Diode-pumped solid-state laser driver for Inertial Fusion Energy

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Topics on Fusion Energy
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Outline

- Project Overview
  - Mercury Laser performance goals
  - International 100 J class systems

- Laser architecture
  - Technology retrospective
  - Design considerations
  - Projected performance

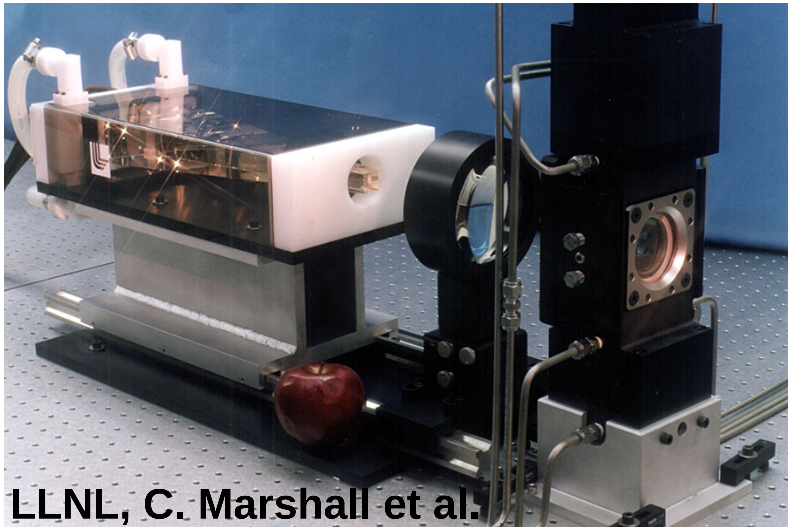
- System performance
  - Pockels cell
  - Diode arrays
  - Crystalline gain media
  - Gas cooled amplifiers
  - Laser operations

- Upcoming activities
  - Frequency conversion
  - Wavefront control
  - Bandwidth

The Mercury Laser Project is currently the largest ytterbium-based system for fusion energy applications

Highlights of high energy Yb:S-FAP lasers:

- 2.2 J, 25 Hz; C. Marshall et al., 1996
- 47 mJ, 2 Hz; C. Bibeau et al., 1996
- 65 mJ, 10 Hz; J. Pierce et al., 1997
- 24 mJ, 50 Hz; H. Ishikawa et al., 2003



Our challenge was to build the next system with:

- 9x larger Yb:S-FAP material (4 x 6 x .75 cm)
- 35x number of diodes (6624 diodes)
- 4x reduction on diode cost ($5/W)
- 45x energy out per pulse (100 Joules in 3-10 ns)

All within the boundaries of Inertial Fusion Energy requirements

Mercury laser requirements are a melding of both NIF and IFE systems but at sub-scales

NIF performance based on target physics:

- Energy: 2 MJ
- Pulse shape: 3 ns shaped
- Smoothness: $\sigma < 0.1$ %
- Wavelength: 0.35 μm

Mercury Laser

- Energy: 100 J
- Pulse shape: 3 ns
- Smoothness: $\sigma < 10$ %
- Wavelength: 0.35 μm

Diodes, crystals, gas cooling, architecture:

- Efficiency: 10 % (w/o utilities)
- Reliability: $>10^8$ diode shots
- Cost: $5/W for diodes
- Repetition rate: 10 Hz

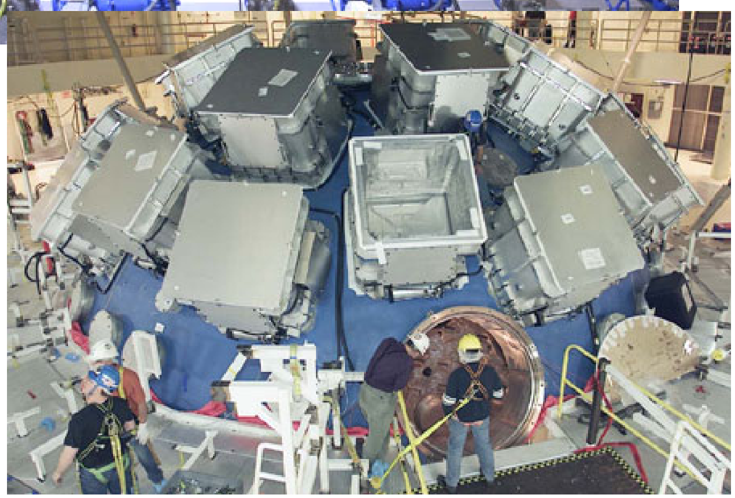
Extending NIF performance requires technological advances

IFE requirements

- Efficiency: 10%
- Reliability: $>10^9$ shots
- Cost: $500/J for laser, $0.05/W for diodes
- Repetition rate: 5-10 Hz

What do IFE scale laser systems look like?

National Ignition Facility
LLNL, United States



Status:

Laser Megajoule Facility
CEA, France

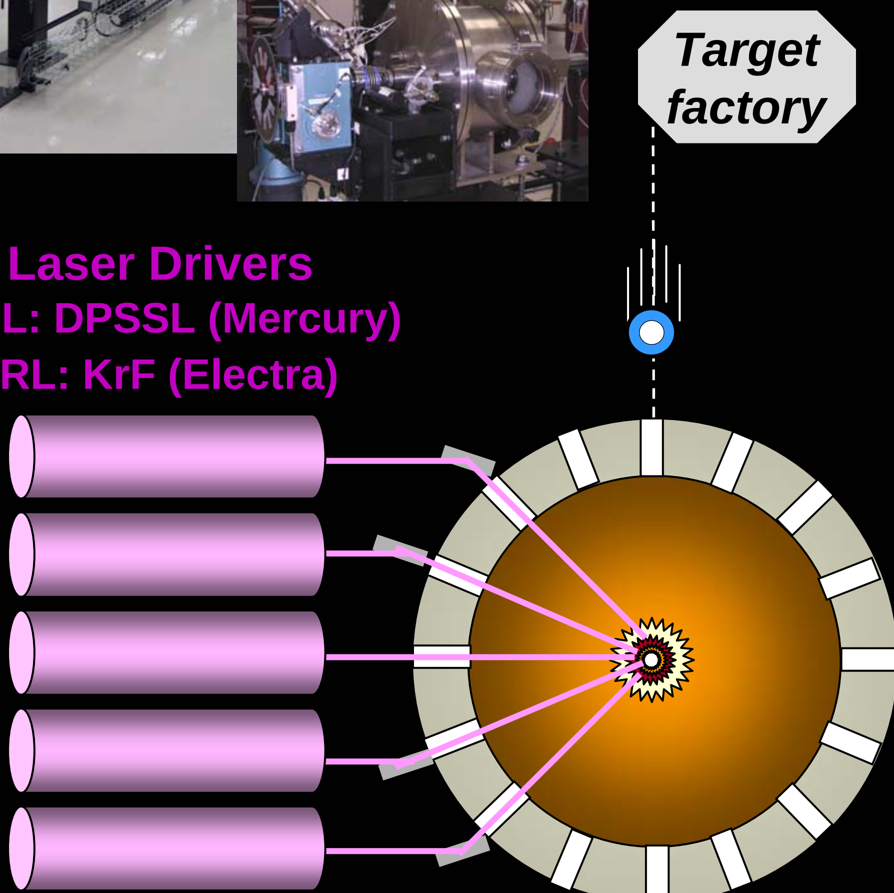
Status:

The U.S. High Average Power Laser Program is a multi-facility effort to develop laser driven inertial fusion energy

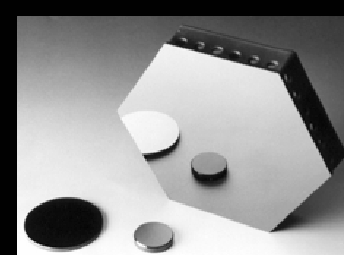
Target Injection
GA, LANL

Target Design and Fabrication
NRL, LLNL, GA, LANL, SCHAFER

Laser Drivers
LLNL: DPSSL (Mercury)
NRL: KrF (Electra)



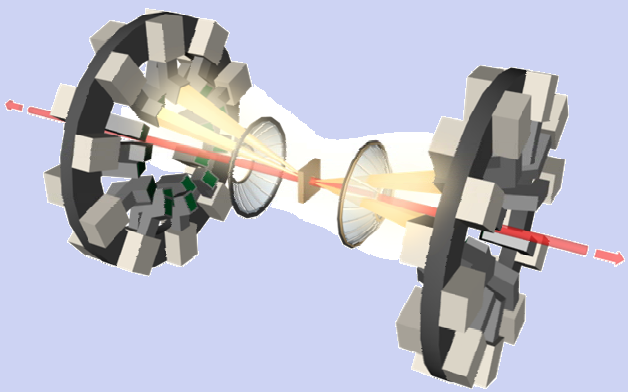
Chambers
SNL, LLNL,
WISC, UCSD,
ORNL, UCLA

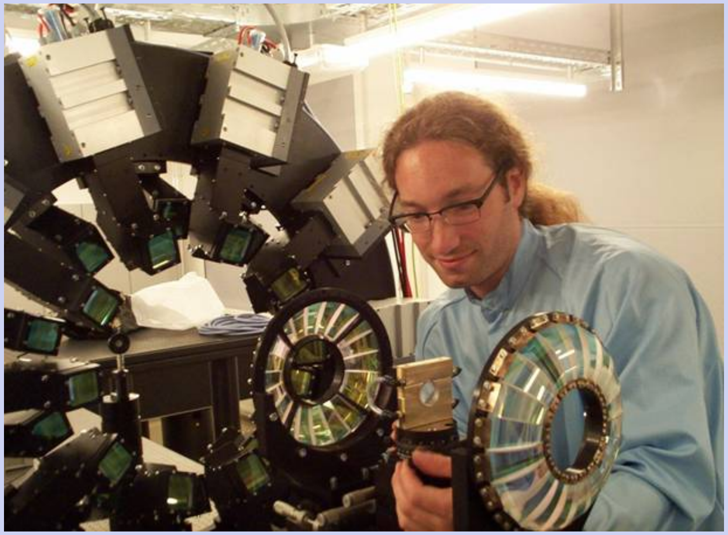


Final Optics
LLNL,
LANL, UCSD

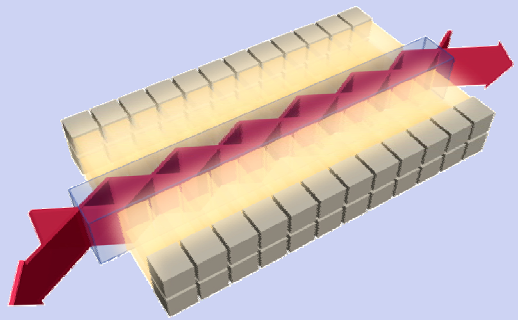
Many different architectural approaches are being considered for rep-rated 100J systems

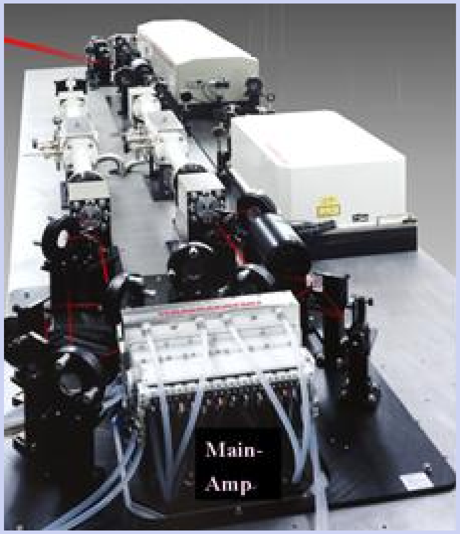
Polaris - Germany
Dr. Joachim Hein
Water cooled, longitudinal pumped
Yb:Flurophosphate disk



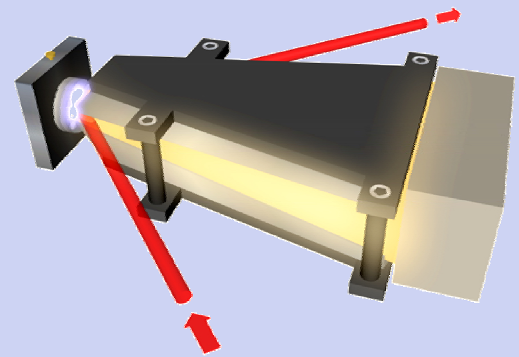


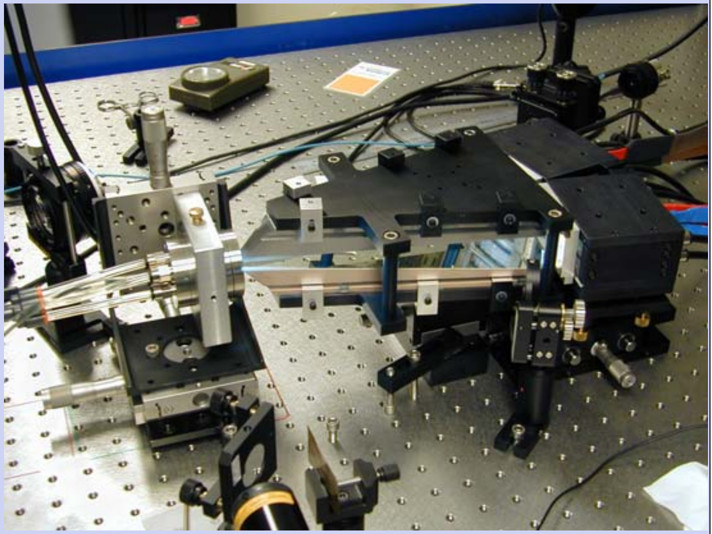
HALNA - Japan
Dr. Yasukazu Izawa
Water cooled, side pumped
Nd:Phospate slab





Lucia - France
Dr. Jean-Christophe Chanteloup
Water cooled, longitudinal pumped
Yb:YAG disk



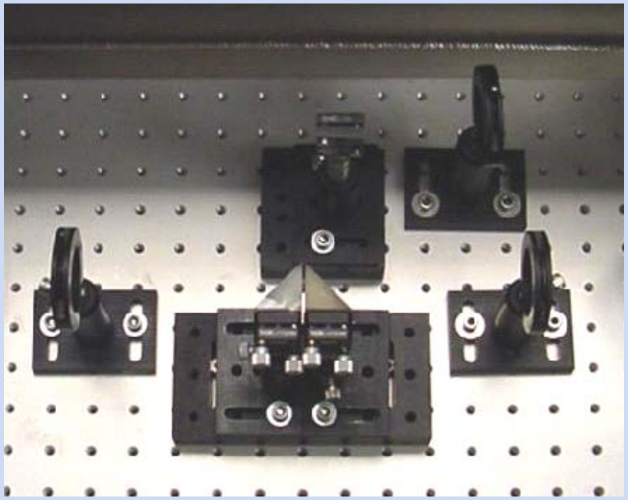


Summary of performance goals

Project	Polaris Germany	HALNA Japan	Lucia France	Mercury United States
Application	High energy radiation source	IFE	Laser matter interaction	IFE and HE/AP uses
Gain Media	Yb:FP glass	Nd:phosphate glass	Yb:YAG and FP glass option	Yb:S-FAP
Wavelength	1.050 um	1.053 um	1.030 um	1.047 um
Energy	150 J	100 J	100 J	100 J
Rep-rate	0.1 Hz	10 Hz	10 Hz	10 Hz
Average Power	15 W	1 kW	1 kW	1 kW
Pulse length	150 fs	10 ns	1-10 ns	3-10 ns
Peak Power	1 PW	10 GW	10 GW	10 GW
Output beam size	900 cm^2	12 cm^2	10 cm^2	15 cm^2
Beam Quality	3 xdl	5 xdl	1.1 xdl	5 xdl
Additional capabilities	-	-	• 1 ps option	• 2ω conversion • 150 GHz smoothing • 10 ps option

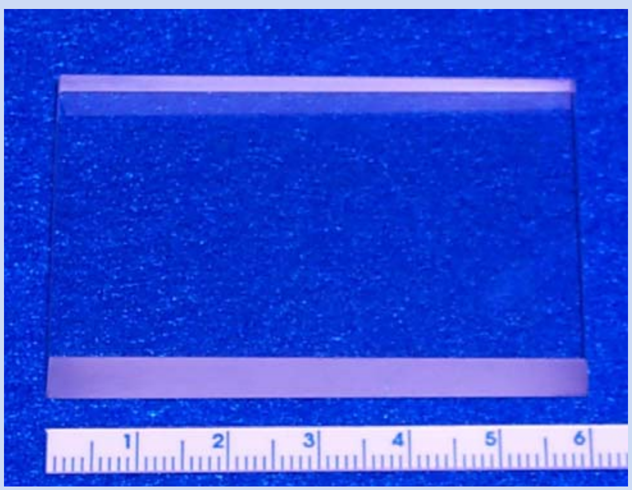
The Mercury Laser employs four key technologies

Angular Multiplexing Closely-spaced Architecture

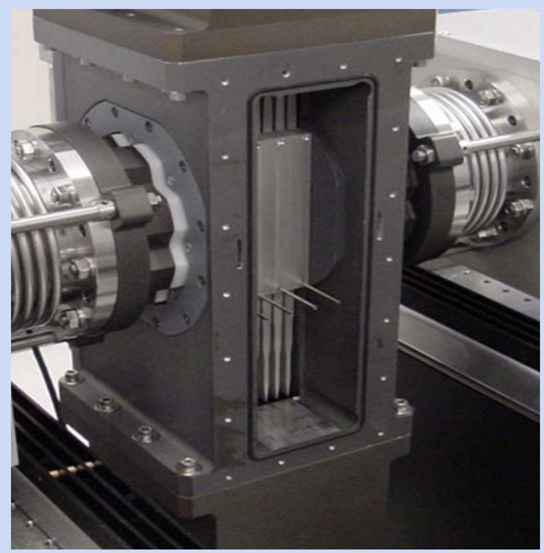


Pump Diode Arrays

Yb:S-FAP Amplifier Slabs

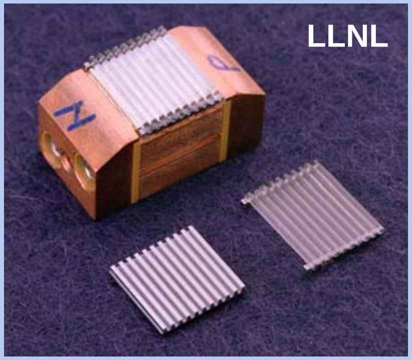


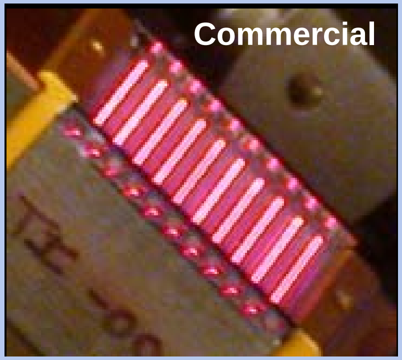
Helium Gas Cooling



1996-2004 Technology Retrospective

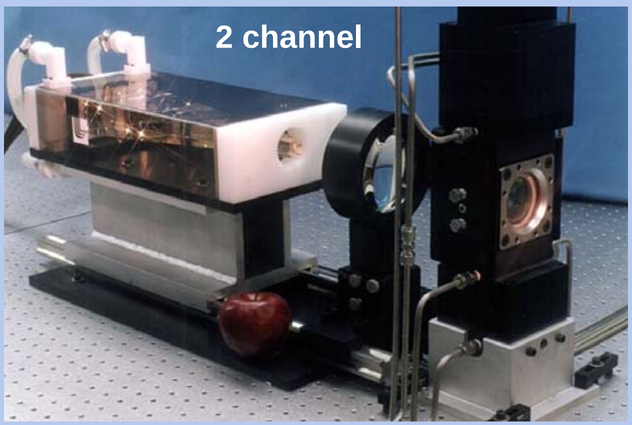
Diode Arrays

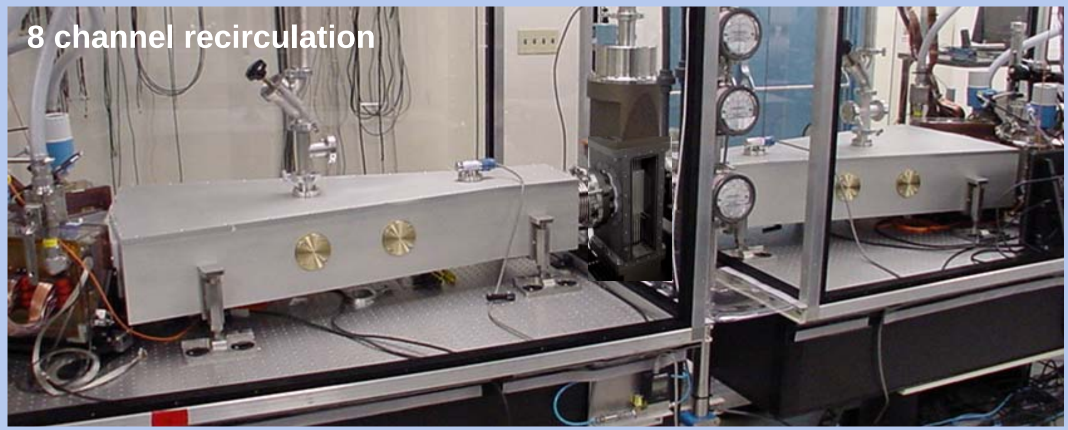




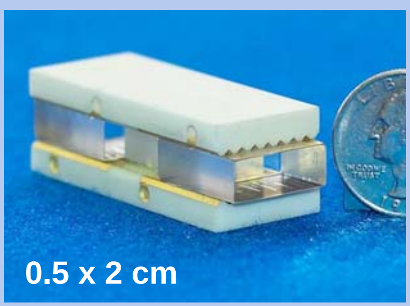
Yb:S-FAP

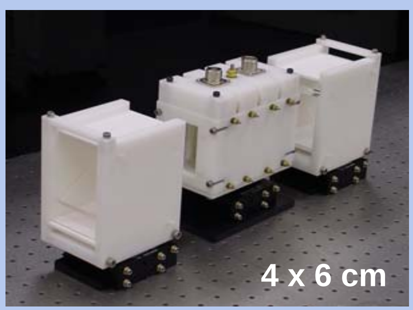
Gas-cooled Amplifier



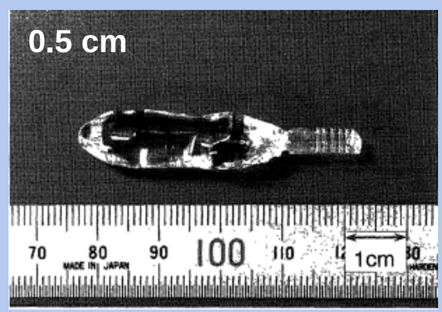


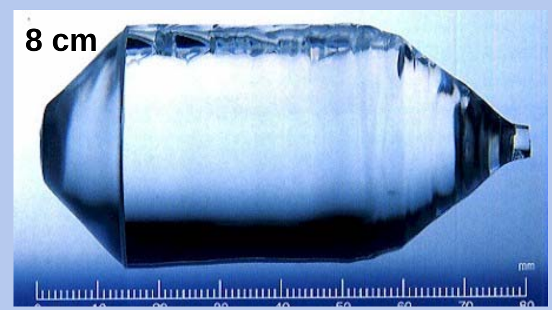
Pockels Cell





YCOB

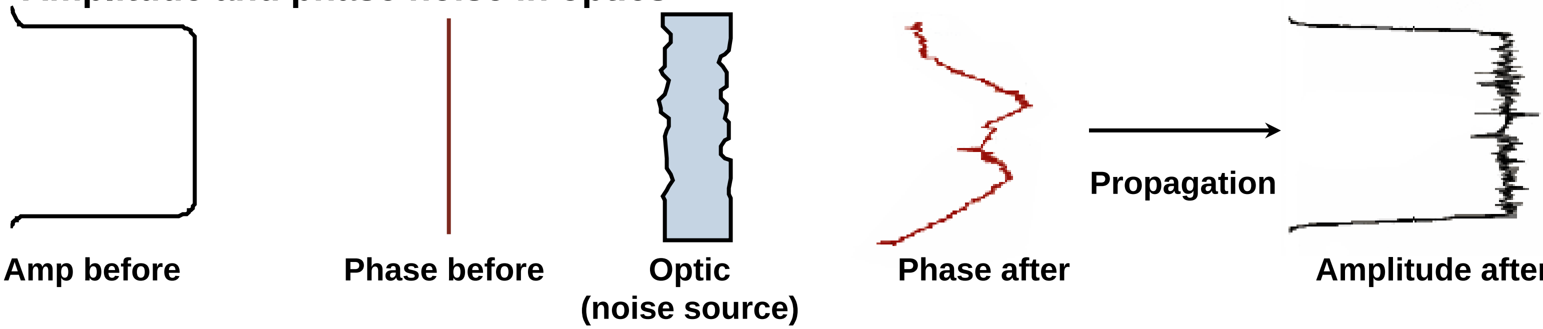




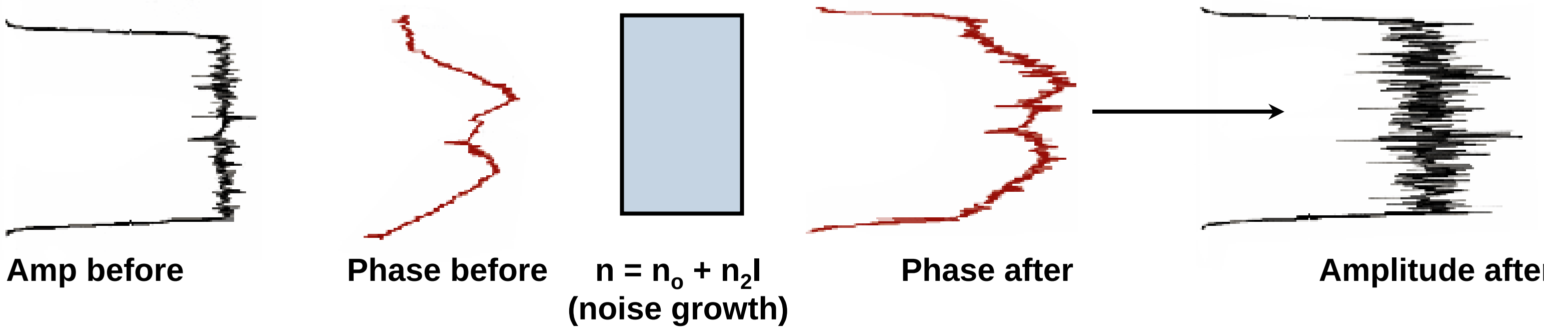
Nonlinear propagation physics were considered in designing the optical layout of Mercury reliability

Sources of amp variations

- Amplitude and phase noise in optics

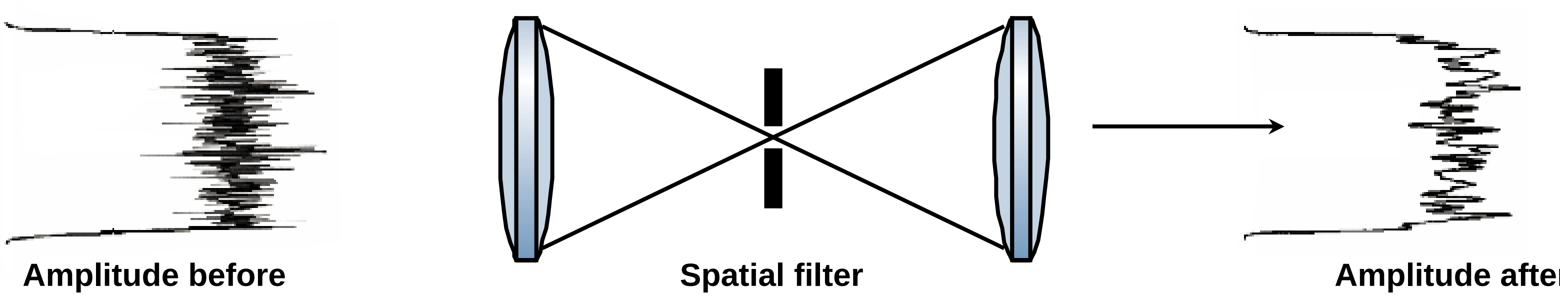


- Nonlinear modulation growth



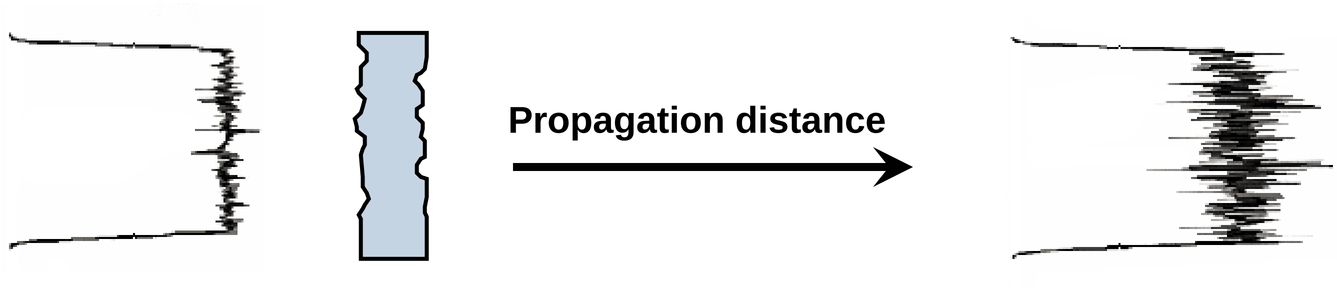
Solution

- Relay the location of near-field planes
- Filter fast growing spatial frequencies
- Design layout to minimize growth
- Minimize source terms through optical specifications

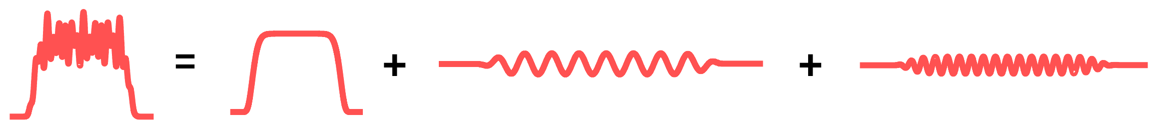


The amplifier spacing studies show spatial frequencies convert from phase to amplitude at different rates

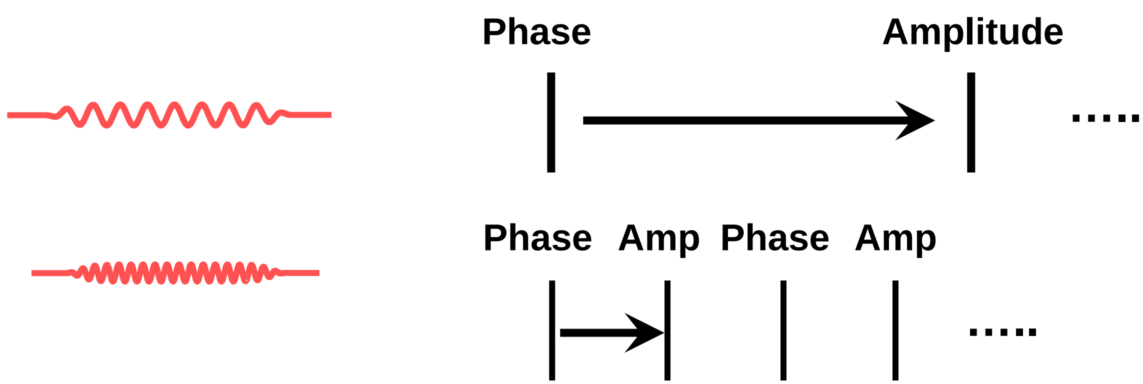
Amplitude Modulation



Phase aberration frequency decomposition



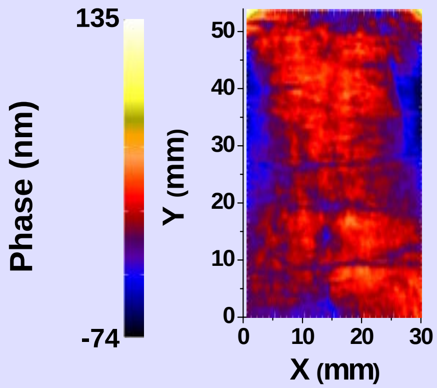
Cycling of phase to amplitude modulation on beam



When propagating, the highest frequency phase aberrations are the first to appear as amplitude modulation

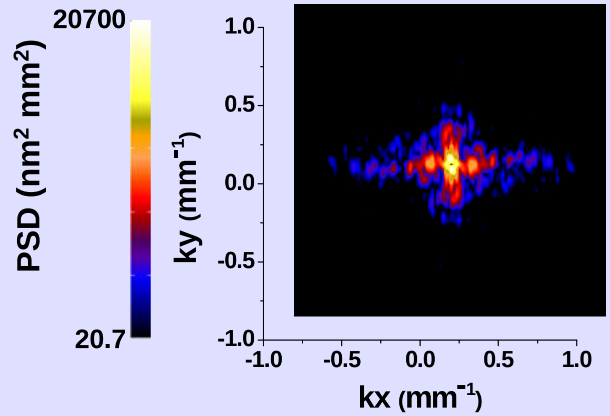
2-D Phase Map

$$\phi_{Phase}(x, y)$$



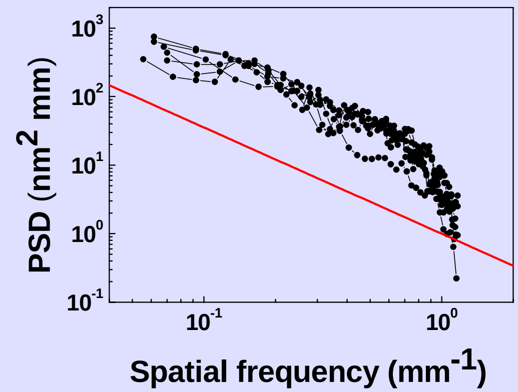
2D Power Spectral Density

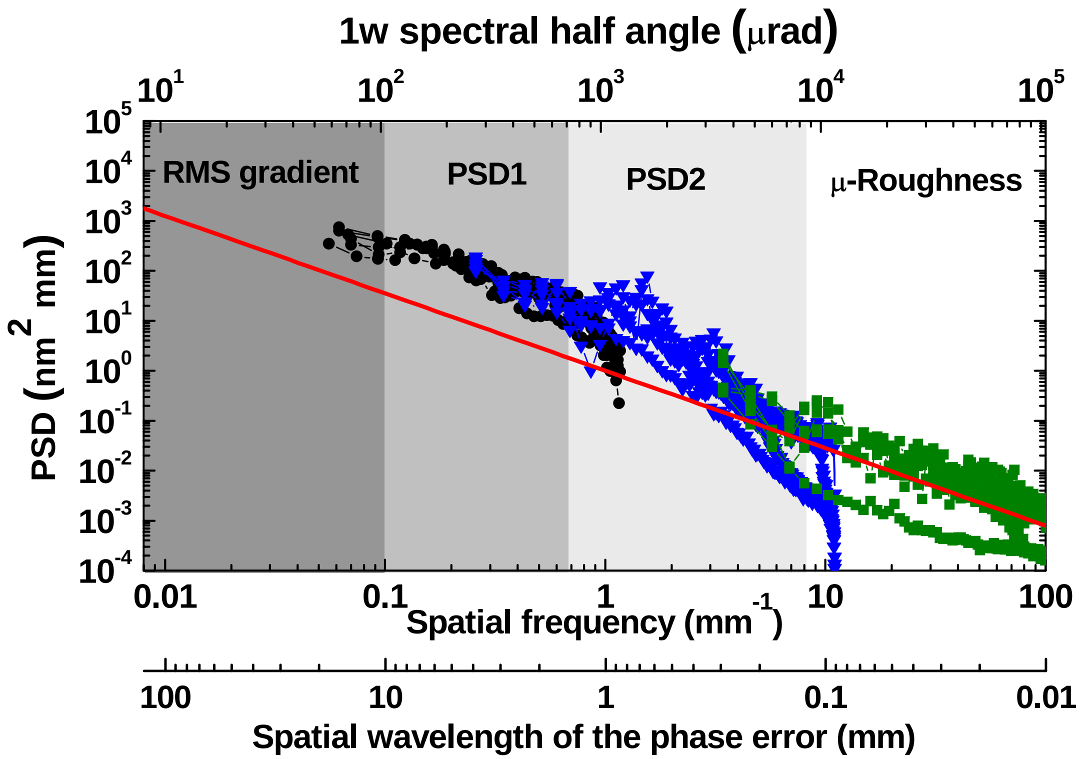
$$PSD(\nu_x, \nu_y) = \frac{\left|\Phi(\nu_x, \nu_y)\right|^2}{\Delta\nu_x \Delta\nu_y}$$



1 D Power Spectral Density

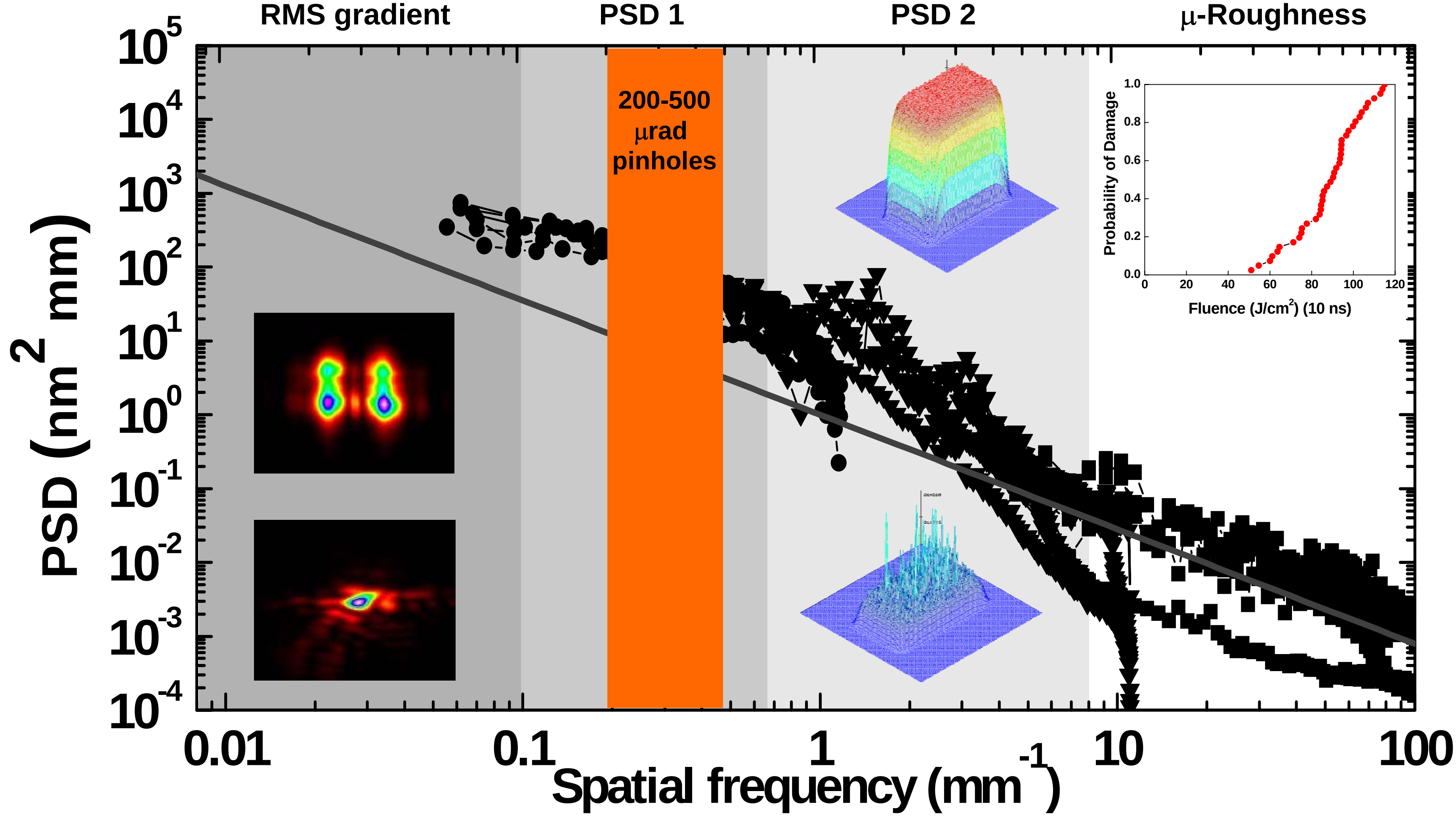
$$PSD(\nu_x) = \int PSD(\nu_x, \nu_y) d\nu_y$$



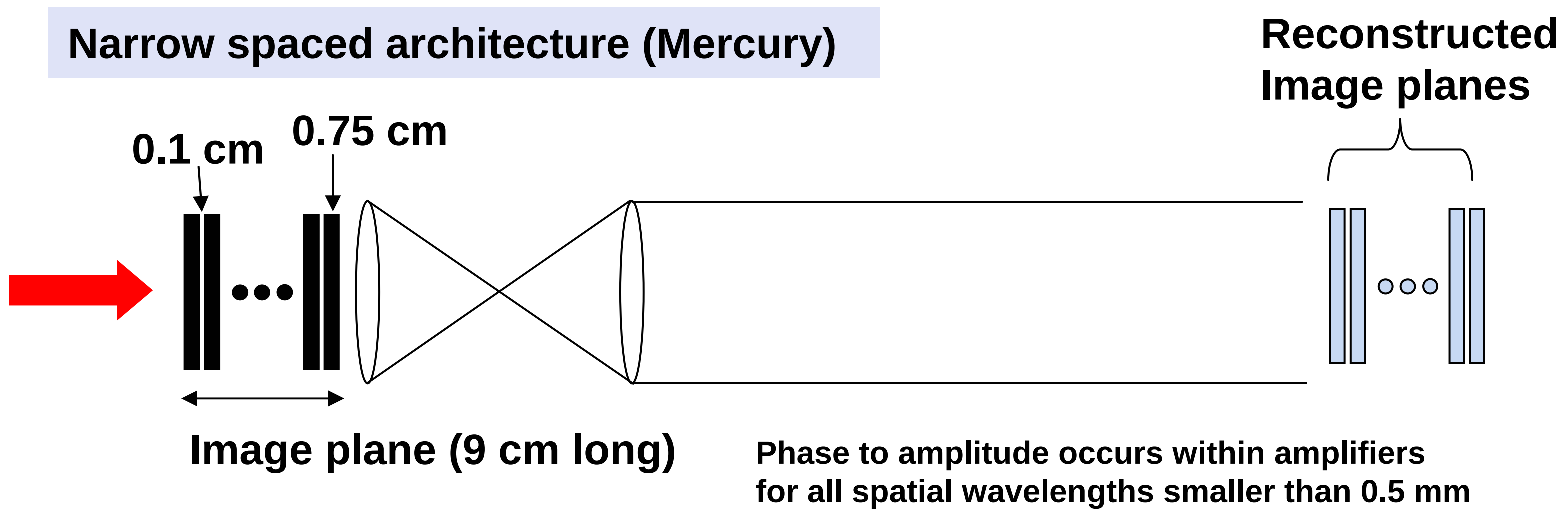


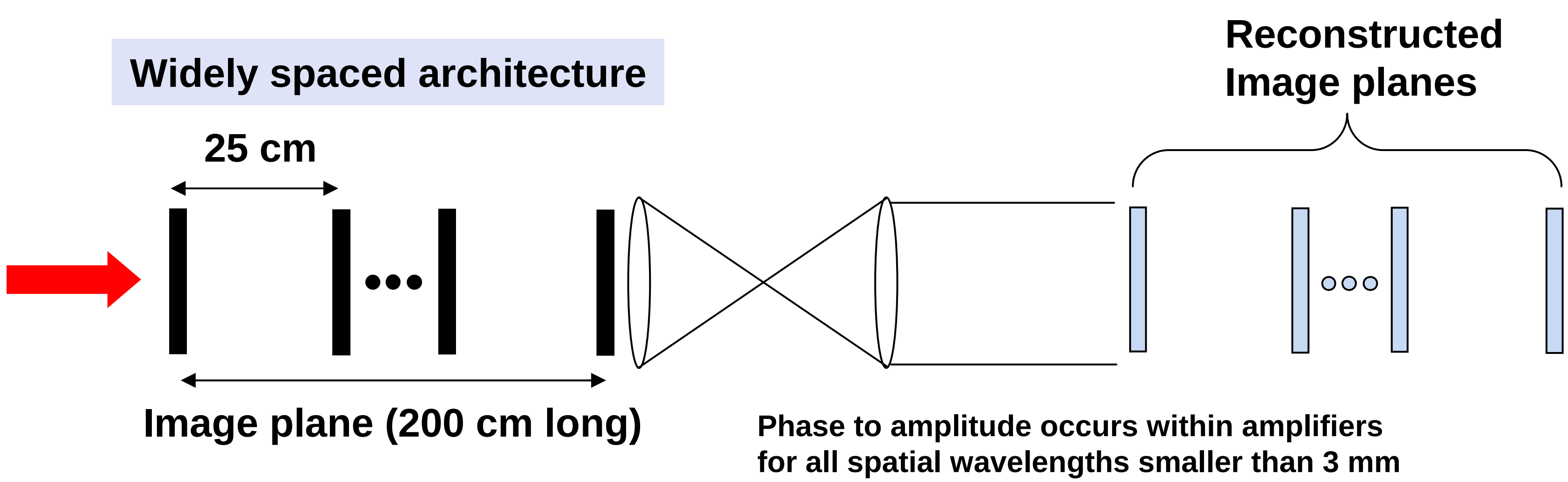
Optical specifications can drive:

Beam focusability | **Pinholes sizes** | **B-integral and filamentation** | **Optical lifetime**



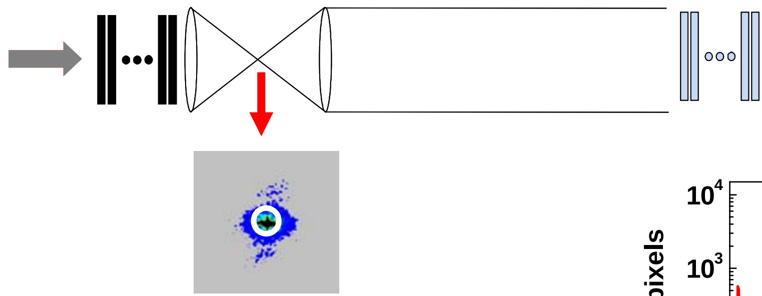
Two architectures were studied to investigate minimizing intensity modulation





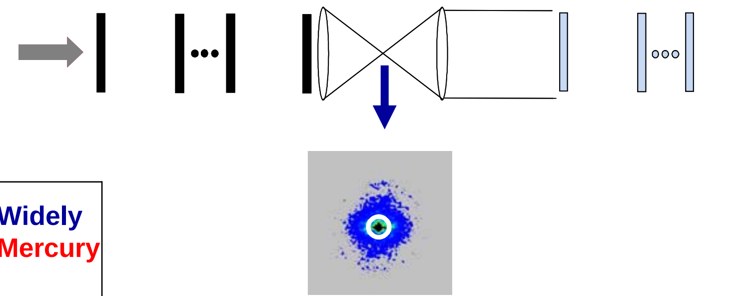
Designing a robust system requires a close interplay between laser architecture and optical specifications

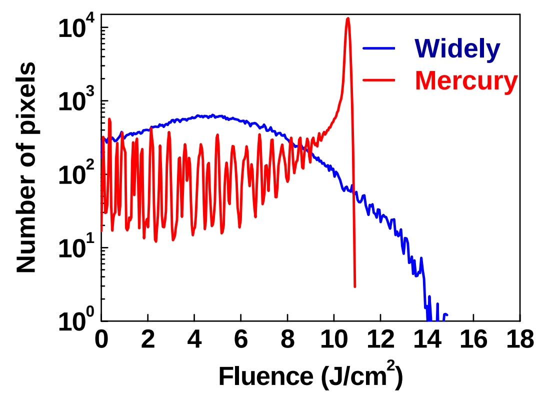
Closely spaced architecture (Mercury)



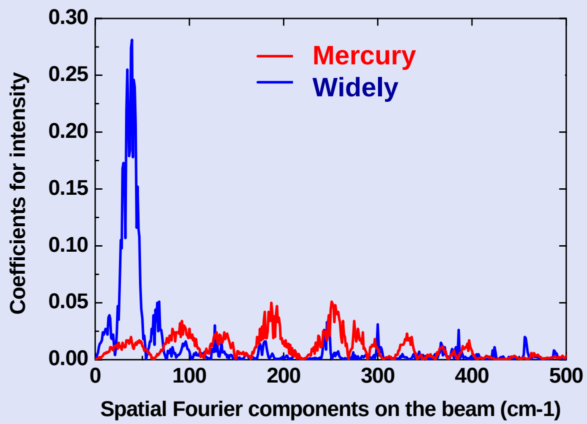
Relay planes

Widely spaced architecture

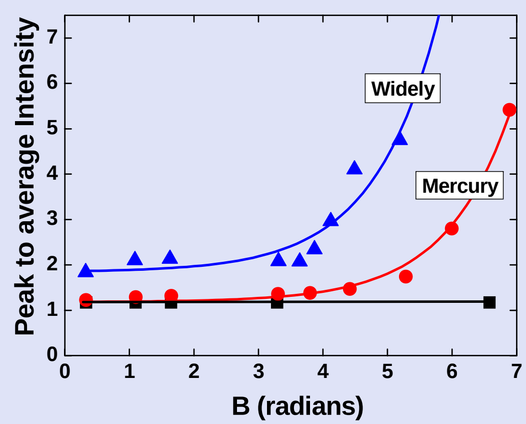




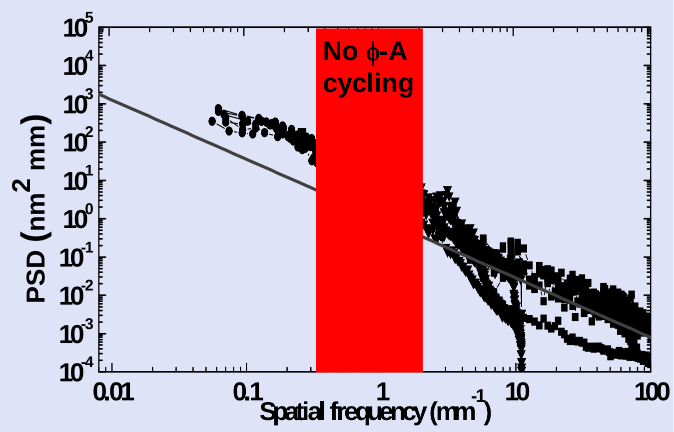
Bespalov-Talanov gain



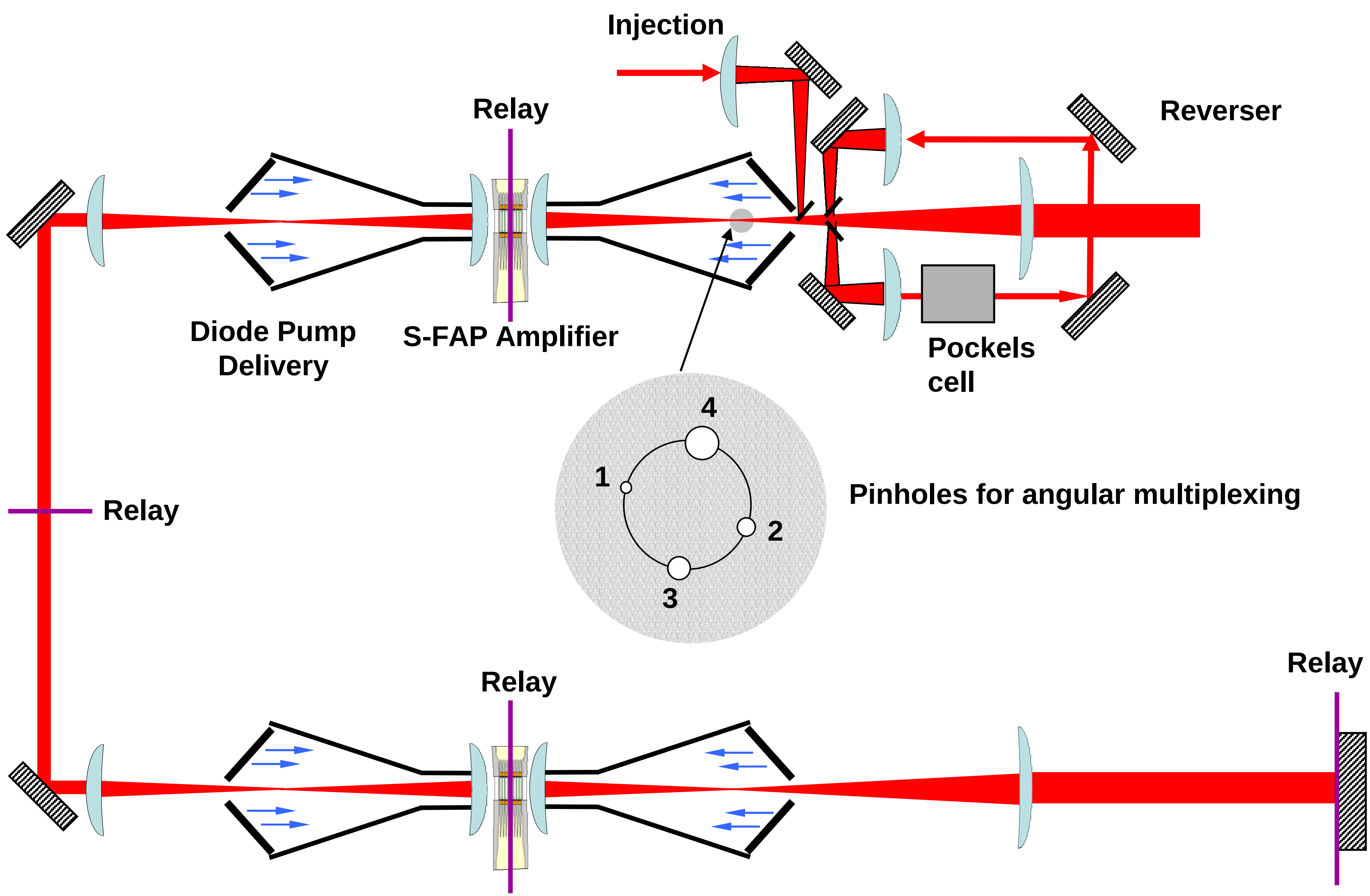
B-Integral



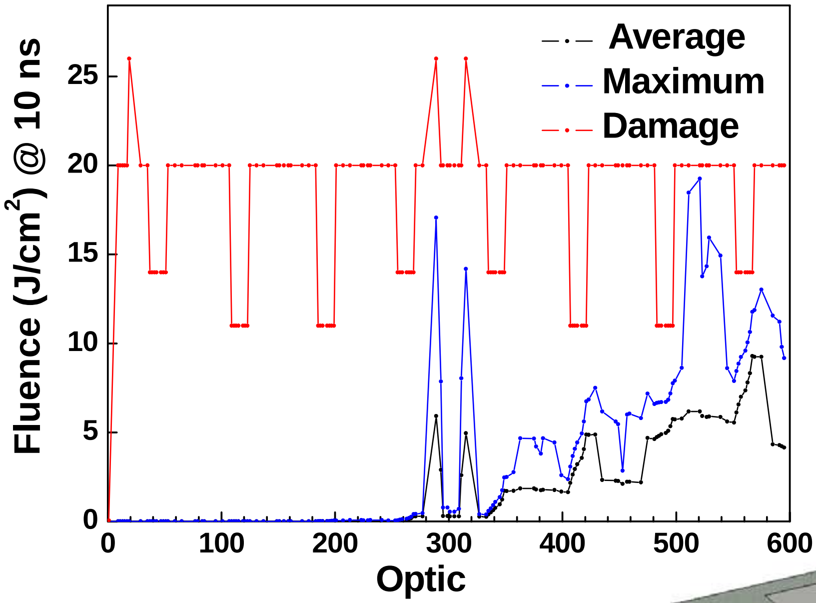
Noise term

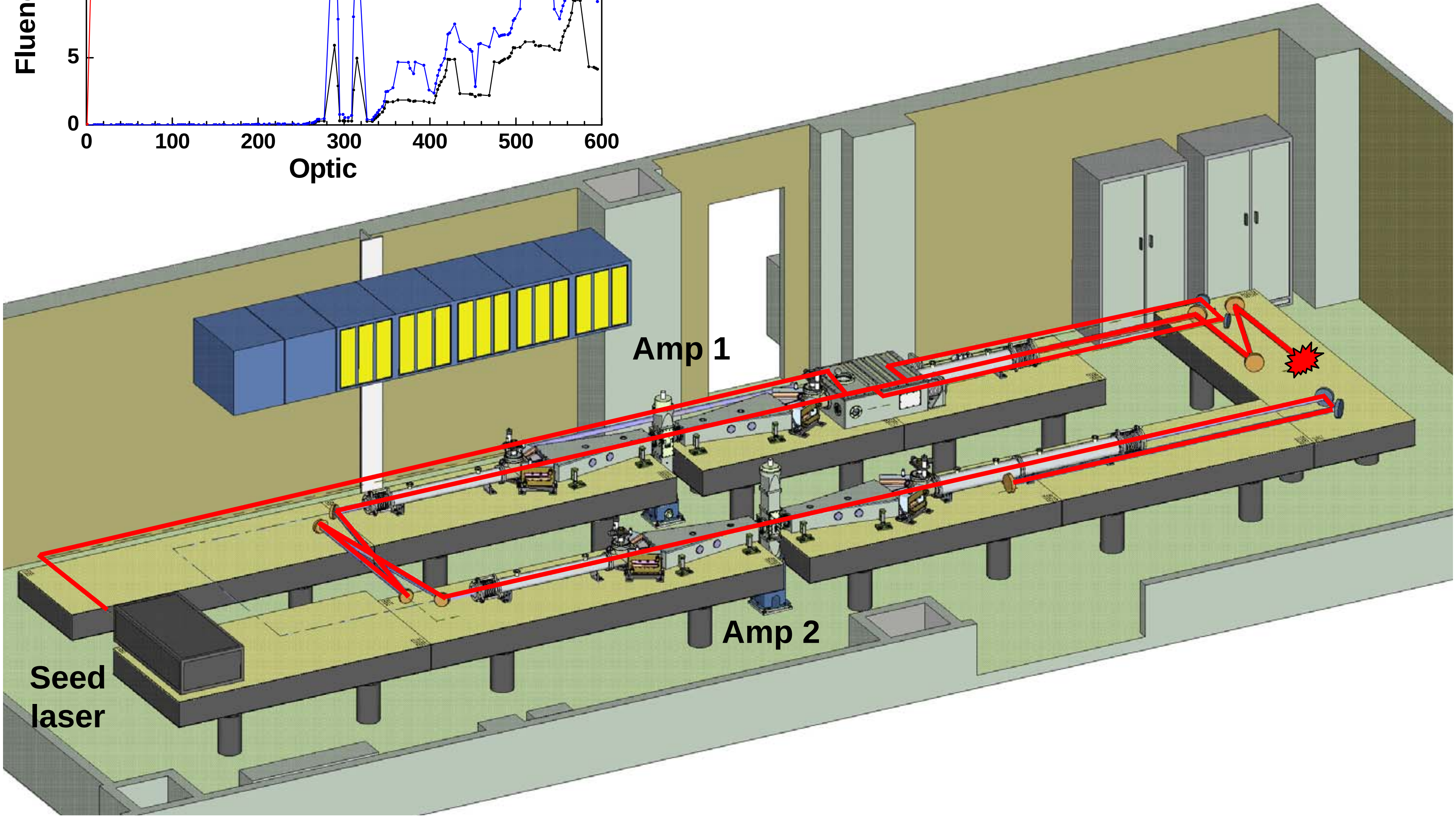


The Mercury laser system positions lenses and amplifiers near relay planes



Propagation modeling indicates that beam modulation is acceptable

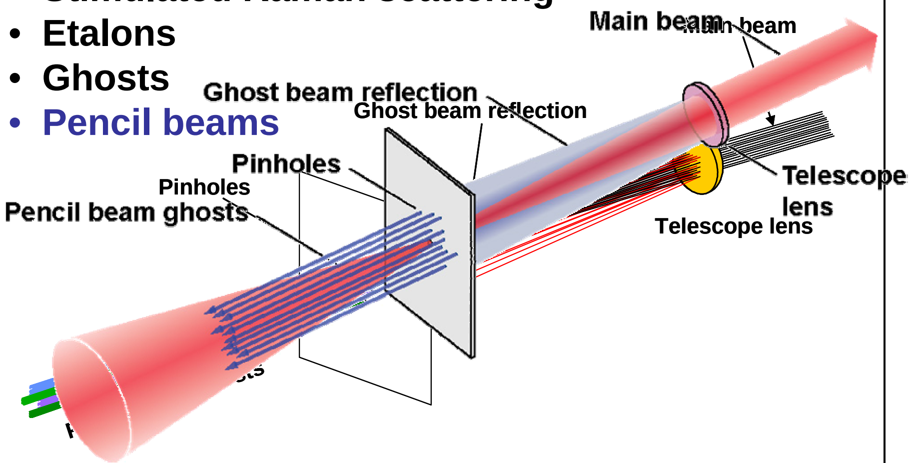




Additional laser modeling was performed to address all aspects of architecture

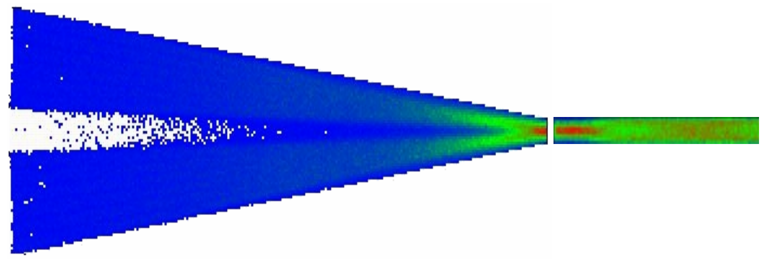
Parasitics

- Amplifier spontaneous emission
- Stimulated Raman scattering
- Etalons
- Ghosts
- Pencil beams



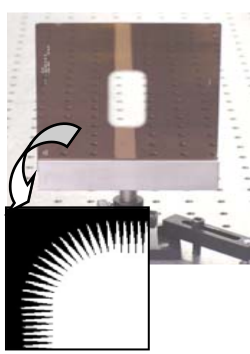
Thermal

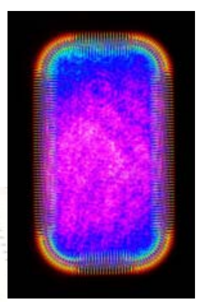
- Pockels cell
- Amplifiers
- Frequency conversion
- Diode arrays
- Diode delivery optics



Beam quality

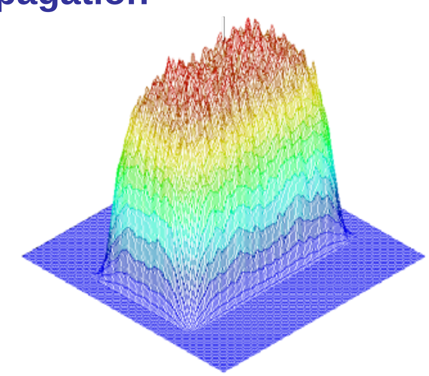
- Optical aberrations
- Pinhole geometry
- Optical specifications (PSD)
- Phase correction
- Serrated aperture



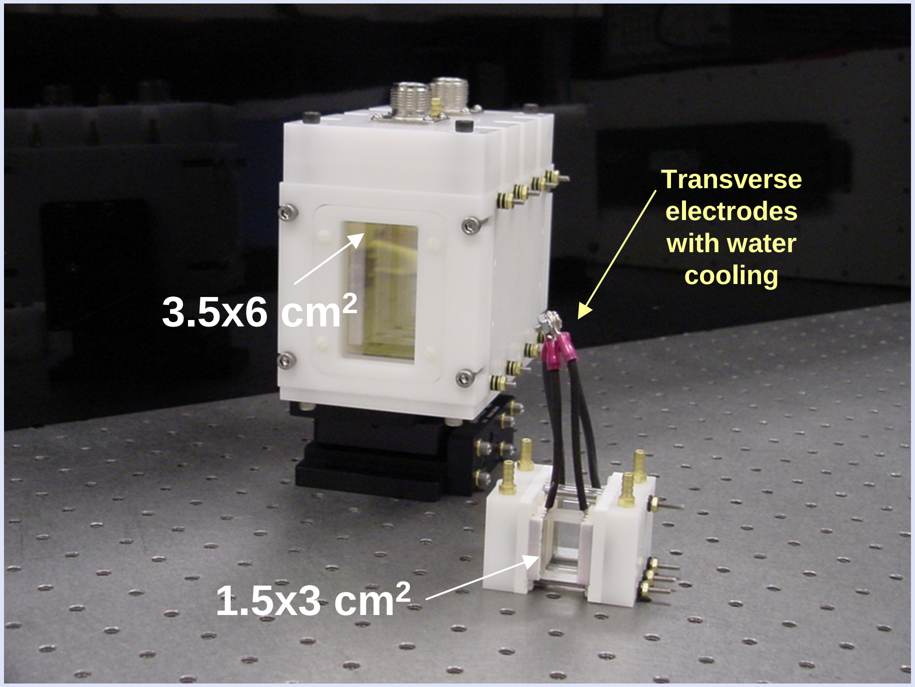


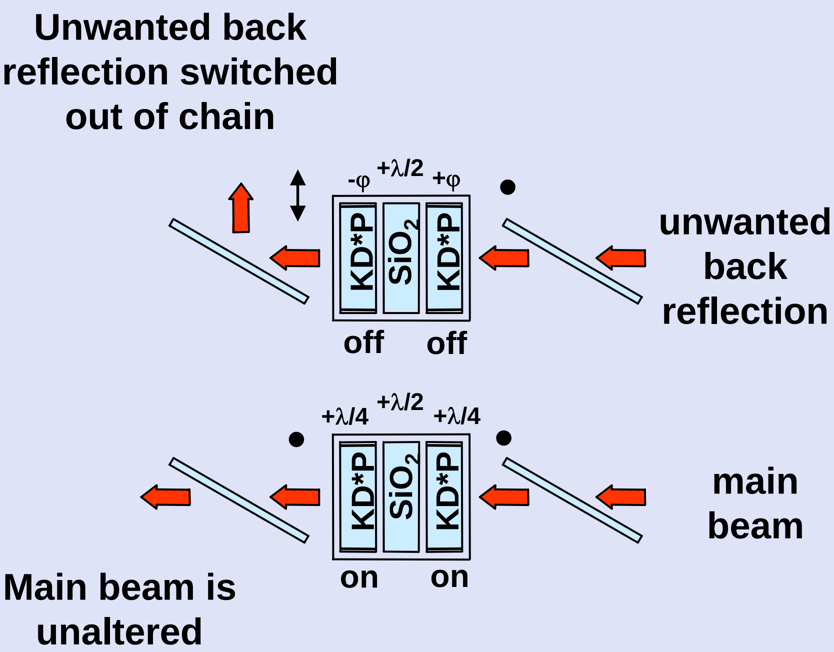
Energy and propagation

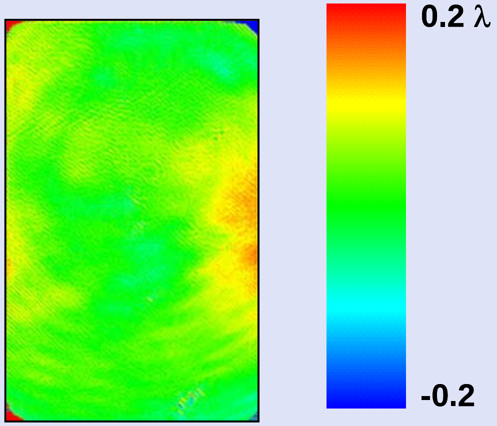
- Diode delivery efficiency
- 1D gain and extraction
- Bespalov-Talanov gain
- 2D MIRO beam propagation



A full size Pockels cell for parasitic beam control was installed in the system







Pockels cell performance:

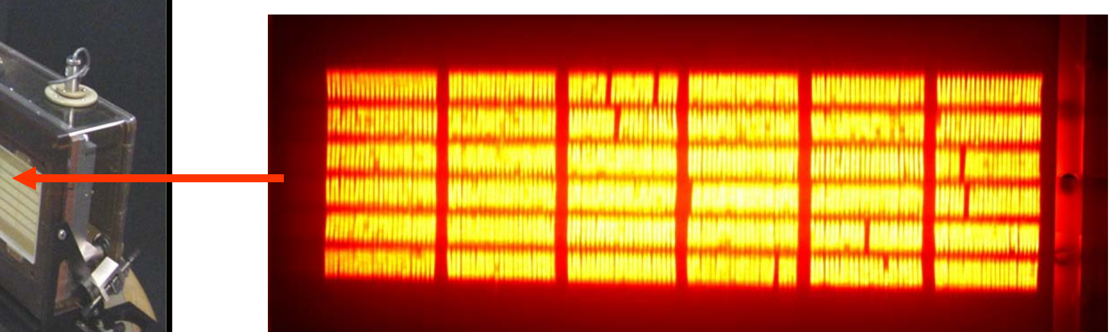
- Wavefront distortion: 0.15λ
- Average contrast: 200:1
- Rise time: 11 ns

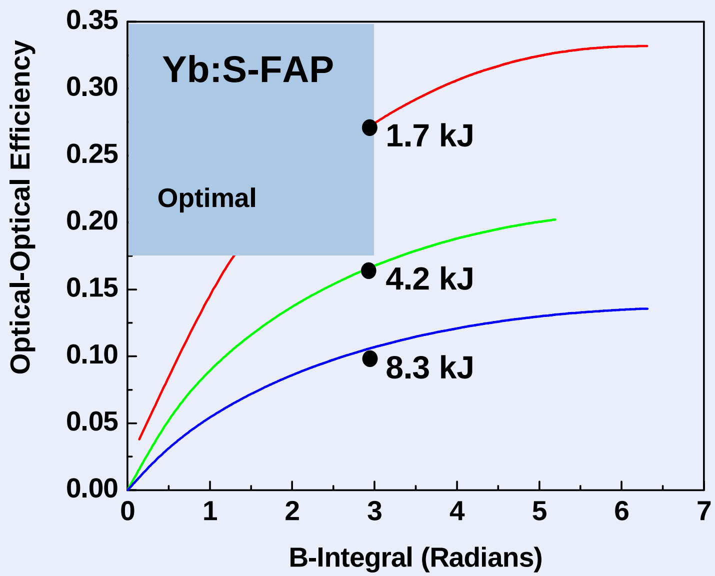
Each amplifier is pumped by 320 kW of peak diode power

2.3 kW tiles (23 bars)

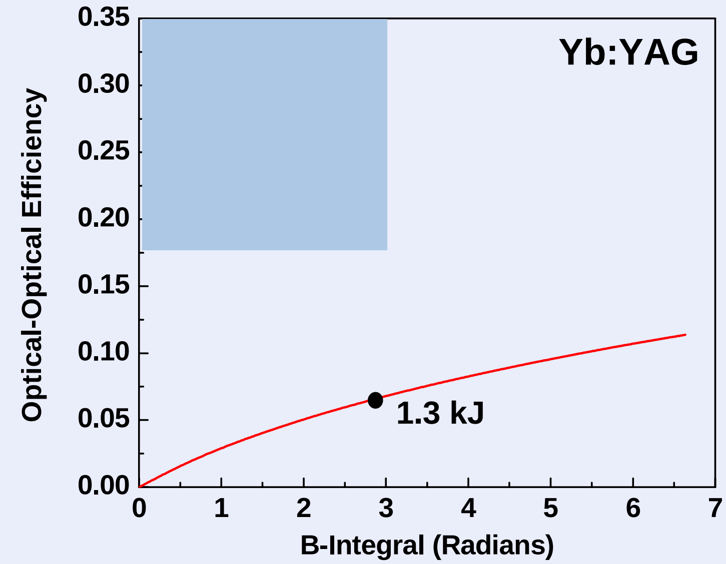
80 kW arrays (36 tiles)

Diode tile attributes	Performance
Power	120 W/ bar
Reliability	10^8 shots at 100 W/bar
Power droop over 1 msec	4.3%
Linewidth	2.3 nm
Integrated linewidth over 1 msec	4.1 nm
Divergence	15 x 140 mrad
Efficiency	45%

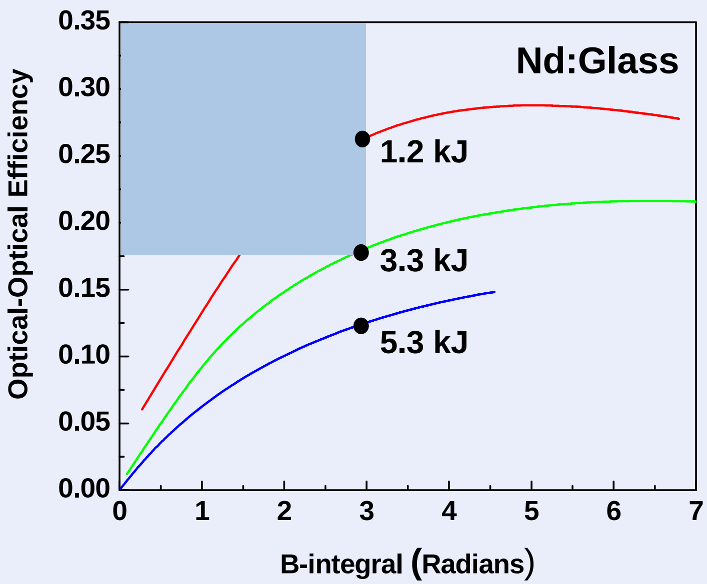




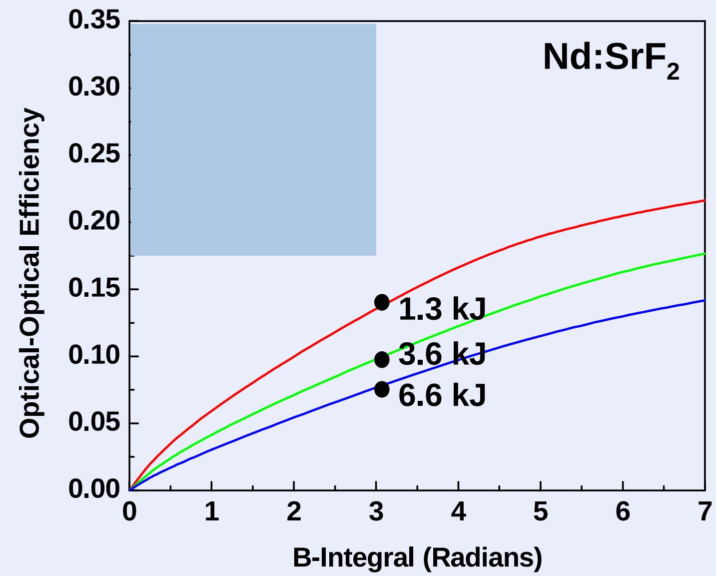
Yb:S-FAP appears most favorable,
but SRS may limit aperture



Efficiency is limited by high saturation fluence
of 9.6J/cm^2, low gain and high n_2



Nd:Glass is favorable for fusion,
but demands reduced cost of diodes

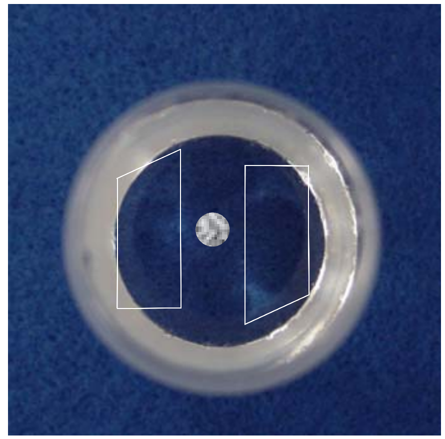


Efficiency is limited by high saturation fluence
of 10.6J/cm^2 and low gain

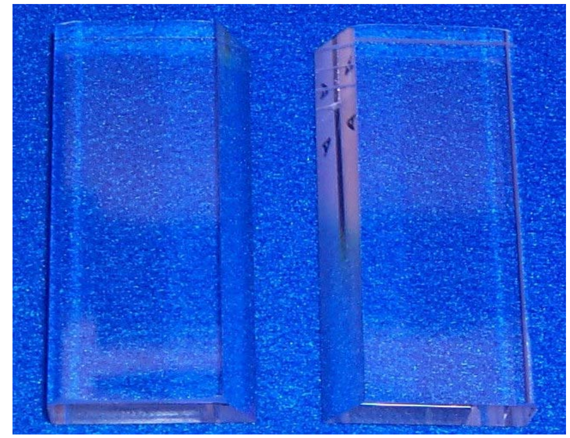
The fabrication of Yb:S-FAP amplifier slabs involves several precision process steps

Growth

Cutting

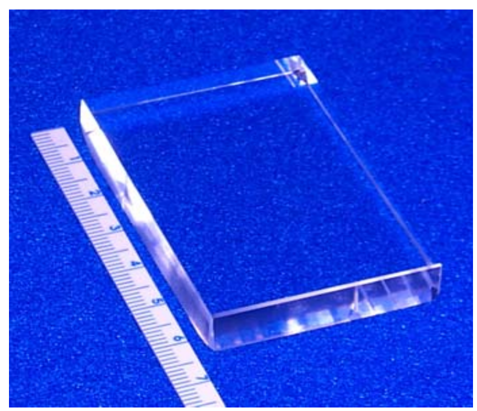


Polishing

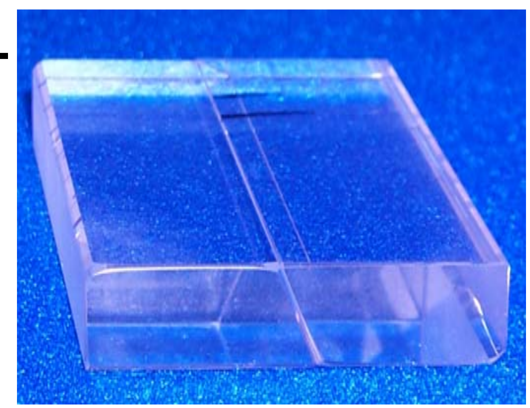


Coating

MRF



Bonding

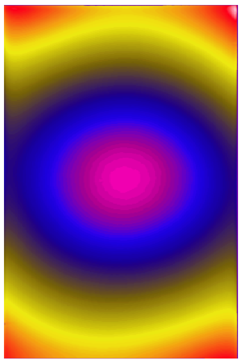


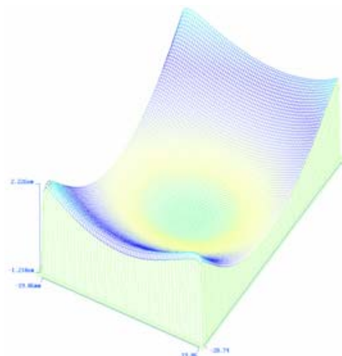
Magneto-rheological finishing (MRF) of the amplifier slabs is used for improving wavefront quality and optical lifetime

Before MRF

Surface wavefront

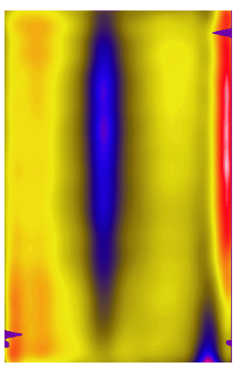
PV: 3.437 um, RMS: 0.815 um

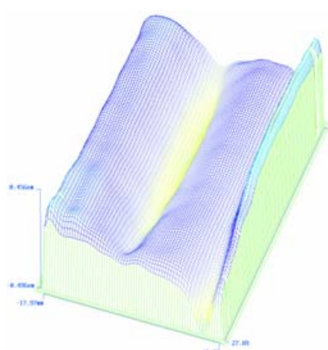




Transmitted wavefront

PV: 0.952 um, RMS: 0.160 um

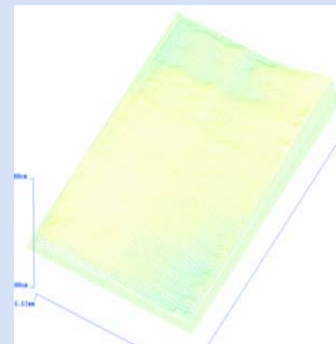




After MRF

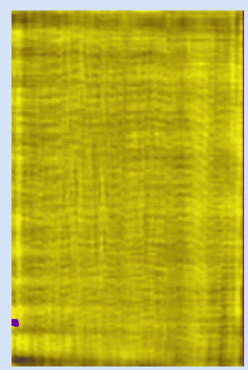
Surface wavefront

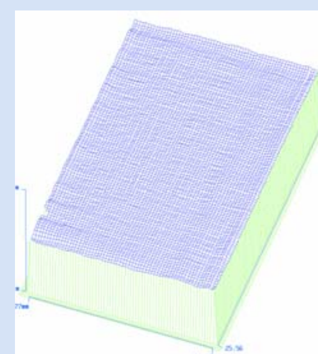
PV: 0.0682 um, RMS: 0.0140 um



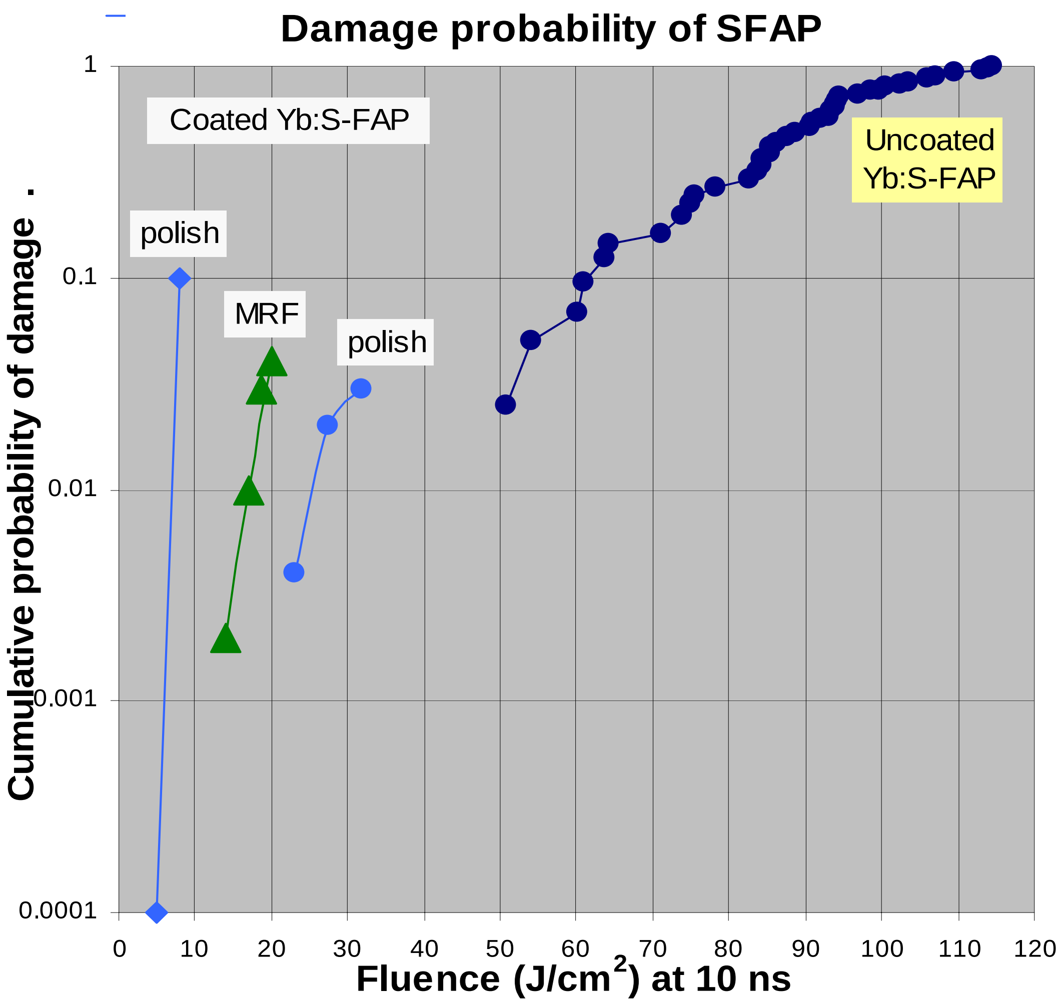
Transmitted wavefront

PV: 0.0755 um, RMS: 0.00695 um

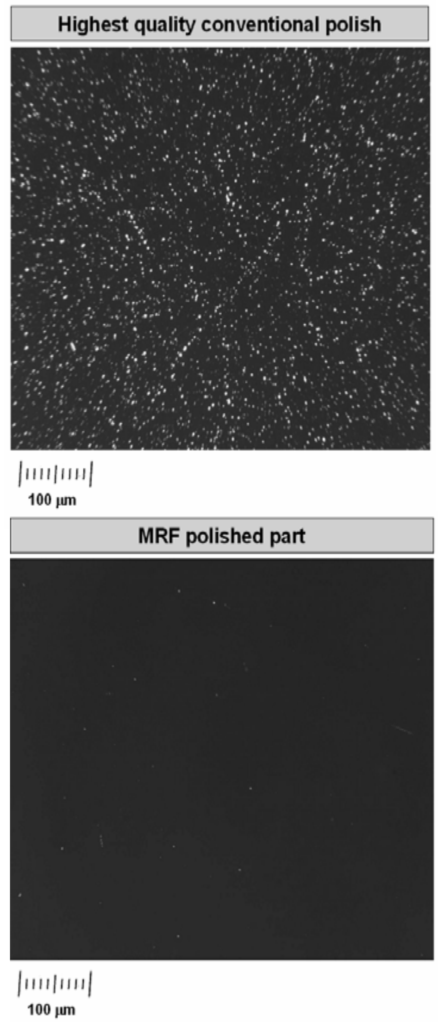




The impact of MRF finishing on 1ω laser damage threshold of coated S-FAP crystals is being evaluated



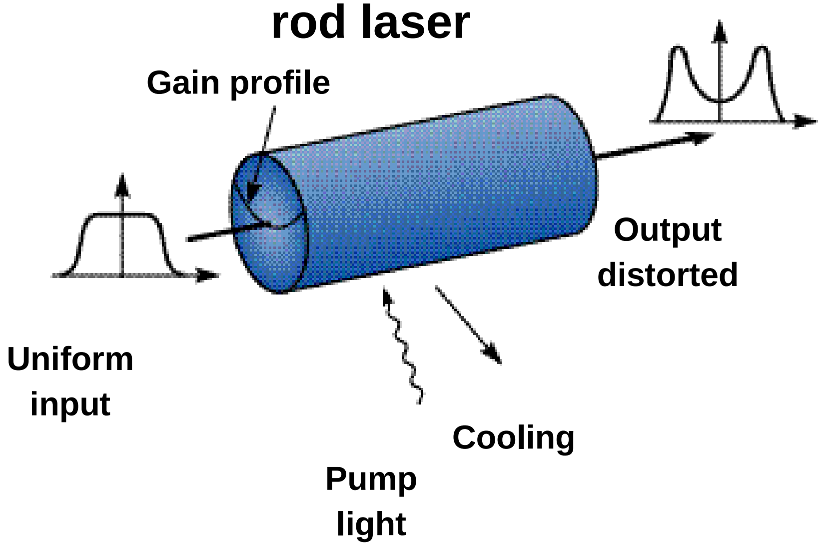
MRF polishing on fused silica reduces subsurface damage*



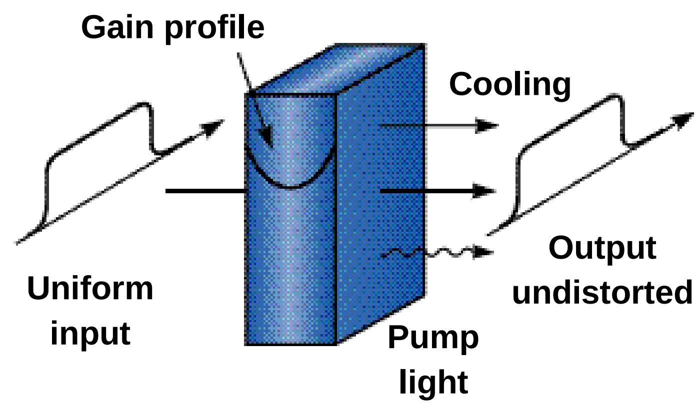
*Menapace et. al “Combined Advanced Finishing and UV-Laser Conditioning for Producing UV-Damage-Resistant Fused Silica Optics”, SPIE **4679**, 56-67, 2002

Face cooling with helium gas offers low scattering losses and thermal distortions

Transversely cooled rod laser



Longitudinally cooled slab laser

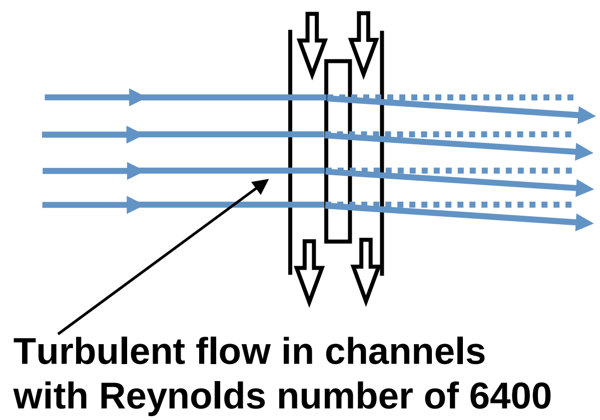


Scattered light: $\propto \quad \Delta n^2$

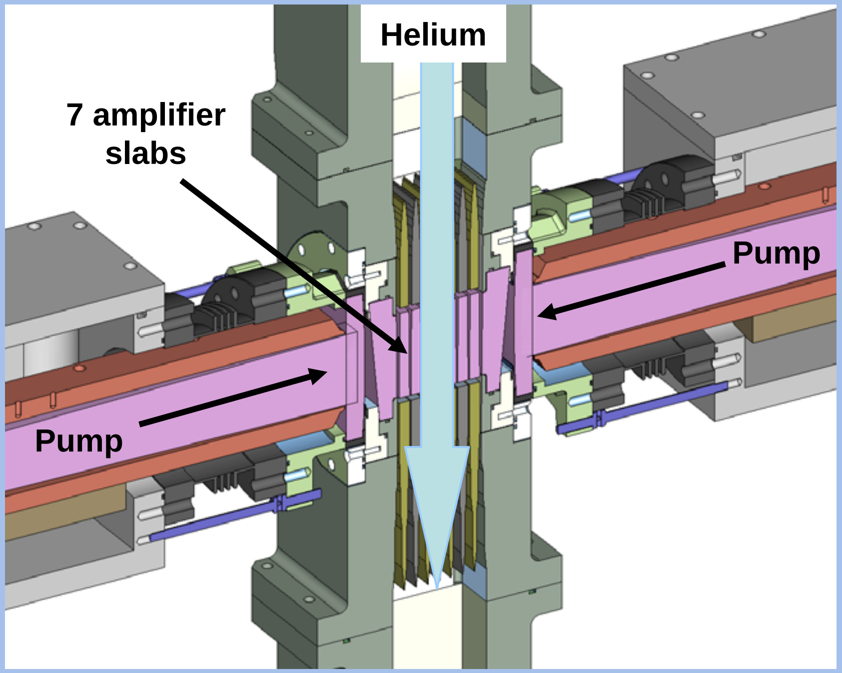
Change in index: $\Delta n = G \, \Delta\rho/\rho$

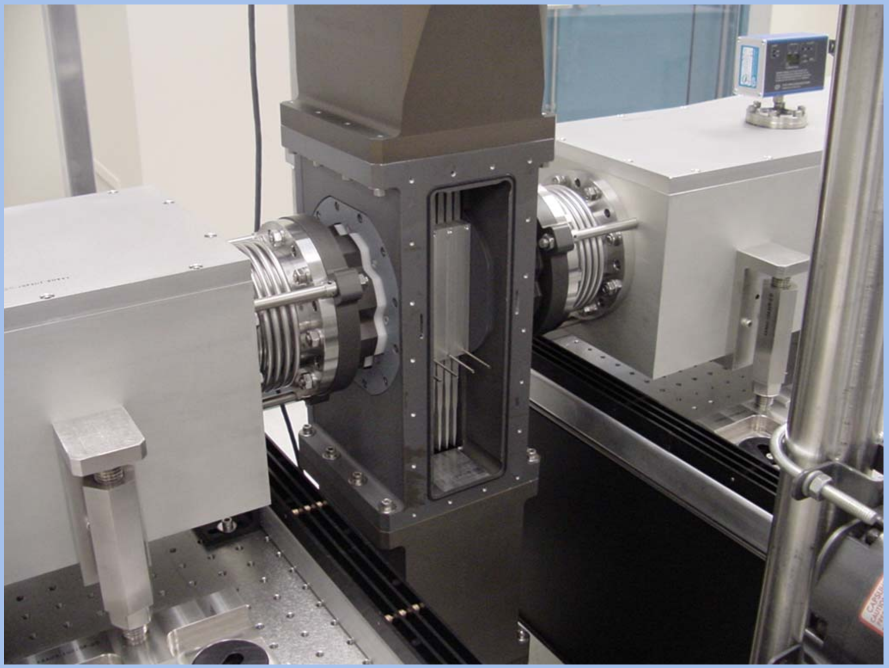
Definitions:
n = gas index
ρ = gas density
G = Gladstone-Dale coeficient
= 0.36×10^4 Helium
= 2.97×10^4 Nitrogen (7.4x larger)
= 2.92×10^4 Air (7.4x larger)

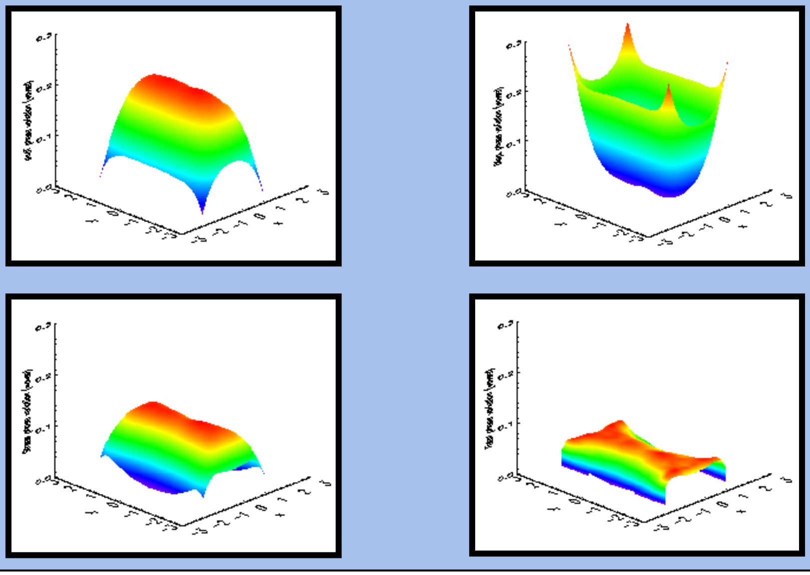
Gas-cooling



Both amplifiers have been deployed with helium gas cooling



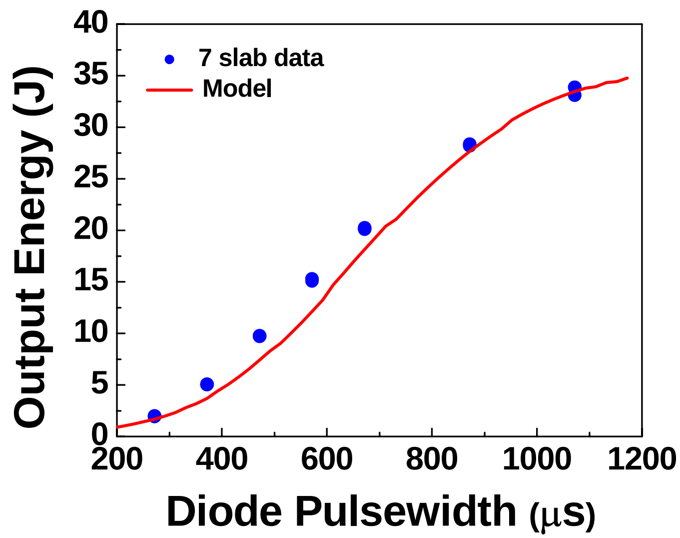


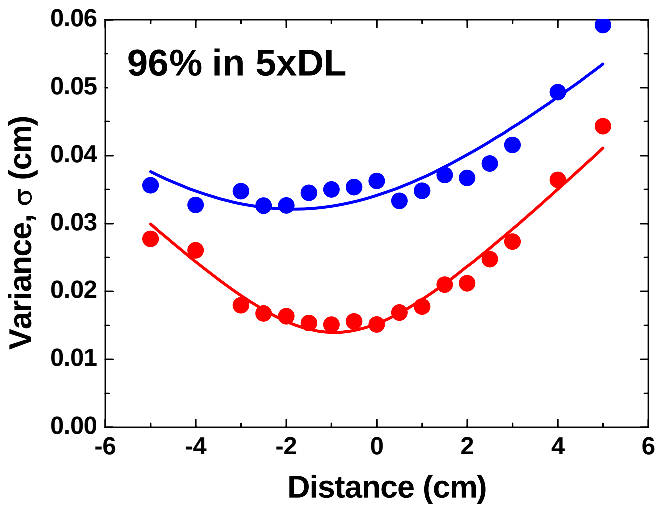



AMPLIFIER # 2
Newport

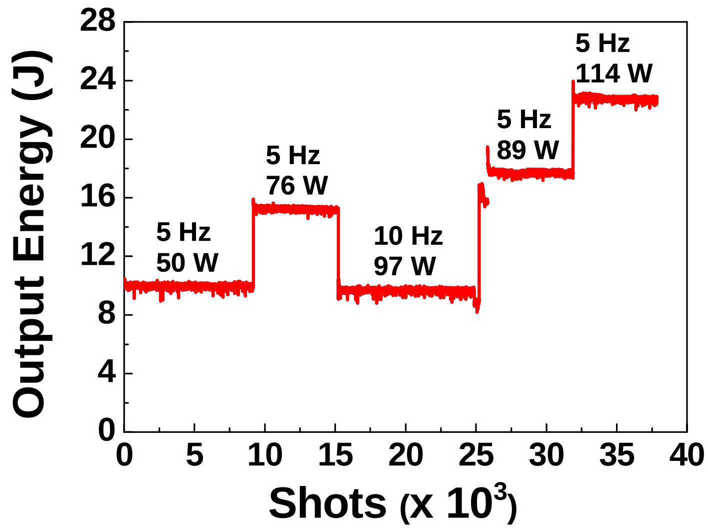
We have extracted up to 34 J single shot and 114 W at 5 Hz with continuous operation for an hour

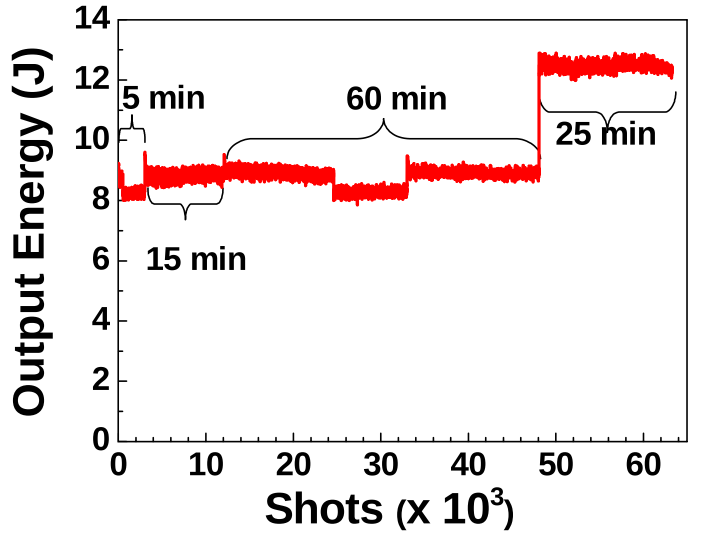
Energetics



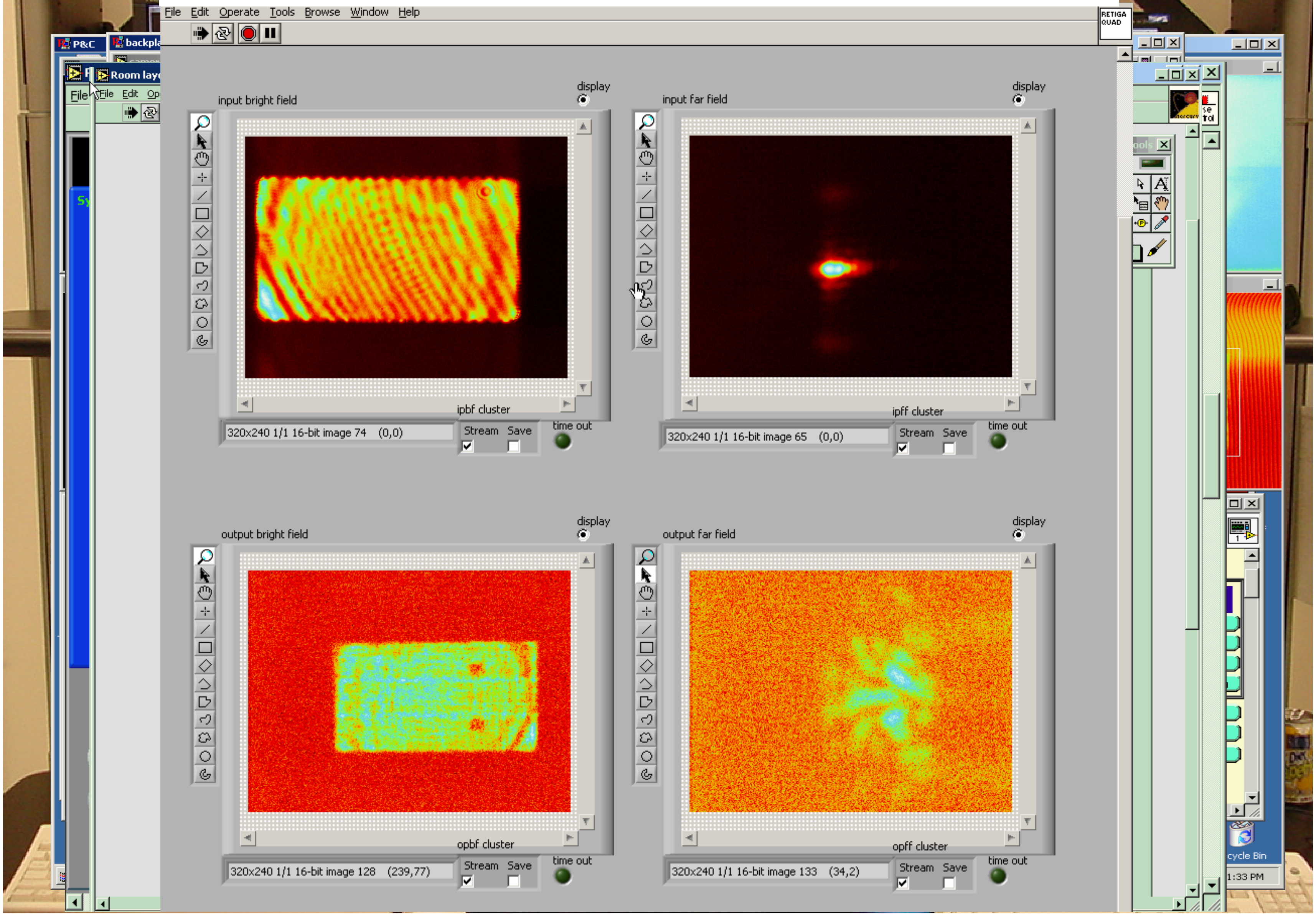


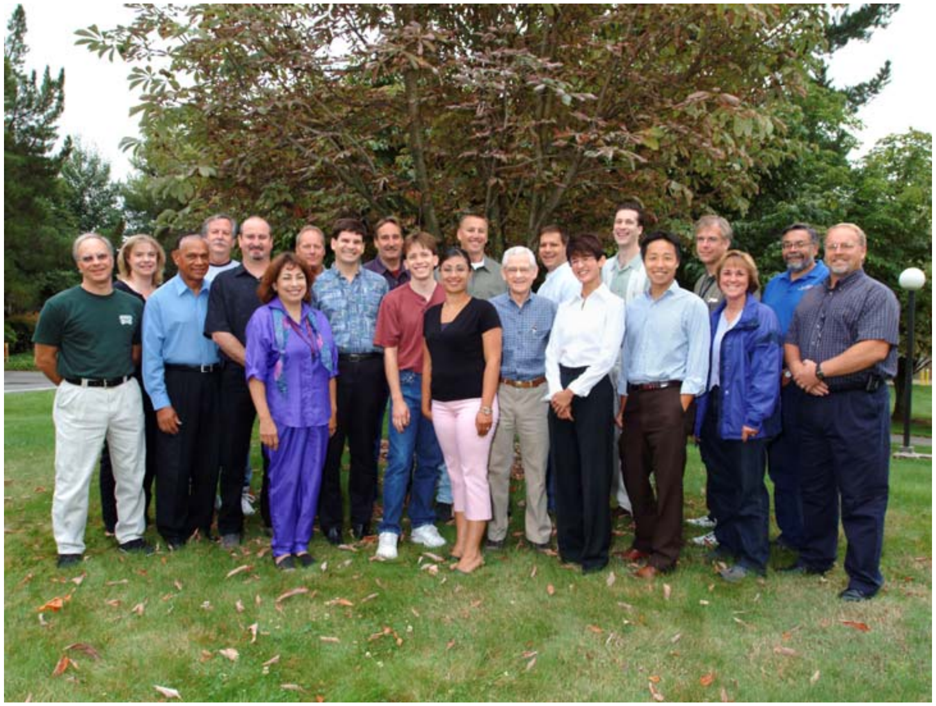
Average Power Operation





Input and output near and far field





Mercury Team

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Manny Carrillo
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Barry Freitas
Keith Kanz
Bob Kent
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Rod Lanning
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Bill Molander
Noel Petersen
Greg Rogowski
Kathleen Schaffers
Ralph Speck
Chris Stolz
Steve Sutton
John Tassano
Steve Telford
Peter Thelin
Everett Utterback

Collaborators

Laboratory for Laser Energetics
CEA (Bordeaux)
Northrop-Grumman
Onyx Optics
Schott Glass Technologies
Spectra Physics
Quality Thin Films
Zygo
CREOL
Coherent
Directed Energy

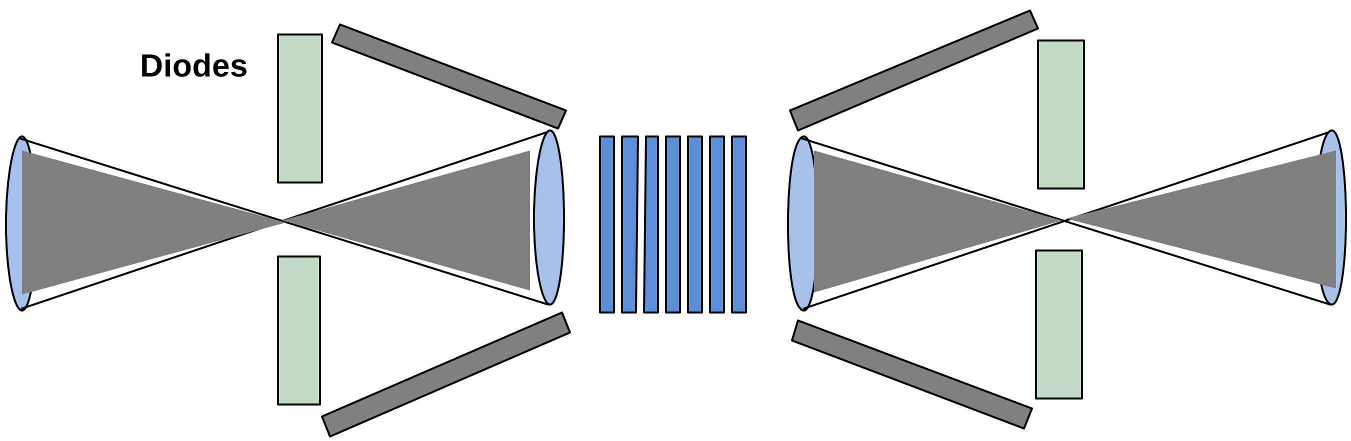
Comparison of NIF and Mercury amplifiers

Mirror

Telescope

Our new architectural layout of optics and amplifiers allows:

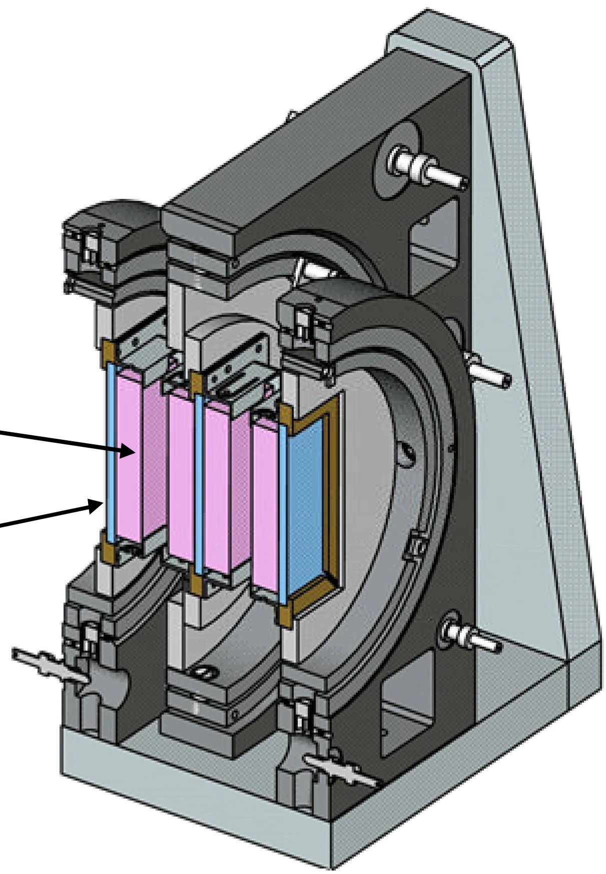
- **More compact amplifier cavity**
  - ***reduces "B-integral" or beam intensity modulations***
- **Collinear diode pumping and beam path extraction**
  - ***improves gain uniformity and beam quality***
- **Closer proximity of telescope lenses to a "relay plane"**
  - ***a location where damage probability is lowest***



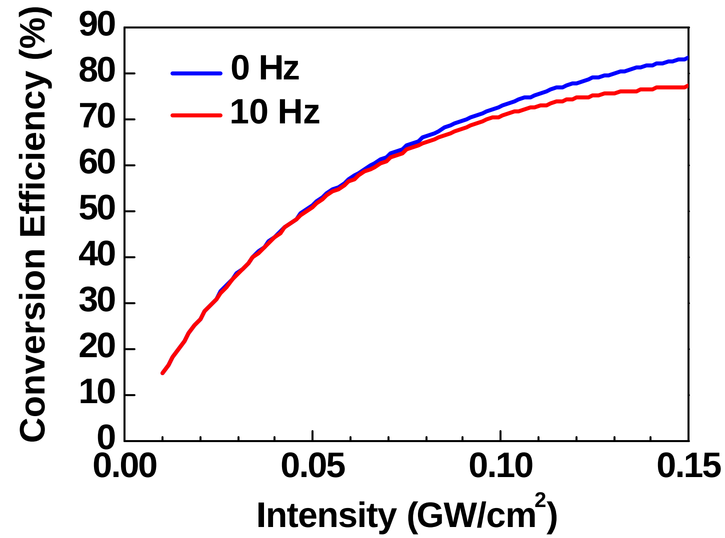
DKDP will first be used commission the cooling hardware

Frequency converter module

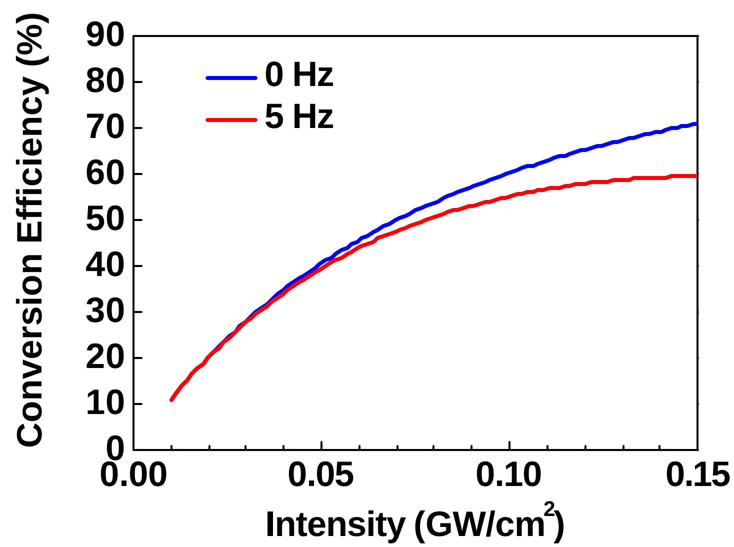
Cut-away view showing KD*P and sapphire heat spreader



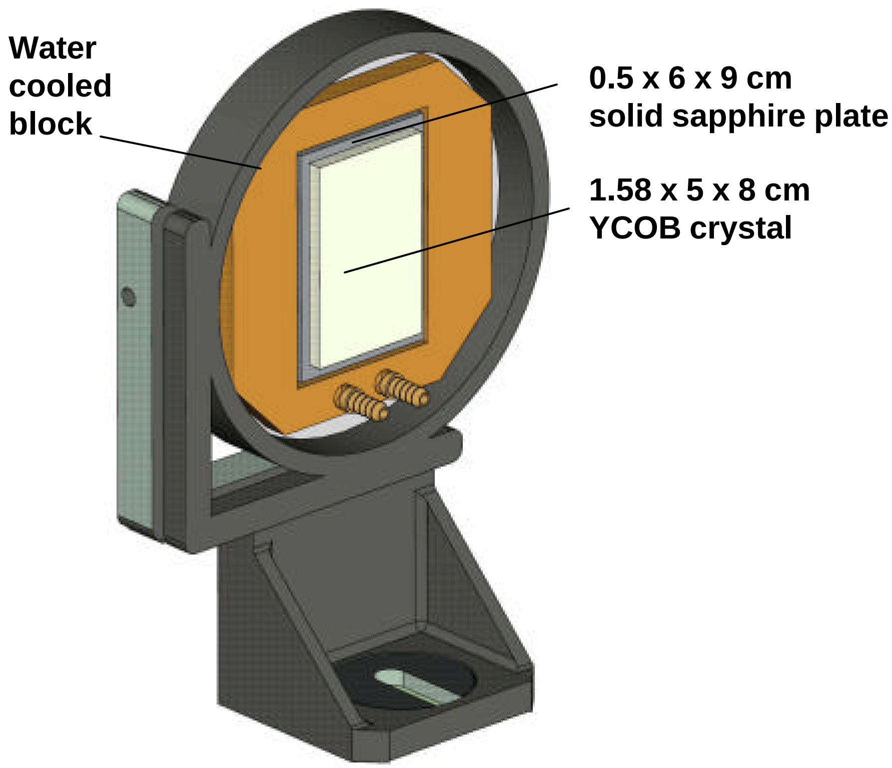
Type I, YCOB, One 1.58-cm thick

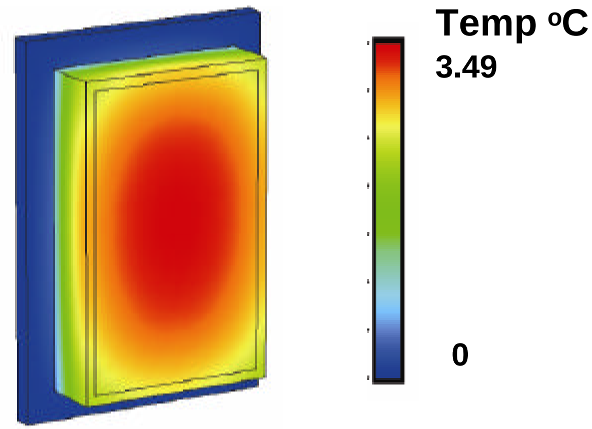


Type I, 97% DKDP, Four 1.5-cm thick

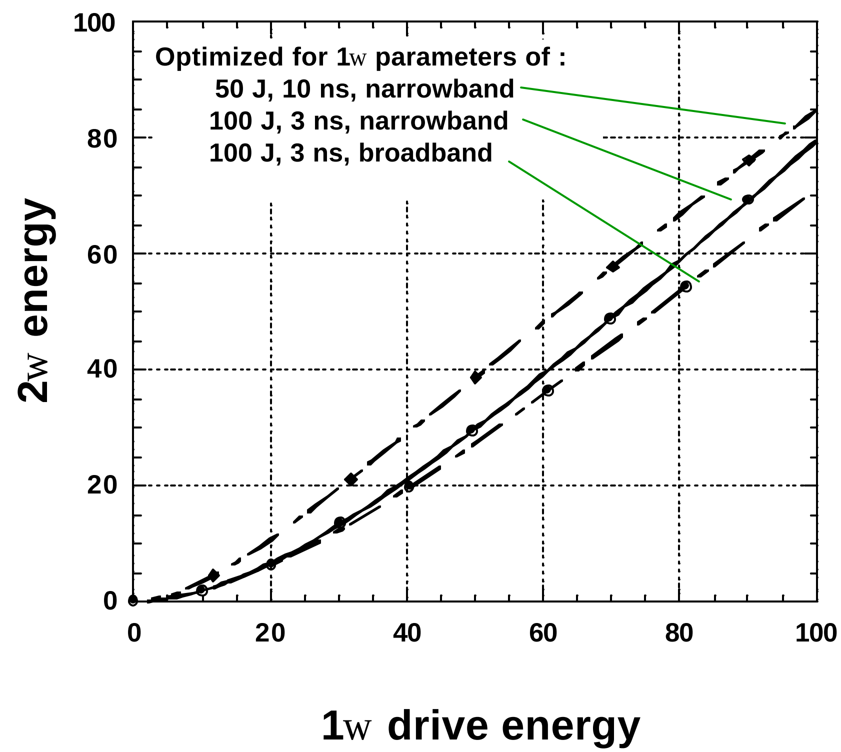


A heat spreader design will be used for cooling the YCOB crystal for 2ω frequency conversion at 10 Hz





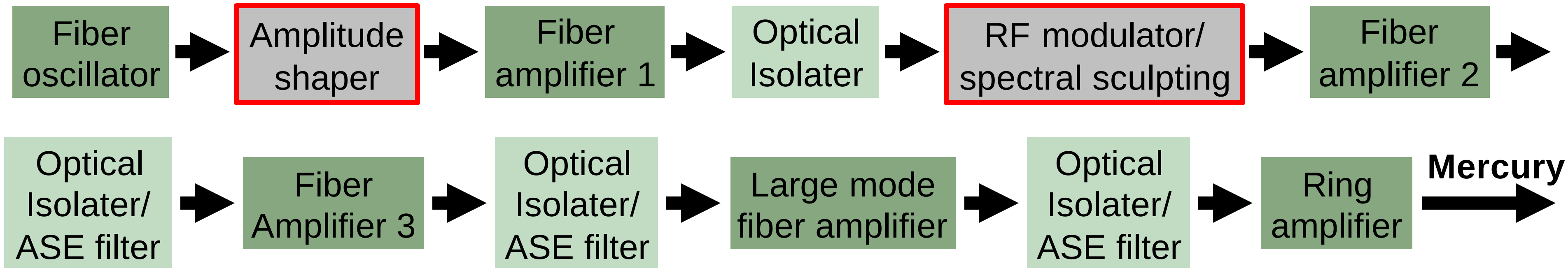
2ω Modeling

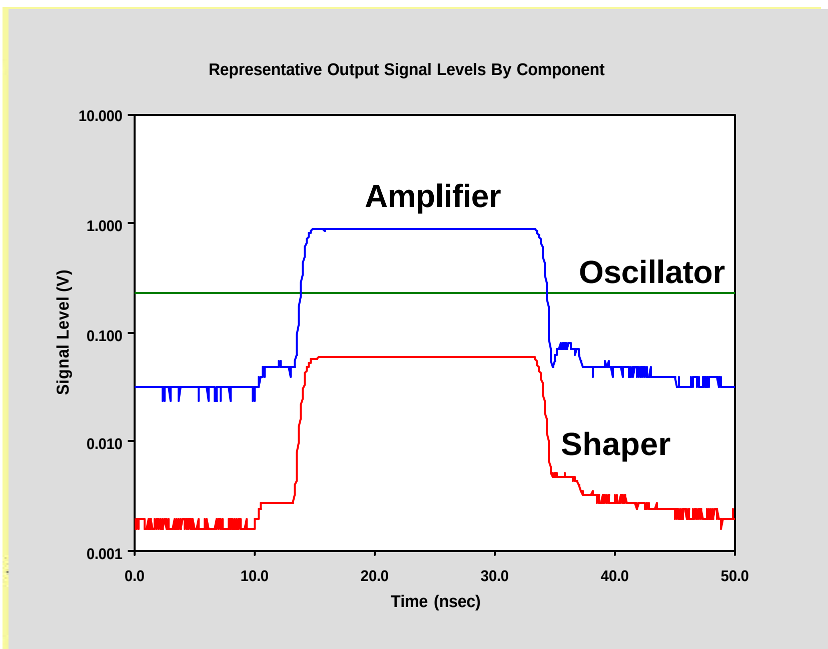


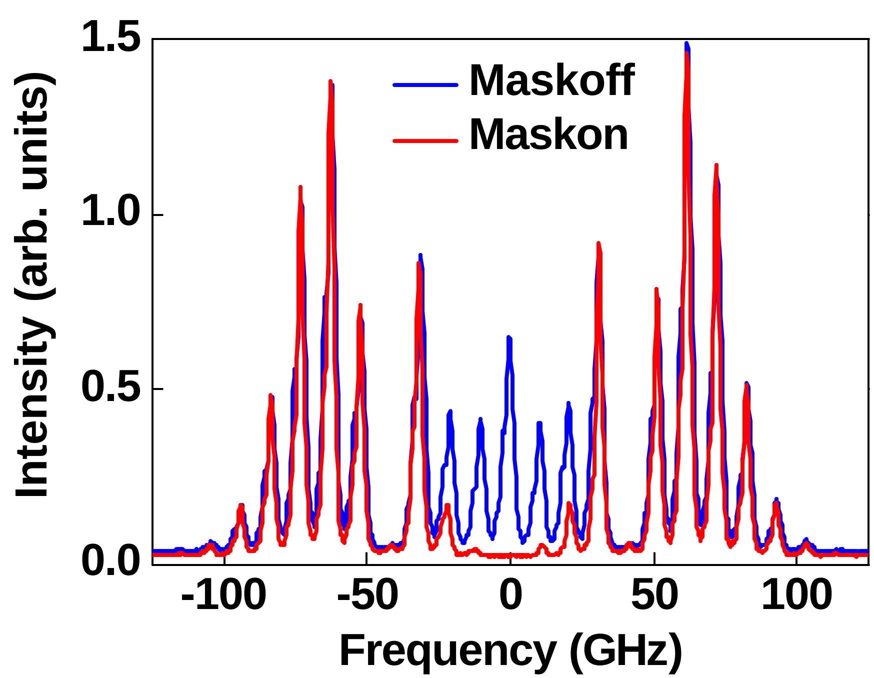
Temperature variation		Wavefront distortion		
Min	Max	YCOB	Sap-phire	Total
0.38	3.49	0.07	0.04	0.11

YCOB temperature acceptance is 22 °C

The front end upgrade will provide spectrally sculpted broadband pulses







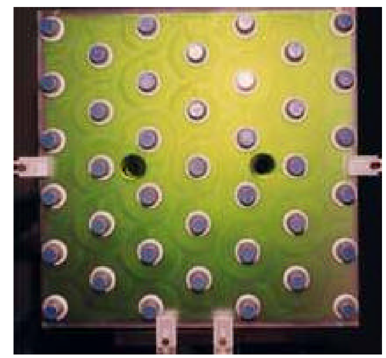
A deformable mirror will be used to correct for dynamic distortions in the laser

<u>Identified Deformable Mirror suppliers:</u>

- LLNL/LLE design deformable mirrors used on NIF
- Zyanetics deformable mirrors used on the HELSTF laser (high average power 30kW)
- Russian Ring deformable mirror used on LULI(France) (high peak power (1.4 GW/cm^2))

•<u>Mercury expected single pass wavefront distortion</u>:

• Static distortion stackup:	19 optics @ l/10	= 1.9 waves
	14 S-FAP@ l/5	= 2.8 waves
• Thermal distortion:	14 S-FAP@ ~l/8	= 2.0 waves
• Dynamic distortions:		~ 2.0 waves
Total wavefront distortion:		= 8.7 waves



<u>Mercury additional optics requirements</u>:

- Average power handling: 600 W
- Peak power handling: 0.64 GW/cm^2 (3 ns pulse)