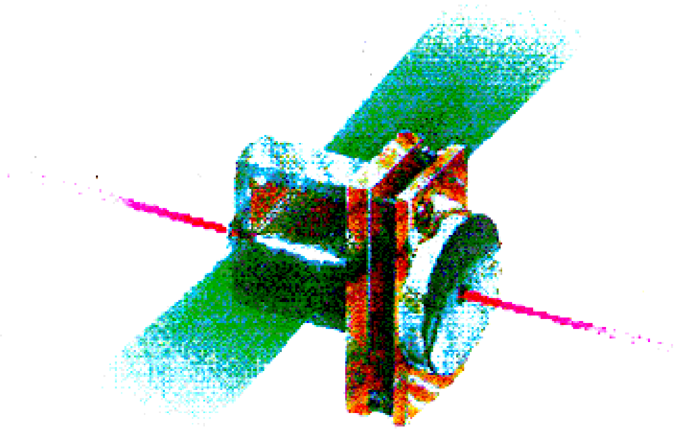
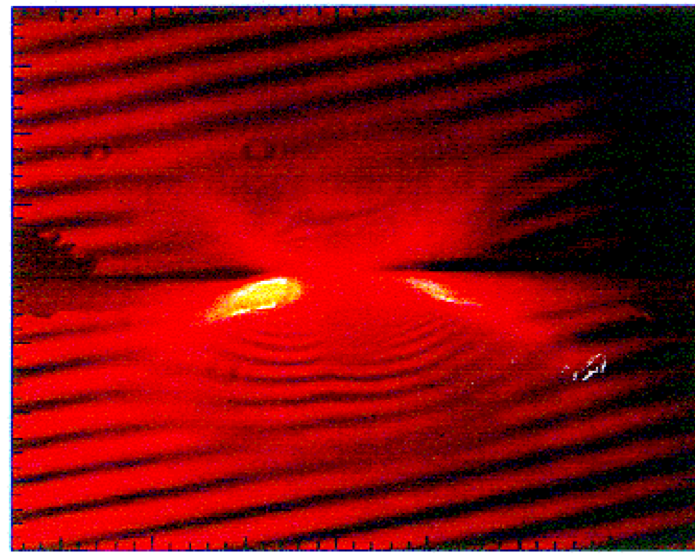
Status and Near Future of Soft X-ray Lasers





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University of California
Lawrence Livermore National Laboratory

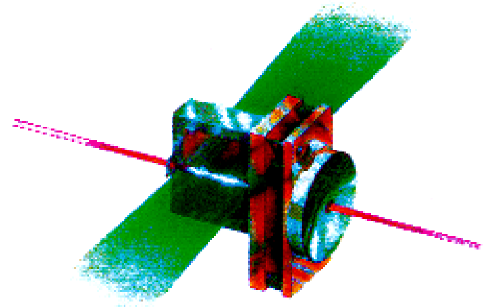
Presented at:

Future Light Source Workshop

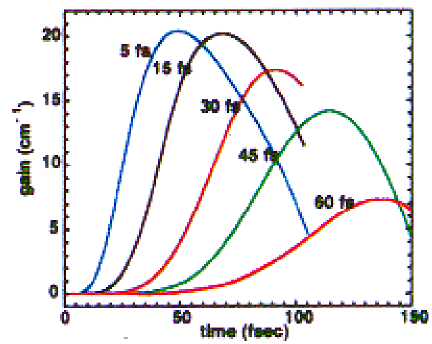
April 7, 1999

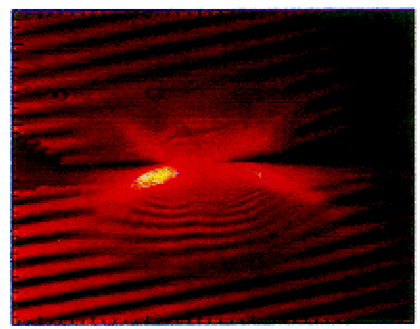
Outline

- Short review of x-ray laser research, the move to collisional systems.



- The shift from large (NOVA) optical pumps to small table top systems
    - PrePulse/Multiple pulse pumped systems
    - Optical Field Ionized x-ray lasers
    - Capillary discharge x-ray lasers
    - Short pulse, transient inversion x-ray lasers.





- "Useful" applications of existing x-ray lasers

Neon-like Collisional x-ray lasers

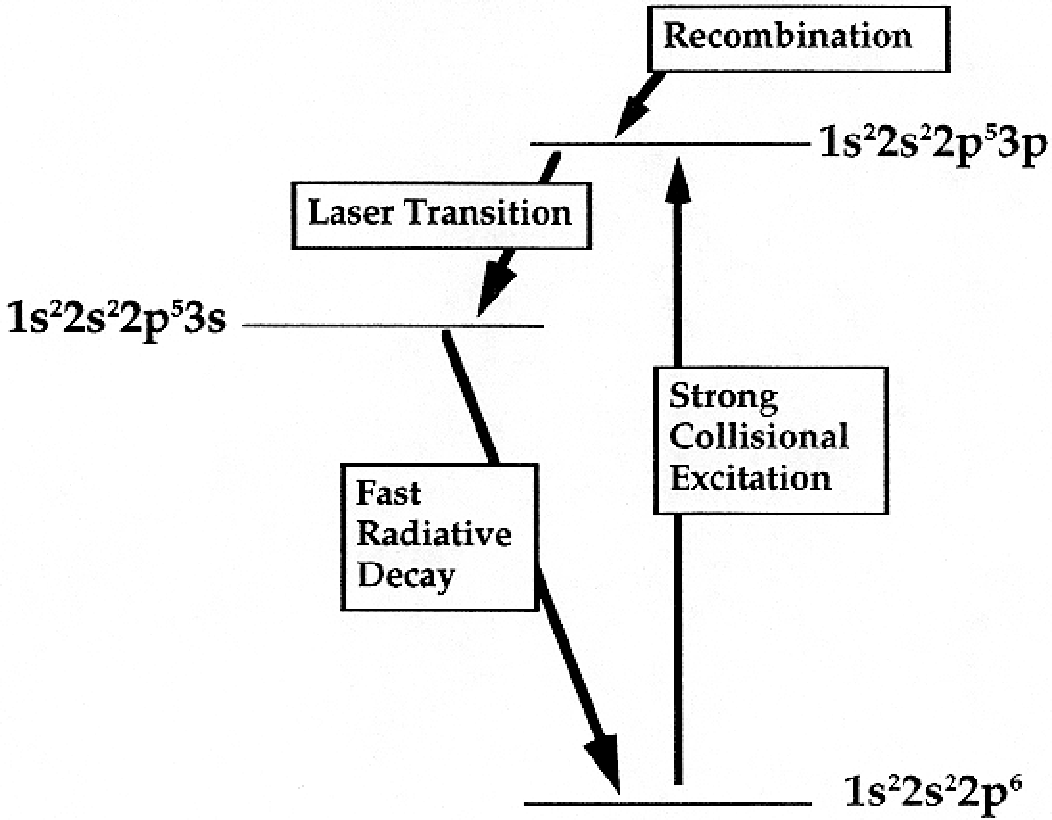
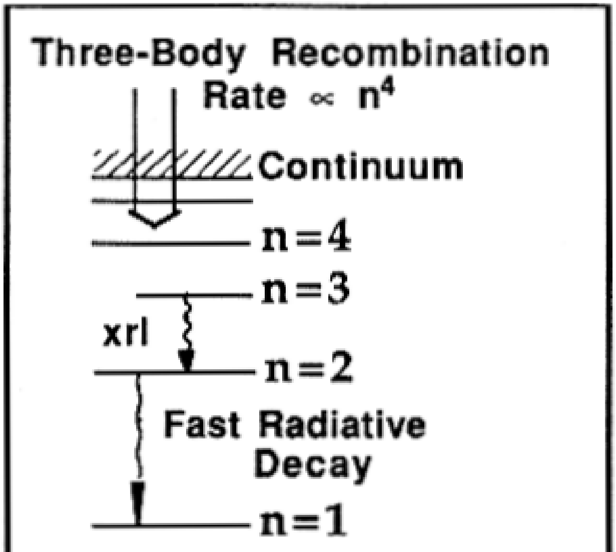


Exhibit :

High Gain (2-8)

Robust - Operate over large parameter space and target designs

Recombination pumped lasers use cooling plasma to produce inversion



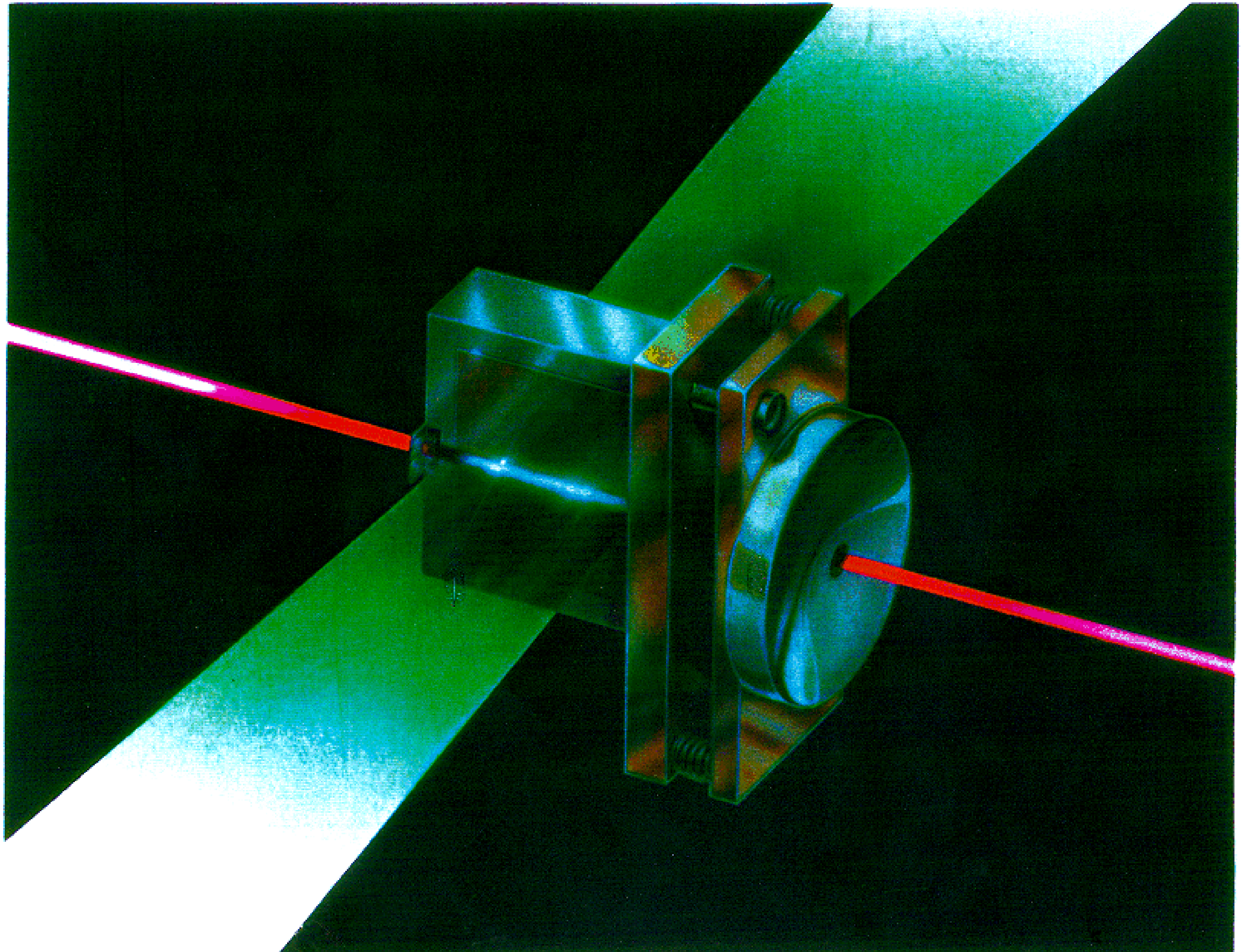
- Plasma ionized beyond lasant ion state then rapidly cooled by plasma adiabatic expansion, thermal conduction or radiation

- Three body recombination favors higher n levels, cascades produce inversion

- There have been many demonstrations of recombination pumped lasers in Li-like, He-like and H-like ions

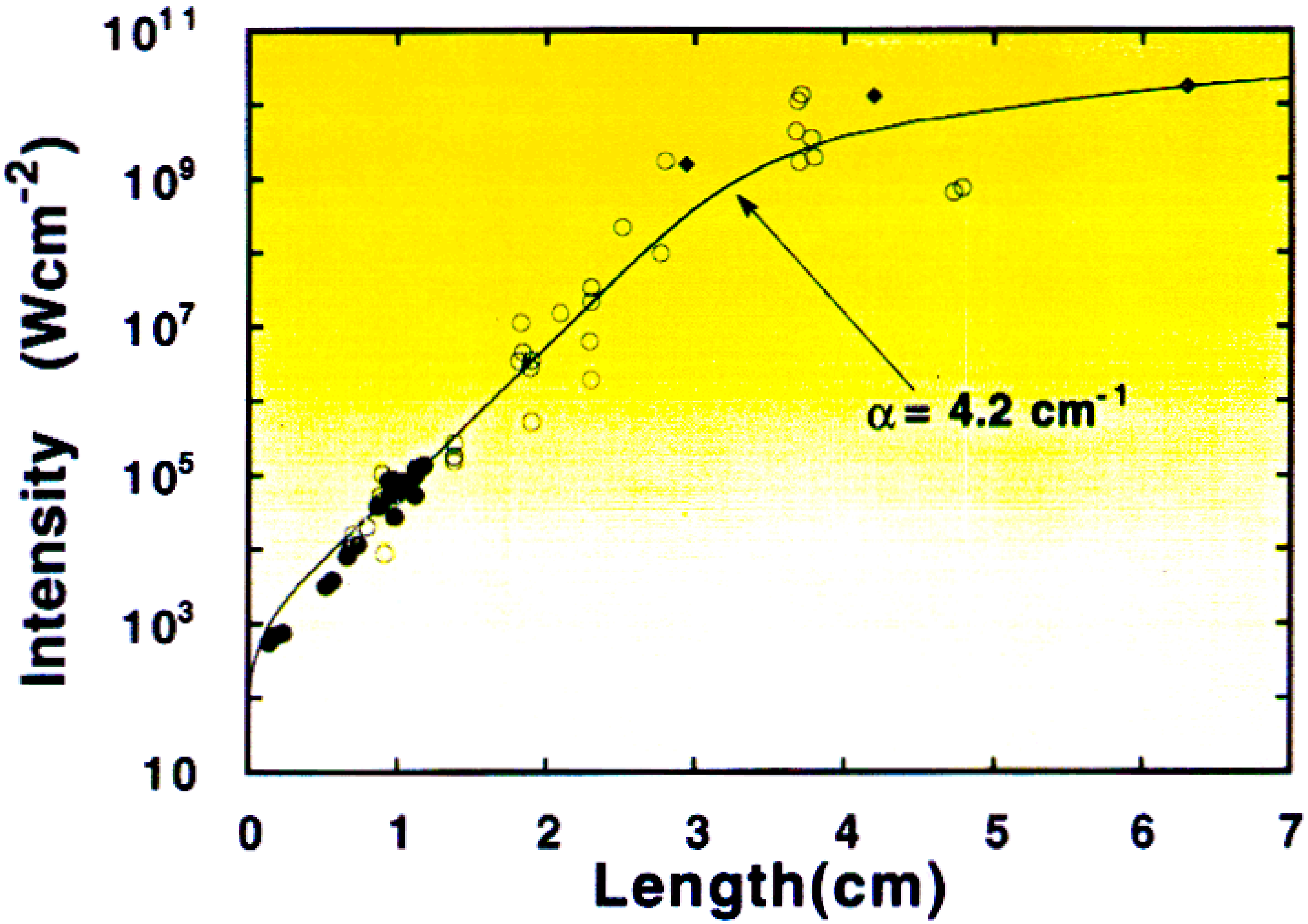
- Problems exist in scaling these lasers beyond initial demonstration, to higher output power

Geometry for laser pumped x-ray lasers

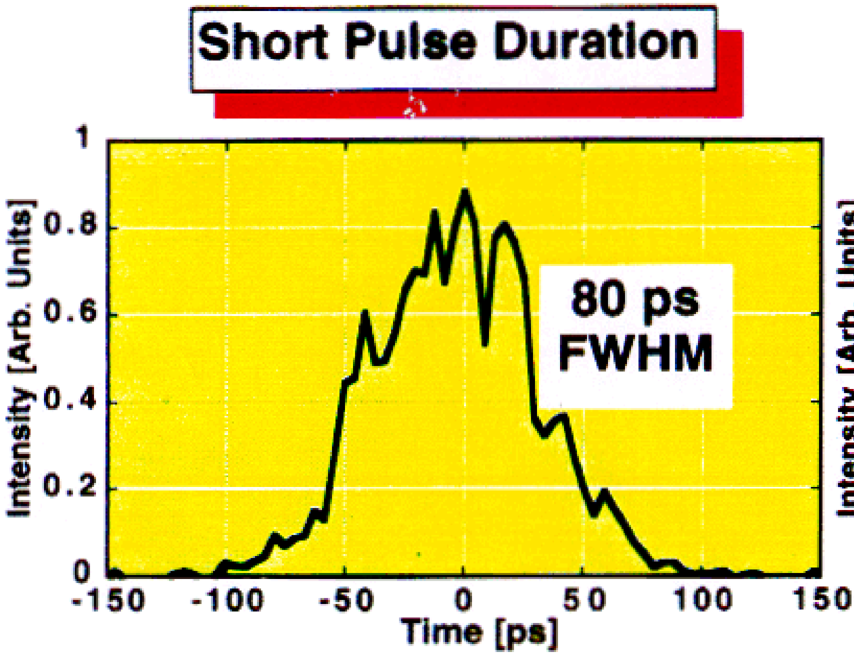


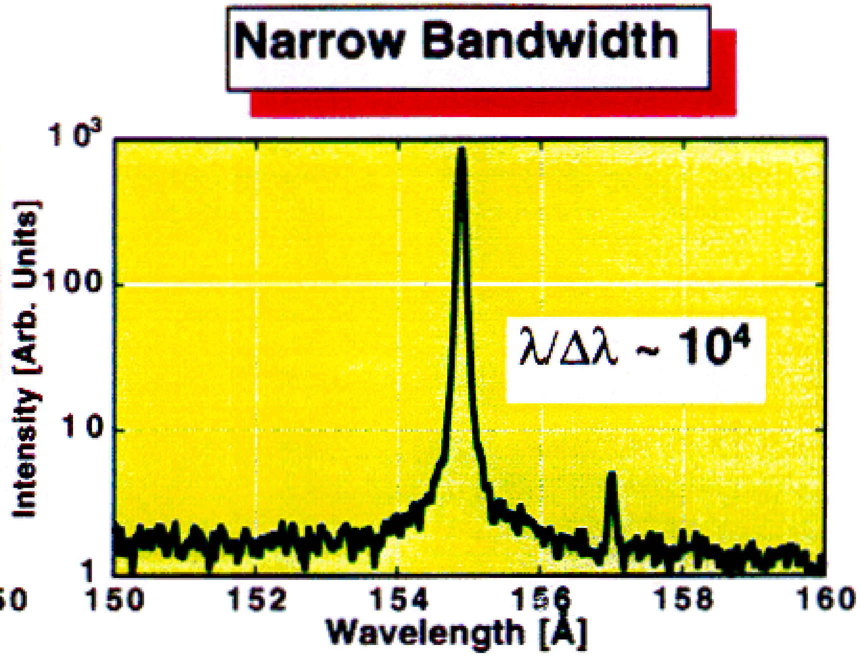
EAG-DaSilva-10/96-01

Saturated output has been measured in Ne-like Se at 206 Å



Characteristics of yttrium x-ray laser are well suited to plasma probing





High Brightness:

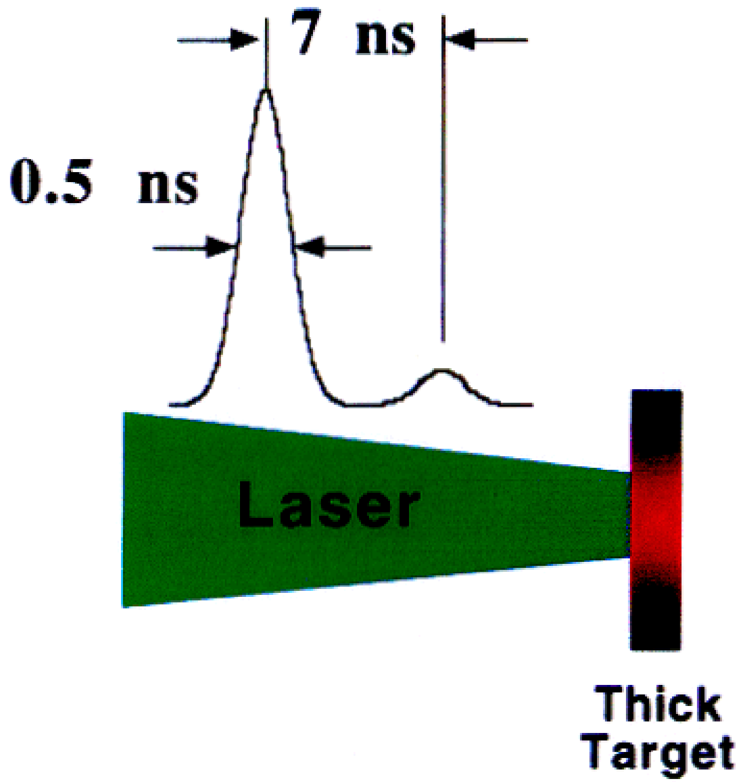
Output Energies ~ 10 mJ

Equivalent Brightness of 6 GeV BlackBody

Convenient wavelength (155 Å):

Well suited to multilayer mirror technology, 65% reflectivity now possible

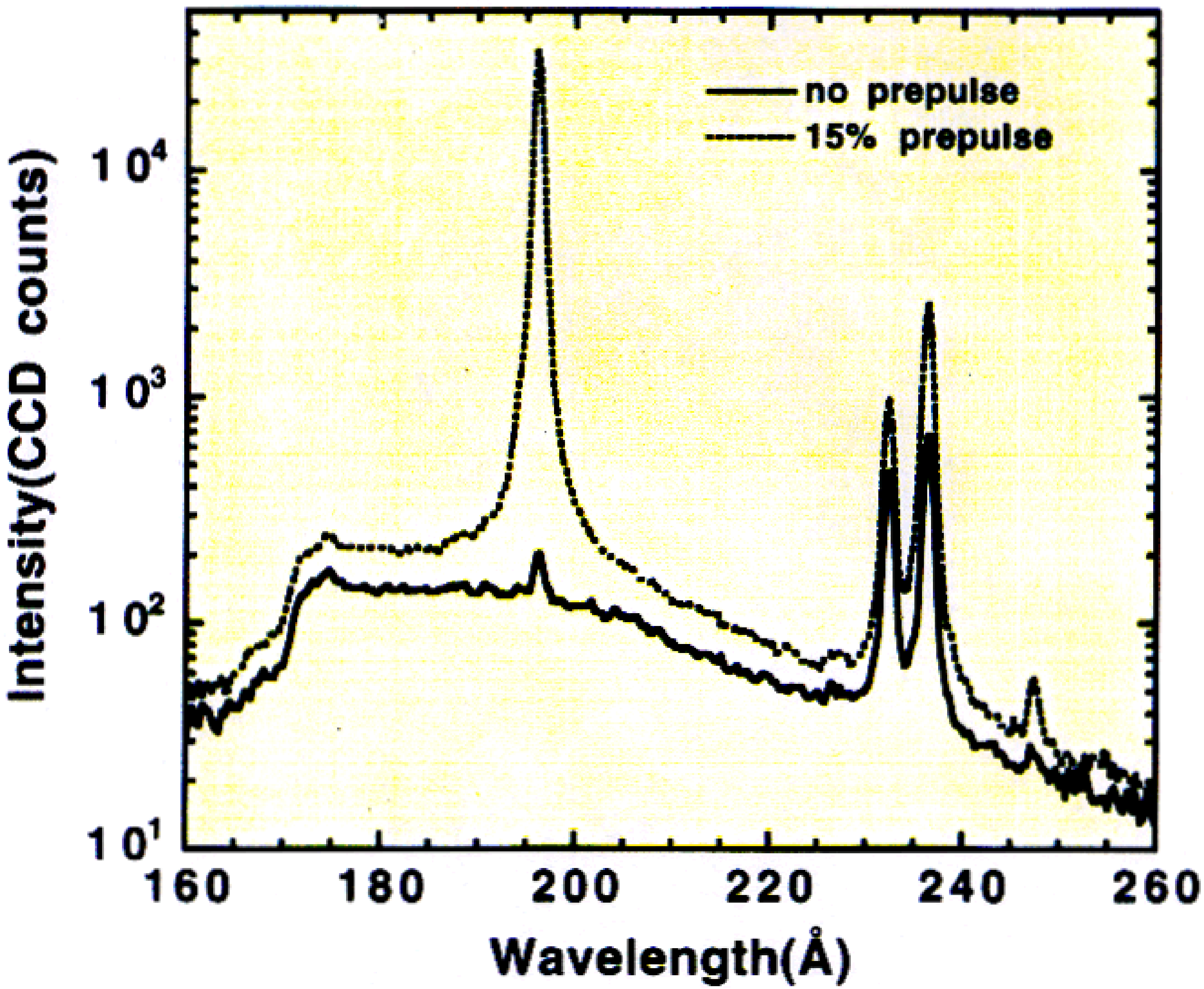
Prepulse techniques have made collisional pumping schemes effective for lower Z materials



First laser pulse produces long scalelength plasma.

Second laser pulse interacts with high density plasma and produces uniform density region for x-ray laser propagation.

Prepulse technique increases Ge 196 Å (J=0-1) laser line by three orders of magnitude



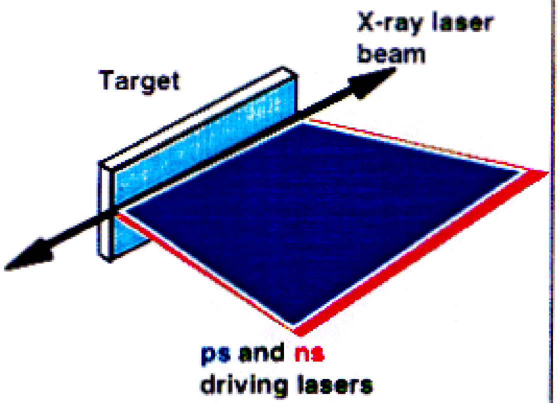
Transient scheme uses 1 ps, 10 TW laser pulse to optimize excitation - Table-Top X-ray Laser

- Nova ~1ns pulse ≥1 kJ to produce Quasi Steady State collisional XRL
  - plasma generation, ionization, excitation with long pulse
- Transient scheme utilizes short pulse for excitation
  - 1 ps pulse, at high intensity 10^{15} W/cm^2 to drive inversion

Two stage process

Long pulse:
- plasma formation
- ionization

Short pulse:
- excitation



Optimize excitation:

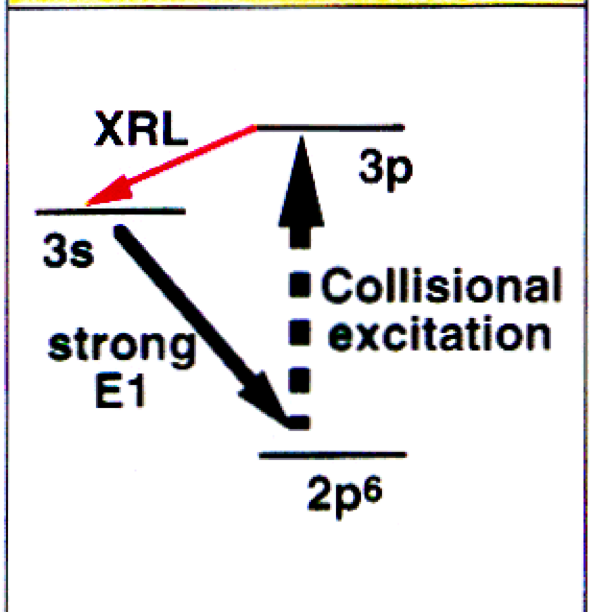
- Pump energy <10 J
- High gain
- Short wavelength
- High shot rate
- Picosecond XRL

1000× reduction in drive energy for transient x-ray laser scheme

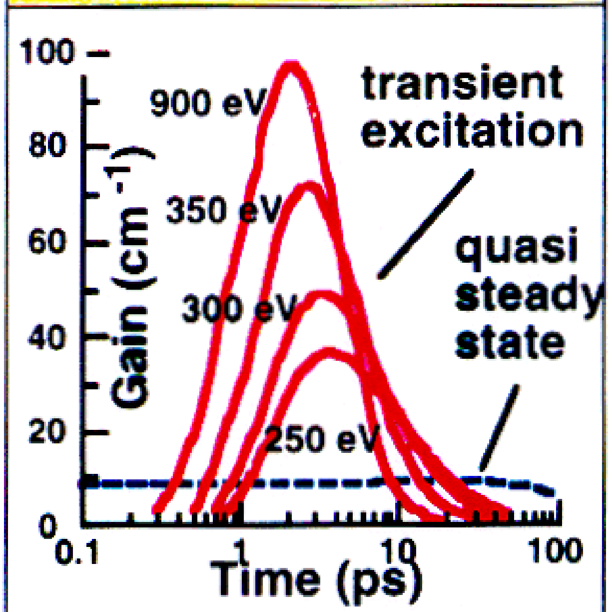
Requirements for collisional excitation x-ray laser

- Highly ionized plasma column
- Stable closed shell ion configuration
- Strong collisional pumping of excited levels from ground state

Ne-like Level Diagram

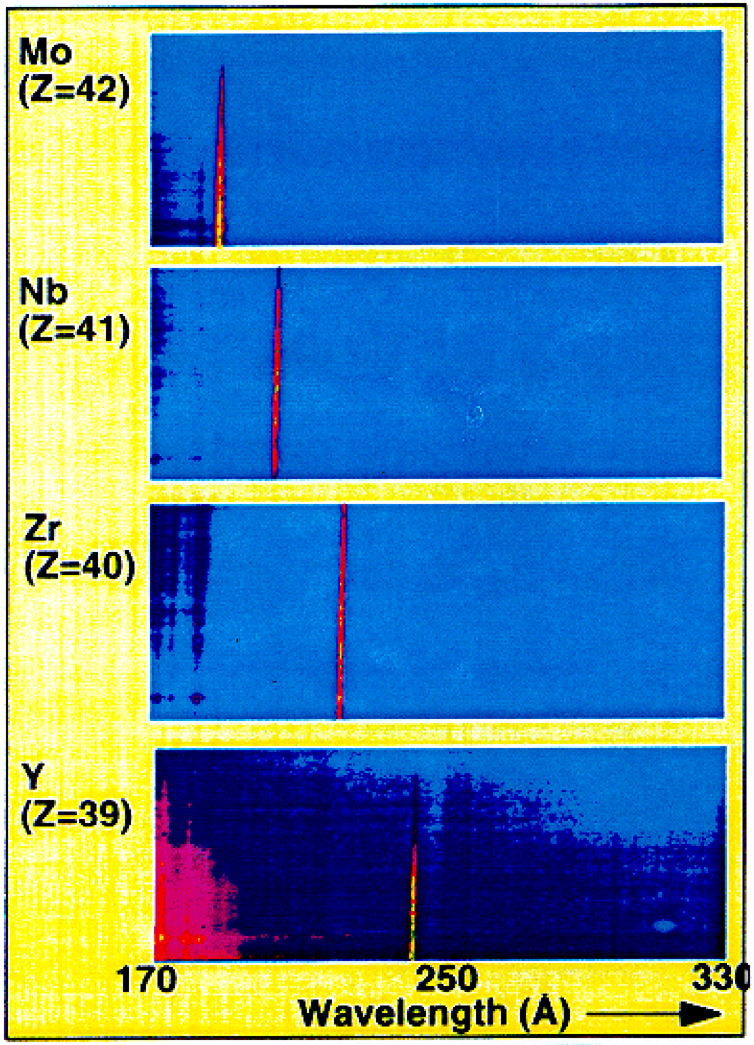


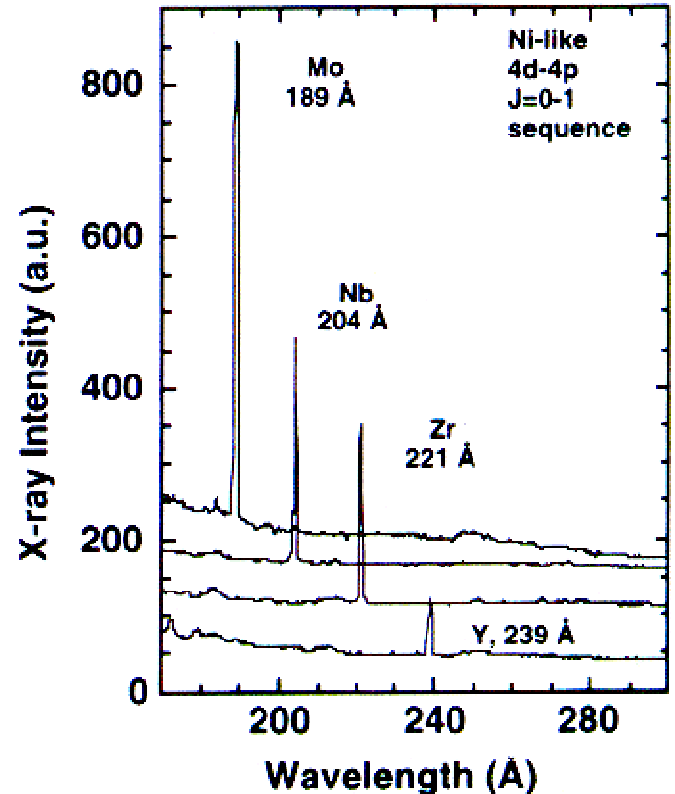
Transient vs QSS gain



10× higher gain ~100 cm-1 is predicted for transient scheme

New lasing lines measured for Ni-like ion sequence Mo to Y pumped with < 5 J from COMET laser





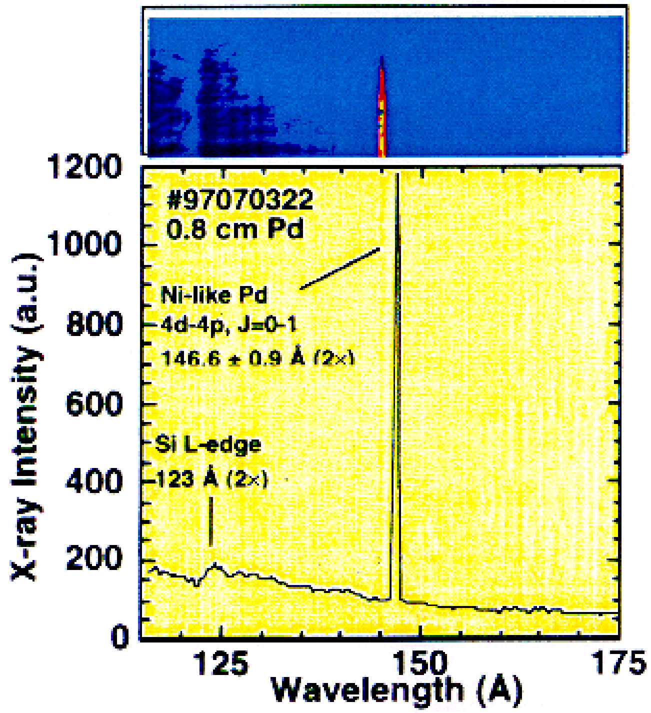
Mo:	188.95 (3) Å
Nb:	203.34 (3) Å
Zr:	220.20 (3) Å
Y:	240.11 (3) Å

Table-top 200 Å Ni-like ion x-ray laser is achieved

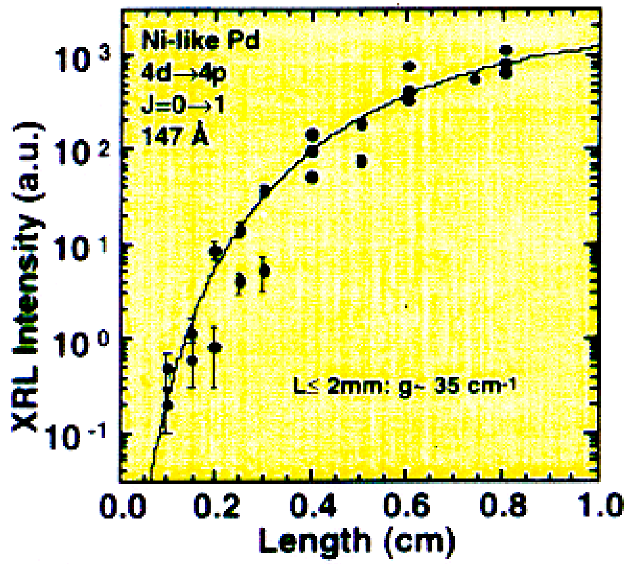
Pd 147 Å XRL was first observation of Ni-like transient scheme for 1-ps laser drive - high gain 35 cm^{-1}

- Output of 147 Å in 2nd order - $g \sim 35 cm^{-1}$ for $L \leq 2mm$, $gL \sim 12.5$
- Gain drops for L>2 mm from finite transit of XRL along plasma column

Ni-like Pd spectrum for 8 mm



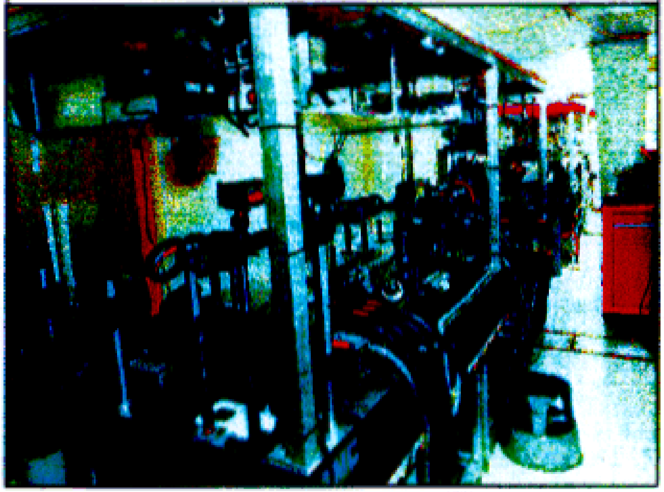
Ni-like Pd 4d-4p intensity vs L



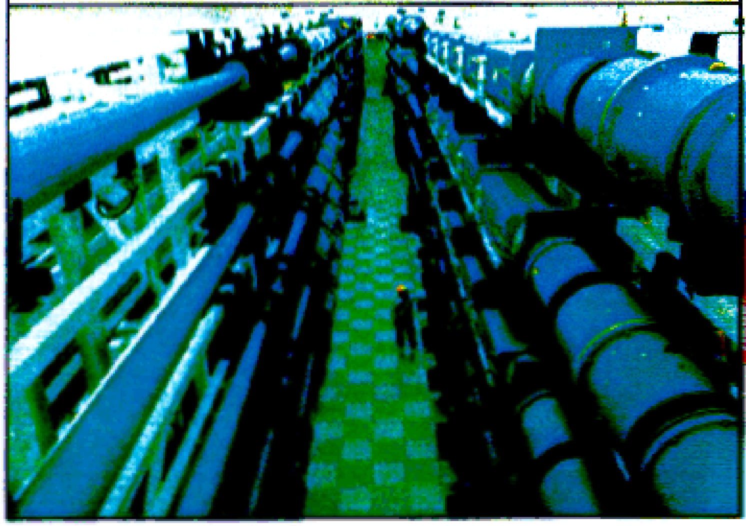
J. Dunn, A. Osterheld, et al, PRL 80, 2825 (1998)

LLNL leads world in x-ray lasers and short pulse laser technology research

Goal: Tabletop X-Ray Lasers



Nova



Transient XRL scheme produces dramatic reduction in size and cost of laser driver

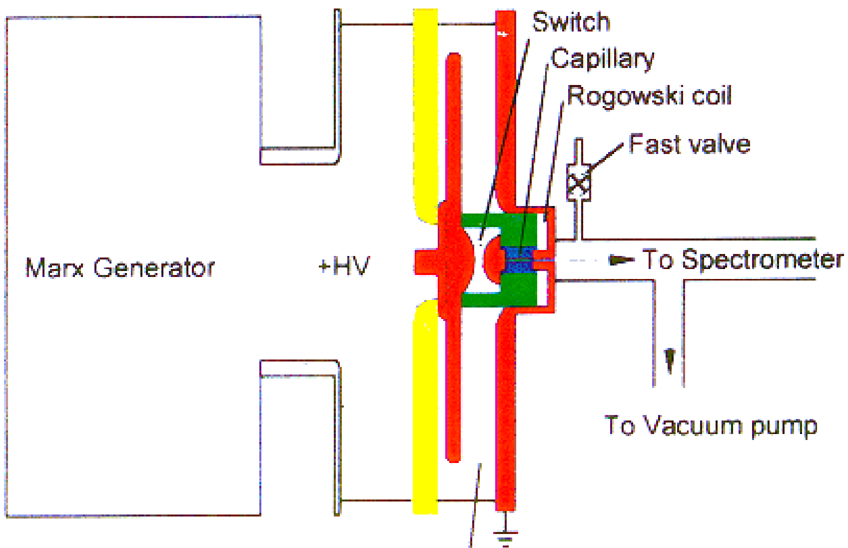
	COMET	Nova
Size	100 sq. ft	>40,000 sq. ft
Cost	\$1 M	>\$100 M
Pump Energy	10 J	5—10 kJ (2 beams)
XRL Gain	35 — 55 cm^{-1}	1 — 8 cm^{-1}
XRL Output	50 — 100 μJ	5 mJ
Shot Rate	50 — 100/day	4 — 6/day
XRL Wavelength	80 → 330	35 → 200
Pulse Duration	1 — 10 ps	45 ps → 200 ps
Brightness	2×10^{23} ph mm^{-2} $mrad^{-2}$ s^{-1} $(0.01\%\ BW)^{-1}$	10^{24} ph mm^{-2} $mrad^{-2}$ s^{-1} $(0.01\%\ BW)^{-1}$
Cost/shot	\$50	\$10K—20K

COMET enables table-top, high gain, short pulse, high repetition rate, ultra-bright x-ray laser source at low cost

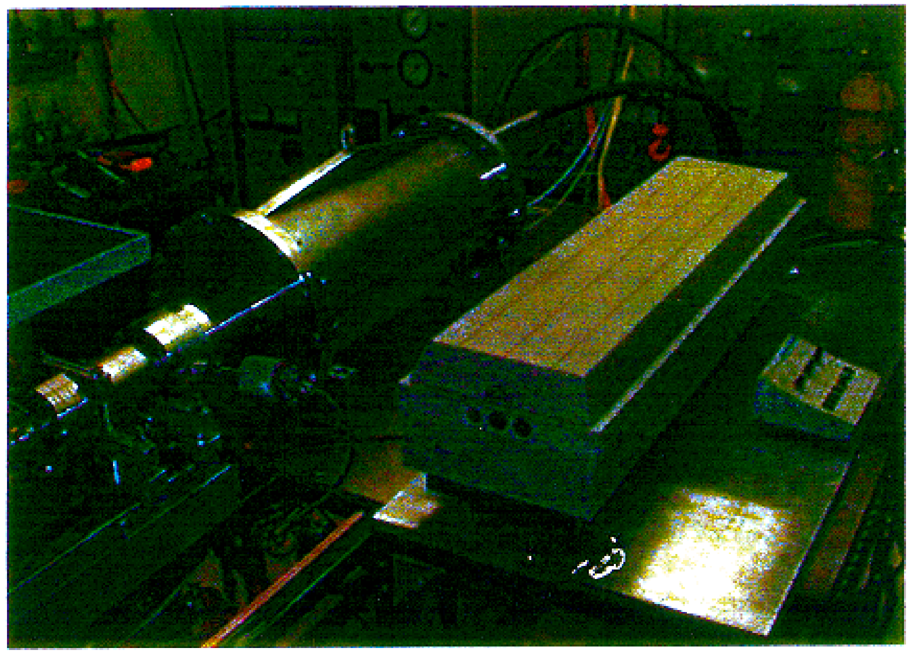
Table-Top Capillary Discharge Soft X-ray Lasers

Size of 1 mW average power discharge pumped laser (λ=46.9 nm) is similar to that of many widely used visible and UV lasers.

Example capillary discharge setup. *



Capillary discharge soft x-ray laser (left) and 0.8 J Nd:YAG laser (right).



* J. J. Rocca et al., Phys. Rev. E, **47**, 1299 (1993).

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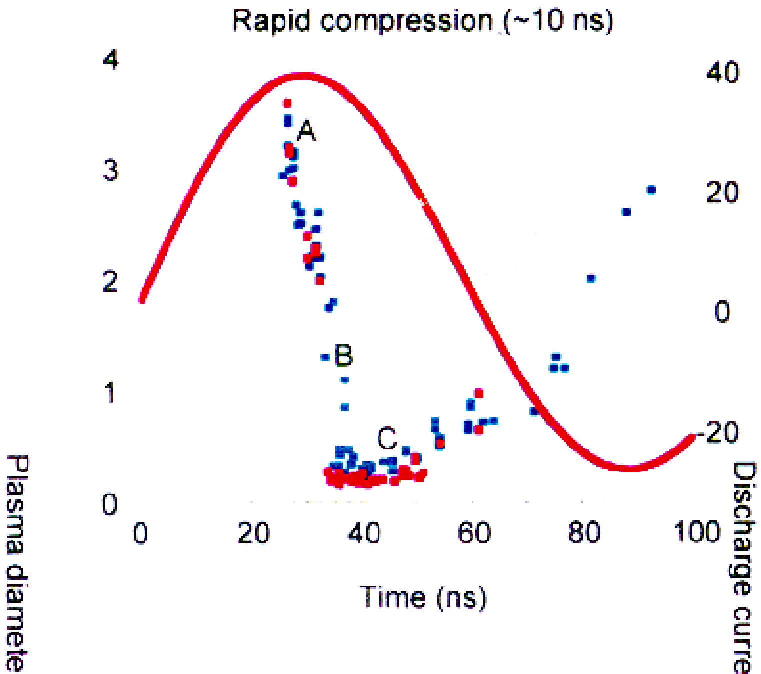
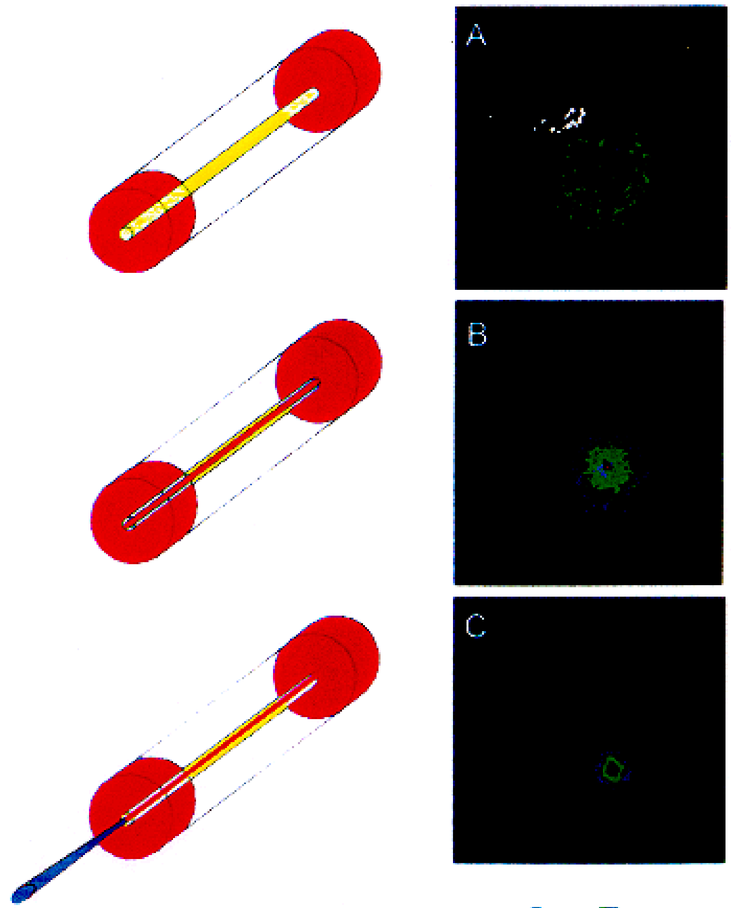
Fast Capillary Discharge Plasmas for Soft X-Ray Lasers

A fast current pulse compresses a plasma creating a hot and dense column with aspect ratio L/d = 1000

- High Axial Uniformity
- Large Gain Volume
  (large output energy)
- High Ionization Efficiency
- Rapid Radial Motion
  (decreased radial resonant absorbtion)





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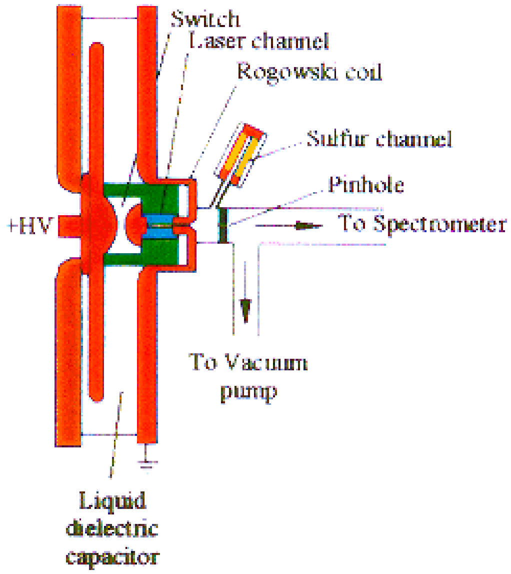
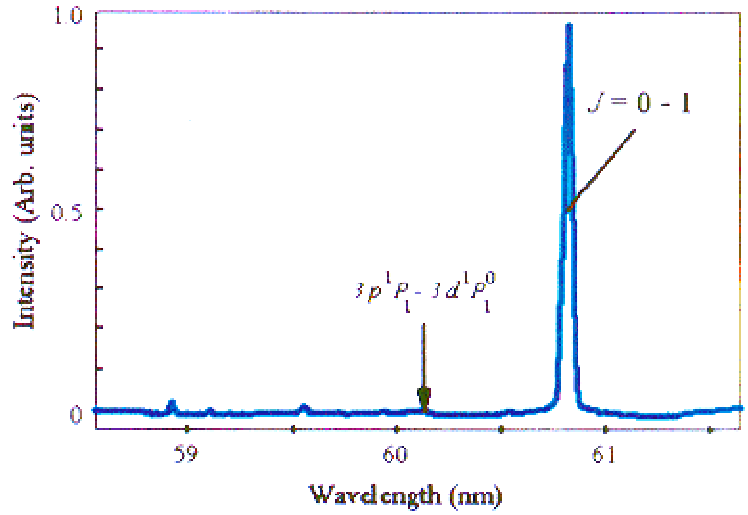
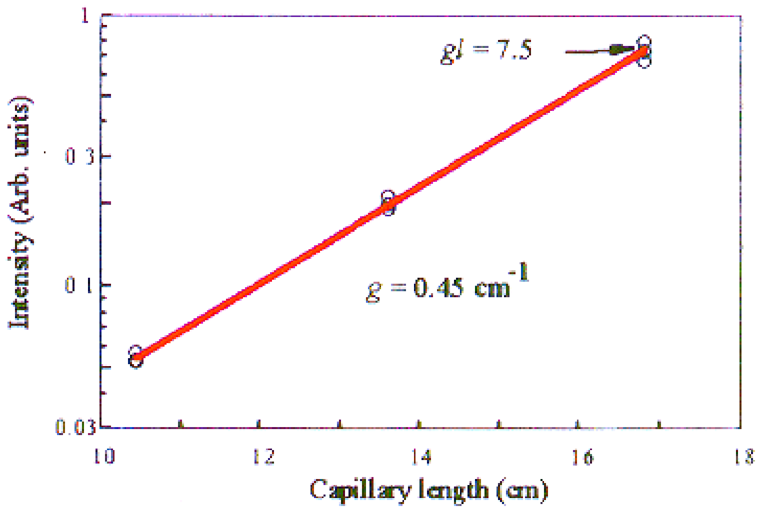
Amplification can also be obtained in elements that are solid at room temperature utilizing discharge ablation.

Demonstration of Amplification in Ne-Like S at λ= 60.8 nm*







*F.G. Tomasel, J.J. Rocca, V.N. Shlyaptsev and C.D. Macchietto, Phys. Rev. A **55**, 1437 (1997).

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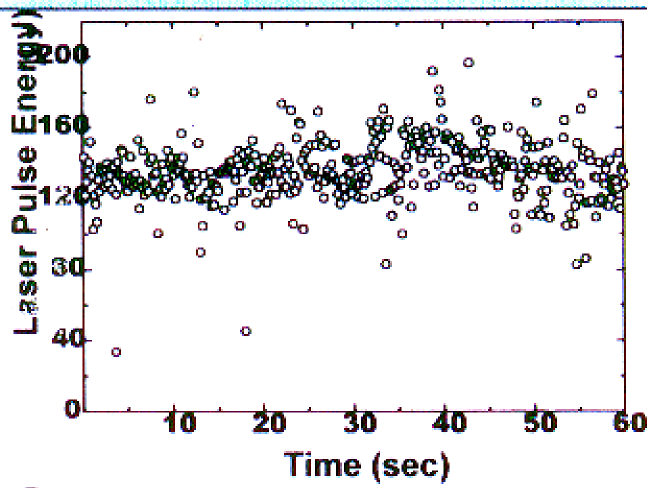
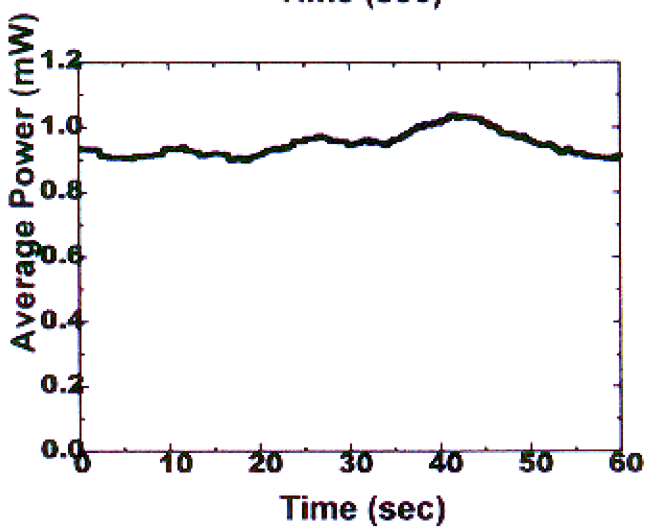
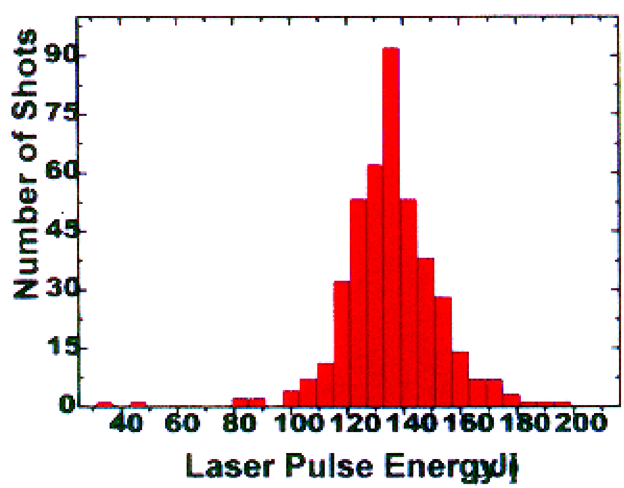
Average Power (λ = 46.9 nm)

1 mW Average Power Demonstrated*
(0.135 mJ/pulse at 7 Hz)







*B.R. Benware, C.D. Macchietto, C.H. Moreno and J.J. Rocca. Phys. Rev. Lett. Dec. 21, 1998.

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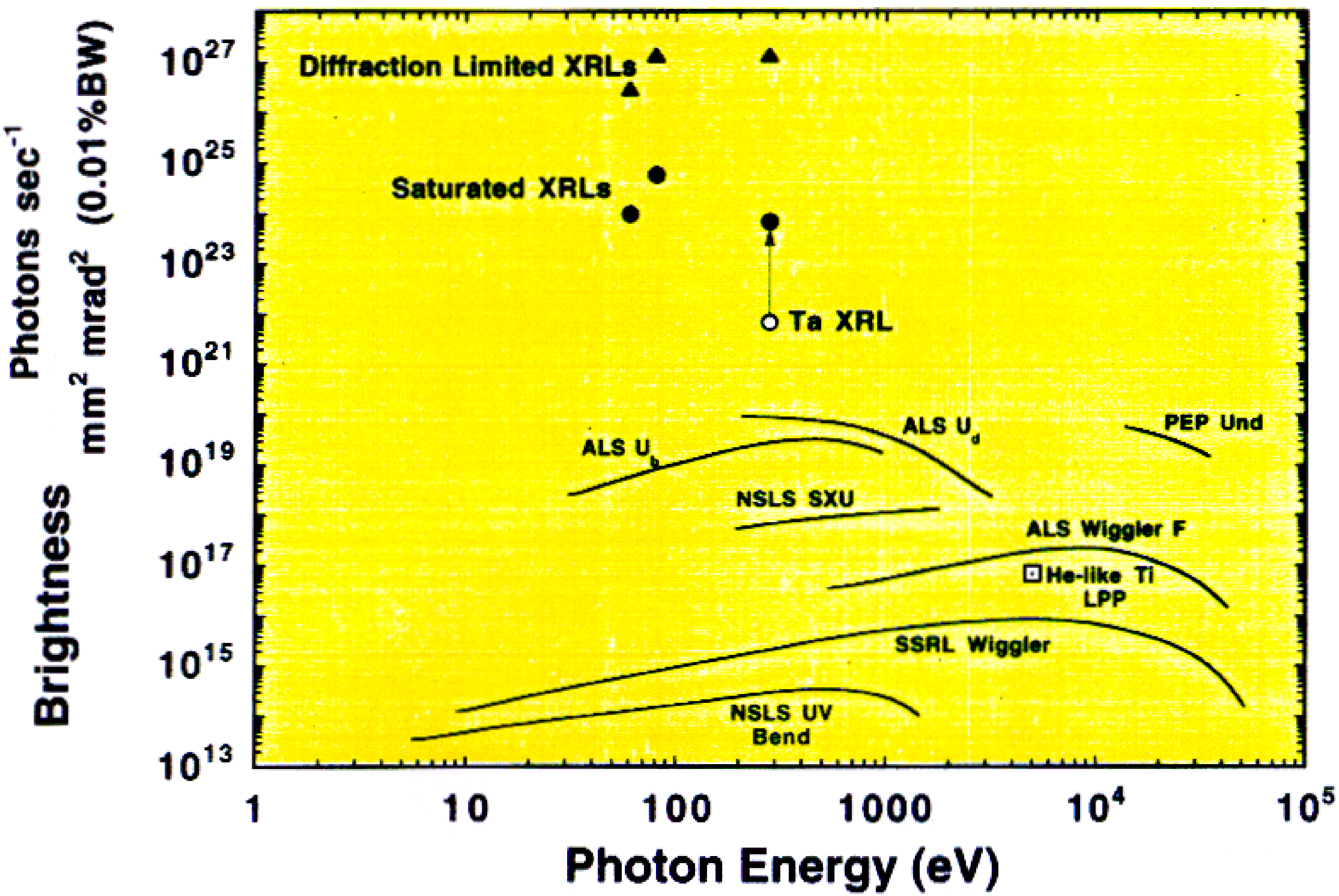
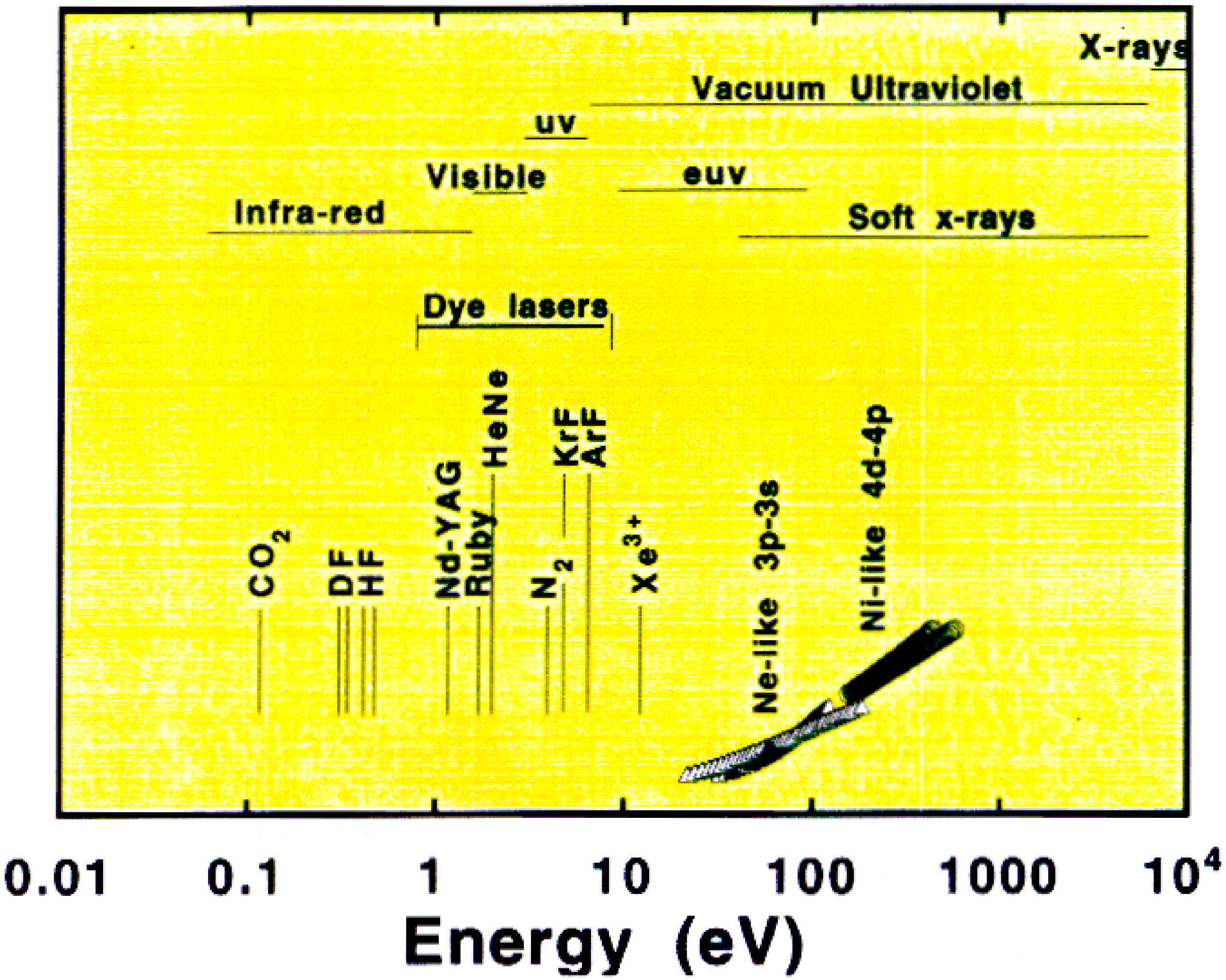
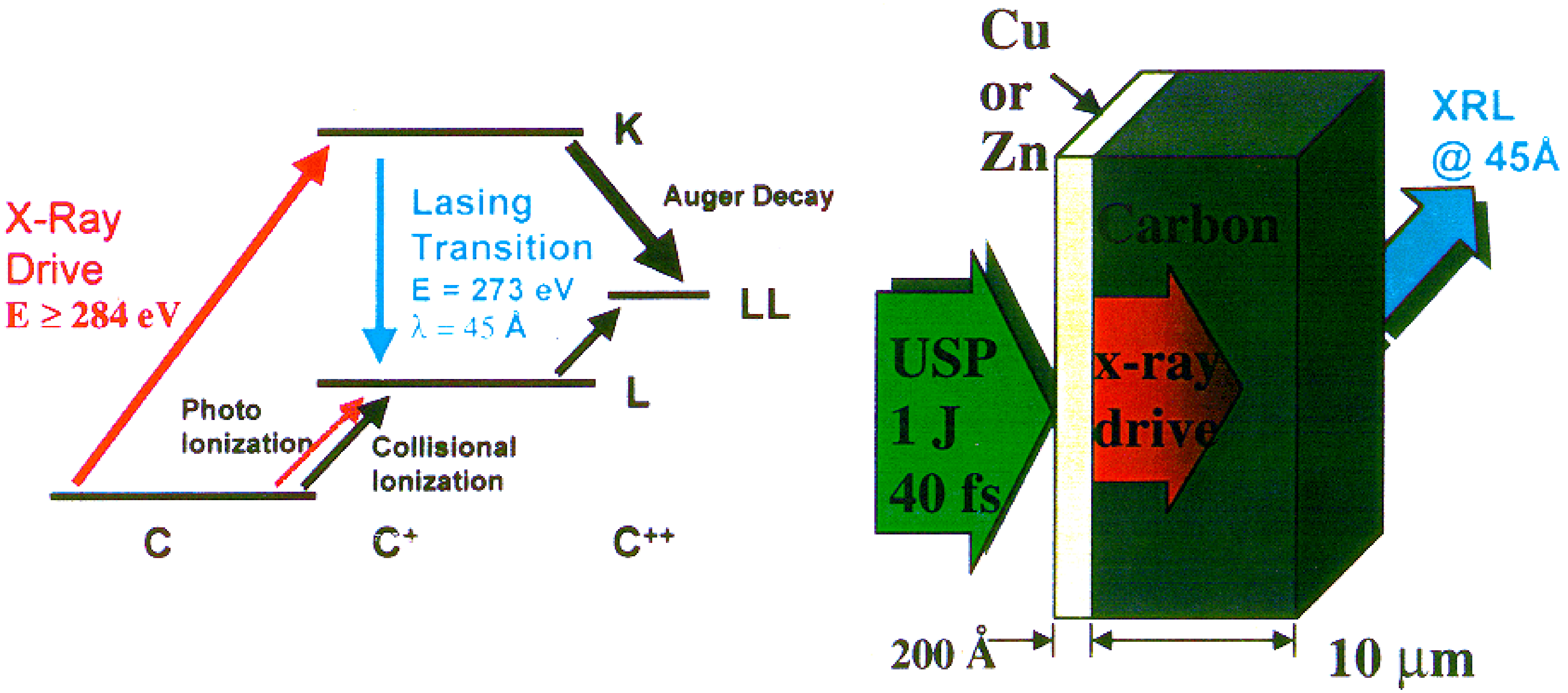
X-ray lasers remain one of the brightest XUV sources currently available



Soft x-ray lasers extend the range of the radiation spectrum covered by laser sources



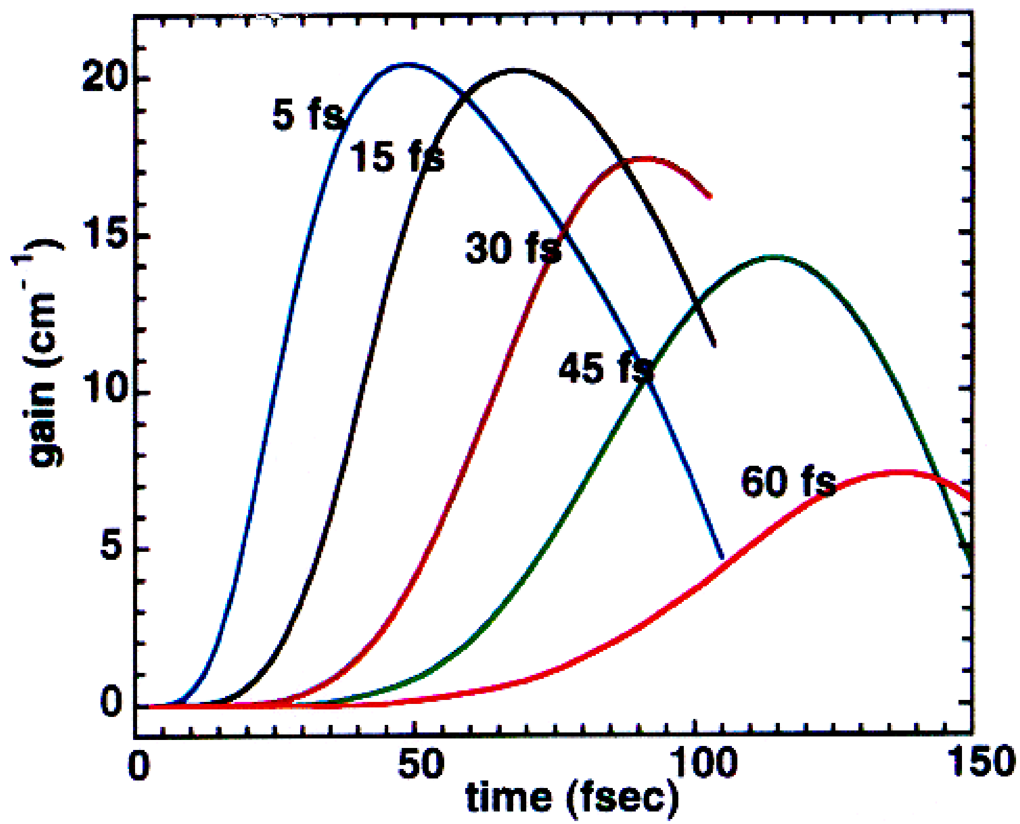
Ultrashort pulse lasers make possible a new class of x-ray lasers



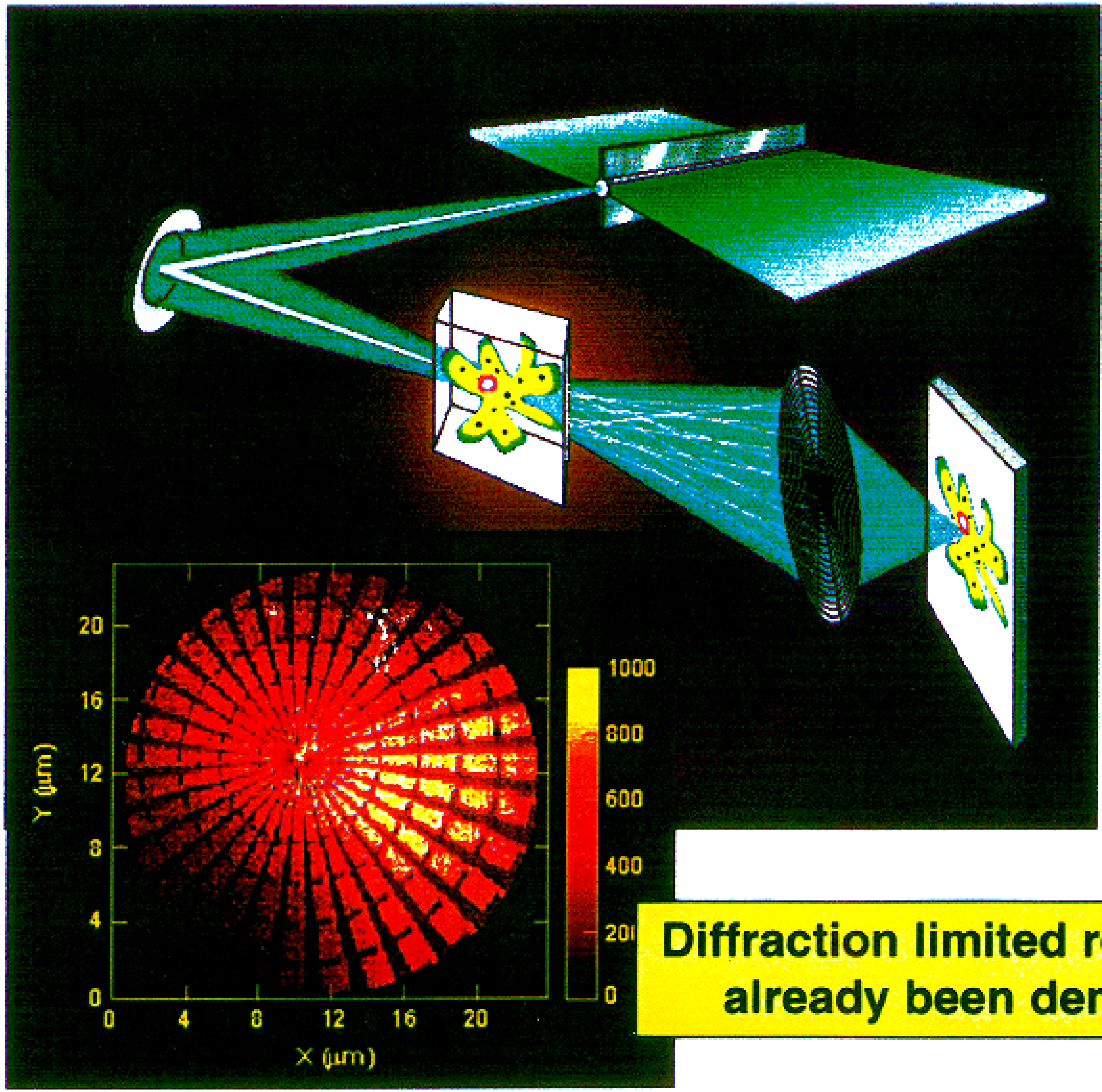
Inner-shell pumped x-ray lasers offer a path to ultrashort pulse width (<20 fs) water window photons with compact pump lasers

Fast Auger rates make it essential to use short pulse width pump lasers

Calculated gains for Carbon 2p-1s laser at 45 Å, using 1J optical pump pulse



High peak brightness of x-ray lasers is ideal for x-ray microscopy of biological specimens



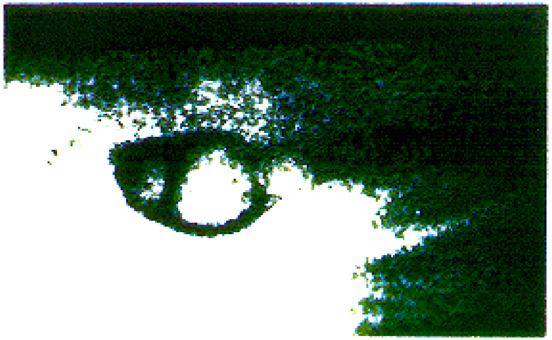
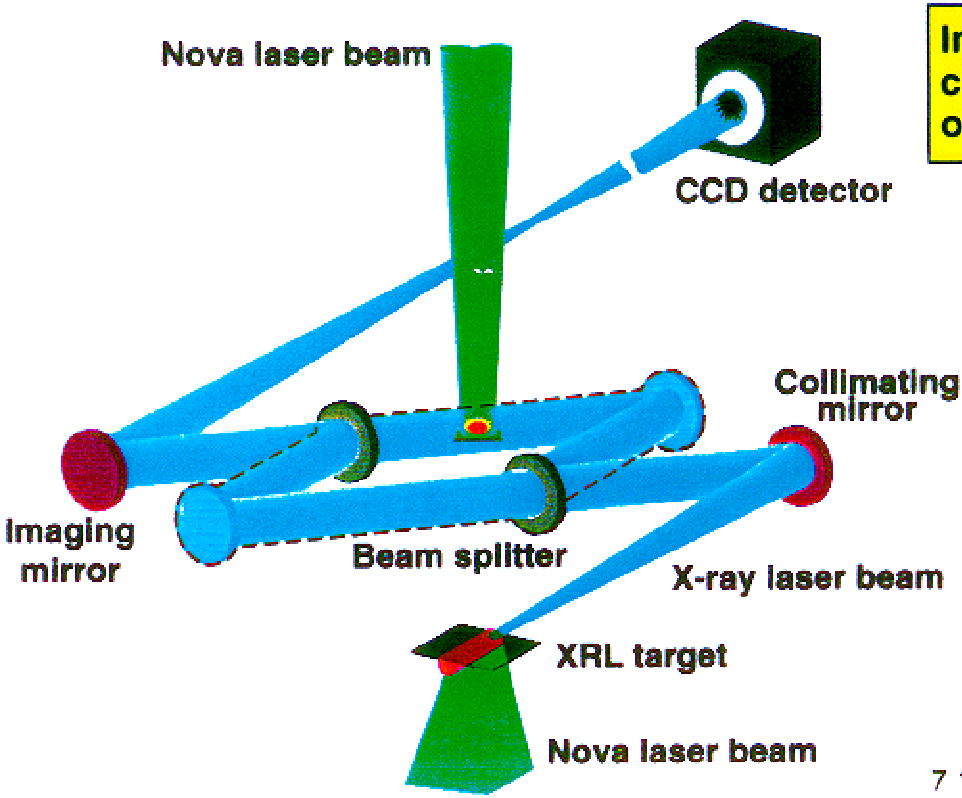


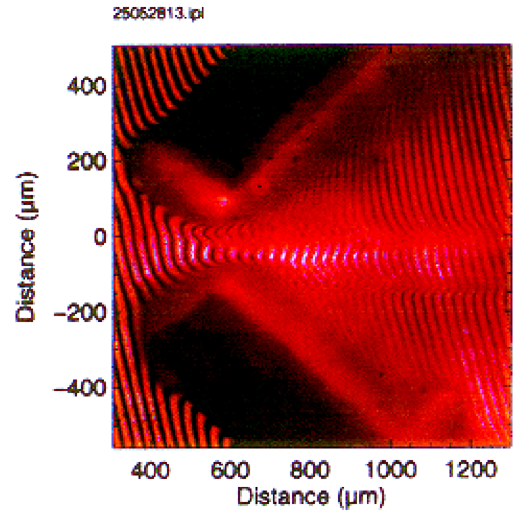
Image of gold labeled rat sperm nuclei (100 ps exposure)

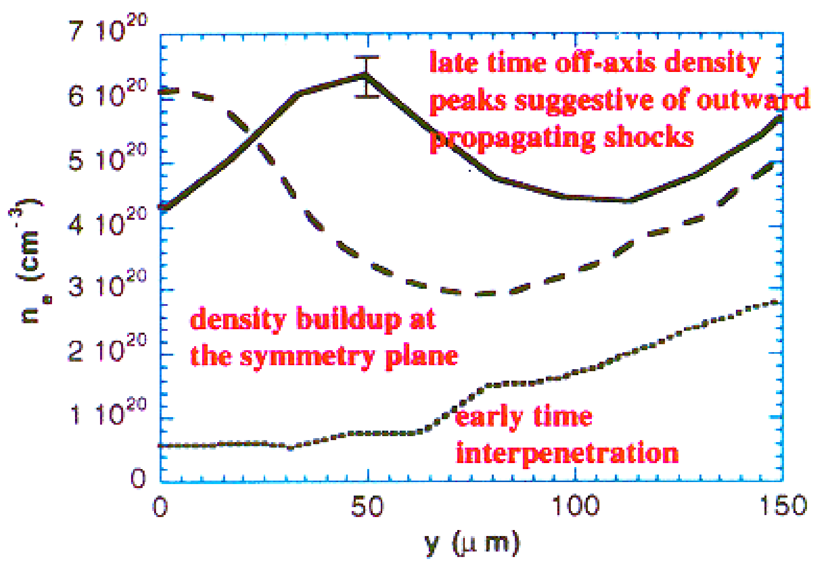
Diffraction limited resolution has already been demonstrated

X-ray laser interferometer is used to accurately diagnose high density plasmas



Interferogram of colliding plasmas clearly showing plasma stagnation and outward propagating shock waves.

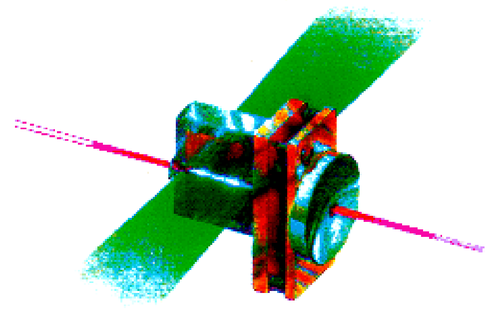




- Yttrium x-ray laser (λ=155 Å, 1 mJ in 80 ps)
- 1 fringe shift -> $n_e = 3\times10^{20}$ cm^{-3}

Summary and Conclusions

- New pumping schemes and methods are making table top x-ray lasers possible
  - PrePulse/Multiple pulse pumped systems
  - Optical Field Ionized x-ray lasers
  - Capillary discharge x-ray lasers
  - Short pulse, transient inversion x-ray lasers.



- High power, short pulse <50 fs optical lasers will open up new possibilities for short wavelength high power x-ray lasers.