The Mercury Laser Project

2002 Fusion Summer Study at
Snowmass Colorado, July 8-19

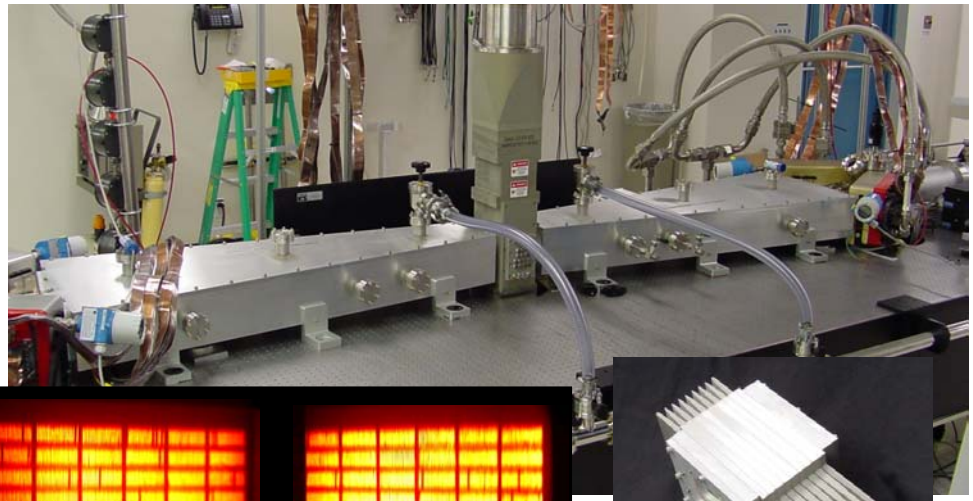
Camille Bibeau
Lawrence Livermore National Laboratory

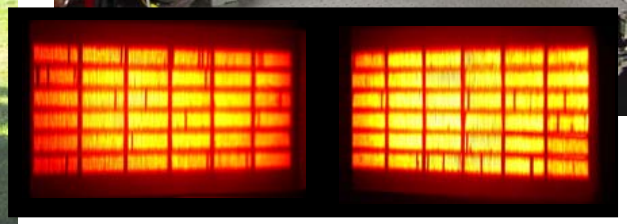
Then and Now……

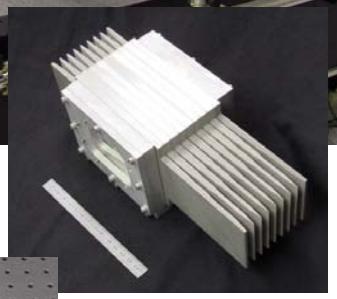
Technology	*1999*	*2002*
Diode Pwr	18.4 kW	320 kW
Tiles	4 (92 diodes)	144 (3312 diodes)
Pwr cond.	1 units	36
4x6 Crystals	1.5x2	4 slabs, 4 in fab, 6 boules
In Amplifier	None	4
Facility	Room	Optics, Utilities, Interlocks…
Control System	Software	Interfaced to equipment
Amplifier	Built	Demo'd
Pump Optics	Design	Two sets installed
Optical train	Design	Installed
Front end	None	200 mJ, serrated beam shaper
Diagnostics	None	4 packages built
Wavefront corr.	Concept	Phase plate installed
Spectral sculpting	-	Demo'd at LLE
Extraction	-	11.8 J, 0.1 Hz

Mercury Team

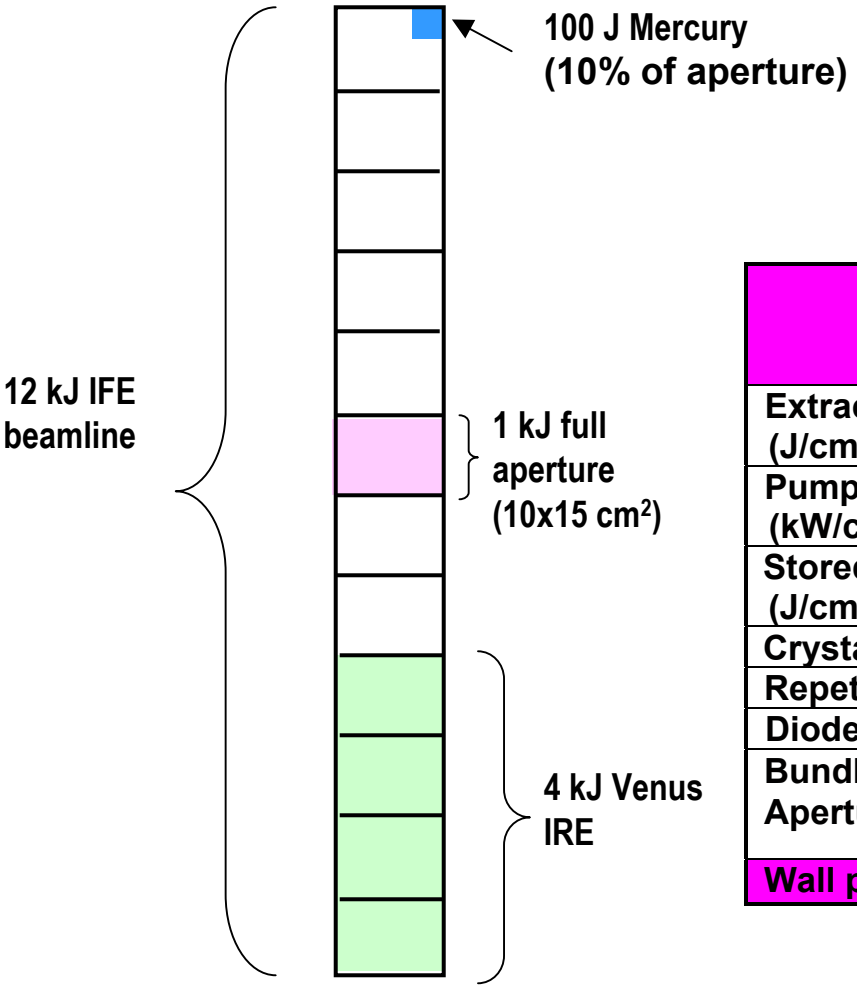
Crystal Growth:	K. Schaffers, J. Dawson
Laser System:	A. Bayramian, R. Beach, C. Bibeau, C. Ebbers, K. Skulina, S. Dixit, S. Payne
Laser Diodes:	R. Beach, B. Freitas, D. Van Lue
Controls:	B. Behrendt, S. Telford
Collaborators:	L. Waxer, J. Kelly, LLE
Industrial Partners:	Coherent, Northrup-Grumman, Onyx Optics, Directed Energy







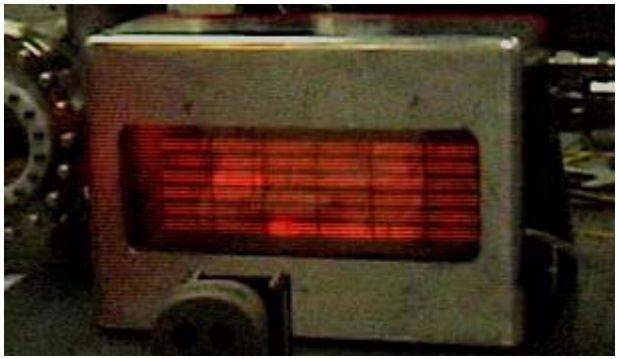
Mercury is 1/10th aperture scale of an IFE beam



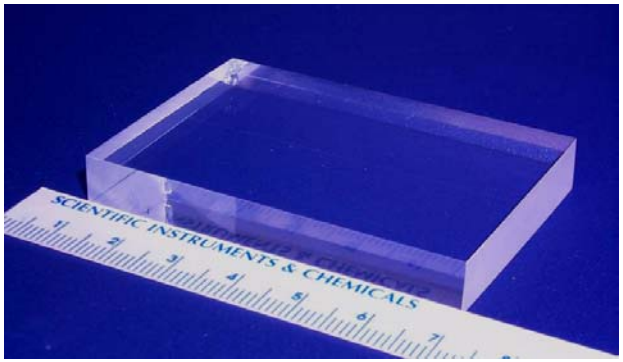
Parameter	100-J Mercury	4-kJ (Venus)	12-kJ (beamline for IFE)	IFE driver (2 MJ, 168 beamlines
Extraction Fluence (J/cm^2)	8	8	8	8
Pump Intensity (kW/cm^2)	10	10	10	10
Stored Energy Density (J/cm^3)	1.2	1.1	1.1	1.1
Crystal Thickness (cm)	0.75	0.75	0.75	0.75
Repetition Rate (Hz)	10	10	10	10
Diode Cost ($/W)	5.4	1.2	-	< 0.05
Bundling Aperture (cm x cm)	- 3 x 5	4 10 x 15	12 10 x 15	12x7 10 x 15
Wall plug efficiency (%)	10 (1ω)	10 (3ω)	>10 (3ω)	>10 (3ω)

Diode cost reduction, beam bundling, and crystal growth scaling will be addressed at the IRE stage

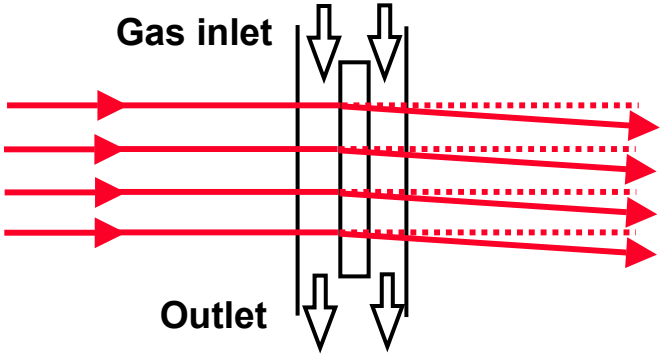
To meet Mercury requirements, we have chosen a diode-pumped solid-state laser employing gas-cooling and crystalline amplifiers



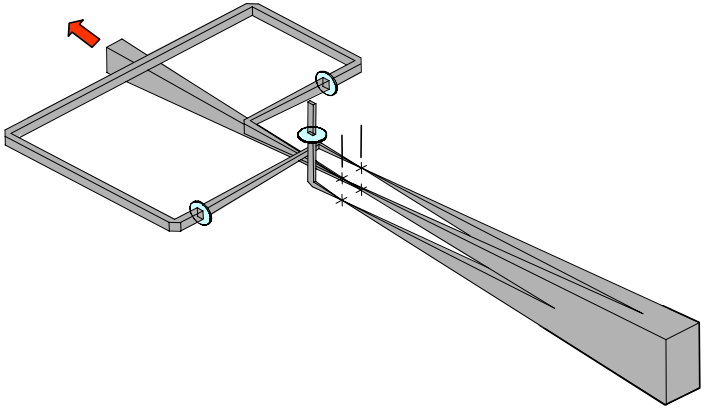
Laser diodes
High efficiency and long lifetime



Yb:S-FAP crystals [$Sr_5(PO_4)_3F$]
Increased energy storage,
extraction efficiency, and thermal conductivity



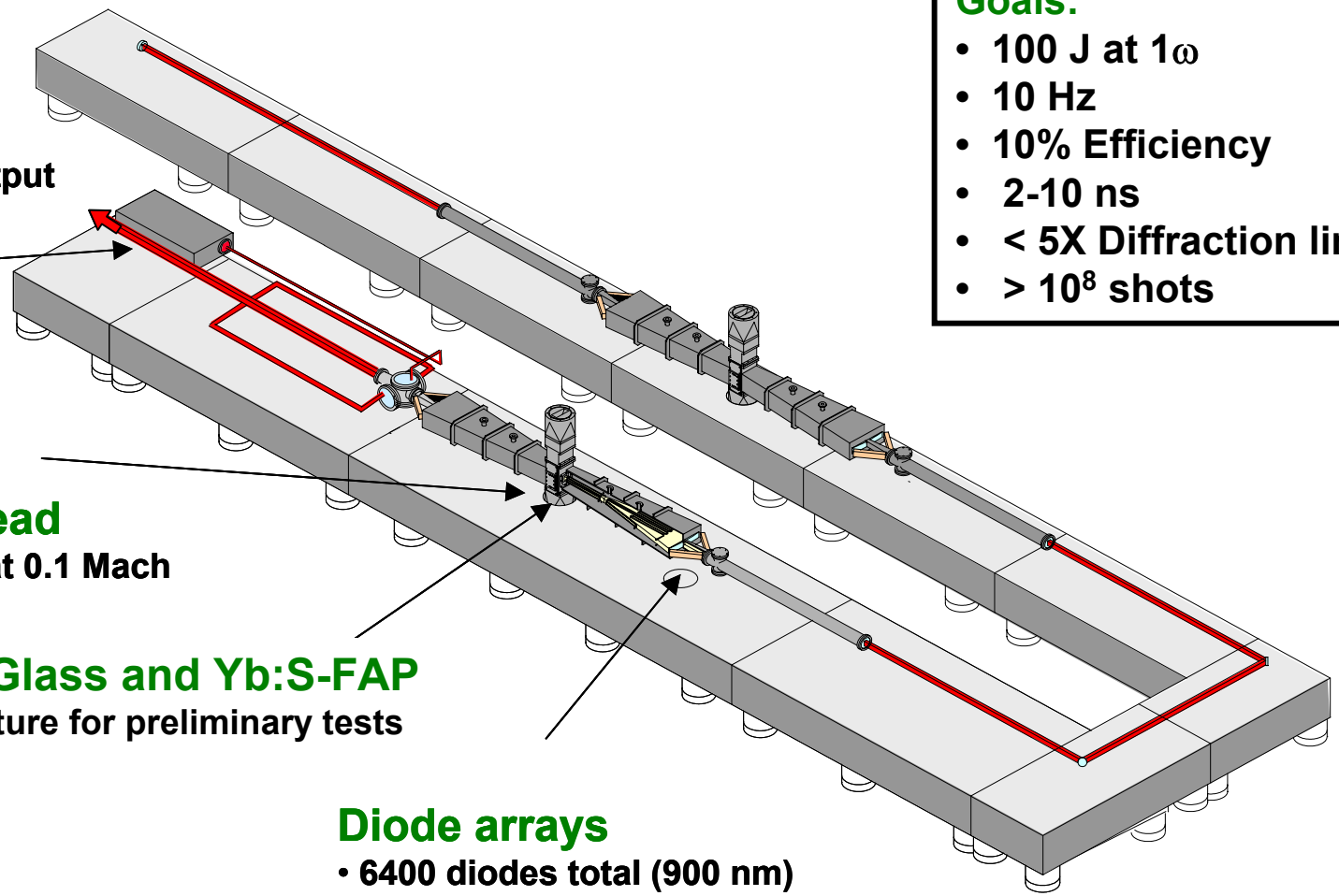
Forced gas-cooling
Aggressive, longitudinal heat removal allows 10-Hz operation



Angular-multiplexed image-relayed architecture
Minimizes damage, no final switching Pockels cell needed

Mercury activation is occurring in several stages

Goals:
- 100 J at 1ω
- 10 Hz
- 10% Efficiency
- 2-10 ns
- < 5X Diffraction limit
- > 10^8 shots



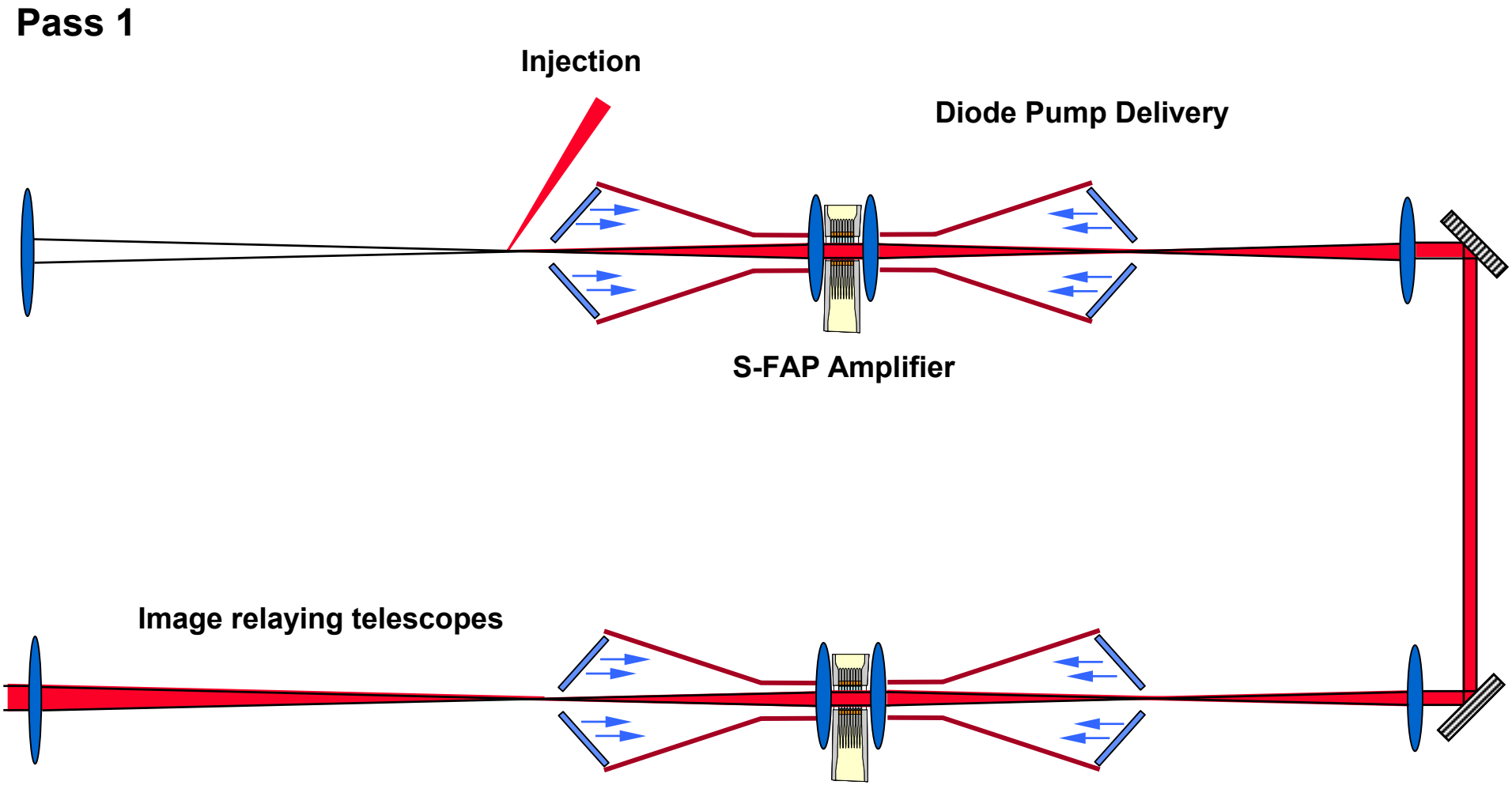
Front-end
- 300 mJ, M^2=1.8

Gas-cooled amplifier head
- He gas flow at 0.1 Mach

Nd:Glass and Yb:S-FAP
- mixture for preliminary tests

Diode arrays
- 6400 diodes total (900 nm)
- 640 kW peak power

The Mercury laser system minimizes damage by arranging the lenses and amplifiers near relay planes



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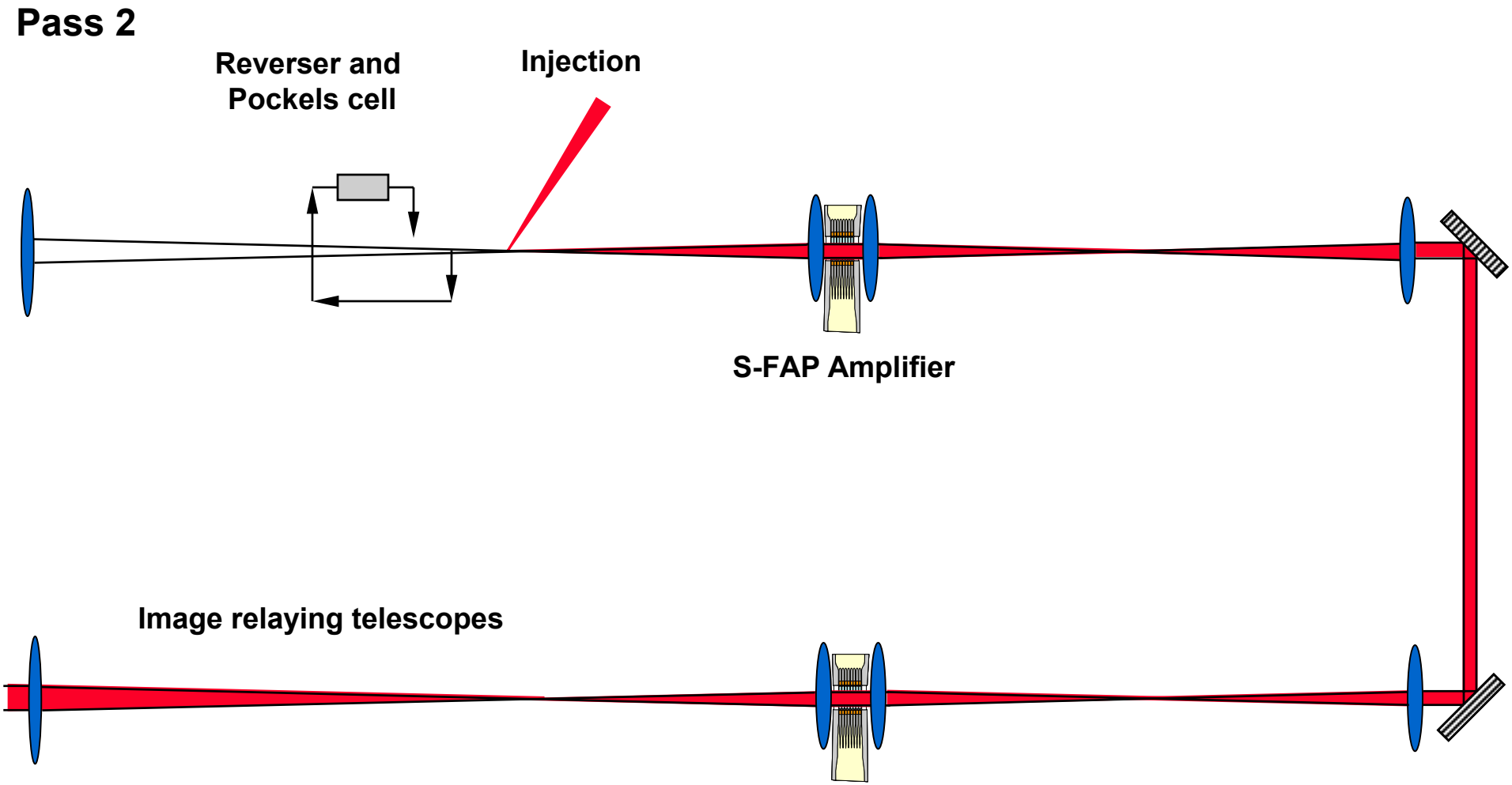

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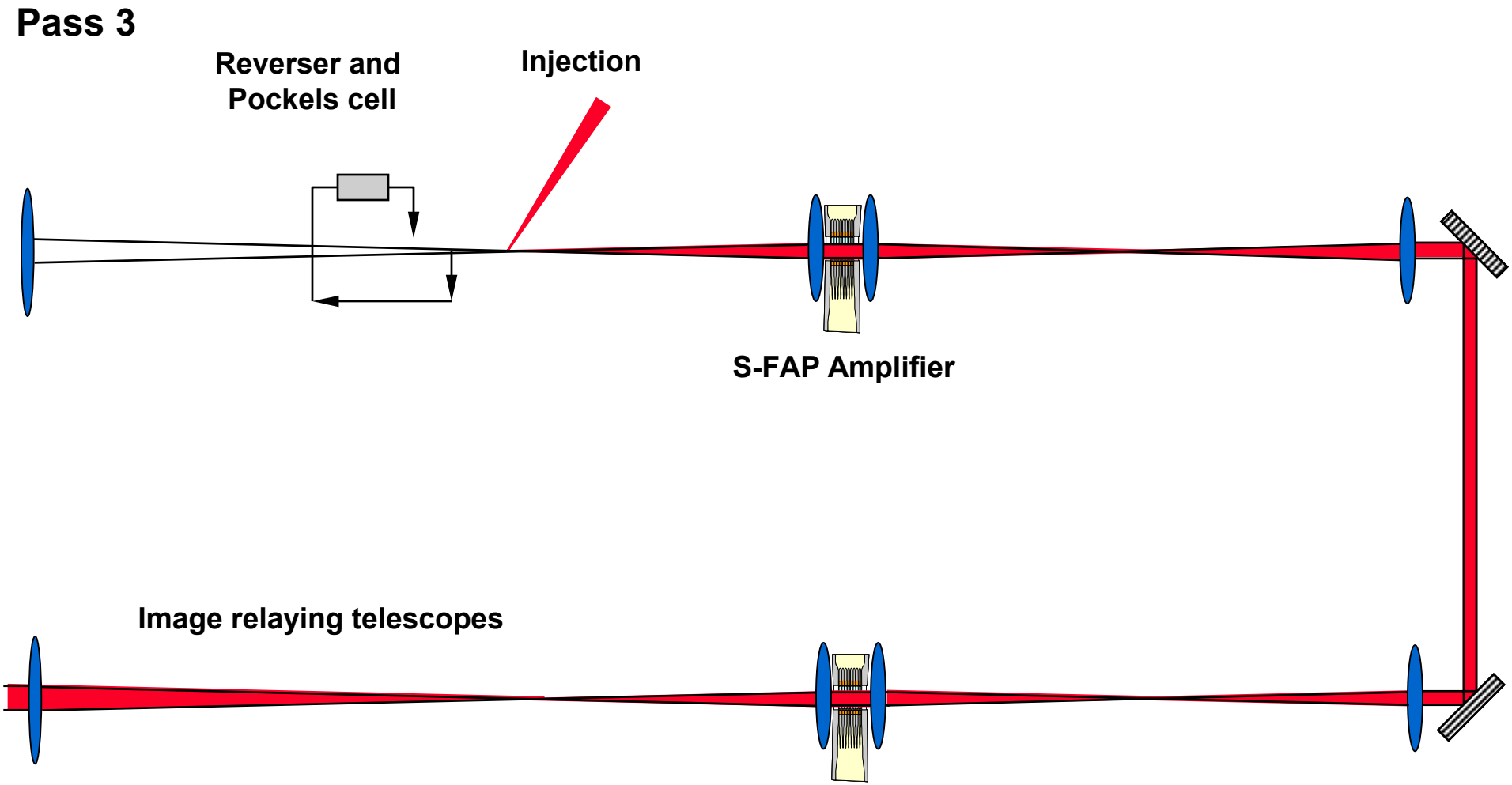

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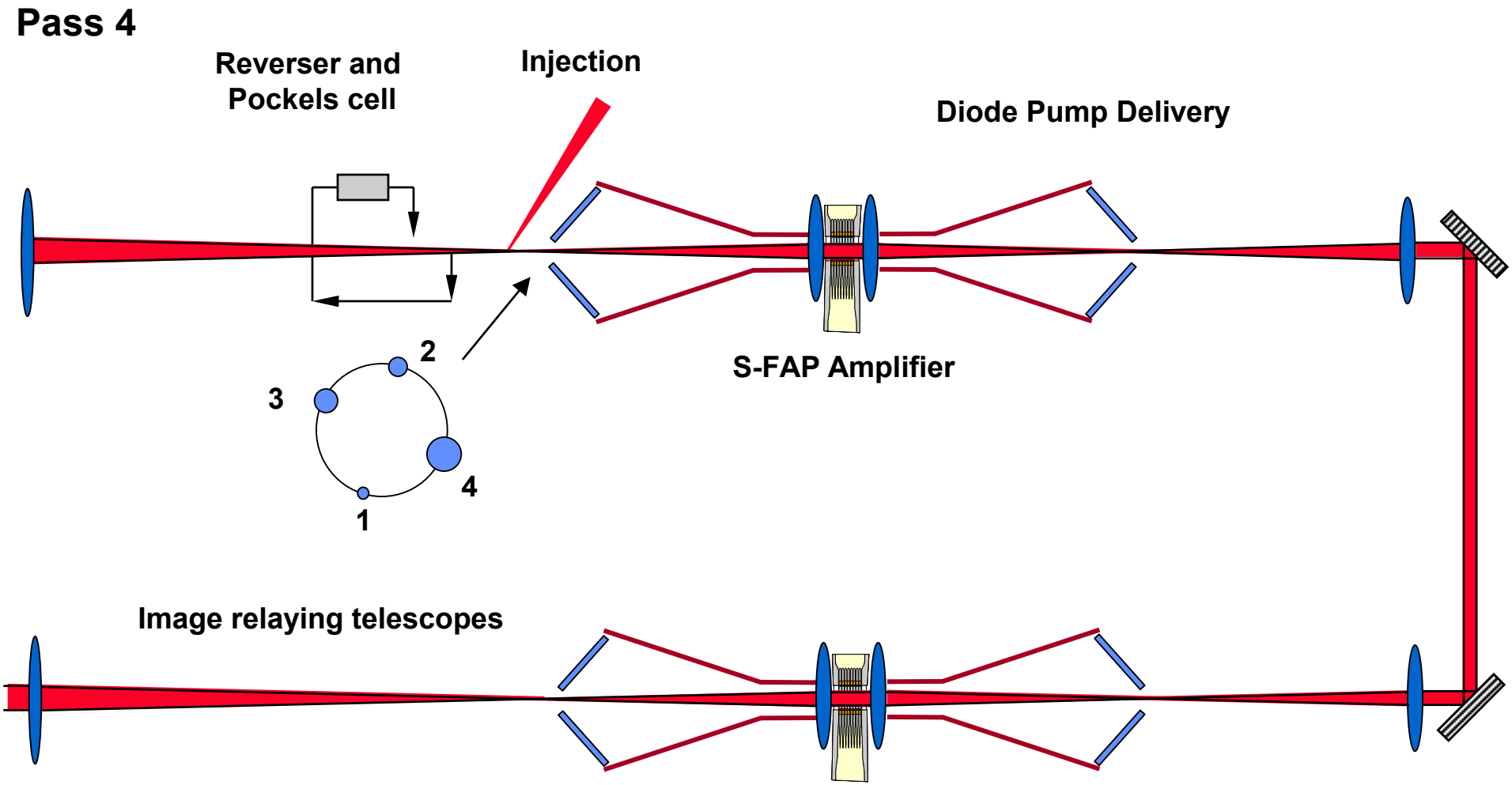
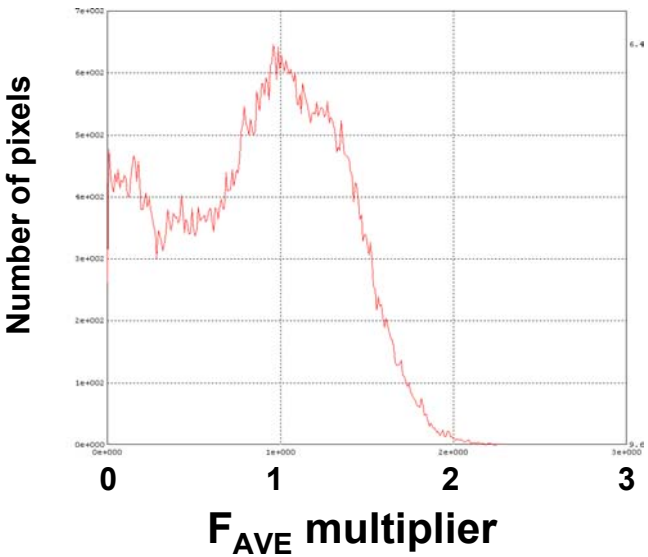
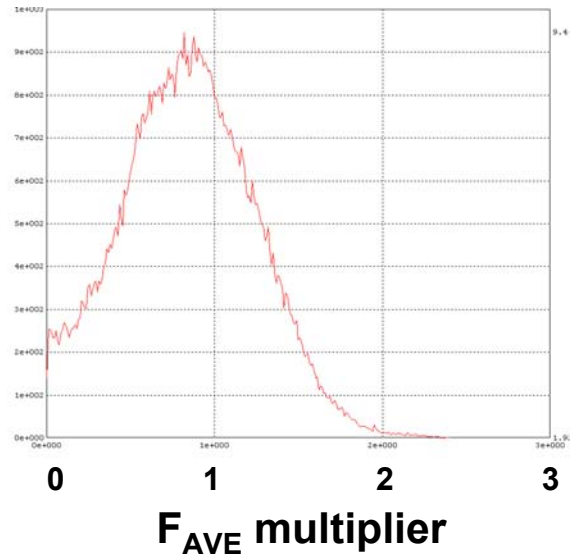


Modeling indicates that Mercury can operate at 100 J at 10 Hz with low probability of amplifier damage

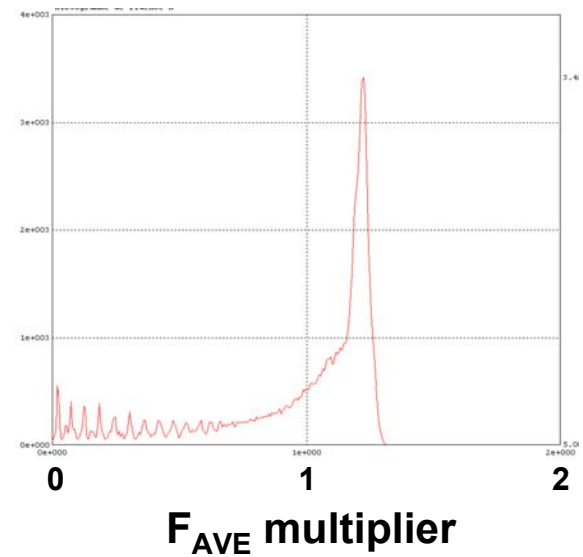
Reverser Mirror
F_{AVE} = 9.38 J/cm^2



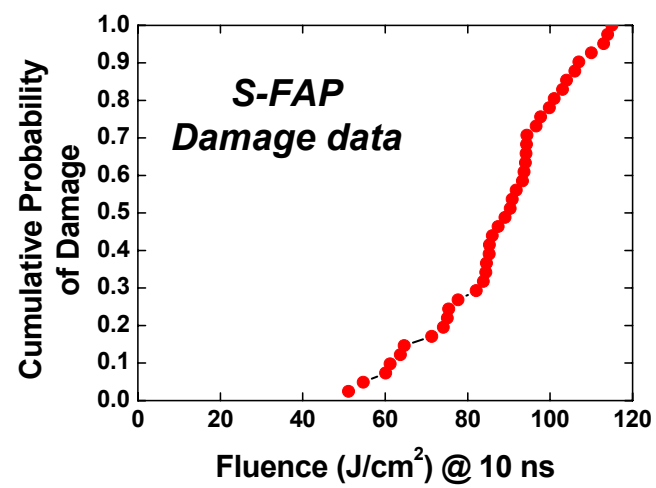
Output Lens
F_{AVE} = 2.75 J/cm^2



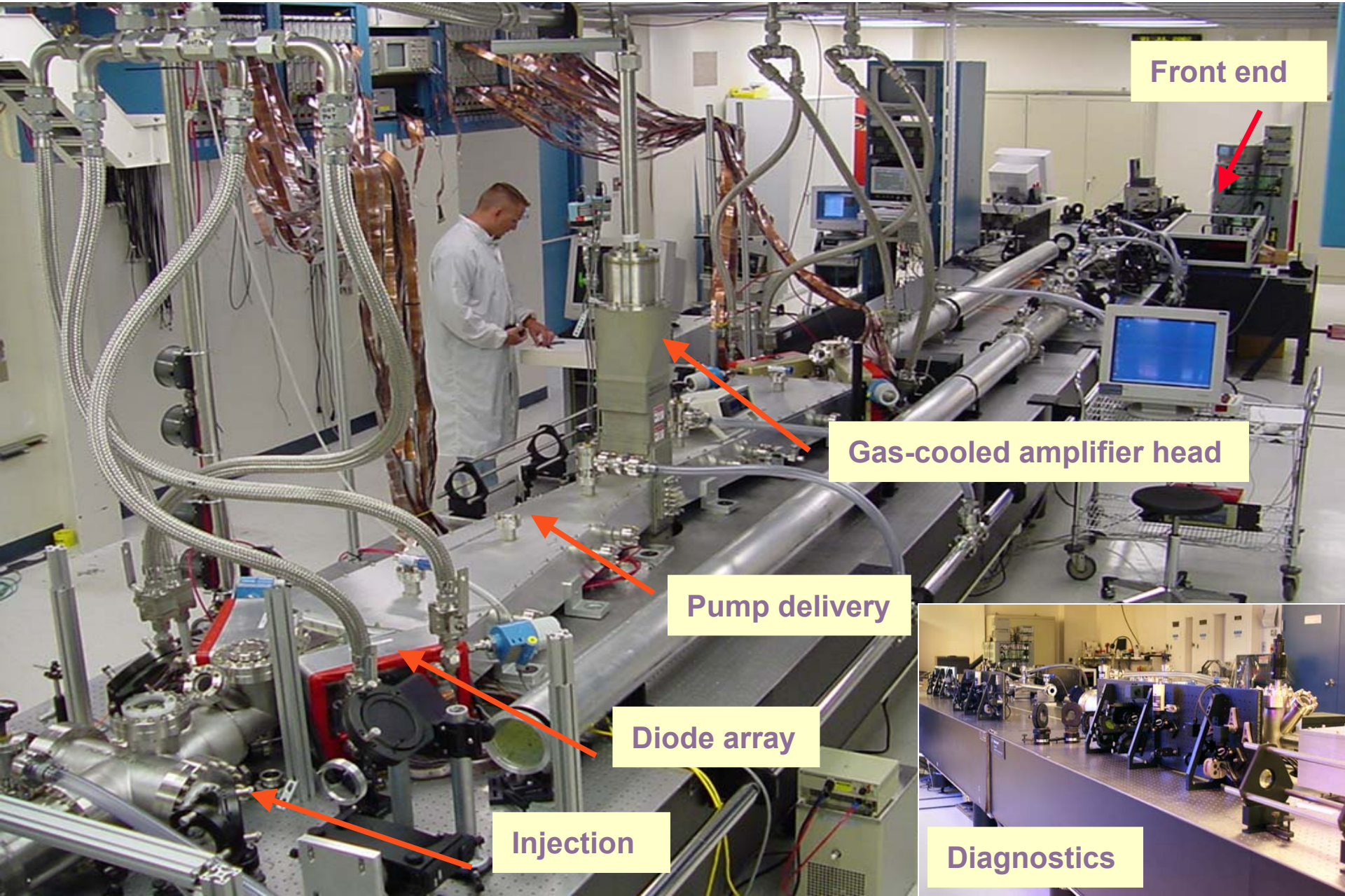
S-FAP Amplifier
F_{AVE} = 5.75 J/cm^2



Fluence histograms at critical optics using French Miro propagation code for 100 J output

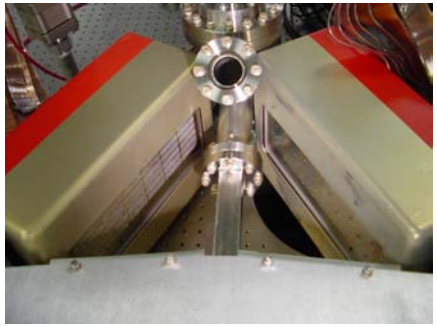


We are activating the Mercury laser

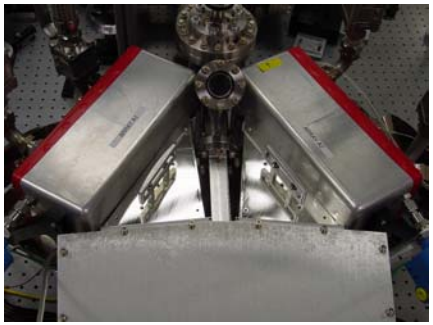


We have operated four 80 kW backplanes in the system and are building four more for the 2nd amplifier

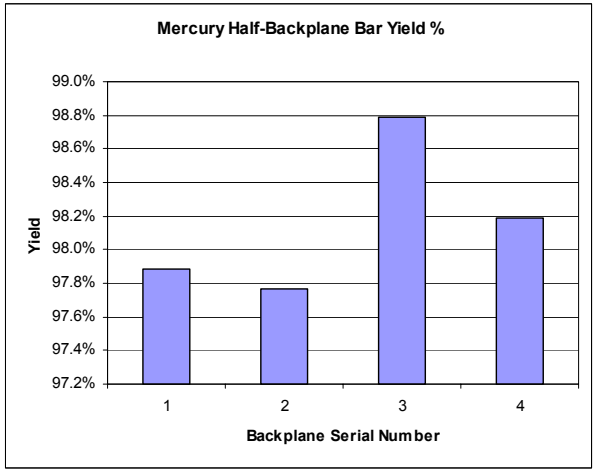
36 Pulsers activated

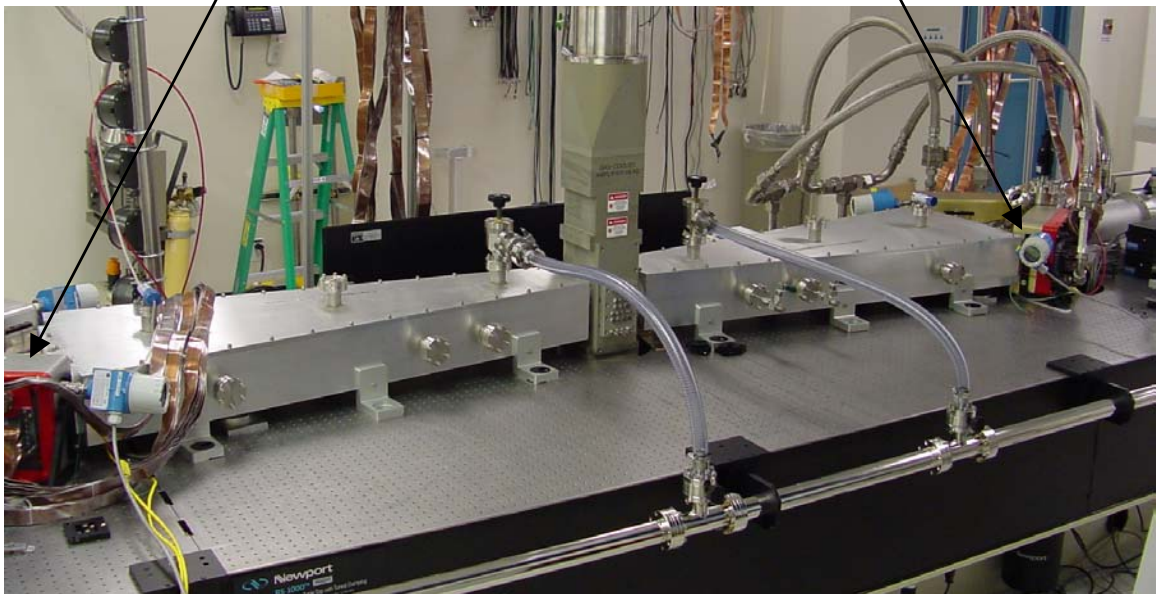


Backplanes 1 & 2



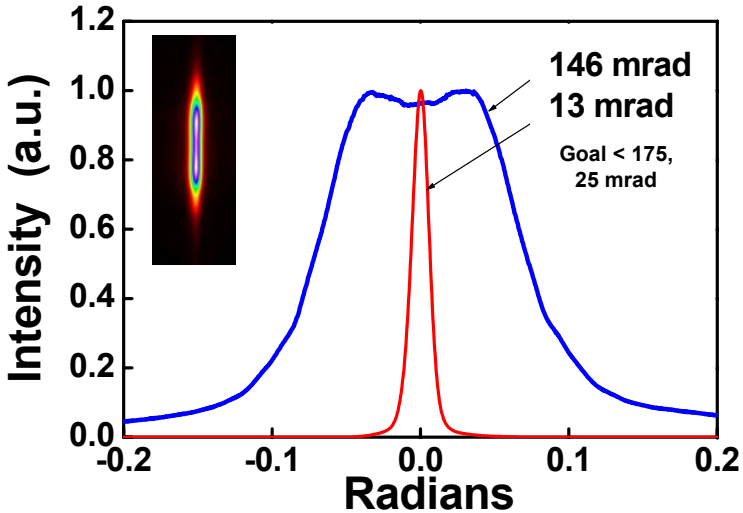
Backplanes 3 & 4



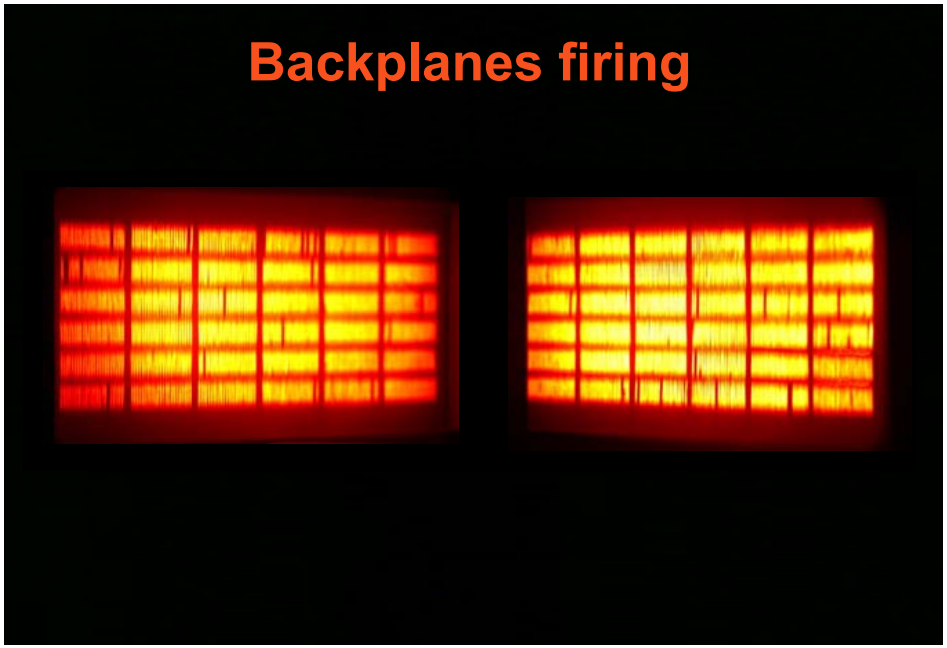


Each backplane meets spectral, droop, and power specifications

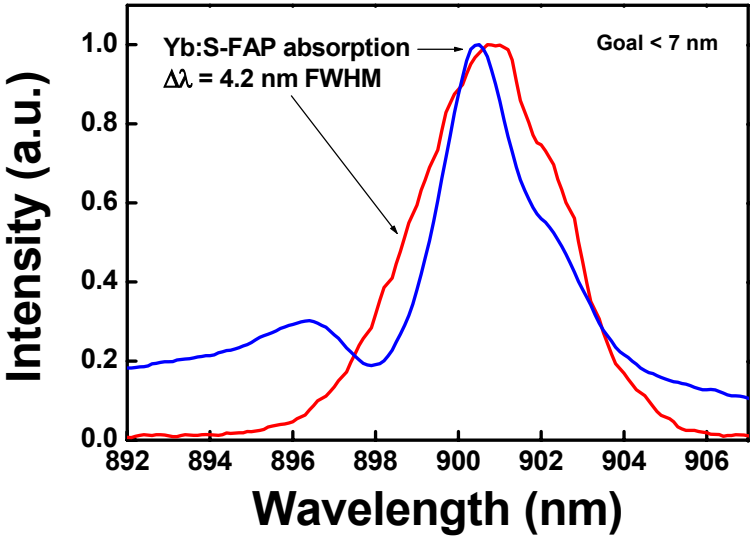
Far field



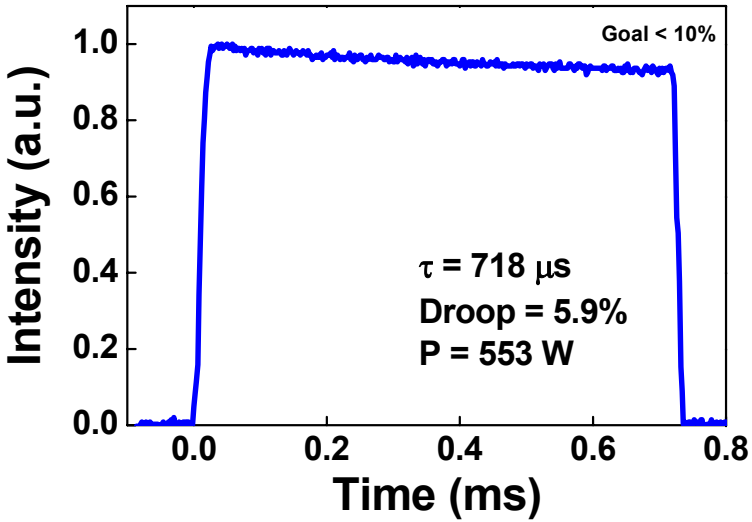
Backplanes firing



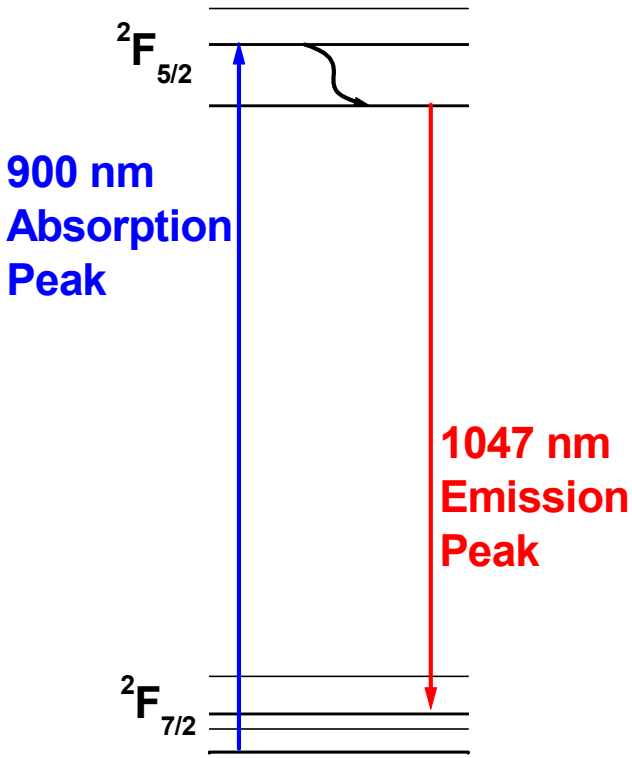
Integrated spectrum

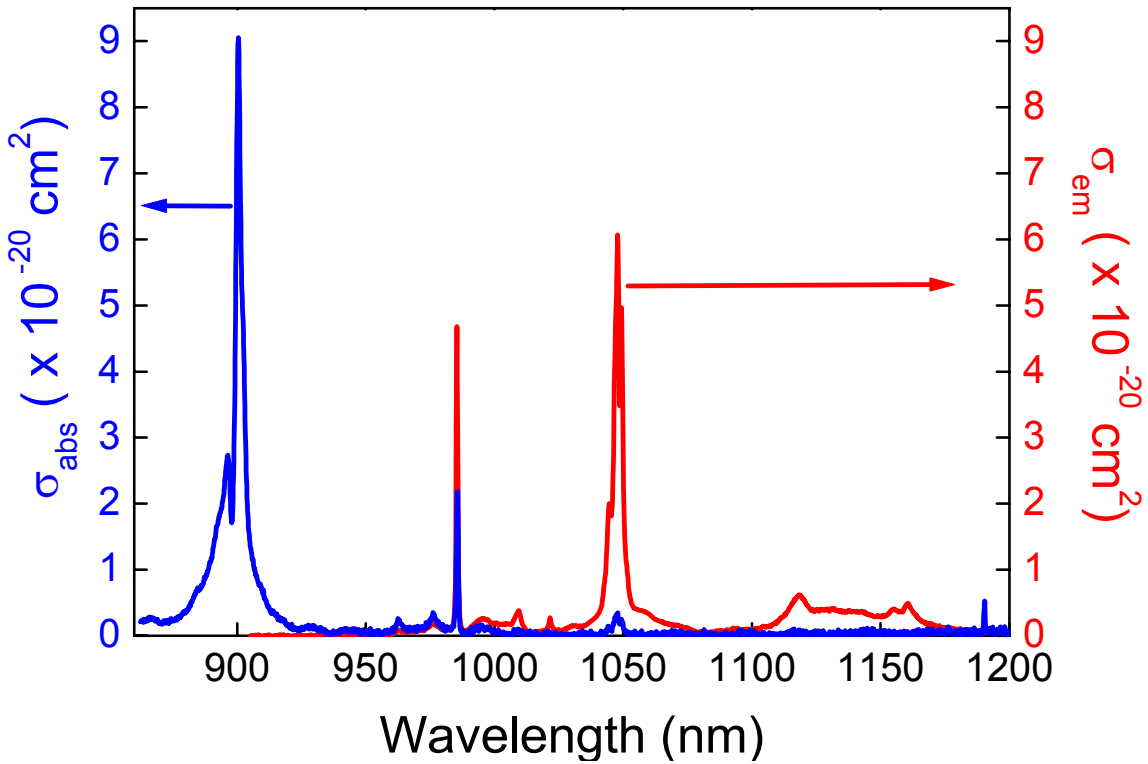


Temporal pulse



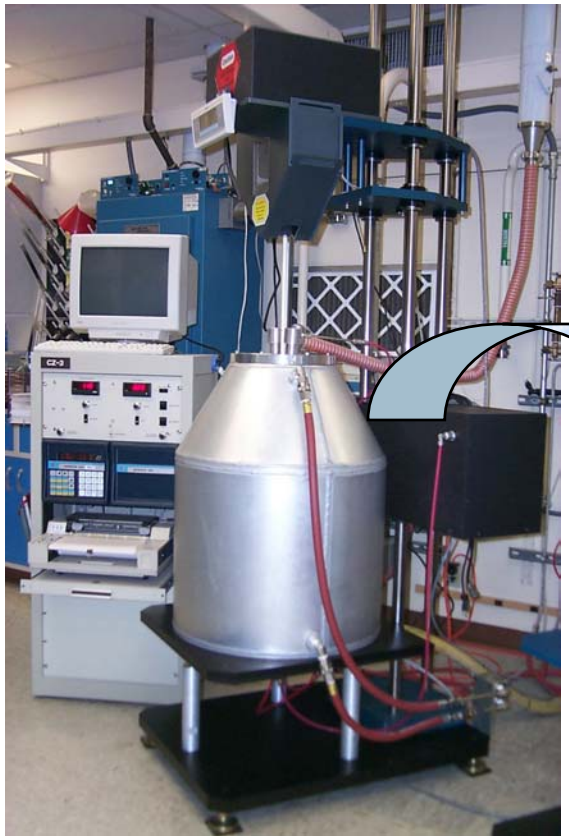
Yb:S-FAP has both high absorption and emission cross sections and long lifetime of 1.14 msec

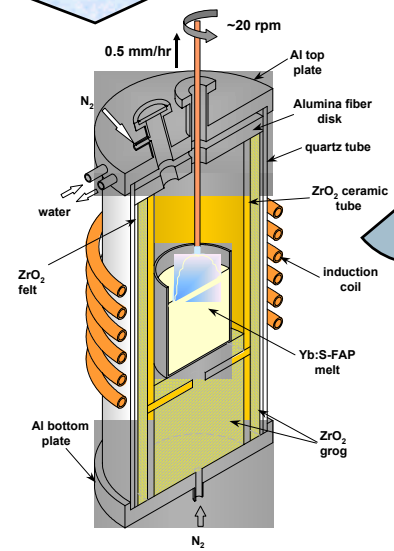


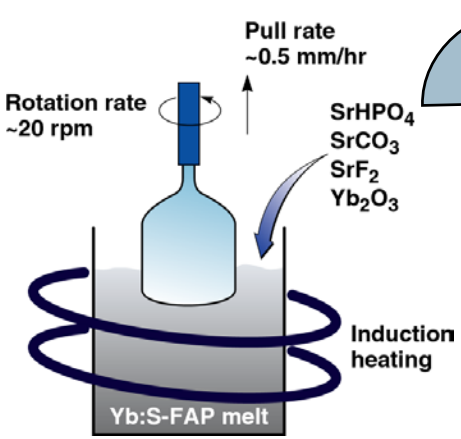


Crystals of Yb:S-FAP are grown by the Czochralski method to produce slabs for the Mercury Laser

Three CZ furnaces are available for the growth of Yb:S-FAP crystals





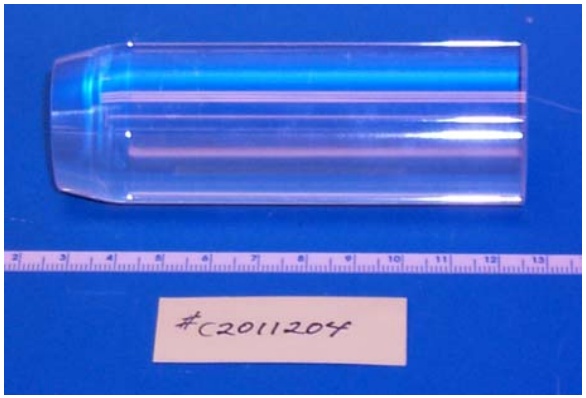


We have developed a successful Yb:S-FAP crystal growth process

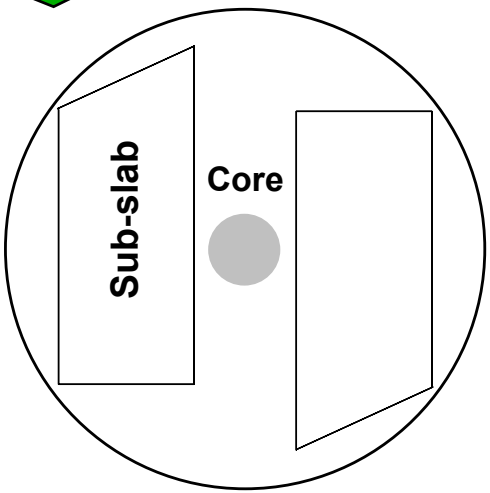
Crystal Orientation……	a-axis			45°	c-axis
Diameter……..	2.5 cm	3-5 cm	2.5 cm	3 cm	3.5 cm
Pull rate…….	1 mm/hr		0.5 mm/hr		
Rotation rate……	20 rpm	20-50	6-15	15 rpm	
Gradient……	Low gradient (~20°C/cm)			~40 (to 70)	
SrF_2 excess……..	5-25 %		33 %		
Yb-doping in melt……..	1 At.%			0.5-1.0	0.65At.%
Interface shape……	convex-invert		Steep convex shape		
Seed extension……			Inhibit grain boundaries		
Cooling in melt…….			Reduce cracking		
Cutting methods……..	Diamond blade, wire saw & free hand				other
Bonding……..				2x2	3x5	4x6

Several polishing and cutting steps are required to fabricate a full sized slab

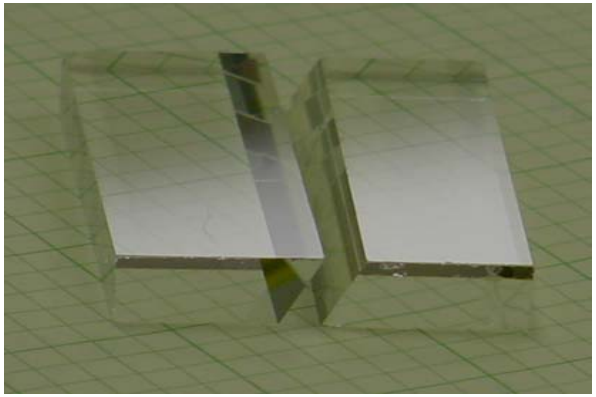
Crystal out of furnace



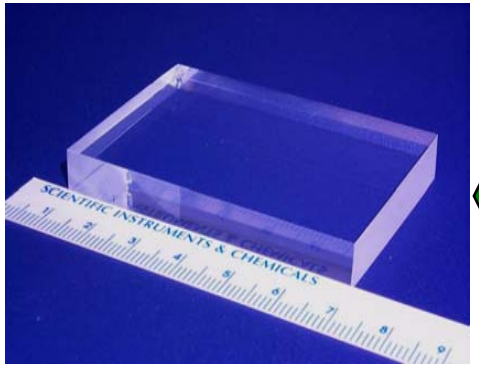
Boule cross section



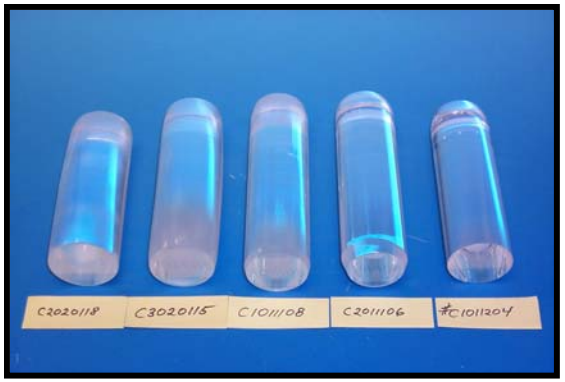
2 half slabs



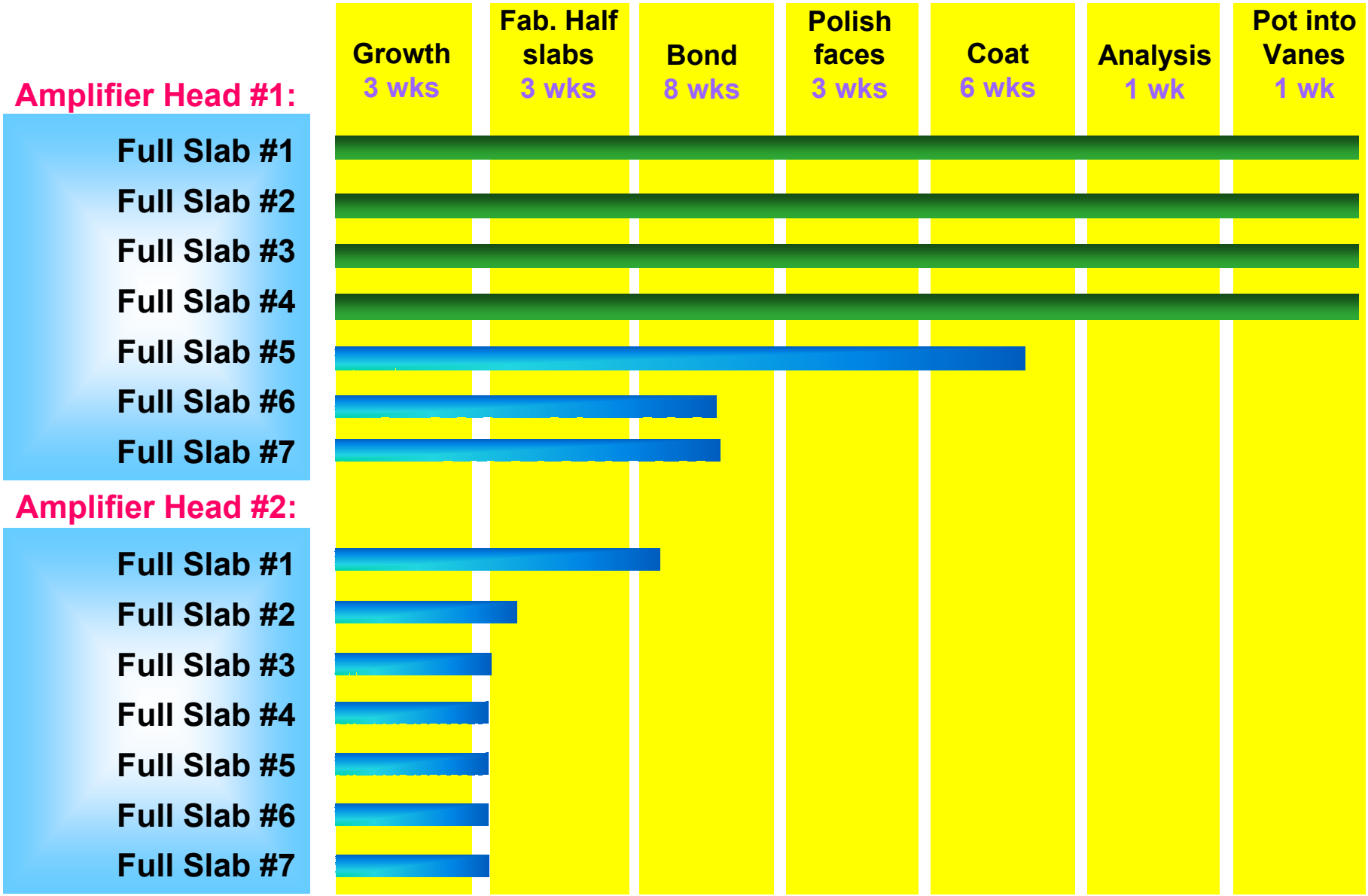
Finished slab



Boules in waiting

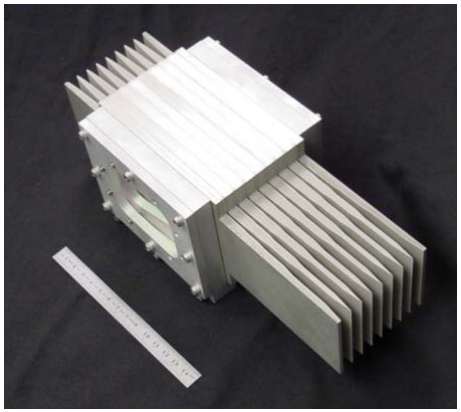


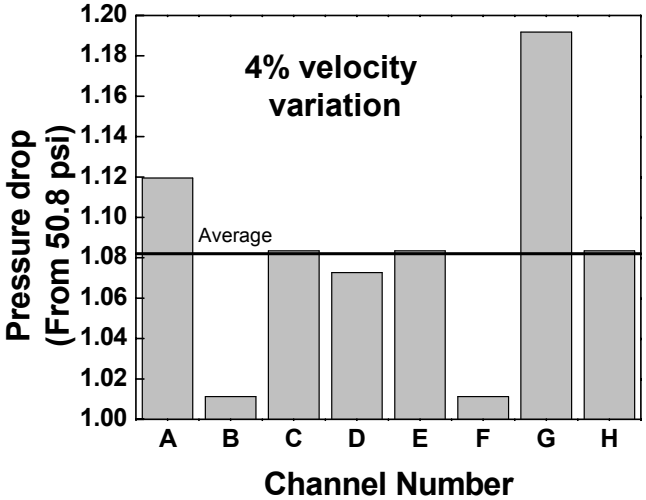
Currently there are four full size slabs (4 x 6 cm) potted in vanes and four boules in fabrication

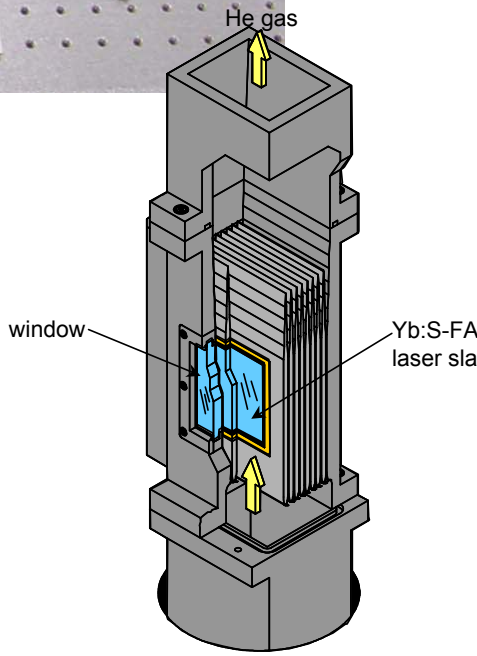


We have performed experiments with one amplifier populated with four Yb:S-FAP crystals

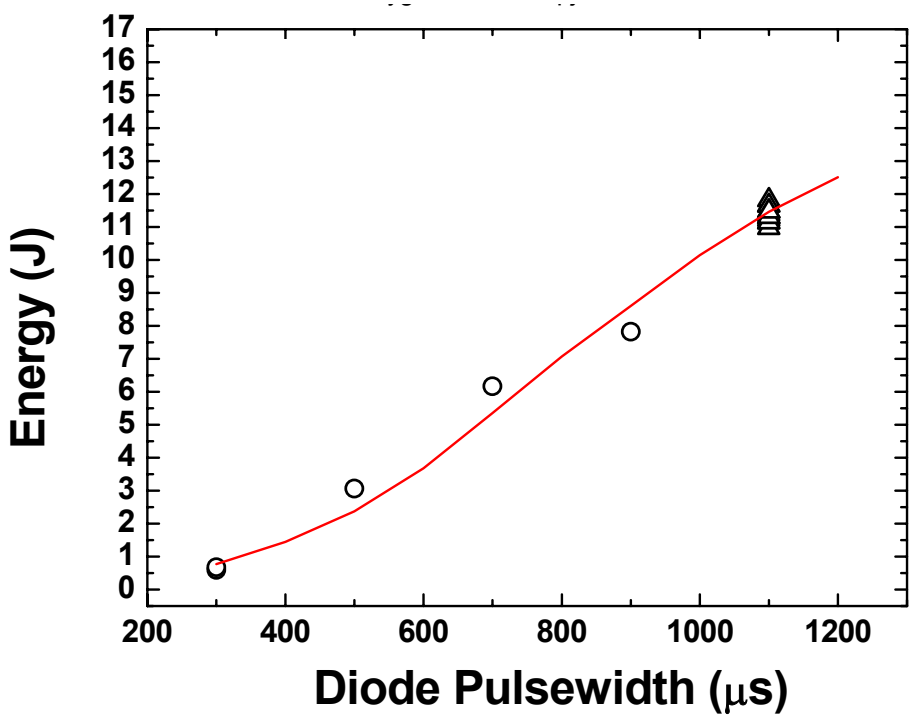
Yb:S-FAP Yb:S-FAP Nd:Glass Nd:Glass Nd:Glass Yb:S-FAP Yb:S-FAP

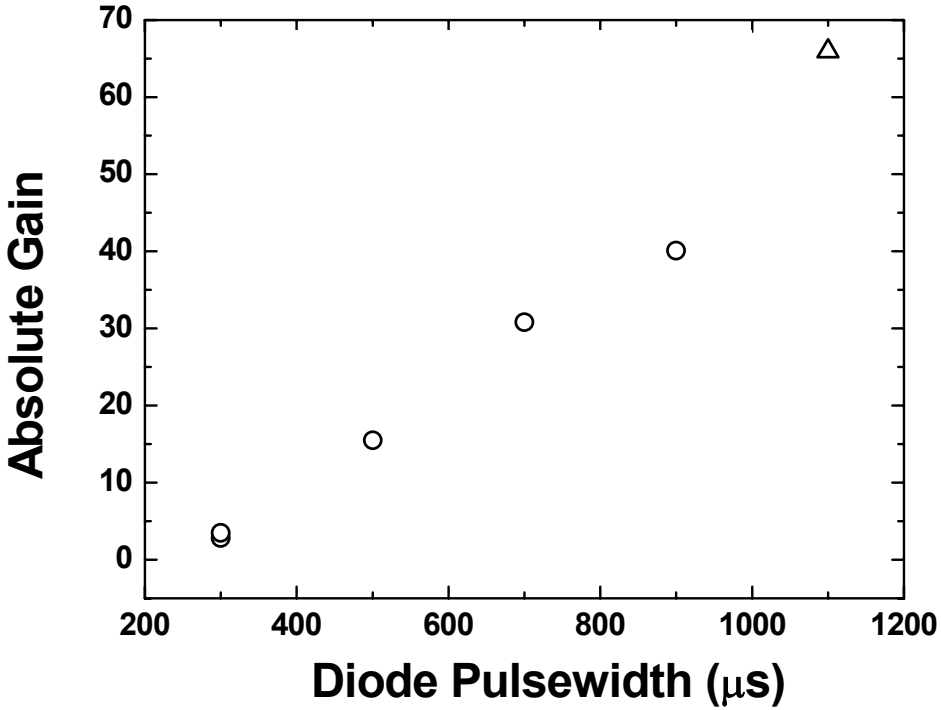






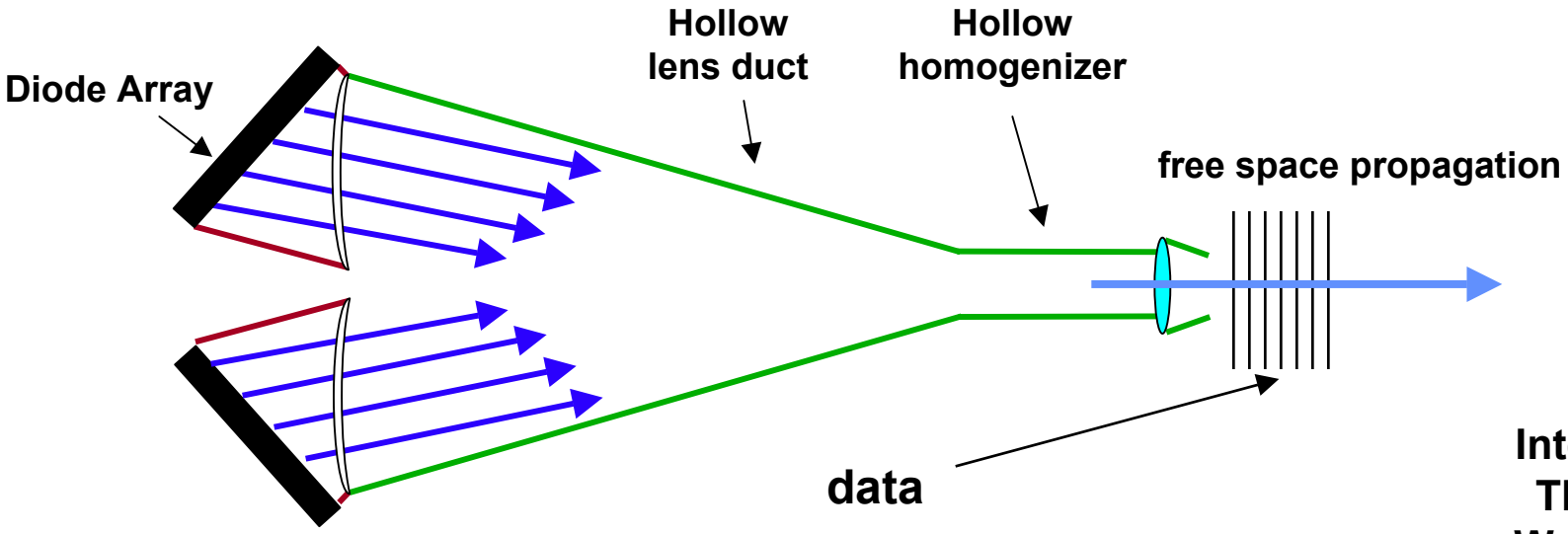
We have achieved "first light" on the Mercury laser

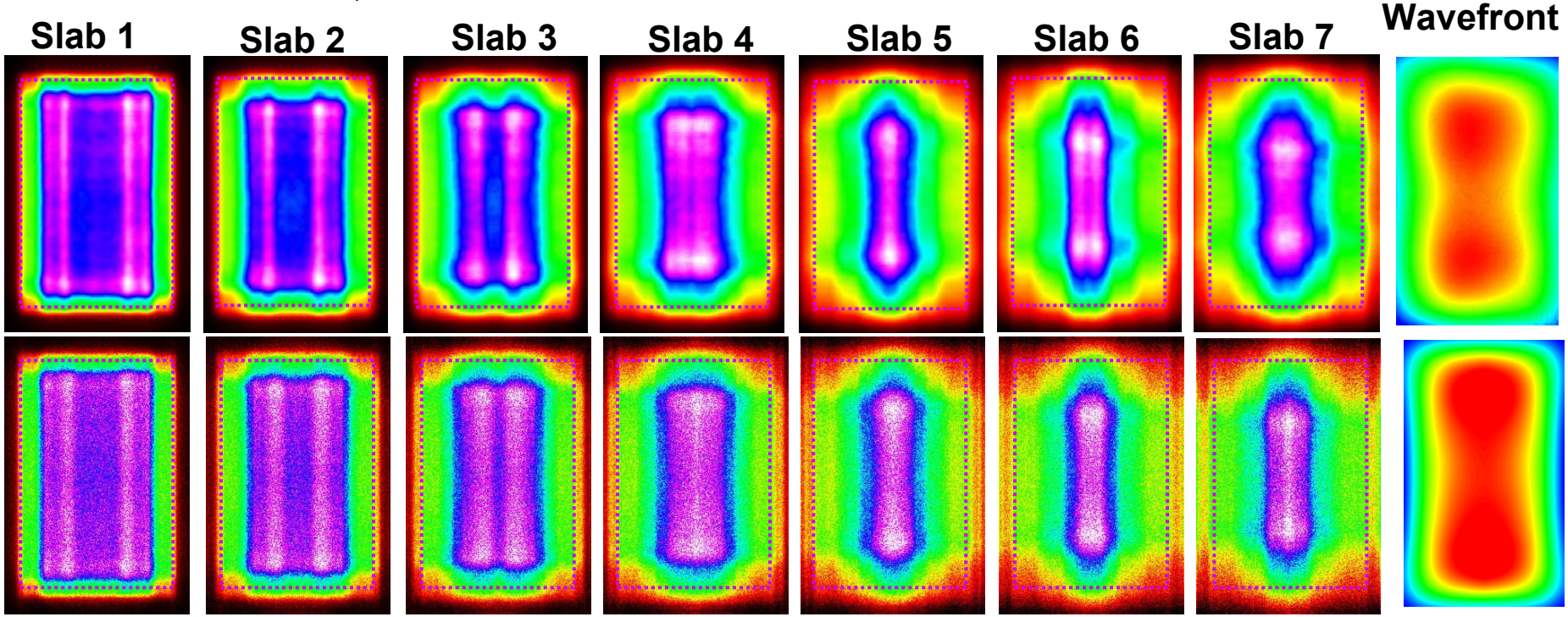




We have extracted 11.8 J energy with the mixed amplifier populated with 4 Yb:S-FAP and 3 Nd:Glass slabs

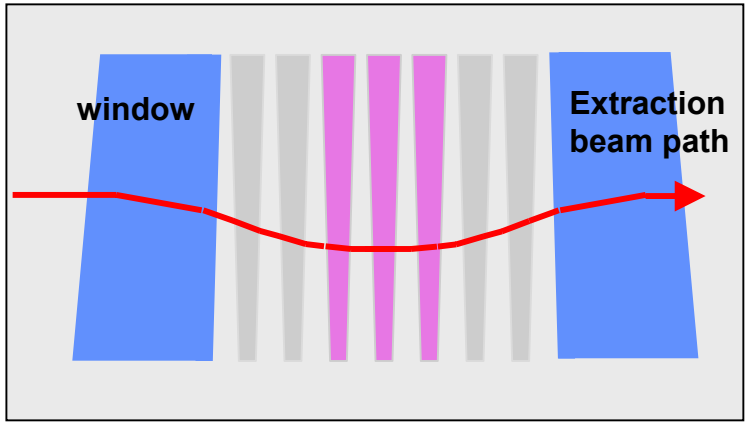
The pump light distribution agrees with model to within 10%





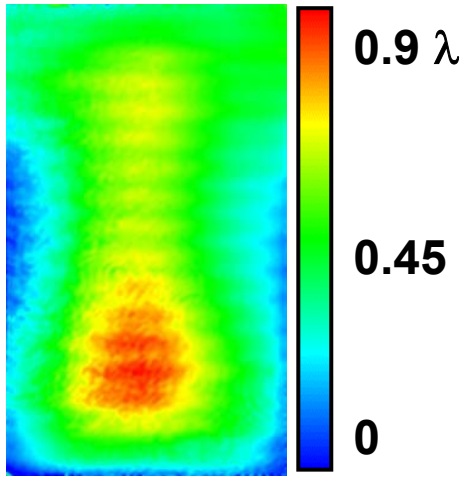
Measured the wavefront of the “mixed” amplifier at 3.3 Hz shows 2.3 waves

3 inner slabs are glass and 2 outer slabs are Yb:S-FAP

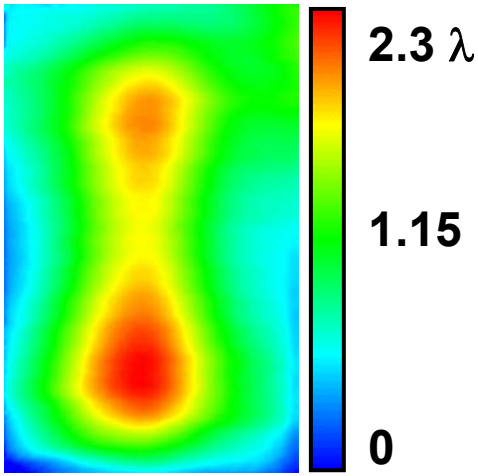


- Calculated residual wavefront for 4 S-FAP slabs is 0.2 waves

1 Hz diode rate

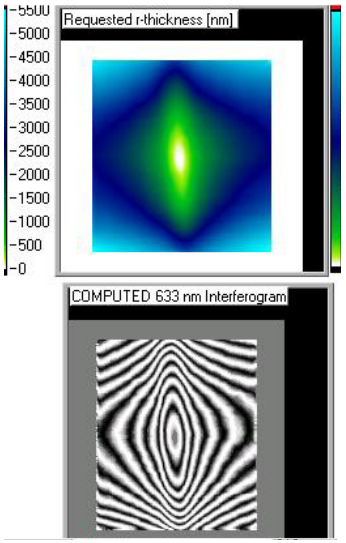


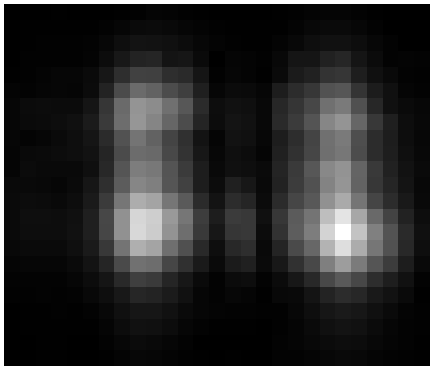
3.3 Hz diode rate



We have tested a phase plate to correct for the low order static distortion in the Yb:S-FAP amplifier slabs

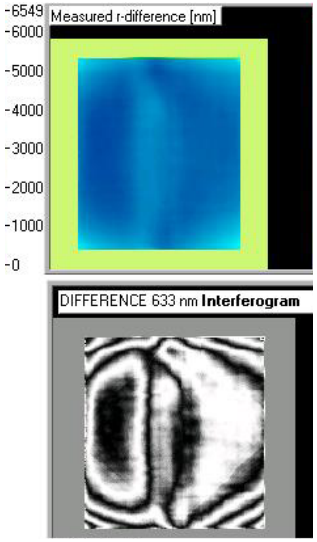
Without phase plate

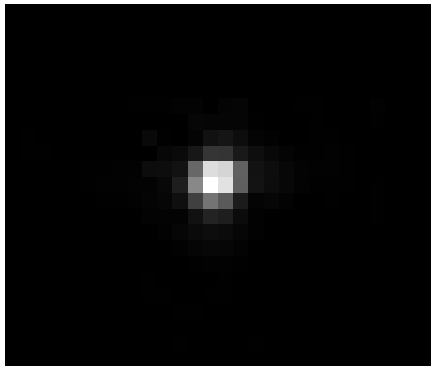




Far field (*no* correction)

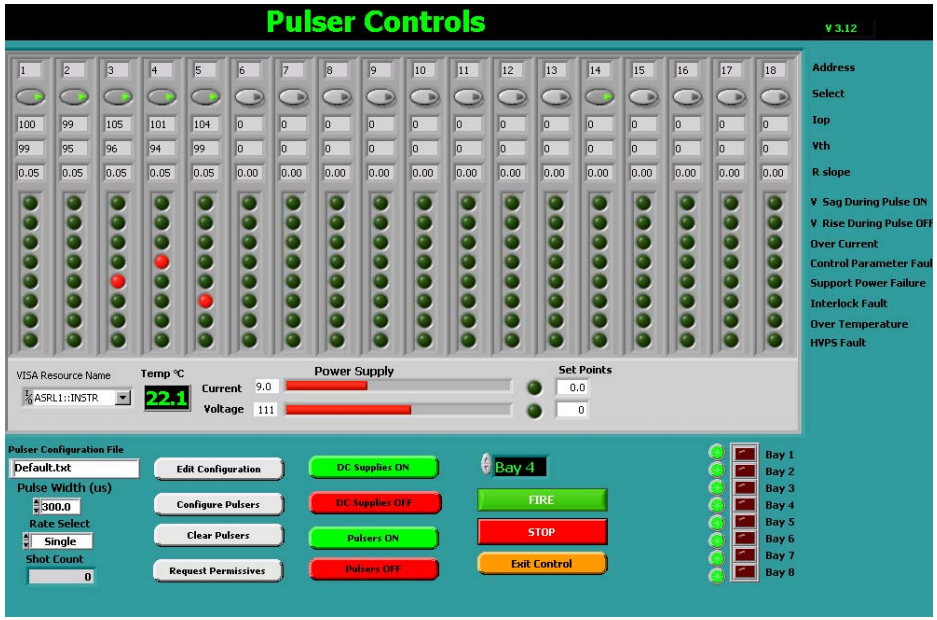
With phase plate



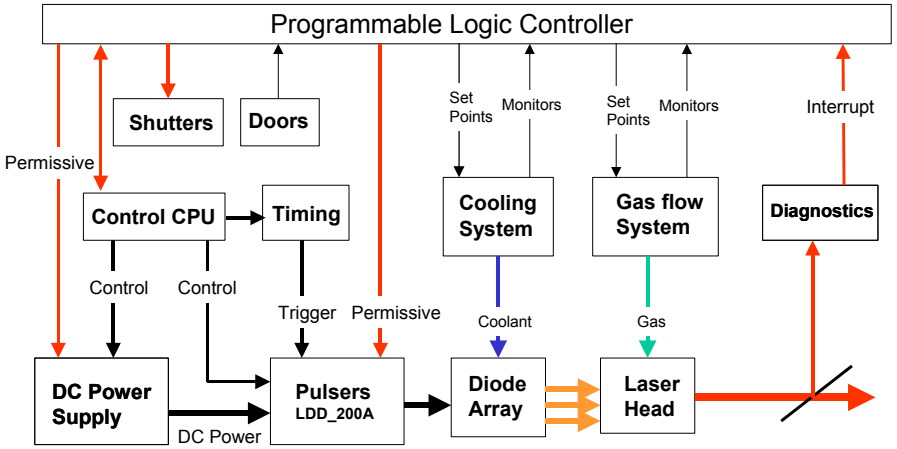


Far field (*with* correction)

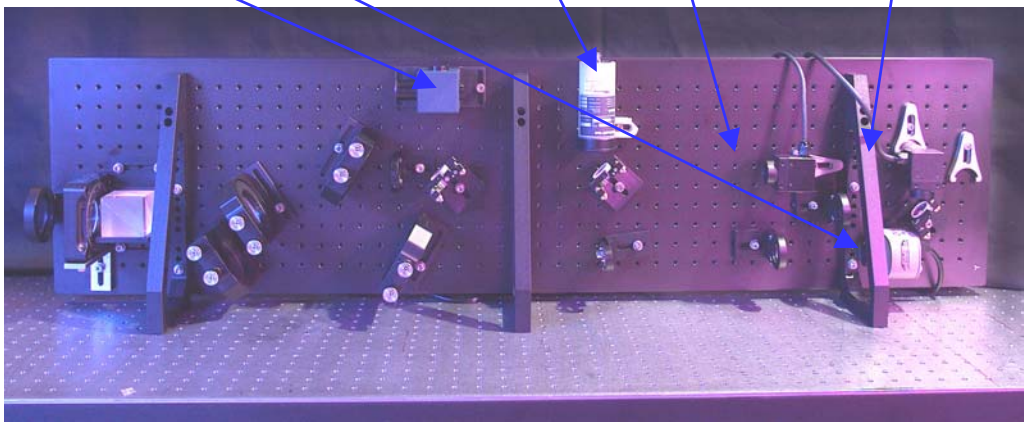
The operating system controls the pulsers and power supplies to operate the diode arrays and monitor utilities



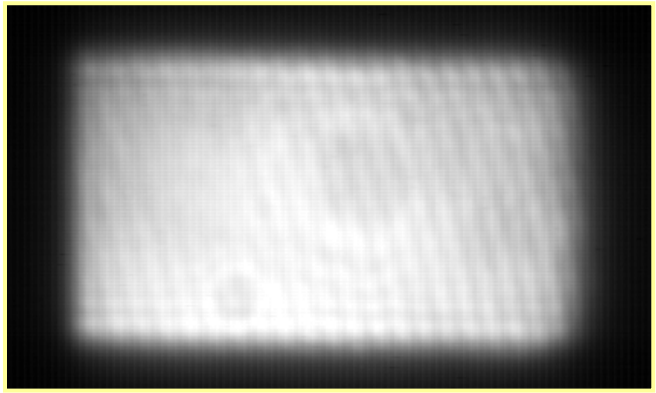
Controls – Hardware Diagram



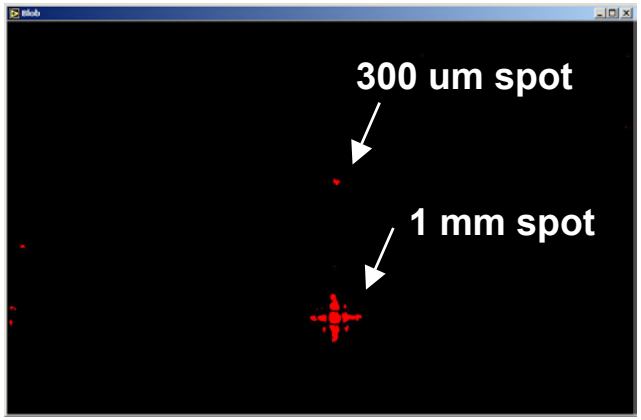
Four diagnostic stations have been built and installed and will be used to characterize the beam on each pass



Near field



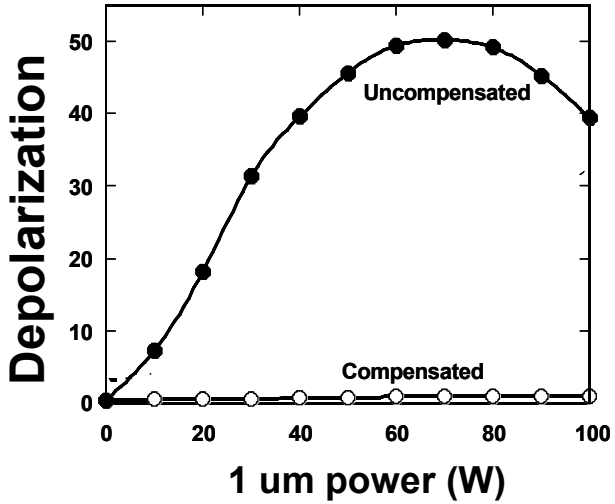
Dark field

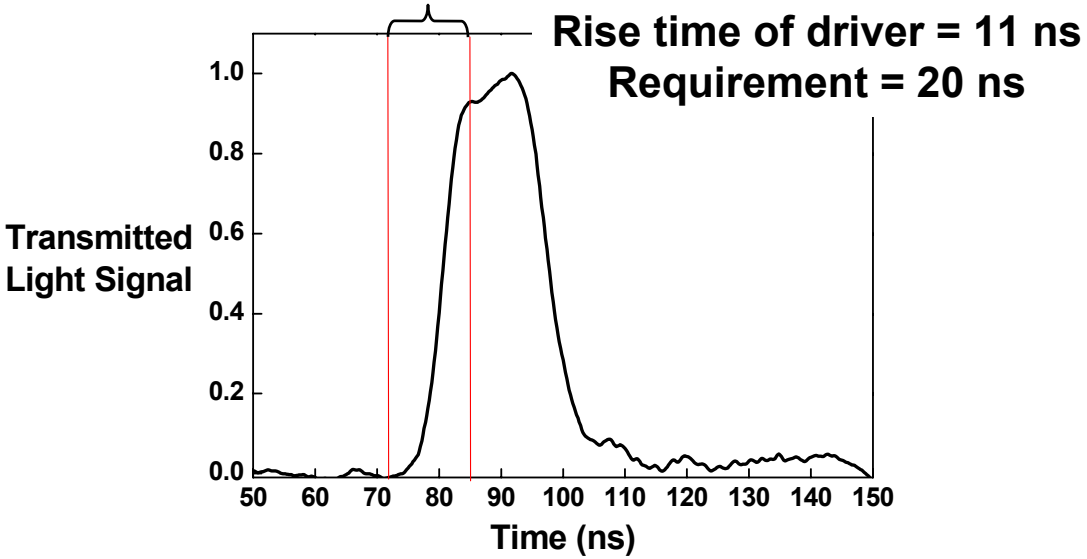


Used for real time detection of damage

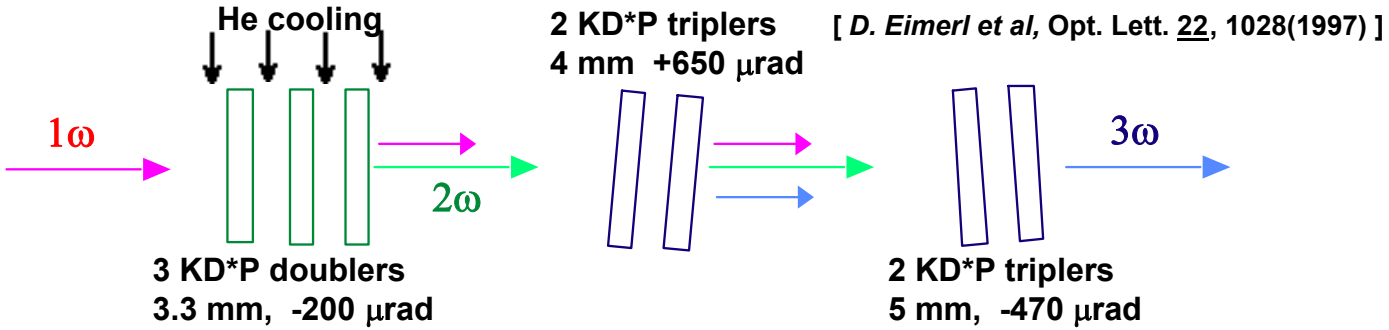
We have made offline tests of a half size Pockels cell and have ordered parts for the full size element

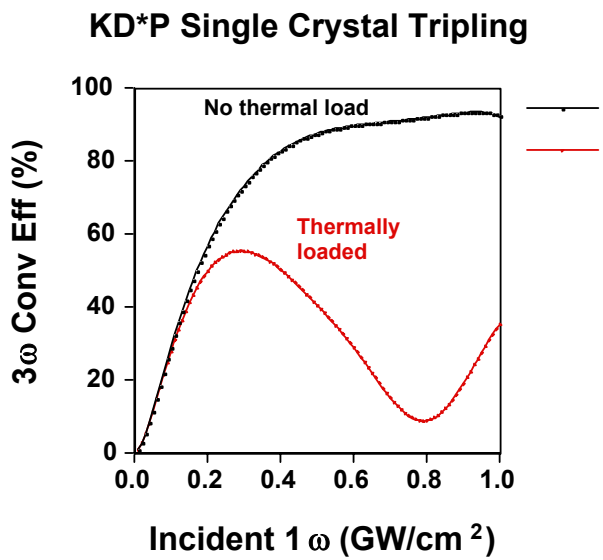
2x3 cm² (1/2 size)

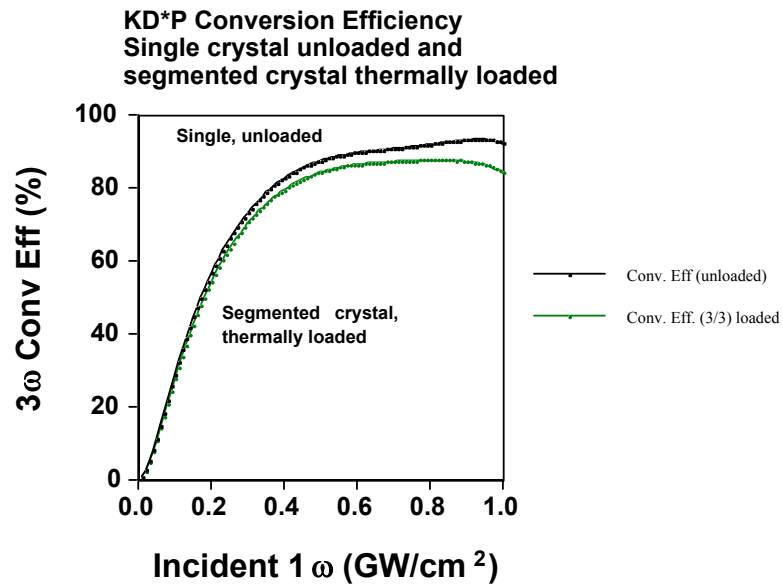




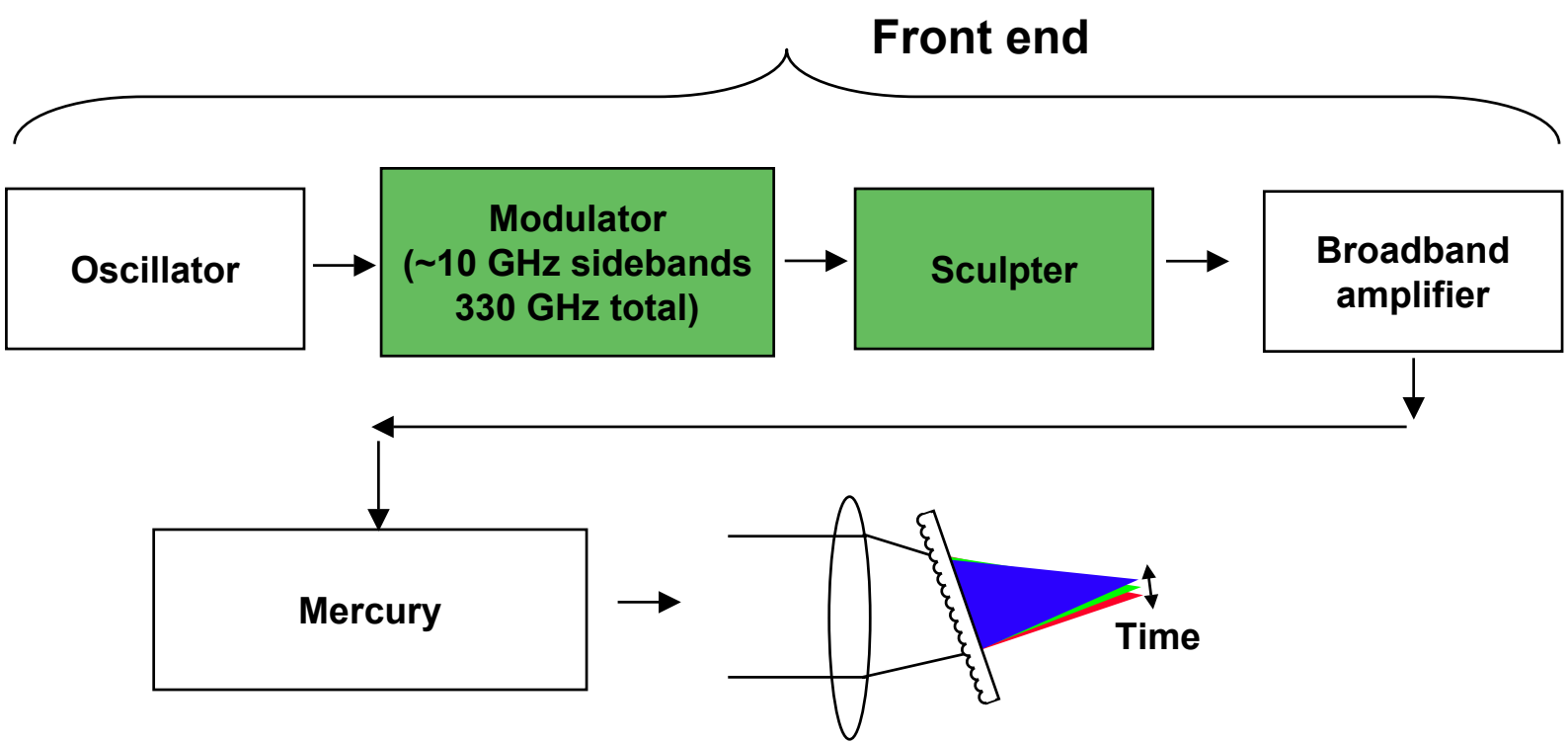
We are exploring frequency conversion materials and concepts that can handle average power loading and required bandwidth







Mercury will have 330 GHz bandwidth ($\Delta\nu$) at 1ω which can produce up to 31 uncorrelated speckle patterns



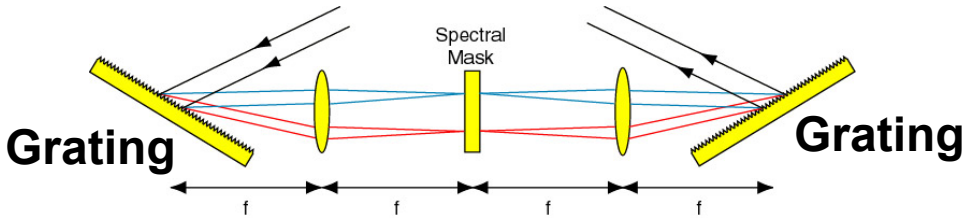
$N_{speckle} = \Delta\nu/(2d \cos\phi)(\lambda * D/c) = 31$

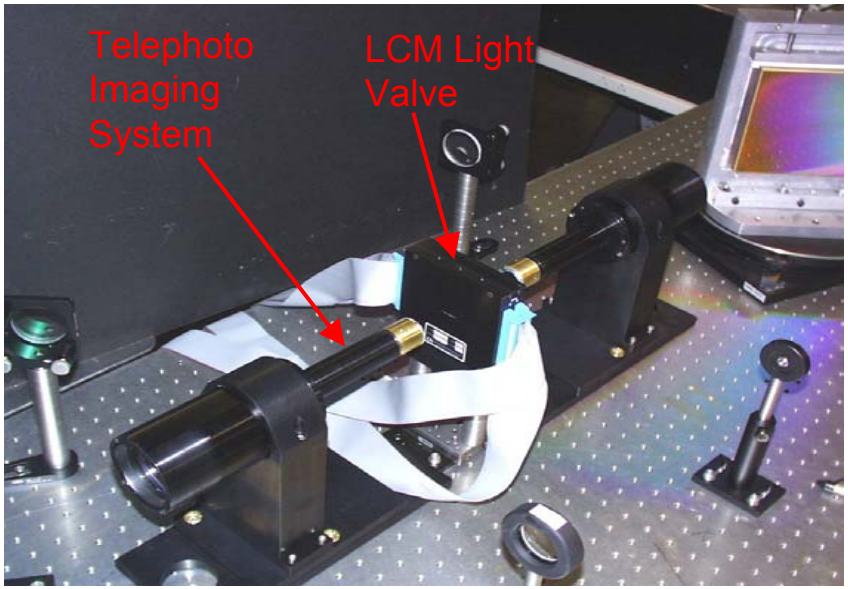
Grating: 1 μm period (d) used in Littrow at 30° (ϕ)

Beam Diameter: 5 cm

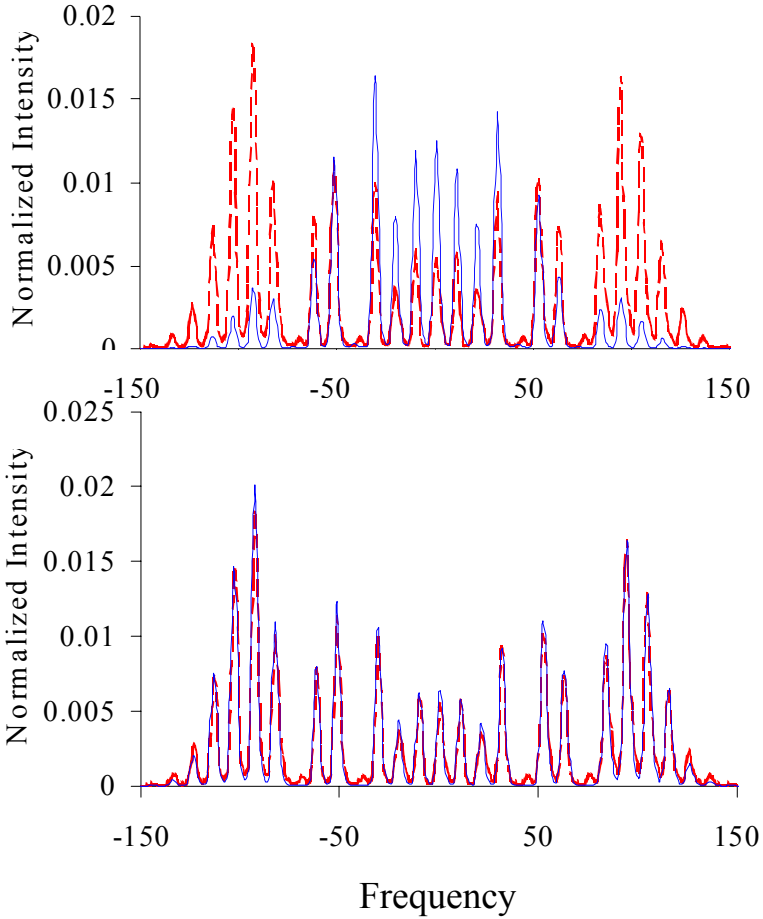
$\sigma = 1/\mathrm{sqrt}(N_{speckle})$ => 82% reduction in contrast in 100 ps (1/10GHz)

A spectral sculptor using a liquid-crystal modulator light valve has been demonstrated with 300 GHz bandwidth





- Sculptor was achieved with ~ 100:1 dynamic range



Summary and Plans

- We have activated four 80 kW arrays producing 320 kW of power
- With 4 Yb:S-FAP slabs and 3 glass slabs in the amplifier head:
  - We achieved first light at 11.8 J at 0.1 Hz
  - Measured a thermal wavefront distortion of 2.3 waves at 3.3 Hz
  - Implemented a static waveplate which improved beam quality to 2xdl

Full amplifier head activation (30J at 10 Hz) is planned for September

The 5-year plan for DPSSL development has yearly milestones and quarterly reviews in place

CY 2001 | CY 2002 | CY 2003 | CY 2004 | CY 2005

Mercury Laser (100 J at 10Hz)

Component Development → Build laser → 1ω Activation

- Wavefront Correction
- Bandwidth (SRS suppression)
- Average Power Frequency Converter

3ω Activation

Beam-Smoothing

IRE Component Development (multi-kJ system)

15 cm S-FAP Crystals and Edge Cladding →

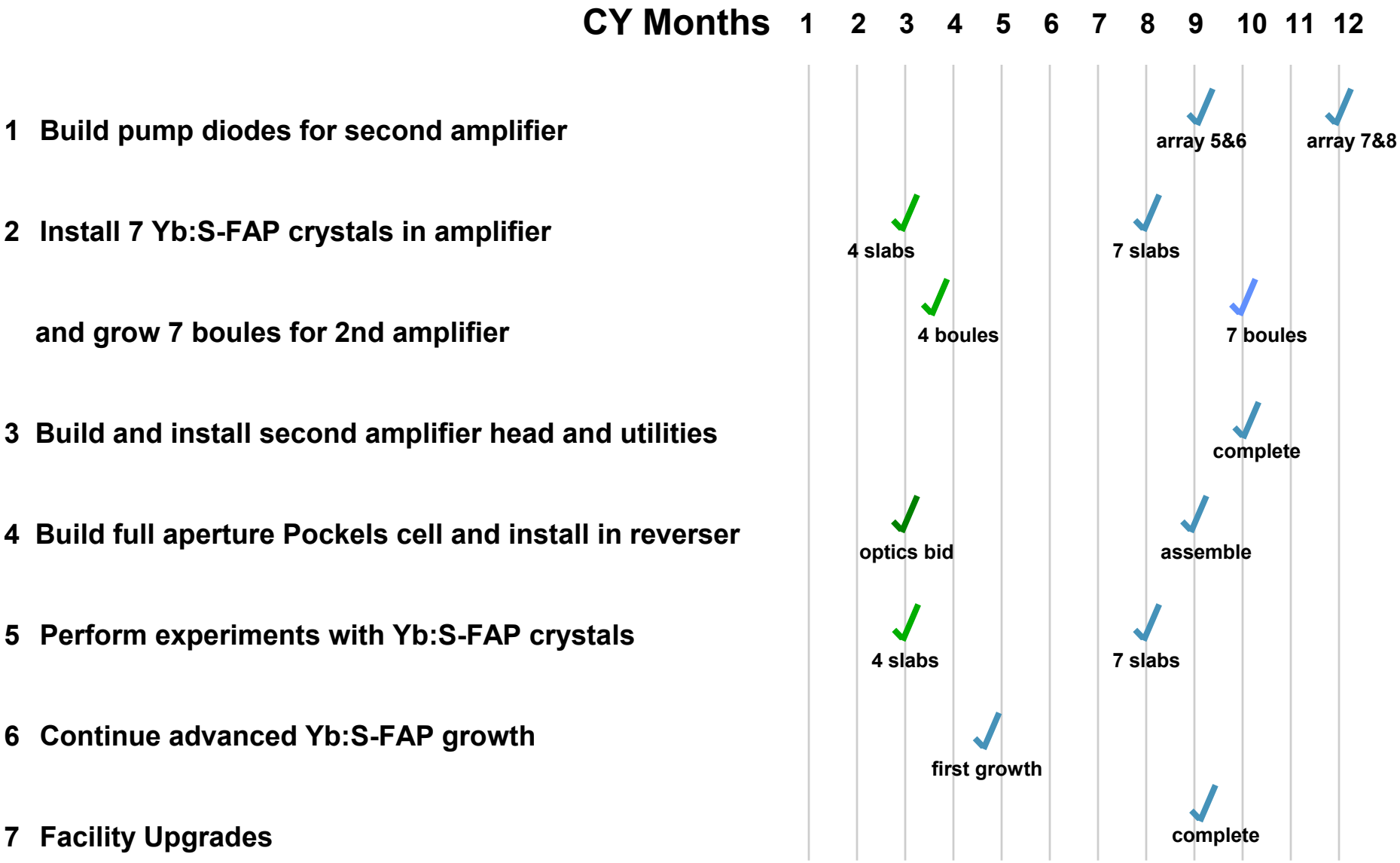
Pockels Cell and Driver →

> 200 W Diode bars →

IRE Architecture

System Design Requirements and Cost Scoping → IRE Design

We are on schedule to produce first light with one amplifier this year



The Mercury architecture has a robust design and addresses many performance issues

- Mercury Laser incorporates encompasses paradigm shifts in efficiency (0.5 to10%), rep-rate (10^{-4} to 10Hz), and reliability ($3x10^4$ to 10^8 shots)

	Gain Media	Cooling	Pumping	Relay Imaging
Traditional Fusion Laser	Nd:Glass F_{sat} = 5.3 J/cm^2 τ_{em} = 0.4 ms	Convective 1 shot / 4 hours	Side pumped with flashlamps	All lenses and most of amplifier far from relay plane
Advanced Diode-Pumped Laser	Yb:S-FAP F_{sat} = 3.1 J/cm^2 τ_{em} = 1.1 ms	High speed helium flow 10 shots/sec	End pumped with diodes	Telescope lens and amplifier in relay plane
Comments and Reasoning	Mitigate damage risk and reduce diode cost	Rep-rated or shot-on-demand experiments	Overall system efficiency increased >10x	Mitigate damage risk

Diode Pumped Solid State Lasers (DPSSLs) can potentially meet all the requirements of an IFE power plant driver

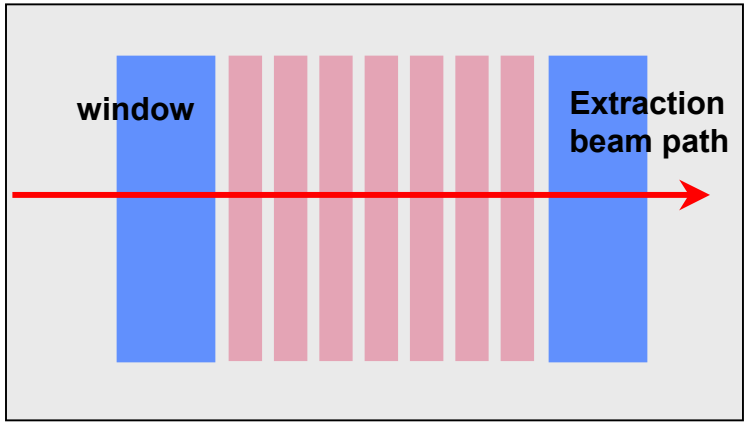
Projected DPSSL Strengths	
Efficiency	10-20% (3ω)
Rep Rate	> 5 Hz
Reliability	> 10^9 shots
Flexible	ps-ms pulses complex temporal pulse shaping
Brightness	≥ 10^{20} W/cm^2 at focus

Development Issues	
Scaling	100J ➡ 2MJ
Cost	\$50000/J_{laser} ➡ \$500/J_{laser}
Beam Smoothness	DPSSL smoothing is equivalent to Omega and NIF; < 1% smoothness at 1 THz bandwidth for direct drive
Frequency Conversion	At high energy and high average power with smoothing

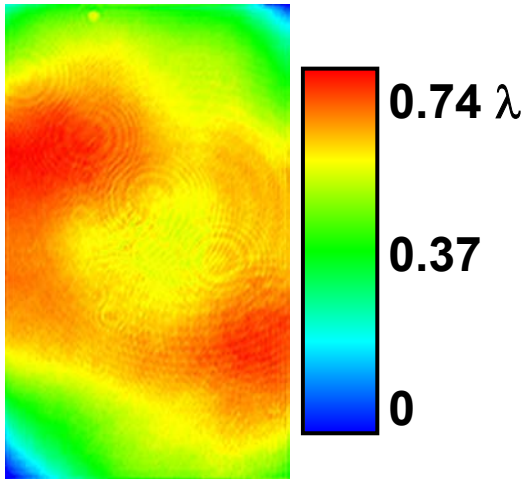
Mercury will begin to address a subset of these requirements and challenges

Interferometry with amplifier (Nd:glass, no wedge) were tested under full diode loading (4-backplanes) showed 1.8 waves

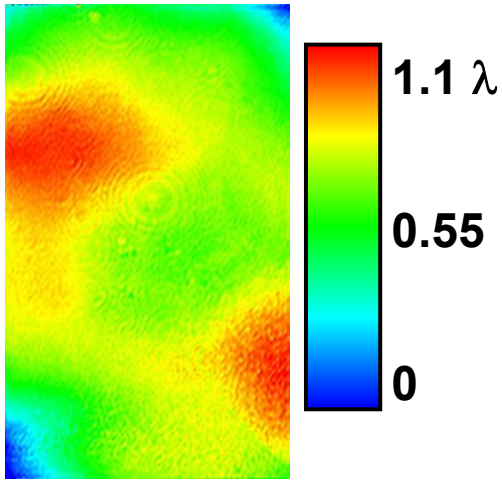
7 glass slabs with no wedge



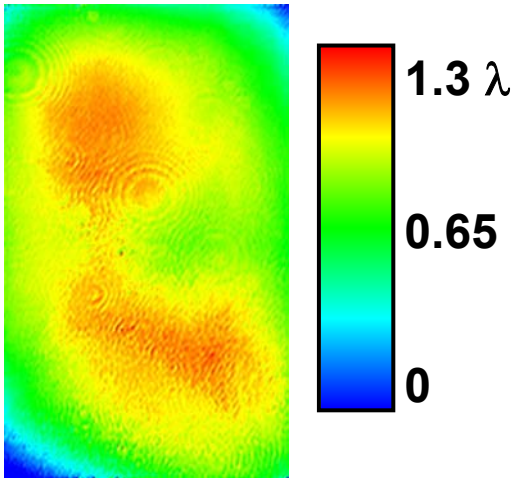
Static



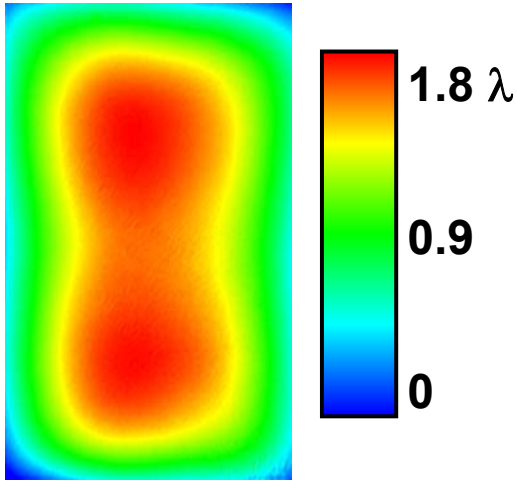
Gas Flow



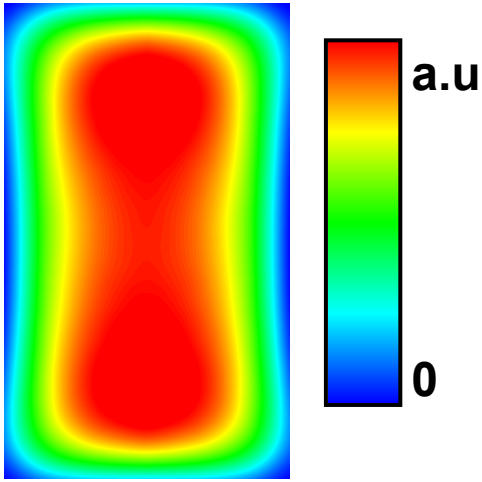
0.1 Hz diode rate



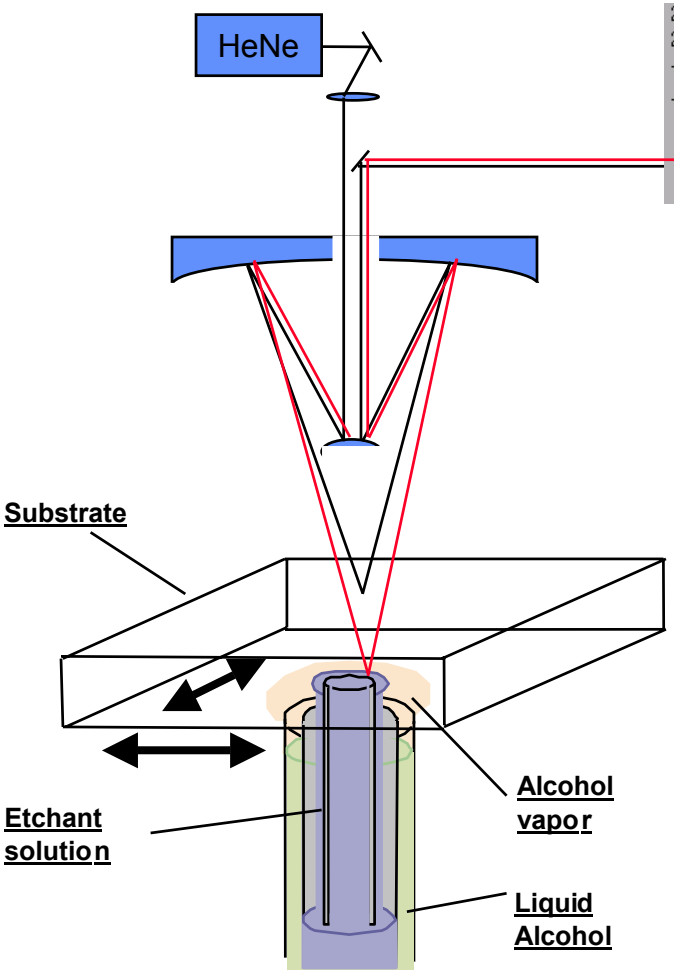
1 Hz diode rate

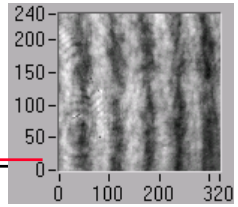


Model



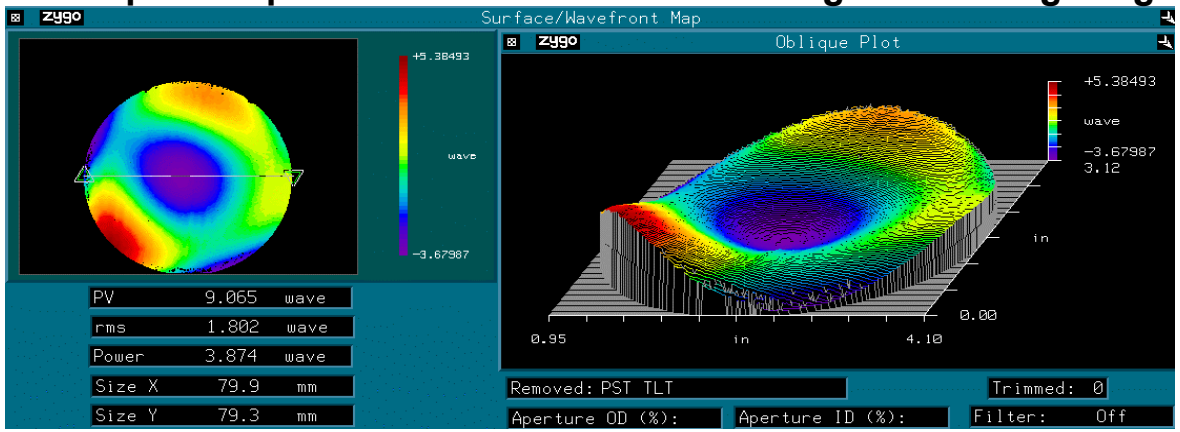
Wet-etch figuring is being used to fabricate the phase corrector for Mercury





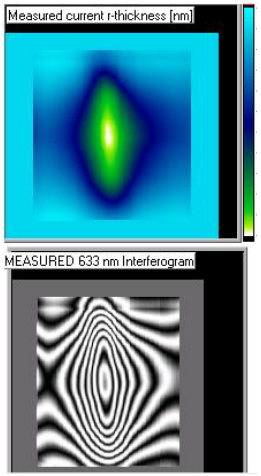
Real-time etch monitoring Removes many of the Parametric sensitivities

Example of a phase corrector fabricated using wet-etch figuring



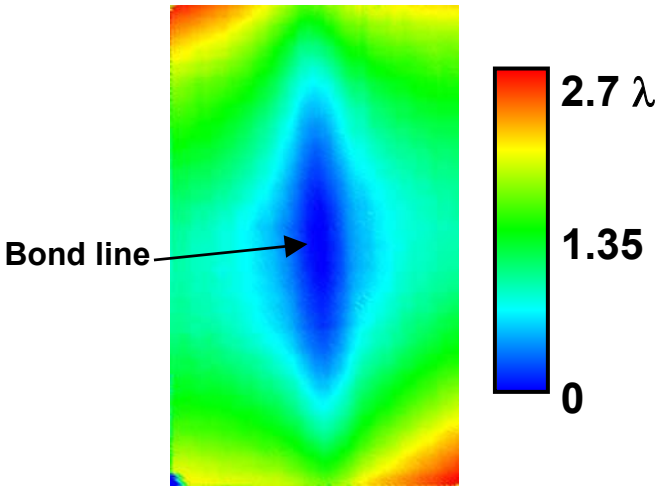
80 mm diameter optic, 380 um thick P-V material removal depth ~ 10 µm

A phase corrector plate for Mercury was fabricated

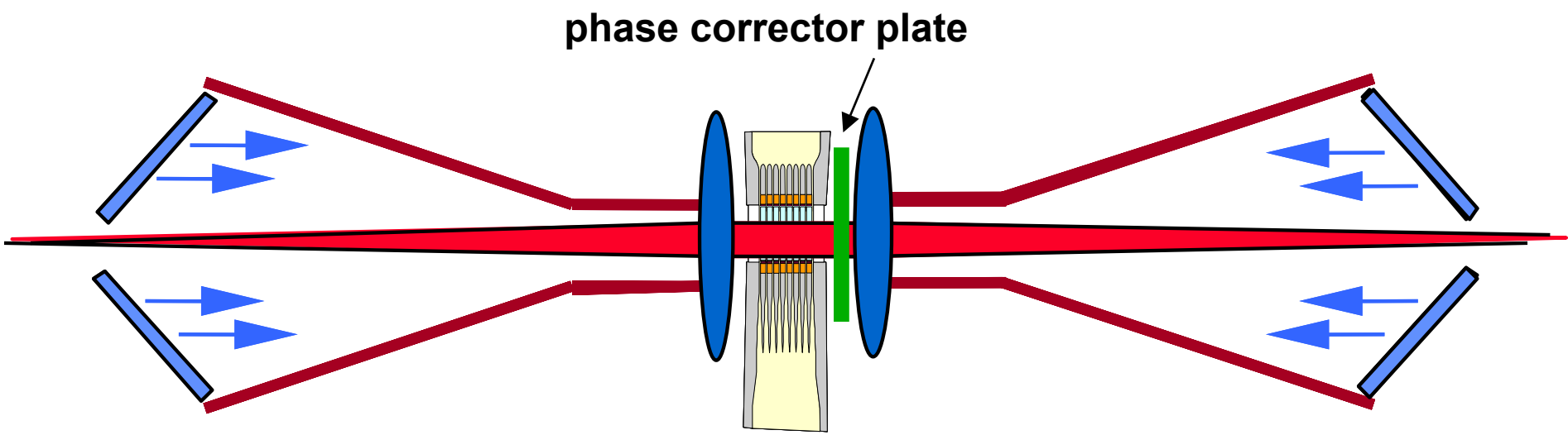


We will use a phase plate to correct for the low order of distortion in the amplifier slabs due to bonding line

Wavefront distortion with helium gas flowing (3 glass and 4 S-FAP slabs)



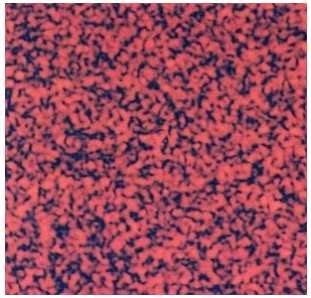
- Primary distortion is due to bonding
- These are the "first" full size S-FAP slabs fabricated
- Improvements in progress
  - LLNL: annealing
  - ONYX: polishing
  - Schott: developing room temp "glass glue"
- Phase plate offers correction and remove distortions near the source



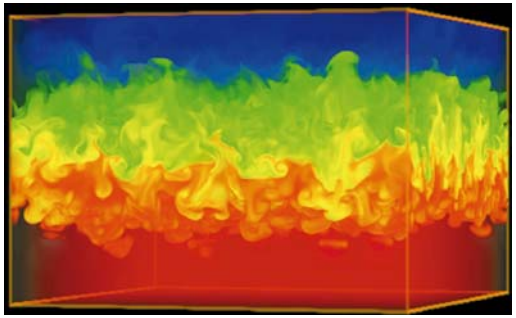
Beam smoothing is a method used to reduce surface instabilities in the target plasma

Problem

Laser speckle



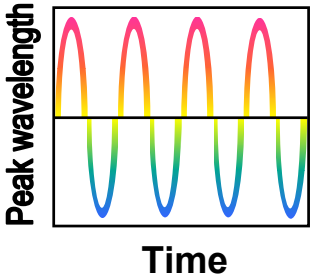
Intensity variations at the target surface cause Rayleigh-Taylor instabilities



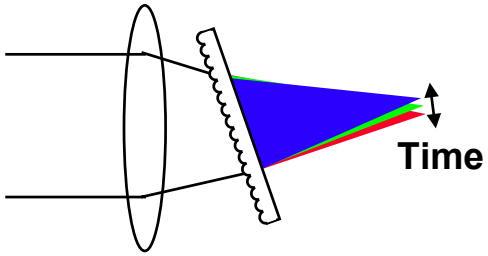
Unstable compression and inefficient burn of target

Solution

Laser with time-varying spectrum



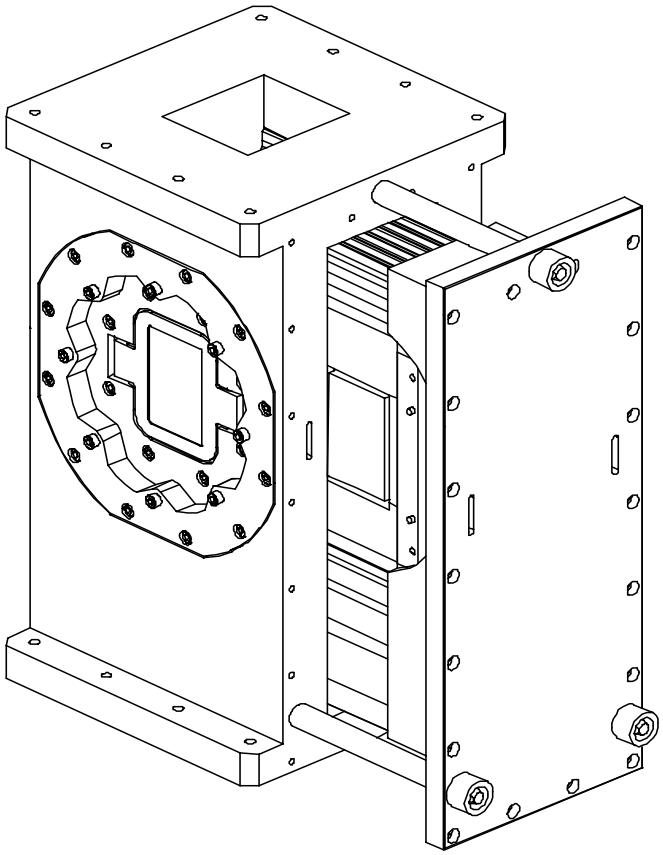
Grating in final optics assembly moves laser speckle on target



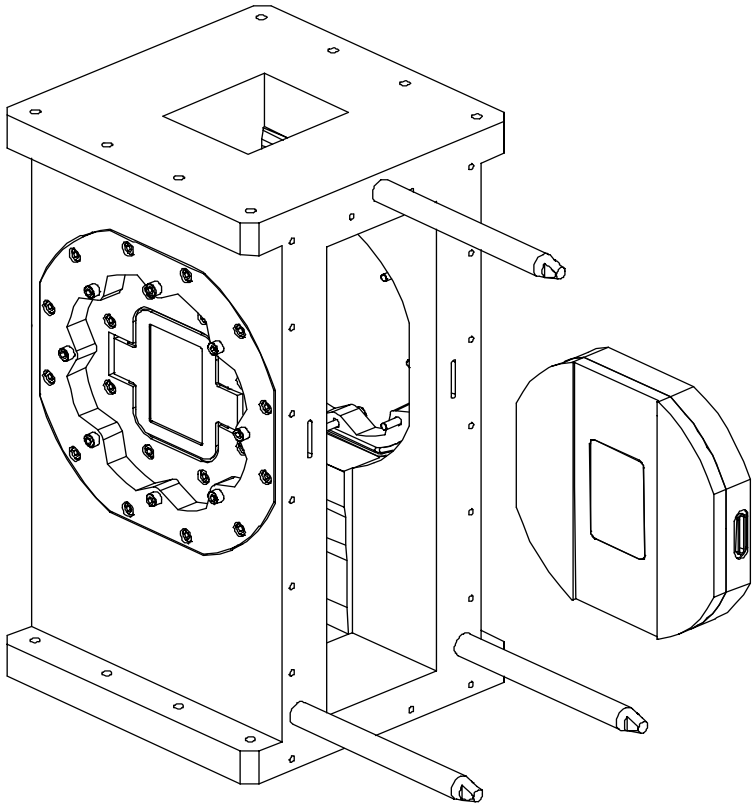
Smoothed intensity at target surface yielding stable compression and efficient burn

The amplifier head has been redesigned to allow for more uniform diode pumping and ease of operation

Amplifier cassette can be removed independent of window fixture and flow plenums

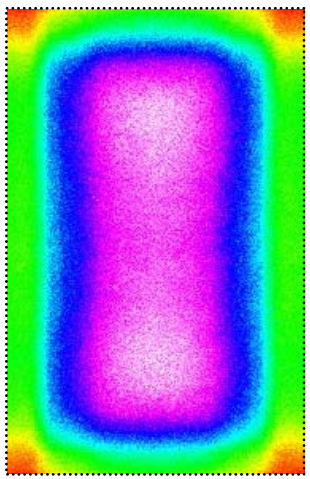


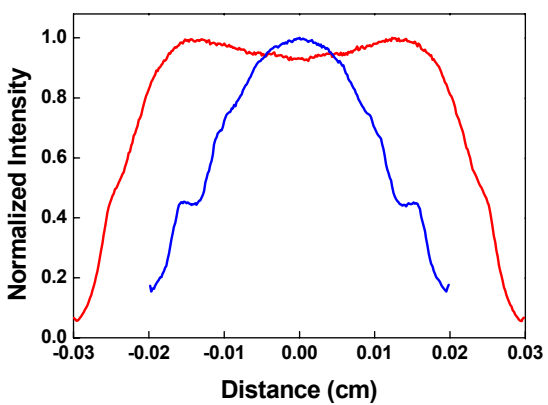
Window frame can be removed without disturbing inner window seal



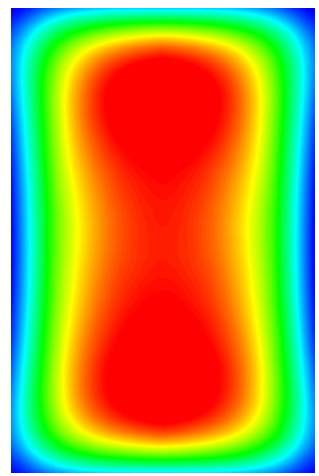
Modified gas-cooled head which allows more uniform pumping

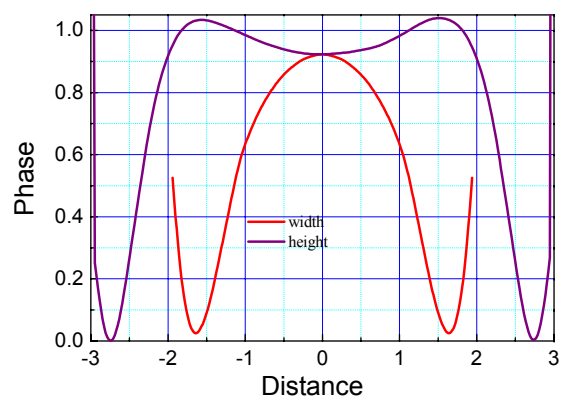
Present gas cooled head integrated gain profile





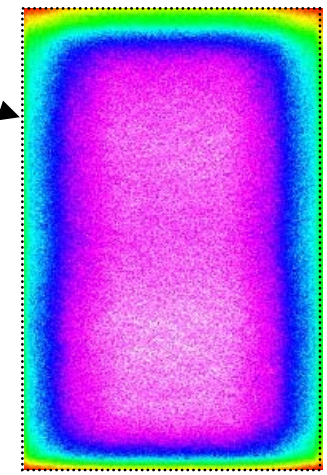
Simulated thermal data using heat transfer pic codes

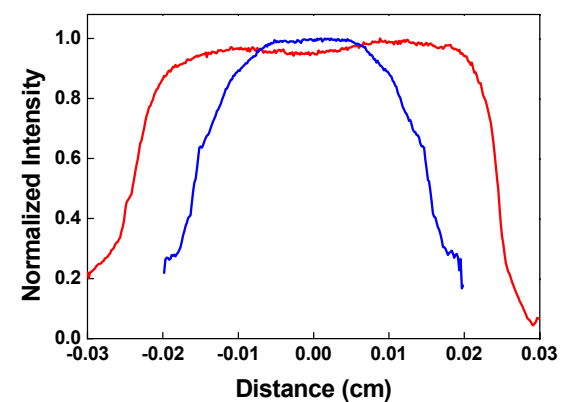




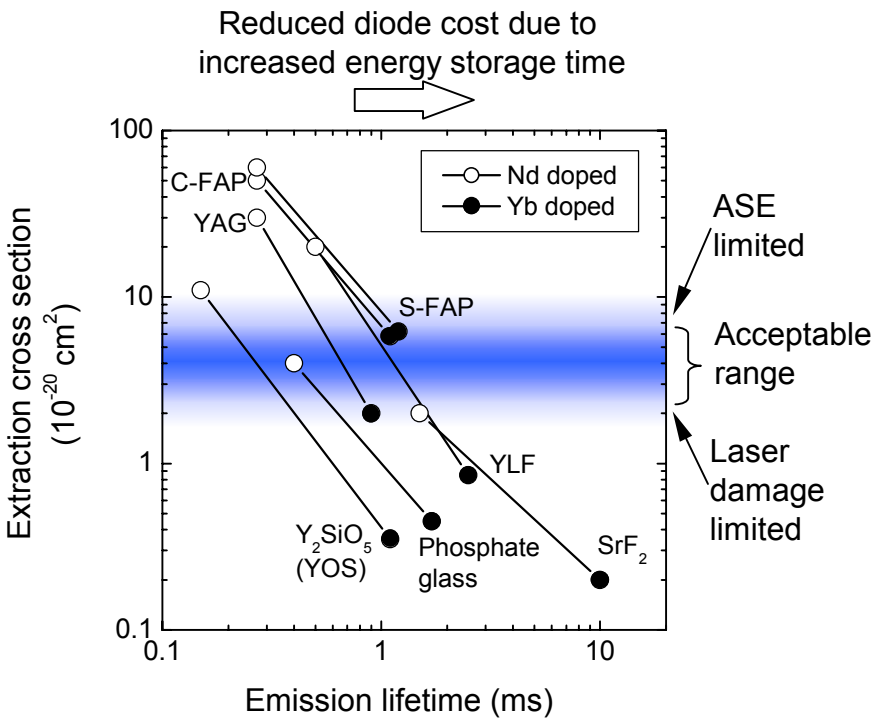
Modified gas cooled head (thermal data not available yet)

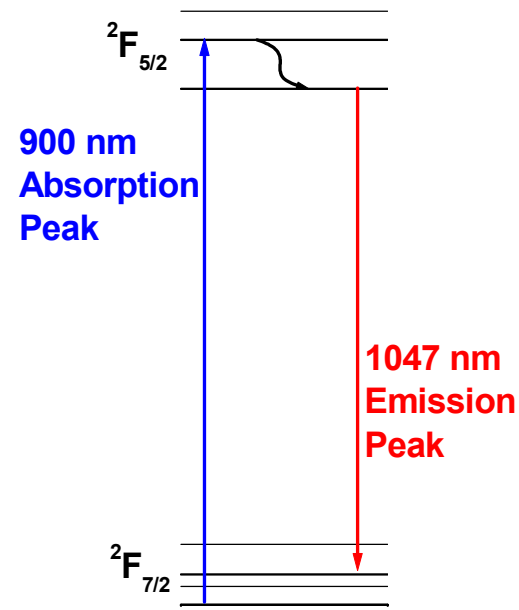
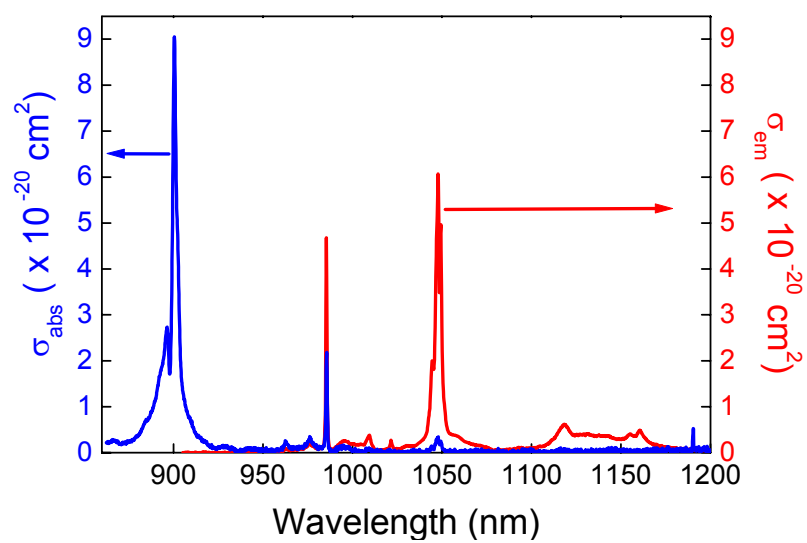
3x5 extracted area





Yb:S-FAP has both high absorption and emission cross sections and long lifetime





	Yb:S-FAP	Nd:YAG	Nd:Glass
Lifetime·(ms)	1.14	-0.23	~0.3
Absorption·cross·section·(x·10^{-20}·cm^2)	9.0	5	2
Emission·cross·section·(x·10^{-20}·cm^2)	6.2	65	~4
Saturation·Fluence·(J/cm^2)	3.1	0.29	4.72
Thermal·Conductivity·(W/m·°C)	2.0	13.0	~1.2
$\partial n/\partial T$·(x·10^{-6}·°C^{-1})	-10	7.3	-