Efficient high power laser drivers for next-generation High Power EUV sources

2019 EUVS Workshop

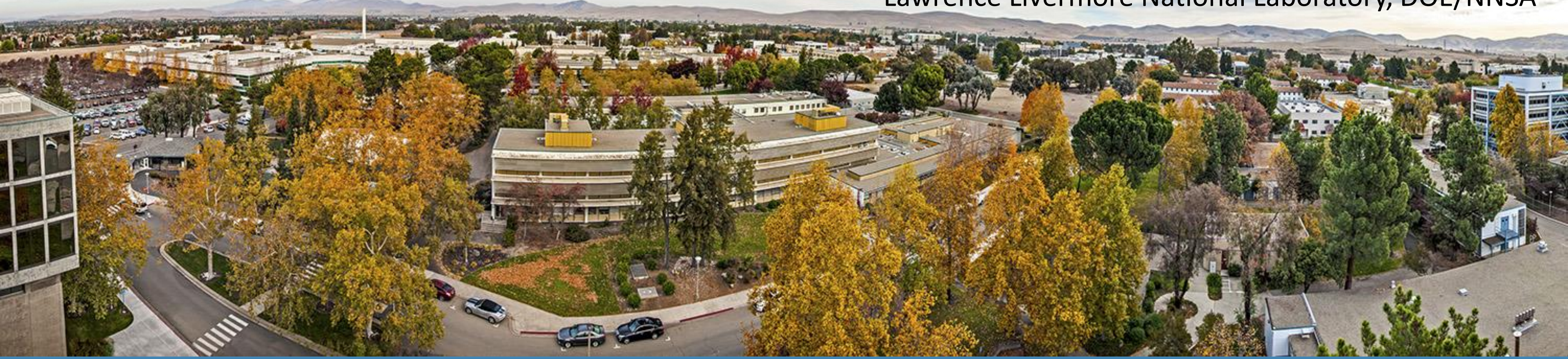
ARCNL, Amsterdam

Craig W. Siders, siders2@llnl.gov
Physicist and Senior Scientist for Advanced Photon Technologies

A.C. Erlandson, T.C. Galvin, H. Frank,
S. Langer, B.A. Reagan, H. Scott, E.F. Sistrunk, T.M. Spinka

Advanced Photon Technologies, NIF & Photon Science
Lawrence Livermore National Laboratory, DOE/NNSA

November 6th, 2019



LLNL-PRES-796037
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

Lawrence Livermore National Laboratory

LLNL is a premier Science-based Stockpile Stewardship Laboratory

NIF: World's highest energy laser

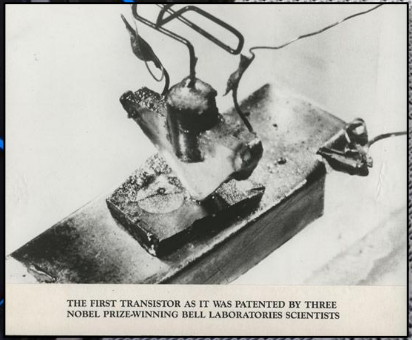
>420000 10-kJ beam-shots
>2500 full system (MJ) shots

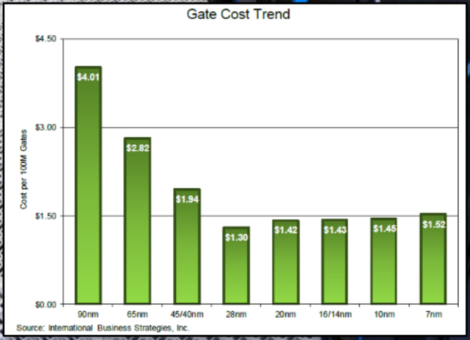
Why does LLNL care about EUVL?

Why does LLNL care about EUVL? Because Stewardship is FLOPS

2023
El Capitan
1 ExaFLOP
(ordered in 2019)

10^{15} transistors


THE FIRST TRANSISTOR AS IT WAS PATENTED BY THREE NOBEL PRIZE-WINNING BELL LABORATORIES SCIENTISTS



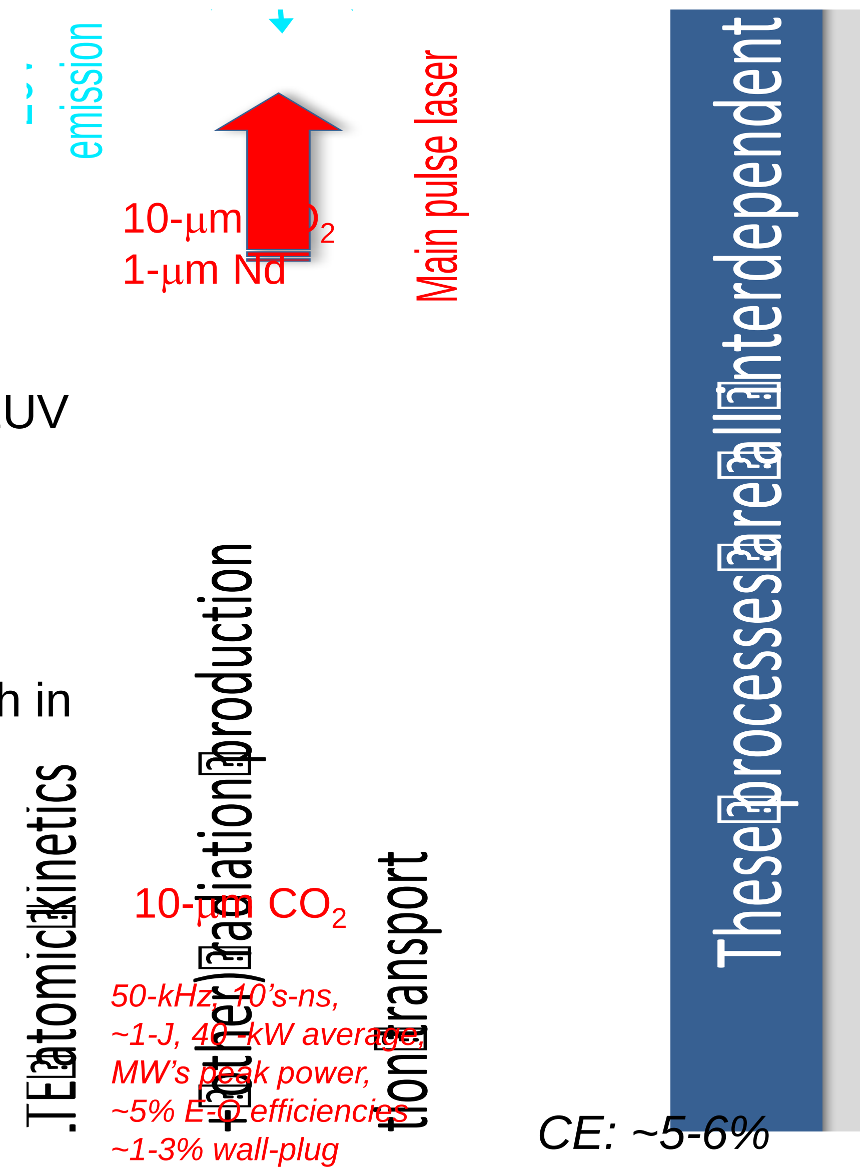
2019
Sierra
125-PetaFLOP

Cost/transistor fundamentally underlies Stewardship.

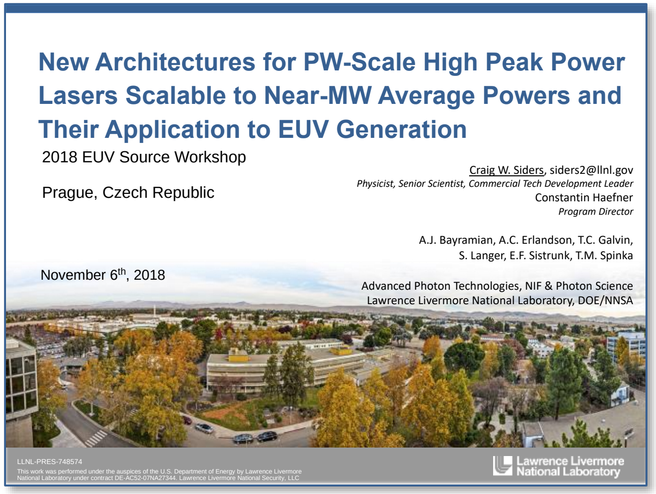
Pulsed 10-µm CO_2 lasers are the drivers of choice for the main pulse in 13.5-nm Sn EUV system

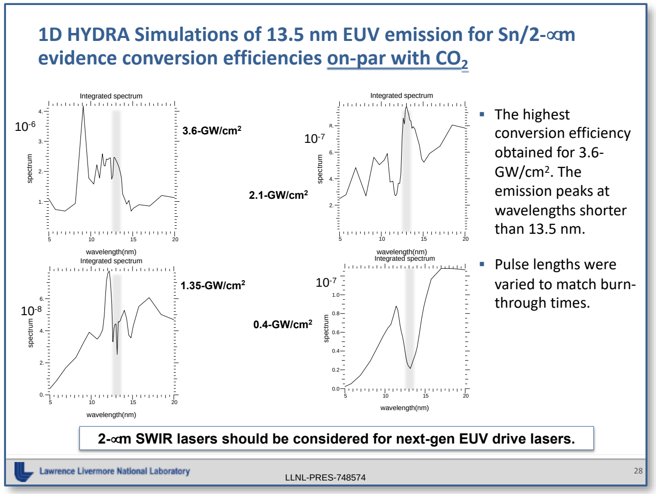
CO_2 lasers were the early choice for 13.5-nm EUV development

- Scalable high-power laser architecture
- Long wavelength well matched for MP interaction
- DPSSL (diode-pumped solid-state laser) tech in infancy



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



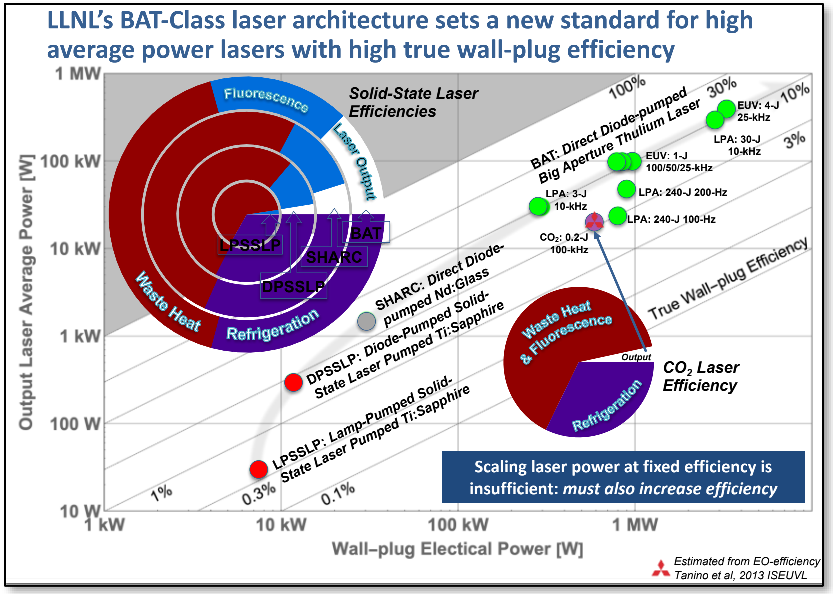


- SHARC (Scalable High-power Advanced Radiography Capability):
  - diode-pumped Nd:Glass, 1-um wavelength
  - 150-J/150-fs/10-Hz
  - for laser-driven secondary x-rays/neutrons

- 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.

At the June 2019 EUV Lithography Workshop, we presented results of detailed laser systems engineering modeling for EUV-tailored design points of the 2-μm BAT architecture.



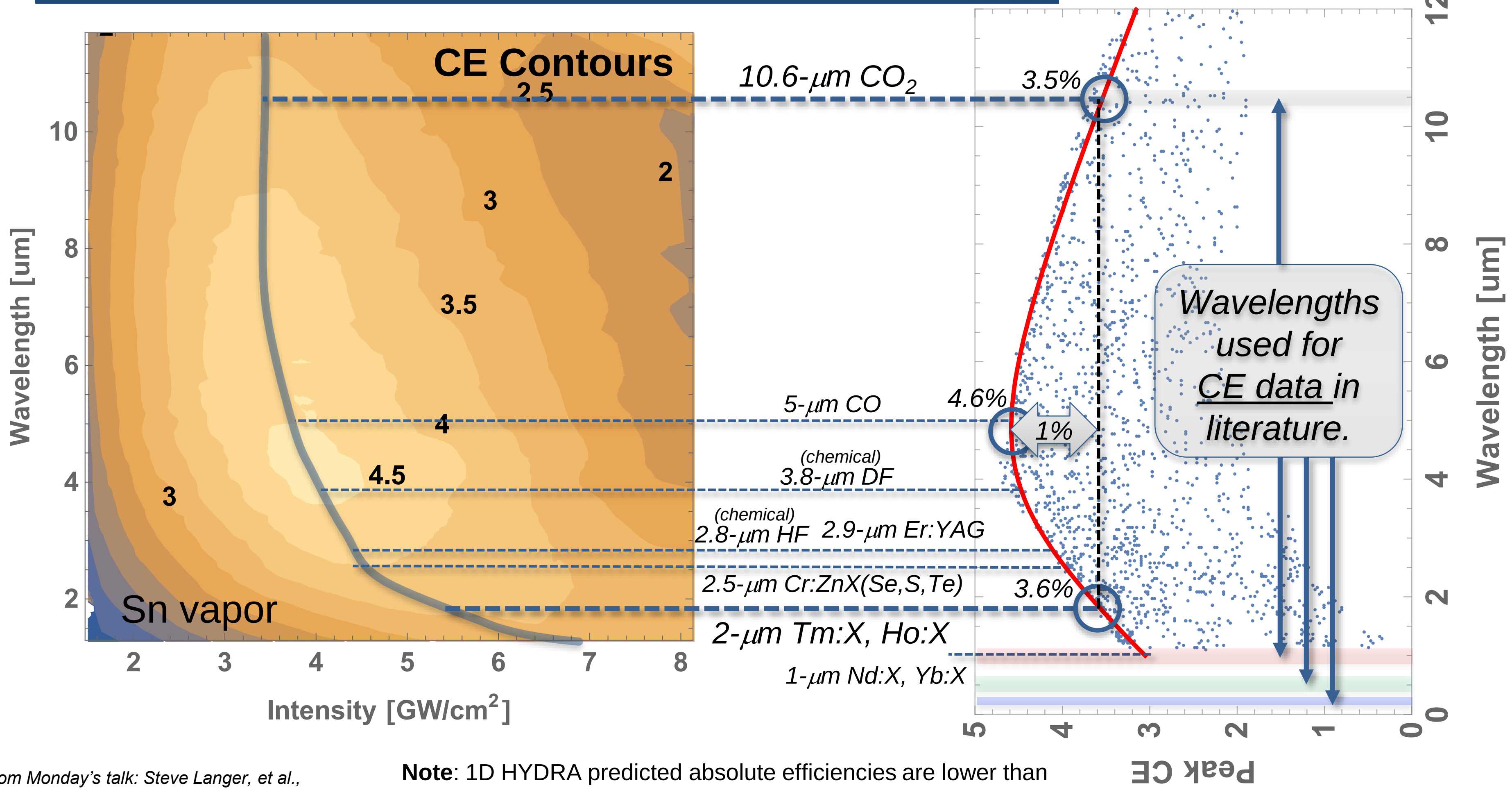
- We developed a 100-kW BAT point design tailored for EUV application
- Design scalable to even higher powers, but unclear if target supports
- Steady-state diode pumping allows for very high pulse-to-pulse energy stability
- Flexible and robust pulse shaping
- Pre- and main-pulse in common amplifier

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
  - 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

For this 2019 EUV Source Workshop, we haven taken the first steps in this system-level EUV source trade study

1D HYDRA ensemble modeling agrees with our earlier on-par CE for 2 vs 10μm, and shows a potential 1% gain (20% relative)



From Monday's talk: Steve Langer, et al., "An Optimization Study of EUV Sources Driven by CO2 and Thulium Lasers"

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

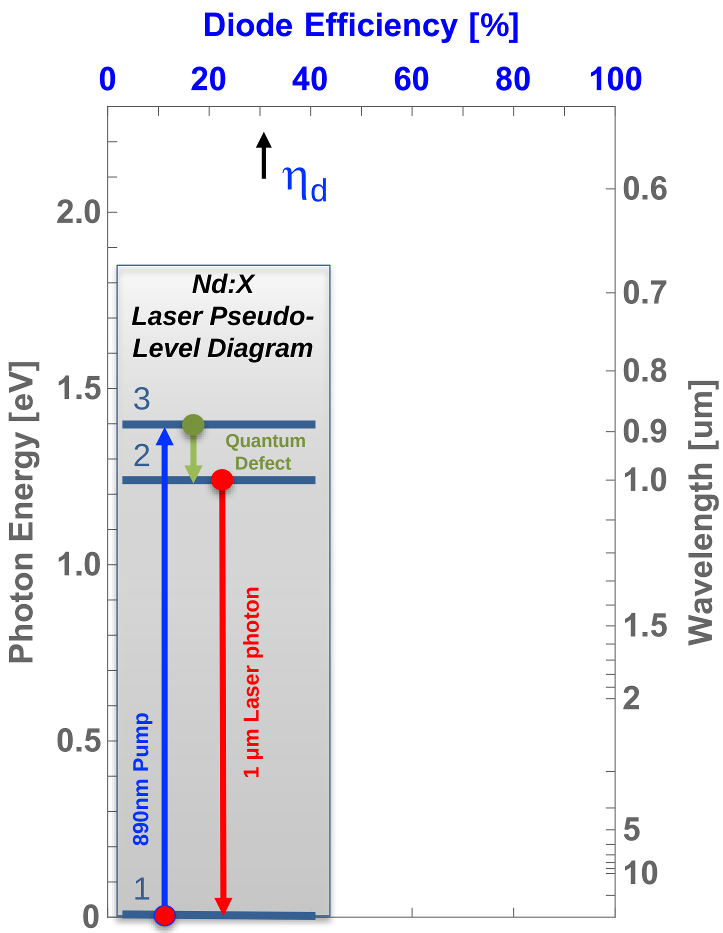
Paramount questions raised by these results

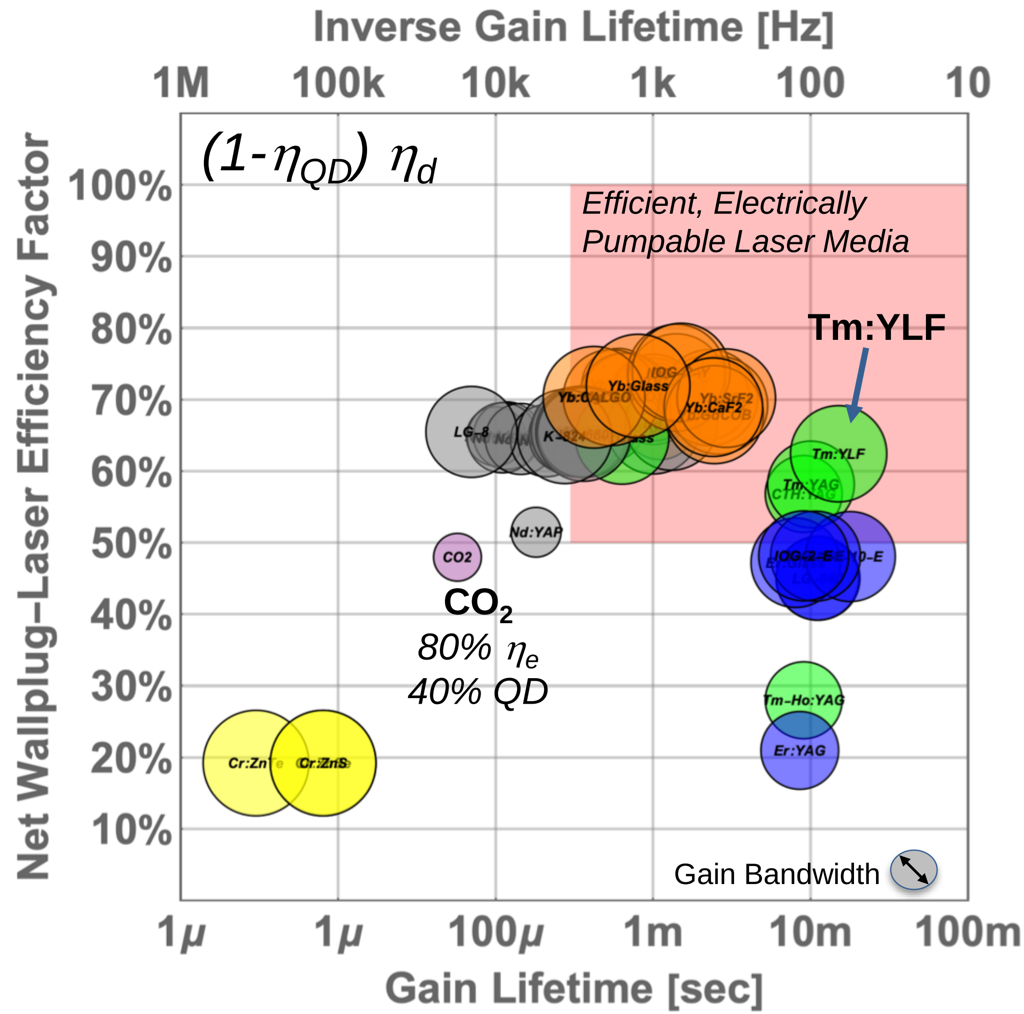
- ***Where is the peak?***
  - There must be a peak – either before (5μm?), at or after 10-μm
  - There is no (?) data between 1-μm and 10-μm

- ***What is the peak? What defines the optimum wavelength?***
  - EUV CE? – *highest emitted EUV energy / incident laser energy*
  - EUV energy/μg-Sn? – *extended useful collector life*
  - Laser wall-plug electrical power to EUV CE? – *highest EUV power / MWe*
  - Wall-plug power to EUV power (*~10^{-6} now)? – max #scanners / MWe*
  - Wall-plug electrical power to EUV power/ μg-Sn? – *max wafers/days/facility*

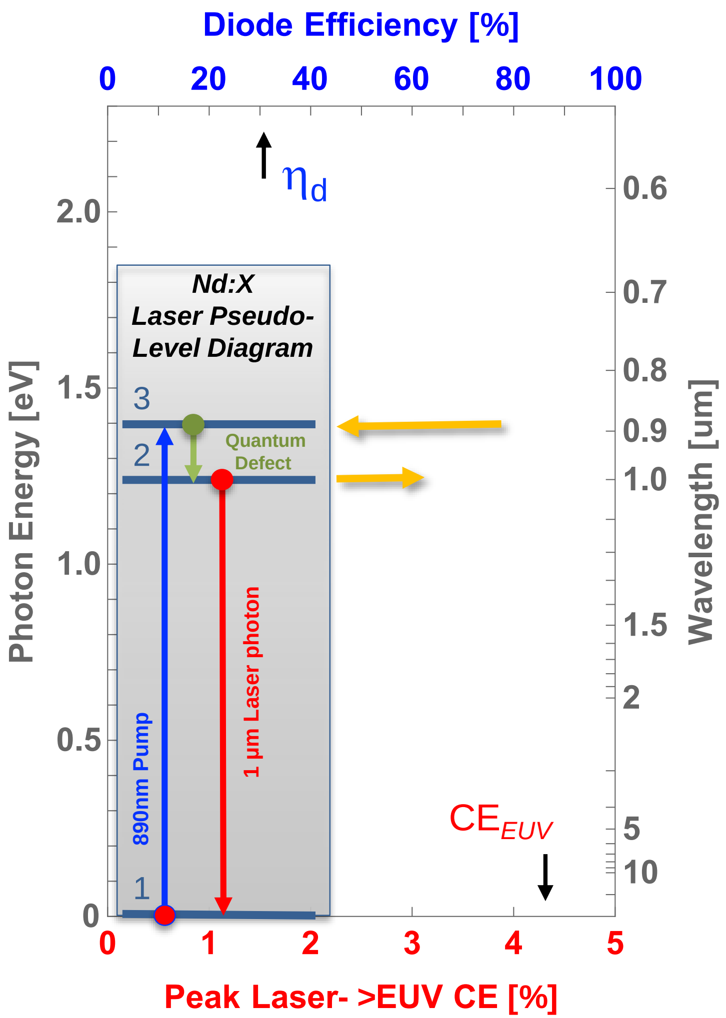
We will examine wall-plug to CE, as an example.

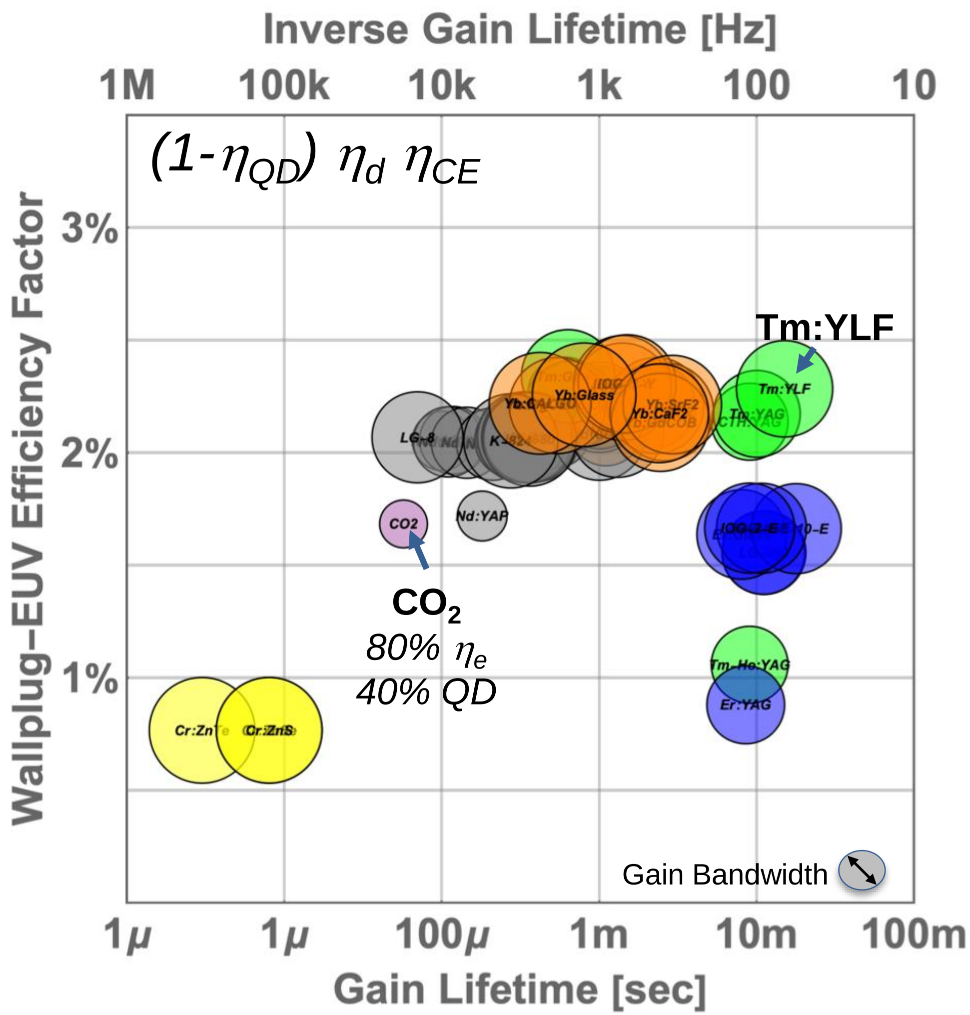
Three key components to DPSSL-EUV system efficiency: *diode efficiency, quantum defect and EUV CE*





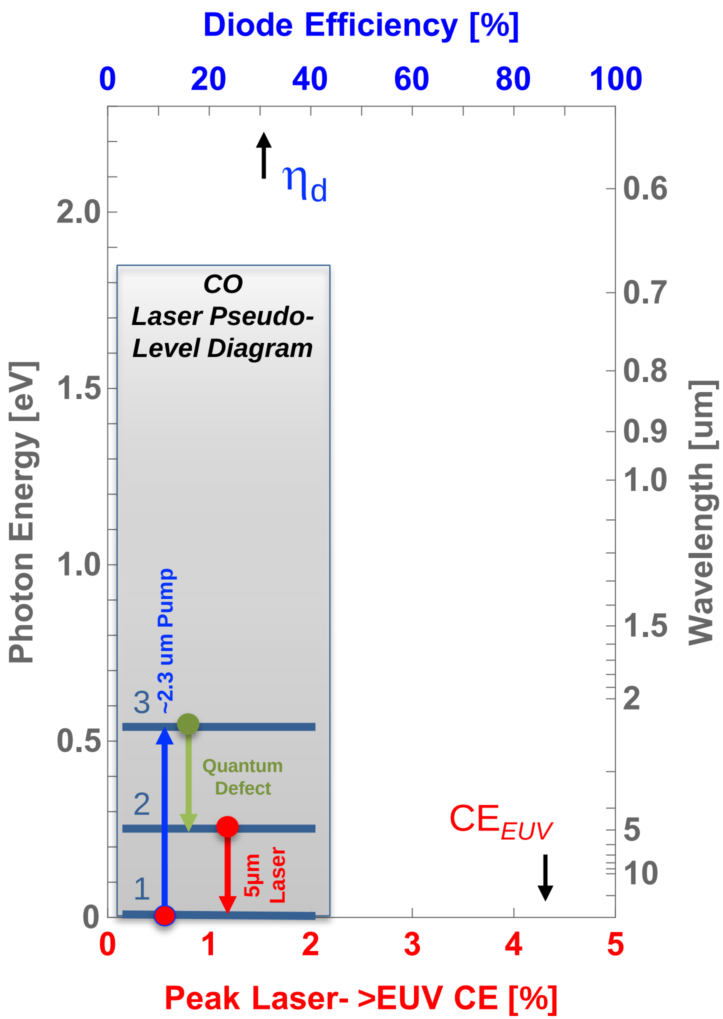
Three key components to DPSSL-EUV system efficiency:
diode efficiency, quantum defect and EUV CE

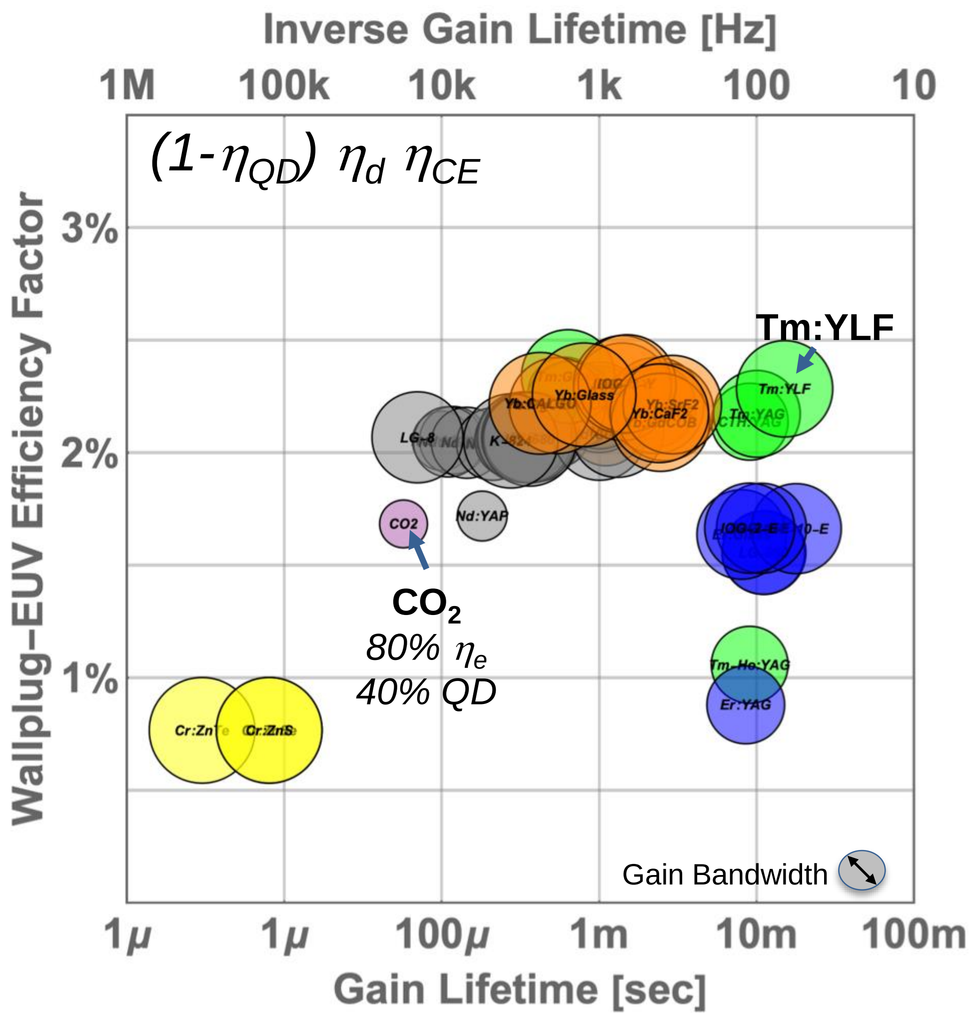




Note: laser optical-optical efficiency not included

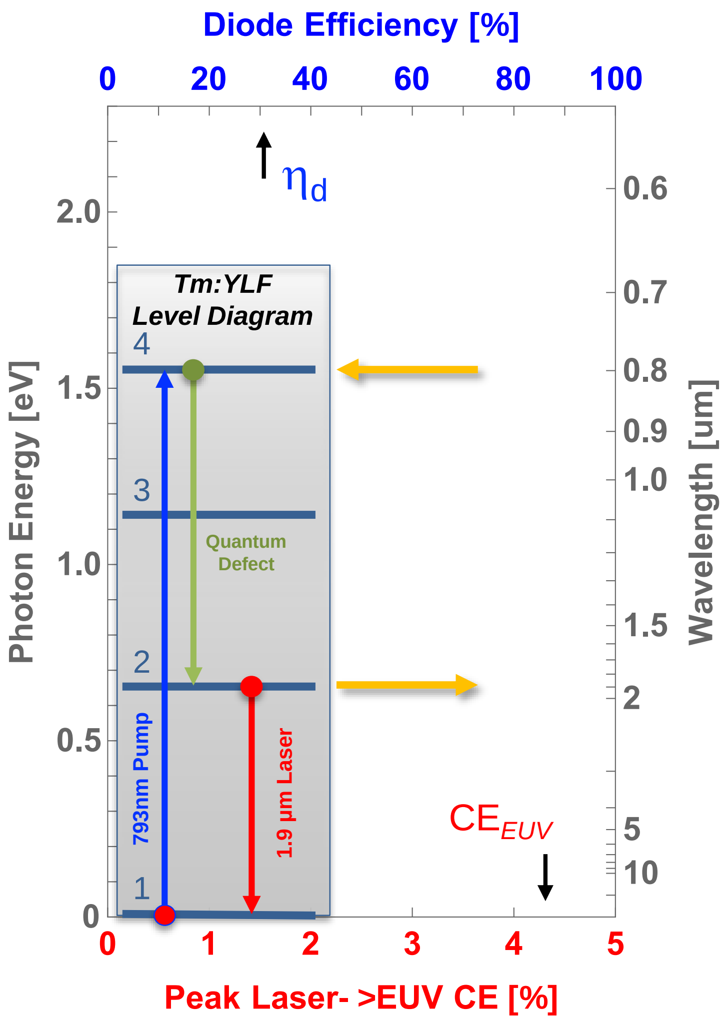
Low(-ish) quantum defect SWIR/MWIR (CO, Cr:X) lasers suffer from poor diode efficiency

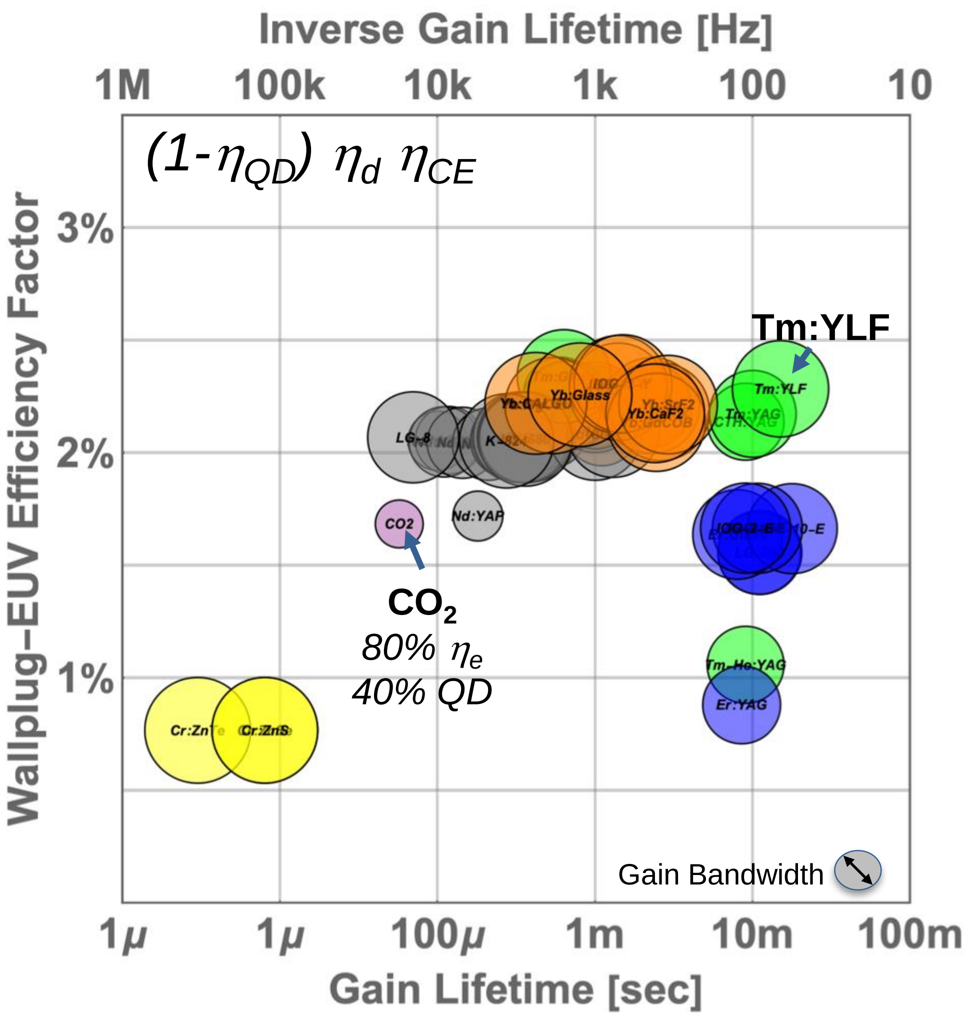




Note: laser optical-optical efficiency not included

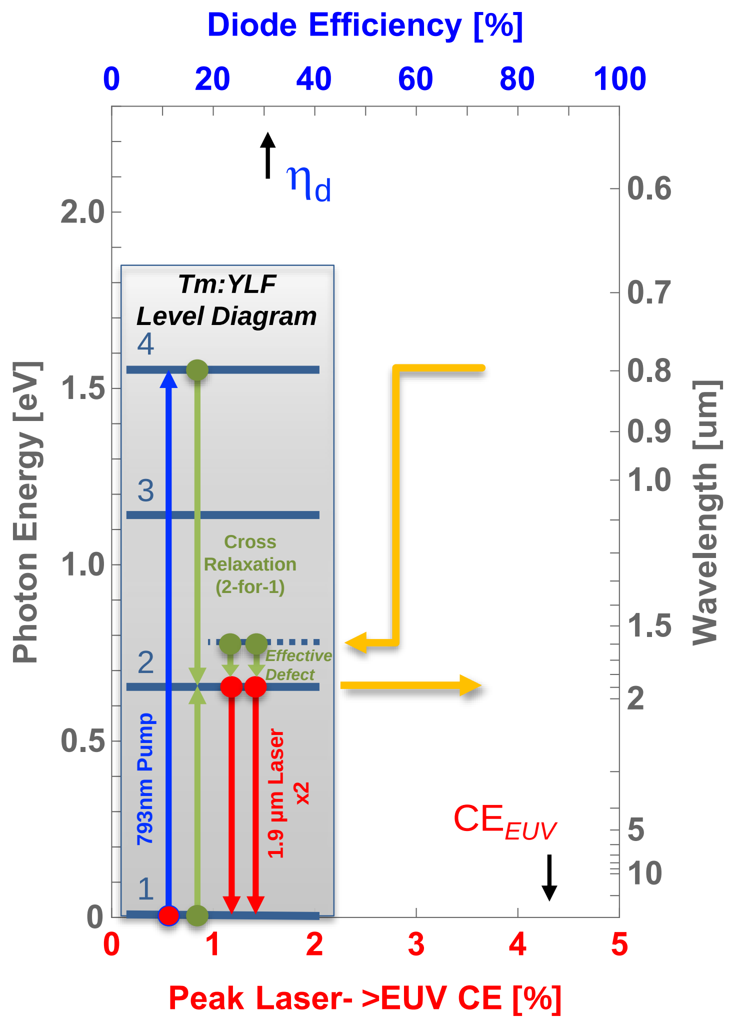
Tm:YLF, pumped by efficient ~800nm diodes, would appear to have a poor quantum defect

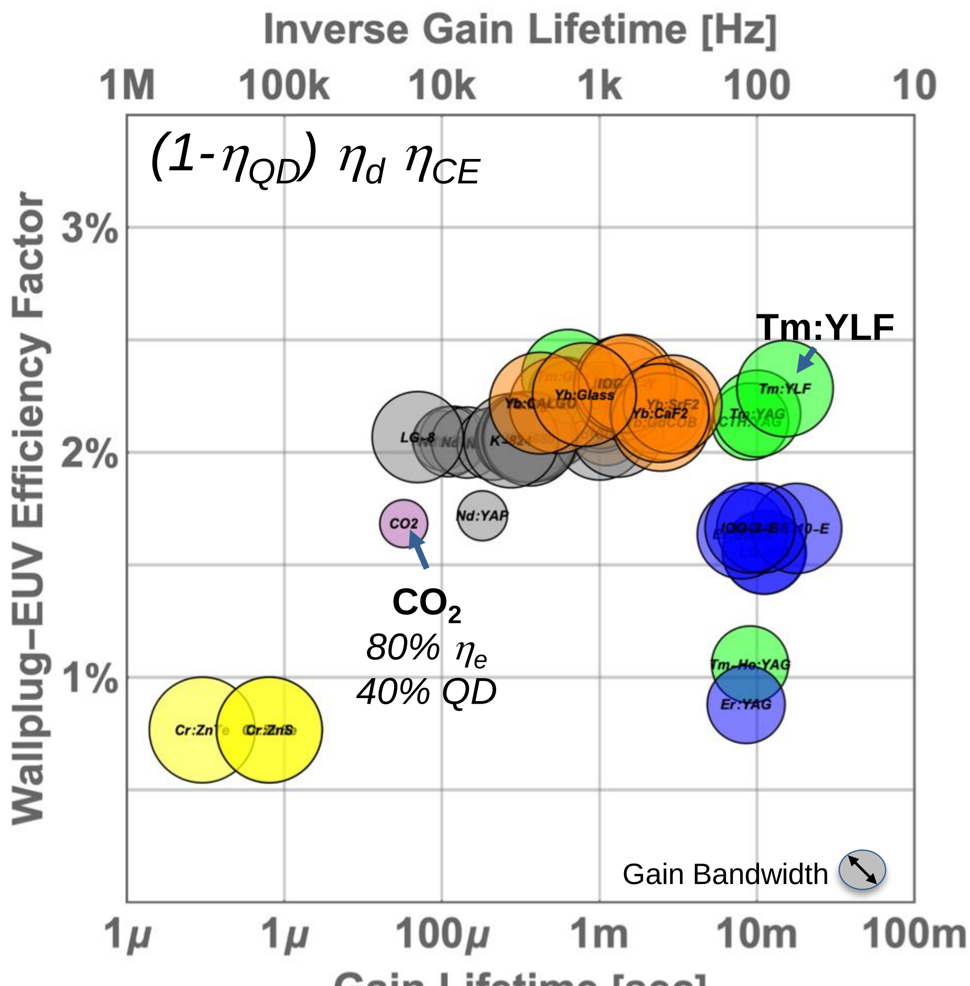




Note: laser optical-optical efficiency not included

Two-for-one pumping in Tm:YLF provides efficient 790-nm diode pumping *and* 2-um SWIR lasing

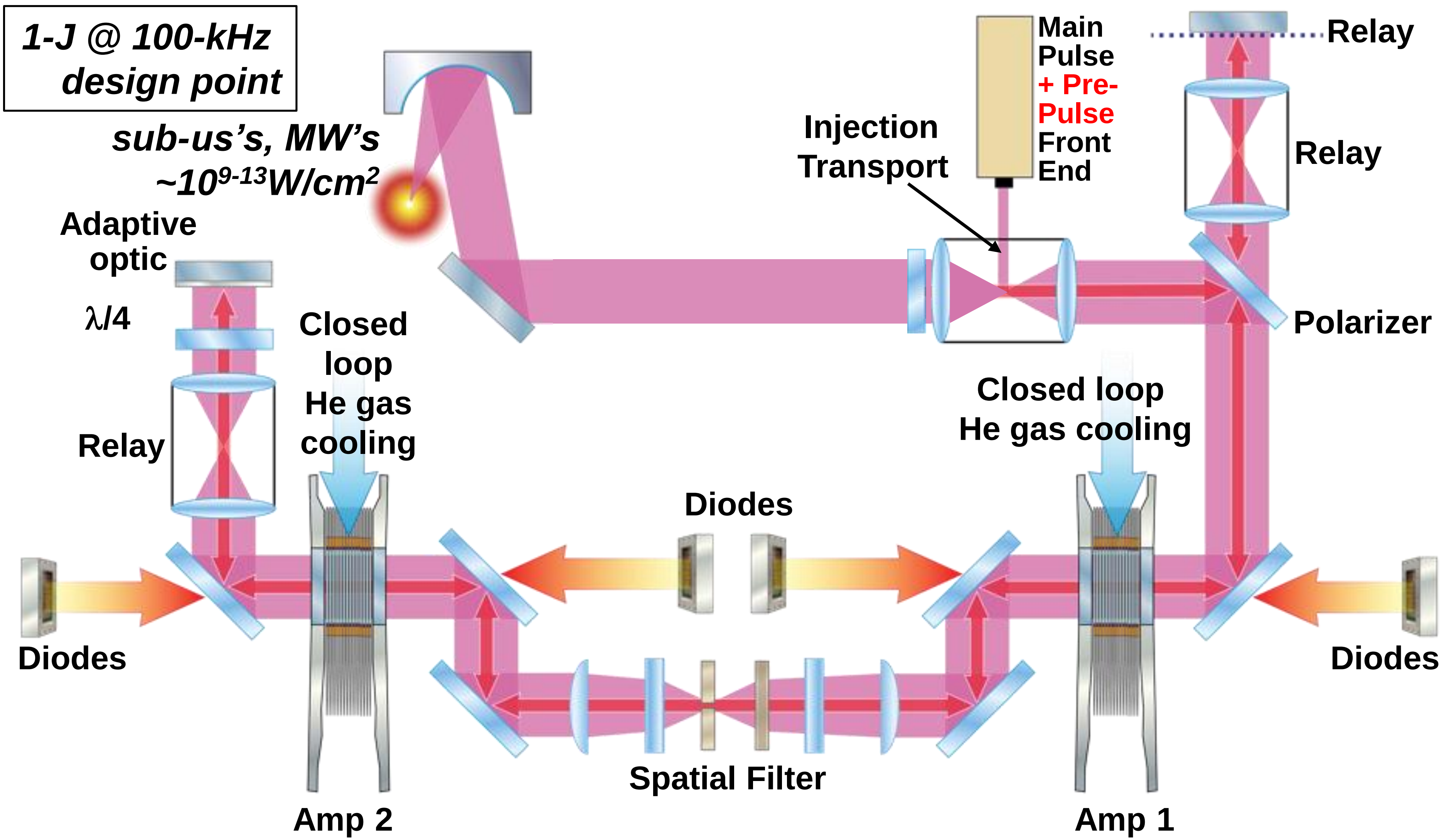




Note: laser optical-optical efficiency not included

Diode-pumped Tm:YLF may be *the* most efficient route to high-power SWIR lasers

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



BAT

Big Aperture Thulium Laser Concept

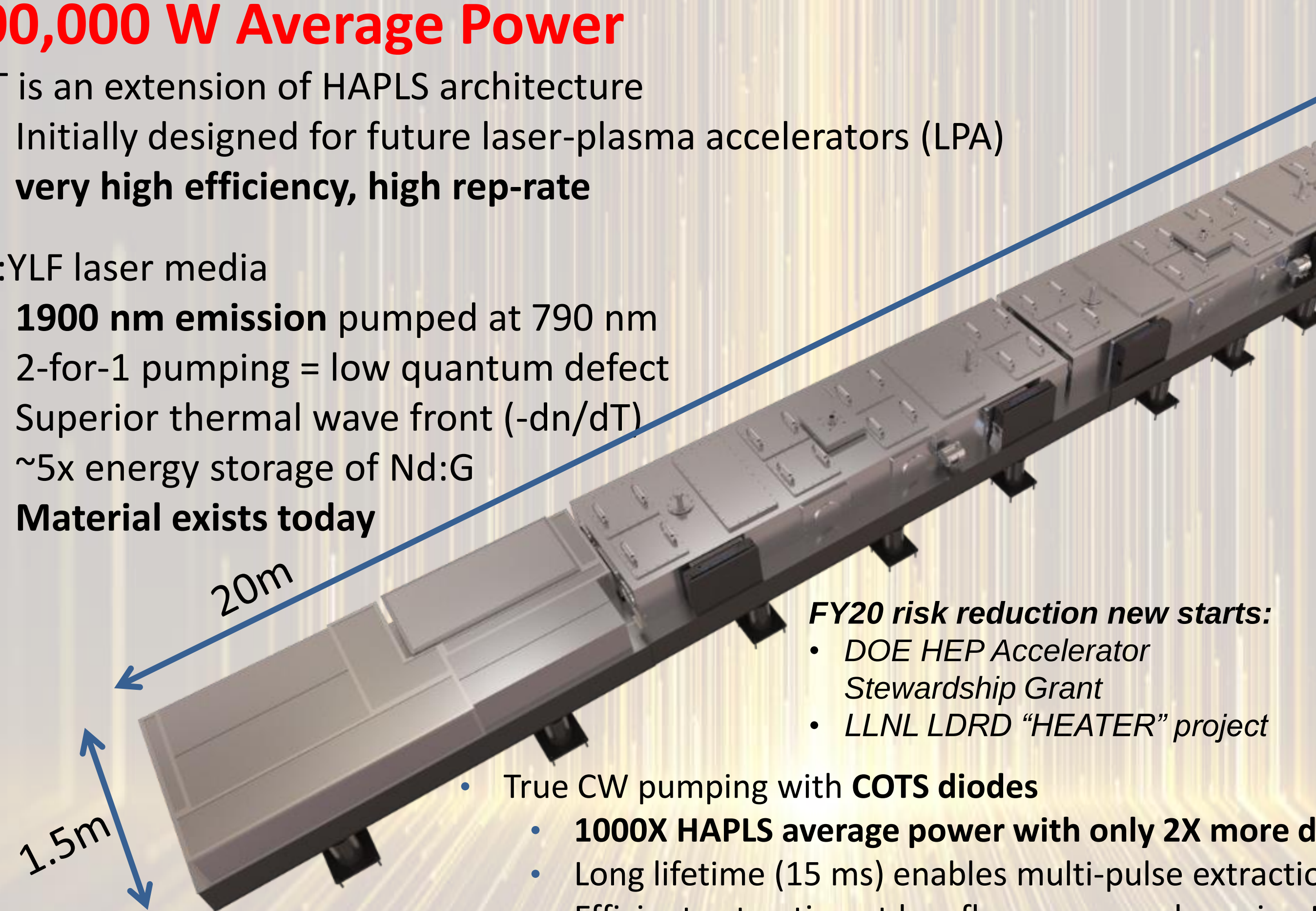
30J, 100fs, 0.3PW, 10kHz (DOE HEP)

240J, 240fs, 1.0PW, 100Hz (EuPRAXIA)

1J, ps-ns, 100-kHz (EUVL)

- **300,000 W Average Power**
- BAT is an extension of HAPLS architecture
  - Initially designed for future laser-plasma accelerators (LPA)
  - **very high efficiency, high rep-rate**

- Tm:YLF laser media
  - **1900 nm emission** pumped at 790 nm
  - 2-for-1 pumping = low quantum defect
  - Superior thermal wave front (-dn/dT)
  - ~5x energy storage of Nd:G
  - **Material exists today**



FY20 risk reduction new starts:
- *DOE HEP Accelerator Stewardship Grant*
- *LLNL LDRD "HEATER" project*

Tm:YLF Boule ~10cm

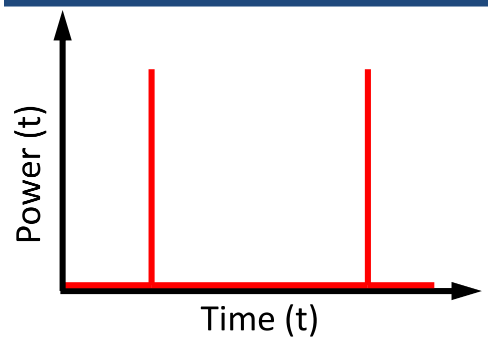
- True CW pumping with **COTS diodes**
  - **1000X HAPLS average power with only 2X more diodes, half the size**
  - Long lifetime (15 ms) enables multi-pulse extraction (MPE)
  - Efficient extraction at <u>low</u> fluence per pulse using MPE (~10^2/gain-lifetime)
    - Low B-integral and below damage fluence

The BAT architecture is a game changer to drive future LPA's with 300kW of average power per stage

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

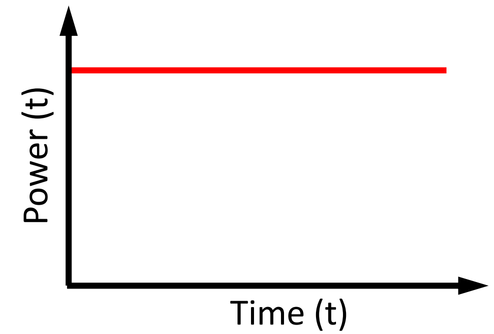
Pulsed Pumping and
Pulsed Cooling

Duty cycle << 100%



Continuous Pumping and
Continuous Cooling

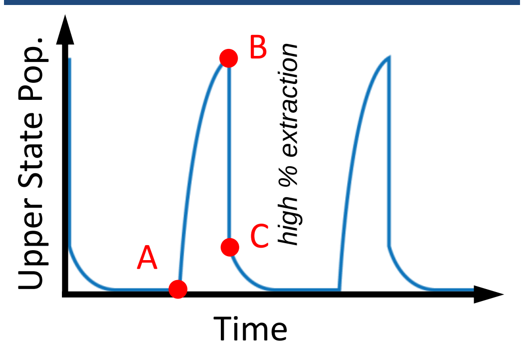
Duty cycle = 100%



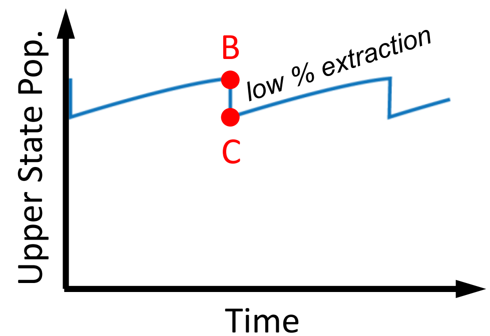
***SPE Energy Storage Density**:*
50kJ / liter

Gain saturation:
pulse distortion

Single Pulse Extraction



Multi-Pulse Extraction

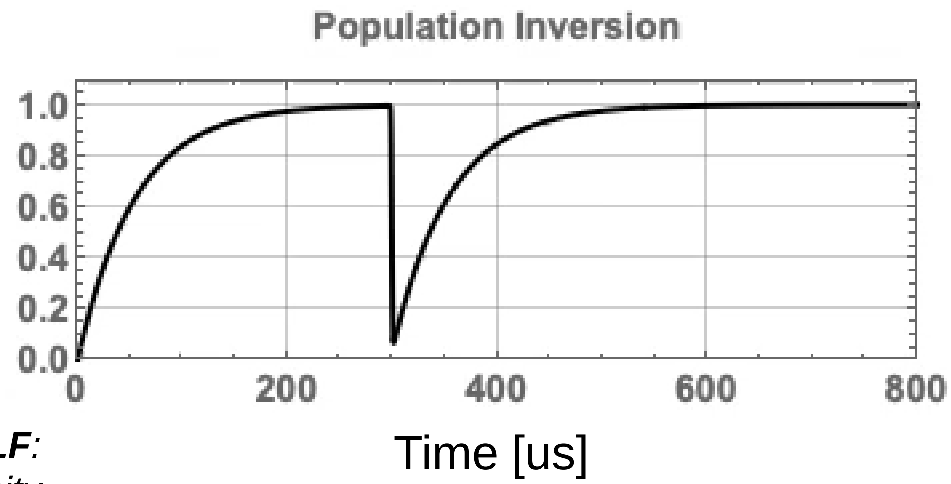


***MPE Energy Storage Density**:*
10kJ / liter

Low gain:
no distortion,
easy shaping

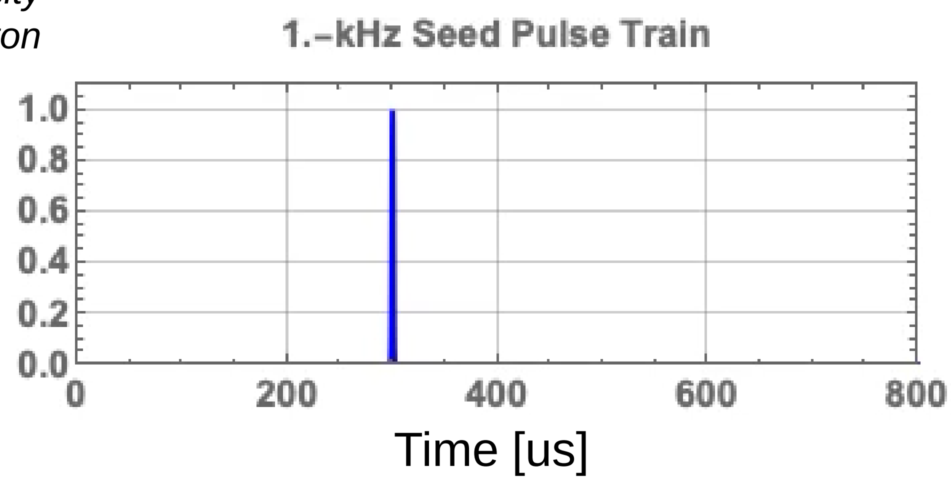
High PRF CO_2 lasers transition into the MPE regime

***SPE Energy Storage Density**:*
~50J / liter



***MPE Energy Storage Density**:*
~J's / liter

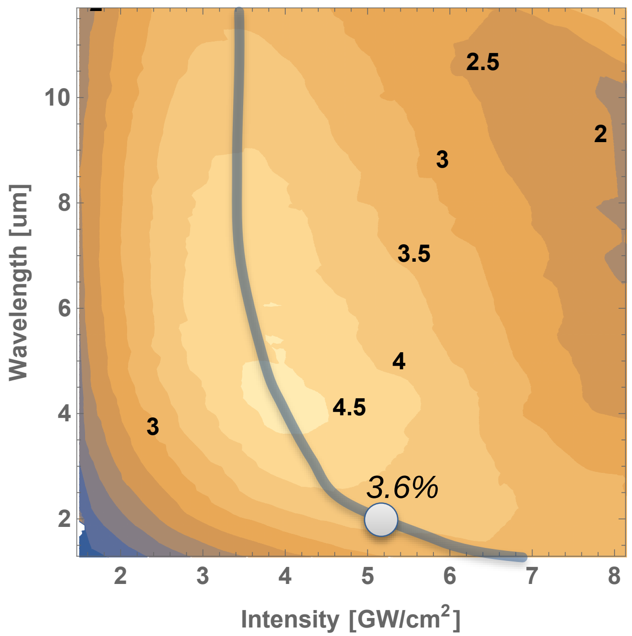
***CO_2 vs Tm:YLF**:*
>100x less inversion density
5x less energy per photon



***CO_2 vs Tm:YLF**:*
EUV PRF's are closer to 1/gain-lifetime, and so are more sensitive to PRF increase and more prone to chaotic pulse-2-pulse instabilities

CO_2 lasers face reduced energy storage & gain as PRF increases. 1) Add stages (at same efficiency) to recover final laser pulse energy. 2) Pump harder. 3) Operate at higher pressure.

Optimized EUV Tm:YLF Design Points based up ensemble results



EUV Tm:YLF design scale nicely to higher PRFs and shows further efficiency increases

Frequency	50 kHz	75 kHz	100 kHz
Shot Energy (J)	0.6	0.6	0.6
Laser Power (kW)	30	46	60
$\eta_{optical \rightarrow optical}$	23.4%	24.4%	26.1%
$\eta_{wallplug \rightarrow optical}$	10.1%	10.6%	11.4%

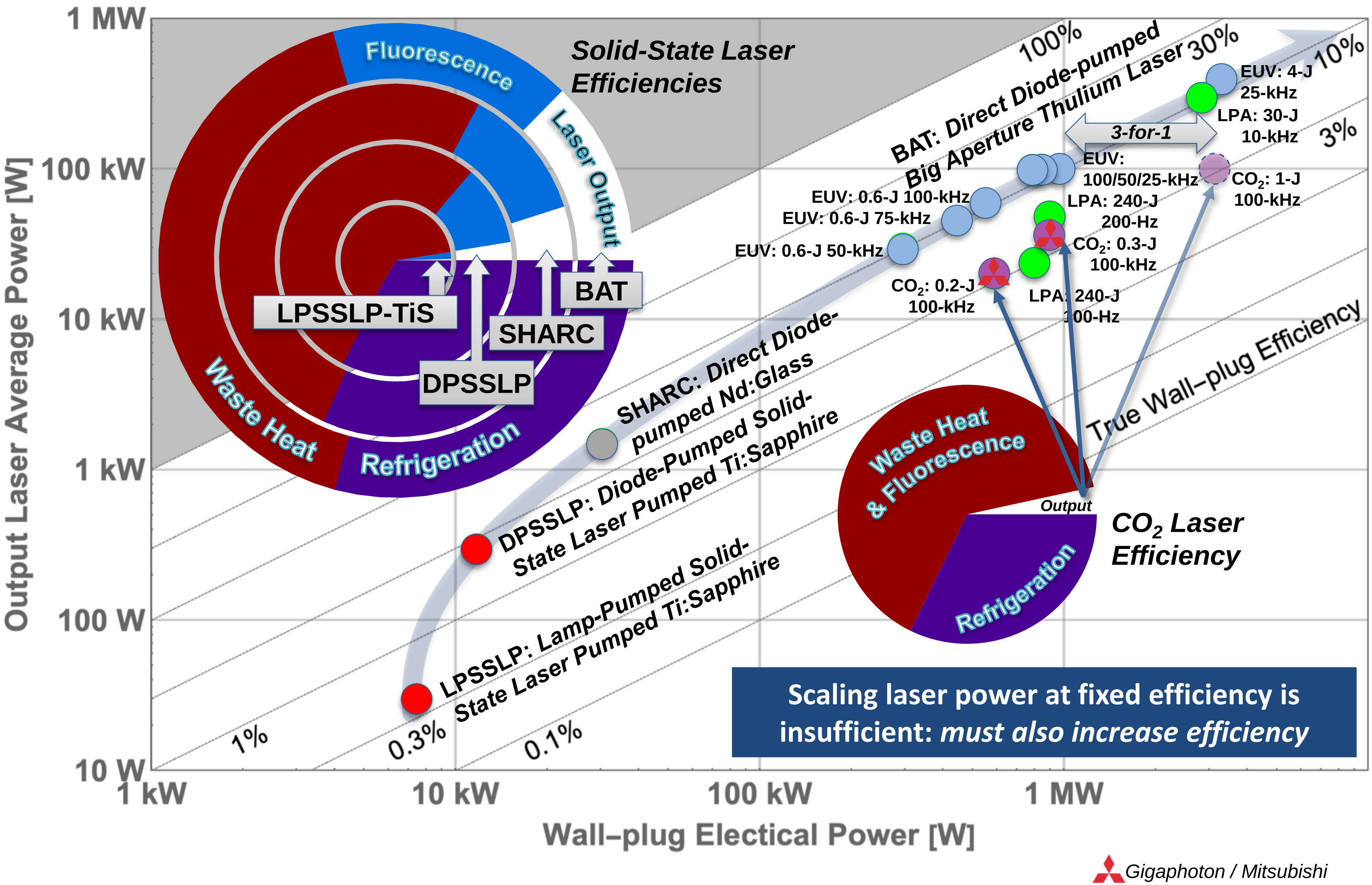
Scaling:
assume 100-ns max,
400-um focus:

$$5\ \mathrm{GW/cm^2} \cdot 100\ \mathrm{ns} \cdot \frac{\pi}{4}(400\ \mu\mathrm{m})^2 \sim 0.6\ \mathrm{J}$$

$$0.6\ \mathrm{J} \cdot 50\ \mathrm{kHz} \sim 30\ \mathrm{kW}$$

Next steps: include laser architecture optimization model, including lasant (Tm, Yb, Nd) and hosts (e.g. YLF, YAG, glass), in the Merlin HYDRA workflow for machine learning optimization of combined EUV system

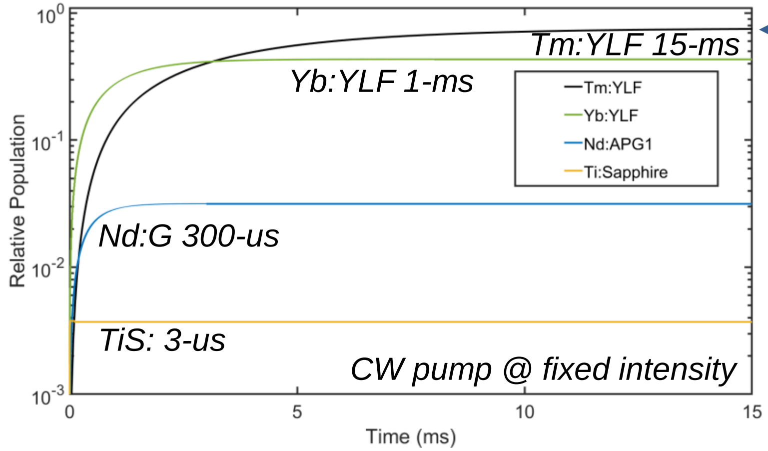
Tm:YLF laser architecture is ~3x more efficient than CO_2 systems: Future 3-for-1 upgrade path for Sn EUV sources? Blue-X CE Trade?



Scaling laser power at fixed efficiency is insufficient: *must also increase efficiency*

Tm:YLF-EUV Source Science Development Path

Longer Storage Time = Greater Storage



***Tm:YLF SPE Energy Storage Density**: 50kJ / liter*

- Thermal management is the chief risk for the high average power EUV Tm:YLF laser concept, which we are actively reducing with FY20 efforts.

- However, shot-on-demand (damage limited) and (~100-pulse) burst-mode operation using the very high (50-kJ/liter) energy storage density of Tm:YLF skirts those 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

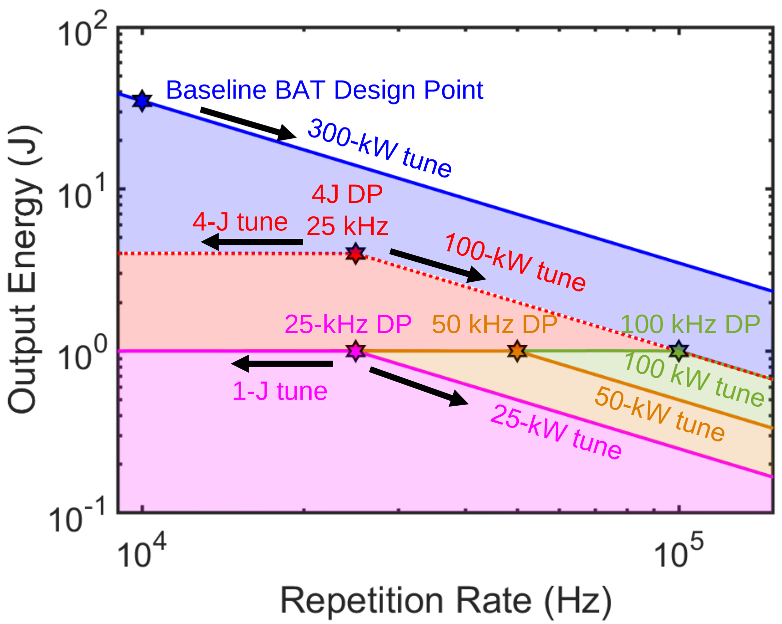
Paramount questions

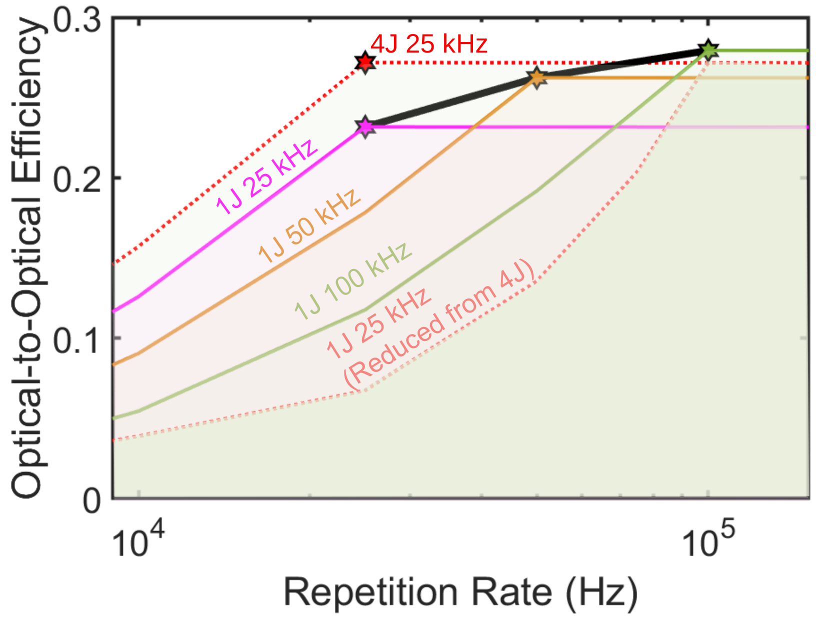
- ***Where is the peak?***
  - There must be a peak – either before (5μm?), at or after 10-μm
  - There is no (?) data between 1-μm and 10-μm
- ***What is the peak? What defines the optimum wavelength?***
  - EUV CE? – *highest emitted EUV energy / incident laser energy*
  - EUV energy/μg-Sn? – *extended useful collector life*
  - Laser wall-plug electrical power to EUV CE? – *highest EUV power / MWe*
  - Wall-plug power to EUV power (*~10^{-6} now)? – max #scanners / MWe*
  - Wall-plug electrical power to EUV power/ μg-Sn? – *max wafers/days/facility*

How close are we to the peak?

Lawrence Livermore National Laboratory

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.