High Peak- and Average- Power Lasers for Use in Advanced Light Source Development

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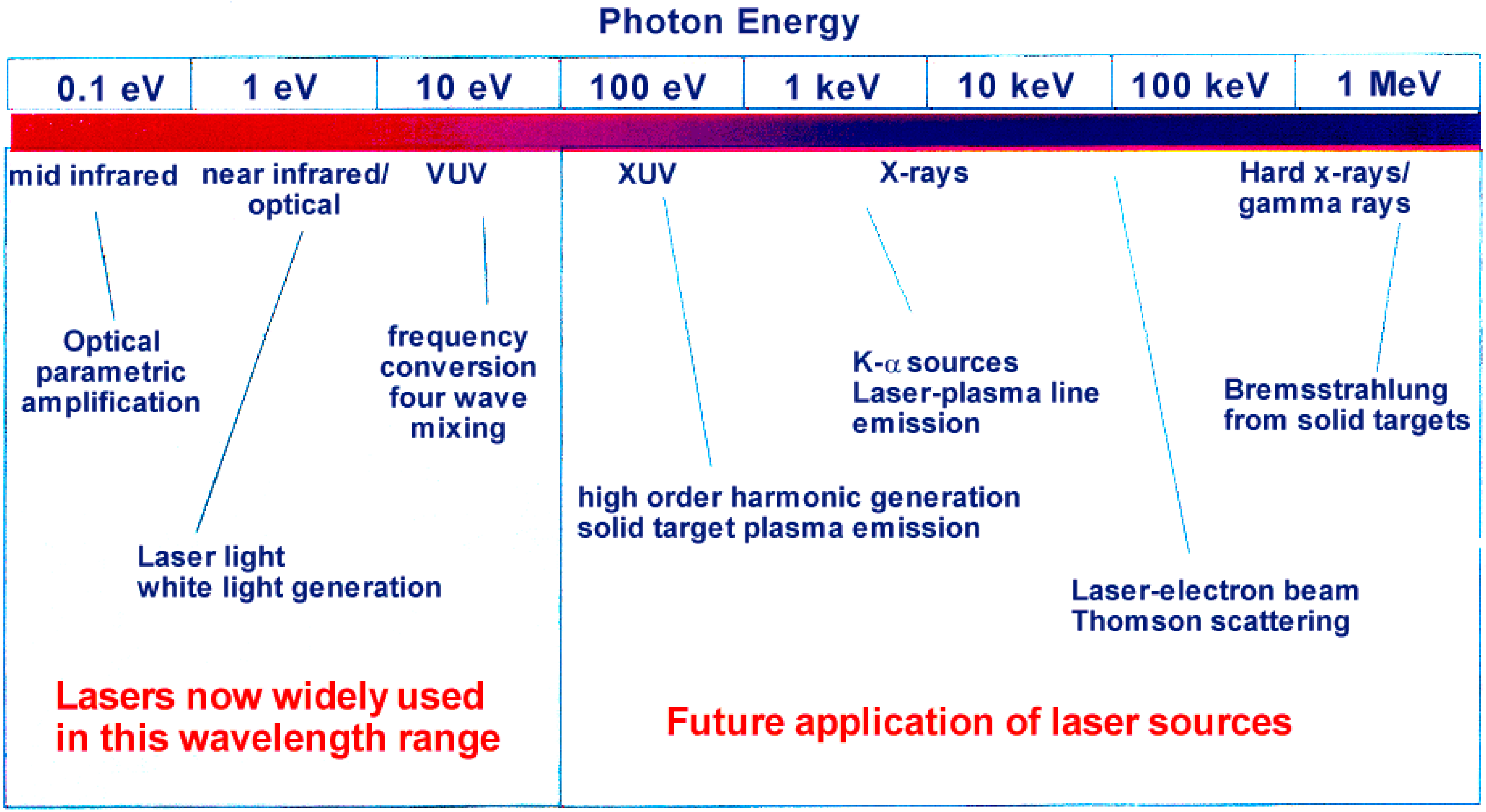
Laser technology coupled to scientific study of light sources ultimately opens new applications

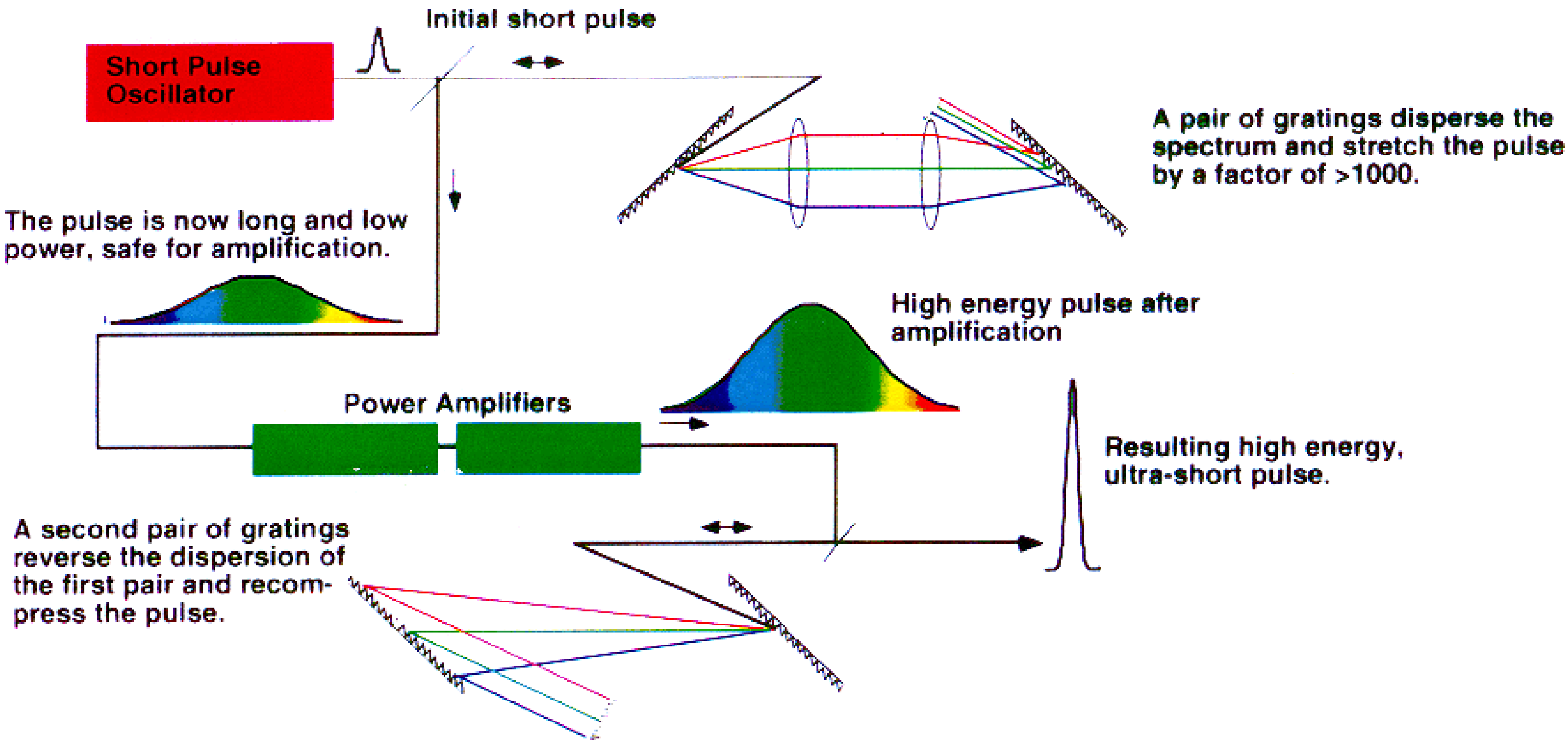
Technology	Science	Applications
High average power femtoseconds lasers	High order harmonics (gas jets, plasmas)	• At-wavelength metrology of EUV lithography optics • Probing high density plasmas
	X-ray lasers (plasmas)	• Microscopy of biological samples • Probing high density plasmas • Sub 100Å imaging
	Thomson scattering (e^- beams)	• Time resolved probing of materials dynamics • Chemical kinetics
	Bremsstrahlung Other plasma sources	• Time-resolved radiography

Using high-rep-rate lasers allows probing of material with a wide range of wavelengths



High repetition rate, laser driven light sources offer a wider and more flexible array of options for probe pulses

Chirped pulse amplification permits construction of table-top scale, high peak power lasers



Current capabilities:

Nd:glass	Ti:sapphire		High average power Ti:sapphire
• peak< 10^{15} W (1 PW)	• peak < 10^{14} W (~ 100 TW)		• peak < 10^{12} W (1 TW)
• pulse width > 500 fs	• pulse width > 20 fs	⟶	• pulse width > 20 fs
• energy < 500 J	• energy < 1 - 10 J		• energy < 20 mJ
• rep rate ~ 1shot/10-100 min	• rep rate ~ 10 Hz		• rep rate ~ 1 kHz

Ultrafast x-ray pulses can be a key component of next generation light source development

Ultrafast x-ray pulses can be used to probe a wide variety of physical, chemical and biological processes

- Applications include:

  Ultrafast probing of dynamics in materials

  Probing electron/phonon coupling dynamics in solids

  Time resolve chemical reaction kinetics

  Time resolve dynamics in photoactive biological molecules

- Ultrafast x-ray sources include
  - nonlinear optical conversion of laser pulses (high harmonic generation)
  - laser plasmas
  - laser-electron beam scattering

Ultrafast x-ray techniques appear promising, but present experiments are limited in time resolution and to repetetive processes by current source constraints

Faster, brighter sources will enable single-shot measurements with a broad range of techniques (EXAFS, absorption, diffraction).

Production of high average power, high brightness ultrashort pulse lasers is limited by several factors

1) The laser material must exhibit a gain-narrowed bandwidth sufficient to support the bandwidth of the short pulse ($\Delta\nu\Delta\tau \approx 0.5$)

10 psec	1 psec	0.1 psec
Nd:YAG	Nd:Glass	Ti:Sapphire
	Yb:YAG	Cr:LiSAF

System Issues: Bandwidth of Optical Components, Etalon Modulation, etc

2) The laser material should exhibit a large saturation fluence and long upper state lifetime for high energy storage and compactness

	Dyes	Excimers	Solid-State
$F_{sat}=$	1 mJ/cm^2	2 mJ/cm^2	5 J/cm^2
τ	1 nsec	a few nsec	100's of μsec

3) Phase front quality must be free of aberrations for diffraction limited focusability (e.g., Thermal focusing/aberrations)

4) Intensity in the amplifiers must be kept less than a few GW/cm^2 in order to avoid self-focusing and catastrophic damage

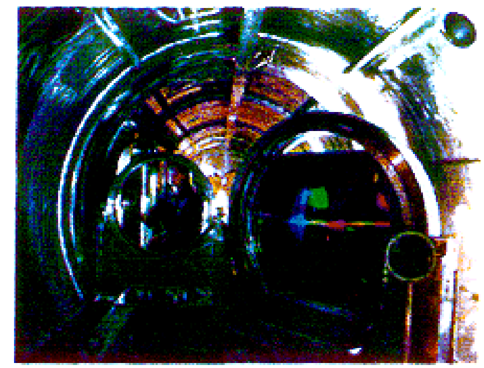
Intensity-dependent refractive index	Nonlinear Phase (B- Integral)	Amplitude Modulation
$n = n_0 + n_2\, I(t)$	$B = (2\pi/\lambda) \int n_2 I(t)\, dz$	Exp (2B)

The Petawatt laser represents a massive scaling of CPA technology in Nd:glass

Broadband Ti:sapphire front end

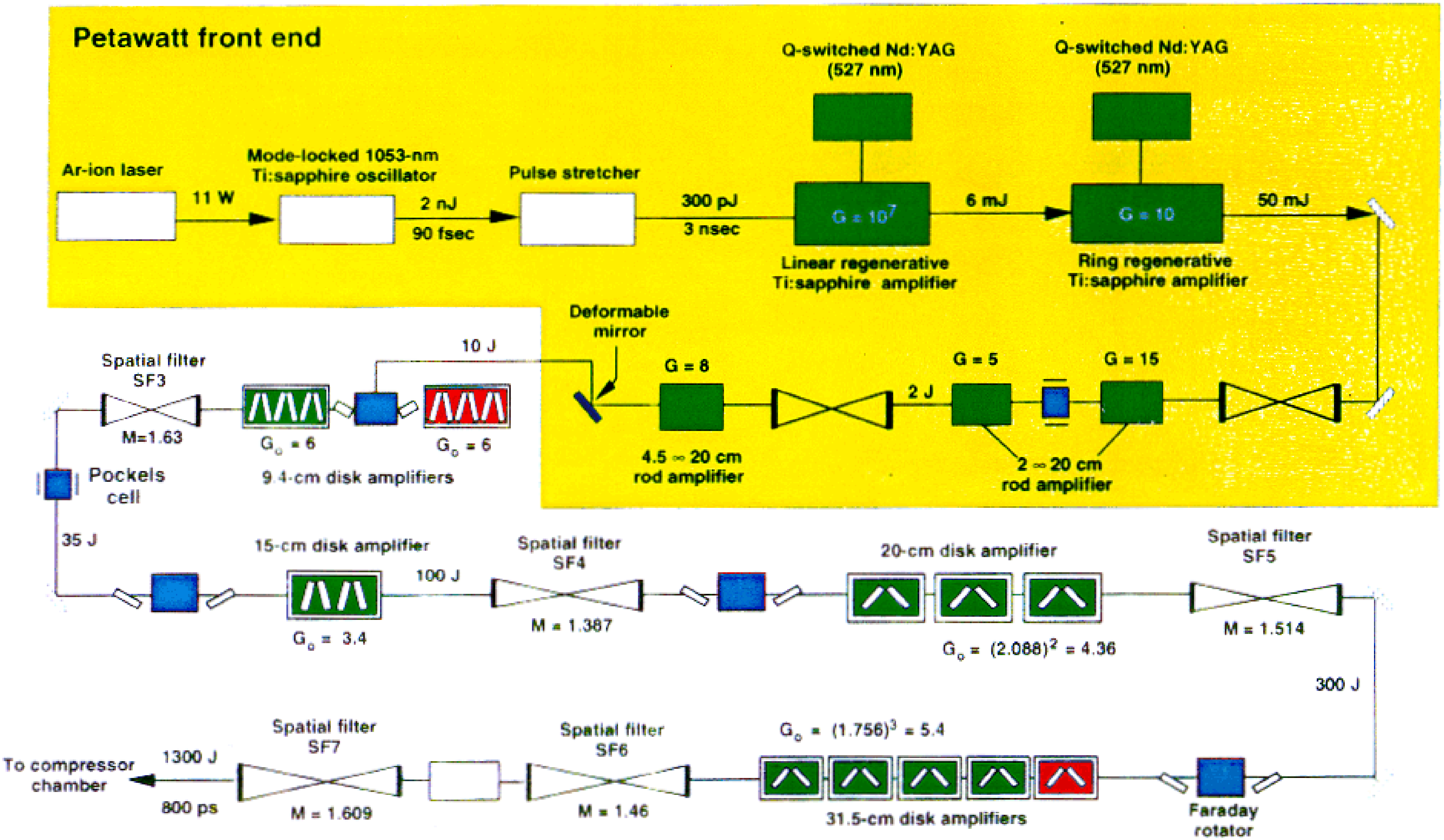
Nd:Glass amplifier chain (Nova beamline #6)

Large aperture (80 cm) vacuum compressor



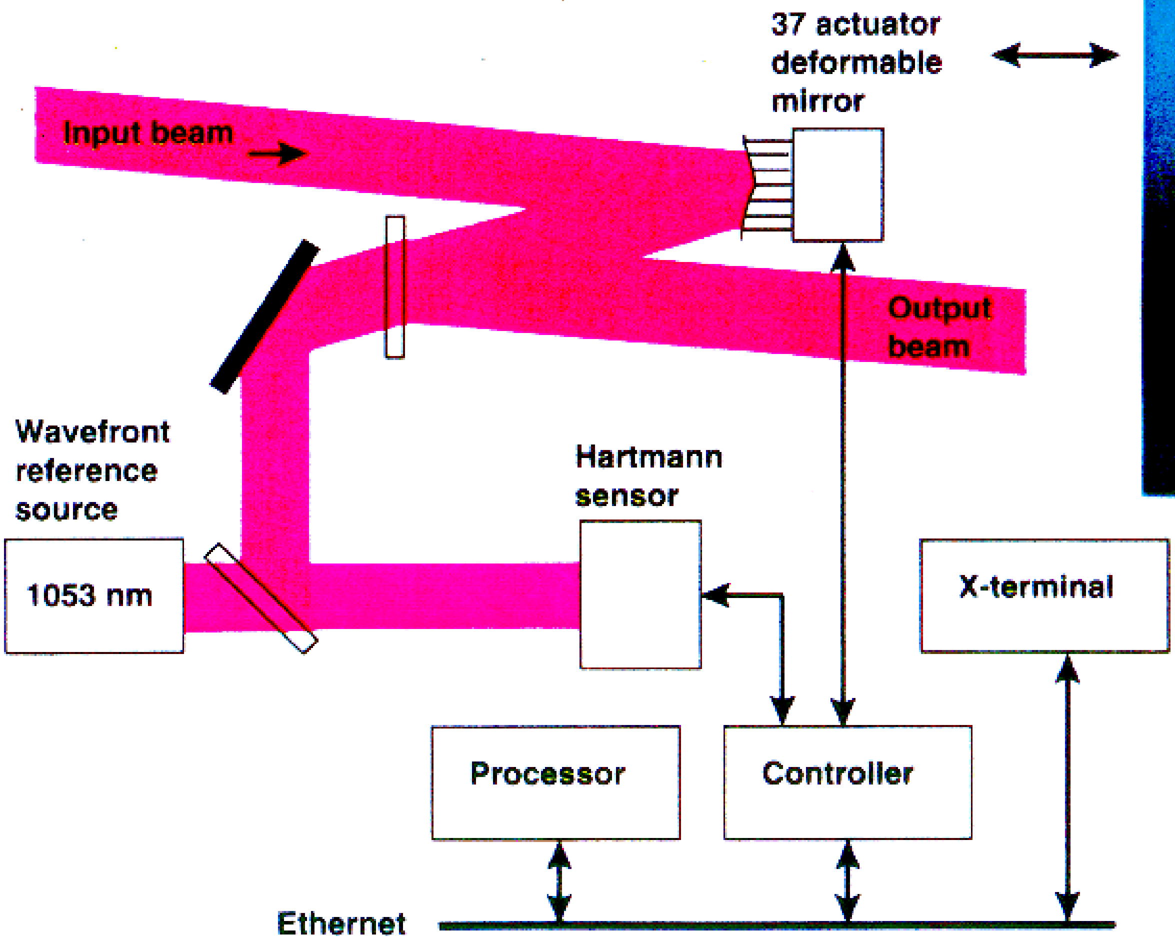
Compressed energy: >500 J
Pulse width: 400 fs
Shot rate:1/hr
Focused intensity: ~10^{21} W/cm^2

Petawatt laser design



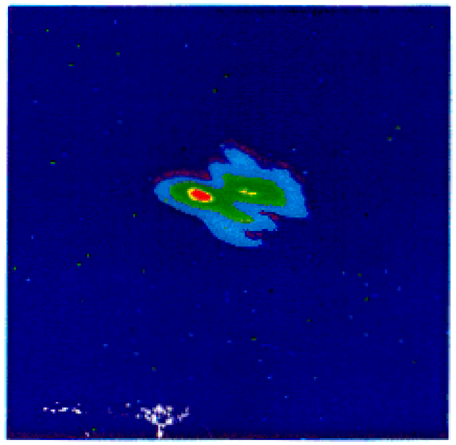
Wavefront correction system

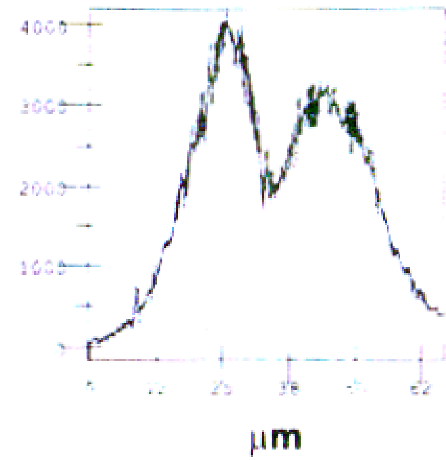
Final control sensor is located at the output of the amplifier chain prior to compression



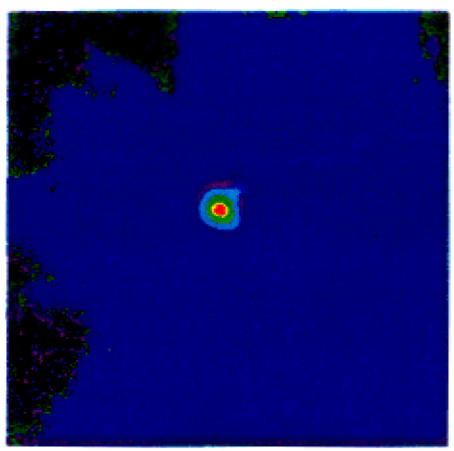
The deformable mirror gives reproducibly smaller focal spots relative to shot with cumulative thermal distortion

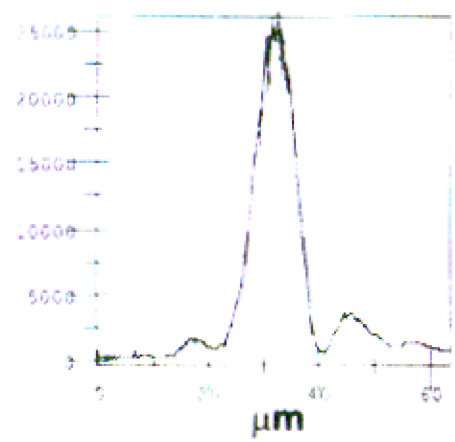
Deteriorated focus in second shot after 7 hr. without DM (291J)





Stable result with DM (626J) (3x intensity/J)





The FALCON laser facility will integrate a 100 TW laser with a 100 MeV electron linear accelerator

FALCON Laser Specifications:

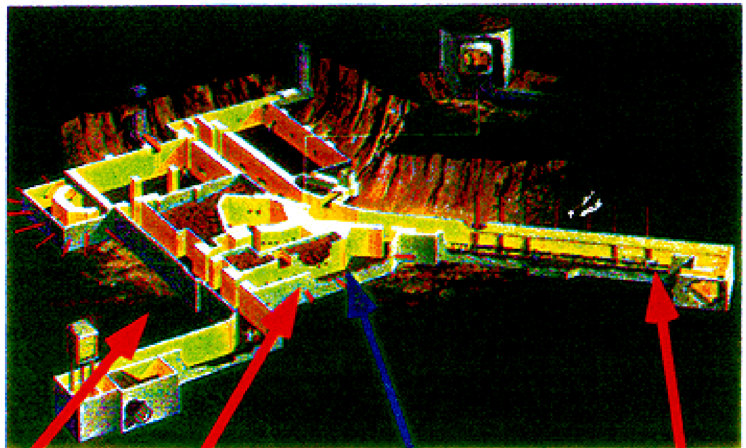
Pulse Energy: > 5 J
Pulse Width: 30 fs
Peak Power: ~200 TW
Repetition Rate: 1 Hz

Focused Intensity: $>10^{20}$ W/cm^2

↕ temporally synchronized

LINAC Specifications:

Electron Energy: 100 MeV
Beam Emittance: $< 2\pi$ mm mrad
Electron Pulse Width: 1 ps
Charge per bunch: 1 nC



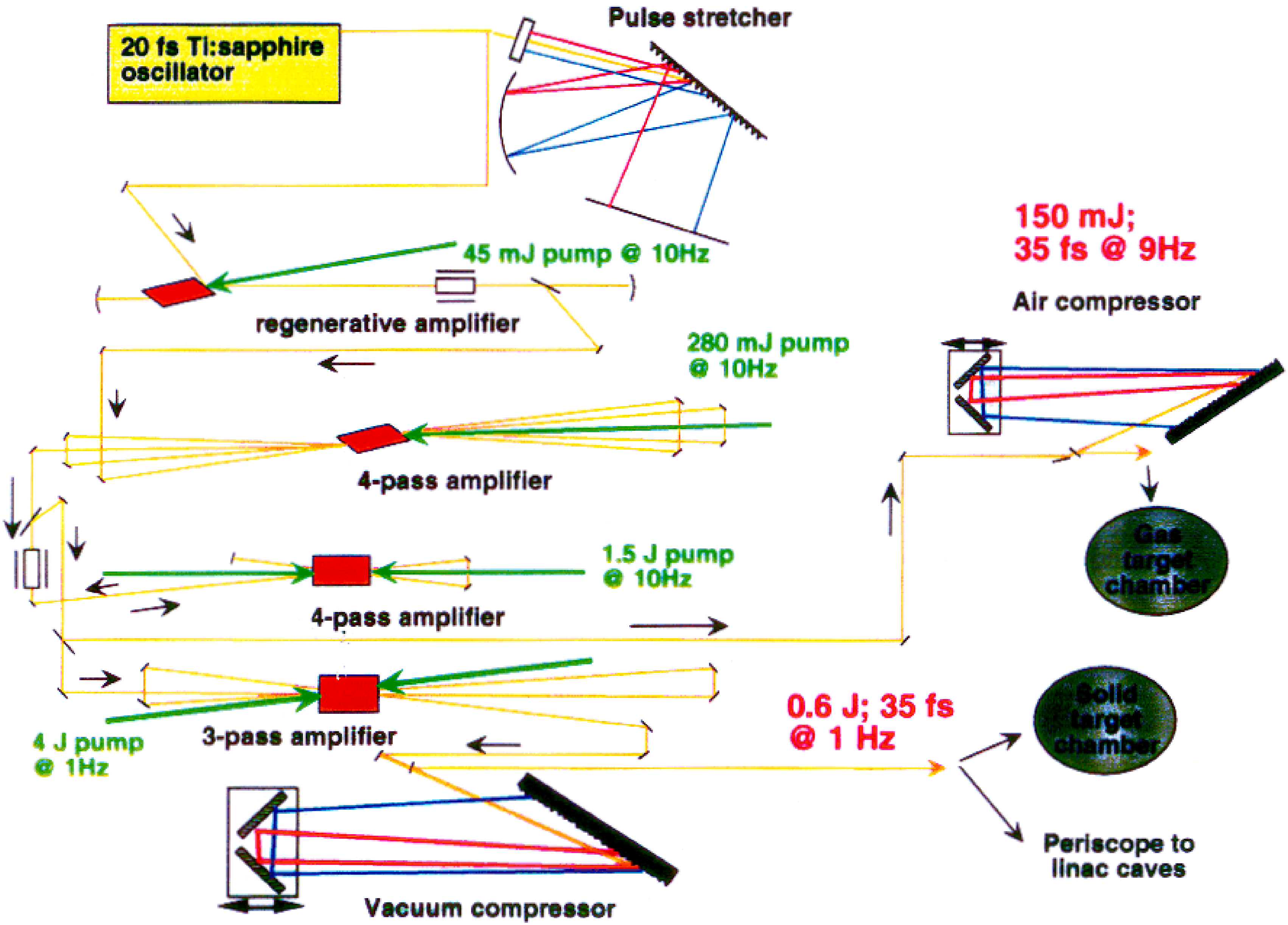
Experimental sites can be located in the Linac cave

FALCON 100 TW Laser

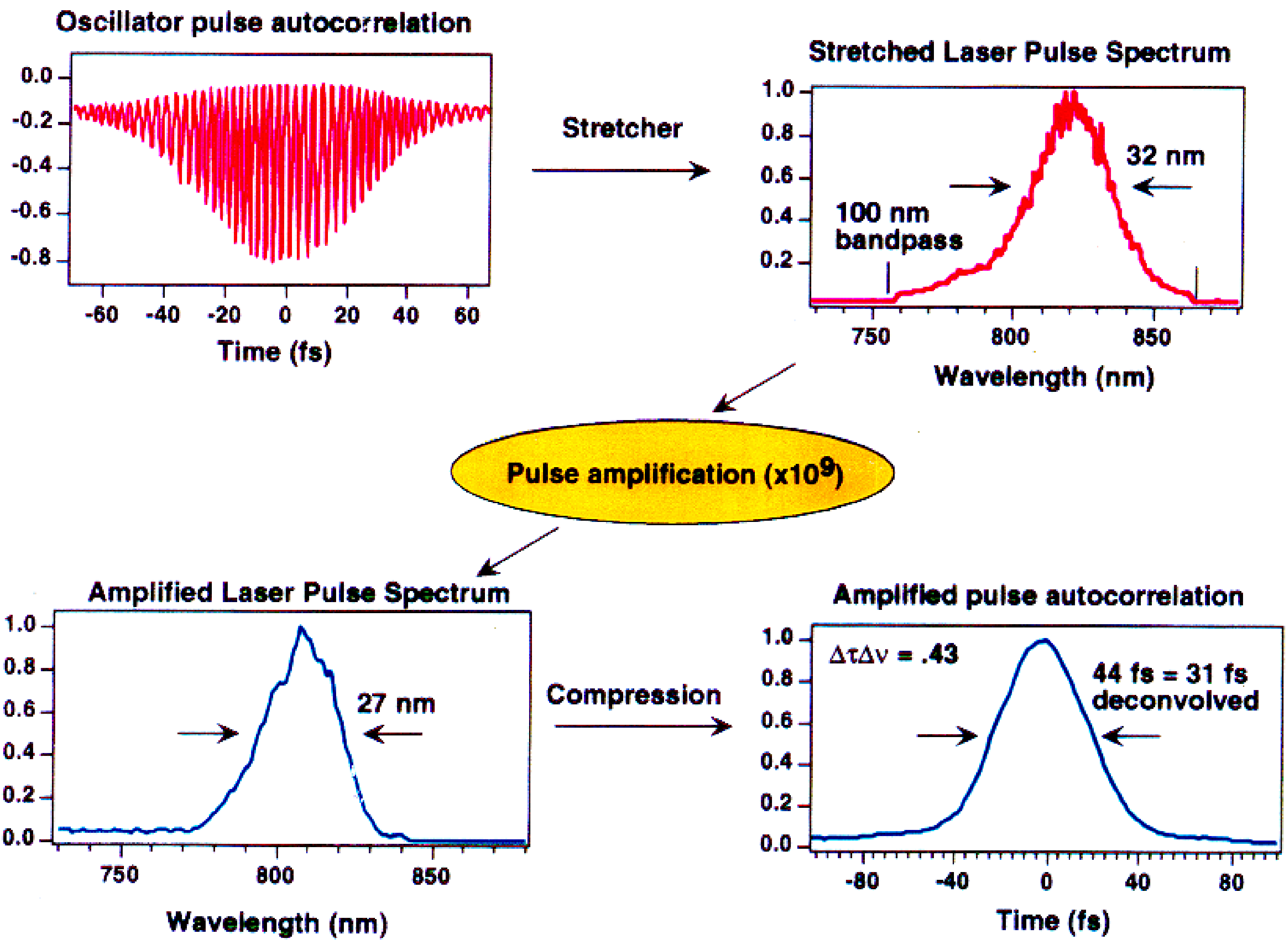
Compressor Chamber

Upgraded 100 MeV Linac

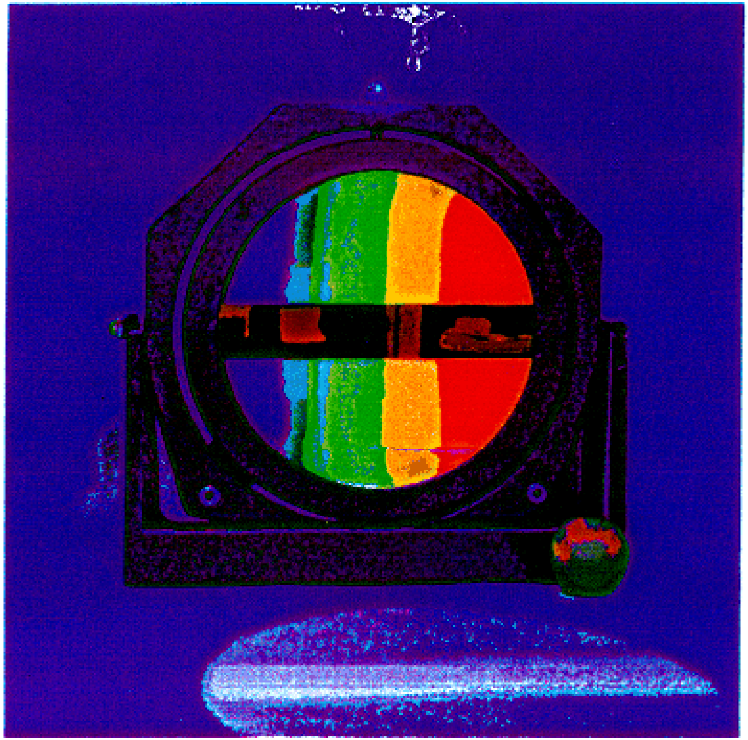
The Falcon laser will be used at the 20 TW level for initial experiments



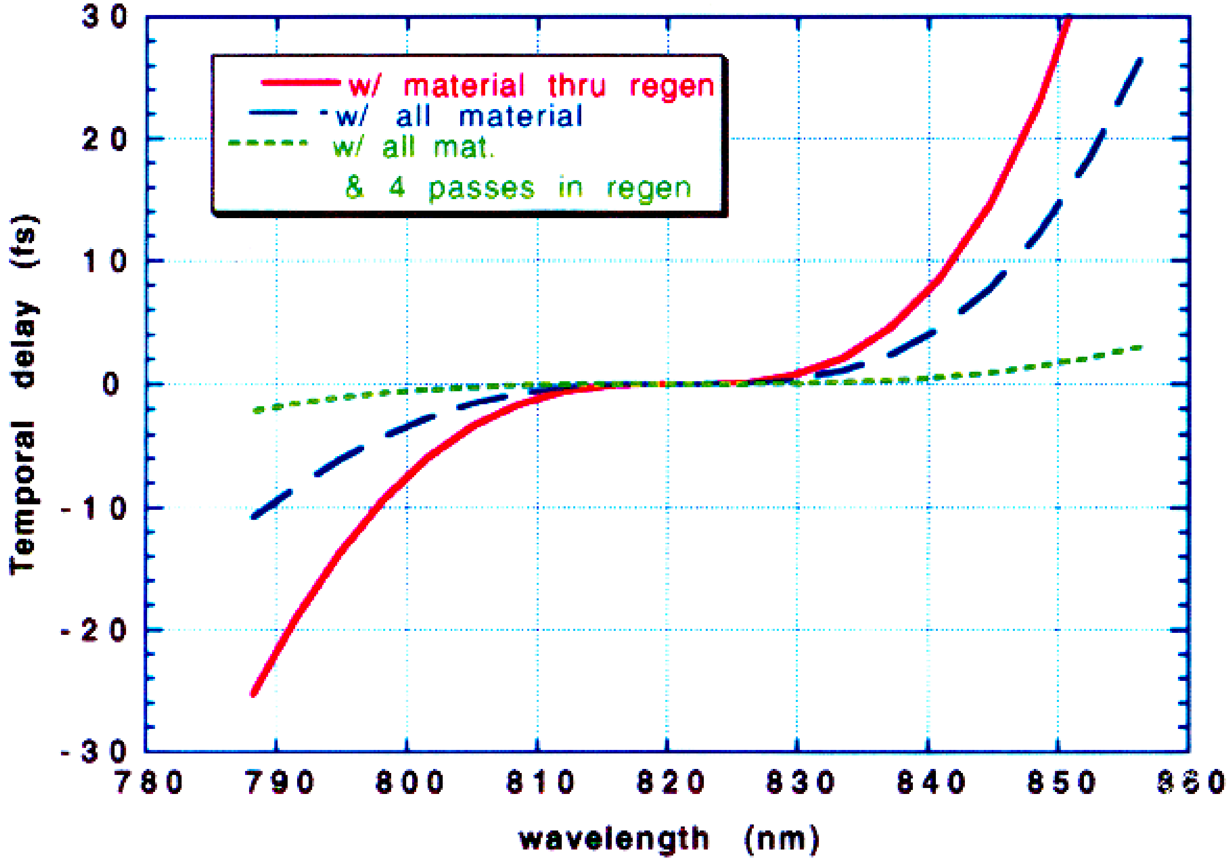
The Falcon laser amplifies very broad bandwidth yielding clean, near transform limited, 30 fs pulses



The stretcher design utilizes an LLNL designed and fabricated grating with a reflective stripe

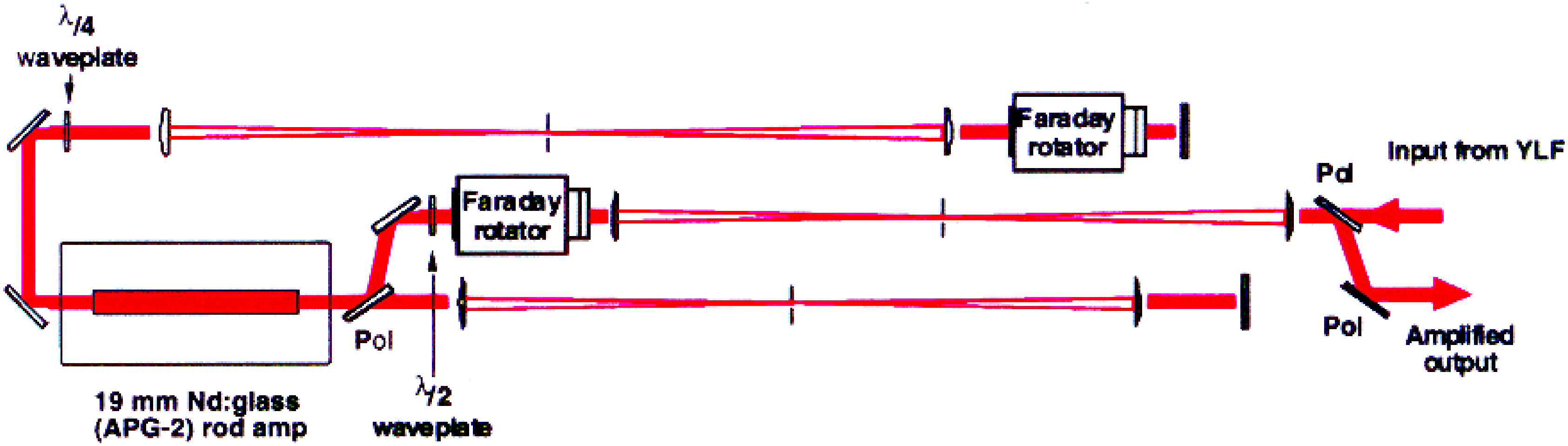


Additional material in path continues to improve recompressed pulse width



We have a basic design for the pump laser required to boost the Falcon laser to >100 TW

The remaining 1ω from each Nd: YLF arm will be amplified in a 19 mm Nd:glass amplifier

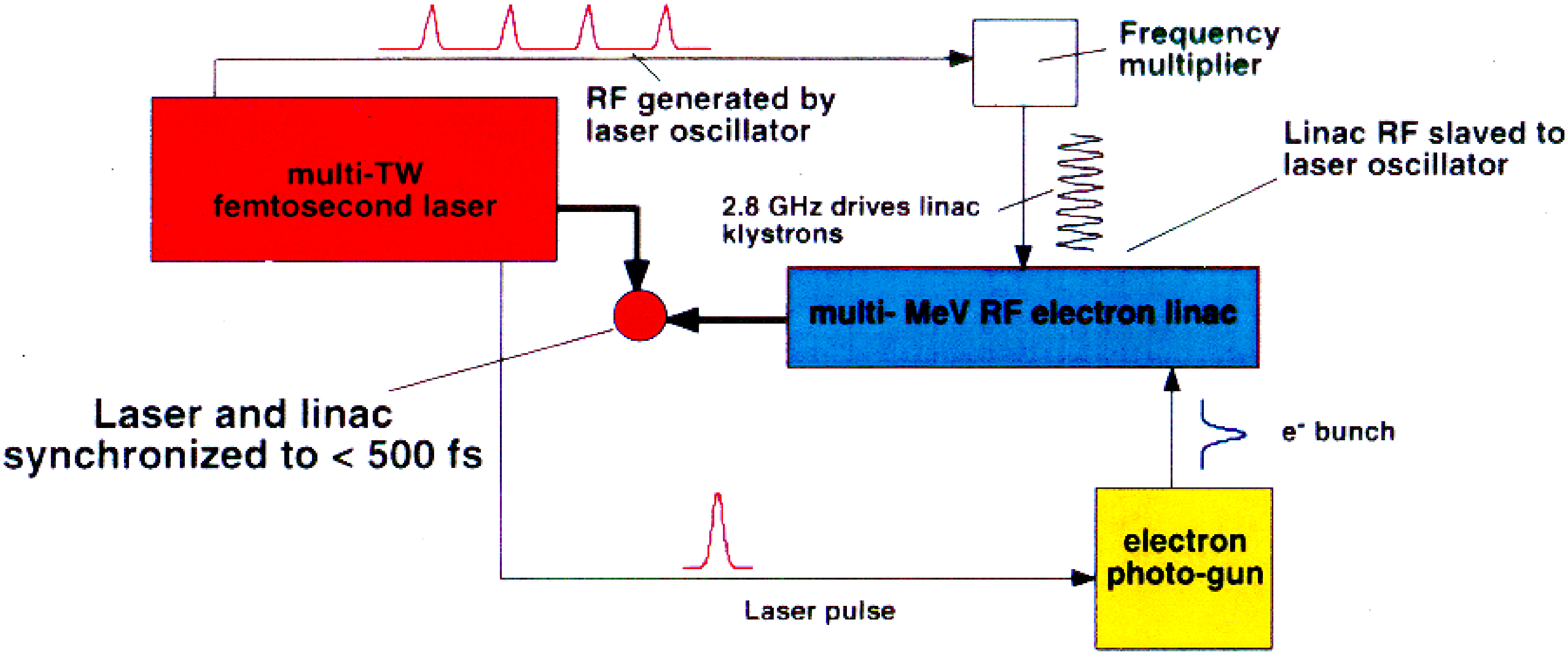


1ω output: 17 J (x2)
2ω output: 10 J (x2)
Rep rate: 0.5 Hz

→

Pumping a 3 cm Ti:sapphire crystal
820 nm output: 7 J uncompressed
4 J compressed

We are developing the technology to synchronize a short-pulse laser with an RF linac to < 500 fs accuracy

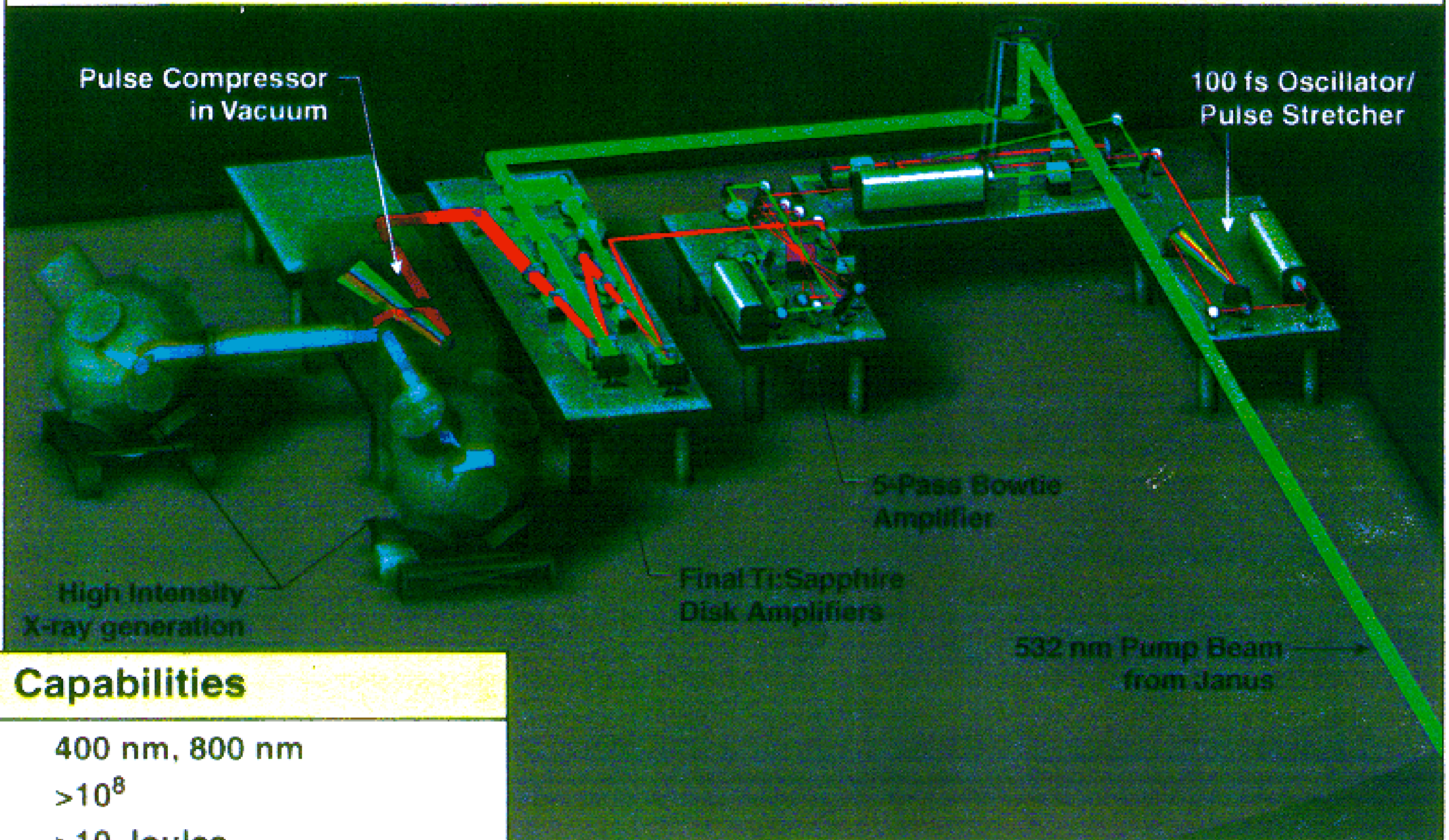


Key issues:	Solution
• Production of electron bunch synchronous with laser →	• Laser driven photo-gun produces electron bunch
• Jitter of RF phase with respect to laser pulse-> jitter in electron bunch →	• Linac RF is slaved to laser oscillator RF -> follows phase jitter

Rosenzweig et al. , UCLA (J.B. Rosenzweig, G.P. Le Sage, Advanced Accelerator Conference, Baltimore, Md., AIP Conference Proceedings, N.Y., N.Y.)
LeSage et al. LLNL (Phys. of Plas. 5, . 2048.. (.1998))

We have built the worlds brightest and highest contrast laser for pursuit of physics above 10^{21} W/cm^2

JanUSP Has Attained 10^{21} W/cm^2

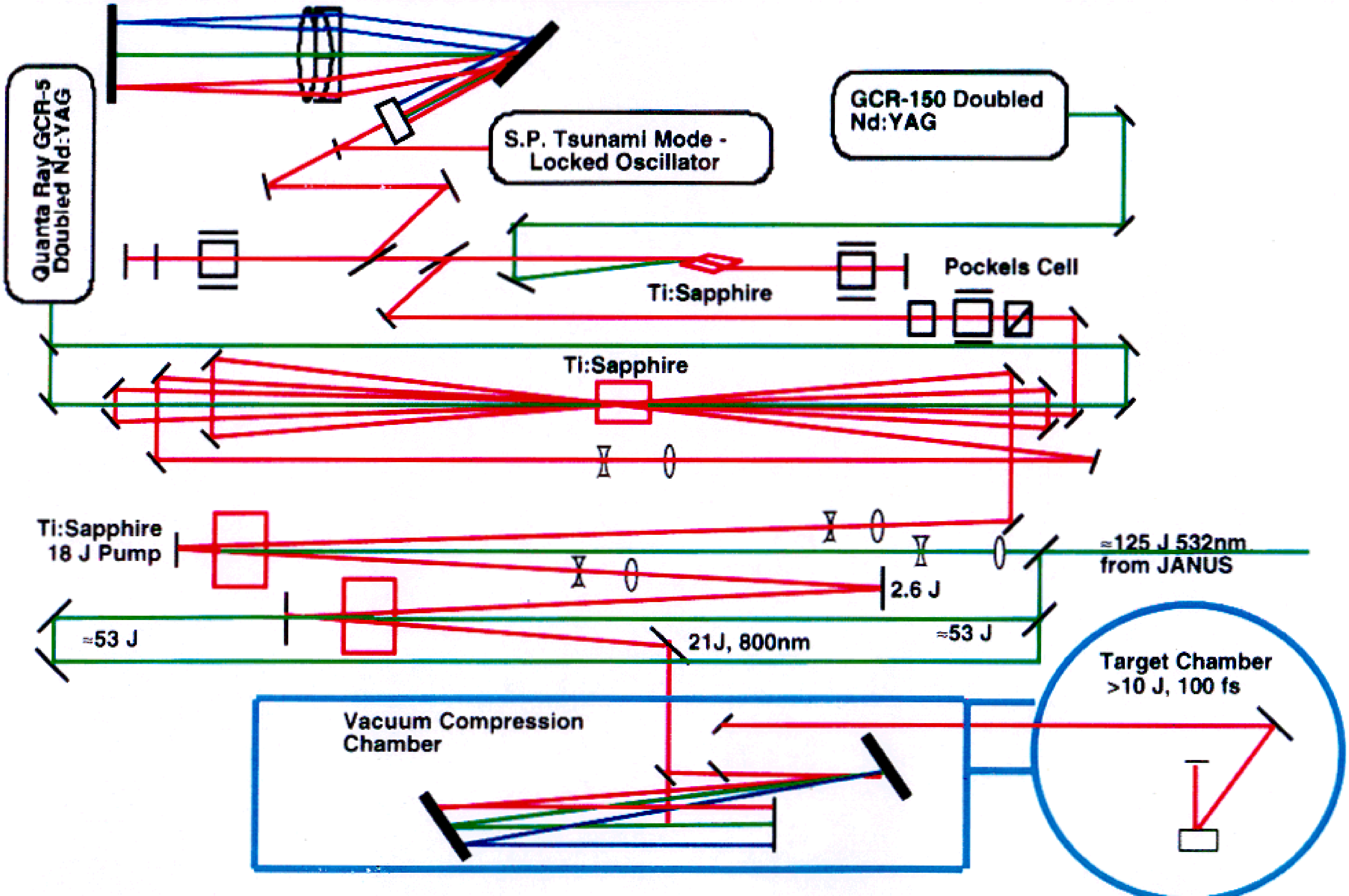


Capabilities

Wavelength	400 nm, 800 nm
Contrast	$>10^8$
Energy at 1ω	>10 Joules
Energy at 2ω	>5 Joules
Pulsewidth	80–100 fs, upgrade to 30 fs
Spot size	<3x diffraction limited
Intensity	$>10^{21}$ W/cm^2
Rep Rate	3/hour

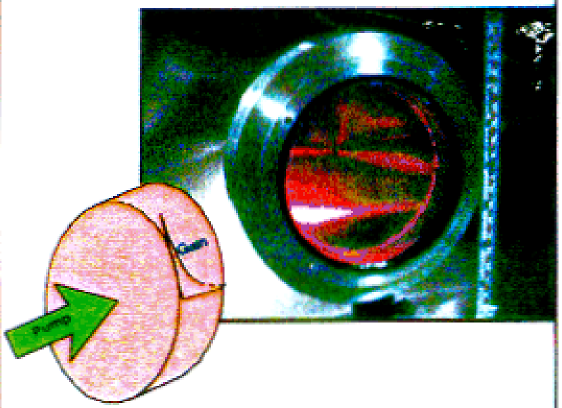
P01183-fgp-u-017

100 TW, 100 fs Ti:Sapphire Laser System



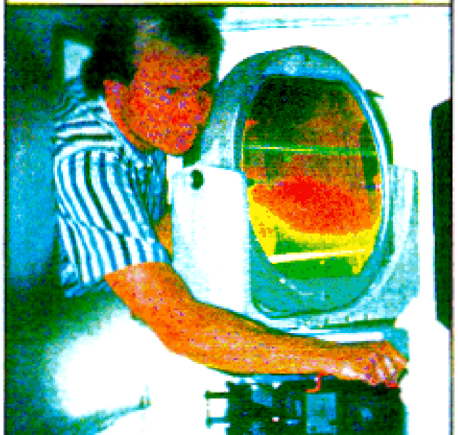
JanUSP is enabled by combining many LLNL technologies

World's Largest Ti:sapphire



- 10-cm diameter
- Subcontracted by LLNL

40 cm Diffraction Gratings

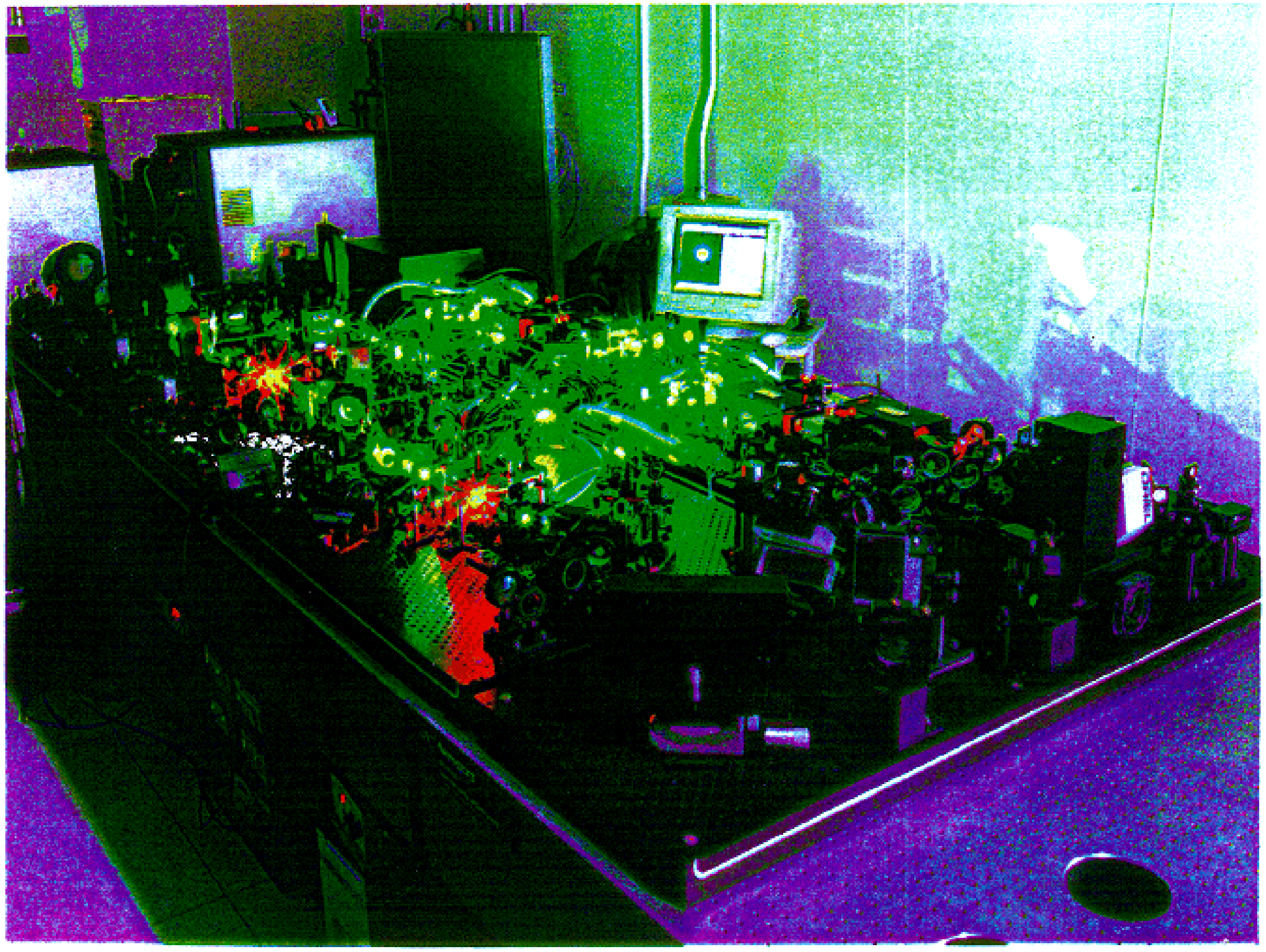


- From Lasers

130 J 532 nm Pump

- JANUS — Optimized for pumping Ti:sapphire

The development of kilowatt-class femtosecond lasers will permit the scaling of laser-driven light sources to high average power

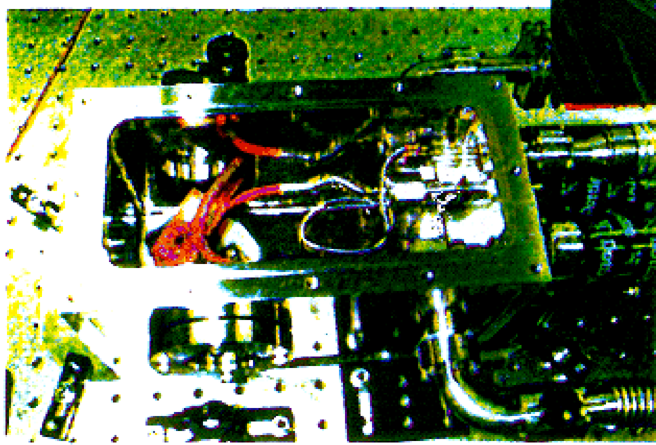


15-W femtosecond cutting laser

High average power diode-pumped Nd:YAG lasers and cryo-cooled Ti:sapphire enable high average power CPA

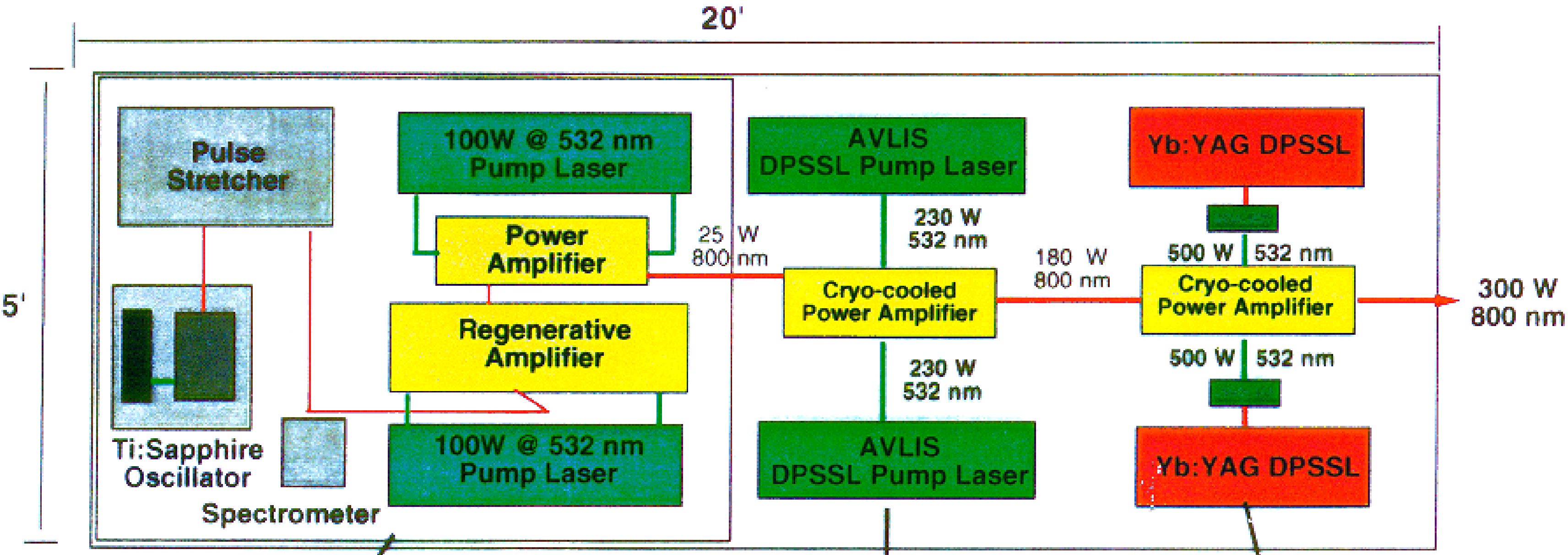
Diode pumped Nd:YAG intra-cavity doubled laser

Cryogenically cooled Ti:sapphire amplifier



Rep. Rate: 10KHz
532nm Output Power = 130 watts
$M^2 < 20$
Power stability < 2%
Diode Pump Power 750 watts

We are developing the laser technology to produce 30 fs pulses at 300 W average power



Exists Today

Exists Today

In develop-
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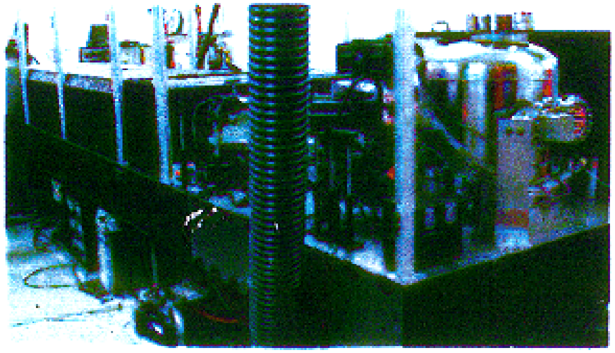
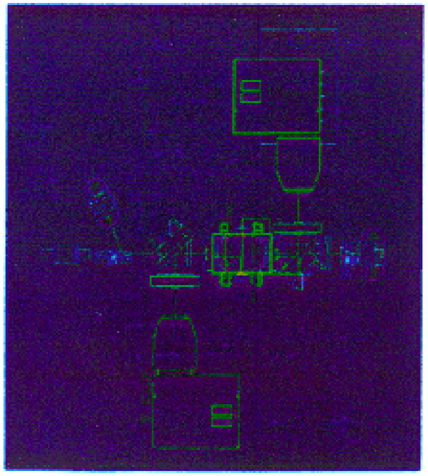
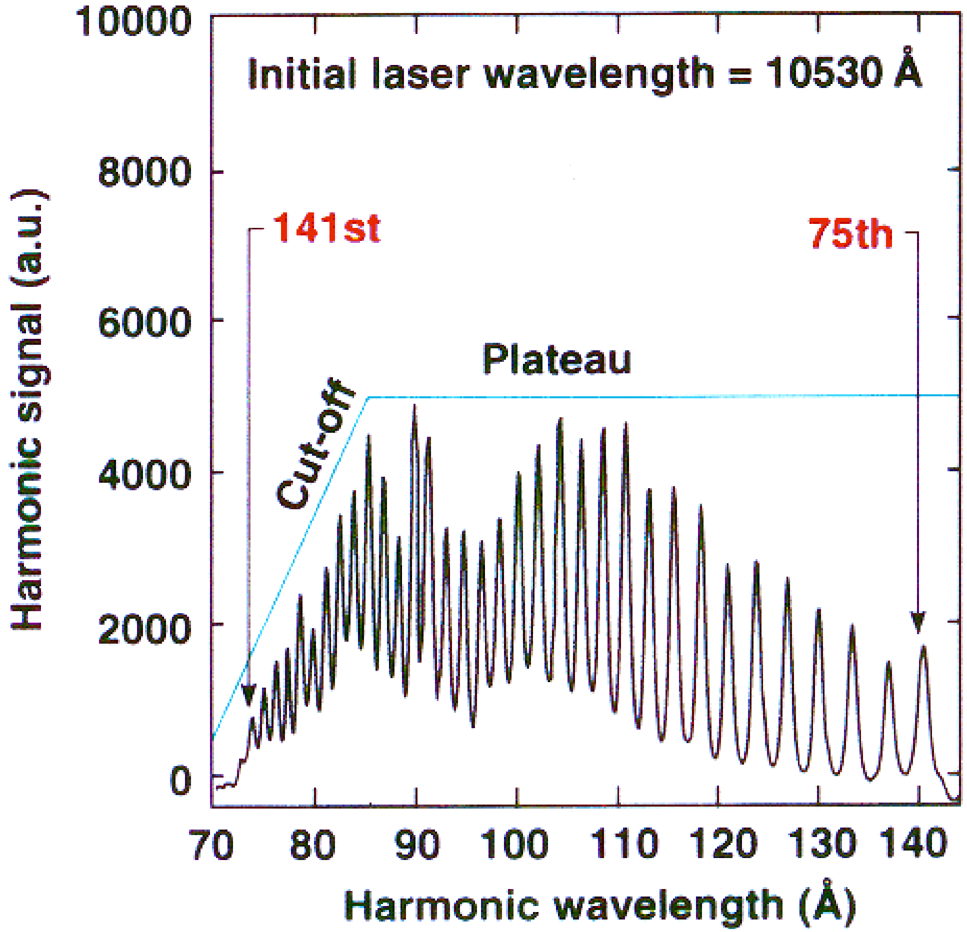




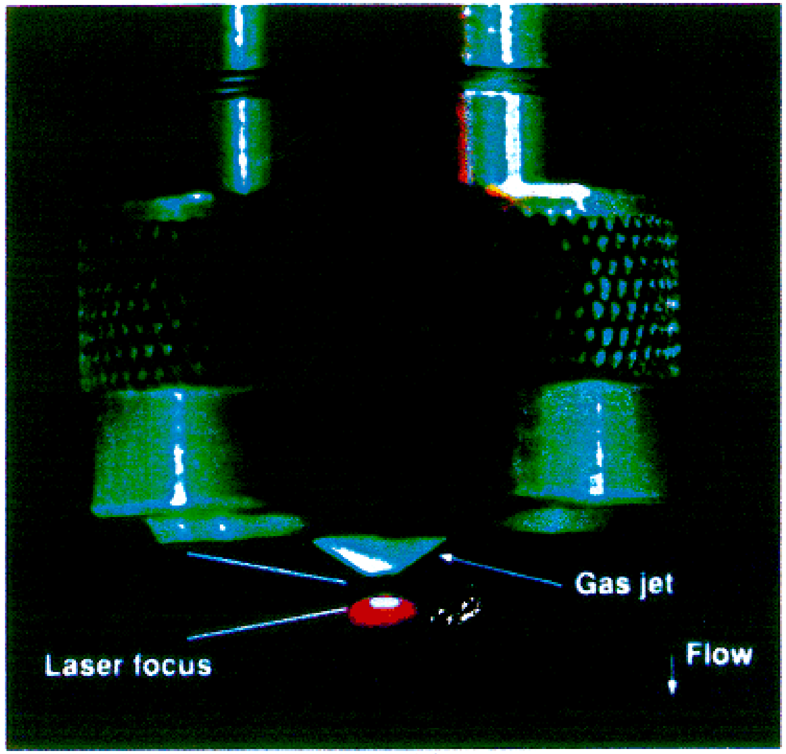
MDPerry
13 Jan 1999

Coherent soft x rays are produced by high harmonic conversion of an intense laser pulse focused in a gas

High harmonics spectrum in Helium



Laser produced plasma in Ne

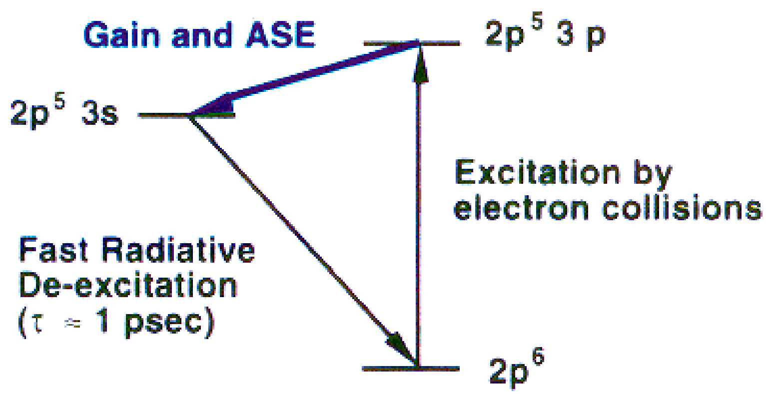


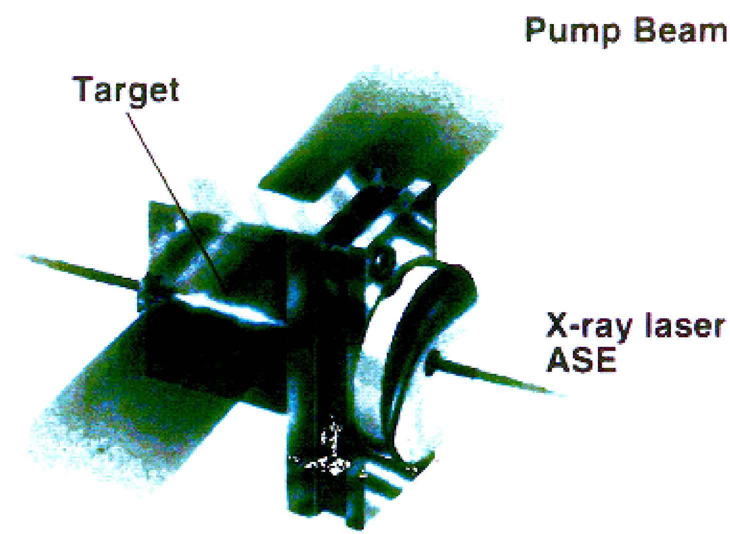
$I = 10^{18}$ W/cm^2 at 527 nm

The harmonics offer a tunable source of and soft x-ray radiation

Novel schemes have allowed scaling of x-ray lasers from large laser facilities to table-top systems

Neon-like Ion Energy Diagram

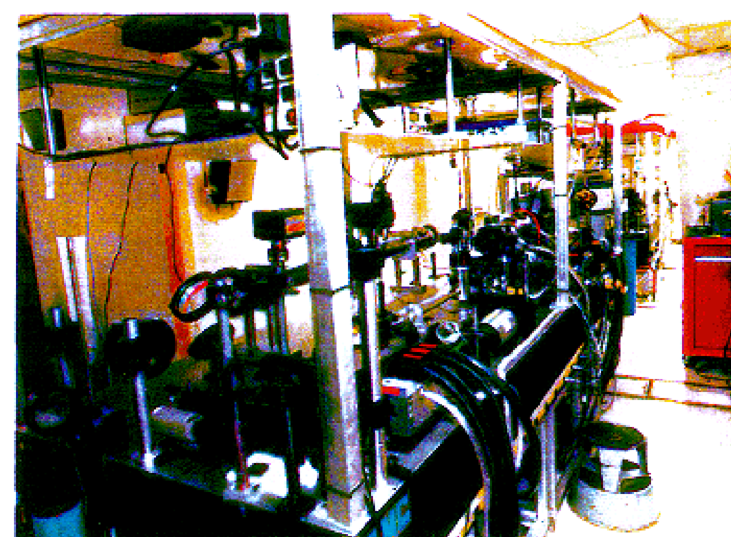




LLNL Nova Laser

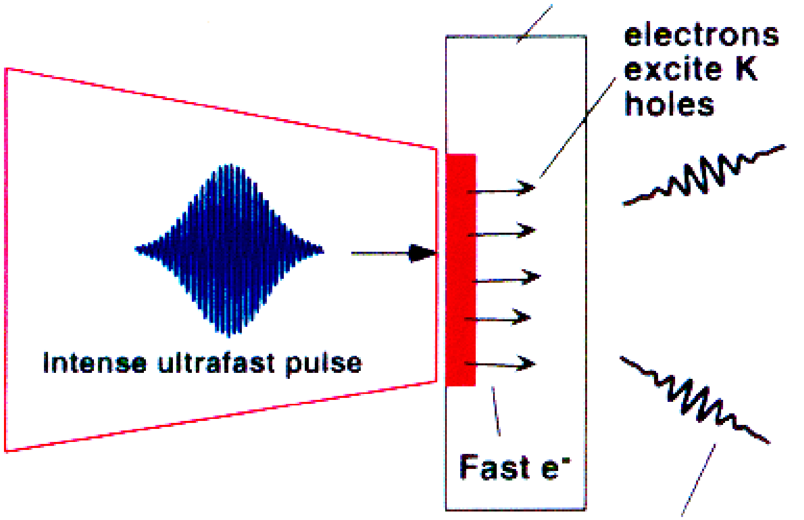
Laser used to drive the first collisionally pumped x-ray laser

LLNL Table-top COMET Laser

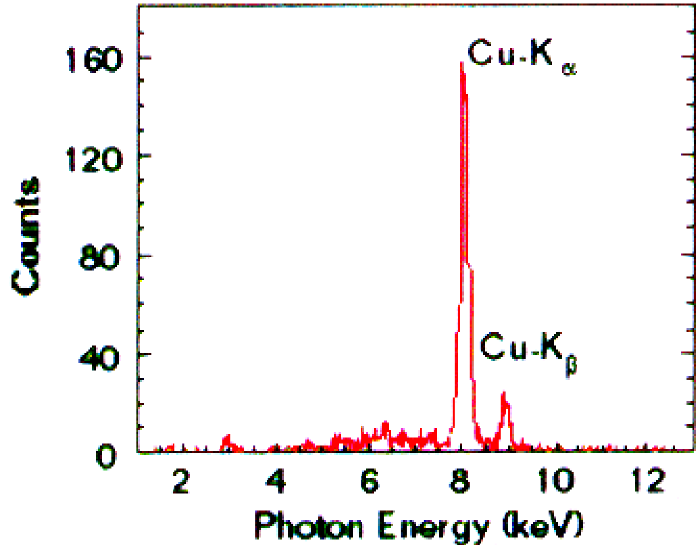


Picosecond laser used to drive a transient gain Ni-like x-ray laser

Hot electrons produced in high intensity laser irradiation of solids can produce ultrafast K-α radiation



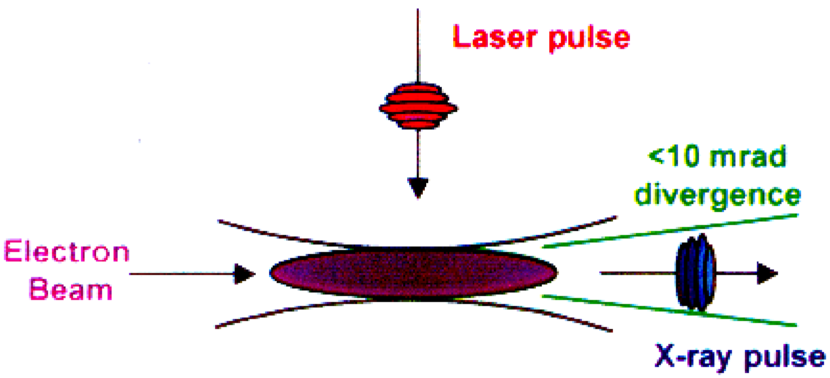
Cu K-α radiation produced from the irradiation of Cu with 20 fs 800 nm laser pulses



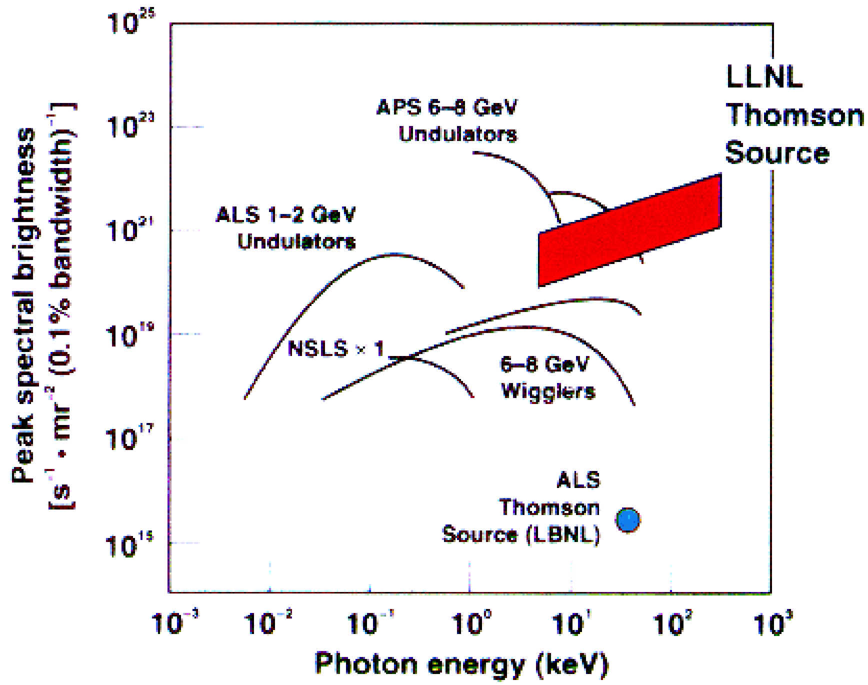
Data take from Wilson, Barty *et al.* UC San Diego

These sources are ideal for many diffraction studies because the radiation is narrow line ($\lambda/\Delta\lambda \sim 10^4$) and the x-ray pulse is ultrafast (~1 ps)

Ultrashort, tunable x-ray pulses will be produced by Thomson scattering of intense laser pulses from a relativistic electron beam

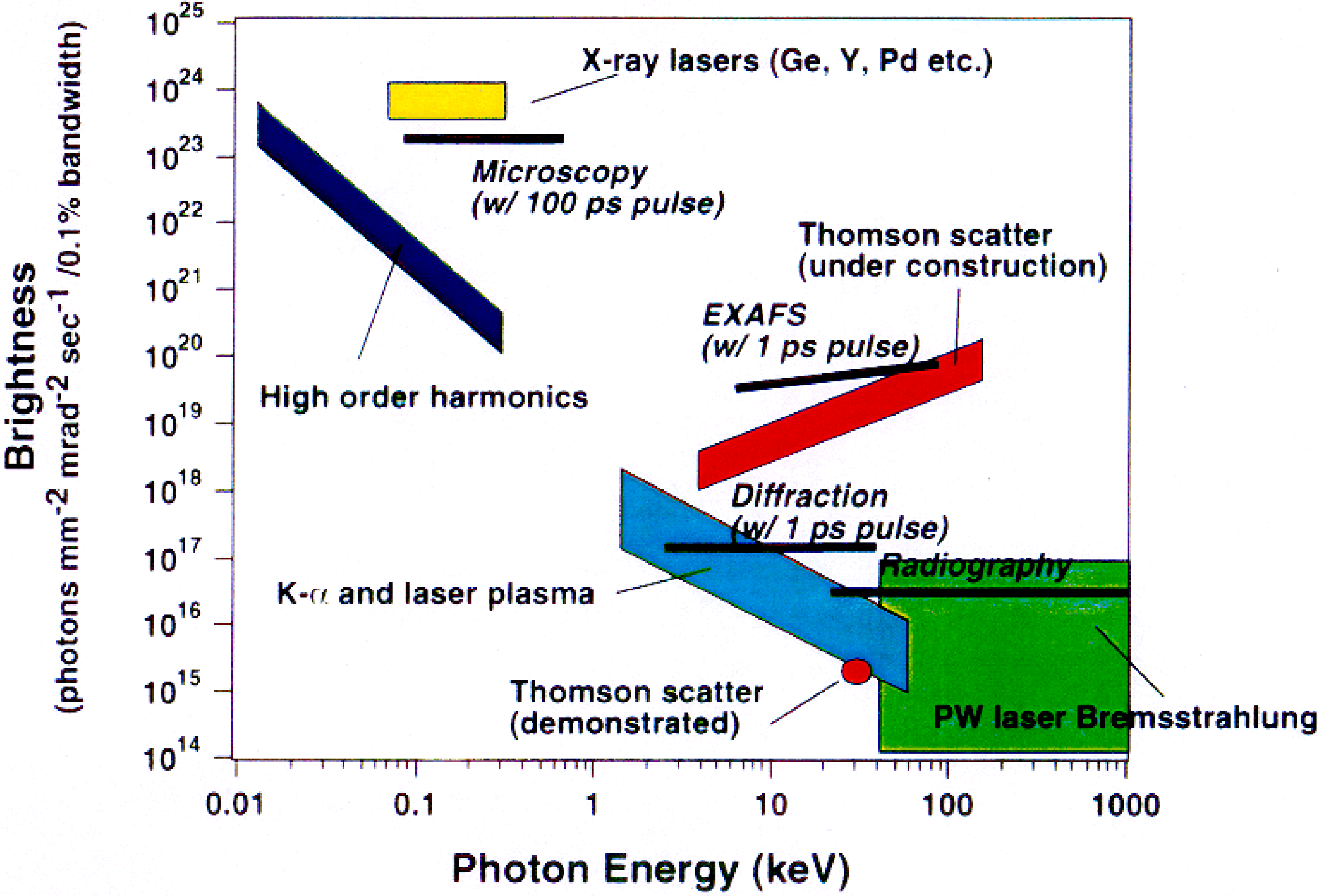


10^{10} γ / pulse
~1 ps pulse width



Peak spectral brightness will exceed present synchrotron sources and extend photon energy range to >100 keV

The peak brightness of many laser-based x-ray sources will permit single shot experiments



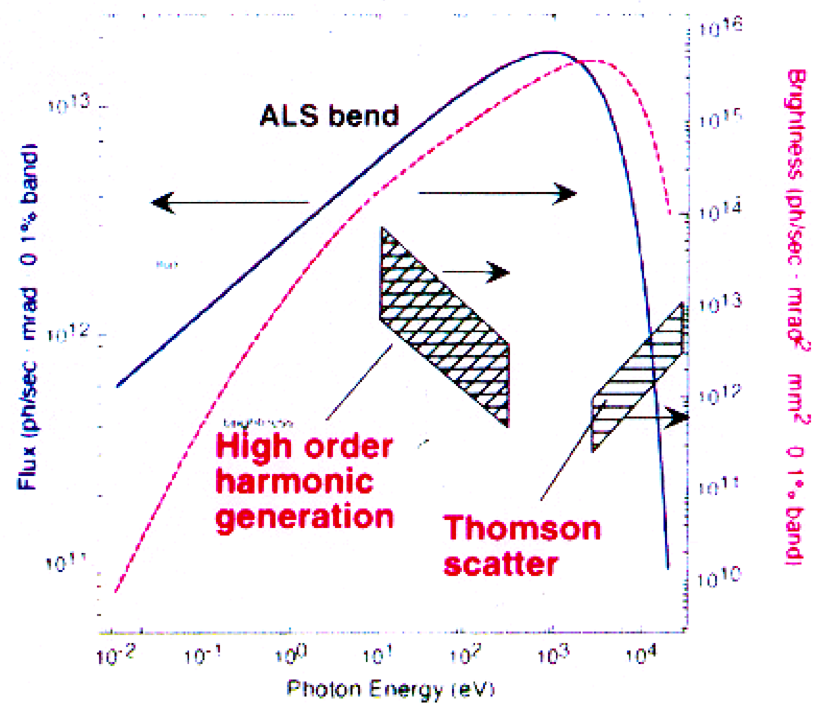
Kilowatt class short pulse lasers are needed to significantly increase the average brightness of laser based x-ray sources

A short pulse laser driven light source has unique advantages:

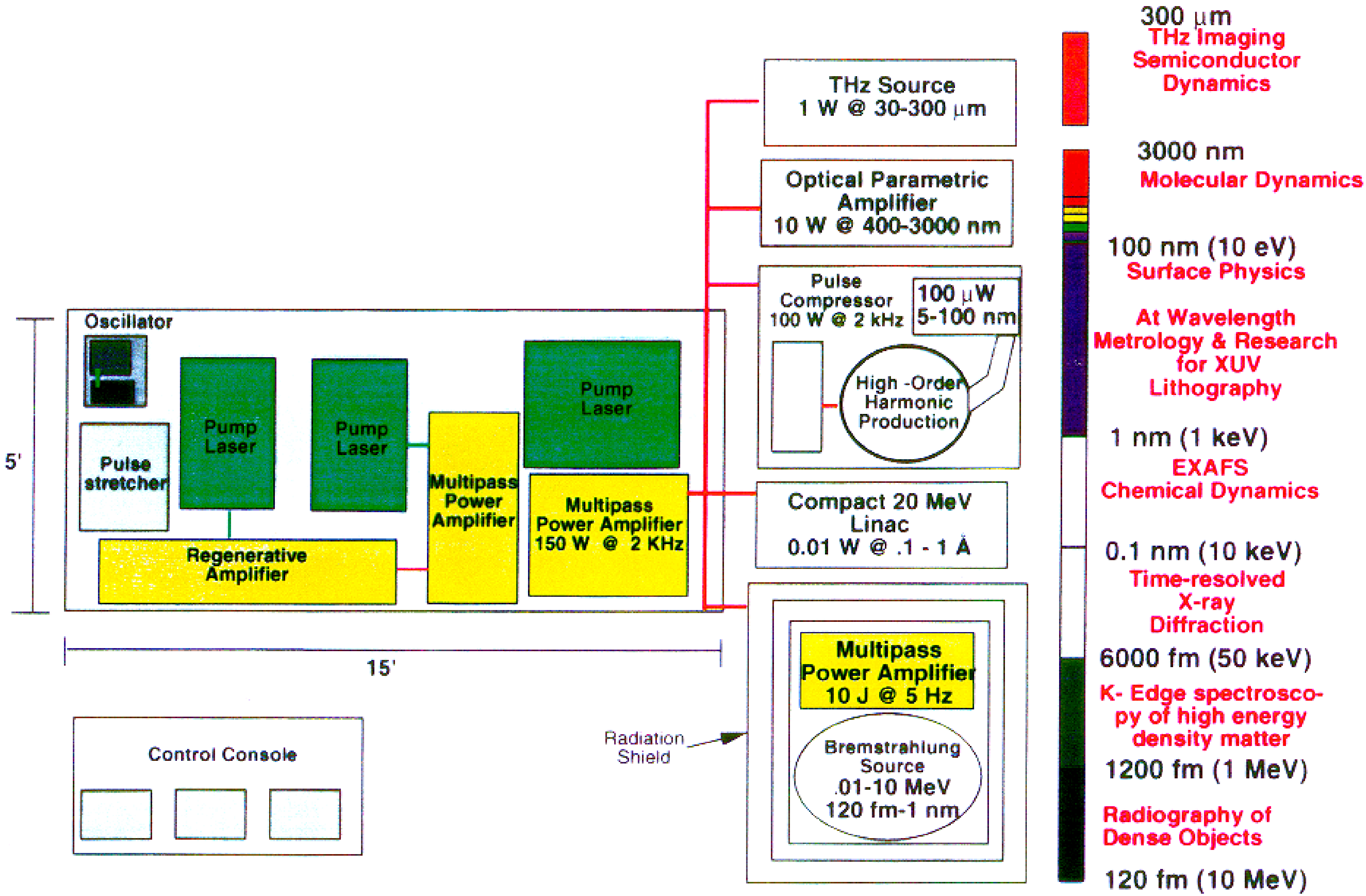
1) Table top
2) Modest cost
3) Ultrafast x-ray pulses (>30 fs)
4) High peak brightness
   (high per pulse flux)

Driving such a source with a high average power laser may permit good signal averaging in experiments

Average brightness of modern syncrotrons and laser based sources driven by a 1 kW laser



High average power femtosecond lasers enable a new class of compact, bright, ultrashort pulse light sources



A laser-based fourth-generation light source would represent a unique machine

- Modest size: table-top laser driving a variety of light source options

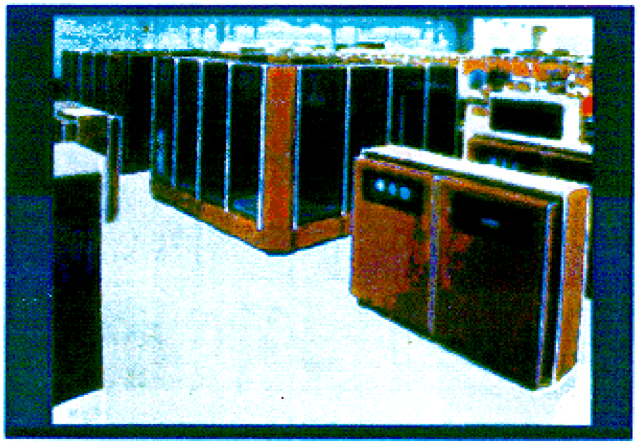
- Modest cost: <$10M per facility

- Modular: a single laser could drive different x-ray sources in surrounding laboratories dedicated to different applications

- Source could be tailored to the range of applications desired (ie low rep-rate, high peak power, or high average power, etc.)

- Such a source could be purchased and operated by a university or modest sized company

Laser driven x-ray sources can provide a small-scale complement to synchrotrons



Multi-user facility

Centralization of users and experiments at one site

Large-scale, high power capability

Single user facility

Distributed among users/ universities

Small scale exploratory research

Advanced Light Source
(Lawrence Berkeley National Lab)

Table top laser/ soft x-ray source
(LLNL)

Conclusion

Ultra-fast → High order harmonics: 20 - 100 fs
X-ray lasers: ~ 10 ps
Thomson scattering: 100 - 1000 fs

pulse width > 20 fs

Ultra-bright → High peak power (10^6 - 10^9 W)

High peak power -- High average power (future)

Spatially coherent,
(harmonics, X-ray lasers)

Ultra-compact → Laser drivers are table top
1 - 100 TW

Table-top scale

Our vision is that by 2005, a compact, 4th generation light source could be purchased by user groups for ~ $10 M