Thulium-based EUV Drive Lasers Scalable to Near-MW Average Powers

2019 EUVL Workshop

CXRO, LBL, Berkeley CA

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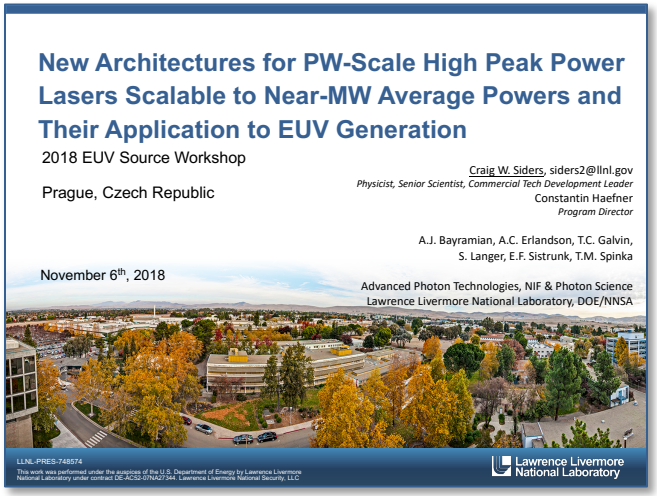
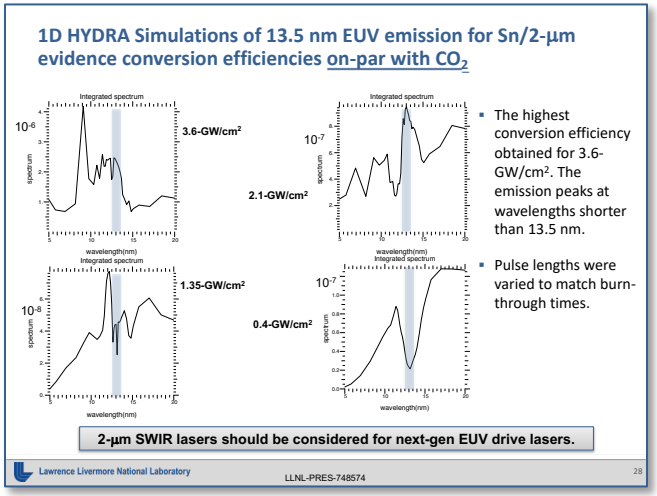
Introduction





At the November 2018 EUV Source Workshop, we introduced novel high average power laser architectures based upon LLNL/ELI-Beamlines HAPLS/L3 laser:

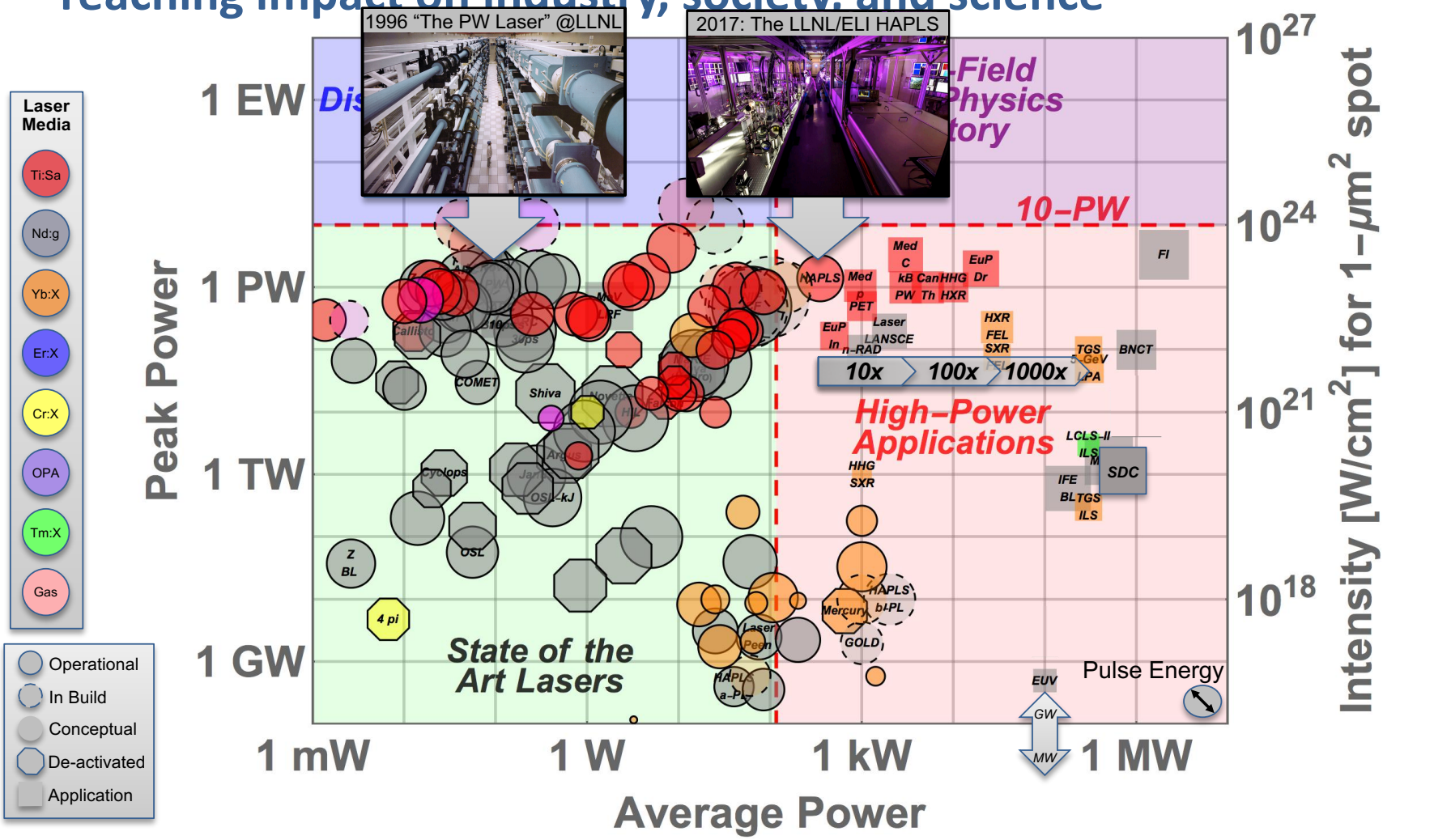
- SHARC (Scalable High-power Advanced Radiography Capability):
  - diode-pumped Nd:Glass, 1-um wavelength
  - 150-J/150-fs/10-Hz
  - for laser-driven secondary x-rays/neutrons
- BAT (Big Aperture Thulium):
  - diode-pumped Tm:YLF, 1.9-um wavelength
  - 30-J/100-fs/10-kHz
  - for laser-driven electron/positron colliders

And we presented promising preliminary CE estimates of 2-um EUV drive lasers on Sn droplets showing on-par with CO_2.

For this 2019's EUVL Workshop, we present results of detailed laser systems engineering modeling* for EUV-tailored design points of the BAT architecture.

*funded by LLNL LDRD office.

High-average Power, High-Intensity Lasers are poised to have far reaching impact on industry, society, and science



Pushing the frontiers of high-power applications and high-intensity science requires next-generation high repetition-rate high-energy solid state lasers.

ELI L3-High-repetition-rate Advanced Petawatt Laser System (L3-HAPLS) is the only PW-class DPSSLP laser operational today

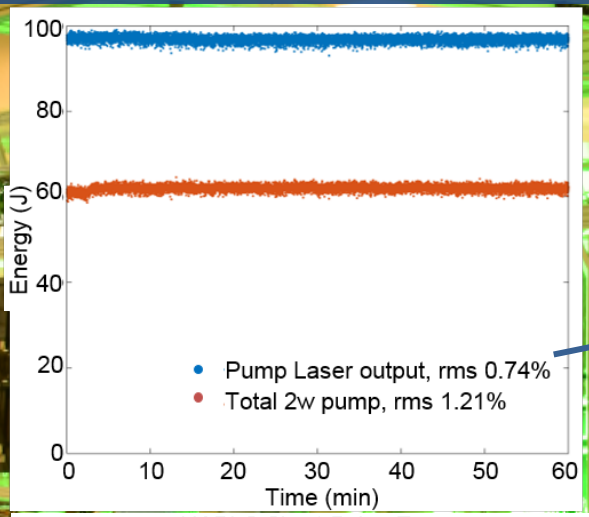
July 2018

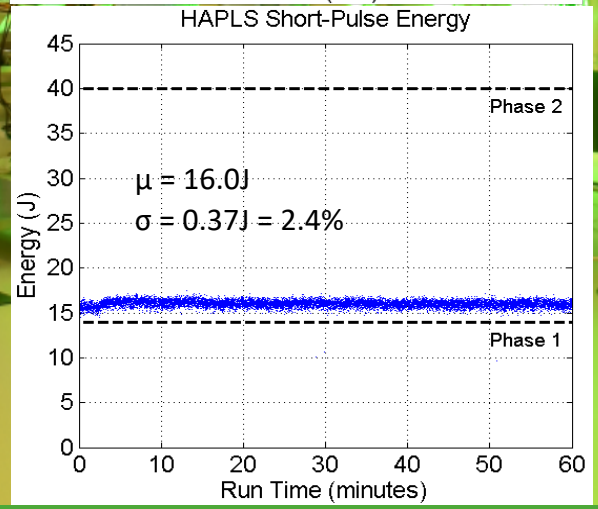

June 2018: HAPLS Final Review

Requirement	Specification
Energy at 820nm	≥30 J (Phase 2)
Pulse Length	≤30 fs
Peak Power	≥1 PW
Pre-pulse Power Contrast	$\leq 10^{-9} \leq c \leq 10^{-11}$
Energy Stability	0.6% rms
Technology	DPSSL pumped Ti:sapphire CPA
Repetition Rate	10 Hz (Phase 2)
Power Consumption	<150 kW

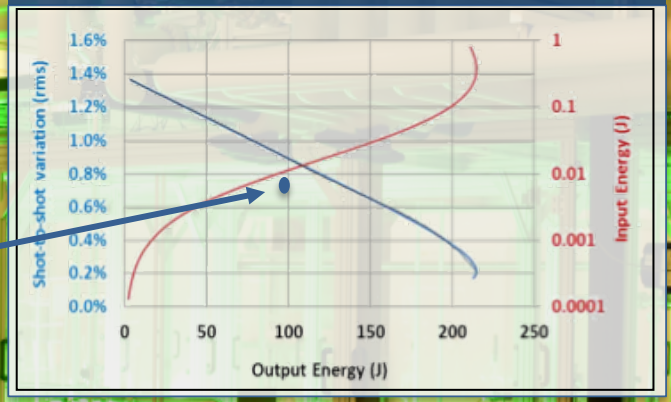
For first experiments HAPLS was configured for ~1/2 PW at 3⅓Hz with a full-aperture pulse duration of 26fs

Energetics

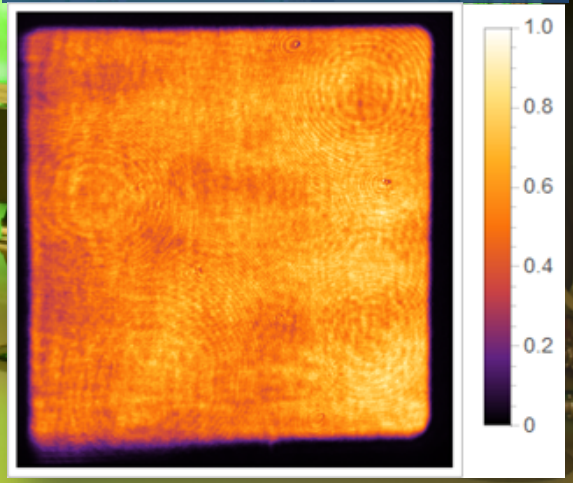




Energy stability scales with output energy. Predicted <0.35% @ 200J



Pump Laser Beam Profile



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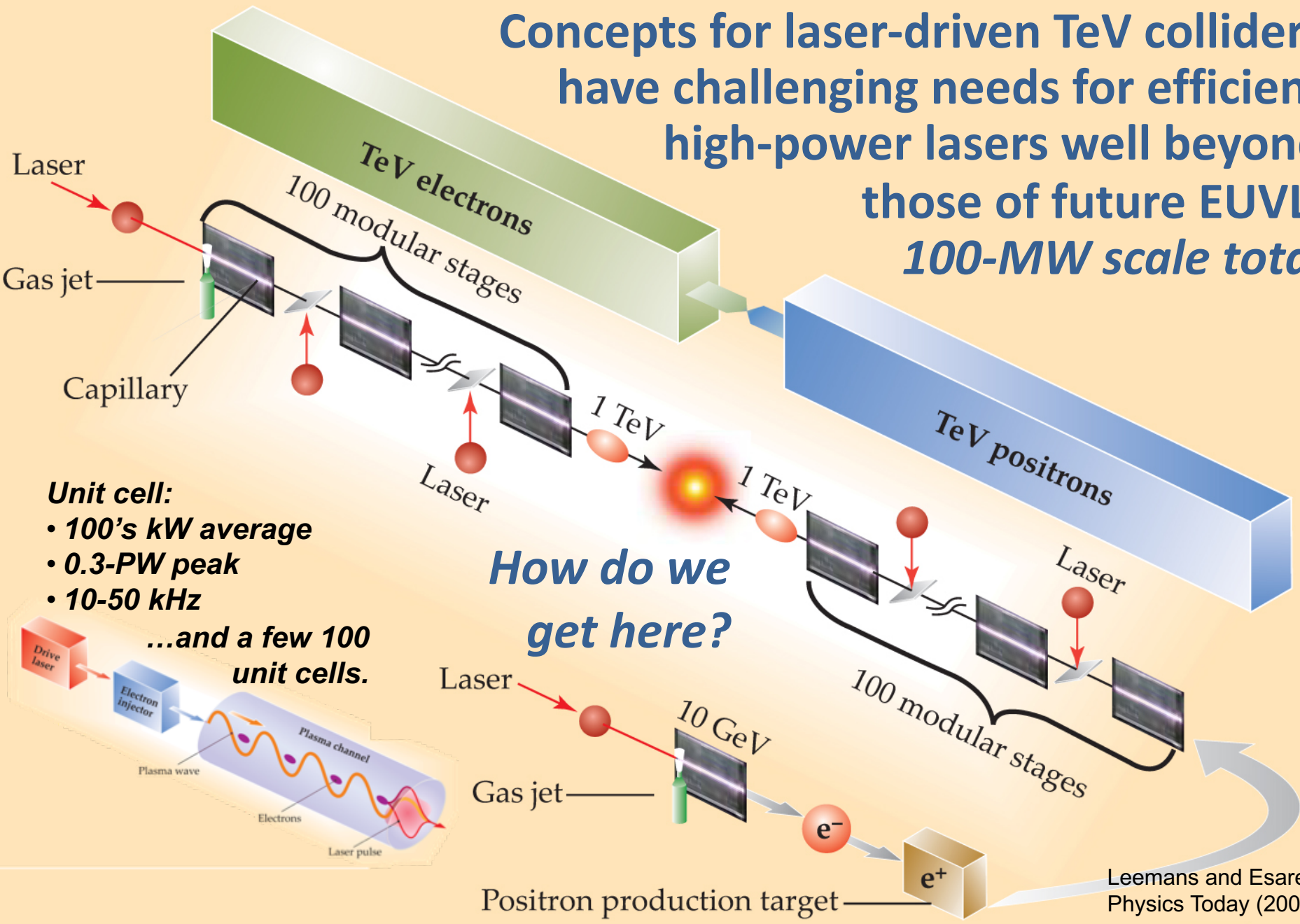
HAPLS is an operational, industry-grade "set and forget" laser system, and is a stepping stone for exploring the science of secondary sources

Concepts for laser-driven TeV colliders have challenging needs for efficient high-power lasers well beyond those of future EUVL: *100-MW scale total*



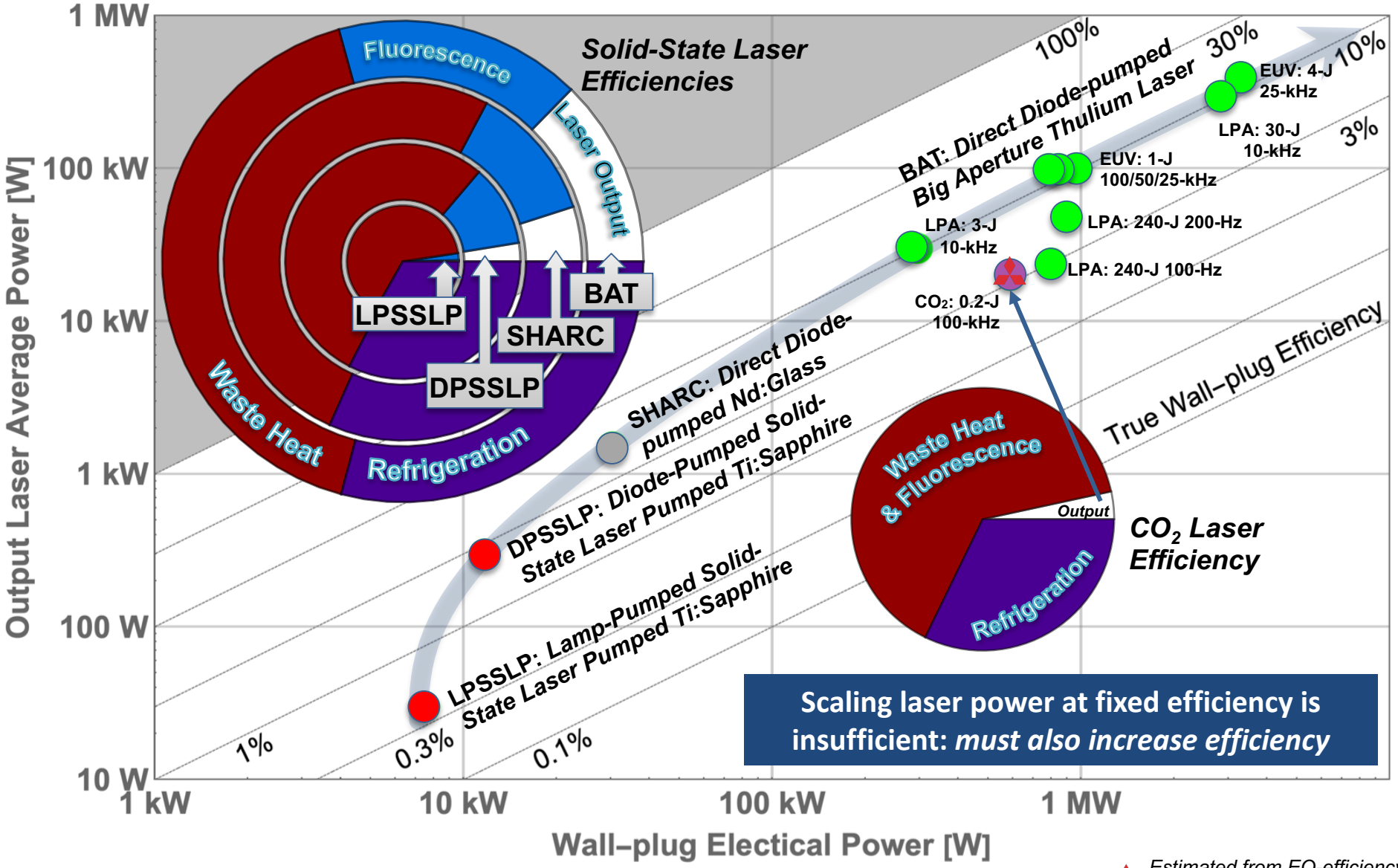
Unit cell:
- ***100's kW average***
- ***0.3-PW peak***
- ***10-50 kHz***

…and a few 100 unit cells.

How do we get here?

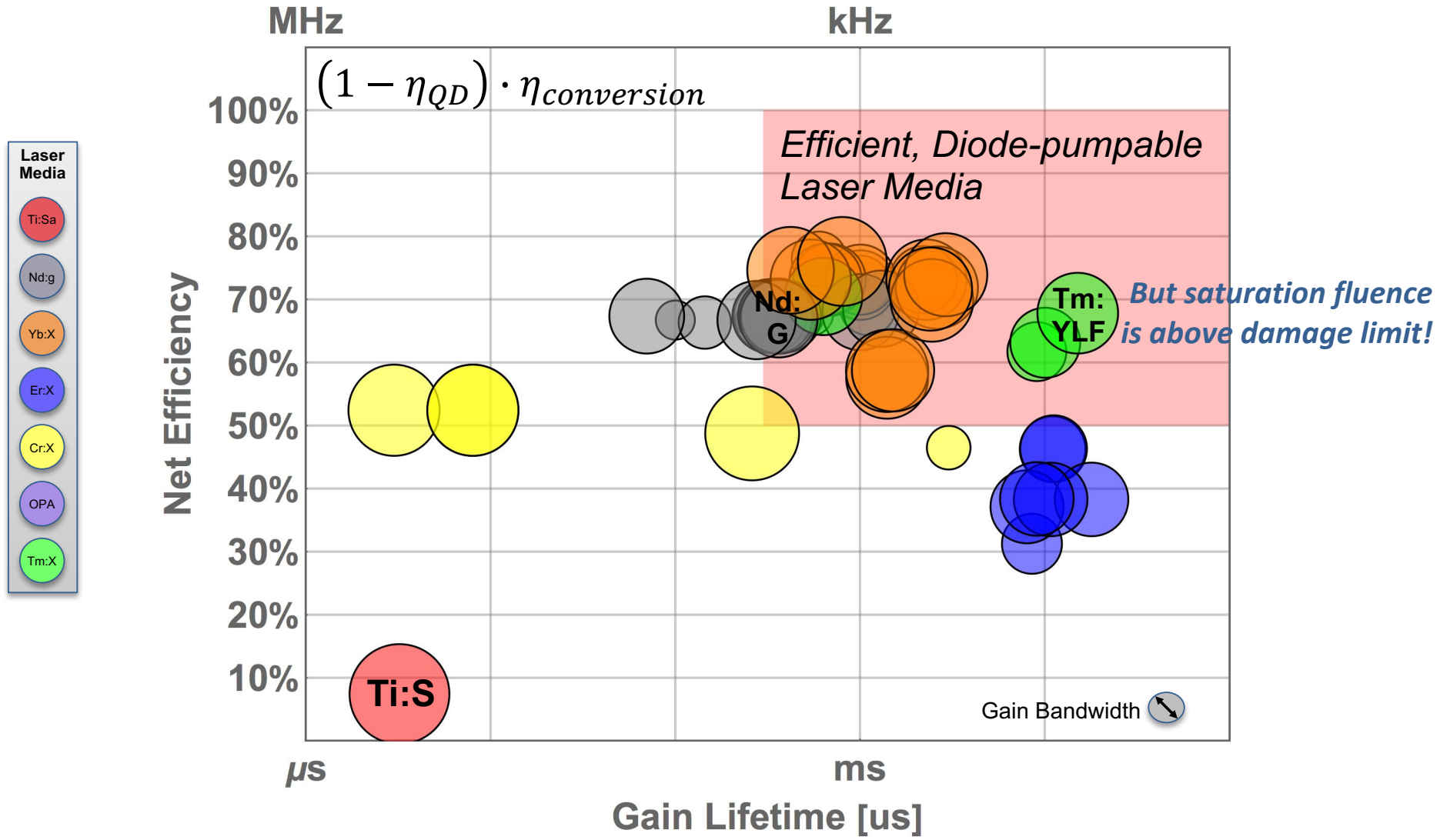
Leemans and Esarey, Physics Today (2009)

LLNL's BAT-Class laser architecture sets a new standard for high average power lasers with high true wall-plug efficiency

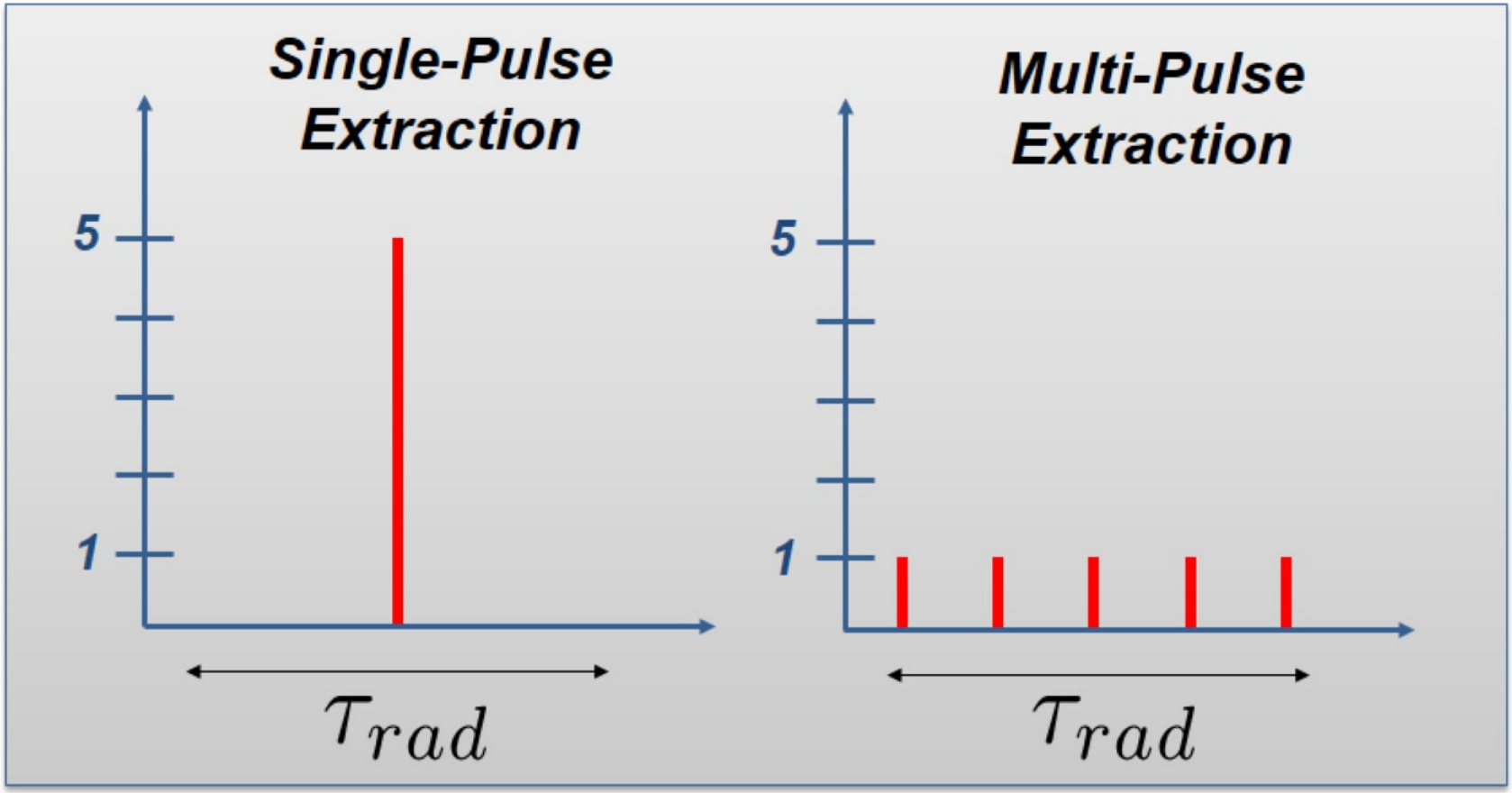


Estimated from EO-efficiency Tanino et al, 2013 ISEUVL

Why Tm:YLF? Long gain-lifetime and efficient diode-pumping with COTS diodes



Stored energy can be extracted from laser medium with a high fluence single pulse, or multiple low-fluence pulses within the radiative lifetime



Multi-pulse extraction reduces the effective fluence in the laser system and therefore moves the operating point into a manageable regime for low cross-section materials

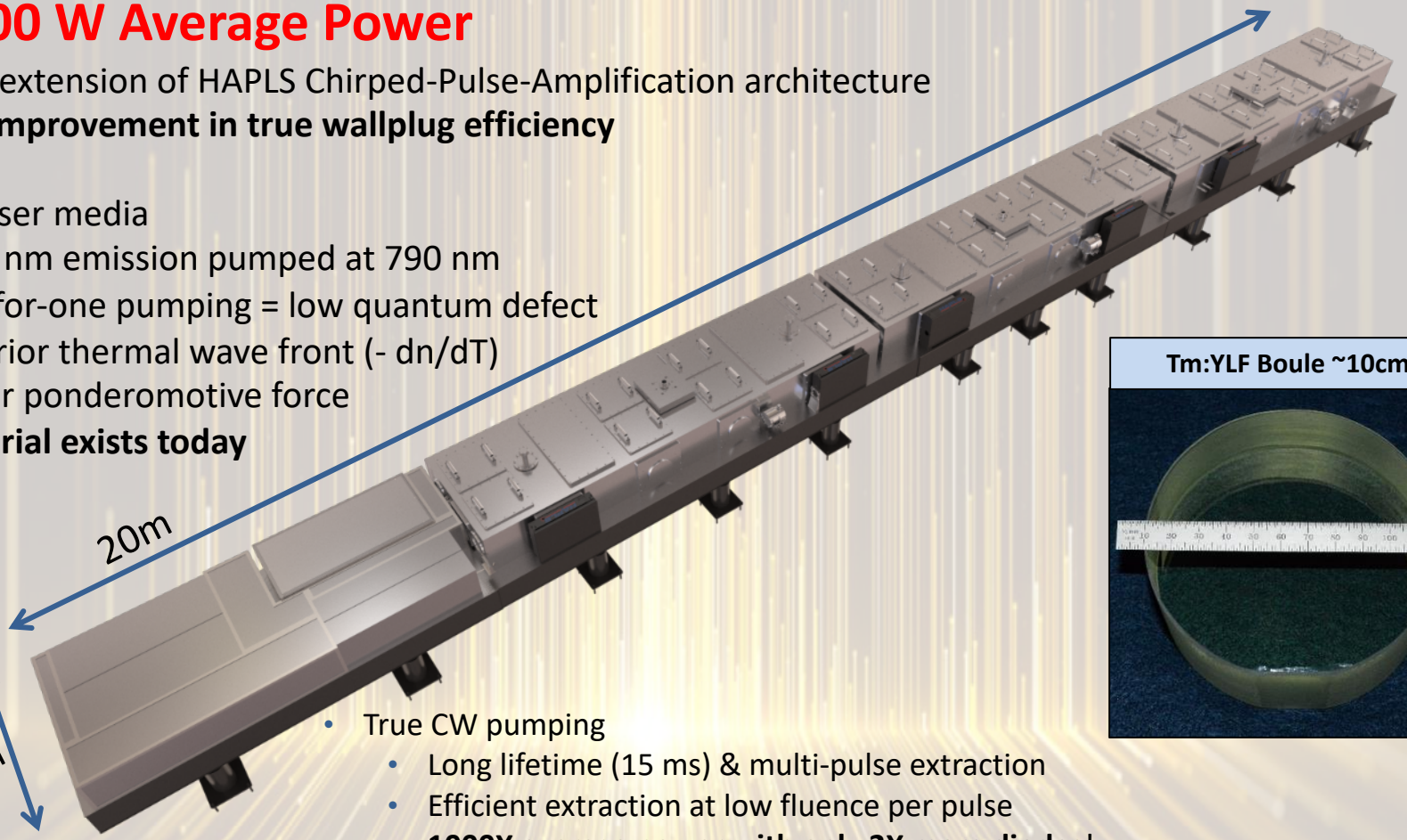
BAT

Big Aperture Thulium Laser Concept

Collider: 30J, 100fs, 0.3PW, 10kHz
LWFA testbeds: 240J, 240fs, 1.0PW, 100Hz

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

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



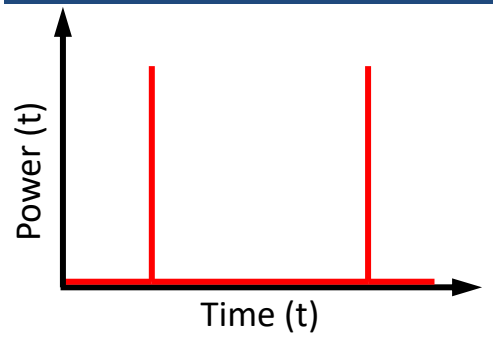
- True CW pumping
  - Long lifetime (15 ms) & multi-pulse extraction
  - Efficient extraction at low fluence per pulse
  - **1000X average power with only 2X more diodes**!

The BAT technology is the game changer to drive LPA with up to 300kW of average power per stage

By operating in a steady-state, multi-pulse extracted BAT lasers optimize efficiency AND pulse-to-pulse stability

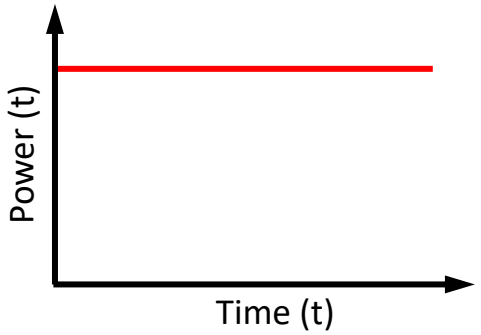
Pulsed Pumping and Pulsed Cooling

Duty cycle << 100%

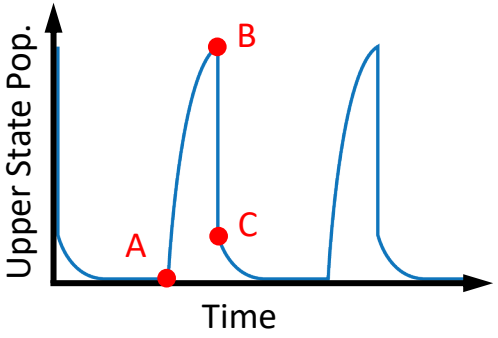


Continuous Pumping and Continuous Cooling

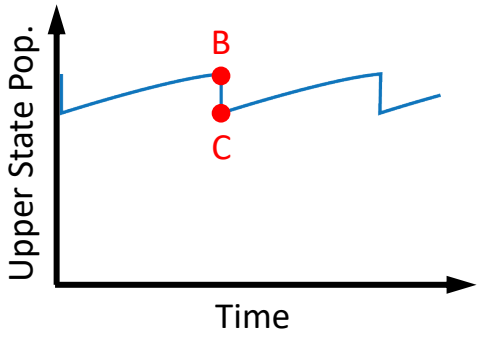
Duty cycle = 100%



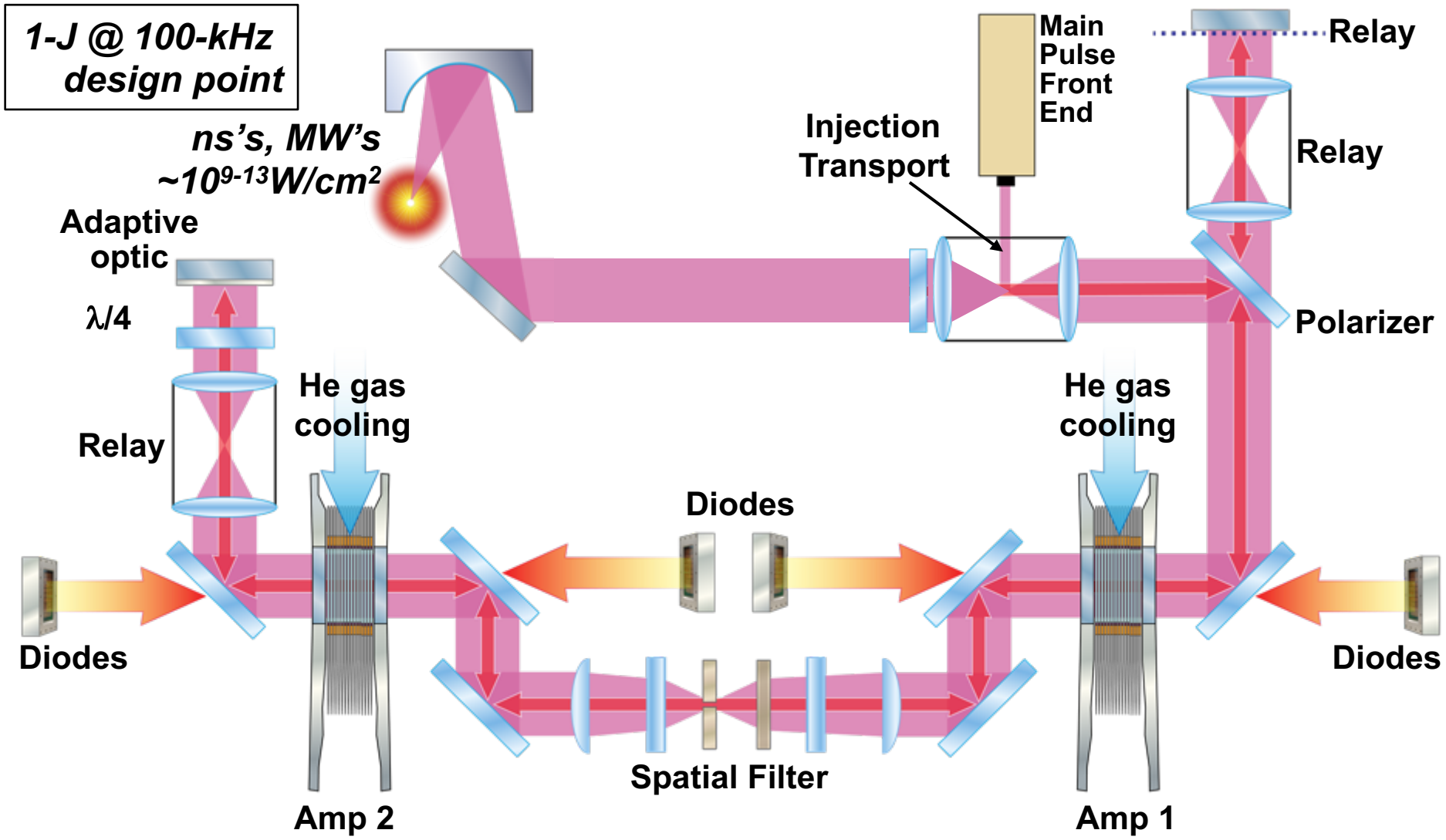
Single Pulse Extraction



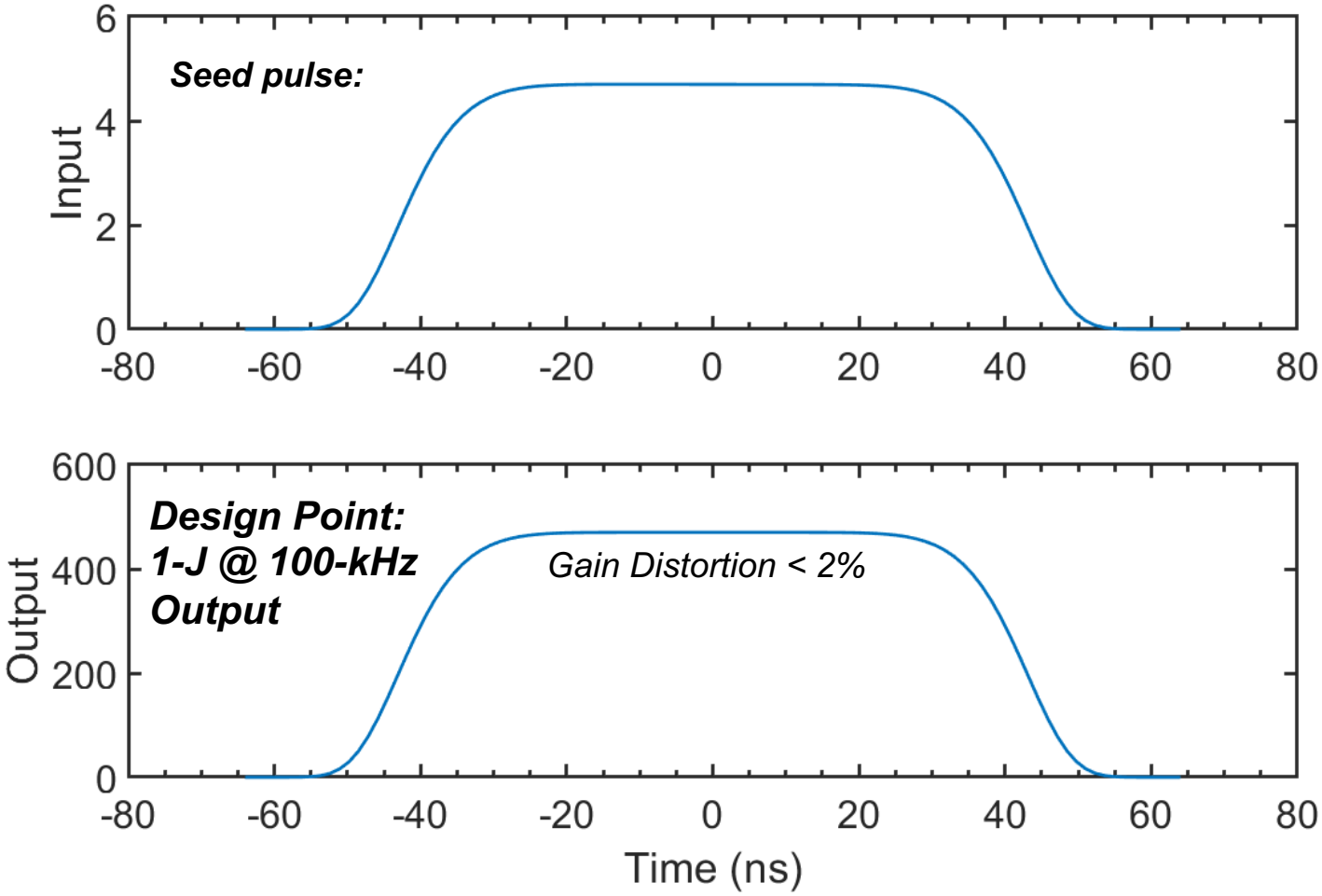
Multi-Pulse Extraction



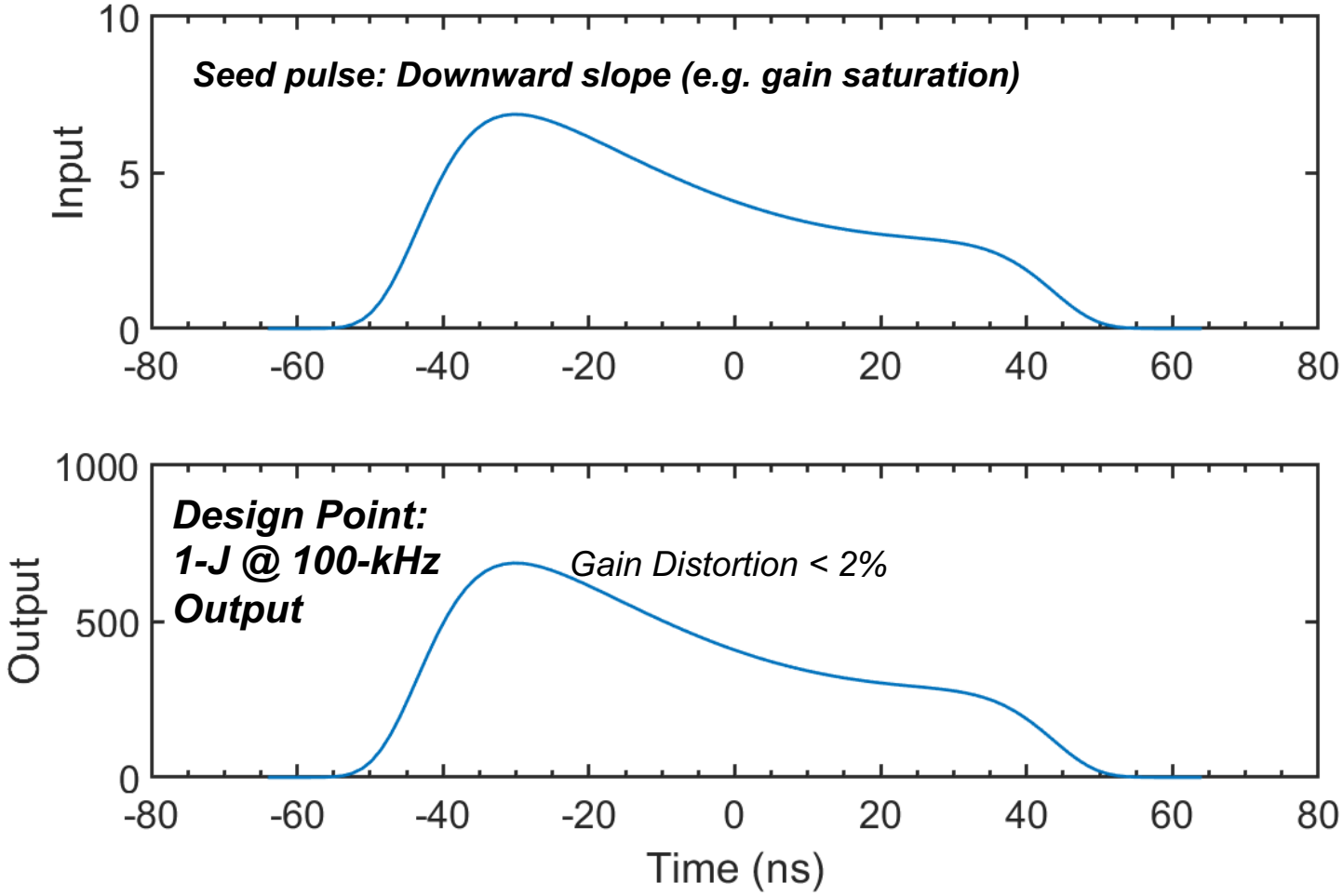
We have developed an EUV-BAT design that consists of a diode-pumped surface-cooled multi-slab amplifier in a 4-pass polarization switched architecture



Our EUV-BAT design point has minimal distortion in amplification: output pulse accurately follows seed pulse



The EUV-BAT design point has minimal distortion in amplification: precise pulse shaping



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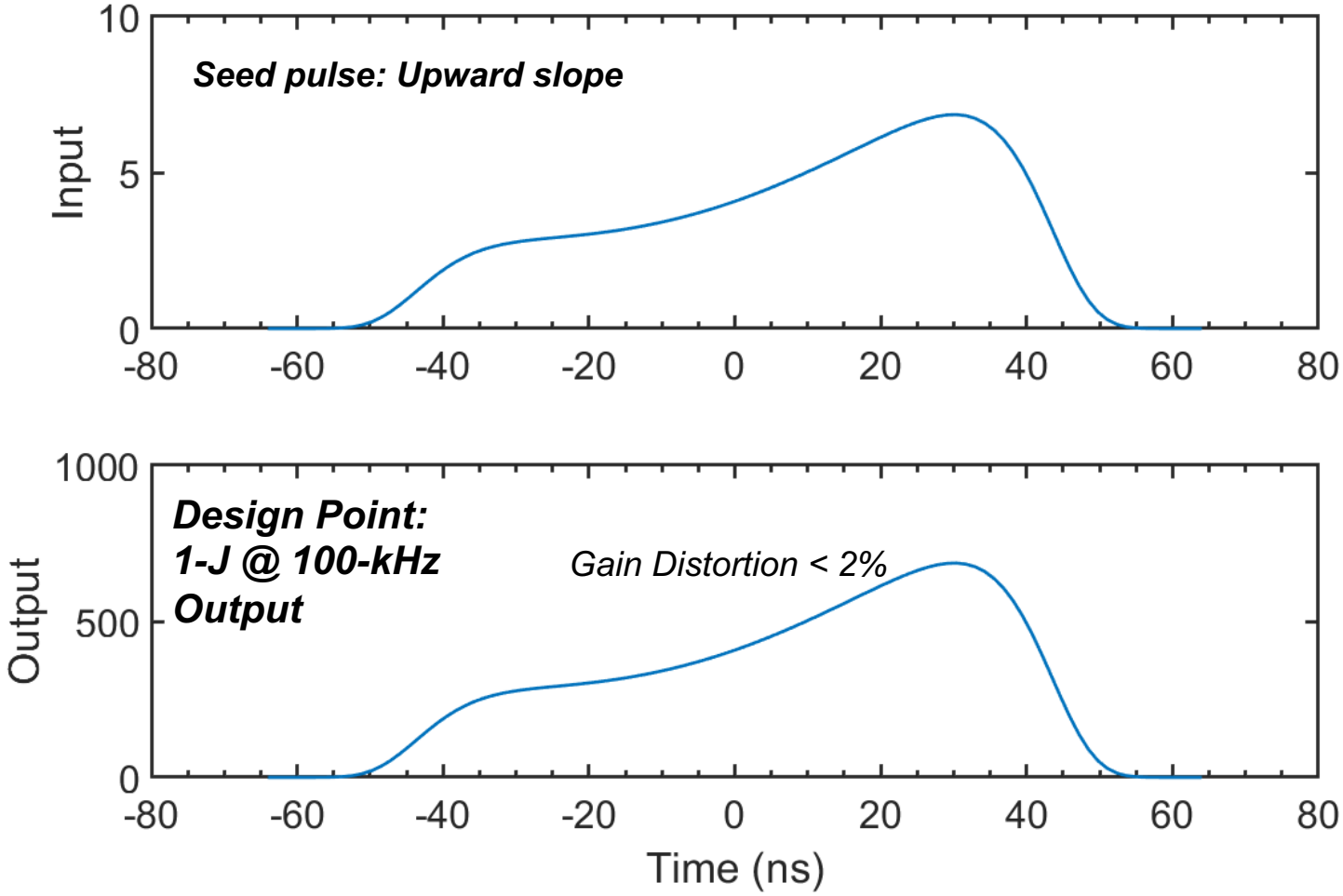

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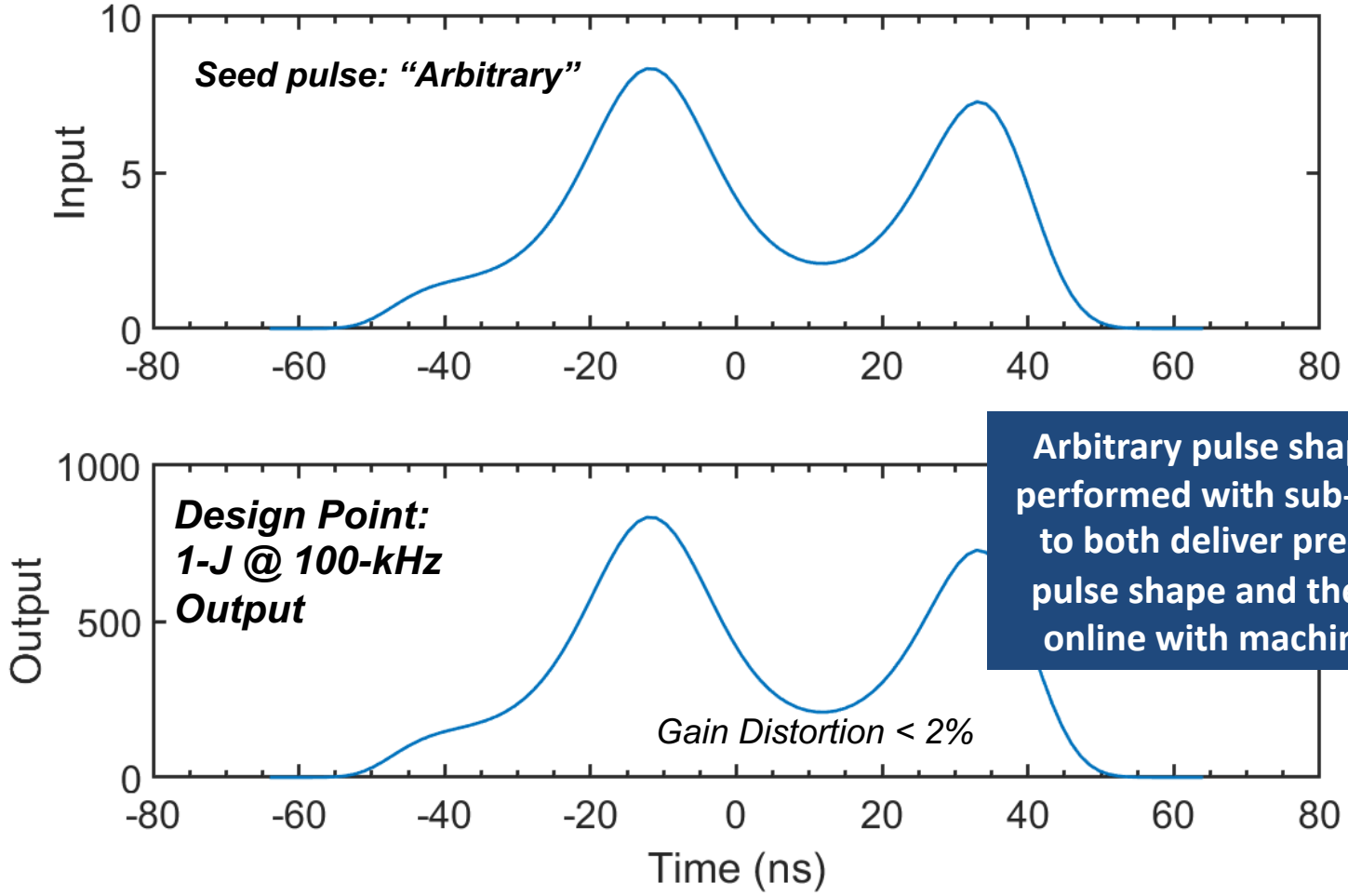
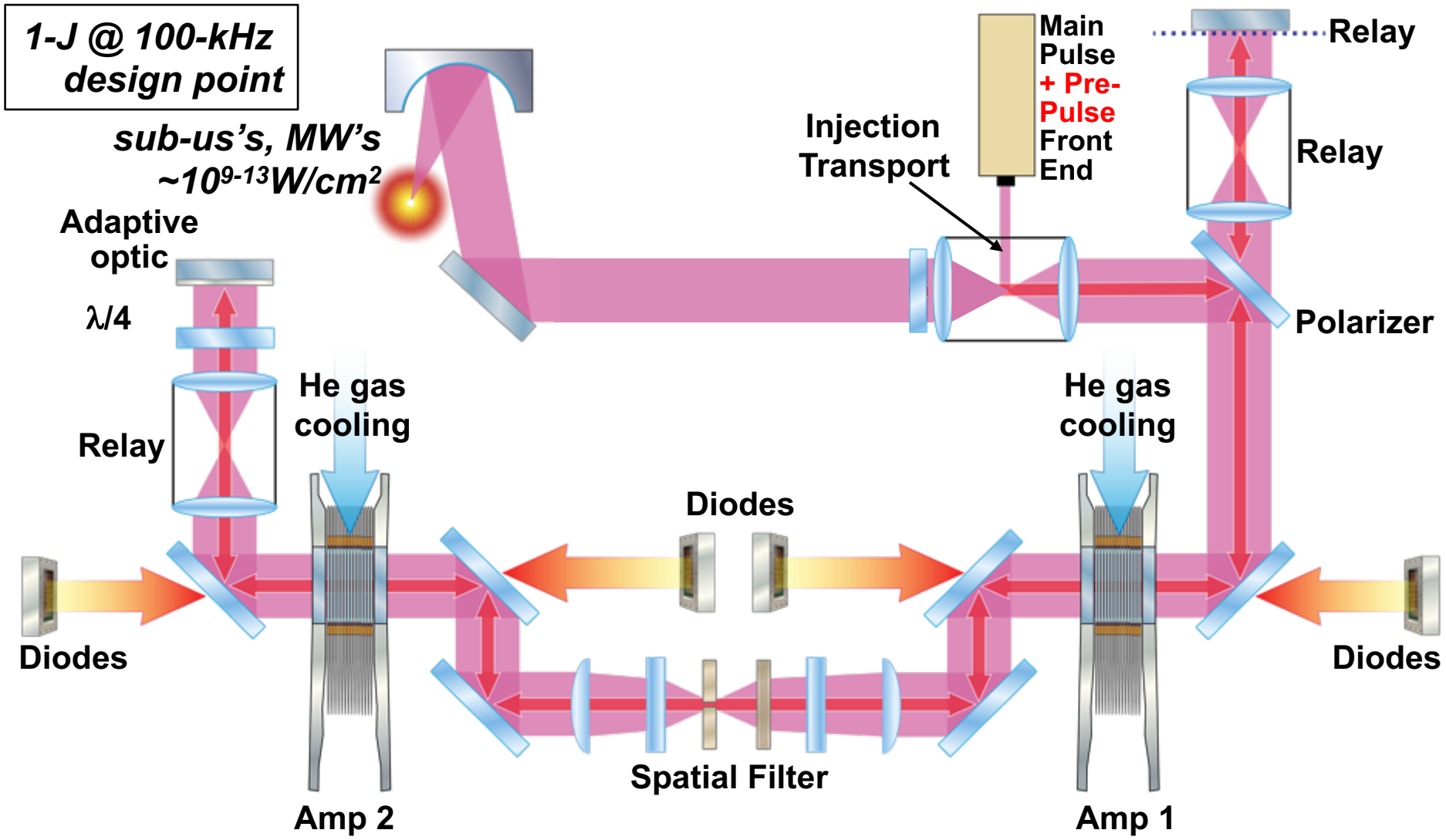
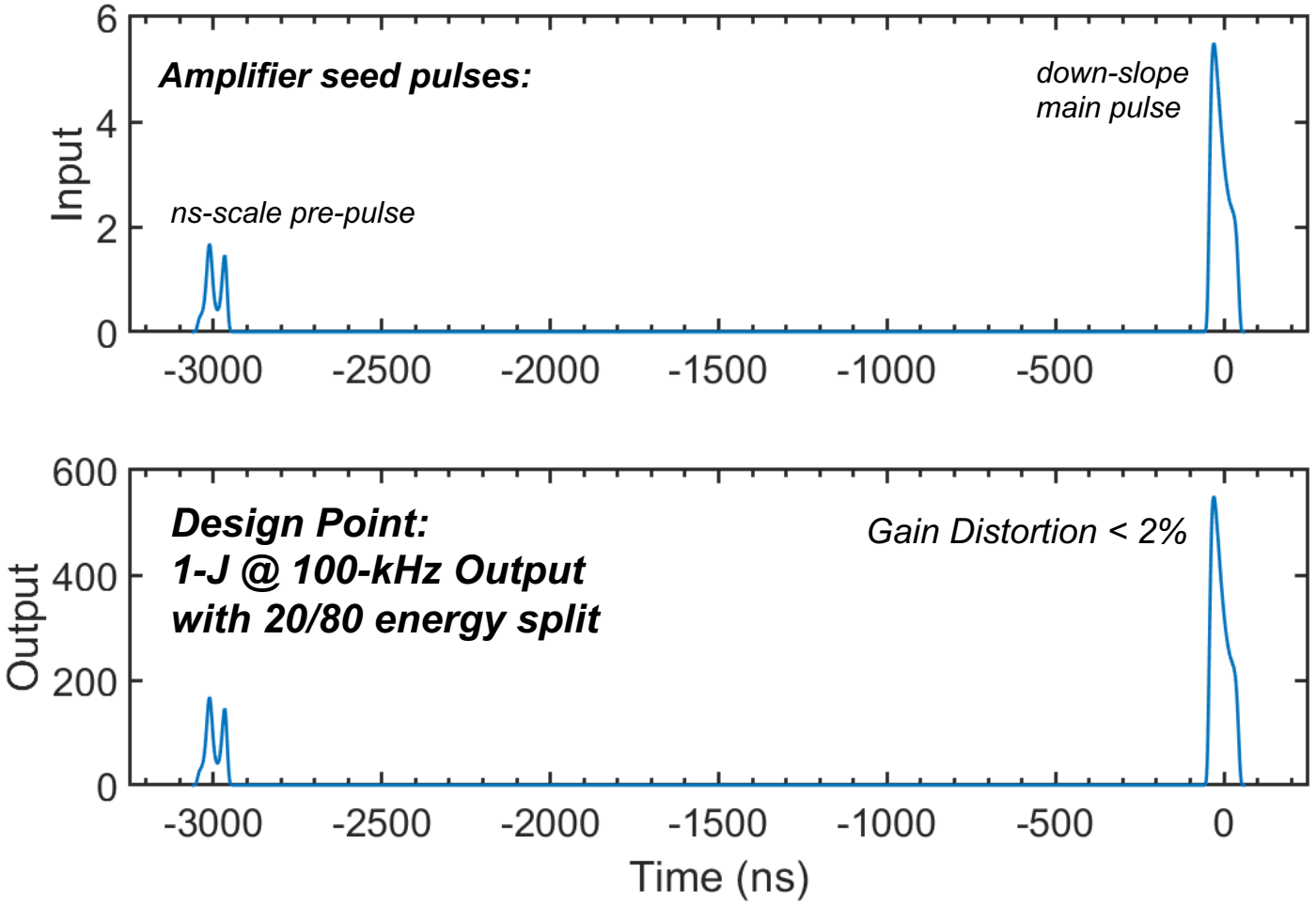


Arbitrary pulse shaping can be performed with sub-ns precision to both deliver pre-computed pulse shape and then optimize online with machine learning

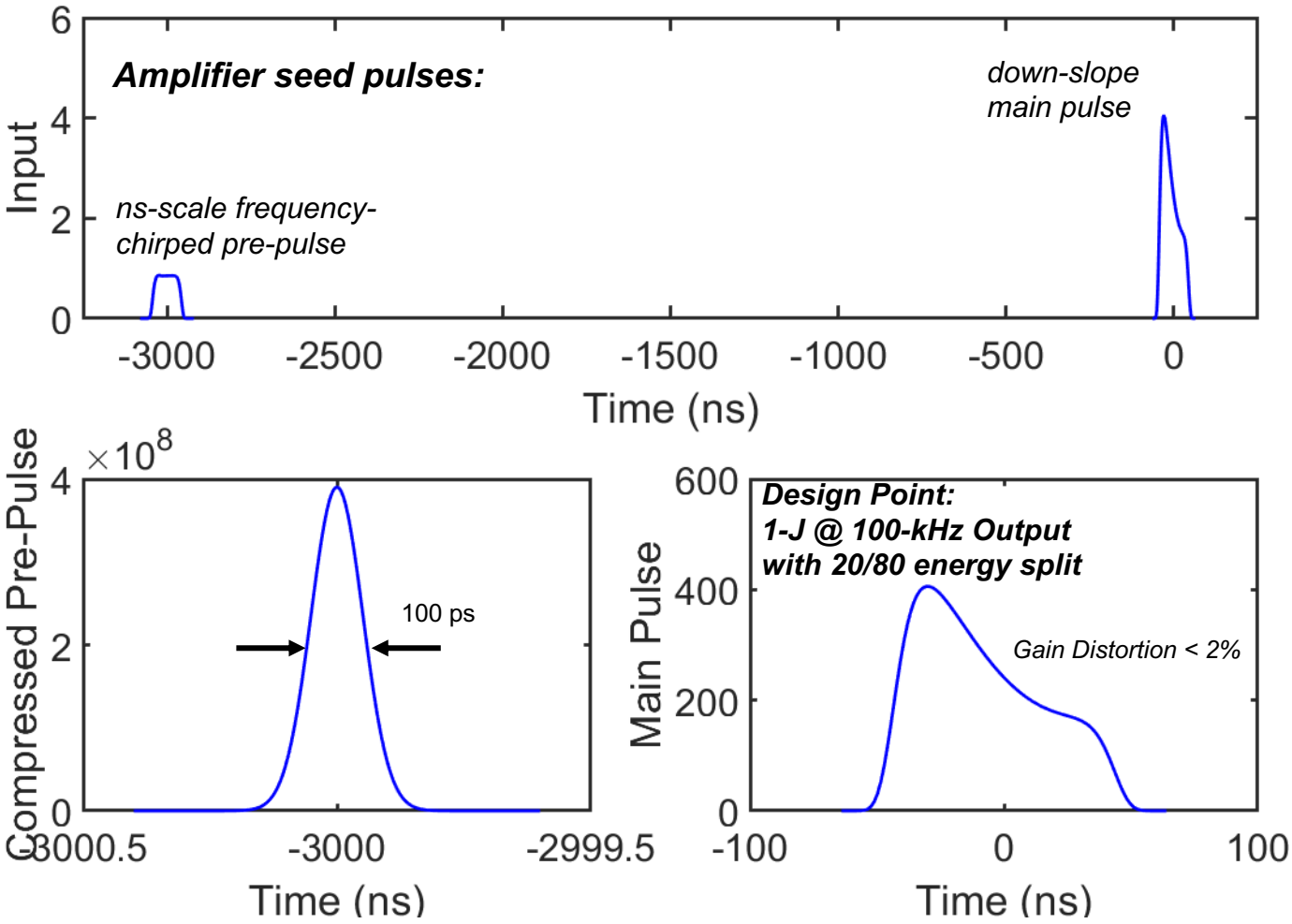
Our EUV-BAT design allows for amplification of a pre-pulse in the same laser



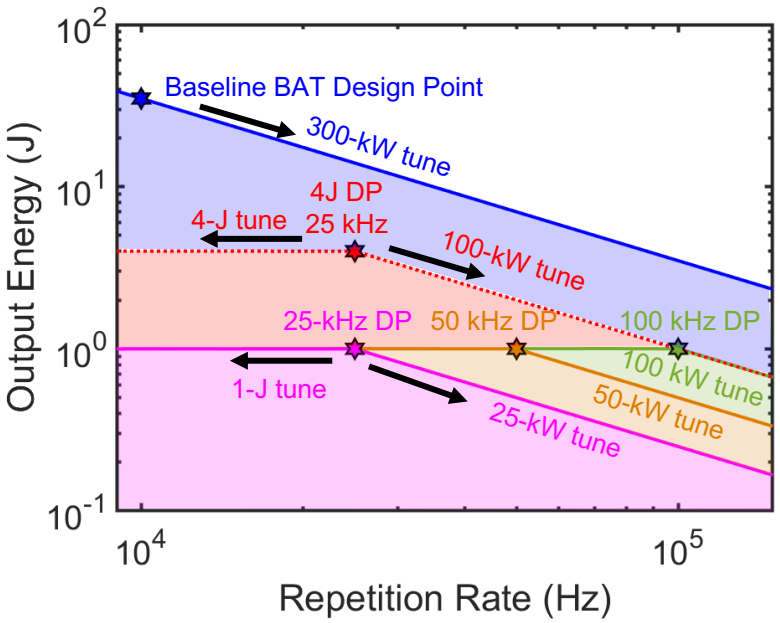
EUV-BAT model results: dual pulse output with sub-us pre-pulse and main-pulse

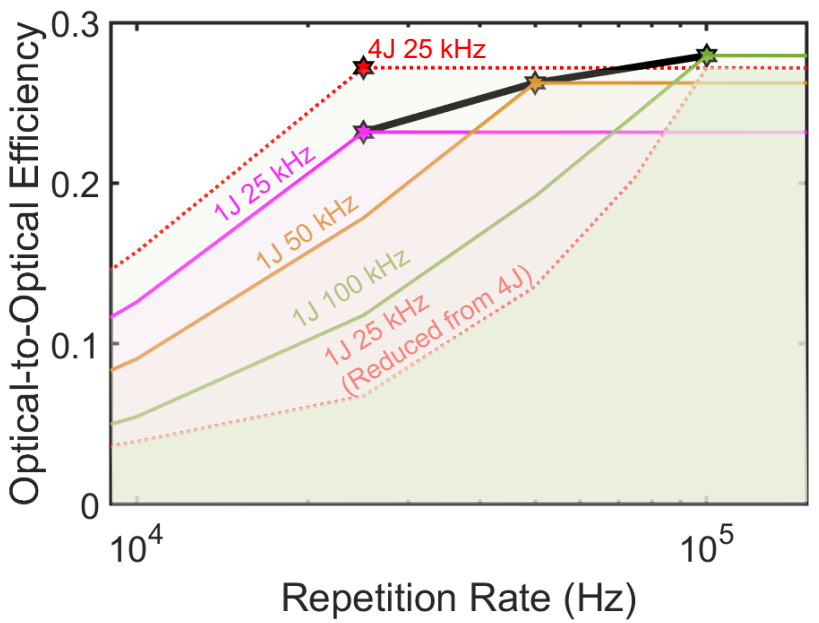


Tm:YLF can support very short (even sub-ps) pulse duration pre-pulse



EUV-BAT model results: rep-rate downscaling at fixed energy, and up-scaling at fixed power

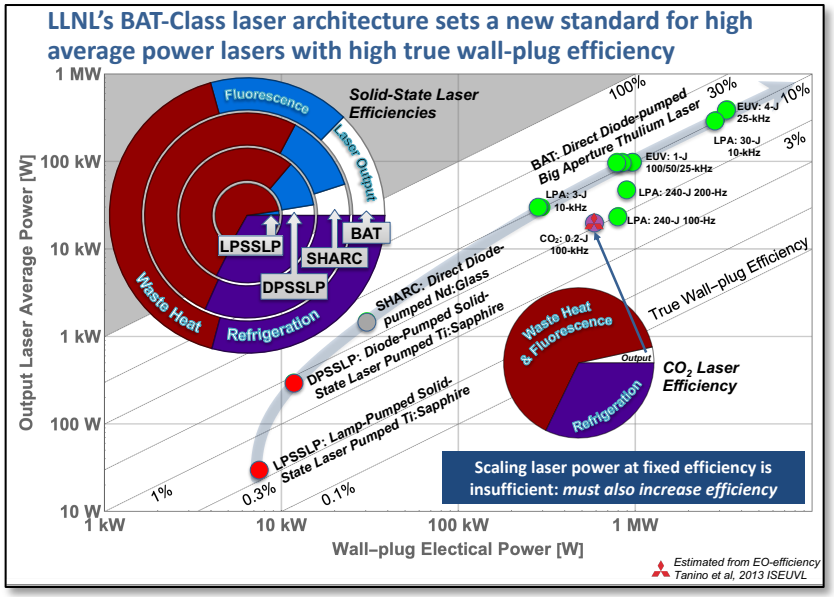




- An as-built amplifier may be run at different power levels and repetition rates than its design point
  - Amplifiers most efficient near design point
- Higher rep-rate → constant average power tuning
  - ***Completely electronic, maintains efficiency***
- Lower rep-rate → constant energy tuning
  - Efficiency can re-optimized at new operating point by down-sizing beam size in laser

The EUV-BAT design is very flexible in its design point, and an as-built system can be tuned over a wide range of rep-rates. A research system would benefit from over-specing (e.g. 4J vs 1J @ 25-kHz) to avoid reconfiguration. Factory systems can be designed to optimum specs.

Diode-pumped Solid-State Thulium Lasers are an attractive candidate for next-gen EUV drivers



- We have developed a 100-kW BAT point design tailored for EUV application
- Design scalable to even higher powers, but unclear if target supports
- Steady-state diode pumping allows for very high pulse-to-pulse energy stability
- Flexible and robust pulse shaping
- Pre- and main-pulse in common amplifier

System-level CE, exposure, and cost trade study will layout development paths:

- Large-scale ensemble modeling of:
  - target model for CE and other important features (next talk)
  - Hydrodynamic (ALEAMR) model of droplet-to-droplet interaction
- Laser system modeling and optimization around ensemble optima
- In parallel, key risk-mitigation and reduction to practice of laser technology

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