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Comparison of Nd:phosphate glass, Yb:YAG and Yb:S-FAP laser beamlines for laser inertial fusion energy

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Lawrence Livermore National Laboratory

High Energy Class Diode Pumped Solid State Lasers Workshop

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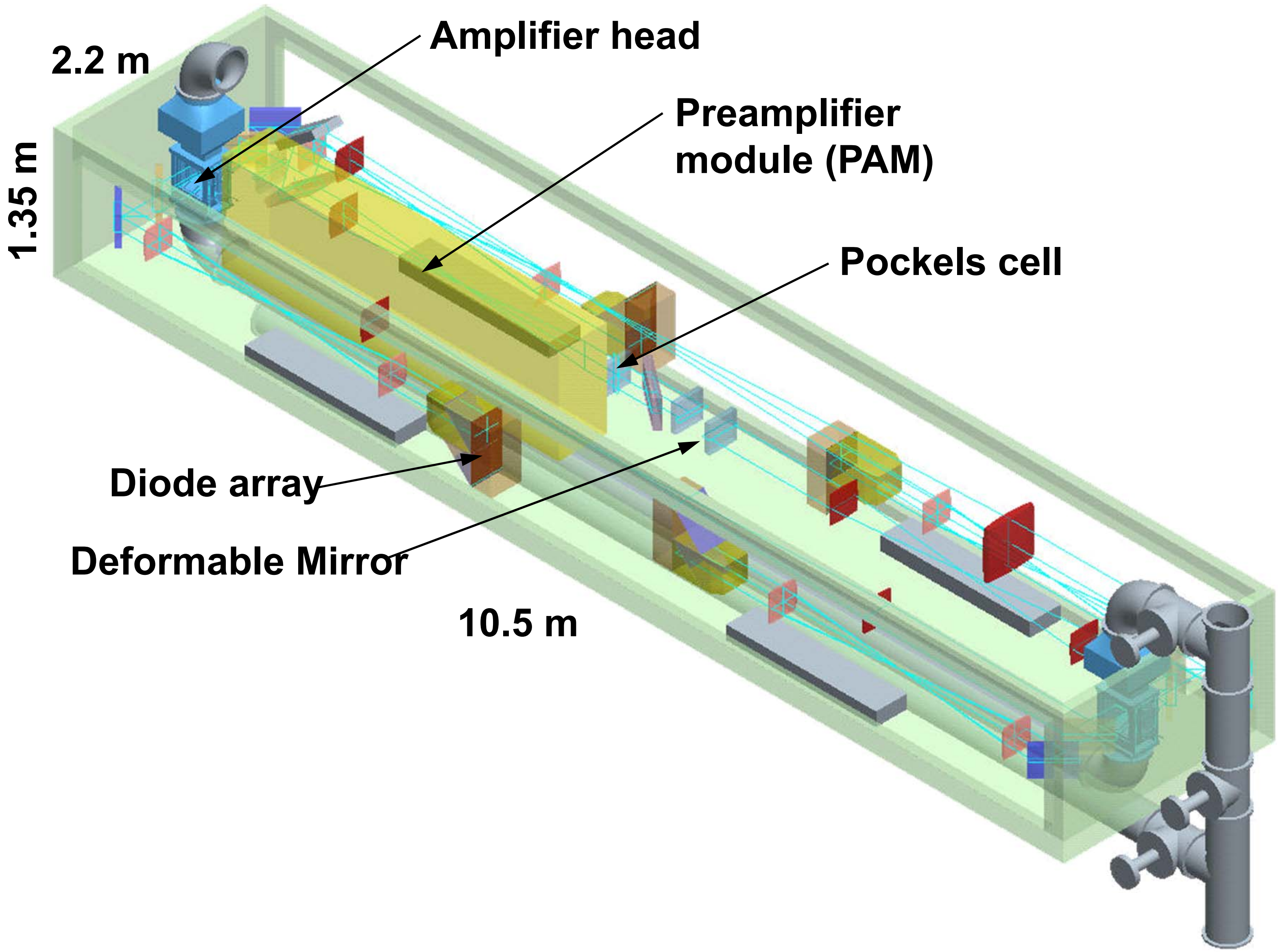
The National Ignition Facility

The entire 1ω beamline can be packaged into a box which is 31 m^3 while providing 130 kW average power



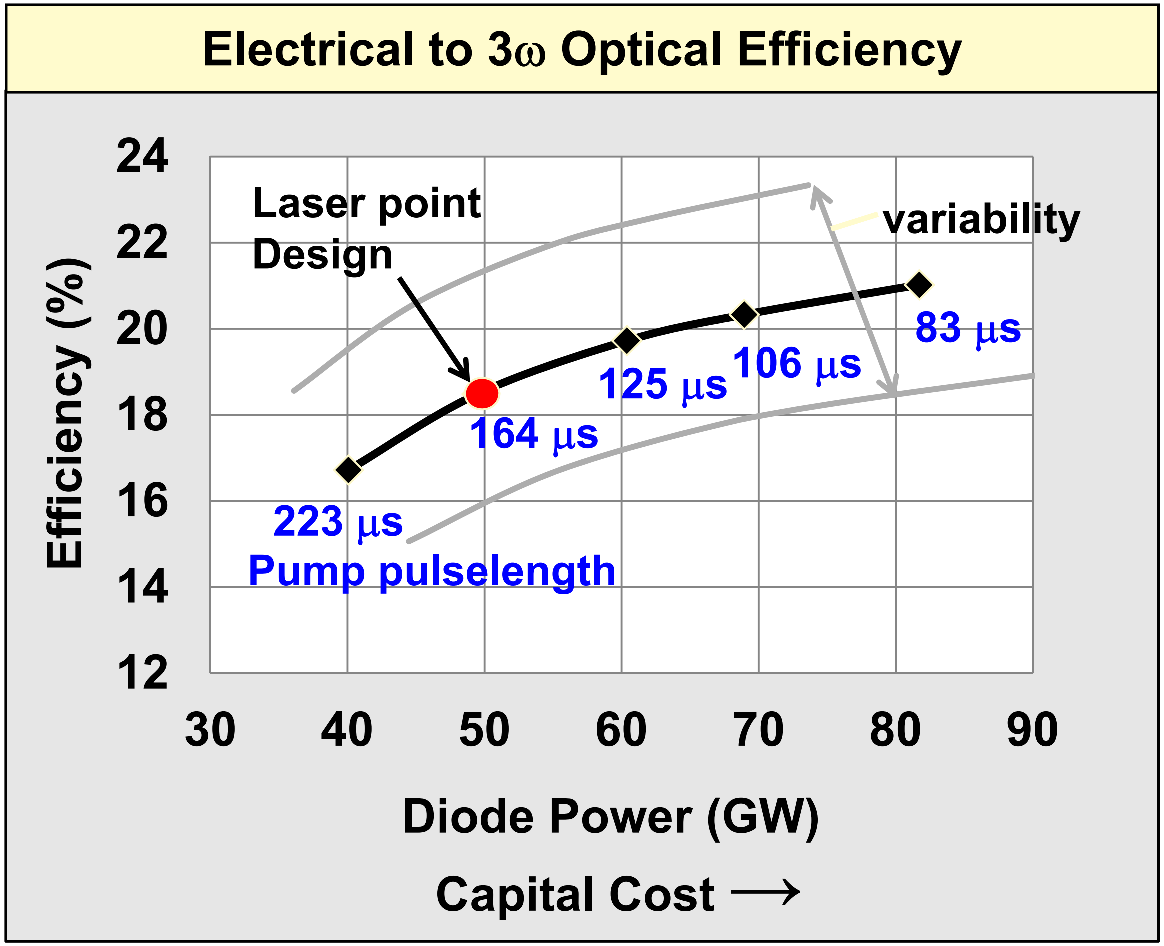
Laser Energetics Modeling Approach

- Perform energetics calculations for current LIFE laser architecture
  - 4-pass APG-1 Nd:glass laser with 25 x 25 cm^2 aperture
  - 3ω beam energy of 5.7 kJ normally, 6.5 kJ with energy to make up for down beamlines
- Include all significant efficiency factors
  - Power conditioning, diode efficiency, pump-light transport
  - Absorption of pump light, SE and ASE losses, nonradiative decay
  - Energy extraction during amplification, depolarization losses, 1ω transport
  - Harmonic-conversion, 3ω transport into the final optic
- Vary design parameters to understand tradeoffs
  - Diode Pump Power vs. Diode Pulse Duration is important with respect to costs
  - Model performance with other candidate gain media, such as Yb:YAG and Yb:S-FAP

High-Efficiency Strategy

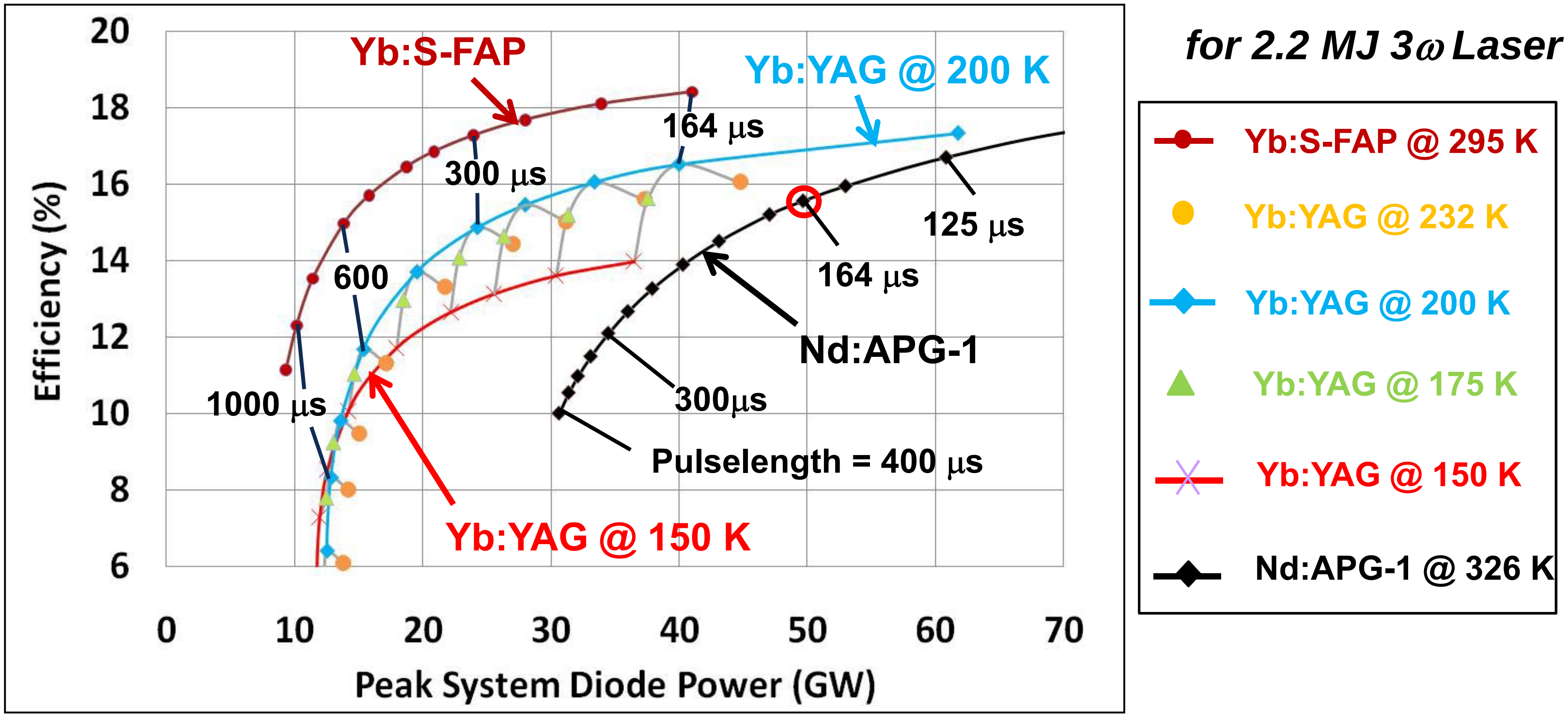
- Minimize decay losses during the pumping process
  - — Pump with high-intensity diode light for a time << decay time
  - — Use apertures smaller than NIF to reduce amplified spontaneous emission loss
- Minimize absorption by the thermally-populated lower laser level and
- Minimize concentration quenching
  - — 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
  - — Use a pump profile with a high fill factor that gain-shapes the extracting beam
  - — Relay the beam to the middle of each amplifier to minimize edge losses

The LIFE laser will achieve high efficiency, optimized at ~18% to balance economic and performance terms



Efficiency-cost tradeoffs: Nd vs. Yb gain media

Efficiency vs. Pump Power vs. Cooling Architecture



for 2.2 MJ 3ω Laser

Erlandson, et al., Invited Paper, Opt. Mat. Express, 2011; *Patent filed: IL-12308*

Our results

- **quantify the benefits of advanced materials**
- **show that cooling architecture is critical to capitalize on Yb:YAG**

Efficiency factors for designs with ~16% efficiency

Efficiency Factor	Nd:APG-1 @ 326 K	Yb:YAG @ 200 K	Yb:S-FAP @295K	Yb relative to Nd
DC Power Supply	95			
Electrical Pulsers	95			
Diodes	72			
Diode Micro-Lenses	98			
Pump-Light Delivery System	93			
Pump-Light Absorption	99	92	92	-
Quantum Defect	83	91	86	+
Spontaneous Emission, Trapping	85	90	86	+
Amplified Spontaneous Emission	89	93	94	+
Transparency	100	88	87	-
Energy Extraction	81	95	95	+
Pump-Light Non-Uniformity	99			
Mode-Match	92			
Infrared transport	92	93	93	
Depolarization	99			
Frequency Conversion	75			
351 nm transport	95			
Electrical-to-Optical Efficiency, without Cooling	18	21	19	+
Cooling Efficiency	87	74	85	-
Electrical-to-Optical Efficiency, with Cooling	16	15	16	

Beamline parameters for designs with ~16% efficiency

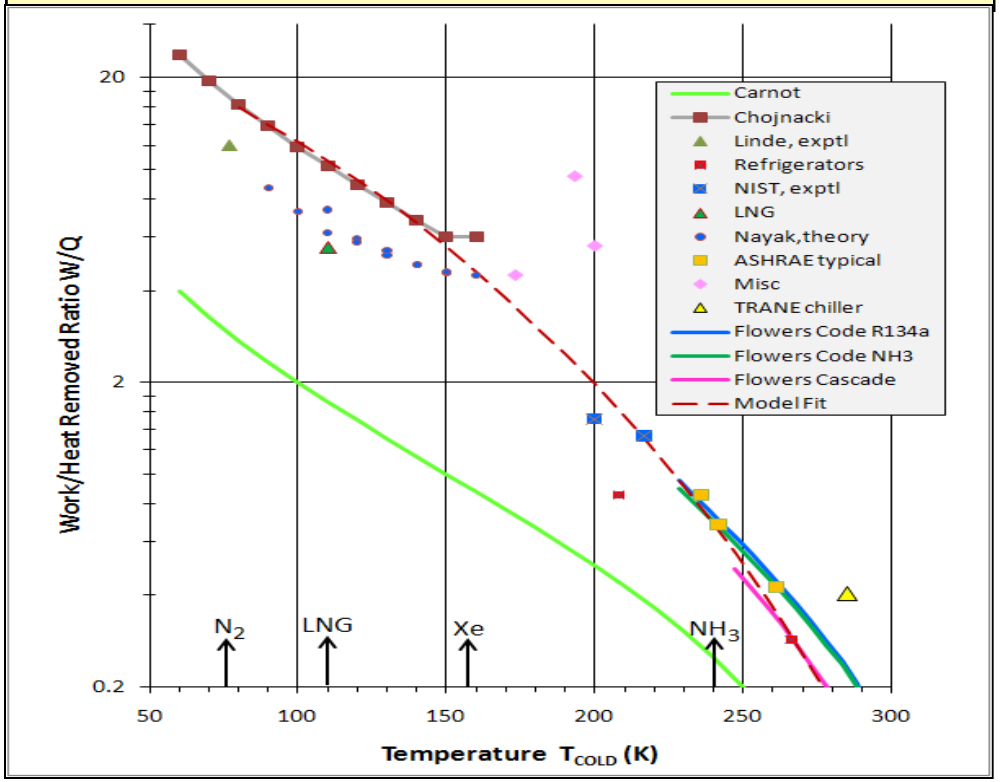
Property	APG-1	Yb:YAG	Yb:S-FAP
Average Slab Temperature (K)	326	200	295
Peak diode power for 2.2 MJ system (GW)	50	27	16
Laser efficiency, including cooling power	15.6	15.5	15.7
Laser efficiency, without cooling	17.9	20.8	18.56
Cooling Efficiency Factor	0.87	0.74	0.85
Number of beamlines used to produce 2.2 MJ	384	390	500
1ω output energy / beamline (kJ)	8.1	7.9	6.3
3ω output energy / beamline (kJ)	5.8	5.7	4.7
1ω output fluence (J/cm2)	15.0	14.6	11.5
Number of laser slabs / beamline	40	14	40
Slab thickness (cm)	1.0	2.0	1.0
Average ion doping concentration ($10^{19}/cm^3$)	7.5	3.5	0.8
Peak diode irradiance incident on slabs (kW/cm^2)	55	30	13.4
Diode pulse duration (μs)	164	250	500
Central pump-diode wavelength (nm)	877	937	898
Average gain coefficient (1/cm)	0.083	0.14	0.11
Average thermal power density in laser slabs (W/cm^3)	2.2	1.37	1.3
Surface-to-center temperature rise in laser slabs (K)	35	4.1	8.0

Performance was predicted with benchmarked models

- The diode-pumping model
  - Traces pump rays through the slab stack (in one dimension)
  - Calculates absorbed power in each slab
  - Integrates over the diode emission spectrum, which includes thermal chirp
  - Integrates the rate equation over time
  - Has been benchmarked against gain measurements on the Mercury laser
  - Uses an amplified spontaneous emission model that has been benchmarked against other ray-trace codes (Spectral averaging, spatial averaging, slab-to-slab transfer, anisotropic)
- The energy extraction model
  - Traces rays through the amplifier chain (gives a line-out across the aperture)
  - Uses Frantz-Nodvik equations
  - Accounts for passive losses through each optic
  - Calculates nonlinear phase shift (B integral)
  - Has been benchmarked against NIF laser energy measurements and two propagation codes (PROP and MIRO)

Refrigeration power consumption will degrade cryo-cooled system efficiency

Cooling Efficiency vs. Temperature



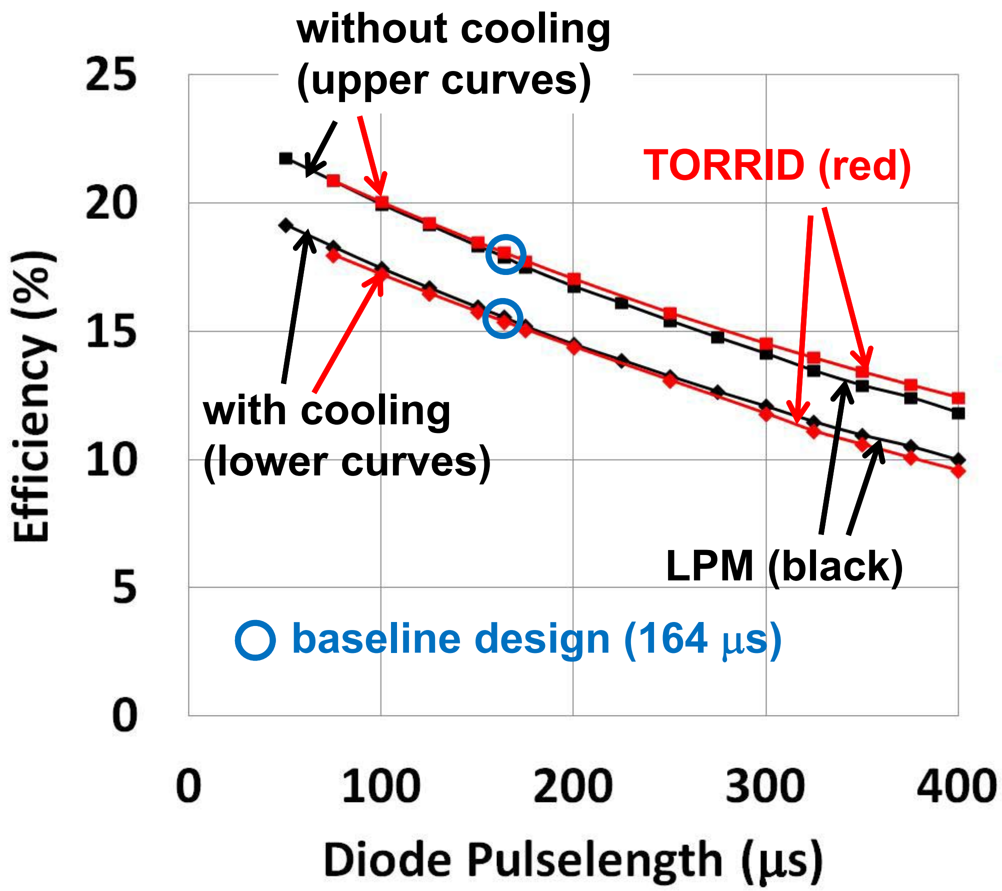
We are using for the cooling system physical models that include key temperature-dependent behaviors

- He refrigerator COP
- Compressor mechanical & polytropic efficiencies
- Heat exchanger size-efficiency tradeoffs

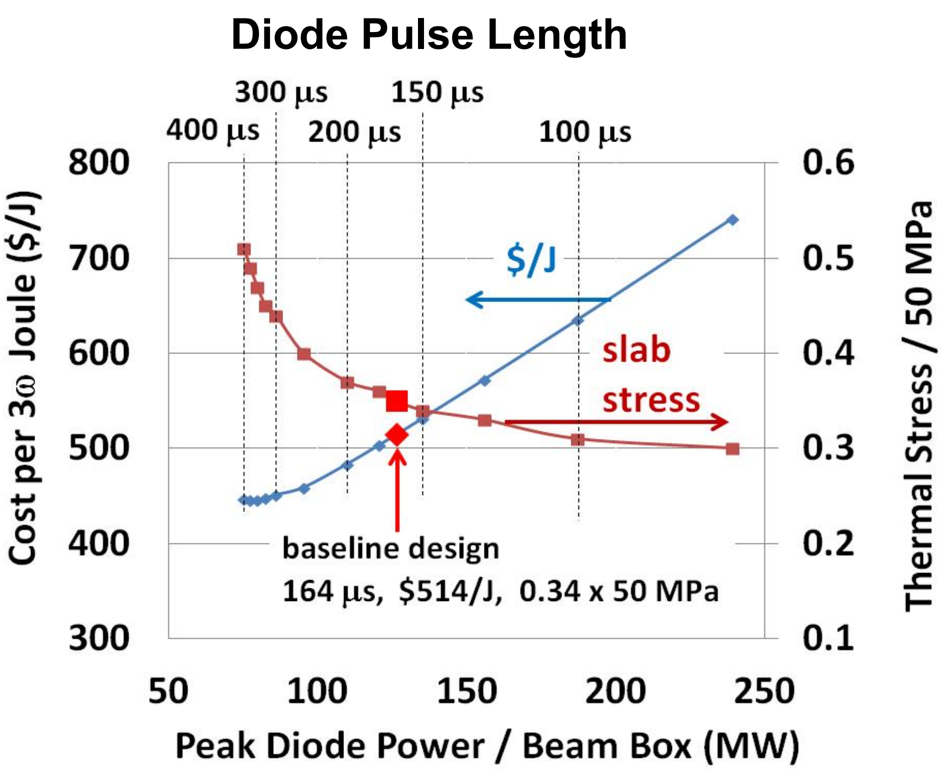
Concerns regarding cryo-operation

- **Additional complication for the cooling system.**
- **Requires separate cooling loop from diodes and other heat sources in the beamline**
- **Extensive cryo gas transport both in the beam box and throughout the plant is subject to heat leaks. Connections difficult.**
- **Room temperature environment requires vacuum jacketed housing for the amplifiers requiring a second window.**

TORRID and LPM (two competing energetics codes) predictions are in good agreement



The baseline design balances cost and thermal risks

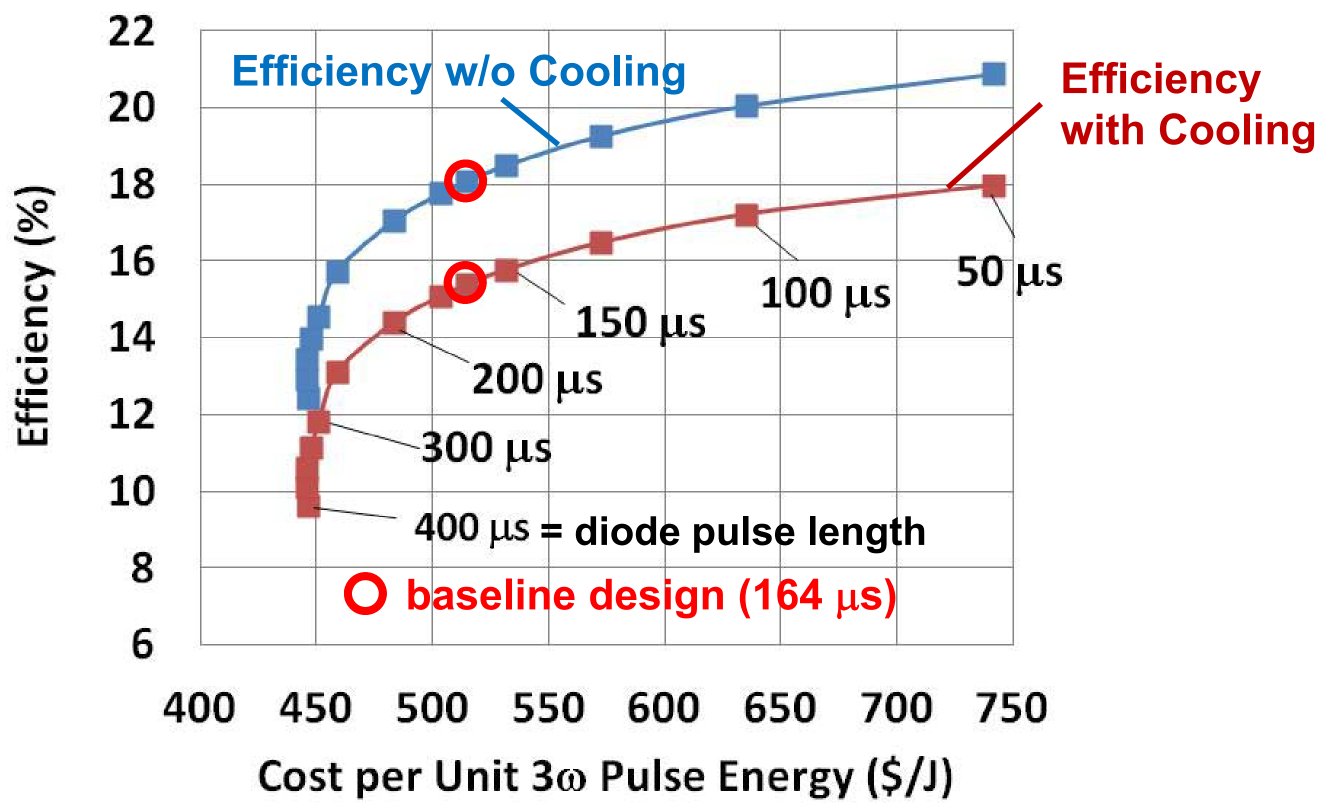


Above ~100 MW / beam box

- laser cost scales ~ linearly with peak diode power
- slab thermal stress decreases slowly with peak diode power

- calculations with TORRID

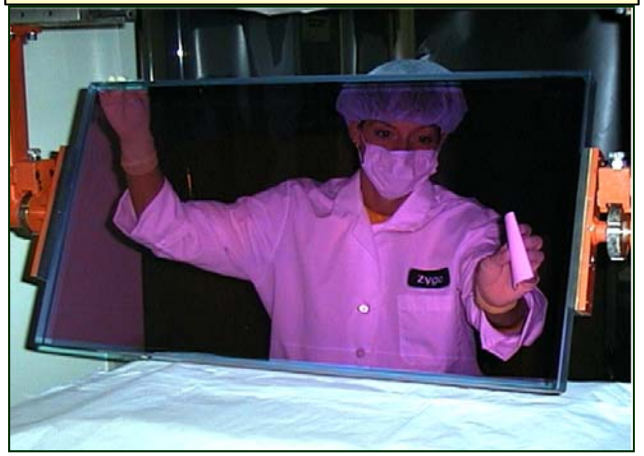
The baseline design also balances cost and efficiency



- calculations with TORRID

The materials chosen for the LIFE laser are based on today's availability to meet schedule

Nd^{3+}: phosphate laser glass



HEM Sapphire & EFG Sapphire waveplates

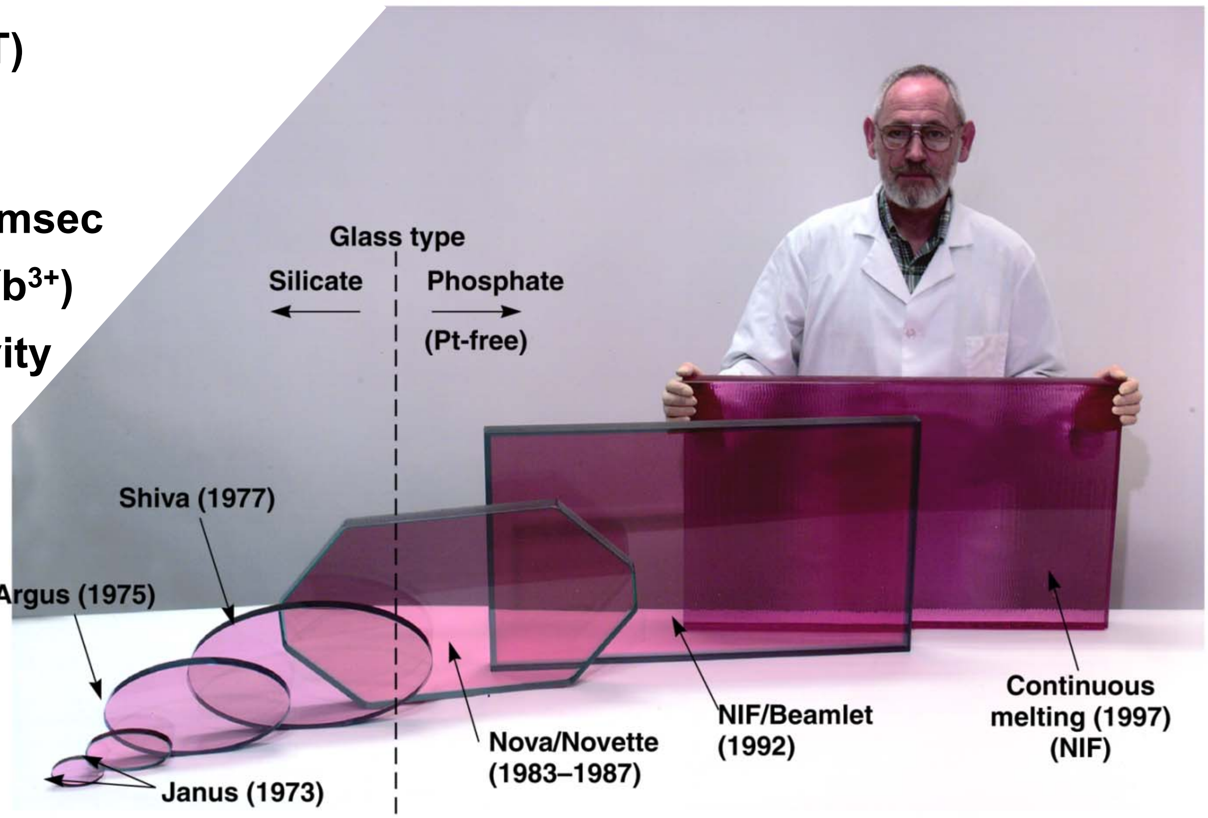
Quartz crystal rotators

KDP and DKDP frequency conversion crystals

Nd^{3+}:Glass — used in many generations of fusion lasers, has been scaled to full size

- Strengths
  - Large apertures (NIF slabs are 40 cm x 70 cm)
    - LIFE slabs are 25 cm x 25 cm aperture
  - Production capability is well established
  - Four - level laser (at RT)

- Weaknesses
  - Nd^{3+} lifetime only 0.36 msec (3x more diodes than Yb^{3+})
  - Low thermal conductivity (~0.0058 W_{th}/cm-°C)
  - Advanced glasses with better thermo-mechanical properties (APG-1) are being considered for rep-rated lasers.



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Nd-glass scaling was demonstrated with the continuous melt process Advanced glasses (APG-1) may be required for LIFE

State-of-the-art fabrication of transparent ceramics for high average power lasers

The world's largest Nd:YAG ceramics have been fabricated by Konoshima/Biakowski

10 x 10 x 2 cm ceramic Nd^{3+}:YAG slabs

10 x 10 x 2 cm ceramic Nd^{3+}:YAG slab with Sm^{3+}:YAG edge cladding co-sintered around the sides

Yb:YAG ceramics appear to be scalable and will be assessed for future LIFE lasers; they would need to be cooled to ~200K for efficiency.

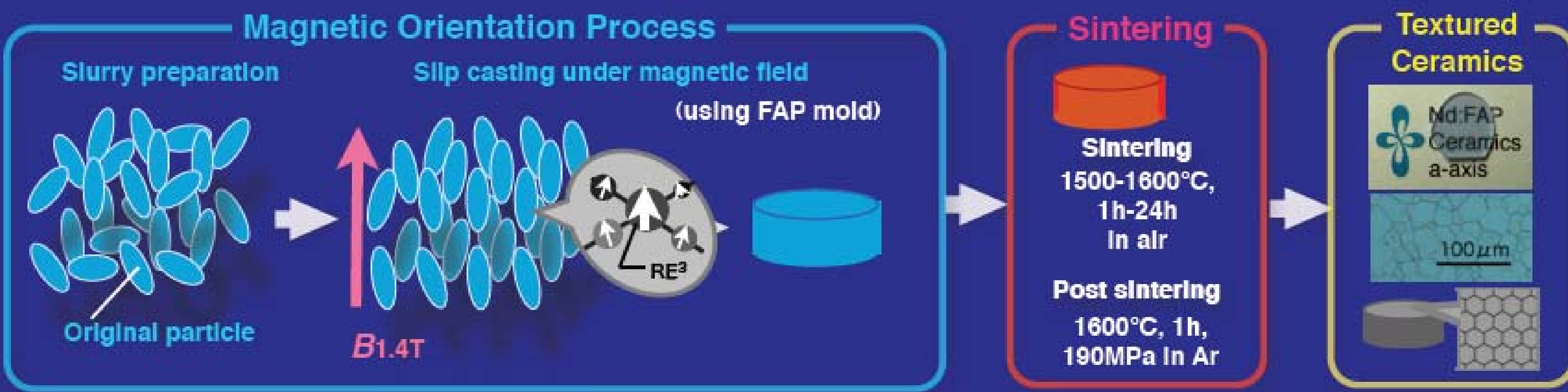
There are several knowns and unknowns regarding transparent ceramics that require consideration

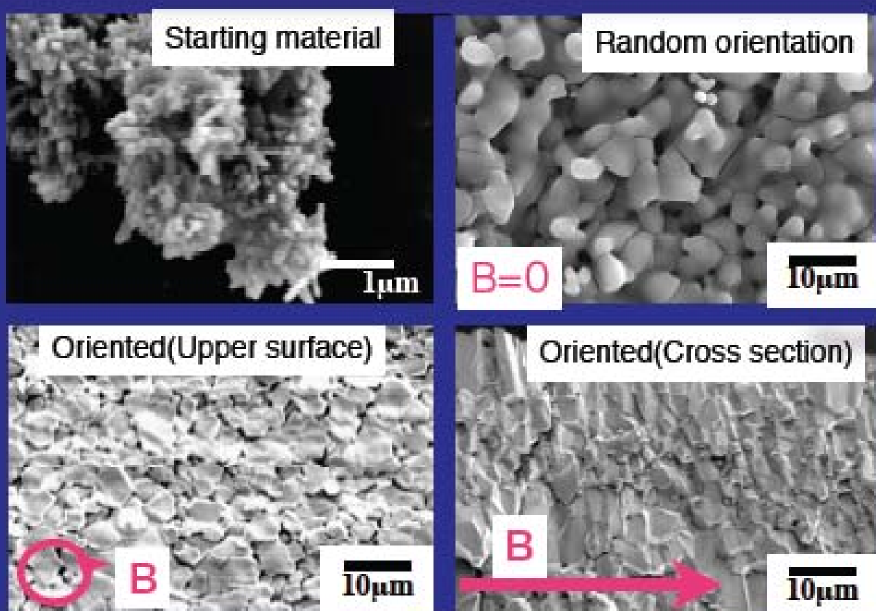
- **Knowns:**
  - — **Robust manufacturability**
  - — **Tougher, high thermal crack resistance**
  - — **Low residual stresses**
  - — **High dopant concentrations possible**
  - — **Uniform distributions of activators**

- **Unkowns:**
  - — **Purity of starting materials a key factor**
  - — **New fabrication technology required for scaling to IFE aperatures**
  - — **Complex polishing: different polish rates from randomly oriented grains**
  - — **Effect of migration of dopant to grain boundaries in high doped materials**
  - — ***"Limited to cubic materials"***

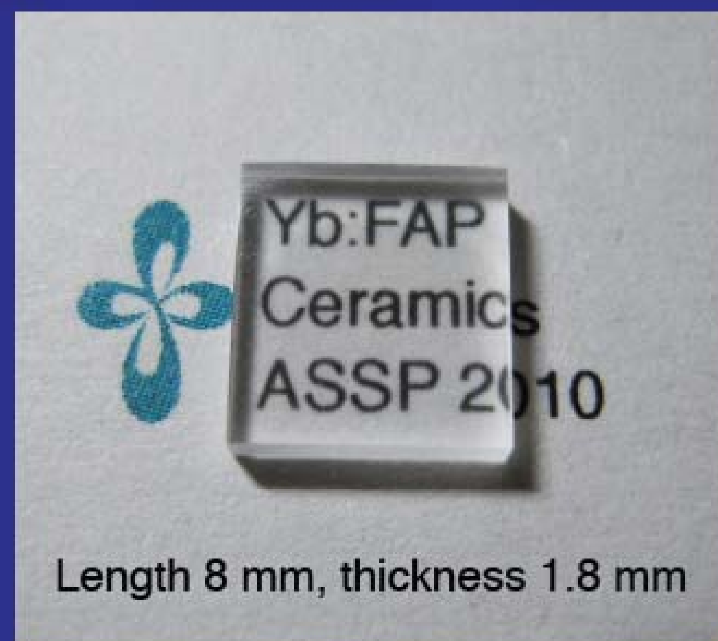
Anisotropic ceramic materials:

RE^{3+} assisted magnetic orientation method





SEM microphotographs of Ca - apatite ceramics



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J. Akiyama, Y. Sato and T. Taira, Opt. Lett, 35(21), 3598 (2010) .

Another interesting material is Nd:SrF_2 which has a 1.1 ms lifetime making it a 4-level room temperature analog to Ytterbium

- This material can be ceramic or crystalline
- Extraction fluences would have to be higher due to lower cross section (~20 J/cm^2)

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SrF_2:Nd^{3+} laser fluoride ceramics

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SrF_2:Nd^{3+} fluoride ceramics of high optical quality was prepared and its spectroscopic and laser properties investigated. Oscillations of different optical centers depending on the excitation wavelength were obtained with a slope efficiency of up to 19%.
OCIS codes: 140.5680, 140.3580, 140.3380.

Strontium fluoride crystal doped with neodymium ions is one of the promising materials for the development of diode pumped solid-state lasers and laser amplifiers [1,2]. It demonstrates rather high absorption and emission cross sections, $\sigma_{abs} = 0.8 \times 10^{-20}$ cm^2 (at 795 nm) and $\sigma_{em} = 1.7 \times 10^{-19}$ cm^2 (at 1036.5 nm) [2], respectively, 100% quantum yield, and a long metastable state lifetime of 1.1 ms for the Nd^{3+} ions in tetragonal site positions. At laser concentrations of 0.5%–1% of Nd^{3+} ions, it demonstrates a much lower level of aggregation and a large ion–ion distance in the pair rhombic site $(Nd–F)_2$ [3]. It leads to a lower concentration of aggregate M-centers $[(Nd–F)_2]$ and a weaker quenching owing to the dipole–dipole Nd–Nd cross relaxation compared to the strongly quenched well-known CaF_2:Nd^{3+} crystal [2]. At the same time, due to strong ionic bonding, the SrF_2:Nd^{3+} crystal demonstrates one of the shortest oscillation wavelengths at both the $^4F_{3/2}$–$^4I_{11/2}$ [4] and $^4F_{3/2}$–$^4I_{13/2}$ [5] Nd^{3+} laser transitions, which is promising for developing efficient pump sources for room-temperature broadly tunable color center lasers (1.03 μm) [6] and for obtaining oscillations and amplification in the telecom spectral range (1.3 μm) [5]. After doubling, tripling, and quadrupling, it can provide a new shorter-wavelength coherent source in the red, green, blue, and UV spectral ranges.

From another point of view, fluoride materials with cubic structure just recently were shown as a very promising material for producing highly efficient LiF:F_2^- [7], CaF_2-SrF_2:Yb^{3+} [8], and CaF_2:Yb^{3+} [9] laser grade ceramics. Fluoride laser ceramics demonstrates the same thermal conductivity as analogous single crystals, large size and scalability of active elements, and higher fracture toughness, cleavage resistance, and laser damage threshold compared to single crystals.

In this Letter we describe the new laser fluoride ceramics based on SrF_2:Nd^{3+} crystal. The SrF_2:NdF_3 (0.5 mol.%) laser ceramics was developed using the hot formation technique from single crystals synthesized by the Bridgman technique. The resulting high-optical-quality sample is shown in Fig. 1.

The measured low-temperature (77 K) absorption spectrum in the region of laser diode (LD) pumping is presented in Fig. 2. The maximum of the absorption spectrum was measured to lie at 796 nm, analogous to that measured for the same single crystal. The measured fluorescence spectrum was similar to that for a SrF_2:Nd^{3+} single crystal [4], with two most intensive lines peaking at 1037 and 1045 nm, as was previously attributed to the fluorescence maxima of the high-symmetry Nd^{3+} tetragonal L-centers in SrF_2 crystal. The time-resolved fluorescence spectra of Nd^{3+} ions in SrF_2 were measured using short-pulse excitation by a Ti:sapphire laser tuned to 793 nm (Nd^{3+} M-center absorption peak maximum) with two gates of 40 μs duration delayed by both 5 and 200 μs from the excitation pulse. As can be seen from Fig. 3, the fluorescence spectrum of tetragonal L-centers has two maxima peaking at 1037 and 1044 nm, while the clustered M-center fluorescence is shifted toward longer wavelengths with two maxima peaking at 1045 and 1060 nm.

The decay curve of Nd^{3+} ions in SrF_2 ceramics was measured using the same short-pulse Ti:sapphire excitation at 793 nm. The resulting curve is shown in Fig. 4 and

Fig. 1. SrF_2:Nd^{3+} ceramics sample.

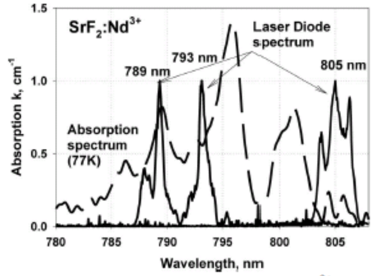

Fig. 2. Low-temperature absorption spectrum of Nd^{3+} ions in SrF_2 ceramics and different LD oscillation spectra.

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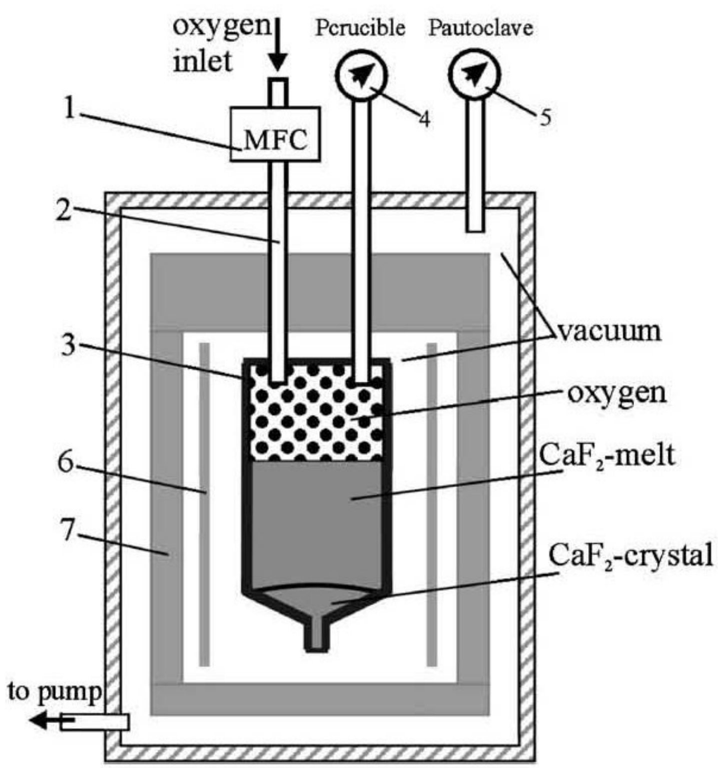
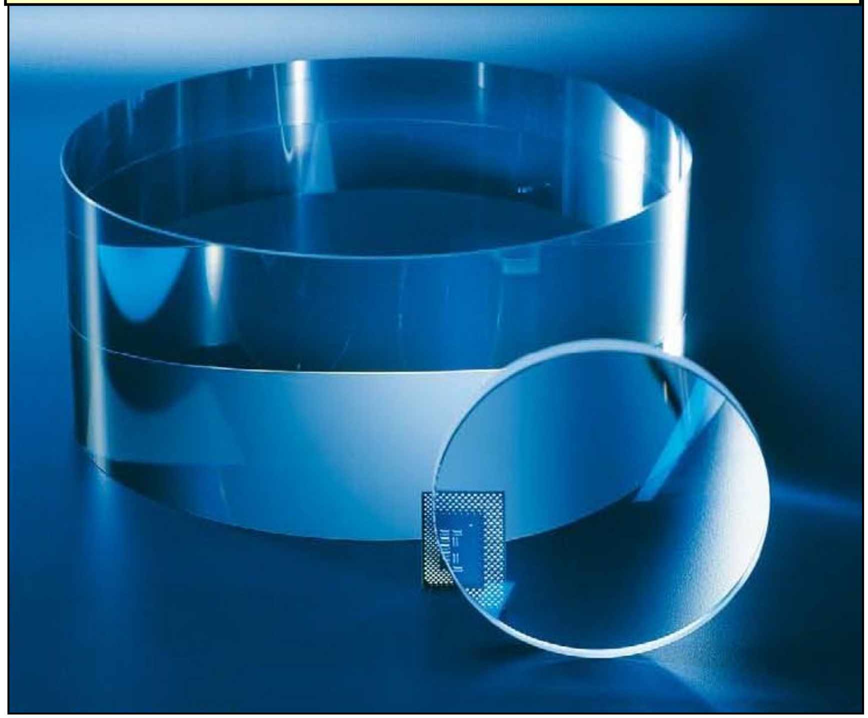
Large scale CaF_2 crystals have been grown by Schott Lithotec

Sketch of CaF_2 Furnace



350 mm Diameter CaF_2 crystal



A similar technology could be applicable to scaling Yb:S-FAP and Nd:SrF_2 crystals

Gain media of the future

- **Several Gain materials have been identified:**
  - **APG-1 (glass)**
    - **Continuous melt 40 x 70 x 2 cm LG-770 Nd:Phosphate glass slabs used in NIF**
    - **Advanced laser glasses at 25 x 25 x 1 cm^3 are being considered for LIFE.**
  - **Yb:YAG (crystals / ceramics)**
    - **It may be feasible to produce large apertures in the future, but Yb:YAG would need to be cooled for use as a LIFE gain medium**
  - **Yb:S-FAP (crystals/ceramics)**
    - **7.0 cm diameter crystals have been routinely produced**
    - **There are possibilities for scaling crystals and ceramics in the future**
  - **Nd:SrF_2 C(crystals / ceramics)**
    - **1-cm scale for both crystals and ceramics**
    - **There are possibilities for scaling crystals and ceramics in the future**

LIFE

LIFE laser/laser materials team

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