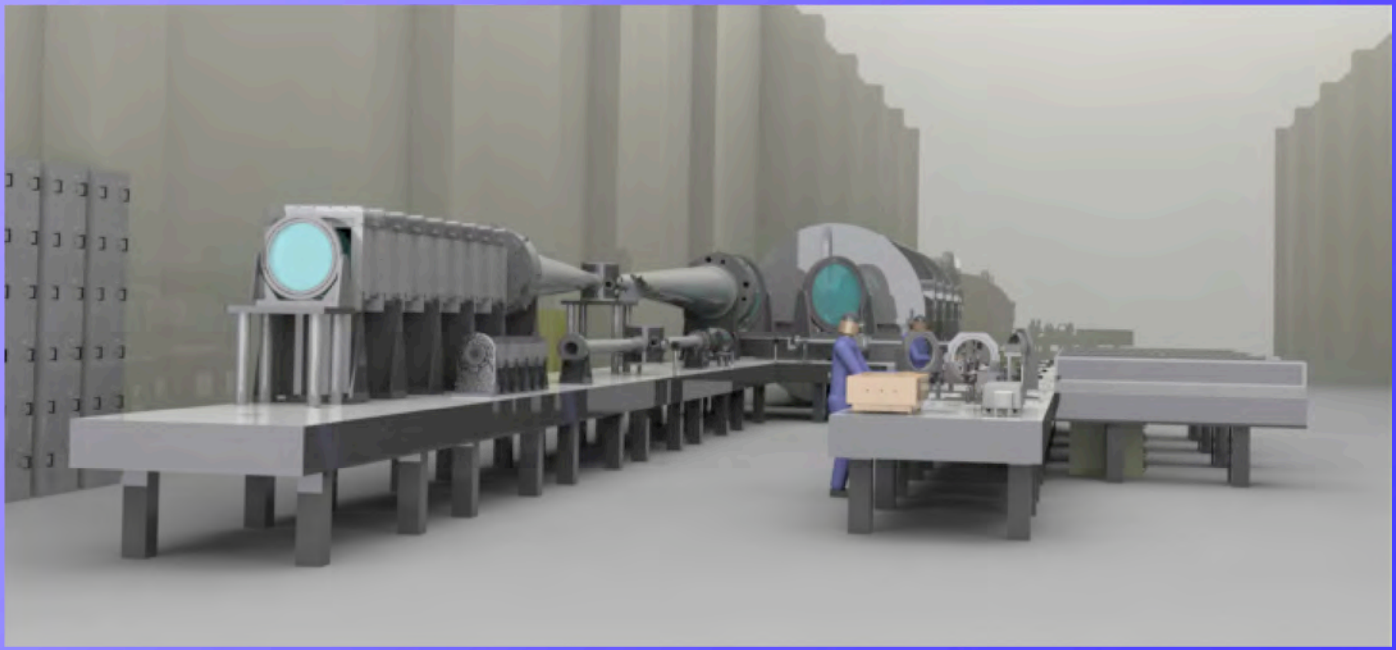
Beyond 1 PW:

What is the next step in ultraintense laser physics and technology?



Presented by:

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Department of Physics
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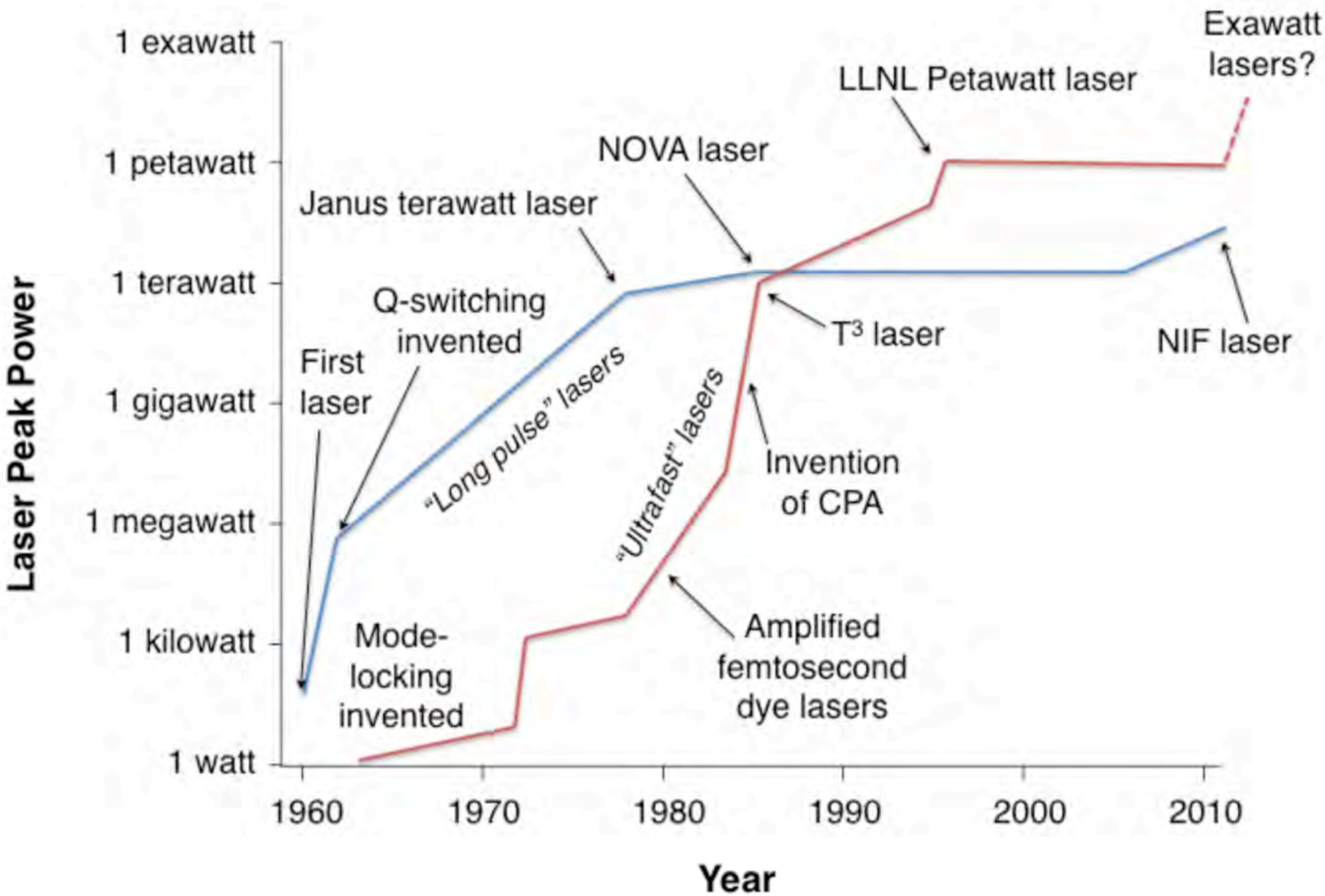
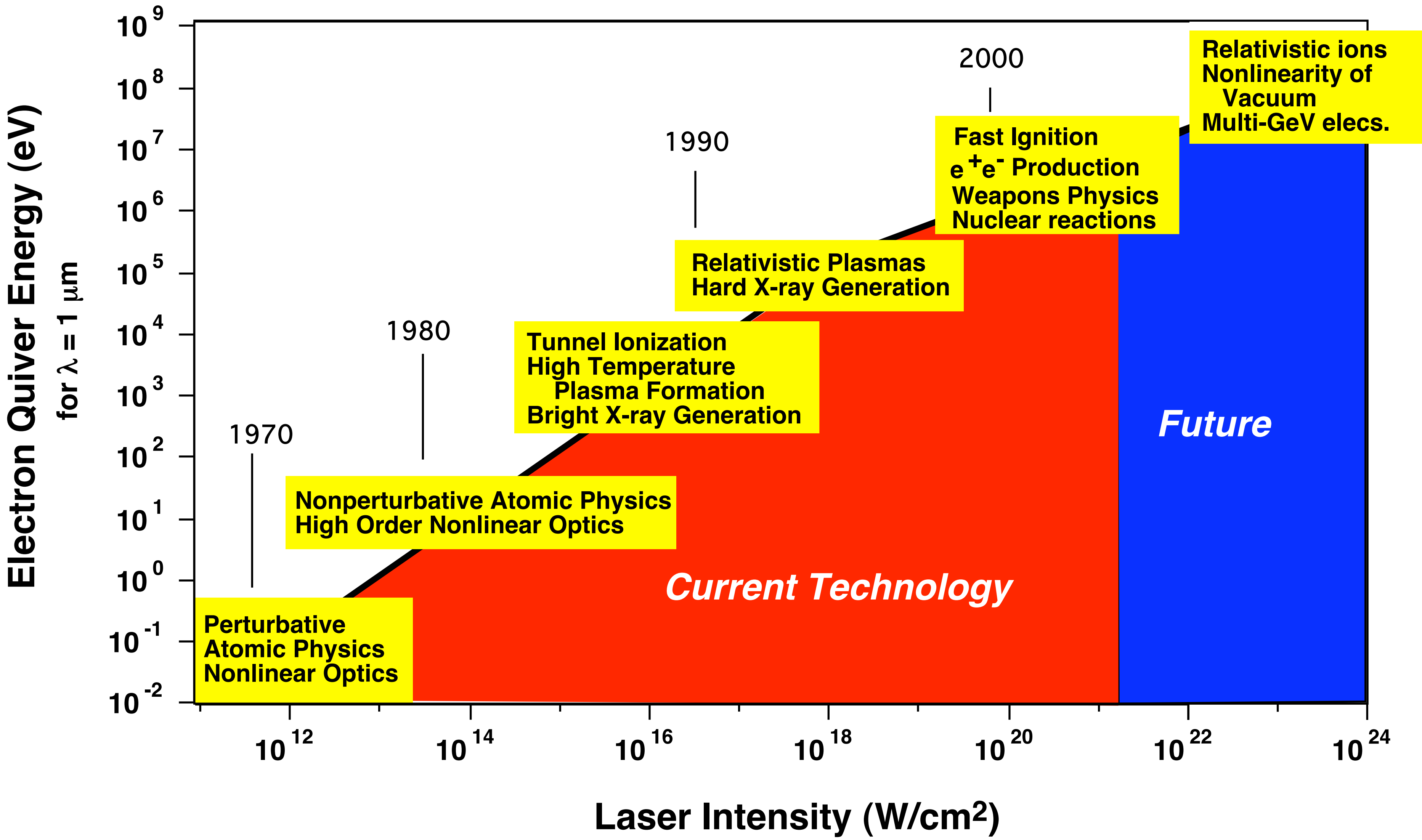
The power that a laser can deliver has increased roughly by a factor of 1000 every 10 years



New and Exotic Physical Regimes Can Be Accessed With Ultra-High Intensity Lasers



The science enabled by an exawatt laser is likely to be exotic and exciting

Focused intensity: > 10^{25} W/cm^2

Electron quiver energy: ~ 10 GeV

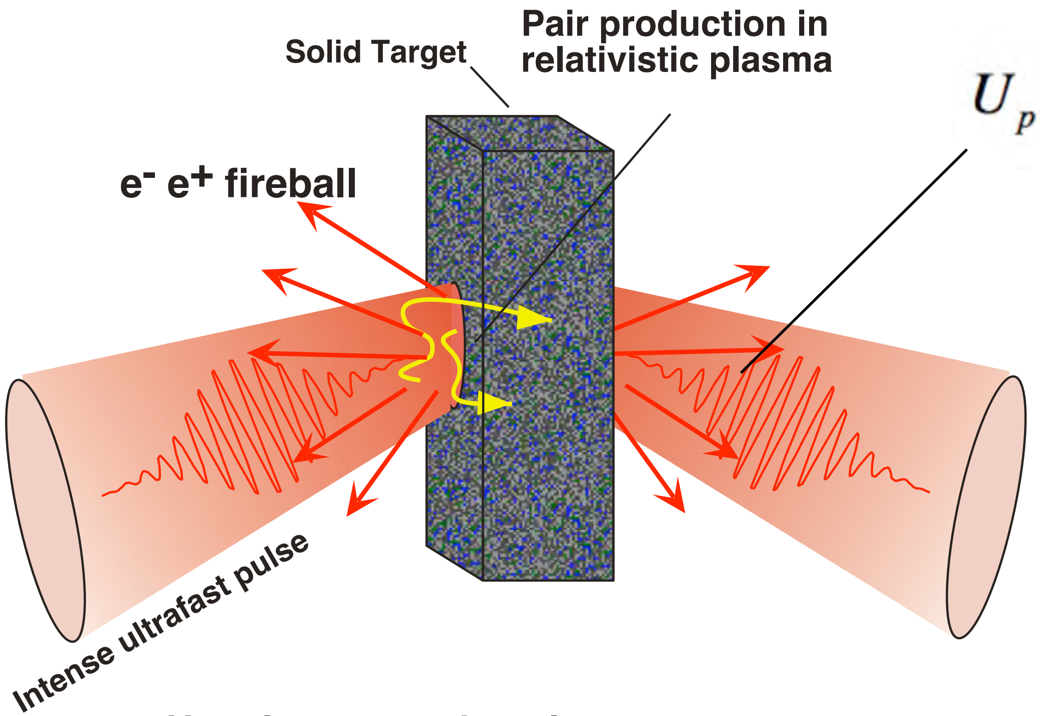
Light pressure: ~ 10^{15} bar

Proton quiver energy: ~ 100 MeV

↓

- ***Macroscopic relativistic electron plasmas (pair plasmas)***
- ***Relativistic ion plasmas***
- ***TeV electron acceleration***
- ***Hawking Unruh radiation***
- ***Vacuum birefringence***
- ***Vacuum pair production ("boiling" the vacuum)***

The quiver energy of electrons at relativistic intensity mimics MeV temperatures and lead to pair plasmas

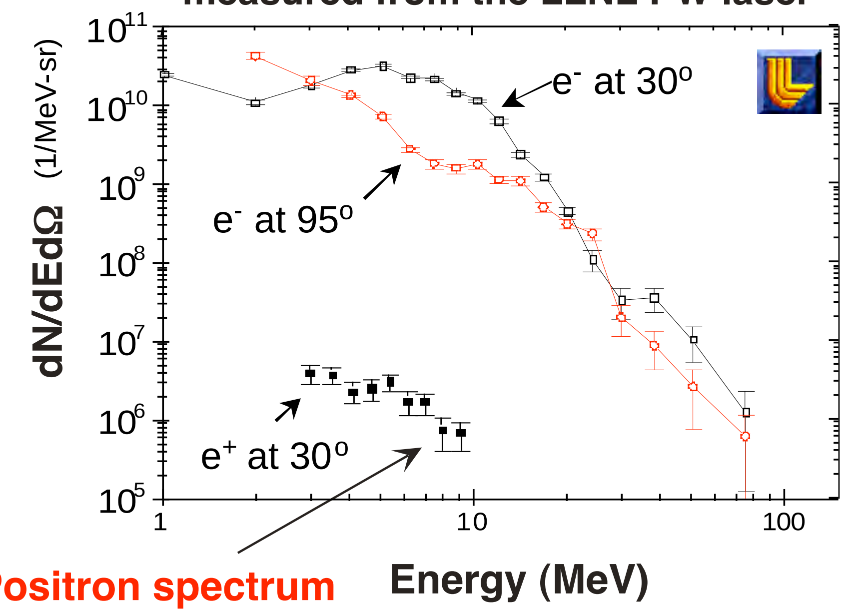


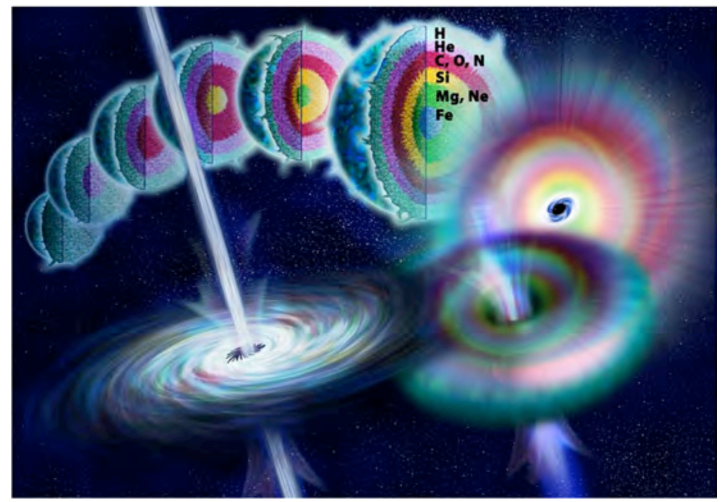
$$U_p = \left(\sqrt{1 + a_0^{\,2}/2} - 1\right) m_e c^2$$

$$a_0 = eE_0\lambda / mc^2$$

a_0 = 10 - 30 yields strongly relativistic plasma
I ~ 10^{21} W/cm^2 over 10 - 100μm
→ P = 10 - 100 PW

Hot electron and positron spectrum measured from the LLNL PW laser

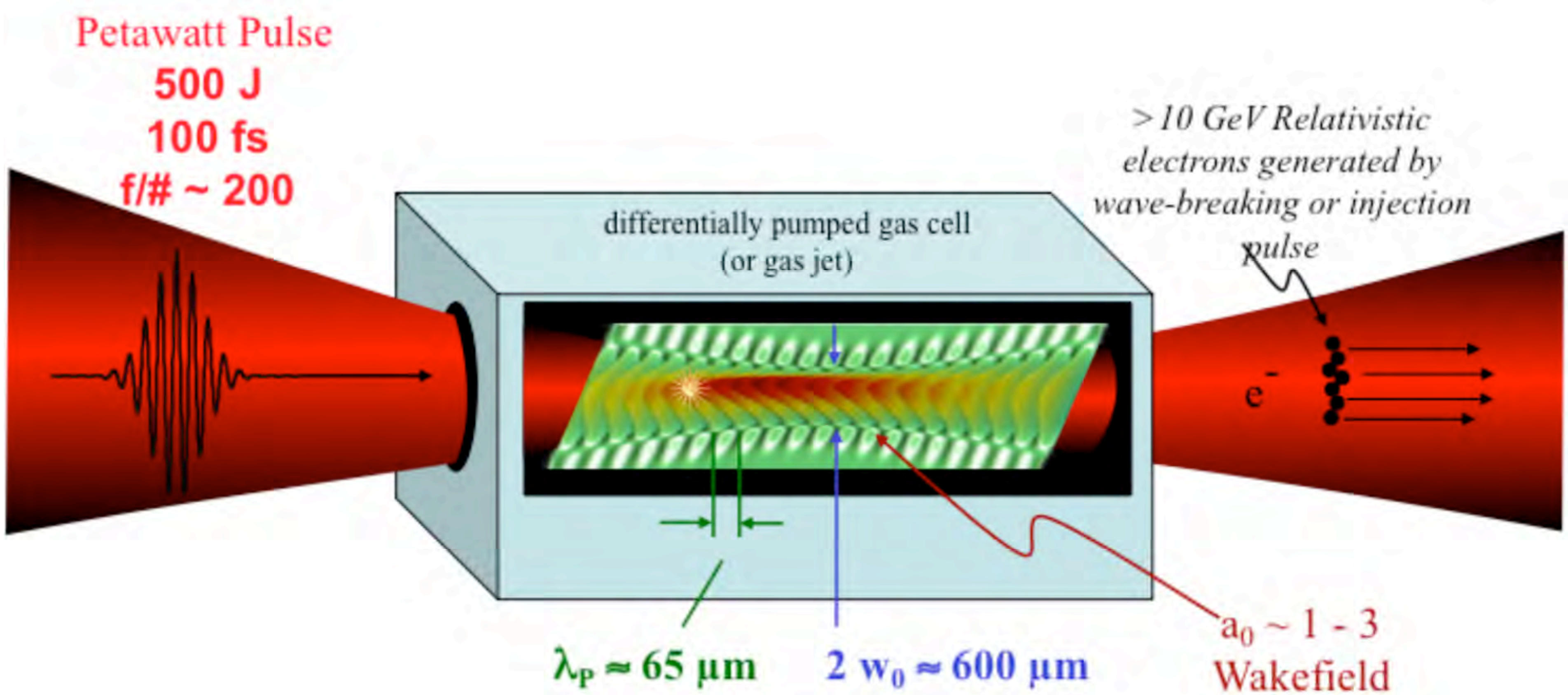




Relativistic pair plasmas near energetic objects like black holes are thought to lead to gamma ray bursts

Note a_0 ~ 1 for protons when I = 2 x 10^{24}

A multi- PW laser could enable wakefield acceleration to > 10 GeV



Multi - Petawatt LWFA Parameters:

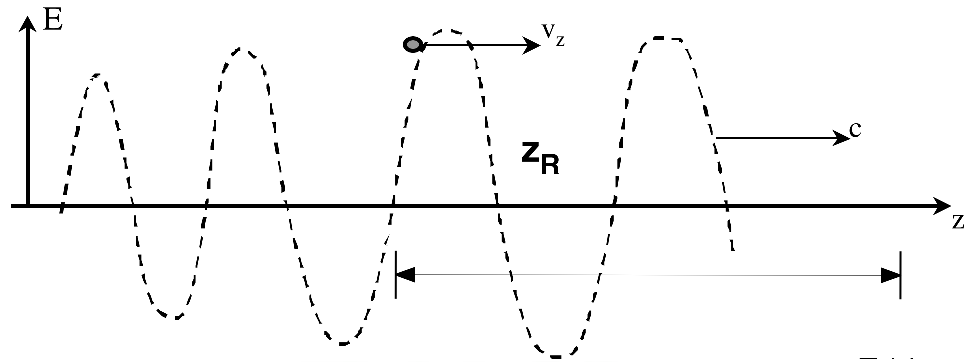
$n_{resonant} \sim 3x10^{17}\ cm^{-3}$ ($P_{He} \sim 5$ Torr)	⇒	negligible ionization distortions
$L_{dephasing} \sim z_{Rayleigh} \sim$ 25 cm	⇒	long accelerating length
$E_z \sim 0.5$ GV/cm	⇒	large accelerating field

Multi-PW lasers may lead to multi-GeV electron ejection upon highly charged ion production

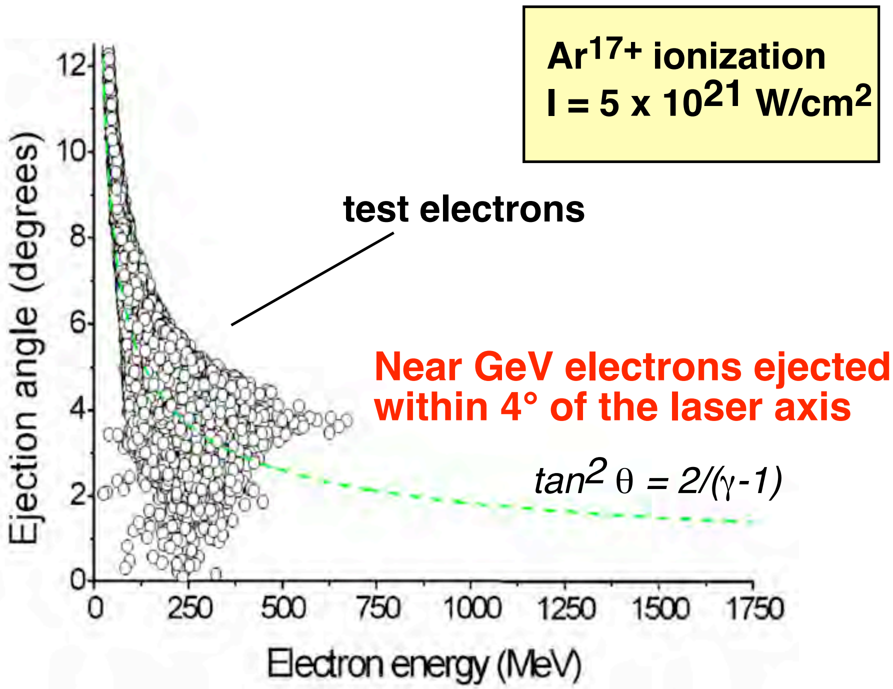
Ultra-relativistic "Above Threshold Ionization"

- Ionization "injects" electrons right at the peak of the field
- This yields much greater energies than if the laser interacts with free electrons

Electrons with large longitudinal momentum can "ride" the laser wave



Monte Carlo simulation using a focused PW beam

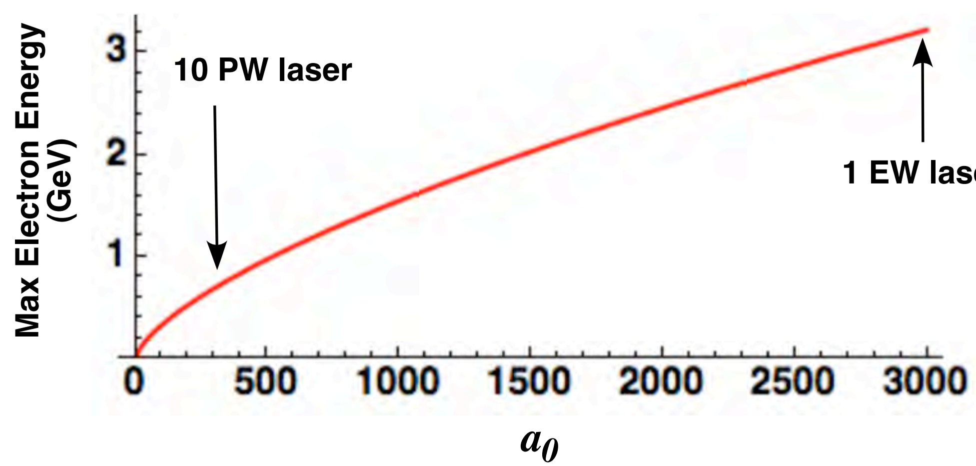


$$\delta\tau_{Gaussian} \approx \frac{z_R}{c}\left(1-\frac{k z_R}{2\gamma^2}\right)$$

Electron dephasing time

$$\gamma_{max} \approx \frac{e}{m_e c^2}\,\frac{E_{max}}{2}\,\theta z_R \sinh^{-1}\left(\frac{c\delta\tau}{z_R}\right)$$

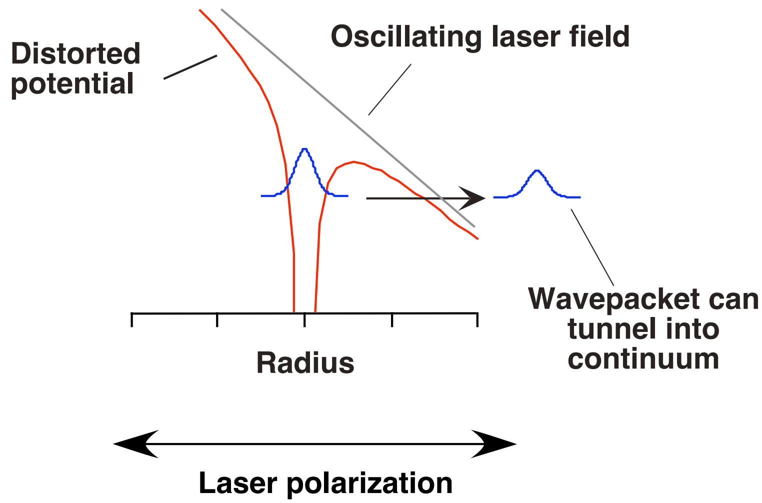
Maximum ejected electron energy



At sufficient intensities it should be possible to observe the optical nonlinearity of vacuum

Atom/vacuum subject to an oscillating field $E = E_0 \sin(\omega t - kz)$

Atom

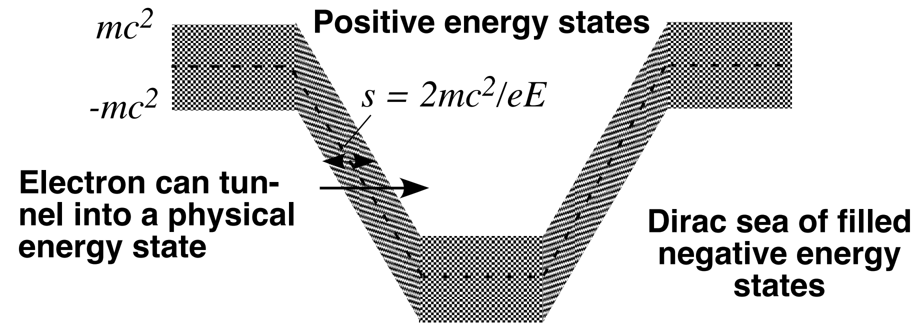


Tunnel ionization rate

$$W \sim \exp\left[-\frac{2}{3}\left(\frac{I_p}{I_H}\right)^{3/2}\frac{E_{at}}{E_0}\right]$$

E_{at} **= 5 x 10^{9} V/cm Intensity~ 3.5 10^{16} W/cm^{2}**

Vacuum



$$W \sim \exp\left[-\frac{s}{\lambda_C}\right] = \exp\left[-2\frac{E_S}{E_0}\right]$$

$$\lambda_C = \frac{\hbar}{mc}$$

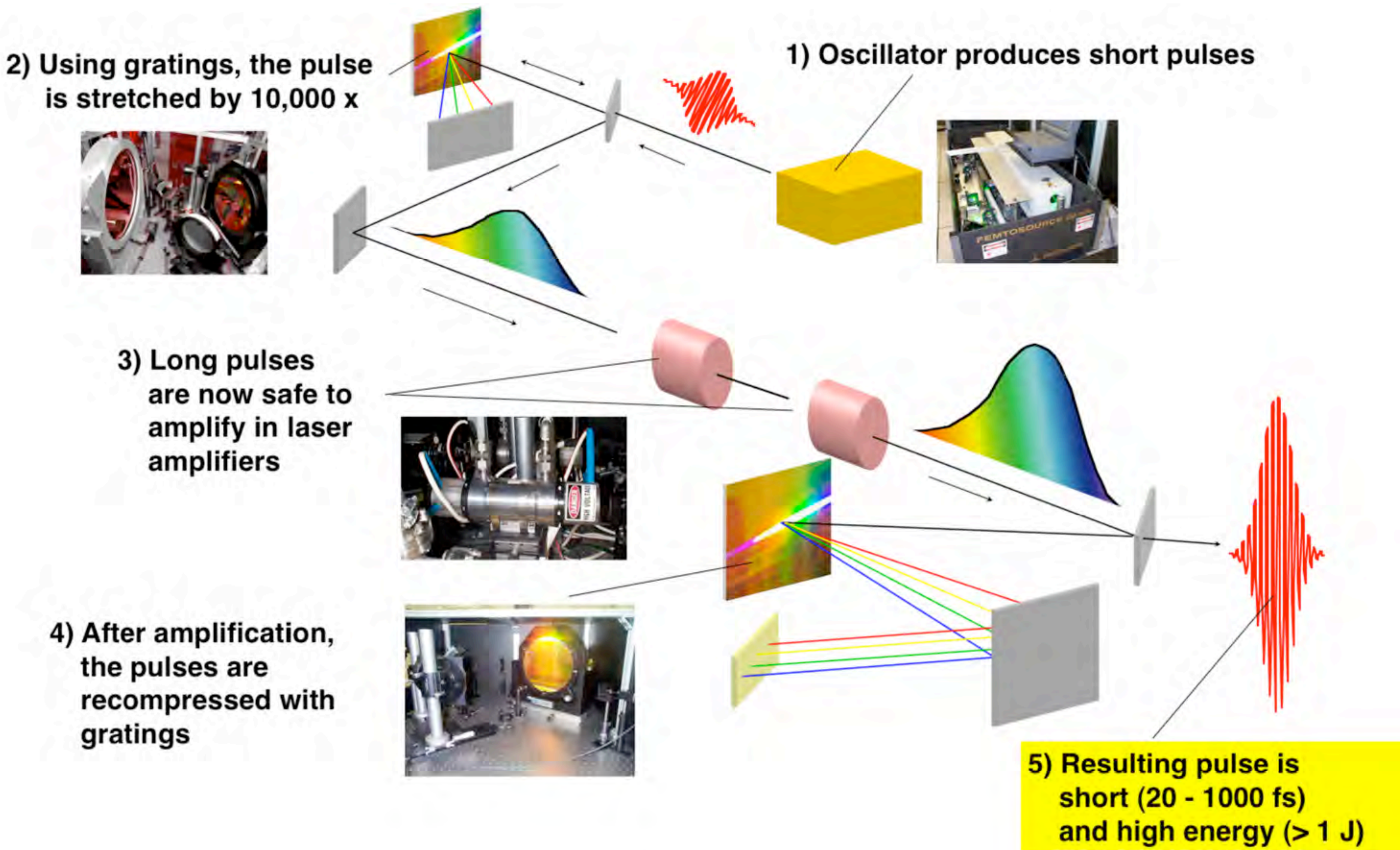
$E_S = m^2c^3/e\hbar$ **=1.3 x 10^{16} V/cm Intensity ~ 2.2 10^{29} W/cm^{2}**

Polarization of atoms gives rise to nonlinearities with $E \sim 0.1\%\ E_{at}$
I ~ 10^{9} W/cm^{2}

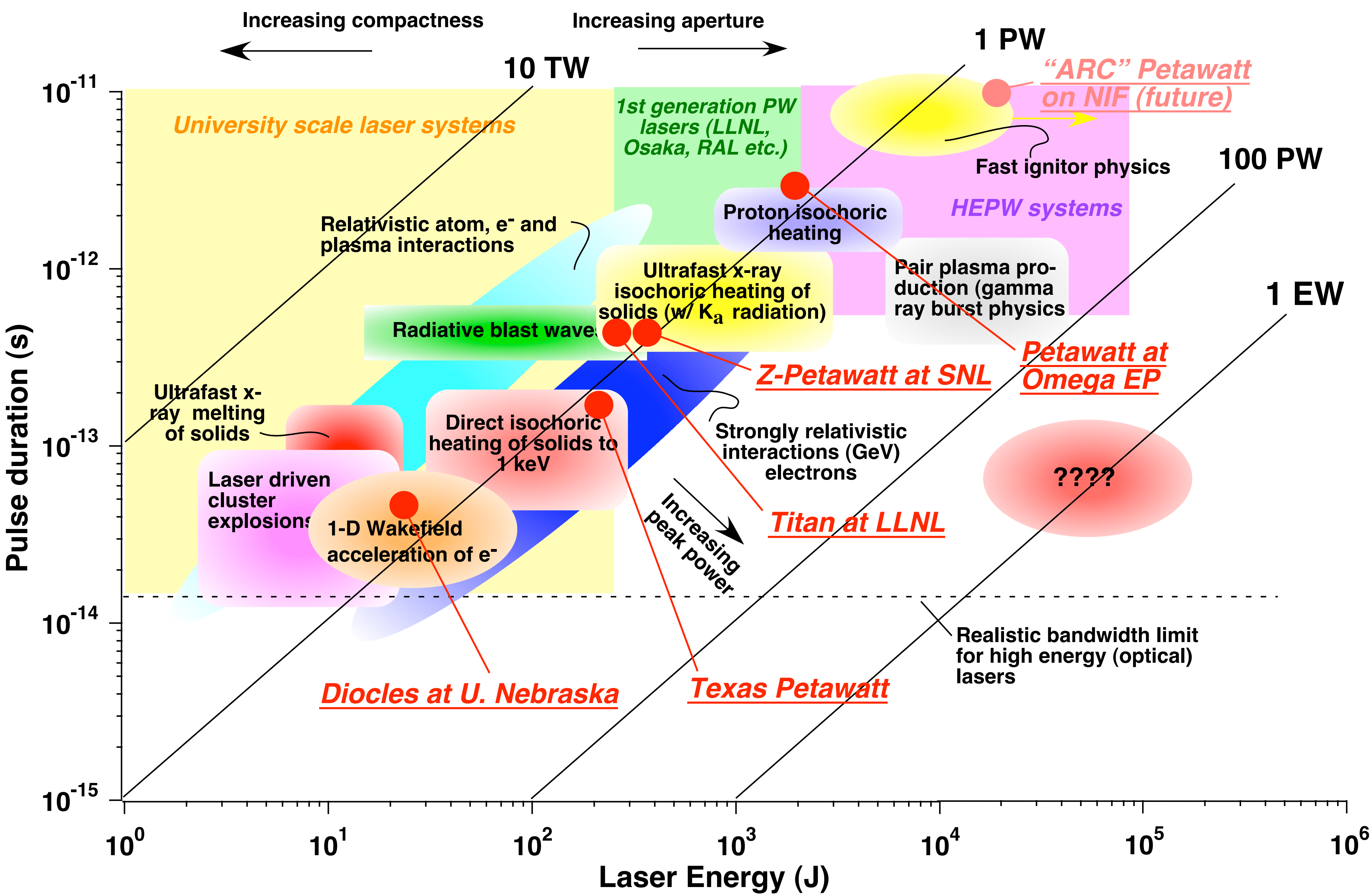
Polarization of vacuum gives rise to nonlinearities with $E \sim 0.1\%\ E_S$
I ~ 10^{22} W/cm^{2}

With a 10 PW laser it might be possible to observe birefringence of the vacuum

Reaching how powers in CPA require temporal phase control and broad bandwidth gain



Petawatt lasers of differing specifications are needed to access a wide variety of science applications

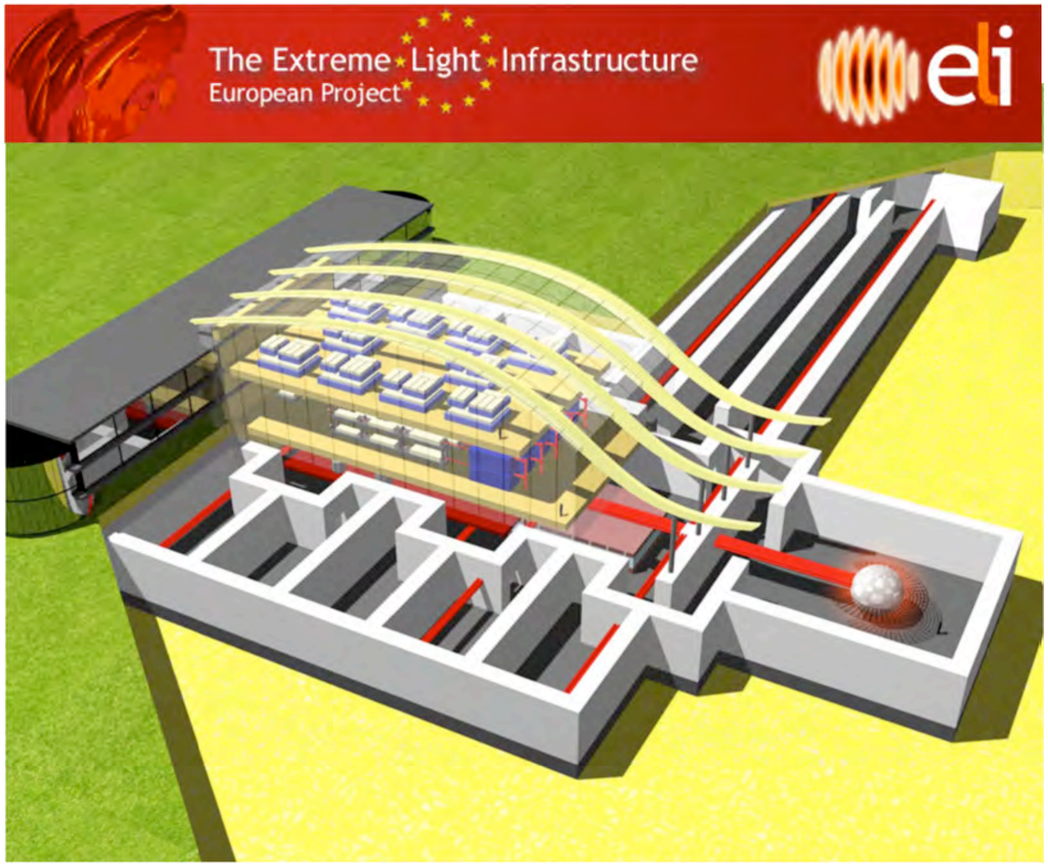


We are presently at a cross roads in examining how to get to move beyond 1 PW powers

- *Can 10 PW be built in 5 years and can exawatt be built in a decade?*
- *Push to shorter pulses or higher pulse energy?*
- *Utilize Ti:sapphire or some other gain medium?*
- *Can OPCPA be employed all the way to an exawatt?*
- *How can 10 PW to exawatt pulses be compressed?*
- *What will it cost to build a 10 PW laser or an exawatt?*

Using hybrid OPCPA/Mixed laser glass technology, ~100 fs PW lasers at E> 100 J are possible and it is possible to build a 10 PW laser on this technology now

The Europeans have initiated an EU funded project to build multiple 10 PW-class lasers



<u>Three ELI Pillars</u>

• **Bucharest, Romania: ELI - NP**
Devoted to nuclear physics with intense lasers and gamma beams

• **Prague, Czech Republic: ELI - CZ**
Devoted to work on electron acceleration

• **Szeged, Hungary; ELI - AS**
Devoted to attosecond pulse generation

The current state-of-the-art ultrafast, ultraintense lasers tends to fall into two categories

Ti:sapphire based CPA lasers:

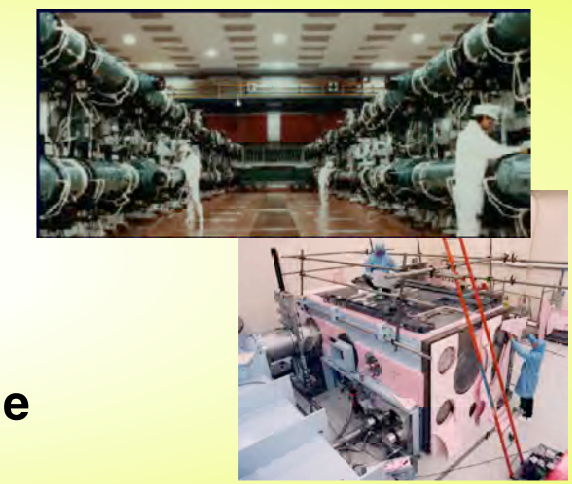
Pulse energy ~ .001 - 30 J,
Pulse duration <30 - 100 fs,
Peak Power < 100 TW; 1 PW
Repetition Rate ~ 1 kHz - 1 Hz

Shortest pulse systems and most "table-top" CPA lasers

Nd:glass based CPA lasers

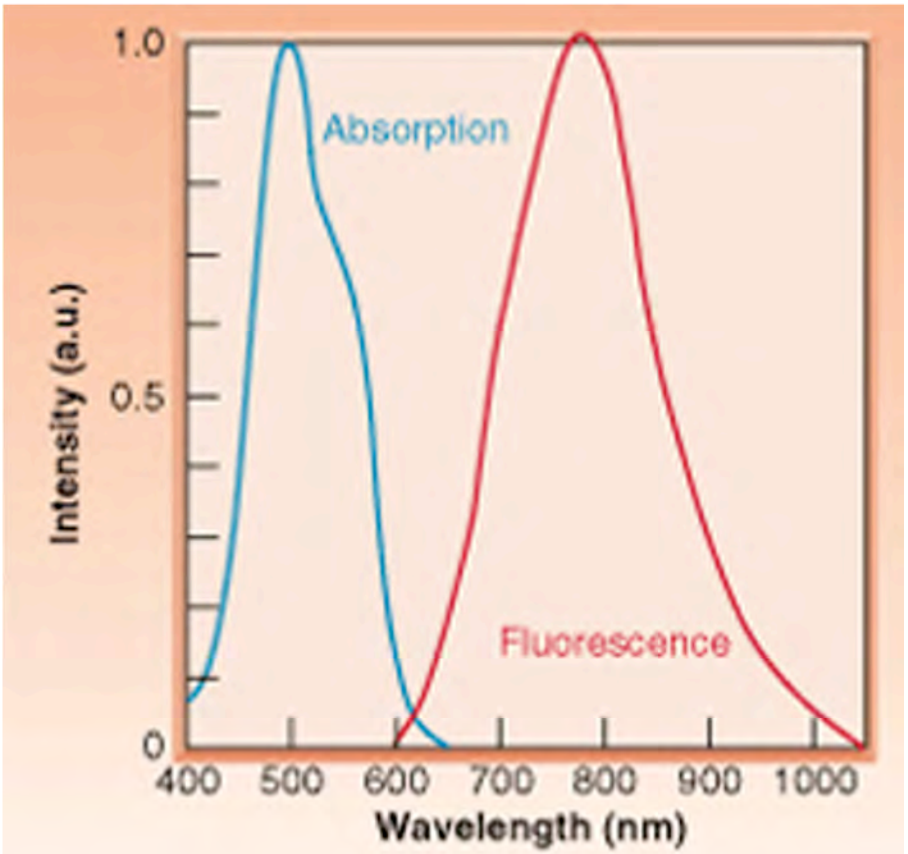
Pulse energy 10 - 1000 J
Pulse duration > 100 fs
Peak power 10 - 1000 TW
Repetition rate ~ 1 shot/min - 1 shot/hr

Highest energy systems, many of "facility" scale



Ti:sapphire has advantages and disadvantages in high power CPA lasers

Absorption and emission spectrum of Ti:sapphire



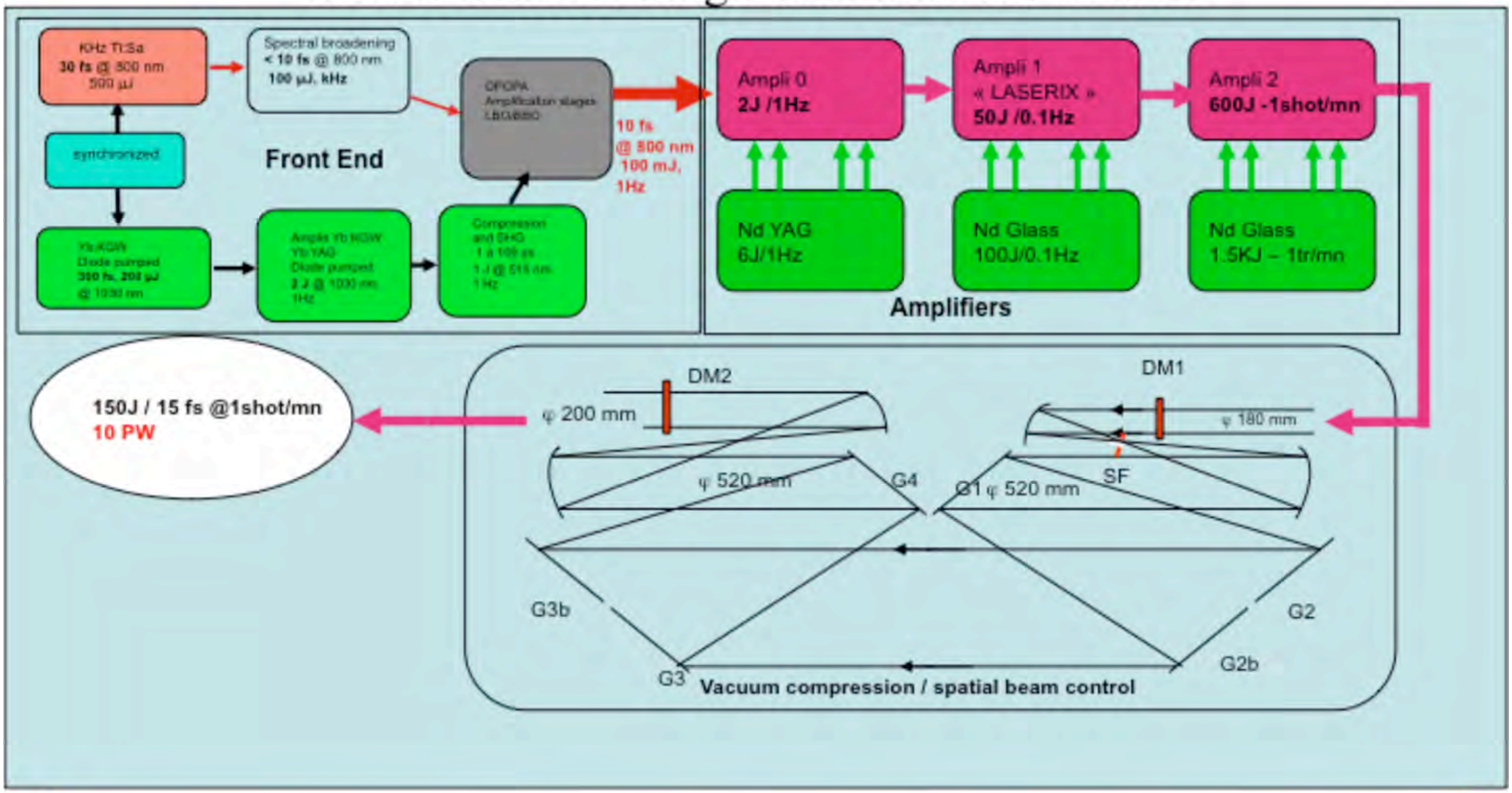
Large scale Ti:sapphire crystals

Gain bandwidth in Ti:sapphire is very large → amplification of pulses as short as 20 fs

High quality Ti:sapphire can only be produced with aperture up to ~10 cm

ILE – APOLLON 10P : A french TiSa project
General scheme

ILE APOLLON Single beamline 10PW laser



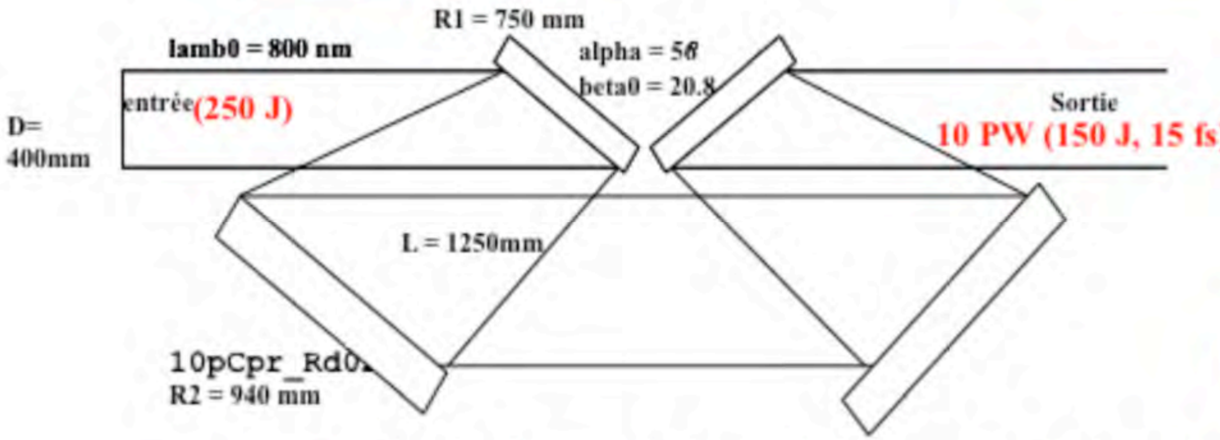
ILE – APOLLON 10P : A french TiSa project
Compressor (Back up solution)

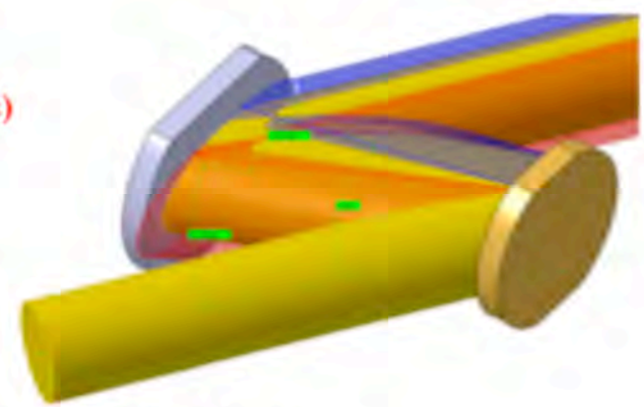
Gold Gratings :

1480 mm-1

940x750mm²
LLNL grating

- **Large dimension : 940 x 750 mm²**
- **Available @ 800 nm for broadband spectrum**
- **Limitation on damage threshold**
  Max fluence on gratings: 0.2J/cm²





Using the world largest Livermore gold gratings (1480 l/mm)

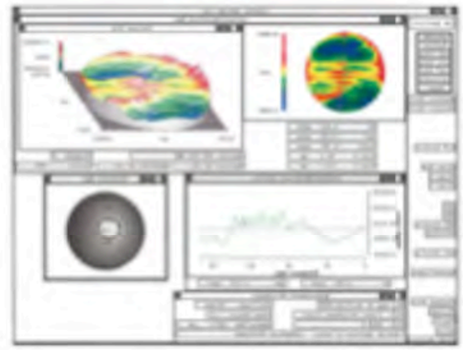
Extremely expensive : 4 gratings (1.1M€), long delivery (18months), need 2 expensive collimators (up and down)

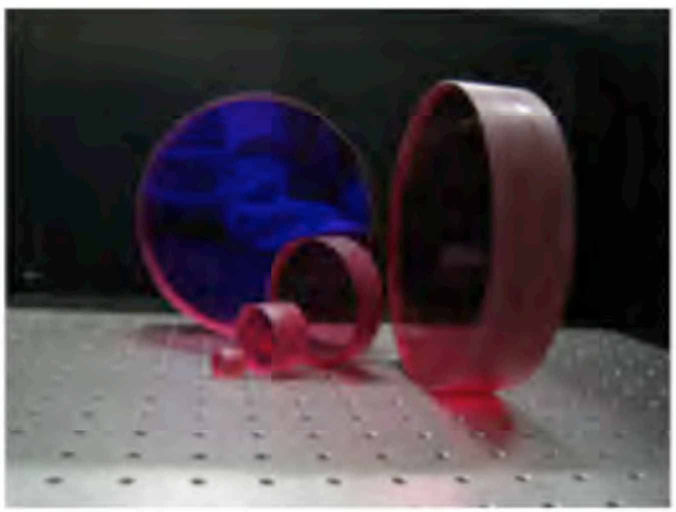
7) Large Size Titanium Sapphire Crystals

*R&D in progress with CRYSTAL SYSTEMS based on HEM to grow size up to 8"

Last result (July 2008)

ILE #4 in the evaluation process.
After processing, the boule diameter is 192 mm,
and the height is 122 mm.





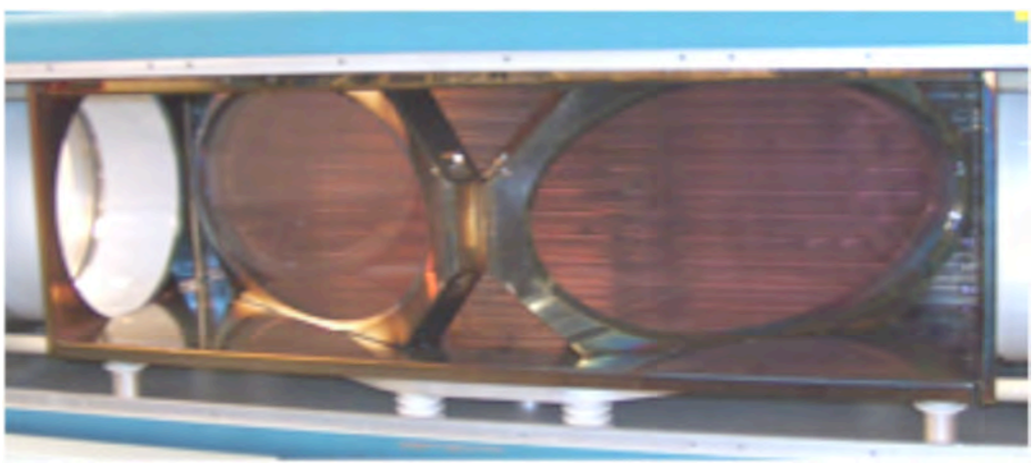
TiSa crystal family from 15 m m à 175 mm

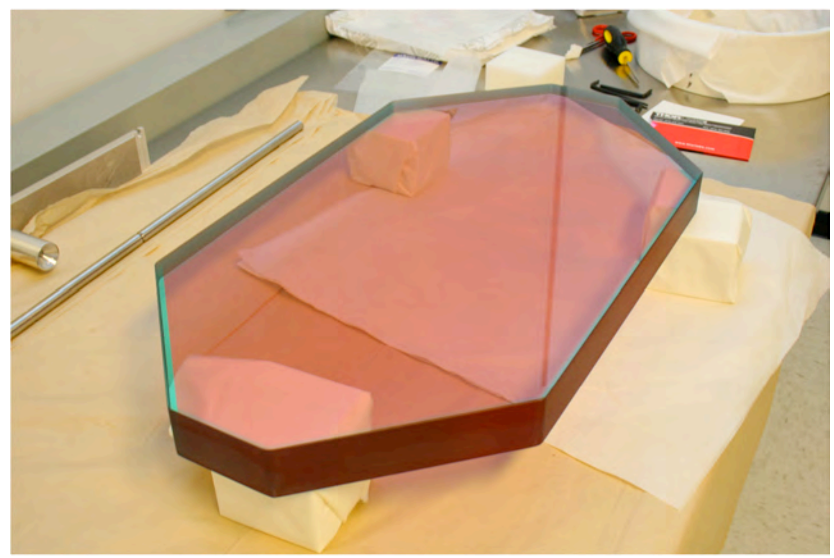
Crystal Systems (GT Solar) uses the HEM technique since years to grow blank sapphire as well as Ti doped sapphire.

3 years ago the maximum size was ~ 15 cm in diameter

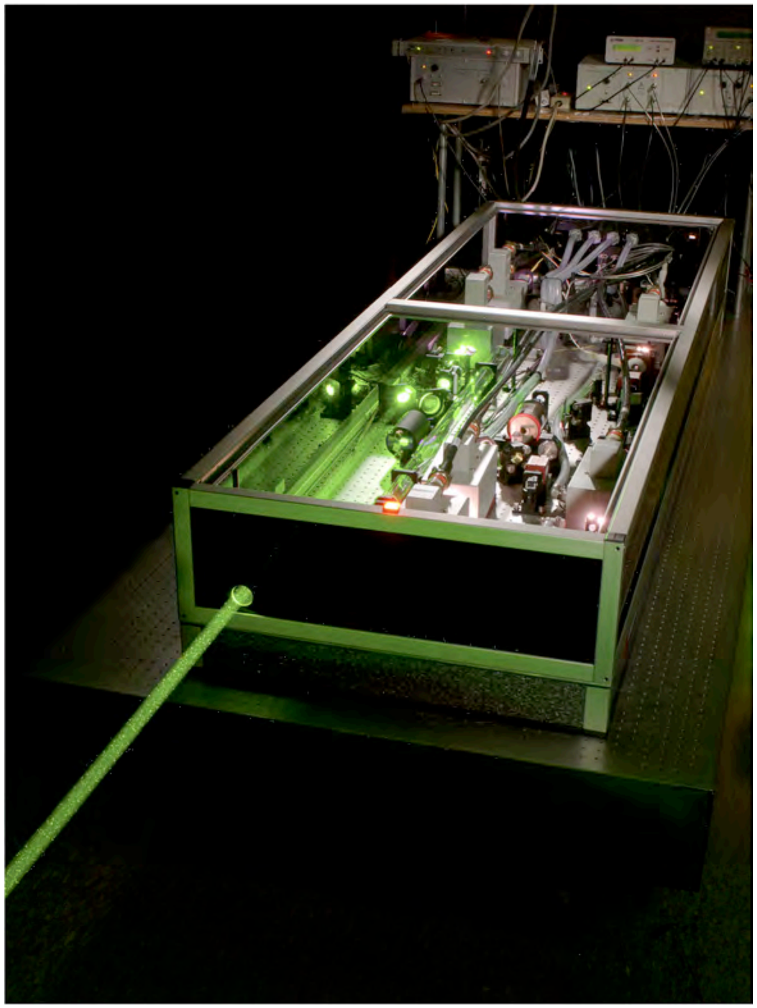
A study has been funded by ILE to obtain rough boules of 20 cm

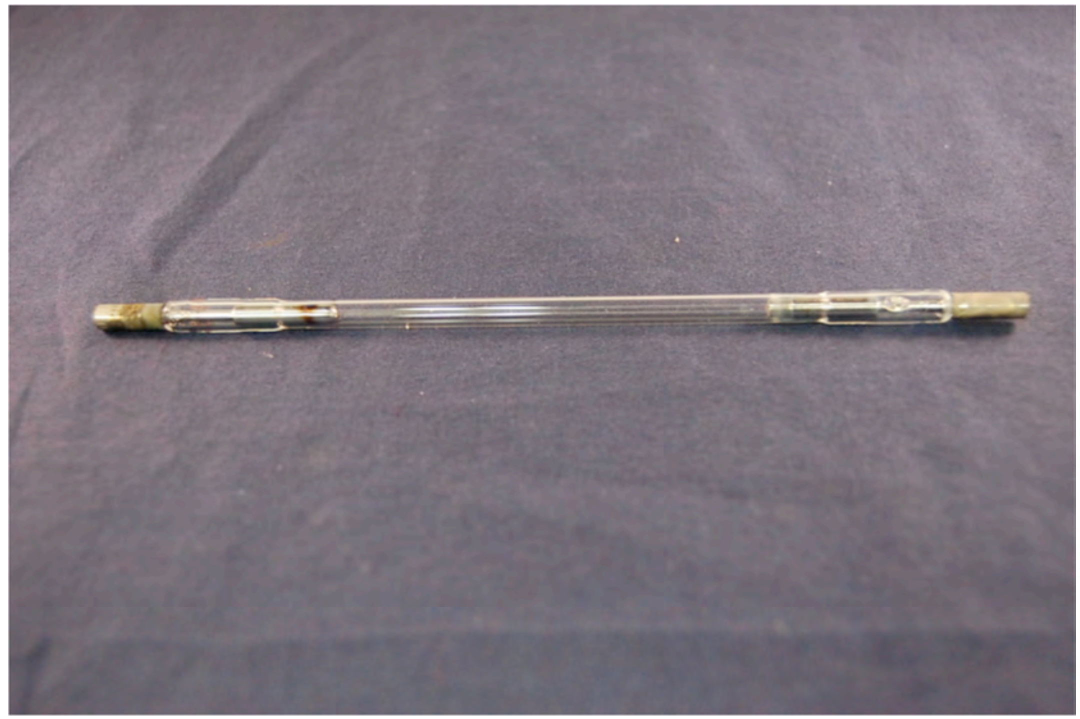
Nd:glass is very attractive for high power lasers because it can be fabricated with large aperture





Direct flashlamp pumping (and ultimately direct diode pumping) have many attractions for high peak power

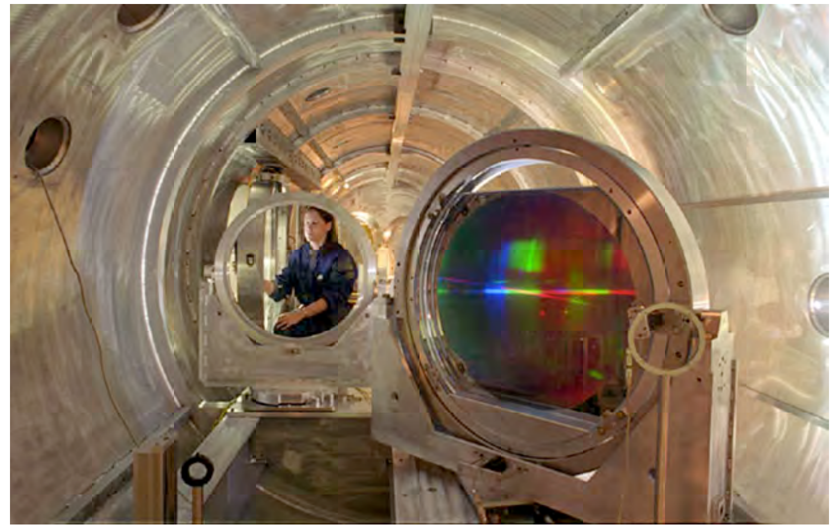




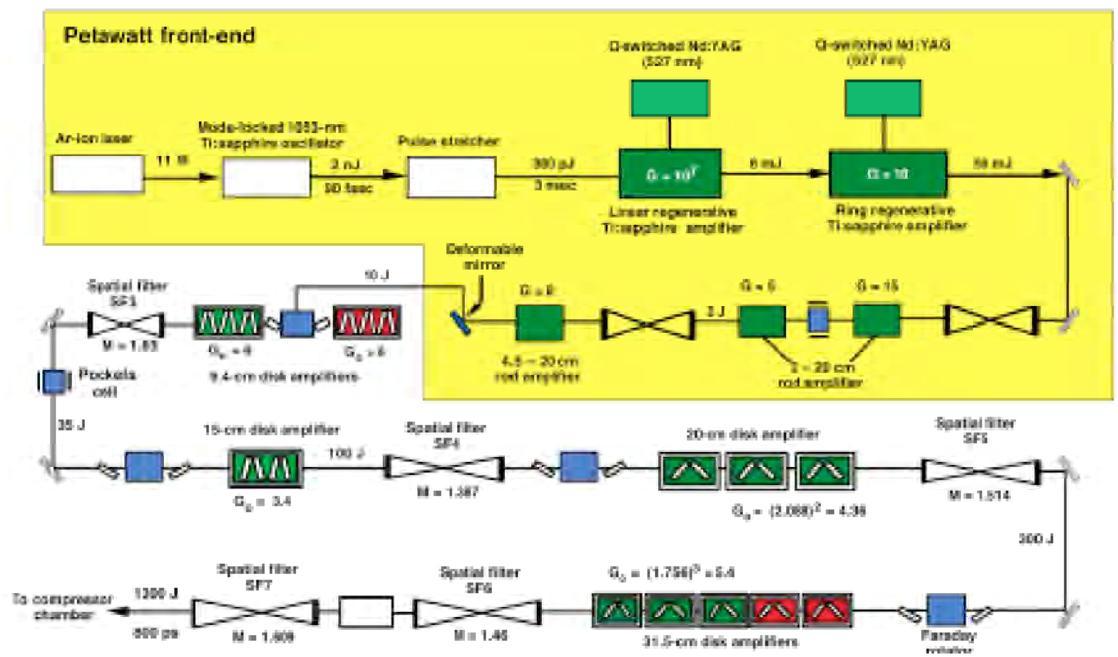
The first Petawatt laser was demonstrated at LLNL by implementing CPA on the Nd:glass NOVA laser

The Petawatt at LLNL

Nova laser



90 cm gratings to compress Nova pulses

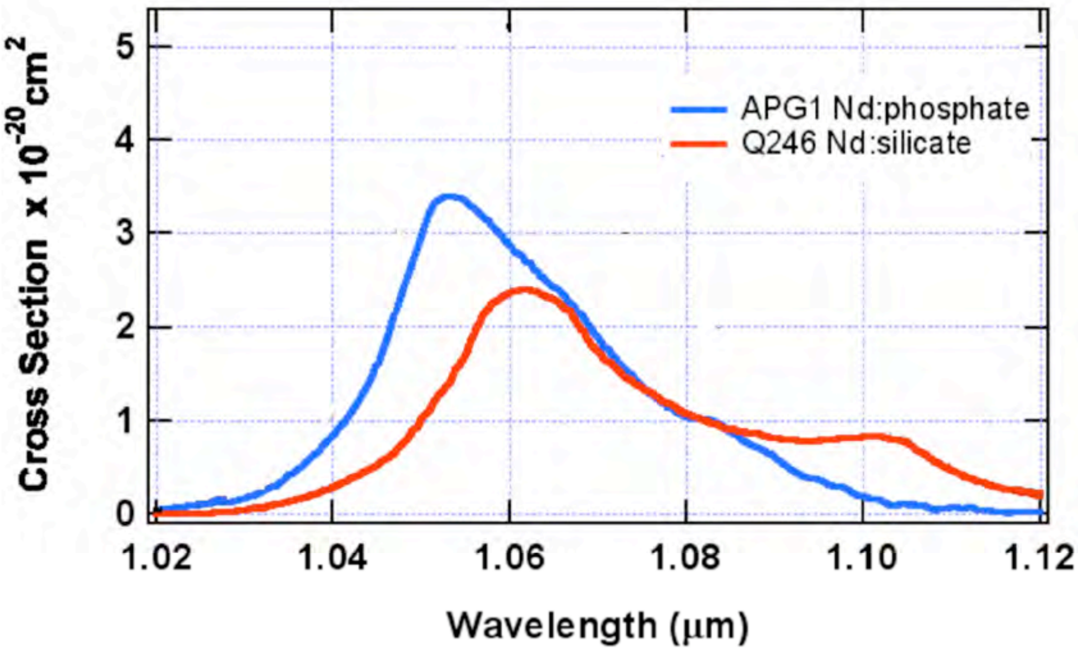


Petawatt specs:
500 J energy
500 fs pulse duration
Peak intensity > 10^{20} W/cm^2

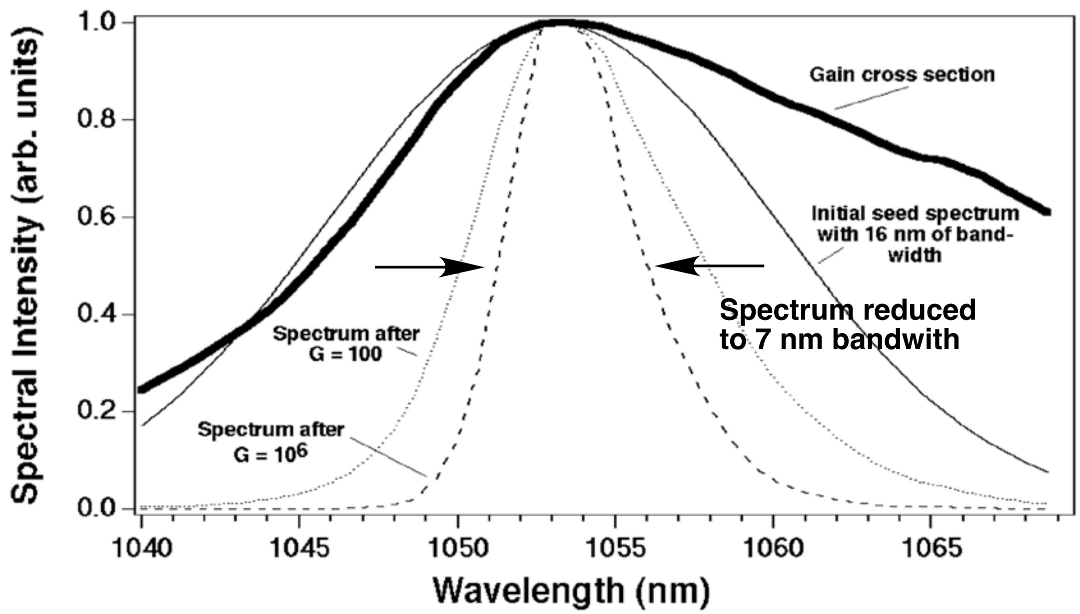
Information derived from M. D. Perry et al "Petawatt Laser Report" LLNL Internal report UCRL-ID-124933.

The principal limitation to the use of Nd:glass in CPA lasers is that it exhibits limited gain bandwidth

Gain spectrum of two kinds of laser glass



Calculation of the effects of gain narrowing in Nd:glass

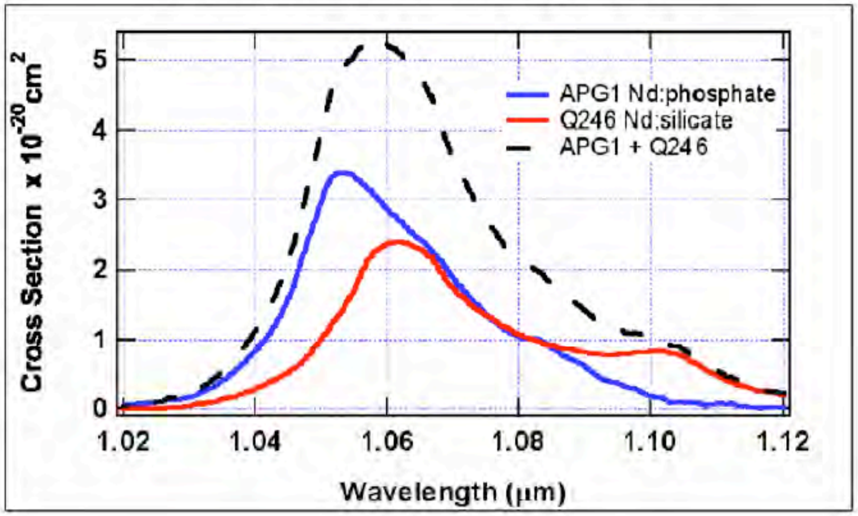


Gain narrowing of the ultrafast pulse spectrum tends to limit Nd:glass CPA lasers to pulse duration of 500 fs

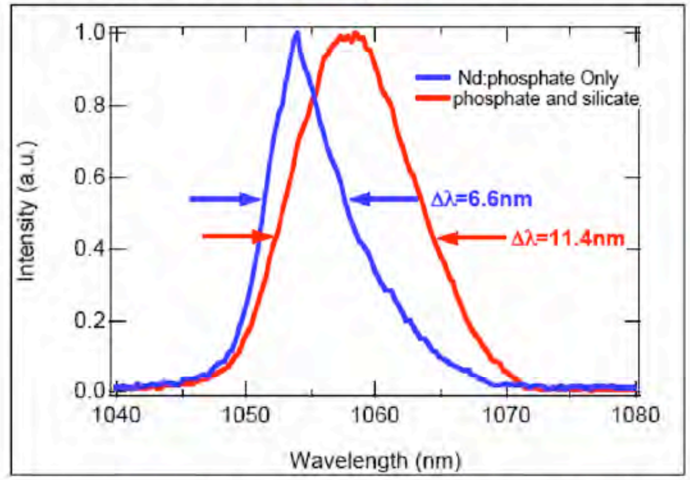
We have chosen a route to 1 PW by mixing glasses and aiming for ~ 100 fs pulses

Mixed glasses combine to yield a broader amplification spectrum.

Combined Gain Cross-Sections of Nd:silicate and Nd:phosphate glasses



Mixed Glass Amplified Spectrum vs. Nd:phosphate Amplified Spectrum



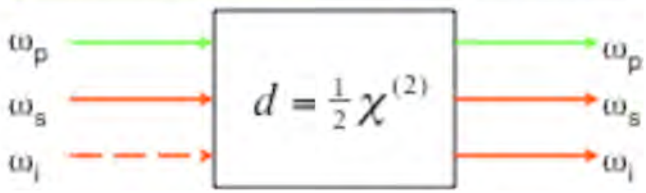
•Seed Bandwidth	10.2 nm FWHM
•Seed Wavelength	1057 nm

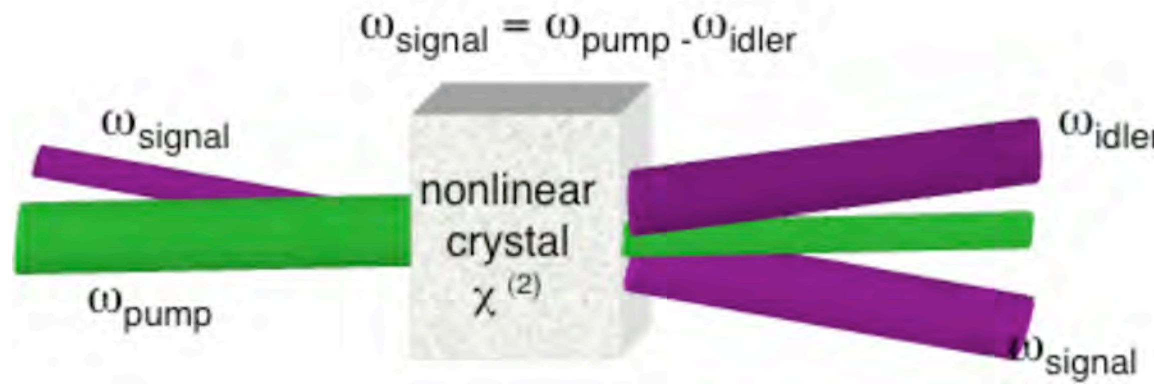
Nd:glass amplification

- **Limit glass amplification to 2 orders of magnitude to minimize spectral gain narrowing.**
- **What is the optimum gain ratio between the 2 glasses?**
- **At what wavelength should the amplifier be seeded?**

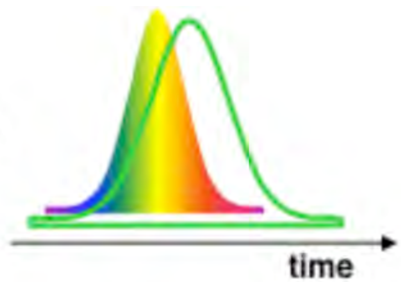
Optical parametric amplification in CPA (OPCPA) offers the potential for very broadband amplification

Difference Frequency Generation

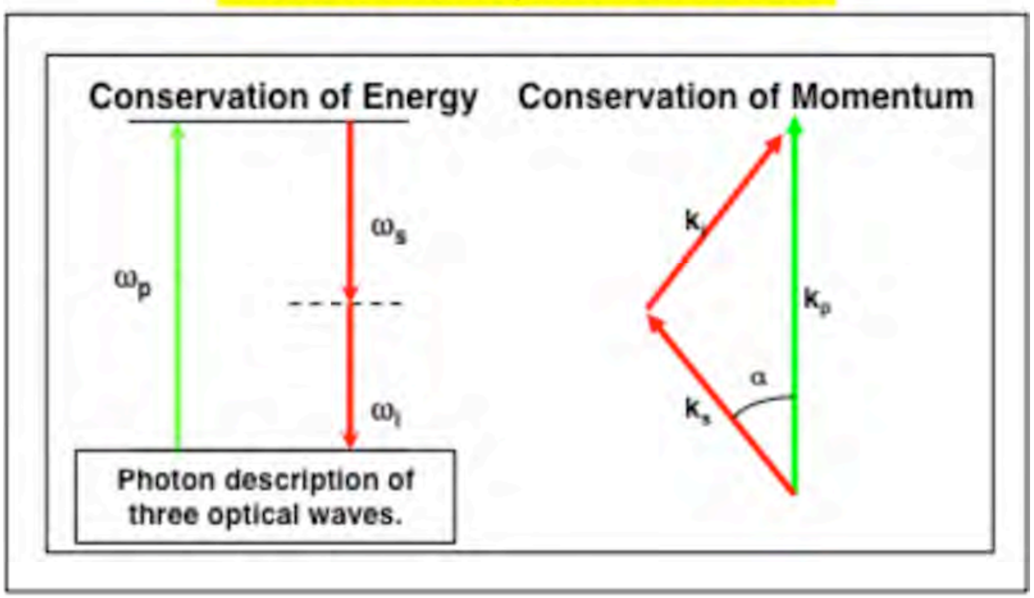


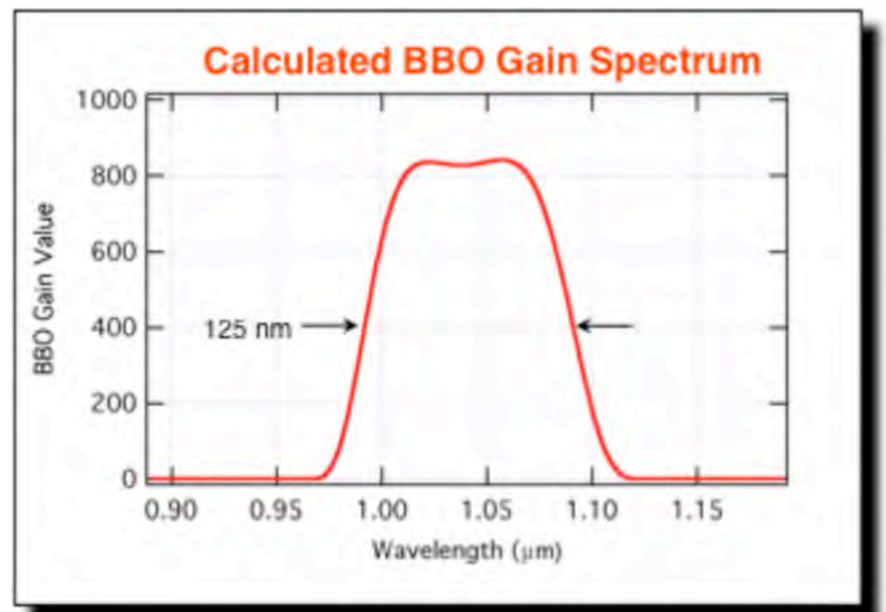


Temporal overlap between pump and seed pulse shapes spectrum

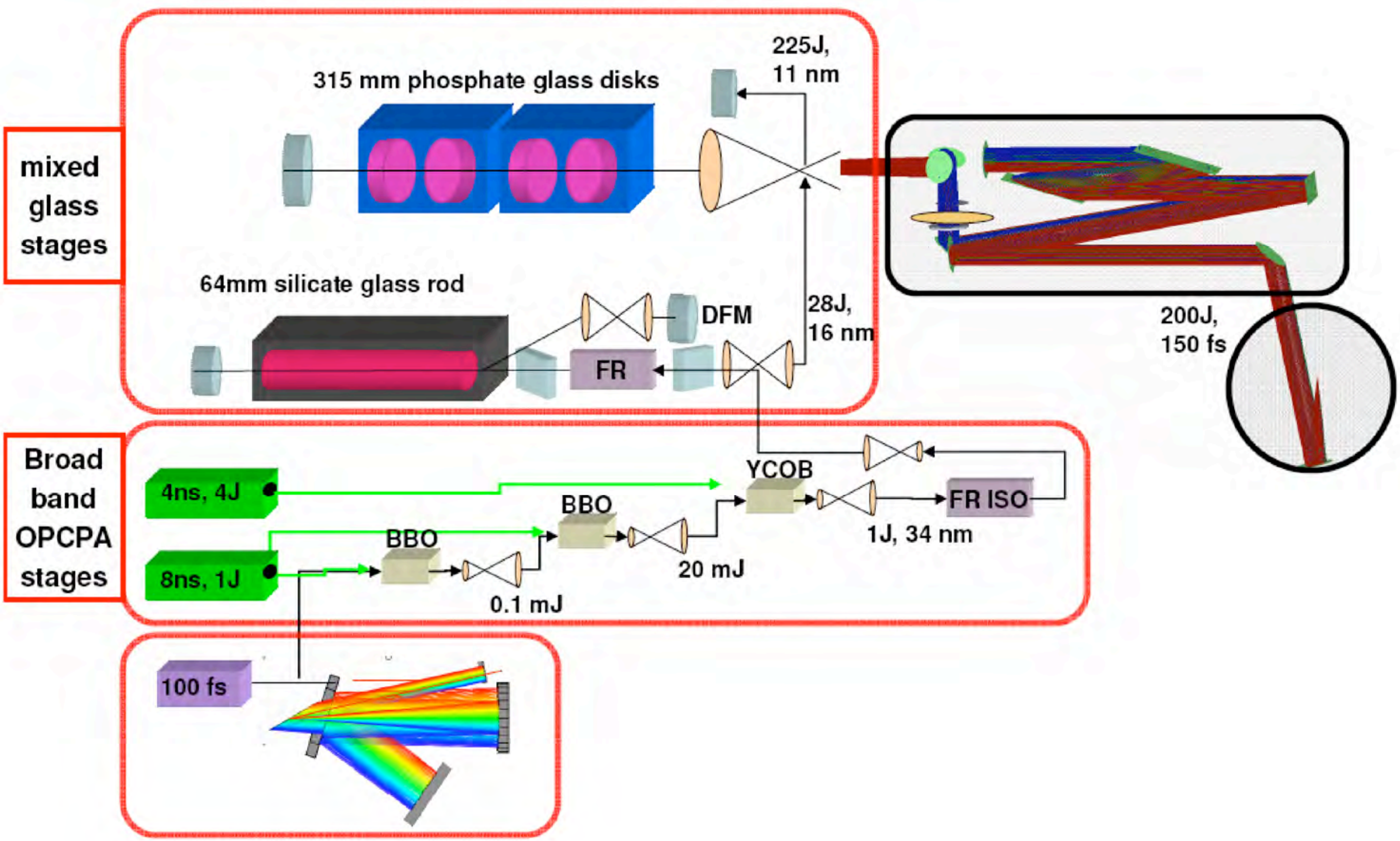


Photon Description of OPCPA

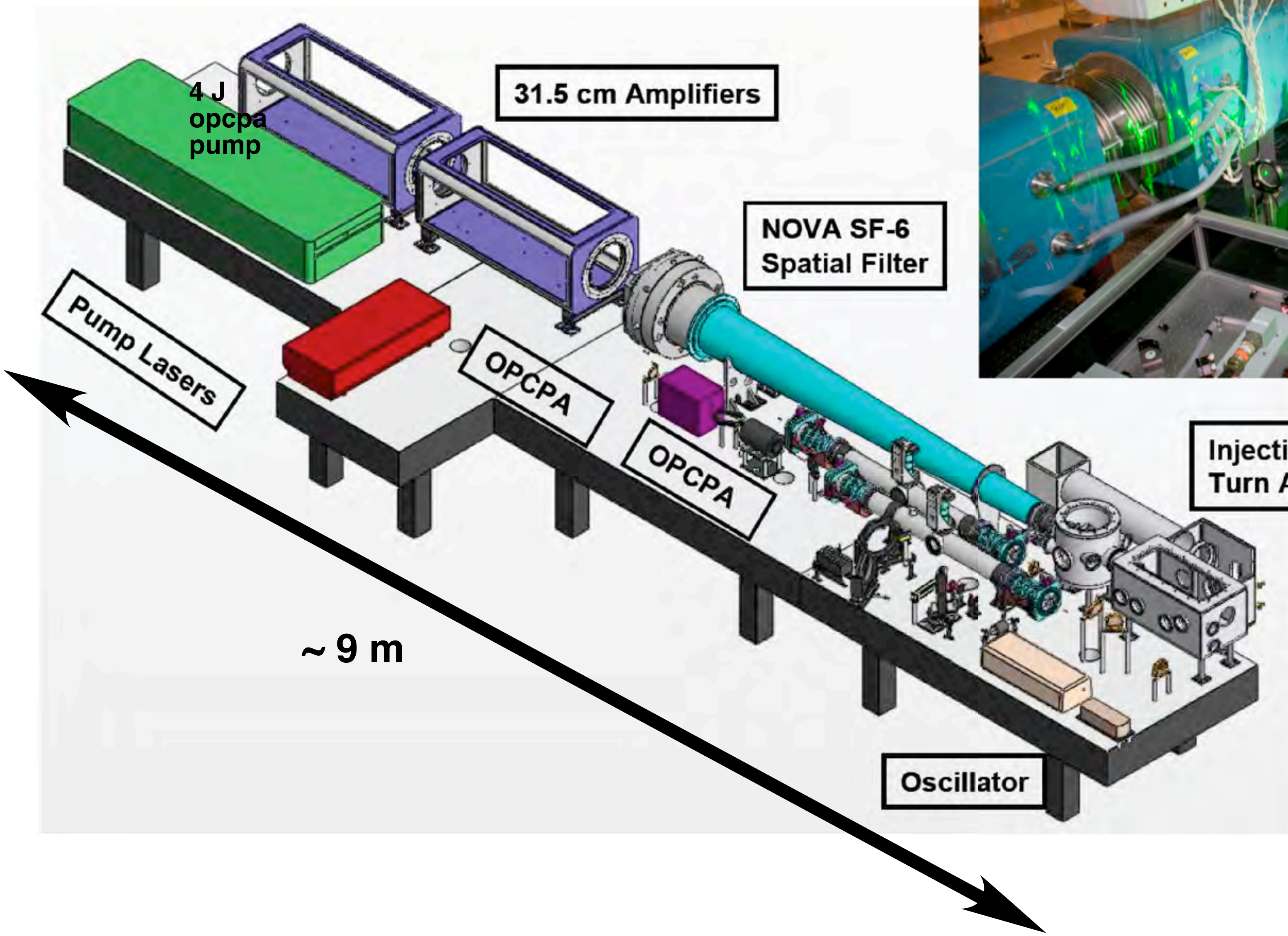


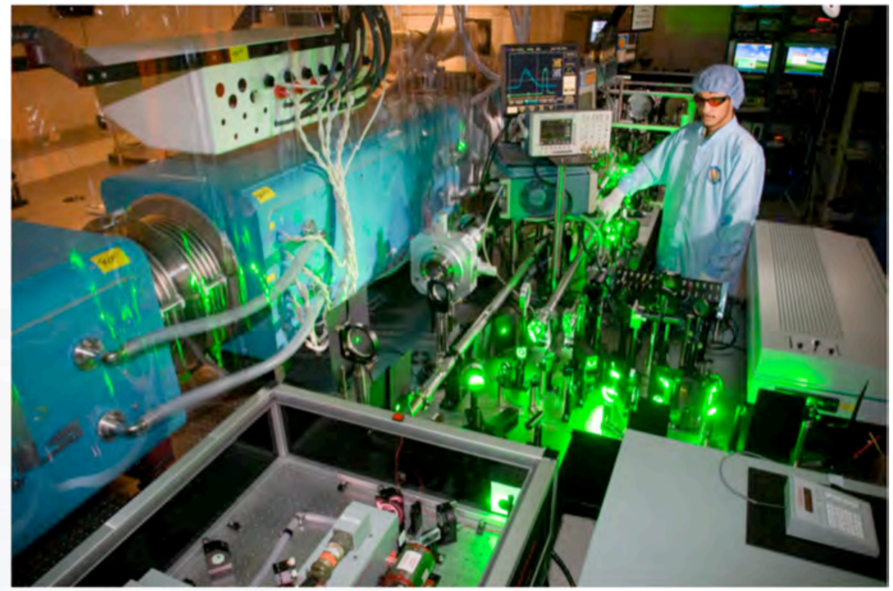


The Texas Petawatt design is based on a 3-stage OPCPA amp and a mixed glass chain

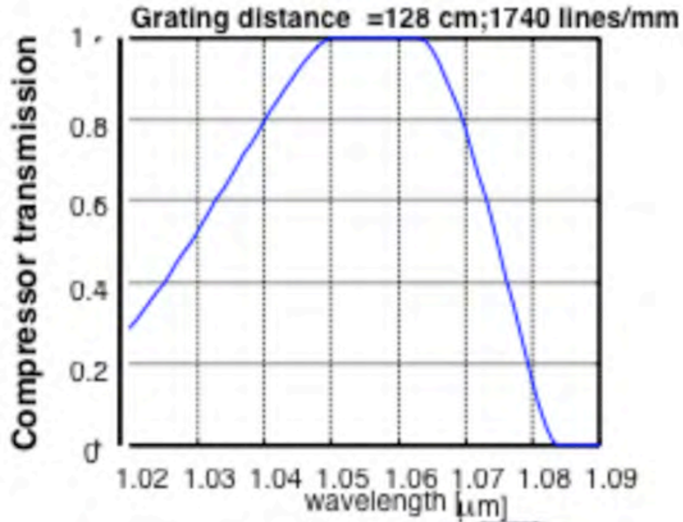


The layout of the amplifier section is compact and rests on four interlocking tables

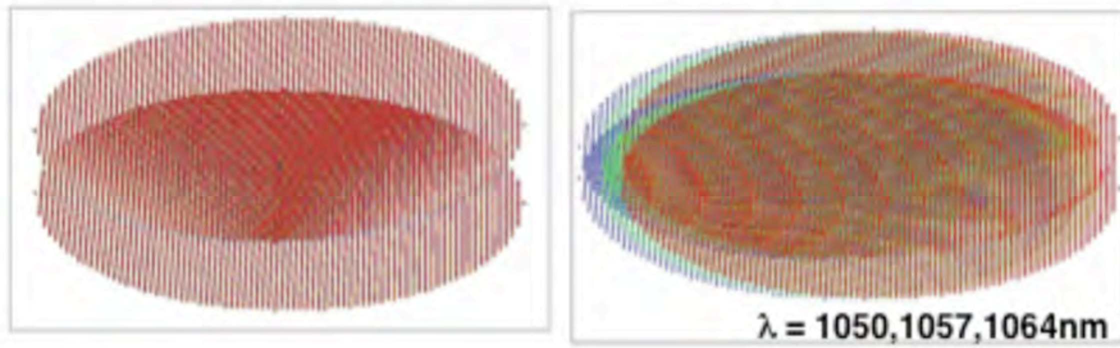


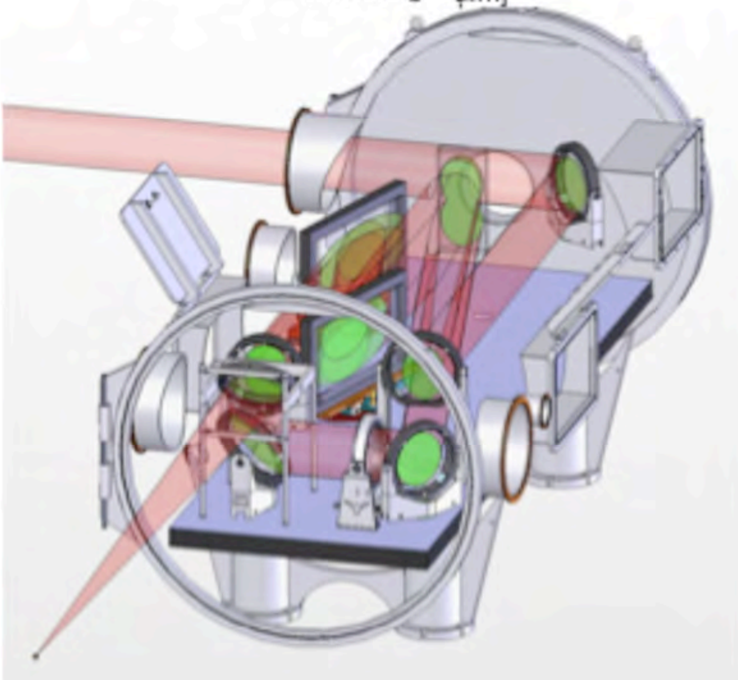


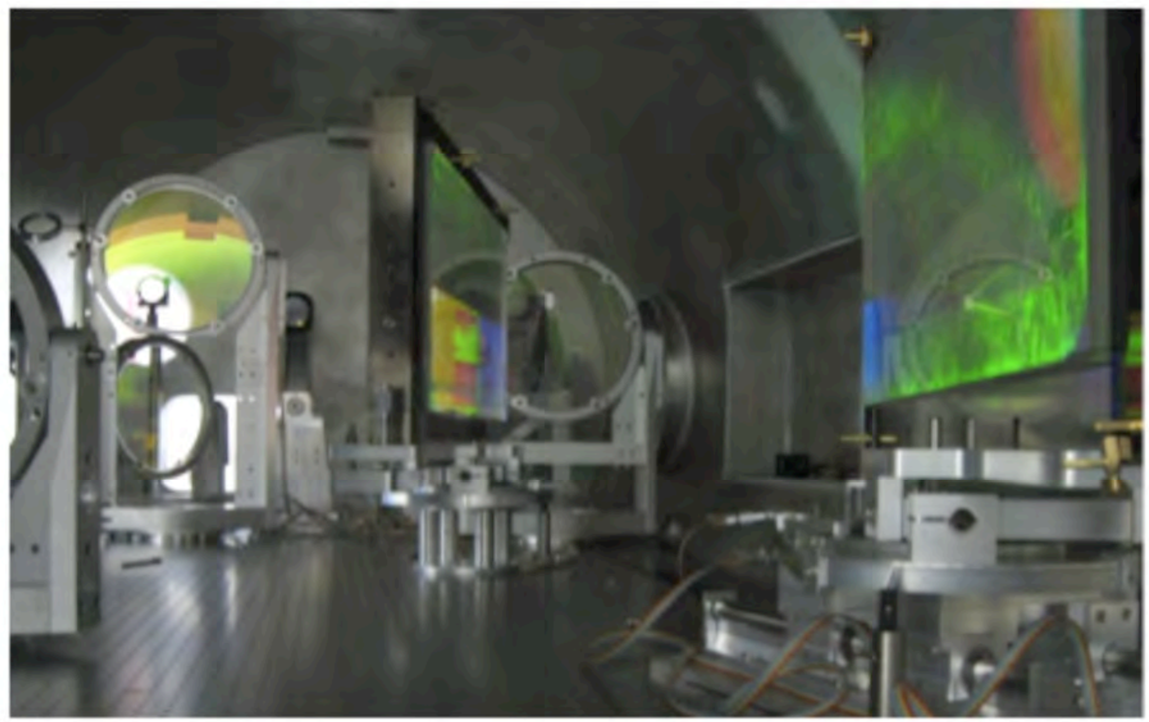
The MLD gratings in the TPW perform well with high diffraction efficiency and ~90% throughput



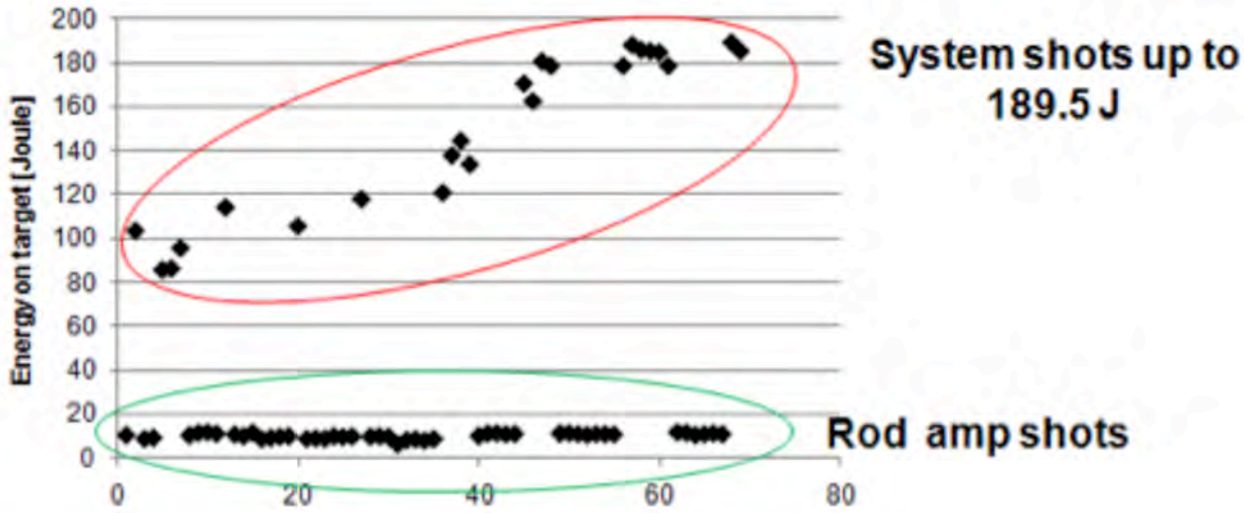
Footprints of beam of both passes overlap partially for efficient use of gratings (405x805 mm² at 1740 l/mm)

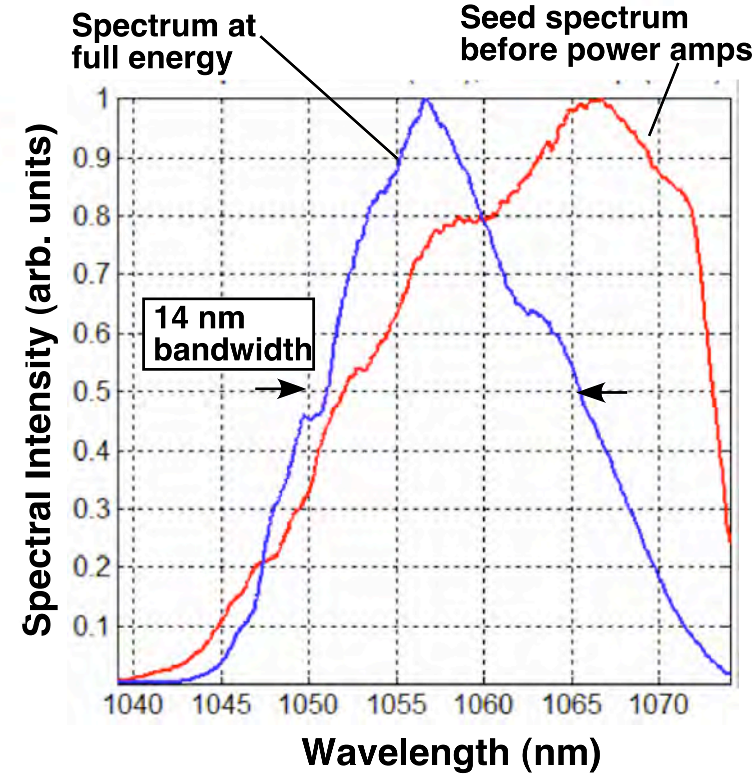




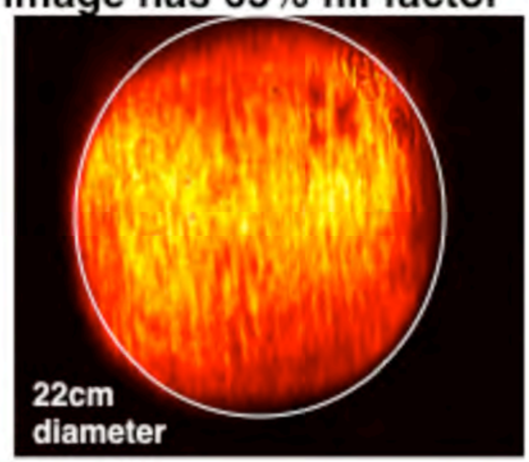


We presently we shoot >1.3 PW on target during the last experimental run

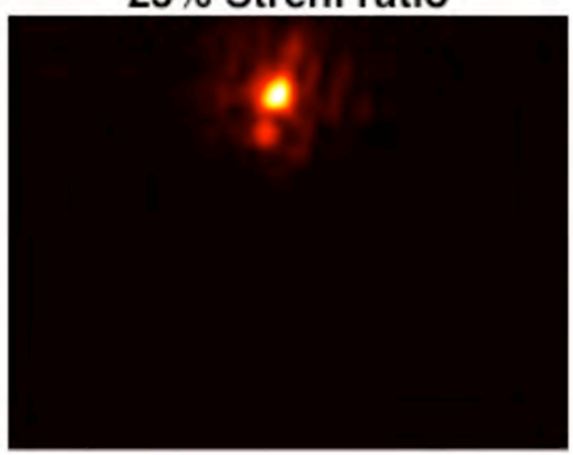




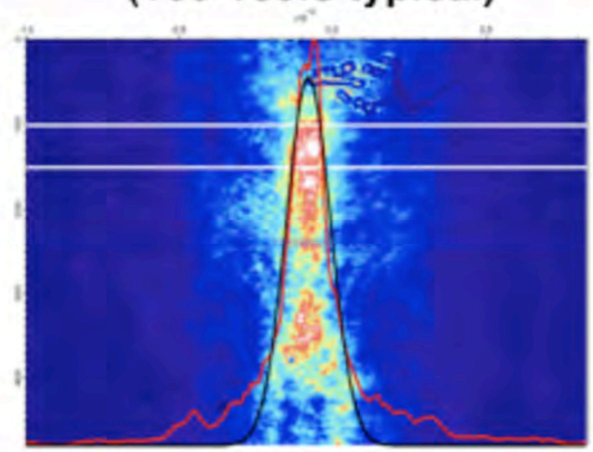
End chain near field image has 65% fill factor



Focal spot has up to 25% Strehl ratio

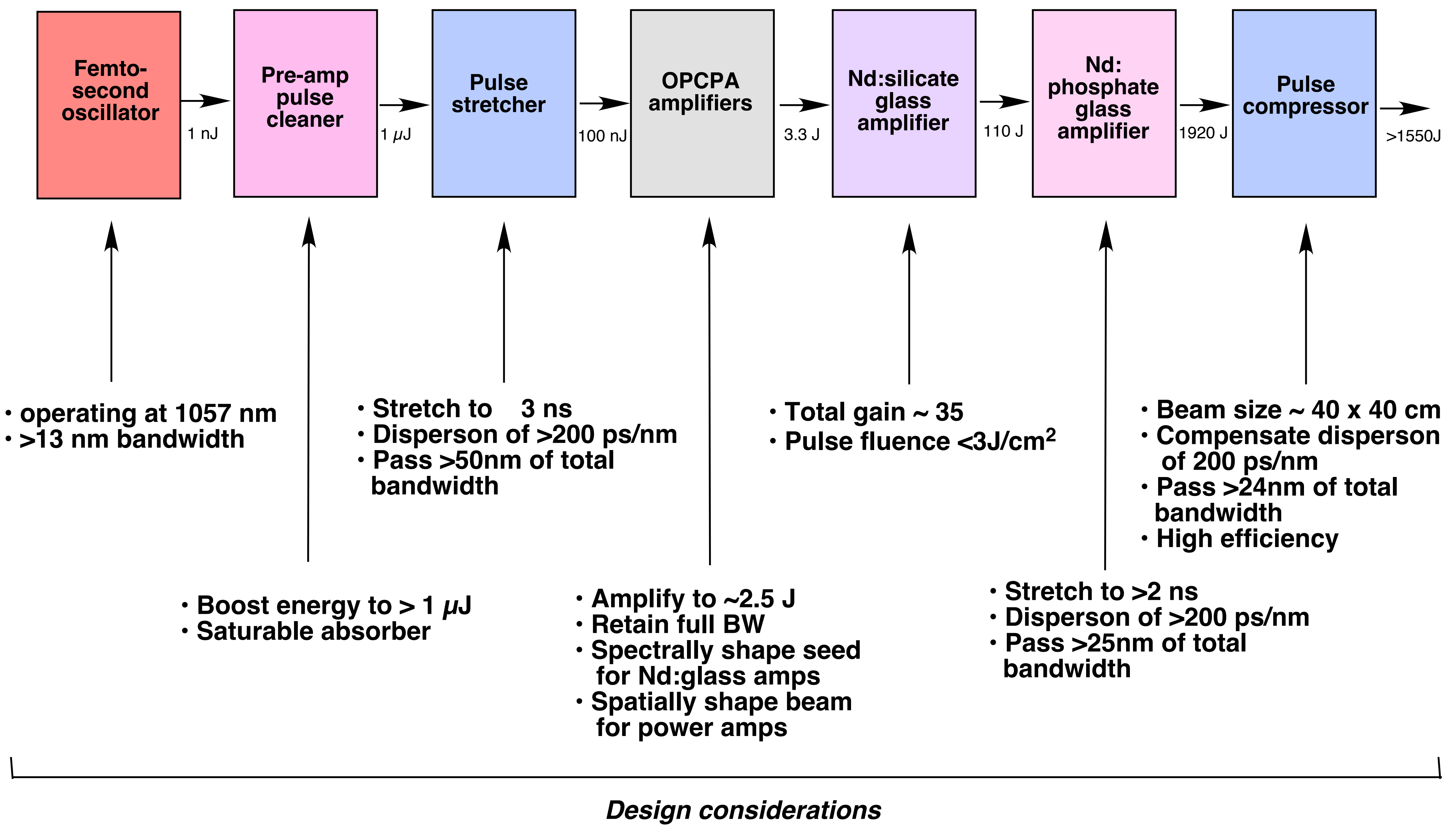


FWHM = 130 fs (130-160fs typical)

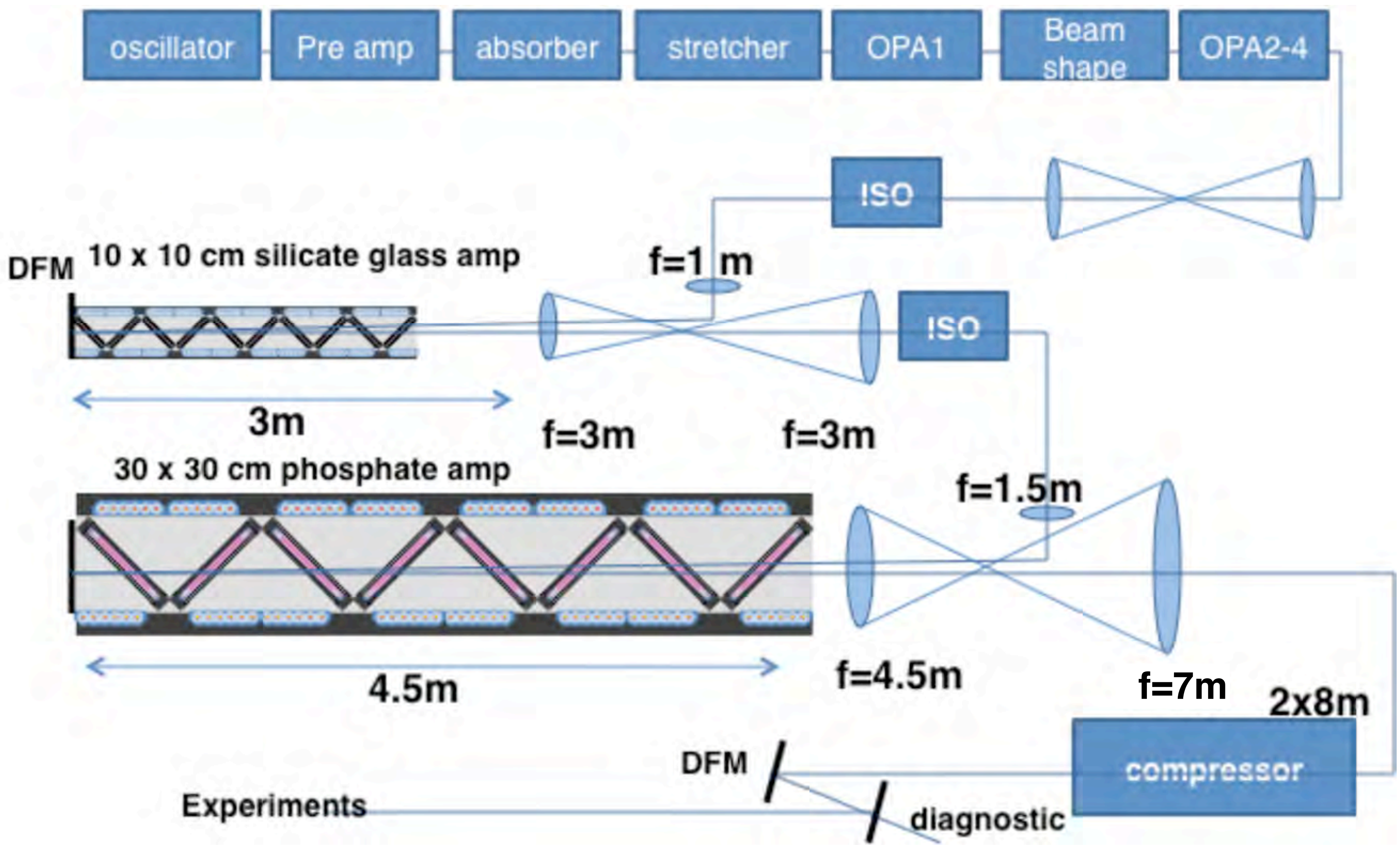


The hybrid mixed glass architecture can be scaled to 10 PW with existing technology

System elements with estimated energies

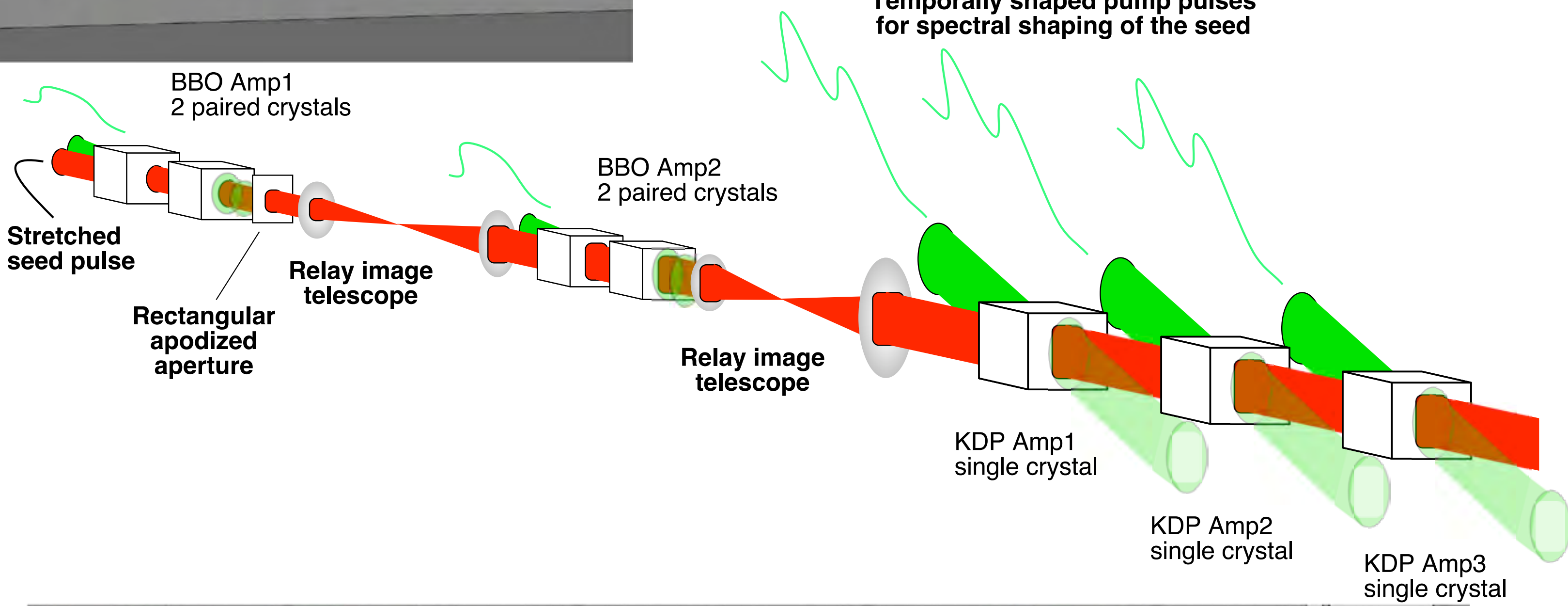


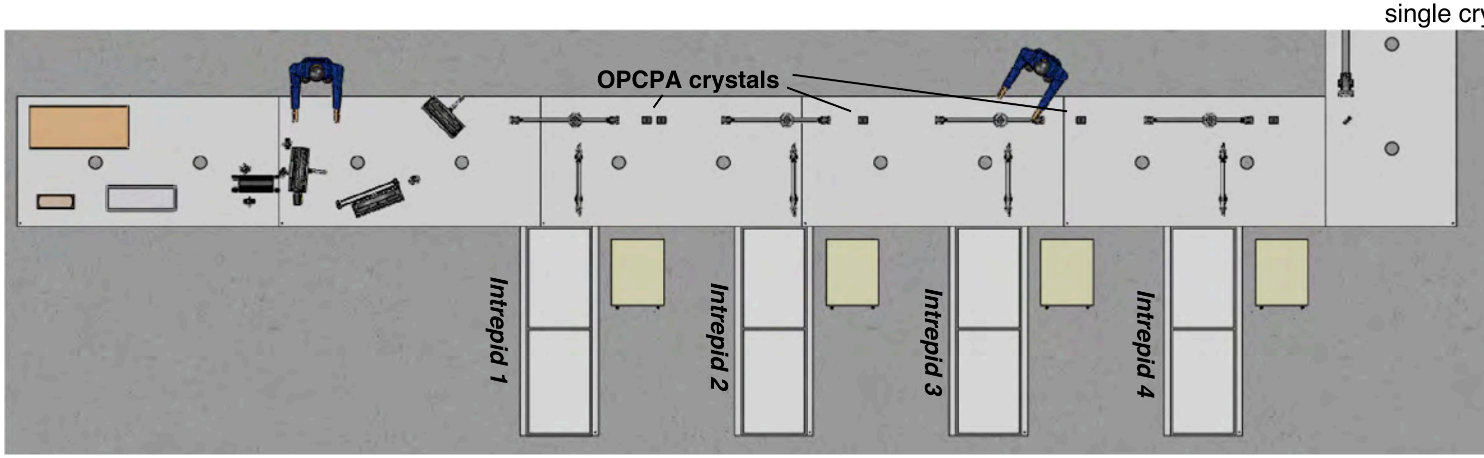
High energy amplification occurs in two stages employing silicate and phosphate slab amps



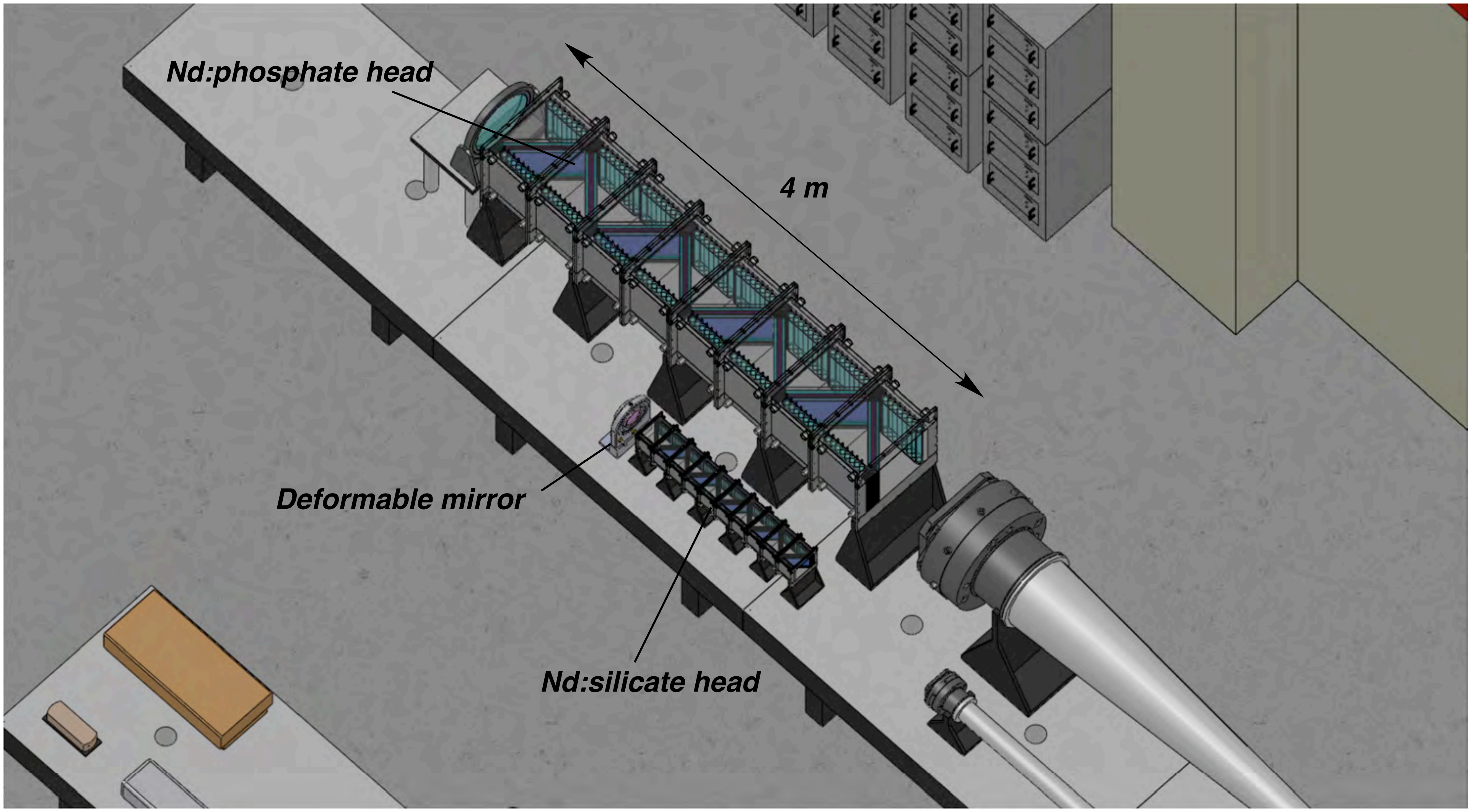
The OPCPA section can be staged with Intrepid pump lasers arranged as spokes off the main chain

OPCPA Output: 3 J; 20 nm bandwidth

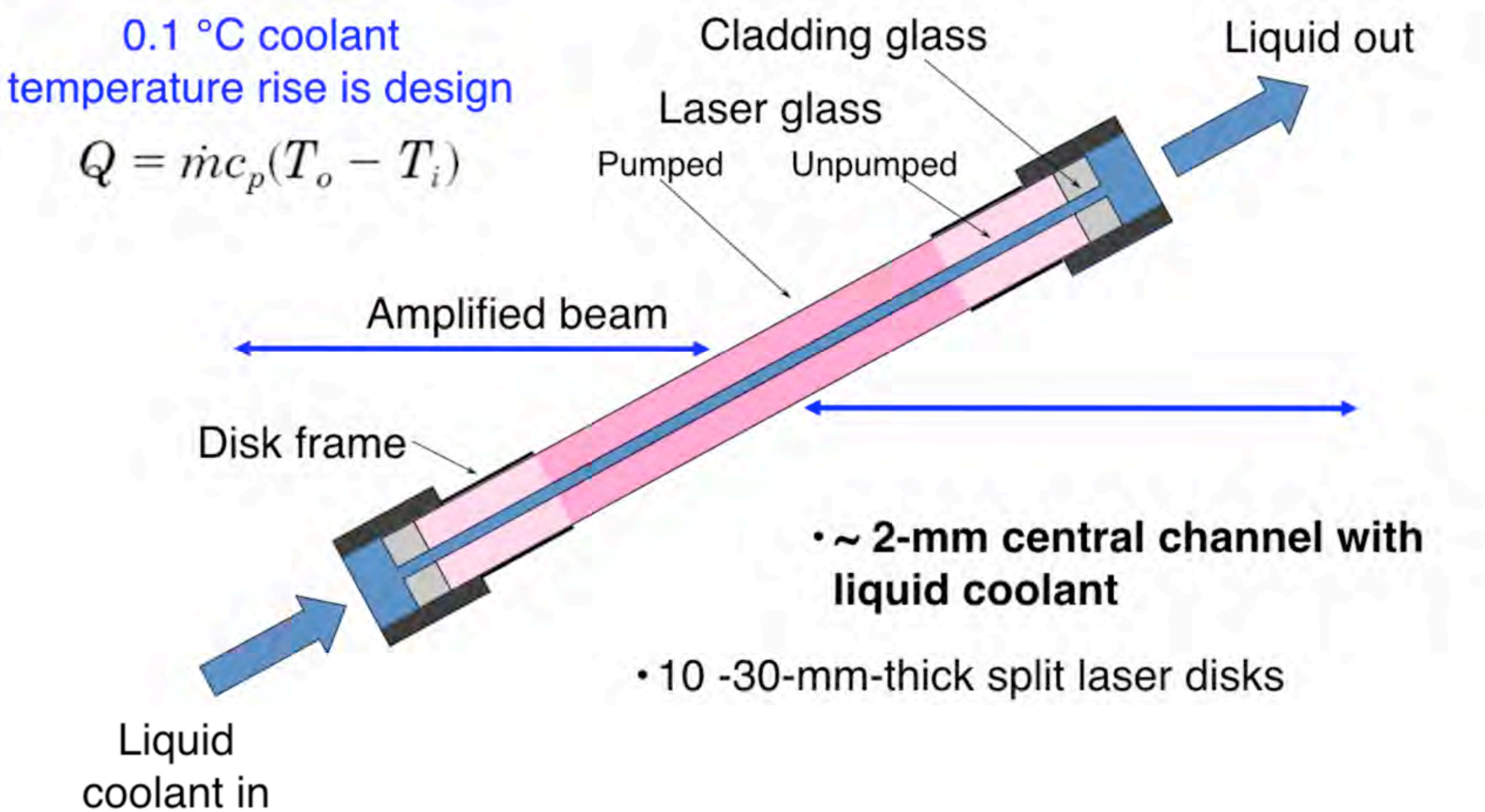




The silicate and phosphate glass amplifiers are arranged in a double pass configuration



We are investigating liquid cooling the faces of glass slabs as a means for dramatically increasing rep. rate

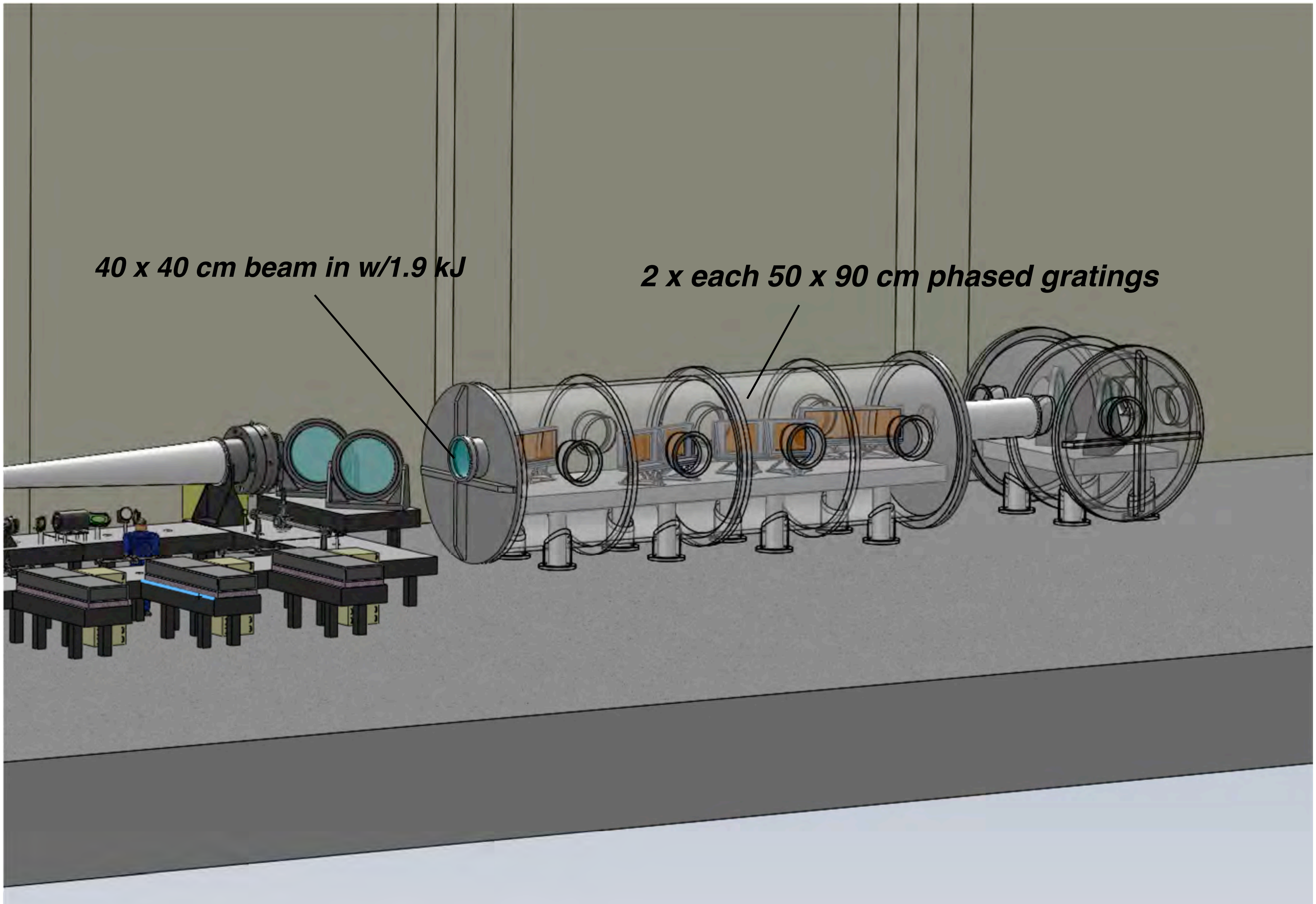


- ~ 2-mm central channel with liquid coolant
- 10 -30-mm-thick split laser disks

This technology will permit operation of large aperture (~ 30 cm) Nd:glass slab amplifiers with rep. rate at least one shot per minute

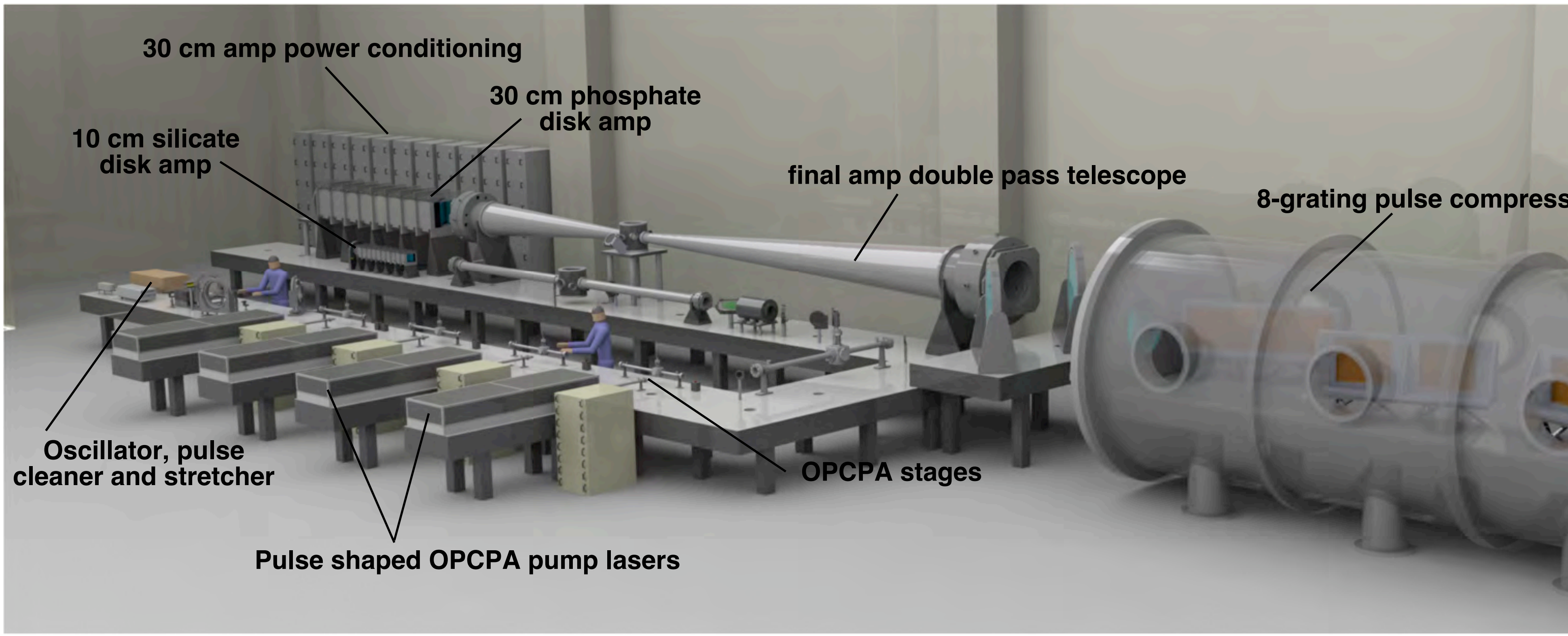
Viewgraph credit: Jon Zuegel (LLE Rochester)

The compressor is constructed from 4 pairs of phased MLD gratings



The hybrid mixed glass architecture would enable construction of a compact 10 PW laser

Mechanical Engineering conception of the 10 PW Hybrid Mixed glass laser



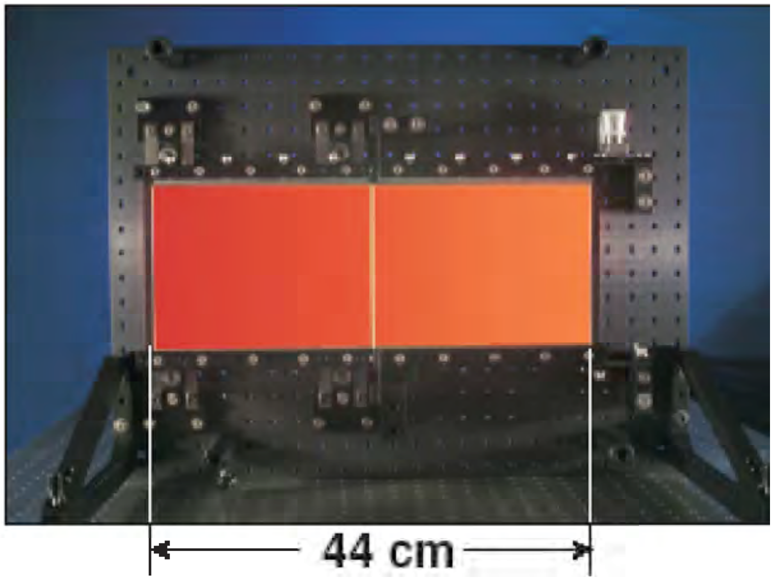
Laser output:
Energy: 1500 J,
Pulse duration: <150 fs
repetition rate: 1 shot/min
Laser Wavlength: 1054 nm
Temporal pulse contrast: 10^{10}:1 at > 10 ps

The high energy amplifier architecture of a near term mixed-glass 10 PW laser could be based on Beamlet

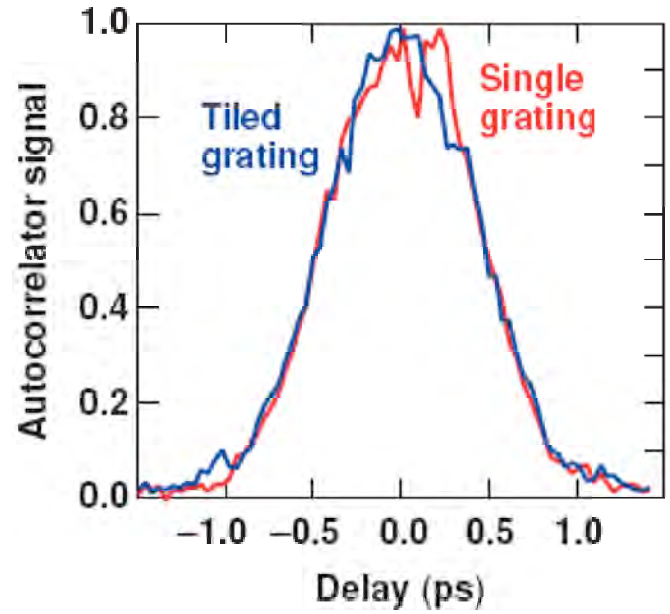
Z-Beamlet laser at Sandia National Laboratories

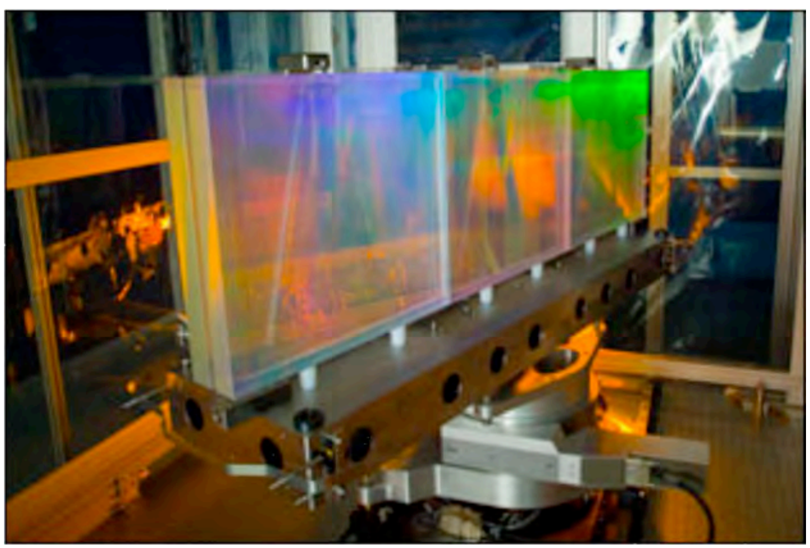
The idea of tiling multiple gratings for compression of 1 μm pulses has been demonstrated at Omega EP

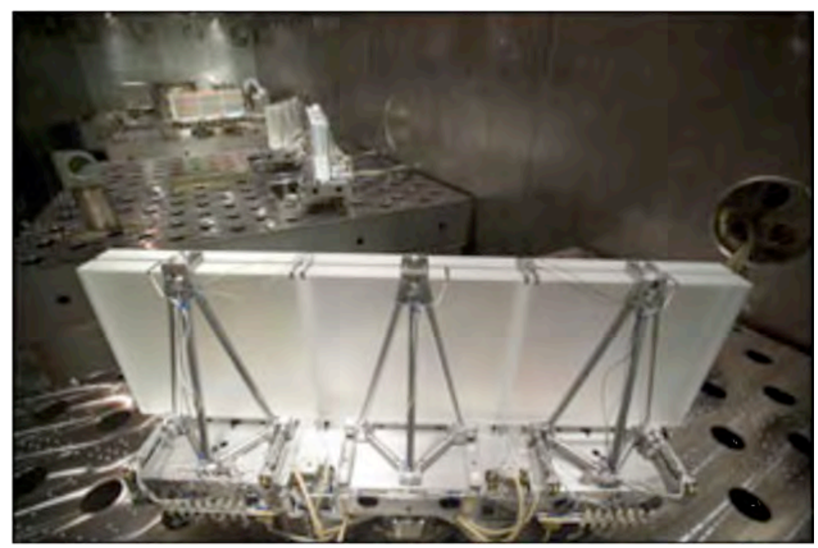
Two-grating phased array at the U. of Rochester



Pulse compression data using the two grating array (U. of Rochester)

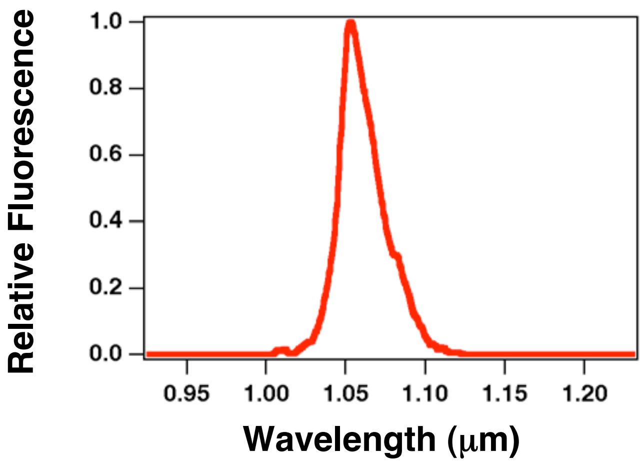






Commonly available Nd:glass is NOT the optimum glass for broadband CPA

LG-760 Phosphate glass



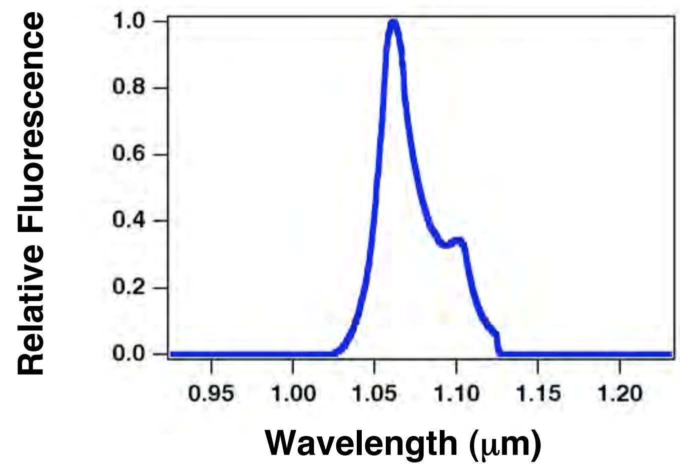
Peak Wavelength: 1054 nm

Peak cross section: 4.3 x 10^{-20} cm^2

Linewidth (FWHM): 21.1 nm

Nd_2O_3 ~3%
P_2O_5 ~ 97%

LG-680 Silicate glass



Peak Wavelength: 1061 nm

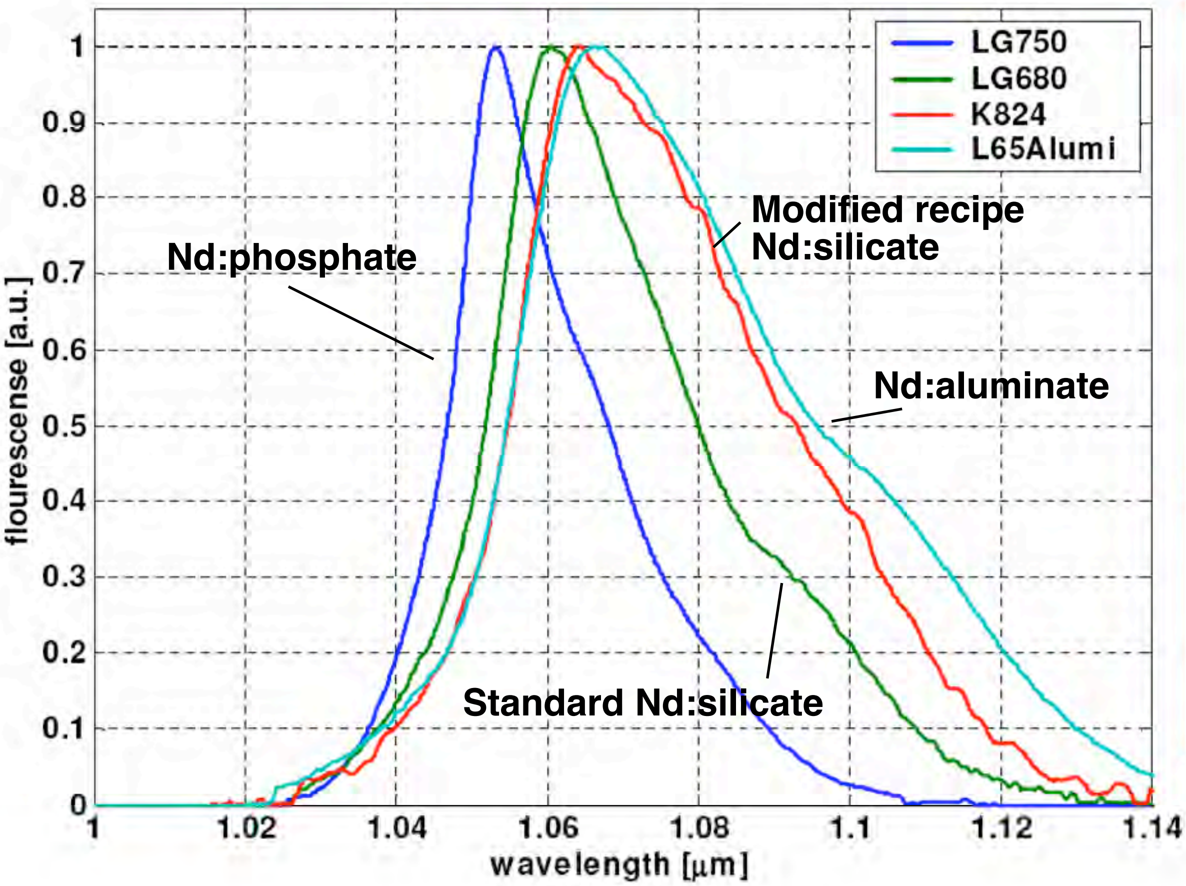
Peak cross section: 2.9 x 10^{-20} cm^2

Linewidth (FWHM): 28.2 nm

Nd_2O_3 ~3%
SiO_2 ~ 97%

Different laser glasses could enhance the band-width of a mixed glass laser chain

These alternative glasses have gain shifted further into the red, broader linewidths and reasonable gain cross sections

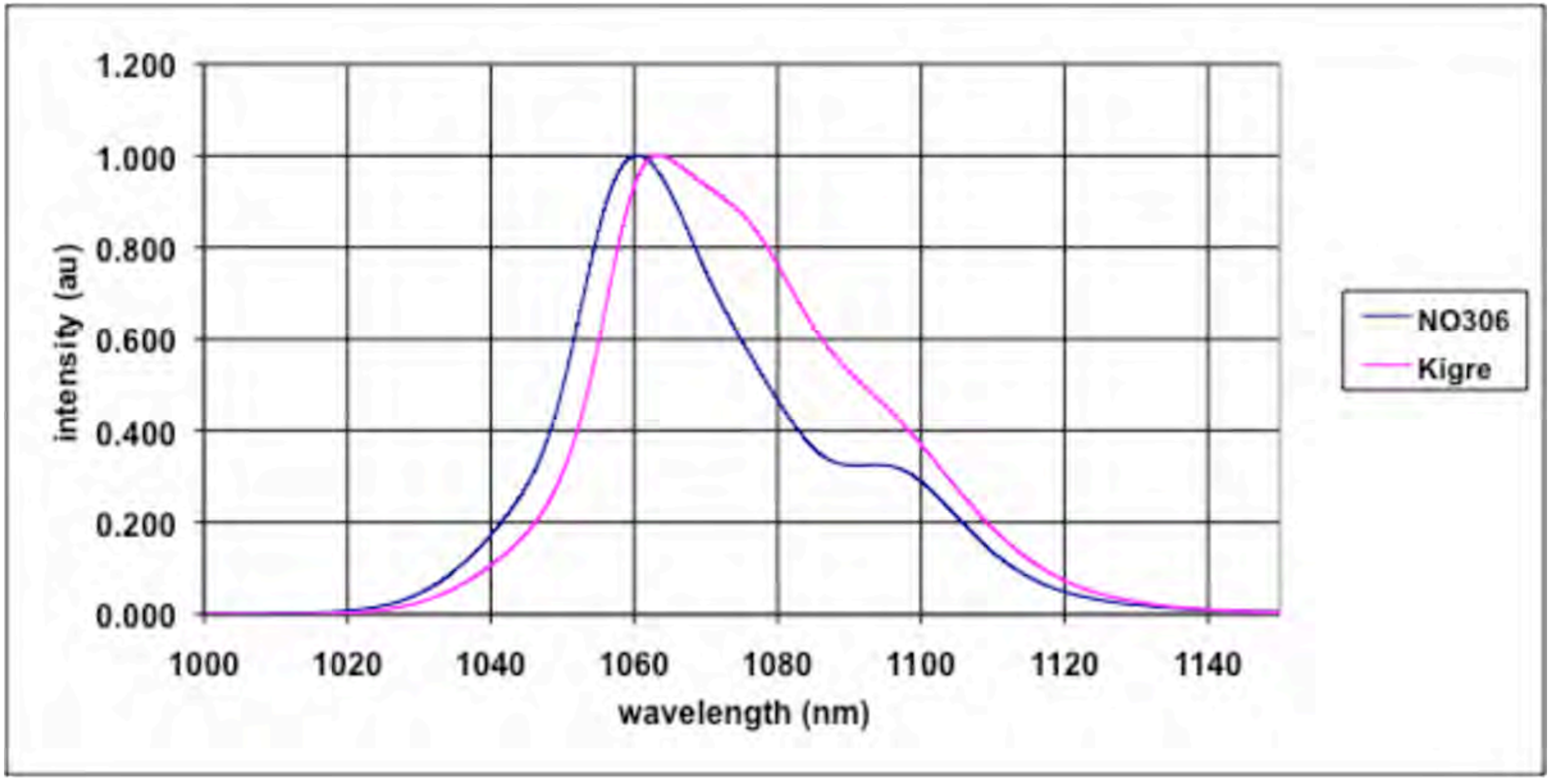


Key properties are reasonable:
- cross section (~70%)
- n_2 (x 1.5-2)
- Lifetime long enough
- Good thermal prop.
- Good mechanical prop.
- Good optical properties

Recipe for K824 and L65Aluminate silicate glass known, but there is no current vendor

S. E.Stokowski, et. al, LLNL-M-95, Laser Glass Handbook 1981

This glass could enable sub-100 fs large scale lasers

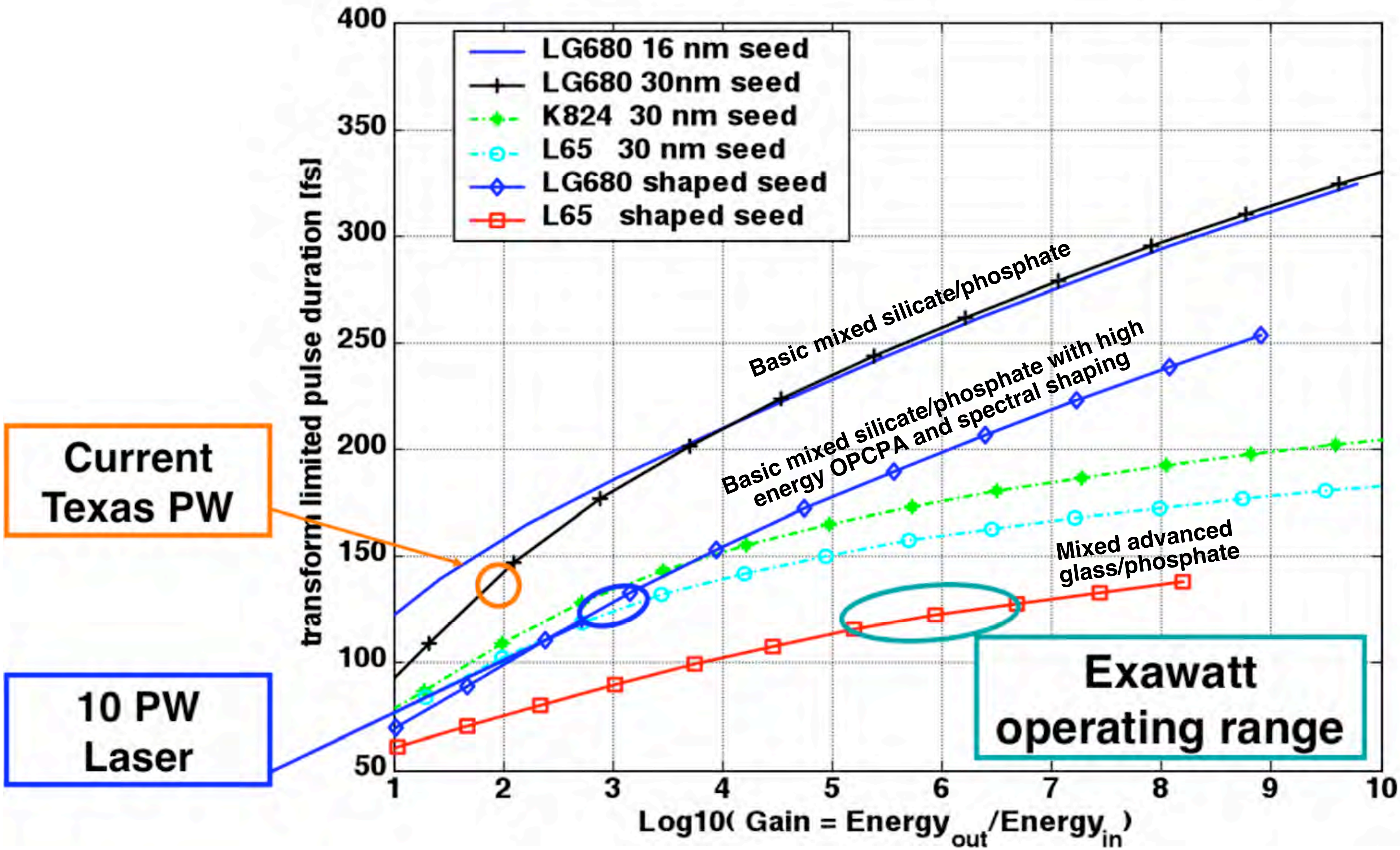


Novel glass bandwidth FWHM: 38 nm (x2 that of Phosphate)

Realistic amplified bandwidth: >20 nm
Corresponding best compressed pulse: 80 fs

New glass performance could make rep-rated glass-based systems operating at 80 fs

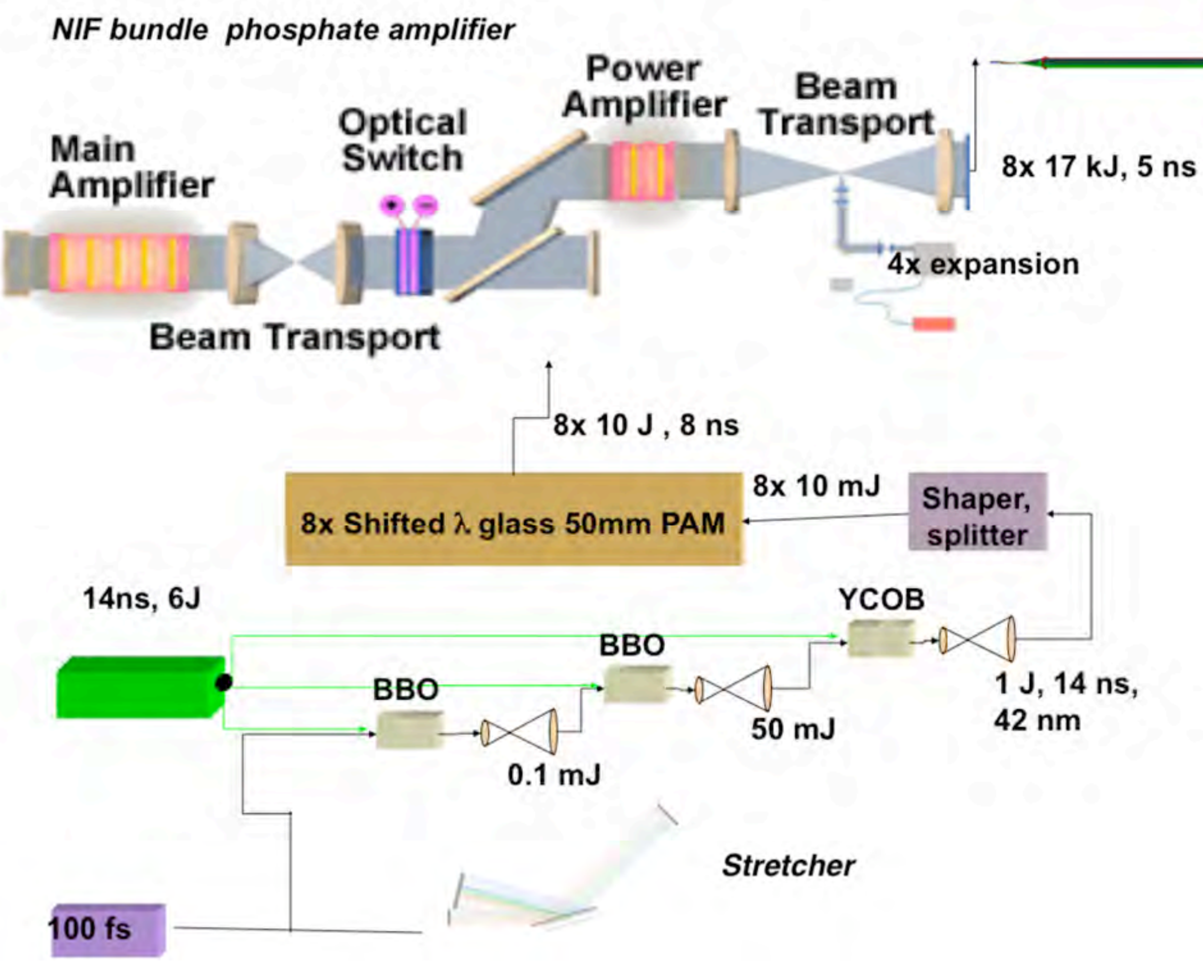
Using these new glasses, a 120 fs, 120 kJ exawatt laser should be possible with existing technology

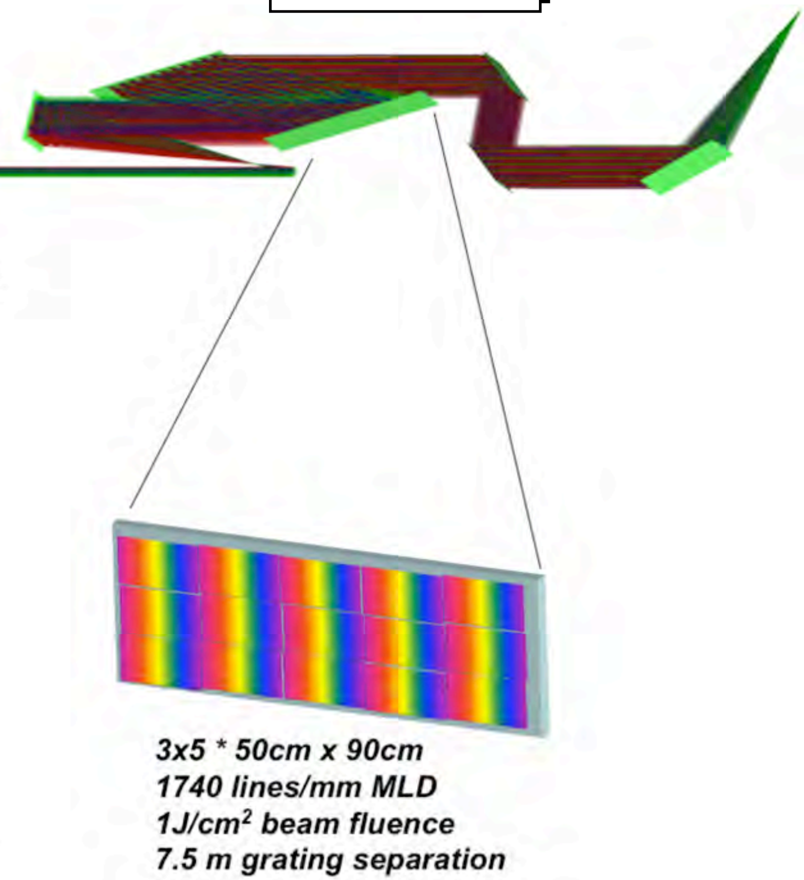


The architecture of a mixed glass exawatt laser would be straightforward

8x 15 kJ = 120 kJ in 120 fs

Final gain would be in 8 NIF-style beamlines





A key element would be in the successful tiling of 15 MLD gratings for each compressor

A hybrid approach to an Exawatt laser has many advantages to other approaches

	Glass	Hybrid	TiSa	OPCPA
Pulse duration [fs]	1000	120	30	30
Pulse energy [kJ]	100	12	3	3
Compressor efficiency	MLD 90%	MLD 90%	Gold 65%	Gold 65%
Grating damage fluence, beam normal [J/cm^2]	3	1	.35	.35
Final stage extraction efficiency [%]	100	100	50	40 seed 40 idler
Energy out of final amplifier [kJ]	111	13.3	5.1	5.1
IR energy out of pump laser [kJ] [50% doubling eff.]	-	-	20.4	25.6
Min. beam size (normal to beam in compressor)	(3.33 m)^2	(1.16 m)^2	(1.21 m)^2	(1.21 m)^2

All compressors require tiled gratings as demonstrated by LLE, LIL,…

Thoughts on the future

- The science case for moving toward 10 PW needs to be ascertained
- New materials should be explored for potential push toward 1 EW
- More work needed on tiling large number (~9 or more) of gratings for large aperture compressors
- Phasing numerous CPA beams to increase on-target intensity
- Liquid cooling of glass slab amplifiers for development of ~ 1shot/min multi-PW to EW lasers

Question