Petawatt to Exawatt Lasers

The technology and applications of the most powerful lasers ever built

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

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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.

Ultrafast optical pulse: \( \sim 3 \times 10^{-14} \text{ sec} \)

One minute: \( 6 \times 10^1 \text{ sec} \)

Age of the universe: \( \sim 2 \times 10^{17} \text{ sec} \)

- Time scale of atomic motions
- Time scale of human motions
- Time scale of interstellar motions
Modern high power lasers are based on the “master oscillator, power amplifier” architecture

**MOPA laser chain**

- Oscillator
- Increasing energy
- 1st amplifier
- Telescope to expand size of laser beam
- 2nd amplifier
- 3rd amplifier
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.

**Short Pulse Oscillator**

- Short pulse - $10^{-13}$ sec long
- 1st amplifier
- Telescope to expand size of laser beam
- 2nd amplifier
- 3rd amplifier
- Damage...ouch!!
- Pulse now very high power

$n = n_0 + n_2 I(r,t)$

Phase delay at high intensity

$I(r,t)$
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.

So...stretch out the spectrum.

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

Grating

\[ d (\sin \theta_m + \sin \theta_i) = m\lambda \]  

Red travels less distance than blue.
Using this stretching trick, we can amplify very short pulses...and then recompress them *after* amplification.

2) Using gratings, the pulse is stretched by 10,000 x

3) Long pulses are now safe to amplify in laser amplifiers

4) After amplification, the pulses are recompressed with gratings

5) Resulting pulse is short (20 - 1000 fs) and high energy (~ 1 J)


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 ~ 0.001 - 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

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

Large scale Ti:sapphire crystals
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.

Nd:glass absorption spectrum

<table>
<thead>
<tr>
<th>Wavelength (Å)</th>
<th>% Absorption</th>
</tr>
</thead>
<tbody>
<tr>
<td>4000</td>
<td>100</td>
</tr>
<tr>
<td>5000</td>
<td>90</td>
</tr>
<tr>
<td>6000</td>
<td>70</td>
</tr>
<tr>
<td>7000</td>
<td>60</td>
</tr>
<tr>
<td>8000</td>
<td>50</td>
</tr>
<tr>
<td>9000</td>
<td>40</td>
</tr>
<tr>
<td>10,000</td>
<td>30</td>
</tr>
</tbody>
</table>
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

- Cross Section $\times 10^{-20}$ cm$^2$
- Wavelength (μm)

- APG1 Nd:phosphate
- Q246 Nd:silicate

$\Delta \lambda \sim 30$ nm

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/cm²

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

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: $4.3 \times 10^{-20}$ cm$^2$
- Linewidth (FWHM): 21.1 nm
- Nd$_2$O$_3$ ~3%
P$_2$O$_5$ ~97%

**LG-680 Silicate glass**
- Peak Wavelength: 1061 nm
- Peak cross section: $2.9 \times 10^{-20}$ cm$^2$
- Linewidth (FWHM): 28.2 nm
- Nd$_2$O$_3$ ~3%
SiO$_2$ ~97%
The Texas Petawatt is designed to maintain broad bandwidth through the entire chain.

- Mode-locked oscillator: 100 fs, (16 nm), 2 nJ
- Broadband OPCPA stages: Gain factor: $10^9$, energy gain: 1.2 J
- Mixed glass stages: Gain factor: 200, energy gain: 250 J
- Compressor: 200 J, 150 fs, 1.3 PW

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

Transform limited pulse duration: $\tau = \frac{.441/c}{\lambda^2/\Delta\lambda}$
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.

- 4J custom laser
- 1J commercial laser
- Pump beam spatial profile @ 4J
- Pump beam temporal profile @ 4J
- Δτ = 4.3 ns
The Nd:silicate rod amplifier has been installed and tested.
Two 315 mm disk amplifiers from NOVA are used in each beamline as the final laser amplifiers.
The pulsed power for the 31 cm disk amplifiers is assembled and delivers 500 kJ of electrical energy.

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

One side of bank drives
One of two 31 cm amps

Two series ignitrons switches

Graph: Flashlamp Current (kA) vs Time (msec)

Texas Petawatt Pulsed Power
Disk Amplifier Shot
V = 21.5kV
I_{max} = 3kA
7/31/07
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/cm²

...of sun light on Earth ~ .14 W/cm²

...of a focused HeNe laser ~ 500 W/cm²

...at the surface of the sun ~ 7000 W/cm²

...near a black hole during a gamma ray burst

~ 10,000,000,000,000,000,000,000 (10^{20}) W/cm²

...of a petawatt CPA laser

> 1,000,000,000,000,000,000,000,000 (a billion-trillion or 10^{21}) W/cm²
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

**High Field Science**

- **High electric fields**
  
  \[ E \sim 10^{11} - 10^{12} \text{ V/cm} \]
  
  Field strength is 100 to 1000 times that of the electric field felt by an electron in a hydrogen atom

- **High electron quiver energy**
  
  \[ U_{osc} = 1 \text{ MeV} - 10 \text{ MeV} \]
  
  Electron motion can become relativistic \( (U_{osc} > m_e c^2 = 512 \text{ keV}) \)

**High Energy Density Science**

- **Concentrated energy**
  
  Energy density in a femtosecond pulse is \( 10^{11} \text{ J/cm}^3 \)
  
  Corresponds to \( \sim 1 \text{ MeV} \) per atom at solid density

- **High brightness and pressure**
  
  Radiance exceeds that of a 1 MeV black body
  
  Light pressure \( P = \frac{l}{c} = 30 - 3000 \text{ Gbar} \)
High energy density matter is created by heating dense plasma to very high temperature.

**Temperature and Density Conditions for Different Plasmas**

- **HED Matter**
- Pressure > 1 Mbar
- Strongly coupled plasmas
- Mean free path > 1 cm
- Debye radius > 1 cm
- DD fusion ignition temperature
- DT fusion ignition temperature
- Solar wind
- Earth plasma sheet
- Earth ionosphere
- Room temperature
- Glow discharge
- High pressure arc
- Shock tubes
- Z-pinches
- Solid target laser plasmas
- ICF/NIF
- Focus
- Short pulse laser heated gases
- Pair plasmas

**Diamond anvil cells**
- **Atmospheric density**

**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.

High Intensity Laser Irradiation (>10^16 W/cm²)

- Single atoms
  - Tunnel Ionization
  - Above Threshold Ionization
  - Electron energies ~ 100 eV

- Molecules
  - Coulomb explosion
  - Ion energies ~ 100 eV

- Clusters
  - Collective phenomena?
  - Ion explosion?
  - High temperature plasma formation
  - Collisional processes
  - Collective phenomena
  - T_e ~ 1000 eV
  - T_i ~ 100 eV

- Solids
  - Laser wavelength

Size scale:

- 1 Å
- 10 Å
- 100 Å
- 1000 Å
- 1 μm
- 10 μm
Highly non-perturbative laser intensities push photo-ionization into the tunneling regime

A strong laser field can ionize an atom by tunneling

Binding atomic potential

Ground state wave packet

Radius

Distorted potential

Oscillating laser field

Radius

Wavepacket can tunnel into continuum

Photo-Ionization Intensity Threshold

Laser Intensity (W/cm²)

Ionization Potential (eV)

Accessible with the Texas Petawatt

Current Laser Technology

Recent evidence for this in UT/UM experiments

Experimentally observed to date

He⁺

He²⁺

Ne⁺

Ne⁶⁺

Ne⁹⁺

Ar¹⁰⁺

Ne⁸⁺

Kr³⁴⁺

U⁸²⁺

U⁹⁰⁺
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

\[ \gamma \approx \frac{c v_z}{c z} \Rightarrow \text{time needed to slide off the peak is} \]

\[ \gamma T \approx 4/T \]

where \( T \) - period of the laser light.

Near GeV electrons ejected within 4° of the laser axis

Monte Carlo simulation using a focused PW beam

Ar\textsuperscript{17+} ionization

\[ I = 5 \times 10^{21} \text{ W/cm}^2 \]

Ionization 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

\[ \gamma_{\text{max}} \approx e E_{\text{max}} \frac{\theta z_R}{2 m_e c^2} \]

Near GeV electrons ejected within 4° of the laser axis

\[ \tan^2 \theta = \frac{2}{\gamma-1} \]
A cluster irradiated by an intense fs laser, violently explodes, ejecting ions with high kinetic energy

1) time = - 100 fs

55 atom argon cluster before irradiation

2) time = - 20 fs

Laser field begins to heat and expel electrons from cluster
electrons confined by space charge forces

3) time = + 20 fs

Ions explode by Coulomb forces

Simulation with $I = 10^{16} \text{ W/cm}^2$
$\Delta \tau = 50 \text{ fs}$
A gas of exploding deuterated clusters can produce a burst of fusion

Length ~ 1-10 mm
Average density ~ $10^{19} - 10^{20}$ cm$^{-3}$

Focused laser in Hot fusion plasma
Cooling jacket
Deuterium cluster plume
Laser in Hot fusion plasma

Relevant fusion reactions:

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

$D + T \rightarrow He^4 (3.5 \text{ MeV}) + n (14.1 \text{ MeV})$
We have produced \( \sim 2 \times 10^7 \) DD fusion n/shot in clusters with the Texas Petawatt Laser (\( \sim 100 \) 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 \( kT \sim 2 \text{keV} \) deuterium ion peaks on 10J rod shots.

\[ kT_i = 20 \text{keV} \]
A 1 MA pulsed power source constructed at Sandia will be installed on the TPW in February

Recent Results with $\frac{1}{2}$ MA Test Chamber

- 400 kA peak current
- Time to peak $\sim$ 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
The 100 fs TPW will allow flat-field resonant, multi-GeV laser wakefield acceleration of electrons

**PETAWATT LWFA PARAMETERS:**

- $n_{\text{resonant}} \sim 3 \times 10^{17} \text{ cm}^{-3}$ ($P_{He} \sim 5$ Torr)  $\Rightarrow$ negligible ionization distortions
- $L_{\text{dephasing}} \sim z_{\text{Rayleigh}} \sim 15 \text{ cm}$  $\Rightarrow$ long accelerating length
- $E_z \sim 0.5 \text{ GV/cm}$  $\Rightarrow$ largex accelerating field
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.

**Diagram Description:**
- Short laser pulse or burst of particles heats material.
- Heated Sample near solid density.
- Measure temperature from blackbody radiation.
- Short optical pulse measures reflectivity and expansion.
- Time resolved emission measures reflectivity and expansion.

**Plasma ρ - T Diagram:**
- Classic Plasma: $P \sim 1$ Gbar.
- Dense plasma: $P \sim 5$ Mbar.
- Degenerate: $\Gamma = 1$.
- Quantum Degenerate Hot Matter: $\Gamma = 100$.
- Conditions deep in a star.
- Adiabatic expansion.
- Heavily heated sample near solid density.
- Measure temperature from blackbody radiation.
- Measure reflectivity and expansion.
- Time resolved emission.
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

$U_p = 50 \text{ keV (} 5 \times 10^{17} \text{ W/cm}^2)$

1) Oscillating laser field accelerates electrons
2) Electrons fly into target
3) Electron bunches are driven into the target spaced by one wavelength
4) Electrons are directed normal to target surface

Overdense plasma (shields field)

<table>
<thead>
<tr>
<th>Energy (eV)</th>
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<tbody>
<tr>
<td>Time (s)</td>
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</table>

Solid Target

Intense ultrafast pulse

Hot dense plasma

$z (\mu m)$

$v_{\text{vacuum}}$

$y (\mu m)$

$z (\mu m)$

$y (\mu m)$

Energy (eV)

Time (s)
With a petawatt laser, very intense, energetic pulses of protons can be produced.

Protons are present on metal foil surfaces in the form of H₂O and hydrocarbons (moderate vacuum ~10⁻⁵ Torr).

**Virtual cathode**

Laser pulse in

I > 10¹⁹ W/cm²;
~ 100 fs to 1 ps

~200 nm

~20 μm

**Typical spectrum**

Exponential; T ~ 5 MeV

Cutoff ~ 40 MeV

Log (f/E)

Energy (MeV)

**Velocity dispersion:**

10s of fs per μm

Electron "sheath"
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 $3 \times 10^{20}$ W/cm$^2$ on LLNL PW laser:

Up to 48J of protons (12% of laser energy) were observed in protons with energy >10 MeV
We have demonstrated proton heating using the LLNL 200 TW Titan laser.
Using hydrodynamic simulations we are able to evaluate various EOS tables for Al in the 10 - 20 eV region.
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.

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.

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.

Intense ultrafast pulse
Solid Target
$e^-e^+$ fireball

Pair production in relativistic plasma

Strong ponderomotive forces drive electrons → $T_{\text{hot}} \sim 1$ MeV

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

Positron spectrum

Hot electron and positron spectrum measured from the LLNL PW laser

Energy (MeV)

$dN/dEd\Omega$ (1/MeV·sr)

- $e^-$ at 30°
- $e^-$ at 95°
- $e^+$ at 30°
How high in laser power can we go using chirped pulse amplification?

Increasing compactness

Increasing aperture

University scale laser systems

1st generation PW lasers (LLNL, Osaka, RAL etc.)

High Energy PW systems

Realistic bandwidth limit for high energy (optical) lasers

1 PW

“ARC” Petawatt on NIF (future)

10 TW

100 PW

10^5 10^6

1 EW

Pulse duration (s)

Laser Energy (J)

10^1

10^2

10^3

10^4

10^0

10^1

10^2

10^3

10^4

10^5

10^6

10^{-11}

10^{-12}

10^{-13}

10^{-14}

10^{-15}

NOVA Petawatt

Titan at LLNL

Diocles at U. Nebraska

Texas Petawatt

Z-Petawatt at SNL

Petawatt at Omega EP

“ARC” Petawatt on NIF (future)
The science enabled by an exawatt laser has yet to be examined in detail

- **Focused intensity**: $> 10^{25}$ W/cm²
- **Electron quiver energy**: $\sim 10$ GeV
- **Light pressure**: $\sim 10^{15}$ bar
- **Proton quiver energy**: $\sim 100$ 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 $1 \text{ cm}^3$ (cylinder $d = 5 \text{ mm}; l = 2 \text{ cm}$)
- Ion density $10^{19} - 10^{20} \text{ cm}^{-3}$
- Inertial lifetime of plasma $10 \text{ ns}$ (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
- $\sim 10^2 - 10^3$ times greater shot rate
Relativistic motion of macroscopic amounts of matter (plasma) might become possible

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

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

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

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

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 $E = E_0 \sin(\omega t - k z)$

**Atom**
- Oscillating laser field
- Distorted potential
- Wavepacket can tunnel into continuum
- Radius
- Laser polarization

**Vacuum**
- Positive energy states
- Dirac sea of filled negative energy states
- Electron can tunnel into a physical energy state
- $s = \frac{2mc^2}{eE}$
- $W \sim \exp\left[-\frac{s}{\lambda_c}\right] = \exp\left[-2\frac{E_S}{E_0}\right]

Tunnel ionization rate

$E_{at} = 5 \times 10^9 \text{ V/cm} \quad \text{Intensity} \sim 3.5 \times 10^{16} \text{ W/cm}^2$

Polarization of atoms gives rise to nonlinearities with $E \sim 0.1\% E_{at}$

$E \sim 10^9 \text{ W/cm}^2$

Polarization of vacuum gives rise to nonlinearities with $E \sim 0.1\% E_S$

$E \sim 10^{22} \text{ W/cm}^2$

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 Wavelength: 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 Tantala/Silicate glass**
- Peak Wavelength: 1065 nm
- Peak cross section: $2.4 \times 10^{-20} \text{ cm}^2$
- Linewidth (FWHM): 38.2 nm

**L-65 Aluminate glass**
- Peak Wavelength: 1067 nm
- Peak cross section: $1.8 \times 10^{-20} \text{ cm}^2$
- Linewidth (FWHM): 41.2 nm

Chemical Composition:

**K-824 Silicate**
- Ta$_2$O$_5$: 57%
- SiO$_2$: 17%
- MgO: 10%
- BaO: 15%
- Nd$_2$O$_3$: ~1%

**L-65 Aluminate**
- Al$_2$O$_3$: 42%
- CaO: 38%
- BaO: 10%
- SiO$_2$: 8%
- Nd$_2$O$_3$: ~4%
The architecture of a mixed glass exawatt laser would be straightforward.

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.

\[ 8 \times 15 \text{ kJ} = 120 \text{ kJ in 120 fs} \]
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