Diode-Pumped Tm:YLF Lasers for Advanced Accelerators

Advanced Accelerator Concepts Workshop 2022

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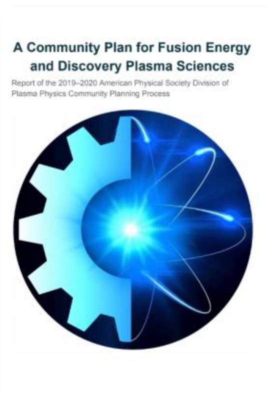
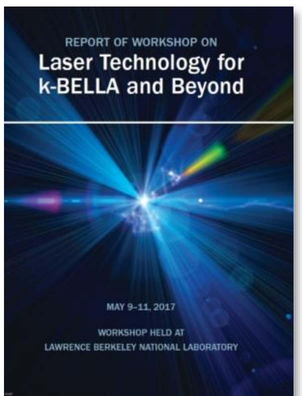
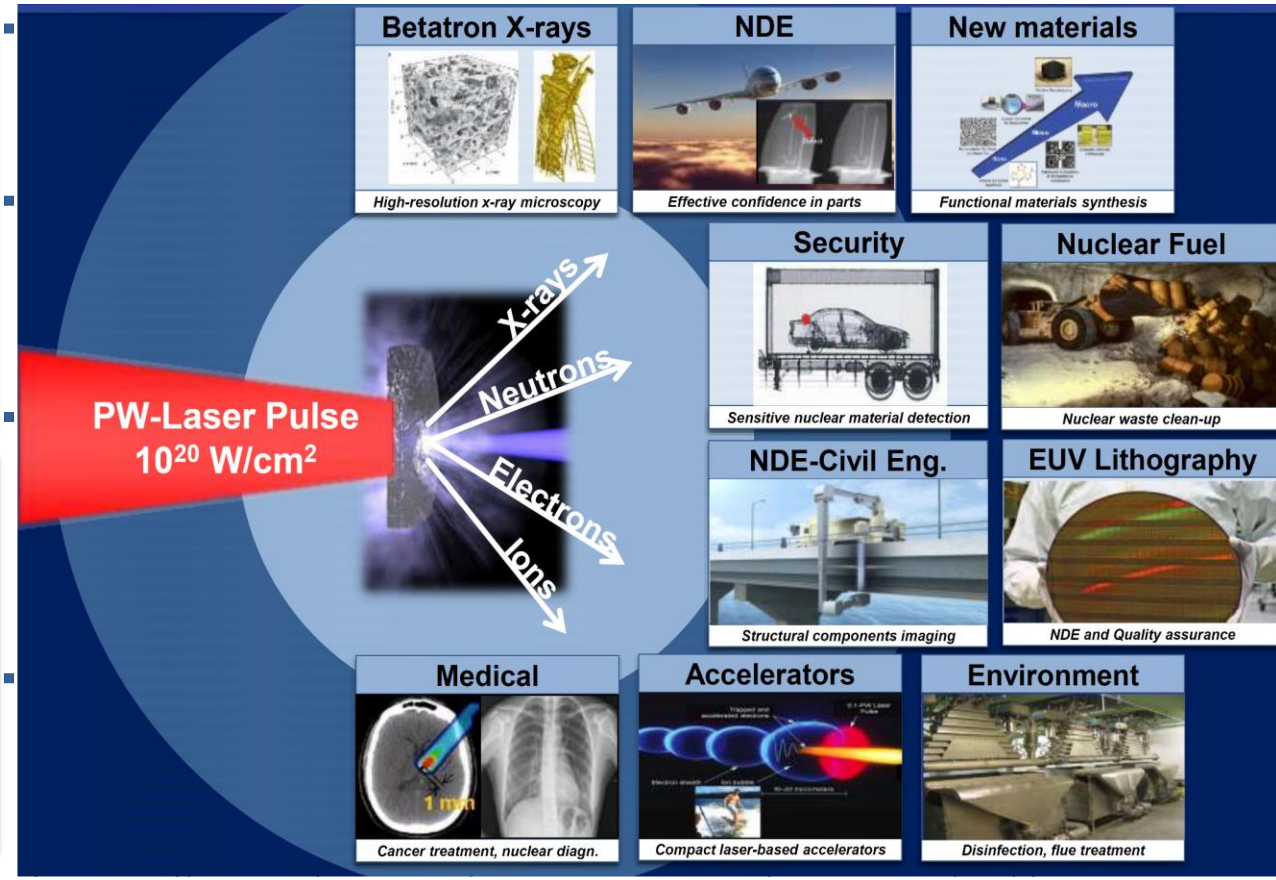
Practical laser-driven accelerators, x/γ-ray sources, ion and neutron sources, and other applications demand efficient high peak and average power short pulse lasers







Need for high repetition rate, high energy short pulse lasers is recognized by the community and industry

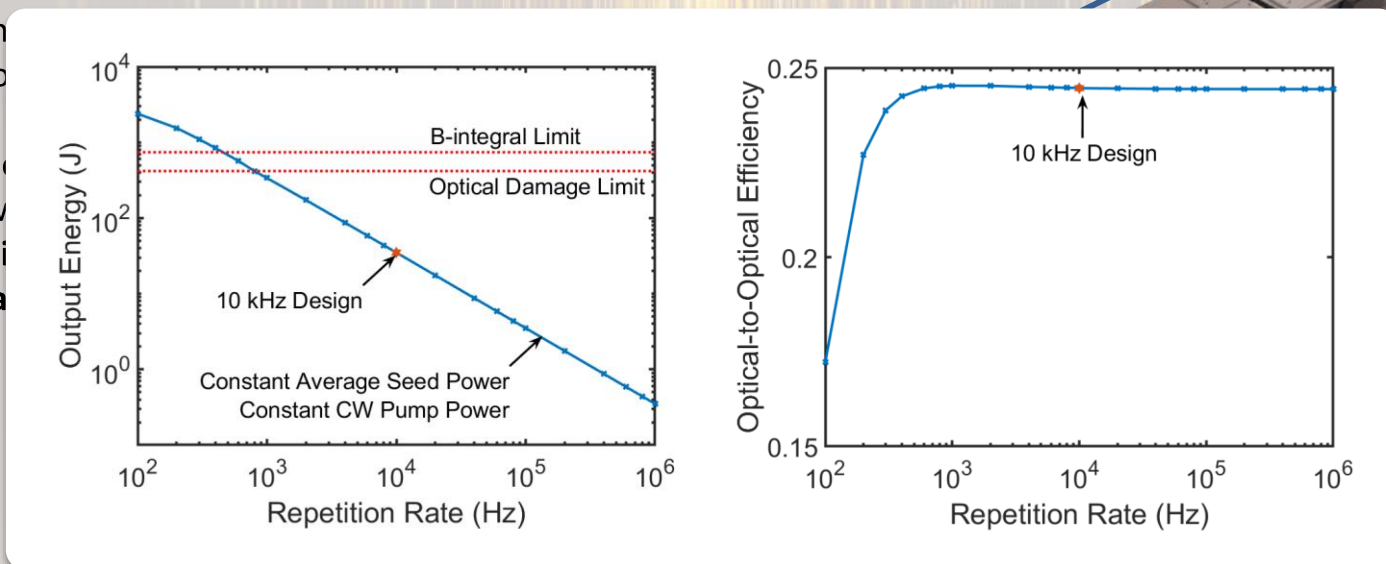
BAT

Big Aperture Thulium Laser Concept

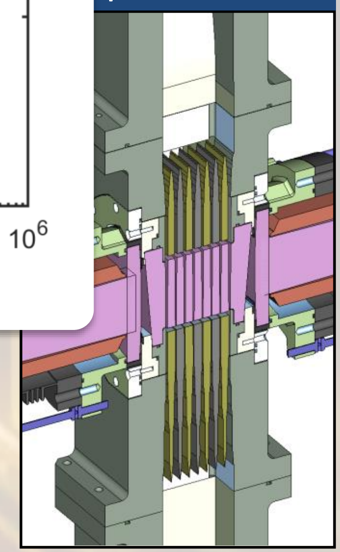
30J, <100fs, 0.3PW, 10kHz

- **300,000 W Average Power**

- Tm:YLF laser media
  - 1900 n
  - Two-fo
    defect
  - Superi
  - Bandw
  - **Materi
    large a**



Gas-Cooled
nplifier Head



- True CW pumping
  - Long lifetime (15 ms) & multi-pulse extraction
  - Efficient extraction at low fluence per pulse
  - Repetition rate and energy can be freely exchanged

BAT technology is a potential game changer for driving laser-plasma interactions

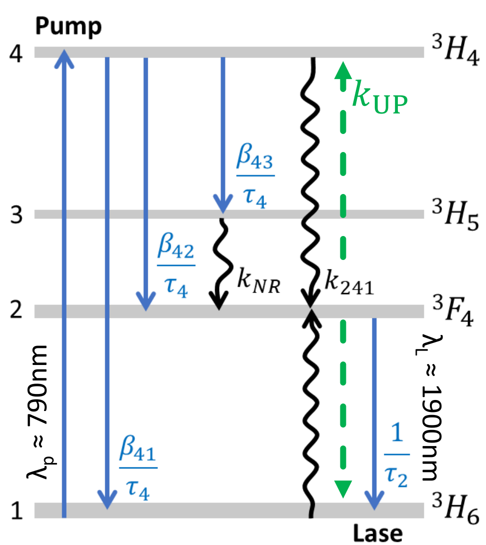
High energy density storage/extraction has not yet been demonstrated in Tm:YLF

- Could Tm:YLF energy storage/extraction compete with Ti:Sapphire or Nd:Glass?

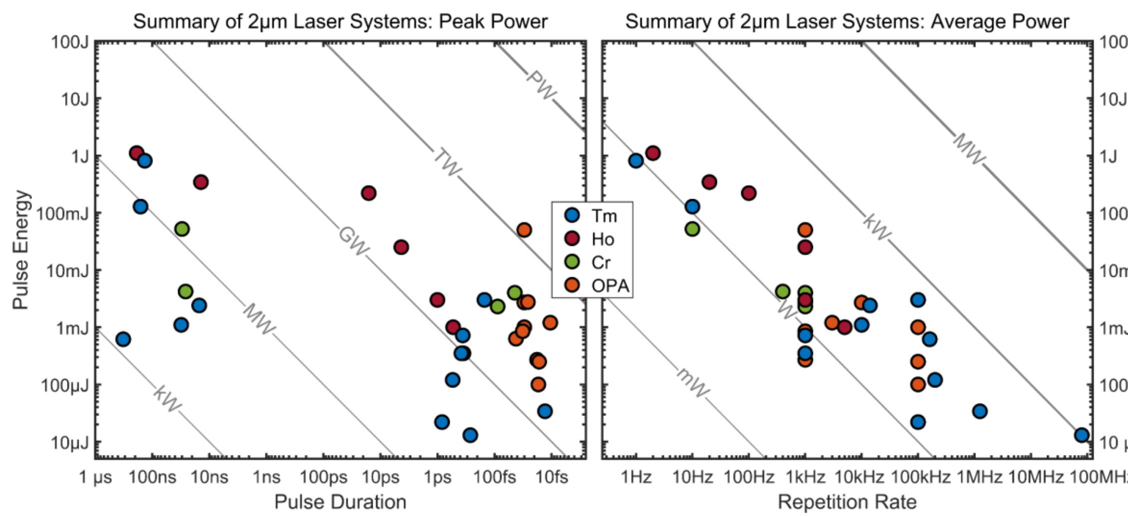
Property	Ti:Sapphire	Nd:APG-1	Tm:YLF
$\tau_{storage}$ (ms)	0.0032	0.36	15
F_{sat} (J/cm^2)	~1	~5	~25

- However, Tm:YLF energy transfer processes are complicated, with many potential unknowns (excited state upconversion, efficiency of cross-relaxation process, etc.)

Tm:YLF Energy Level Diagram

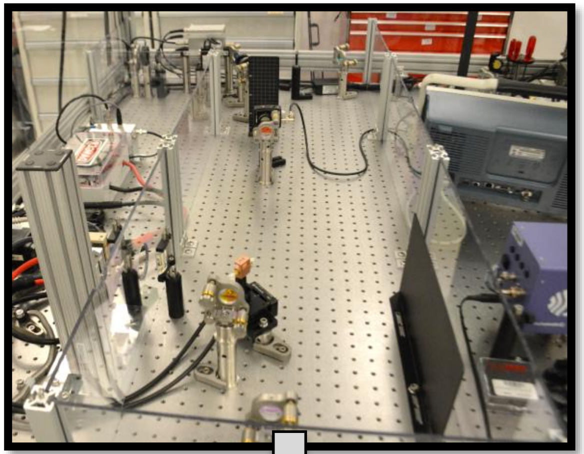


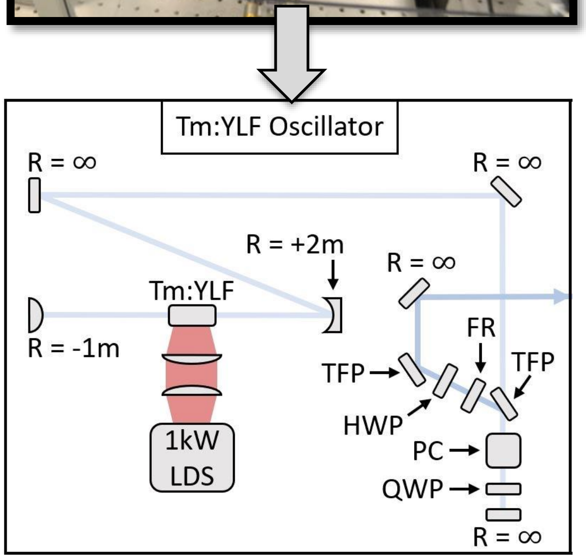
- Prior to this investigation, joule-level energy extraction has not been demonstrated in Tm:YLF
  - Highest reported extracted energy: 300mJ in 450µs duration pulses [M. Petros et al., "300-mJ diode-pumped 1.9-µm Tm:YLF laser," Proc. SPIE 4484 (2002)].
- What about other Tm-based lasers or laser systems operating near 2µm?
  - Highest reported extracted energy: 4J with free-running oscillator [C. Li et al., "Flash-lamp-pumped acousto-optic q-switched Cr-Tm:YAG laser," Optical Review 7, 1 (2000)]



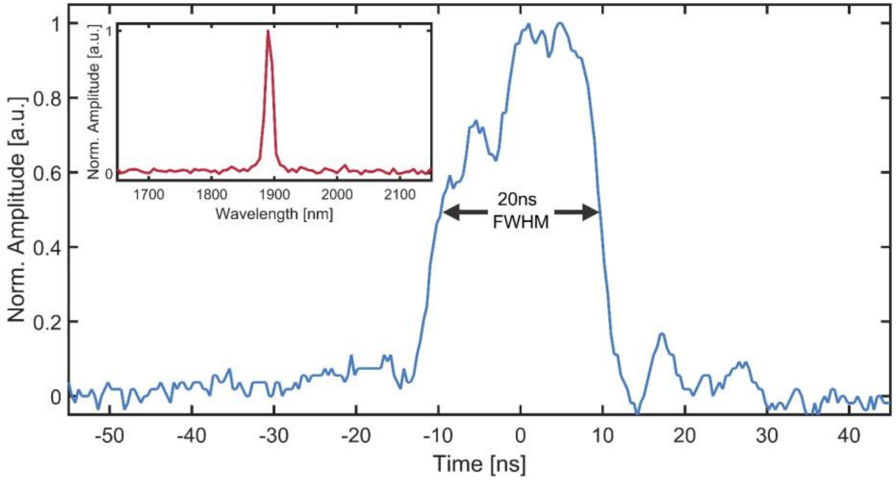
Tm:YLF-based seed source for Tm:YLF power amplifier

- Tm:YLF oscillator parameters:
  - 6%-at.-doped, 5x5x10mm^3, Brewster-cut crystal
  - Pumped by 793nm, 1kW laser diode stack for 15ms
  - Q-switched, cavity-dumped operation enabled by RTP Pockels cell, thin film polarizer, and quarter waveplate
  - Output: 1880nm, >30mJ, 20ns FWHM, 1Hz



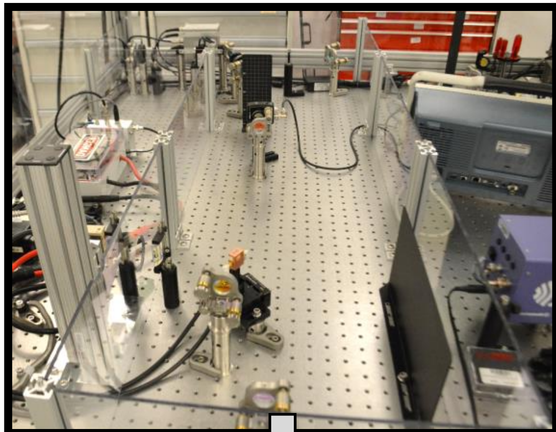


Temporal profile and spectrum (inset)

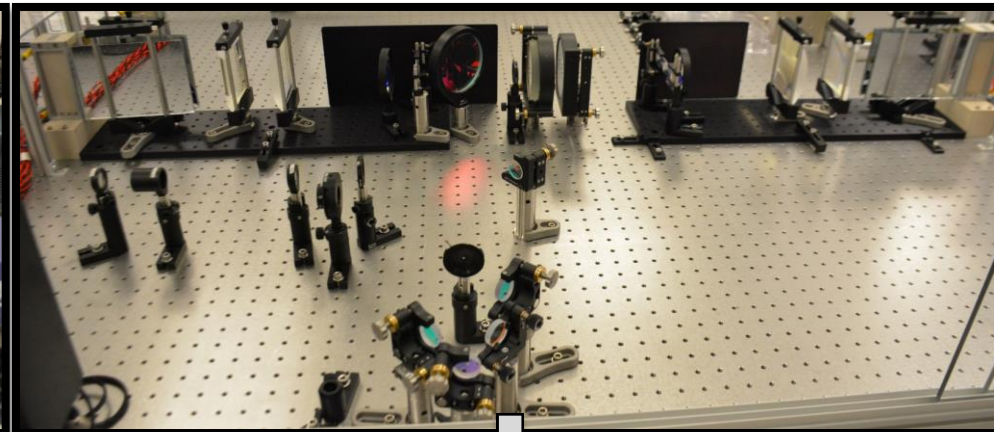


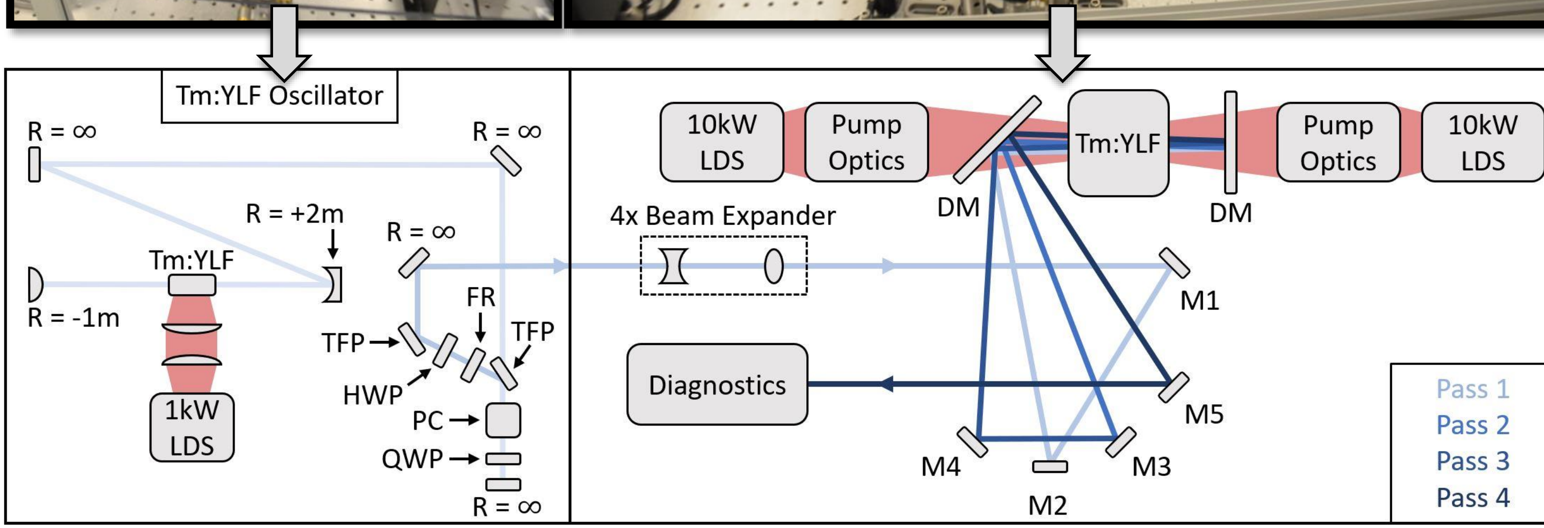
High energy demonstrator setup

Diode-Pumped Tm:YLF Oscillator



Diode-Pumped Tm:YLF Multi-Pass Amplifier



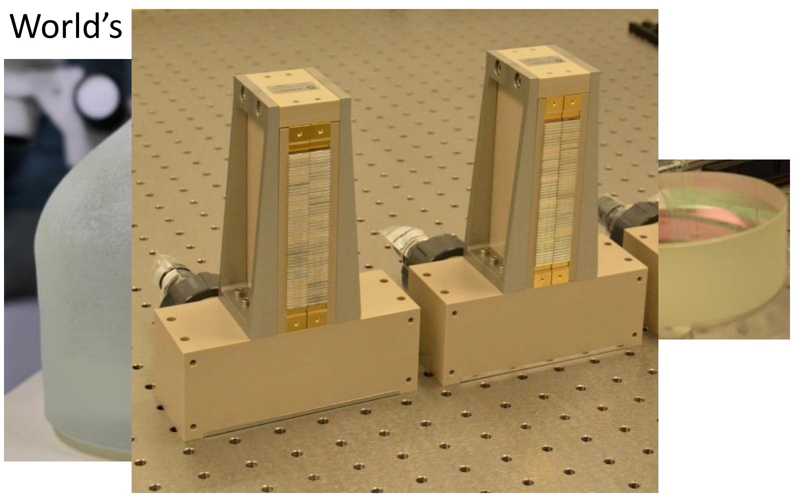


High energy demonstrator setup

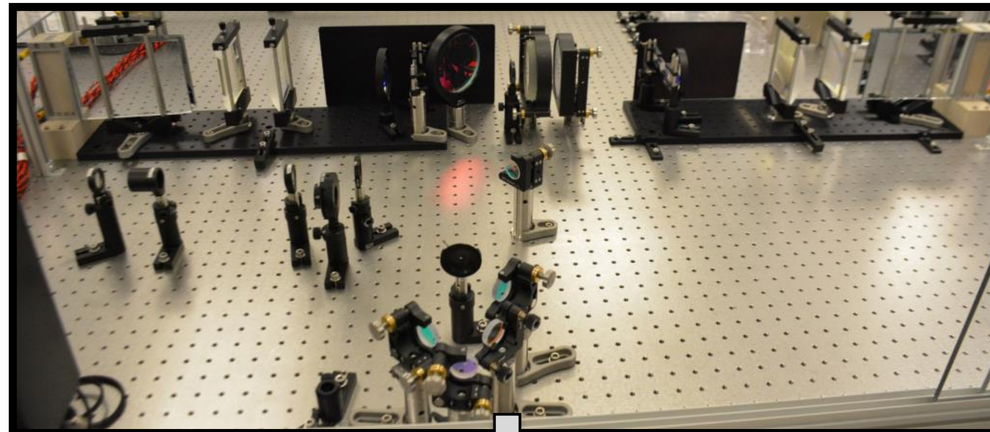
- Tm:YLF power amplifier parameters:
  - 6%-at.-doped, 100mm diameter, 35mm thick, AR-coated
  - Pumped by 793nm, 2x10kW laser diode stacks for 15-30ms

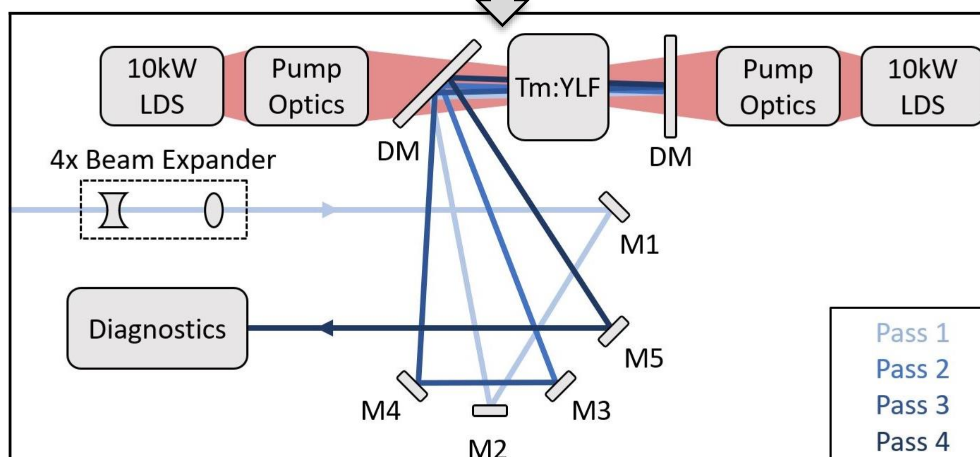
2x(2x50) Laser Diode Stacks

World's



Diode-Pumped Tm:YLF Multi-Pass Amplifier

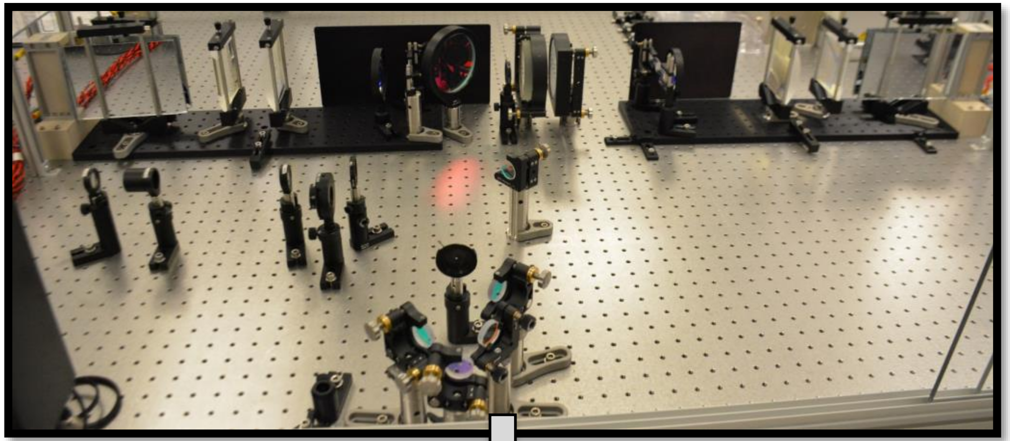


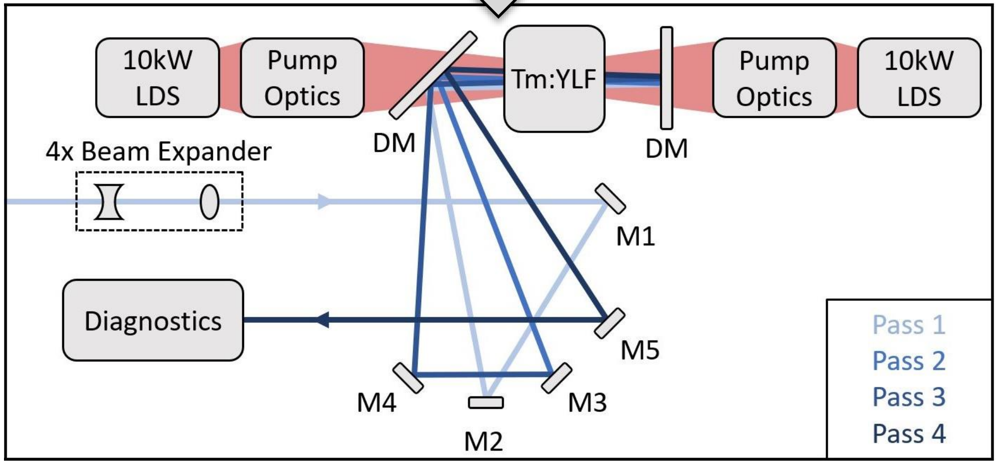


High energy demonstrator results: four-pass output energy

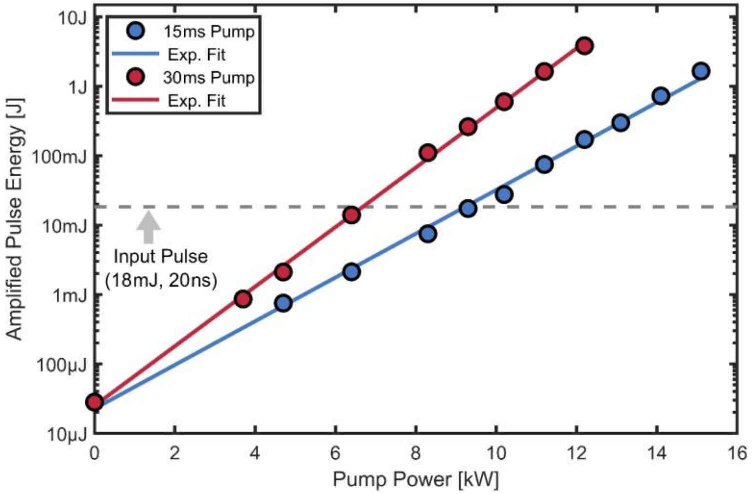
- Tm:YLF power amplifier parameters:
  - 6%-at.-doped, 100mm diameter, 35mm thick, AR-coated
  - Pumped by 793nm, 2x10kW laser diode stacks for 15-30ms
  - Four-pass amplified pulse energy of **3.88J** in 20ns within 1cm^2 spot size (net gain ~ 210x)

Diode-Pumped Tm:YLF Multi-Pass Amplifier



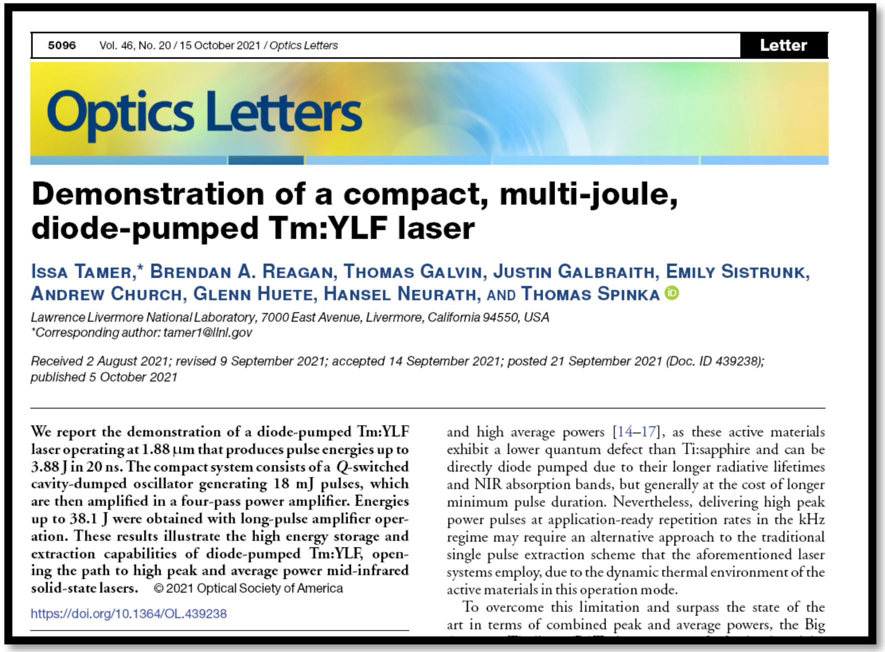


Four-pass Output Energy vs. Pump Power



High energy demonstrator results: four-pass output energy

- 4-pass amplified pulse energy (20ns pulse): **3.88J**
- Laser-induced damage threshold not yet confirmed for amplifier components/coatings
  - Conservative value of 4J/cm^2 for ~ns pulses
- Seed with longer pulses to safely demonstrate higher energy extraction → switch oscillator to free-running mode to generate few-ms pulses (<< τ_{rad} = 15ms)
- 4-pass amplified pulse energy (long pulse):
  - 30.6J with 16.9kW, 30ms pumping
  - **38.1J** with 16.9kW, 40ms pump
    - >100x previous Tm:YLF world record[1]
    - 10x previous world record pulse energy for all ~2µm lasers [2]
- Spot size 1cm^2 → crystal area 79cm^2 → multi-kJ capability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Optics Letters

Demonstration of a compact, multi-joule, diode-pumped Tm:YLF laser

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We report the demonstration of a diode-pumped Tm:YLF laser operating at 1.88 µm that produces pulse energies up to 3.88 J in 20 ns. The compact system consists of a *Q*-switched cavity-dumped oscillator generating 18 mJ pulses, which are then amplified in a four-pass power amplifier. Energies up to 38.1 J were obtained with long-pulse amplifier operation. These results illustrate the high energy storage and extraction capabilities of diode-pumped Tm:YLF, opening the path to high peak and average power mid-infrared solid-state lasers.

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and high average powers [14–17], as these active materials exhibit a lower quantum defect than Ti:sapphire and can be directly diode pumped due to their longer radiative lifetimes and NIR absorption bands, but generally at the cost of longer minimum pulse duration. Nevertheless, delivering high peak power pulses at application-ready repetition rates in the kHz regime may require an alternative approach to the traditional single pulse extraction scheme that the aforementioned laser systems employ, due to the dynamic thermal environment of the active materials in this operation mode.

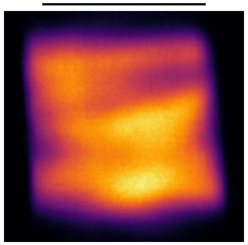
To overcome this limitation and surpass the state of the art in terms of combined peak and average powers, the Big

[1] M. Petros et al., "300-mJ diode-pumped 1.9-µm Tm:YLF laser," Proc. SPIE 4484 (2002).
[2] C. Li et al., "Flash-lamp-pumped acousto-optic q-switched Cr-Tm:YAG laser," Optical Review **7**, 1 (2000).

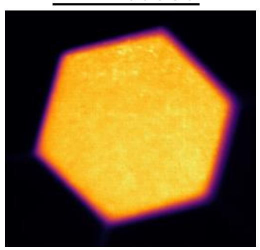
LDS pump delivery upgrade

- Pump upgrade using microlens arrays (MLAs)
- Total power: 19.3kW (from 20kW LDS)
- Beam size: 14mm FWHM
  - Adjustable solely by swapping final lens
  - Edge sharpness <1mm
  - Homogeneity: ± 1.2% RMS fluctuation

Snout-based

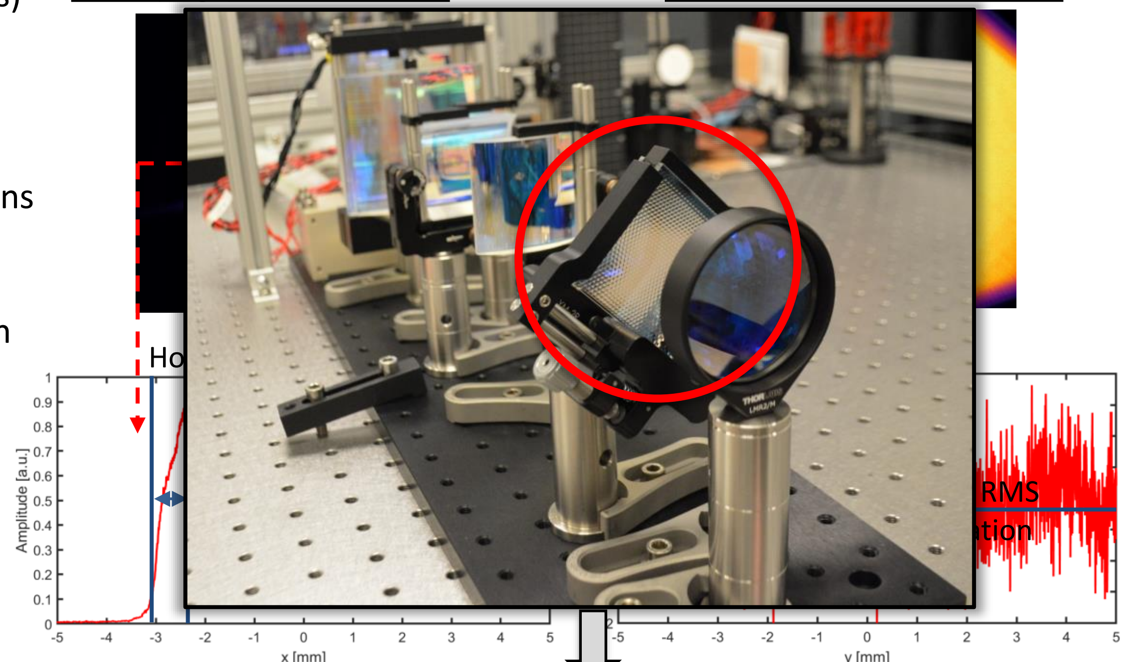


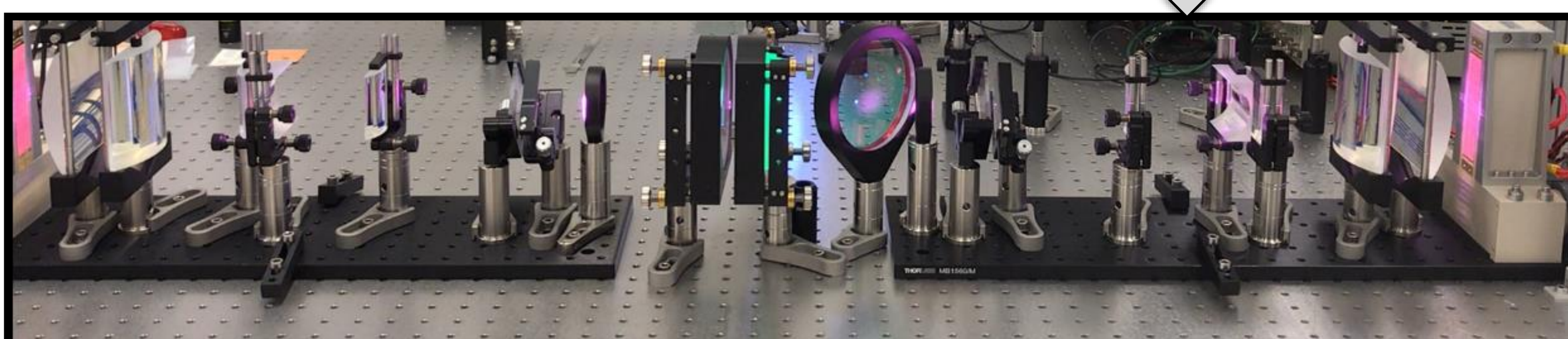
MLA-based



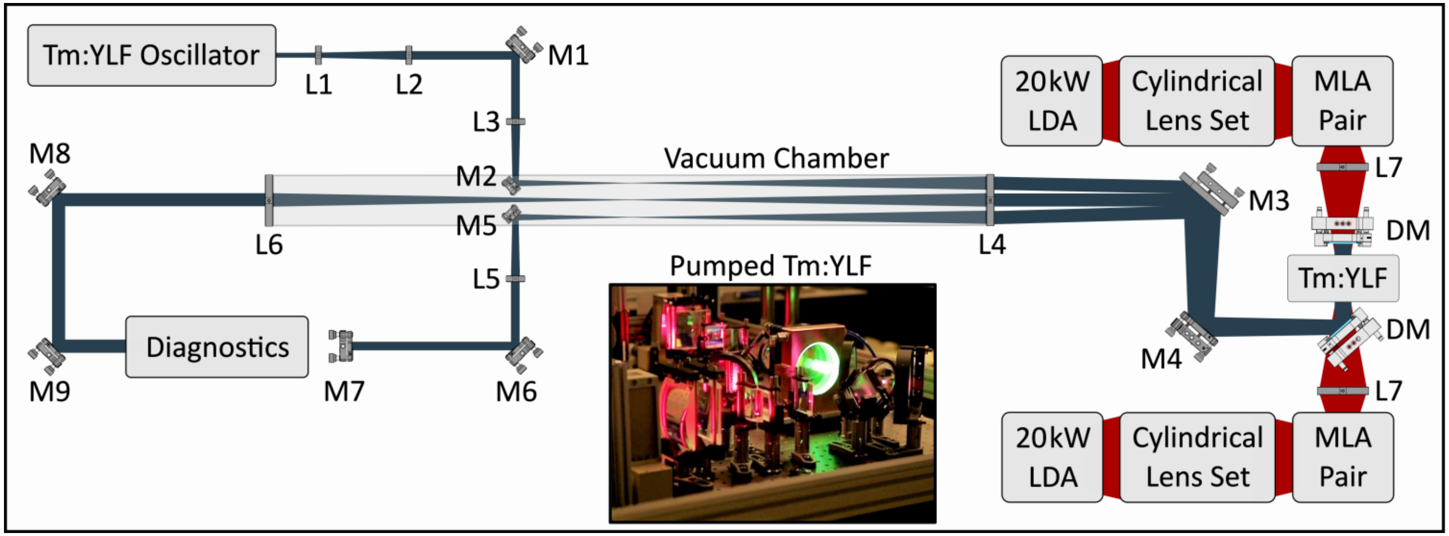
Beam (edge) incident on CCD

Beam (center) incident on CCD

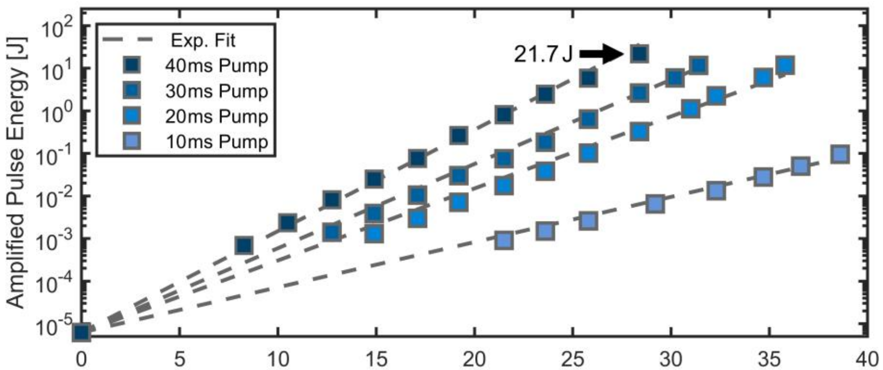




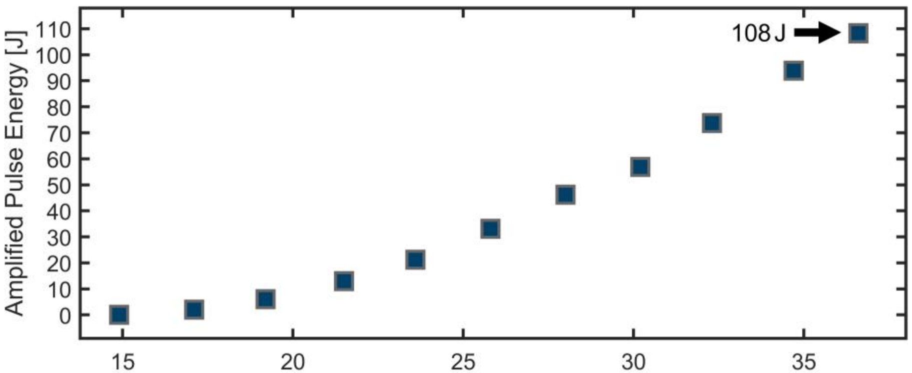
High energy demonstrator setup upgrade



4-pass amplified pulse energy (20ns pulse)



6-pass amplified pulse energy (long pulse)

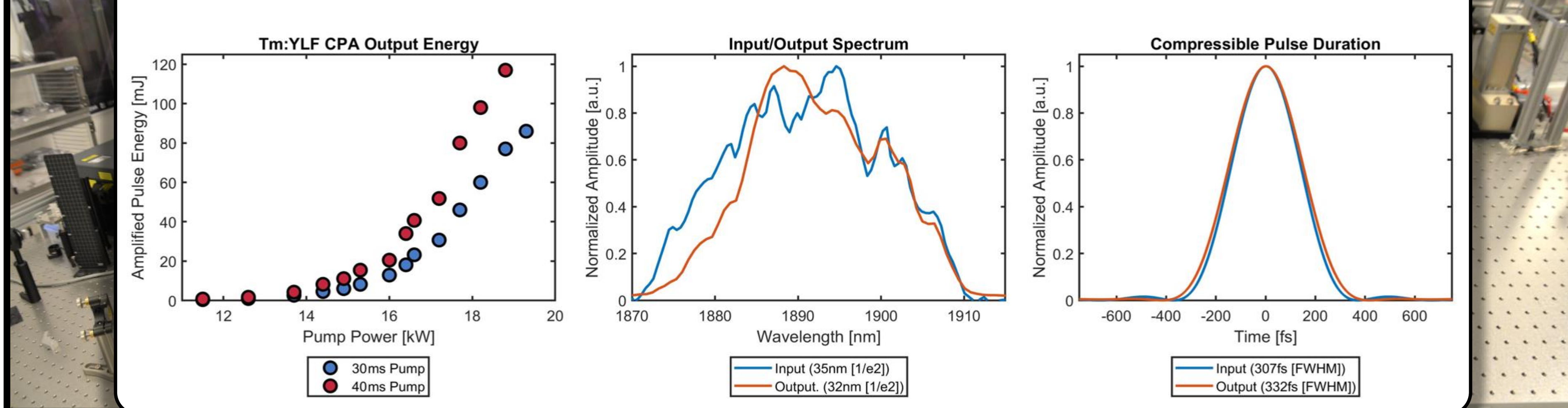


Highest reported energy for any 2µm laser

Tm:YLF CPA – Preliminary Results

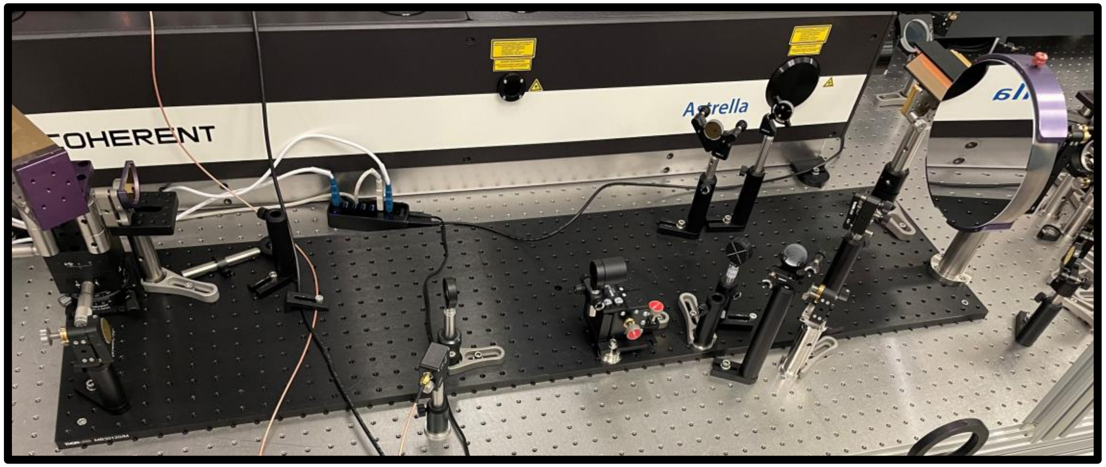
- Generate broadband 2μm source for CPA (chirped pulse amplification) demonstration
  - *Astrella* (Coherent)-pumped *TOPAS* (Light Conversion)
  - Astrella: Ti:Sapphire, 800nm, 7mJ, 60fs, 1kHz
  - TOPAS: 3-stage OPA (optical parametric amplifier), 1.89μm, 1mJ, 40fs,1kHz
  - Martinez stretcher: 40fs → 280ps
  - Stretched pulse seeds 8-pass Tm:YLF power amplifier → ~120mJ compressible to 330fs

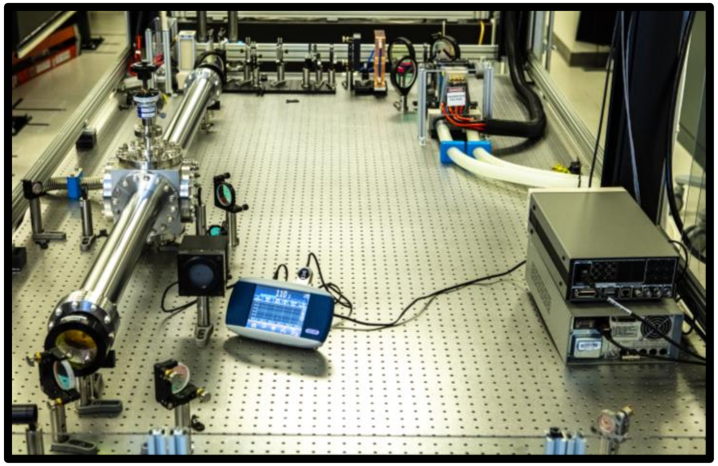
First chirped pulse amplification of high energy pulses in Tm:YLF



Conclusions and Outlook

- High energy storage and extraction capability of diode-pumped Tm:YLF has been demonstrated within long, short, and ultrashort pulse durations. We are pushing this even further. → Joule-level ultrashort pulses
- Simultaneously conducting BAT architecture validation demonstrations:
  - Gas cooling experiments for extracting ~10× higher heat per unit area than existing state-of-the-art lasers
  - Developed efficient, broadband MLD gratings operating at 1.9 µm for chirped pulse amplification setup
  - Constructing at-scale BAT laser amplifier head for multi-J-class kHz-class system
- We envision a future BAT laser that will efficiently deliver up to PW-level peak powers pulses at multi-100kW average power to support exciting applications and diagnostics, particularly laser-driven proton/electron acceleration, X-ray, and muon generation





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