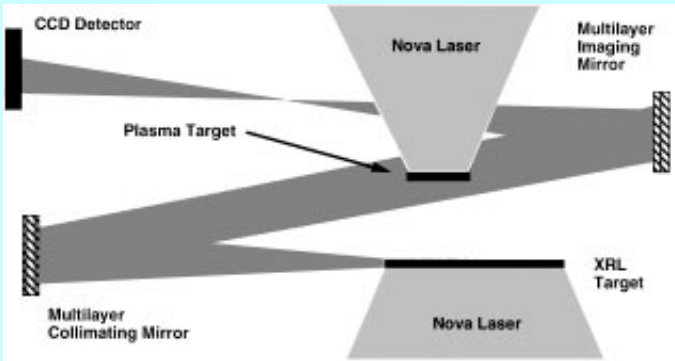
Early X-ray laser effort (1985 – 1996) was performed on the Nova laser: collisional excitation scheme was developed

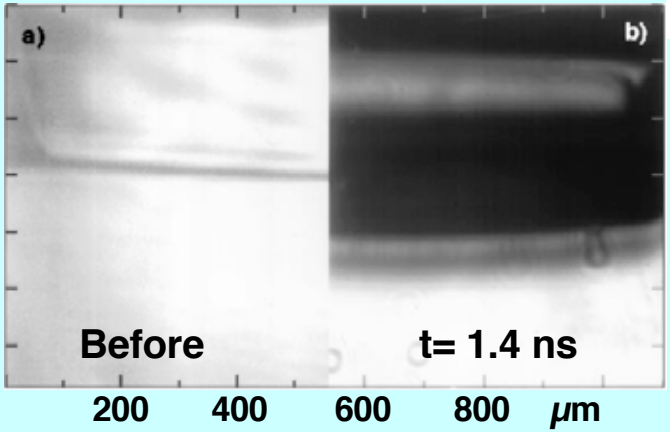


- Substantial infrastructure investment
- 2-beam target chamber was designed for X-ray laser research activities
- Soft x-ray diagnostics, optics, materials and instrumentation were developed

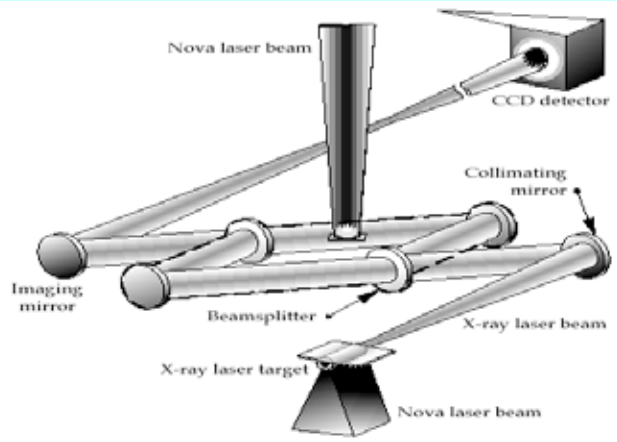
Many applications were developed using the 5 kJ Nova-driven X-ray laser during 1990s:

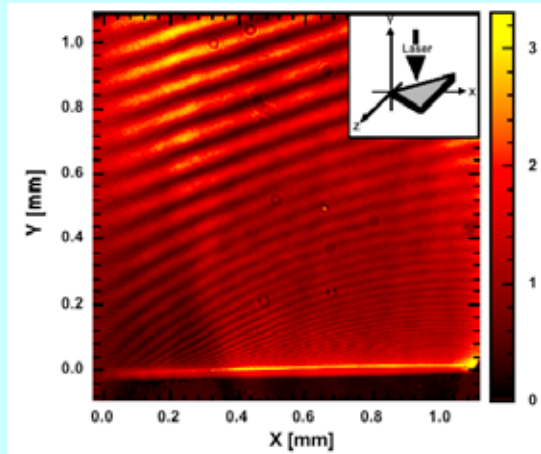
XRL Radiography Imaging of laser-heated Al Foil	XRL Interferometry of Laser Plasmas	X-ray Laser Microscopy of Biological Cells at 4.5 nm



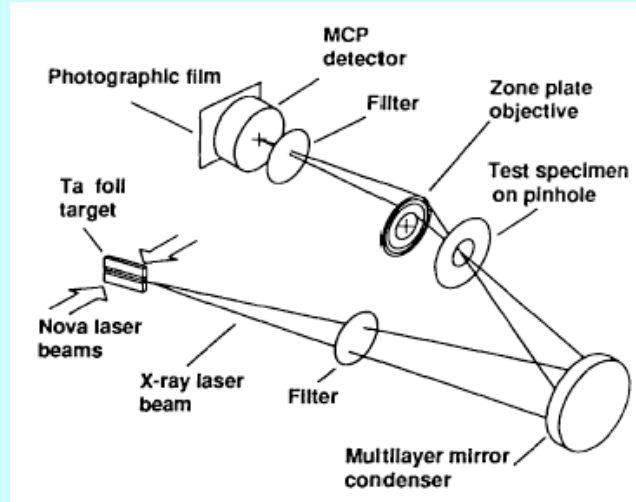


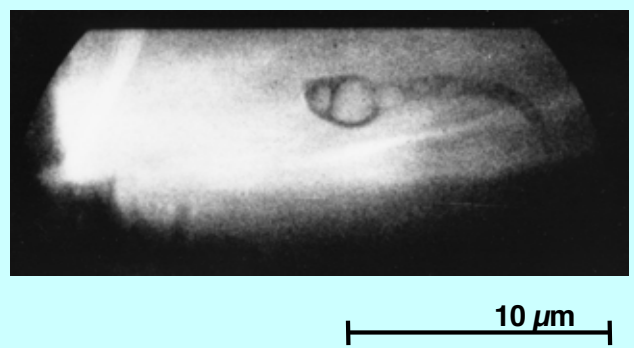
R. Cauble et al, PRL 74, 3816 (1995)





Da Silva *et al*, PRL 74, 3991 (1995).





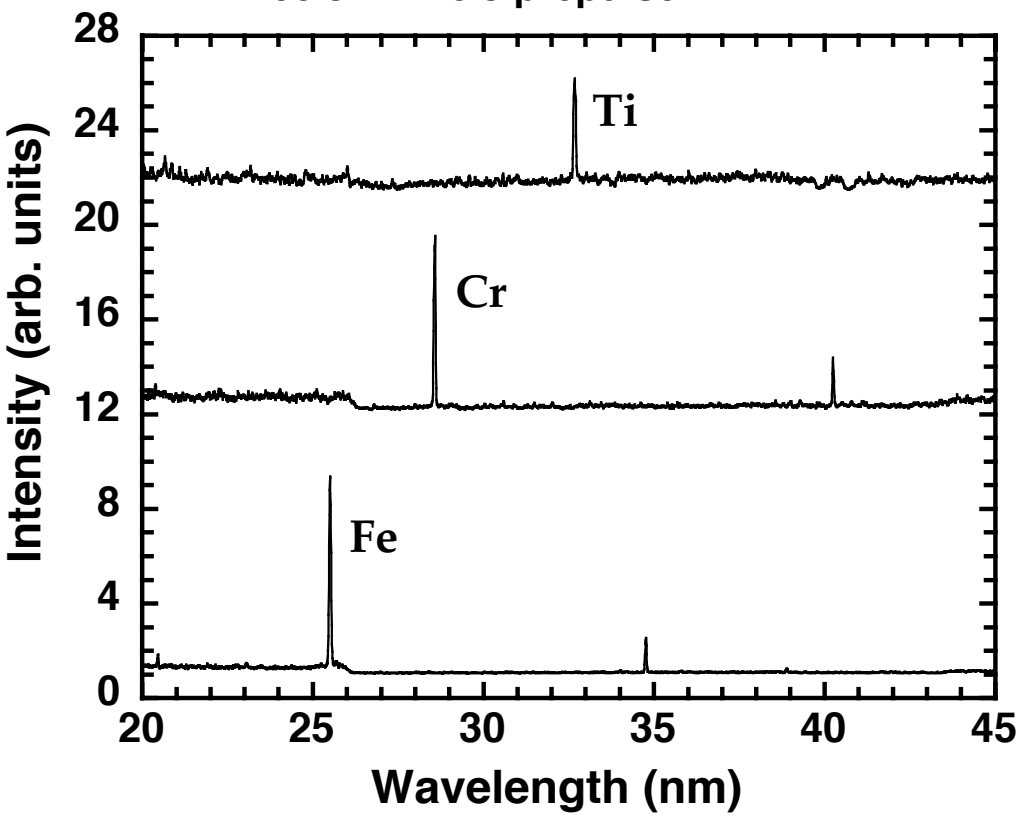
L. Da Silva *et al.*, Science 258, 269 (1992)

Pre-pulse technique using slab targets was developed using Nova laser and improved at the Asterix laser

Allowed Ne-like 3p - 3s (J = 0 - 1) line to lase and eliminated need for exploding foil targets

1992 Nova experiments

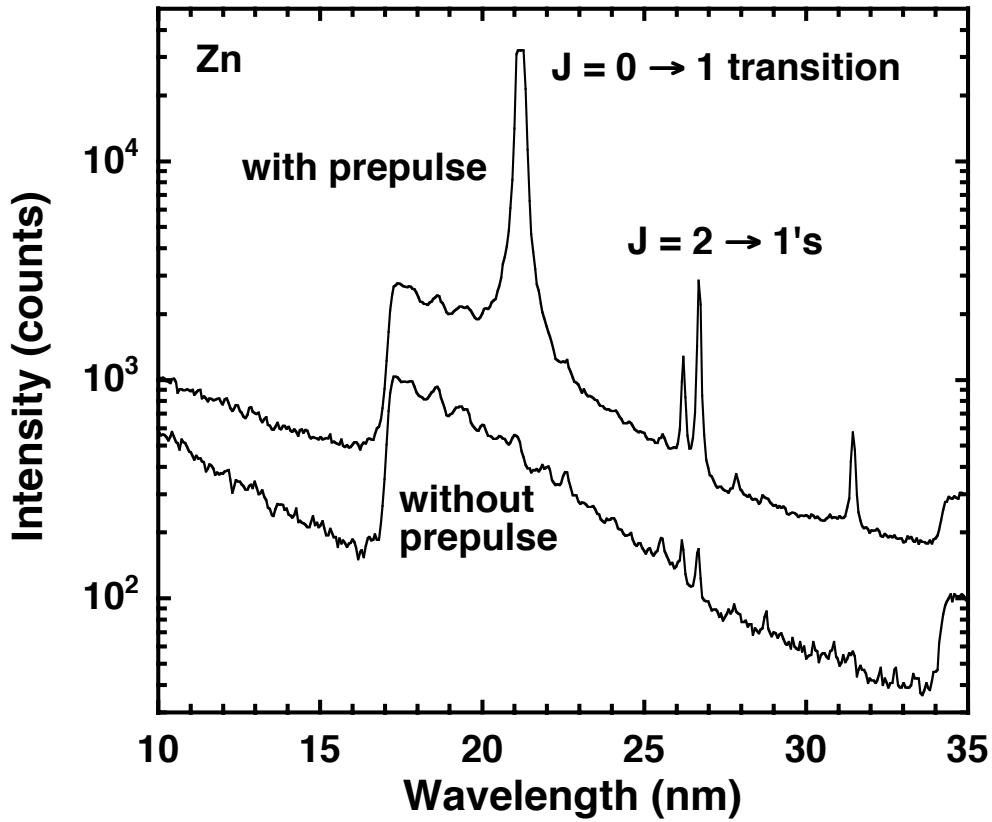
1100 J with 6 J prepulse



J. Nilsen, B. J. MacGowan, L. B. Da Silva, J. C. Moreno, Phys. Rev. A 48, 4682 - 4685 (December 1993).

1994 Asterix experiments

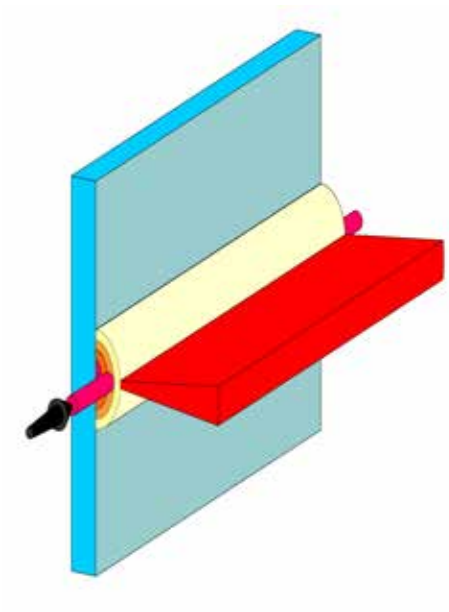
400 J with < 30 J prepulse

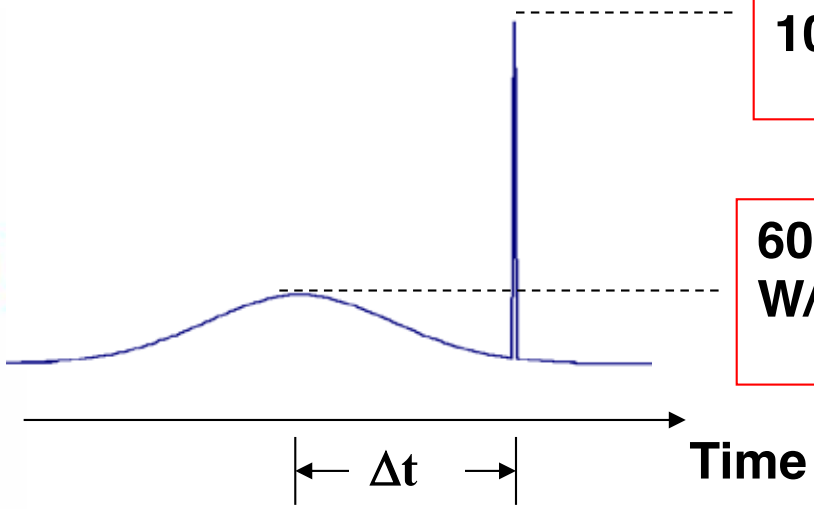


E. E. Fill, Y. Li, D. Schlögl, J. Steingruber, J. Nilsen, Opt. Lett. 20, 374 - 376 (February 15, 1995).

Pre-pulse technique combined with psec lasers are two breakthroughs that enabled table-top X-ray laser systems to be built

Pd target



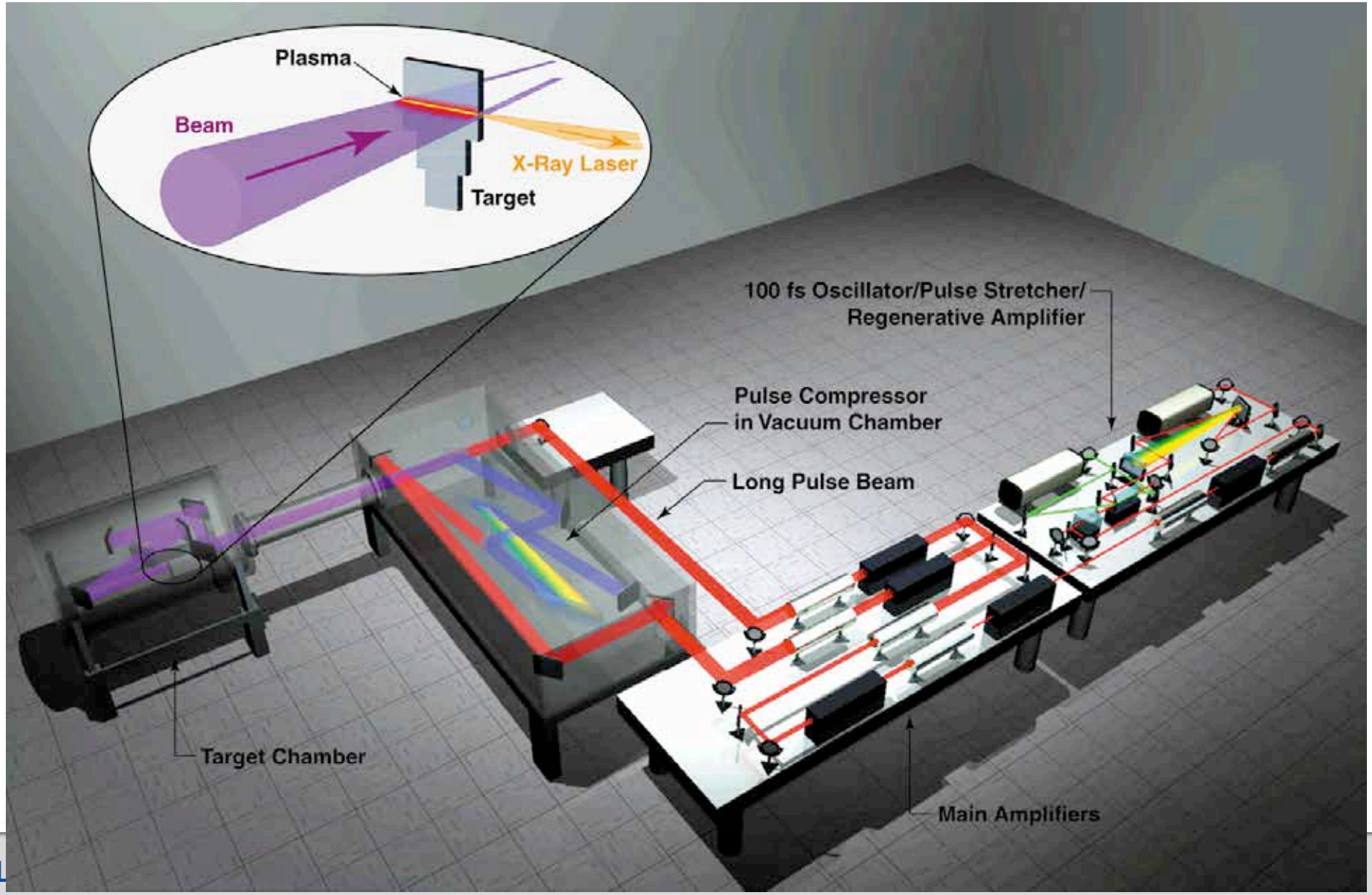


6 ps FWHM, 6 J, 5 × 10^{13} W/cm^2

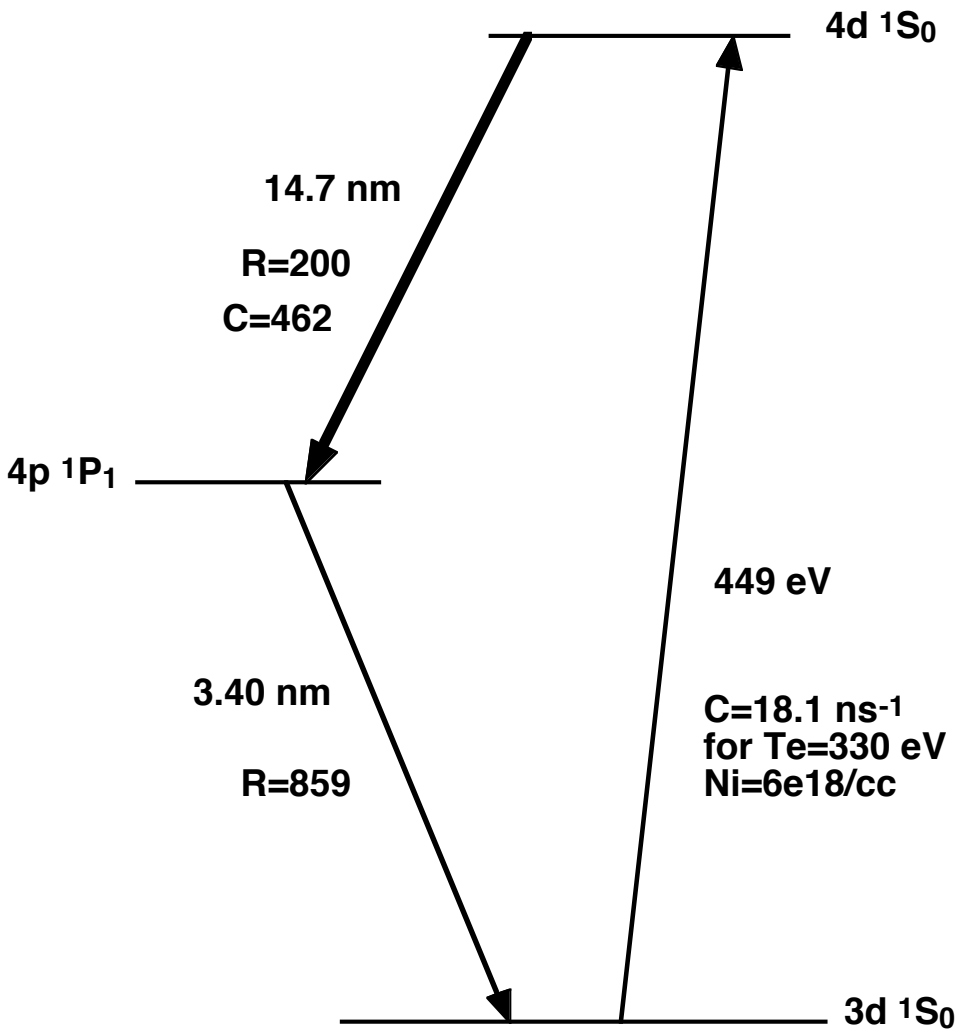
600 ps FWHM, 1 J, ~ 10^{11} W/cm^2

1.6 cm by 120 μm line focus traveling wave geometry

With the advent of psec lasers in 1990's X-ray laser experiments could be done every 3 minutes at the COMET laser facility at LLNL using less than 10 J of energy



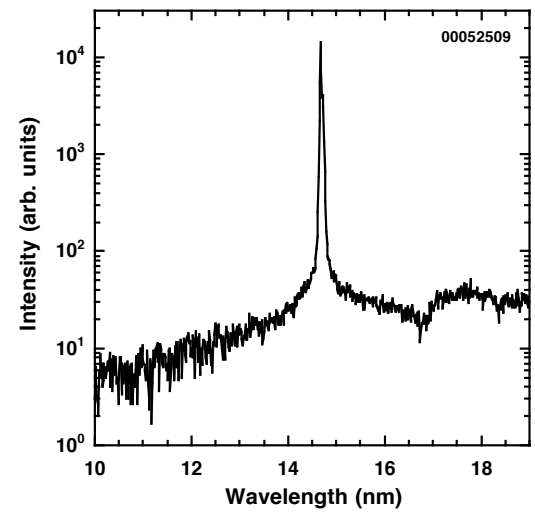
Ni-like Pd laser at 14.7 nm can be modeled as a 3 level system driven by collisional monopole excitation



Ni-like Pd (IP=814 eV)

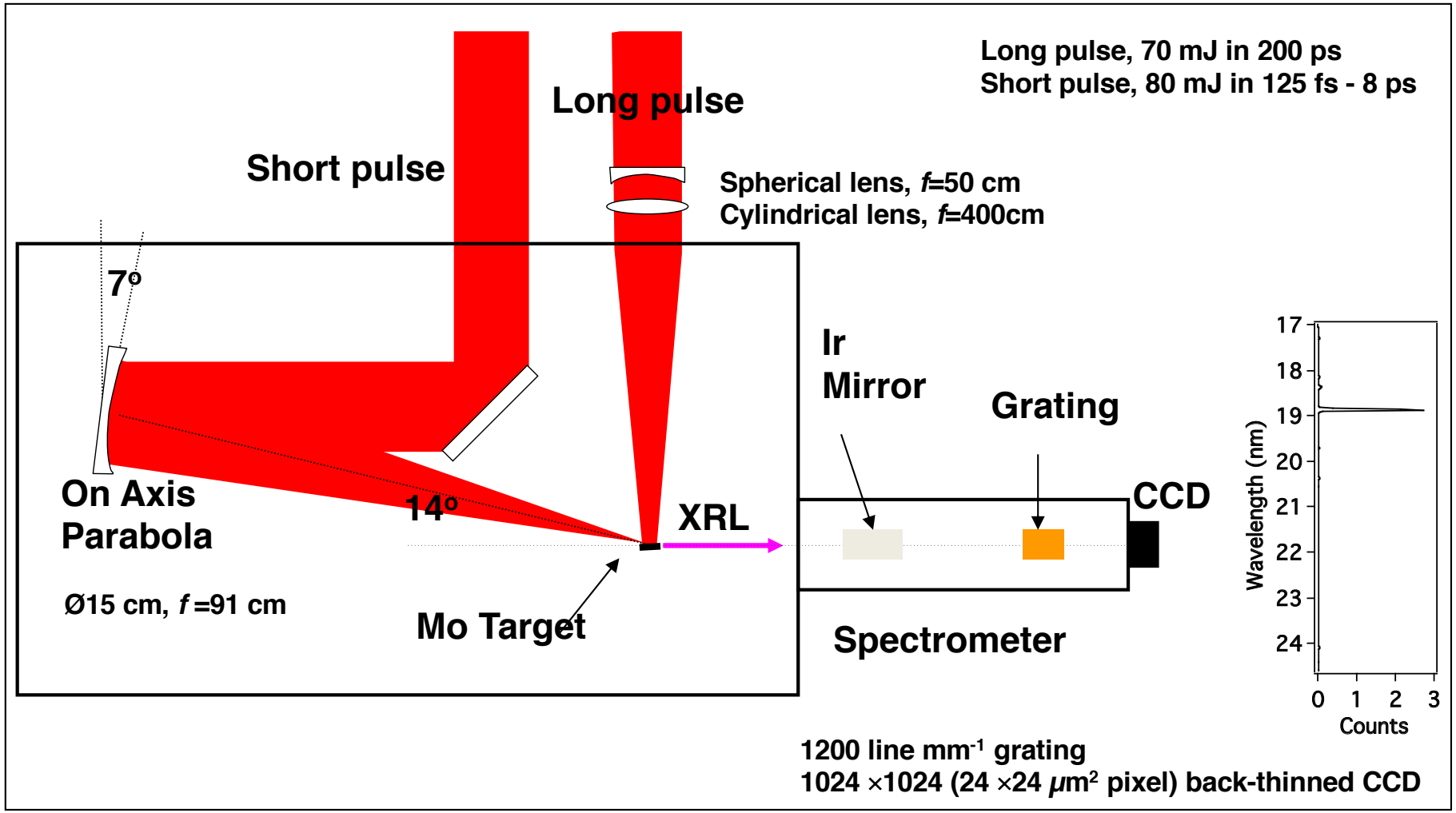
Ni-like ground state has $1s^2 2s^2 2p^6 3s^2 3p^6 3d^{10}$ electrons

Rates in (nsec^{-1})
Diagram not to scale
100 eV = 1,160,400 degrees K



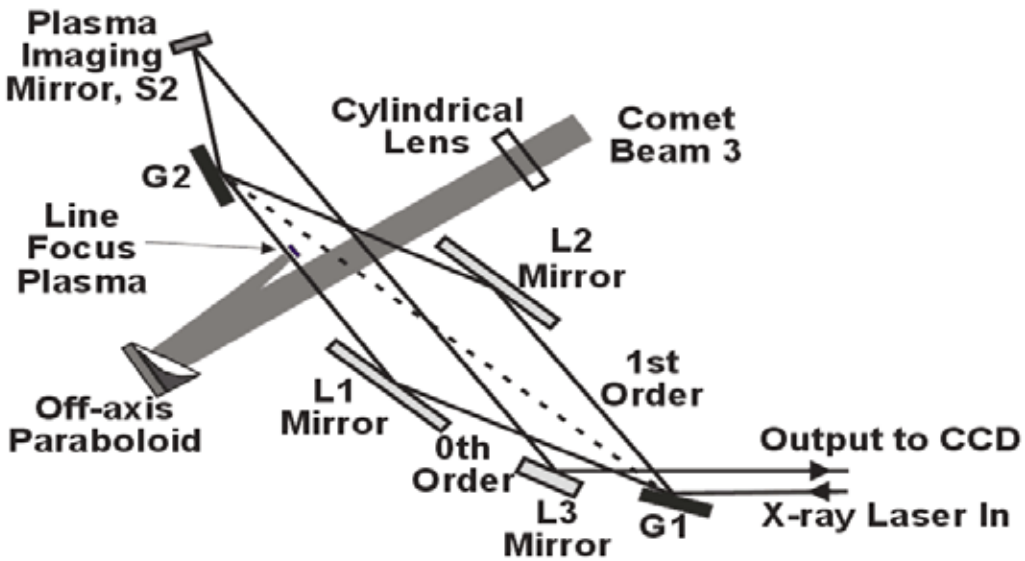
Target: 1.0 cm Pd
E_L = 1-2 J, 600 ps
E_S = 5.5 J, 1 ps
120 μm by 1.1 cm line
Delay = 700 ps

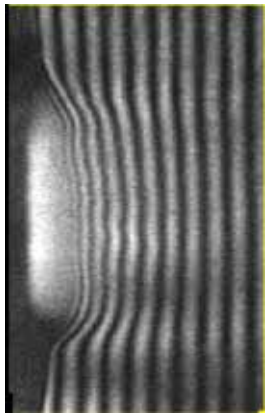
Grazing Incidence Pumping (GRIP) enabled higher repetition rate and lower energy: Ni-like Mo laser at 18.9 nm driven with 150 mJ of energy at 10 Hz

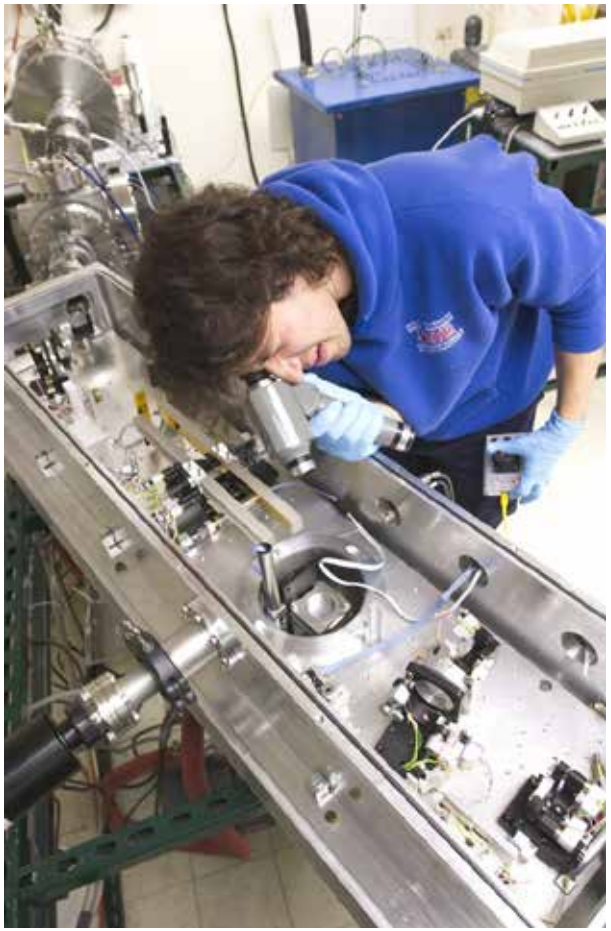


Total energy of 150 mJ at 10 Hz incident on 4 mm long target

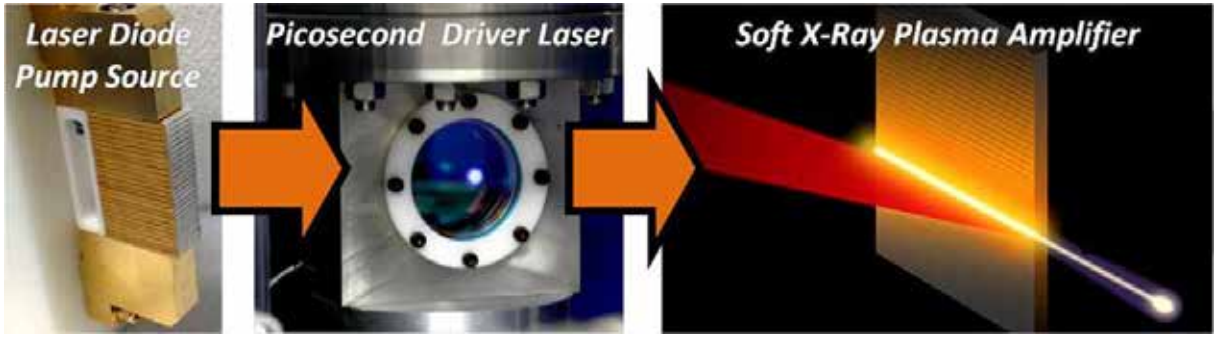
Combining Pd X-ray laser and multi-layer X-ray optics the X-ray laser interferometer is used to measure the 2D electron density profile of plasmas

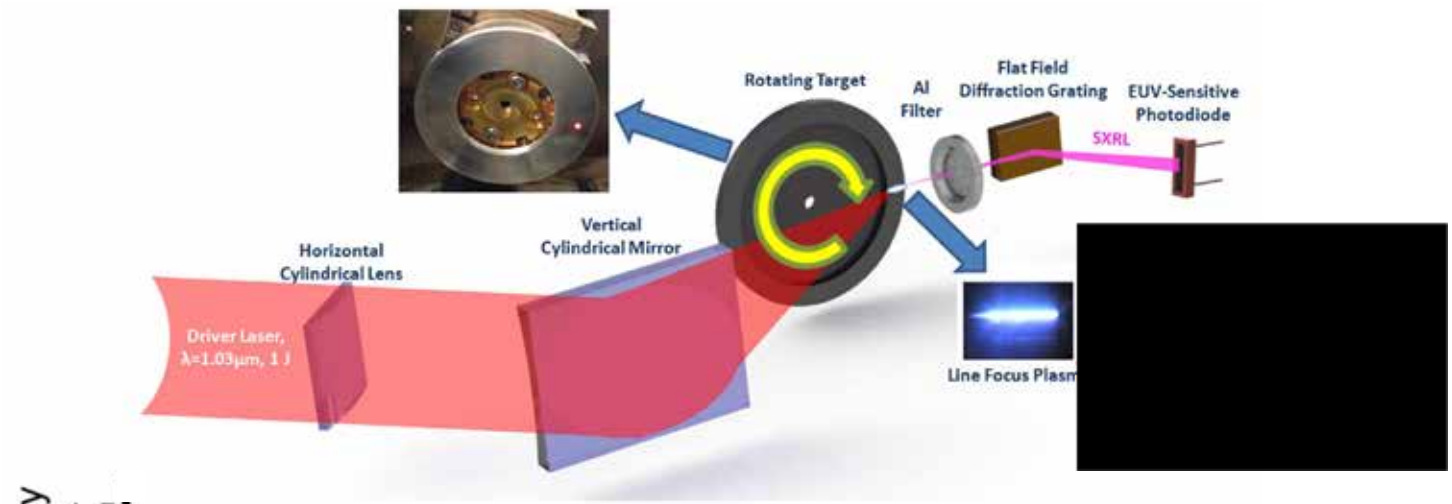


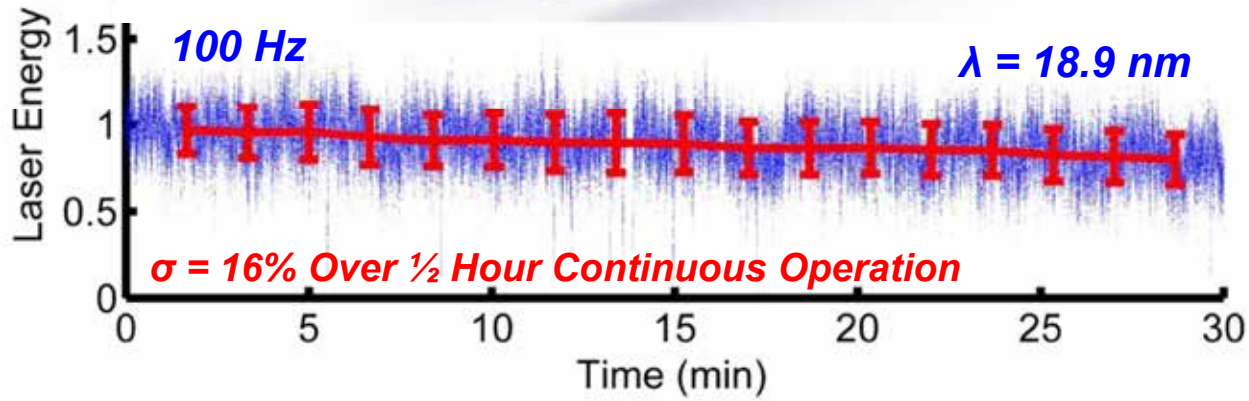




A 100 Hz diode-pumped table-top X-ray laser operated for 180,000 consecutive shots at Colorado State University

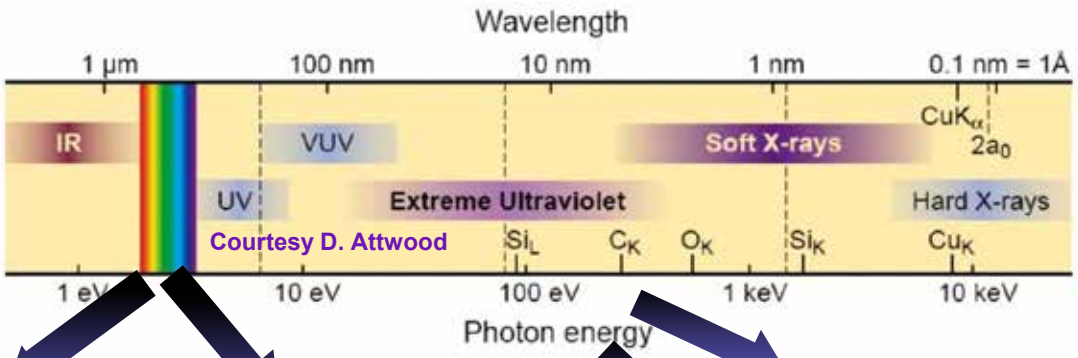


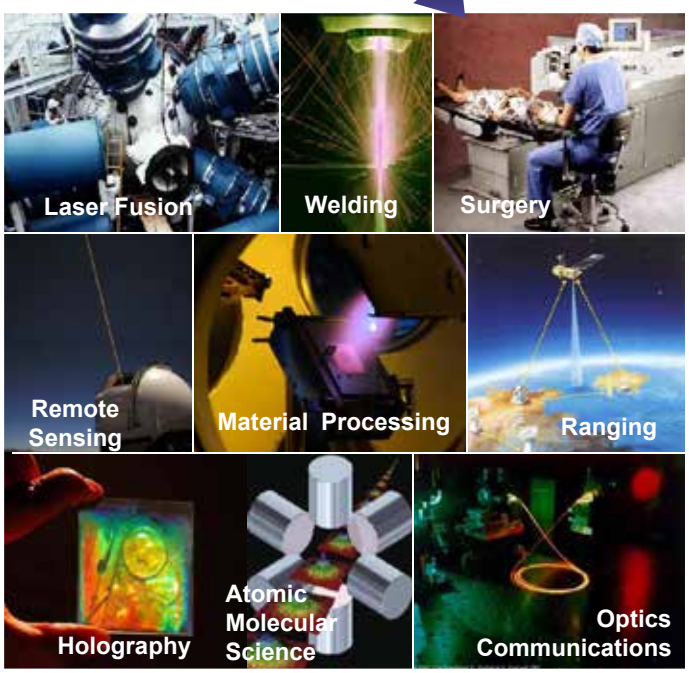


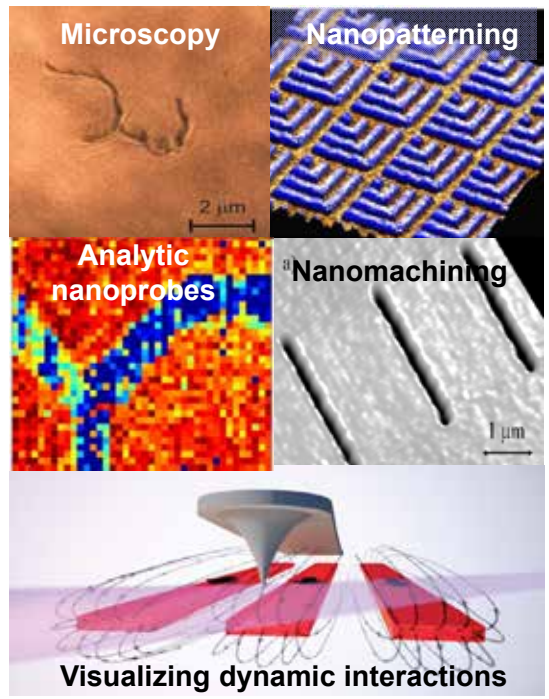


Courtesy Jorge Rocca

Bright table-top soft X-ray lasers are opening new opportunities for scientific research







Courtesy Jorge Rocca – Colorado State University

X-ray lasers have evolved from a Star Wars missile defense system to a table-top research tool

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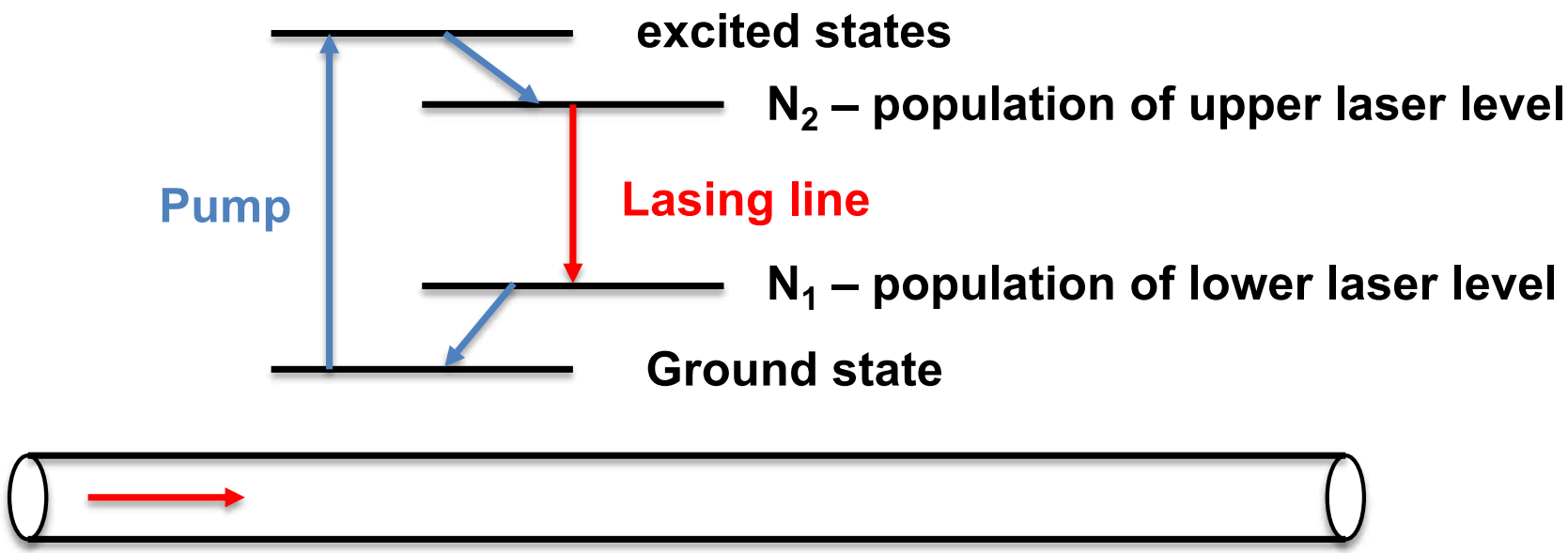
Backup slides

Lasing 101: Light Amplification by Stimulated Emission of Radiation



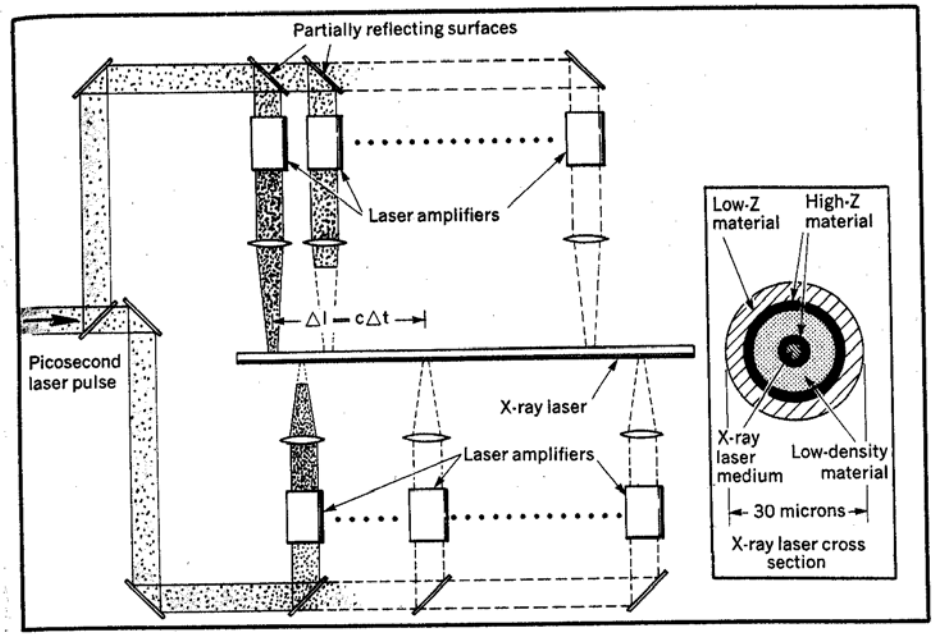
Lasing requires creating a population inversion where $N_2 > N_1$

NIF is a 4-level laser using Nd^{3+} glass as gain media

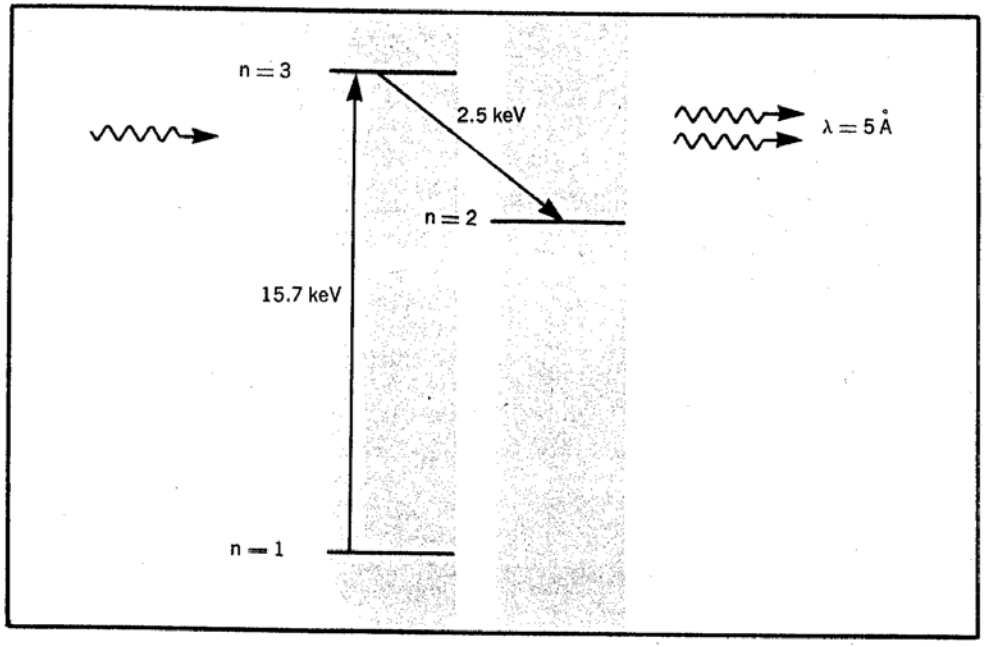
g (gain) = σ [$N_2 - N_1$] where σ is cross section

I (intensity) = $I_0 e^{(gL)}$ where L is length of gain media

Proposed X-ray laser scheme from Physics Today article uses psec lasers and traveling wave geometry



A conceptual design for an x-ray laser. A picosecond laser pulse from a master oscillator–preamplifier chain is fed in portions, via beamsplitters and final amplifiers, onto the x-ray laser target axis. The pulses are sequenced to cause an ultrastrong heating wave to move down axis with the speed of light. The concentric cylindrical target (inset) focusses radial shocks into the x-ray laser medium to produce the inner-shell vacancies needed. Figure 3



Hydrogenlike krypton provides a possible x-ray laser transition, with a spontaneous radiative lifetime of about 10^{-14} sec and a cross section of about 10^{-18} cm^2 for stimulated emission. Lasers powerful enough to provide the needed pumping are not yet available. Figure 4

Soviets publish paper on X-ray laser experiments in 1977 using Ne-like Ca but results never confirmed

JETP Lett., Vol. 25, No. 12, 20 June 1977

Concerning the problem of lasers for the far ultraviolet $\lambda \sim 500$–700 Å

A. A. Ilyukhin, G. V. Peregudov, E. N. Ragozin, I. I. Sobel'man, and V. A. Chirkov

P. N. Lebedev Physics Institute, USSR Academy of Sciences
(Submitted May 19, 1977)
Pis'ma Zh. Eksp. Teor. Fiz. **25**, No. 12, 569–574 (20 June 1977)

Results are reported of experimental investigations aimed at obtaining lasing in the far ultraviolet region of the spectrum ($\lambda \sim 600$ Å on the transitions $2p\,^5 3p$–$2p\,^5 3s$ of the neon-like ion Ca XI) in a plasma produced by laser heating of a calcium target.

Media takes interest in X-ray laser

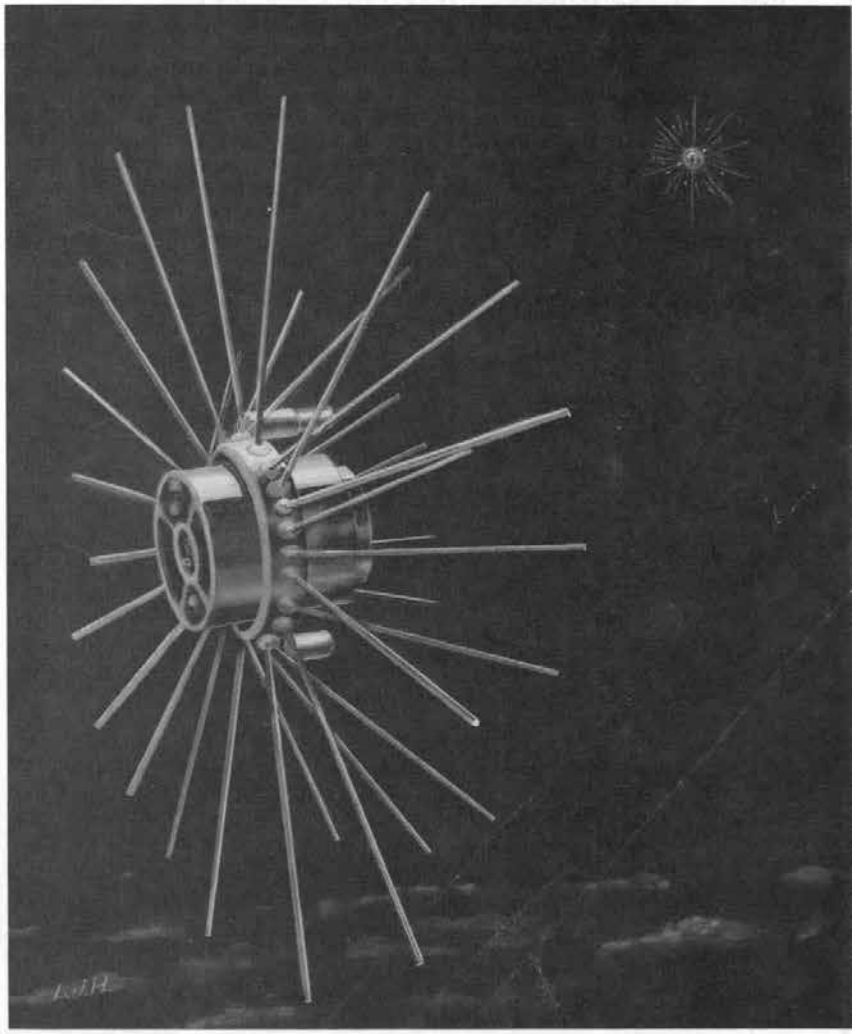
Aviation Week & Space Technology, February 23, 1981

By Clarence A. Robinson, Jr.*

Washington—High-energy laser technological breakthrough scored by the Lawrence Livermore Laboratory has the potential to blunt a Soviet nuclear weapons attack on the U.S., according to Defense Dept. and congressional officials.

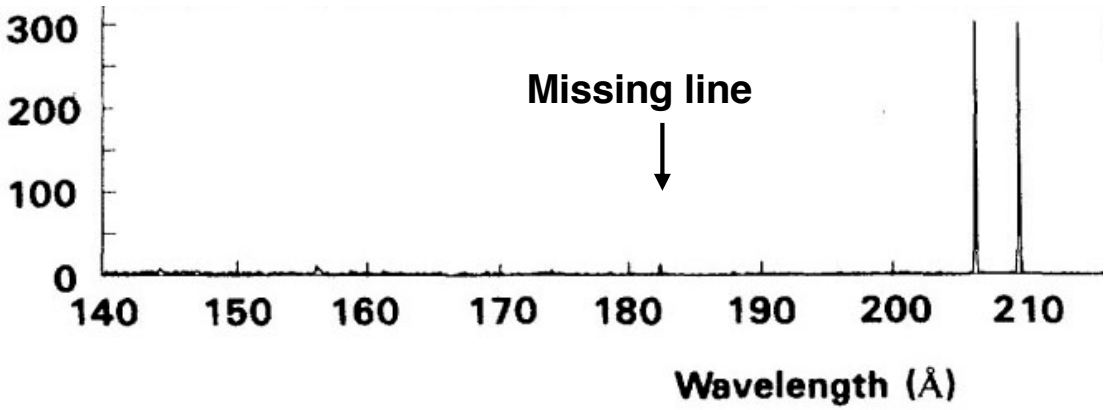
In a recent test at the Nevada underground nuclear test site, the laboratory demonstrated—in a vacuum chamber simulating space—a very small, compact laser device pumped by X-rays from a small nuclear detonation.

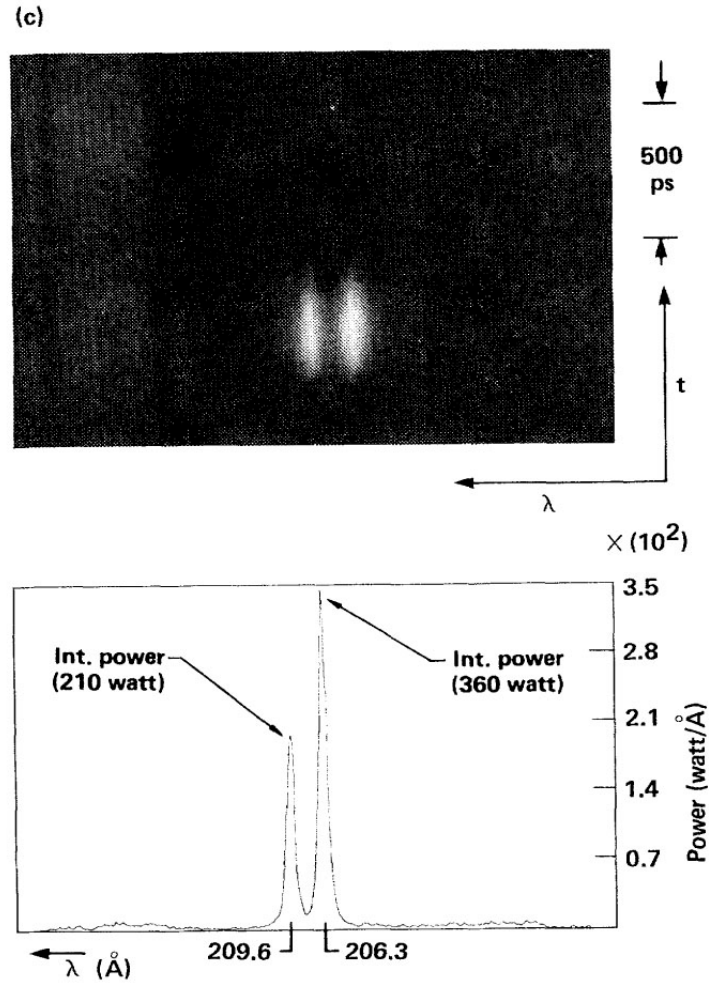
The laser operates in the X-ray wavelength at 0.0014 microns and produces a pulsed beam of very high intensity—several hundred terawatts (trillions of watts). The beam pulse is "in the order of nanoseconds, one of the shortest pulses measured by Livermore," one U.S. official said.



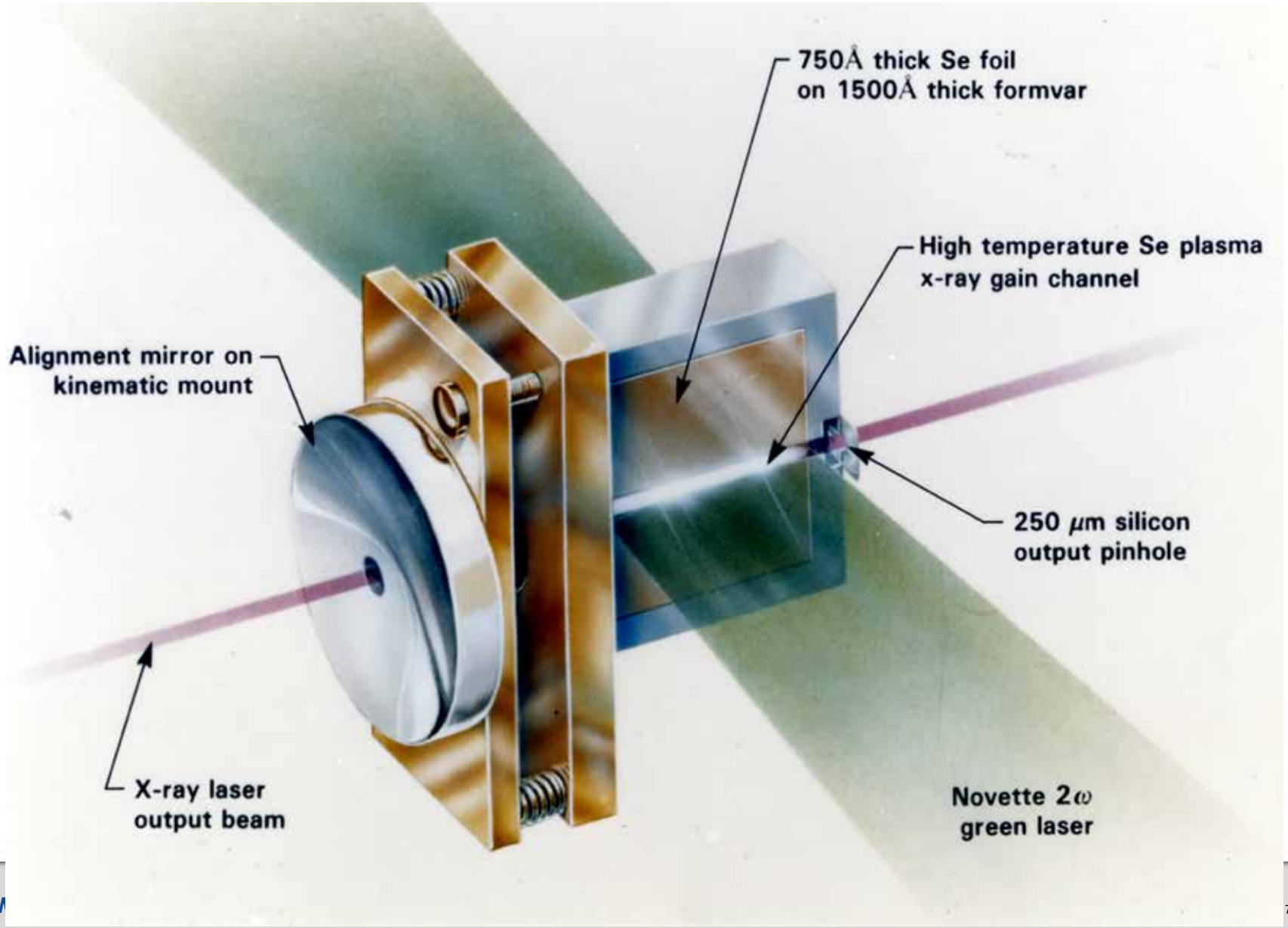
Small X-ray wavelength laser pumped by the X-ray in a nuclear explosive is depicted in an artist's drawing. The laser rods of solid, dense material are arrayed around the pumping mechanism and are designed to move in various directions to point and track a target. Each rod is trained on a target, and once the device is detonated each produces terawatts of power in a laser beam to destroy a target by shockwave. Many of the rings could be based in space or fired aloft on boosters in response to a Soviet attack. The lasing material and pumping device have been tested successfully at an underground Nevada test site.

In early LLNL experiments lasing was observed on lines at 20.6 and 20.9 nm and not observed on the 18.2 nm line that was predicted to have the largest gain in Ne-like Se





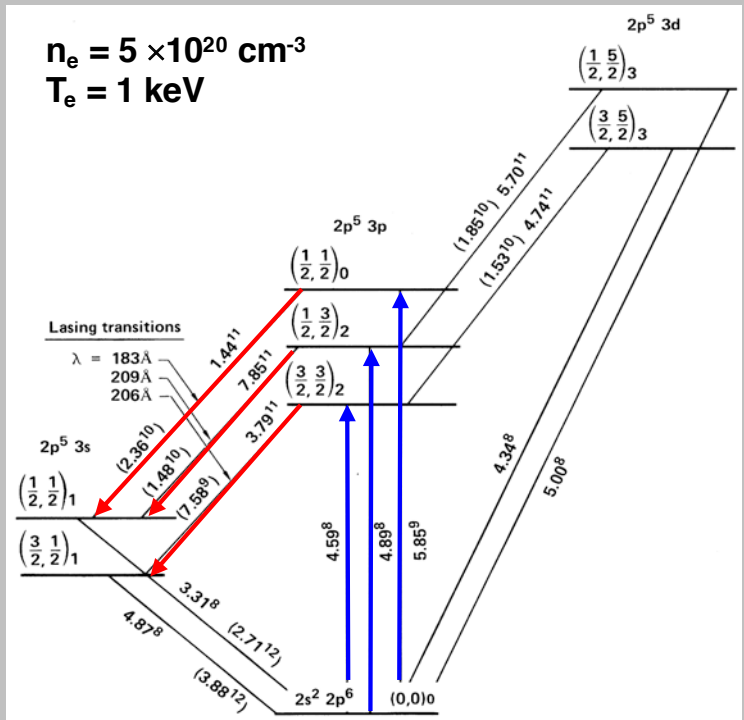
X-ray laser plasma was created by illuminating exploding foil target from both sides by 2.5 kJ, 500 ps beams of green Nova light focused to 120 μm by 2 cm line



Large scale Inertial Confinement Fusion (ICF) driver used for first X-ray laser experiments: Main laser amplifier bay on Nova laser

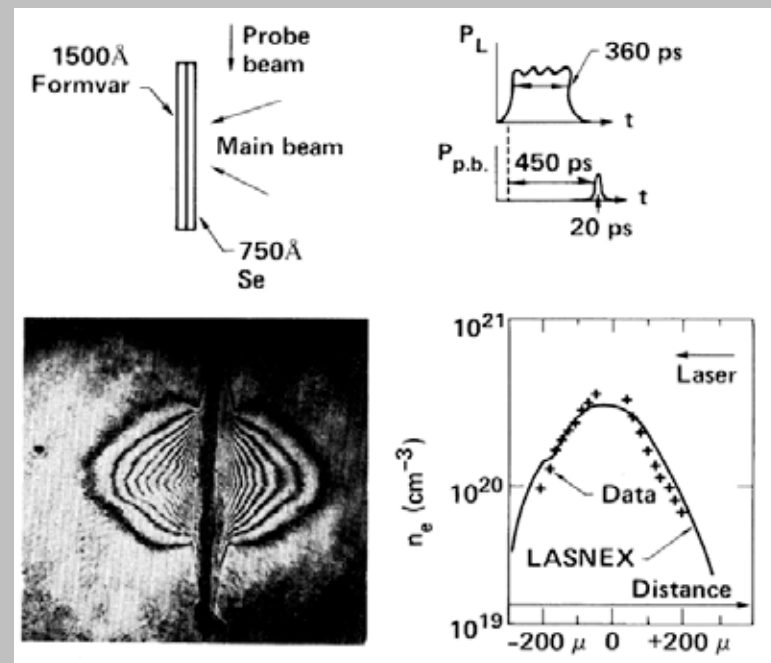
Exploding foil target and X-ray laser was designed after substantial modeling and experimental characterization effort

Ne-like Se Simplified Level Diagram



- 2-D LASNEX hydro simulations combined with XRASER atomic kinetics code (100's of levels included)
- Gain on following lines: 18.3, 20.6, 20.9 nm

Density Profile Measurements

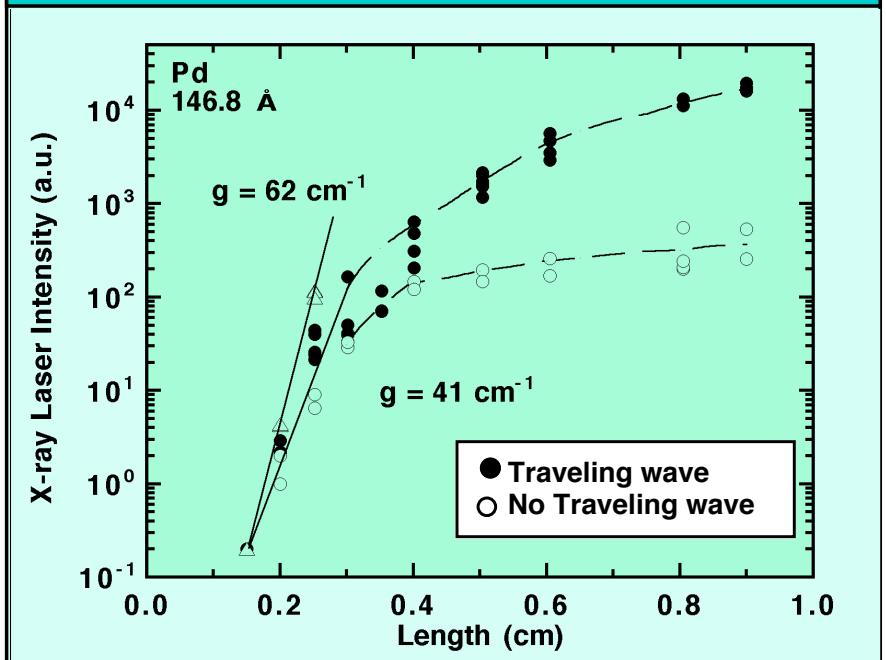


- Exploding Se foil compared with 2-D LASNEX simulations for laser irradiation conditions (n_e density profile)
- T_e ionization conditions measured

M. D. Rosen et al, PRL 54, 106 (1985)

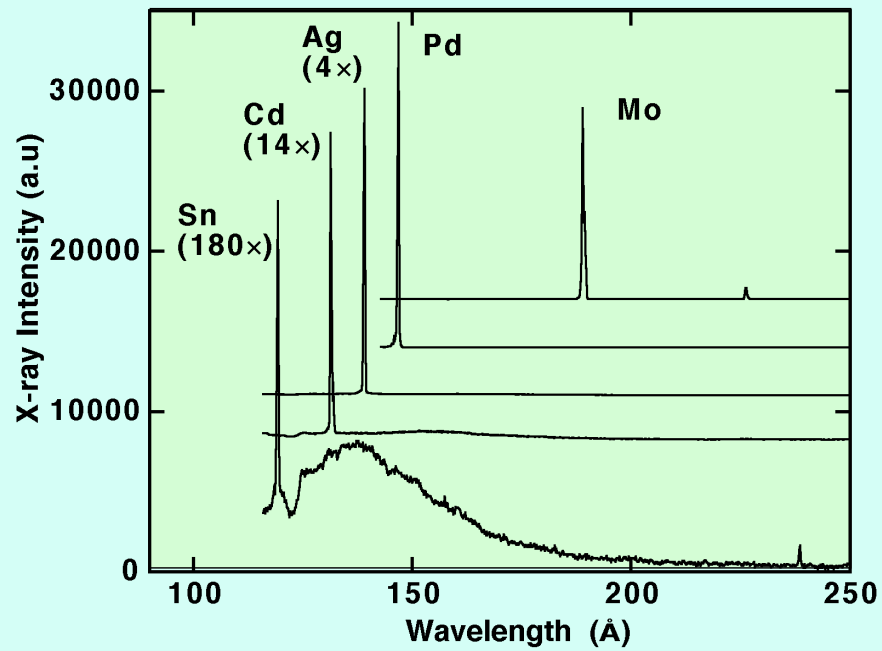
Ni-like Pd X-ray laser at 14.7 nm is driven into gain saturation regime using 5 to 7 J of energy

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

Many Ni-like ions lase well

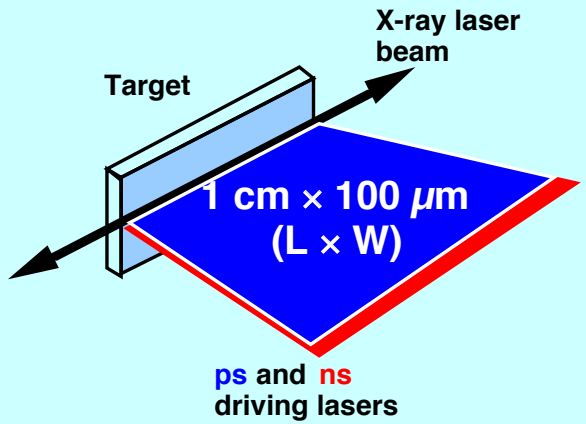


Higher efficiency of Ni-like XRL well matched to small driver

Output still increasing with length - extract more XRL energy

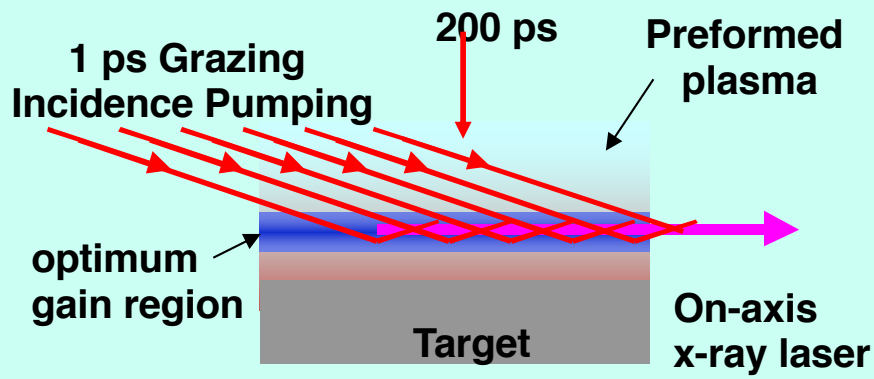
Grazing Incidence Pumping (GRIP): Novel method for efficient X-ray lasers uses controlled refraction of pump

Transverse Pumping of plane slab target



- Short pulse energy absorbed near n_c
- Low absorption in gain region ~0.1 n_c
- Traveling wave irradiation required

GRIP: psec laser incident at ϕ_r= 10 - 20° to surface



- Plasma formed by 200 ps pre-pulse laser
- 1 ps laser at grazing incidence pumps XRL
- Traveling wave pump inherent to GRIP scheme

GRIP Advantages:

- Increase absorption transverse from 5-8% to 50%
- Selectively pump only active volume
- Density at turning point optimized for XRL
- No restrictions on target length

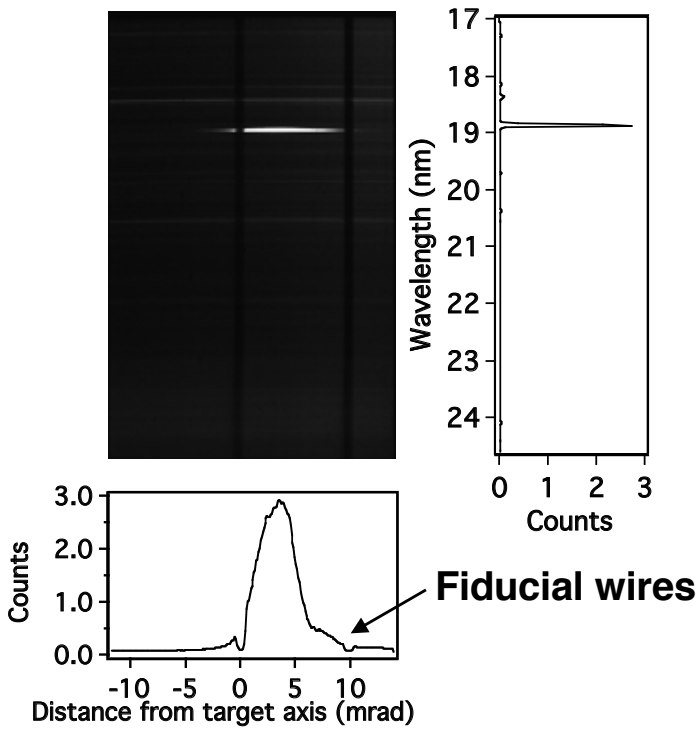
Refraction angle, ϕ_r:

$\phi_r = (n_{eo}/n_{ec})^{1/2}$

n_{eo} - plasma density max.
n_{ec} - crit. density @ pump laser wavelength

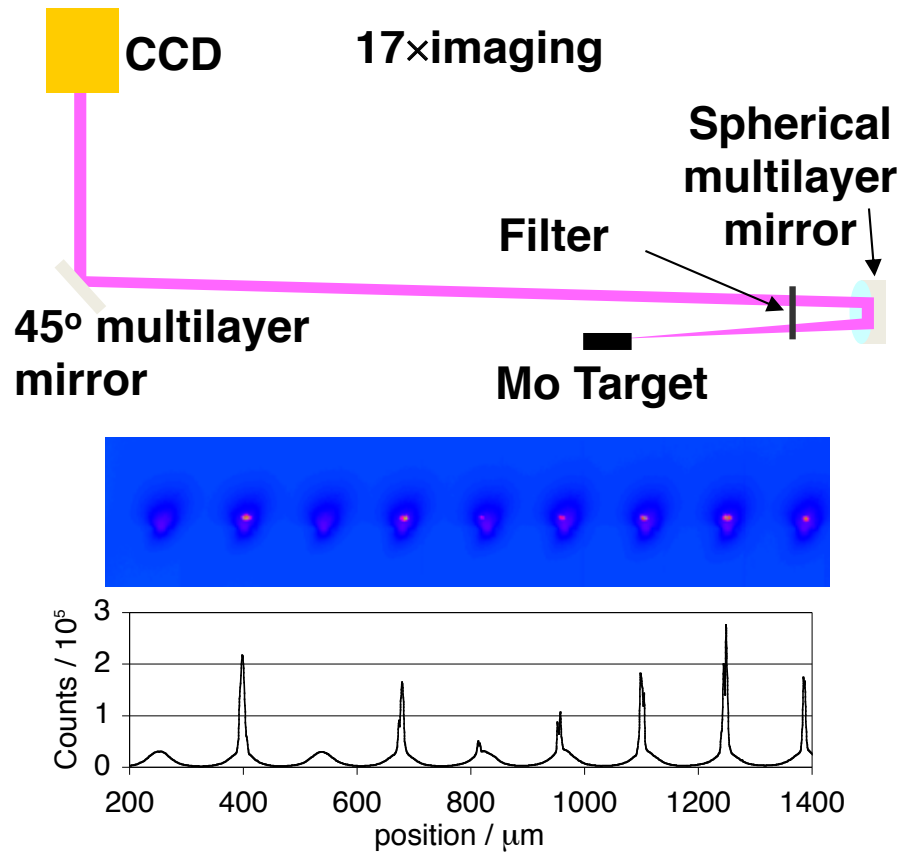
Ni-like Mo 18.9 nm, 10 Hz X-ray laser demonstrated using 150 mJ of 800 nm laser energy

Spectrometer: Wavelength, Refraction and Divergence Angle



4.5 mrad deflection angle
3 mrad (FWHM) beam divergence

Imaging XRL with multilayer optics: exit size, beam line reproducibility

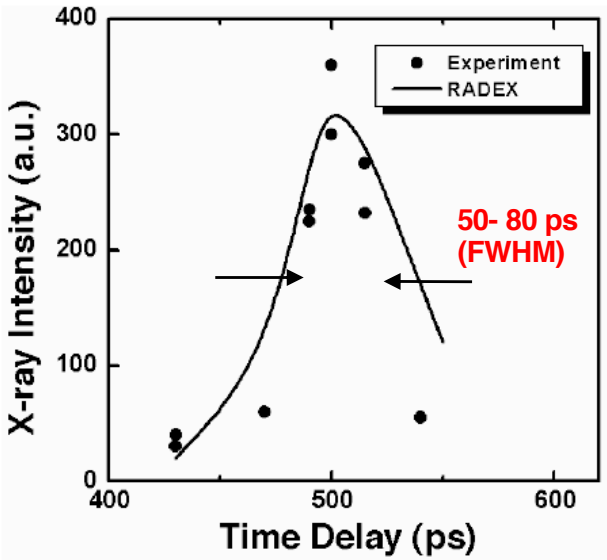


Mo:Si multilayers courtesy of J. Nilsen, T.W. Barbee, Jr.

XRL has good characteristics but sensitive to pump laser overlap

Pumping conditions optimized to maximize Ni-like Mo 18.9 nm X-ray laser output

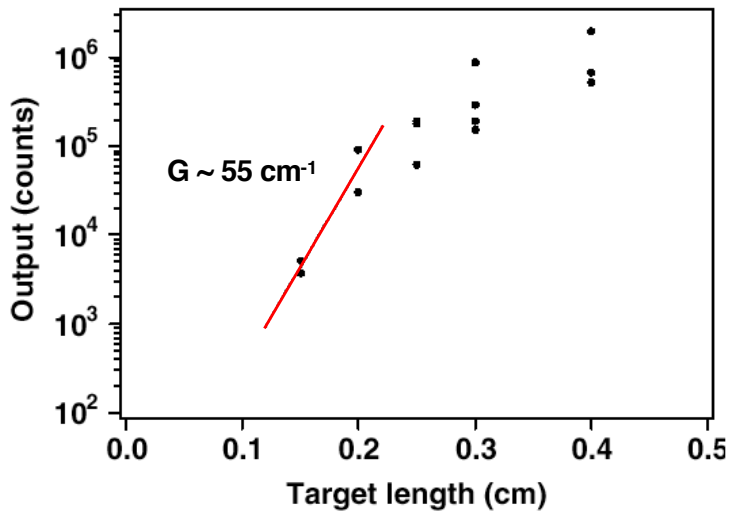
Delay between laser pulses with modeling



Plasma produced by narrow 15 μm LP line focus strongly affects window for optimized lasing

XRL output shows saturation-like behavior at 4 mm

SP = 1.5 ps, Δt = 500 ps



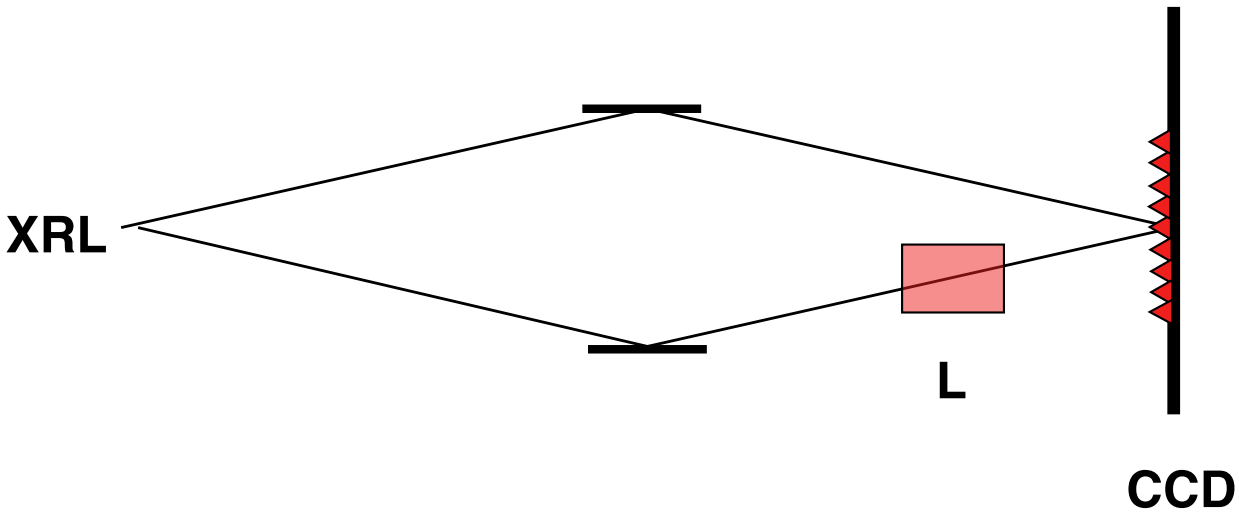
R. Keenan et al, Phys. Rev. Lett. 94, 103901 (March 2005)

Gain-length product ~ 14 : close to saturation
Estimated XRL output of > 10 nJ

High XRL gain observed for very small laser energy pump and experimental delay between pulses in agreement with simulations

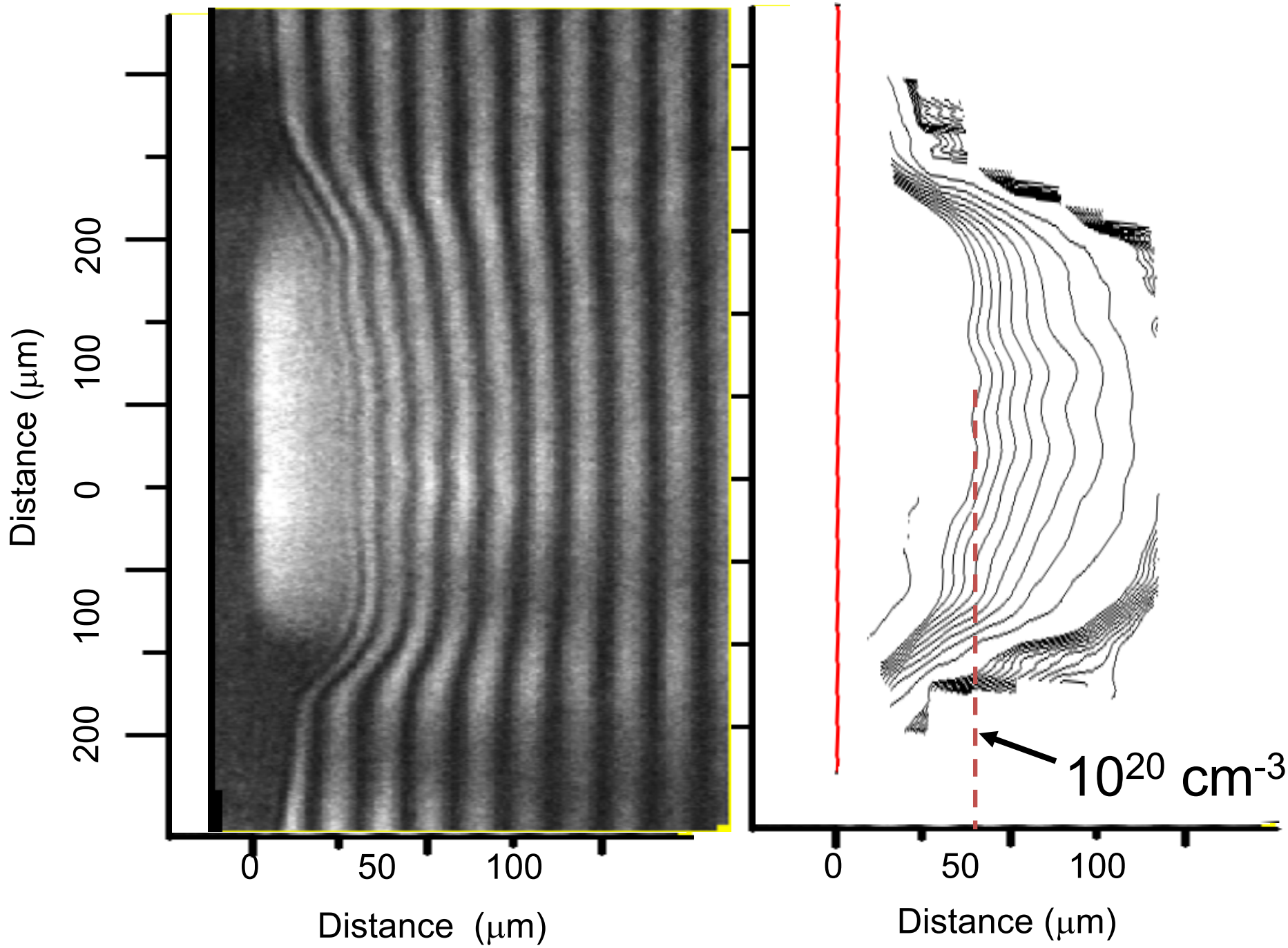
Interferometer measures the electron density by counting the number of fringe shifts which is proportional to the path length integral of (1 - n) through the plasma of length L

Assume index of refraction $n = [\,1 - (n_e / n_{crit})\,]^{1/2} \cong 1 - (n_e / (2\, n_{crit}))$

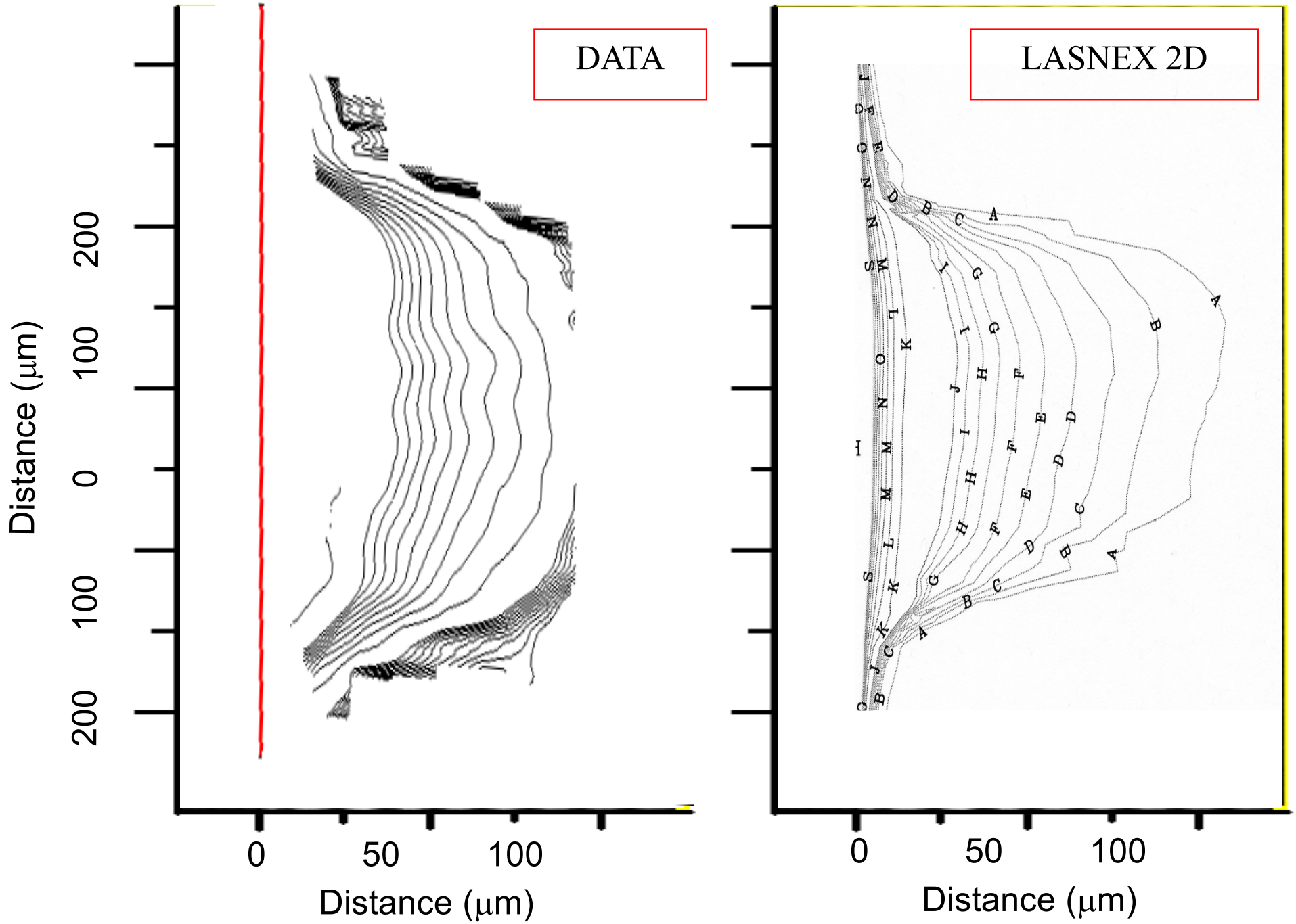
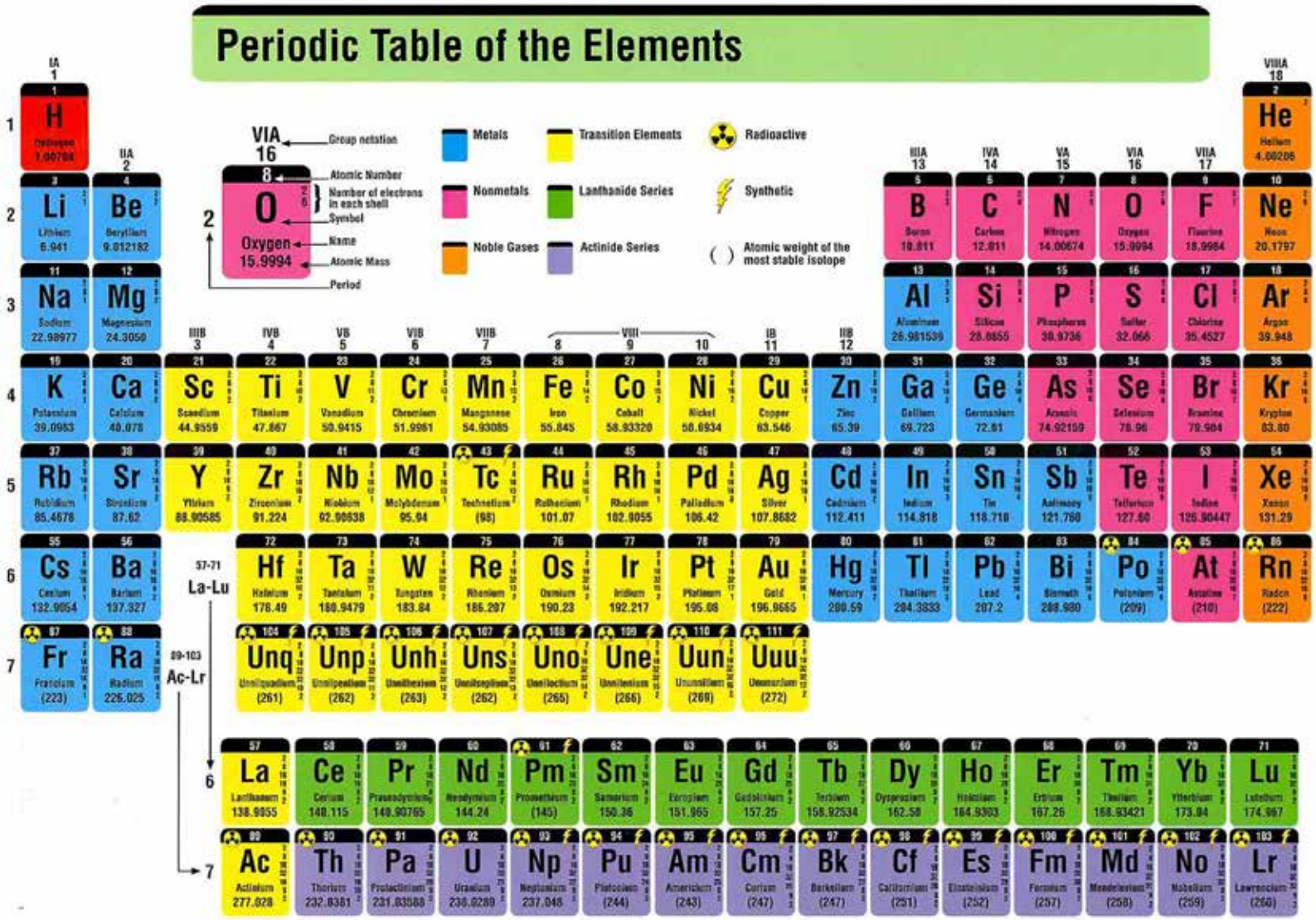


$$N_{fringe} = (1 - n)\, L / \lambda \cong n_e\, L / (2\, n_{crit}\, \lambda)$$

Interferogram of Pd plasma 700 ps after prepulse



2D Lasnex simulations give good agreement with experiment for 700 ps delay



Many elements across the periodic chart have lased