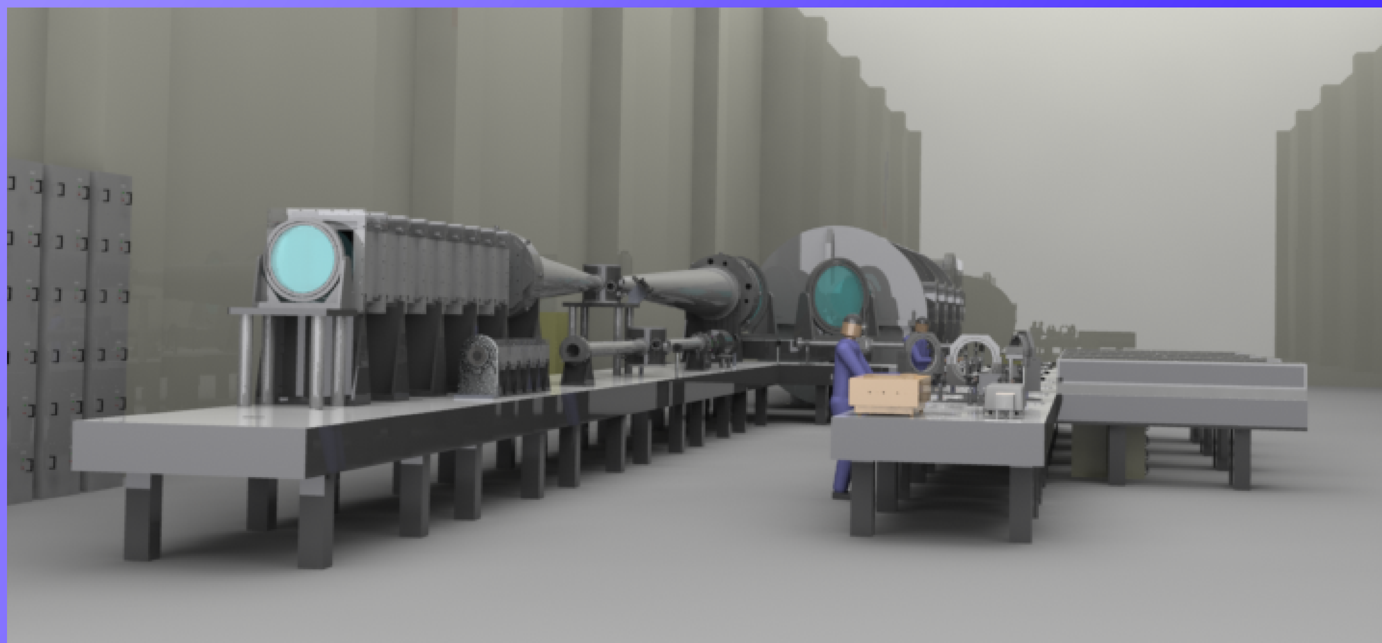
Toward Rep-Rated Multi-Petawatt Lasers



Presented by:
Todd Ditmire

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

and National Energetics, Inc.

This work is an extensive collaboration

<u>National Energetics</u>
Todd Ditmire
Erhard Gaul
Mikael Martinez
Gilliss Dyer
Will Grigsby
Aaron Bernstein
Doug Hammond
Gavin Friedman
Ramiro Escamilla
Mike Donovan

<u>Schott Glass N. America</u>
Matt Roth
Eric Urruti
Nathan Carlie
Simi George

<u>Logos Technologies</u>
Mike Campbell
Jason Zweiback
Dave Eimerl (Eimex)
Bill Krupke

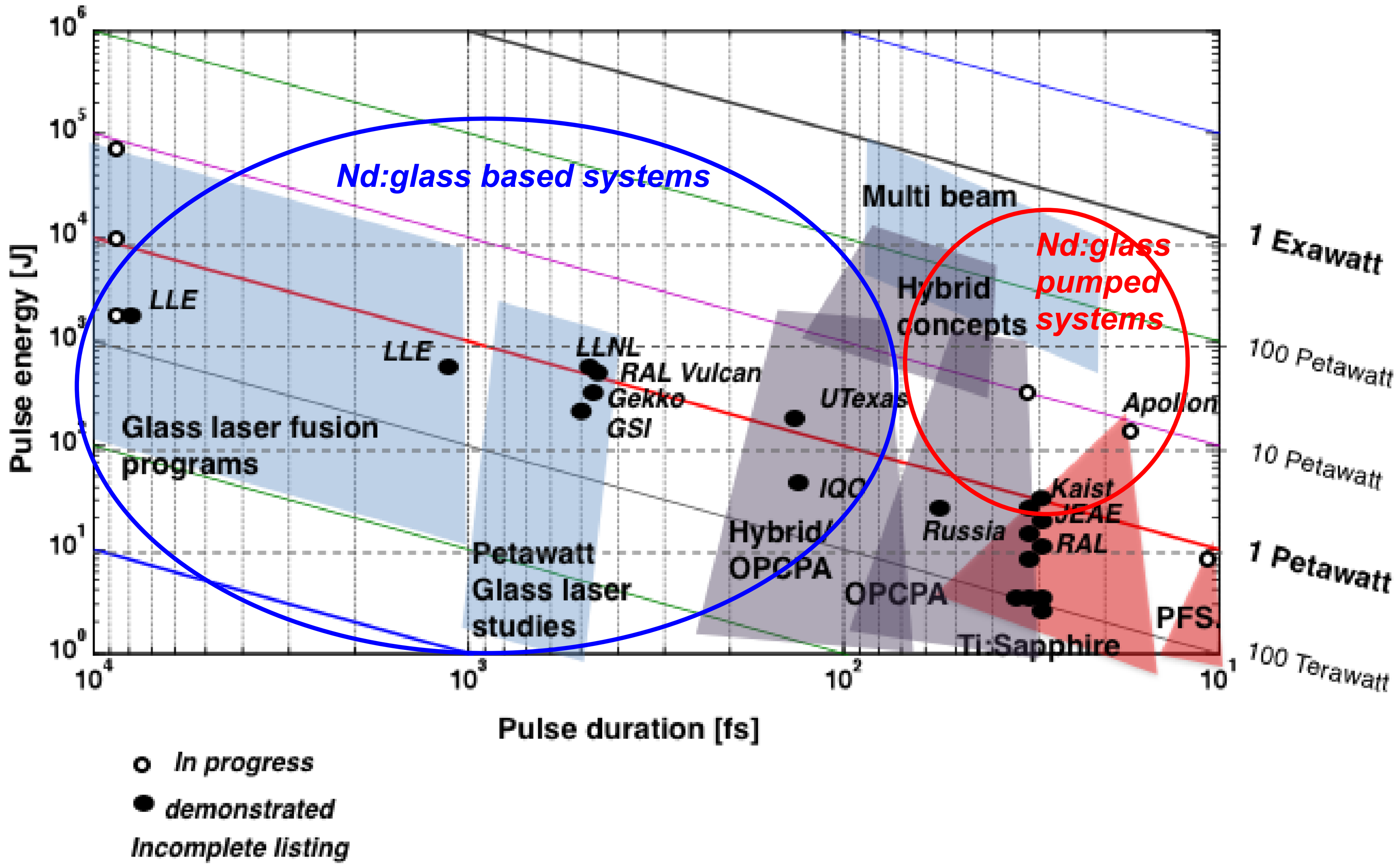
<u>ILE/ENSTA</u>
Jean-Paul Chambaret
Gilles Cheriaux

<u>CEA-CESTA</u>
Bruno LeGarrec

<u>LLE Rochester</u>
Jon Zuegel

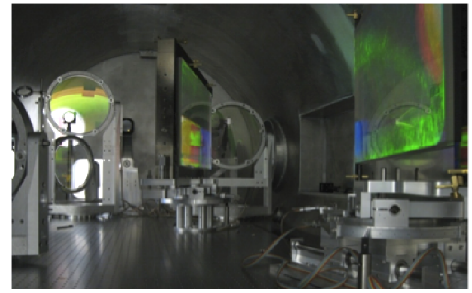
<u>Continuum</u>
James Norby
Neil Scott
Curt Frederickson

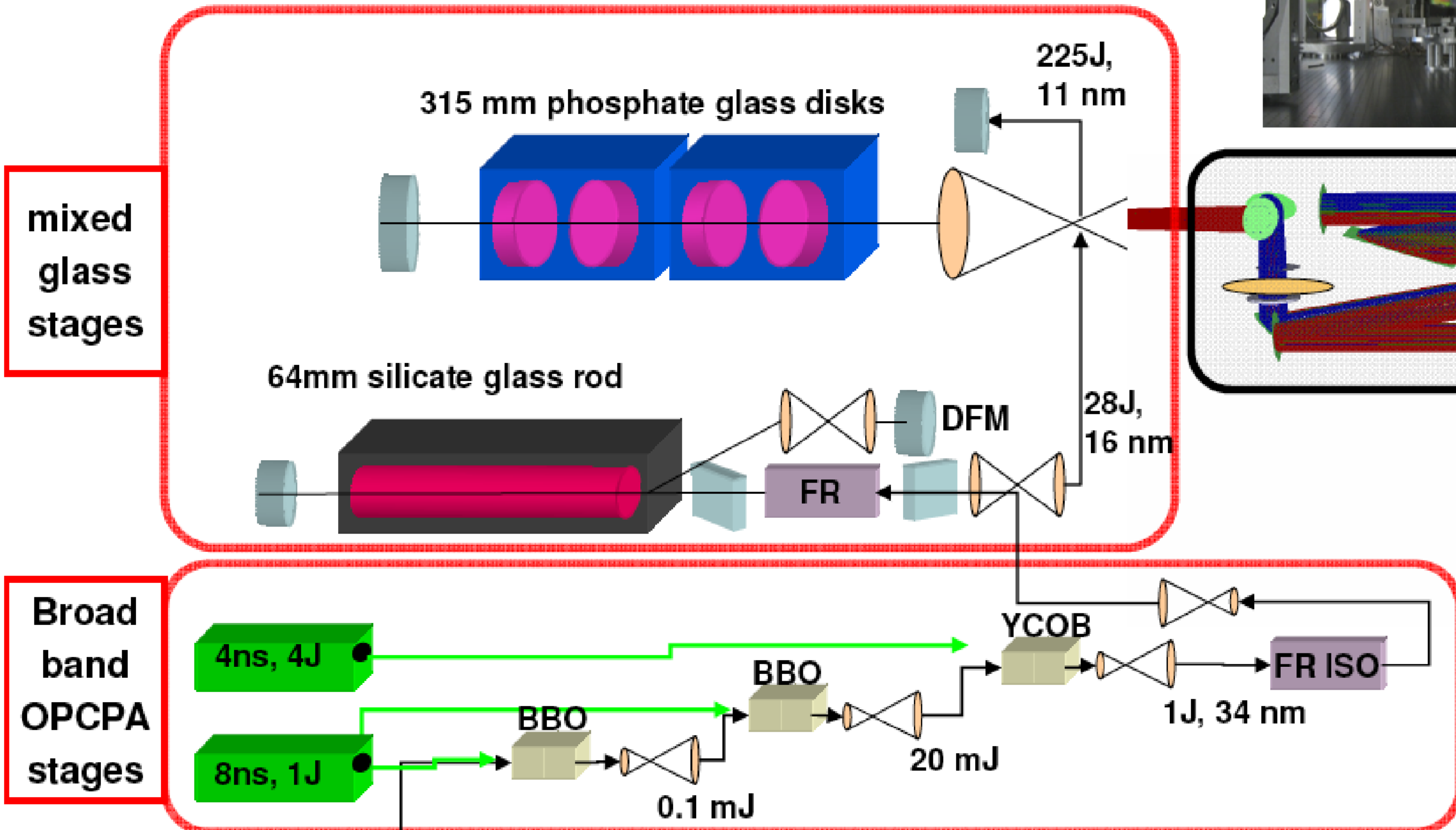
There are really two avenues to get to 10 PW but the road to an exawatt is more challenging

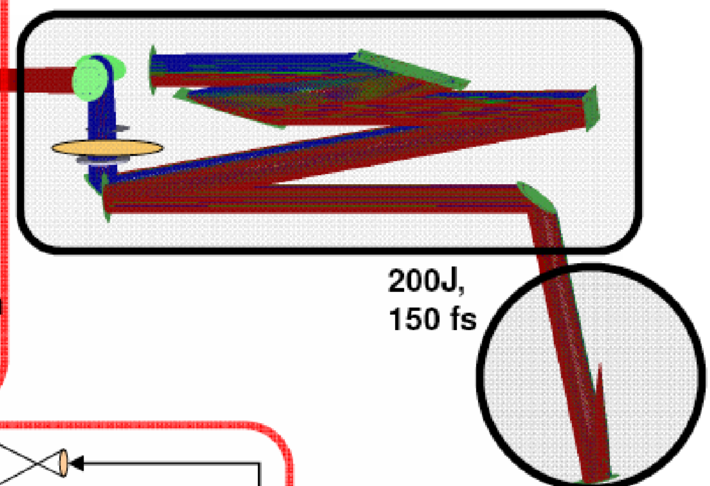


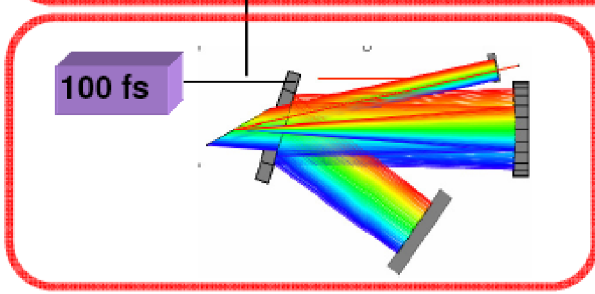
The Texas Petawatt design is based on a 3-stage OPCPA amp and a mixed glass chain

High diffraction efficiency multi-layer dielectric gratings



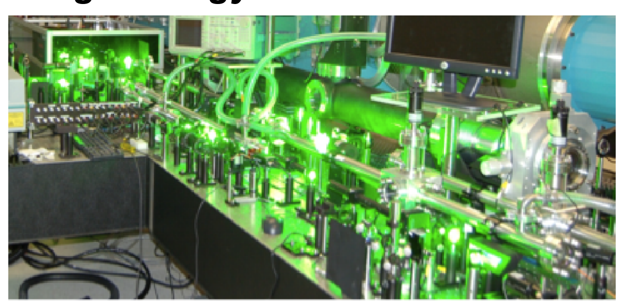






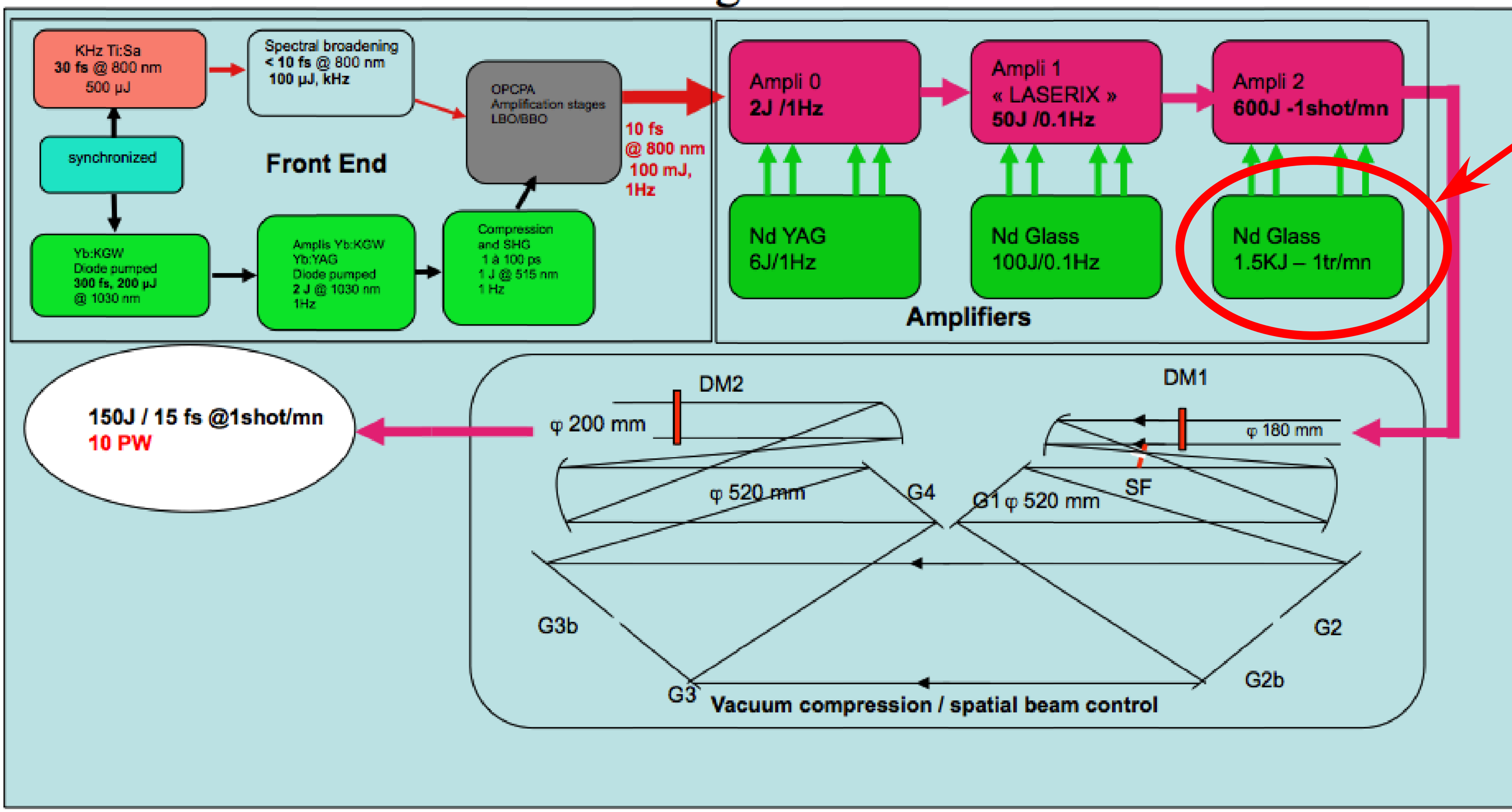
Mixed silicate/phosphate glass amps

High energy OPCPA front end

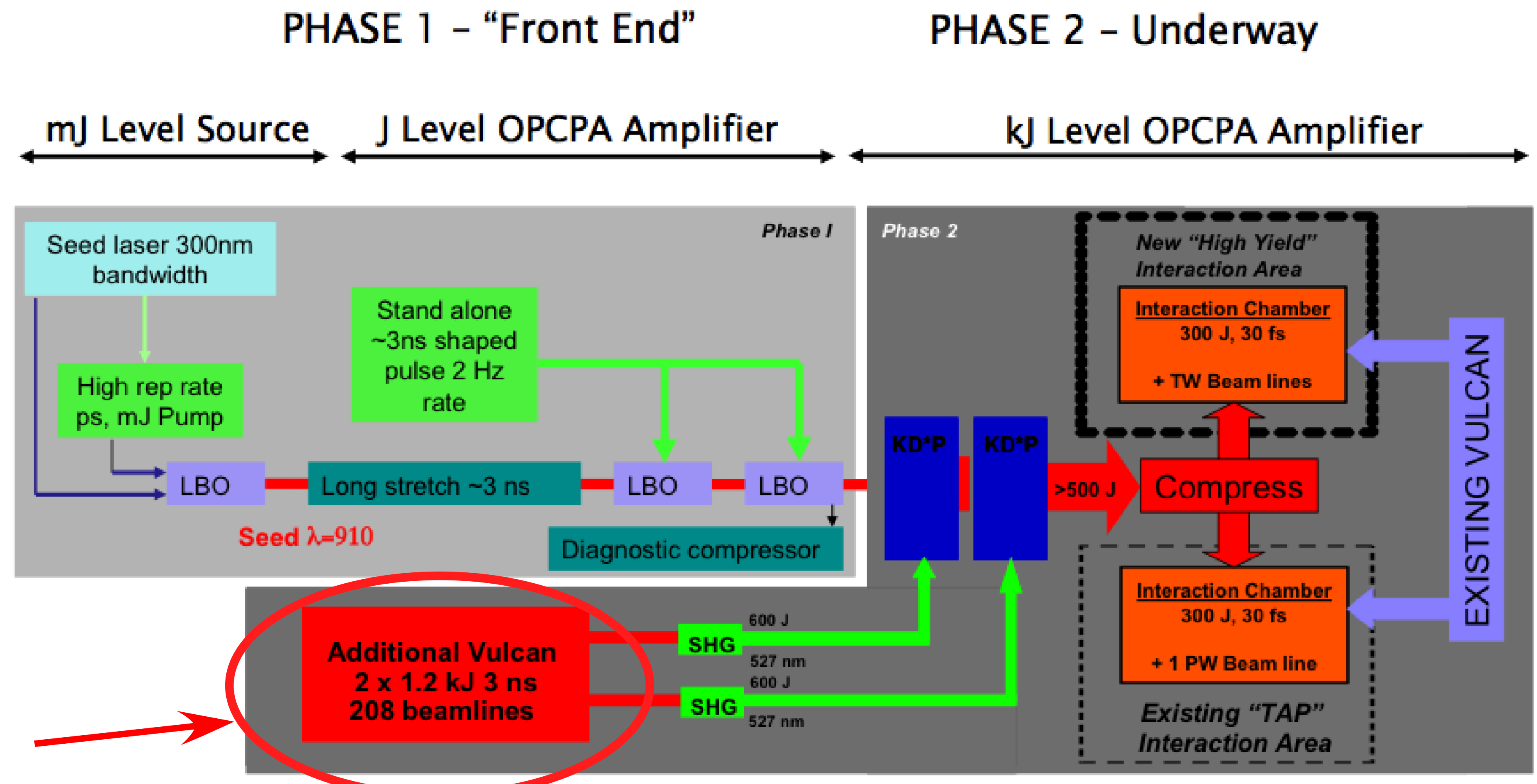


ILE – APOLLON 10P : A French TiSa project
General scheme

ILE APOLLON Single beamline 10PW laser



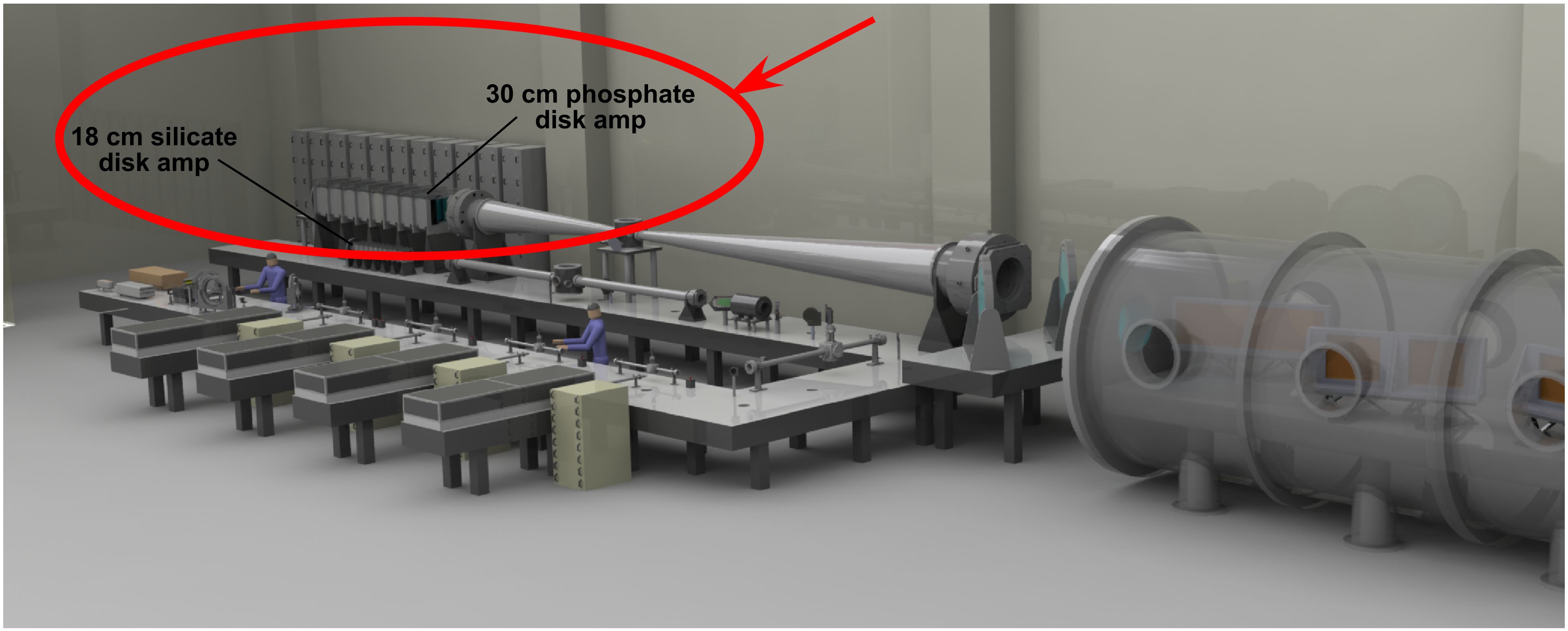
Overall 10PW Schematic



- Will be based on a combination of LBO and KD*P
- 3 stages of amplification (some old Nova !)
- Optical Efficiency 10-15%

Next generation multi-PW lasers based on Nd:glass will need amplifiers at ~30 cm aperture

Mechanical Engineering conception of the 10 PW Hybrid Mixed glass laser



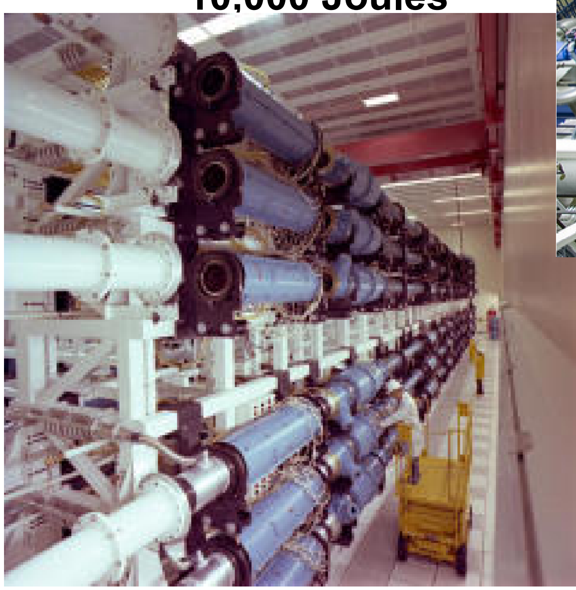
High energy Nd:glass lasers (above 100 J) have been based on the same technology for 40 years

Cyclops laser (1974)
1 beam
100 J

Argus laser (1976)
2 beams
1000 Joules of energy

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

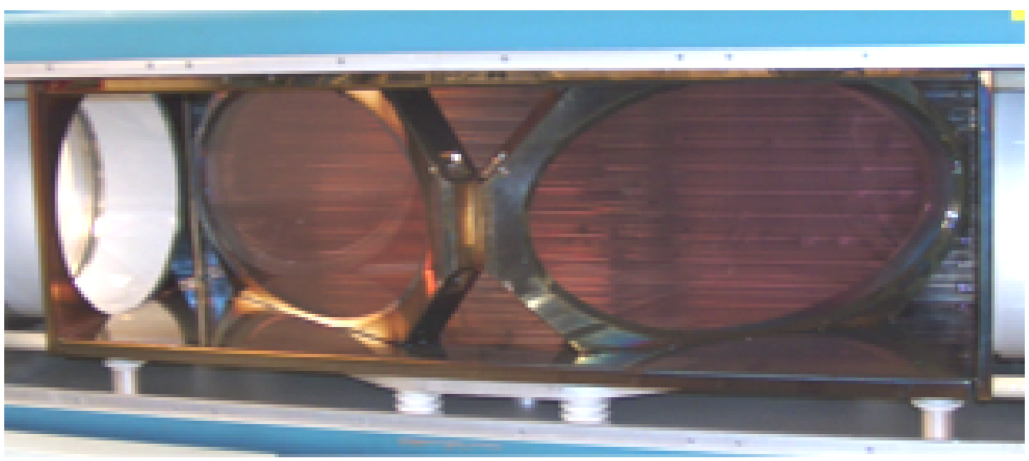
Shiva laser (1978)
20 beams
10,000 Joules



Nova laser (1985)
10 beams
100,000 Joules

Large aperture Nd:glass laser amplifiers are based on a completely ubiquitous architecture

Examples of Brewster angle, free mounted, multi-slab integrated, flashlamp pumped Nd:glass slab amplifiers



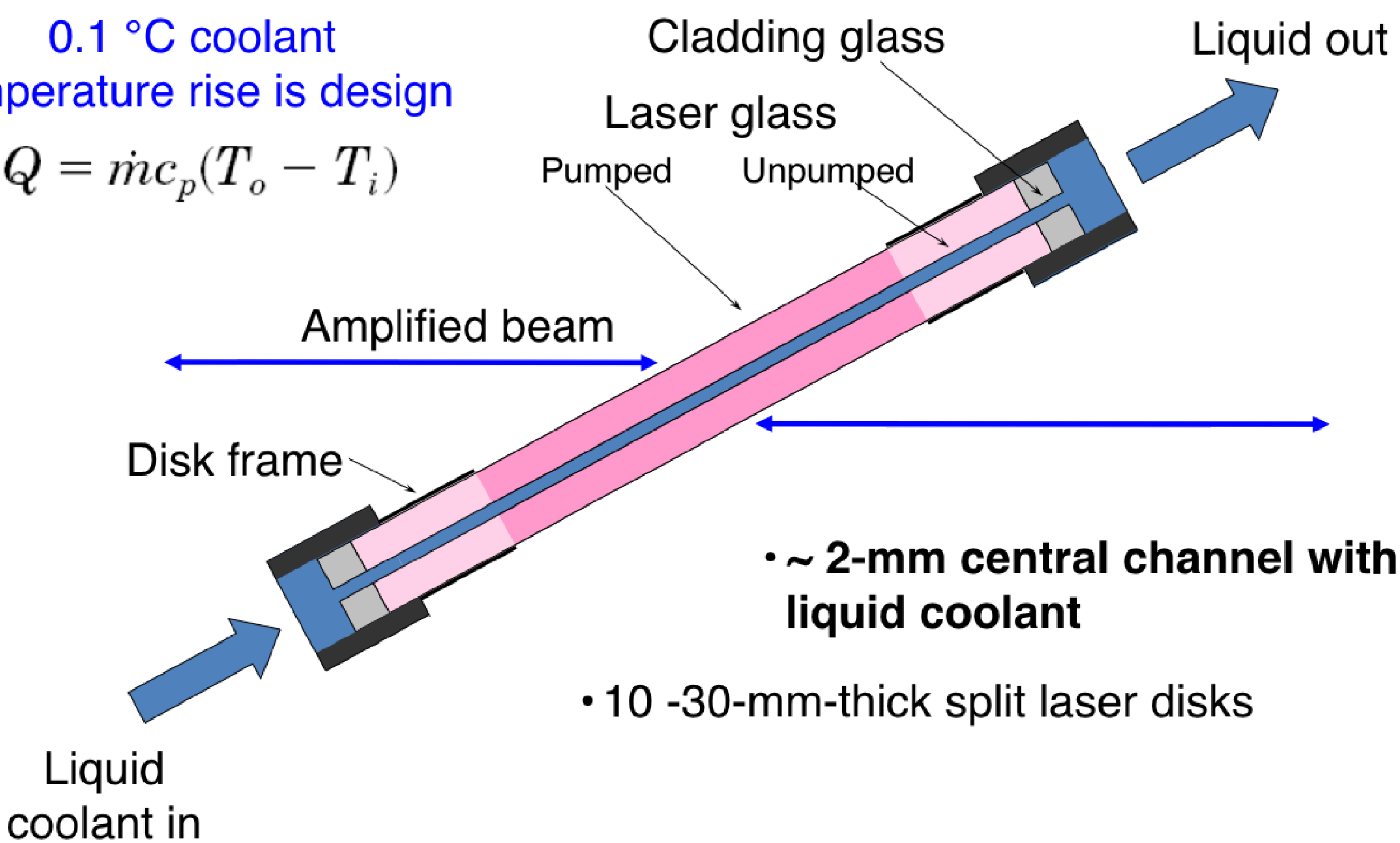
Repetition rate of these amplifiers is limited to thermal cooling by heat conduction into the surrounding air - repetition rates of 1 shot/30 min-3 hrs are typical

Can traditional slab amplifiers be reengineered for cooling and ease of use?

We are investigating liquid cooling the faces of glass slabs as a means for dramatically increasing rep. rate

0.1 °C coolant temperature rise is design

$$Q = \dot{m}c_p(T_o - T_i)$$

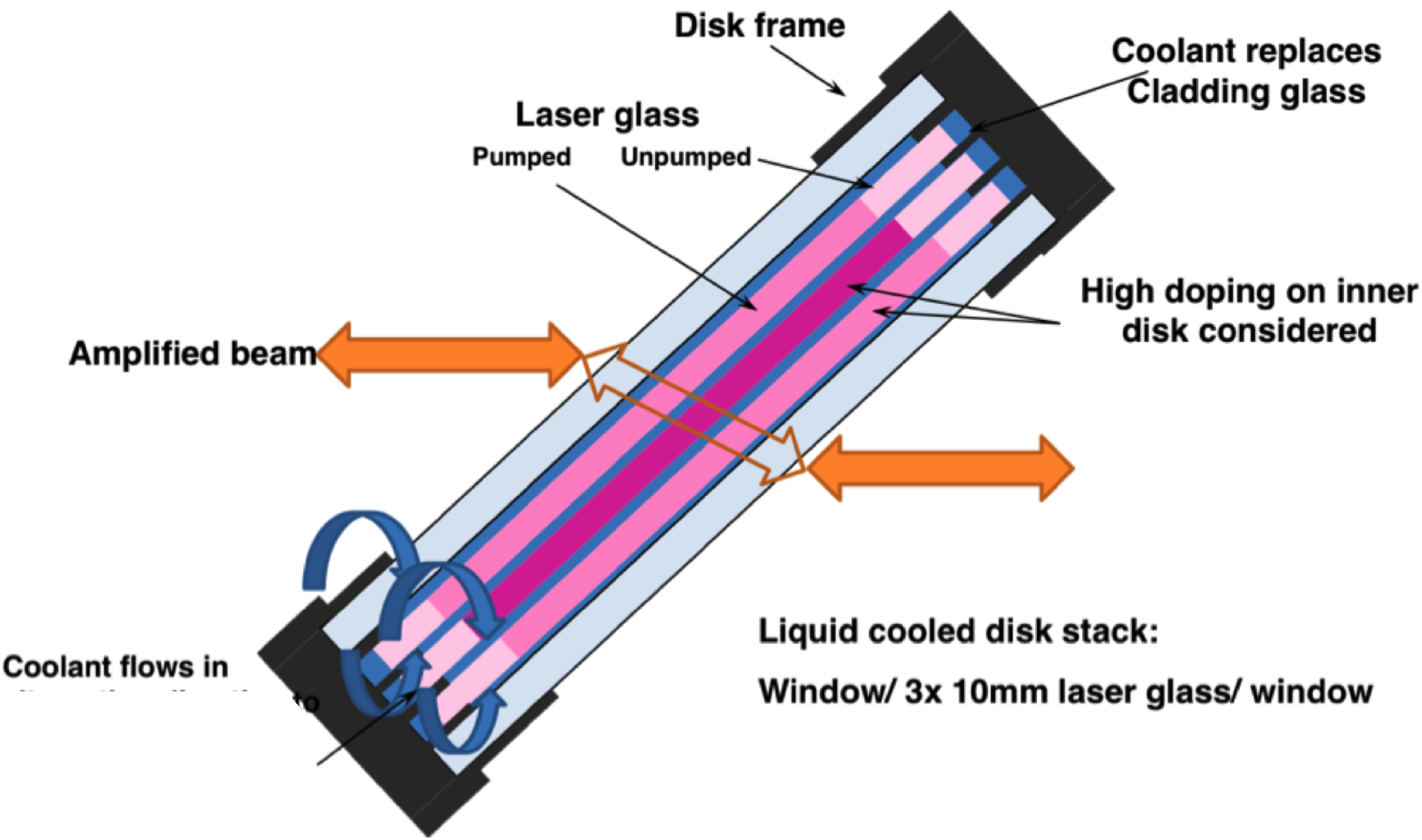


- **~ 2-mm central channel with liquid coolant**
- 10 -30-mm-thick split laser disks

This technology will permit operation of large aperture (~ 20 cm) Nd:glass slab amplifiers with rep. rate at least one shot per minute

Viewgraph credit: Jon Zuegel (LLE Rochester)

A multiple split disk design allows for more aggressive cooling

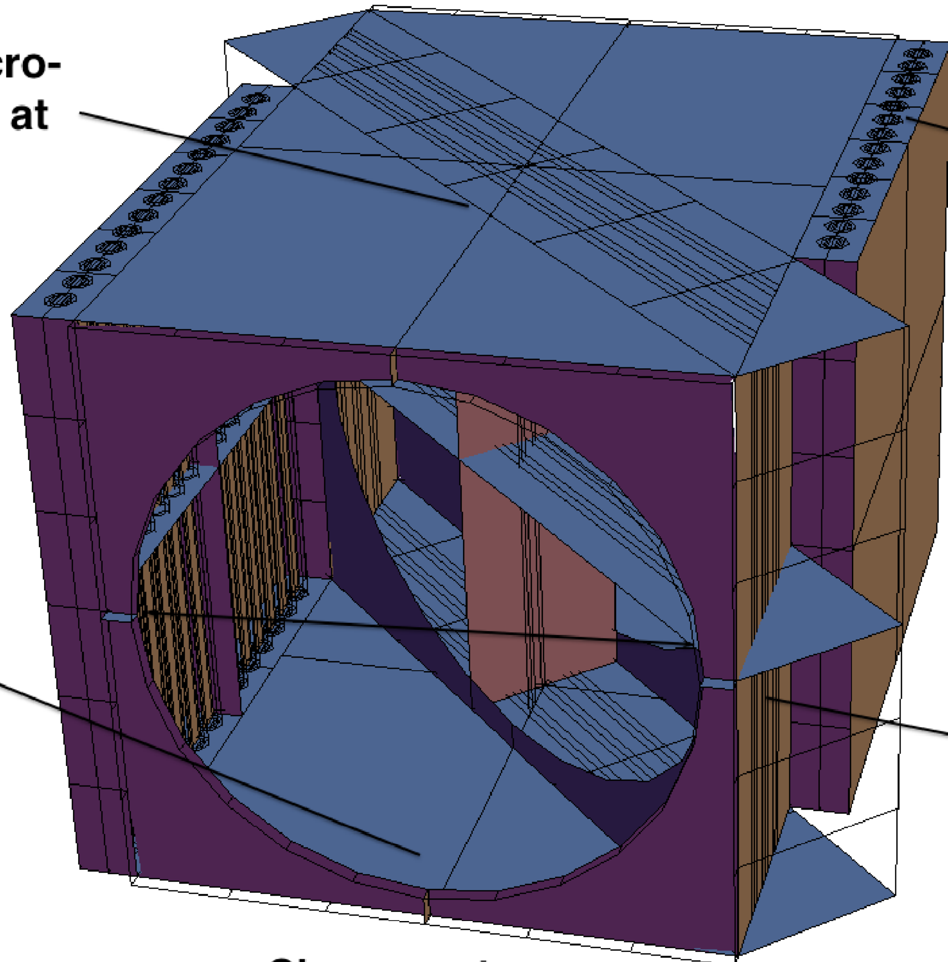


Traditional flashlamp configurations require multiple slab pump cavities

NATIONAL ENERGETICS

NOVA 31 cm disk amplifier flashlamps and pump cavity

We have designed a modular liquid cooled slab architecture



AR coated macro-slabs oriented at ~45°

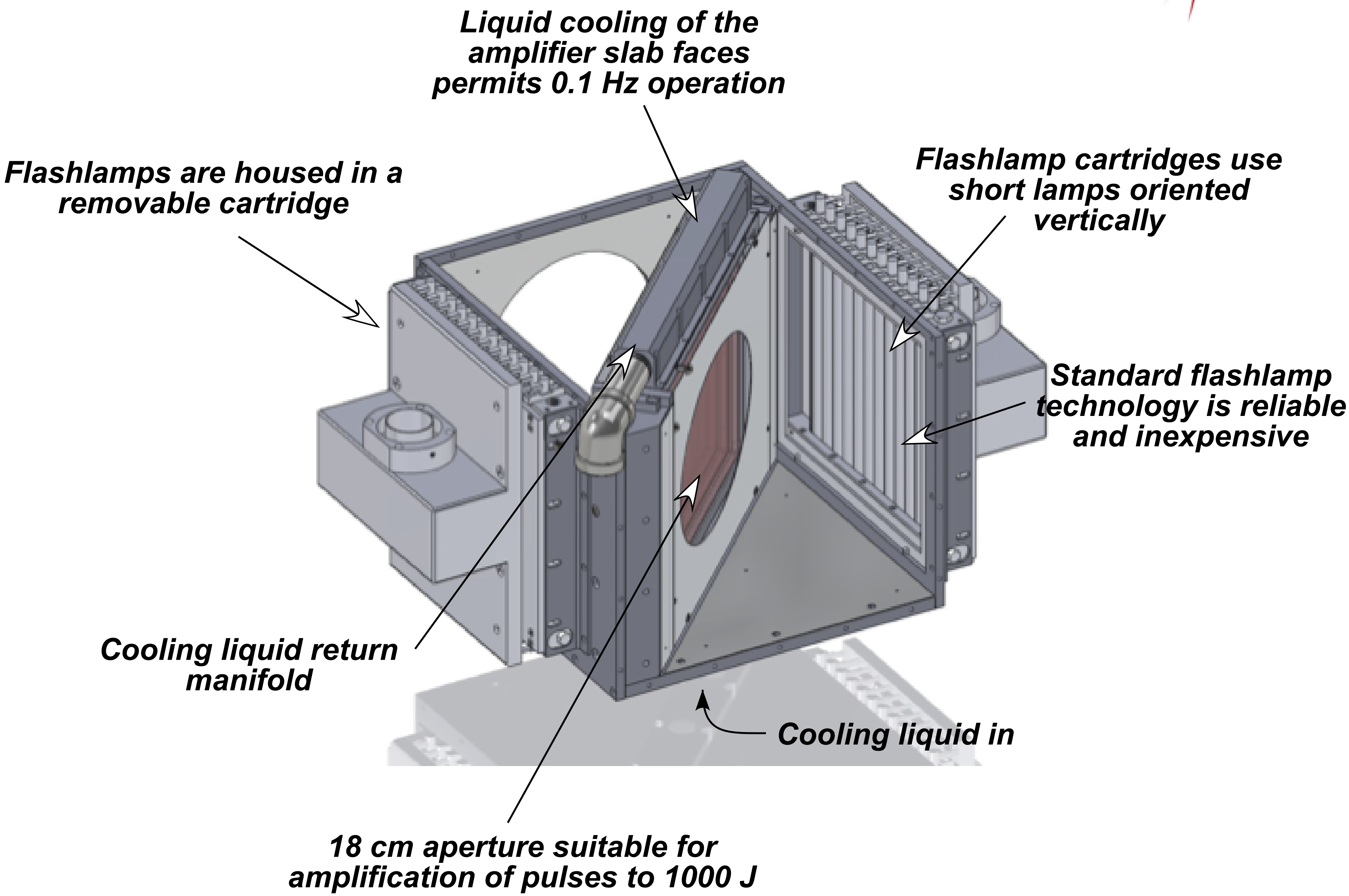
Vertically oriented flashlamps in independent cartridges

Macro-slab and flashlamp modules are assembled in a reflective box

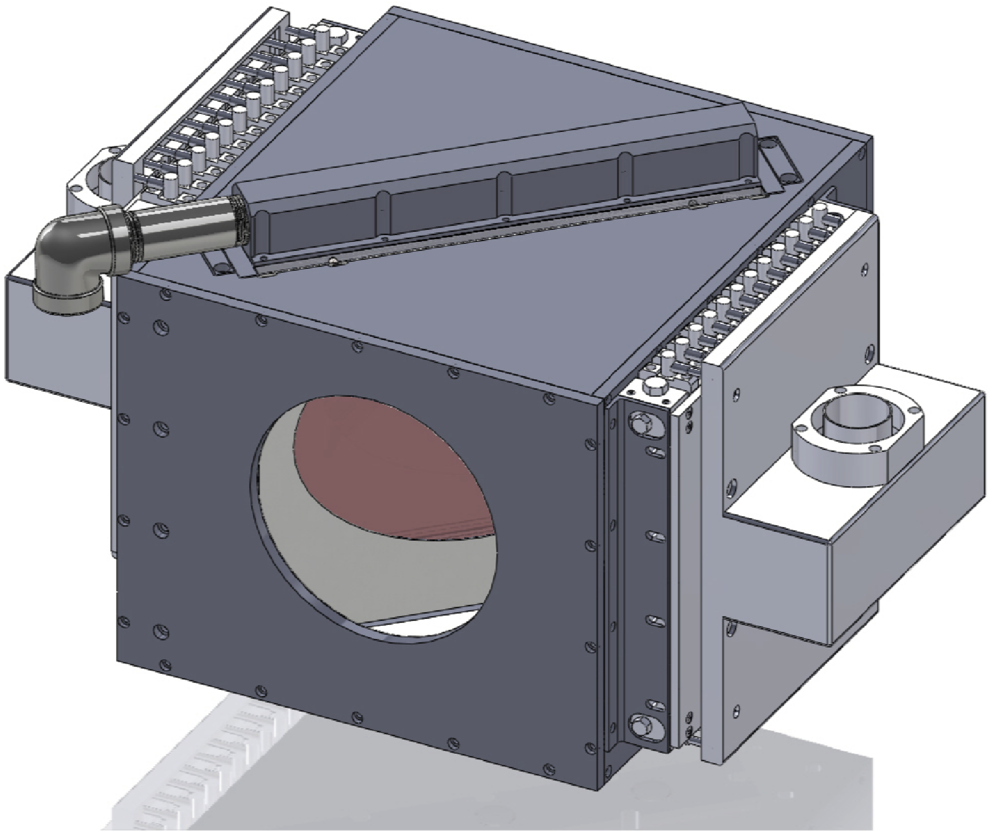
Self contained macroslab has 3 Nd:glass slabs and passive window faces

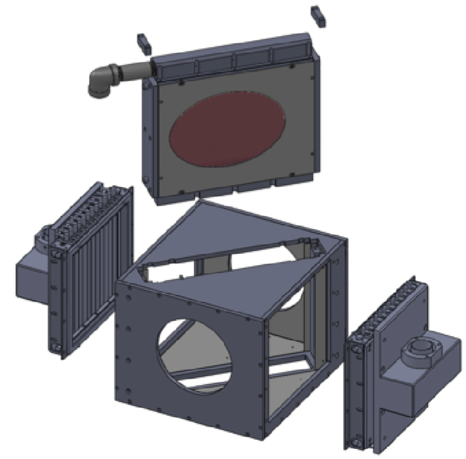
Clear aperture = 18 cm

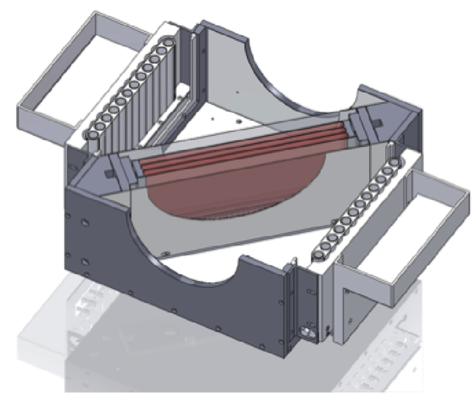
The modular liquid-cooled slab concept enables easy to use large aperture CPA and pump lasers



An integrated unit is a compact, single macroslab amplifier pumped with 31 kJ of flashlamp energy

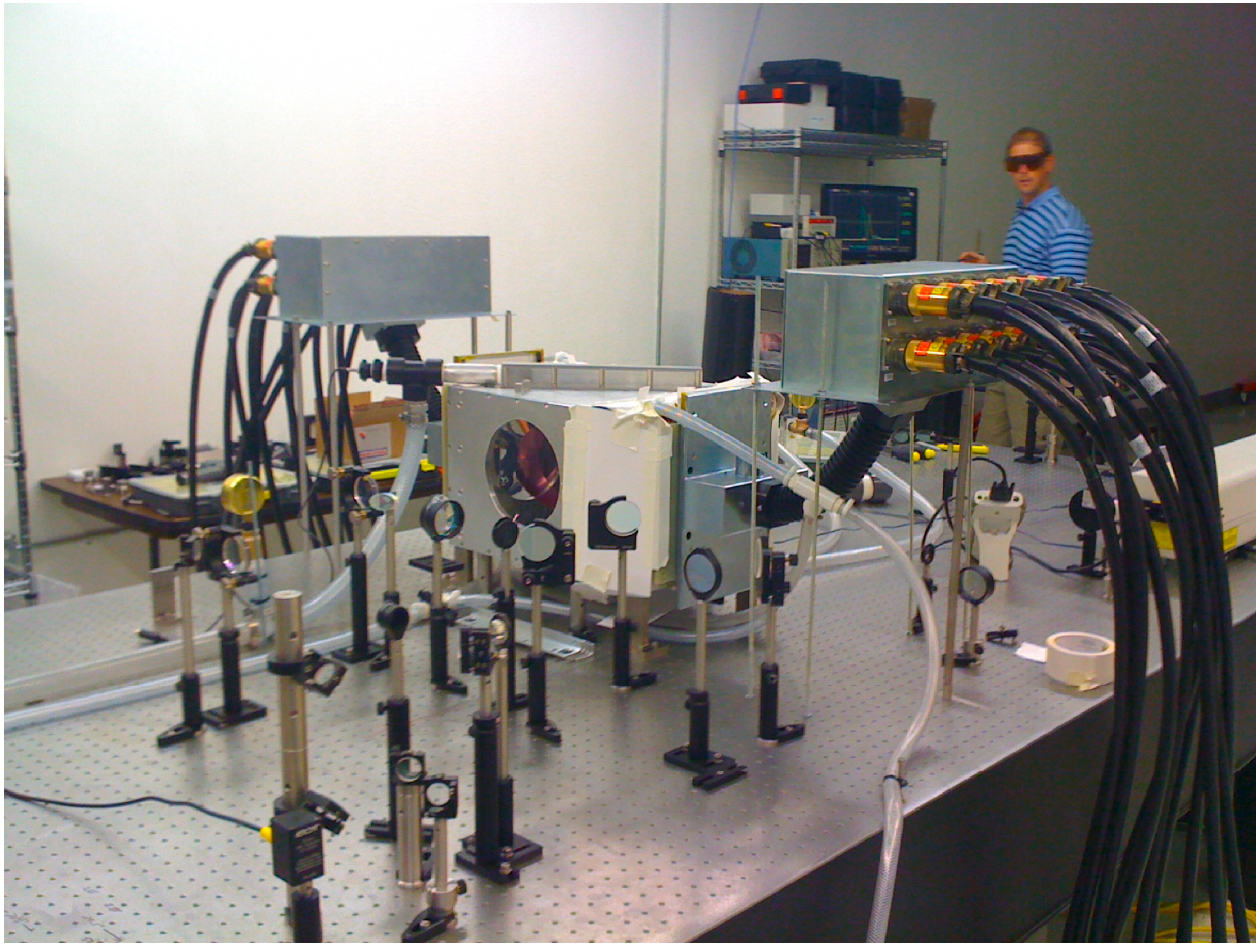






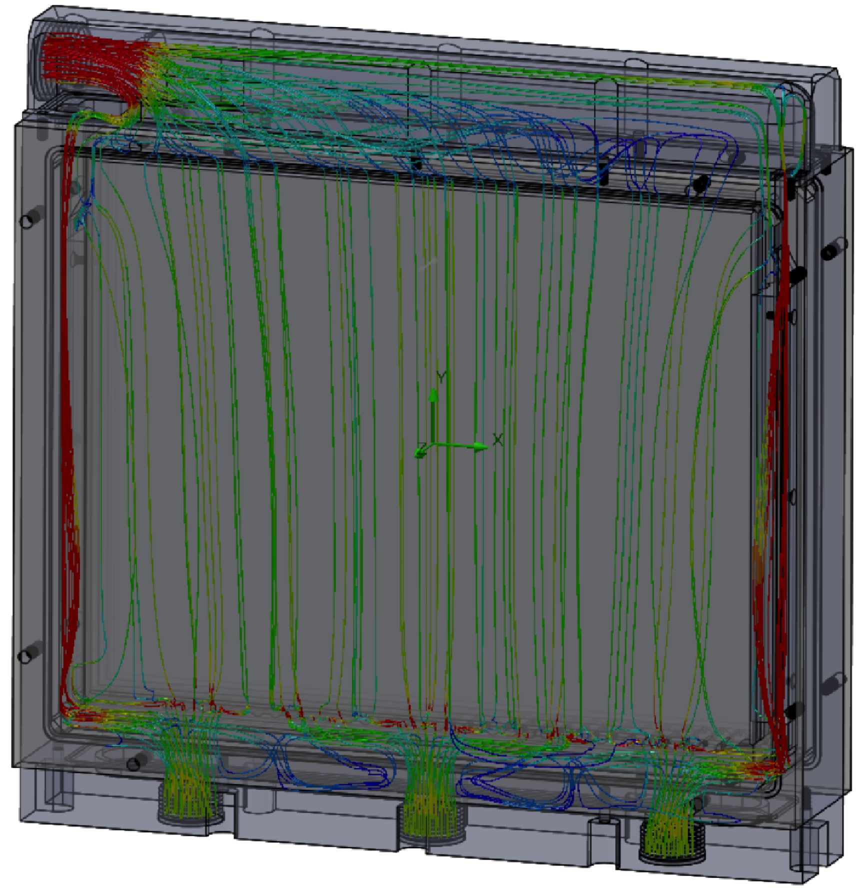
Amplifier has 18 cm clear aperture: 250 cm^2 amplifier area
At 5 J/cm^2 amp is suitable for amplification of >1 kJ pulses
(Each module has ~ 250 J stored energy)

We have constructed an 18 cm Nd:glass slab prototype module for rep-rated testing



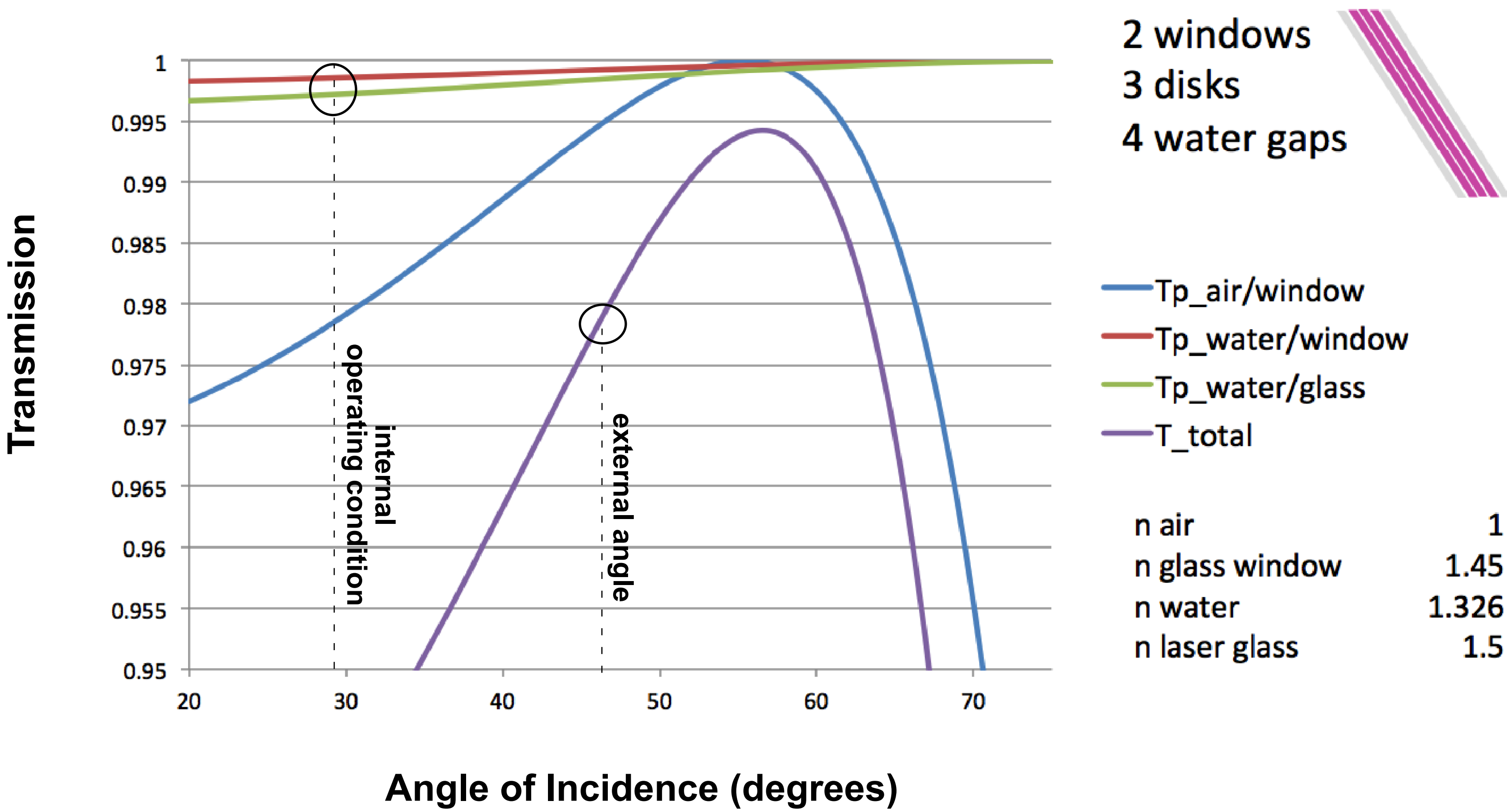
The split disk cassette is designed to yield smooth liquid flow in the optically usable aperture

Photo of bubbles rising in slab cassette

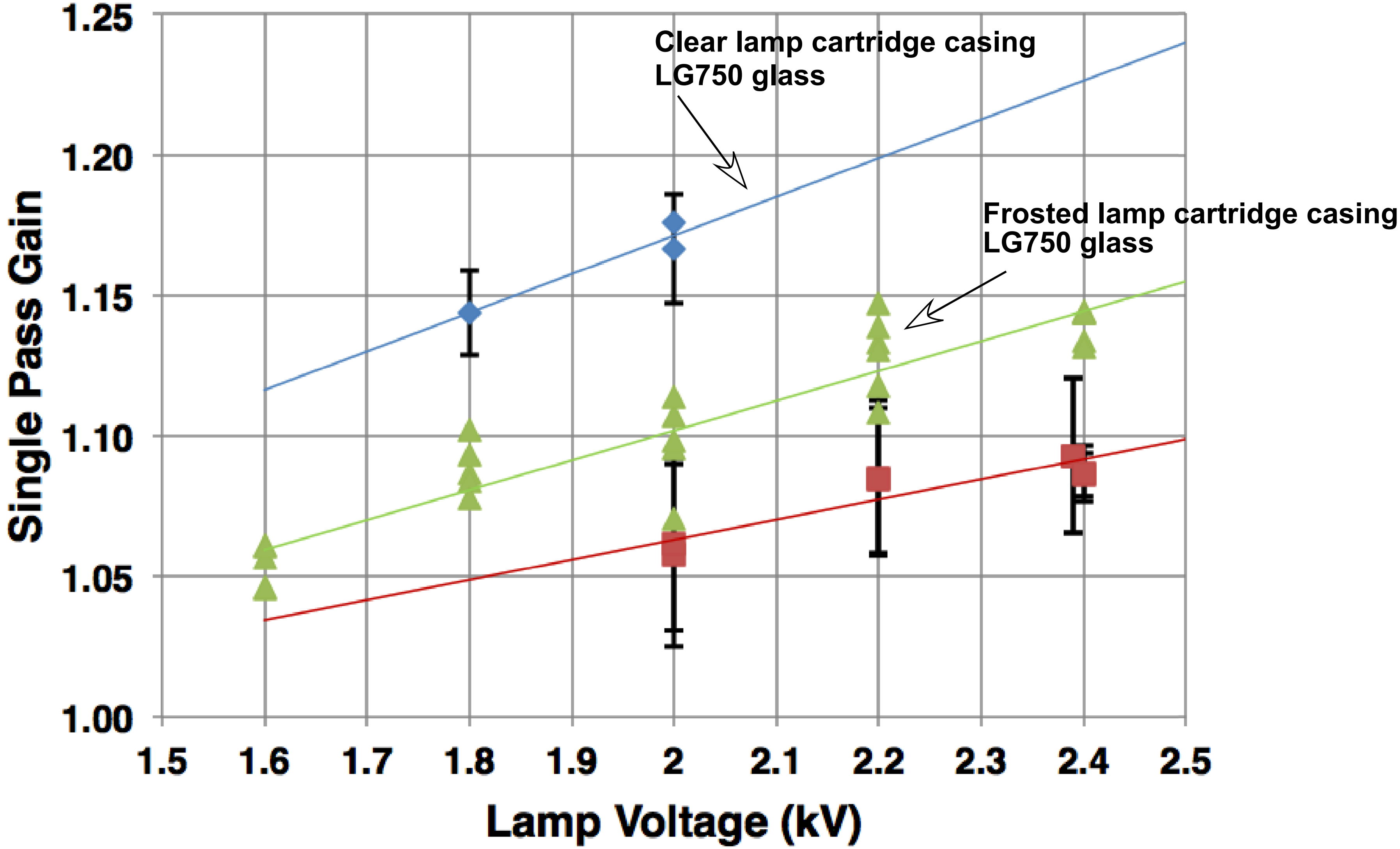


Calculated velocity flow lines

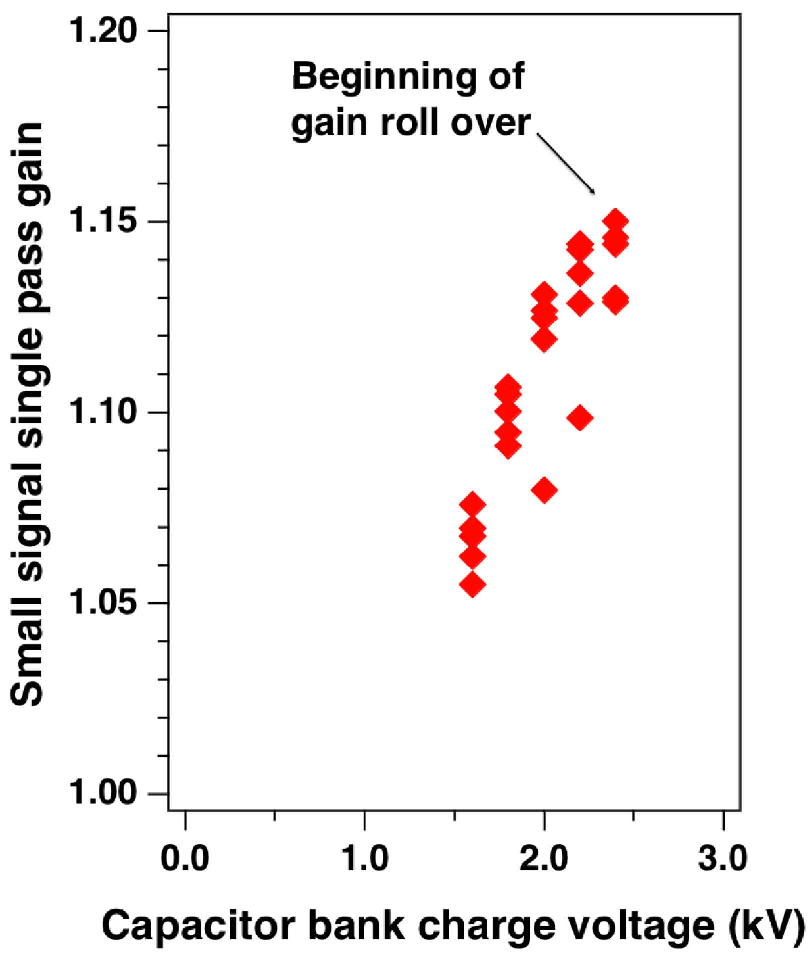
Losses at the slab-water interfaces are small

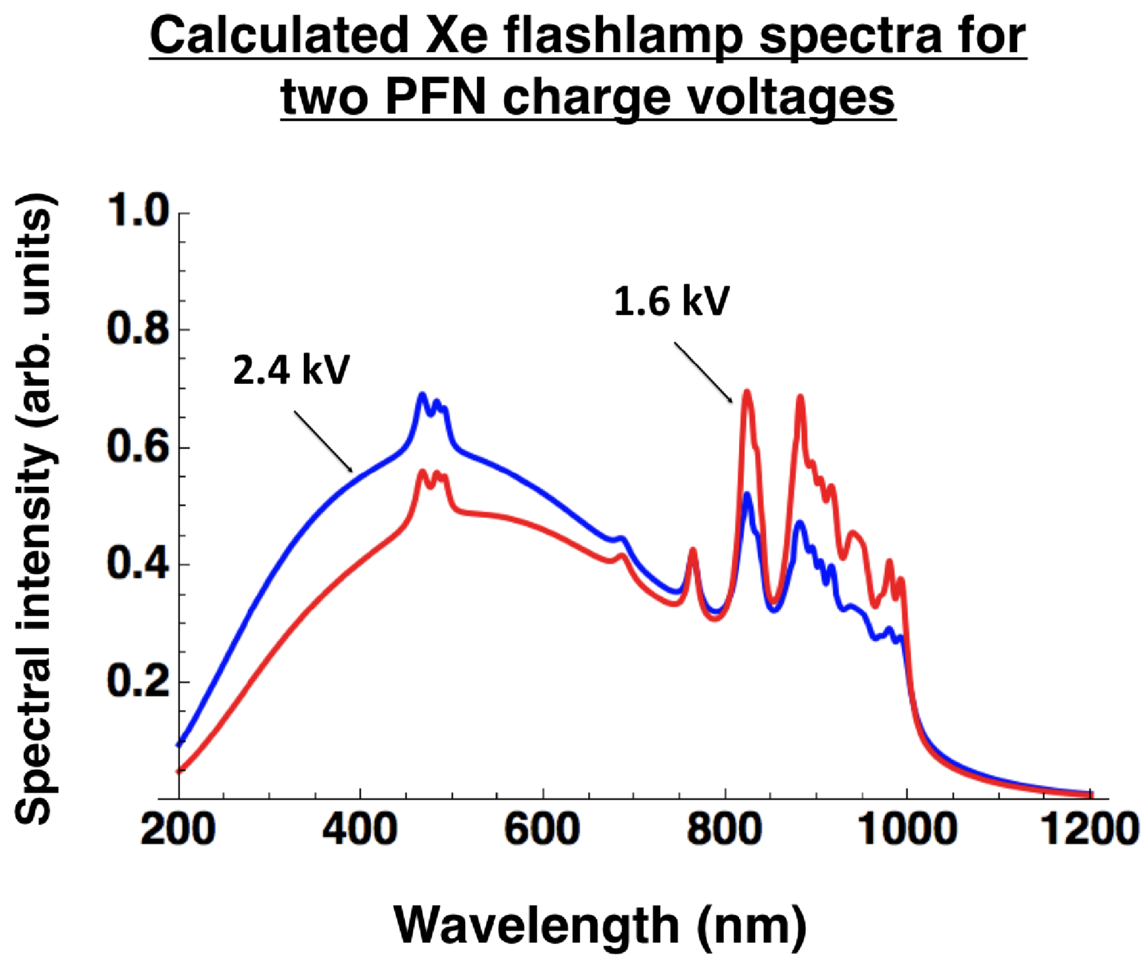


Small signal gain was measured at various points in the amplifier aperture



Flashlamp spectral blue-shifting at high discharge voltages cause a roll over in small signal gain





Use of higher gain glass than in the prototype unit will boost small signal single pass gain

NATIONAL ENERGETICS

Nd:glass used in prototype module

LG-750 Phosphate Laser Glass

For High Energy Applications

Neodymium Laser Properties	
Emission Peak, λ [nm]	1053.7
Emission Width, $\Delta\lambda_{em}$ [nm]	26.0
Radiative Lifetime τ_{Rad} [µsec]	347
Emission Cross Section σ_{em} [$10^{-20}cm^2$]	3.7
*Quenching Constant-Zero Concentration Lifetime, τ_o [µsec]	356
*Quenching Constant-Q Factor, Q [$10^{20}cm^{-3}$]	17.0

*Lifetime as a function of neodymium content is approximated by: $T=T_o/(1+(Nd/Q)^2)$, Nd=Nd concentration in 10^{20} ions/cm^3

Nd:glass to be used in production amp

LG-760 Phosphate Laser Glass

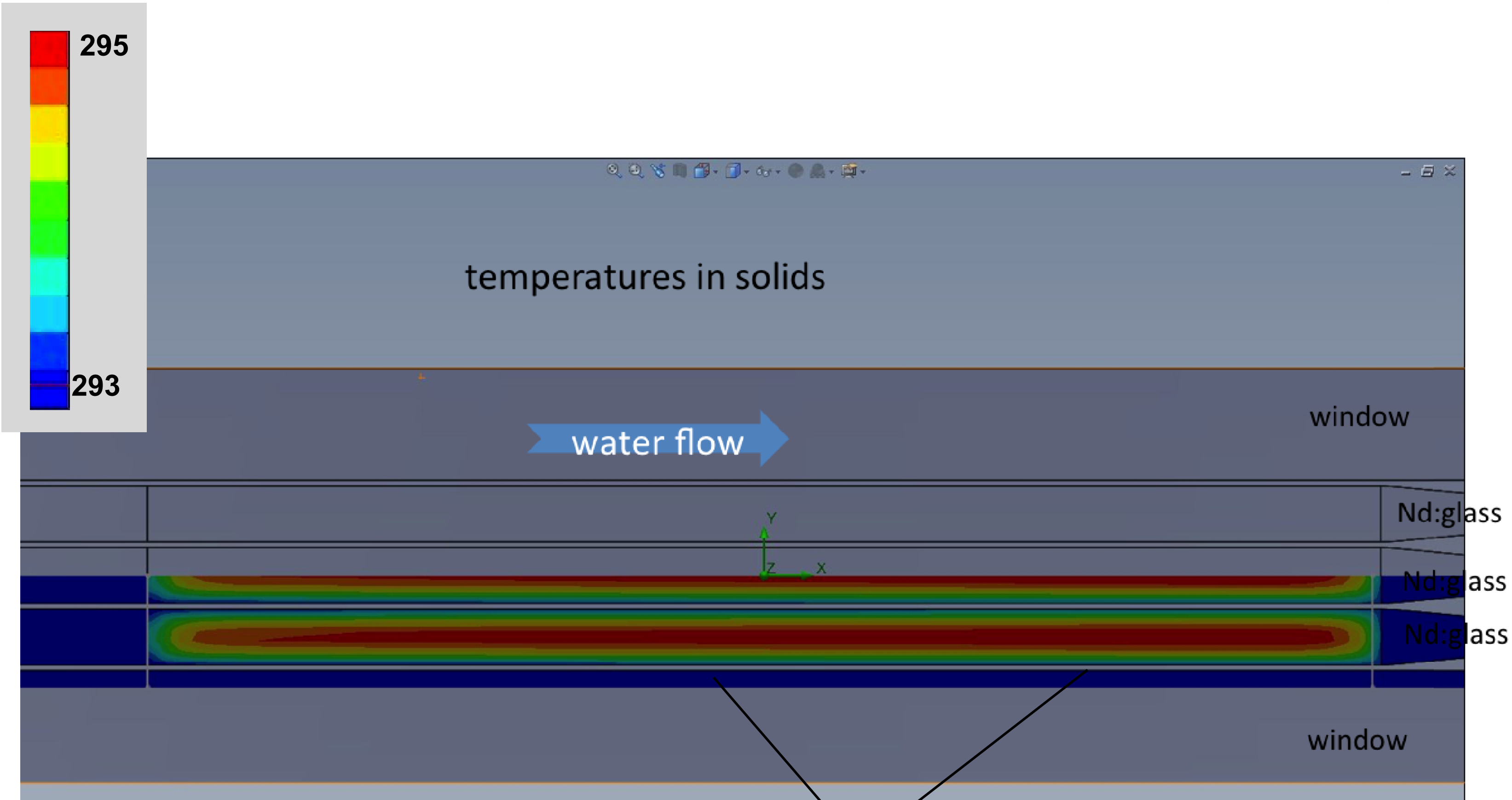
For High Energy Applications

Neodymium Laser Properties	
Emission Peak, λ [nm]	1054
Emission Width, $\Delta\lambda_{em}$ [nm]	24.3
Radiative Lifetime τ_{Rad} [µsec]	323
Emission Cross Section σ_{em} [$10^{-20}cm^2$]	4.5
*Quenching Constant-Zero Concentration Lifetime, τ_o [µsec]	330
*Quenching Constant-Q Factor, Q [$10^{20}cm^{-3}$]	10.0

*Lifetime as a function of neodymium content is approximated by: $T=T_o/(1+(Nd/Q)^2)$, Nd=Nd concentration in 10^{20} ions/cm^3

With recently demonstrated pump efficiency we will achieve gain of ≥ 1.21 per macro-slab with LG760 glass

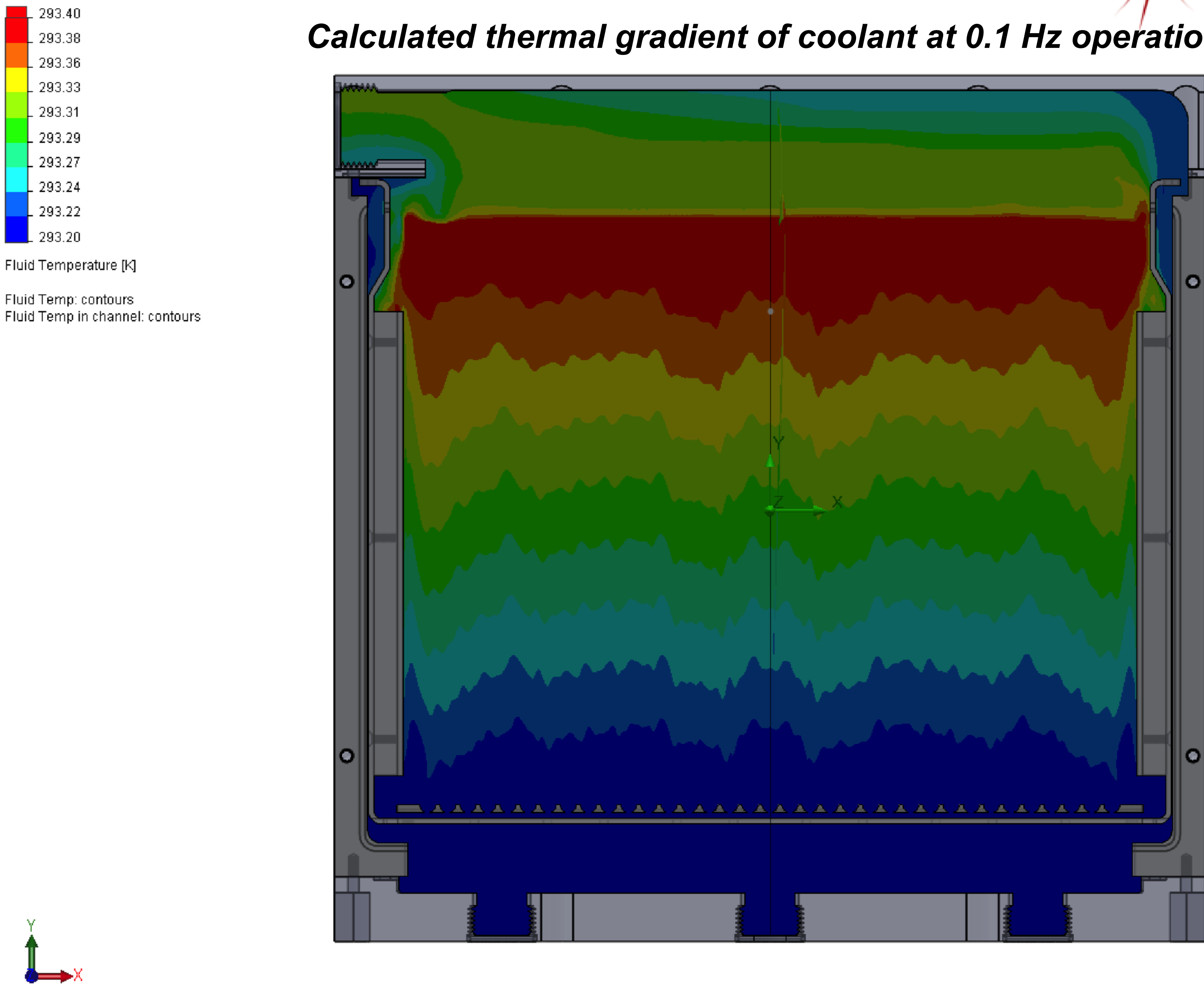
Thermal modeling shows temperature from slab center to edge to vary by ~2°



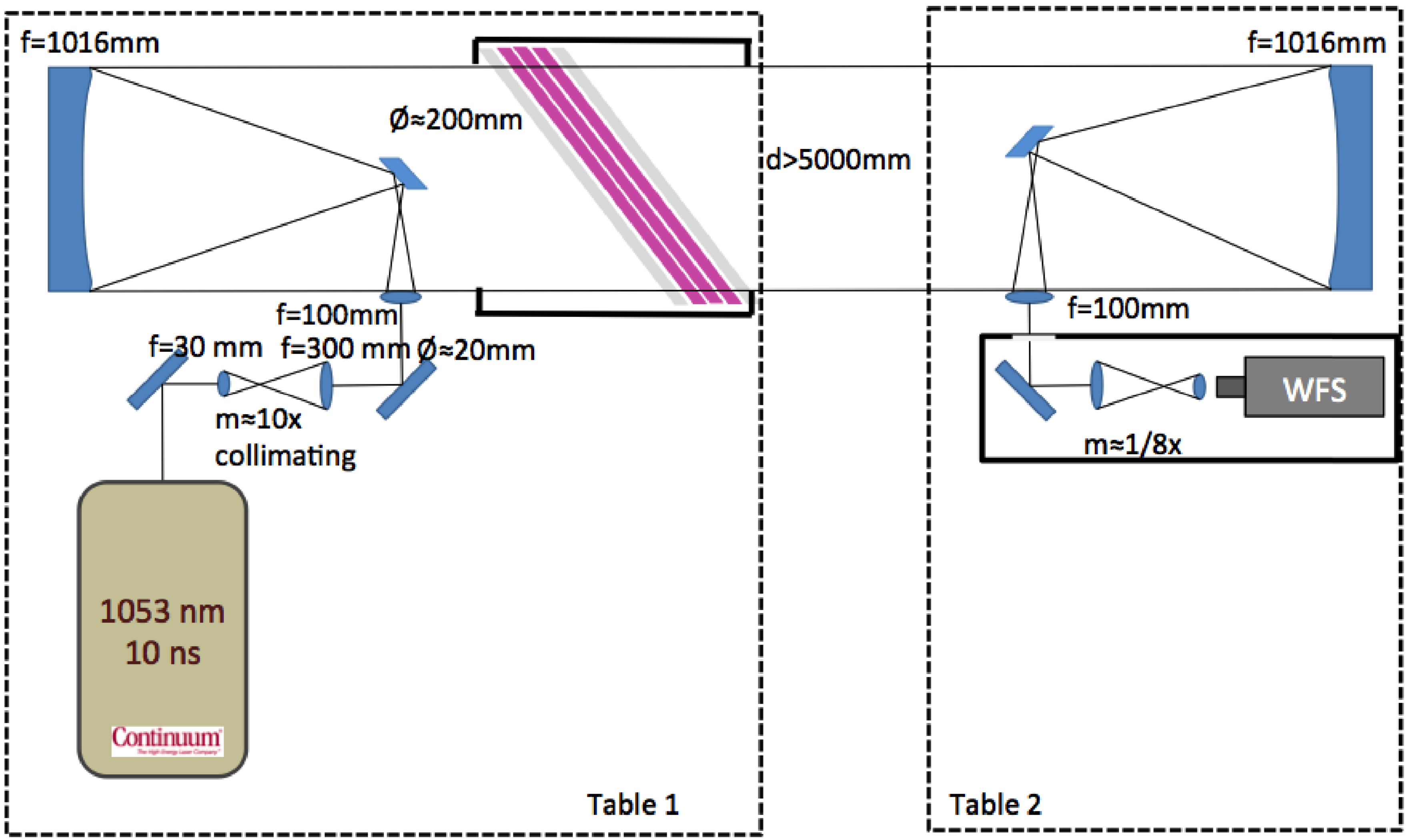
Gentle temperature gradient along slabs

Heat flow calculations predict a linear thermal variation up the slabs with less than a 1° gradient

Calculated thermal gradient of coolant at 0.1 Hz operation

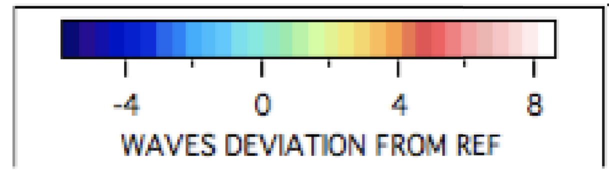


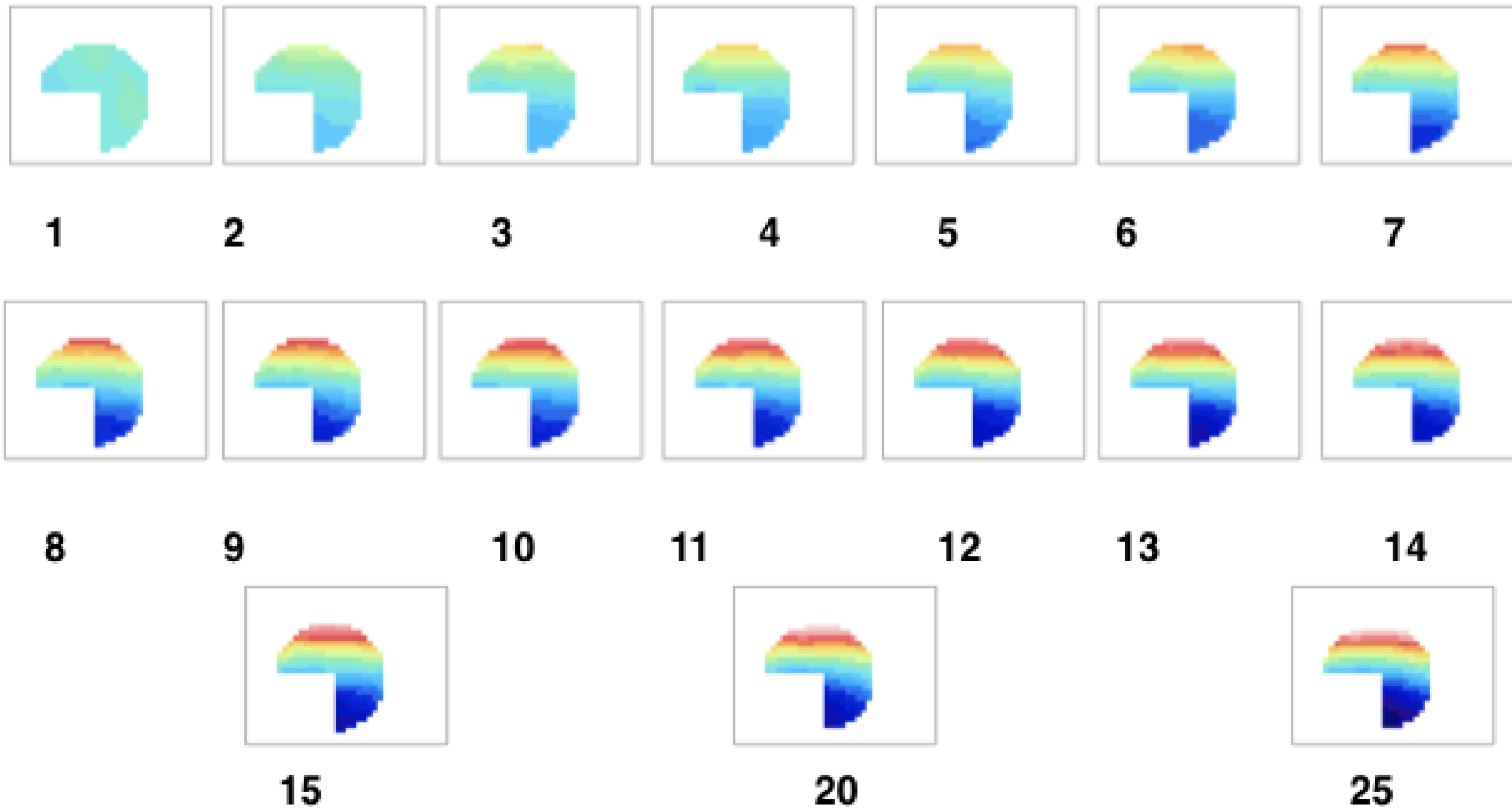
We have performed optical wavefront measurements on the pumped amplifier



We have measured beam wavefront quality through the slab while it is run at 0.07 Hz

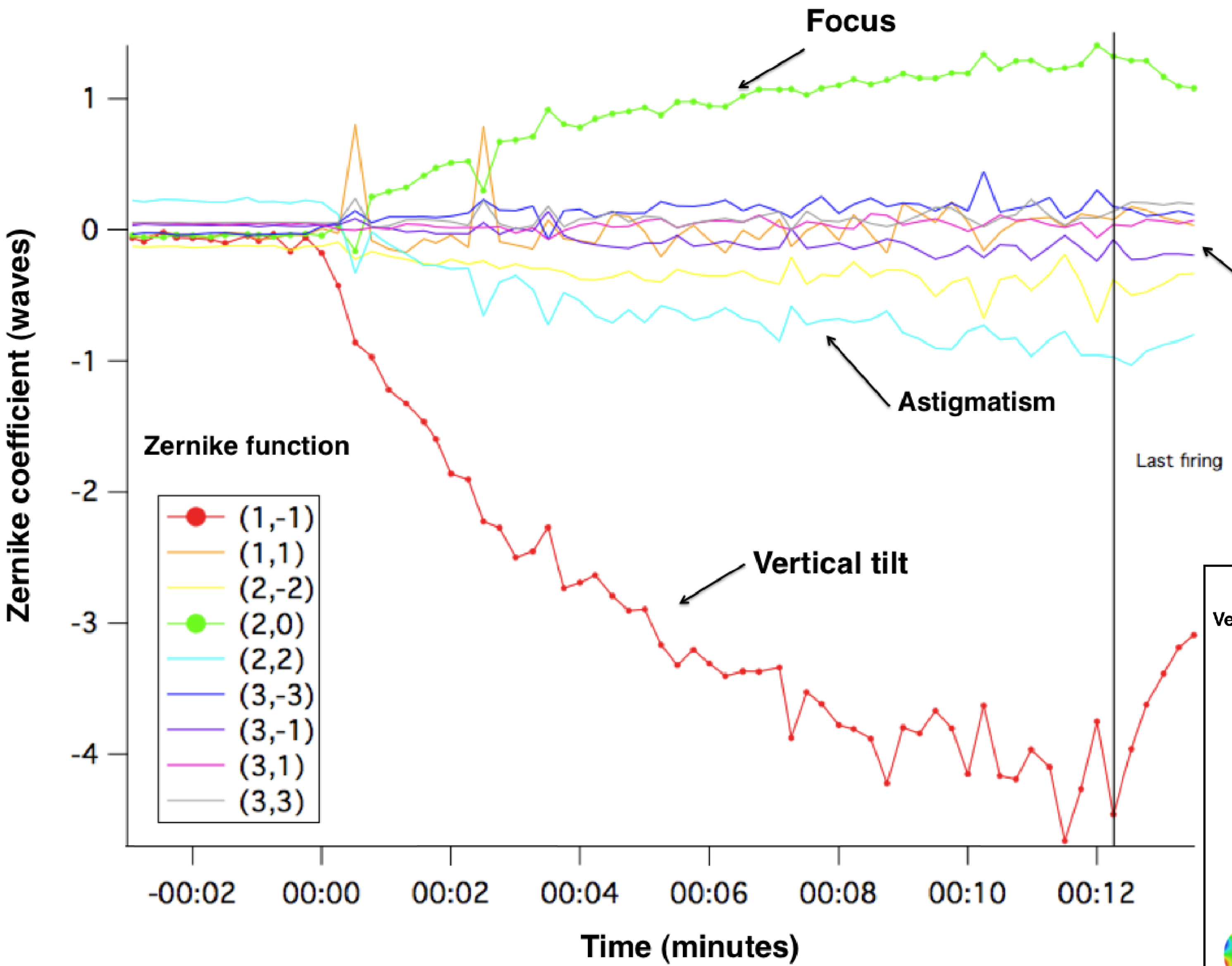
15 seconds between each shot. Reference subtracted.
All set to same (final) scale:



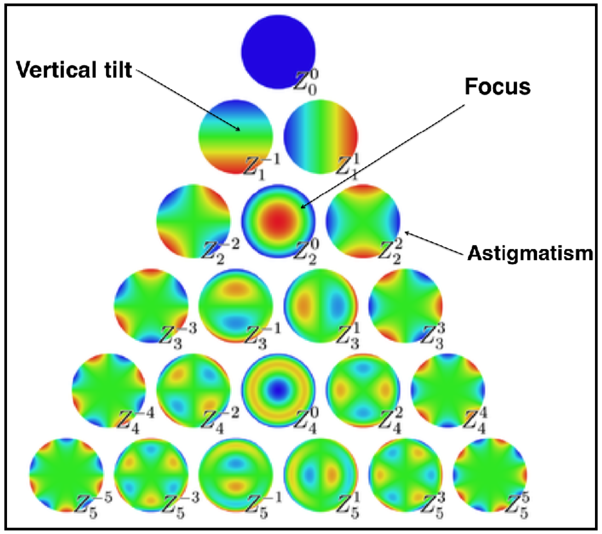


Wavefront polynomial fit indicates the wavefront distortion is <1 wave under thermal loading

Full aperture wavefront measurement at 1 shot/15 sec (0.07 Hz)



Residual phase terms less than 1 wave –
And they remain constant (so can be easily compensated with the DFM)



Small regions of the amplifier were also examined to look for small scale wavefront distortions

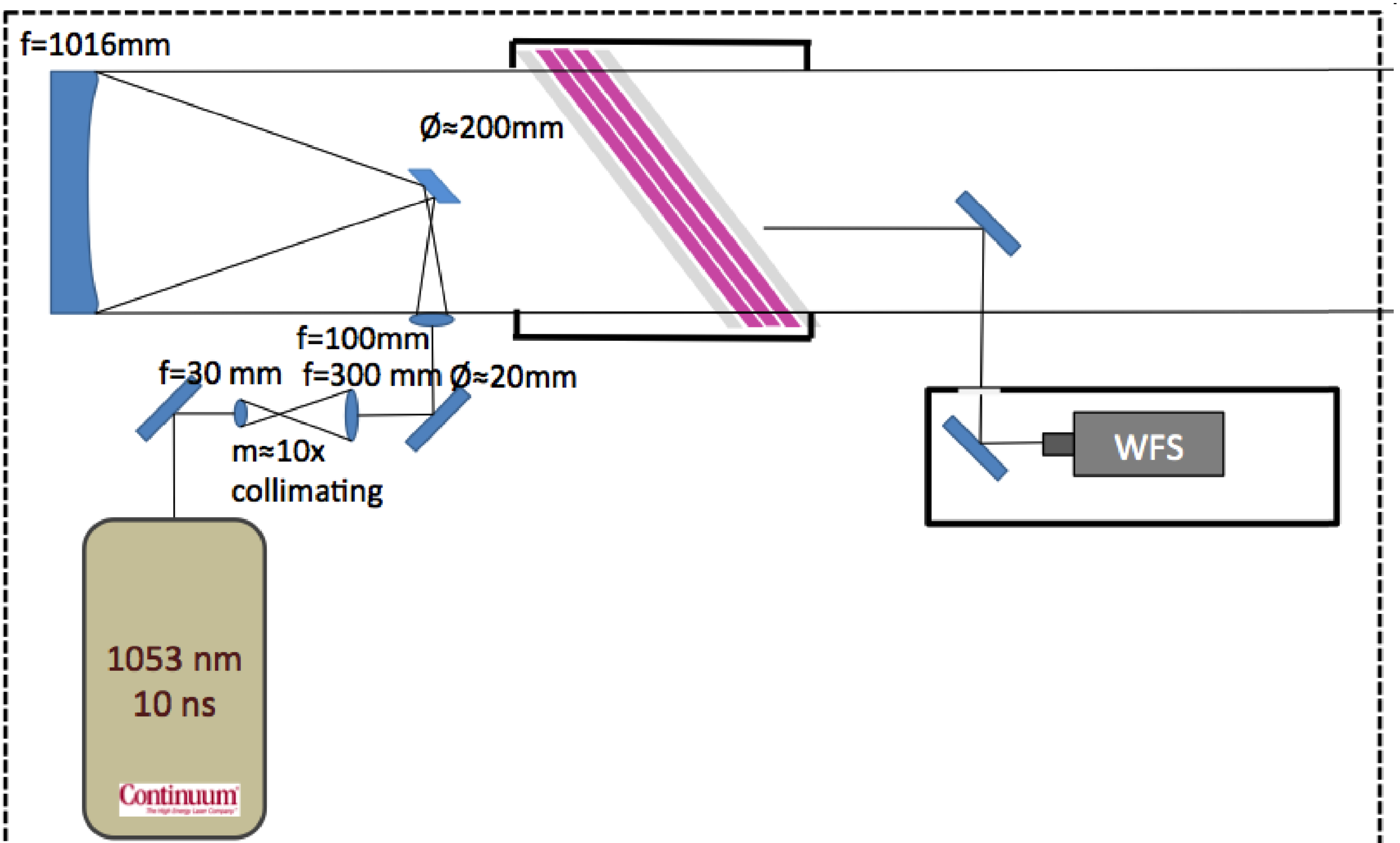
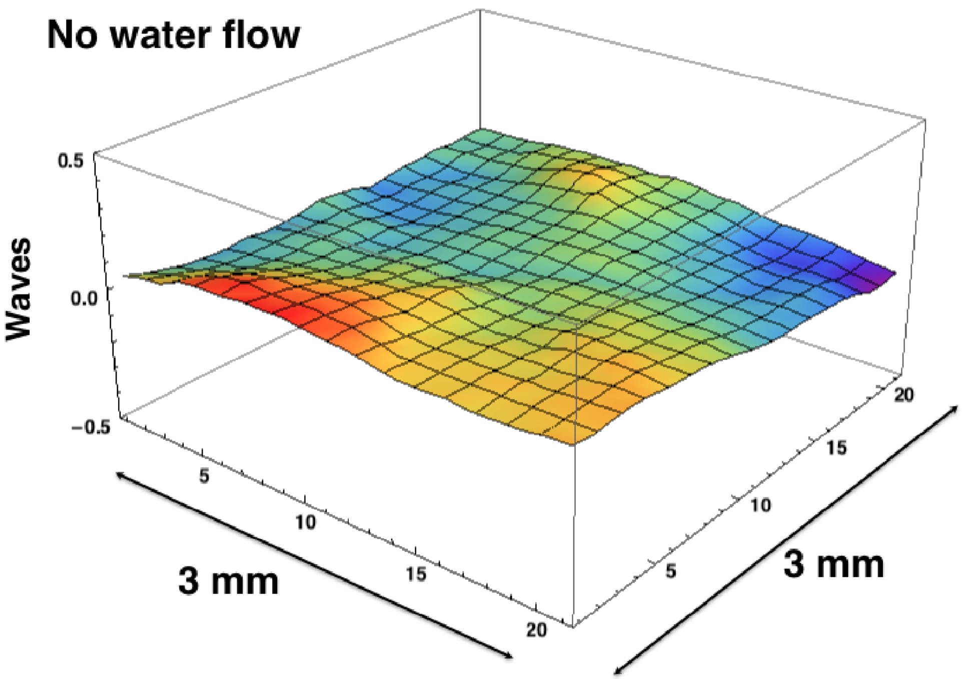
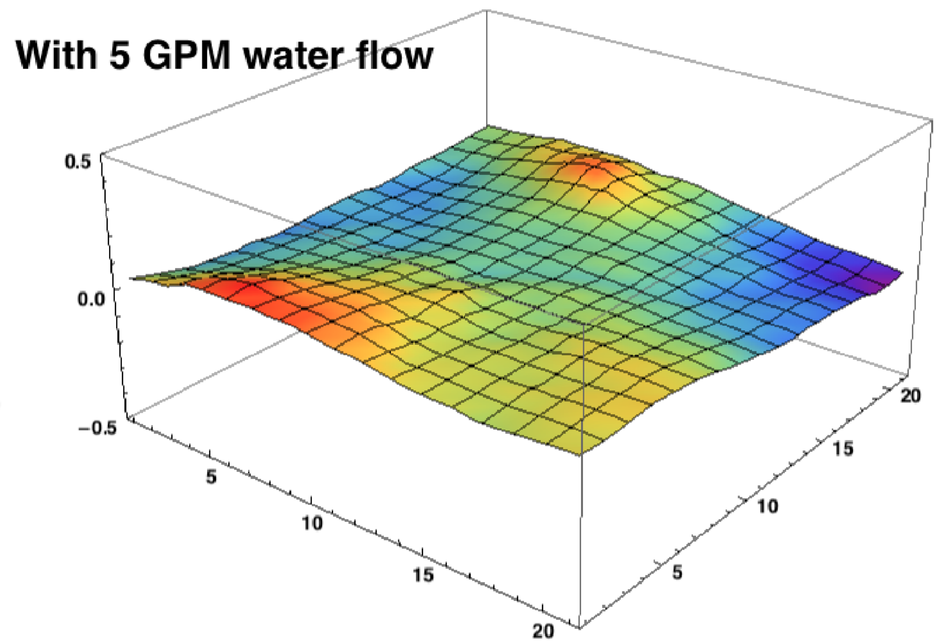
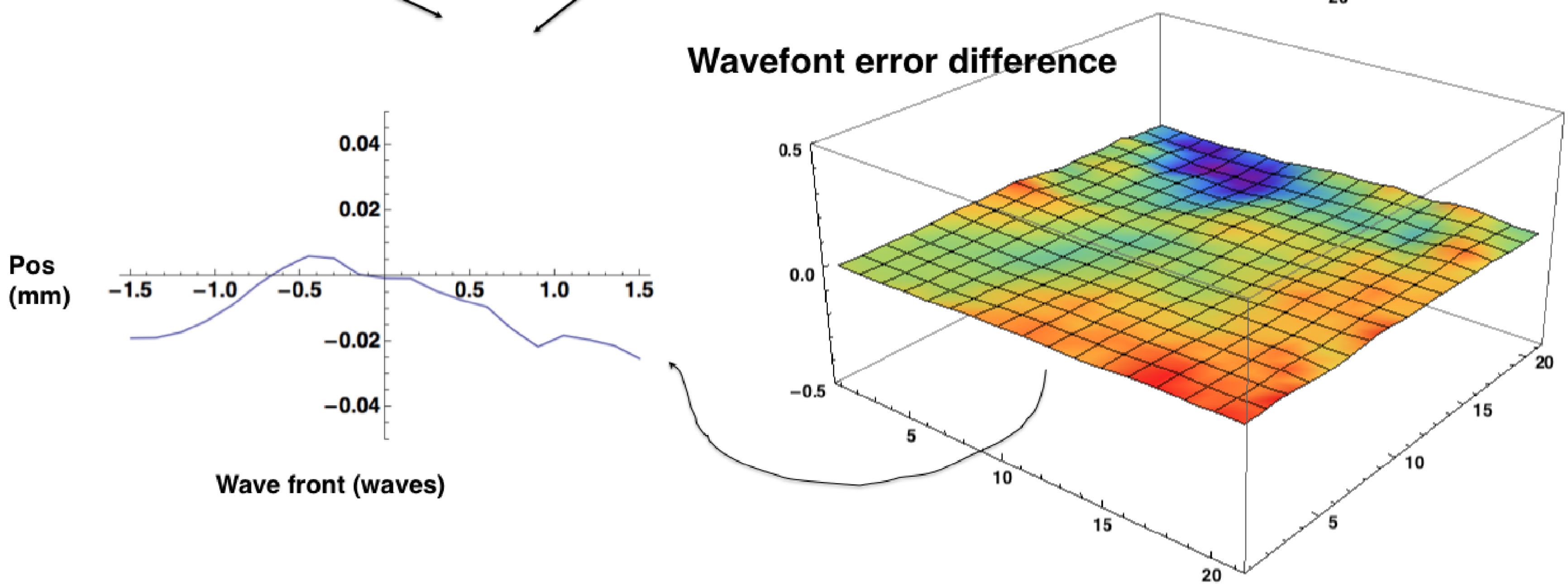


Table 1

There is no evidence of small scale wavefront distortion in the flowing water



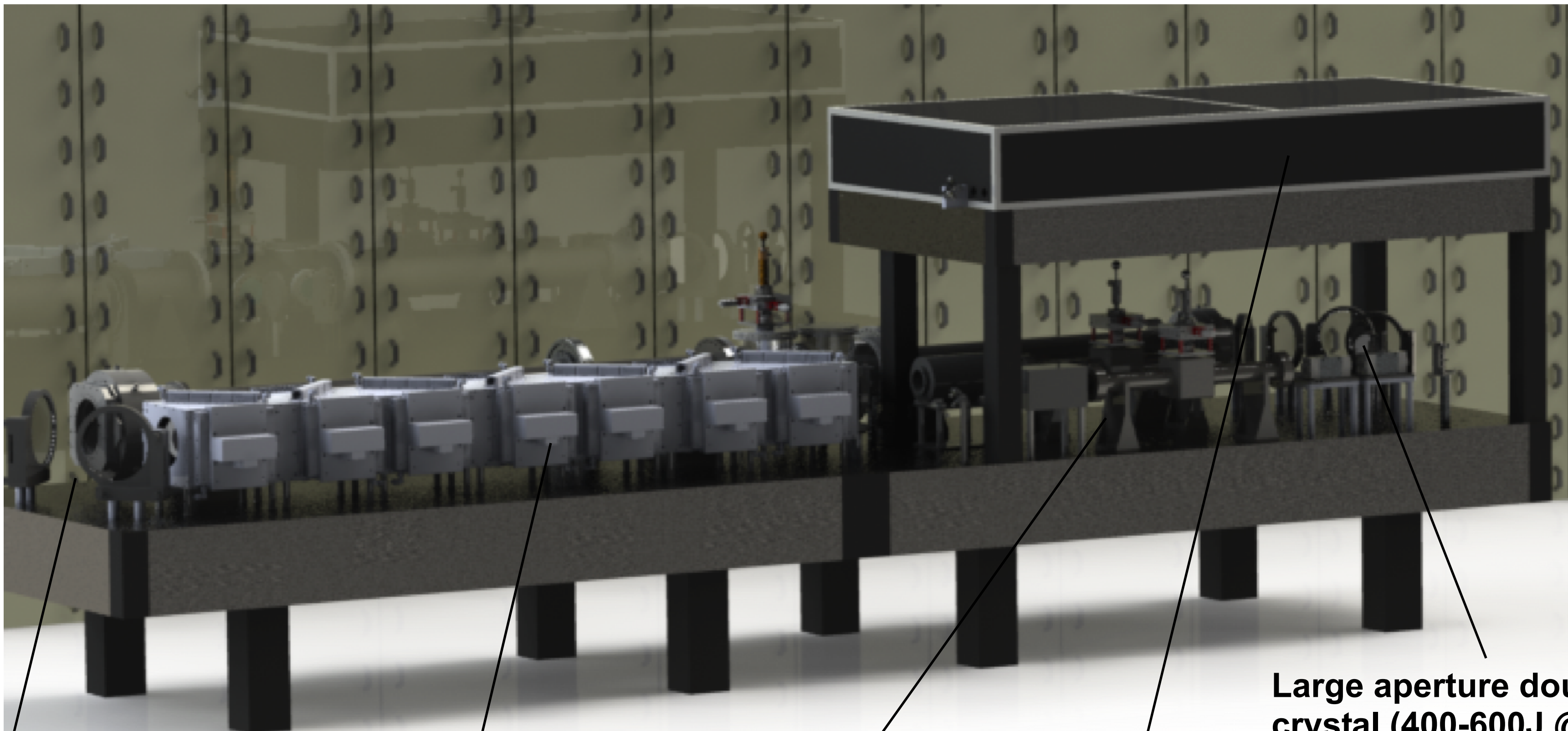




Integration of the split-disk amplifiers allows construction of compact, kJ-class lasers

NATIONAL ENERGETICS

Conceptual design for a 400 J, 527 nm Ti:sapphire pump laser operating at 0.1 Hz



Large aperture doubling crystal (400-600J @ 527 nm)

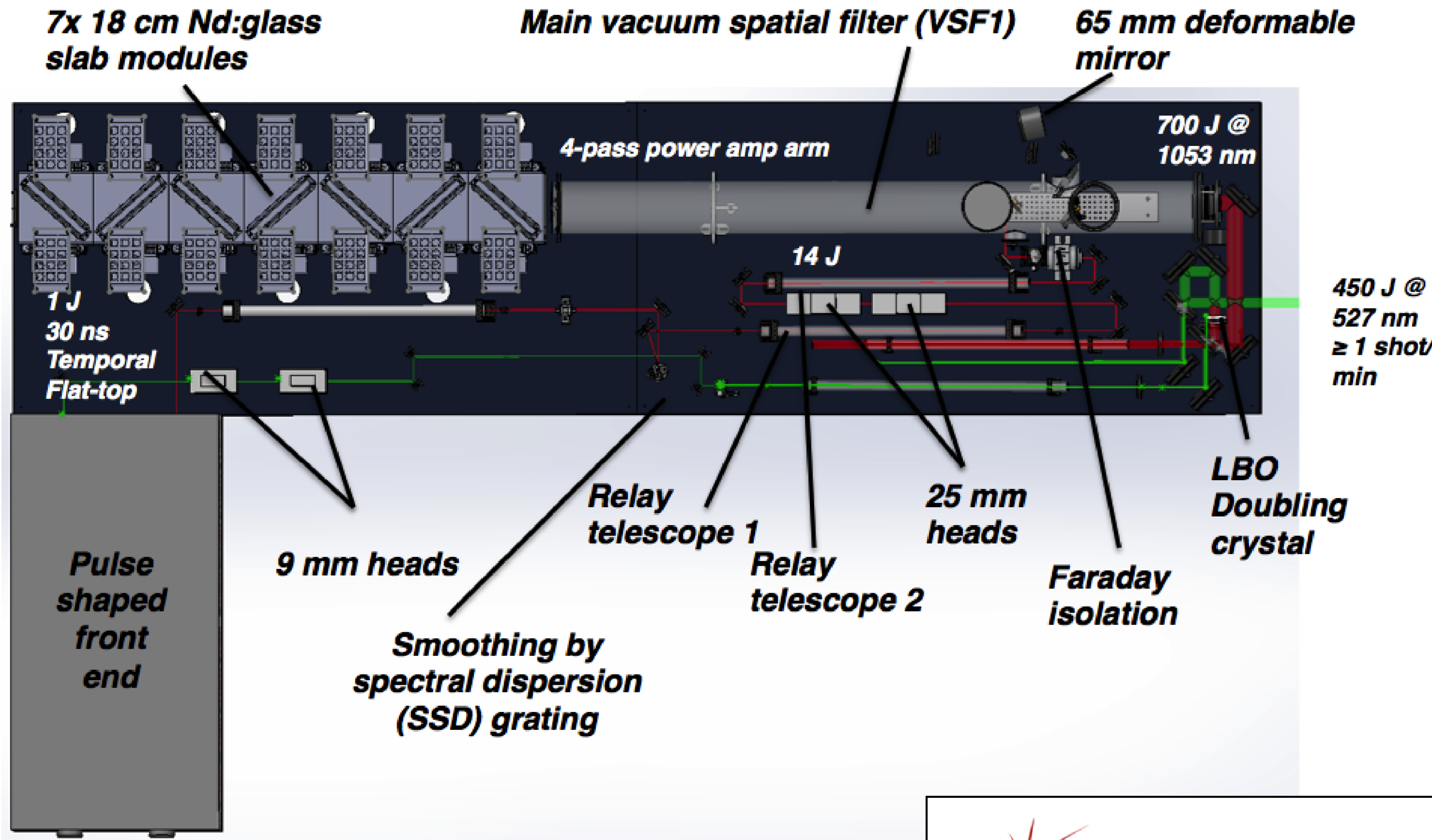
Chain of split disk amplifiers

Temporally pulse shaped front end (1 J, 10-30 ns duration, flat-top in time)

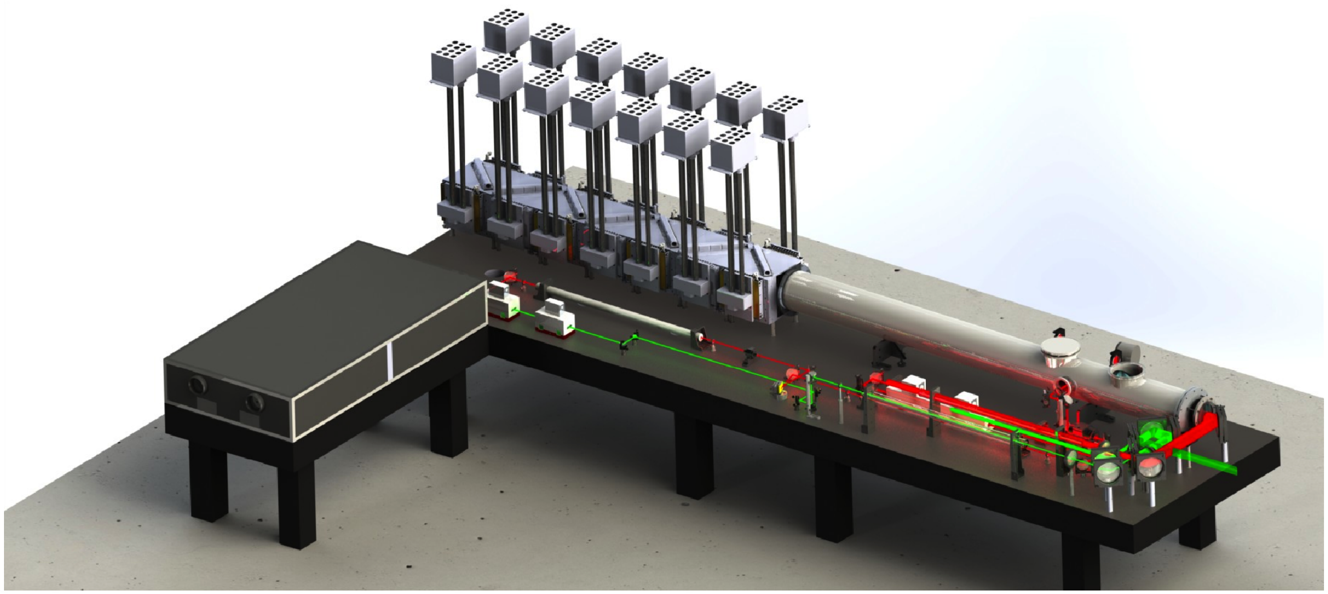
Mutli-pass relay image spatial filter (~600-900J out)

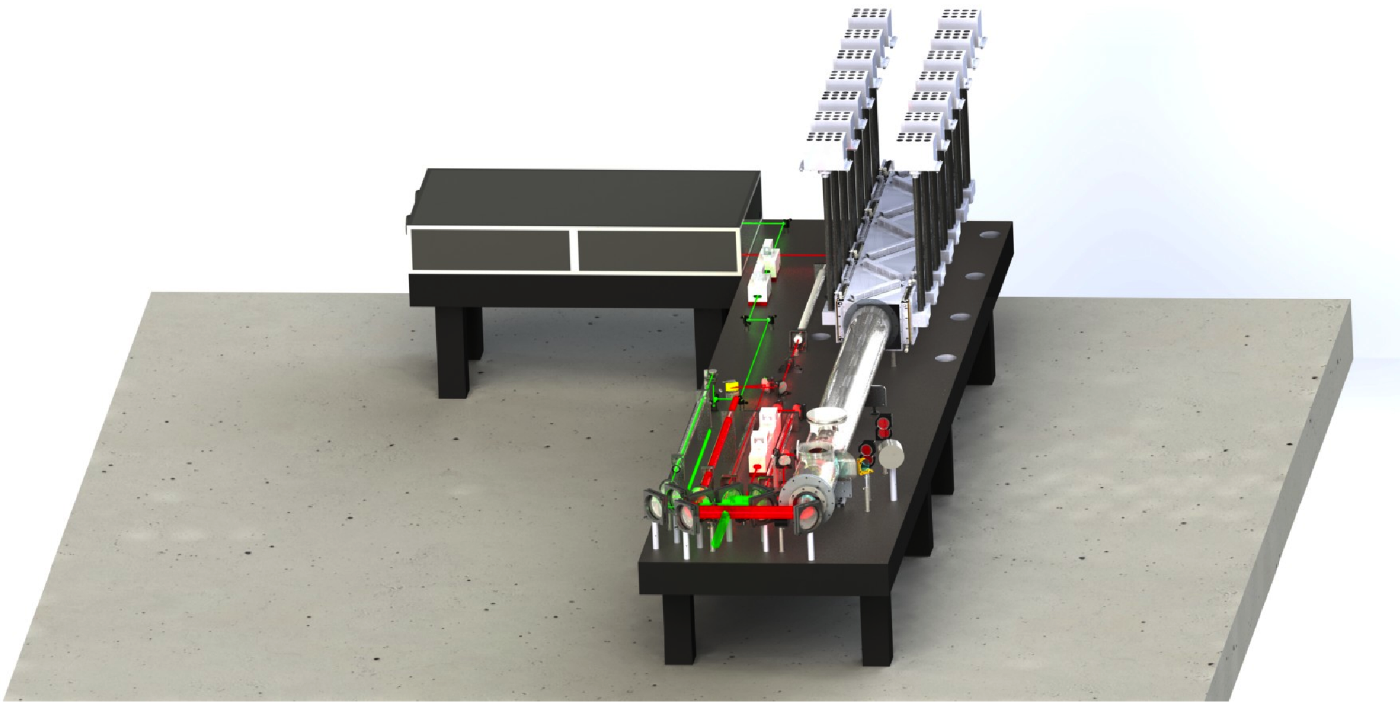
Pre-amplifier optics (~15 J, spatially shaped to flat-top, SSD optics etc.)

The Apollon 400 J 2ω pump laser is presently under construction

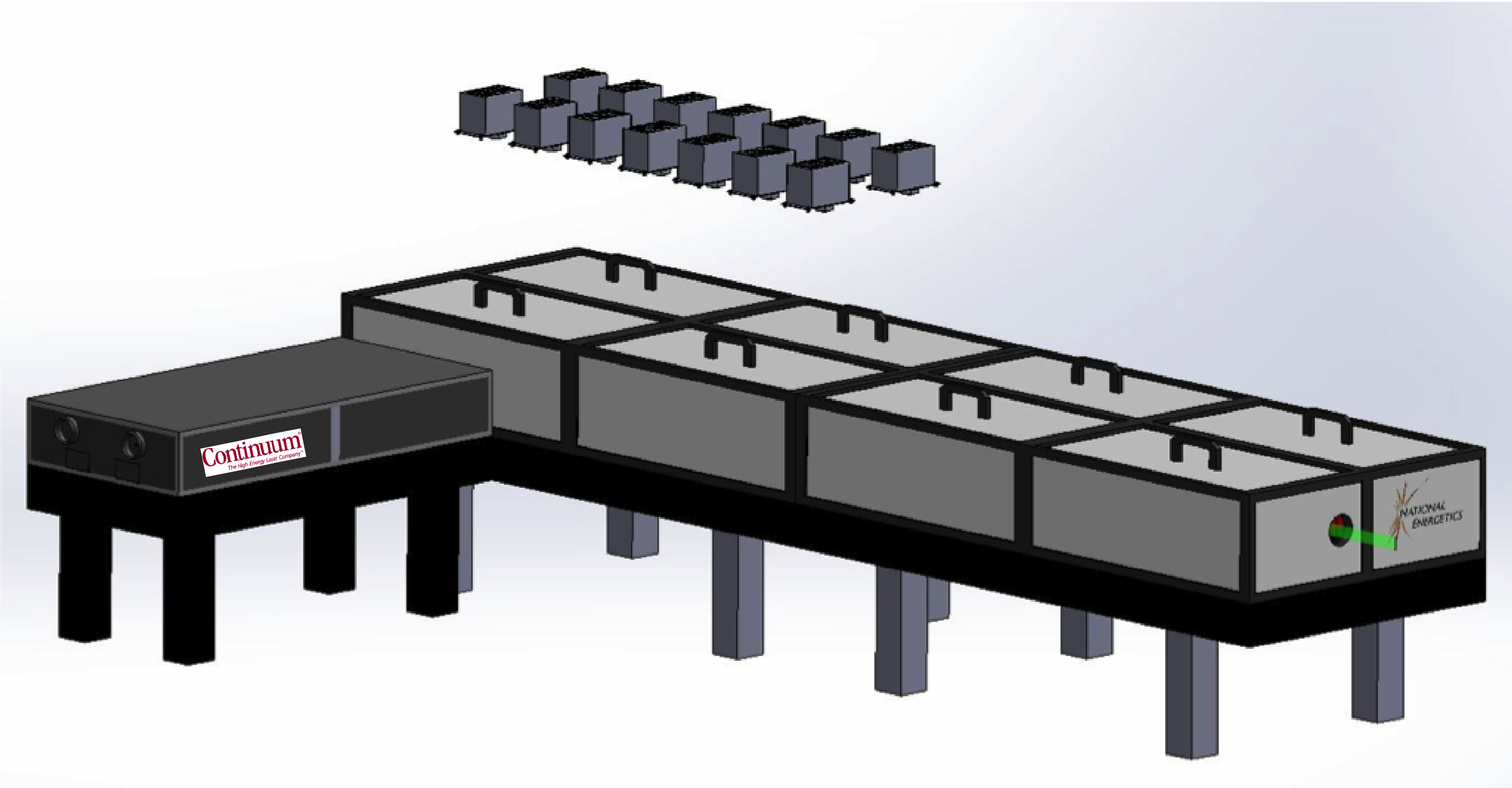


The Apollon pump laser will be a compact system delivering 400 J/527 nm pulses at > 1 shot/min



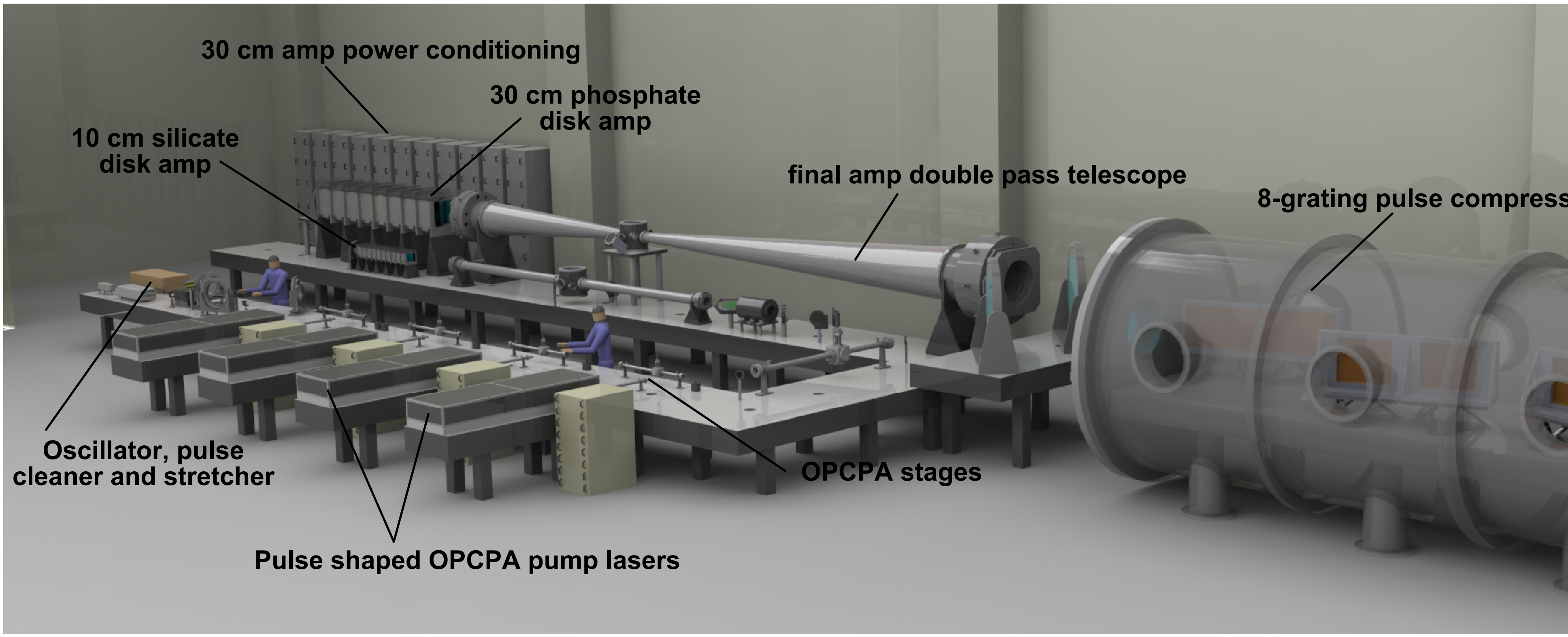


kJ-class Nd:glass lasers can now be packaged in compact forms



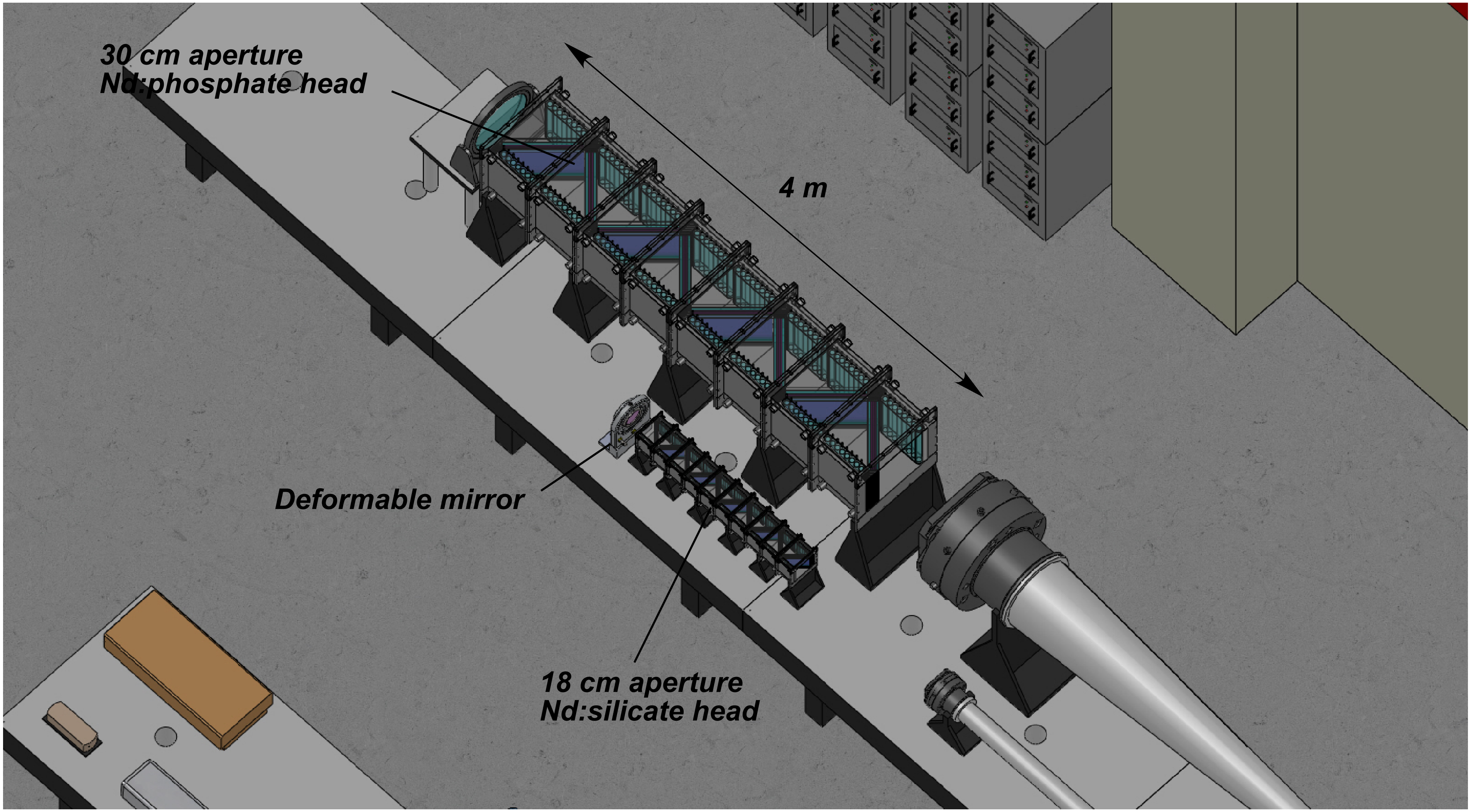
The conceptual design for the Czech ELI 10 PW laser involves Nd:glass amplifiers at 30 cm aperture

Mechanical Engineering conception of the 10 PW Hybrid Mixed glass laser



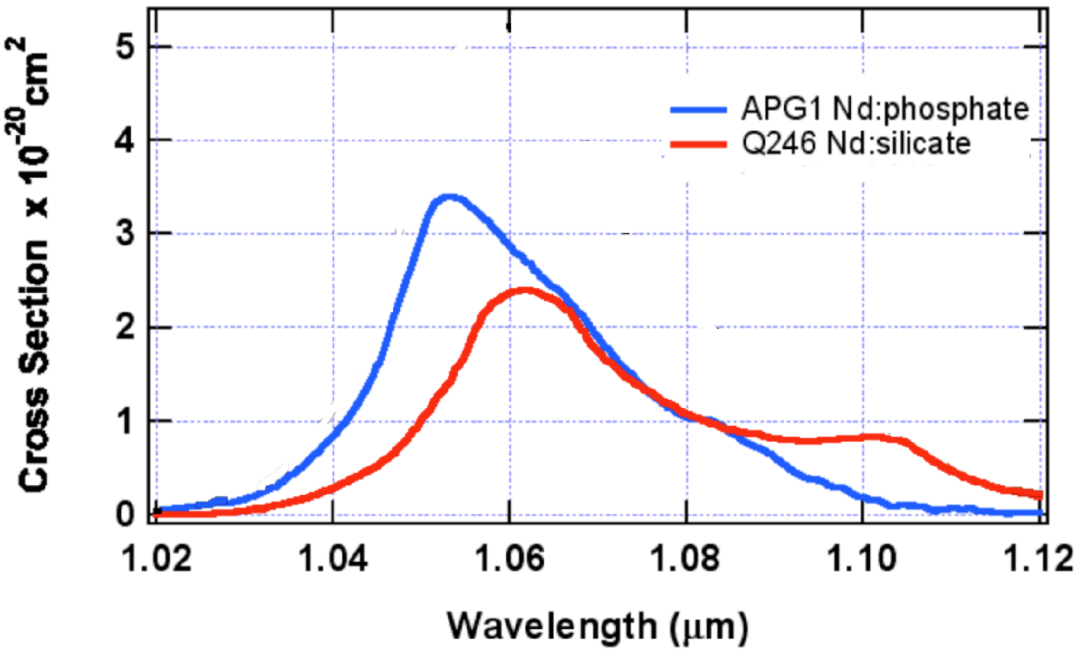
Laser output:
Energy: 1500 J,
Pulse duration: <150 fs
repetition rate: 1 shot/min
Laser Wavelength: 1054 nm
Temporal pulse contrast: 10^{10}:1 at > 10 ps

The split disk architecture can be adapted to rep-rated high energy (kJ-class) CPA lasers

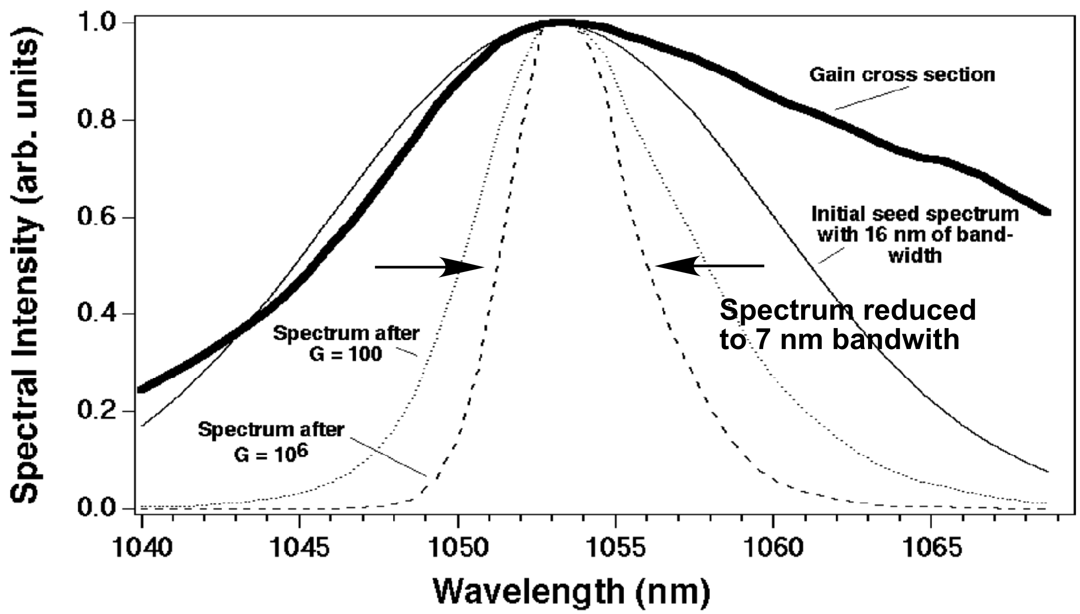


The principal limitation to the use of Nd:glass in CPA lasers is that it exhibits limited gain bandwidth

Gain spectrum of two kinds of laser glass



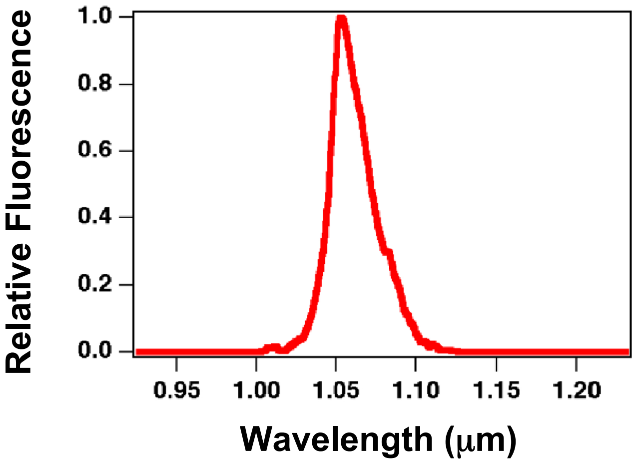
Calculation of the effects of gain narrowing in Nd:glass



Gain narrowing of the ultrafast pulse spectrum tends to limit Nd:glass CPA lasers to pulse duration of ³ 500 fs

Commonly available Nd:glass is NOT the optimum glass for broadband CPA

LG-760 Phosphate glass



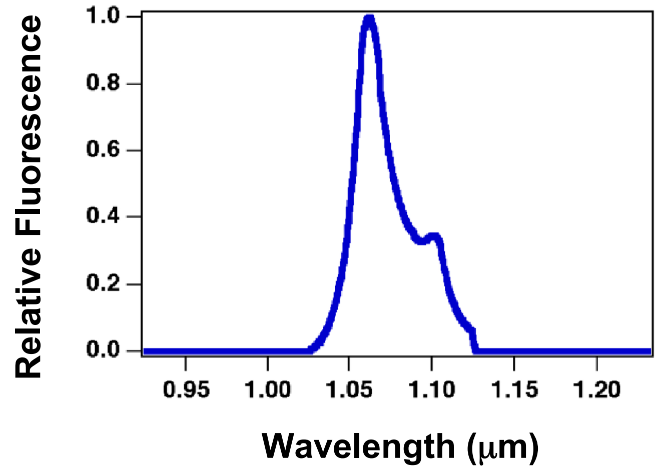
Peak Wavelength: 1054 nm

Peak cross section: 4.5 x 10^{-20} cm^2

Linewidth (FWHM): 21.1 nm

Nd_2O_3 ~3%
P_2O_5 ~ 97%

LG-680 Silicate glass



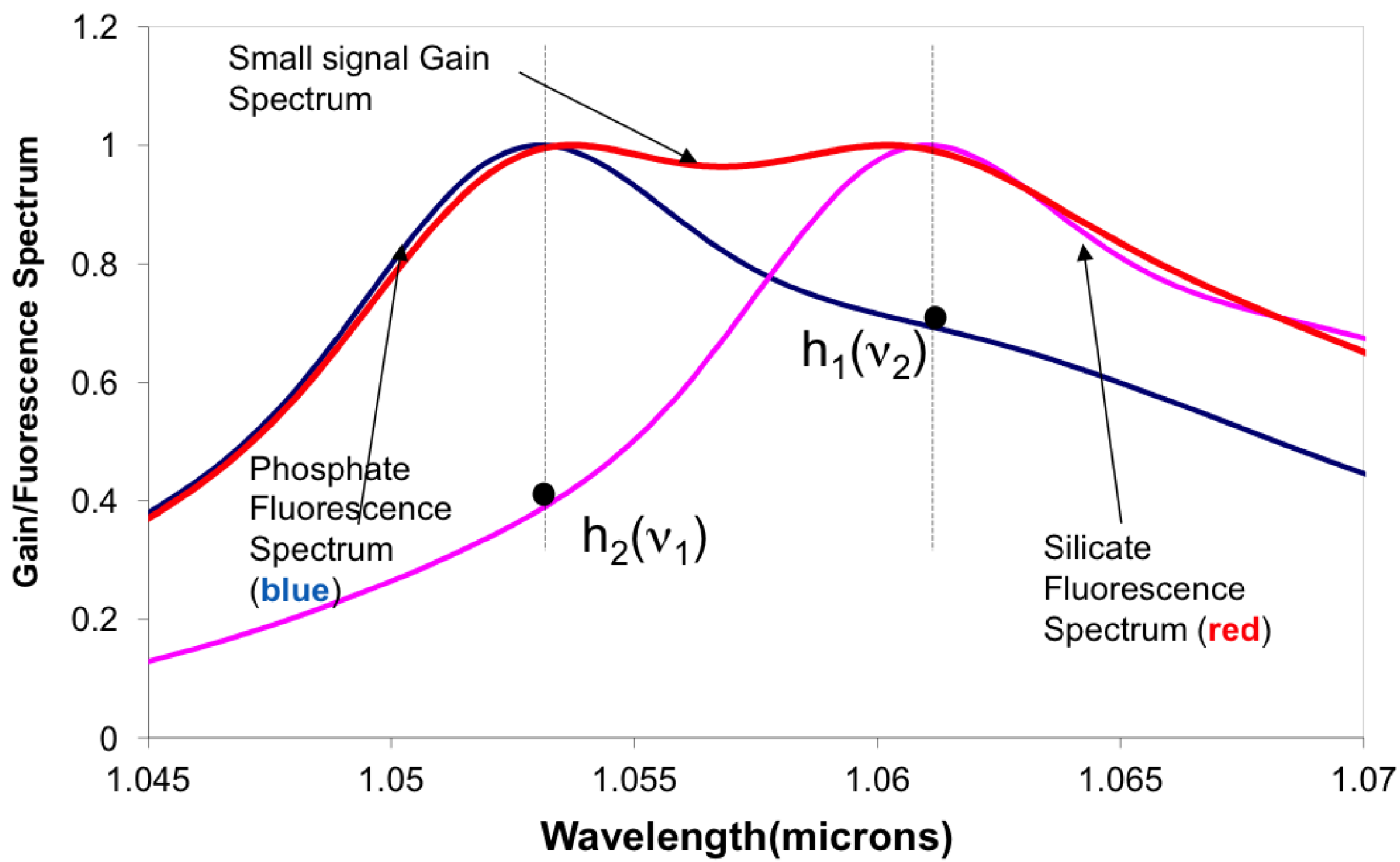
Peak Wavelength: 1060 nm

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

Linewidth (FWHM): 28.2 nm

Nd_2O_3 ~3%
SiO_2 ~ 97%

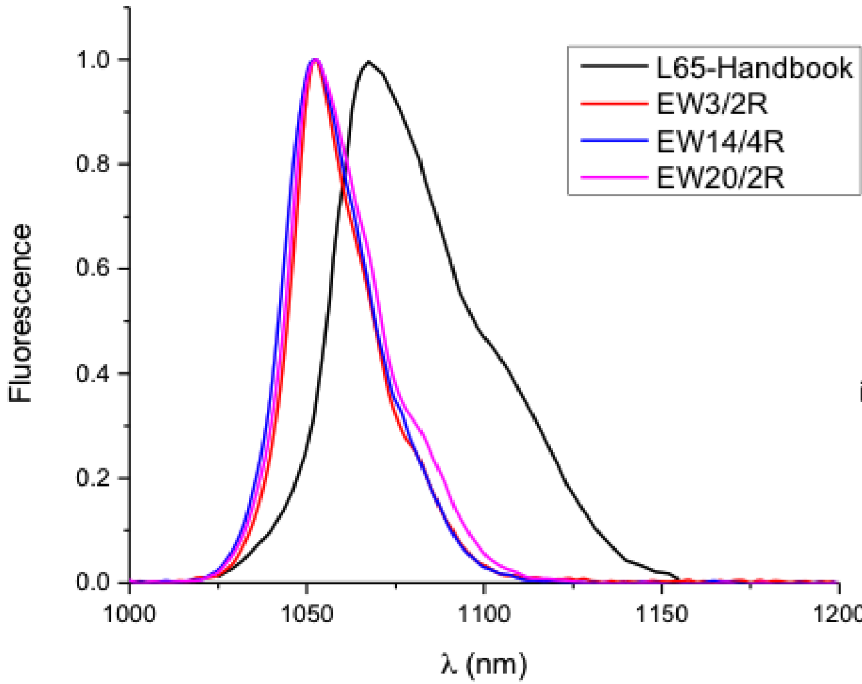
The key parameter in a mixed glass CPA laser is separation between gain peaks of the glasses

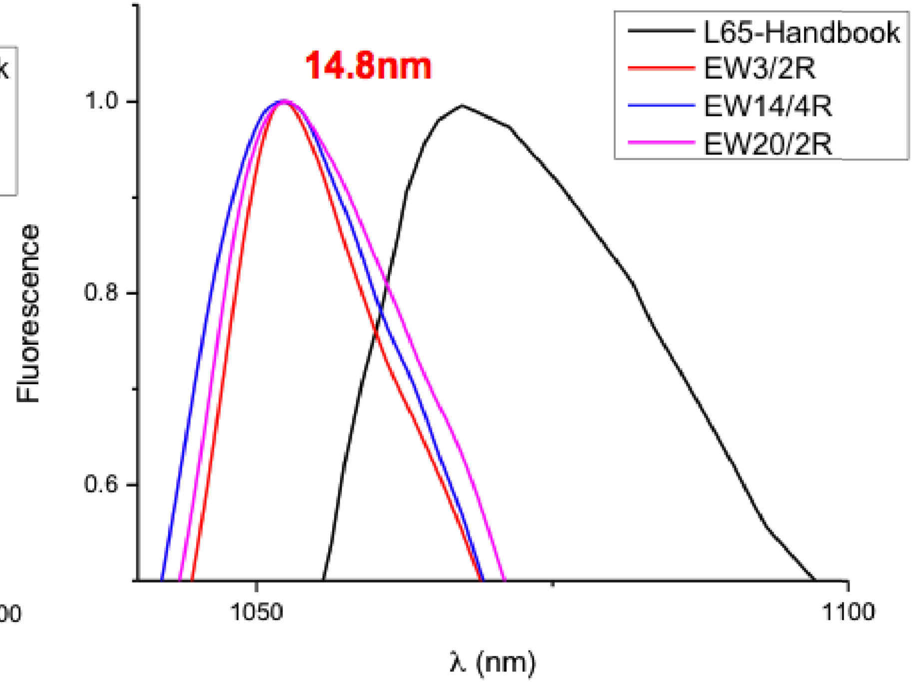


At gain ~ 10^3 - 10^4 bandwidth is typically ~ $\lambda_2 - \lambda_1$ + 8 nm

e.g. LG750 - LG680 $\Delta\lambda$ = 6 nm ⟶ 14 nm amplified BW ⟶ 130 fs pulses

Schott is developing new glasses which push the peak gain away from the 1057 nm central wavelength





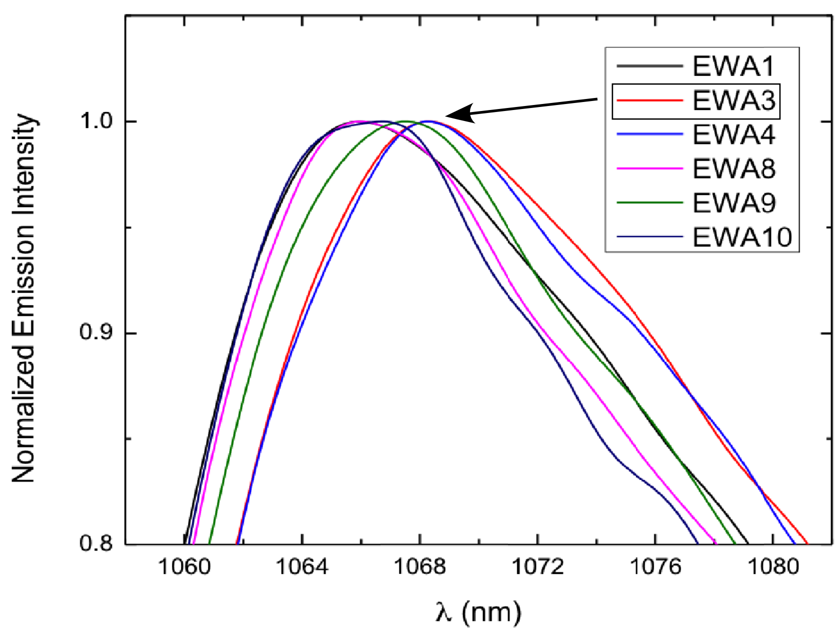
Laser Property	LG-770	LG-680	EW-20	EW-3	EW-14
Non-linear Refractive Index, n_2 [10^{-13} esu]	1.08	1.6	1.00	1.06	1.14
Peak Emission Wavelength, λ_{Peak} [nm]	1053.7	1059.7	1052.5	1052.25	1052.24
Effective Emission Bandwidth, $\Delta\lambda_{eff}$ [nm]	26.0	36.1	32.4	28.42	31.23
Maximum Emission Cross Section, σ_{em} [cm^2]	3.7	2.54	2.4	3.55	3.22
Radiative Lifetime, t_{Rad} (msec)	356	361	453.9	344.8	338.8

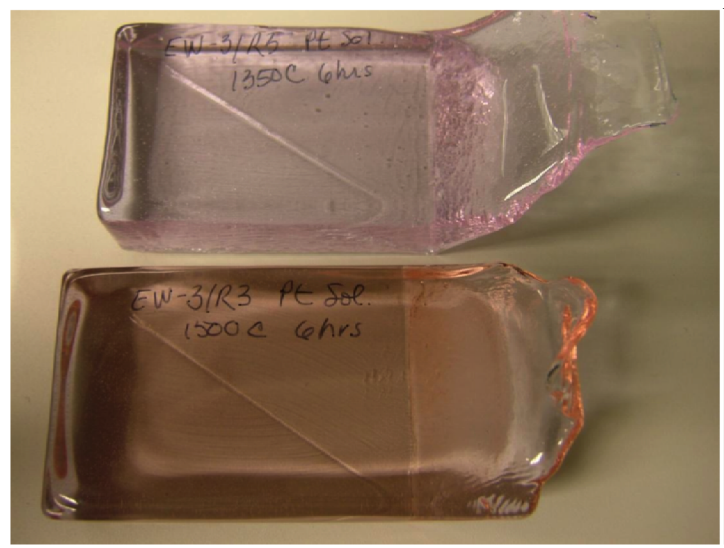
SCHOTT
glass made of ideas

Viewgraph courtesy of Simi George, Schott North America

Schott is developing new glasses on both the red and blue side of the spectrum near 1057 nm

	LG680	APG-1	L-65	EW-3
	Silicate	Phosphate	Aluminate	Phosphate
Active Ion(s)	Nd	Nd	Nd	Nd
Diode or Flashlamp pumped	Both	Both	Diode?	Both
Target Rep-rate?	Few Hz	Few Hz	1/ min-1/30min	1/ min-1/30min
Platinum-free?	No	Yes	???	Yes
Laser Properties				
Peak Emission Wavelength, l_{Peak} [nm]	1059.7	1053.9	1068.8	1052.2
Effective Emission Bandwidth, Dl_{eff} [nm]	35.9	27.8	47.5	28.4
Maximum Emission Cross Section, s_{em} [10^{-20}cm^2]	2.54	3.4	2.0	3.6
Saturation Fluence J/cm2			<4	<10
Radiative Lifetime, t_{Rad} [µsec]	361	361	304	345





Viewgraph courtesy of Simi George, Schott North America

New glasses from Schott may also have superior thermal properties for high rep-rate CPA lasers

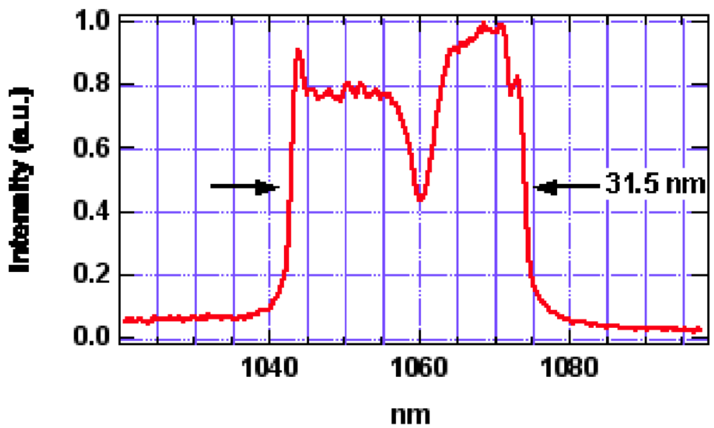
NATIONAL ENERGETICS

ID:	APG-1	LG760	LG770	EW3	EW14	EW20
Comment	Commercial	Commercial	Commercial	Develop	Develop	Develop
Optical/Thermal/Physical Property						
Refractive Index, n_d	1.53700	1.51900	1.50860	1.52843	1.53530	1.51055
Abbe Number, V_d	67.7	69.20	68.4	69.18	66.92	69.48
Density, r [g/cm^3]	2.633	2.600	2.585	2.592	2.661	2.541
Indentation Fracture Toughness for 3.0N Load, K_{IC}	0.78	0.47	0.48	na	na	na
Indentation Fracture Toughness for 9.8N Load, K_{IC}	0.91	na	na	na	0.946	0.96
Thermal Conductivity @ 25C, K_{25C} [W/mK]	0.78	0.57	0.57	na	0.8544	0.9471
Thermal Conductivity @ 90C, K_{90C} [W/mK]	0.83	0.60	0.63	na	0.8969	1.0037
Poisson Ratio, n	0.24	0.267	0.25	na	0.22	0.24
Young's Modulus, E [GPa]	70	53.70	47.29	na	75.43	77.84
Linear Coef. of Thermal Expansion, $a_{20\text{-}300C}$ [10^{-7}/K]	99.6	150.4	133.6	73.3	72.9	51.8
Linear Coef. of Thermal Expansion, $a_{20\text{-}40C}$ [10^{-7}/K]	76	na	116.1	na	na	na
Softening Point, T_{sp} [C]	na	na	na	na	na	na
Glass Transition Temperature, T_g [C]	450	350	461	577	580	>700
Knoop Hardness, HK	450	340	330	na	491.0	470.4
$a_{3.333mm}$ [cm^{-1}] (A measure of residual OH content)	na	na	0.8	0.698	1.543	0.695
$a_{3.0mm}$ [cm^{-1}] (A measure of residual OH content)	na	na	2	1.413	4.405	0.531
FOM_{TM}	**8.3**	**2.6**	**3.6**	**na**	**12.0**	**18.2**

SCHOTT
glass made of ideas

We have performed simulations of high energy CPA lasers based on these new glasses

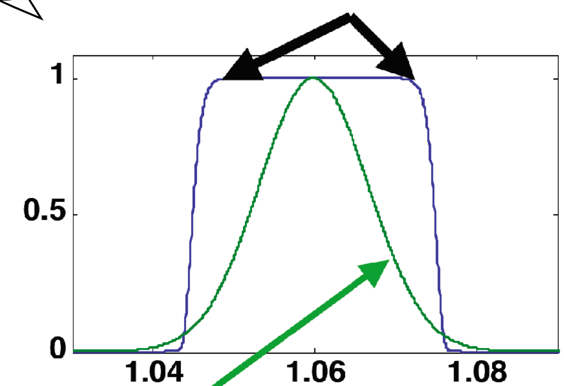
Assume a broad seed spectrum from an OPCPA front end



Seed is modeled as super Gaussian with 31 nm of bandwidth

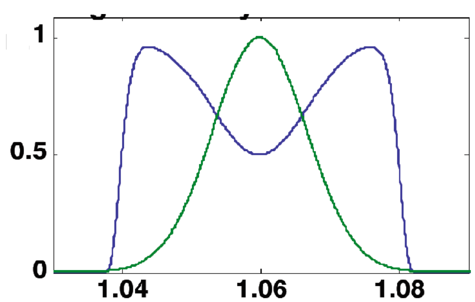
Simulation uses Gaussian and 30 nm SuperGaussian

Add much more energy in the spectral wings



100fs/ 16nm oscillator is commercially available

Spectral pre-shaping is also considered

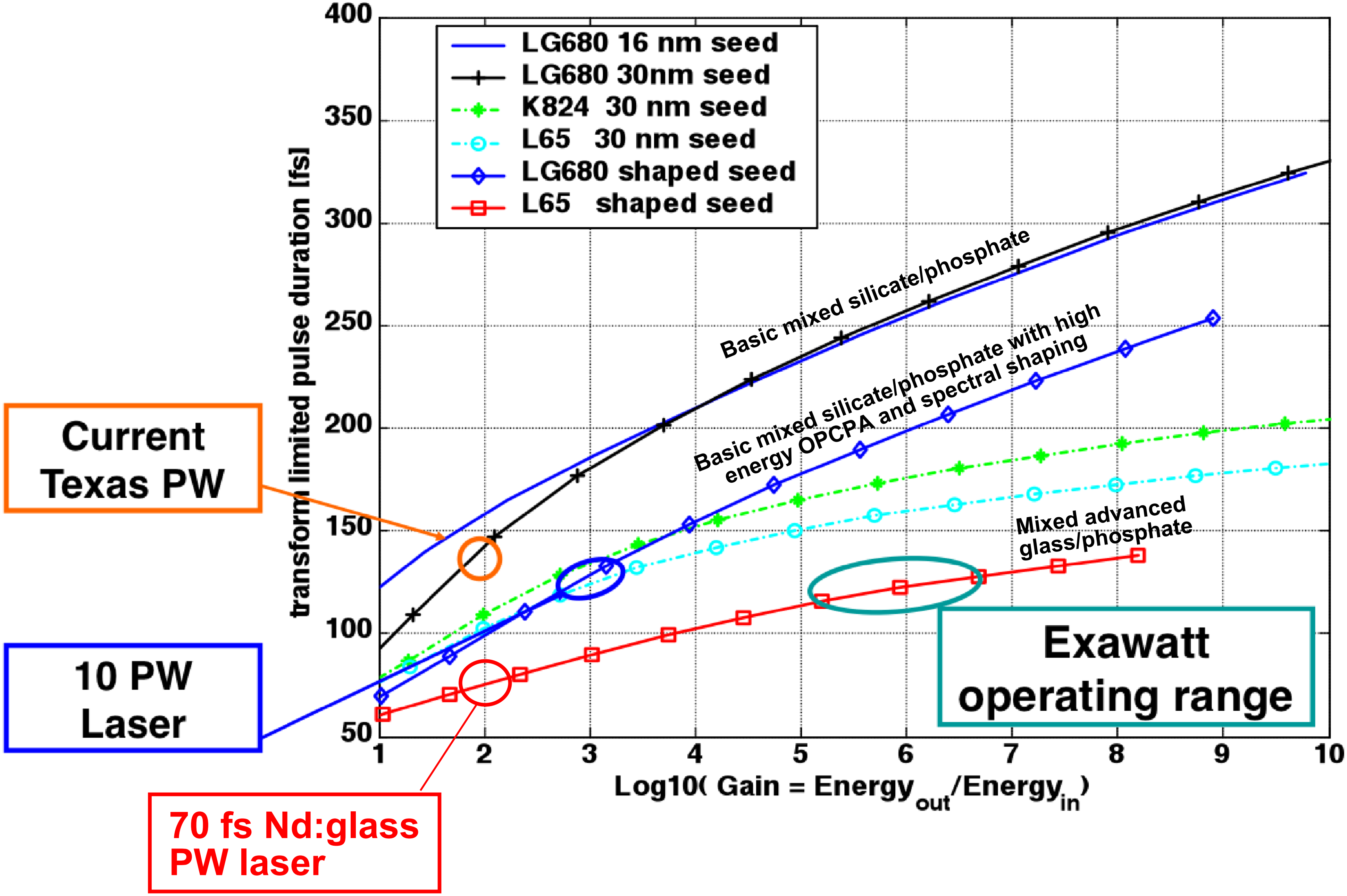


Gain balanced in two stages for best bandwidth

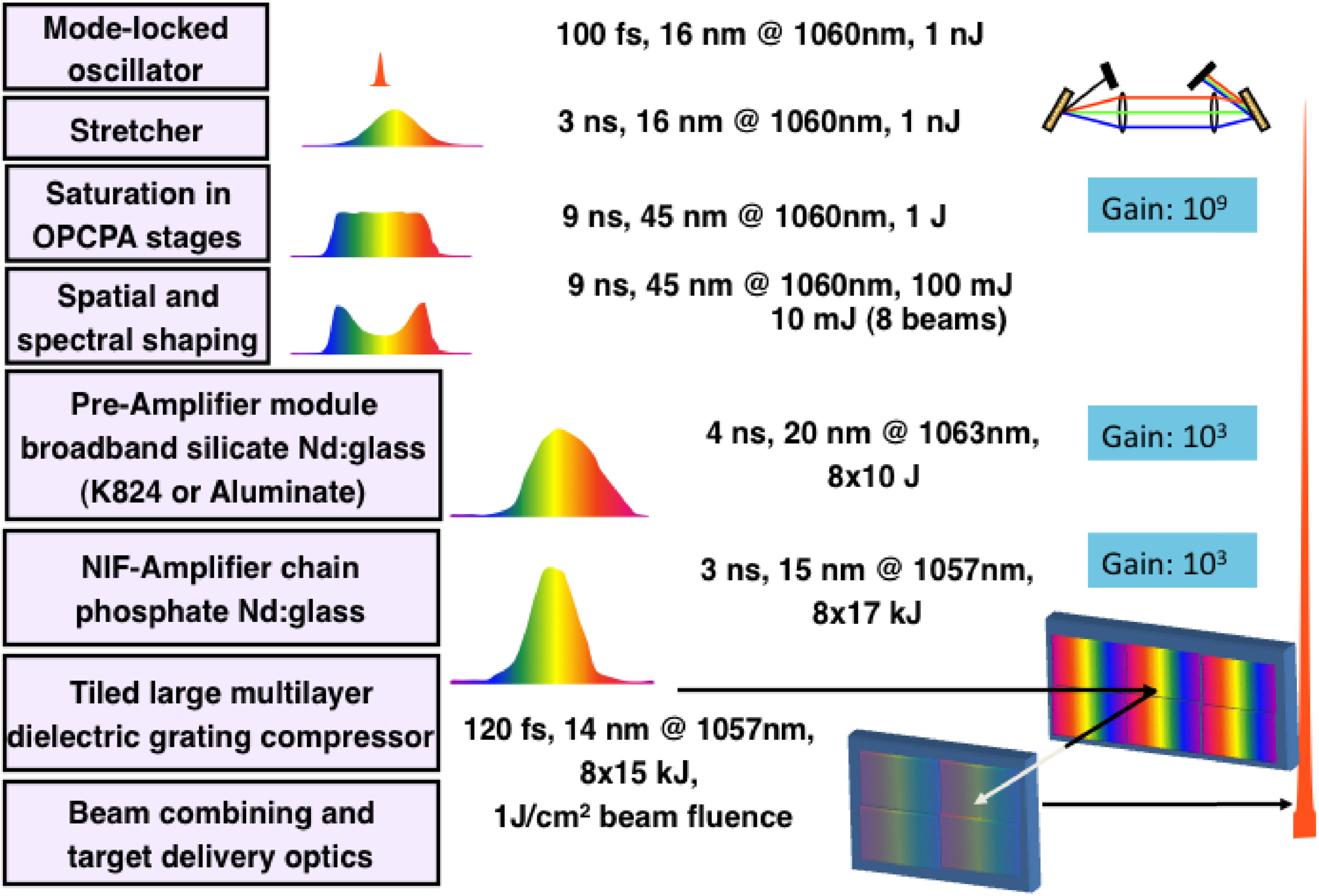
Saturated OPCPA output → 1 J → New glass stage (LG680, K824 or L65) → Final phosphate glass stage (LG750) → Compression

Total gain varied

Using these new glasses, a 120 fs, 120 kJ exawatt laser should be possible with existing technology



A good approach to achieving an exawatt would be to implement an OPCPA seed into mixed glass



A hybrid approach to an Exawatt laser has many advantages to other approaches

	Glass	Hybrid	TiSa	OPCPA
Pulse duration [fs]	1000	120	30	30
Pulse energy [kJ]	100	12	3	3
Compressor efficiency	MLD 90%	MLD 90%	Gold 65%	Gold 65%
Grating damage fluence, beam normal [J/cm^2]	3	1	.35	.35
Final stage extraction efficiency [%]	100	100	50	40 seed 40 idler
Energy out of final amplifier [kJ]	111	13.3	5.1	5.1
IR energy out of pump laser [kJ] [50% doubling eff.]	-	-	20.4	25.6
Min. beam size (normal to beam in compressor)	(3.33 m)^2	(1.16 m)^2	(1.21 m)^2	(1.21 m)^2

All compressors require tiled gratings as demonstrated by LLE, LIL,…

Thoughts on the future

- Liquid cooling of Nd:glass slab amplifiers will enable
  ~ 0.1 Hz to 1shot/min multi-PW to EW lasers

- New Nd:glass materials will enable sub-100 fs multi-PW lasers and a 120 fs EW laser

- New glasses might also improve rep-rate of these flashlamp pumped lasers

- More work needed on tiling large number (~9 or more) of gratings for large aperture compressors