Solid state Tm:YLF lasers for driving EUV Sources

2021 EUV Source Workshop

October 28, 2021

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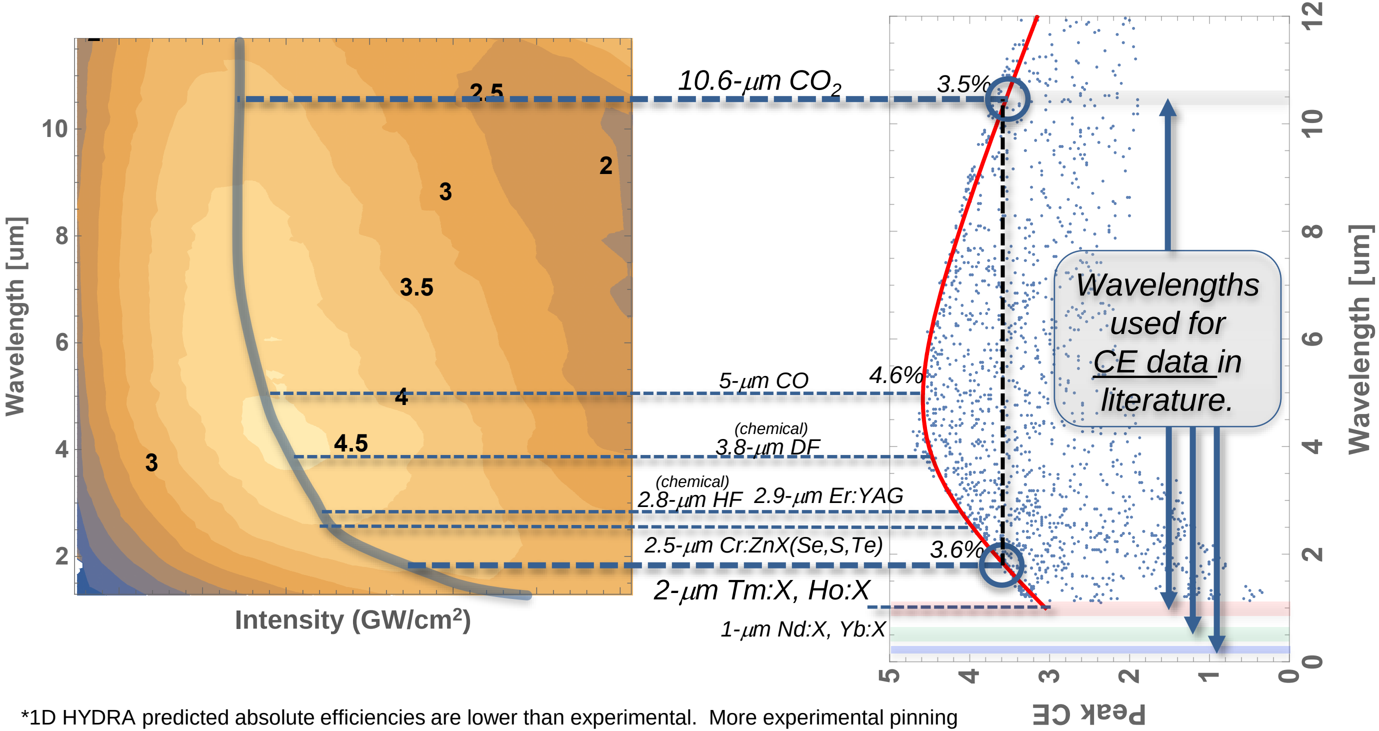
At previous EUV Workshops we have presented preliminary 1-D HYDRA results showing similar CE for 2µm and 10µm driven plasmas



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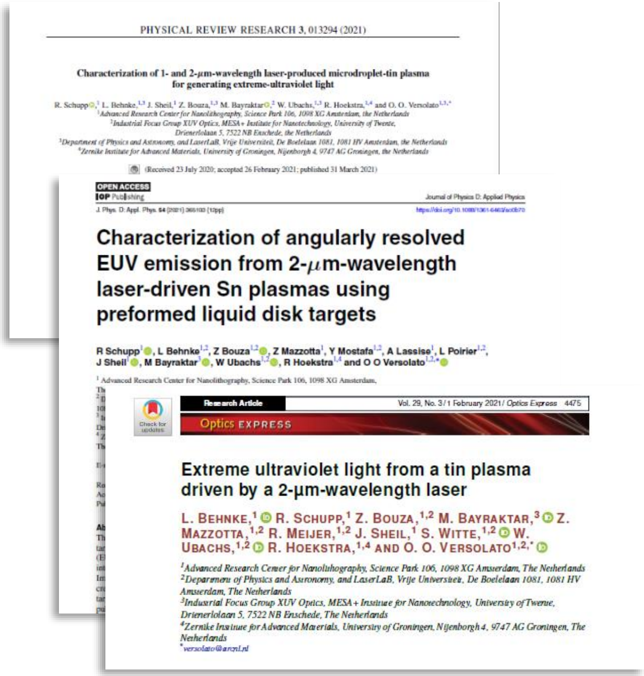

PHYSICAL REVIEW RESEARCH 3, 013294 (2021)

Characterization of 1- and 2-µm-wavelength laser-produced microdroplet-tin plasma for generating extreme-ultraviolet light

R. Schupp, L. Behnke, J. Sheil, Z. Bouza, M. Bayraktar, W. Ubachs, R. Hoekstra, and O. O. Versolato

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Journal of Physics D: Applied Physics

Characterization of angularly resolved EUV emission from 2-µm-wavelength laser-driven Sn plasmas using preformed liquid disk targets

R Schupp, L Behnke, Z Bouza, Z Mazzotta, Y Mostafa, A Lassise, L Poirier, J Sheil, M Bayraktar, W Ubachs, R Hoekstra and O O Versolato

Research Article
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Extreme ultraviolet light from a tin plasma driven by a 2-µm-wavelength laser

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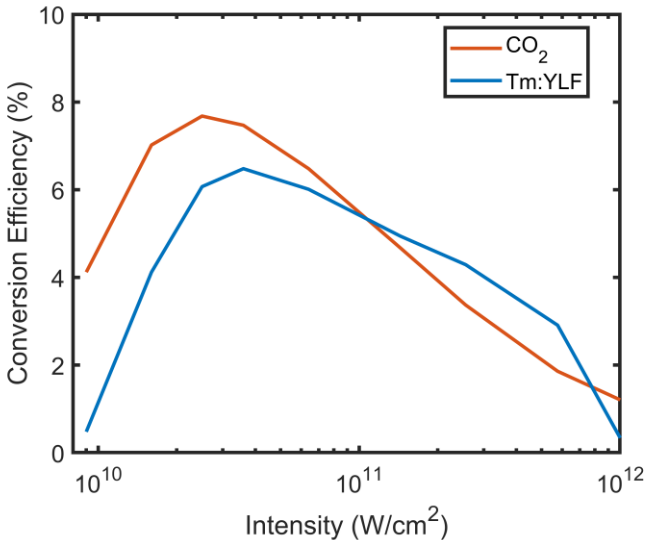
- Recent λ=2µm-driven EUV experimental work at ARCNL has demonstrated promising results.
- CE ~2x higher compared to λ = 1µm laser drivers.
- CE ~2x lower compared to state-of the-art CO_2 laser driven sources.
- May not optimized, but these results already show the potential for higher system-level efficiency.

Wavelength [um]

*1D HYDRA predicted absolute efficiencies are lower than experimental. More experimental pinning required to correct absorbed laser energy. Relative comparisons are more valid.

Preliminary HYDRA simulations of blue-X source based on Gd plasmas driven by CO2 vs. Tm:YLF lasers



- 1-D HYDRA simulation
- Thick, solid Gd target
- 12 ns flat in time pulse duration
- Gd atomic model constructed using configuration averaged data from FAC
- CE calculated with +/-1% spectral width centered near simulated emission peak near 7nm.

- Preliminary hydrodynamic/atomic physics simulations predict comparable emission between λ = 10μm and 2 μm drivers.

Steve Langer and Howard Scott, LLNL

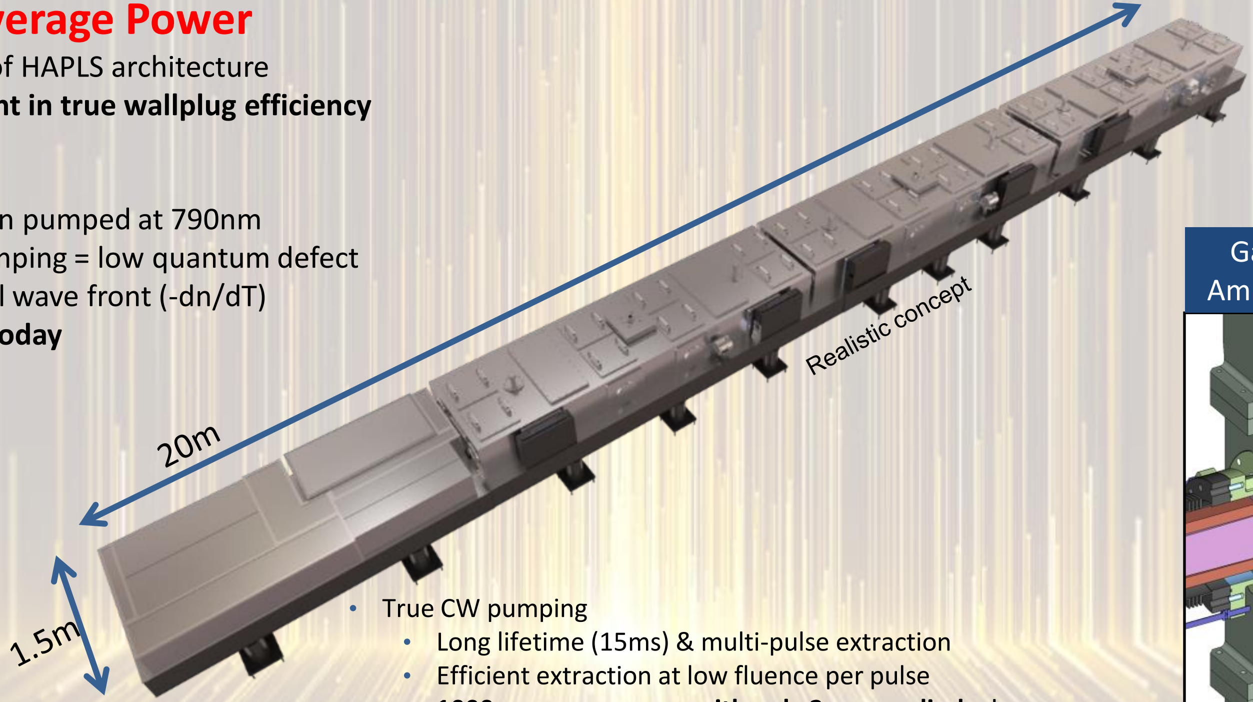
BAT

Big Aperture Thulium Laser Concept

30J, <100fs, 0.3PW, 10kHz
150J, <100fs, 1.5PW, 100Hz

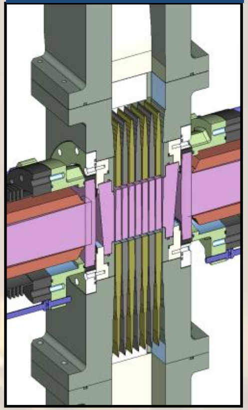
- **300,000 W Average Power**
- BAT is an extension of HAPLS architecture
  - **14× improvement in true wallplug efficiency**

- Tm:YLF laser media
  - 1900nm emission pumped at 790nm
  - Two-for-one pumping = low quantum defect
  - Superior thermal wave front (-dn/dT)
  - **Material exists today**

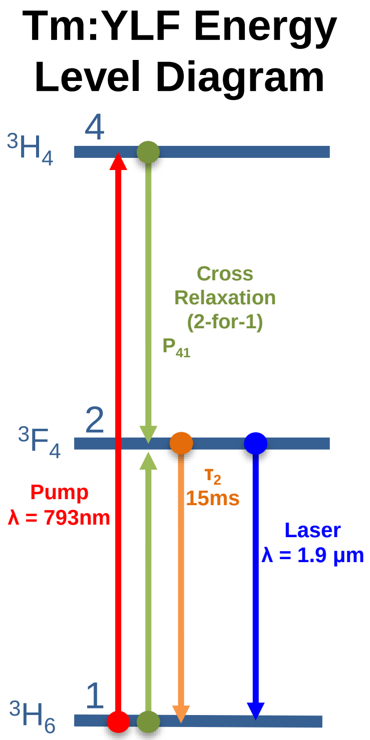


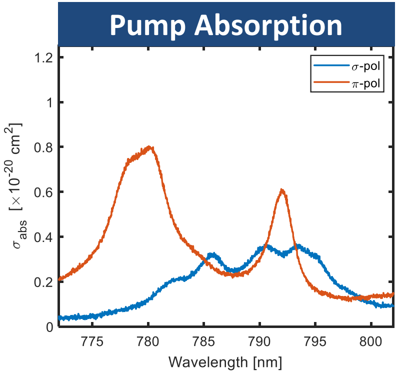
- True CW pumping
  - Long lifetime (15ms) & multi-pulse extraction
  - Efficient extraction at low fluence per pulse
  - **1000× average power with only 2× more diodes**!

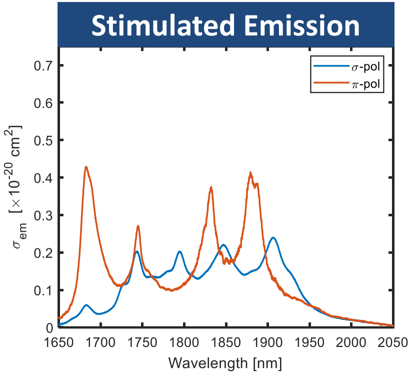
Gas-Cooled Amplifier Head



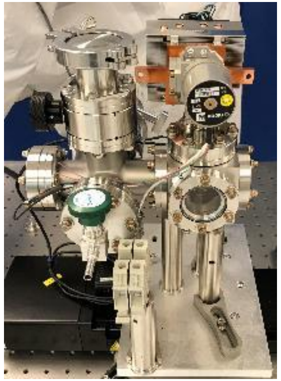
Tm:YLF properties are well-suited for efficient, high average power operation



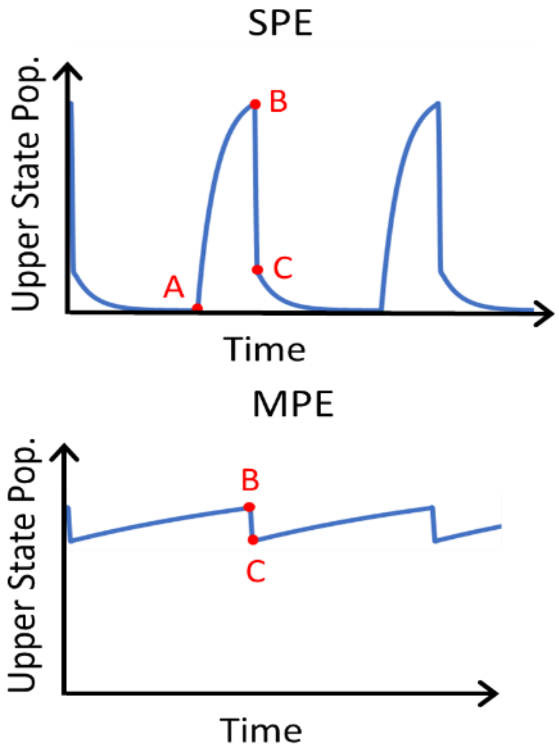


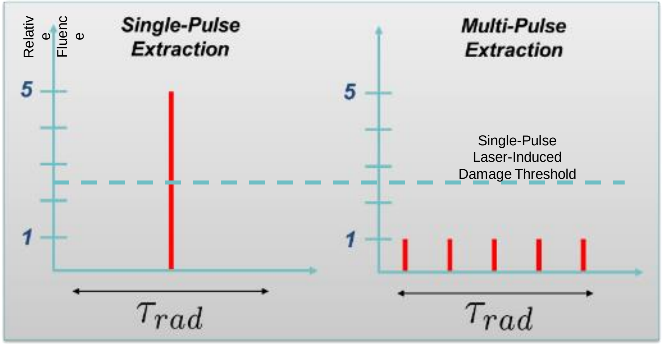


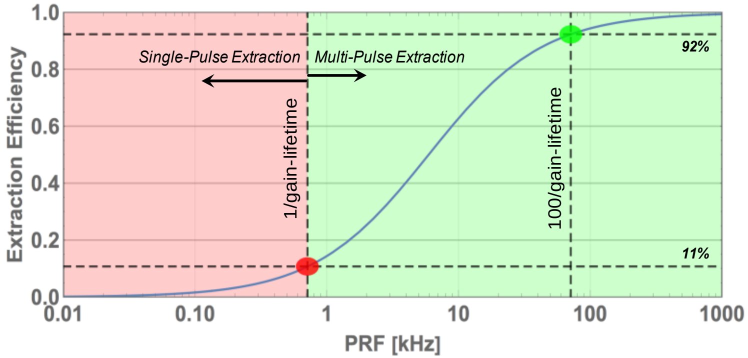
- λ_{pump} ≈ 790nm
  - Commercially available, high power and efficiency laser diodes
- λ_{laser} ≈ 1.88µm
- Fast nonradiative cross-relaxation populates laser upper level
  - 2-for-1 pumping → ~16% thermal defect
- Long 15ms radiative lifetime
  - High energy storage
  - Efficient multi-pulse extraction



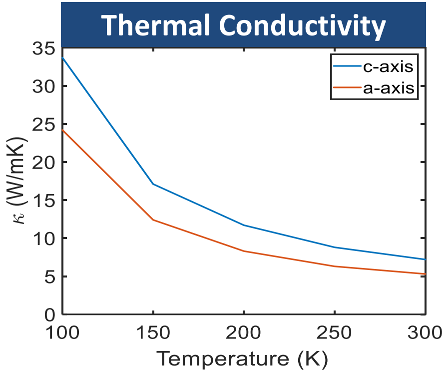
Multi-Pulse Extraction (MPE) enables the efficient operation of amplifiers based on high F_{sat} materials

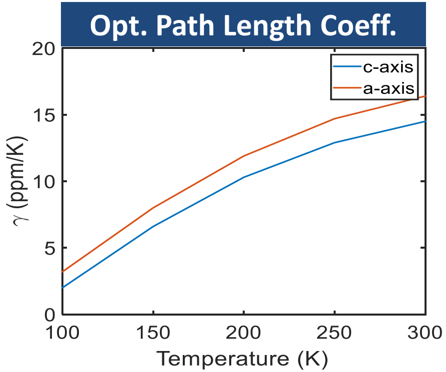


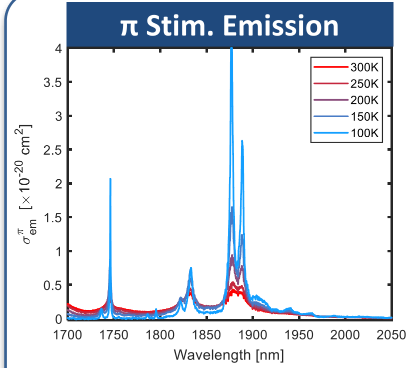


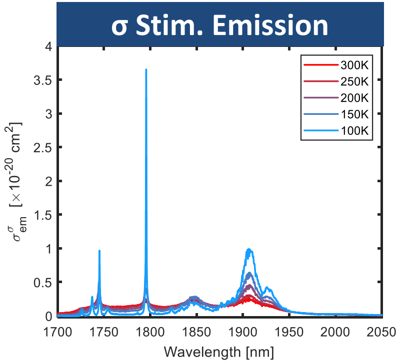


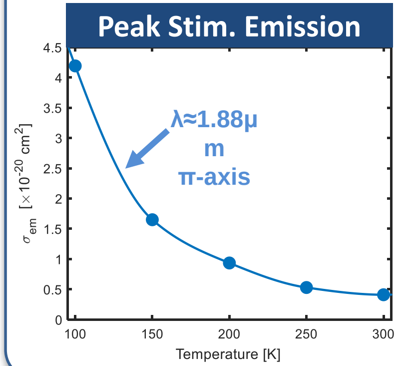
Tm:YLF thermal and spectroscopic characteristics are improved at low temperature

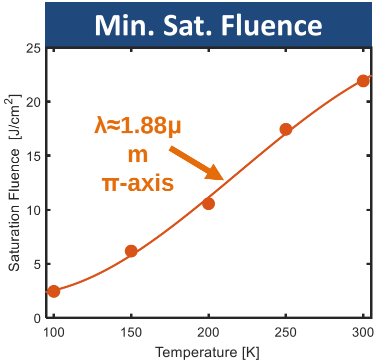






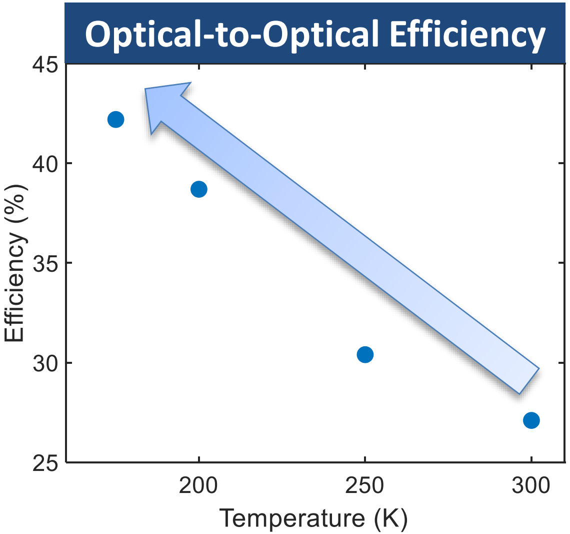


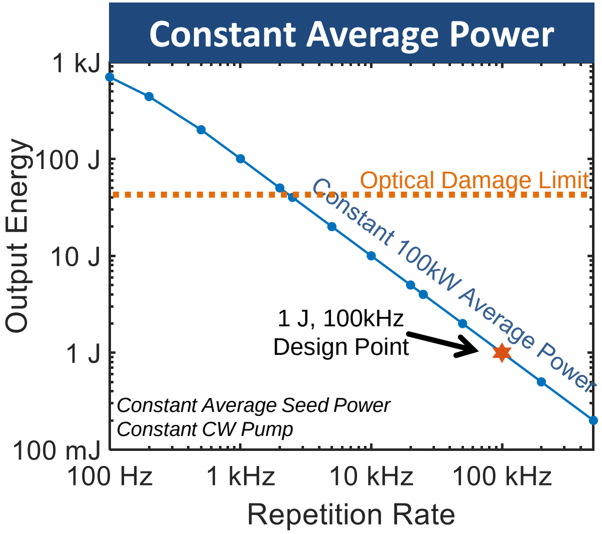




Data from: R.L. Aggarwal et al, *Jour. Appl. Phys.*, (2005).

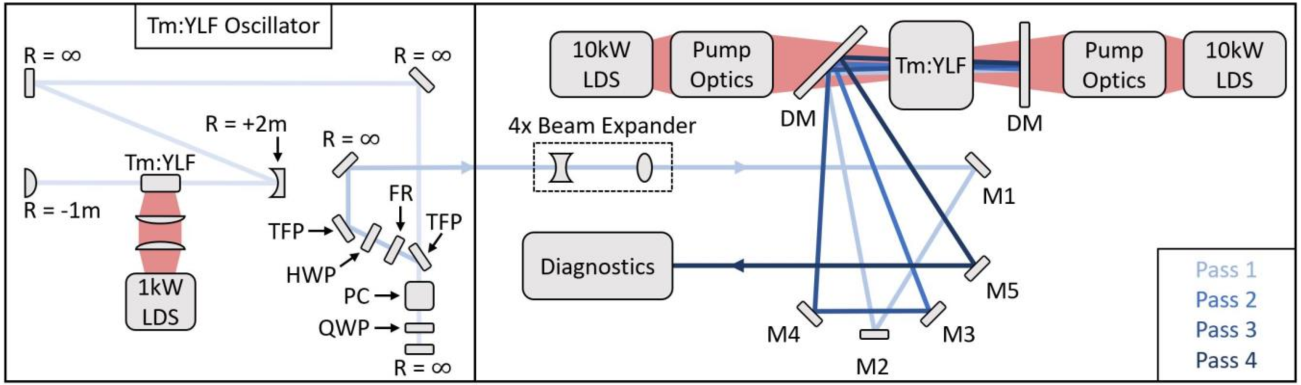
Warm Cryo EUV-BAT: 1J, 100kHz, 100 kW Concept





- Far-field multiplexed, 4-pass, single head amplifier geometry.
- Optical to Optical Efficiency >40%.
- Constant average power over wide range of Rep. Rates/ Pulse Energies.
- Wallplug efficiency approaching 20%.

Recent development efforts have focused on a demonstration system:



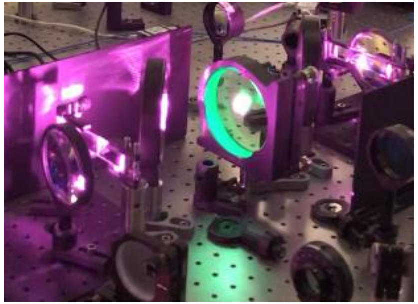
- Q-switched cavity-dumped oscillator currently producing up to 10's mJ pulses at 20 ns
- Pulse duration conservative to remain below damage thresholds

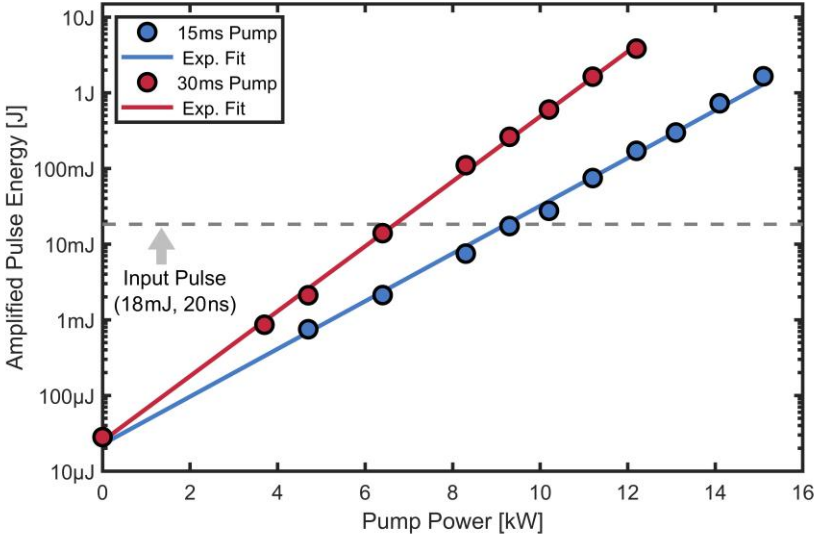
- 4 Pass Amplifer
- Pump source is a pair of 10 kW CW laser diode arrays operated for 10's of ms
- Energy deposited in crystal is adjusted using both diode current and pulse duration

I. Tamer, *et al*., Opt. Lett. (2021)

Single Shot Demonstration: 4 Joule, λ = 1.88µm 20ns pulses from Tm:YLF Amplifier

Amplified Pulse Energy vs. Peak Diode Pump Power



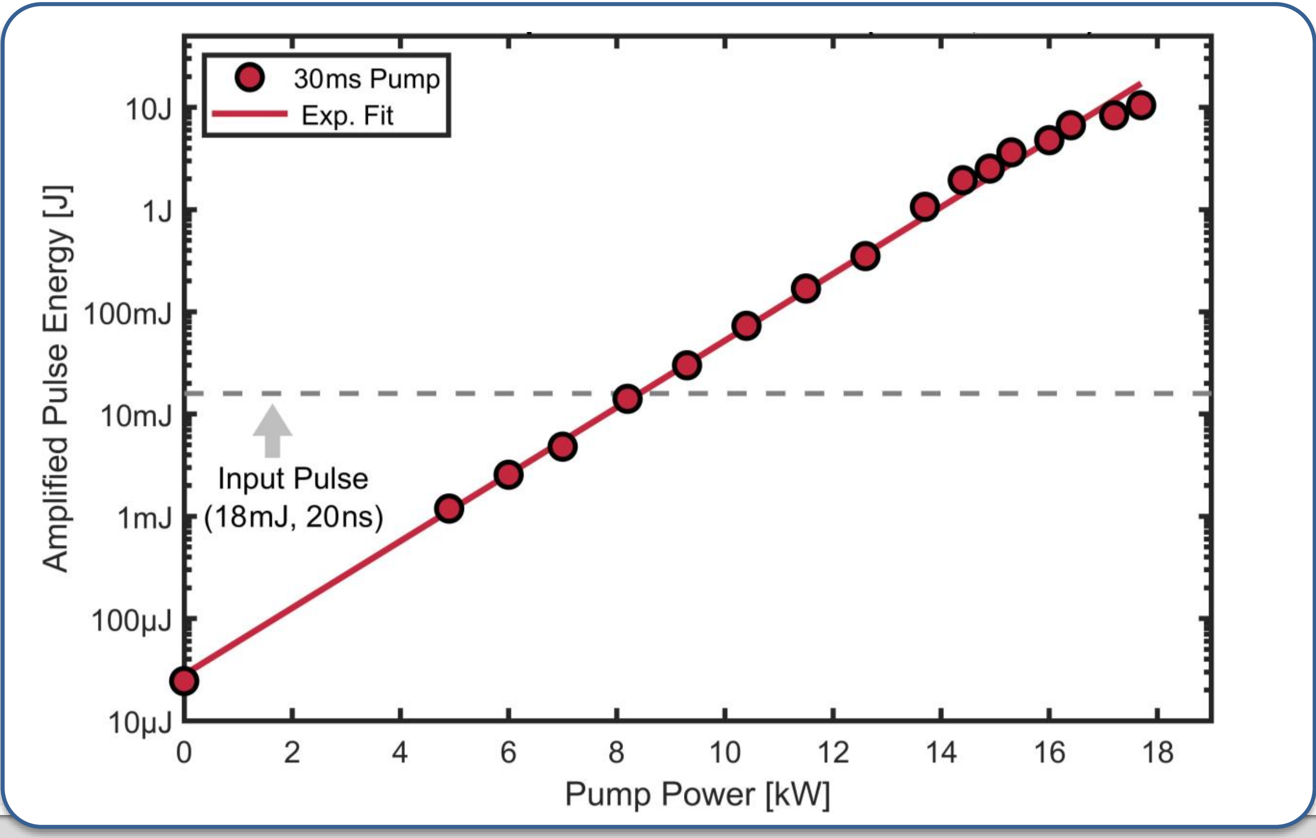


- Single stage, four pass, diode-pumped amplifier seeded with ~20 mJ, 20ns pulses from a cavity-dumped oscillator.

- Essentially all small signal gain: Much more energy stored in material.

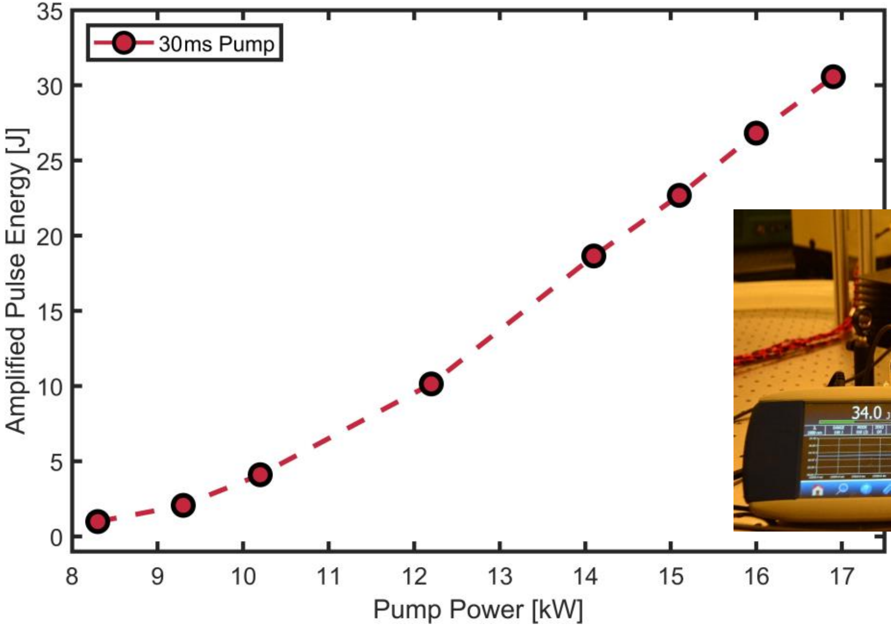
I. Tamer, *et al*., Opt. Lett. (2021)

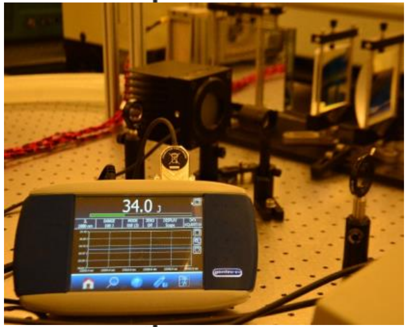
Single Shot Demonstration: 10 Joule, λ = 1.88µm 20ns pulses from Tm:YLF Amplifier



amer, *et al*., Opt. Lett. (2021)

Single Shot Demonstration: >30 J Pulse Energy Extracted in Long Pulse Mode





- World record pulse energy from Tm materials.
- Demonstrated high energy storage and extraction confirms gain physics and models.

I. Tamer, *et al.*, Opt. Lett. (2021)

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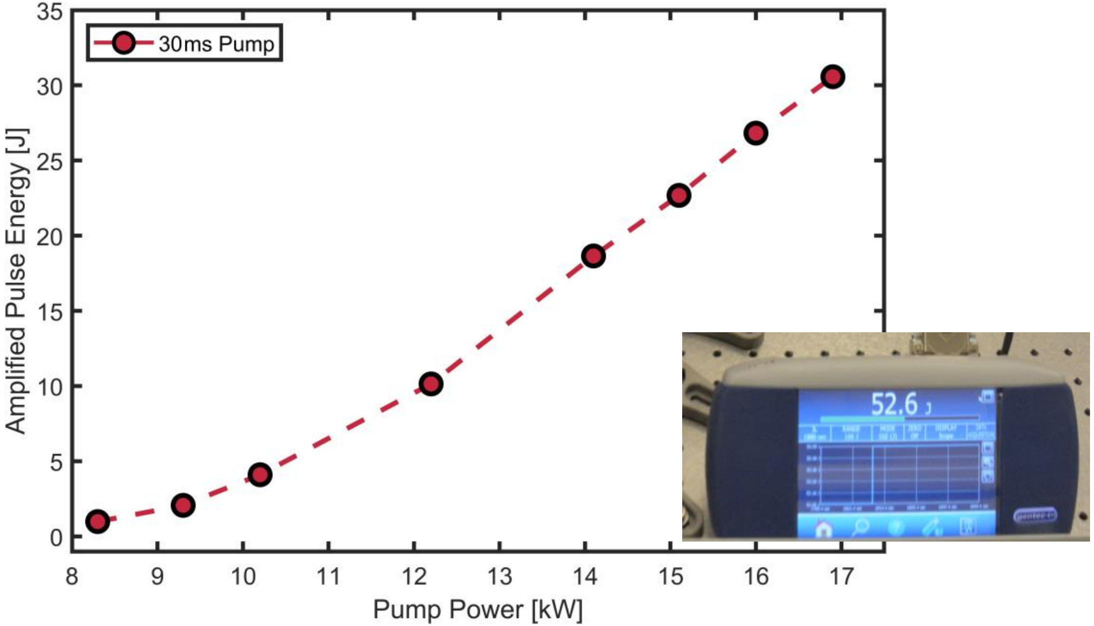

- World record pulse energy from Tm materials.
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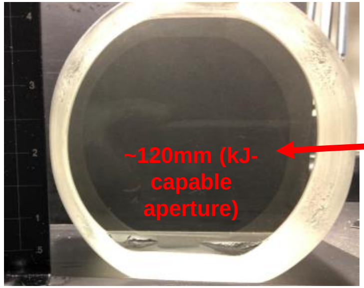
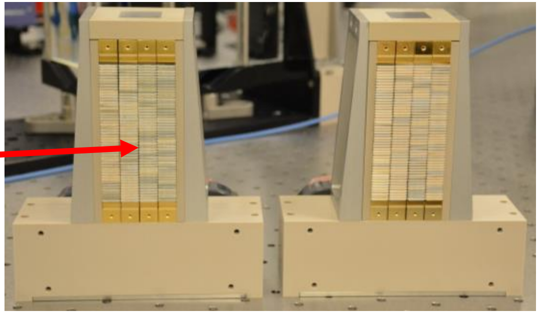
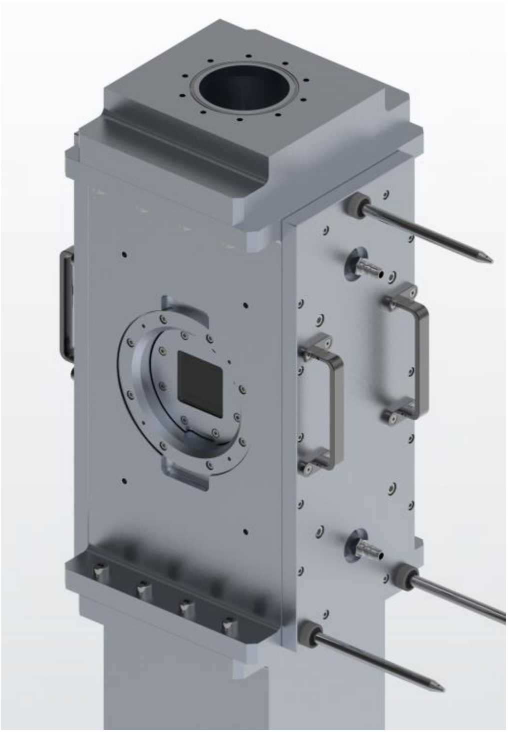
I. Tamer, *et al.*, Opt. Lett. (2021)

We aim to demonstrate that He gas can effectively cool Tm:YLF laser slabs in realistic BAT laser amplifier conditions

- We have designed and are fabricating a Tm:YLF-based gas cooling test stand
- Commercial diode pumps, laser-quality Tm:YLF gain material, and He flow hardware are in-hand
- We will deliver 40 kW of CW diode light to the Tm:YLF amplifier head to demonstrate ~10× higher areal heat flux to the gas coolant than state-of-the-art laser systems







This laser amp head design is *at scale* for multi-J-class kHz-class systems

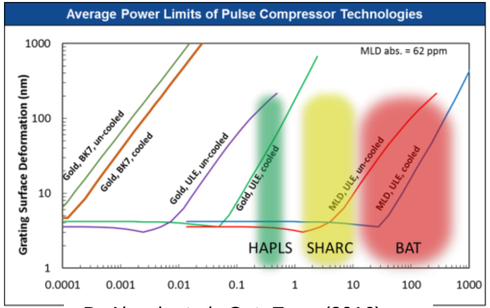
Producing shorter, high peak power pulses requires scaling of CPA techniques to longer wavelengths:

- Previous results indicate that multilayer dielectric (MLD) gratings on actively cooled ultra-low expansion (ULE) substrates are required for pulse compression of 100's kW avg. power

- We have developed efficient, broadband MLD gratings for 1.9 μm use wavelength

- LIDT tests by Enam Chowdhury's group at OSU have demonstrated damage thresholds >100 mJ/cm^2 for 50 fs pulses at 1.9 μm (S. Zhang, *et al*. Opt. Expr. (2021))

- Pulse compressor supporting Joule-level pulses is under development.



D. Alessi, *et al*., Opt. Expr. (2016)


Femtosecond damage experiments and modeling of broadband mid-infrared dielectric diffraction gratings

Simin Zhang[1], Michael Tripepi[2], Abdallah AlShafey[2], Noah Talisa[2], Hoang T. Nguyen[3], Brendan A. Reagan[3], Emily Sistrunk[3], David J. Gibson[3], David A. Alessi[3] and Enam A. Chowdhury[1,2,*]

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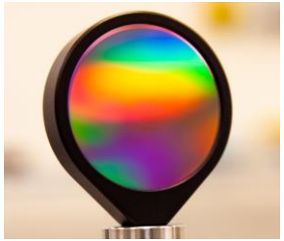
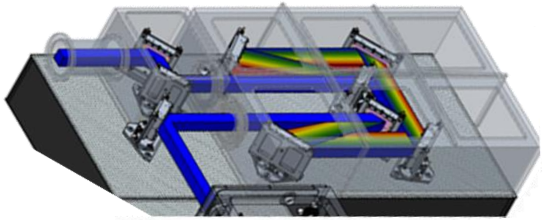
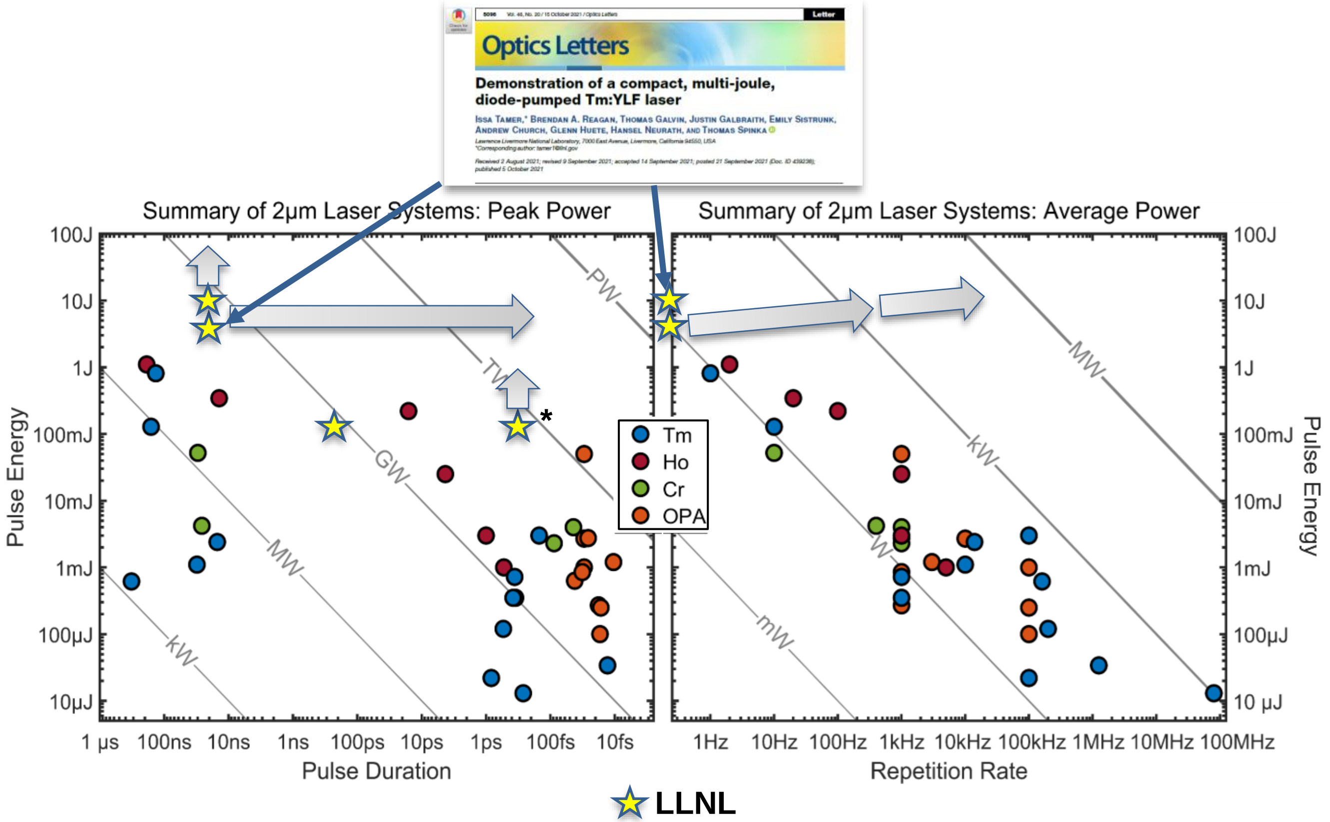




Summary of demonstrated λ ≈ 2 µm lasers



***Compressible Duration**

Directly diode-pumped, Tm:YLF lasers are candidates for driving future sources for lithography

- True wall plug efficiency ~20% allows increased productivity at higher driver laser power.
- Low gain distortion enables pulse shape tailoring for system-level efficiency optimization.
- Demonstrated 10 J, 20 ns pulses from a compact diode-pumped Tm:YLF amplifier.

Current/Future Directions for Tm:YLF driven EUV:

- **Thermal management** is the chief risk for the high average power EUV Tm:YLF laser concept, which we are actively reducing with current efforts.

- **System Optimization:** Combine laser amplifier and plasma simulations to optimize wall plug efficiency of entire system.
  - Laser parameters include energy, pulse duration, and wavelength/material
  - EUV-plasma parameters include intensity, focus size, rep. rate, etc.
  - Plasma simulation studies: Driver wavelength vs. CE for shorter wavelength source

- **EUV Driver Prototype:** Shot-on-demand (damage limited) and (~100-pulse) burst-mode operation using the very high energy storage density of Tm:YLF temporarily sidesteps thermal issues and enables *compact and portable* system designs which are *much nearer term.*
  - We envision a burst-mode Tm:YLF EUV driver which could be brought to EUV source development sites for collaborative test & simulation campaigns.

Work supported by the LLNL LDRD program under project numbers: 19-DR-009 and 21-ER-016 and by the U.S. Department of Energy Accelerator Stewardship Program, Office of High Energy Physics, Office of Science under award SCW1648.

We have open postdoc and scientist positions for individuals excited about developing the next generation of high average power lasers!

Advanced Photon Technologies Postdoc:
www.llnl.gov/join-our-team/careers/find-your-job/all/REF1087R

llnl.gov/careers

Email: reagan2@llnl.gov

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