Intense Lasers: High Average Power talk I
High Energy DPSSL Technology

Advanced Summer School on "Laser Driven Sources of High Energy Particles and Radiation"
Anacapri, Italy July 9-16, 2017

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Andy Bayramian

When overheated I just think of the Harding Ice Fields in Alaska

Amplification of Single Wavelength (Narrowband) High Energy Lasers Used for High Energy Density Science

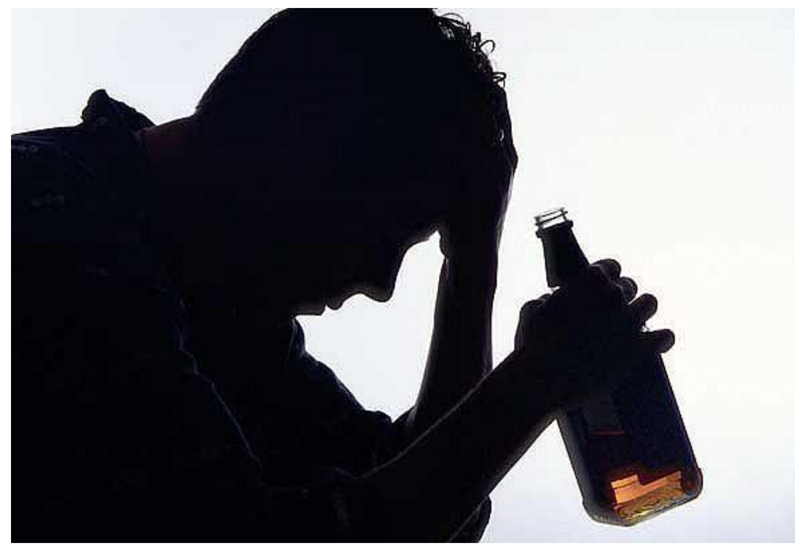
Depiction of scientists who must amplify narrowband radiation

Class #1

Amplification of Multiple Wavelengths (Broadband) typically needed for short pulse operation & secondary sources

Depiction of scientists who must amplify broadband radiation

Class #2

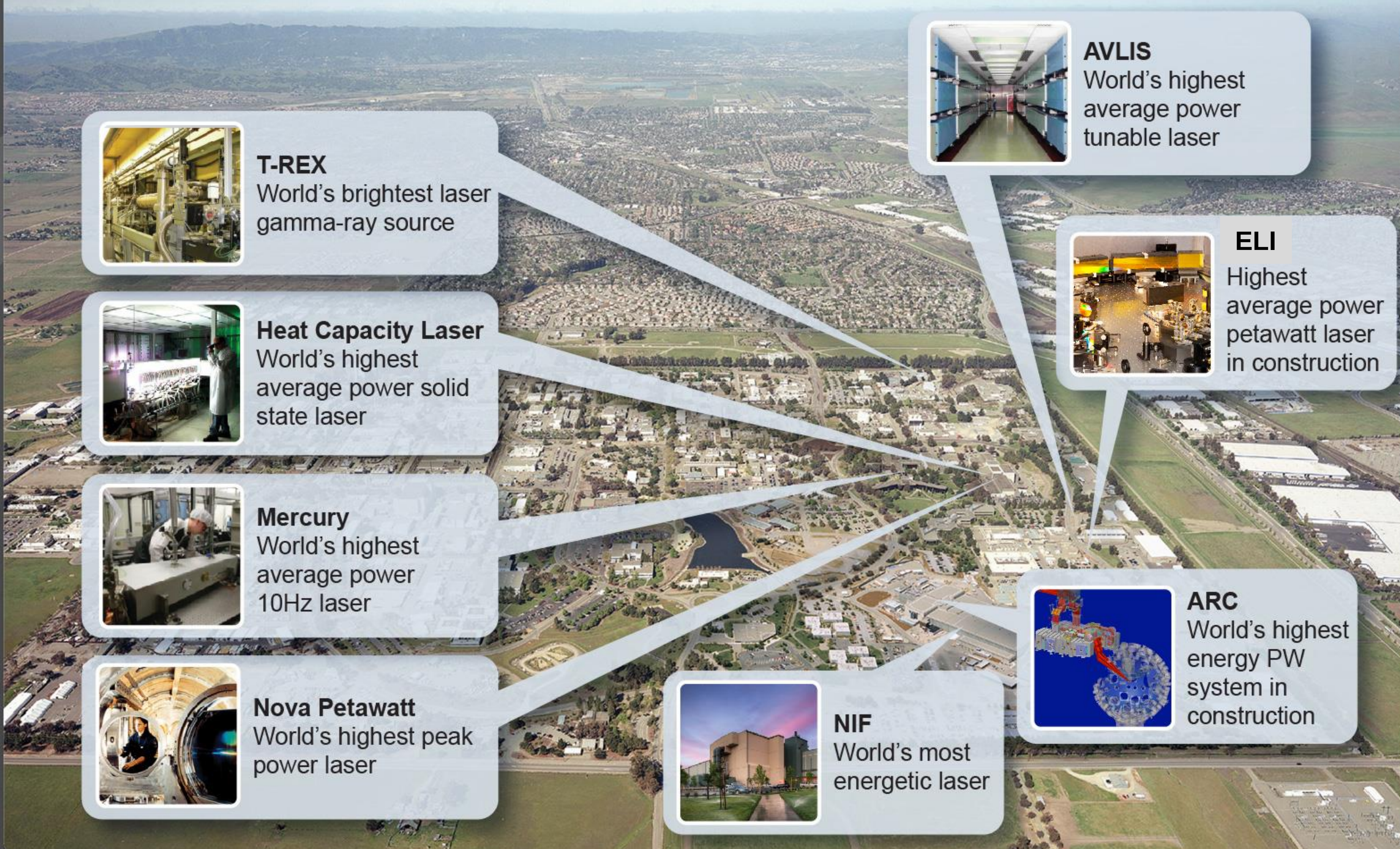


Depiction of Scientists Who Must Do Both at Average Power

Class #3

….Remember those Harding Ice Fields

40 years of Lasers at LLNL



The NIF has the highest-energy pulsed laser in the world

4 MJ at 1ω
2 MJ at 3ω
192 laser beamlines
~1-20 ns pulse

- **NIF uses a flashlamp-pumped, harmonically-converted, Nd:glass laser for a variety of experiments:**
  - **Inertial confinement fusion**
  - **High-energy-density physics**
  - **Laboratory astrophysics**
  - **Equation-of-state experiments**

NIF is the largest in a series of Nd:glass fusion lasers developed for ICF research

100 J IR

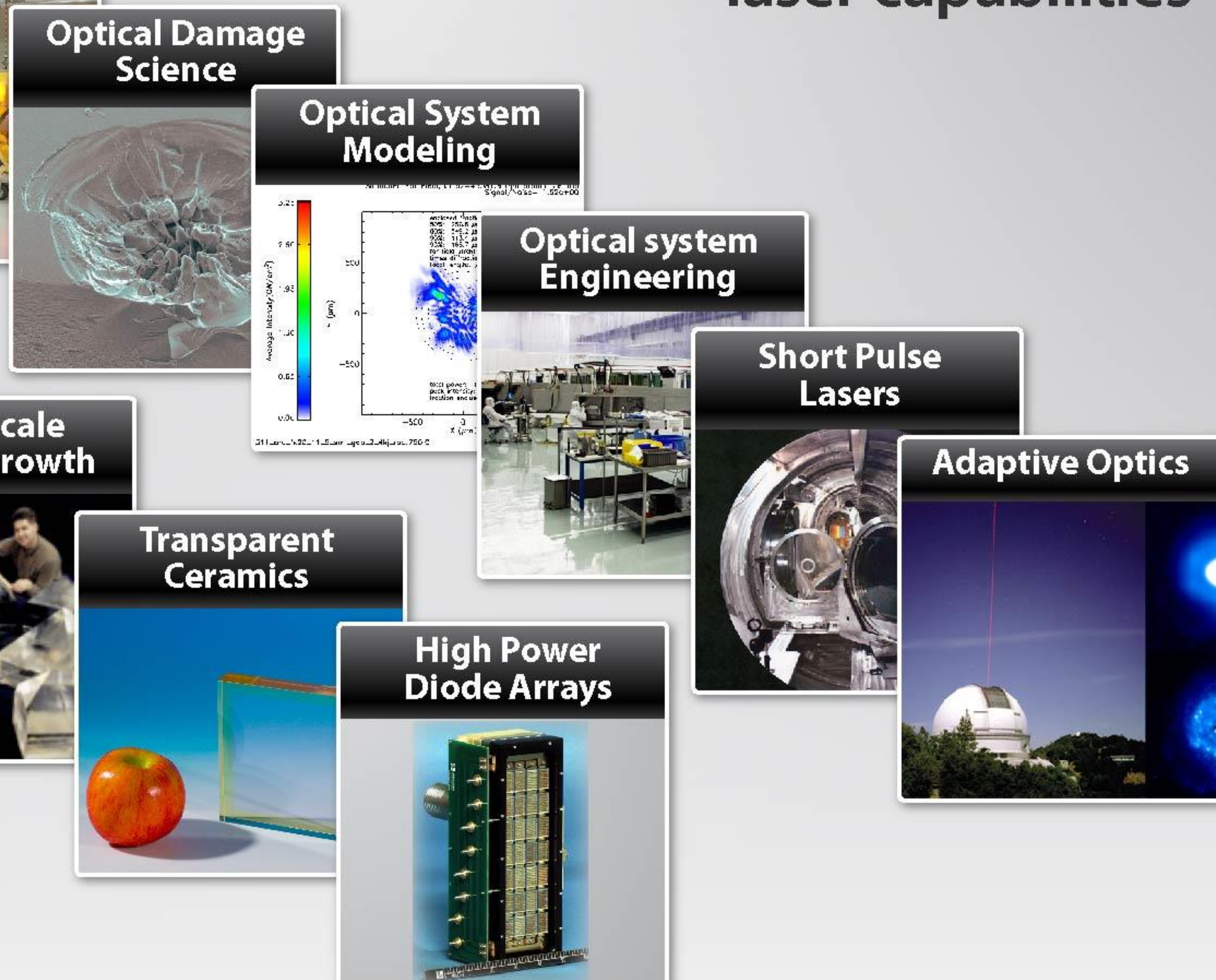
1 kJ IR

10 kJ IR

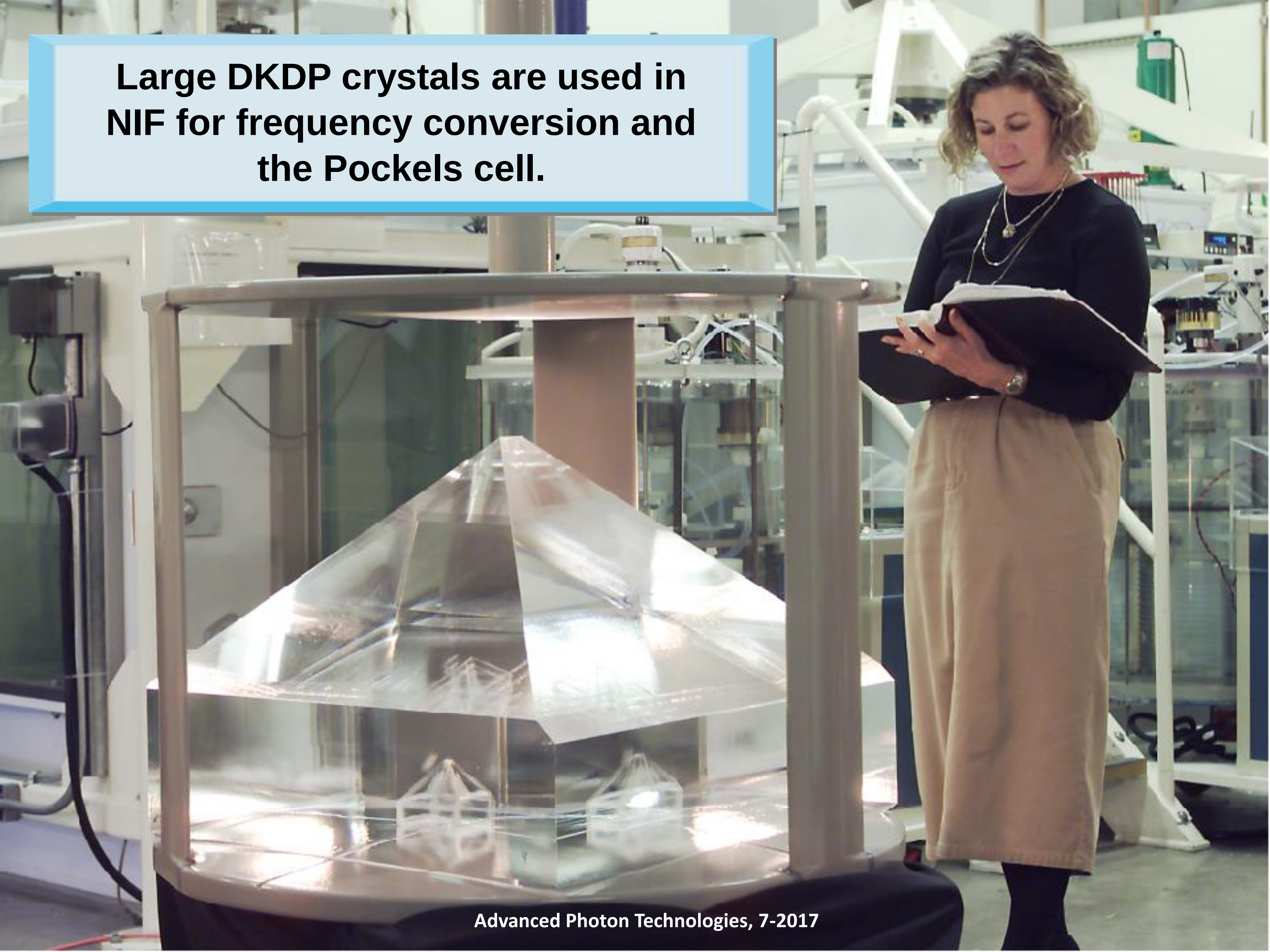
30 kJ UV

1.8 MJ UV

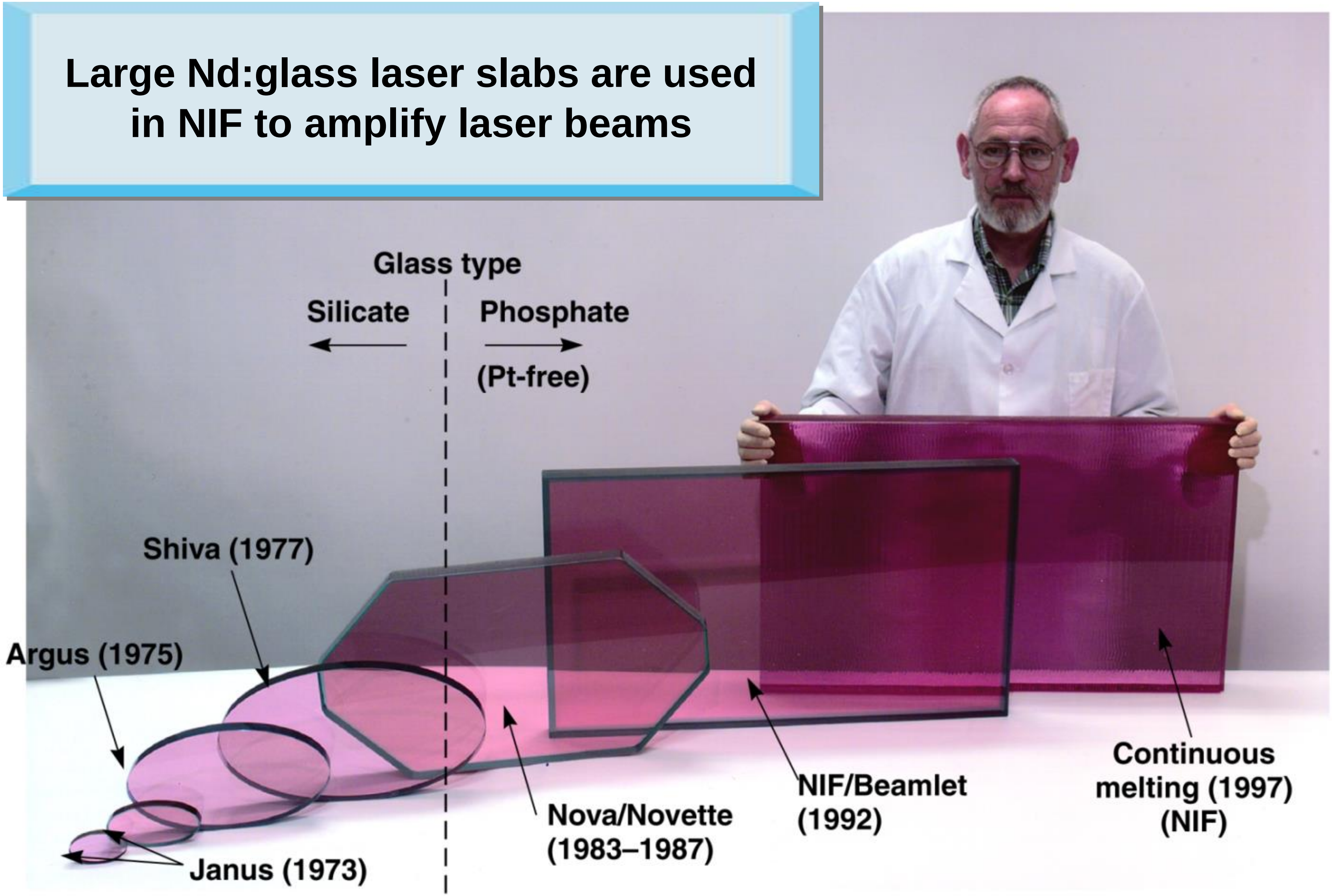
LLNL's expertise in a wide range of critical technologies underpins its laser capabilities



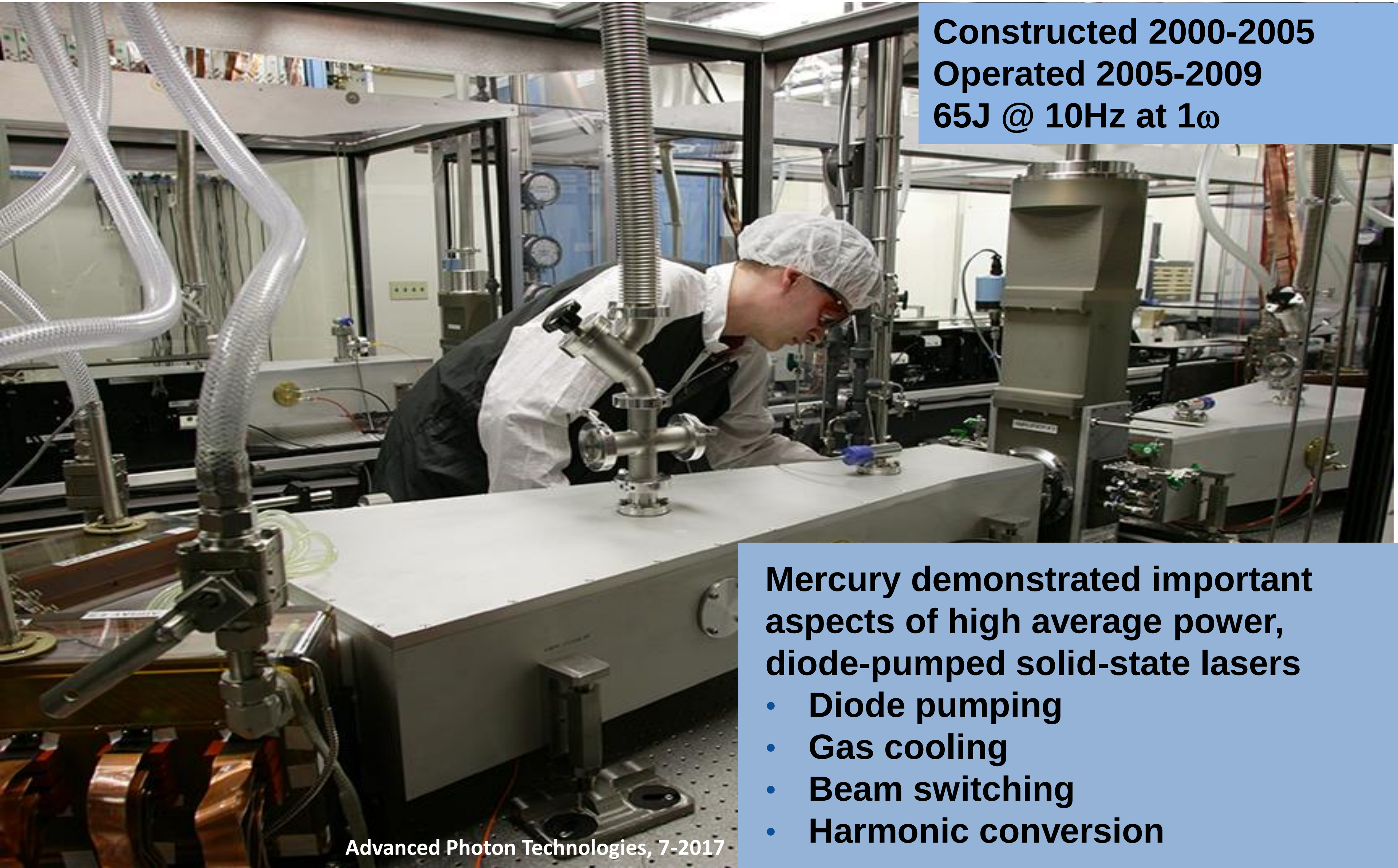
Large DKDP crystals are used in NIF for frequency conversion and the Pockels cell.



Large Nd:glass laser slabs are used in NIF to amplify laser beams



We built and tested Mercury, a scale prototype of a diode pumped solid-state laser driver for Inertial Fusion Energy



Constructed 2000-2005
Operated 2005-2009
65J @ 10Hz at 1ω

Mercury demonstrated important aspects of high average power, diode-pumped solid-state lasers

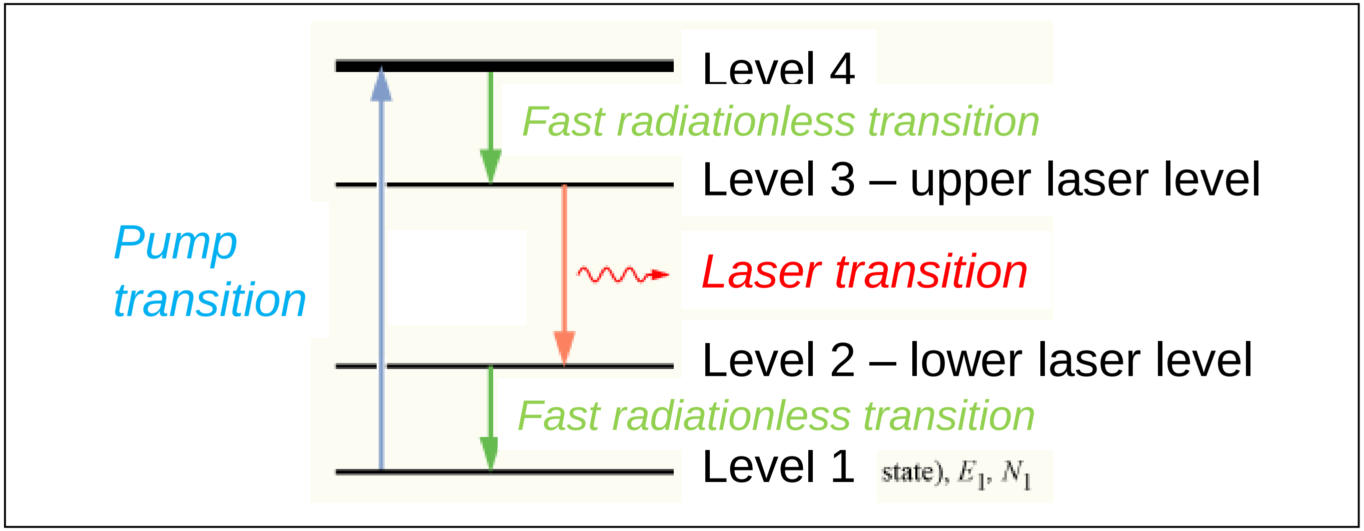
- **Diode pumping**
- **Gas cooling**
- **Beam switching**
- **Harmonic conversion**

Outline

- **Design issues for high-energy pulsed lasers**
- **Design issues for DPSSLs**

Laser gain depends on achieving a population inversion

Example: a 4-level laser



$$G(\lambda) = N_u \, \sigma_u(\lambda) - N_l \, \sigma_l(\lambda)$$

$G(\lambda)$ = gain coefficient (1/cm or 1/m)

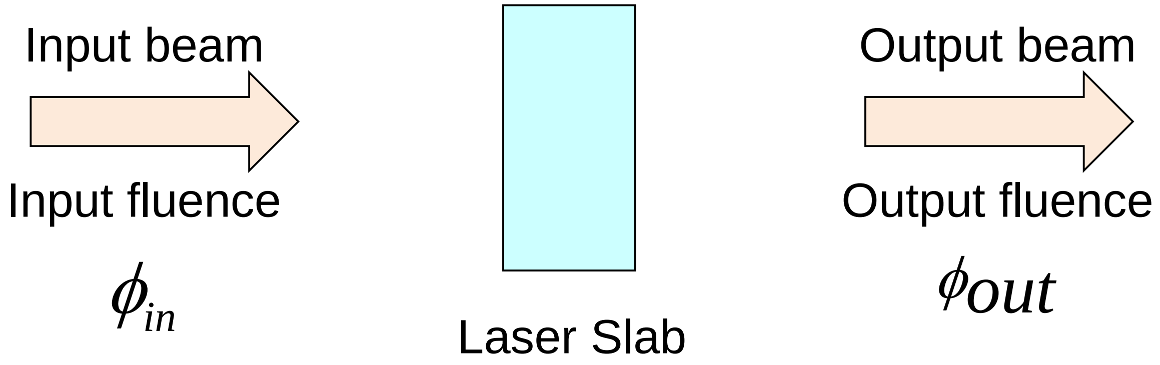
N_u = upper laser level population density

N_l = lower laser level population density

$\sigma_u(\lambda)$ = stimulated emission cross section for the upper laser level

$\sigma_l(\lambda)$ = absorption cross section for the lower laser level

Amplification extracts energy from the gain medium



Extractable stored fluence for a 4-level laser

$$\phi_{stored} = h\nu_l \int_0^L N_u(z)dx$$

Energy conservation says

$$\phi_{out} - \phi_{in} = \phi_{stored,initial} - \phi_{stored,final}$$

The Frantz-Nodvik model for saturating amplifiers simplifies gain calculations

$$e^{G_{s,inital}} = \frac{e^{G_{out}} - 1}{e^{G_{in}} - 1}$$

where $e^{G_{s,inital}}$ is the initial small-signal gain

$$G_{s,initial} = \frac{\phi_{stored}}{\phi_{sat}} \qquad G_{in} = \frac{\phi_{in}}{\phi_{sat}} \qquad G_{out} = \frac{\phi_{out}}{\phi_{sat}}$$

and $\phi_{sat} = \frac{h\nu_l}{\sigma_e}$ is the saturation fluence for a four-level laser

L.M. Frantz and J.S. Nodvik, Theory of Pulse Propagation in a Laser Amplifier, Journal of Applied Physics 34, pp. 2346-2349 (1063)

Energy extraction efficiency is often an important operating parameter of the laser

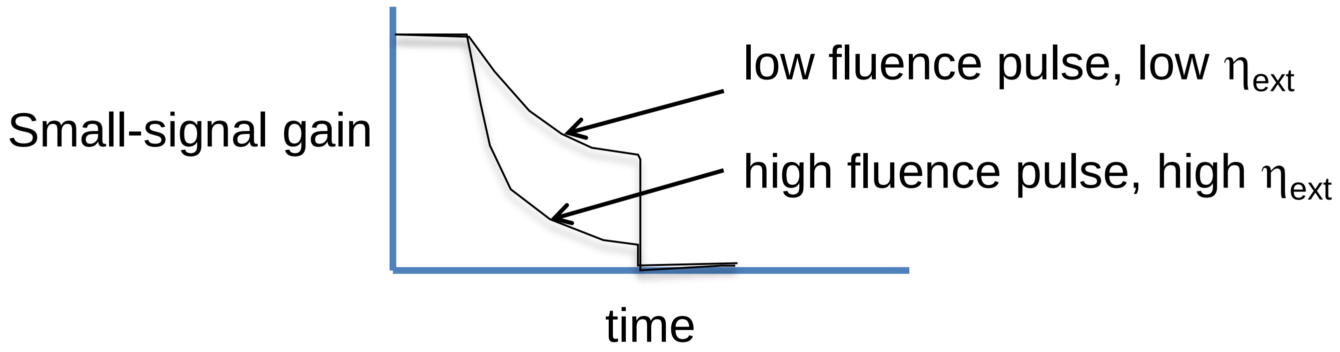
$$\eta_{ext} = \frac{\phi_{stored,init} - \phi_{stored,final}}{\phi_{stored,init}}$$

$$= \frac{G_{s,initial} - G_{s,final}}{G_{s,initial}}$$

- **Stored energy often goes hand in hand with the cost of the amplifier**
- **High extraction efficiency is important for getting the most out of investments**

High extraction efficiency causes the amplified pulse to be distorted

Gain in the amplifier falls as energy is extracted

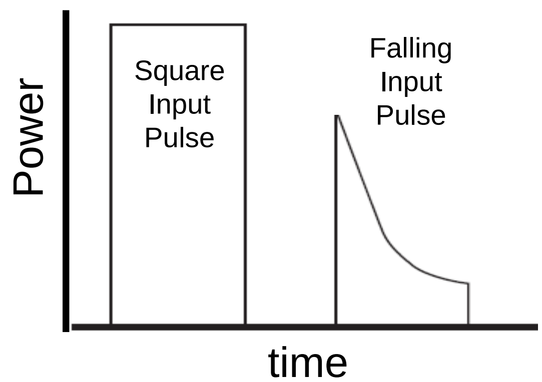


"Square pulse distortion" (SPD) is used to quantify the beam shape distortion

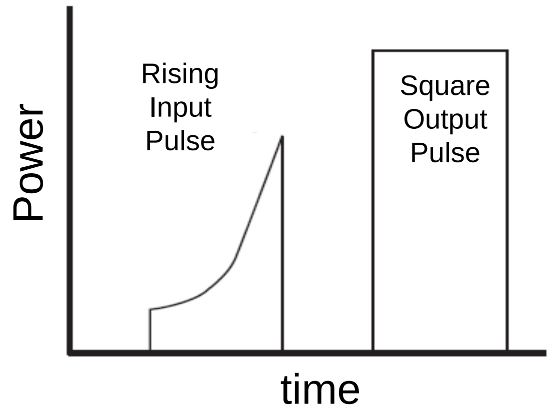
$$SPD = \frac{\text{Gain of the first photon into the amplifier}}{\text{Gain of the last photon into the amplifier}}$$

The input pulse can be shaped to compensate for gain saturation

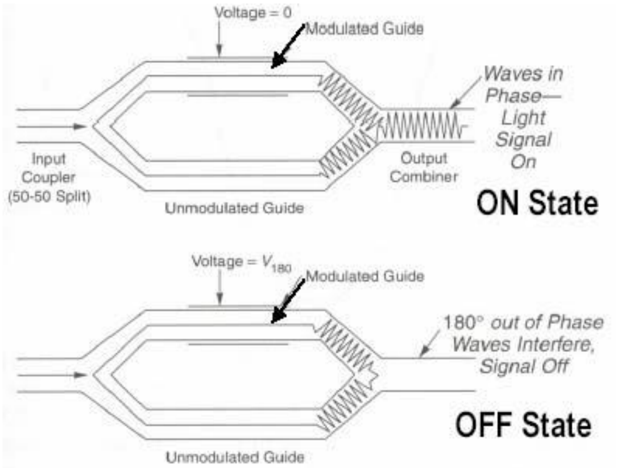
<u>Without compensation</u>



<u>With compensation</u>



For example, pulse shaping can be accomplished using EO modulators to make an "arbitrary waveform generator" (AWG)



- **Waveguides on a $LiNbO_3$ chip**
- **Voltage applied across one of the arms of the interferometer changes transmission**
- **The NIF AWGs have a temporal contrast ratio of ~ 275:1**
- **SPD of ~ 20:1 or more can be compensated**
- **Repetition rate is 960 Hz**

Le Nguyen Binh and Itzhak Shraga, "An Optical Fiber Dispersion Measurement Technique and System," MECSE-14-2005, Monash University Technical Report, Monash University, Australia (2005).

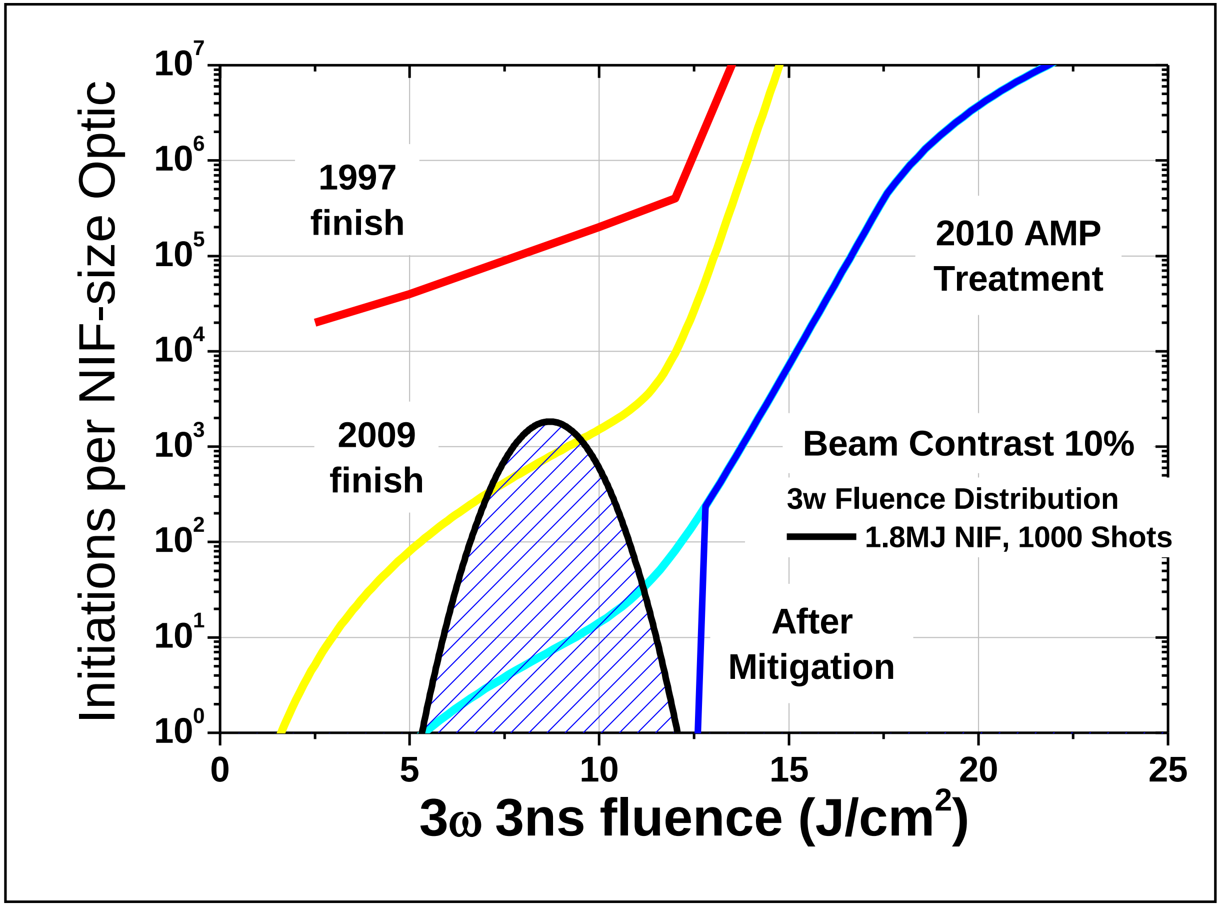
Optical damage is an important consideration in laser design

- **Damage at ns pulselengths is typically not intrinsic to optical materials**
- **Damage occurs when small defects in optics absorb enough laser energy to cause adjacent material to undergo change**
  - **often in optical coatings and just beneath polished surfaces**
- **Damage depends on the defect type and on laser fluence and pulselength**
- **Defect types, sizes and densities depend on manufacturing techniques**

Damage is the typical limiting issue for operating fluences & extraction efficiency

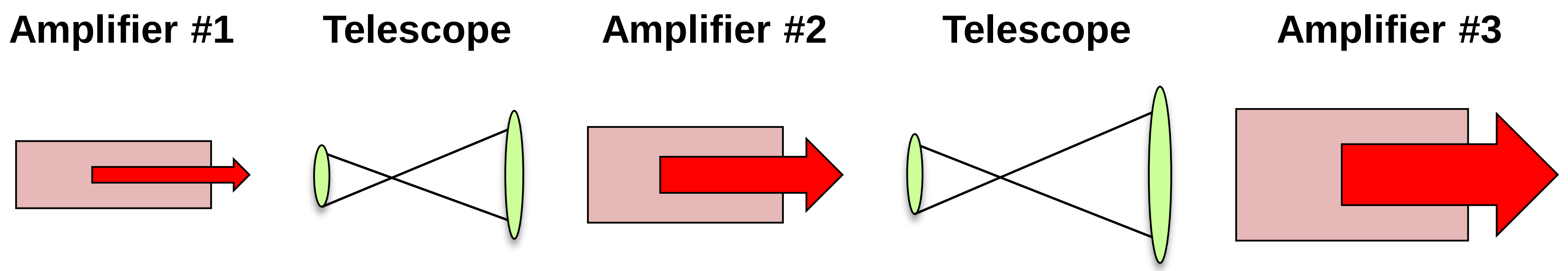
On the optical side, it is critical that every effort be made to improve the quality of the optic and its surfaces

Example: NIF fused silica 3w optics



LLNL has developed methods for quantifying and reducing damage

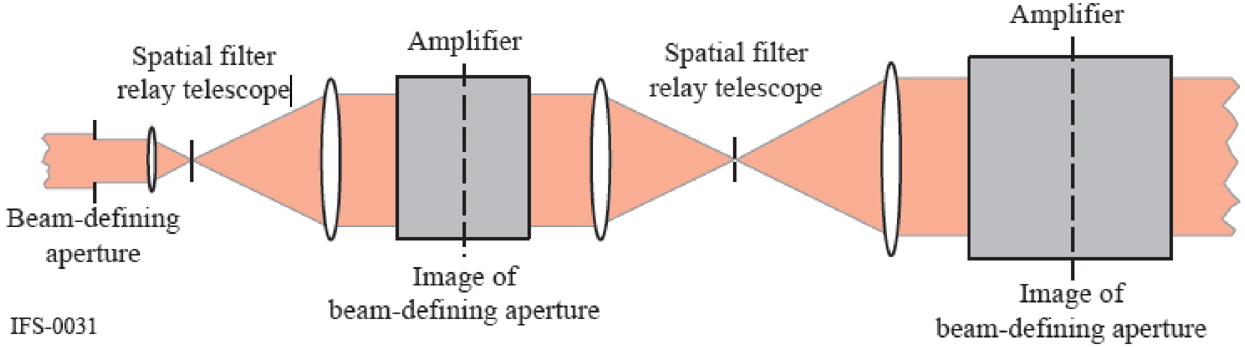
Magnifying the beam size between amplifier stages reduces damage risk



Concept

- Amplify the beam up to the safe operating fluence in each stage
- Use a magnifying telescope to increase the beam size and to reduce fluence
- Amplify the beam up to the safe operating fluence again
- Repeat the process until sufficient energy has been produced

Image relaying and spatial filtering by the telescopes reduces the growth of small-scale intensity modulation



- **Small scratches, contaminate particles and other defects on the optics seed the beam with small phase and amplitude modulation**
- **Diffraction causes small phase and amplitude modulations to grow as the beam propagates**
- **The effective propagation distance is reduced by re-imaging a beam-defining aperture to the middle of the amplifiers**
- **Passing the beam through a small aperture at the focal spot (Fourier plane) of the telescope removes high-spatial-frequency features**

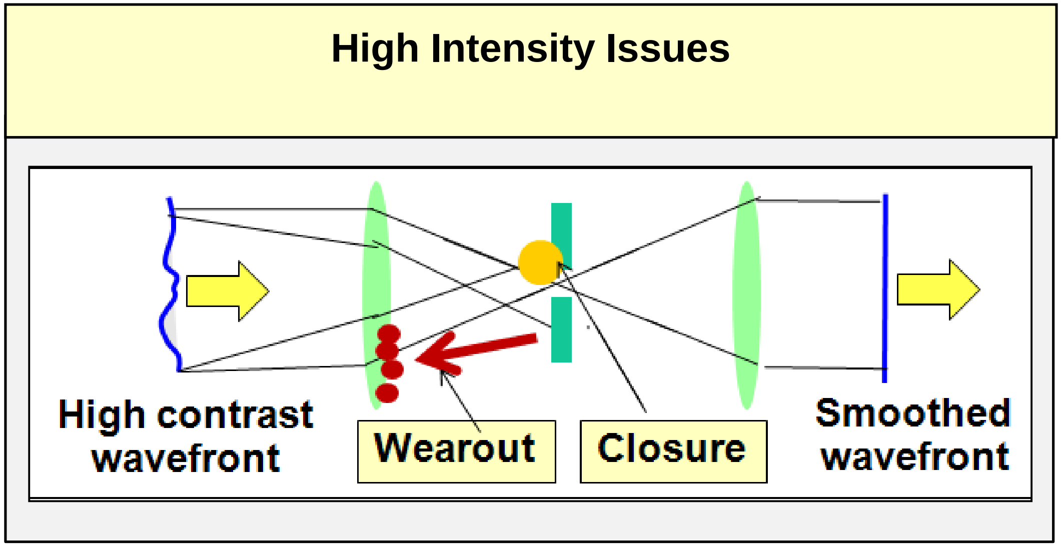
Apodization is used to control diffraction at the beam edges

- Diffraction ripples develop near the edges of the beam if the beam has a sharp intensity cutoff

  - intensity spikes increase damage risk

- Apodization, in which the intensity is decreased gradually near the edge, is used to control edge diffraction
- In designing apodizers, diffractive effects trade off against beam fill factor
- Apodizers can be made using serrated apertures or with metallic masks deposited on a transparent substrate using photolithography

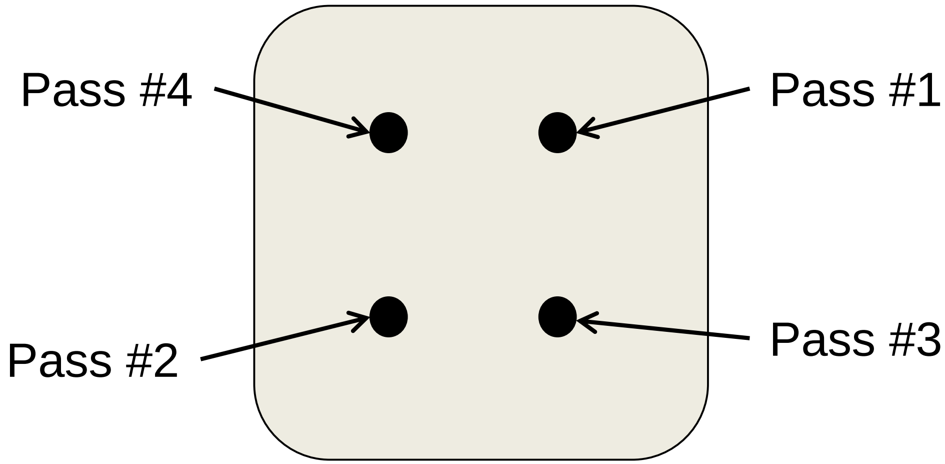
High intensity at spatial filters is an issue



- Temperature exceeds pinhole melt / vaporization threshold causing pinholes degrade over time
- Vaporized material can coat telescope optics
- Plasma expands into the beam and absorbs light or causes wavefront distortion (“pinhole closure”)

A solution to pinhole closure on multipass systems is separate spatial-filter pinholes for each pass

Example: 4 pinholes at the focal plane of a spatial filter



Cavity end mirrors are tilted to align beam focal spots to the pinholes

Non-linear effects can cause intensity modulation to grow

- **Beam intensity can be high enough to change the refractive index**

$$n = n_0 + \gamma I$$

where: **n_0 is the refractive index at zero irradiance**
γ is the nonlinear index coefficient
I is the irradiance

- **Intensity spikes cause a local lens which self-focuses the spike, causing irradiance to increase, which causes more self-focusing…runaway!**

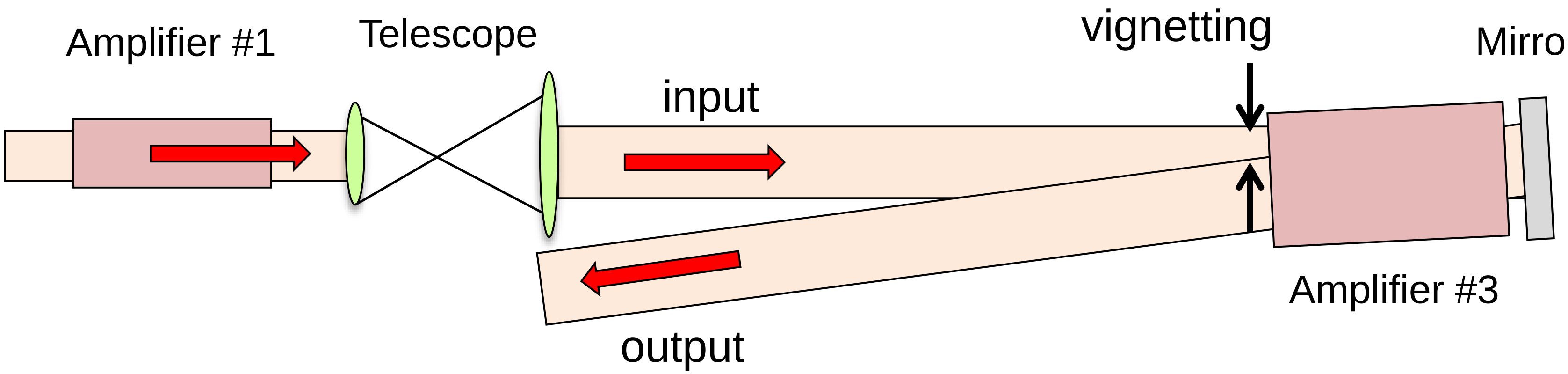
- **Nonlinear propagation effects scale with the nonlinear phase shift, which is given by the "B" integral along the beam path:**

$$B = \frac{2\pi}{\lambda} \int \gamma \, I(z) \, \mathrm{dz}$$

- **Keeping B < ~ 2 radians between spatial filters is good practice for avoiding excessive growth of small-scale features, depending on optics quality**

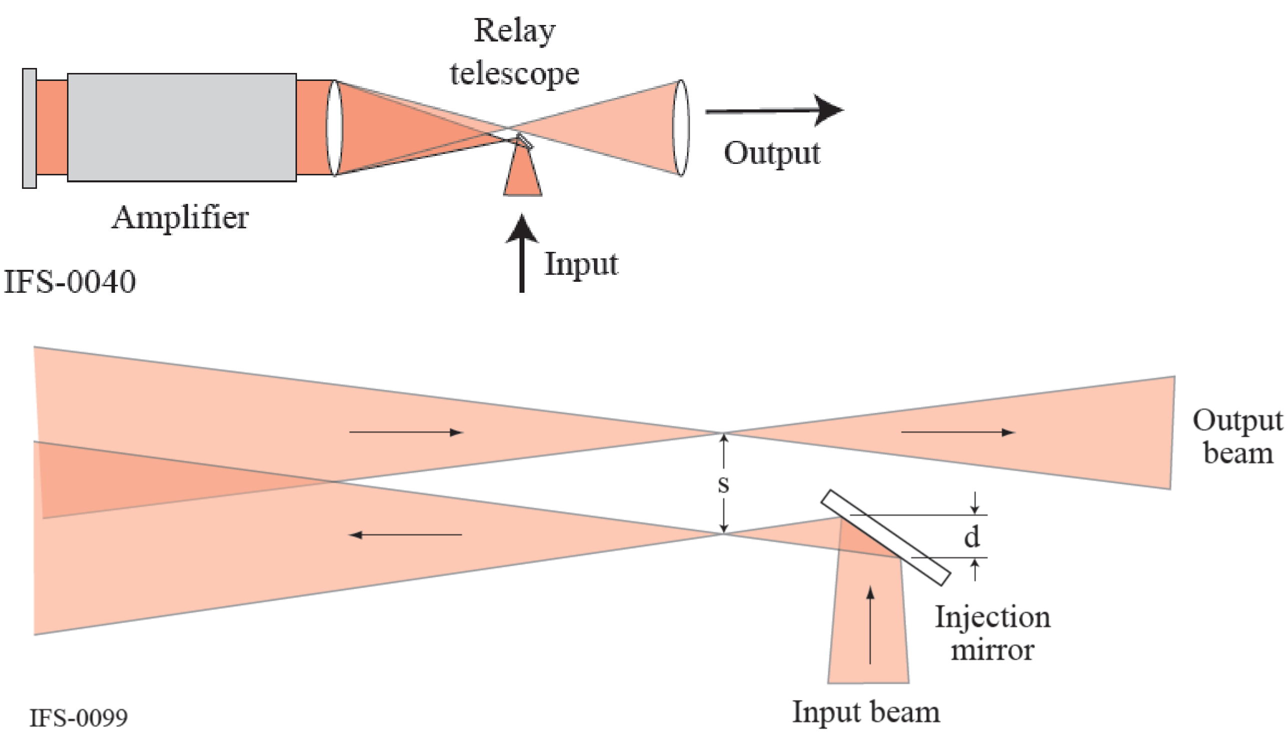
Double-passing the beam through an amplifier reduces cost by improving extraction efficiency

Example: near-field angle multiplexing



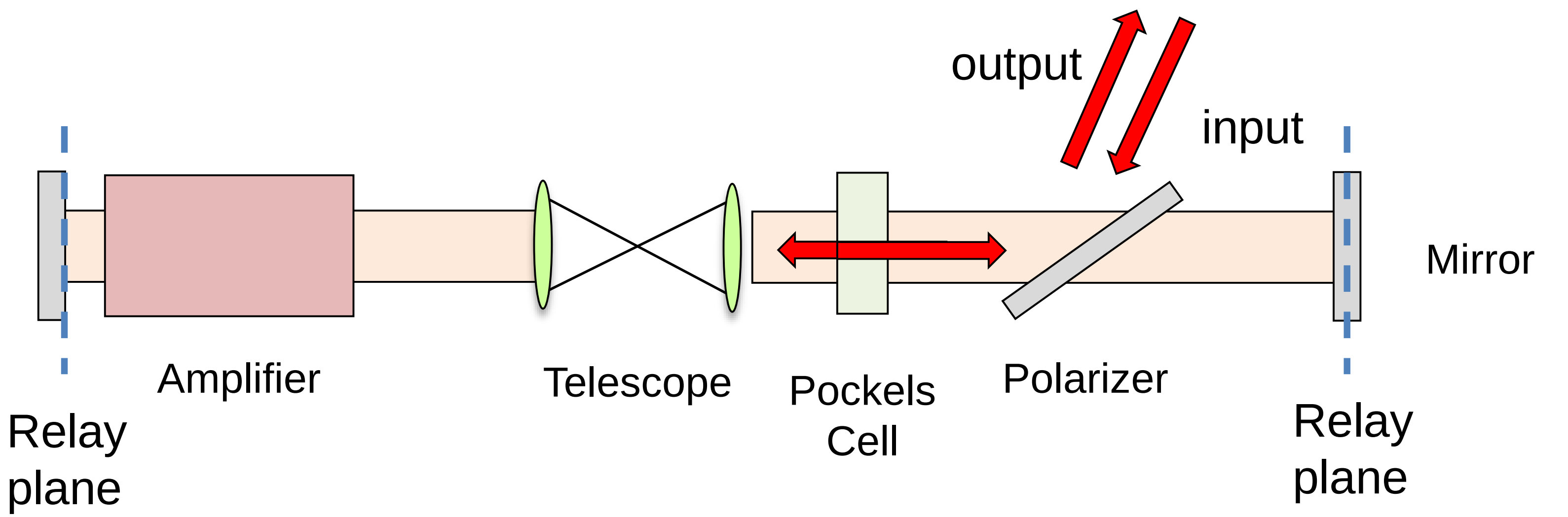
- **The middle amplifier, #2, has been eliminated!**
- **You don't get something for nothing, however**
  - **it may be necessary to store more energy in amplifier #3 to make up for the energy provided previously by amplifier #2**
  - **the aperture of amplifier #3 might need to be made larger to accommodate the offset of the beam between passes ("vignetting")**

Far-field multiplexing is another way to lower cost and improve extraction efficiency



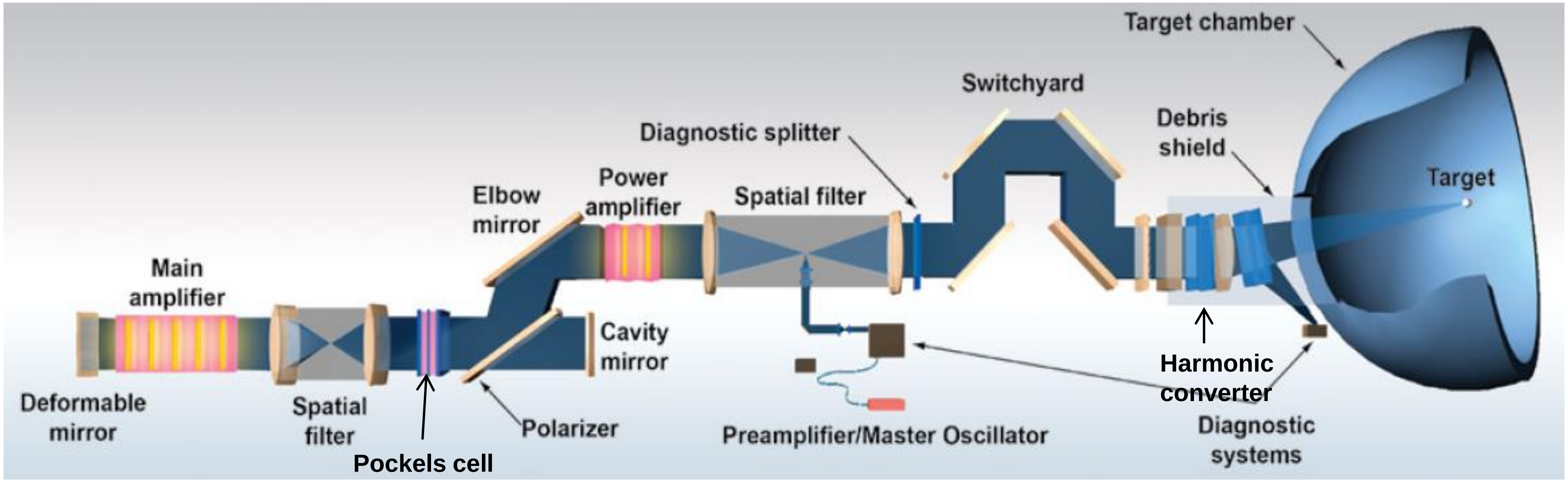
- There is less vignetting loss than for near-field multiplexing
- The offset between pinholes must be sufficient for the output beam to miss the injection mirror

Active polarization control is another way to achieve lower cost and efficient extraction



- **The Pockels cell is a voltage-controlled waveplate**
  - **that does not rotate the beam polarization when voltage applied is zero**
  - **that rotates the polarization by 90° when an appropriate voltage is applied**

The NIF laser uses the features we've discussed



NIF uses:

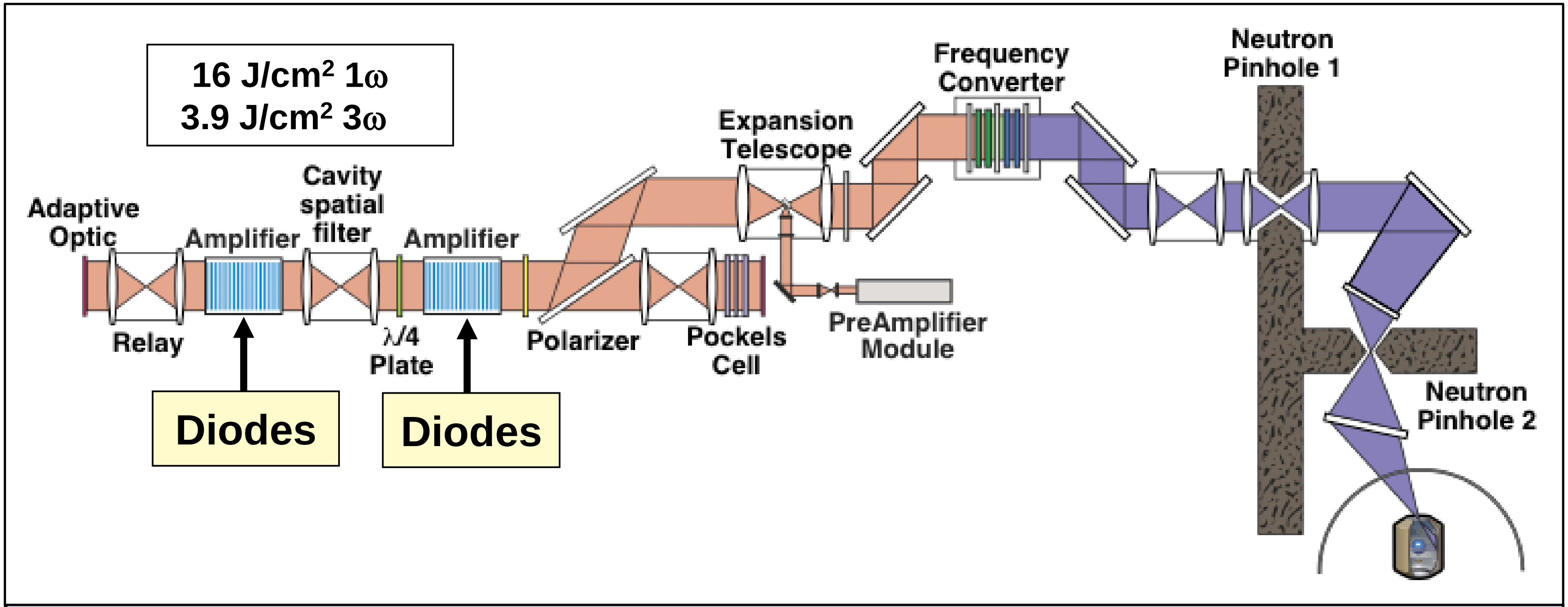
- gain saturation
- beam apodization
- image relaying
- spatial filtering
- far-field angle multiplexing
- active polarization control using a Pockels cell

What changes do we need to make

to design

a high energy laser at high average power?

We designed a DPSSL for inertial fusion energy that uses gas-cooled Nd:glass amplifiers (~2012)



Diode pumps	→	high efficiency (18%)
Helium cooled amps	→	high repetition rate (16 Hz) with low stress
Normal amp slabs	→	compensated thermal birefringence, compact amp
Passive switching	→	performs at repetition rate
Lower output fluence	→	less susceptible to optical damage

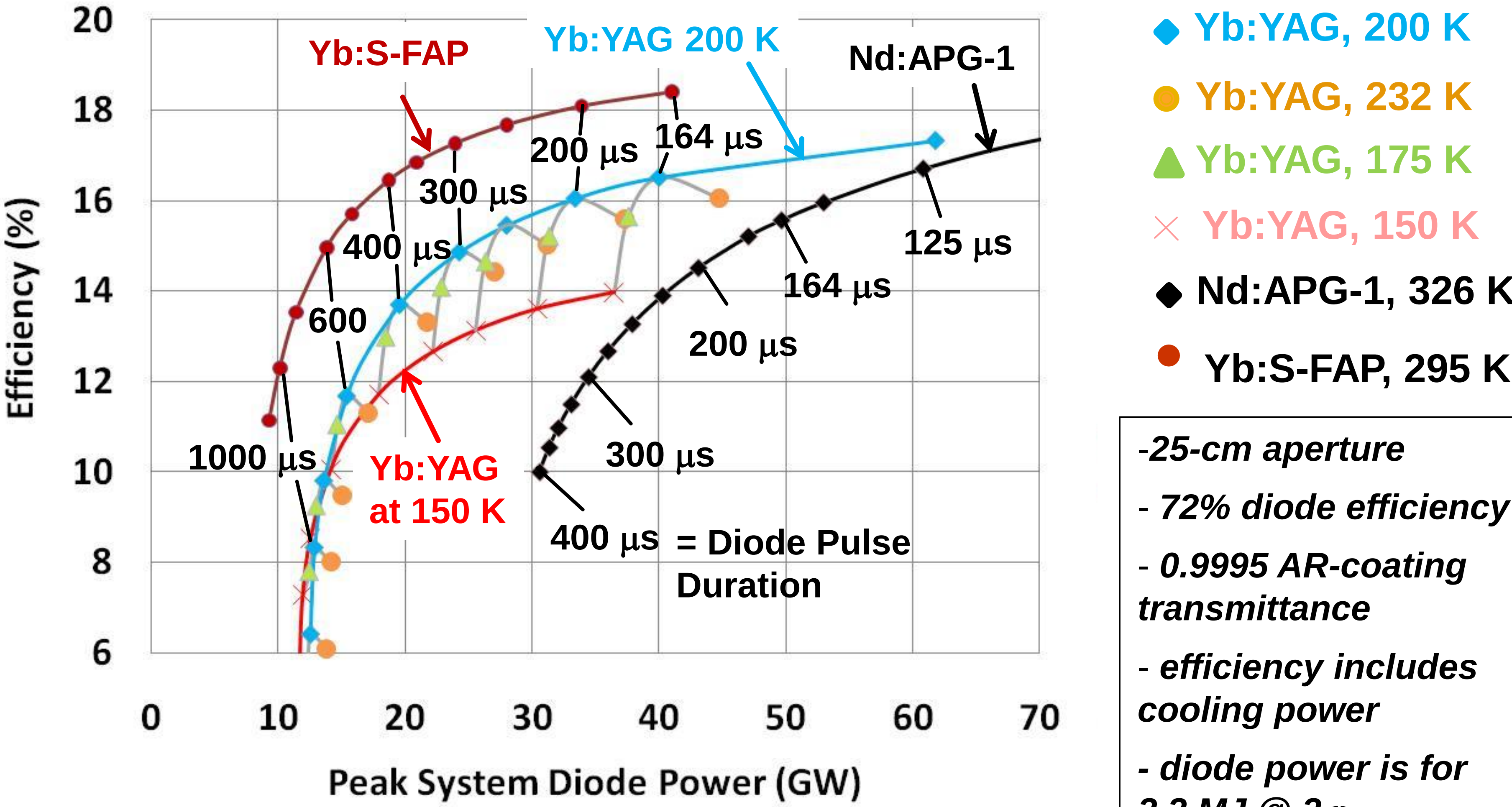
Key issues

- **Achieving high overall efficiency**
- **Managing thermal wavefront distortion, birefringence and stress that arises from heating and cooling of components**
    - **Laser slabs**
    - **Pockels cell**
    - **Harmonic converter**
- **Avoiding wearout of the spatial filter apertures**

High-efficiency strategy

- Minimize decay losses during the pumping process
  - Pump with high-intensity diode light for a time << decay time
  - Use apertures smaller than NIF's to reduce amplified spontaneous emission loss
- Use a pump profile with a high fill factor that gain-shapes the extracting beam
- Minimize absorption by the thermally-populated lower laser level (cooling)
- Minimize concentration quenching
  - Use low ion-doping concentrations
- Absorb nearly all the pump light
  - Stack slabs so pump light has a long absorption path length
- Extract nearly all the available stored energy
  - Operate at fluences well above the saturation fluence
    - Use stored fluence several times the saturation fluence
    - Use circularly-polarized light (1/3rd less nonlinear phase shift)
- Multipass the extracting beam
- Keep passive optical losses low
- Relay the beam to the middle of each amplifier to minimize edge losses

Relative to Nd:APG-1, Yb:YAG needs fewer diodes to meet efficiency goals but must operate at cryo temperatures



-25-cm aperture

- 72% diode efficiency

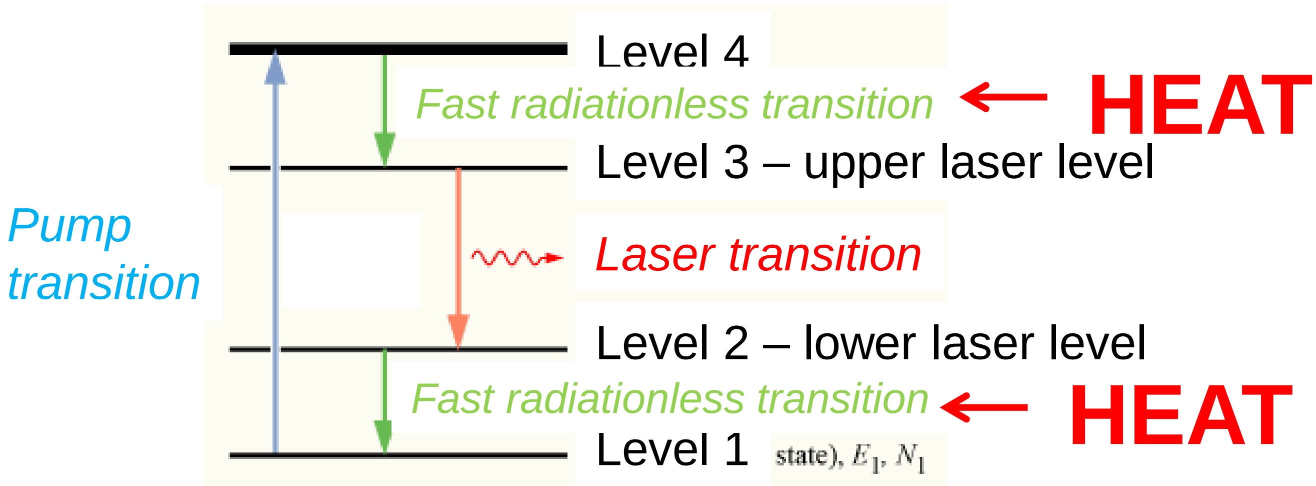
- 0.9995 AR-coating transmittance

- efficiency includes cooling power

- diode power is for 2.2 MJ @ 3ω

- Yb-doped gain media have ~ 3x longer storage lifetimes
- But cryo Yb:YAG requires more power for cooling

A fraction of the absorbed pump light is converted to heat in the laser slabs



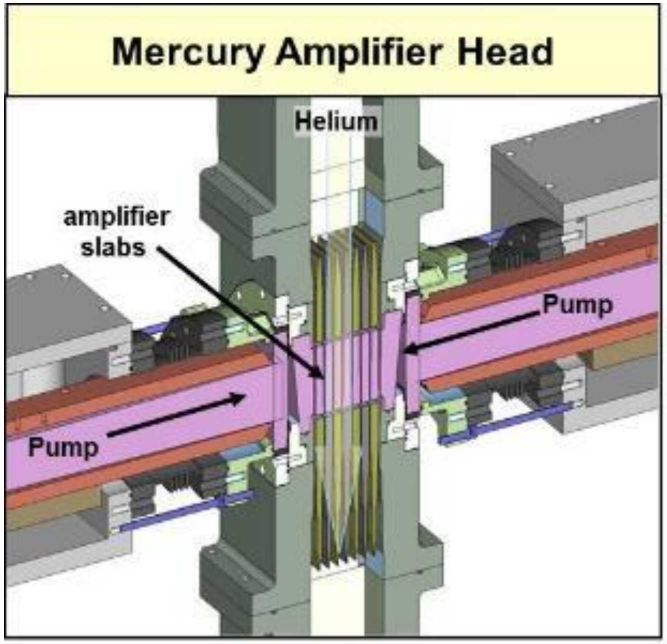
- **Radiationless transitions occur when excited ions give up energy to phonons in the substrate matrix**
- **The approximate fraction of absorbed energy converted to heat is the "quantum defect"**

$$\text{heat fraction} \approx 1 - \frac{h\nu_{laser}}{h\nu_{pump}} = 1 - \frac{\lambda_{pump}}{\lambda_{laser}}$$

LLNL uses helium gas cooling to remove heat from the slabs first on Mercury and now on HAPLS systems

Helium gas cooling for laser amplifiers was developed by LLNL in 1989*

Method first fully deployed at high average power on Mercury laser project (2000)

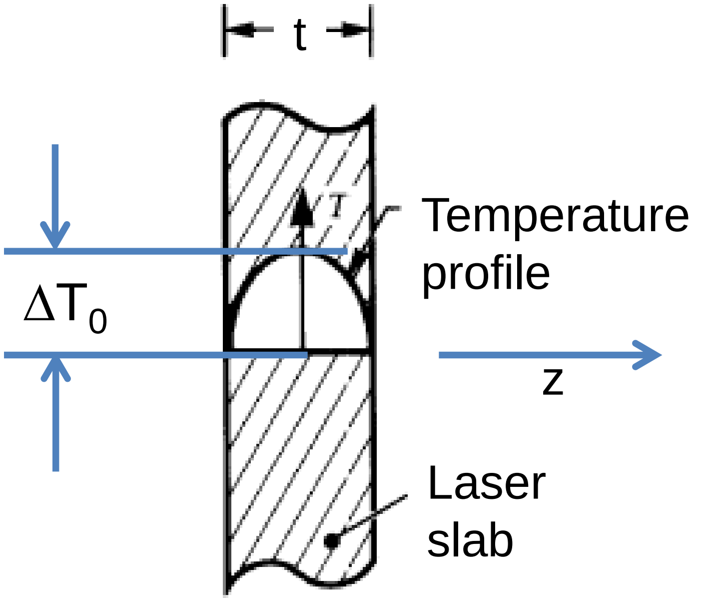


Details

- **14 Yb:S-FAP slabs**
- **Fast helium flow between slabs**
- **Aerodynamic vanes**

G. F. Albrecht ; J. Z. Holtz ; S. B. Sutton ; W. F. Krupke, “Gas cooled slab scaling laws and representative designs,” *Proc. SPIE,* **1040**, 56-65,1989.

Pumping and cooling produce an nearly parabolic temperature profile through the slab thickness



$$\Delta T(z) = \Delta T_0 \left(1 - \frac{4z^2}{t^2}\right)$$

$$\Delta T_0 = \frac{P_v t^2}{8\kappa}$$

$$\sigma_T = \frac{2\alpha \Delta T_0 E}{3(1-\nu)}$$

P_v is the thermal power per unit volume

κ is the thermal conductivity

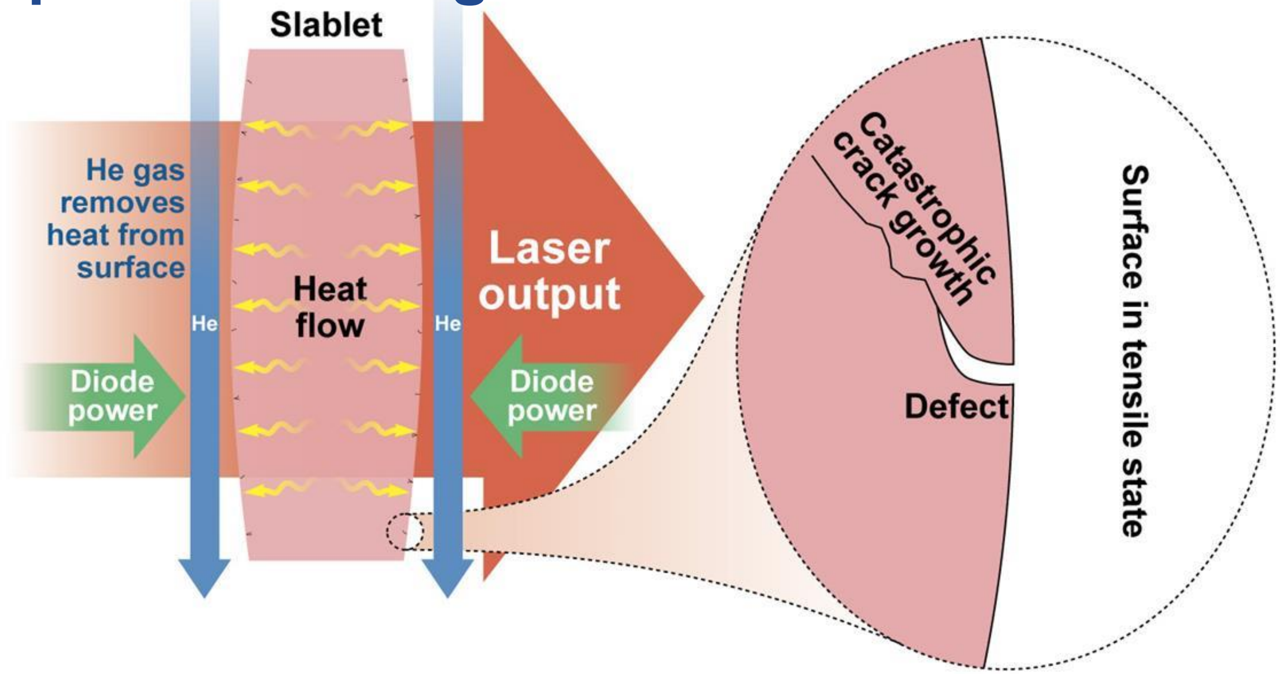
E is Young's modulus

α is the thermal expansion coefficient

υ is Poisson's ratio

JL Emmett, WF Krupke and WR Sooy, The Potential of High-Average-Power Solid State Lasers, UCRL-53571, Lawrence Livermore National Laboratory, Livermore, CA (1984)

Optical finishing defects are seed locations for “high average power” crack growth



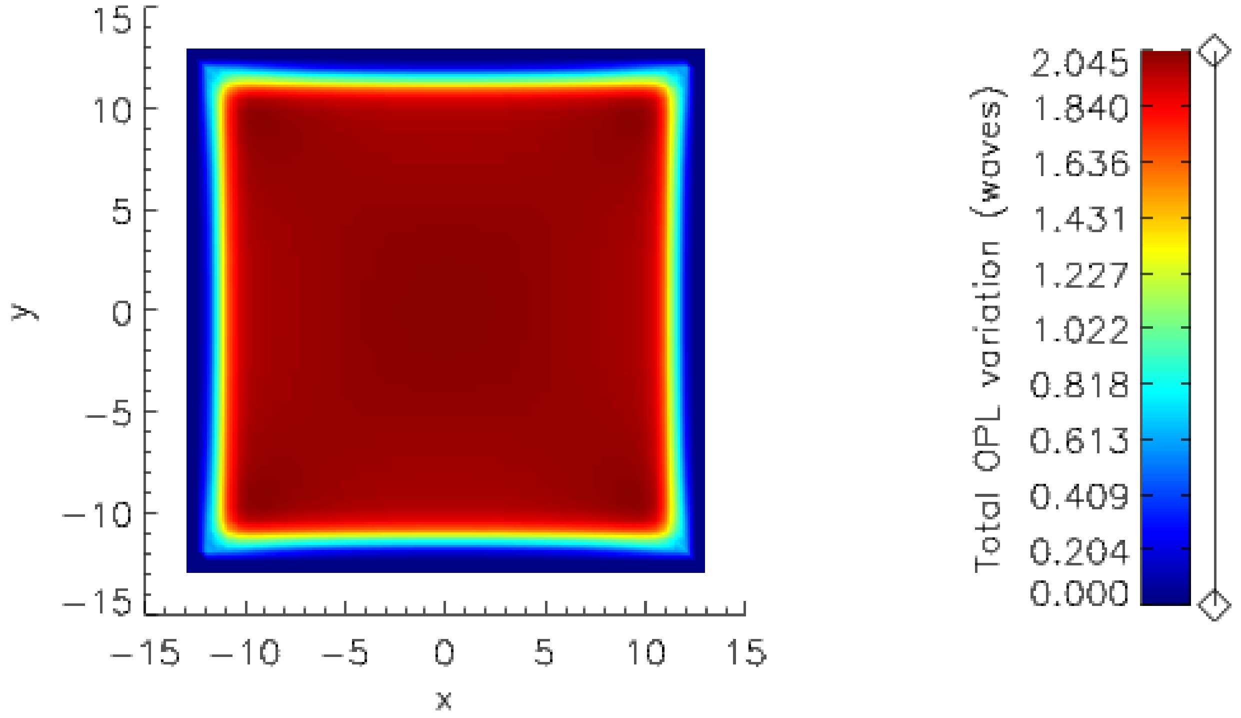
- To avoid fracture, it is wise to keep tensile stress << yield stress
- Yield stress can be estimated from the Griffith fracture criterion

$$\sigma_{yield} = \frac{K_{1C}}{\sqrt{2\pi a}}$$

where K_{1C} is the fracture toughness of the material, and a is the radius of the crack

J. Menck, *Strength and fracture of glass and ceramics*, Elsevier, New York, pp. 99-151 (1992)

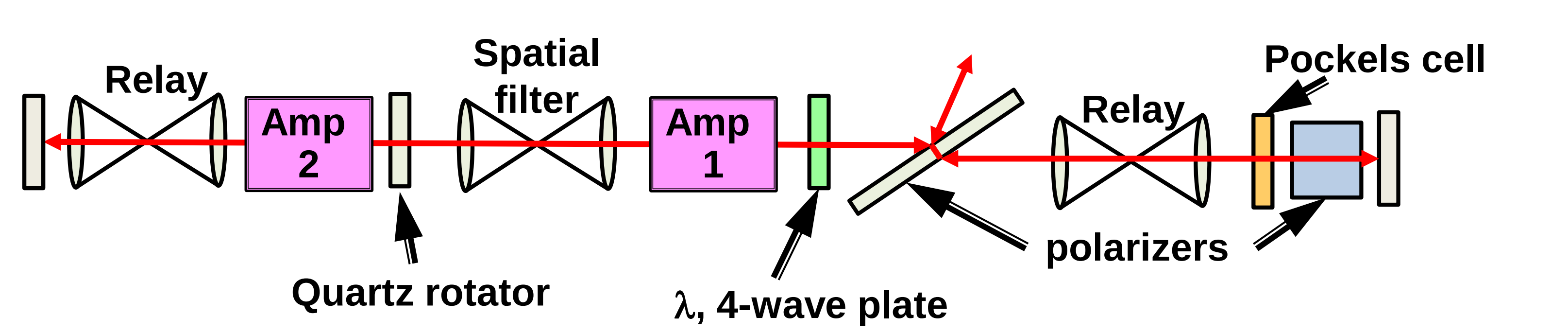
Slabs develop transverse temperature gradients causing optical path length gradients and stress depolarization



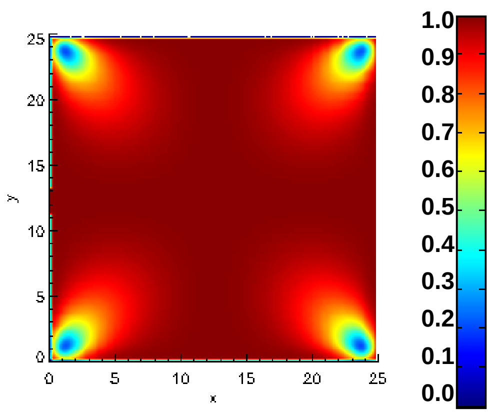
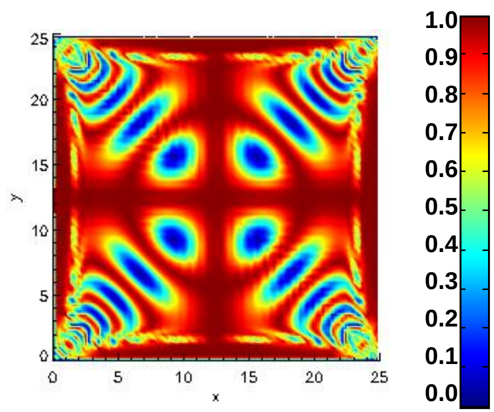
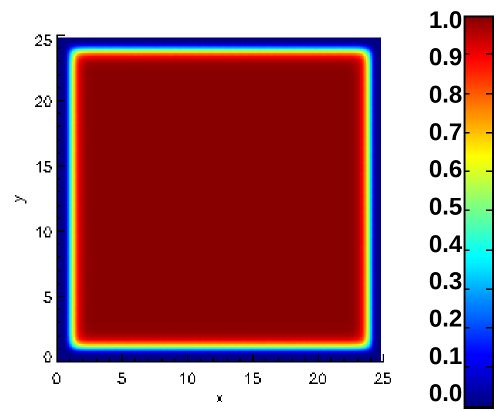
Static corrector plates placed near the amplifiers compensate for most of the wavefront distortion

Thermally induced depolarization in isotropic media can be minimized with polarization rotation

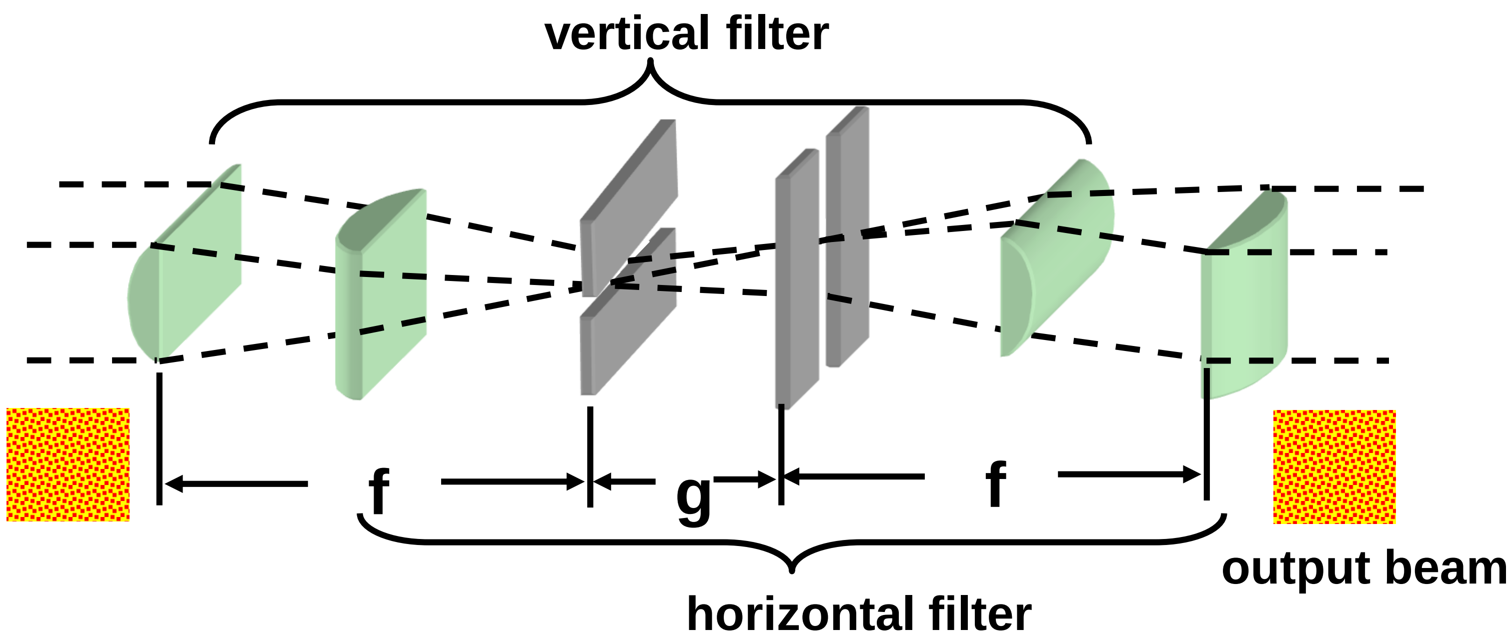
Architecture



Polarized transmission of amplifier components

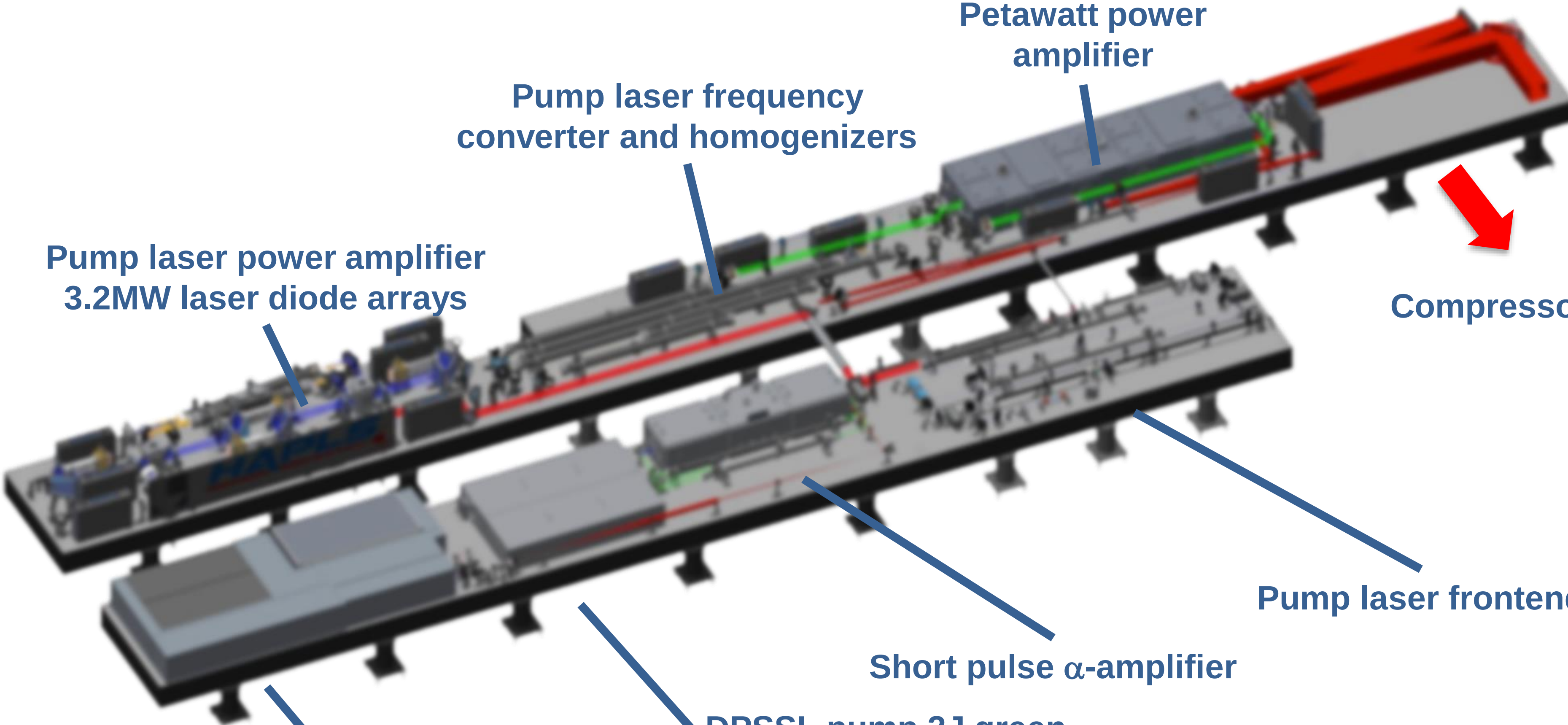
1 slab	1 amplifier (22 slabs)	2 amplifiers (compensated)
		

Spatial filtering with orthogonal slits demonstrated on HAPLS to eliminate wearout of the spatial filters



- Fluences at the slits are much lower than fluences at the round pinholes
  - below thresholds for material ablation and for plasma formation
  - no "pinhole closure", sputtering of material onto optics nor enlargement of the pinhole with time

LLNL delivered HAPLS, a petawatt system capable of 30J compressed to 30fs at 10Hz to ELI-Beamlines



The system has demonstrated performance up to current milestone of 15 J @ 3.3 Hz

Class #1

Conclusion for the “easy” part

- In the last year both the Rutherford DiPOLE 100 system based on Yb:YAG and the LLNL HAPLS system based on Nd:glass succeed and prove that high average power DPSSLs are a working solution
- This is an exciting and interesting time to compare and contrast performance tradeoffs of these systems
- The future looks promising to go to even higher energies and average power



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