What is developed in Academia?

Cryogenic high energy high average power lasers

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HEPTech Workshop, Nov 12, 2014

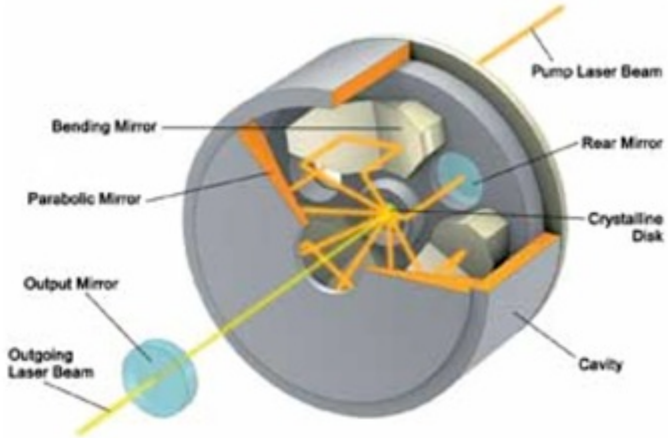
Outline

- Overview: Laser architectures for high energy pulsed high average power diffraction limited laser amplifiers
- Results from different academic groups
- Cryogenic amplifiers
  - Rod-type amplifiers
  - Composite thin disc (CTD) amplifiers
- Future Scalability

Laser architectures

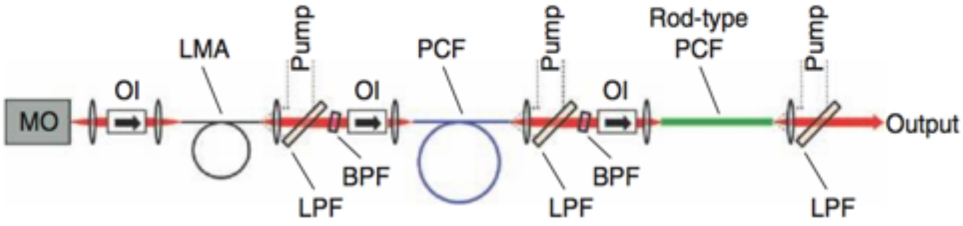
Thin disk

Large Surface / Volume



C.R.E Baer et al, Opt. Lett. 35, 2302 (2010)

Fiber

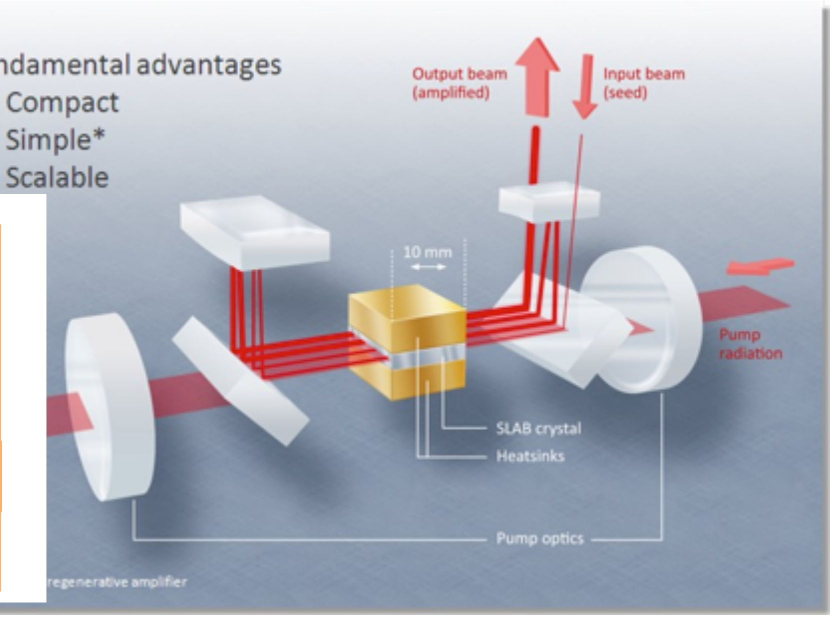


Almost a disk

Inno-Slab

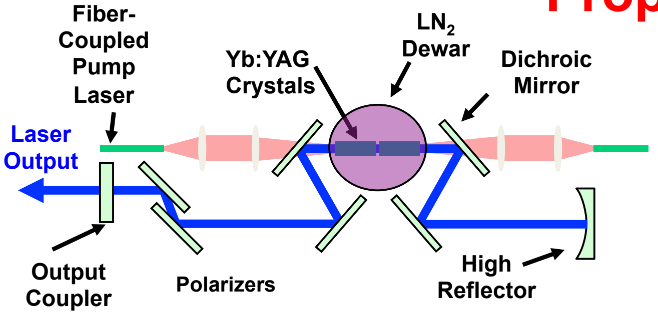
Fundamental advantages

- Compact
- Simple*
- Scalable



Cryogenic

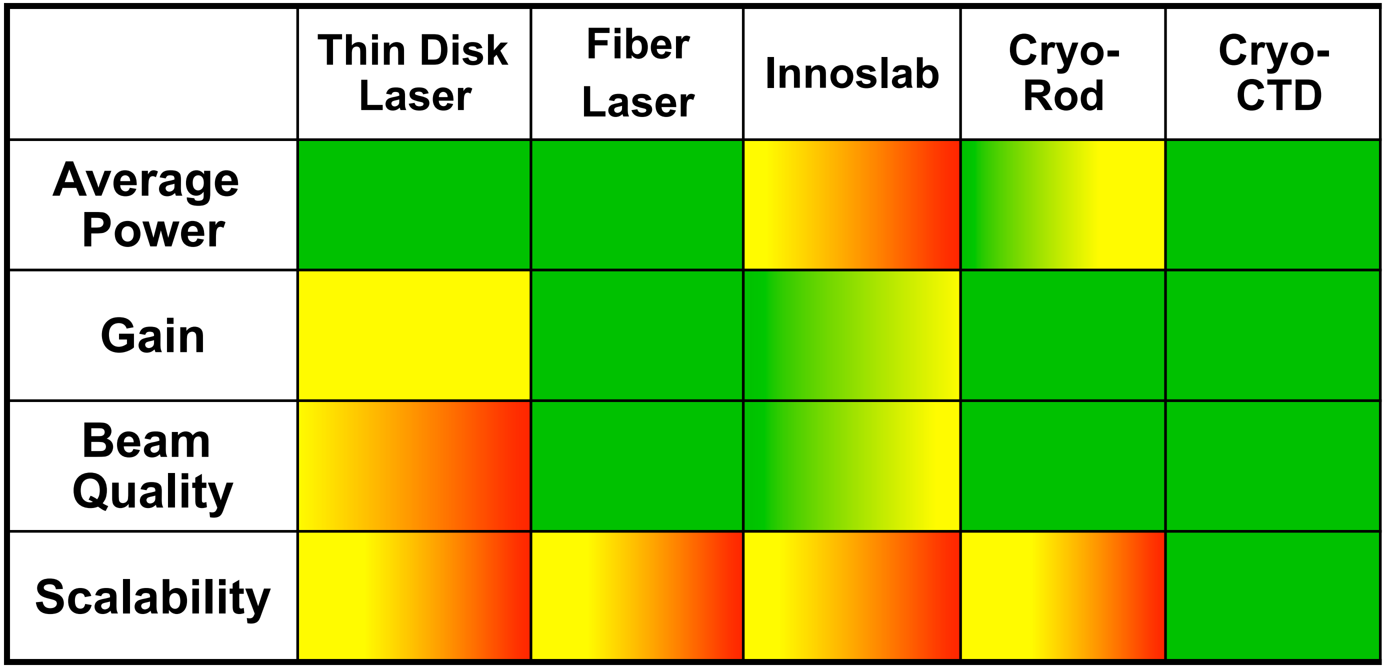
Material Properties



Laser Schematic

T. Y. Fan, MIT Lincoln Laboratory

Architecture



	Thin Disk Laser	Fiber Laser	Innoslab	Cryo-Rod	Cryo-CTD
Average Power	🟩	🟩	🟨🟥	🟩🟨	🟩
Gain	🟨	🟩	🟩🟨	🟩	🟩
Beam Quality	🟨🟥	🟩	🟩🟨	🟩	🟩
Scalability	🟨🟥	🟨🟥	🟨🟥	🟨🟥	🟩

Any of these technologies serves a certain patronage!

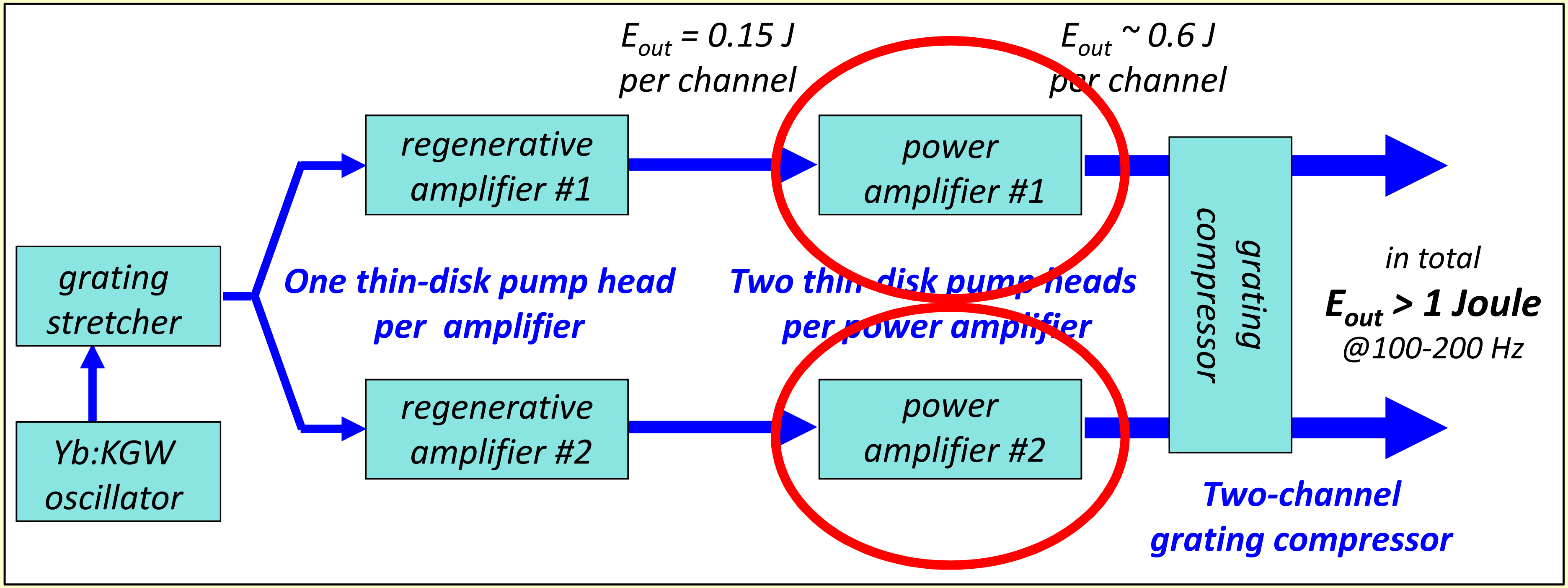
The most attractive approach to high peak and average power scaling is the cryogenic CTD. But: combines several advanced technologies!

Courtesy of Luis Zapata

Room temp. thin disk laser results: MBI

Layout of the two-channel development laser

Max Born Institute



E_{out} = 0.15 J per channel

E_{out} ~ 0.6 J per channel

One thin-disk pump head per amplifier

Two thin-disk pump heads per power amplifier

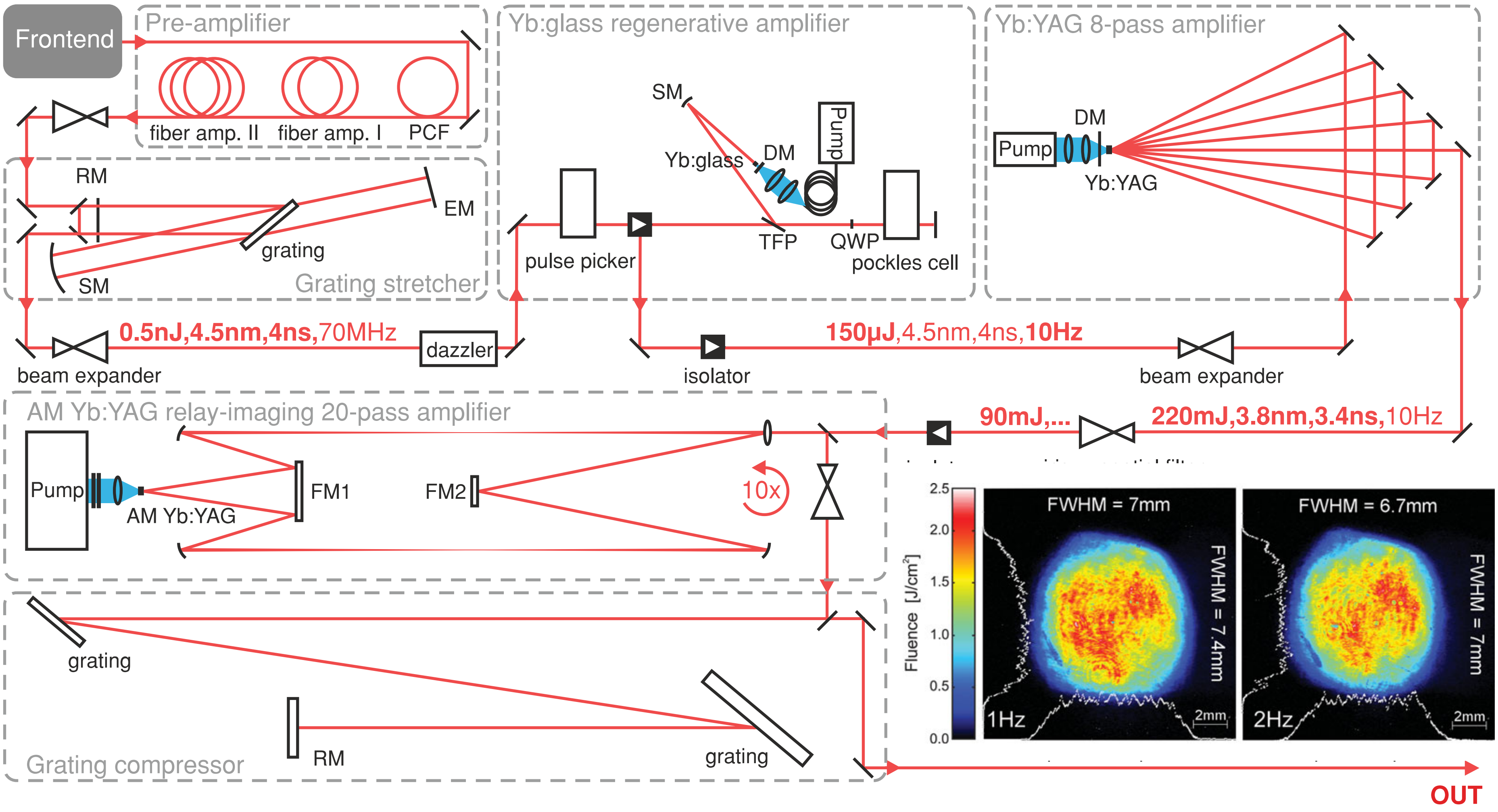
in total **E_{out} > 1 Joule** @100-200 Hz

Two-channel grating compressor

- Pump energy: E_{pump} = 6 … 12 J
- Pump density: I_{pump} = 6 …10 kW/cm^2
- Pump pulse duration: T_{pump} = 1 ms
- Gain per reflection: G = 15 … 30 %

Courtesy of I. Will, MBI

Thin disk laser results: MPQ-IOQ

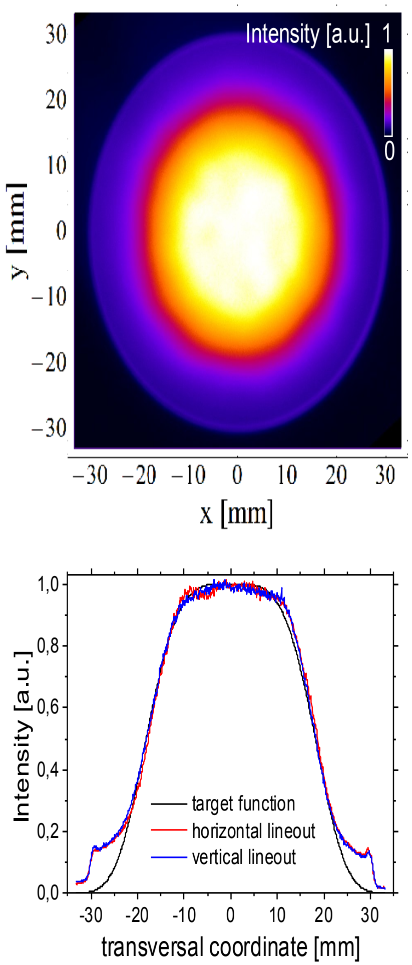


> 1 J, 1-2 Hz, < 1 ps @ 11 kW pump

Ch. Wandt et al, LPR 8, 875–881 (2014)

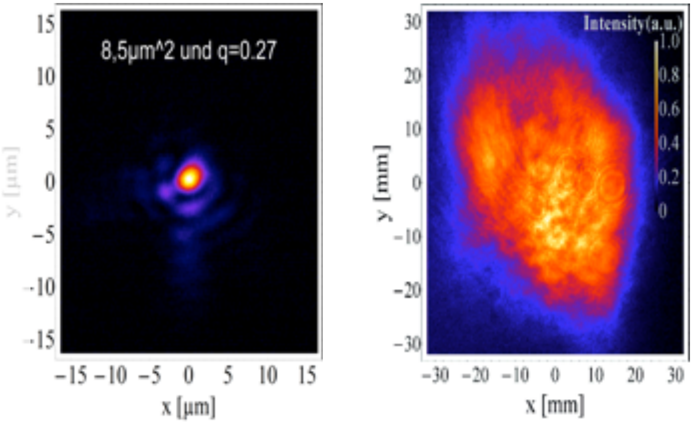
POLARIS A5 - output characteristics

Measured pump profile:

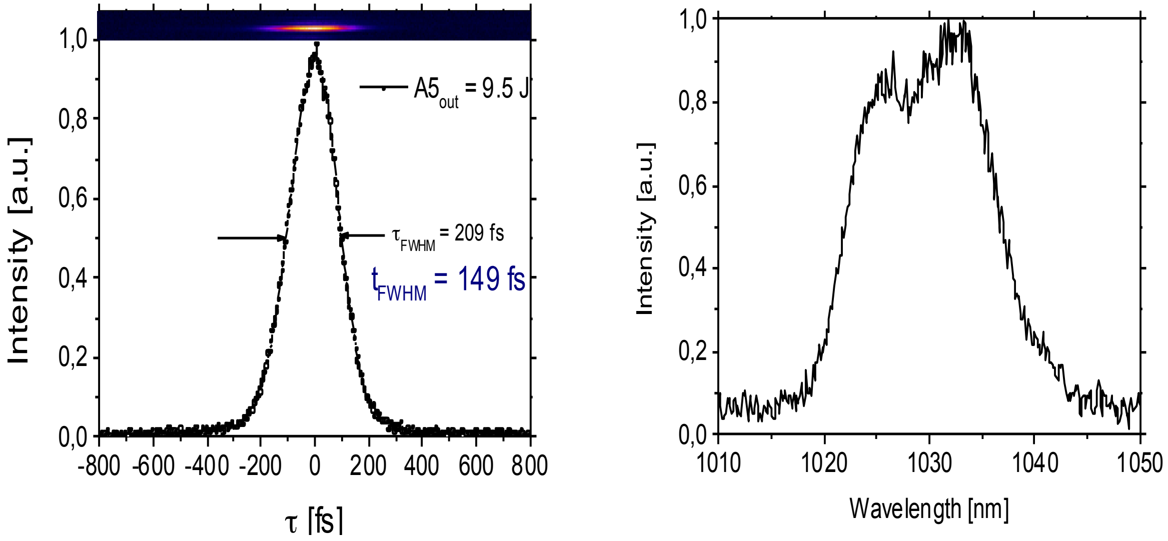


- Output energy up to 16.6 J
- Compression down to 149 fs
- f/2.5-focusing to $A_{FWHM} = 8.5\ \mu m^2$
- Ultra-high temporal contrast ($>10^{12}$)
- Repetition rate 1 Hz

Far- and nearfield profile:



Pulse duration and spectral intensity distribution:



A. Kessler et al., “16.6 J chirped femtosecond laser pulses from a diode-pumped Yb:CaF_2 amplifier”, Optics Letters, Vol. 9, issue 6, p 1333-1336 (2014).
M. Hornung et al., “The all-diode-pumped laser system POLARIS – an experimentalist’s tool generating ultra-high contrast pulses with high energy”, High Power Laser Science and Engineering, Vol. 2, e20 (2014).

Cryogenic laser amplifiers

Research Laboratory of Electronics

Hua Lin (now with Shanghai SIOM)
Ronny Huang
Eduardo Granados (now with SLAC)
Kyung-Han Hong

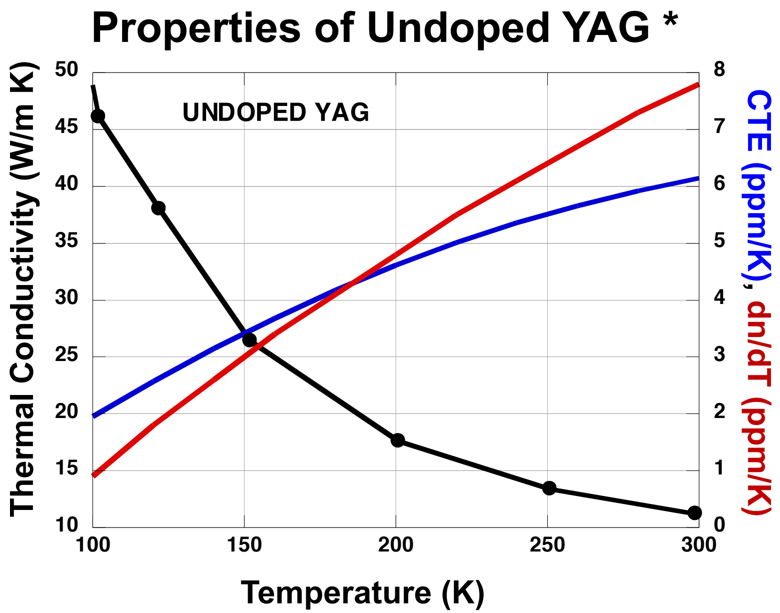
Lincoln Laboratory

T. Y. Fan
Darren Rand
John Zayhowski
Dan Miller
Dennis Harris

Center for Free Electron Laser Science

Luis Zapata
Kelly Zapata
Huseyin Cankaya
Anne-Laure Calendron
Fabian Reichert
Michael Hemmer
Sergio Carbajo
Lars Gumprecht

Cryogenic operation – thermal wavefront


Properties of Undoped YAG *

- **Thermo-optic material properties improve at low temperature**

- **Modest LN_2 requirements (requires ~ 6 l/hr at 1 kW)**

Wavefront (OPD) figure of merit

$$\mathrm{FOM} = \frac{k \cdot \lambda}{\chi_{QL} \cdot \left(\frac{dn}{dT} \right)}$$

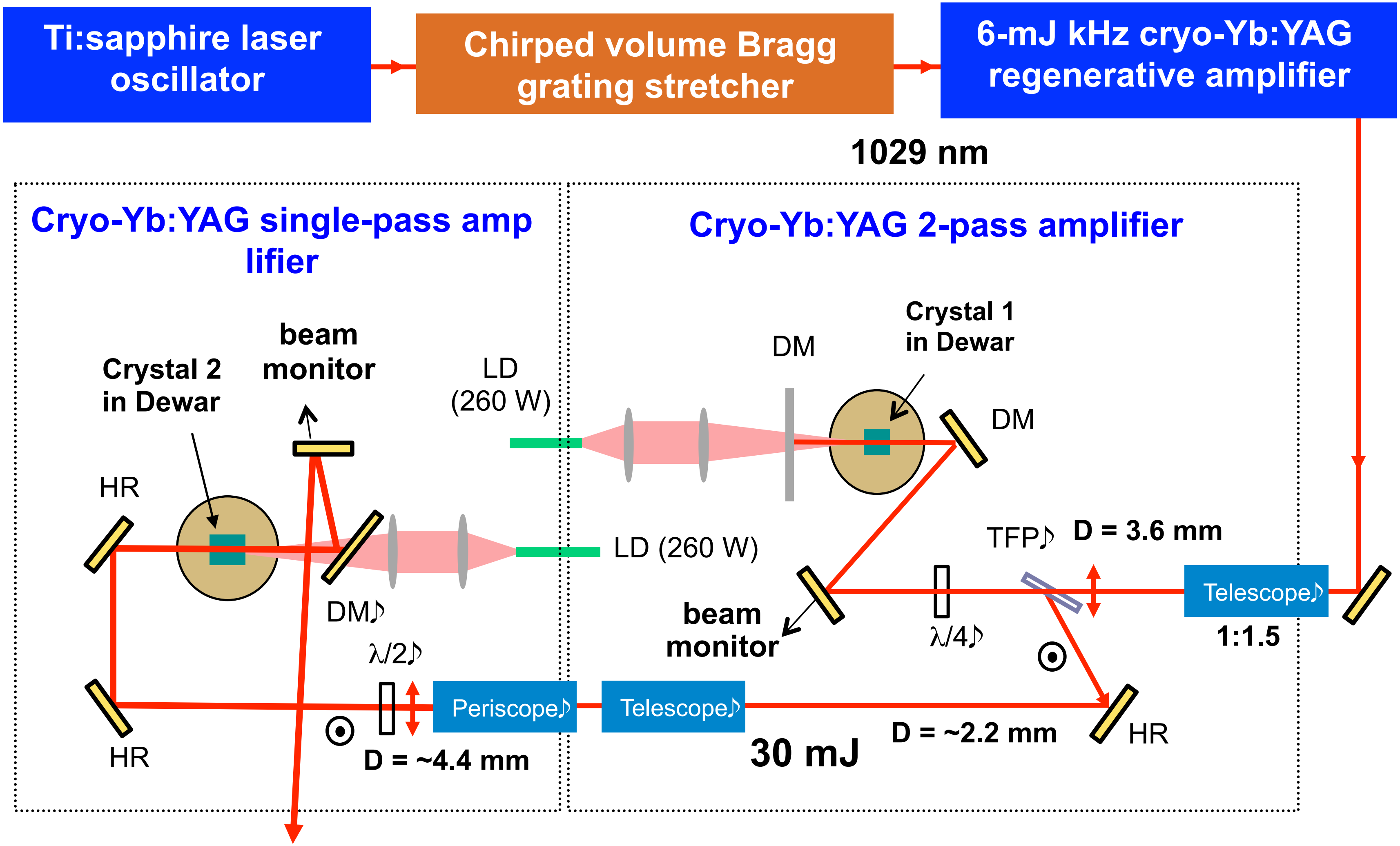
	100 K Yb:YAG	**100 K Yb:YLF**	**300 K Nd:YAG**
FOM (rel. Nd:YAG)	**97**	**187**	**1**
quantum-limited thermal load χ_{QL}	9.6%	5.9%	32%
bandwidth $\Delta\lambda$ (nm)	1.0	17	0.6

T. Y. Fan et al. JSTQE (2007)

Some cryogenic HEP-HAP results

Material	Power / W	P-Energy / J	P-width / ps	Rep.rate / Hz	Reference
Yb:YAG	2300	--	--	cw	J. K. Brasseur et al., *Proc. SPIE*, vol. 6952, (2008)
Yb:YAG	100	1	8.5	100	B.A. Reagan, CLEO 2014, SM1F.4.
Yb: YAG	50	0.050	5.5	1,000	K-H. Hong, OL 2014
Yb:YLF	100	0.010	0.850	10,000	D.E. Miller, OL 2012

High-energy kHz cryo-Yb:YAG amplifier chain



Ti:sapphire laser oscillator

Chirped volume Bragg grating stretcher

6-mJ kHz cryo-Yb:YAG regenerative amplifier

1029 nm

Cryo-Yb:YAG single-pass amp lifier

Crystal 2 in Dewar

beam monitor

LD (260 W)

HR

DM♪

λ/2♪

Periscope♪

HR

D = ~4.4 mm

Cryo-Yb:YAG 2-pass amplifier

DM

Crystal 1 in Dewar

DM

LD (260 W)

TFP♪

D = 3.6 mm

beam monitor

λ/4♪

Telescope♪

1:1.5

Telescope♪

30 mJ

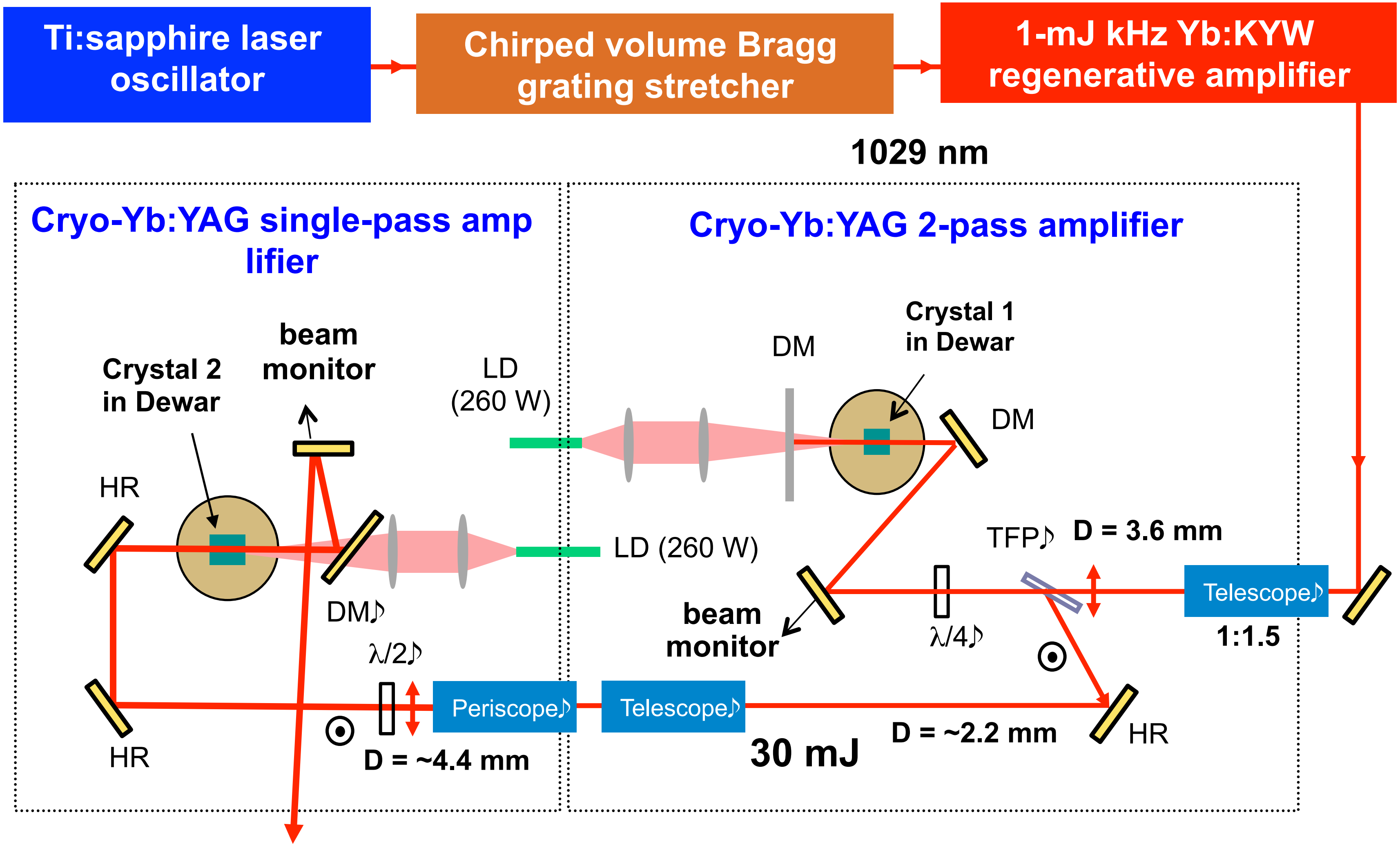
D = ~2.2 mm

HR

56 mJ (42 mJ, 17 ps after compressor), with 500 W pump power

K.-H. Hong *et al.*, Opt. Lett. 39, 3145-3148 (2014)

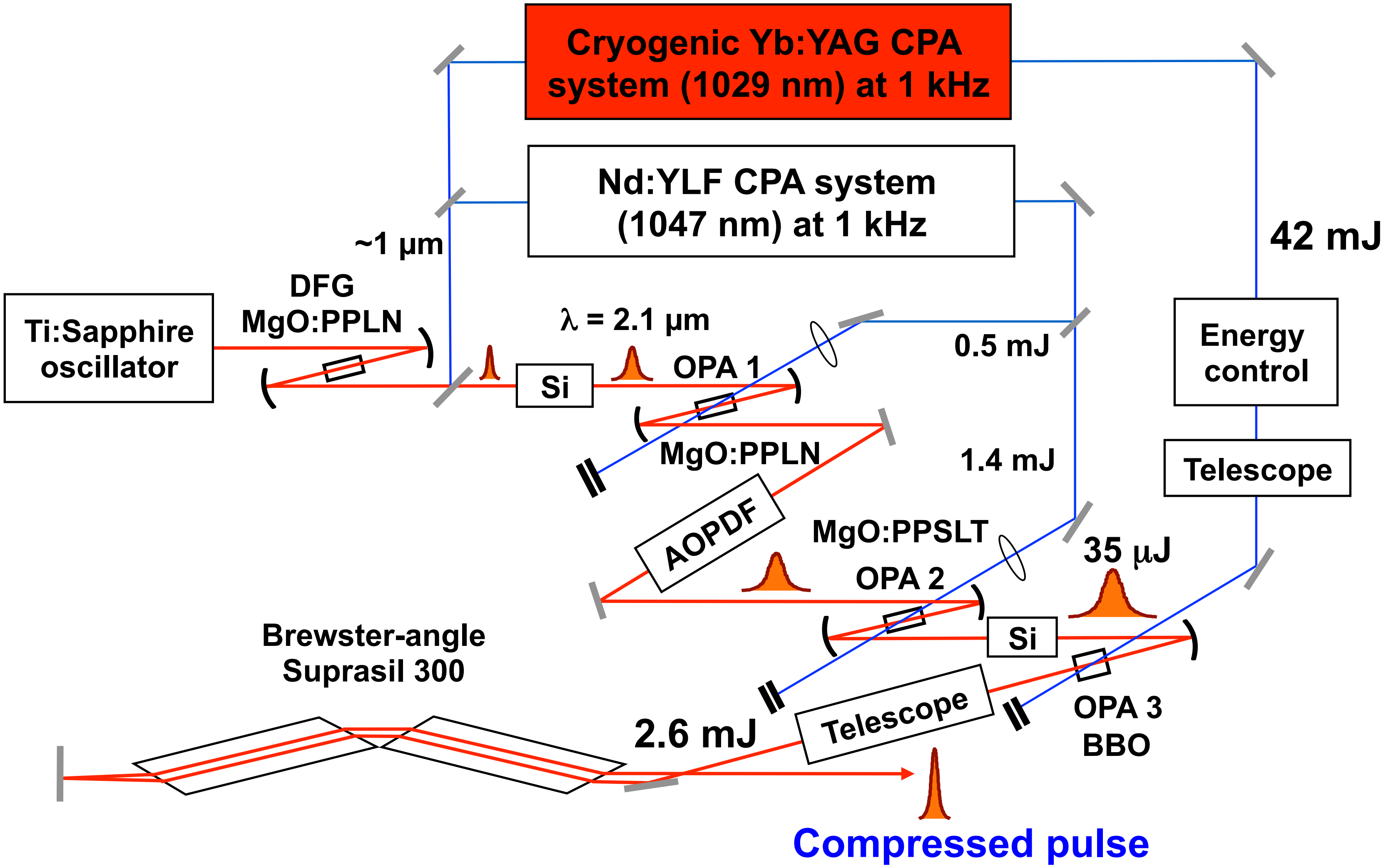
High-energy kHz cryo-Yb:YAG amplifier chain



70 mJ (55 mJ, 5 ps after compressor)

14% Efficiency!

2-mJ, 1-kHz, 2.1-μm broadband OPCPA



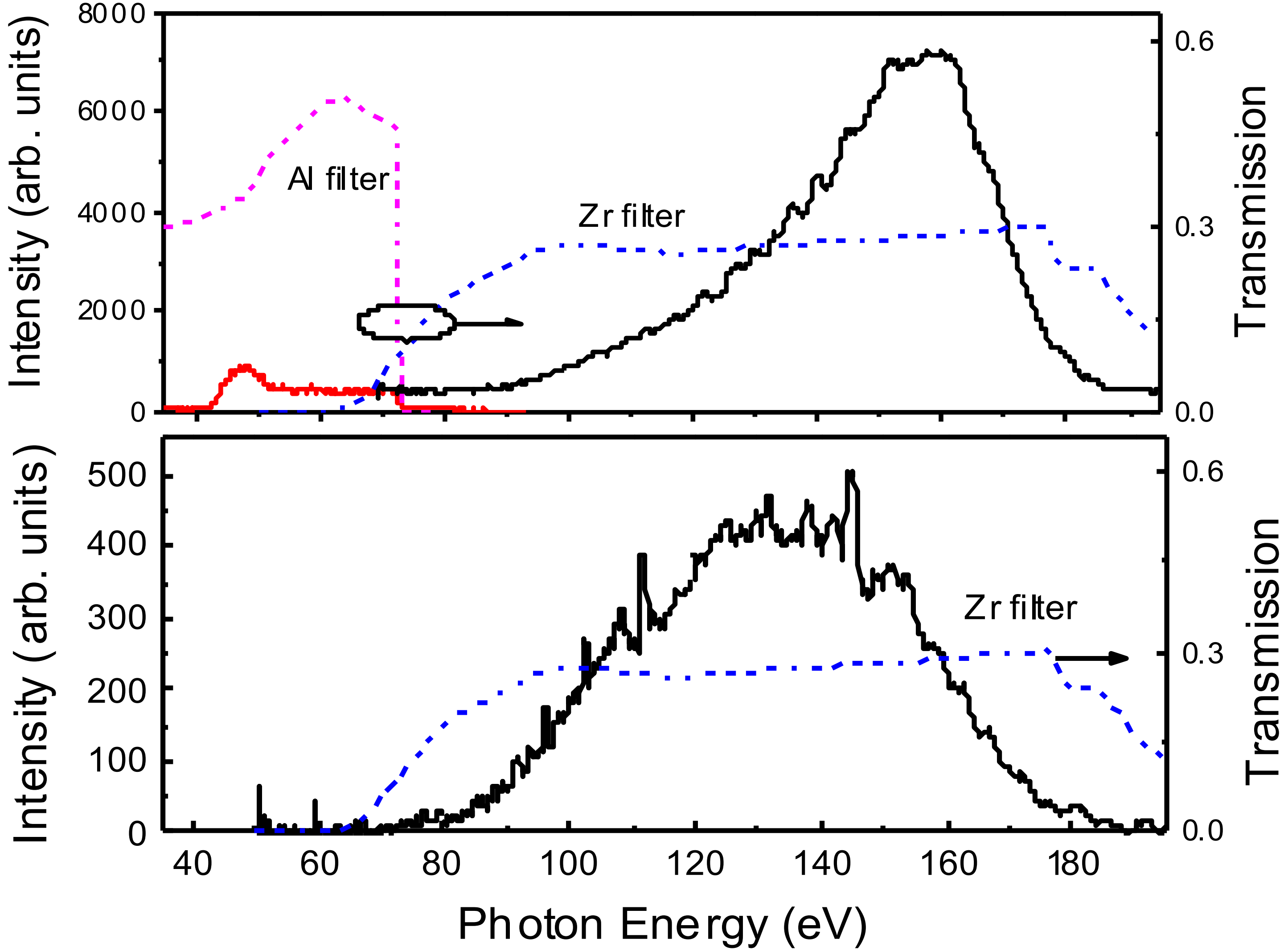
40 fs, 2.1 mJ, compressed pulses at 1 kHz with good beam profile

K.-H. Hong *et al.*, Opt. Lett. 39, 3145-3148 (2014)

High-flux soft X-ray HHG in gas cell

Ar

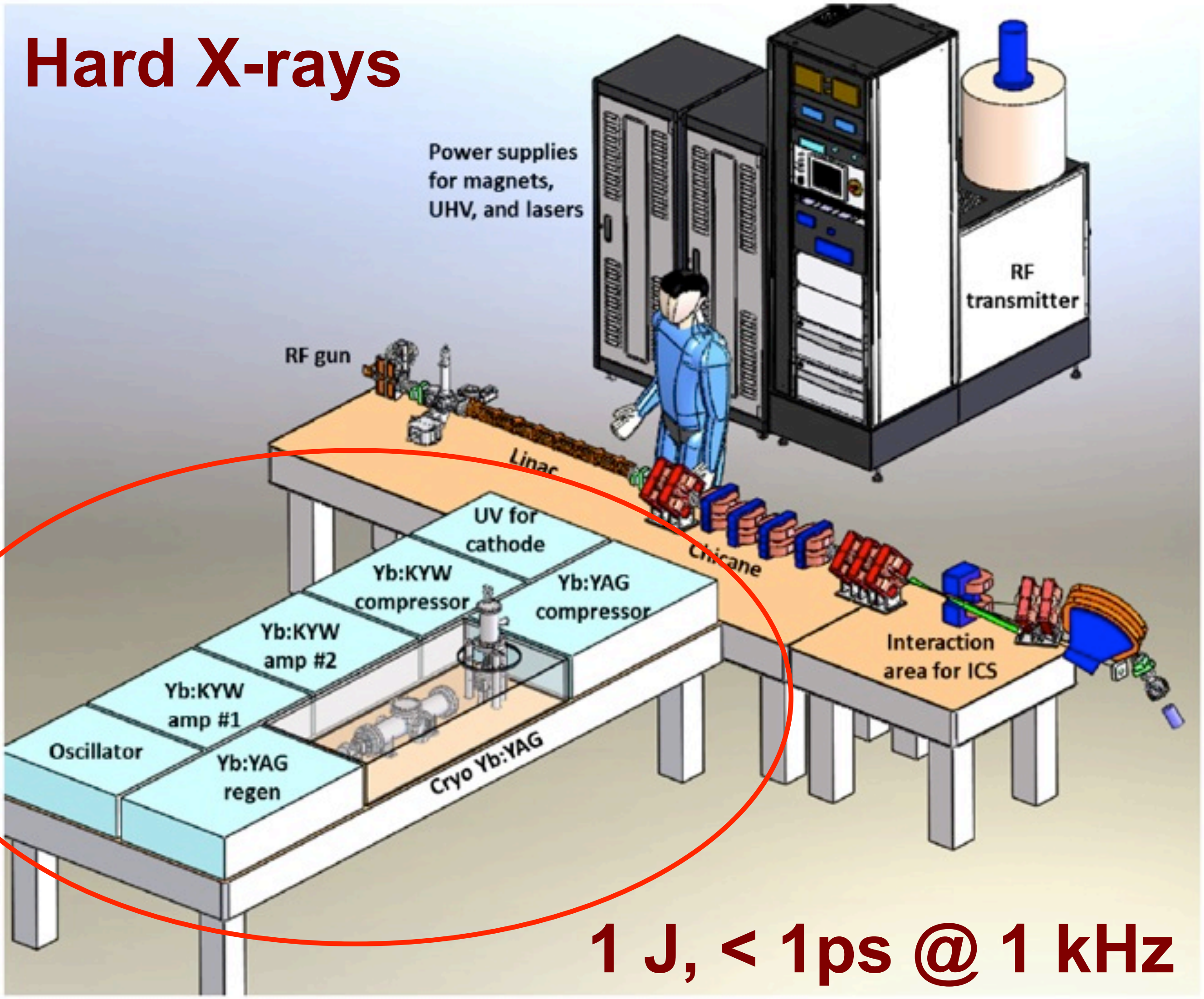
N$_2$



Soft X-ray flux of 2x10^8 photons/s/1% bandwidth at 160 eV from Ar

K.-H. Hong *et al.*, Opt. Lett. 39, 3145-3148 (2014)

Compact inverse Compton scattering source

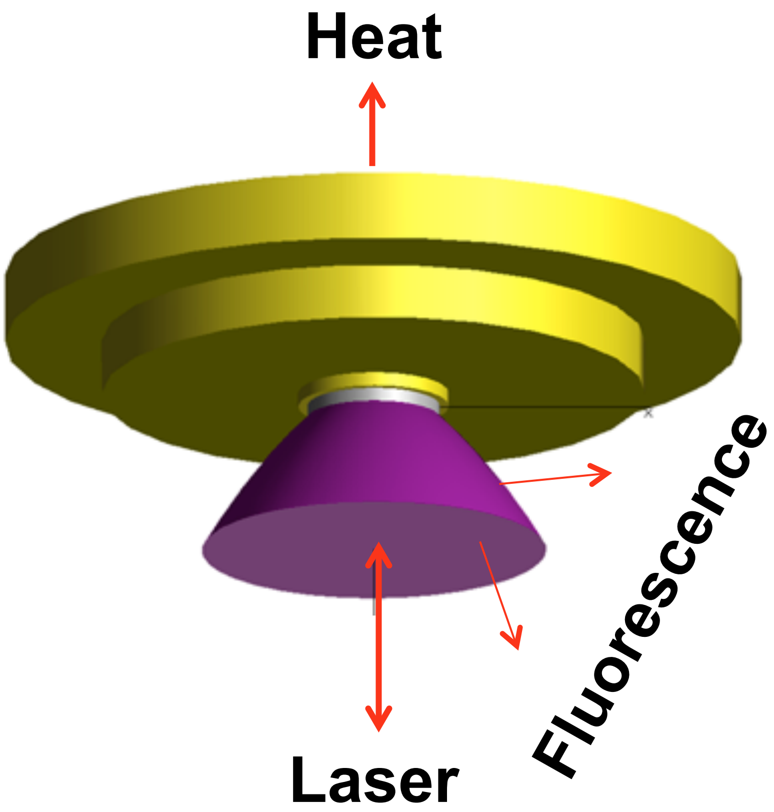


Hard X-rays

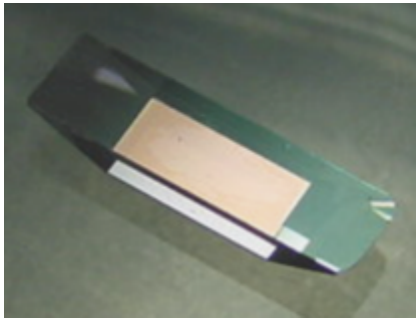
1 J, < 1ps @ 1 kHz

Courtesy of W. Graves, MIT

Face-pumped cryogenic composite-thin-disk



- ✓ High gain
- ✓ High Average power
- ✓ Beam quality
- ✓ Efficiency
- ✓ **Scalability**



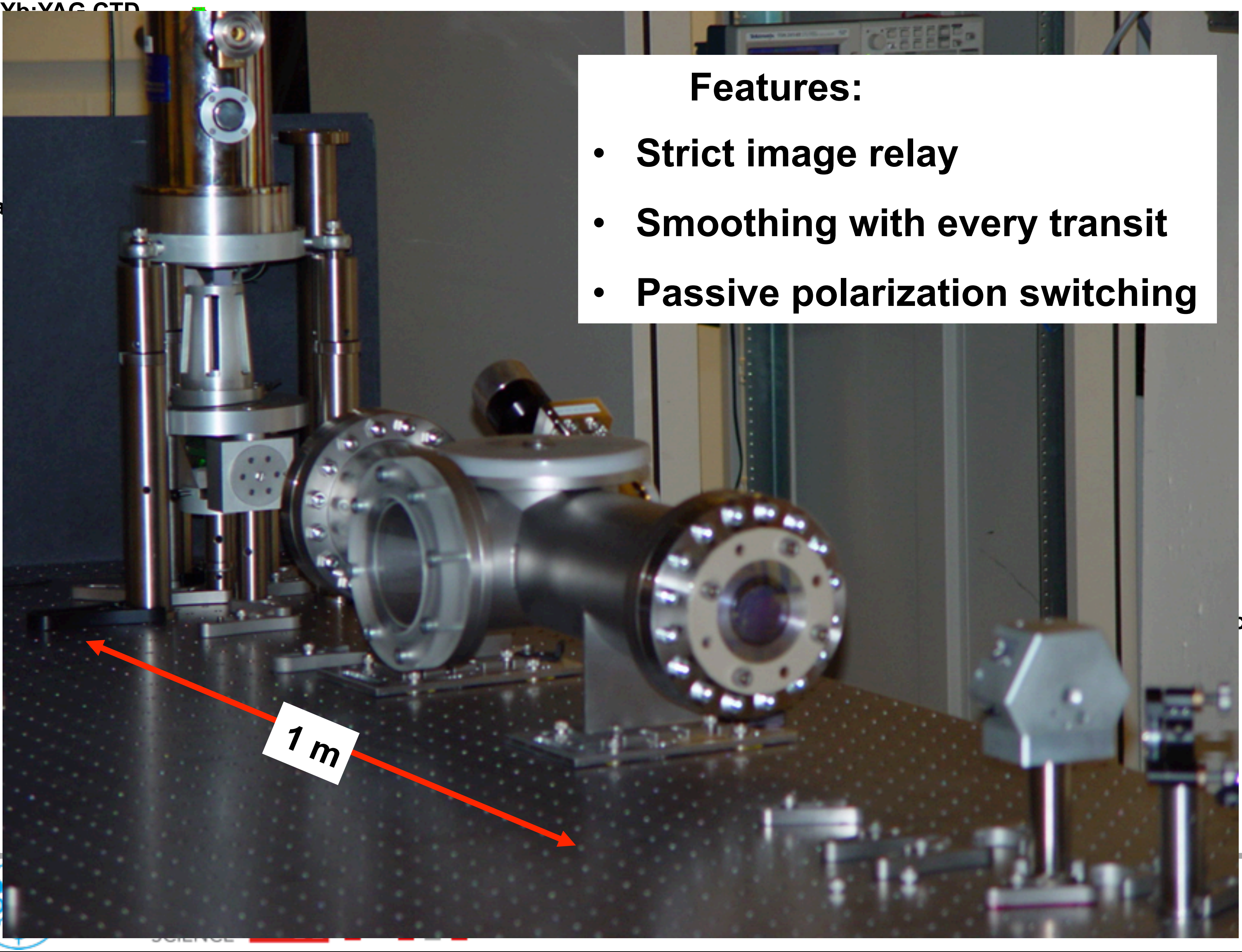
* Scalable Thin Disk Laser L. E. Zapata, R. J. Beach, and S. A. Payne; LLNL;
Capt. S. M. Massey U. S. Air Force; SSDLTR-2003 conference Albuquerque, NM

12-pass amplification architecture

Cryogenic
Yb:YAG CTD

Features:

- Strict image relay
- Smoothing with every transit
- Passive polarization switching



ka

chyard

← In

The composite-thin-disk advantage

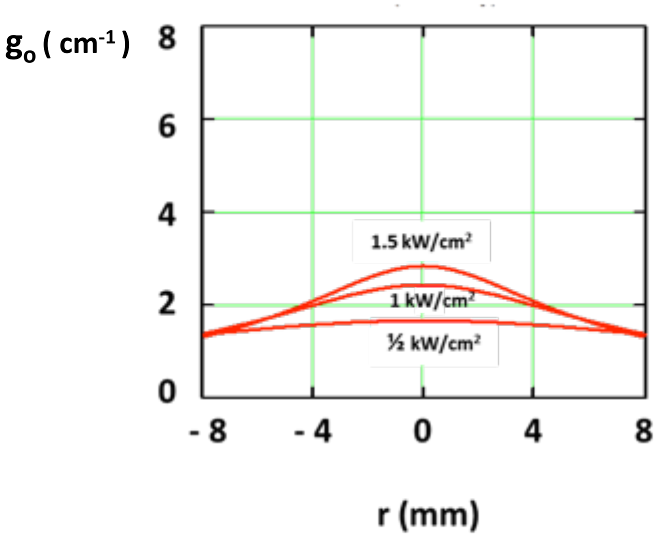
- ✓ **Added volume dilutes ASE**
- ✓ **ASE-limited aperture is larger**

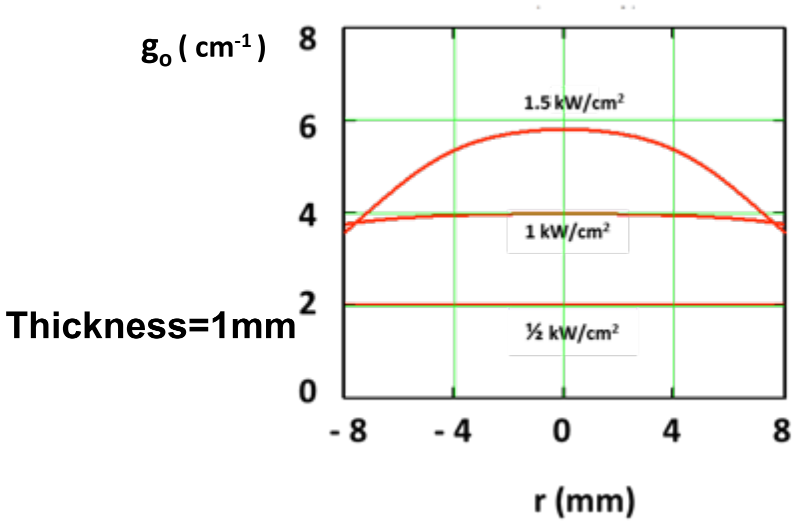
Enables:

- ➢ **Aperture scaling**
- ➢ **Higher gain**

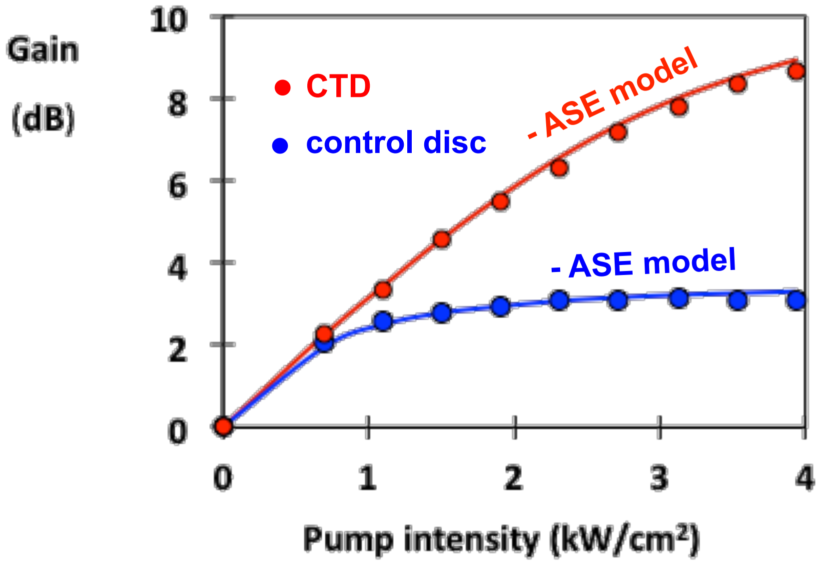
$e^{g_o D} \sim 30$

$e^{g_o D} \sim 3000$





ASE-control and gain hold-off



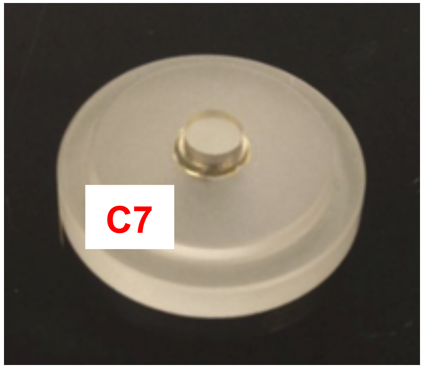
THE PREDICTED

INCREASE IN

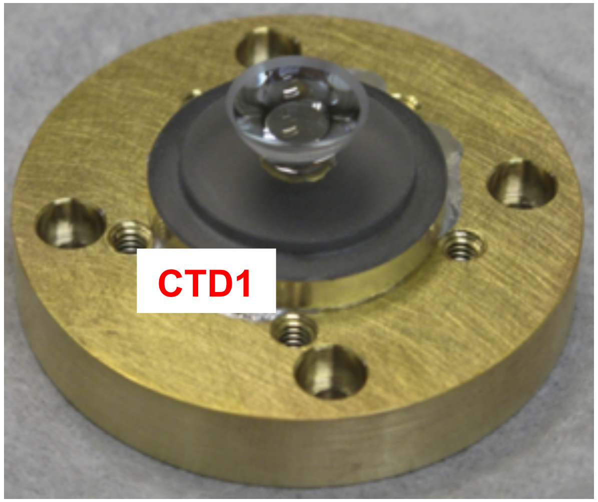
GAIN HOLD-OFF WAS

REALIZED

Control disk



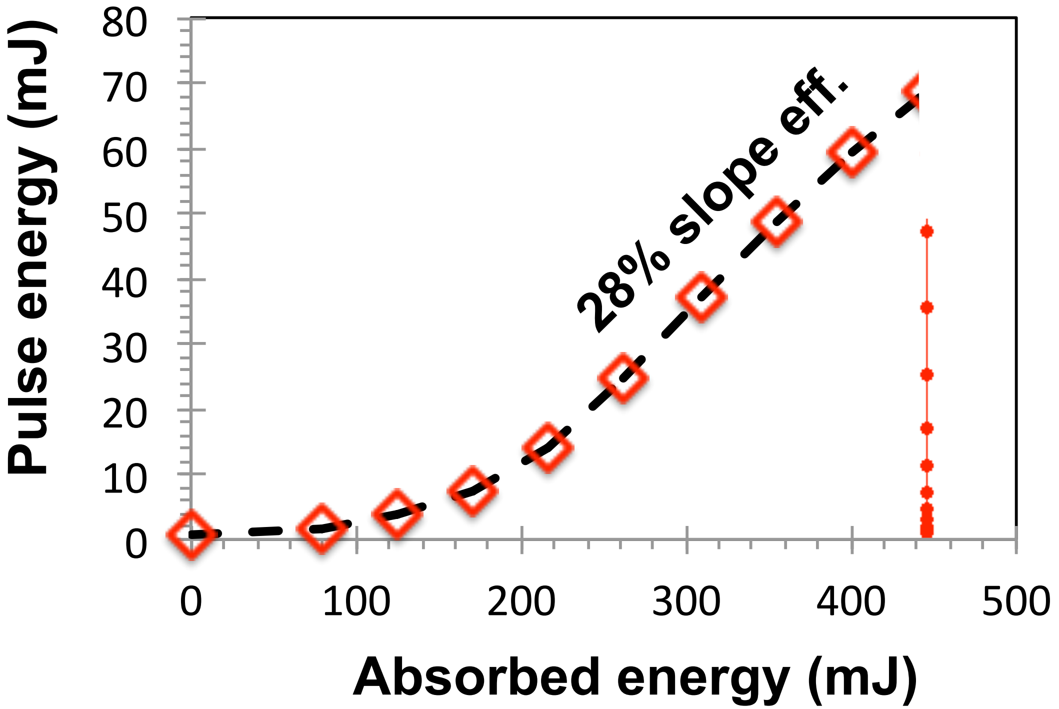
Composite disk with fashioned edges



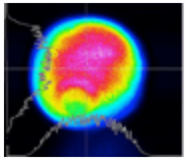
Chirped pulse amplification

- 68 mJ pulse energy at 300 Hz
- Maximum intensity ~ 10 GW/cm^2
- The output was stable at all rep. rates

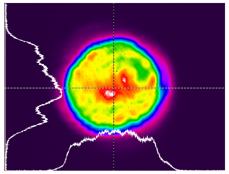
→ Franz-Nodvik calc. verified gain/loss measurements



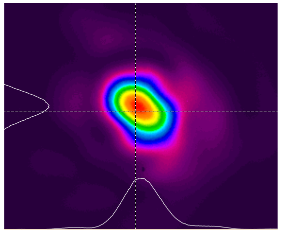
Input beam



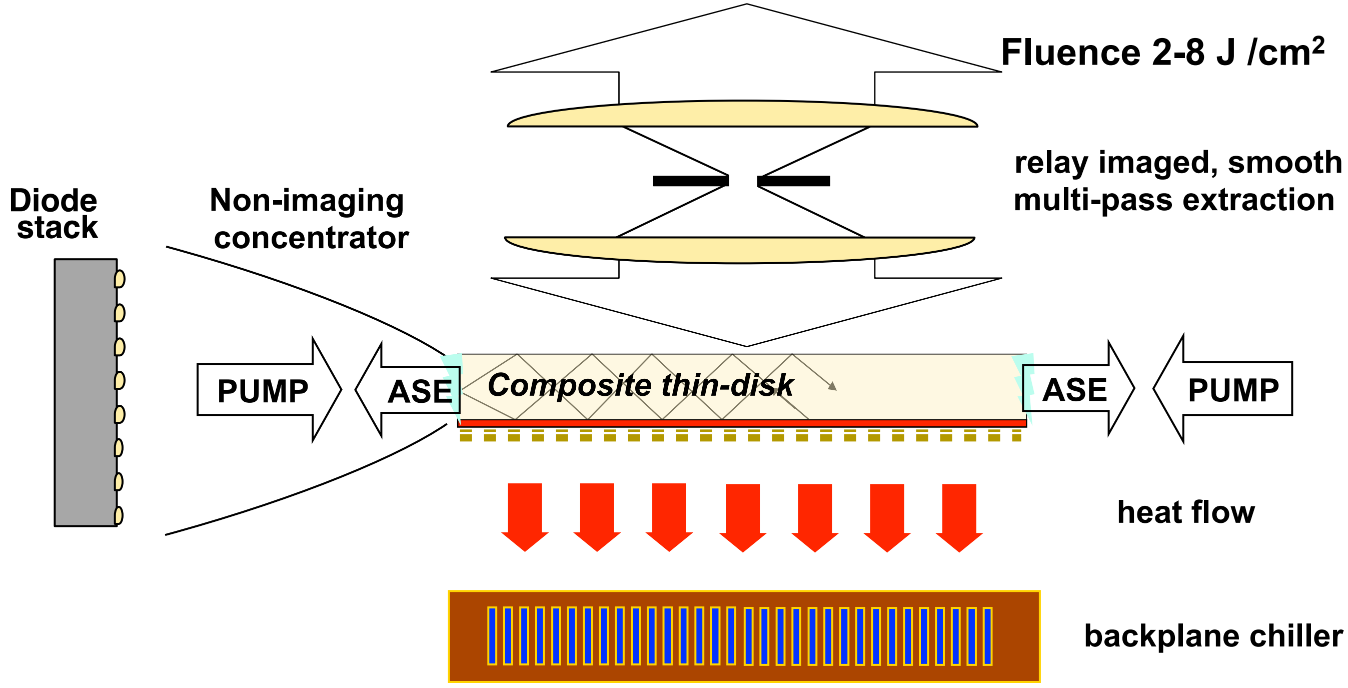
Near field



Far field



The cryogenic CTD-laser combines advanced technologies



*Heat-spreader+boiling

Higher average power only limited by the backplane cooler

1. *Cryo-Yb^{3+}:Host Laser*
2. *Off-axis 4·f telescope, multiplexed geometry*
3. *Diffusion bonded-"CAP"*
4. *Bright diode stacks*
5. *Low thermal-impedance HR coating*
6. *High performance coolers*

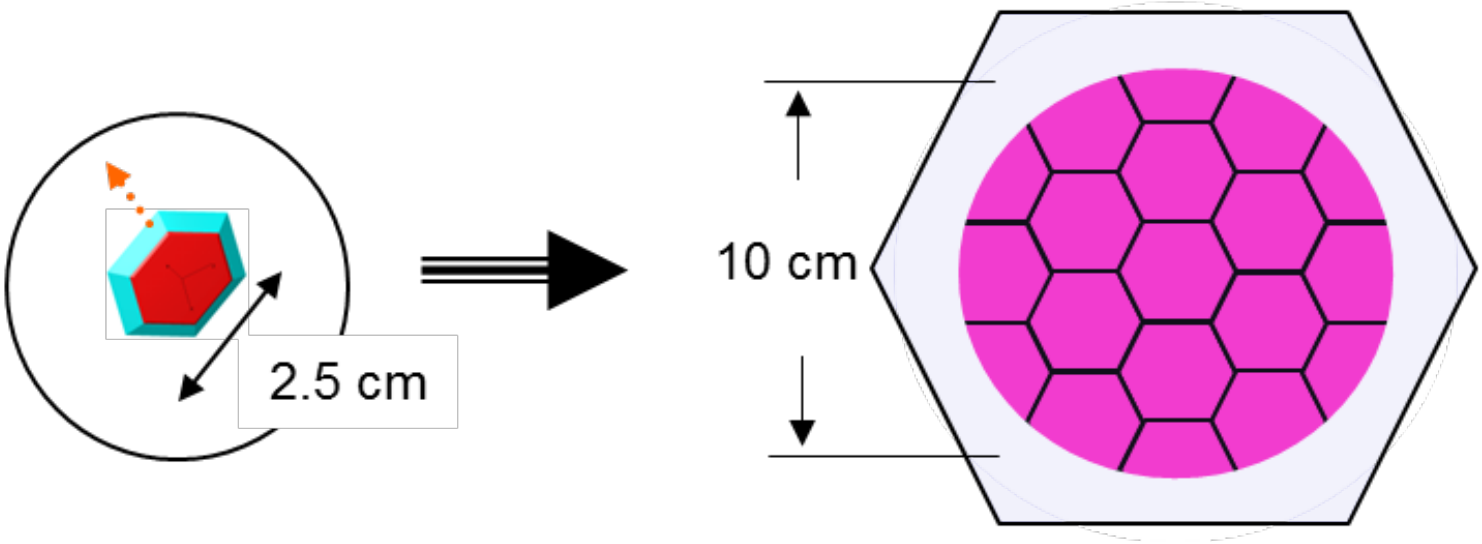
CTD-technology: Further scaling possible

ASE-LIMITED
SINGLE APERTURE

~ 4 J, 500 Hz

MONOLITHIC ARRAY of
GAIN CELLS (MAGiC)

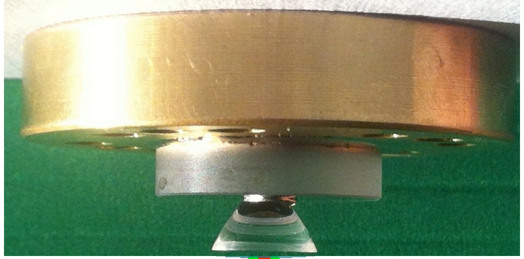
> 50 J, 500 Hz

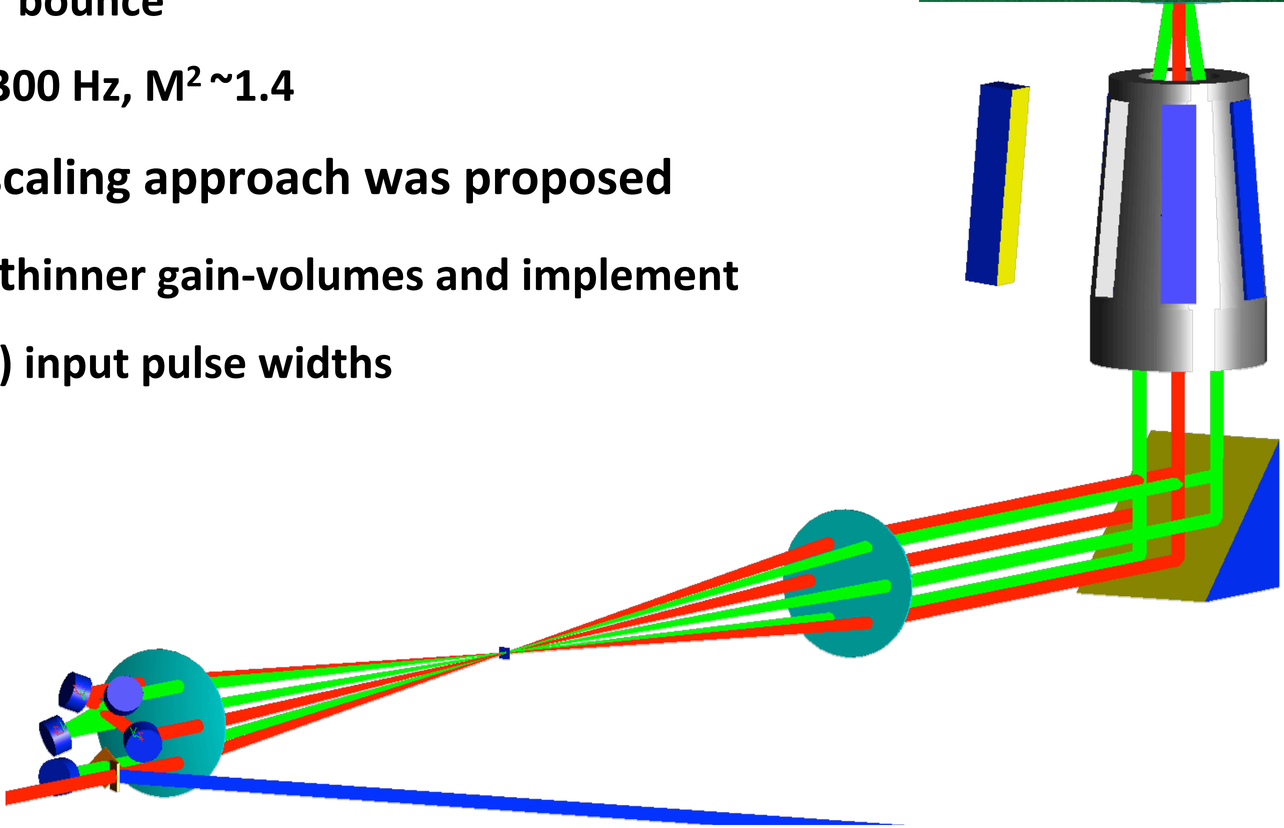


...Fabrication issues remain!

Summary

- A Cryogenic composite thin-disk was tested
  - ✓ 8 dB per bounce
  - ✓ 50mJ@300 Hz, M^2 ~1.4
- The MAGiC scaling approach was proposed
- We will test thinner gain-volumes and implement longer (CFBGs) input pulse widths





Zapata et al, submitted to Optics Letters

US Patent submission

Thank you!