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High average power frequency conversion

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Lawrence Livermore National Laboratory

High Energy Class Diode Pumped Solid State Lasers Workshop

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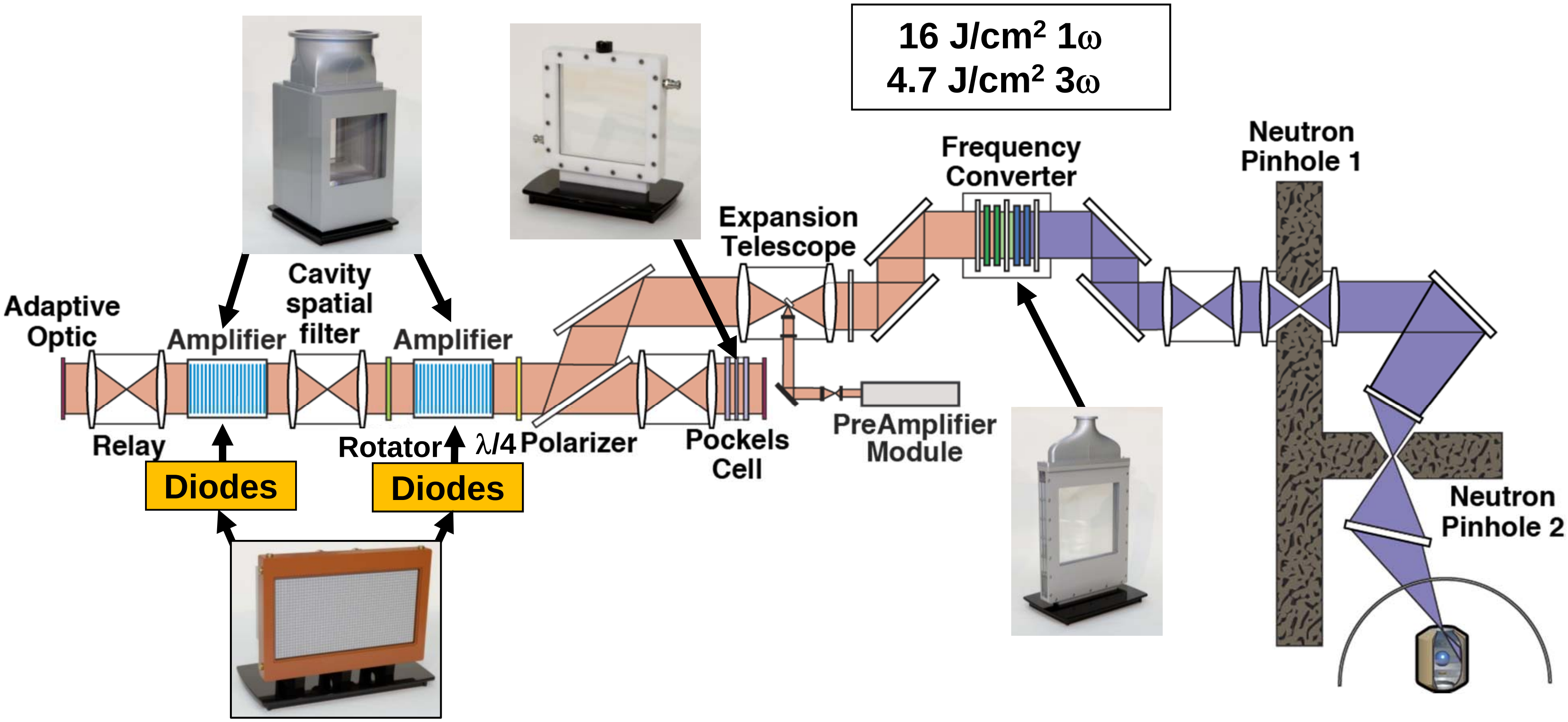
LIFE combines the NIF architecture with high efficiency, high average power technology



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

Frequency conversion material comparison shows LBO or BBO to be materials of choice

Material	DKDP	LBO	BBO	YCOB
Availability	99% DKDP limited to small growths to date	Limited production. Scaling yield issues	Extensive production, core limits aperture	No longer / limited commercial
Lead Time (months)	>6 mo	3 mo - 12 mo	3 mo	3 mo
Aperture (mm^2)	400 x 400	30 x 30	30 x 30	50 x 80
Demonstrated capability	LIFE thermal solution: gas-cooled slabs	115 J /85% eff 100 W Nd:YAG		320 W, 10 Hz, Mercury
Damage Threshold (J/cm^2) / (GW/cm^2)	10.9 / 8.4	24.6 / 18.9	12.9 / 9.9	29.1 / 2.4
d_{eff} (pm/V)	0.23	0.83	2.01	0.972
n (@ 1064 nm)	1.525	1.626	1.674	1.725
Angular acceptance (mrad.cm)	2.51	8.99	1.13	1.63
Temperature acceptance (K.cm)	11.32	7.03	39.71	142.51
Notes	Thermal absorption (0.003 cm^{-1}), weak crystal, water sensitive, low thermal acceptance (incl. absorption)	Sensitive to temperature, but non absorbing, requires oven	Very sensitive to beam quality, non absorbing	Sensitive to beam quality, non absorbing.

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

Nd^{3+}: phosphate laser glass

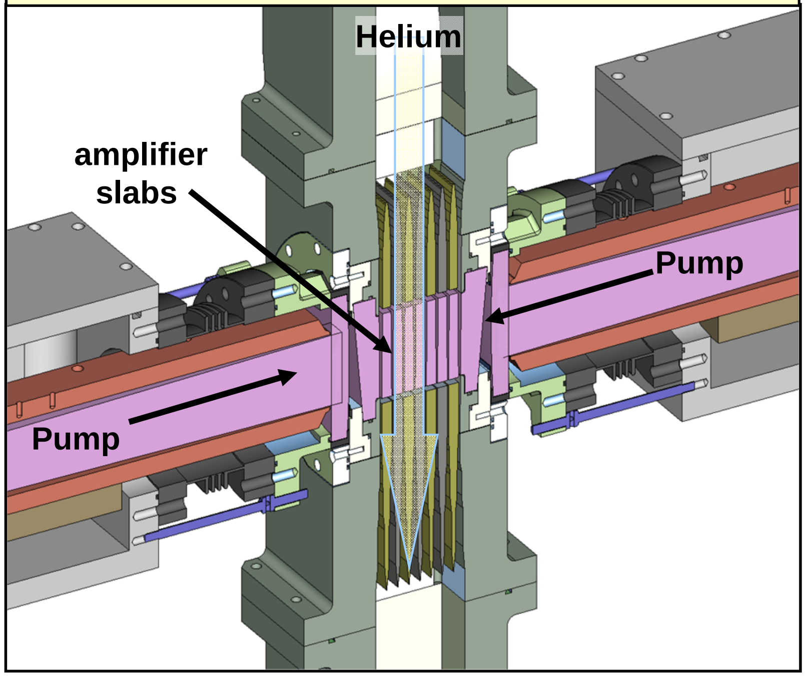
HEM / EFG Sapphire waveplates

Quartz crystal rotators

DKDP frequency conversion crystals

DKDP High average power frequency conversion will employ gas-cooling similar to the amplifiers

Gas Cooled Amplifier Head



Details

- **2 DKDP doubler crystals**
- **2 DKDP tripler crystals**
- **Aerodynamic vanes**
- **5 atm Helium at 2 C**
- **Flow rate Mach 0.1**

The amplifier version was prototyped and thermal / gas cooling codes benchmarked on the Mercury laser system

Thermally robust frequency converter progress summary

- **Obtained experimental data to improve selection of DKDP properties used in design & simulation**
  - **E.g.; to address literature discrepancy on DKDP thermal conductivity**
- **Completed first spiral of thermally robust converter design**
  - **Propagation model incorporates steady-state thermal loading**
    - **Thermal loading calculated from position-dependent conversion**
    - **Includes gas cooling model**
    - **Does not include thermal OPD, crystal bowing, or stress optic effects**
  - **Converter designed for this thermal loading**
    - **Reasonable margin for DKDP thermal fracture**
- **Results of first model**
  - **Thermal loading has small impact on conversion efficiency (<0.2%), if crystal angles are optimized**
  - **Anticipated thermal wedge (0.1 K) has negligible impact**
- **Next steps**
  - **Consider effects of OPD, crystal bowing, & stress optic effects**
  - **Determine whether crystal angles must be retuned when beamlines run hot (8/7 mode)**

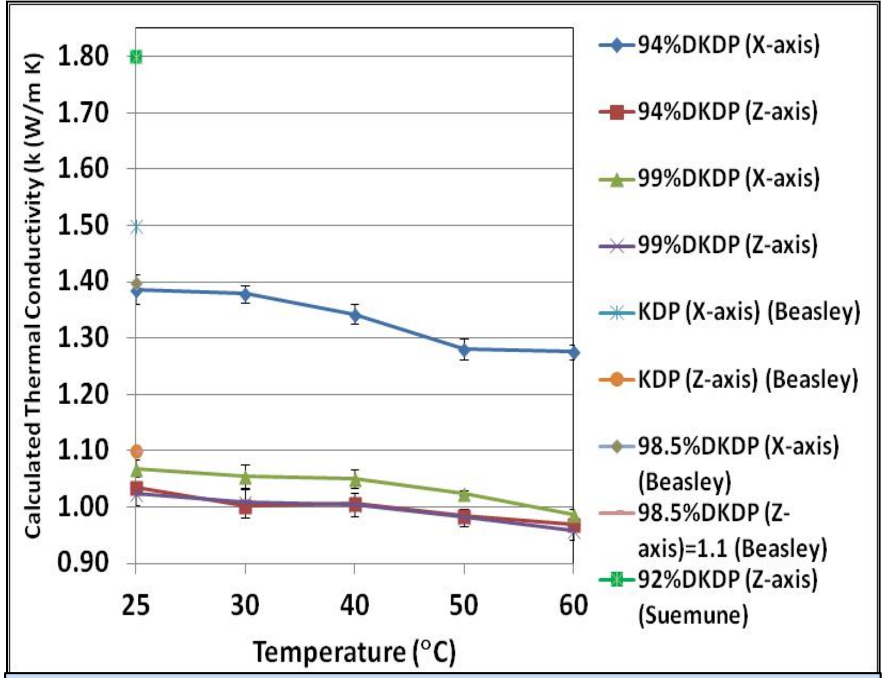
Thermo-mechanical and absorption parameters have been measured for 94% and 98%DKDP samples

Parameter	KDP	70%DKDP	94%DKDP	98.5%DKDP
Density	2.3383	2.3555	2.3070*	2.3063*
Heat Capacity (J/kg·K)	857	850	852*	852*
Thermal Conductivity (W/m·K)	x=1.5** z=1.1**	x=1.4** z=1.1**	x=1.39* z=1.04*	x=1.07* z=1.02*
Absorption (ppm/cm)***				
1064nm	x=68600 z=21100	x=17000 z=6000	x=6000 z=2600	x=3200 z=2200
532nm	x=1500 z=1300	x=1400 z=1500	x=1500 z=1200	x=1100 z=1400
351nm	x=600 z=500	x=810 z=750	x=1100 z=1900	x=1100 z=1400

* Values taken from AFRL measurements
** Values taken from Beasley report
*** Values taken from Gooch & Housego(Ohio) measurements

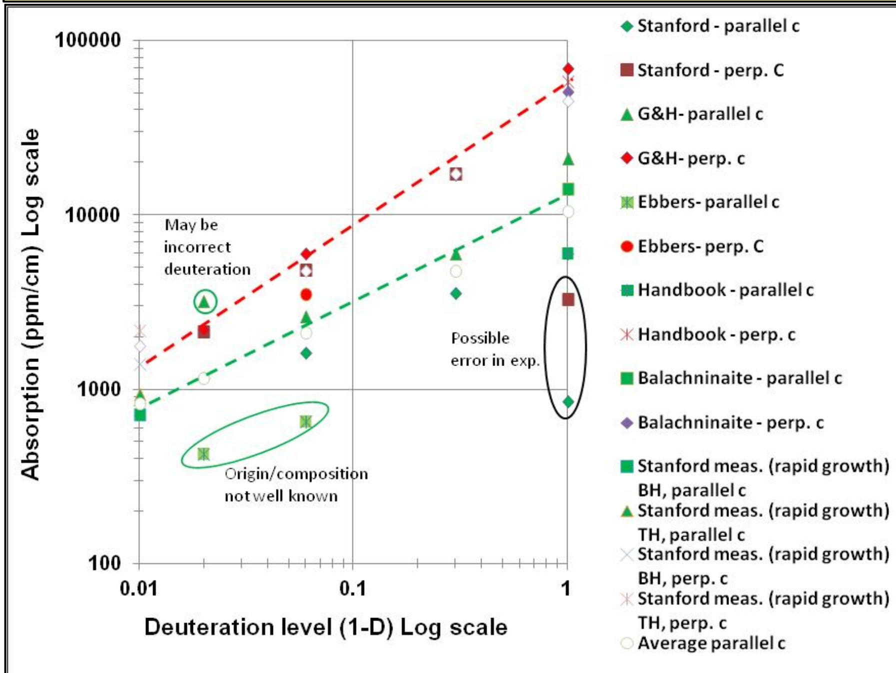
DKDP Thermo-mechanical and absorption data were obtained to support device simulations

DKDP/KDP thermal conductivity



DKDP Thermal Conductivity calculated from literature KDP heat capacity data and AFRL diffusivity data

1064nm Absorption in KDP/DKDP

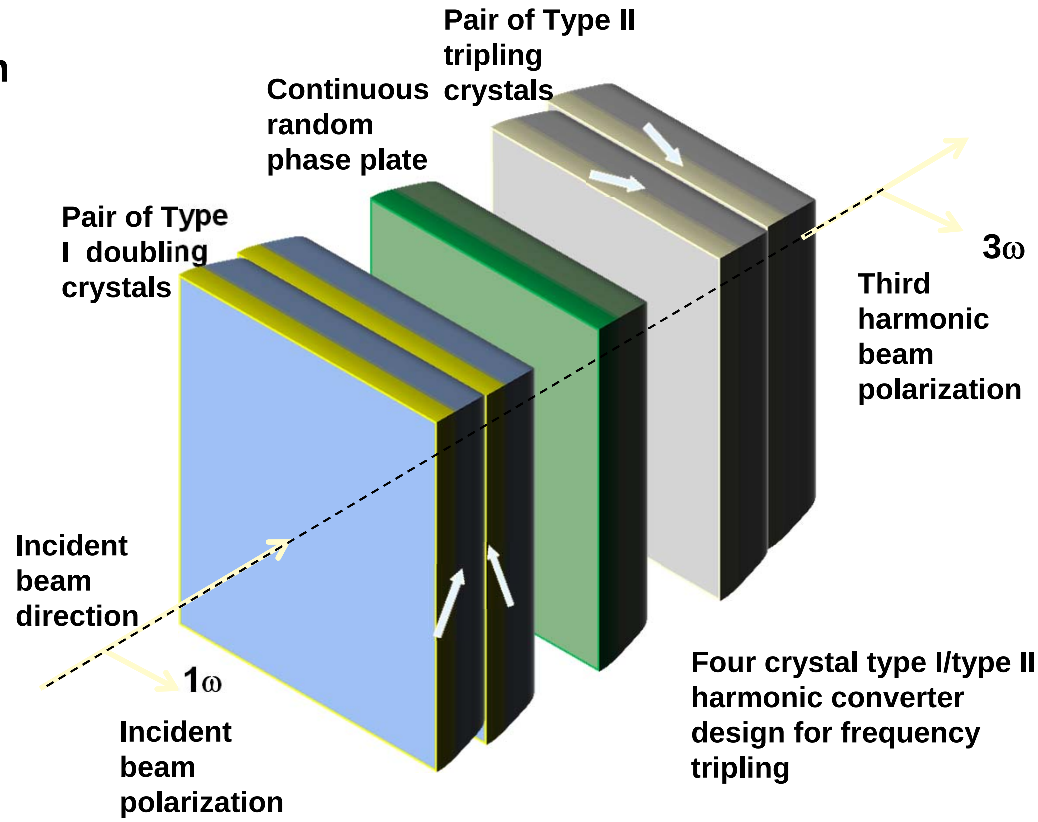


DKDP [(D_{1-x})KDP] absorption data from the literature and measurements made at several vendors

Data collected for thermal conductivity, thermal diffusivity, specific heat, thermal expansion, and absorption at 1064nm, 532nm and 351nm.

Four-Crystal Type I/Type II Frequency Converter for LIFE

- Crystal dimensions: 43 cm x 43 cm
- Clear aperture: 41.5 cm x 41.5 cm
- He gas cooling



Baseline Conversion Efficiencies, No Thermal Load

Operation type	Foot	Drive	Foot+Drive
Nominal	67.3%	76.9%	74.5%
8/7 Elevated	70.1%	78.9%	76.7%

Operation under Steady-State Heat Load

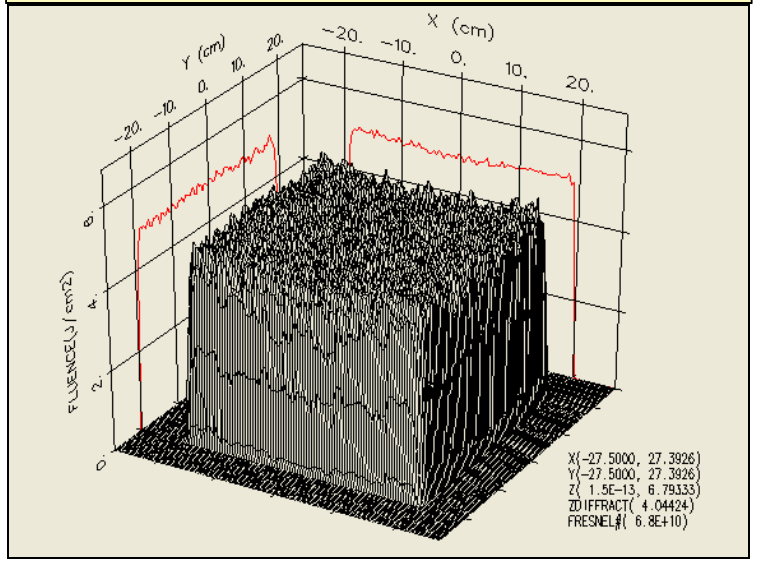
- **Highest heat load: foot pulse operating at 8/7 elevated energy**
- **Angle tuning of converter crystals compensates average temperature rise**
- **Thermally compensated conversion efficiency drops by only 0.2% compared to the non-thermally loaded case**

Foot 1ω input, 8/7 operation = 9.9 kJ

Compensation	3ω output (kJ)	Foot efficiency
No angle tuning	4.5	45.3%
With angle tuning	6.9	69.9%

Foot efficiency for no thermal load: 70.1%

3ω Beam Shape at Tripler Output

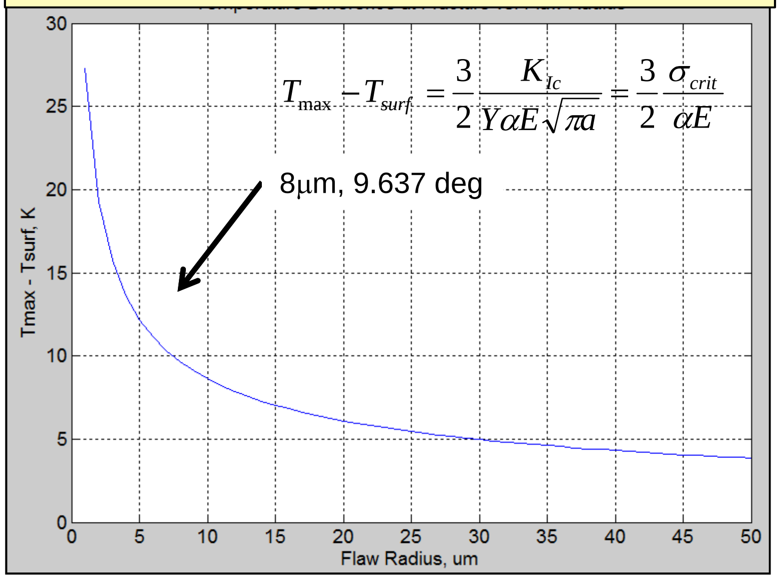


Crystal	Average temperature rise, degrees
1	2.4
2	2.4
3	0.6
4	1.6

Fracture Analysis of the thermally loaded converter confirms robust LIFE design

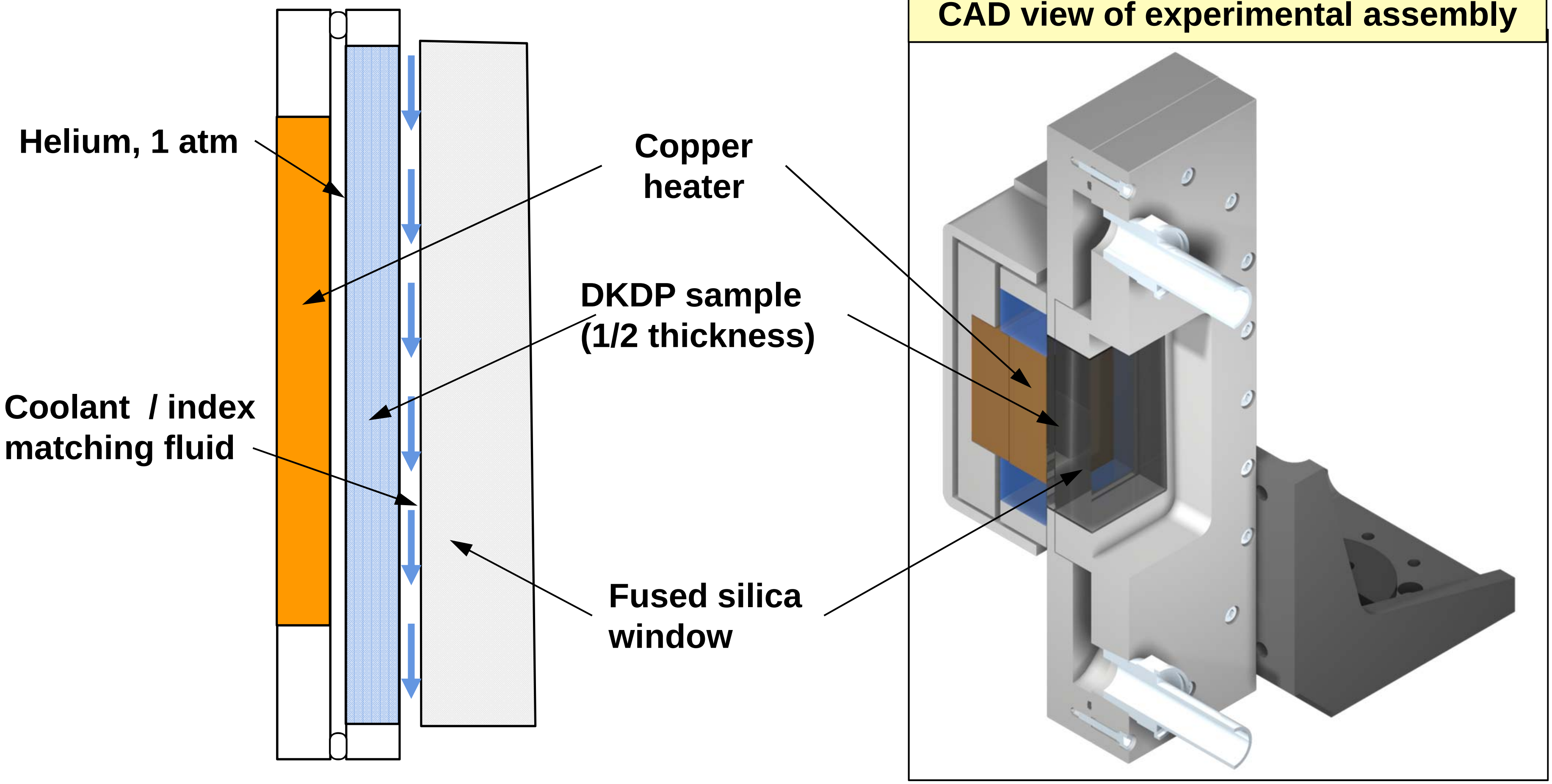
- Temperature difference between maximum and surface temperature, $T_{max} - T_{surf}$, is related to critical stress at fracture.
- Fracture relates to flaw radius.
- MRF finishing for an 8 μm flaw radius is needed to remain 3x-4x below fracture.
- For an 8 μm flaw radius, the temperature gradient corresponding to fracture is 9.637 degrees.
- Fracture experiment will be performed to test thermal fracture limits of DKDP and verify fracture calculations.

Temperature difference at fracture vs flaw radius



Crystal	ΔT (T_{max} - T_{surf})	Times below fracture
1	3.1	3.1
2	3.1	3.1
3	0.8	12.5
4	2.1	4.5

We will be performing thermal fracture experiments utilizing substrate fabrication and thermal environments which closely match LIFE design

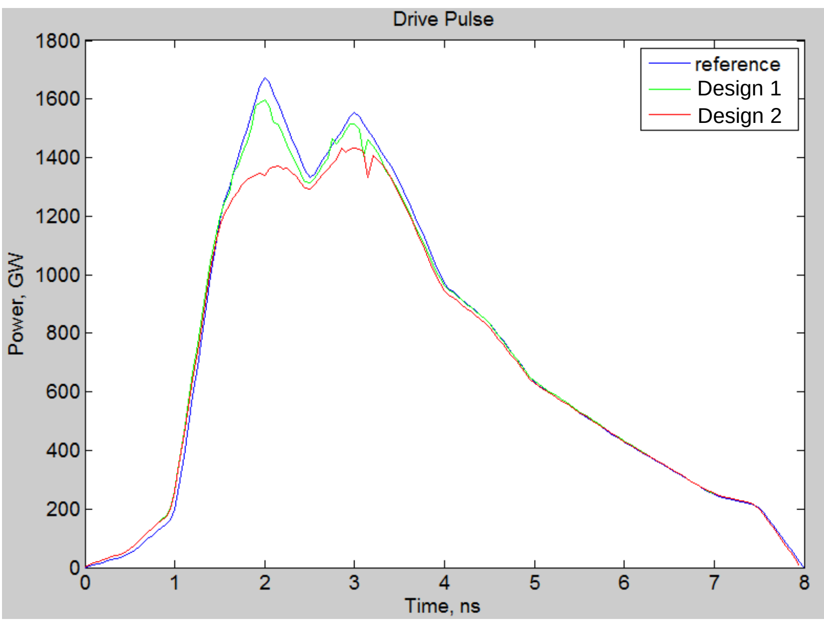


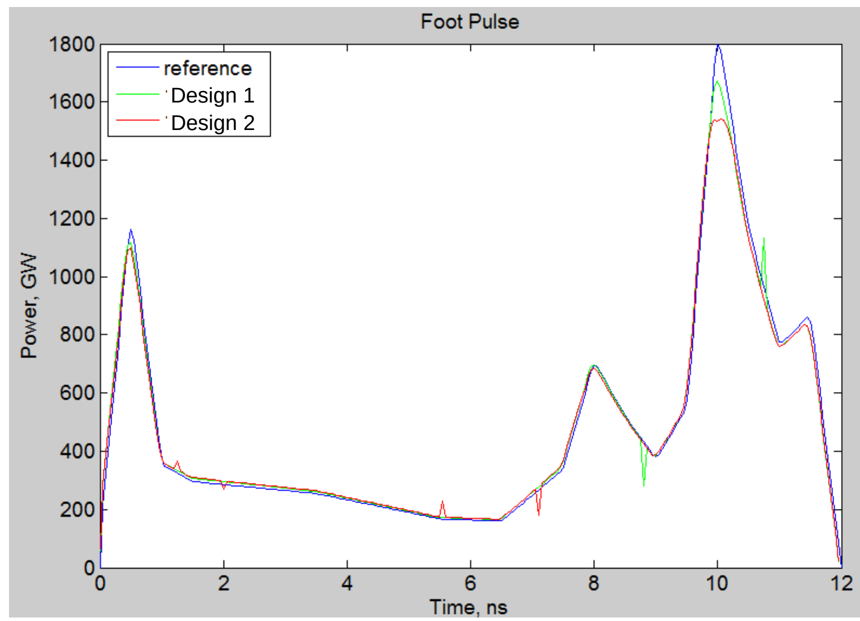
CAD view of experimental assembly

- **Assembly of experimental apparatus is complete**
- **Testing (to failure) to begin soon**

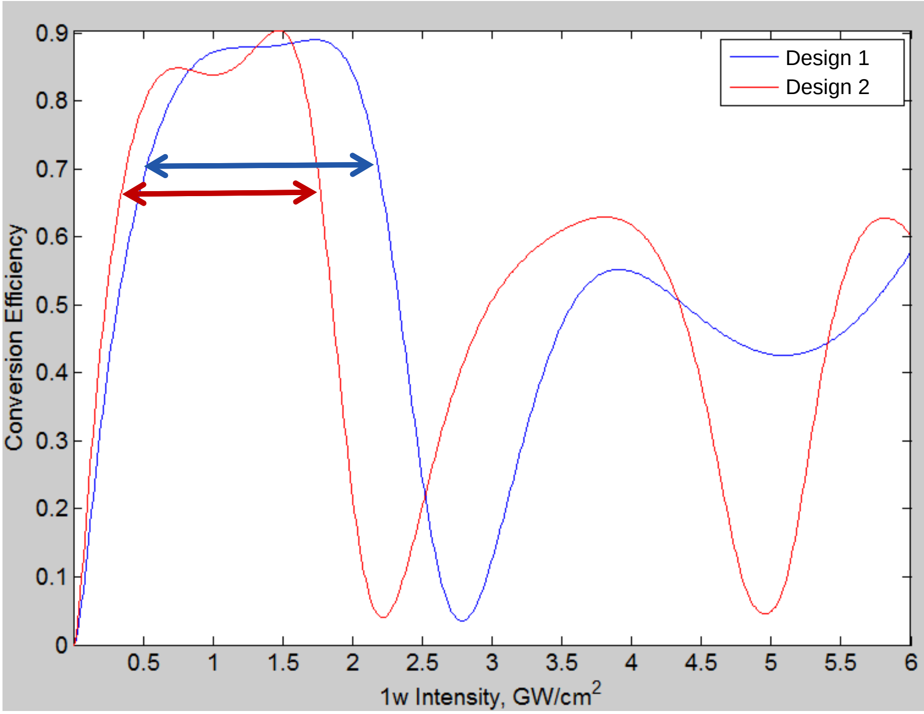
Meeting Peak Power Requirements

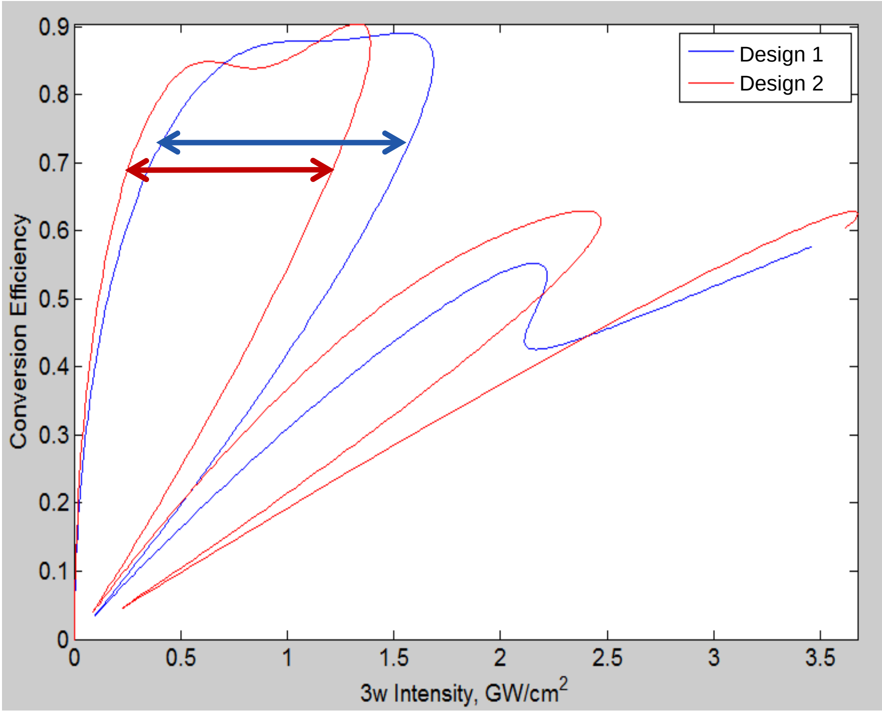
- Crystal thickness optimization
  - Early design 1 missed the foot and drive peak power due to back conversion and lack of dynamic range.
  - This required thickness optimization, and thermal fracture required crystal splitting
- Current - design 2
  - More thermally robust with no crystal splitting needed.
  - Trade-off slightly less energy efficient than the design 1
  - Increased dynamic range: May further adjust power in the 1ω pulse at the peaks to achieve the required 3ω peak power to better than a few percent.





Converter efficiency curves have been optimized for greater dynamic range to accommodate pulse shaping





The plots above show that a Design 2 has increased dynamic range to achieve the needed peak power when compared to a Design 1.

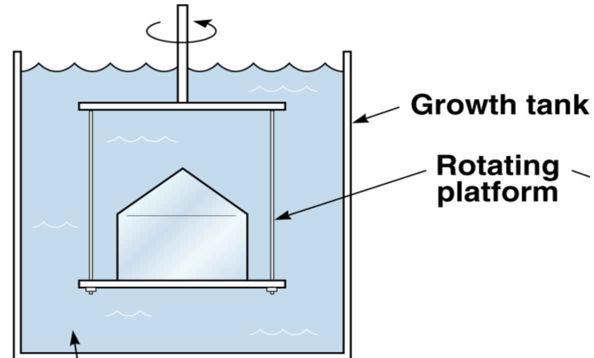
Large DKDP crystals are the LIFE baseline for frequency conversion and the Pockels cell.

Highly deuterated 98% DKDP crystals are required for the Pockels cell and frequency conversion

- Crystals of 70% DKDP have been grown to very large sizes and with high optical homogeneity
- Laser conditioning gives high damage thresholds at 1053, 526 and 351 nm (1w, 2w, 3w)
- Demonstrated 3w conversion efficiencies of 80%
- Deuteration (~70%) suppresses SRS (stimulated raman scattering) in the tripler crystal for NIF
- LIFE designs require ~98% deuteration to suppress absorption and heating due to 10-16 Hz repetition rate
  - Need to assess absorption & uniformity
  - Multiple plates required to minimize heating effects
  - SRS threat mitigated by lower operational fluence (4 J/cm^2 vs 10 J/cm^2)

LIFE needs to develop large scale (41.5cm x 41.5cm apert.) “rapid growth” 98% DKDP to meet LIFE schedule

The KDP crystals are grown by the “rapid growth” method by lowering the temperature of a super saturated solution in ~3-4 months

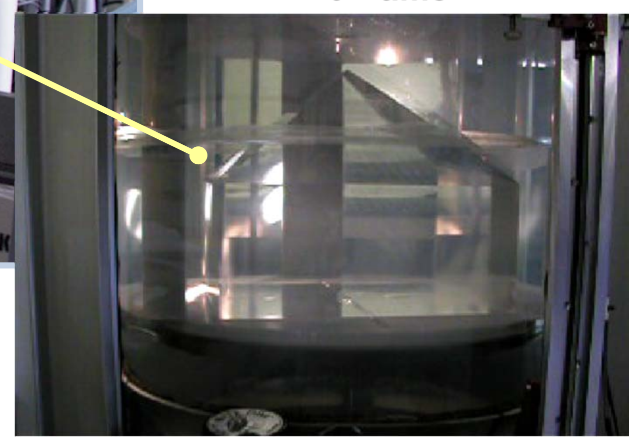


$$T_g = T_i - k(t) \cdot t$$

T_i = Starting temp

$k(t)$ = cooling rate (°C/day)

t = time



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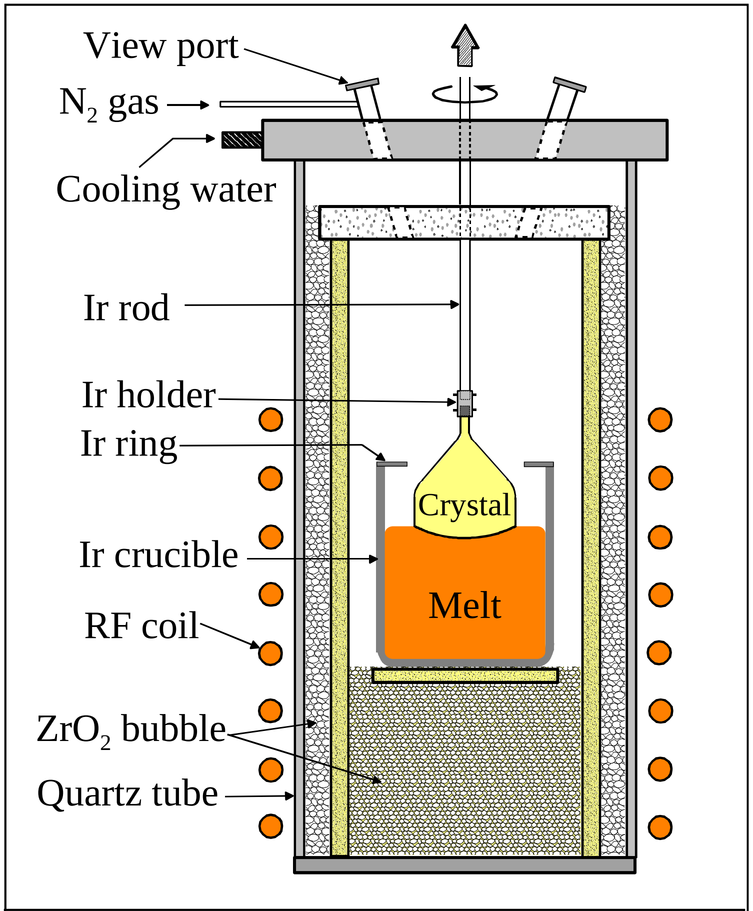
Tremendous progress has been made on growing large size, optical quality YCOB [$YCa_4O(BO_3)_3$]

Knowns

- **3x thermal conductivity of KDP and DKDP**
- **3x nonlinear coefficient of DKDP (thinner crystal)**
- **Thermally insensitive operation at 2ω**
- **Hardness of quartz – takes hard AR coating**

Unknowns

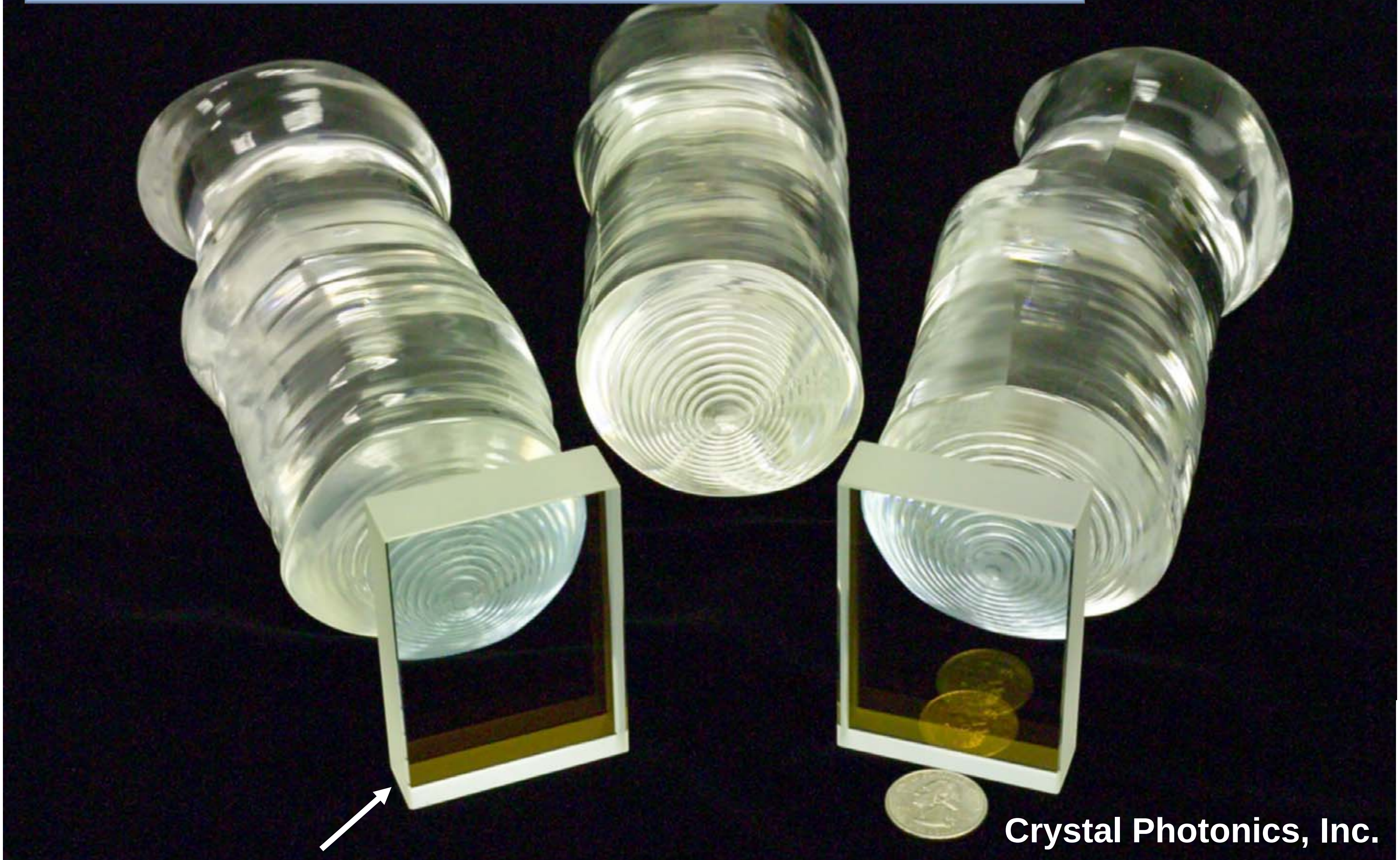
- **Fracture strength (higher than DKDP)**
- **Scaling limitations – (Czochralski or Bridgman)**



- **Rotation rate: 3-10 rpm**
- **Pull rate: 0.5-1.0 mm/h**
- **Growth axis: b-axis**
- **Melting point: 1510 °C**

*First characterized by G. Aka and T. Sasaki (1997); Large boules grown at Crystal Photonics Inc.

Growth of YCOB enables straightforward implementation of high average power second harmonic generation.

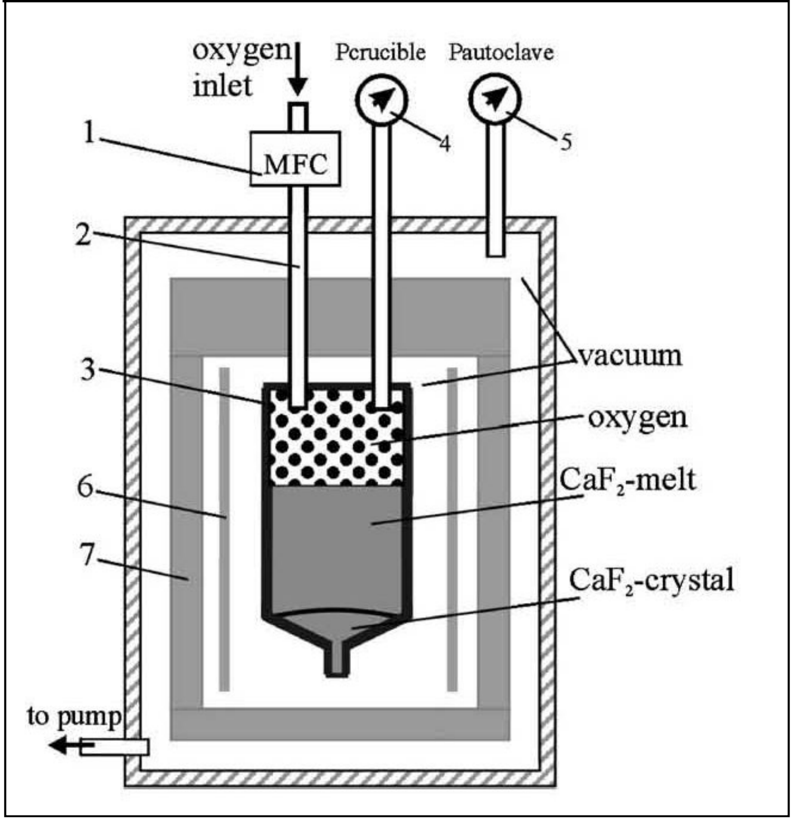


Crystal Photonics, Inc.

Finished Mercury frequency converters (5 x 8 x 1.5 cm^3)

Large scale CaF2 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 YCOB crystals

Future work for scalable high average power frequency converter applications

- DKDP
  - Thermal fracture experiments
  - Detailed simulations on effects of thermal deformation and sensitivity to operational variants – energy, wavefront, thermal
  - We are considering the feasibility of growing near 98% deuterated DKDP by the rapid growth
- YCOB / other scalable nonlinear materials
  - Crystal Photonics produced large aperture crystals for the Mercury Laser
  - Potential scaled growth via HEM method – Schott Lithotec CaF2.

LIFE

LIFE laser/laser materials team

Bob Deri	Mark Henesian
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Amber Bullington	Sam Rodriguez
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Al Erlandson	Mary Spaeth
Steve Fulkerson	Chris Stolz
Glenn Huete	Tayyab Suratwala
Travis Lange	John Trendholme
Rod Lanning	Steve Telford