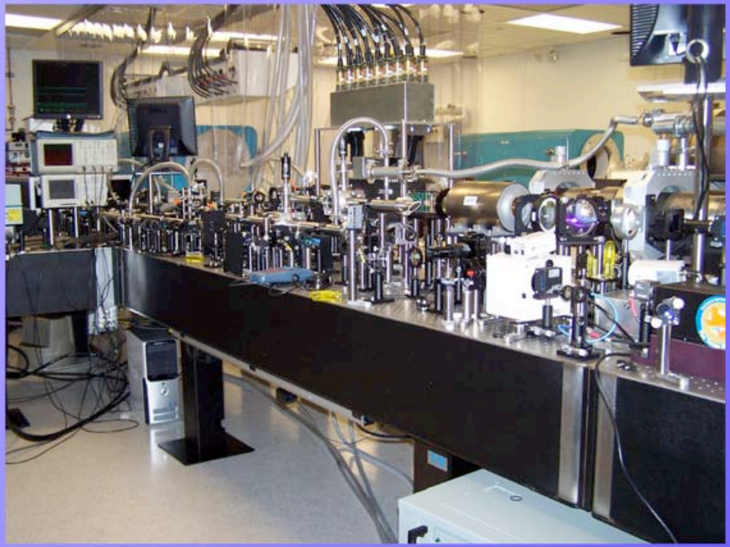
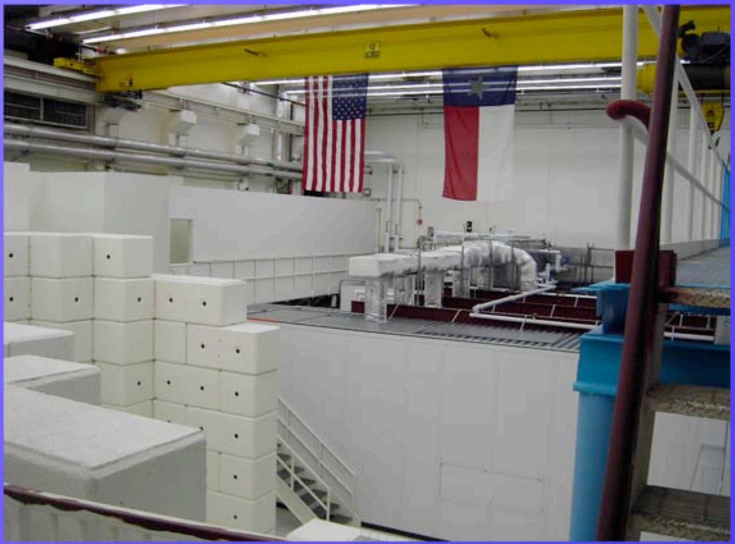
# Petawatt to Exawatt Lasers

## *The technology and applications of the most powerful lasers ever built*






Presented by:

***Todd Ditmire***

**Center for High Energy Density Science**
**Department of Physics**
**University of Texas at Austin**


***Or... Ultrafast, ultrapowerful lasers create ultraintense light to study the ultrahot***

# Most important: The people who do the work

***Center Faculty:***
*Roger Bengtson*
*Todd Ditmire*
*Mike Downer*
*John Keto*
*Michael Marder (CNLD)*
*Eric Taleff (Mech Eng)*

***Center Senior Scientists:***
*Aaron Bernstein*
*Erhard Gaul*
*Gilliss Dyer*
*Hernan Quevedo*
*Alan Wootton*

***Center Sabbatical Visitor:***
*Jack Glassman*

***Closely Collaborating Scientists:***
*Jens Osterholz (Dusseldorf)*
*Aaron Edens (Sandia)*
*Alex Arefiev (IFS)*
*Stephan Bless (IAT)*
*Boris Breizman (IFS)*
*Charles Chiu*
*Richard Fitzpatrick (IFS)*
*Wendell Horton (IFS)*
*Gennady Shvets (IFS)*

***Graduate students:***
*Woosuk Bang*
*Joel Blakeney*
*Sam Feldman*
*Ahmed Ehlal*
*Nirmala Kandadai*
*Intai Kim*
*Donghoon Kuk*
*Sean Lewis*
*Matt McCormick*
*Nathan Riley*
*Kristina Serratto*
*Nicholas Pedrazas*
*Craig Wagner*
*Matt Wisher*

***Post Docs:***
*Kay Hoffman*
*Rashida Jafer*
*Robert Morgan*
*Heiko Thomas*

***Undergraduates:***
*Wilson Bui*
*Jennifer Chae*
*Lindsay Fuller*
*Blake Griffith*
*Andrew Lafferty*
*Trevor Latson*
*Emily Leos*
*David Nicholson*
*James Pruet*
*Giovanni Rossi*

***U. Texas Petawatt and Exawatt Team***
*Franki Aymond*
*Woosuk Bang*
*Aaron Bernstein*
*Joel Blakeney*
*Ted Borger*
*Mike Donovan*
*Gilliss Dyer*
*Ramiro Escamilla*
*Erhard Gaul*
*Jack Glassman*
*Doug Hammond*
*Donghoon Kuk*
*Srdjan Marijanovic*
*Mikael Martinez*
*Marty Ringuette*
*Craig Wagner*
*Dave Nicholson*
*Lindsay Fuller*
*David Bui*
*Giovani Rossi*
*Andrew Lafferty*
*Blake Griffith*

***LLNL***
*Rick Cross*
*Chris Ebbers*
*Al Erlandson*
*John Caird*
*Brent Stuart*
*Bill Molander*
*Tim Weiland*
*Ralph Page*
*Jerry Britten*

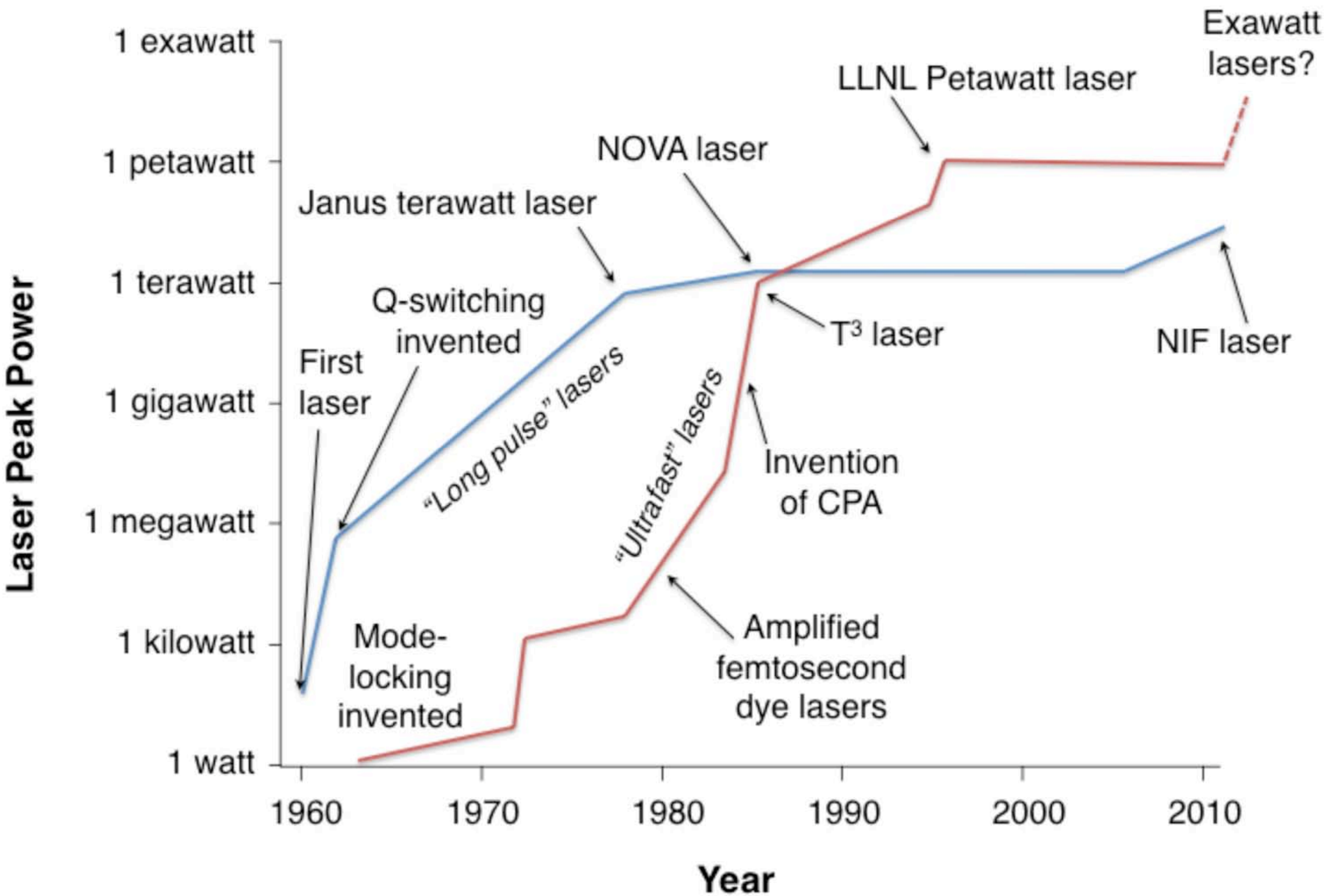
***Schott Glass N. America***
*Matt Roth*
*Eric Urruti*
*Nathan Carlie*

***Logos Technologies***
*Mike Campbell*
*Jason Zweiback*
*Dave Eimerl (Eimex)*
*Bill Krupke*

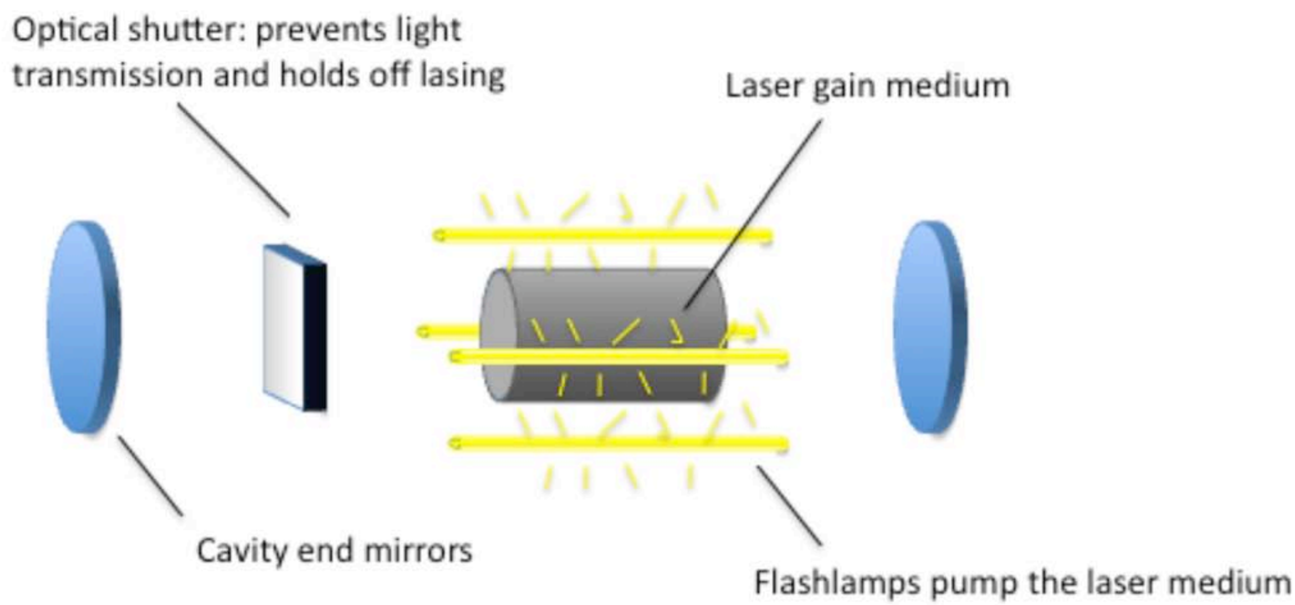
***Continuum Lasers***
*Curt Frederickson*
*Larry Cramer*

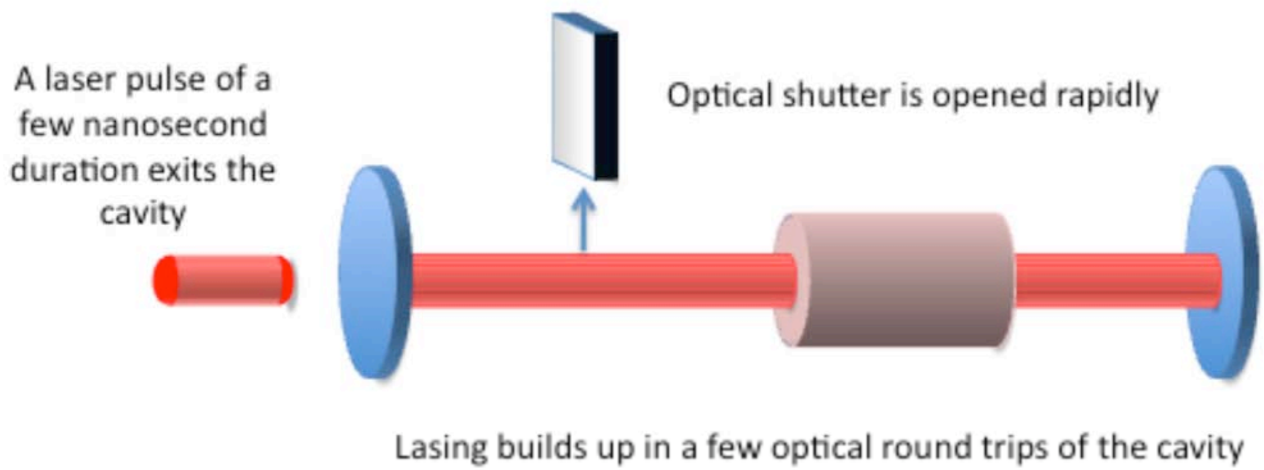
***LLE Rochester***
*Jon Zuegel*

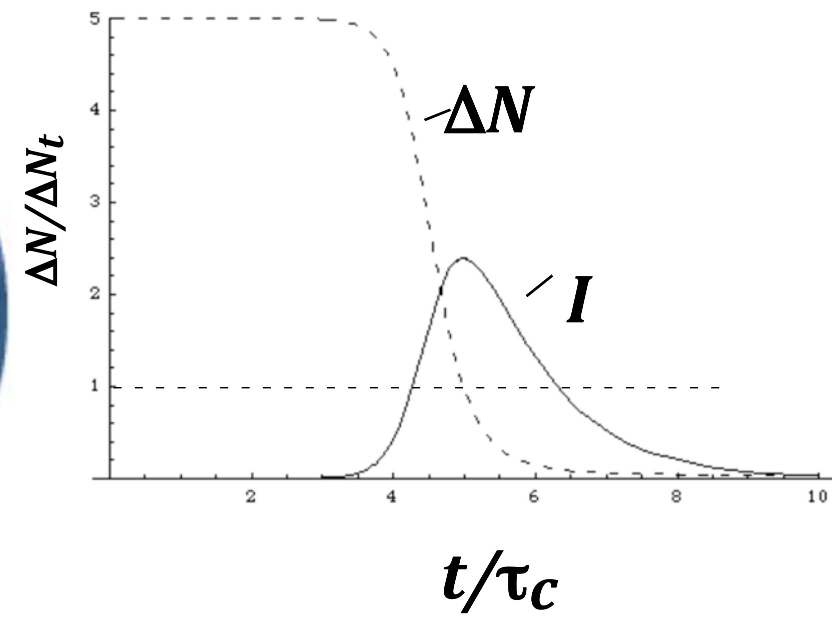
# Leaps in laser power have been made over the past 40 years because of technical break-throughs



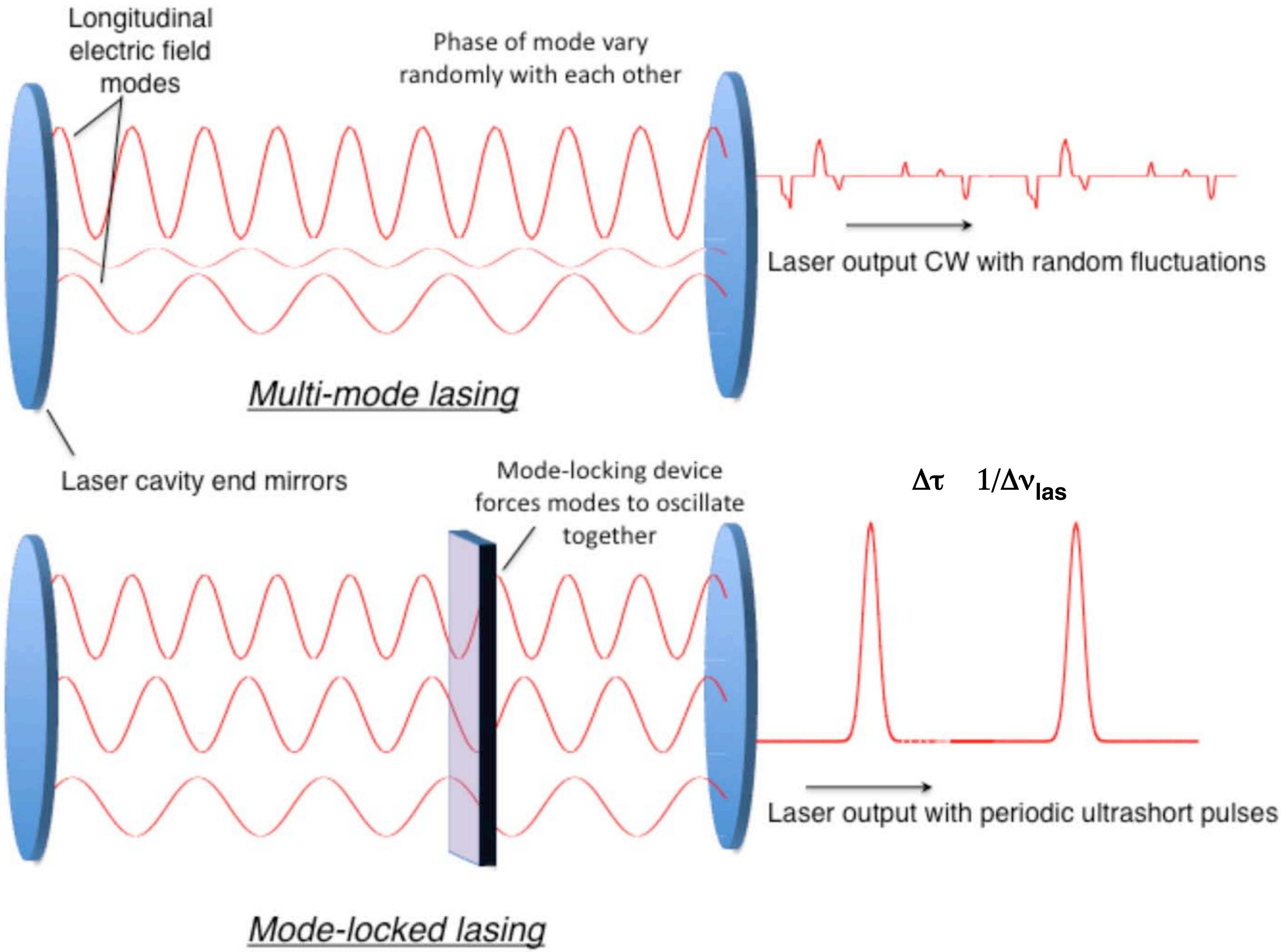
# In 1961 Q-switching was demonstrated enabling production of MW peak power, ns pulses



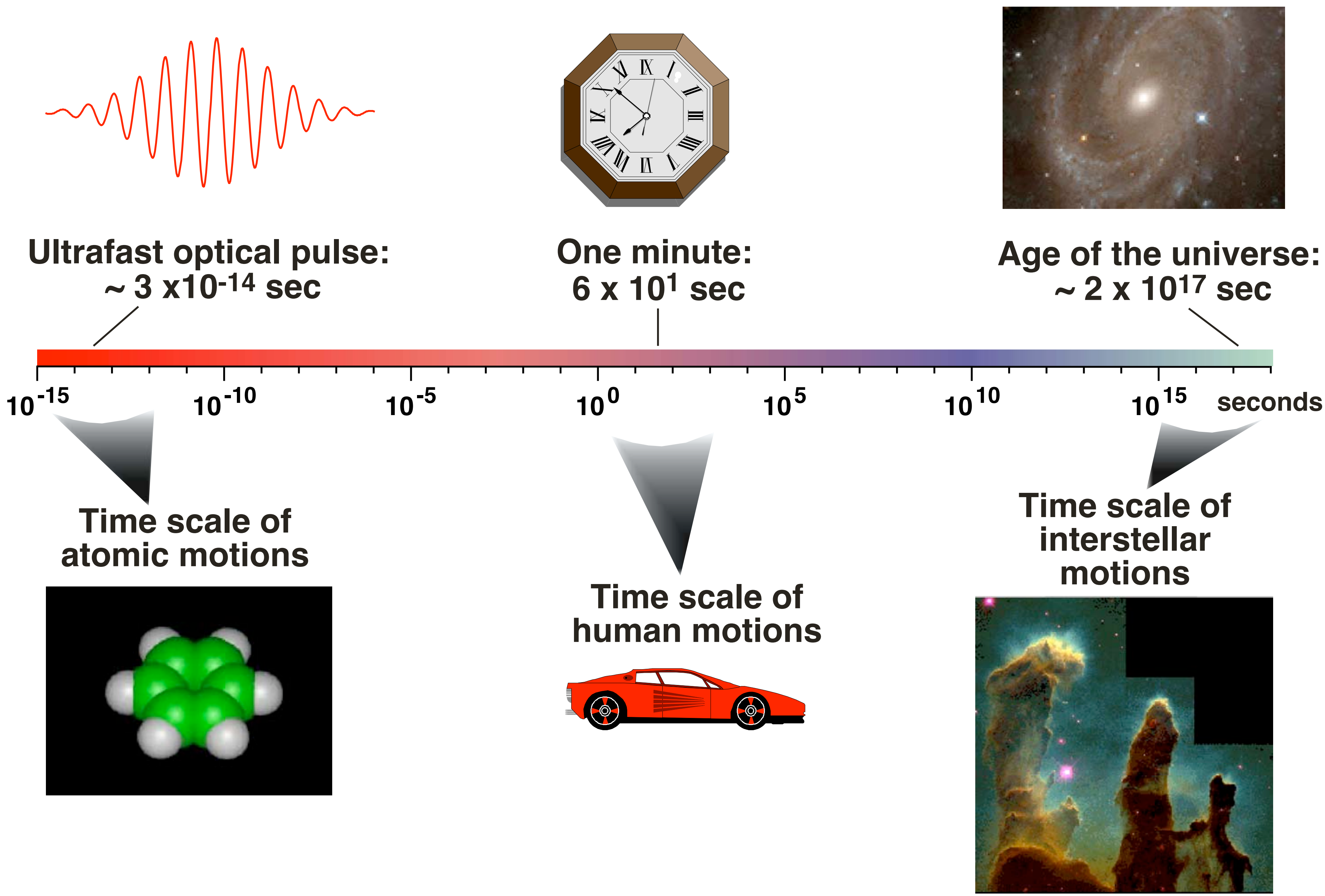



# In 1964 mode locking was demonstrated, enabling ultrafast pulse production

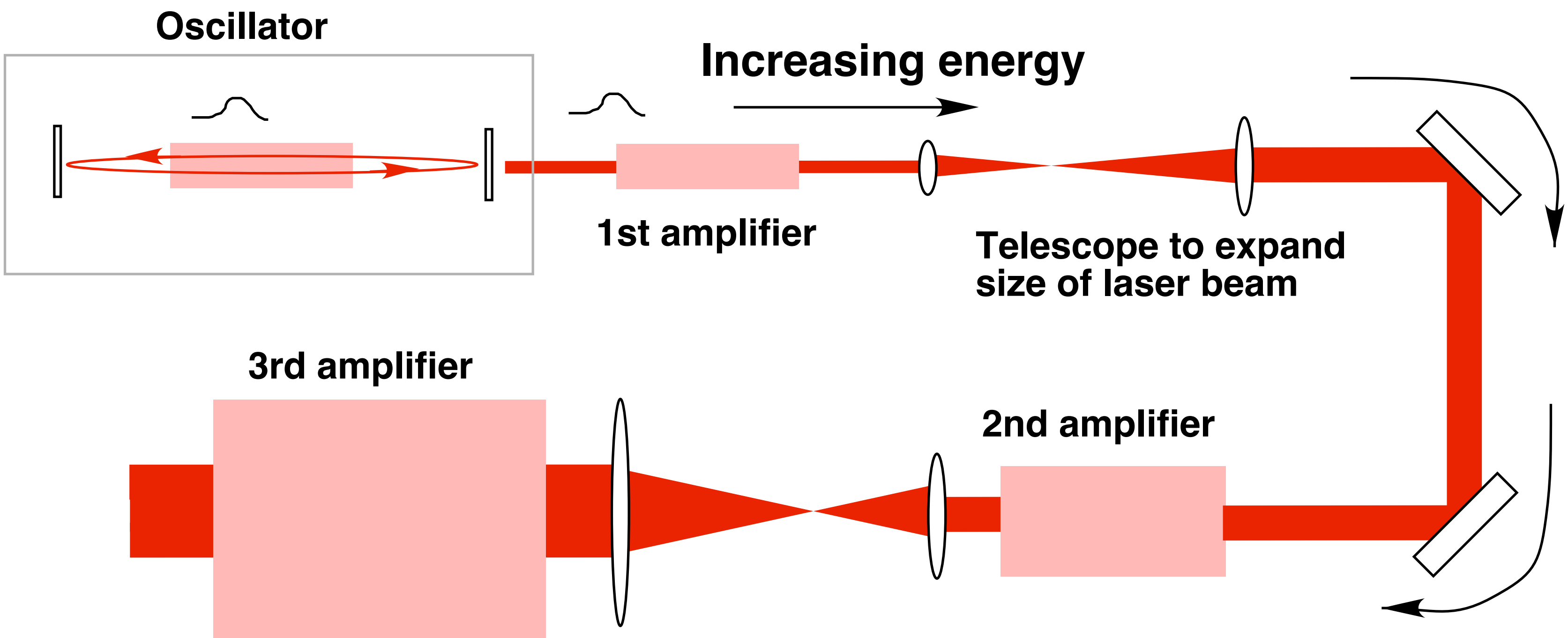


# A 30 femtosecond laser pulse is the same fraction of one minute that one minute is of the age of the universe



# Modern high power lasers are based on the "master oscillator, power amplifier" architecture

## *MOPA laser chain*

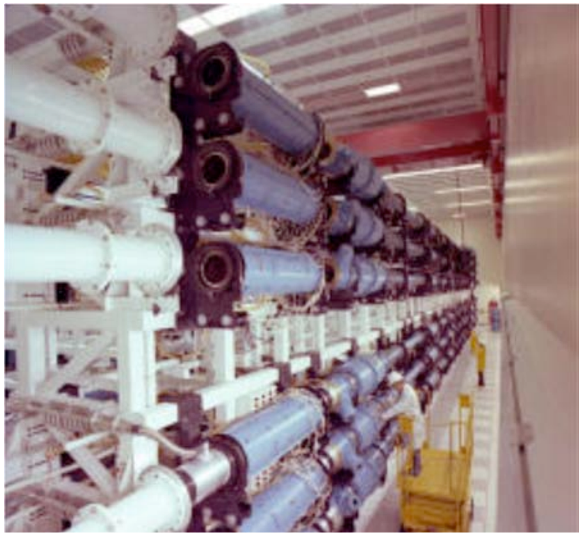


# Livermore has pushed MOPA architecture through a number of generations to higher and higher energy

**Cyclops laser (1974)**
**1 beam**
**100 J**

**Argus laser (1976)**
**2 beams**
**1000 Joules of energy**

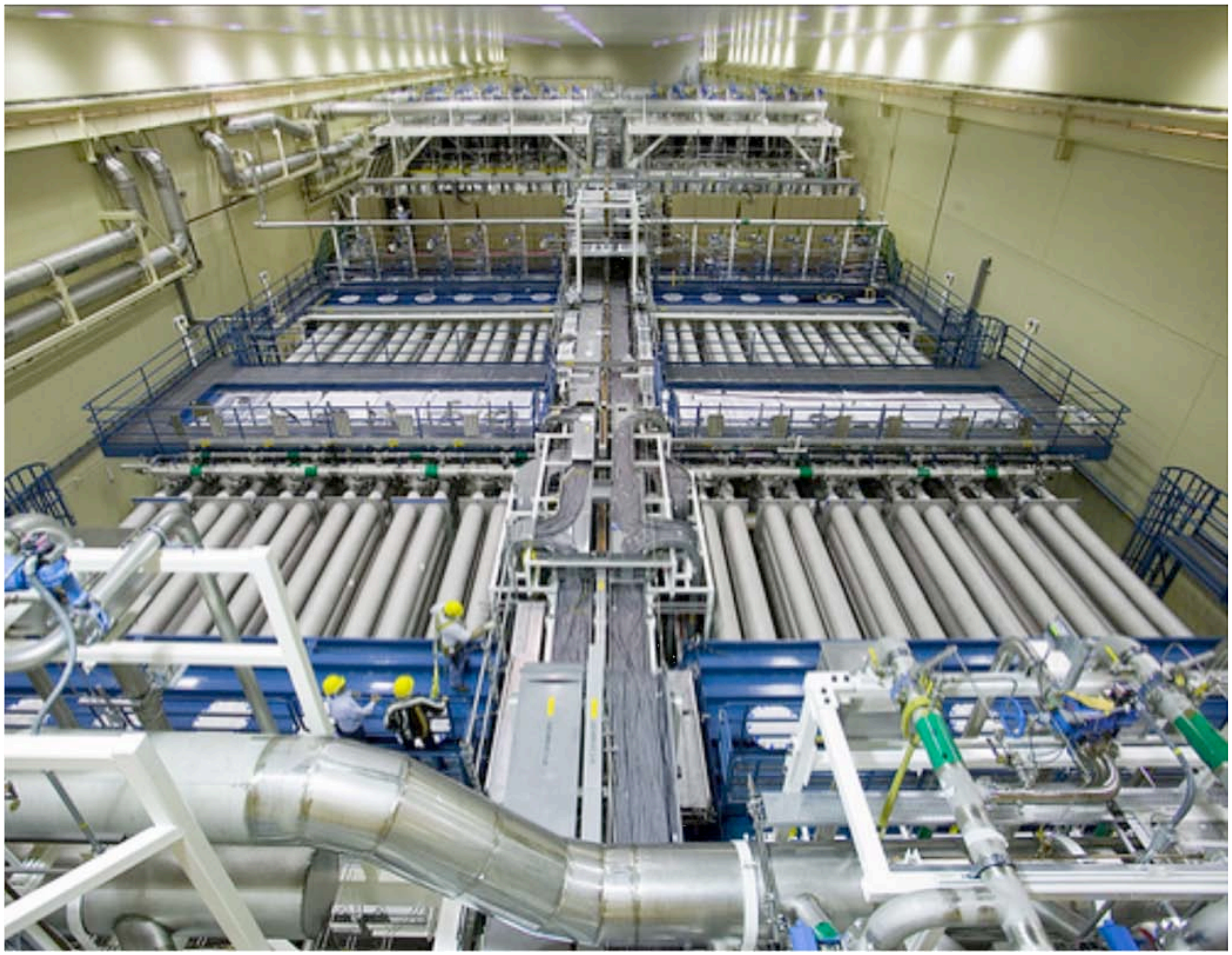
**Shiva laser (1978)**
**20 beams**
**10,000 Joules**



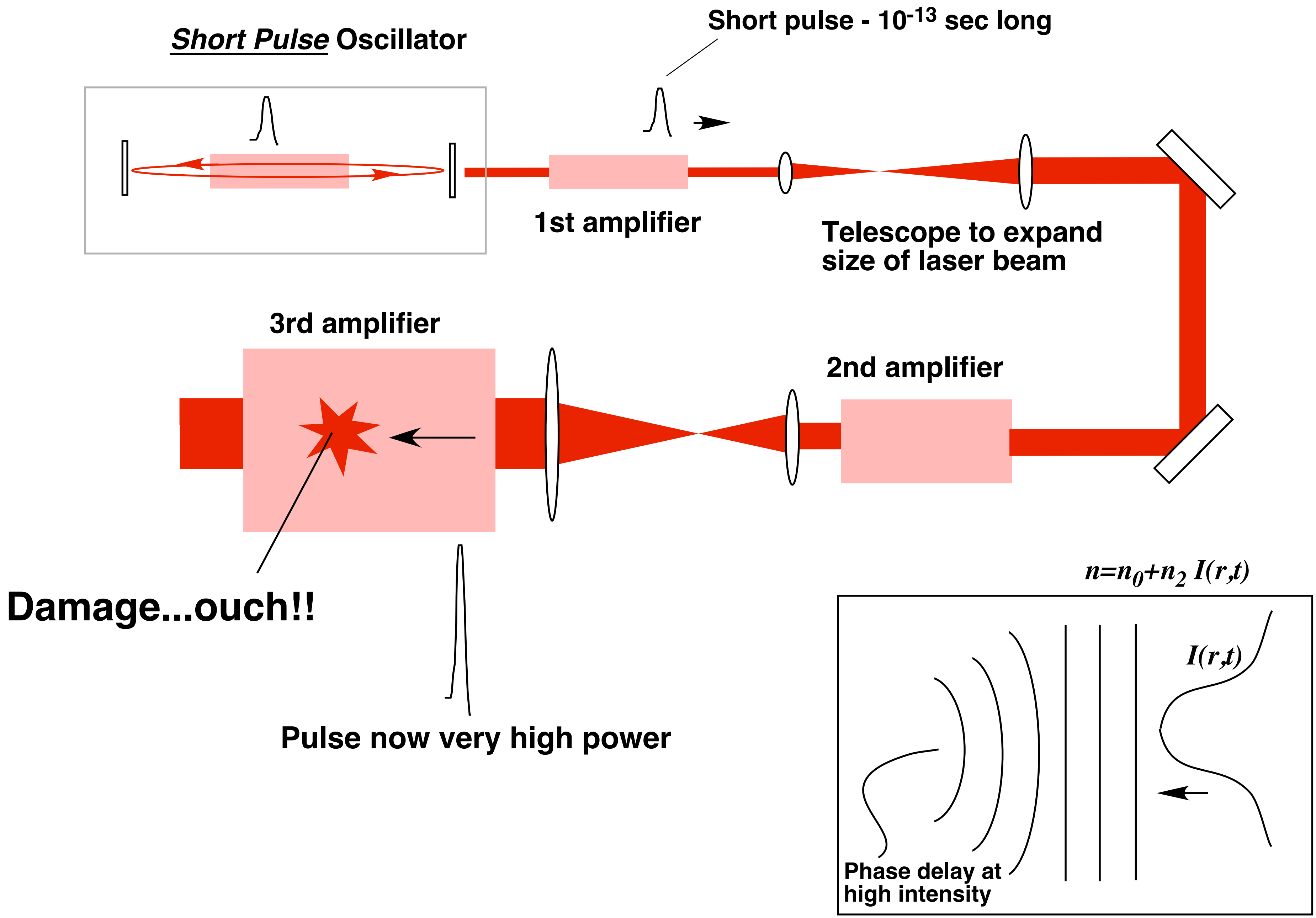
**Nova laser (1985)**
**10 beams**
**100,000 Joules**

# The National Ignition Facility, recently completed at LLNL is the highest energy laser in the world

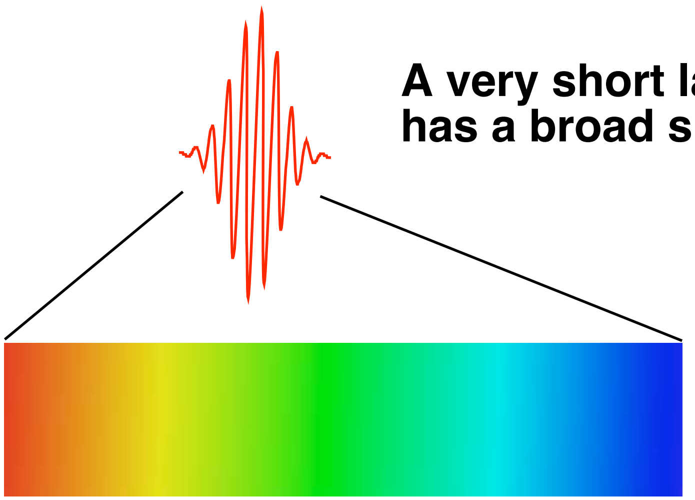
**National Ignition Facility - NIF (2009)**
**192 beams**
**1,800,000 Joules @ 351 nm**



# In the mid 1980's, the question of whether a short laser pulse could be amplified in a MOPA chain was broached



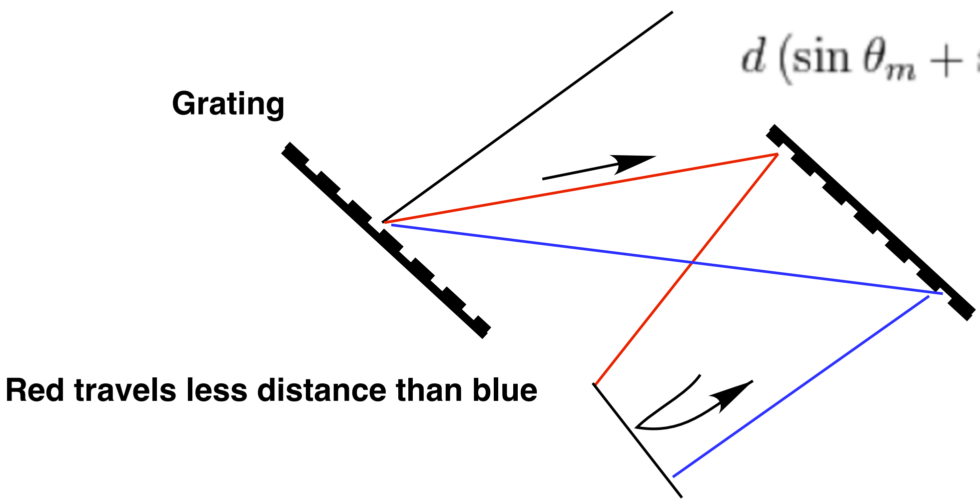
# The trick to amplify such short pulses is to stretch them out in time temporarily



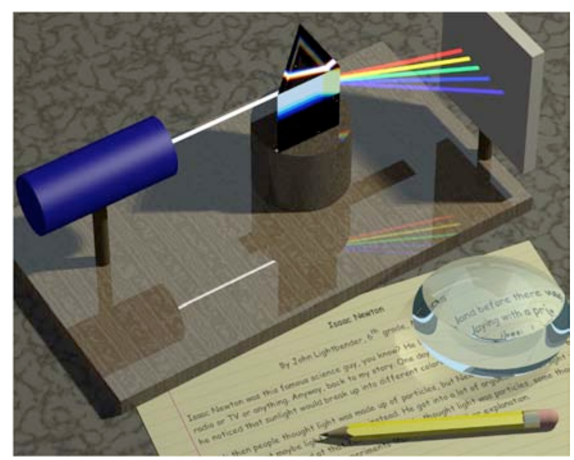
**A very short laser pulse actually has a broad spectral bandwidth**

*To disperse colors out in time, we spread them out in space*

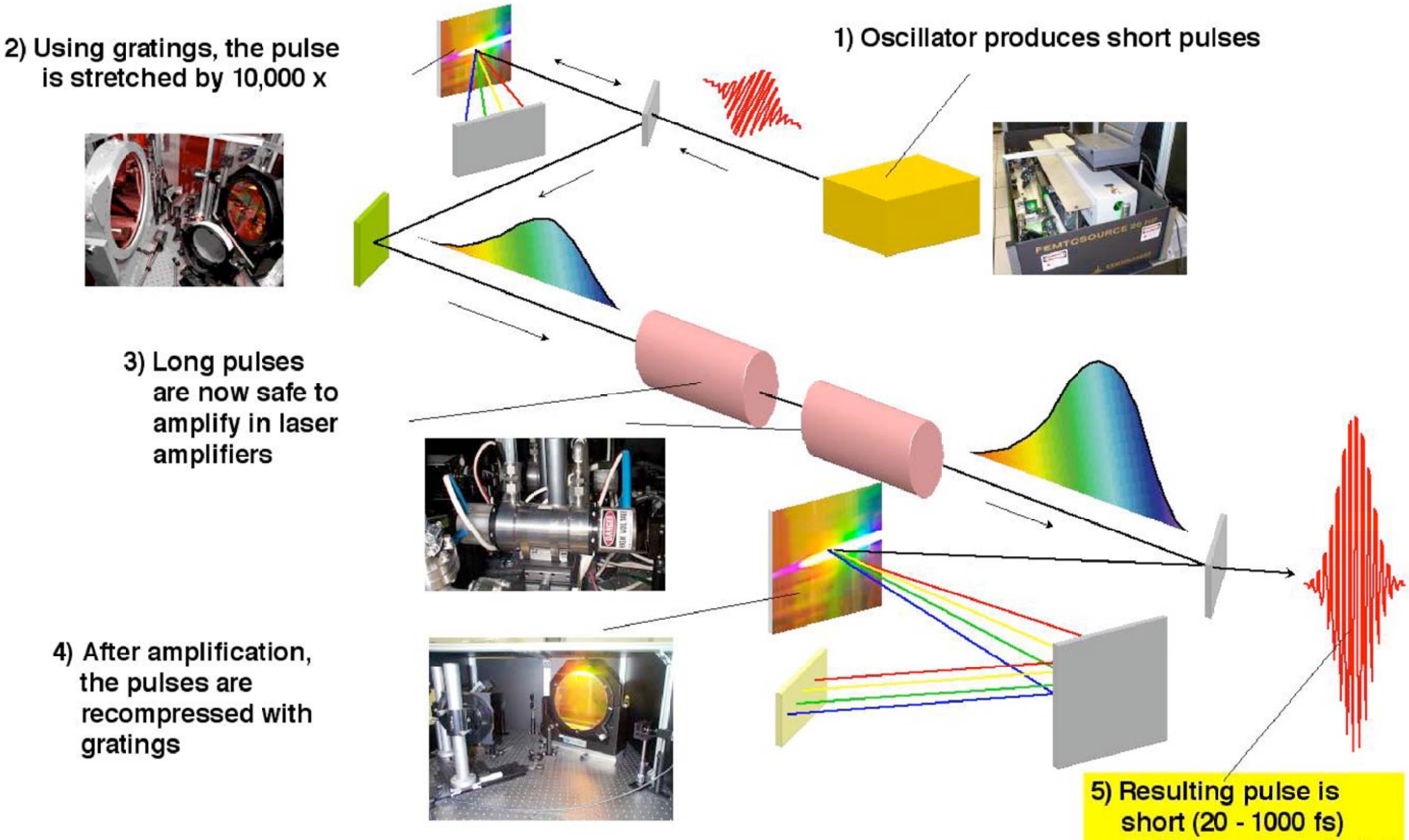
**So...stretch out the spectrum**




$$d\,(\sin\theta_m + \sin\theta_i) = m\lambda$$



# Using this stretching trick, we can amplify very short pulses...and then recompress them *after* amplification




• Strickland and Mourou *Opt. Comm.* 56, 219 (1985)

**This technique has come to be called "Chirped Pulse Amplification" (CPA)**

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

***Ti:sapphire based CPA lasers:***

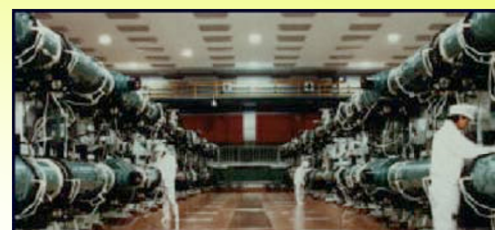
**Pulse energy ~ .001 - 30 J,**
**Pulse duration <30 - 100 fs,**
**Peak Power < 100 TW; 1 PW**
**Repetition Rate ~ 1 kHz - 1 Hz**

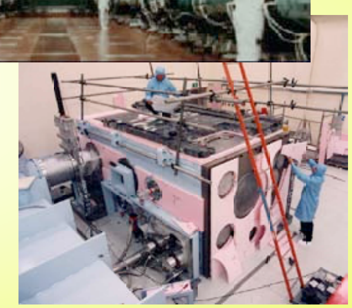
**Shortest pulse systems and most "table-top" CPA lasers**

***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**

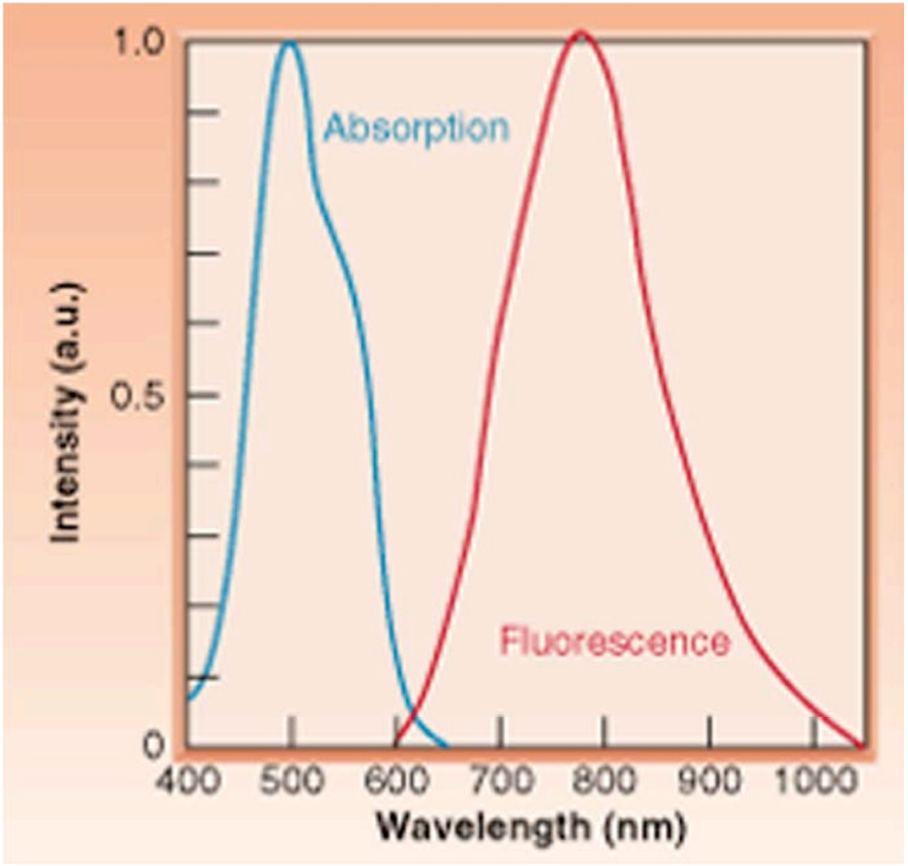
**Highest energy systems, many of "facility" scale**





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

**Absorption and emission spectrum of Ti:sapphire**




**Large scale Ti:sapphire crystals**

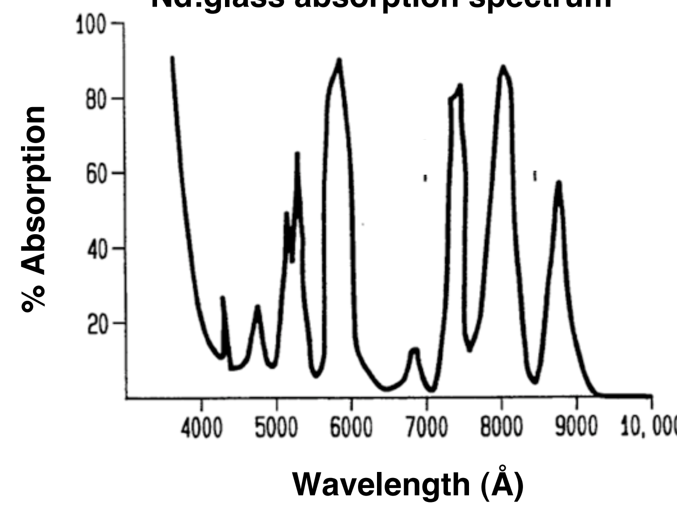
**Gain bandwidth in Ti:sapphire is very large → amplification of pulses as short as 20 fs**

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

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

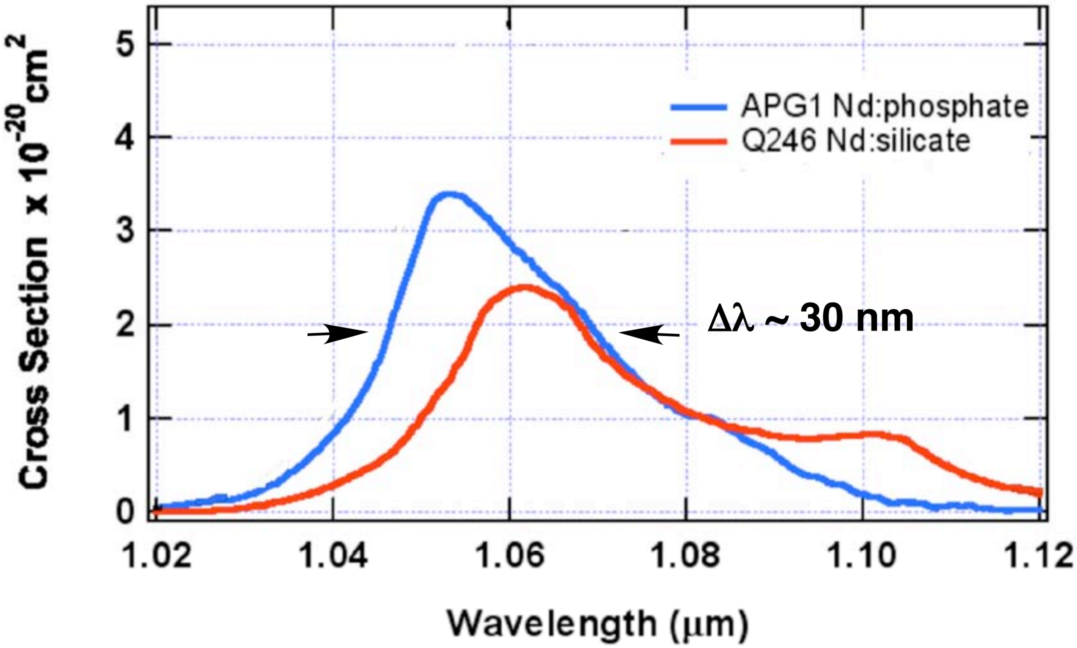
*Large aperture amplifiers can be fabricated*

*Nd:glass can be efficiently pumped by flashlamps*

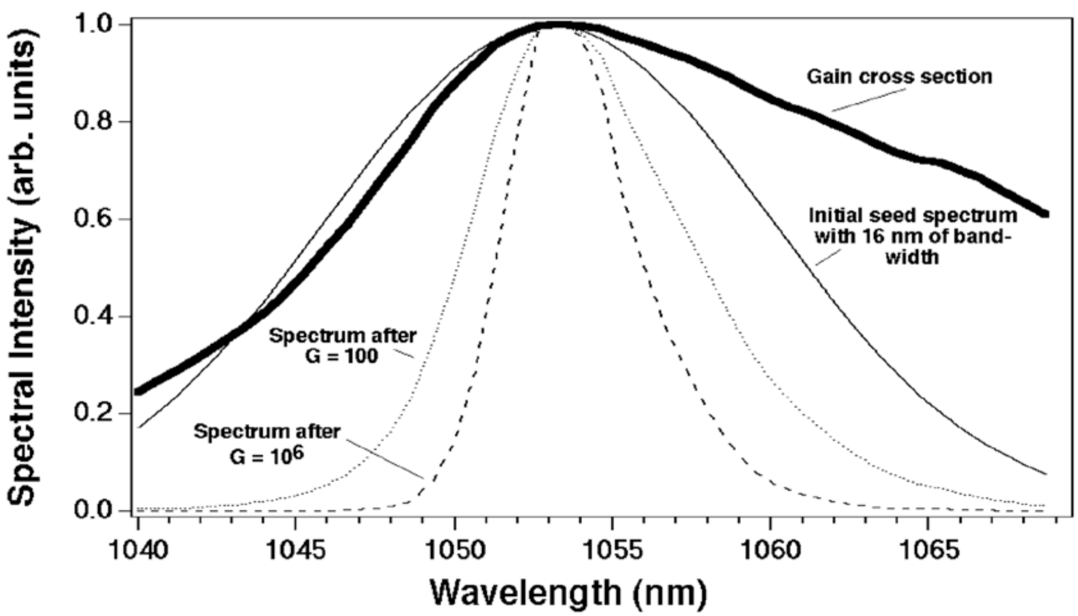


# The principal limitation to the use of Nd:glass in CPA lasers is that it exhibits limited gain bandwidth

*Gain spectrum of two kinds of laser glass*




*Calculation of the effects of gain narrowing in Nd:glass*

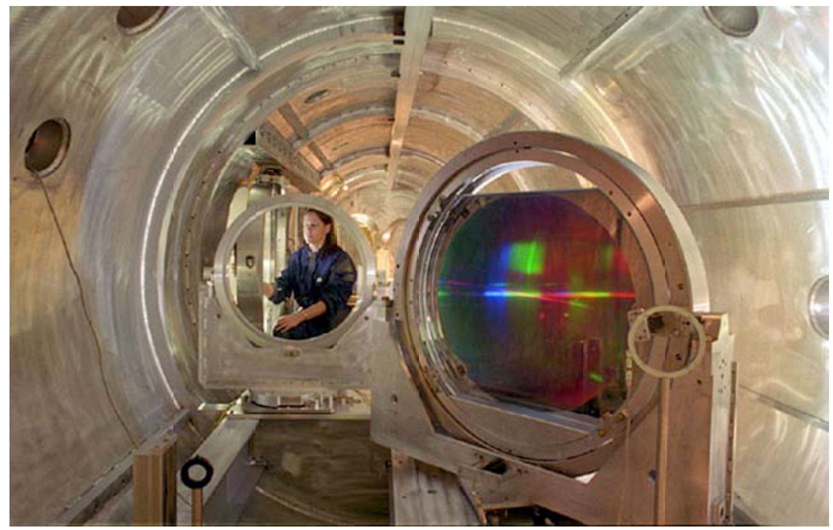



**Gain narrowing of the ultrafast pulse spectrum tends to limit Nd:glass CPA lasers to pulse duration of 500 fs**

# The first Petawatt laser was demonstrated at Lawrence Livermore by implementing CPA on the NOVA laser

## The Petawatt at LLNL

**Nova laser**



**90 cm gratings to compress Nova pulses**

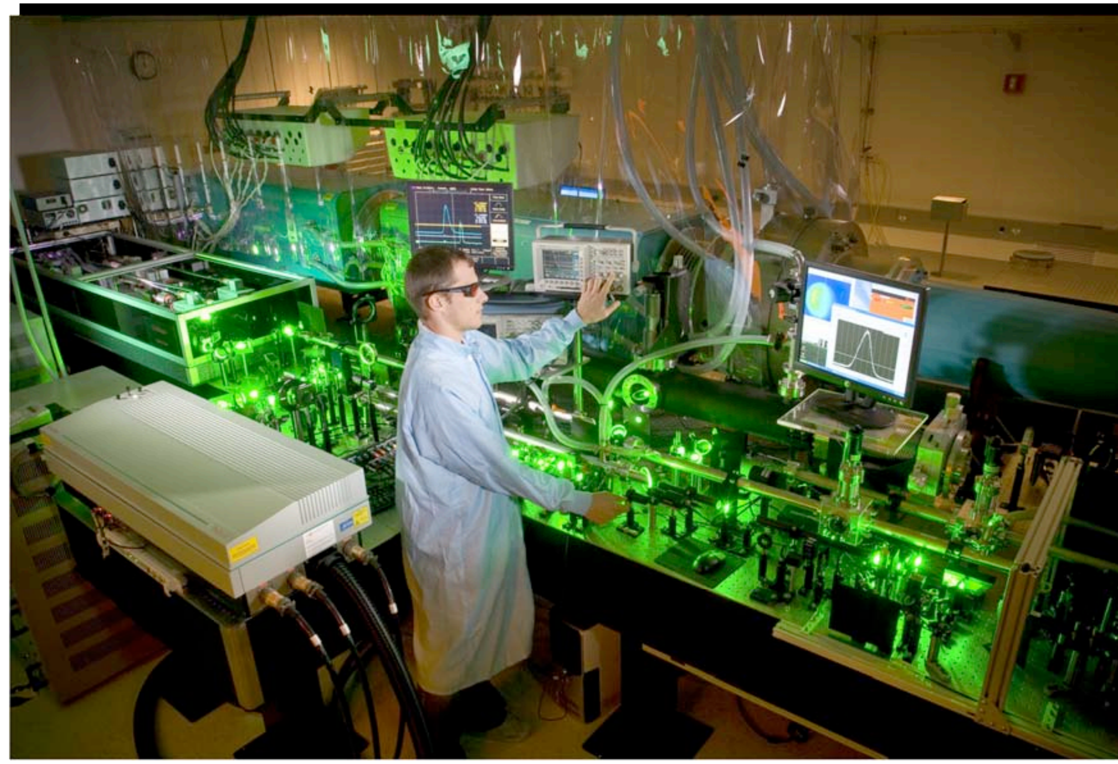
Petawatt specs:
500 J energy
500 fs pulse duration
Peak intensity > $10^{20}$ W/cm$^2$

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

# A “Petawatt” is many times more power than all the power delivered by all the power plants in the US

**Power output of U.S. electrical grid:**
**~ 80,000 GWh/week = 0.5 TW**

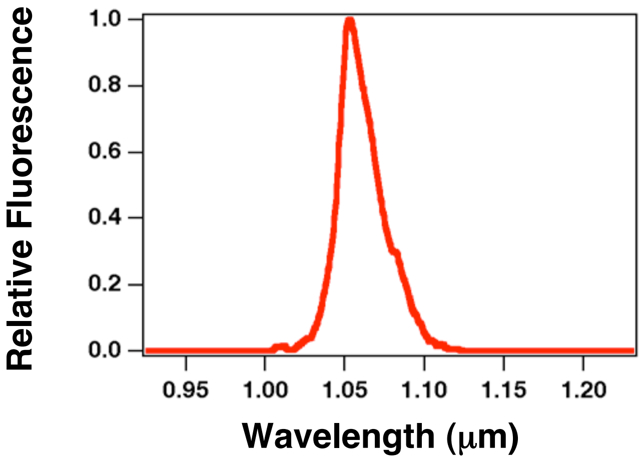
**Petawatt laser**



*A state-of-the-art petawatt laser has 2000 times the power output of all power plants in the US*

# There are different kinds of laser glass which each have slightly different center wavelengths

## Q-98 Phosphate glass



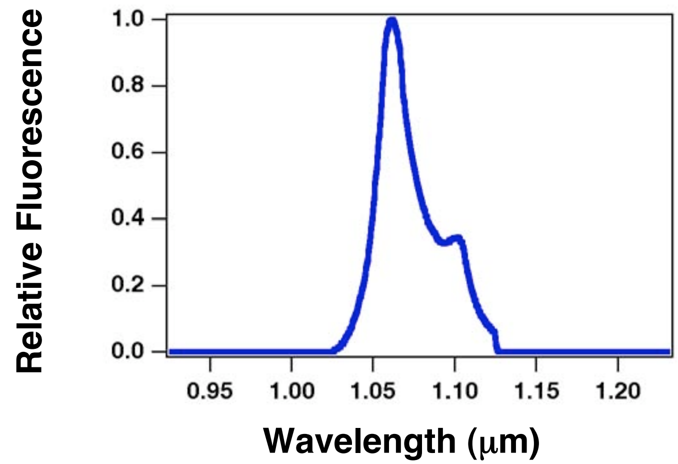

**Peak Wavelength: 1054 nm**

**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



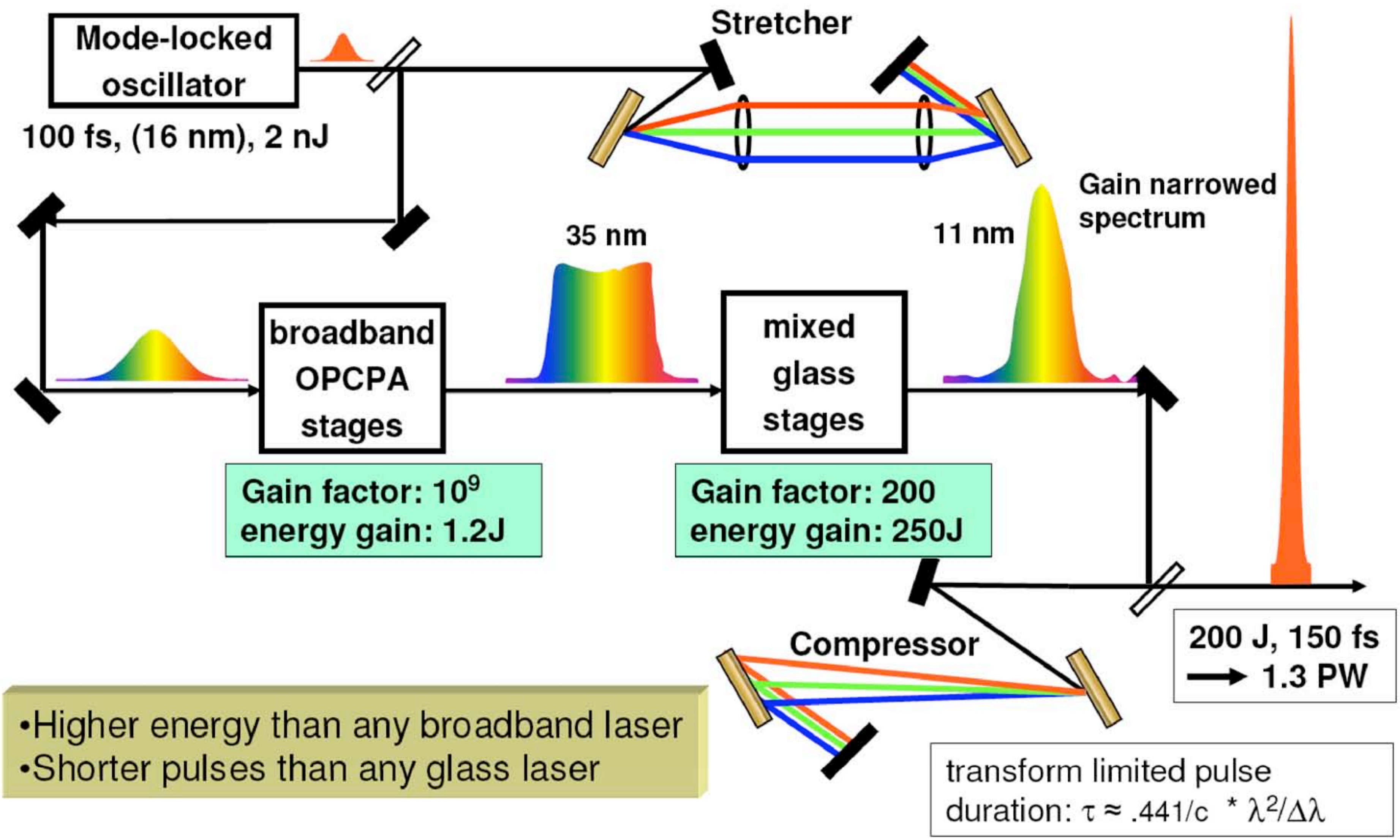

**Peak Wavelength: 1061 nm**

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

**Linewidth (FWHM): 28.2 nm**

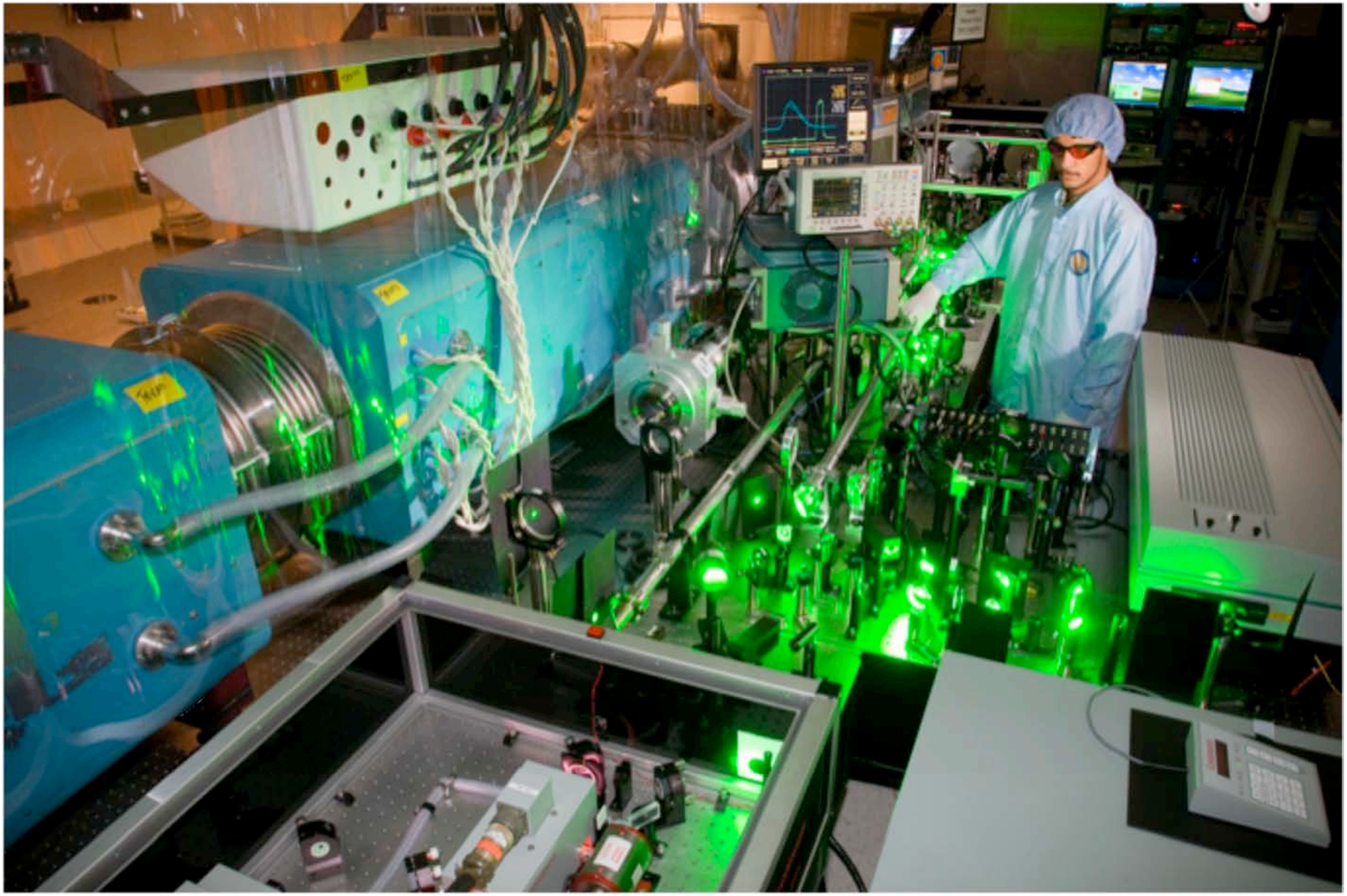
**$Nd_2O_3$ ~3%**
**$SiO_2$ ~ 97%**

# The Texas Petawatt is designed to maintain broad bandwidth through the entire chain



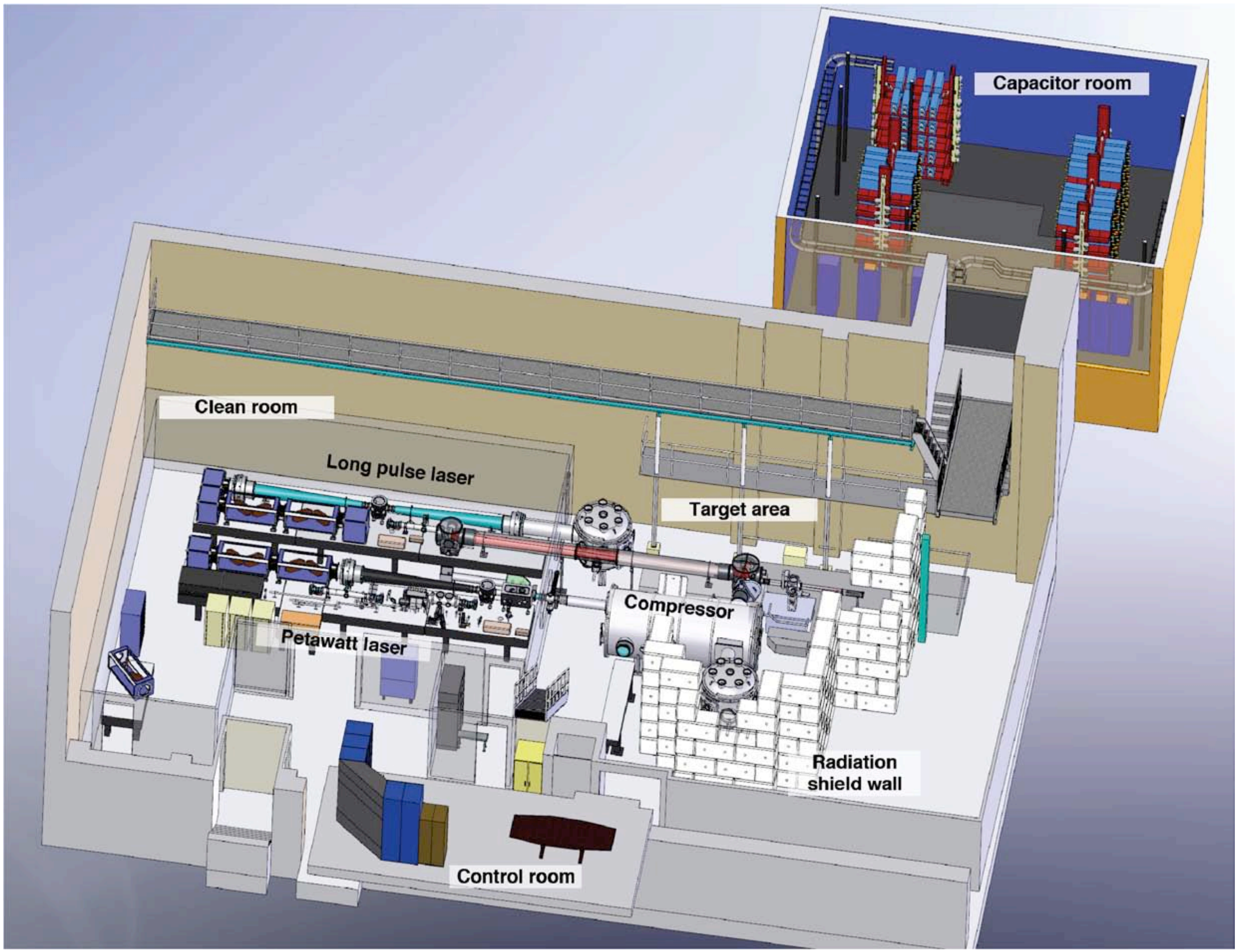

- Higher energy than any broadband laser
- Shorter pulses than any glass laser

# The Texas Petawatt uses four-passes in NOVA 31 cm disk amplifiers

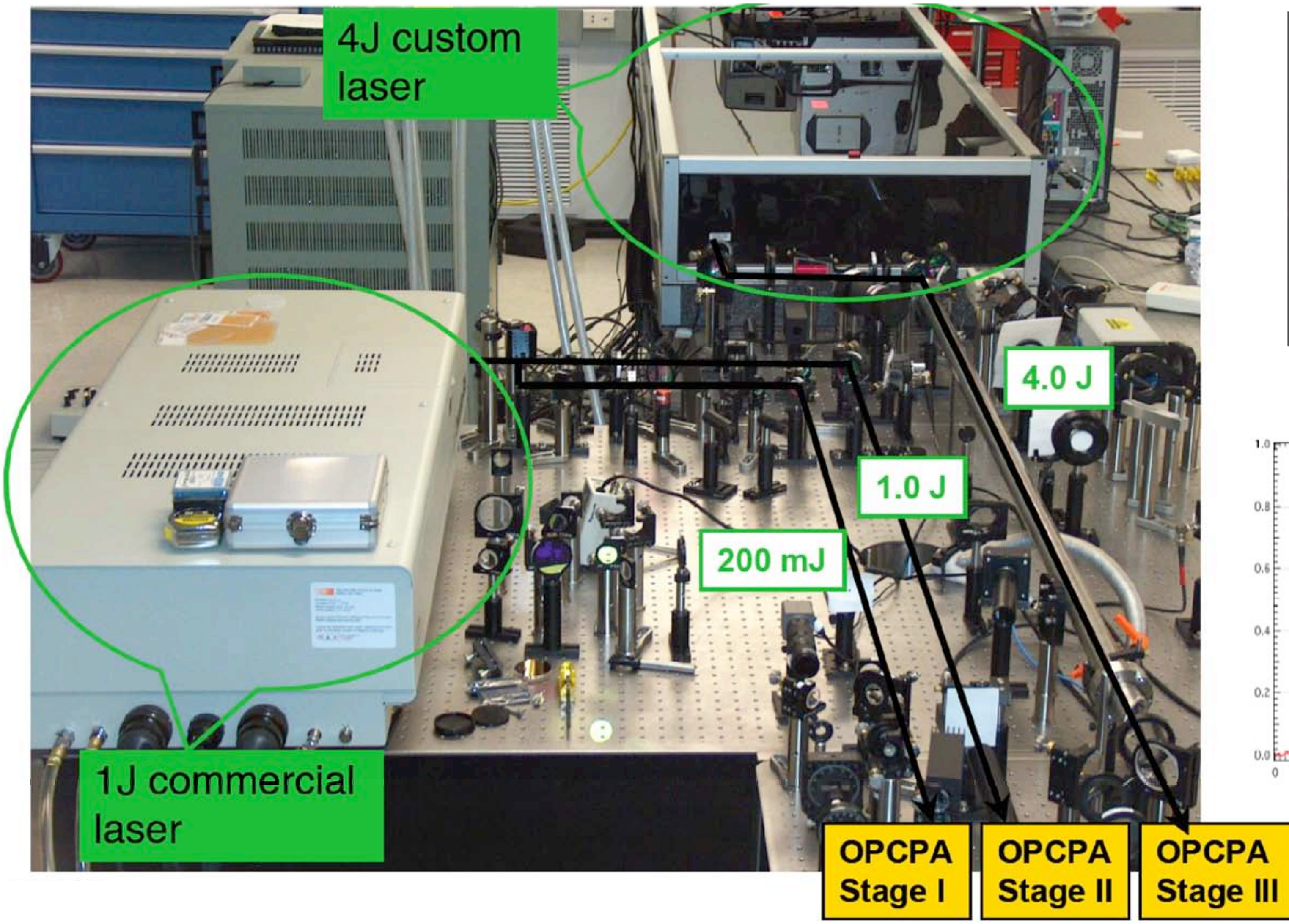


# The Texas Petawatt Laser is housed in the RLM High Bay

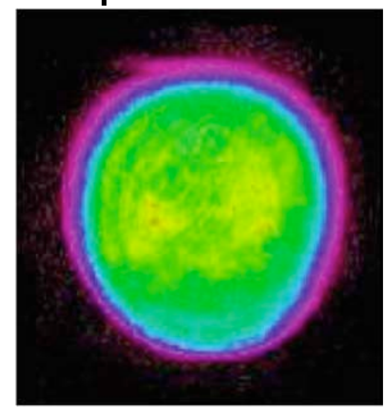
## *Layout of the Texas Petawatt Facility in the Robert Lee Moore Basement*



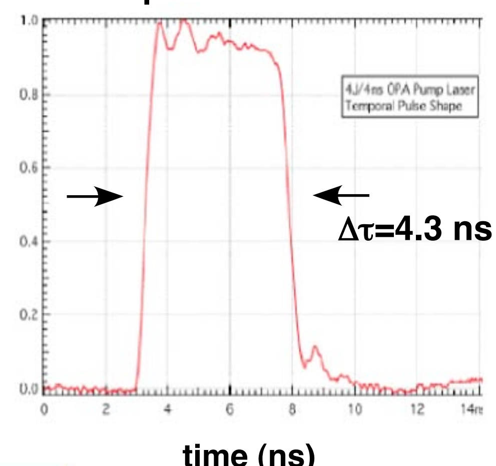
# We are operating an OPCPA front end whose principal component is a custom 4J pump laser




**Pump beam spatial profile @ 4J**



**Pump beam temporal profile @ 4J**



# The Nd:silicate rod amplifier has been installed and tested

The capacitor bank is above the cleanroom

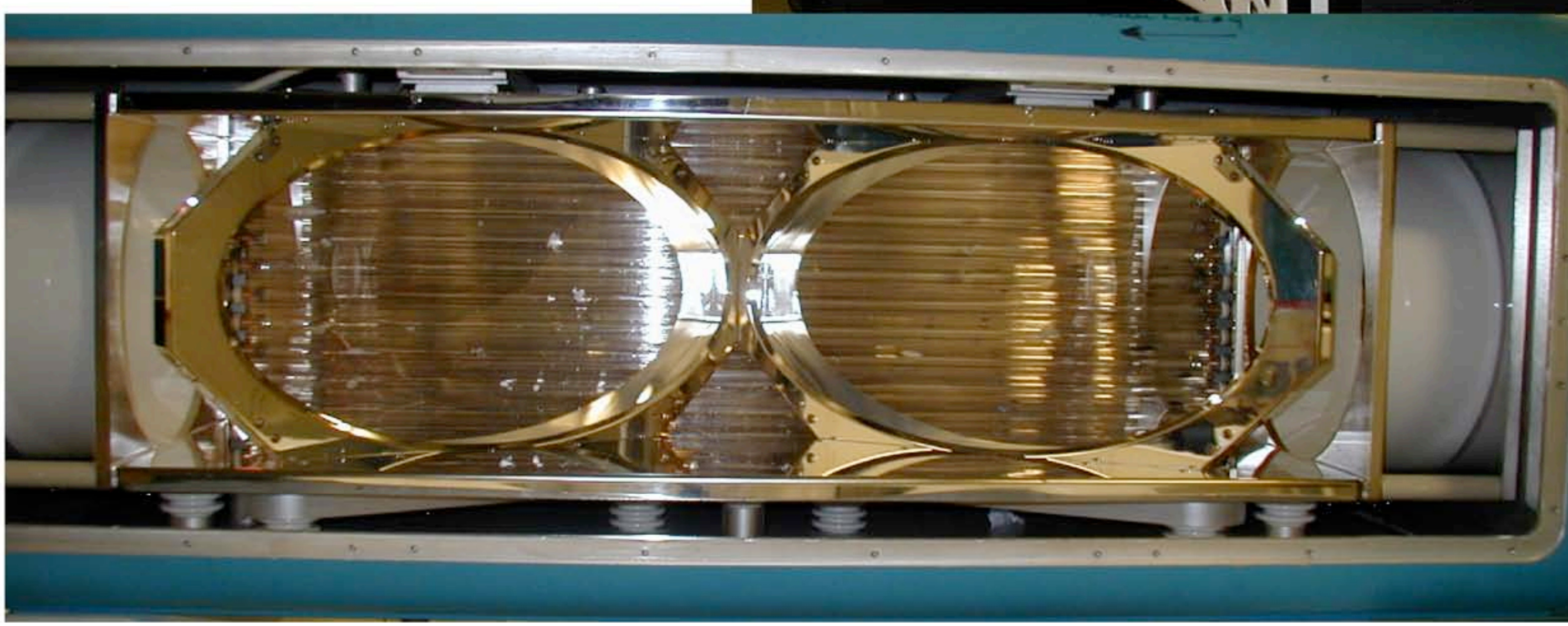
64 mm rod amplifier with N0306 silicate glass

70 mm static Faraday rotator

# Two 315 mm disk amplifiers from NOVA are used in each beamline as the final laser amplifiers

**The NOVA Laser at LLNL**

**31 cm Disk amps from NOVA**

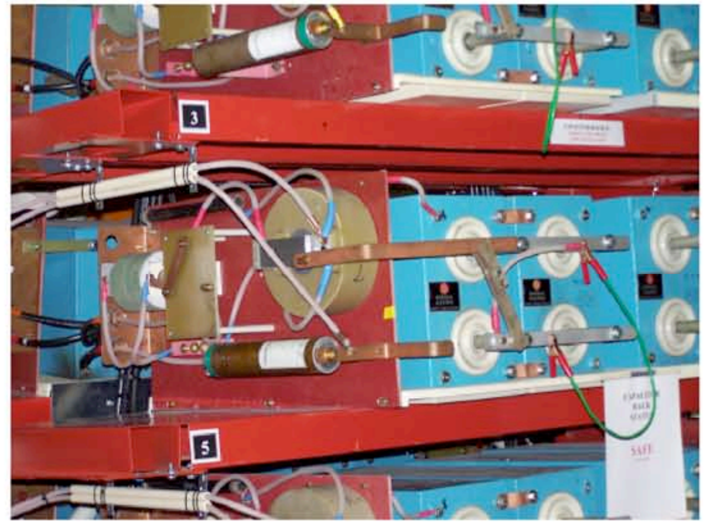


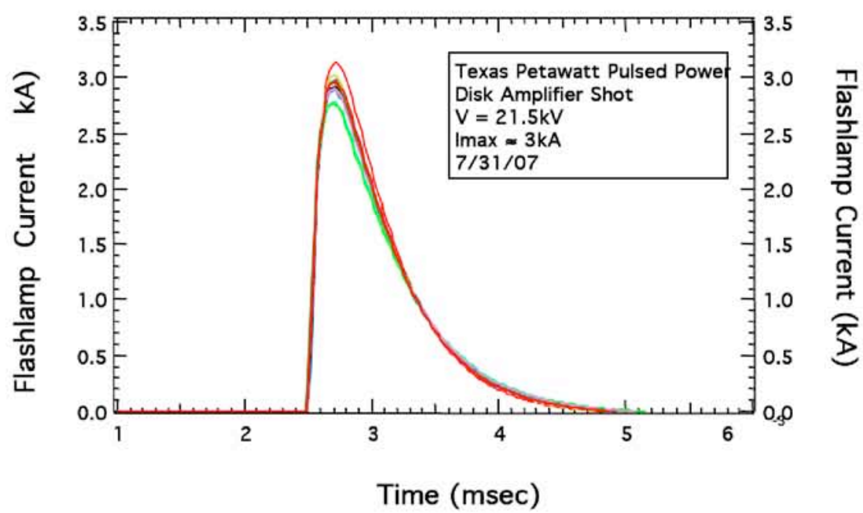
# The pulsed power for the 31 cm disk amplifiers is assembled and delivers 500 kJ of electrical energy

One side of bank drives
One of two 31 cm  amps

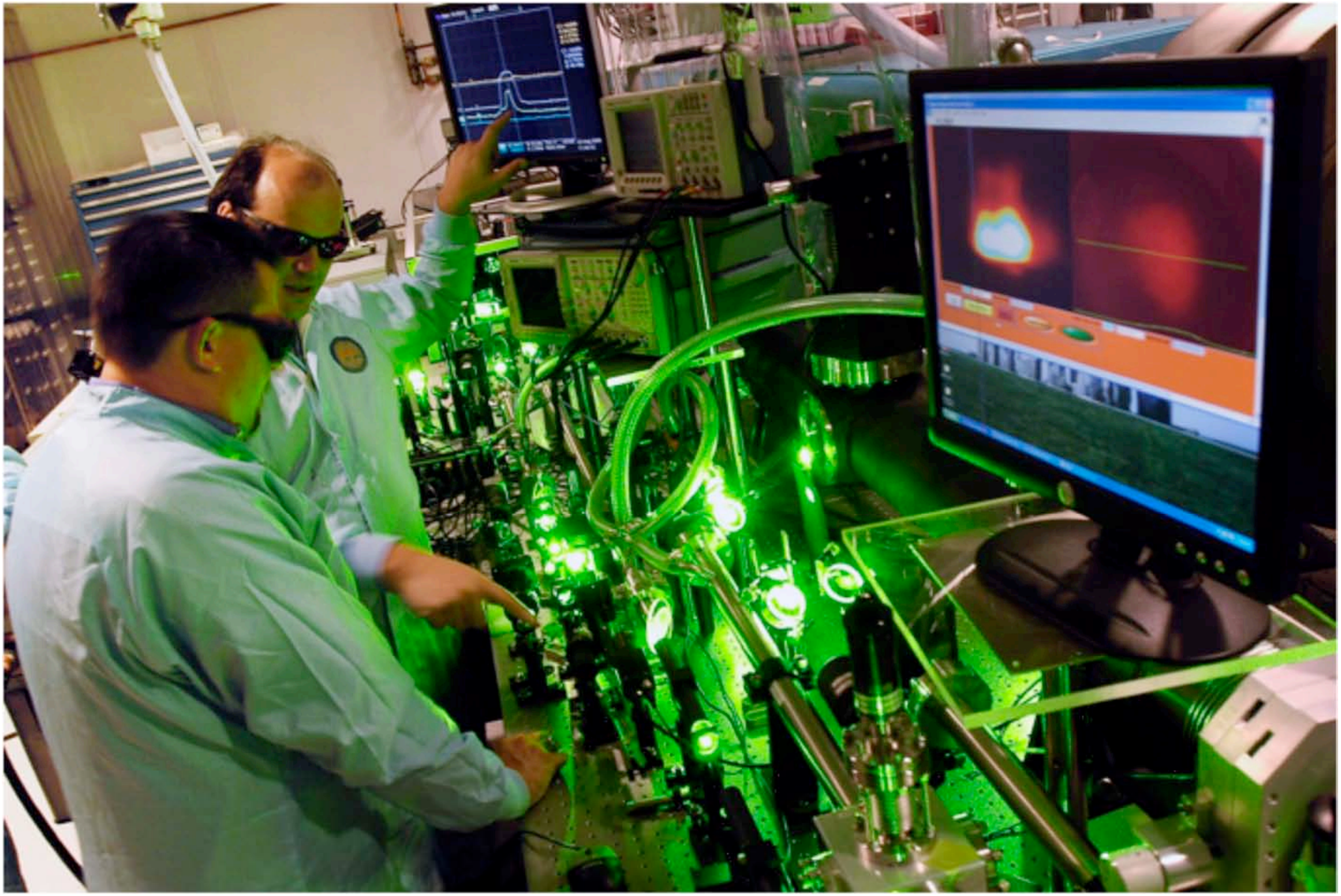
Two series ignitrons switches

Pulse forming networks:
2 52uF Capacitors
1 450uH Inductor
Critically Damped @ 400mS

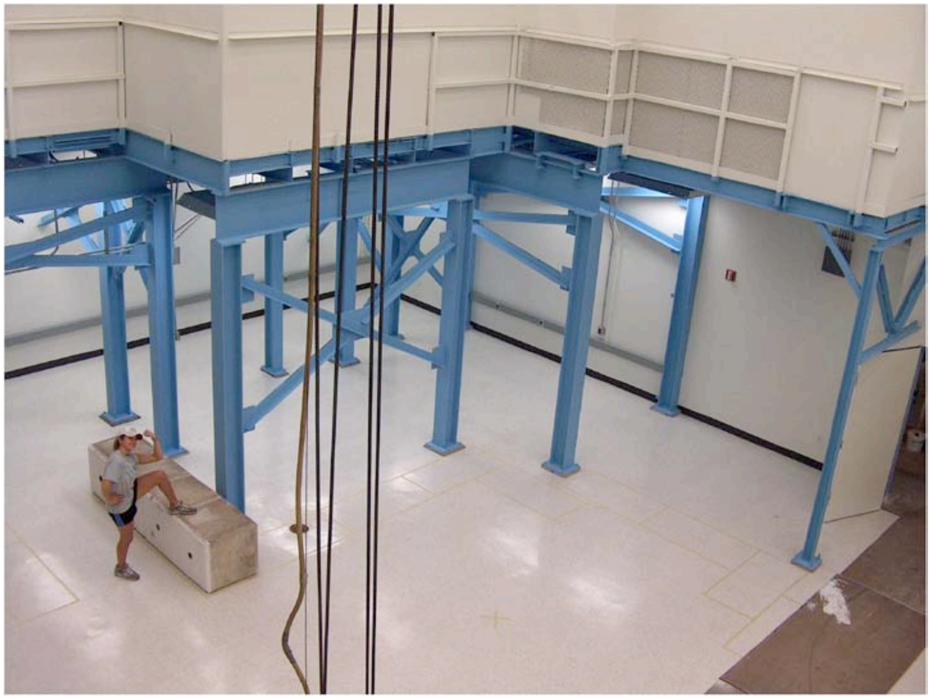




# Here Erhard Gaul explains to Todd Ditmire what a "laser" is



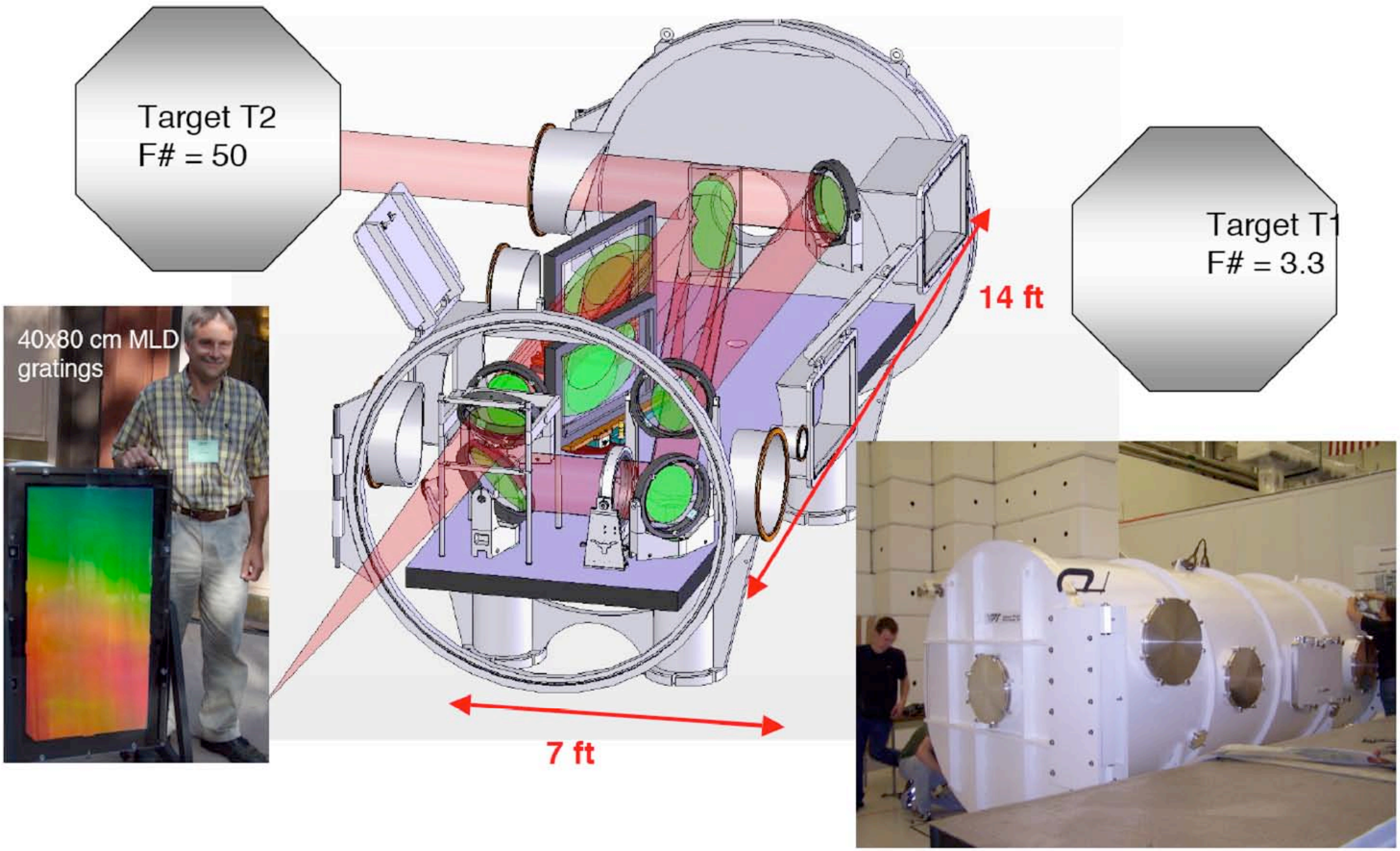
# Concrete shielding blocks have been installed in the target bay



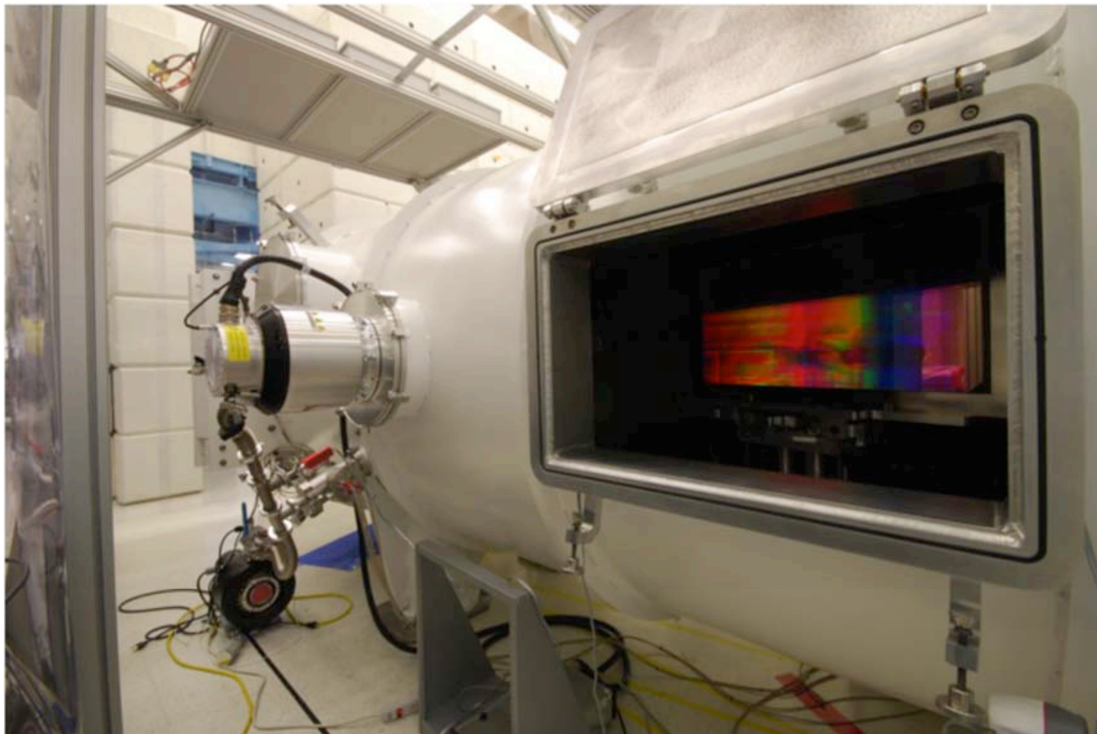
Texas Petawatt Target Bay prior to shielding installation

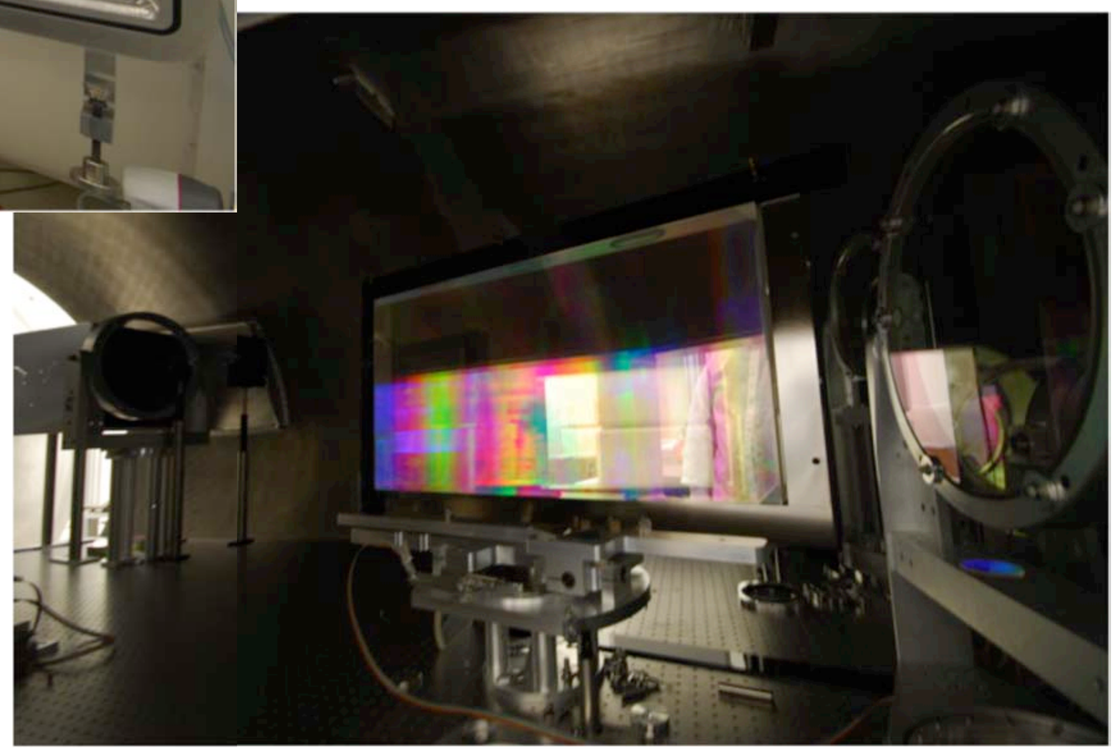
Texas Petawatt Target Bay with shielding installed around the Petawatt beam target area

# Two MLD 80x40 cm gratings compress the TPW pulse

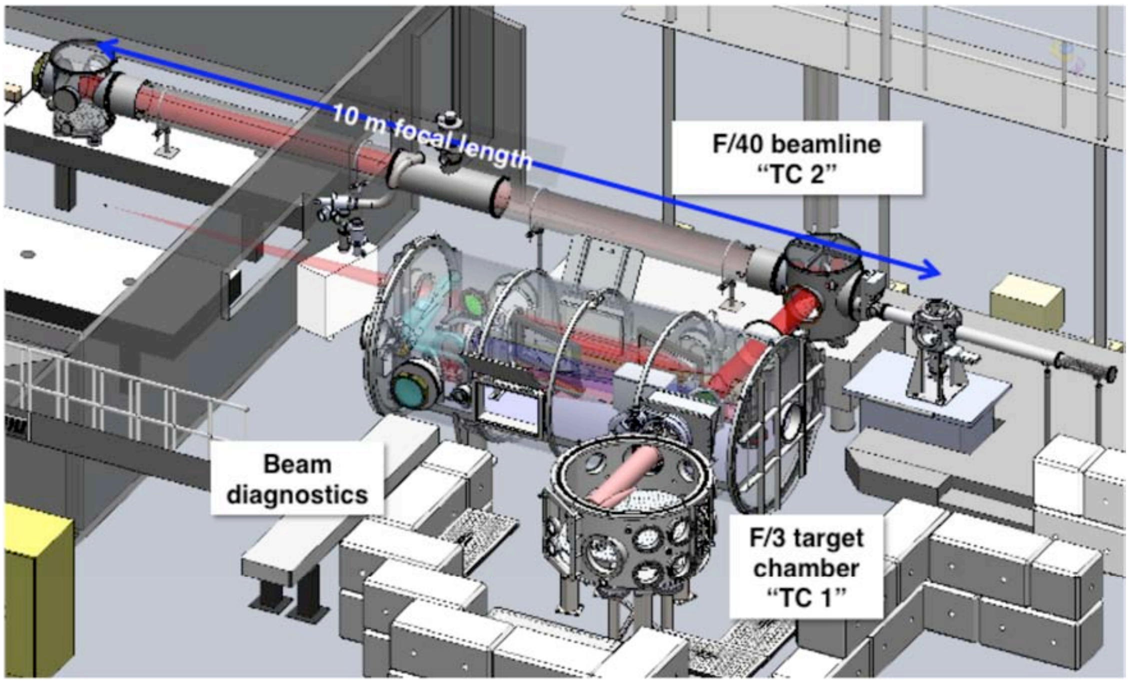


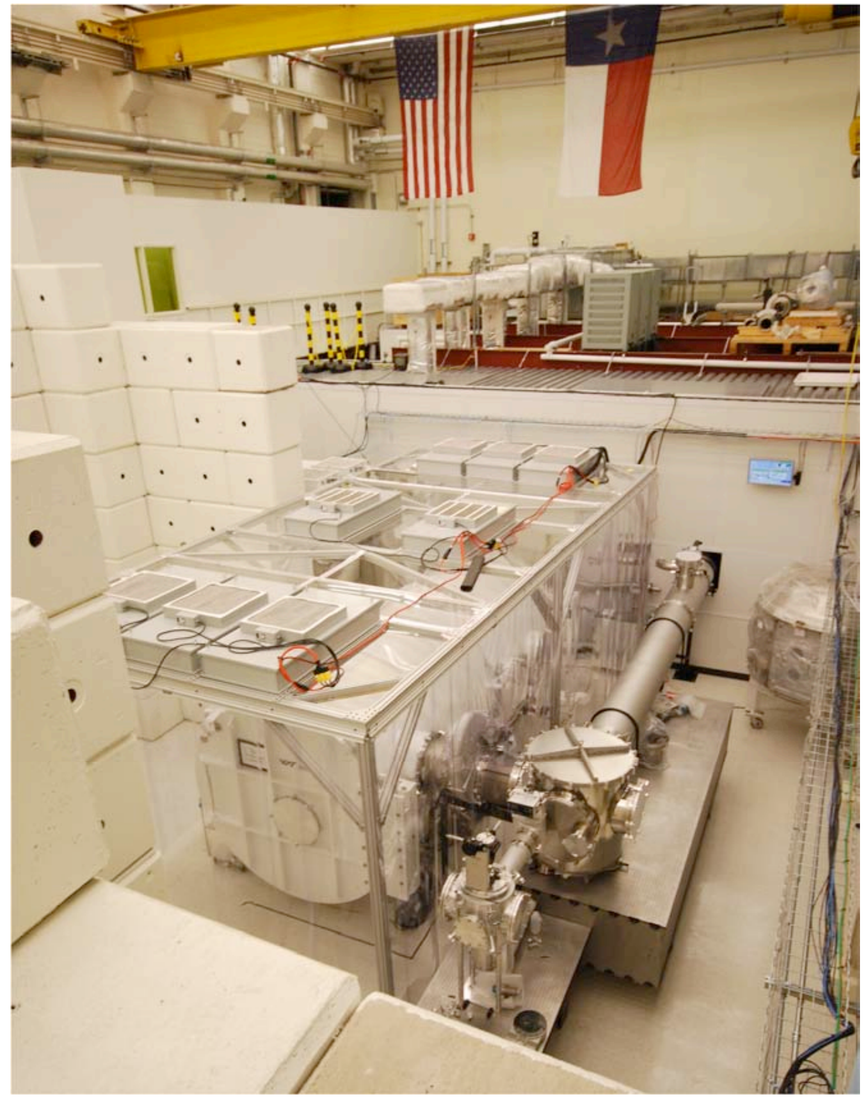
# The MLD gratings in the TPW perform well with high diffraction efficiency





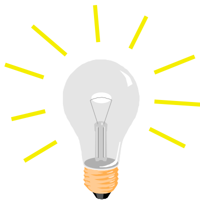
# The Texas Petawatt Laser has multiple target areas



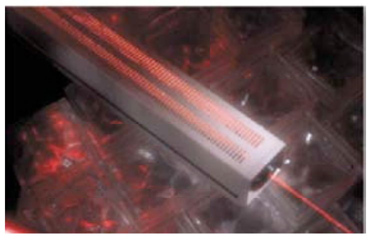
# A modern ultra intense laser is the brightest known source of light

## Light intensity...



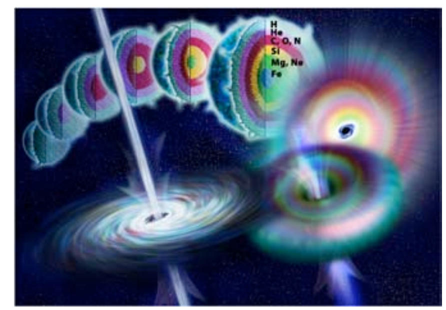
...near a light bulb ~ .03 W/cm$^2$

... of sun light on Earth ~ .14 W/cm$^2$



...of a focused HeNe laser ~ 500 W/cm$^2$

...at the surface of the sun ~ 7000 W/cm$^2$

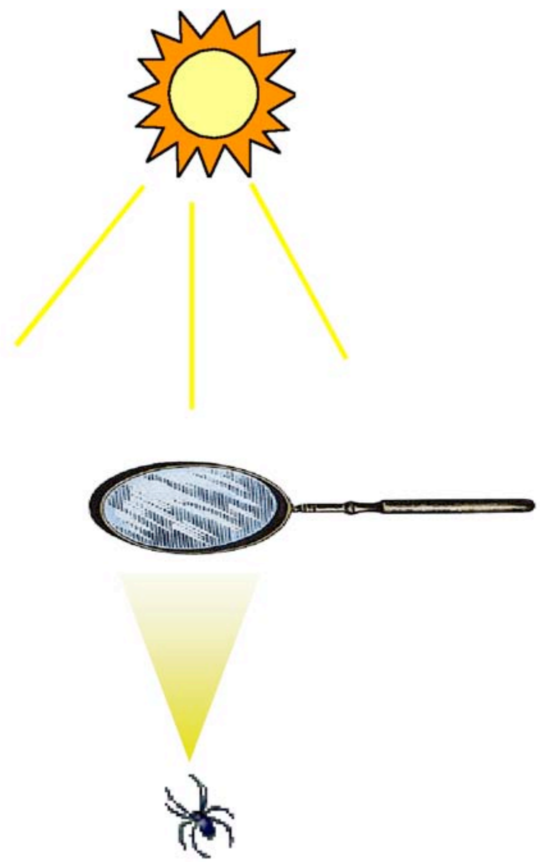



...near a black hole during a gamma ray burst
~ 10,000,000,000,000,000,000 ($10^{20}$) W/cm$^2$

*...of a petawatt CPA laser*
*> 1,000,000,000,000,000,000,000*
*(a billion-trillion or $10^{21}$) W/cm$^2$*

# What happens to matter irradiated at such extreme intensities?

# What happens to matter irradiated at such extreme intensities?



It gets hot!

# Petawatt lasers access extreme regimes of physical parameter space

PW laser focused to <10 μm

↓

Focused light intensity of

> $10^{20}$ - $10^{22}$ W/cm$^2$

### *High Field Science*

**High electric fields**

E ~ $10^{11}$ - $10^{12}$ V/cm

Field strength is 100 to 1000 times that of the electric field felt by an electron in a hydrogen atom

**High electron quiver energy**

$U_{osc}$ = 1 MeV - 10 MeV

Electron motion can become relativistic ($U_{osc} > m_e c^2$ = 512 keV)

### *High Energy Density Science*

**Concentrated energy**

Energy density in a femtosecond pulse is $10^{11}$ J/cm$^3$

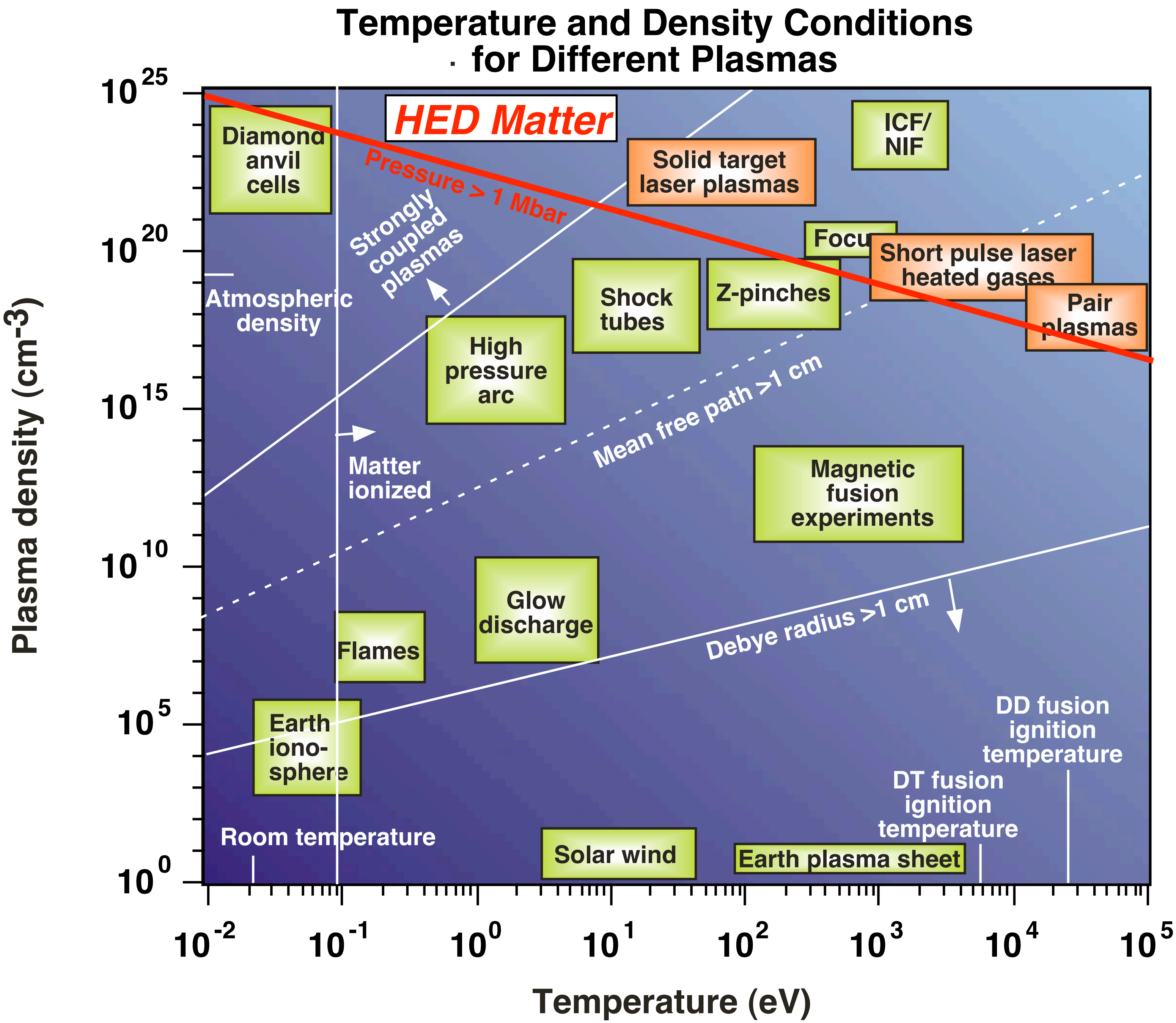
Corresponds to ~ 1 MeV per atom at solid density

**High brightness and pressure**

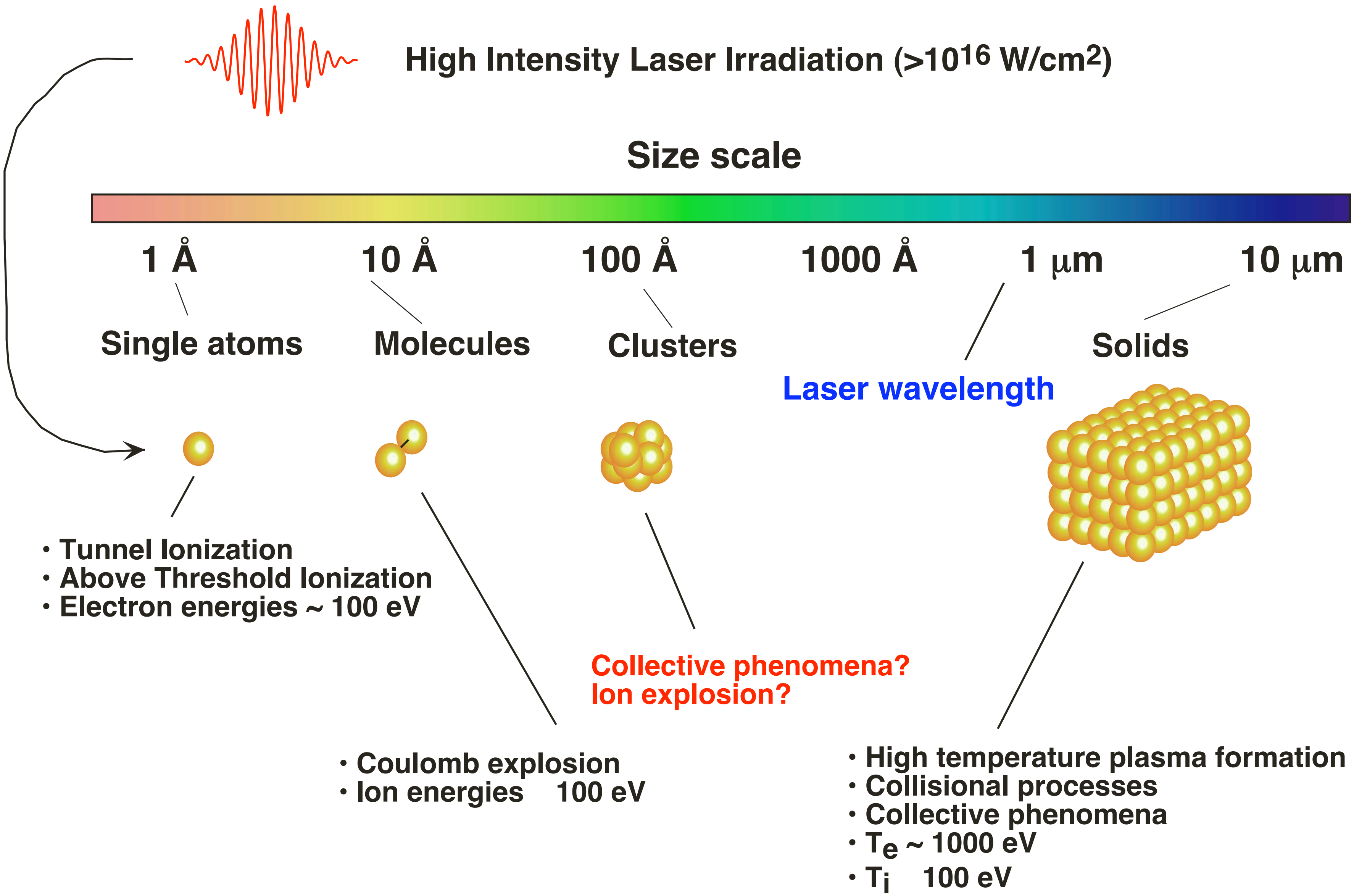
Radiance exceeds that of a 1 MeV black body

Light pressure P = I/c = 30 - 3000 Gbar

# High energy density matter is created by heating dense plasma to very high temperature

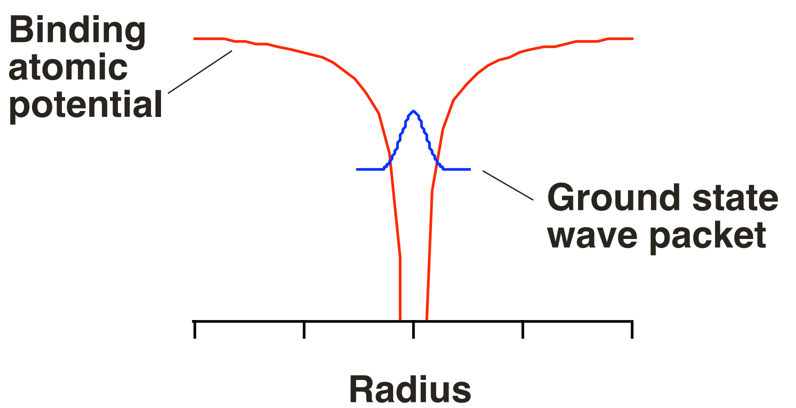


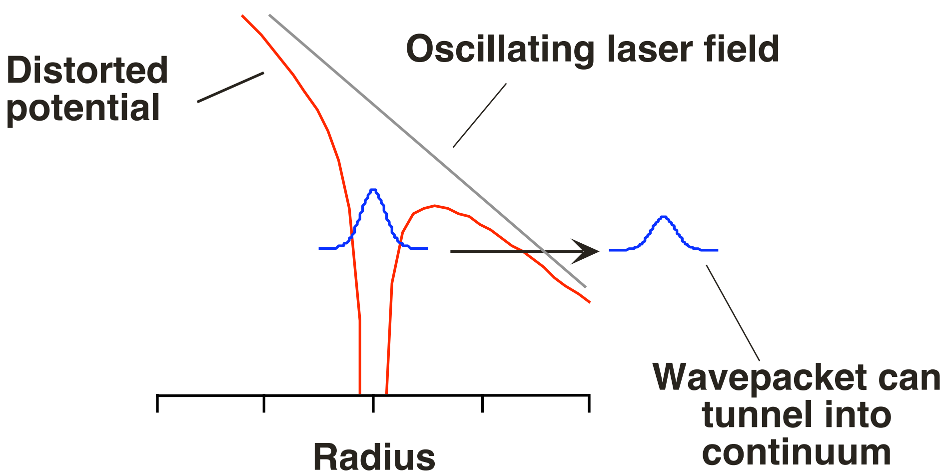
# The interaction of intense laser pulses with different targets leads to quite different physical effects

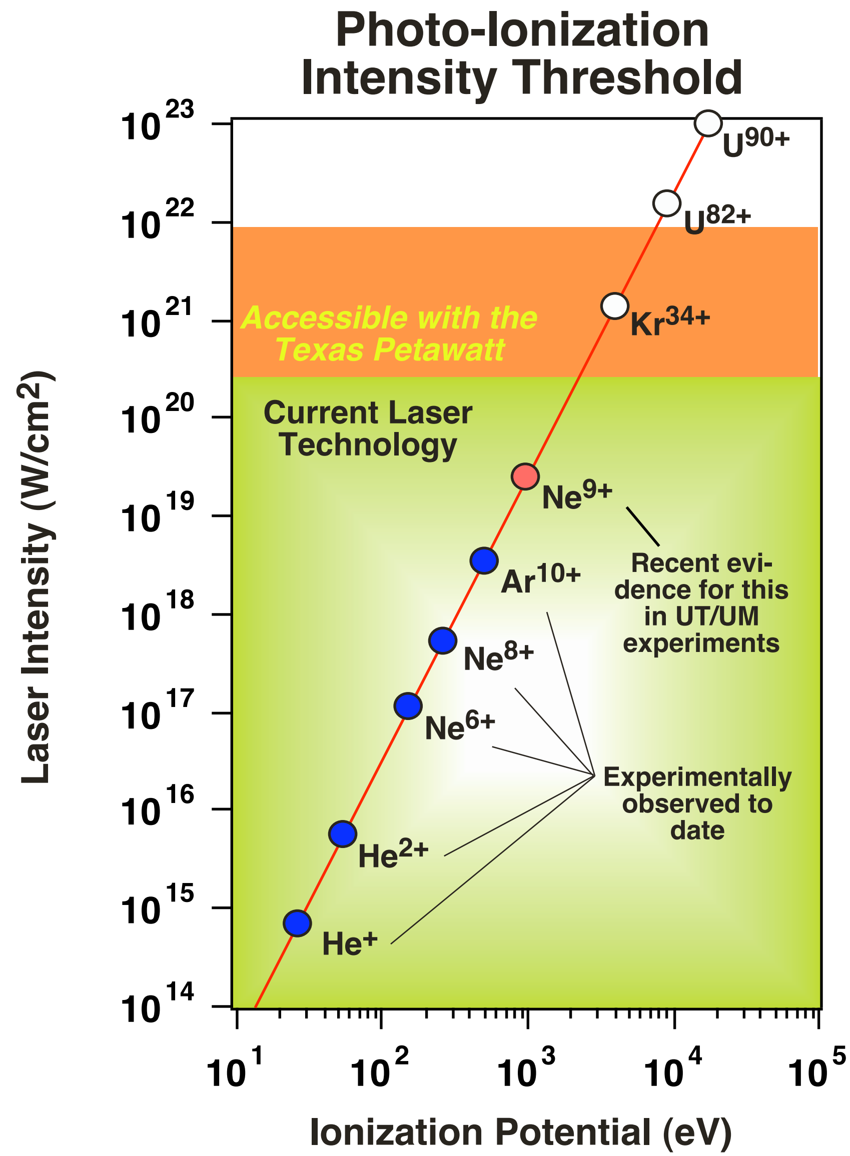


# Highly non-perturbative laser intensities push photo-ionization into the tunneling regime

**A strong laser field can ionize an atom by tunneling**



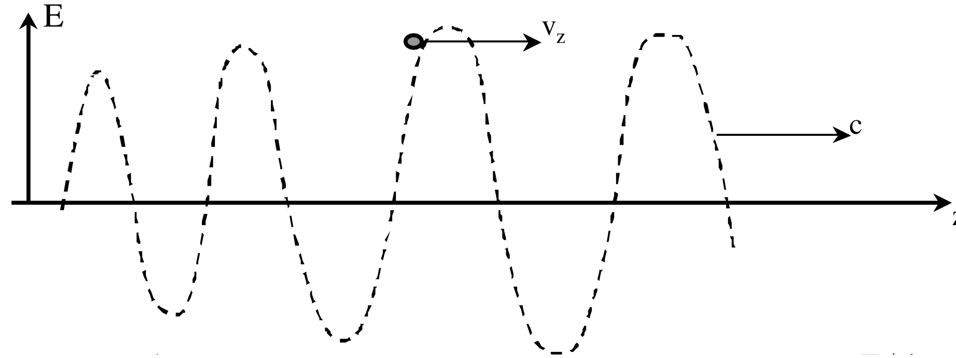



# Ionization in a strongly relativistic beam will be accompanied by strong, free-wave acceleration of the ejected electrons

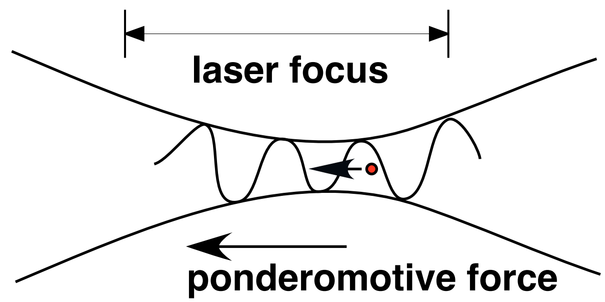
- Ionization "injects" electrons right at the peak of the field
- This yields much greater energies than if the laser interacts with free electrons

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

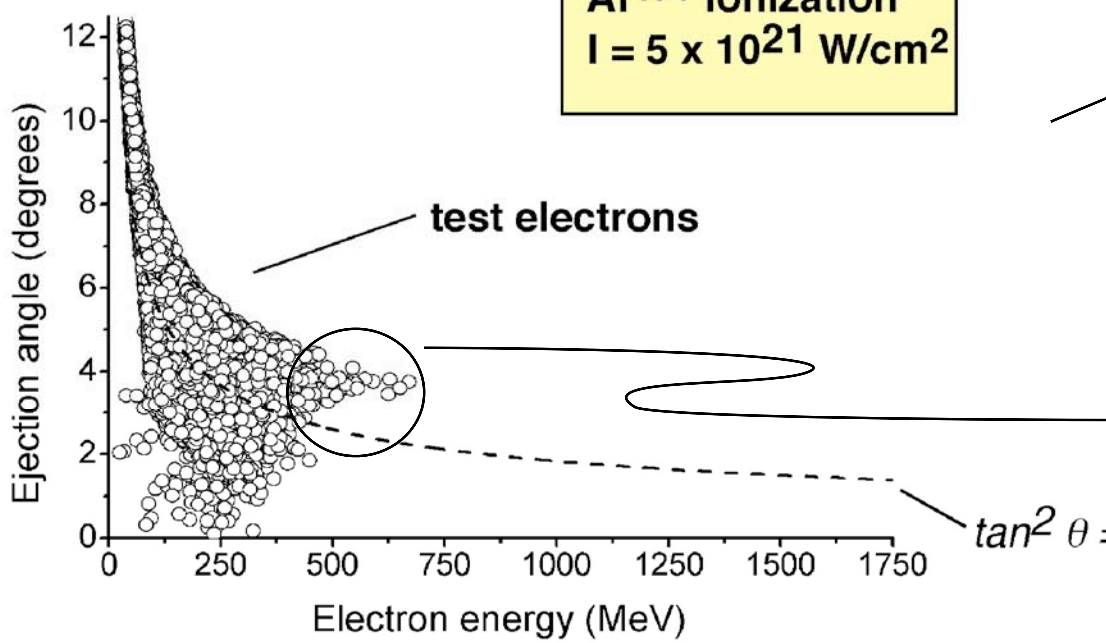



Monte Carlo simulation using a focused PW beam

$Ar^{17+}$ ionization
$I = 5 \times 10^{21}$ W/cm$^2$




$$\gamma_{\max} \approx eE_{\max}\theta z_R / 2m_e c^2$$

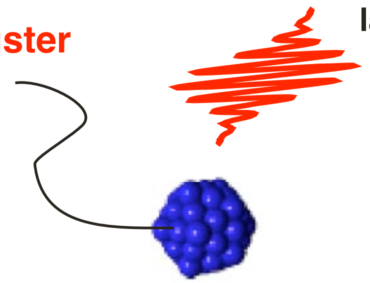



$\tan^2\theta = 2/(\gamma-1)$

Near GeV electrons ejected within 4° of the laser axis

# A cluster irradiated by an intense fs laser, violently explodes, ejecting ions with high kinetic energy

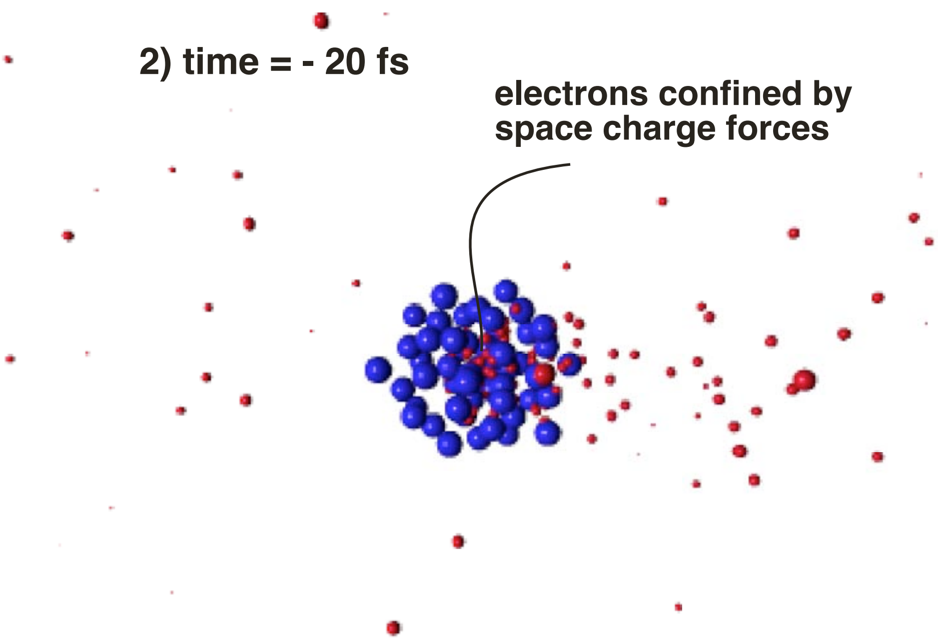
55 atom argon cluster
before irradiation




Simulation with I = $10^{16}$ W/cm$^{2}$
$\Delta\tau$ = 50 fs

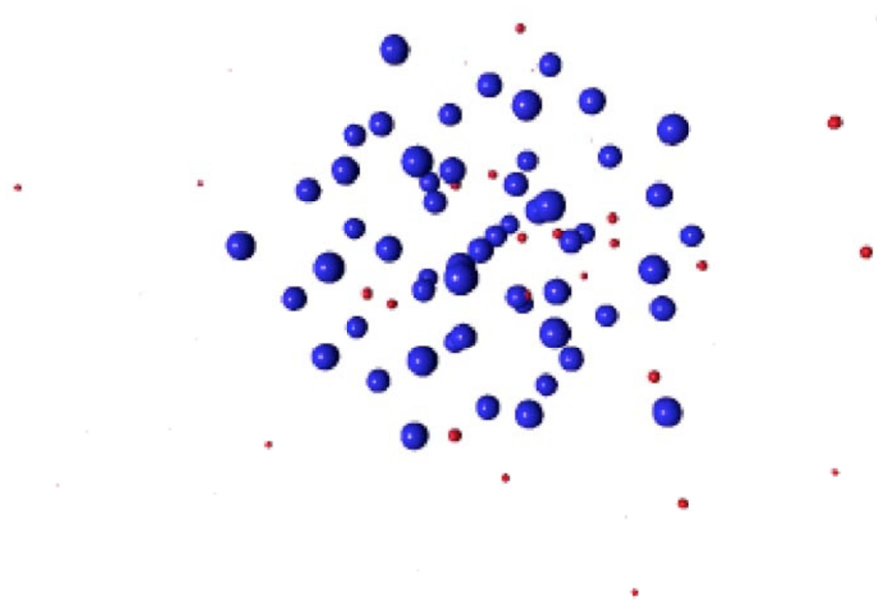
1) time = - 100 fs

2) time = - 20 fs



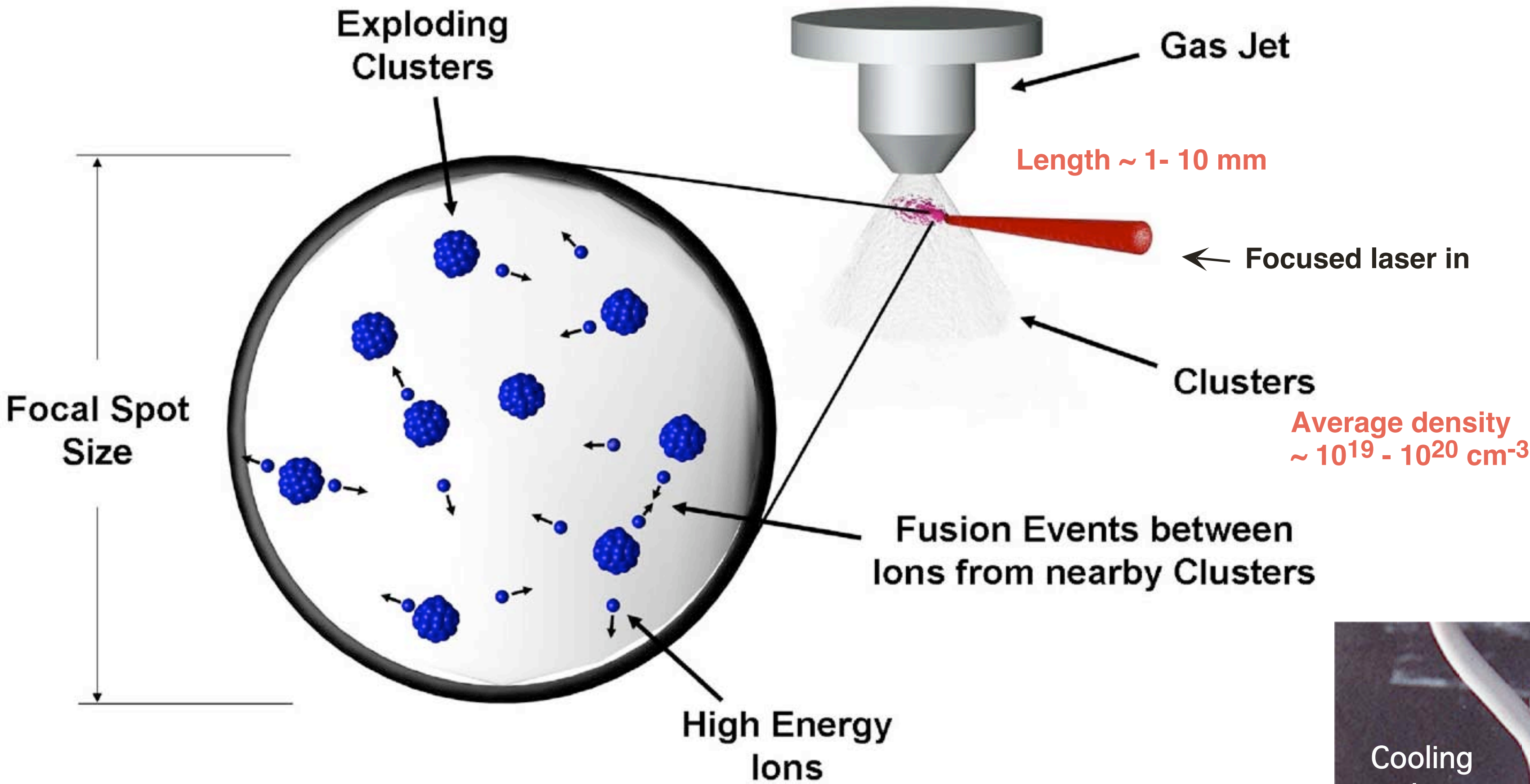

Laser field begins to heat and
expel electrons from cluster

3) time = + 20 fs



Ions explode by Coulomb forces

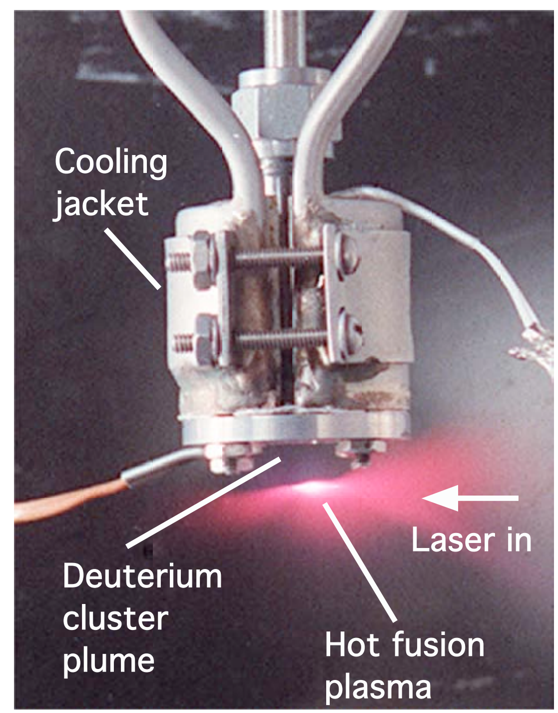
# A gas of exploding deuterated clusters can produce a burst of fusion




**Relevant fusion reactions:**

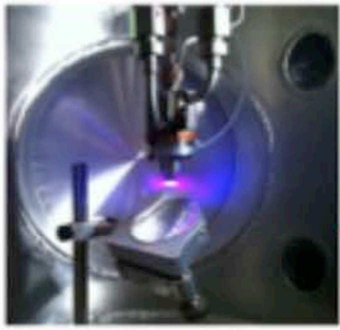
$D + D \rightarrow He^3$ (0.82 MeV) + n (2.45 MeV)

$D + T \rightarrow He^4$ (3.5 MeV) + n (14.1 MeV)



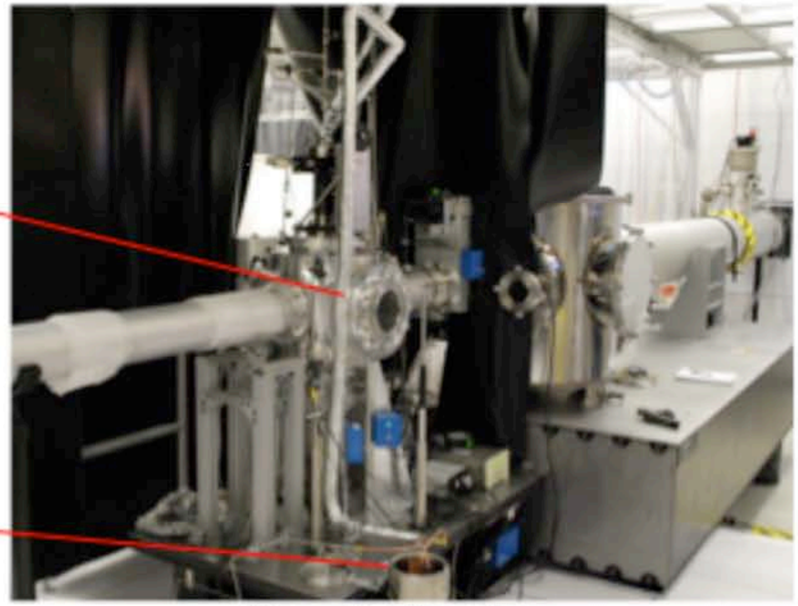
# We have produced ~ 2 x $10^7$ DD fusion n/shot in clusters with the Texas Petawatt Laser (~ 100 J energy)

Target area of the Texas Petawatt for the cluster fusion experiment



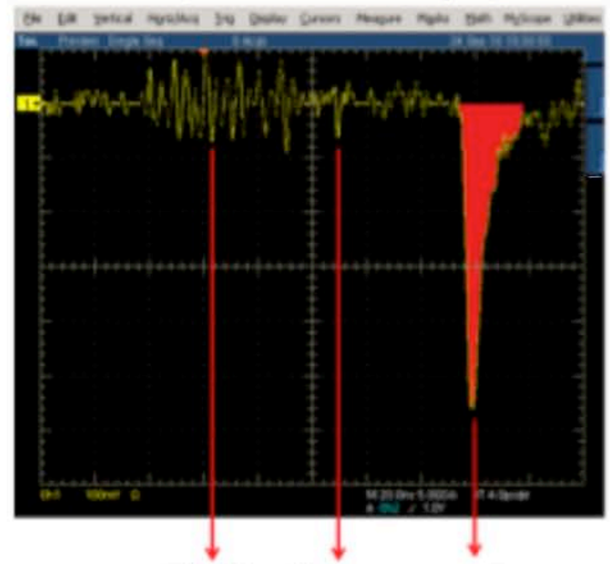
Deuterium plasma (OPA shot w/ DFM)

LN2 cooling line



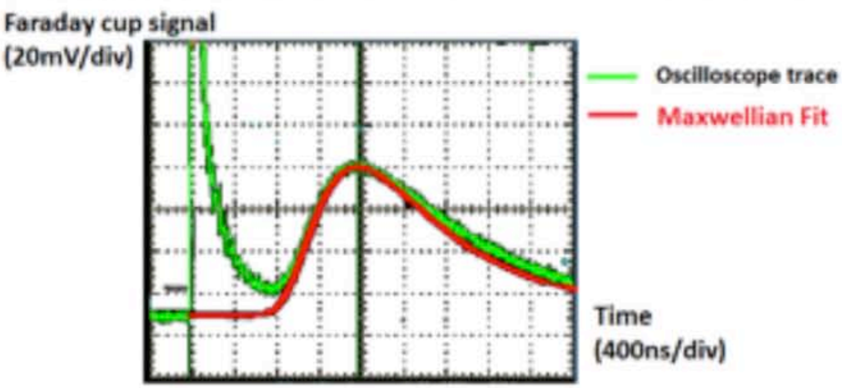
Target chamber

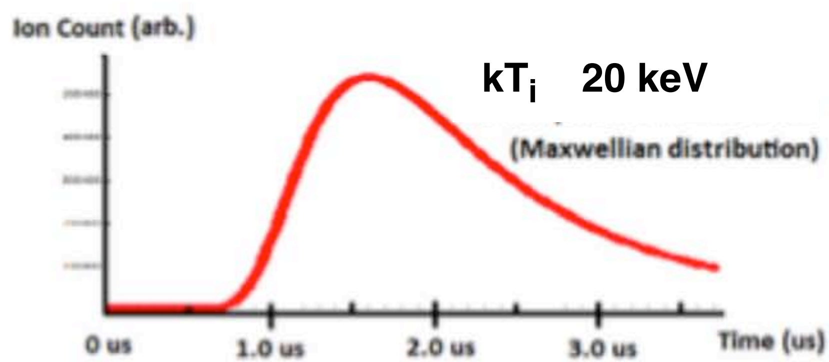
Shot 1282, deuterium 750psi, -186°C



EMP X-ray neutron

Faraday cup data showed kT=2keV deuterium ion peaks on 10J rod shots.

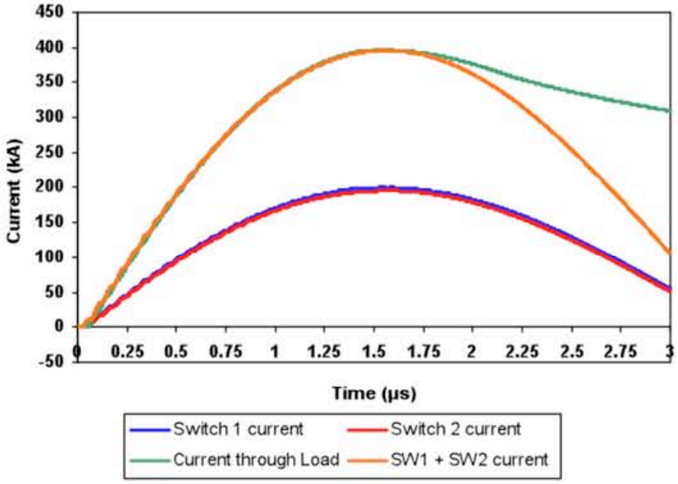


# A 1 MA pulsed power source constructed at Sandia will be installed on the TPW in February

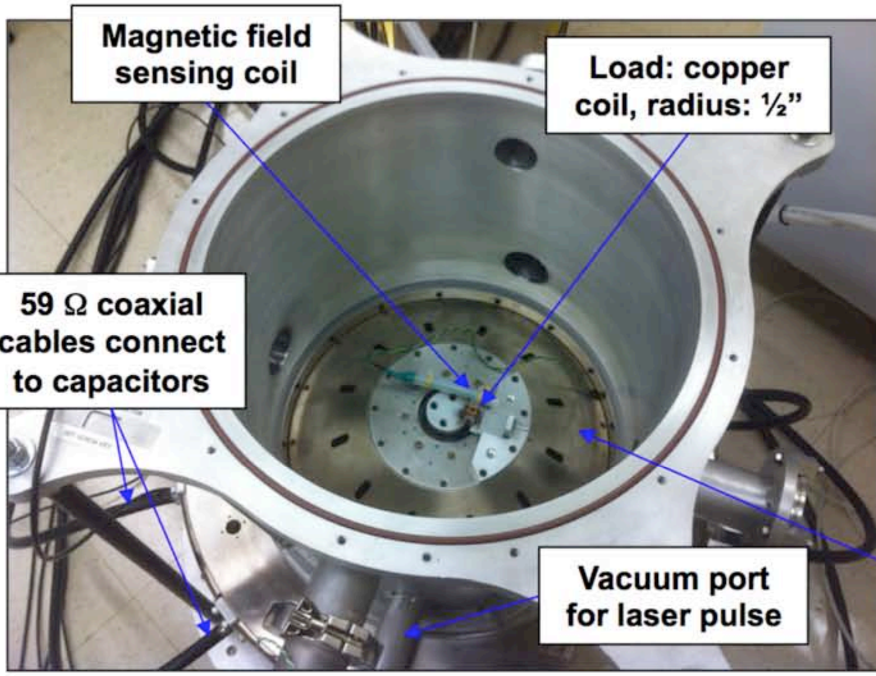
## Recent Results with ½ MA Test Chamber

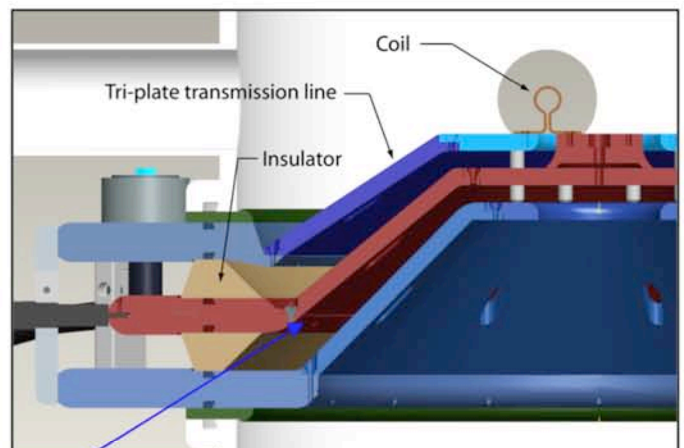
- 400 kA peak current
- Time to peak ~ 1.5 ms
- Load: SS shorting bar
- Estimated 28 T for present coil geometry




x 4 units to be installed on Texas Petawatt

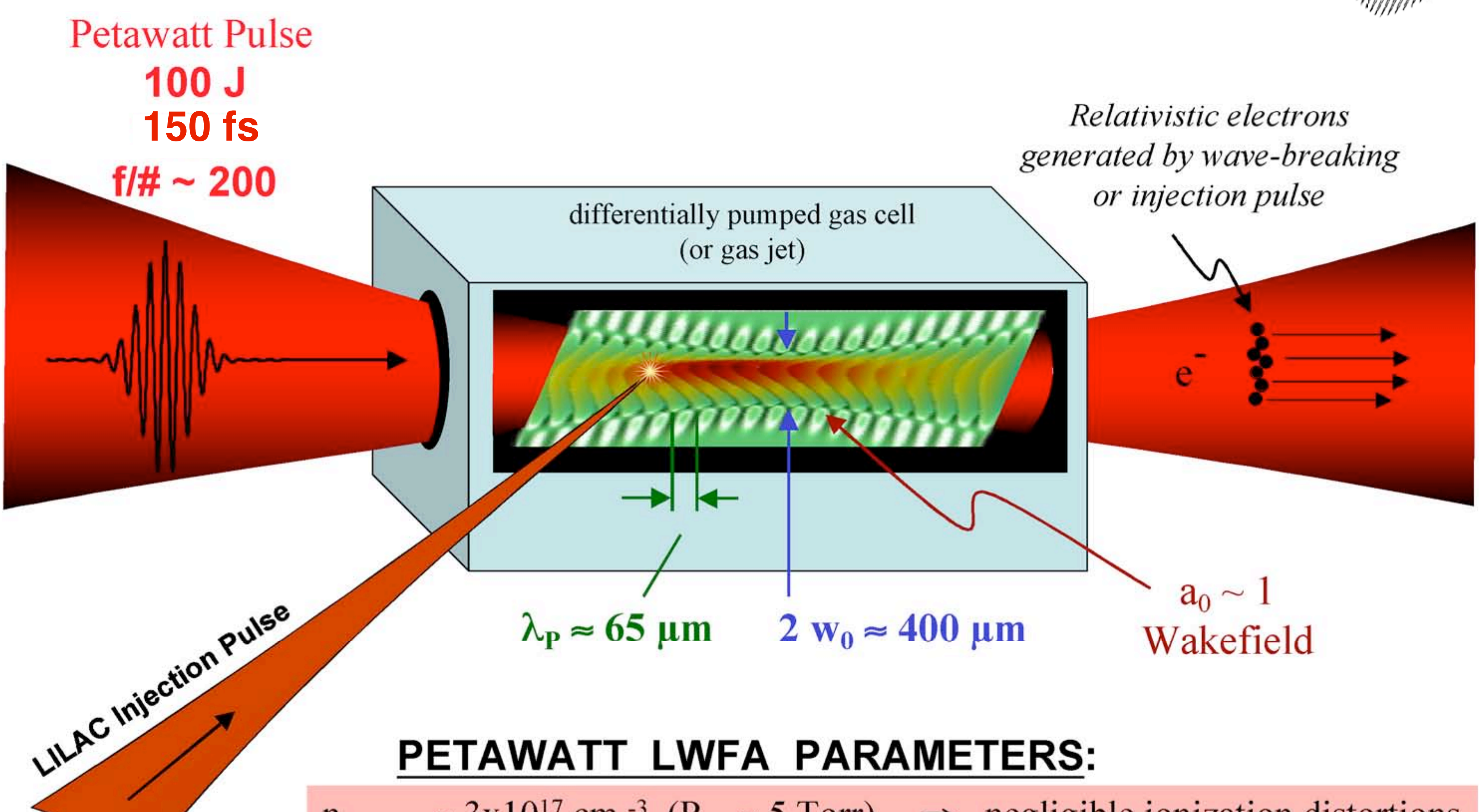
- Anticipate 150 - 200 T




Conical transmission line, similar to Z Machine

# The 100 fs TPW will allow flat-field resonant, multi-GeV laser wakefield acceleration of electrons




Umstadter, PRL ('96)

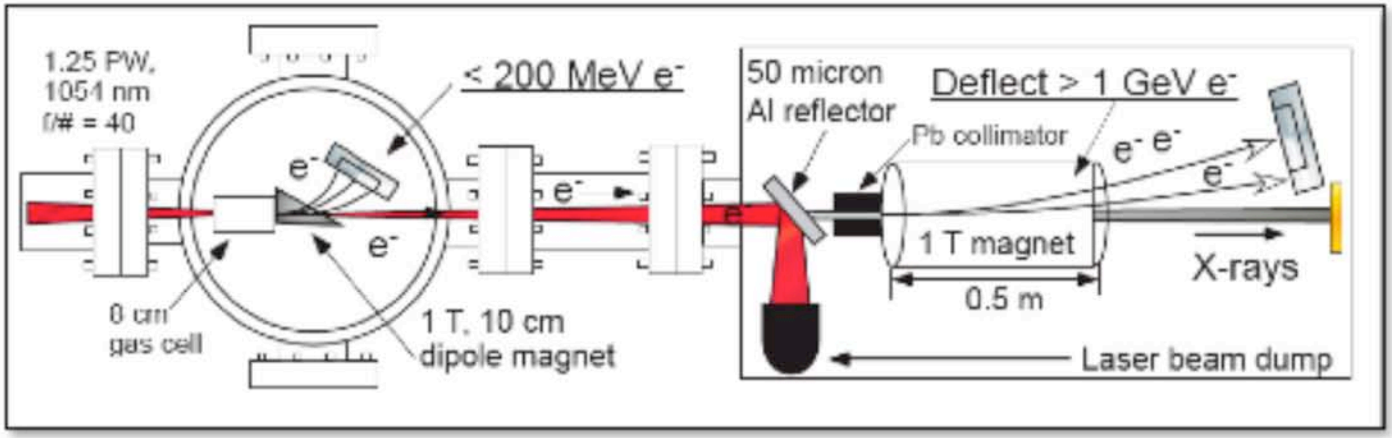
## PETAWATT LWFA PARAMETERS:

| | | |
|---|---|---|
| $n_{resonant} \sim 3x10^{17}\ cm^{-3}$ ($P_{He} \sim 5$ Torr) | ⇒ | negligible ionization distortions |
| $L_{dephasing} \sim z_{Rayleigh} \sim$ 15 cm | ⇒ | long accelerating length |
| $E_z \sim 0.5$ GV/cm | ⇒ | largex accelerating field |

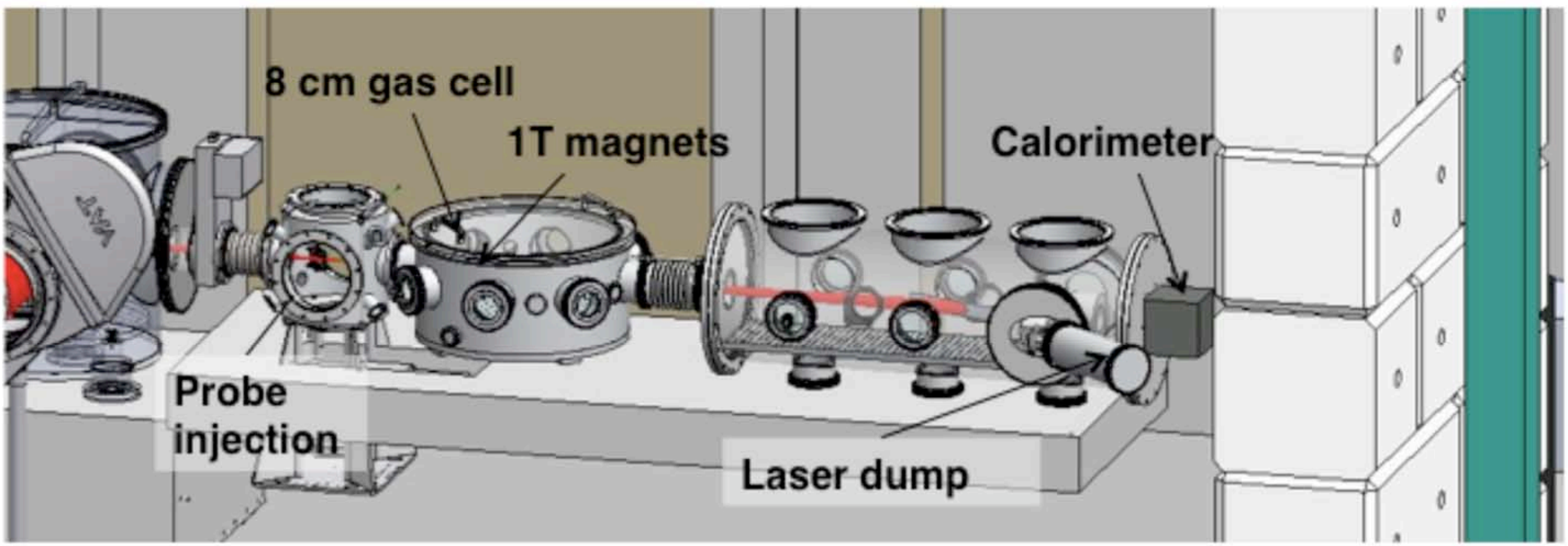
Linear wakefield best driven by fs pulses

**Accelerating gradient ~ $n_e^{1/2}$ ⟶ $n_e \sim (1/\Delta t_{pulse})^2$**

# Electron acceleration on the TPW will be explored at electron energies up to the 10 GeV level

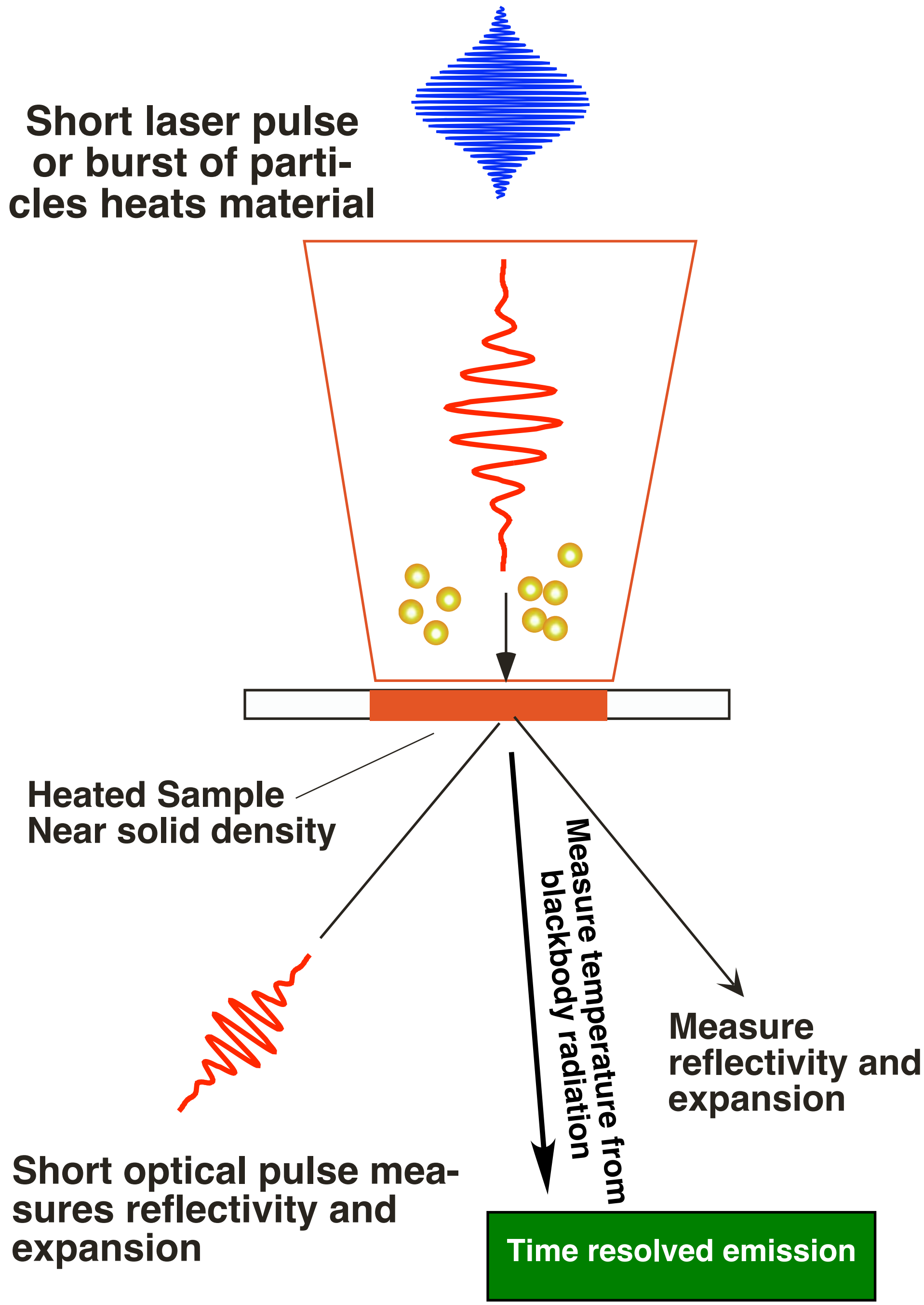


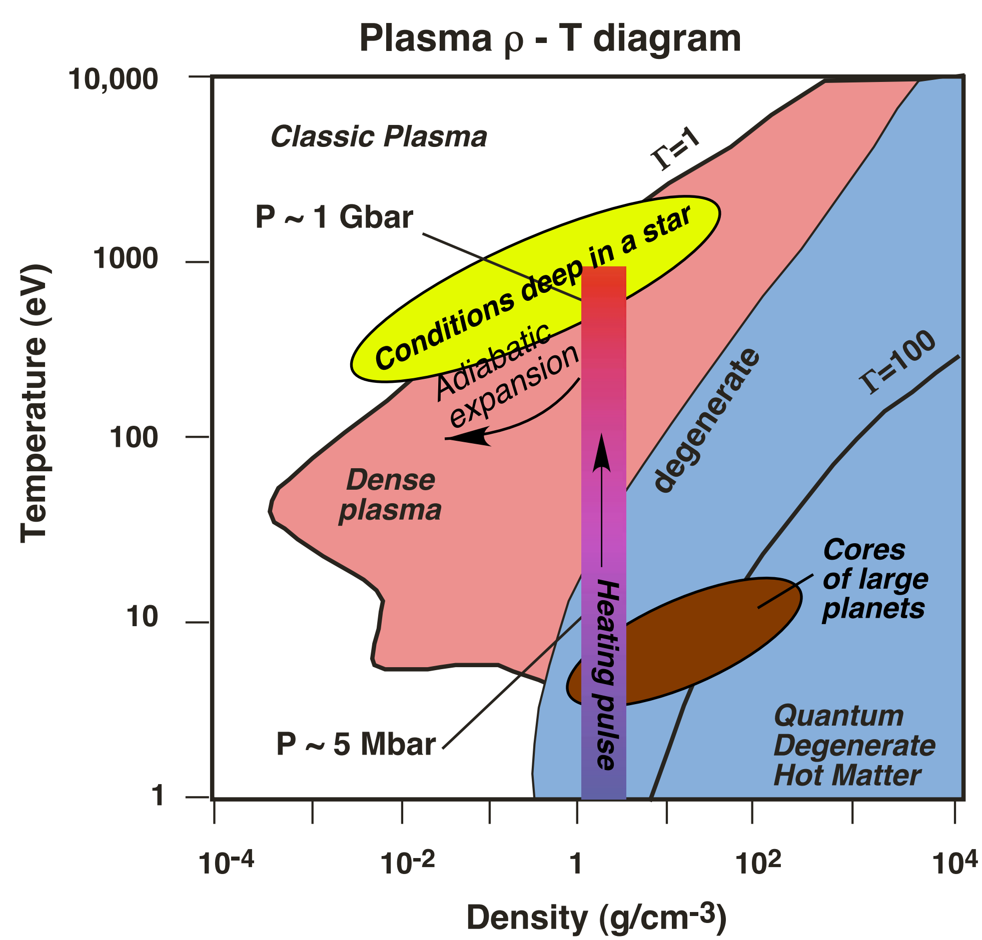

- > 1 GeV electrons predicted
- Frequency domain holography visualization
- Challenge of 1/hr shots



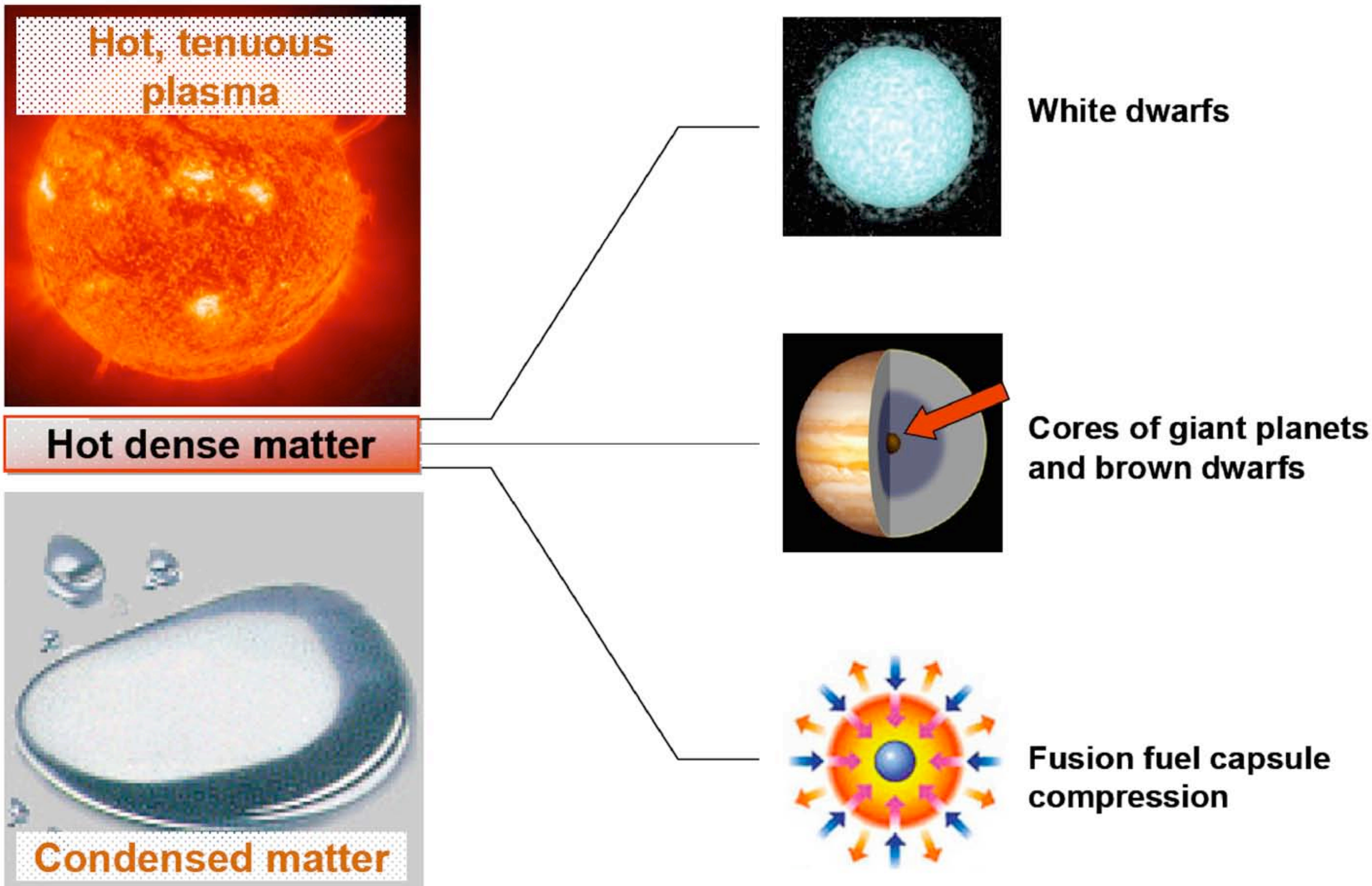

These chambers will be useful for future experiments

# Isochoric heating can be combined with optical and x-ray probes to derive information about a hot dense plasma



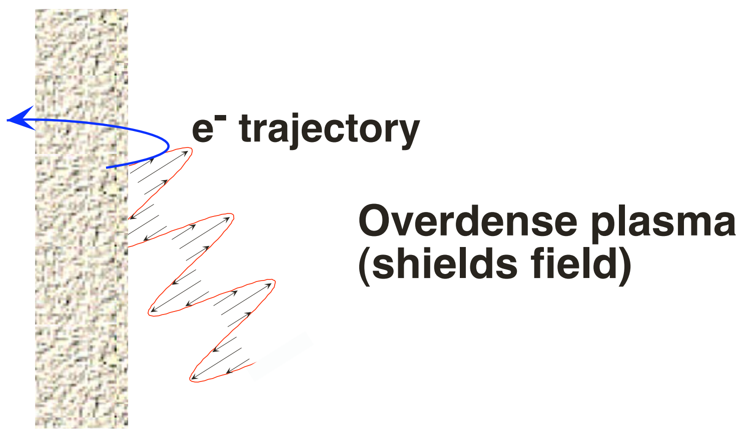
# A quantitative understanding of these HED plasma physics issues is of considerable practical importance

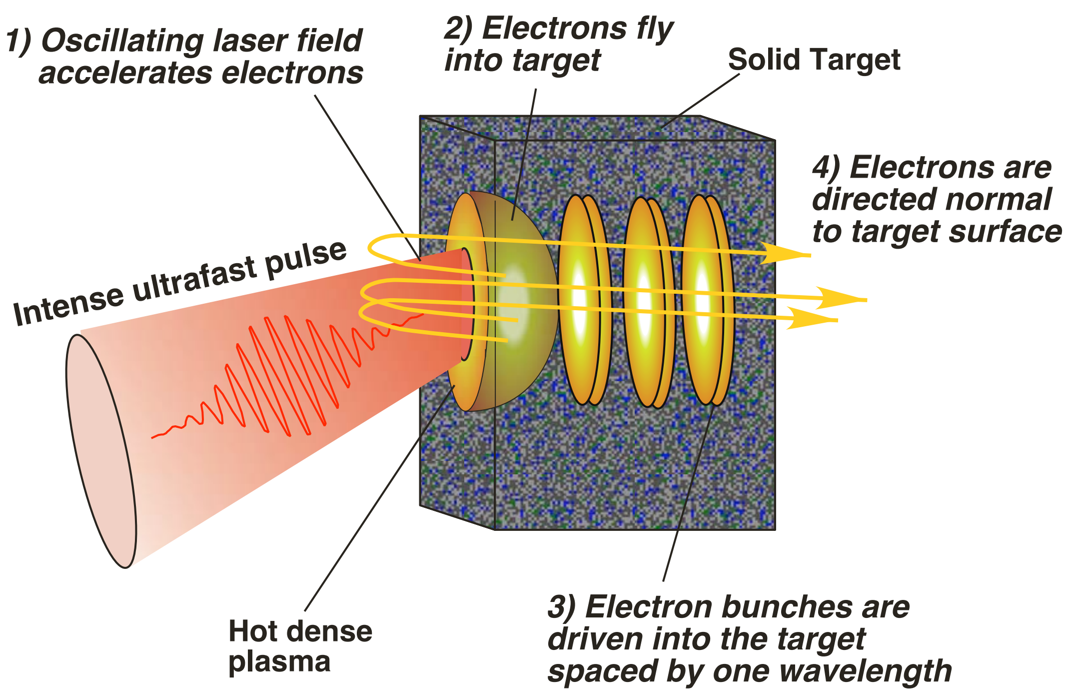


# “Rescattering” of laser driven electrons at the surface of a sharp plasma gradient can produce pulses of fast electrons

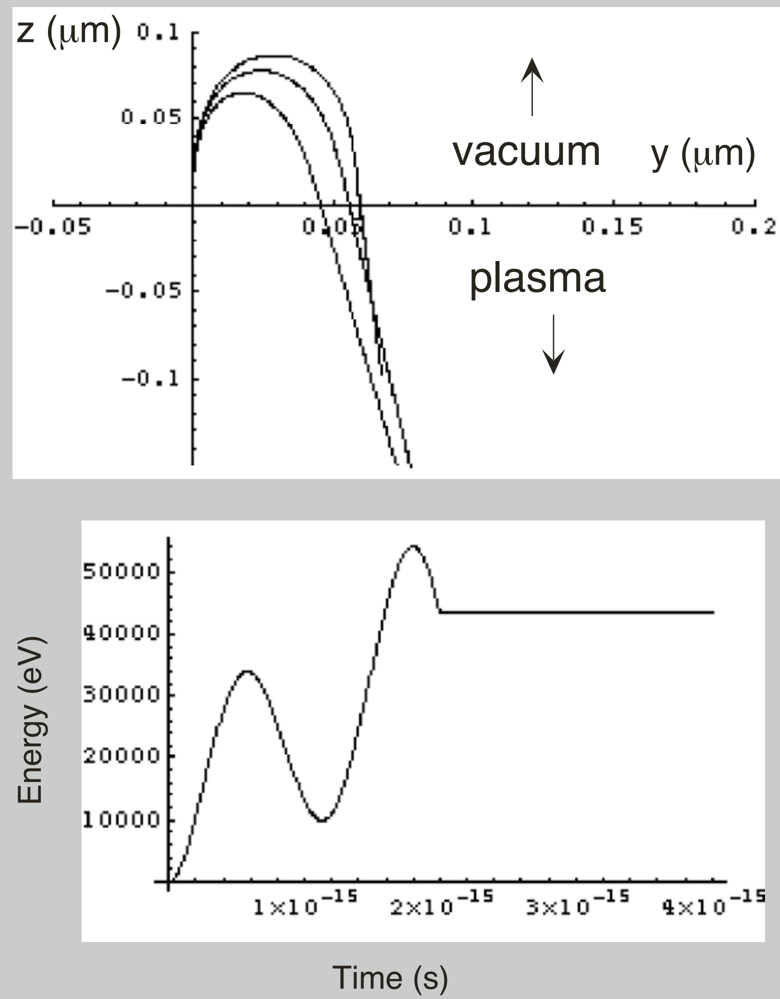
**Scattering at the conducting surface breaks the adiabaticity of the laser oscillation**

→ "**Brunel absorption**"



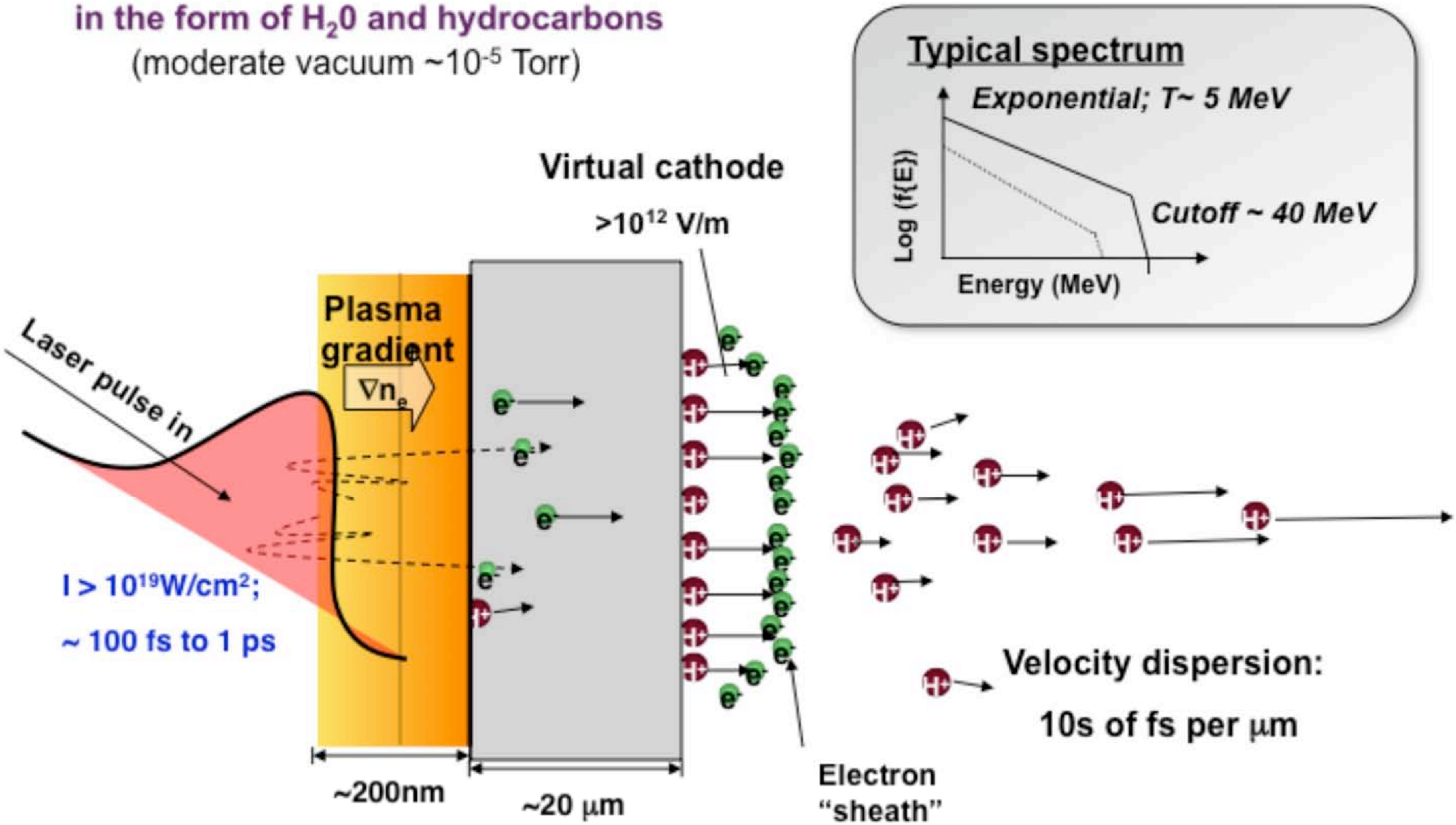




**Simulated e⁻ trajectories and energy in relativistic field at plasma surface**
**$U_p$ = 50 keV (5 x $10^{17}$ W/cm$^2$)**



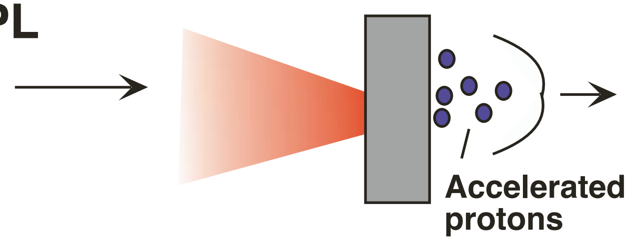
# With a petawatt laser, very intense, energetic pulses of protons can be produced

Protons are present on metal foil surfaces in the form of $H_2O$ and hydrocarbons
(moderate vacuum ~$10^{-5}$ Torr)



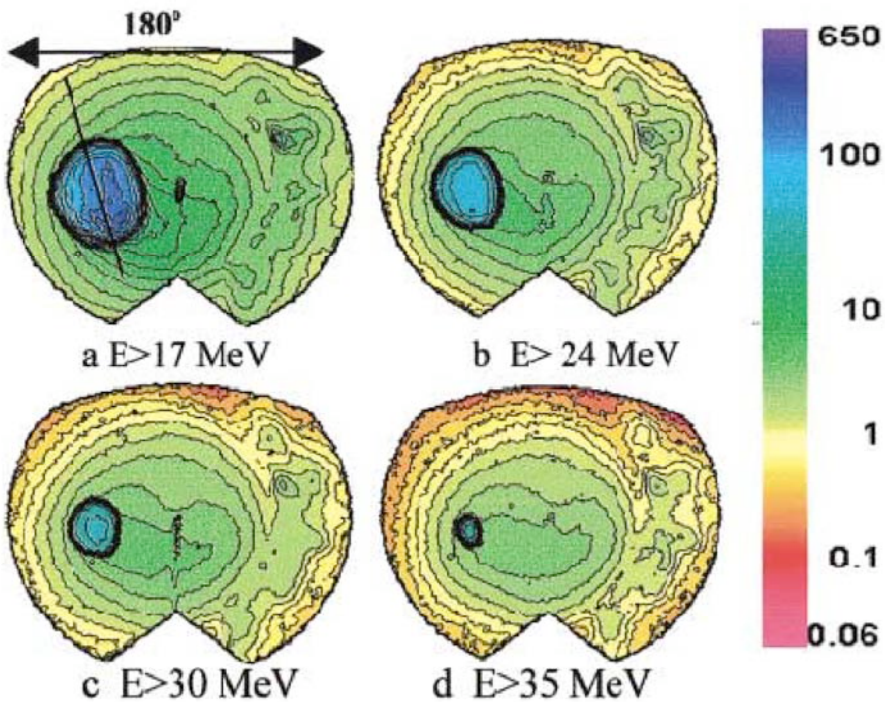
# Target normal sheath acceleration of protons to >10 MeV was observed first at the LLNL Petawatt Laser

**Relativistic electrons produced by a SPL can accelerate protons from a solid**

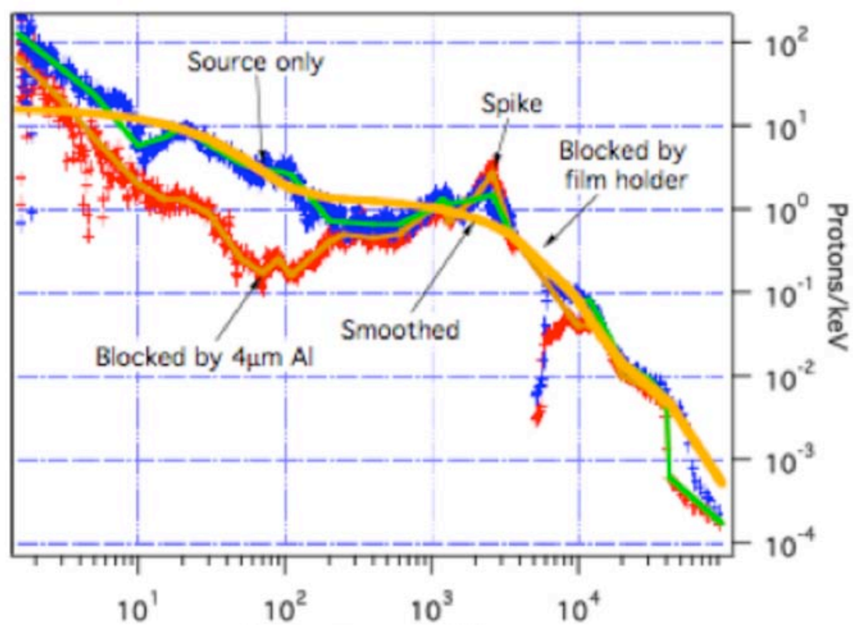



**At 3 x $10^{20}$ W/cm$^2$ on LLNL PW laser:**

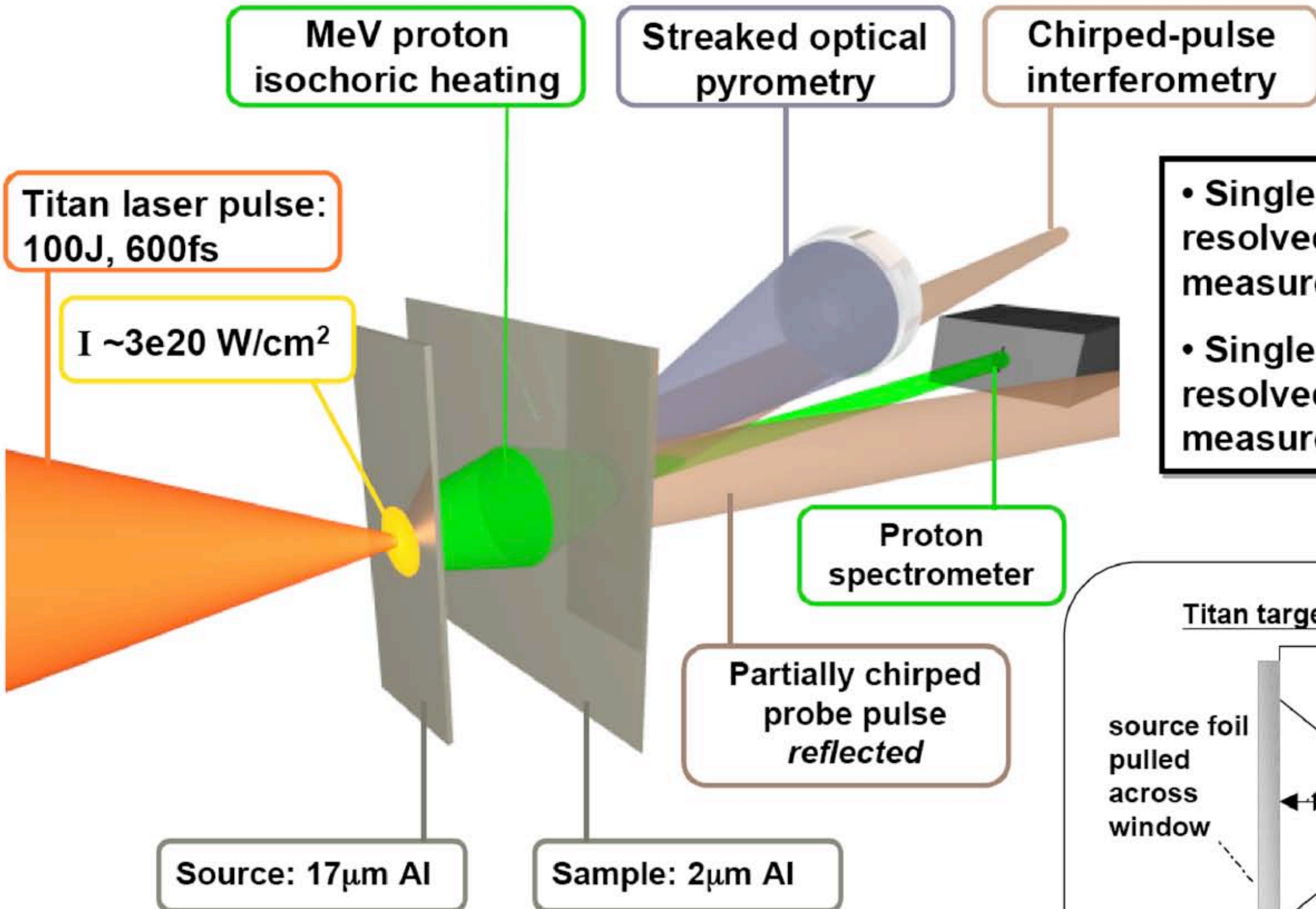
**Up to 48J of protons (12% of laser energy) were observed in protons with energy >10 MeV**



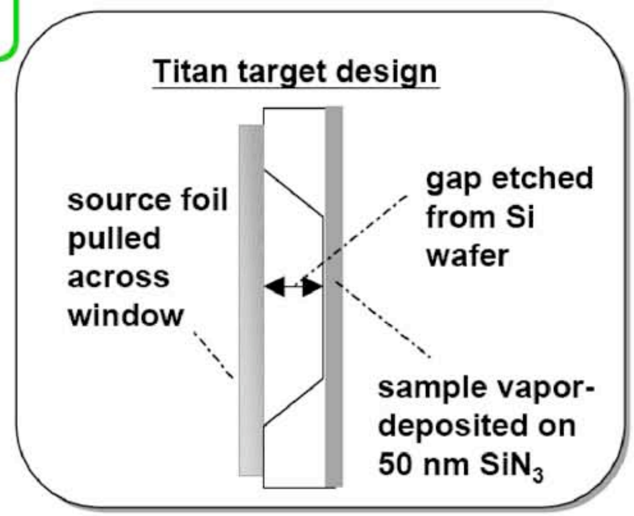

**Proton spectrum taken on the Titan 250 TW laser**



# We have demonstrated proton heating using the LLNL 200 TW Titan laser

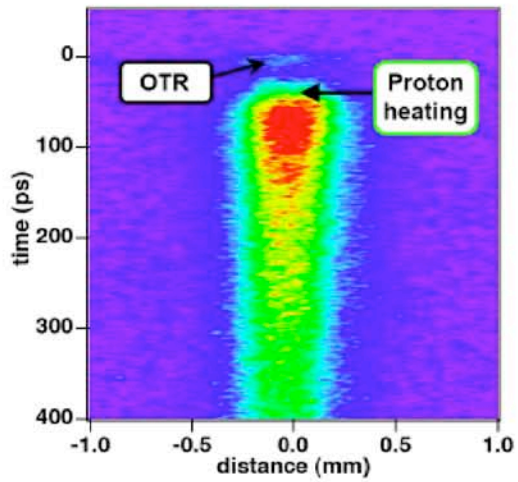



- Single shot time resolved thermal measurement (SOP)
- Single shot time-resolved expansion measurement (CPI)

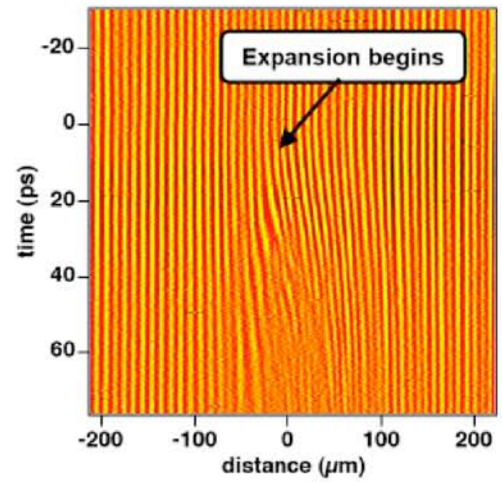


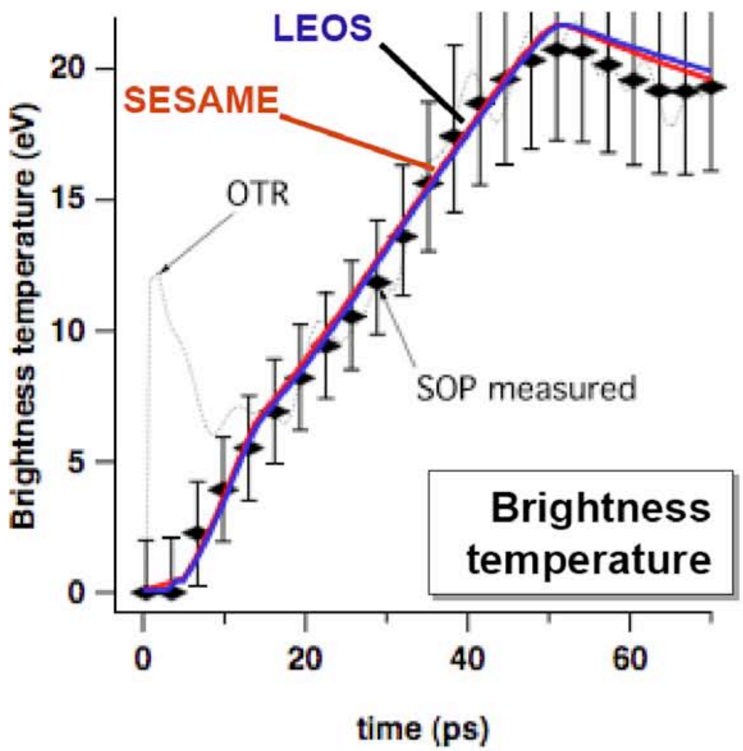
# Using hydrodynamic simulations we are able to evaluate various EOS tables for Al in the 10 - 20 eV region

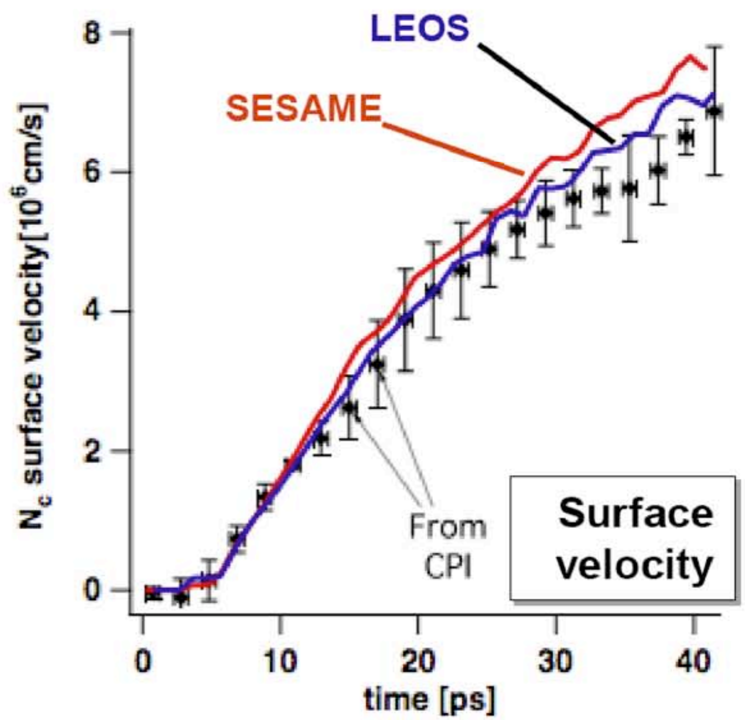
SOP: Time-resolved temperature




CPI: Time-resolved expansion



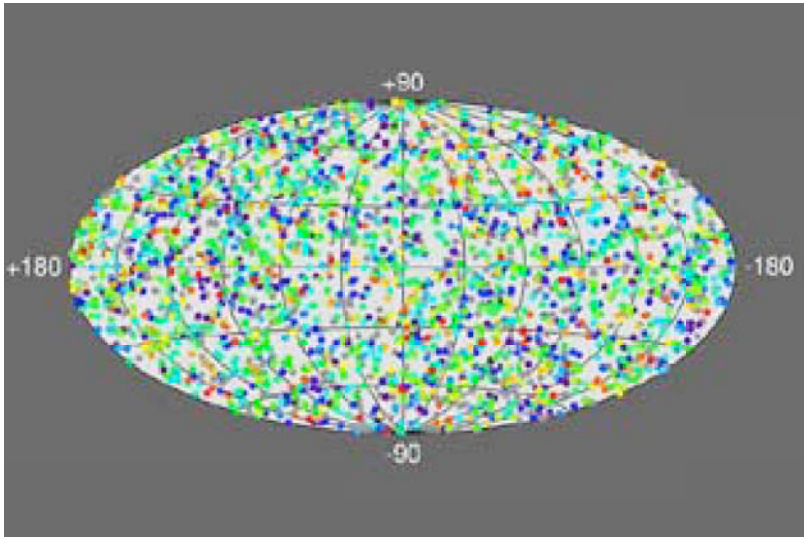



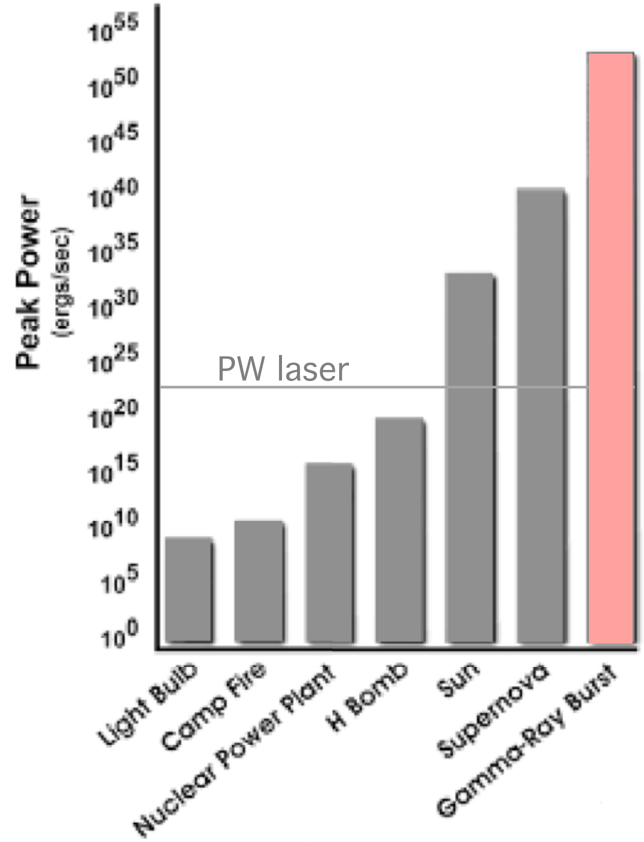




Agreement within 10%

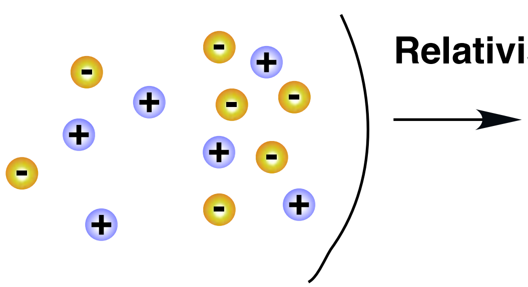
# Gamma Ray Bursts are among the most energetic and enigmatic events in the Universe

**The distribution of gamma-ray burst sources on the sky**




**One possible mechanism is the production of internal shocks in relativistic plasma jets - collisions of electron positron plasmas**

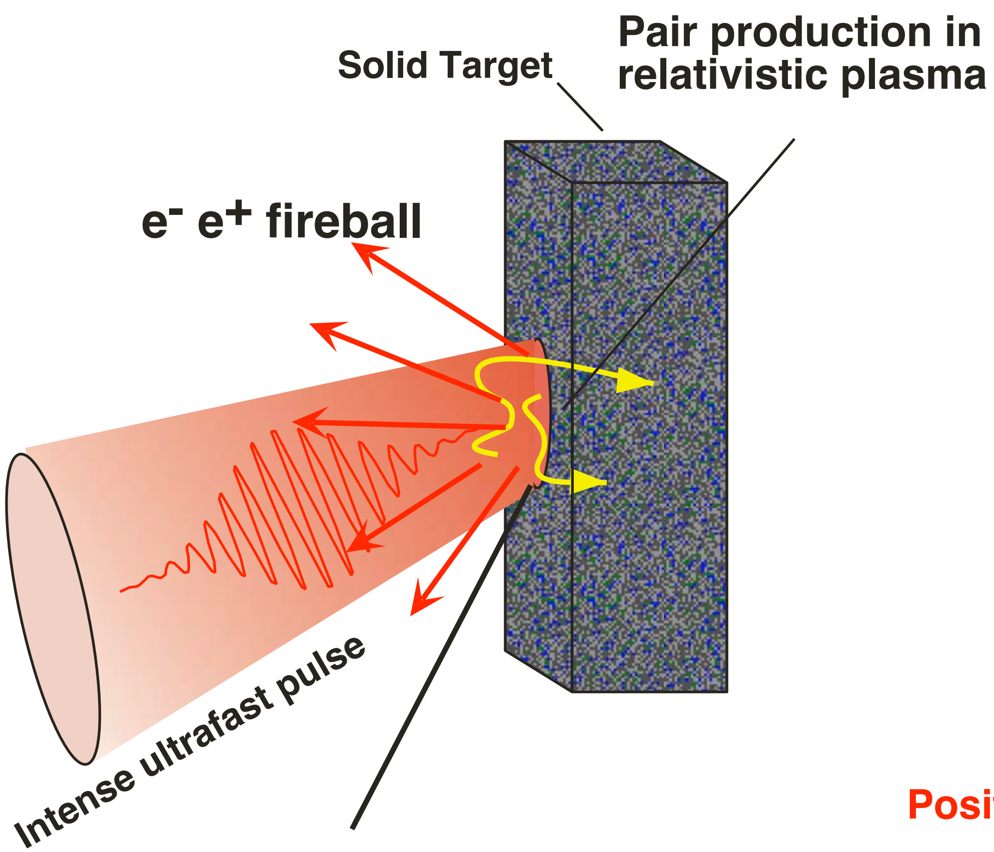



***Matter- antimatter plasma (electrons and positrons)***

**Pair plasmas may exist near black hole candidates and may play a role in GRBs**

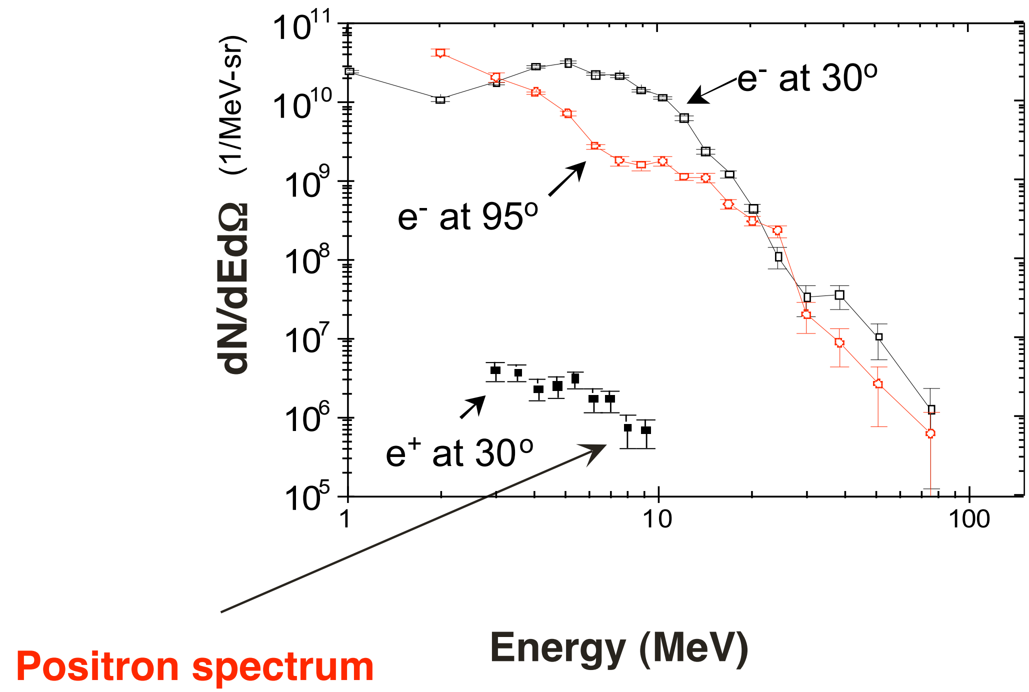
# At sufficiently high intensity, direct positron production by laser driven electrons is possible

**Experiment proposed by Liang et al. PRL 81, 4887 (1998)**



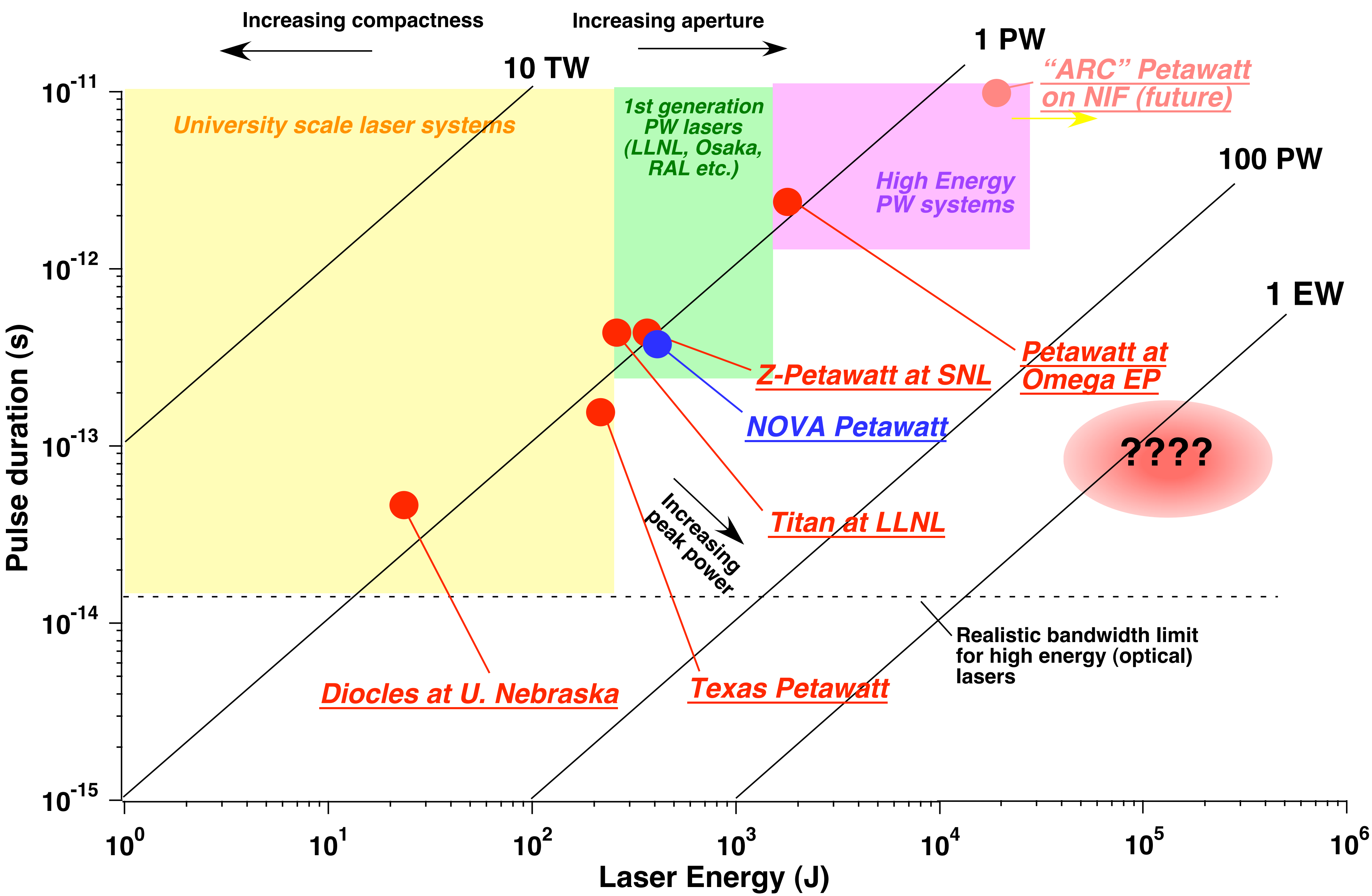

**Strong ponderomotive forces drive electrons → $T_{hot}$ ~ 1 MeV**

**Hot electron and positron spectrum measured from the LLNL PW laser**




**Production of a pair plasma results and the explosion of this plasma results in an e⁻e⁺ fireball → with potential relevance to gamma ray bursts**

# How high in laser power can we go using chirped pulse amplification?



# The science enabled by an exawatt laser has yet to be examined in detail

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

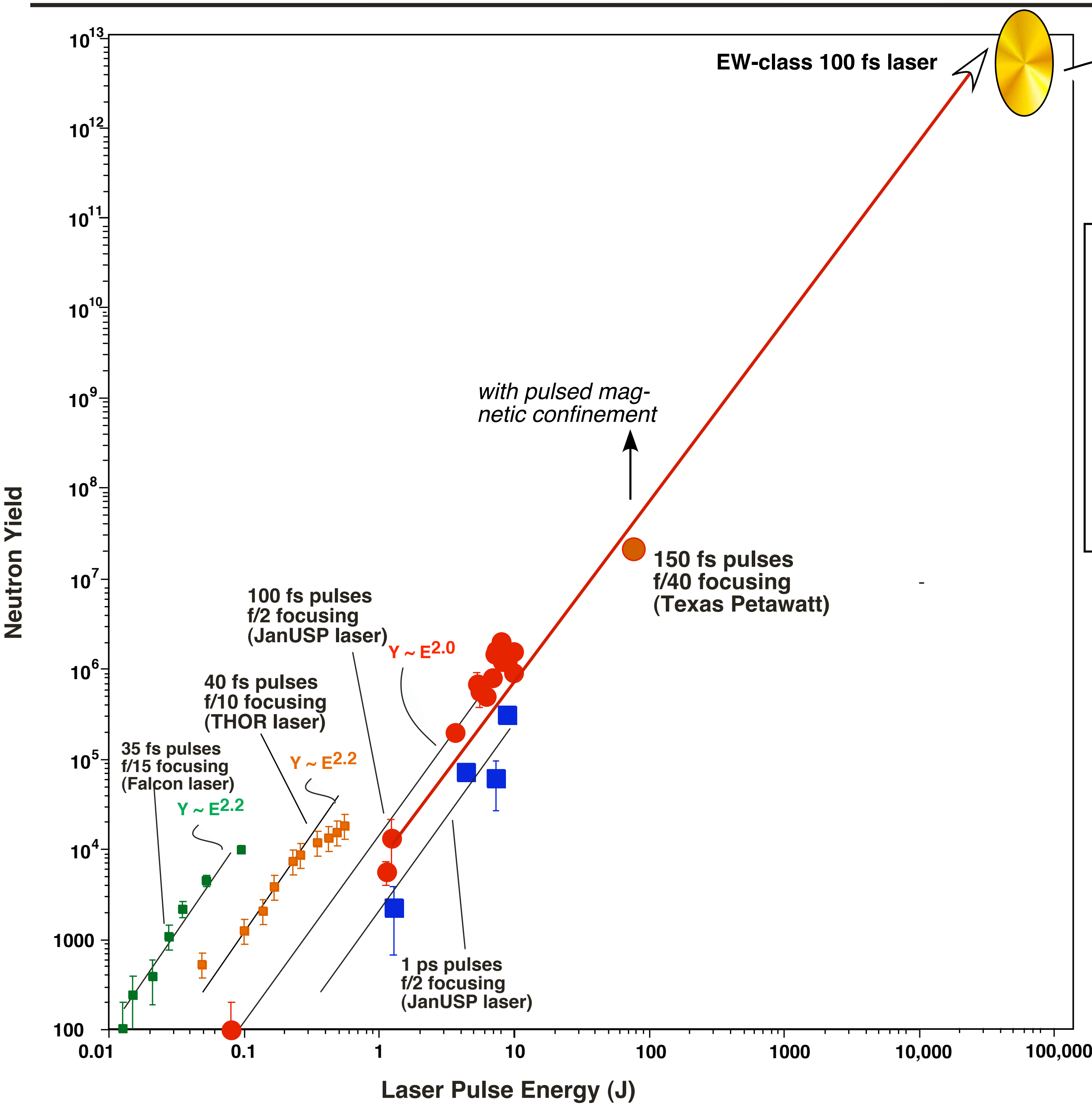
*Electron quiver energy: ~ 10 GeV*

*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*

# An exawatt-class laser could produce a unique plasma environment for possible nucleosynthesis experiments




**Plasma conditions:**
**$kT_i$ 20 keV**
**plasma volume 1 $cm^3$**
**(cylinder d = 5 mm; l = 2 cm)**

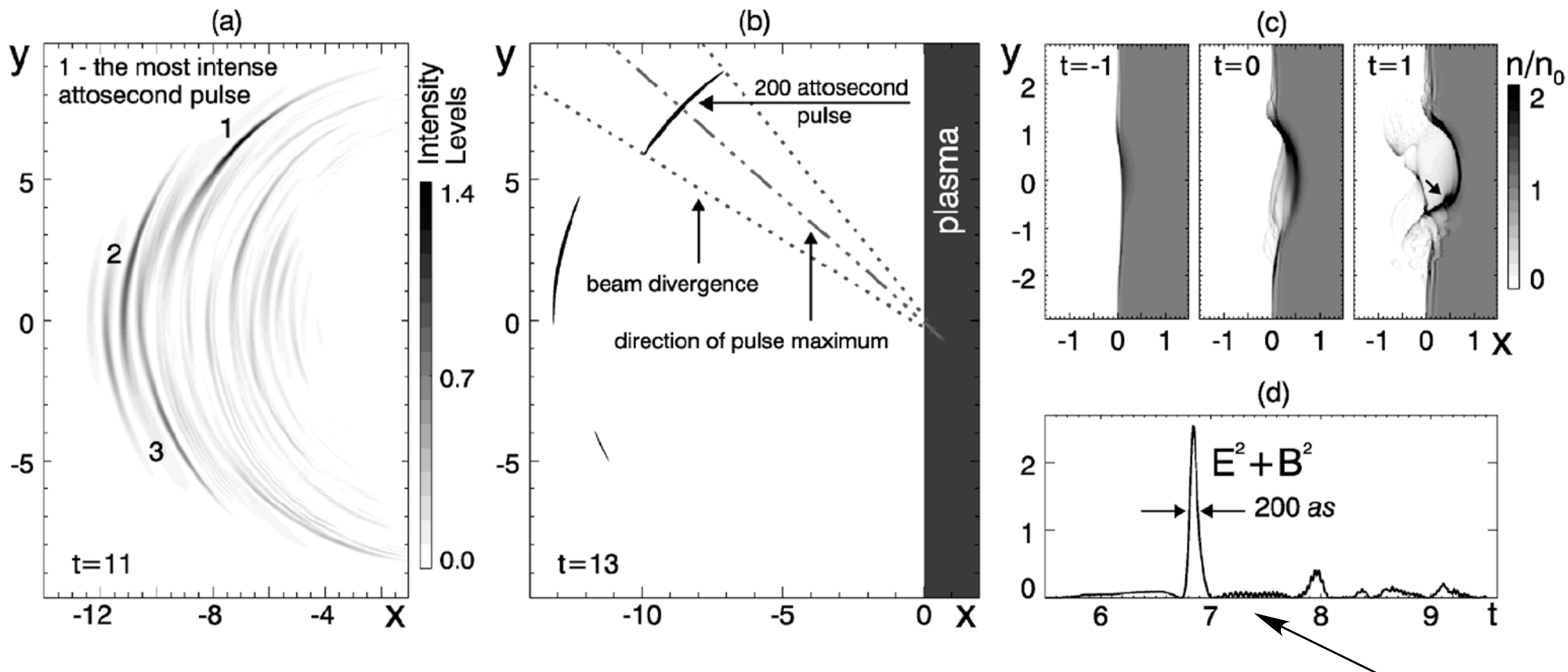
**ion density $10^{19}$ - $10^{20}$ $cm^{-3}$**

**Inertial lifetime of plasma 10 ns**
*(possibly longer with addition of pulsed magnetic field)*

***Possible environment for nucleosynthesis?***

**$10^7$ less density than NIF but...**
**$10^3$ times longer plasma life**
**$10^2$ - $10^3$ times greater volume**
**~ $10^2$ - $10^3$ times greater shot rate**

# Relativistic motion of macroscopic amounts of matter (plasma) might become possible

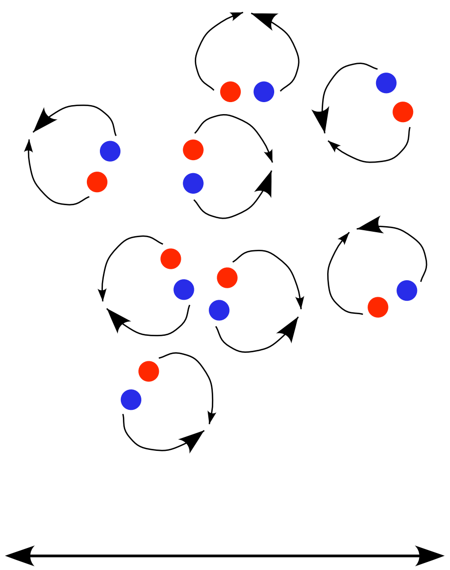



**Attosecond pulses are reflected from the relativistically moving plasma surface**

N. M. Naumova et al. "Relativistic Generation of Isolated Attosecond Pulses in a $\lambda^3$ Focal Volume" Phys. Rev. Lett. 92, 063902 (2004)

# A strong field can induce effects in virtual pairs produced in the vacuum

*Cartoon of virtual pairs in the vacuum*



Polarizing field

Virtual $e^-e^+$ pair lifetime $\Delta t \sim \hbar/mc^2 \approx 10^{-21}$ s

Field required to accelerate electron to $mc^2 \approx eEc\Delta t$

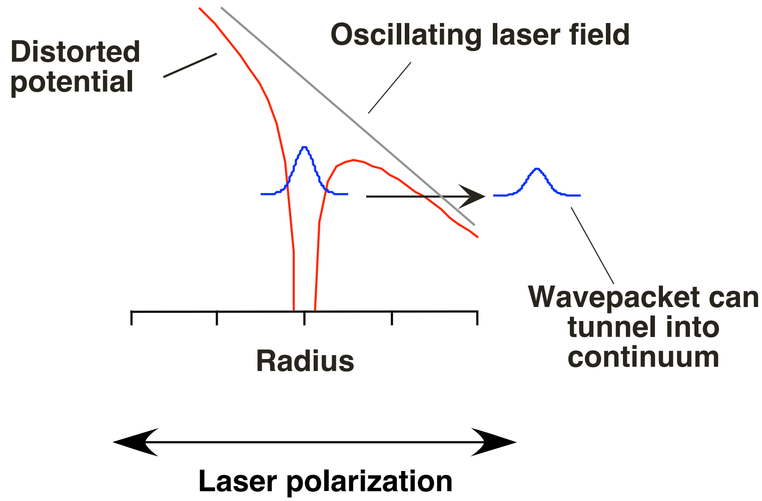
$$E_{crit} = m^2c^3/e\hbar = 1.6 \times 10^{16} \text{ V/cm}$$

**Vacuum physics at extreme fields has never been explored**
**Unanswered questions in QED/Standard Model:**
**e.g. why don't vacuum fluctuations gravitate?**

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

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

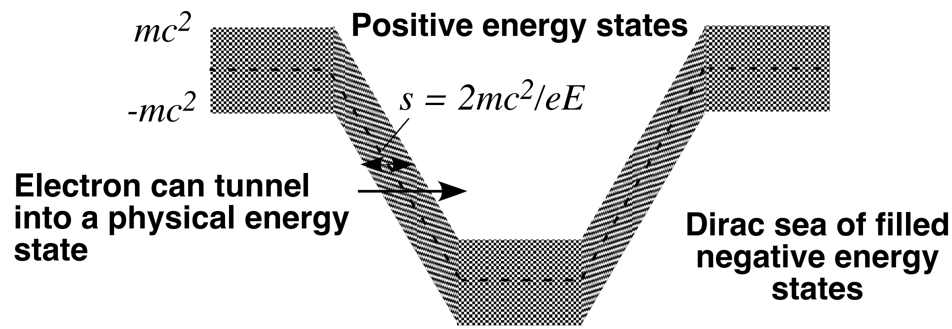
## *Atom*




**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 x 10$^{16}$ W/cm$^2$**

## *Vacuum*




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

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

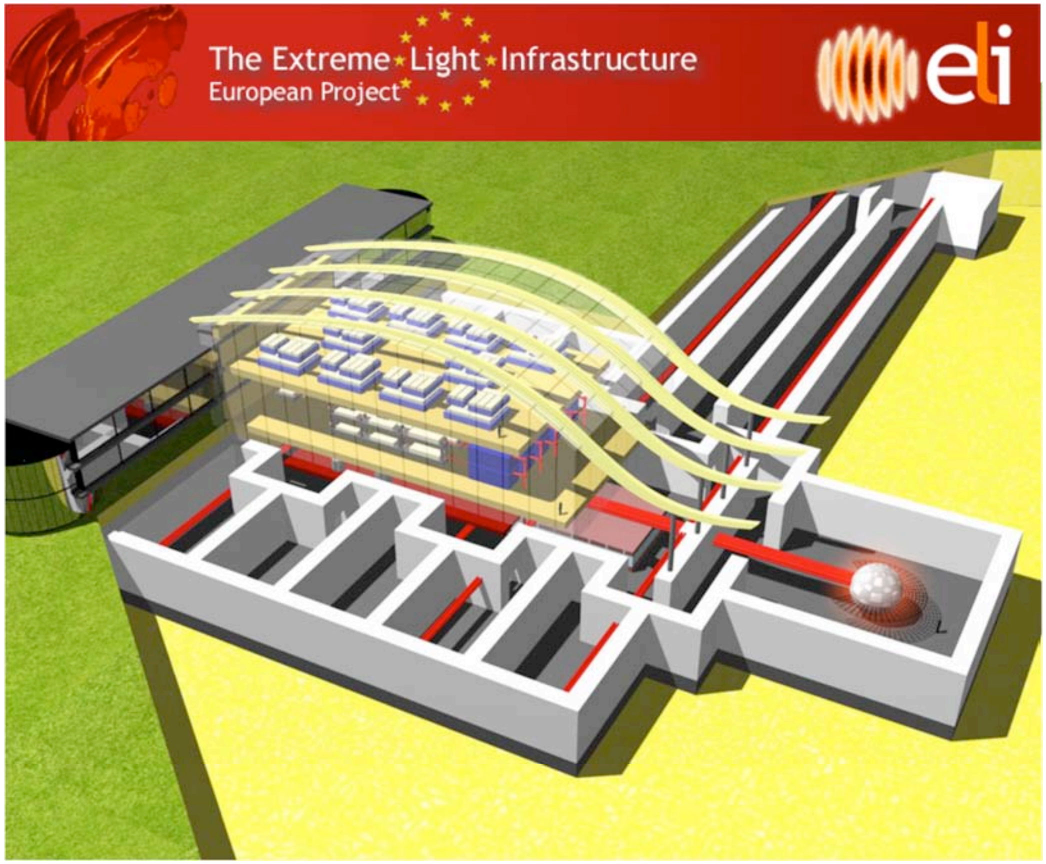
$E_S = m^2c^3/e\hbar$ **=1.3 x 10$^{16}$ V/cm  Intensity ~ 2.2 10$^{29}$ W/cm$^2$**

**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 10-100 PW laser it might be possible to observe birefringence of the vacuum**

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




**Three ELI Pillars**

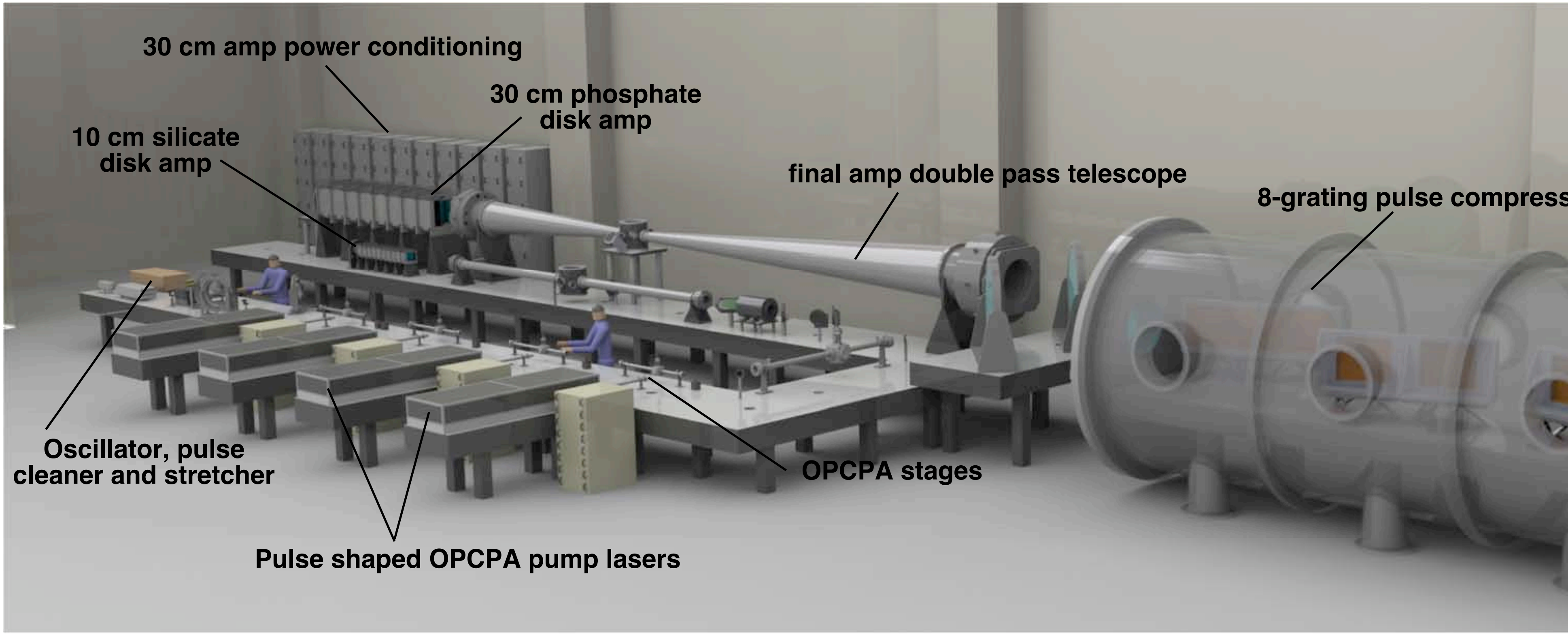
• **Bucharest, Romania: ELI - NP**
**Devoted to nuclear physics with intense lasers and gamma beams**

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

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

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

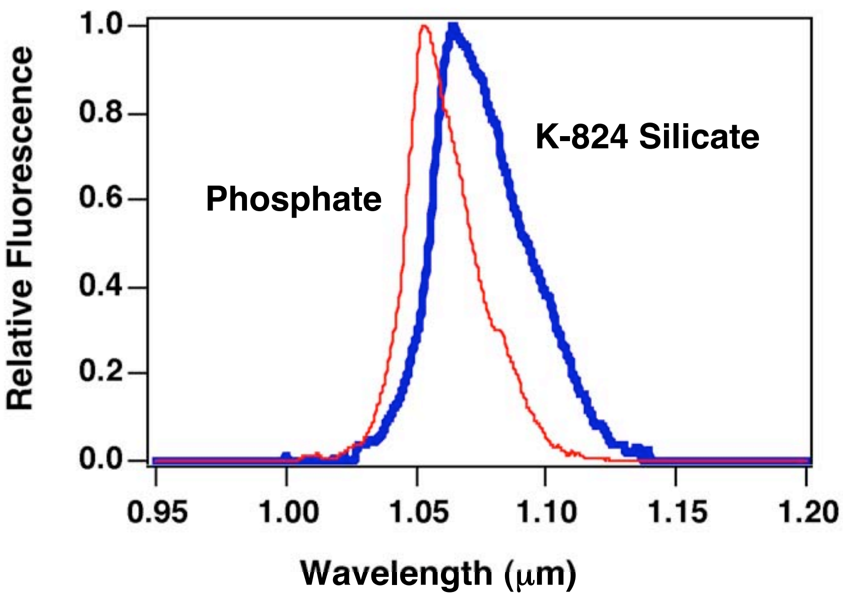
***Mechanical Engineering conception of the 10 PW Hybrid Mixed glass laser***




**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**

# We have isolated two candidate glasses which have a broad gain spectrum and good gain properties

## K-824 Tantalate/Silicate glass



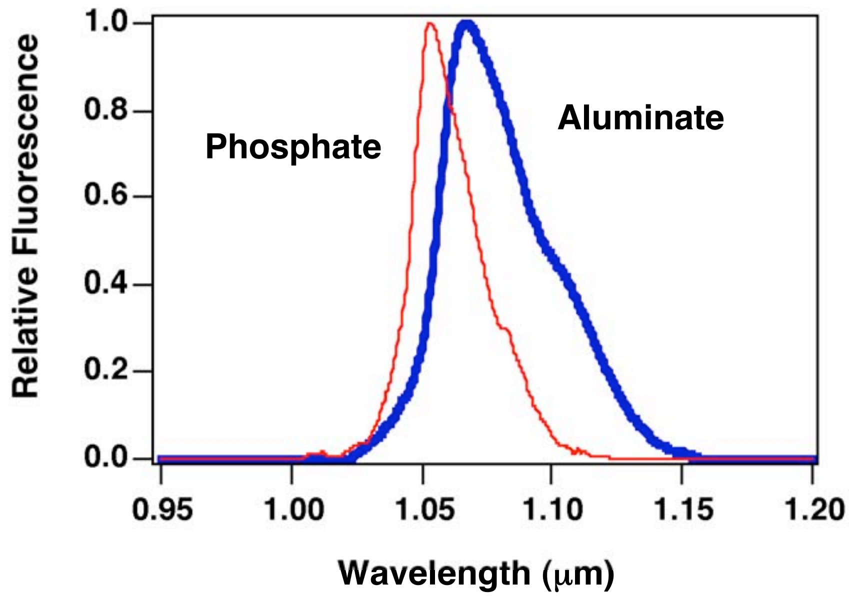

Peak Wavelength: 1065 nm

Peak cross section: 2.4 x $10^{-20}$ $cm^2$

Linewidth (FWHM): 38.2 nm

| | |
|---|---|
| $Ta_2O_5$ | 57% |
| $SiO_2$ | 17% |
| MgO | 10% |
| BaO | 15% |
| $Nd_2O_3$ | ~1% |

## L-65 Aluminate glass




Peak Wavelength: 1067 nm

Peak cross section: 1.8 x $10^{-20}$ $cm^2$

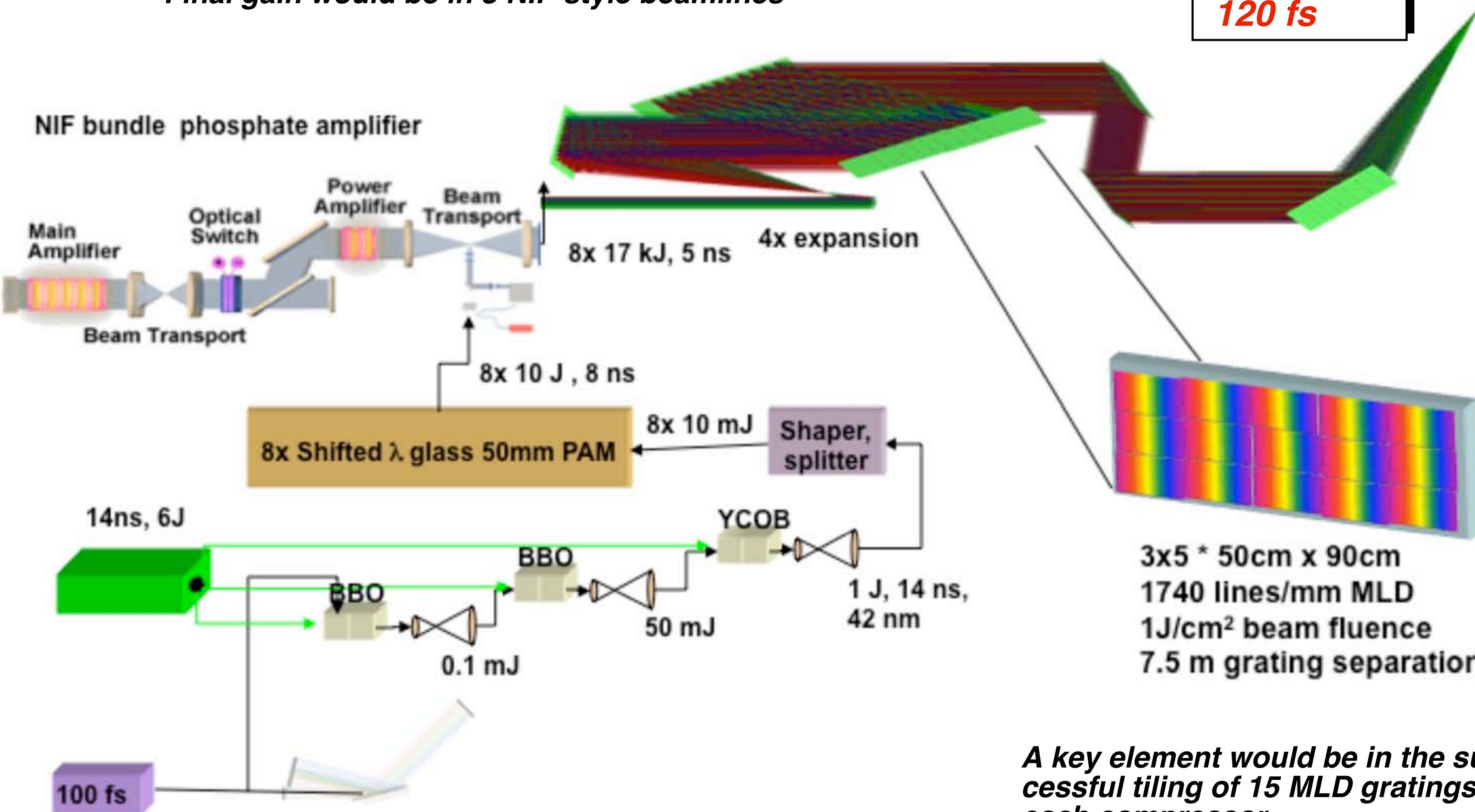
Linewidth (FWHM): 41.2 nm

| | |
|---|---|
| $Al_2O_3$ | 42% |
| CaO | 38% |
| BaO | 10% |
| $SiO_2$ | 8% |
| $Nd_2O_3$ | ~4% |

# 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*

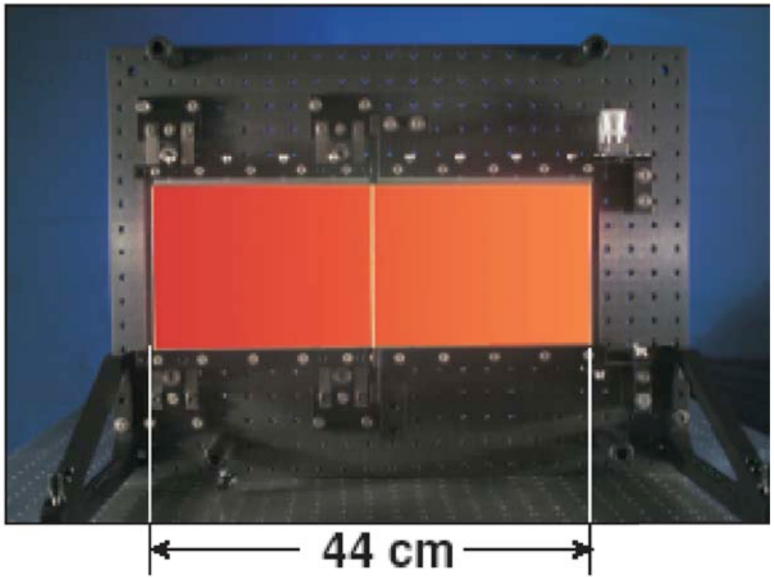



*A key element would be in the successful tiling of 15 MLD gratings for each compressor*

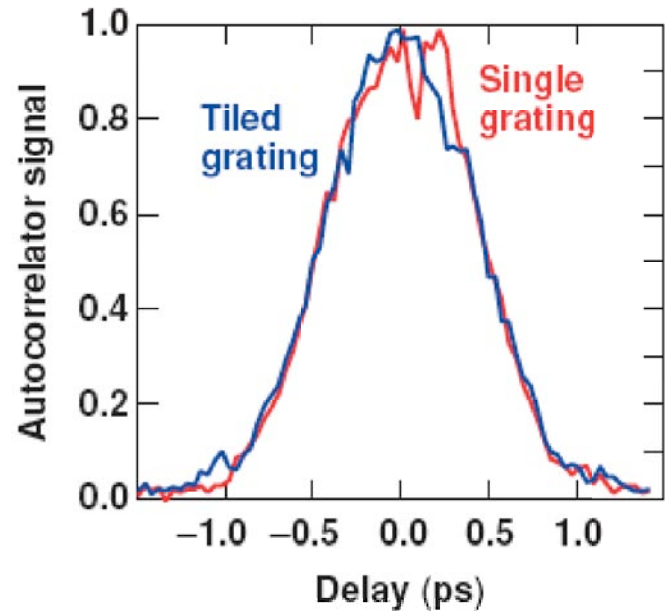
# The high energy amplifier architecture of a mixed-glass Exawatt laser would be based on NIF technology

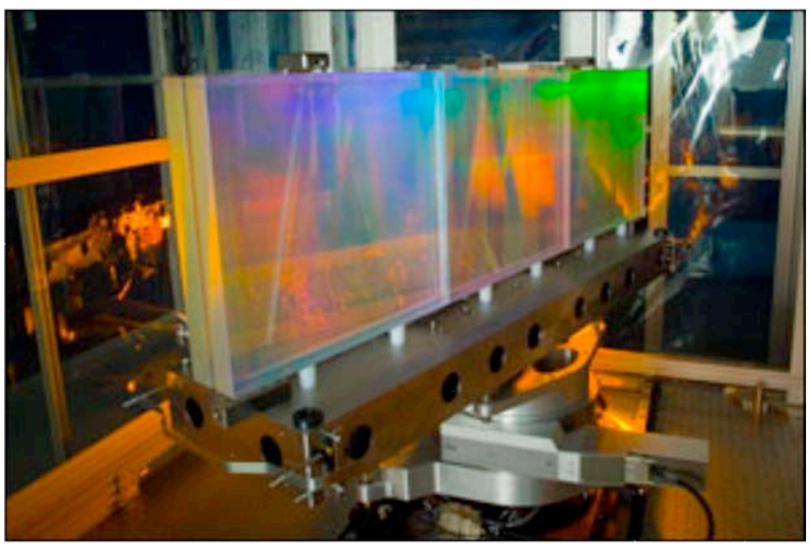
# The idea of tiling multiple gratings for compression of 1 μm pulses has been demonstrated at Omega EP

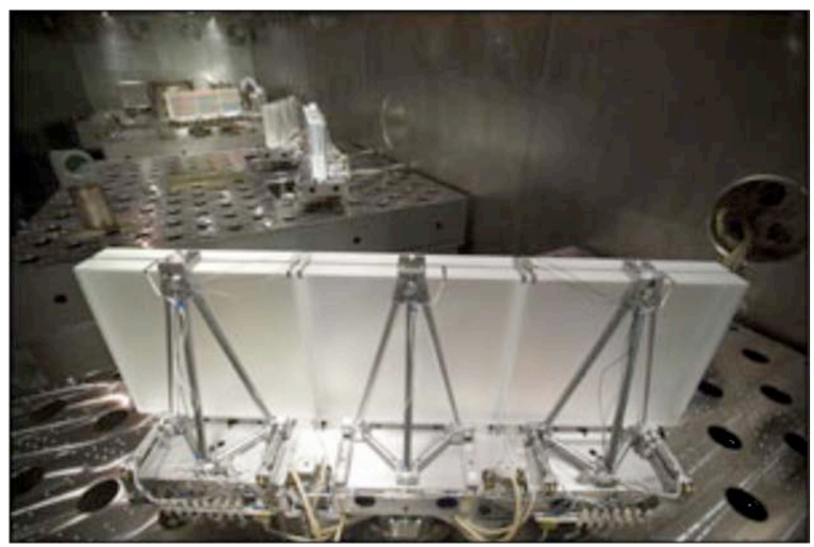
*Two-grating phased array at the U. of Rochester*




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





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

- *Can 10 PW be built in five years and*
- *Is there a technology route to an exawatt 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 > 100J are possible and it is possible to build a 10 PW laser on this technology now***