

Tm:YLF lasers for driving EUV Sources

EUVL Workshop – June 6th, 2024

P35

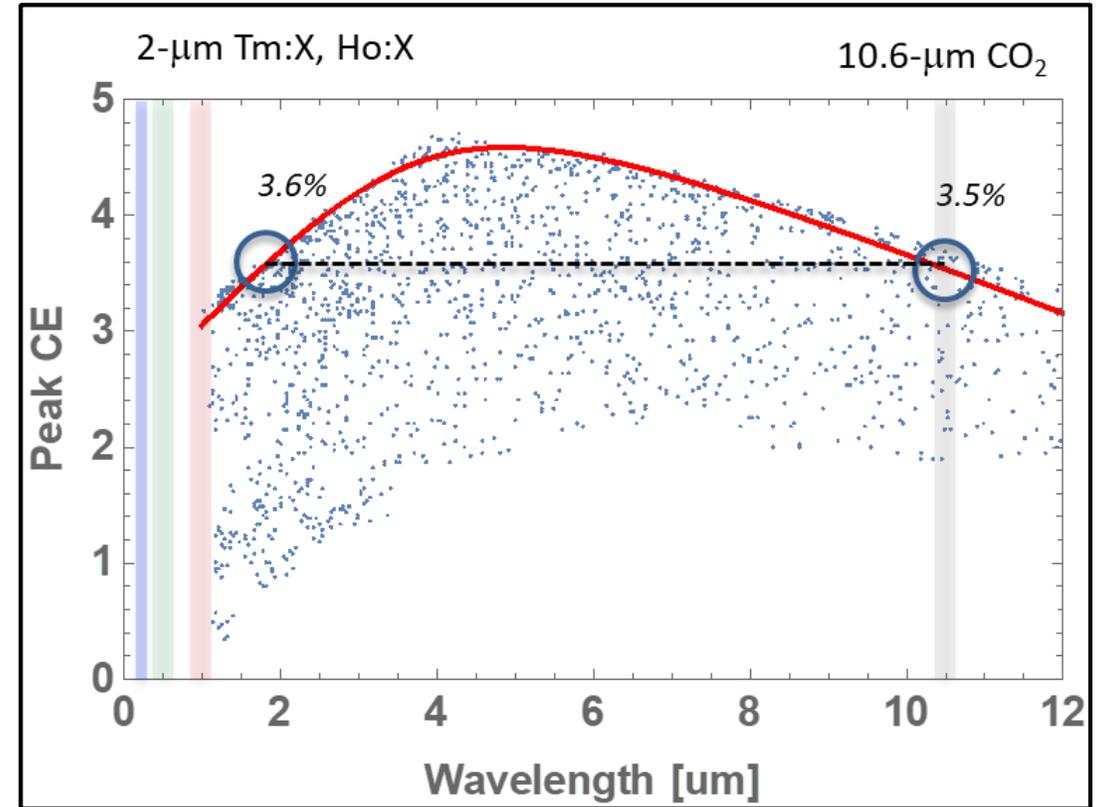
Zbynek Hubka,

Issa Tamer, Leily Kiani, Jason Owens, Andrew Church, Frantisek Batysta, Thomas Galvin, Drew Willard, Andrew Yandow, Justin Galbraith, David Alessi, Colin Harthcock, Brad Hickman, Candis Jackson, James Nissen, Sean Tardif, Hoang Nguyen, Emily Sistrunk, Thomas M. Spinka, and Brendan A. Reagan



High rep. rate 2 μ m with high peak power as potential candidates for driving EUV sources

- **Benefits of a Tm:YLF based laser systems linked to EUV generation**
 - ✓ CE to in-band EUV photons using 2 μ m laser driver on par with 10 μ m CO₂ laser driver*, better than 1 μ m
 - ✓ EUV production by 2 μ m laser produced plasma with 5% eff. demonstrated**
 - ✓ Wall-plug to EUV efficiency ~ 10%
 - ✓ Energy and power scalable
 - ✓ Arbitrary pulse shaping available for eff. optimization
 - ✓ Viable drivers for High Harmonics Generation



HYDRA simulations, shown in previous EUV Workshops

* B. Reagan, et al., *Photon Sources for Lithography and Metrology*, Chapter 23 (2023),

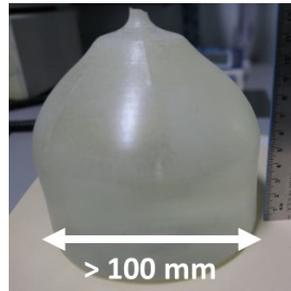
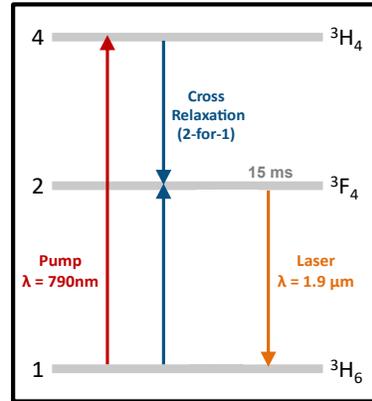
** Y. Mostafa, et al., *Appl. Phys. Lett.* 123, 234101 (2023)

Tm:YLF properties enabling high rep. rate architecture

Tm:YLF

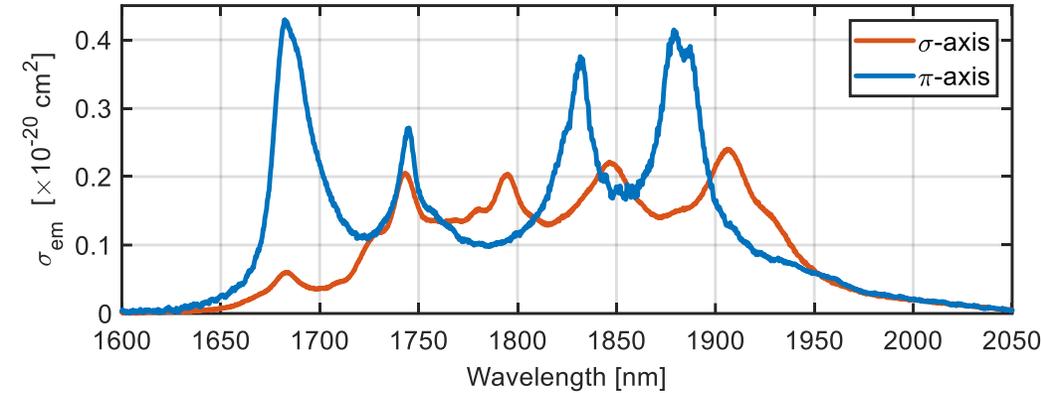
- Bandwidth supports short pulses (< 100 fs)
- Direct diode pumping available, strong absorption
- 2 for 1 effect, still efficient
- Long lifetime (15 ms) supports efficient operation while CW pumping
- Naturally support high power operation (birefringent, negative dn/dT)

Tm:YLF energy level diagram

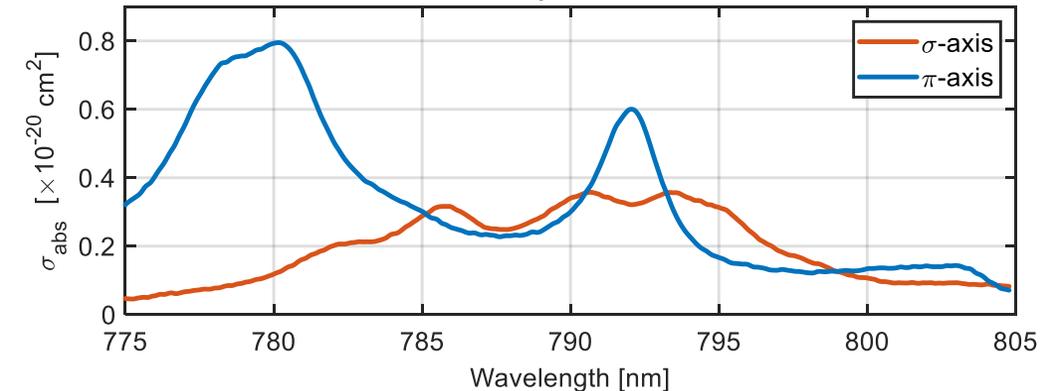


Commercial high power laser diodes

Tm:YLF emission cross section



Tm:YLF absorption cross section



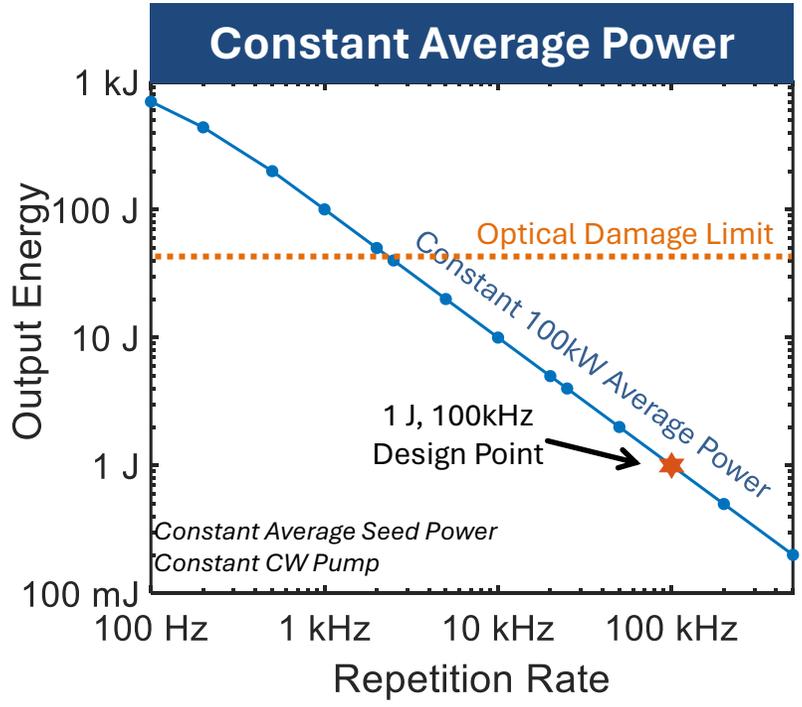
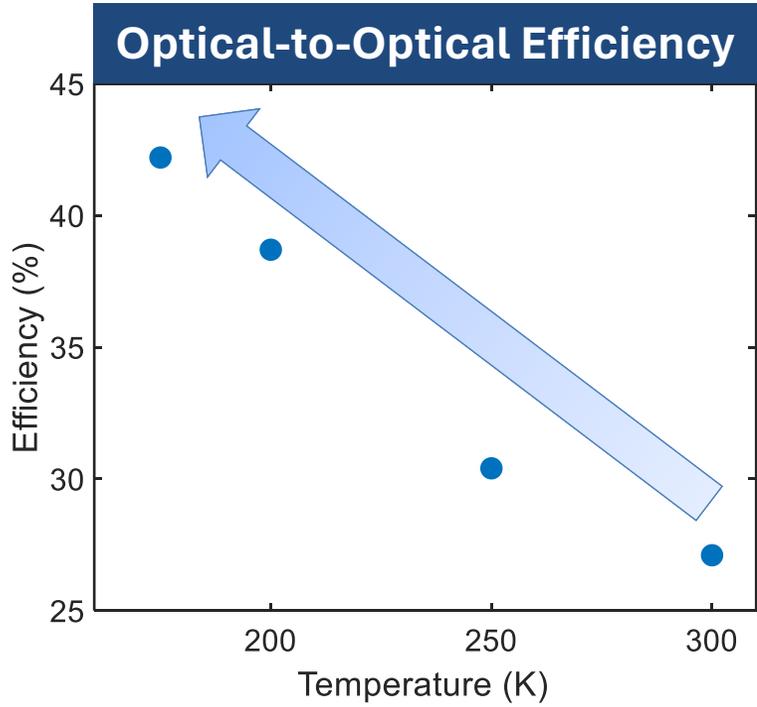
Warm Cryo (175 K) EUV-BAT: 1J, 100kHz, 100 kW Concept



BAT

Big Aperture Thulium Laser Concept

- Wall-plug efficiency 20%
- power requirement 500 kW



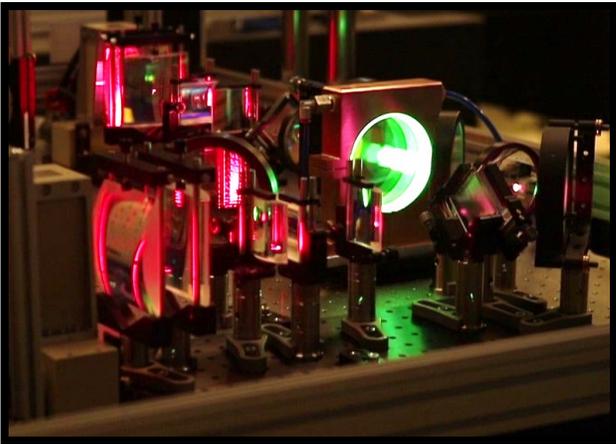
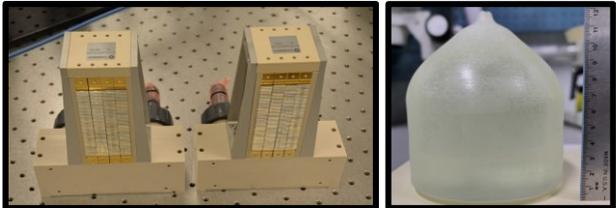
From Photon Sources for Lithography and Metrology, Chapter 23 (2023)

We have conducted a series of experiments to demonstrate proof-of-concept for the Tm:YLF-based BAT laser



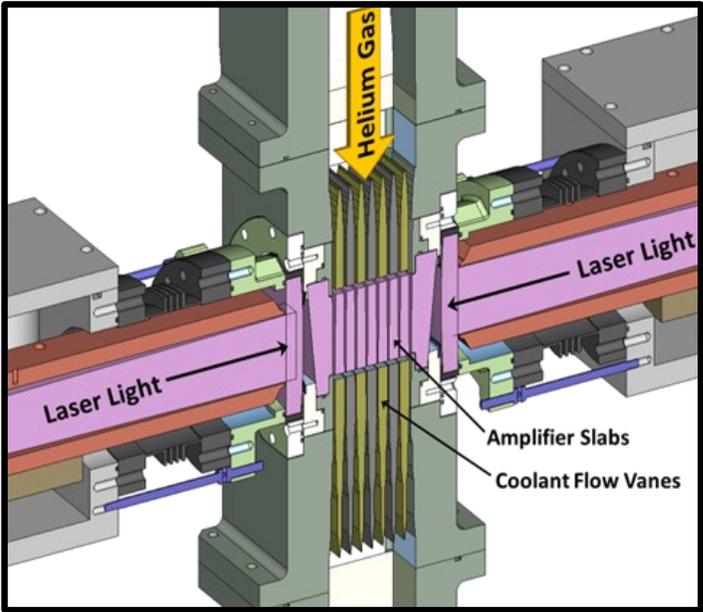
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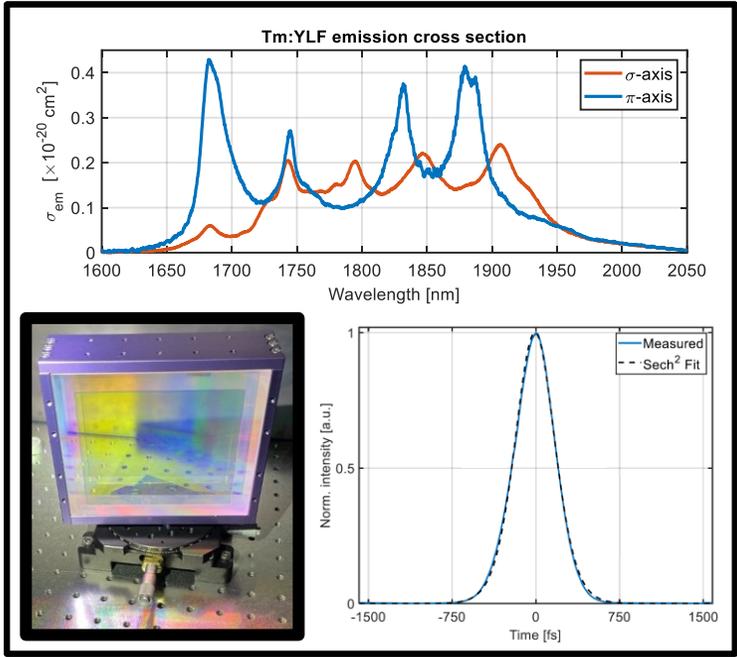
High energy demonstration

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High average power handling capability demonstration

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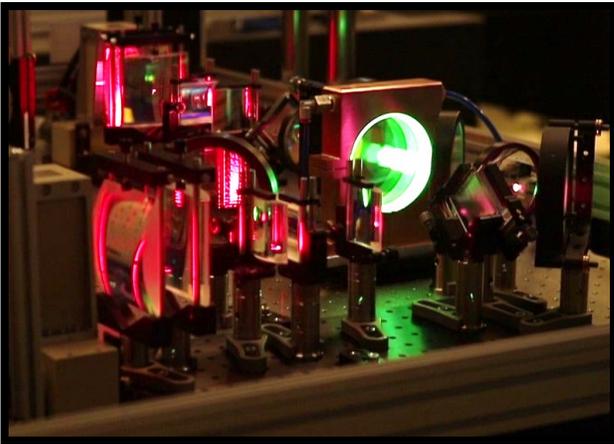
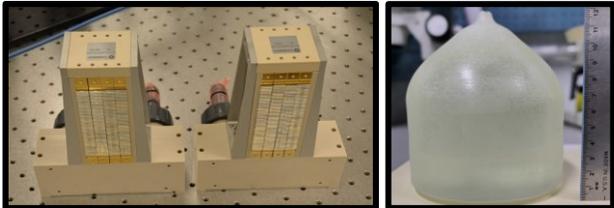
High peak power demonstration

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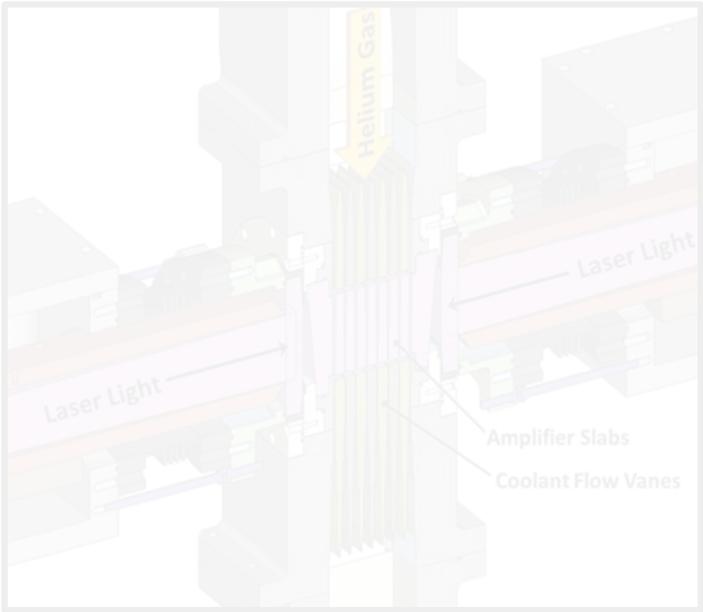
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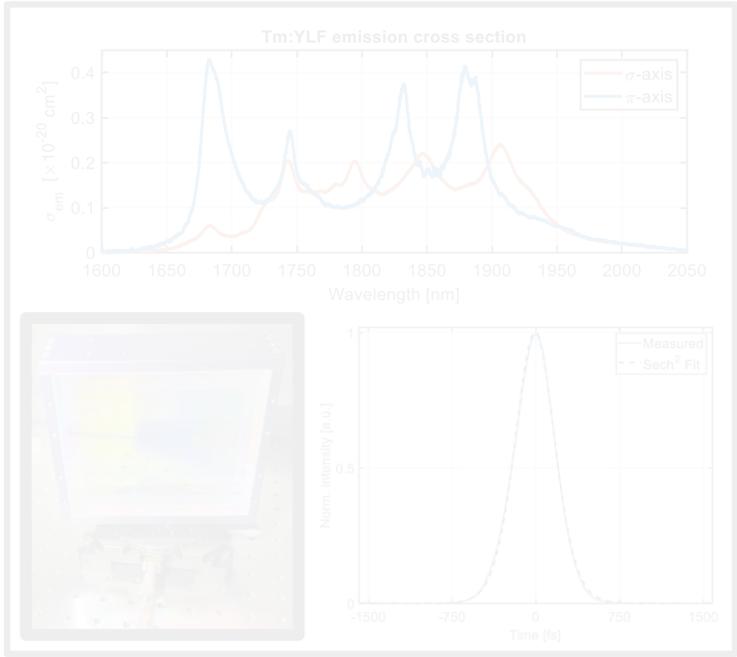
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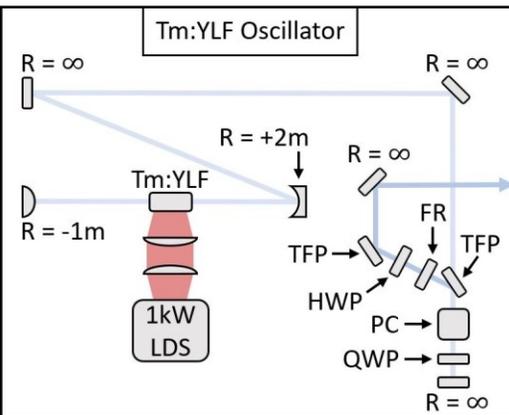
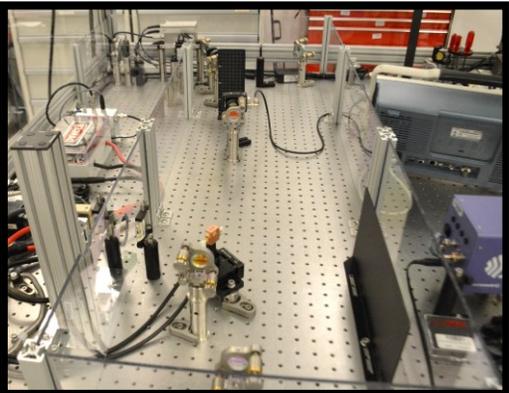
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High peak power demonstration

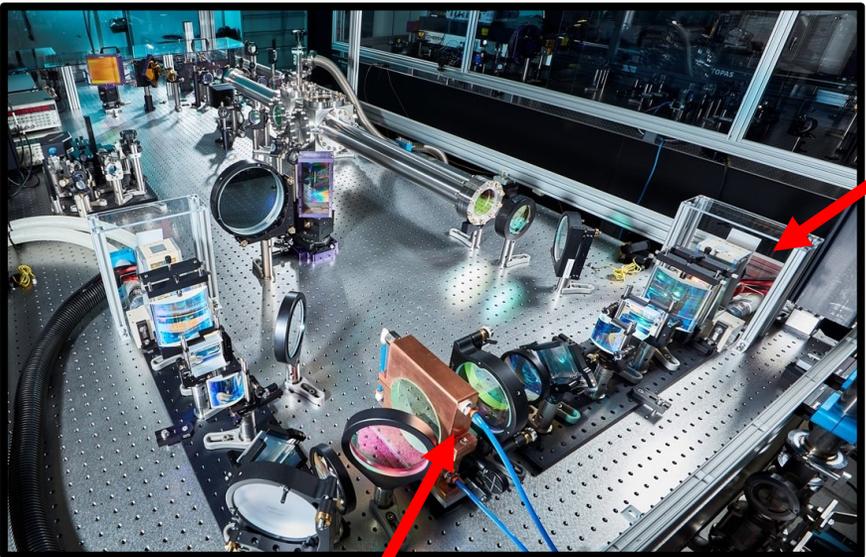
Amplification of ns pulses from in-house built oscillator, showing record breaking output energies from 2 μm system

Diode-Pumped Tm:YLF Oscillator



- Tm:YLF oscillator – 4 mJ, 20 ns, @ 1880nm

Diode-Pumped Tm:YLF Multi-Pass Amplifier



- 35 mm thickness, 100 mm diameter
- 6% at. doping



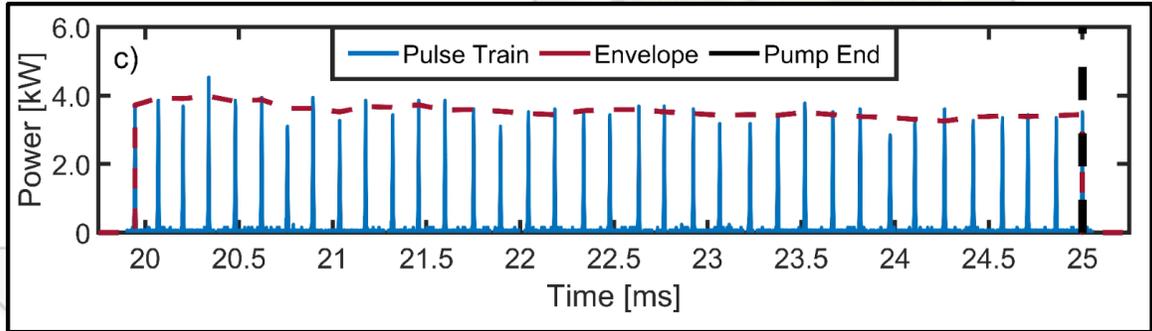
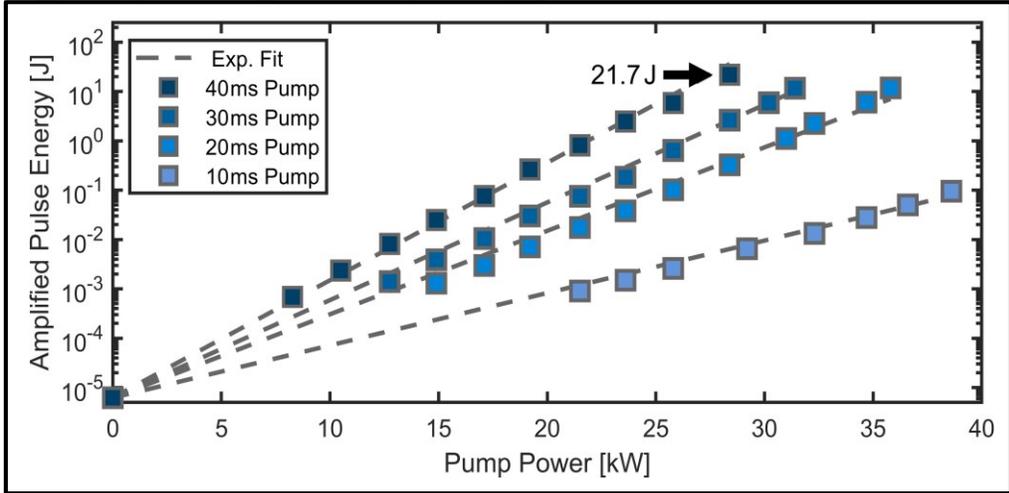
- 4x50 Laser Diode Arrays
- 793 nm, 20 kW each, pulsed at 40 ms

Amplification of ns pulses from in-house built oscillator, showing record breaking output energies from 2 μm system

Diode-Pumped Tm:YLF Oscillator



Diode-Pumped Tm:YLF Multi-Pass Amplifier



- Demonstrated 21.7 J, 20ns, single shot
- Highest demonstrated energy from a 2 μm ns laser system

- Demonstrated burst operation
- ~ 0.5 J per pulse @ 6.8 kHz, 19% o-o efficiency

• Tm:YLF oscillator – 4 mJ, 20 ns, 1 Hz @ 1880nm

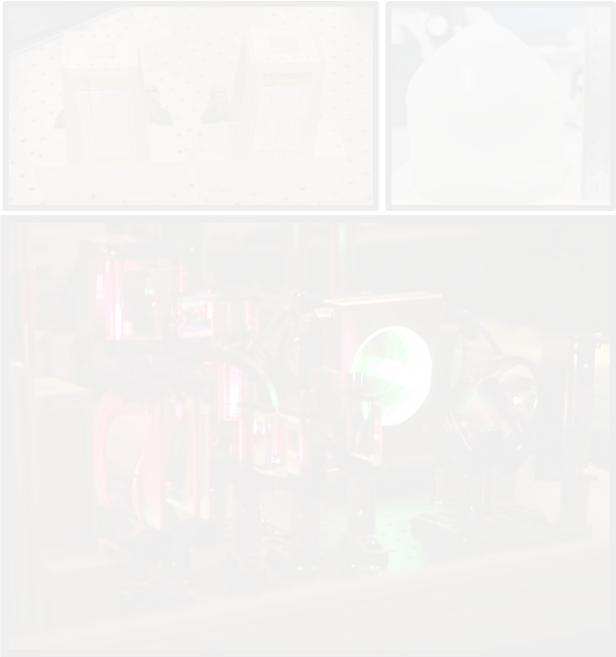
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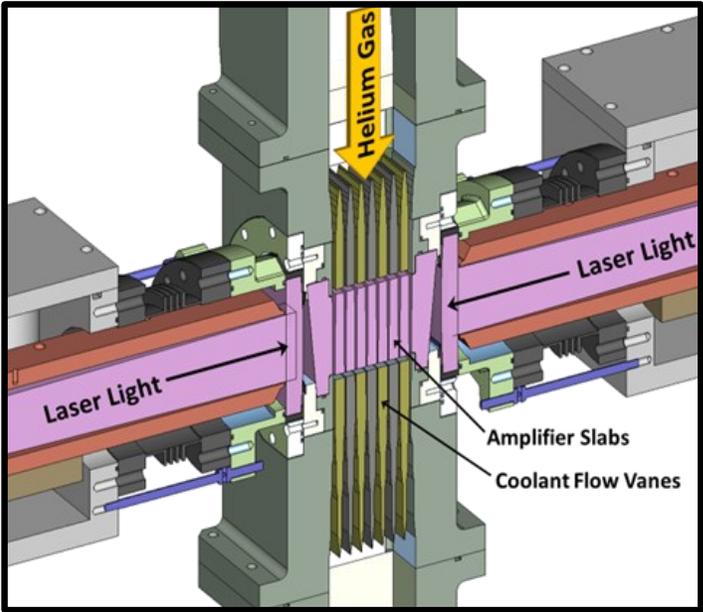
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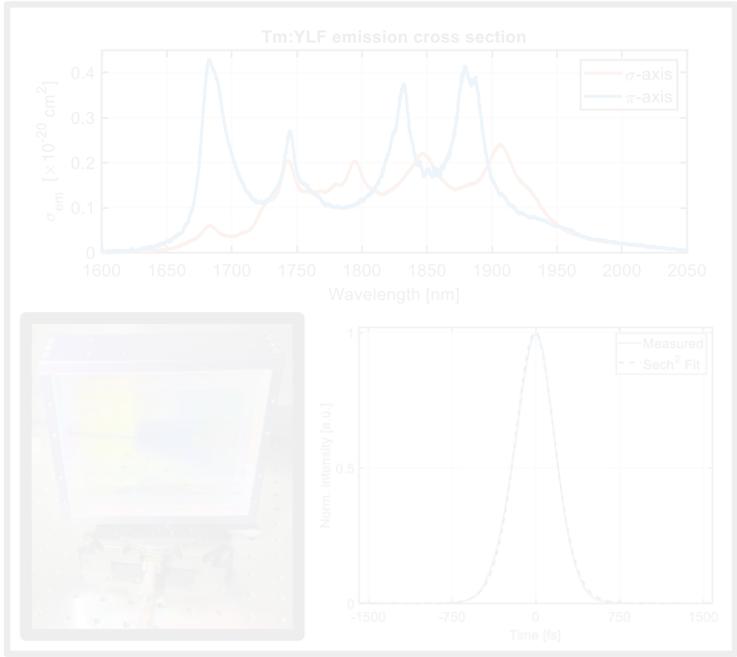
High energy demonstration

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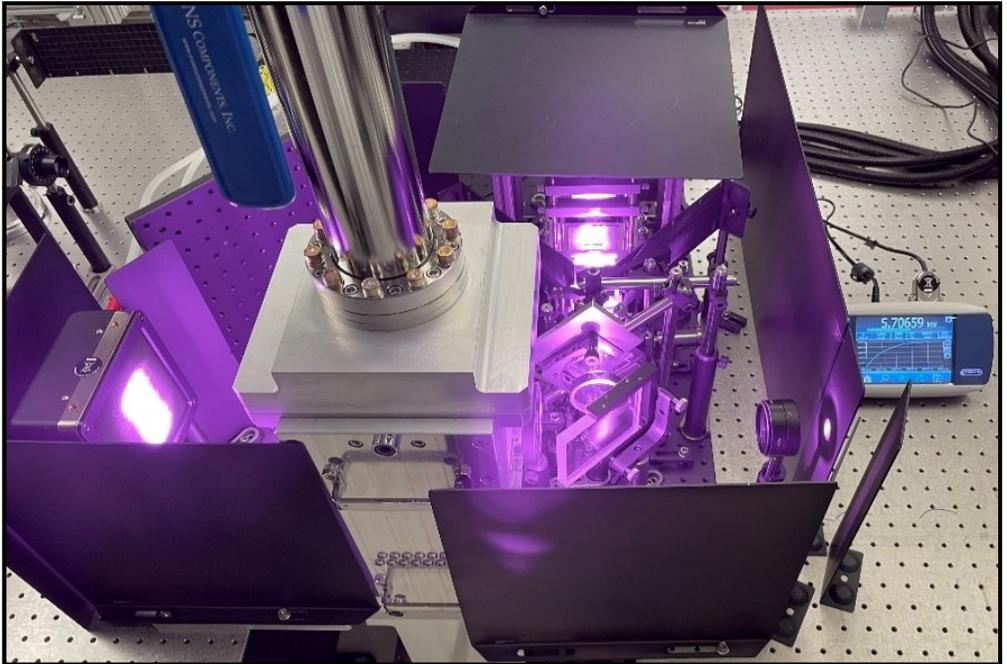
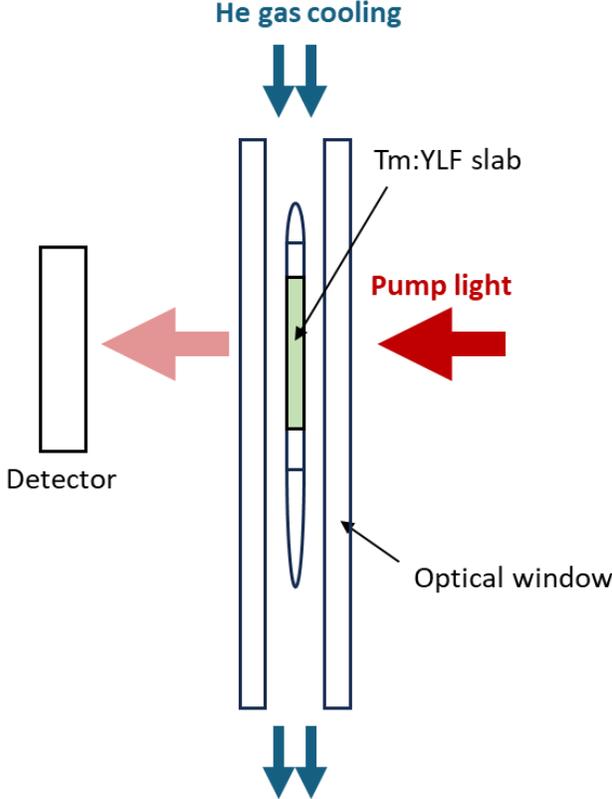
High average power handling capability demonstration

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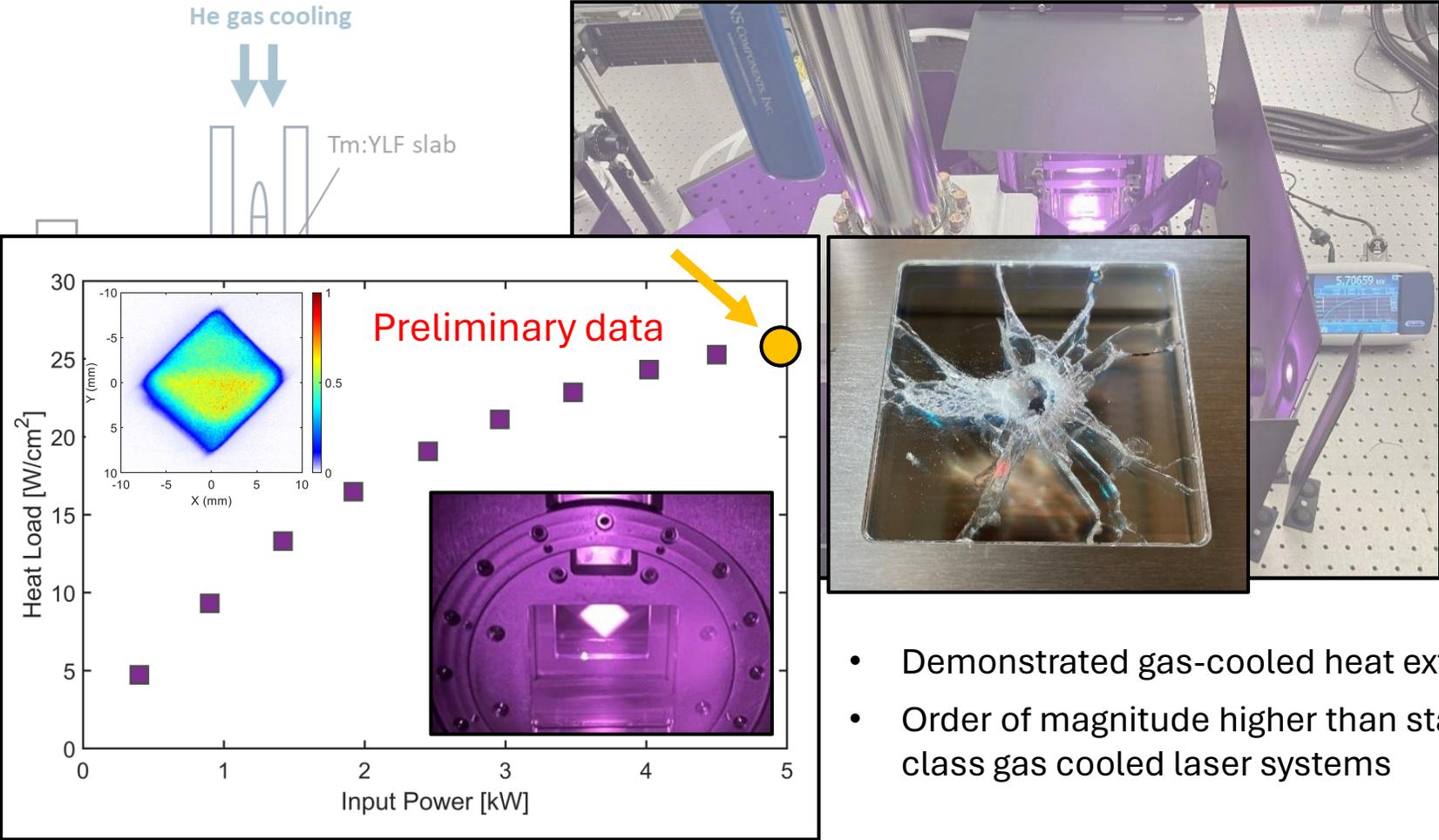


High peak power demonstration

CW pumped gas cooled Tm:YLF slab experiment, aiming at heat removal of $> 20 \text{ W/cm}^2$



CW pumped gas cooled Tm:YLF slab experiment, aiming at heat removal of $> 20 \text{ W/cm}^2$



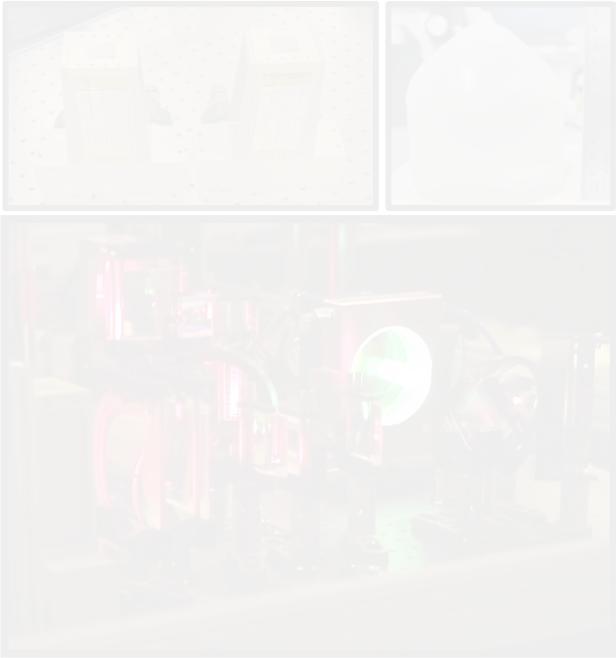
- Demonstrated gas-cooled heat extraction $> 20 \text{ W/cm}^2$
- Order of magnitude higher than state-of-the-art for PW-class gas cooled laser systems

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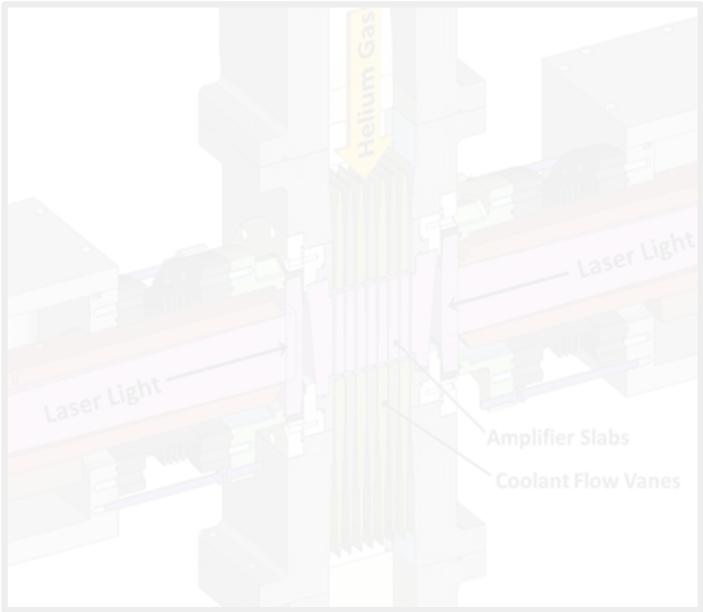
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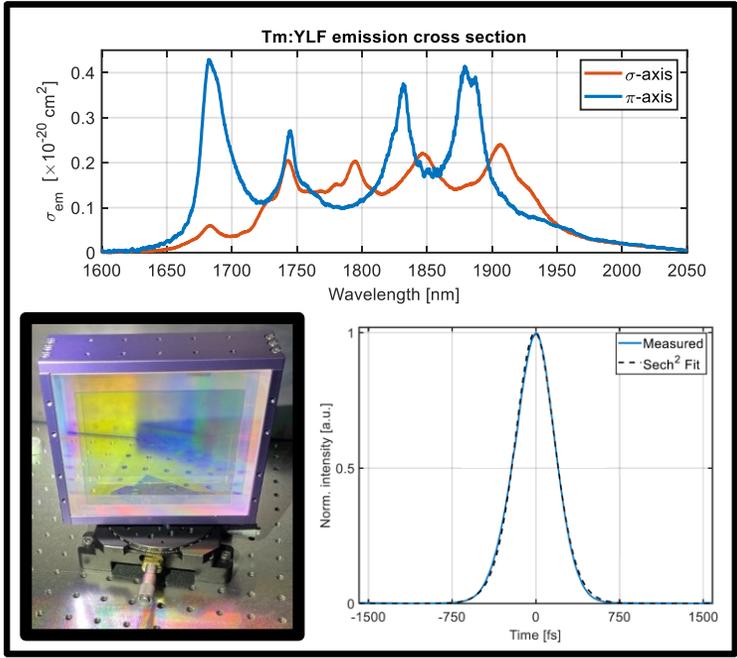
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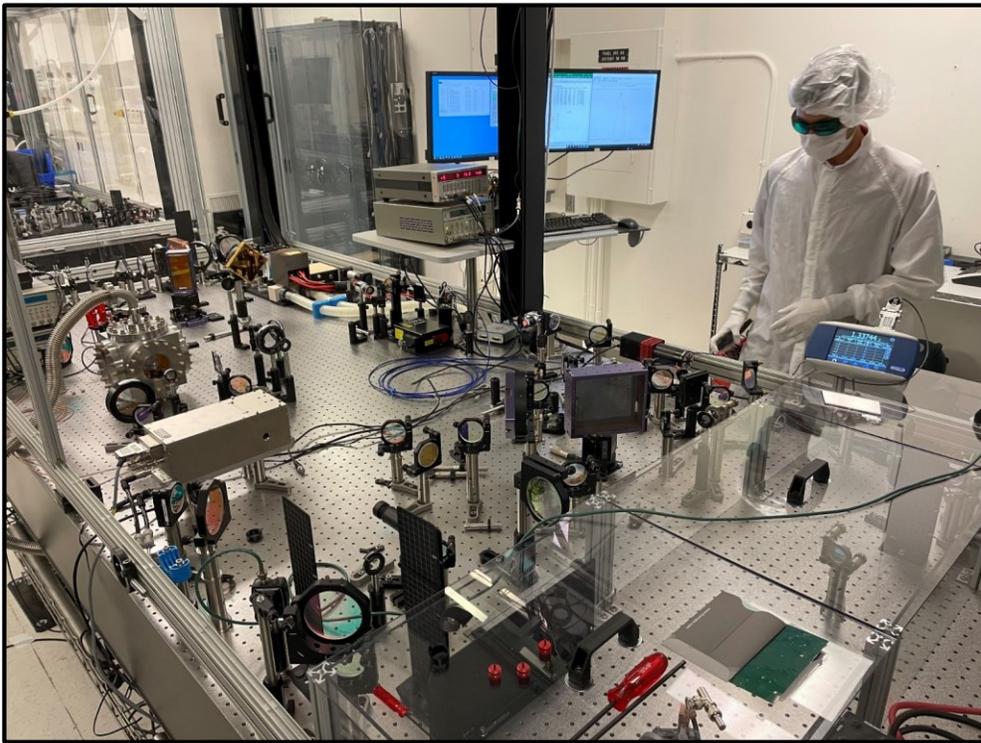
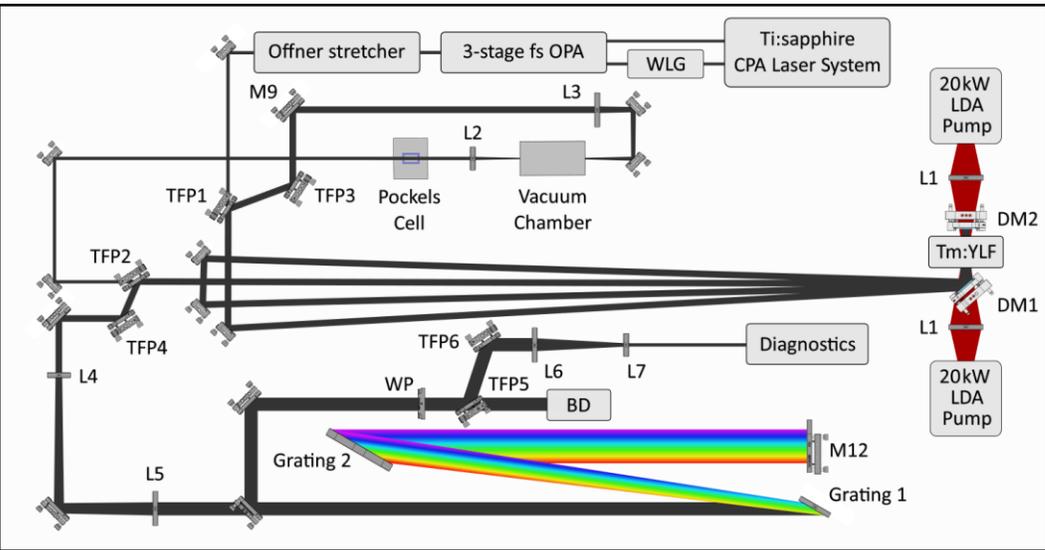
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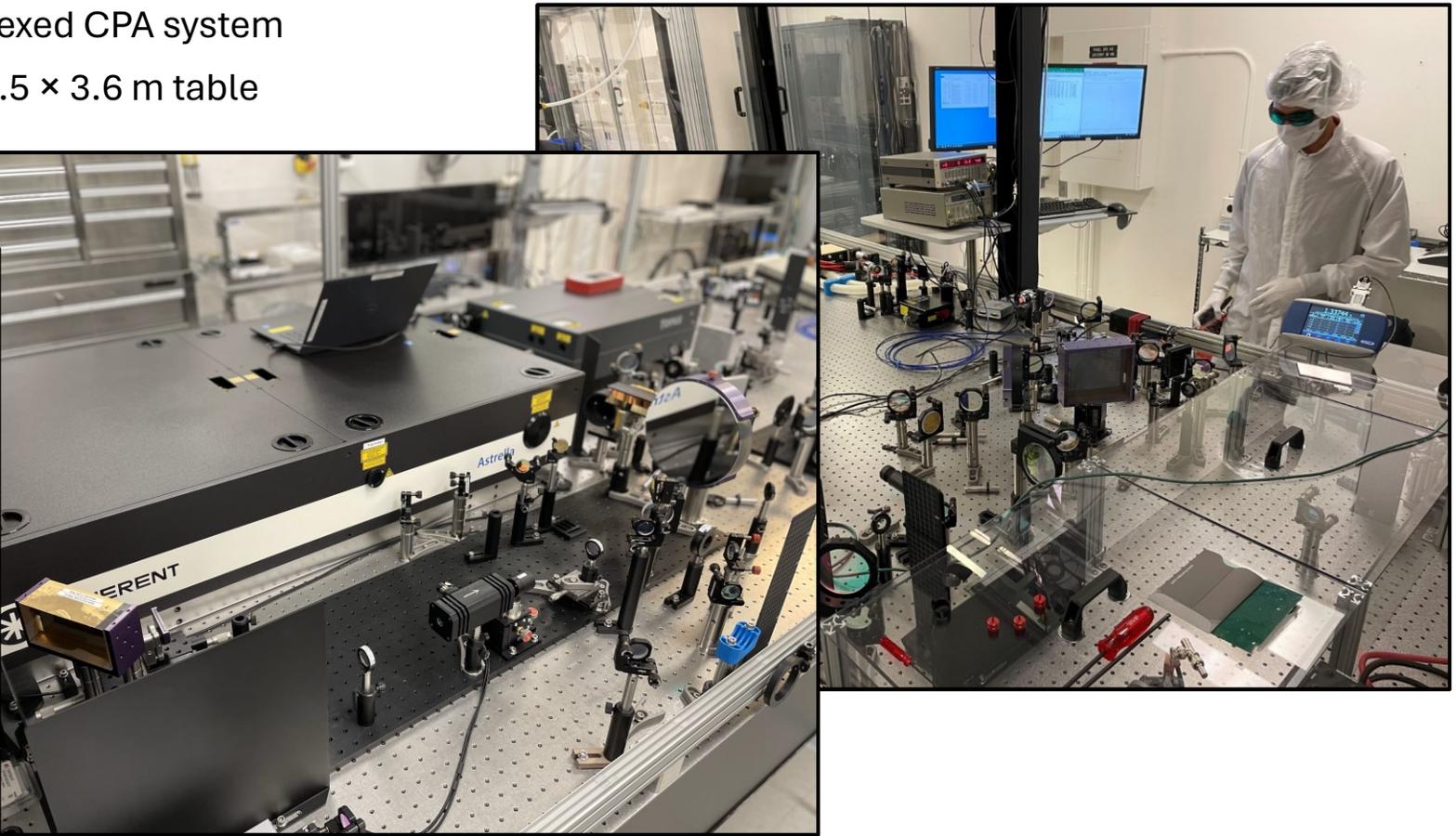
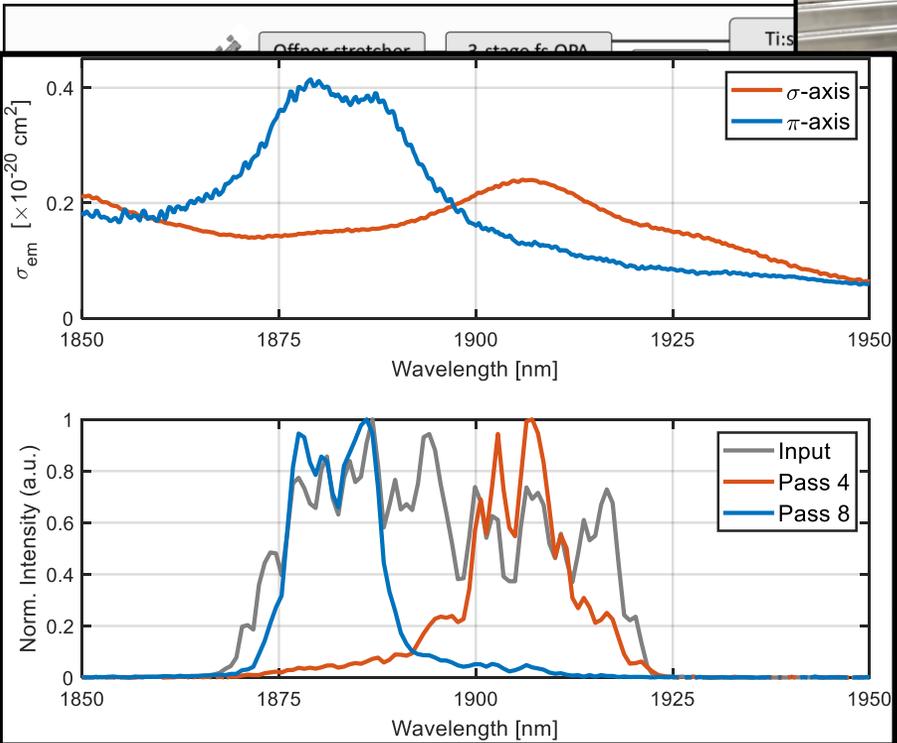
Compact Chirped Pulse Amplification setup built to demonstrate TW peak power

- 8-pass, near-field and polarization multiplexed CPA system
- Tm:YLF amplifier and compressor fits on 1.5 × 3.6 m table
- 1 kHz, 1900nm, 50nm, 500ps front-end

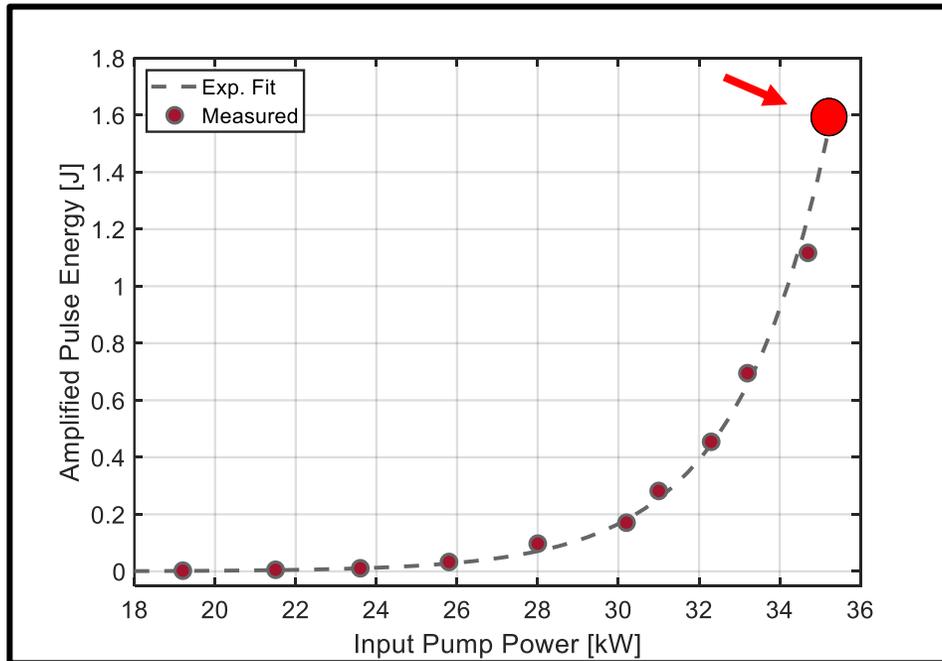


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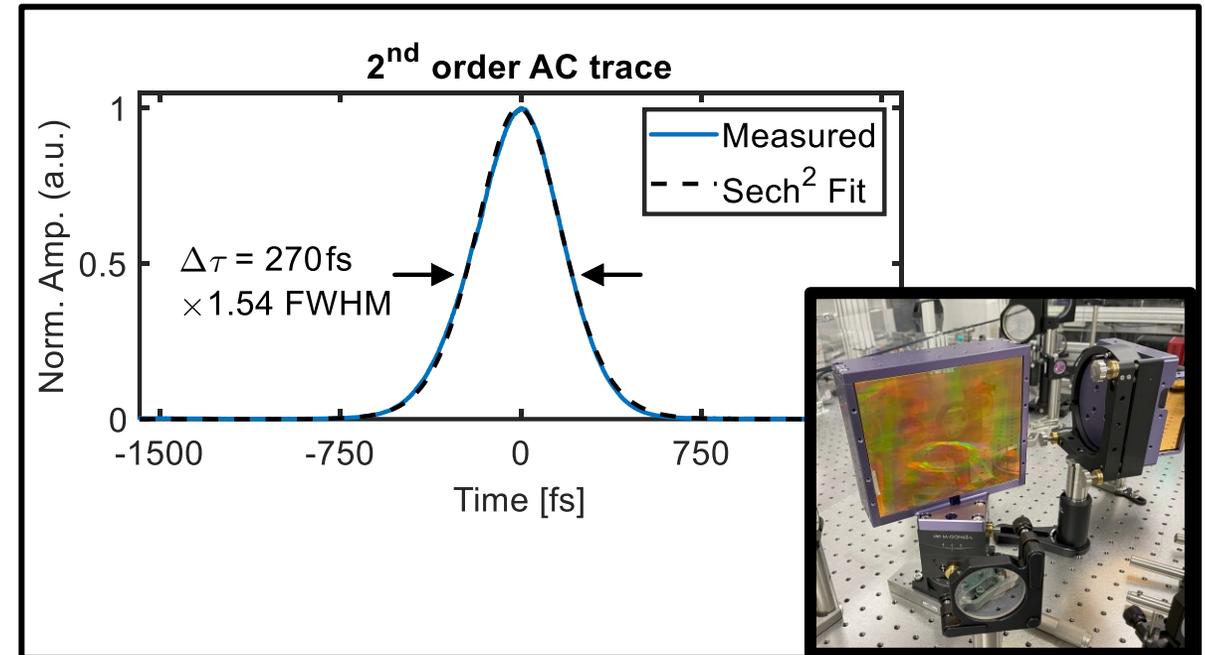
- 8-pass, near-field and polarization multiplexed CPA system
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1.59 J reached after 8 passes, 270 fs with J-level pulses

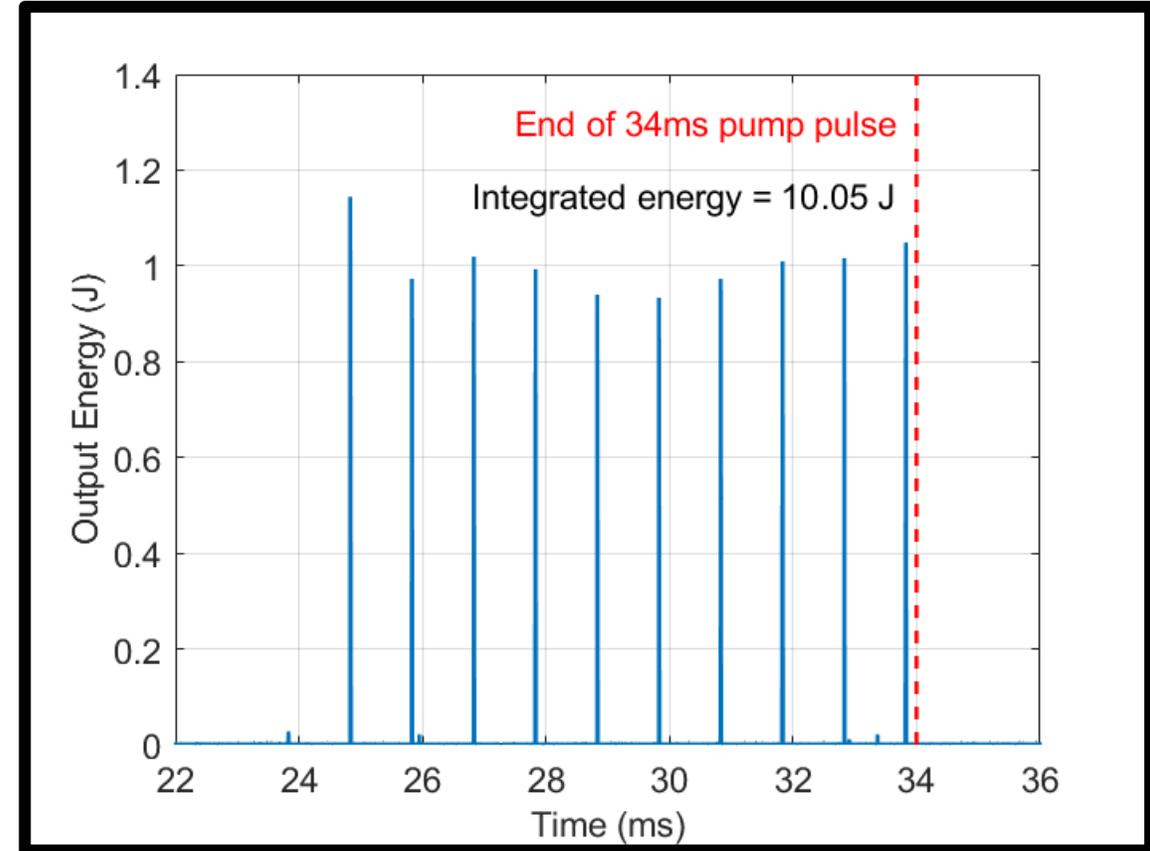
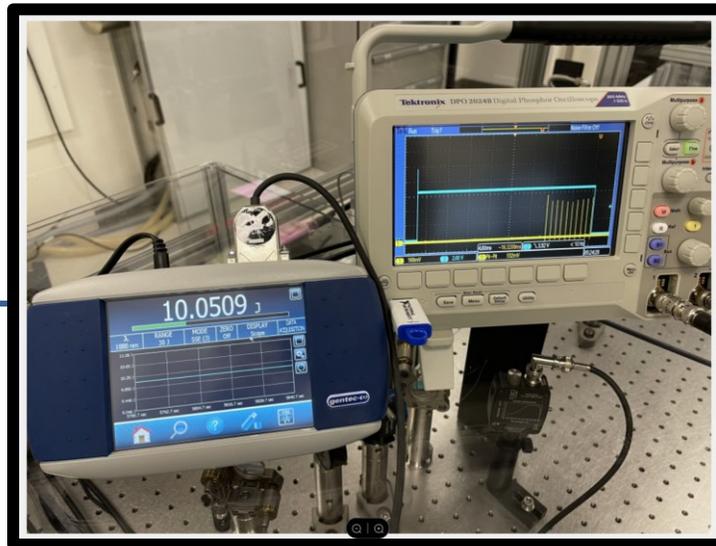
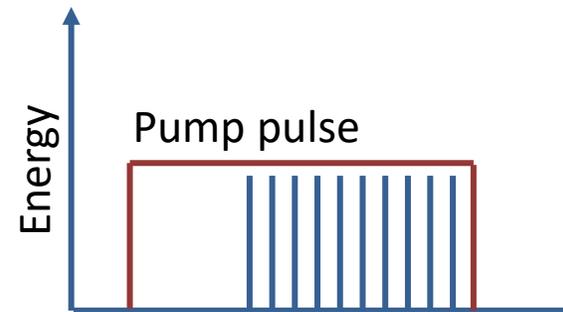
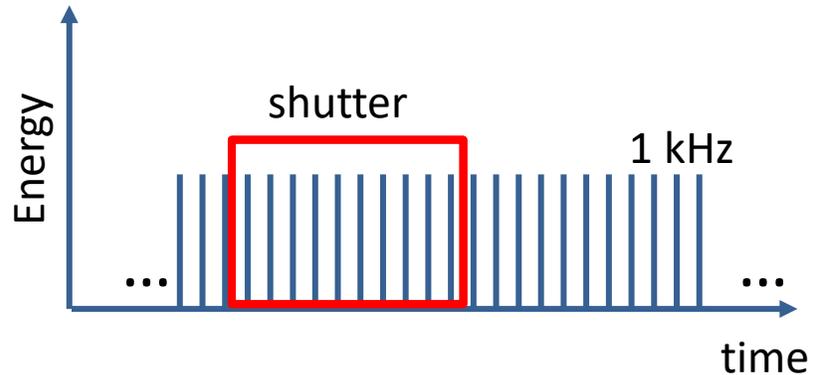


- Demonstrated 1.59 J at 35.3 kW pumping, single shot
- Joule level broadband pulses for the first time in Tm:YLF CPA



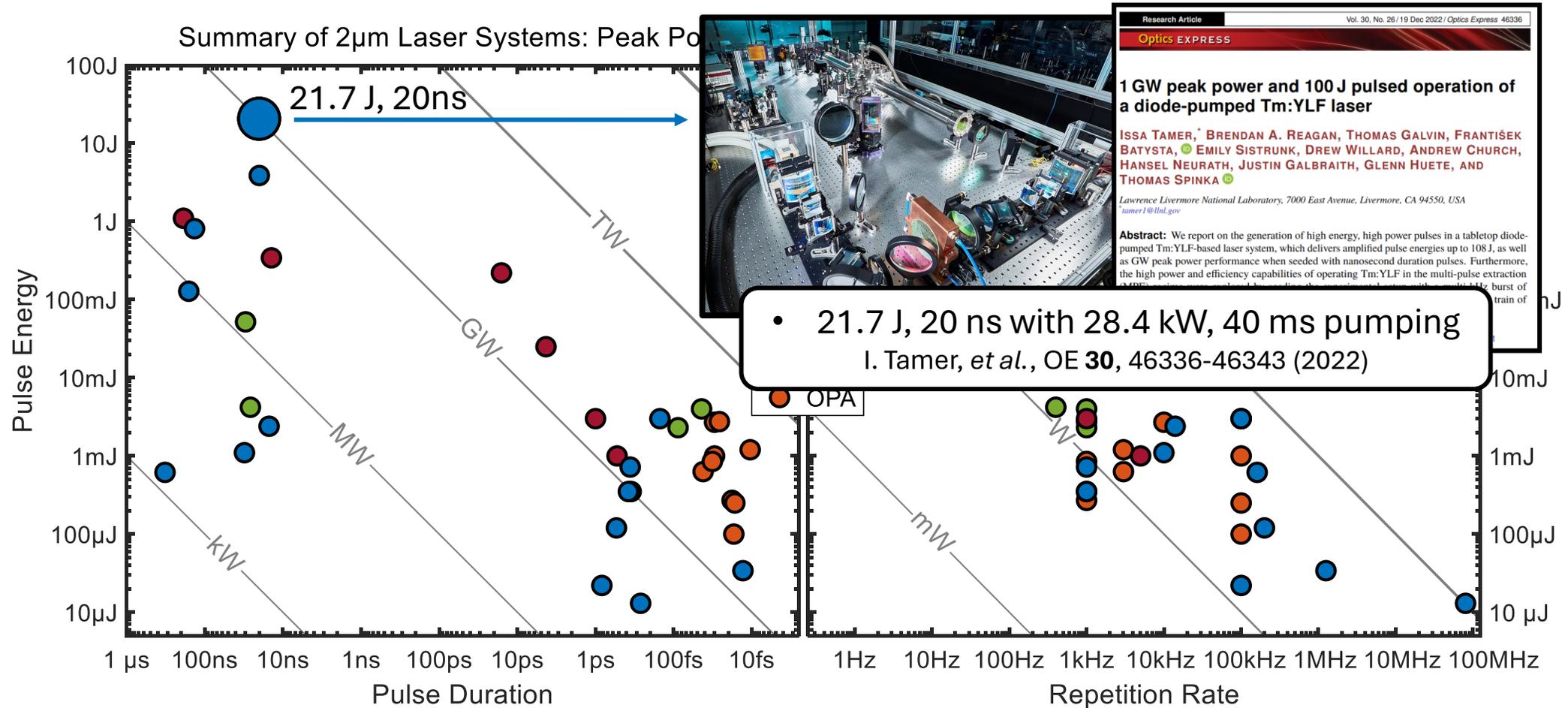
- Demonstrated 270 fs compressed at full energy
- Single shot measurement, compressor eff. 42 %
- 1.7 TW peak power

Broadband, single shot burst operation - 10 J reached with 10 pulses



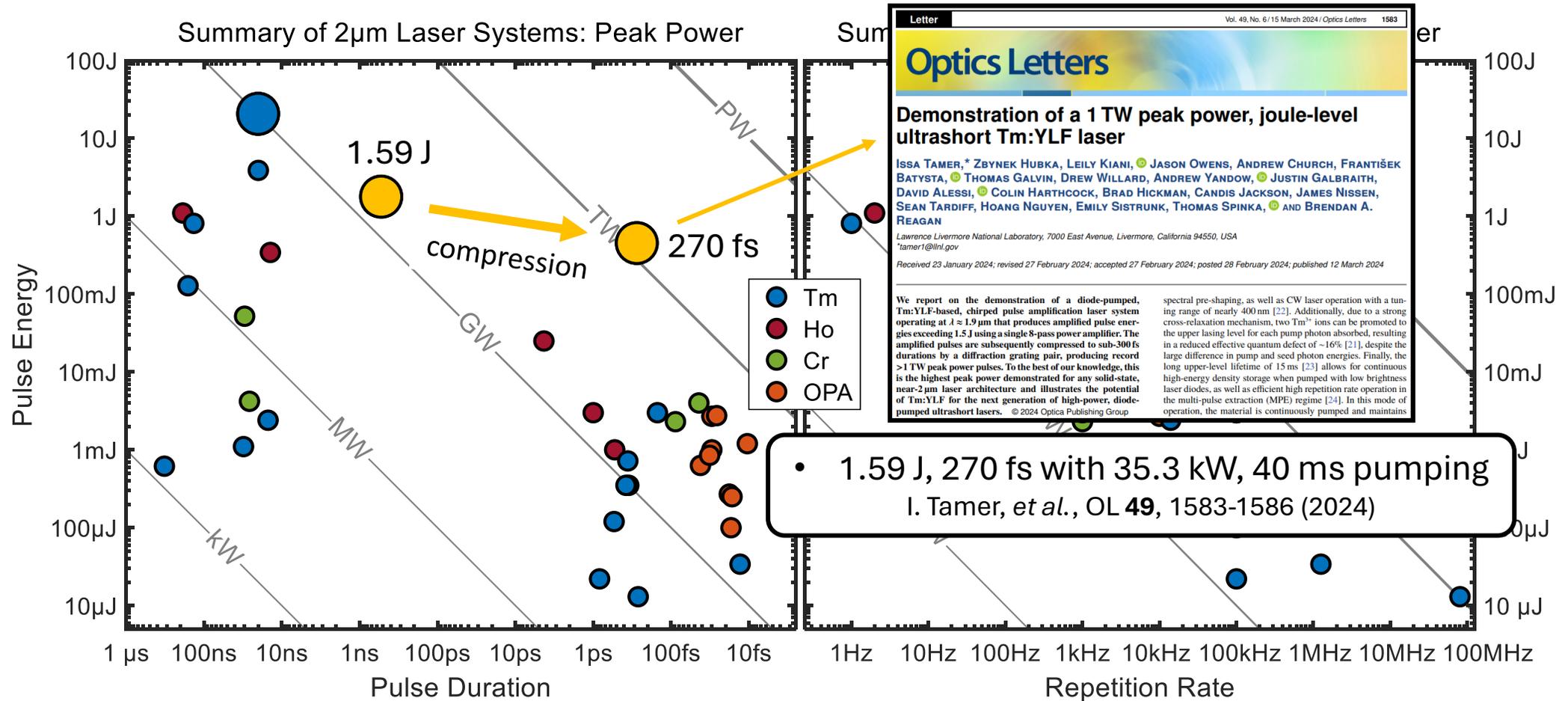
- Demonstrated 10 J with 10 pulses at 38.2 kW pumping
 - Joule level broadband burst

Demonstrated results compared to other 2 μm laser systems



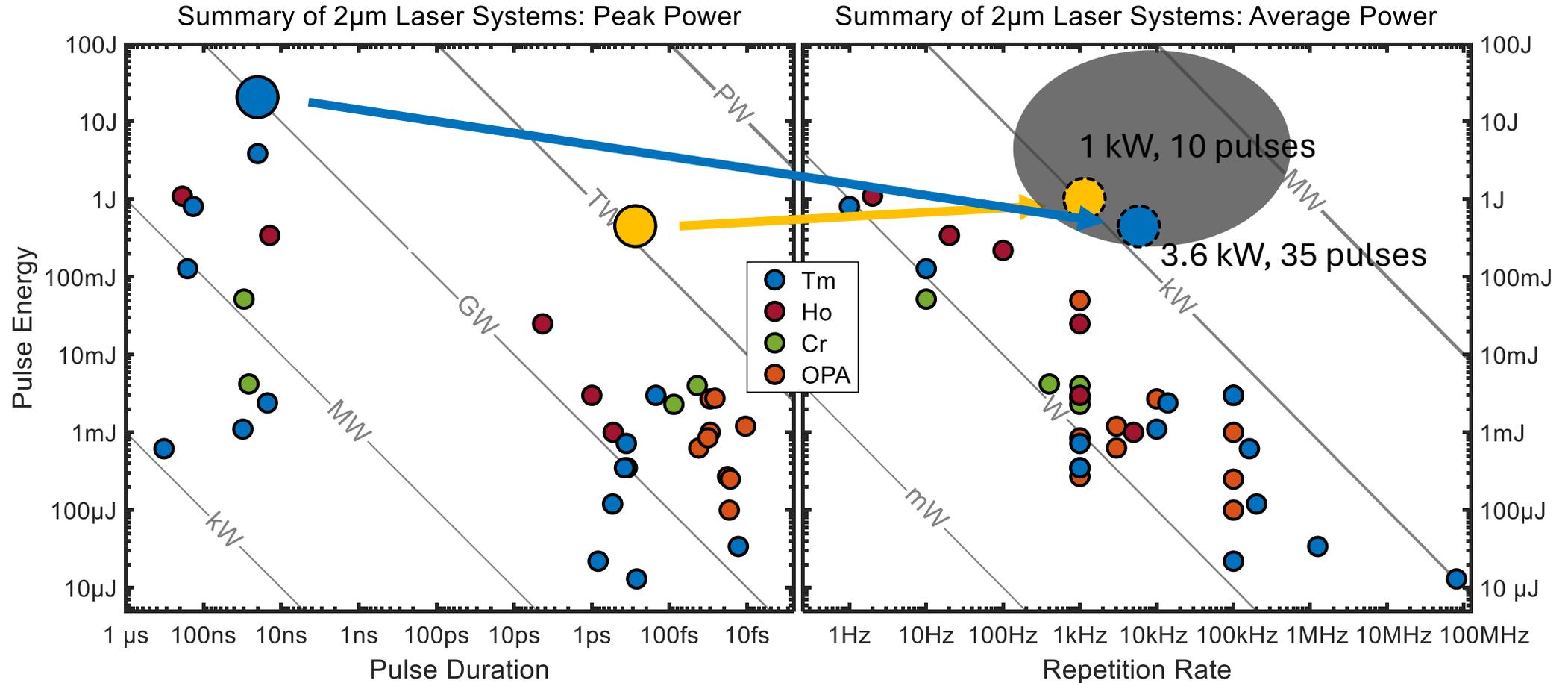
B. A. Reagan, et al., Chapter 23 in Photon Sources for Lithography and Metrology, SPIE Press, pp. 999–1025 (2023).

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Demonstrated burst mode results at low duty cycle



B. A. Reagan, et al., Chapter 23 in Photon Sources for Lithography and Metrology, SPIE Press, pp. 999–1025 (2023).

Summary and Outlook

- **Tm:YLF tabletop system:**

- ✓ Narrowband results: 21.7 J in 20 ns, burst mode 3.6 kW, 19% o-o eff.
- ✓ Gas cooling experiments:
Record breaking heat removal of $>20 \text{ W/cm}^2$
($\sim 10\times$ higher than state-of-the-art lasers), avg. power scaling viable
- ✓ Broadband CPA results:
amplified pulse energies up to 1.59 J
pulses at Joule-level compressed to 270 fs FWHM
demonstrating $> 1 \text{ TW}$ peak power at $2 \mu\text{m}$
- ✓ 10 J with 10 pulses in 1 kHz burst mode (broadband)

- **Future - Scaling peak and average power**

- Generation of higher energy, shorter duration pulses
- Gas-cooled, multi-slab amplifier for high rep rate operation



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