High efficiency, diode pumped Petawatt lasers for the next generation particle accelerators and secondary sources

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LLNL-PRES-730848

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The laser: 50 years of discoveries
Testimony by Charles Townes

“The history of the laser is a perfect example of the impact of basic research, not only on science, but also on economy – a spectacular impact, often completely unexpected.”

1996: The First Petawatt Laser, invented at LLNL: 600 J, >1 PW

Petawatt achievements and discoveries:

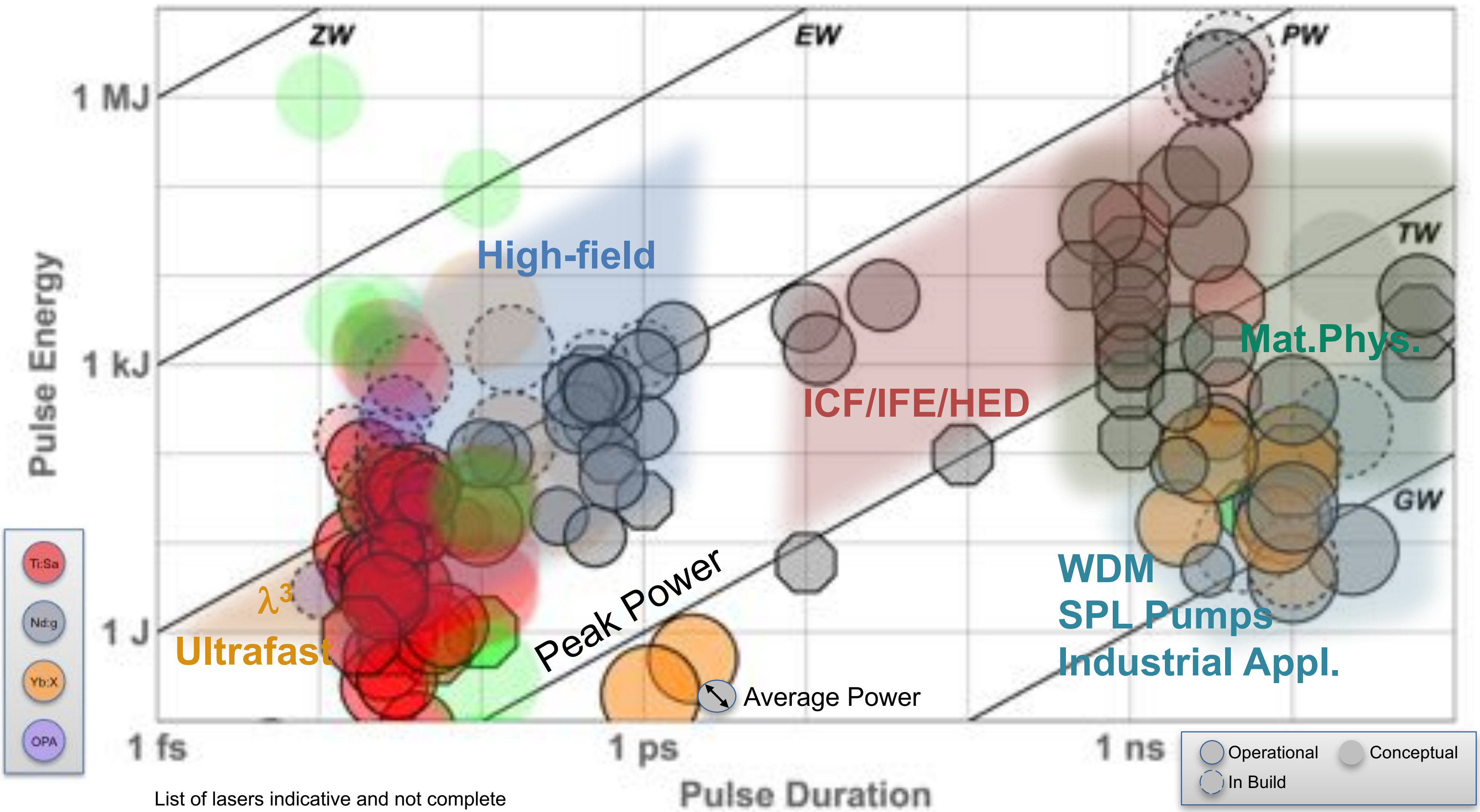
- 1.3-PW = 1,300,000,000,000,000 Watts
- $\sim 10^{21}$ W/cm^{2}
- 10-100-MeV electron beams
- Laser made proton beams
- Hard x-rays and gamma-rays
- Photo-fission

High-repetition-rate Advanced Petawatt Laser System (HAPLS)

20 years later:

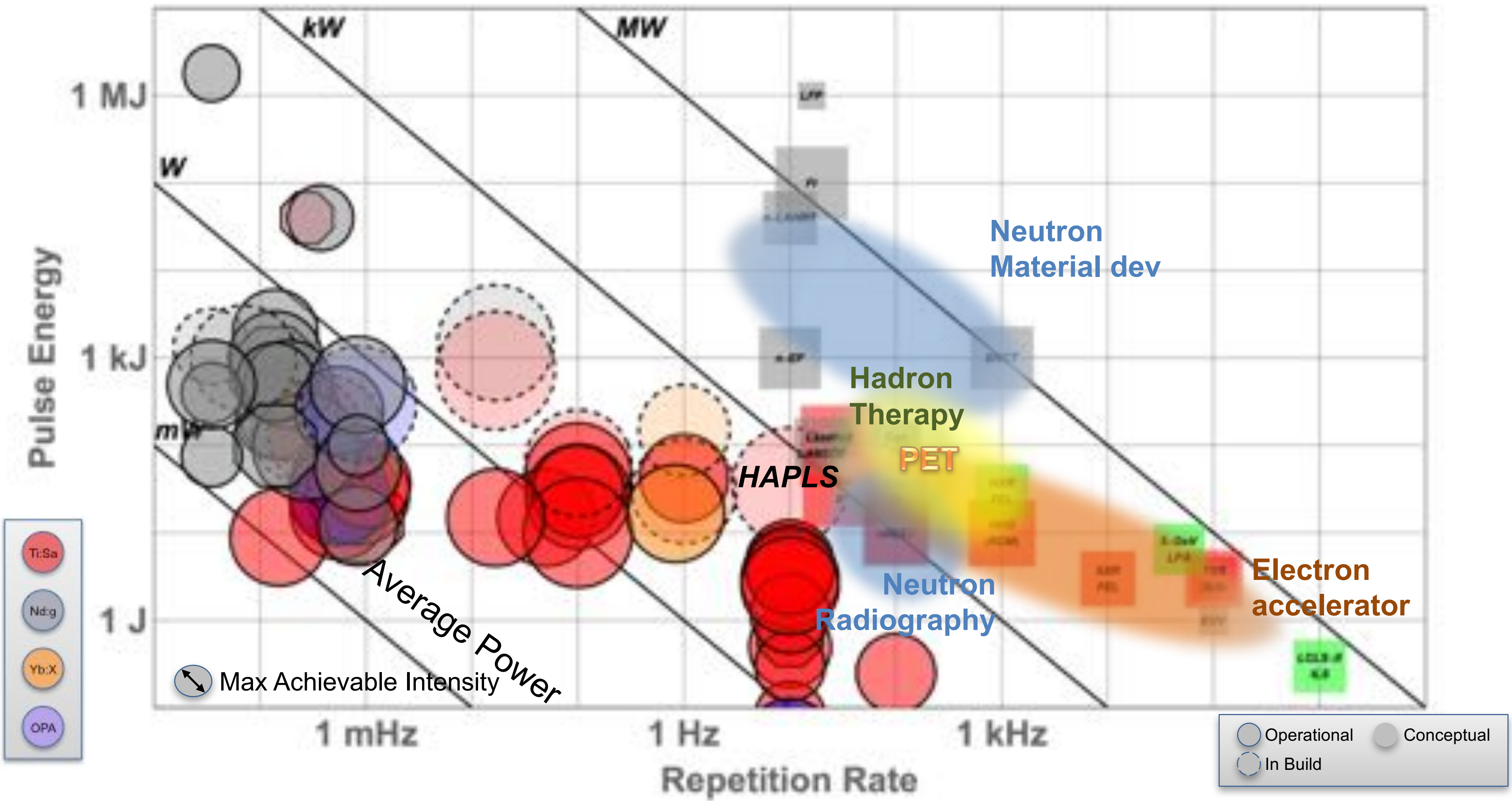
HAPLS laser runs 200,000 times faster than the original 1996 Petawatt

Worldwide scientific laser facilities mostly meet the demands for proof of principle experiments

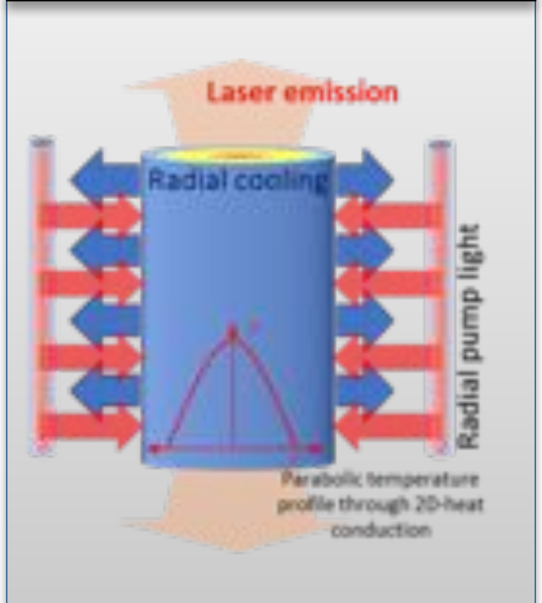
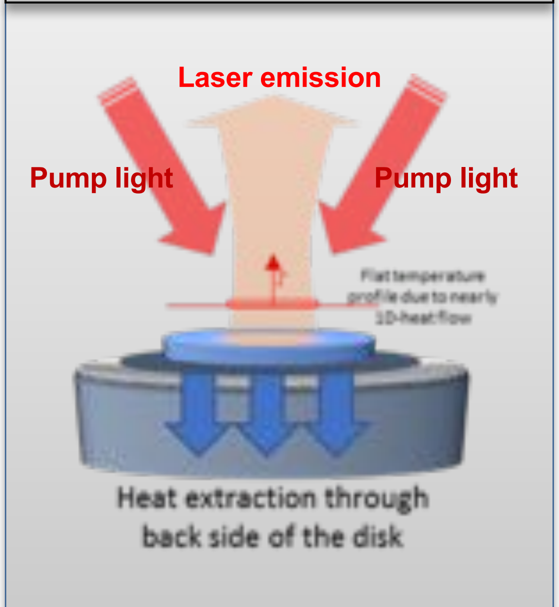
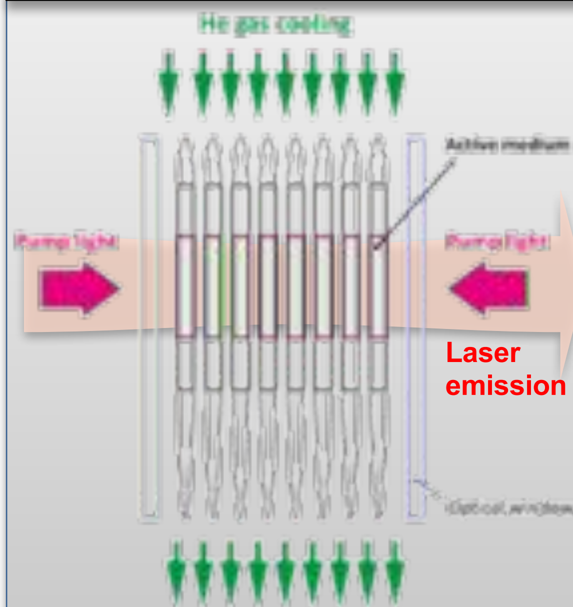


List of lasers indicative and not complete

Commercial and advanced scientific short pulse laser applications require high repetition rate

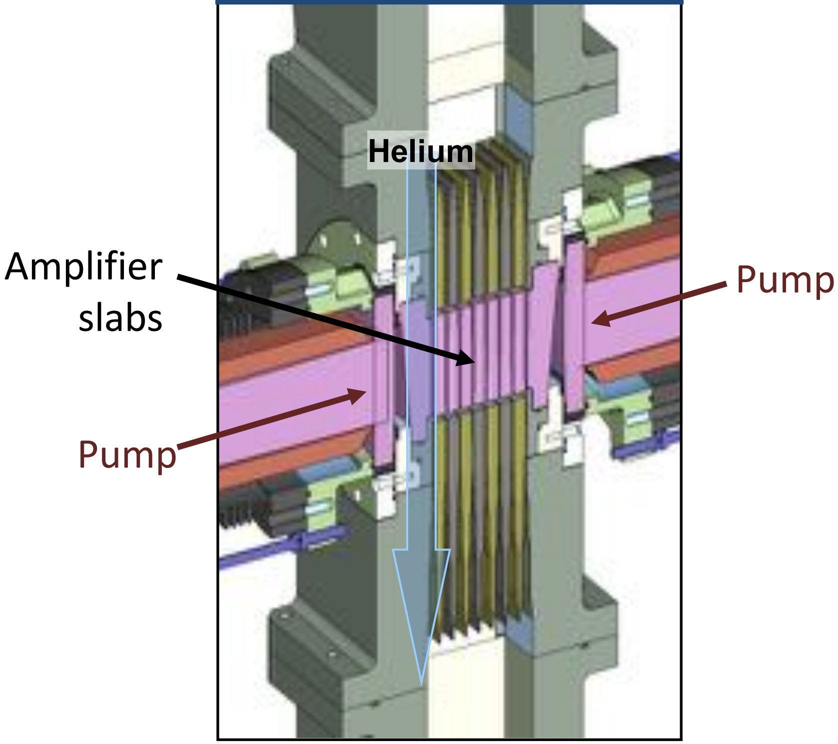


Heat can be extracted through the "edge" or the "face"

Rod amplifiers	THIN DISK: "active mirror"	multislab-face-cooling
		
• Conductive cooling through edges • Stress orthogonal to laser beam • High energy storage	• Conductive cooling through back side • Stress parallel to laser beam • Low energy storage	• Conductive/convective cooling with liquid (National Energetics) or Helium gas (LLNL, RAL) • Stress parallel to laser beam • High energy storage

LLNL pioneered gas-cooling of high energy laser amplifiers in the eighties: slabs are cooled by rapidly flowing He-gas

Gas-cooled amplifier schematic



HAPLS production Amplifier Assembly

- Face cooled Nd:Glass slabs
- Room temperature Helium gas coolant
- Gas acceleration vanes Mach 0.1
- Cooled ASE Edge claddings

Two architectures for high energy DPSSL recently demonstrated: the LLNL's "HAPLS", and Rutherford's "DiPOLE100"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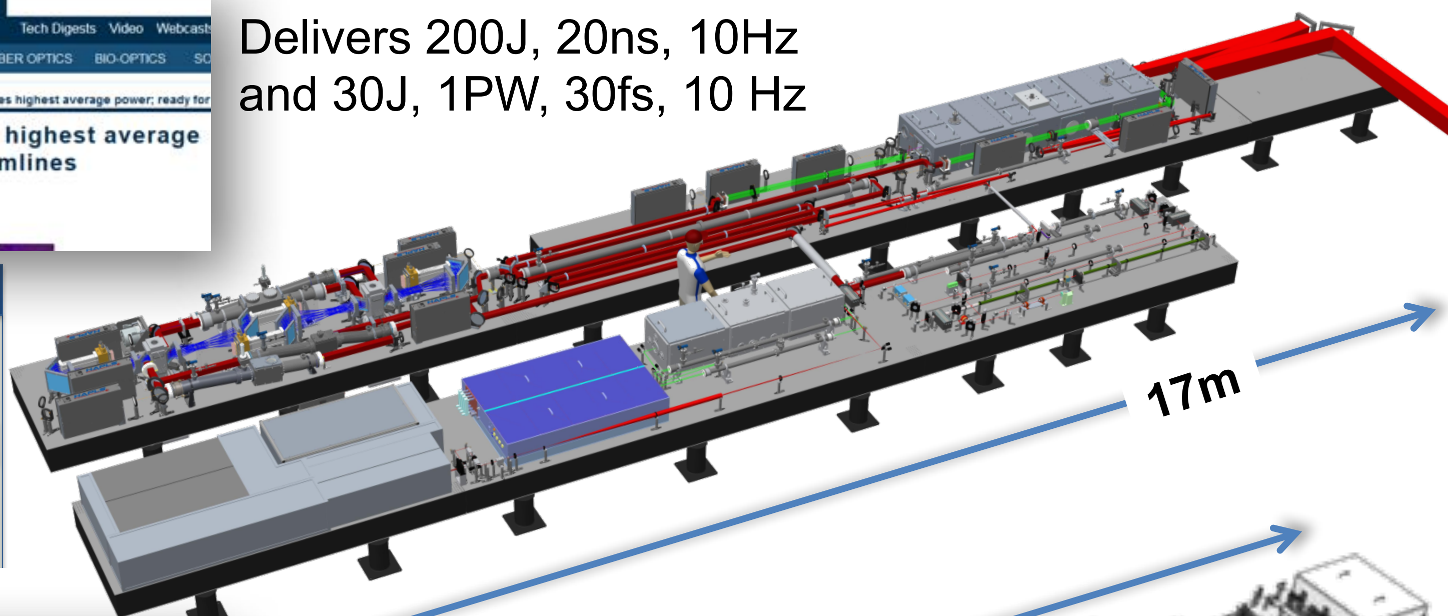
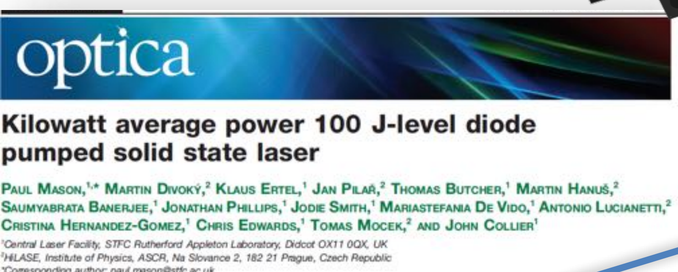
LLNL HAPLS petawatt laser reaches highest average power; ready for delivery to ELI Beamlines

02/08/2017
Posted by Gail Overton
Senior Editor

Delivers 200J, 20ns, 10Hz
and 30J, 1PW, 30fs, 10 Hz




optica

Kilowatt average power 100 J-level diode pumped solid state laser

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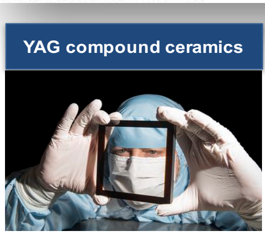
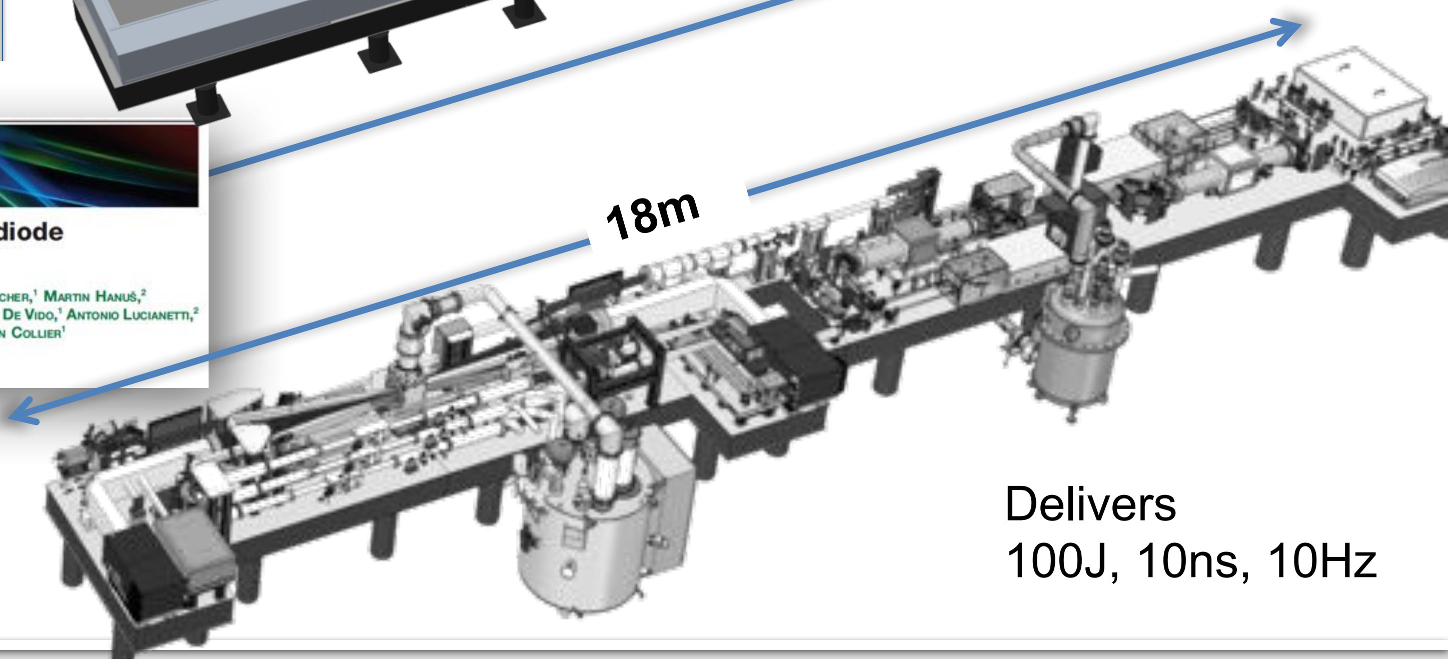


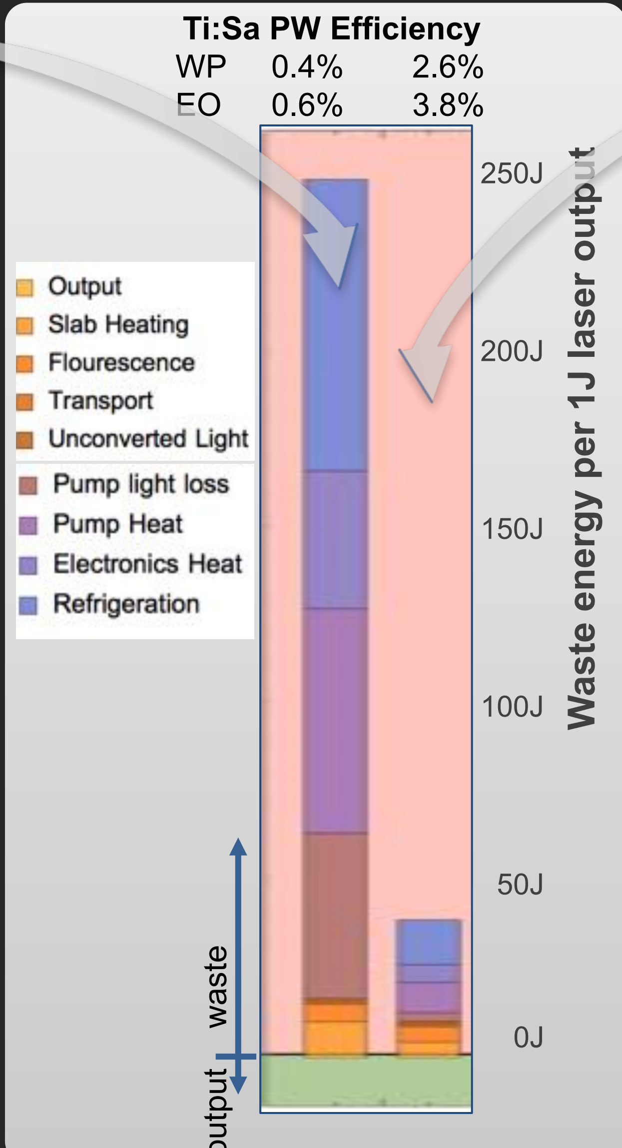


Delivers
100J, 10ns, 10Hz

Diode pumping has a significant impact on system efficiencies

Flashlamps

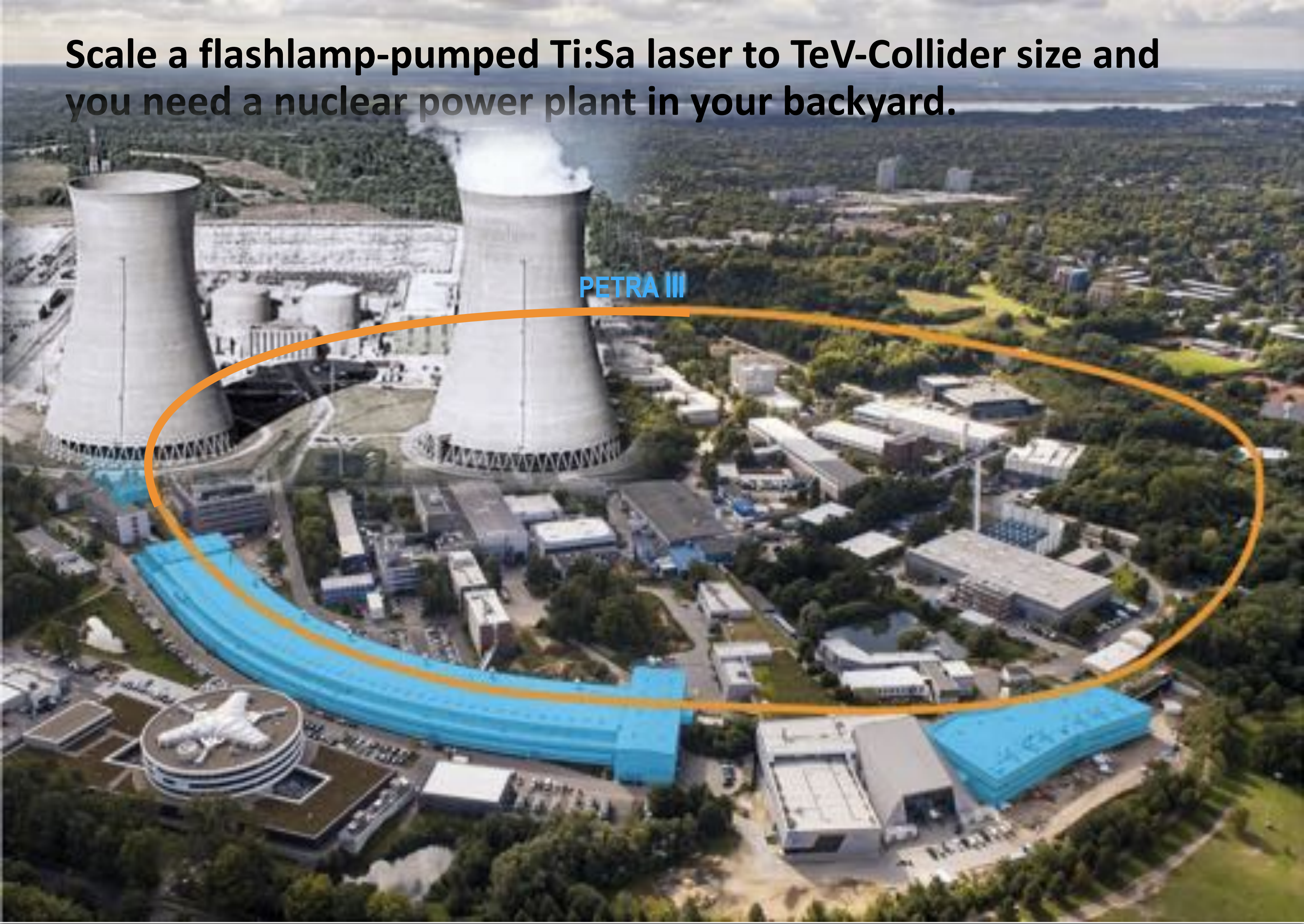
10% electrical-optical efficiency



Diodes

60% electrical-optical efficiency

Scale a flashlamp-pumped Ti:Sa laser to TeV-Collider size and you need a nuclear power plant in your backyard.



HAPLS is designed to deliver Petawatt peak power laser pulses at energy 30J and 10Hz repetition rate = 300 Watt

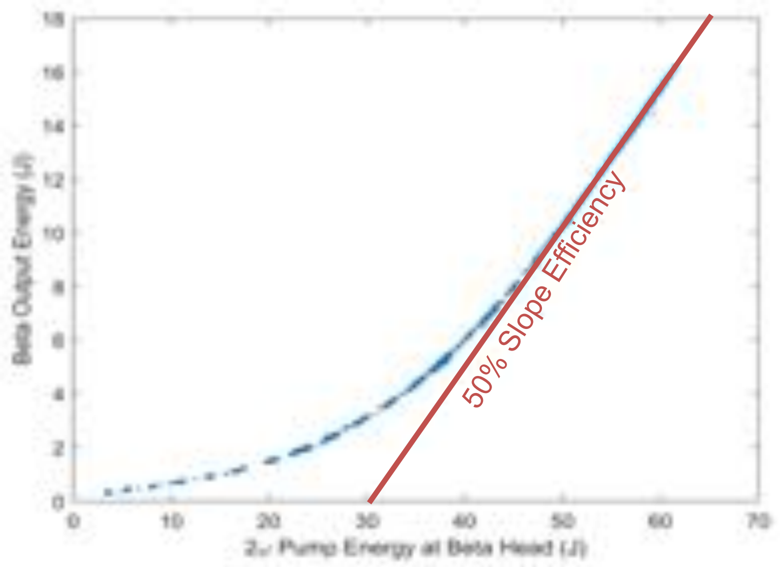
Requirement	Specification
Energy 0.8 μm	≥30 J
Pulse length	≤30 fs
Peak power	≥1 PW
Pre-pulse power contrast	$\leq 10^{-9} \leq c \leq 10^{-11}$
Energy stability	0.6% rms
Technology	DPSSL pumped Ti:sapphire CPA
Repetition rate	10 Hz
Electrical consumption	<150 kW

eli beamlines

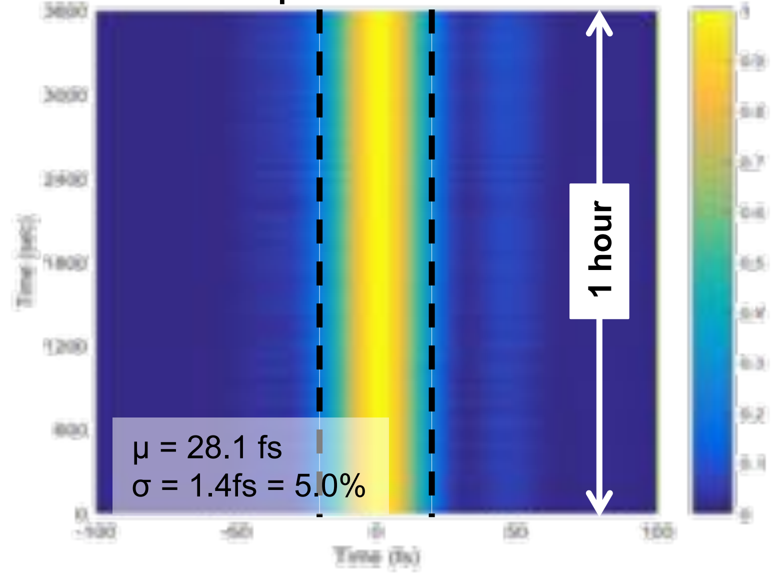

LASER ON
High Power Operations
Eyewear Required

HAPLS today….at ELI Beamlines ready for installation

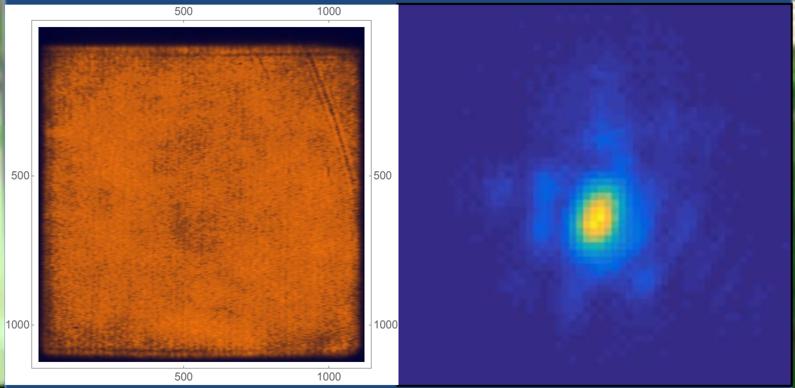
Today, the HAPLS delivers 16J of broadband laser pulses at 3.3 Hz; full aperture is pulse duration 28fs



Full Aperture Pulse duration

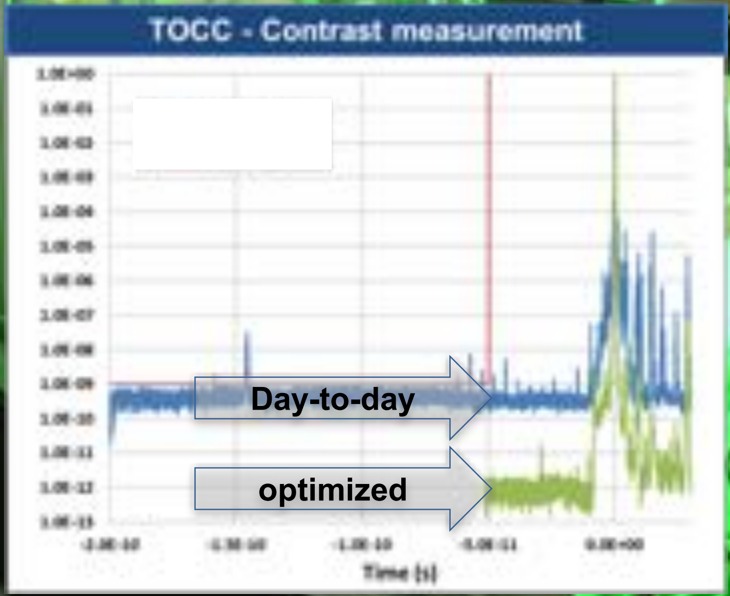


NF and FF Profiles at energy
(first results, adaptive mirror not active)

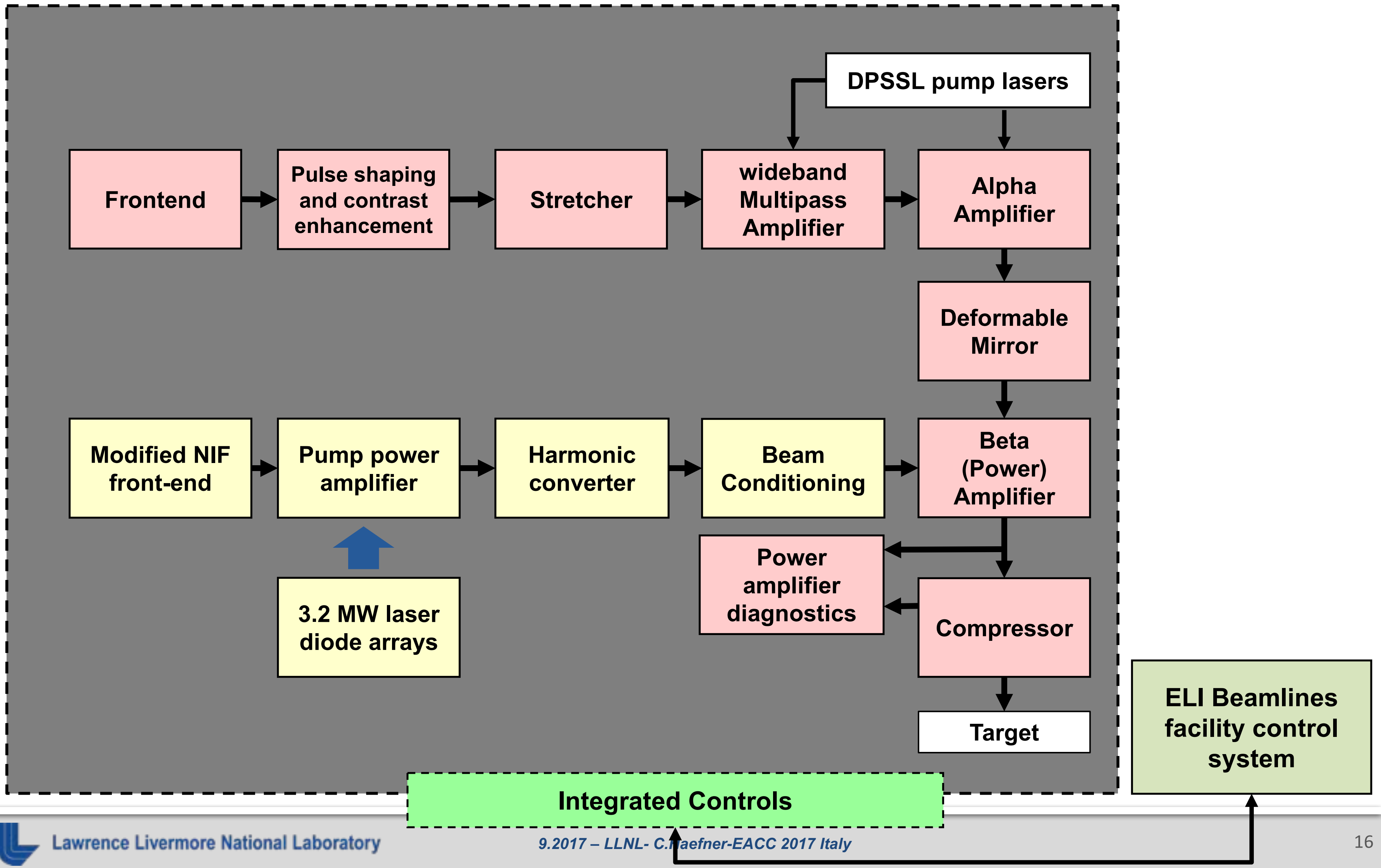


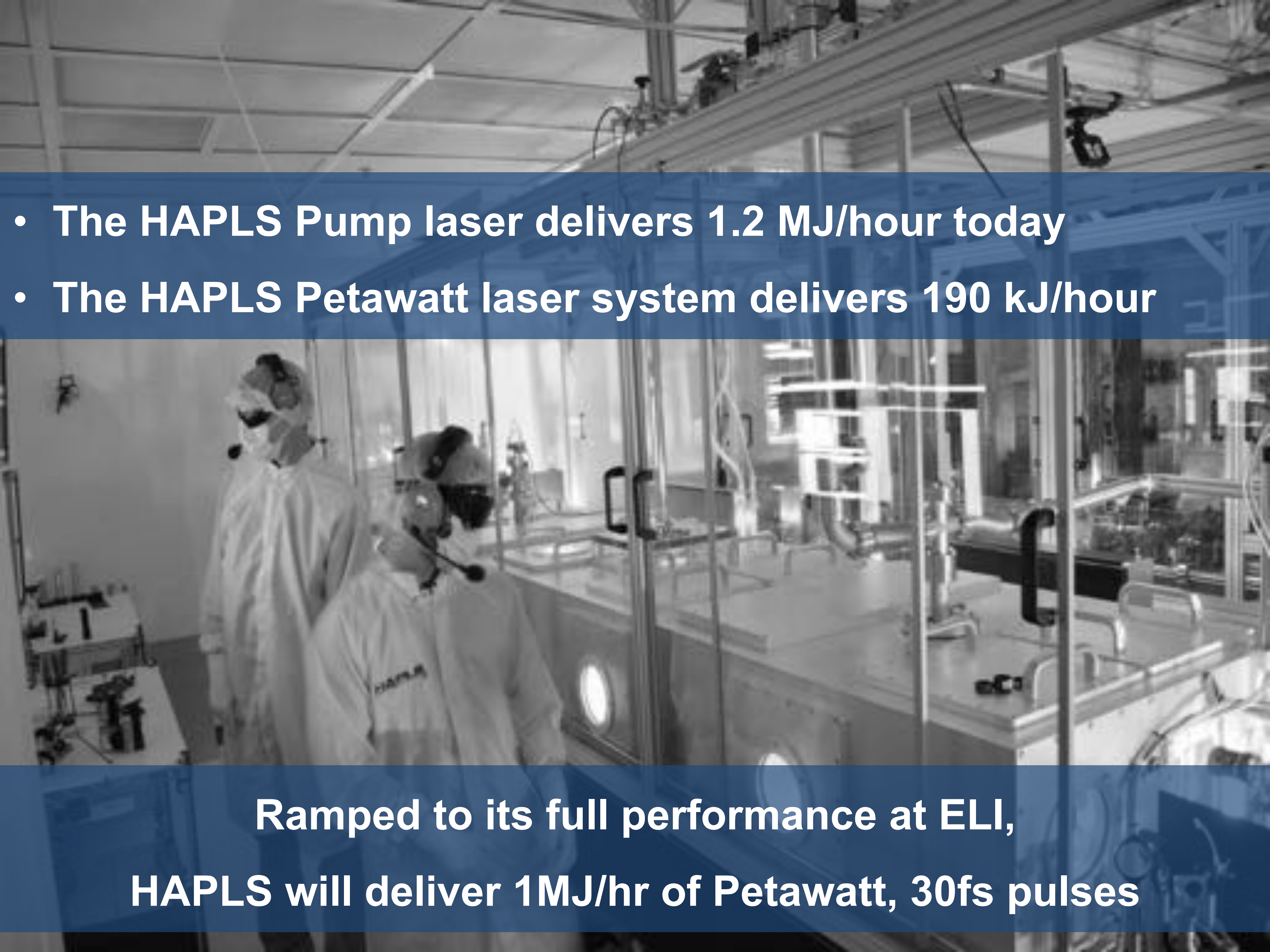
HAPLS output NF

Encircled energy in DL spot = ~0.5



HAPLS relies on a diode pumped, indirect chirped pulse amplification architecture (”diode pumped laser pumped laser”



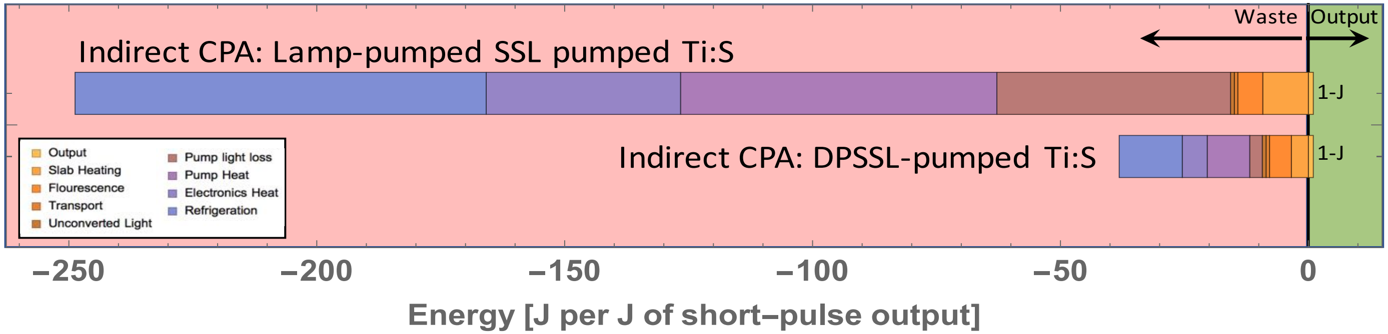


- The HAPLS Pump laser delivers 1.2 MJ/hour today
- The HAPLS Petawatt laser system delivers 190 kJ/hour

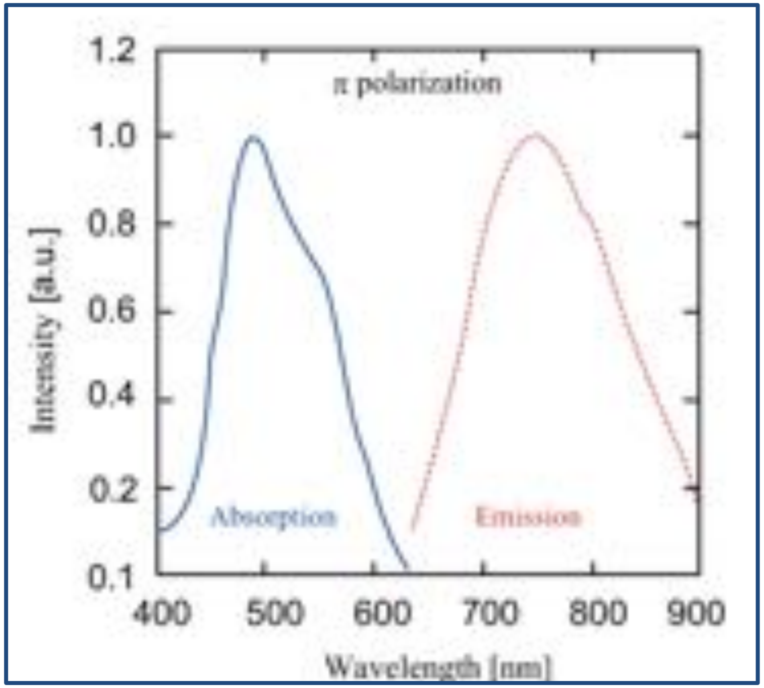
Ramped to its full performance at ELI,

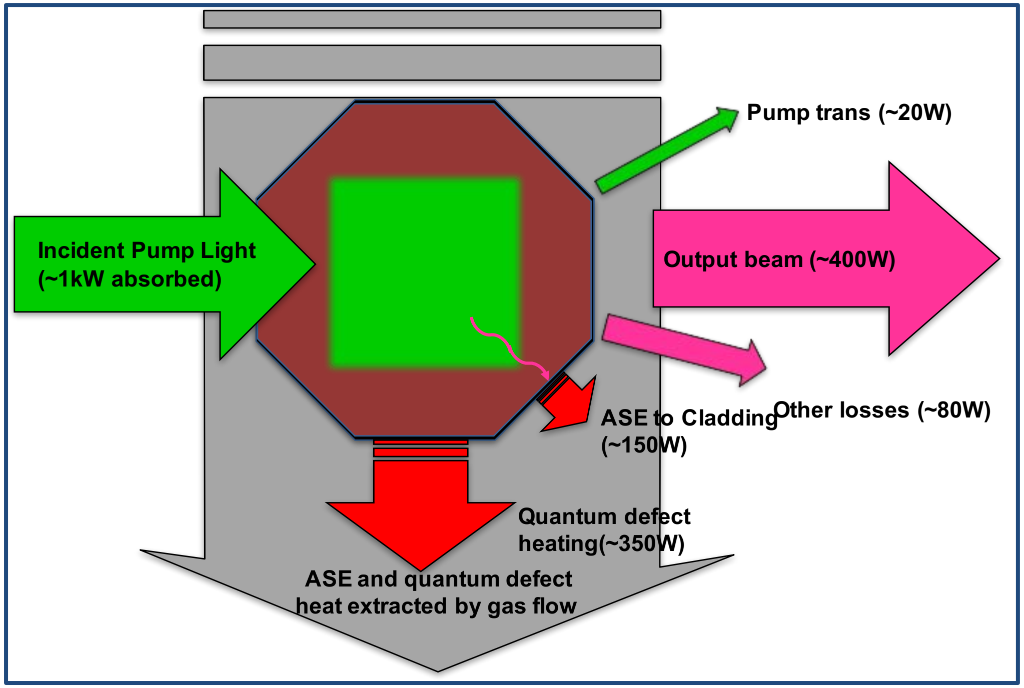
HAPLS will deliver 1MJ/hr of Petawatt, 30fs pulses

The average power scalability of energetic Ti:Sapphire (and OPCPA) laser is constrained by the availability of pump lasers



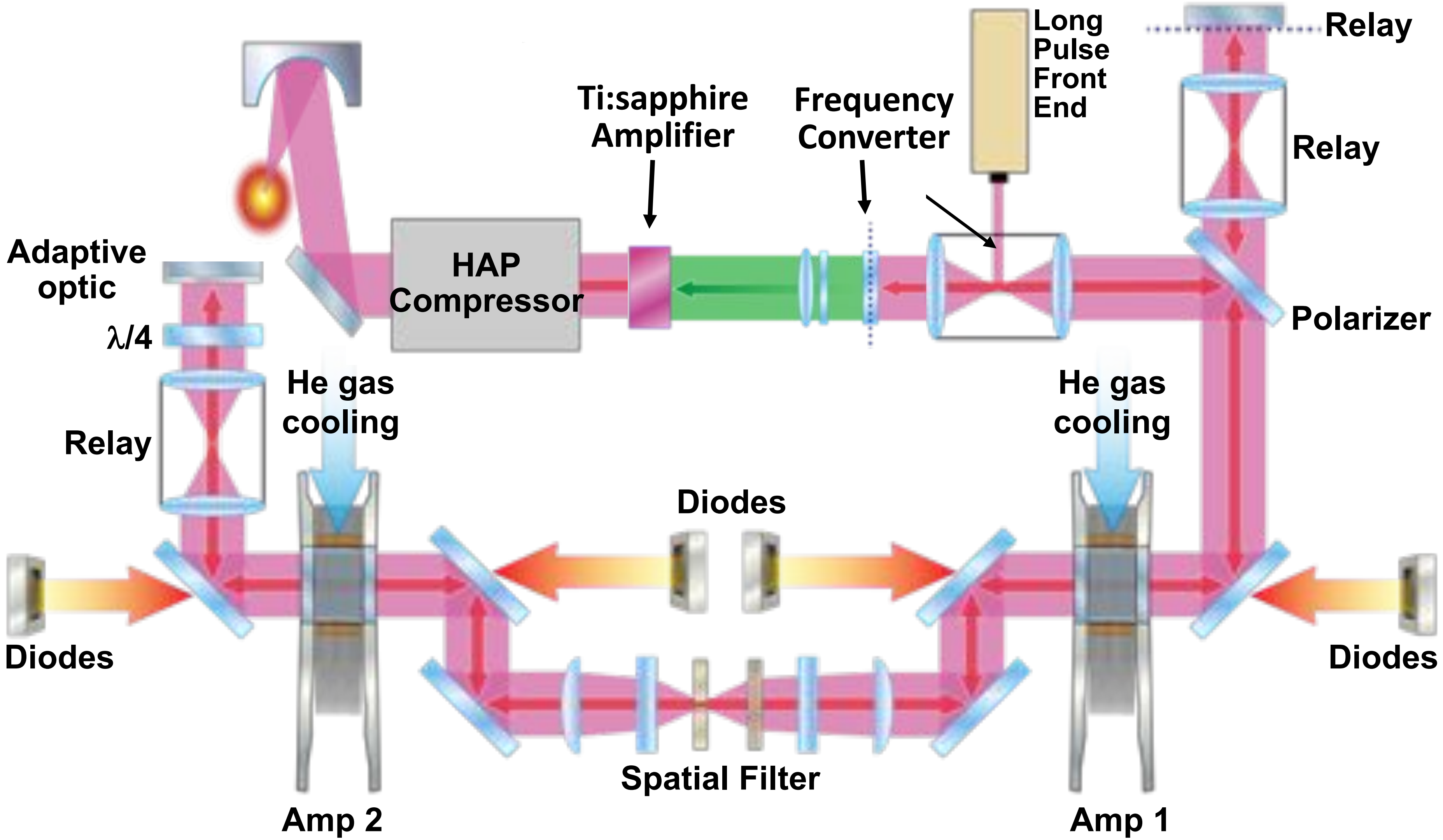
Efficiency WP	EO
0.4%	0.6%
2.6%	3.8%



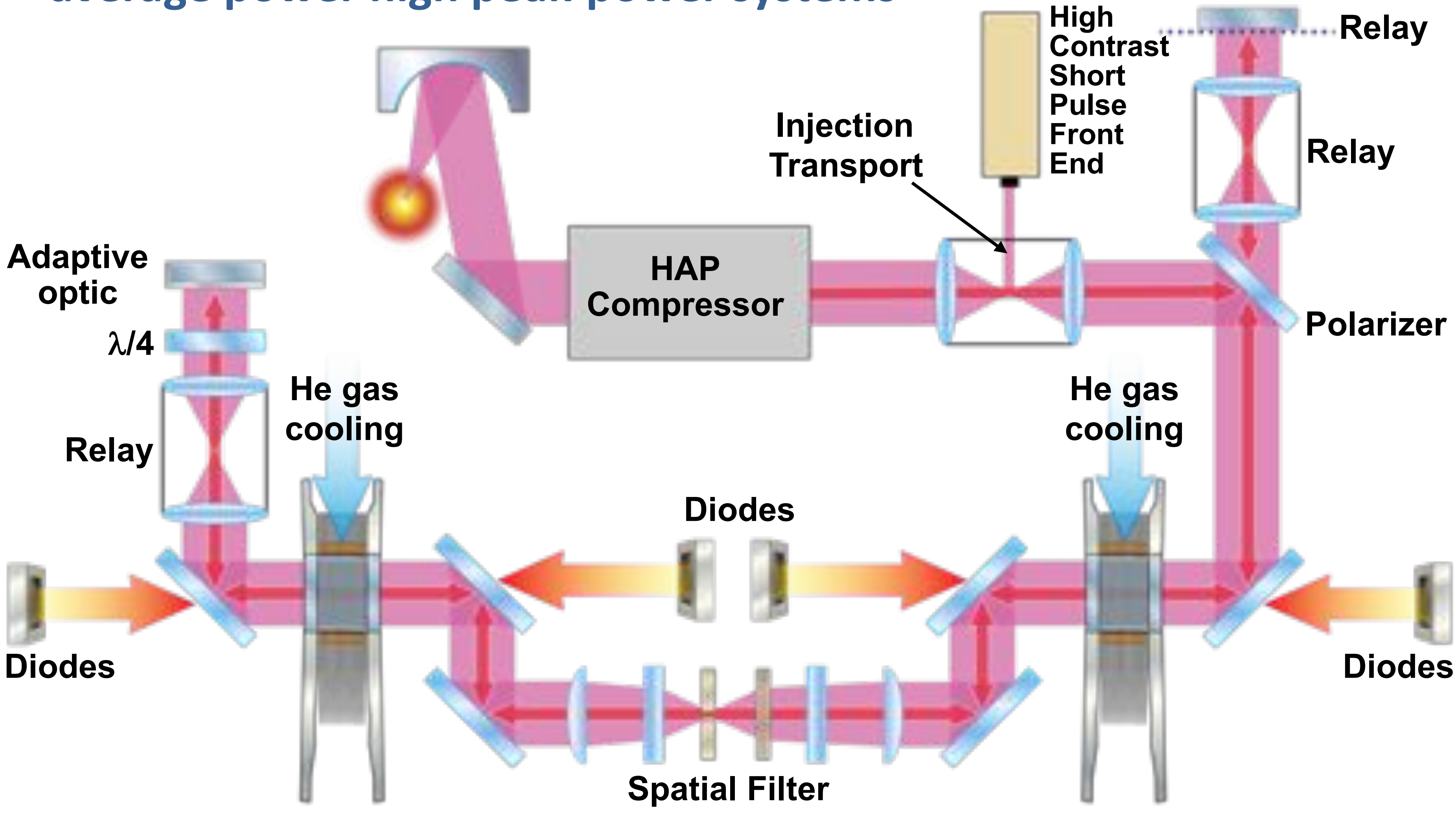


The short gain lifetime and the large quantum defect make Ti:Sapphire drives the cost of the pump laser and makes it an unattractive HAP laser medium

The HAPLS pump architecture utilizes dual diode-pumped surface-cooled multislab amplifiers in a 4-pass polarization switched architecture



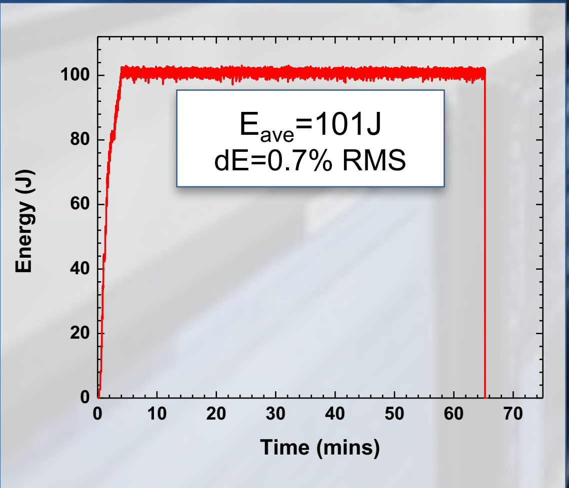
The dual diode-pumped surface-cooled multislab amplifier in a 4-pass polarization switched architecture is a template for high average power high peak-power systems



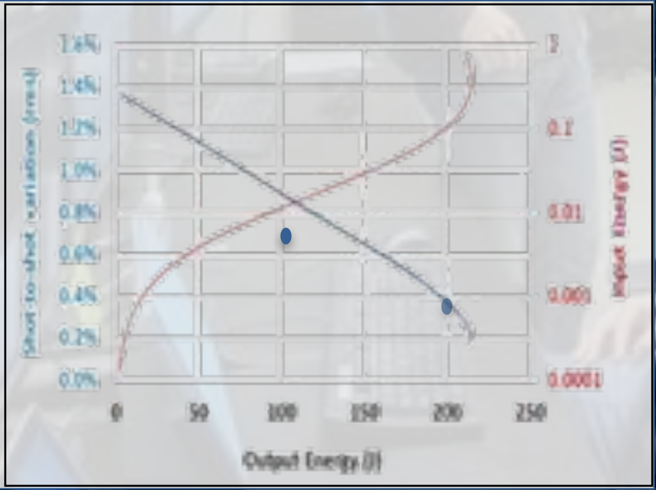
Example: Scalable High-power Advanced Radiography Capability (SHARC)

The HAPLS pump laser could be converted to a 150J, 150fs, 10Hz secondary source driver: SHARC

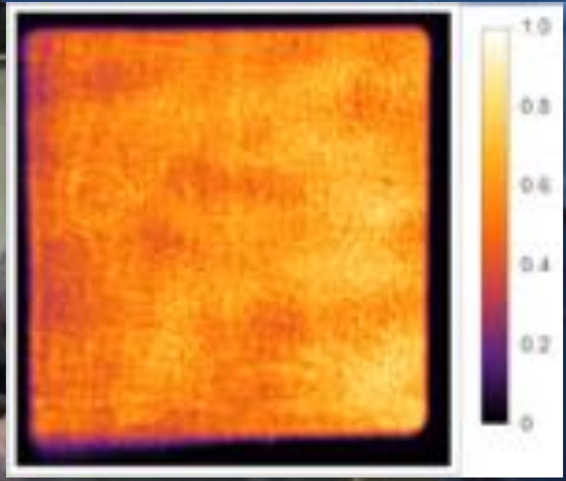
Continuous 1hr run delivering 100Joule pulses at 340W



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



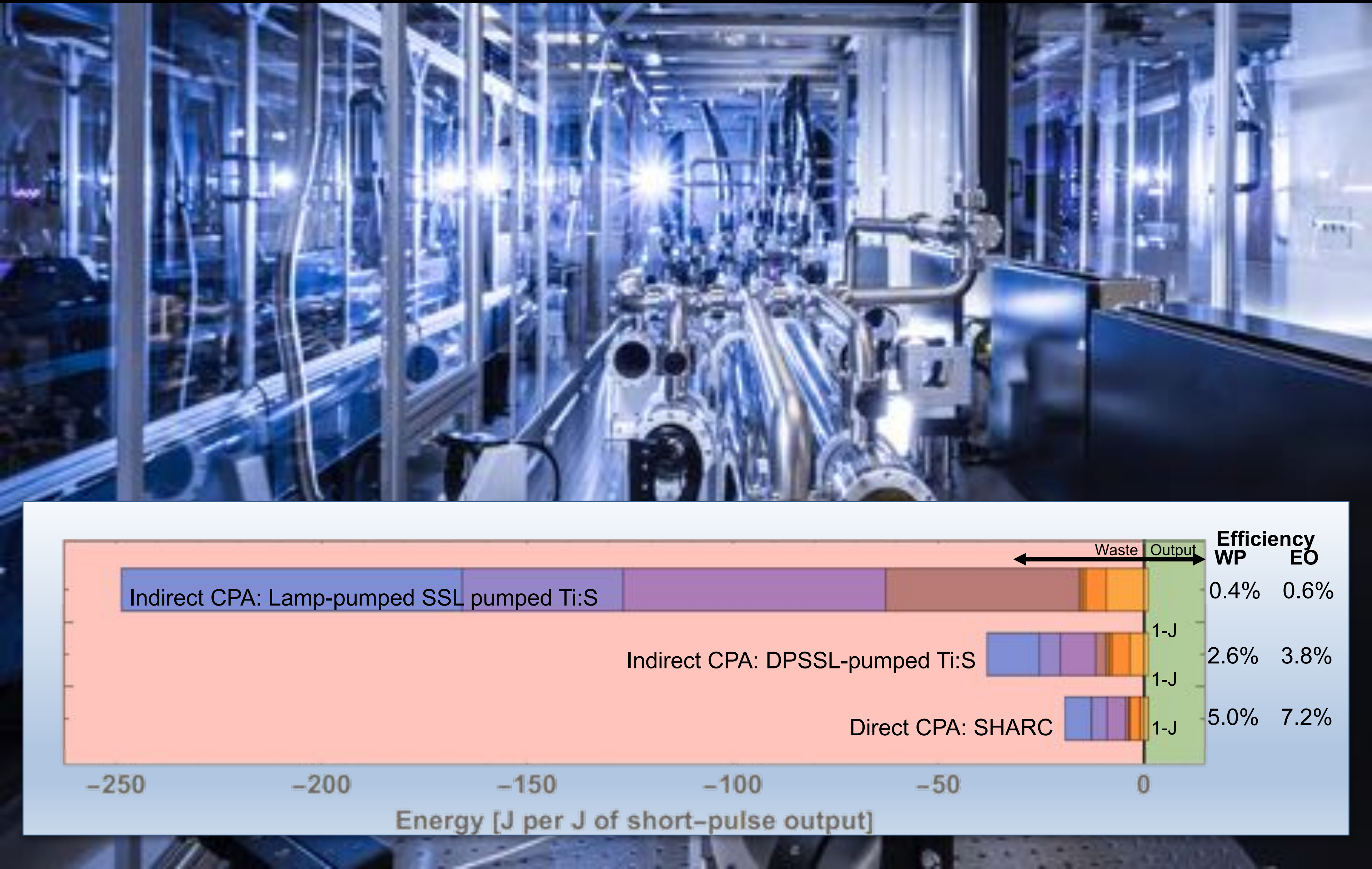
Output beam profile



Based on HAPLS pump laser and NIF ARC technology, LLNL has developed a concept for a *Scalable High-average-power Advance Radiographic Capability (SHARC)*

- **SHARC is a low-risk high-TRL extension of HAPLS pump laser technology**
- **150J, 150fs, 10Hz, 90/110 dB temporal contrast**
- **10-Hz PW (150J/150fs) at greater efficiency than HAPLS (~5% Wall plug efficiency)**
- **HAPLS diode-pumped Nd:Glass pump laser with broadband mixed-glass frontend and LLE's Short Pulse OPA seed technology**
- **High efficiency, actively cooled MLD-grating laser pulse compressor**
- **Application space targets proton-/neutron-particle beam and high brightness x-ray generation**

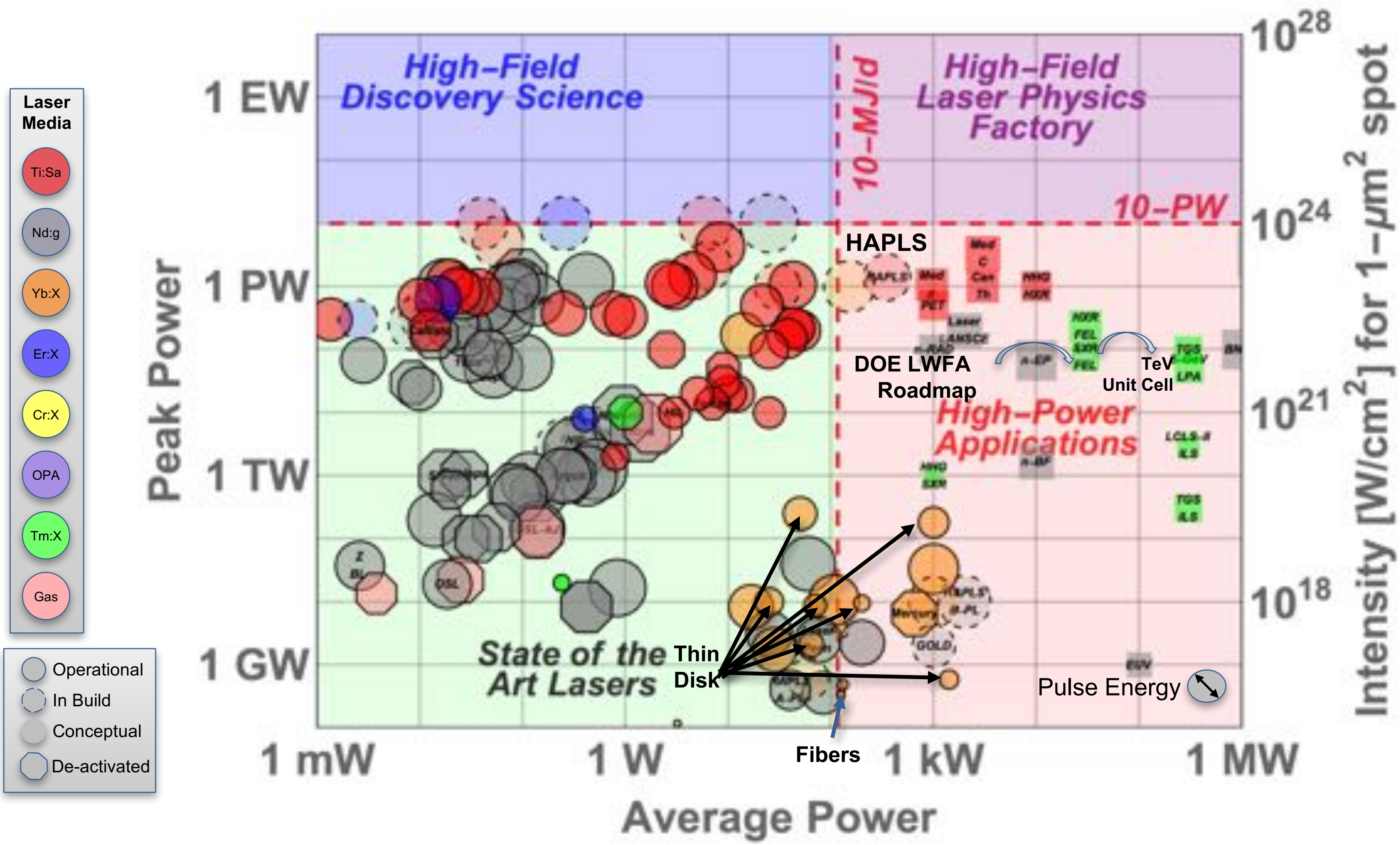
Based on HAPLS pump laser and NIF ARC technology, LLNL has developed a concept for a *Scalable High-average-power Advance Radiographic Capability (SHARC)*



HAPLS-100 and SHARC could get us to kW to ~10kW of average power (at Petawatt peak power).

But we need 100s of kW for TeV Collider stage.

High-Power Single-Aperture Laser Beamline Performances



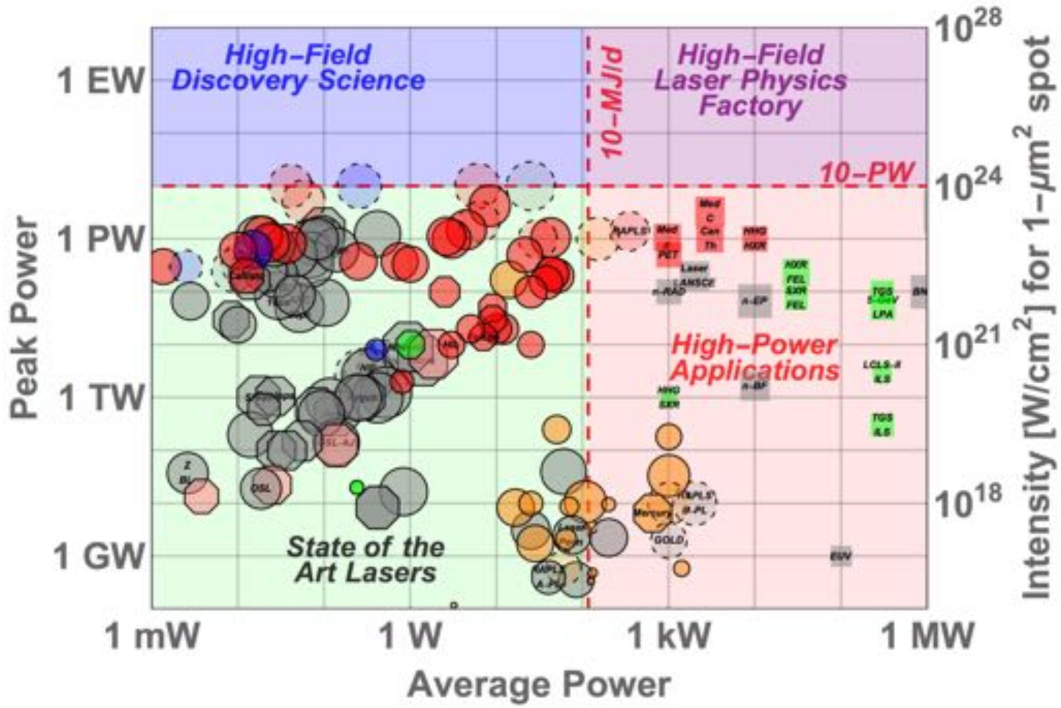
Pushing the frontiers of high-power applications and high-intensity science requires next-generation high repetition-rate high-energy solid state lasers.

Transitioning from Application Space to Laser Media Space

If we normalize this plot by the beam area in the final amplifier, the axes become proportional to laser media parameters: photon energy, gain cross-section, gain lifetime, gain bandwidth (ie transform limited pulse duration).

PW/cm^2

$$\frac{h\nu}{\sigma} \cdot \Delta\nu$$



kW/cm^2

$$\frac{h\nu}{\sigma} \cdot \frac{1}{\tau_{gain}}$$

Power Scaling for Energy-Storage Laser Media (simple scaling w/o architecture considerations)

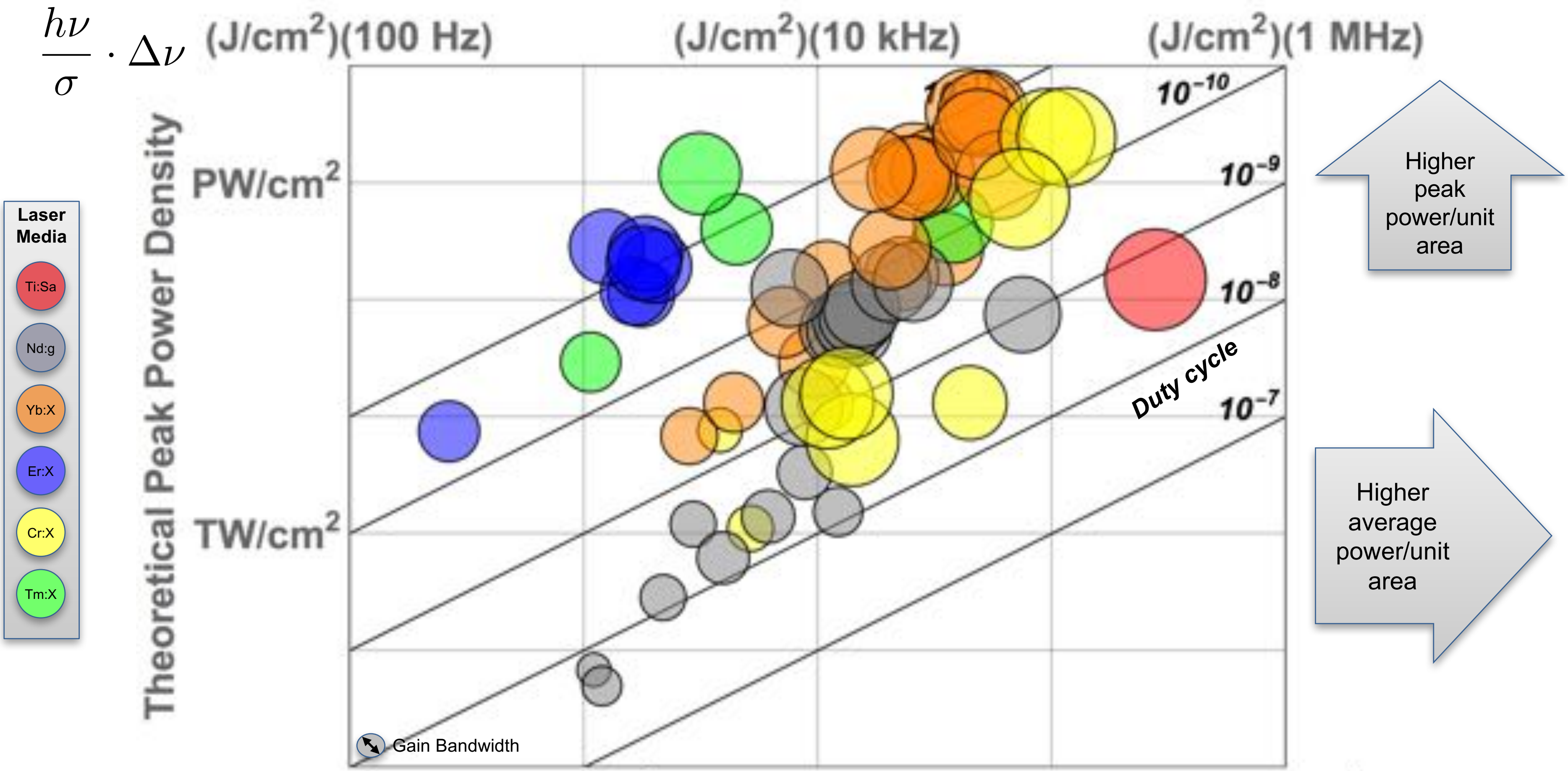
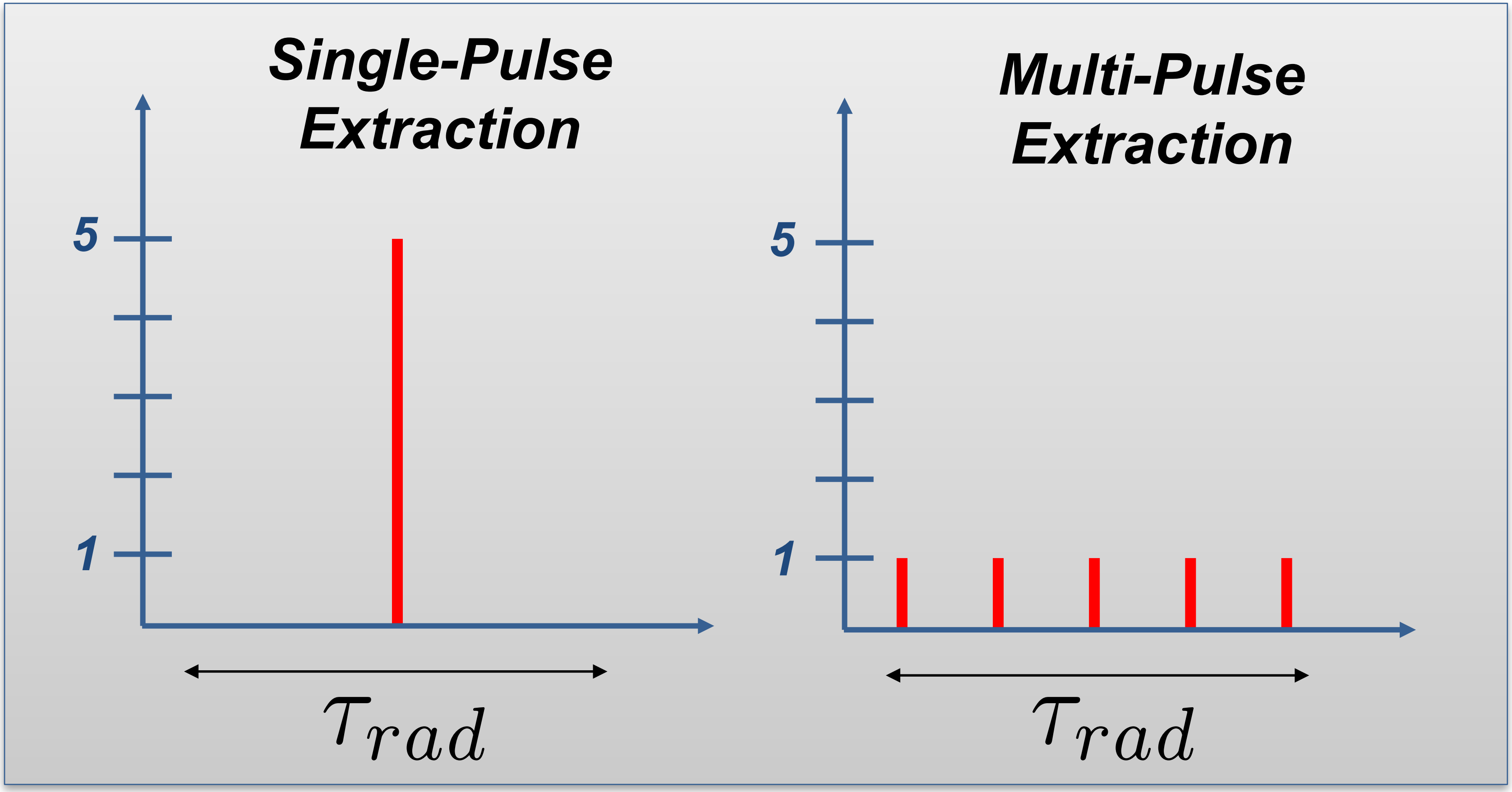


Table 1. Theoretical peak power.

Laser type	Cross section (10^{-20} cm²)	$\Delta\lambda$ (nm)	τ (fs)	P_{th} (TW/cm²)
Nd:glass phosphate	4	22	80	60
Nd:glass silicate	2.3	28	60	100
Nd:glass combination	1.5	60	30	400
Ti:sapphire	30	120	8	120
Alexandrite	1	100	10	2000
Cr:LiSAF	3	50	15	300

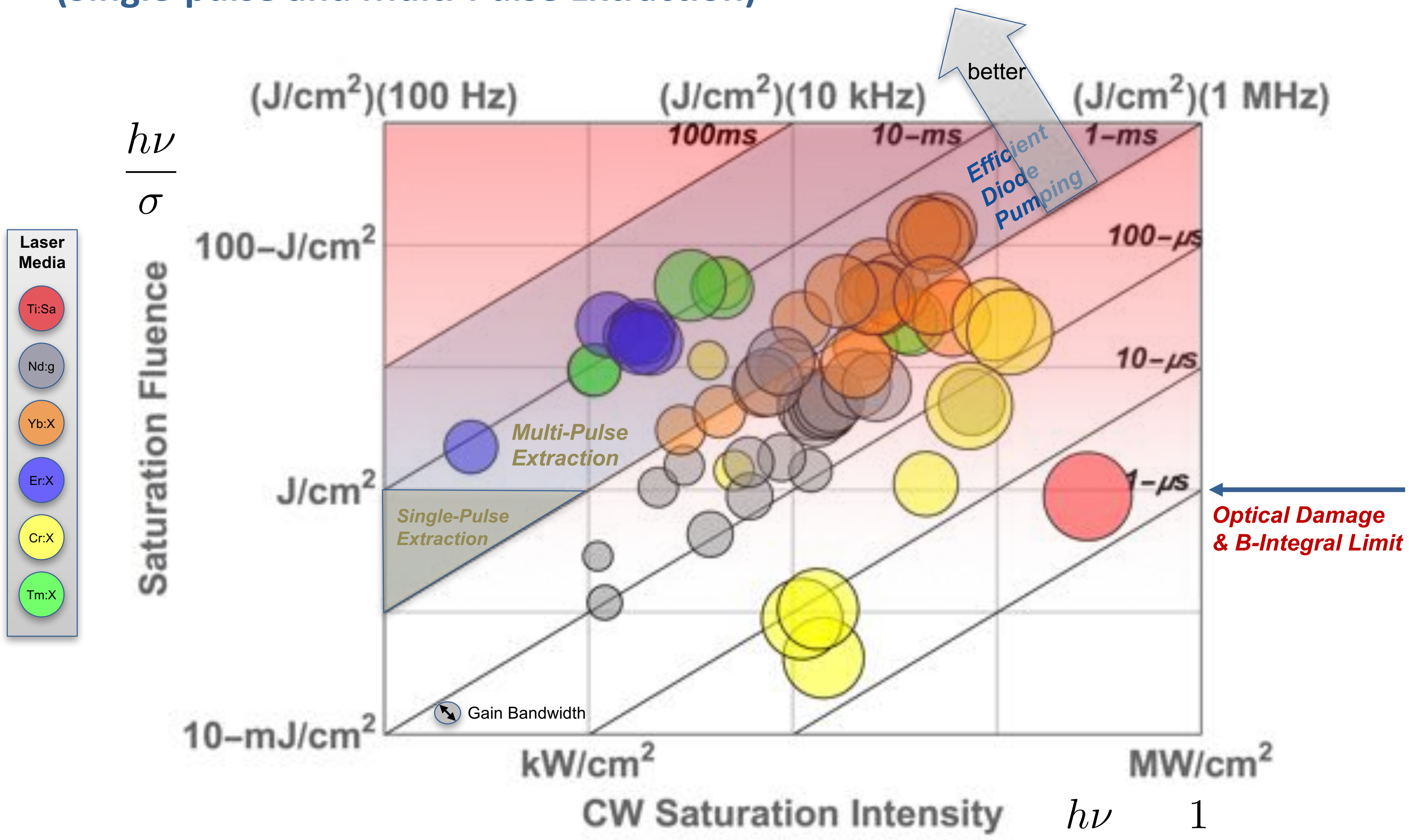
[1] M. D. Perry and G. A. Mourou, Science **264**, 917 (1994).

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

Efficient Diode-Pumped Media for High-Power Lasers (Single-pulse and Multi-Pulse Extraction)

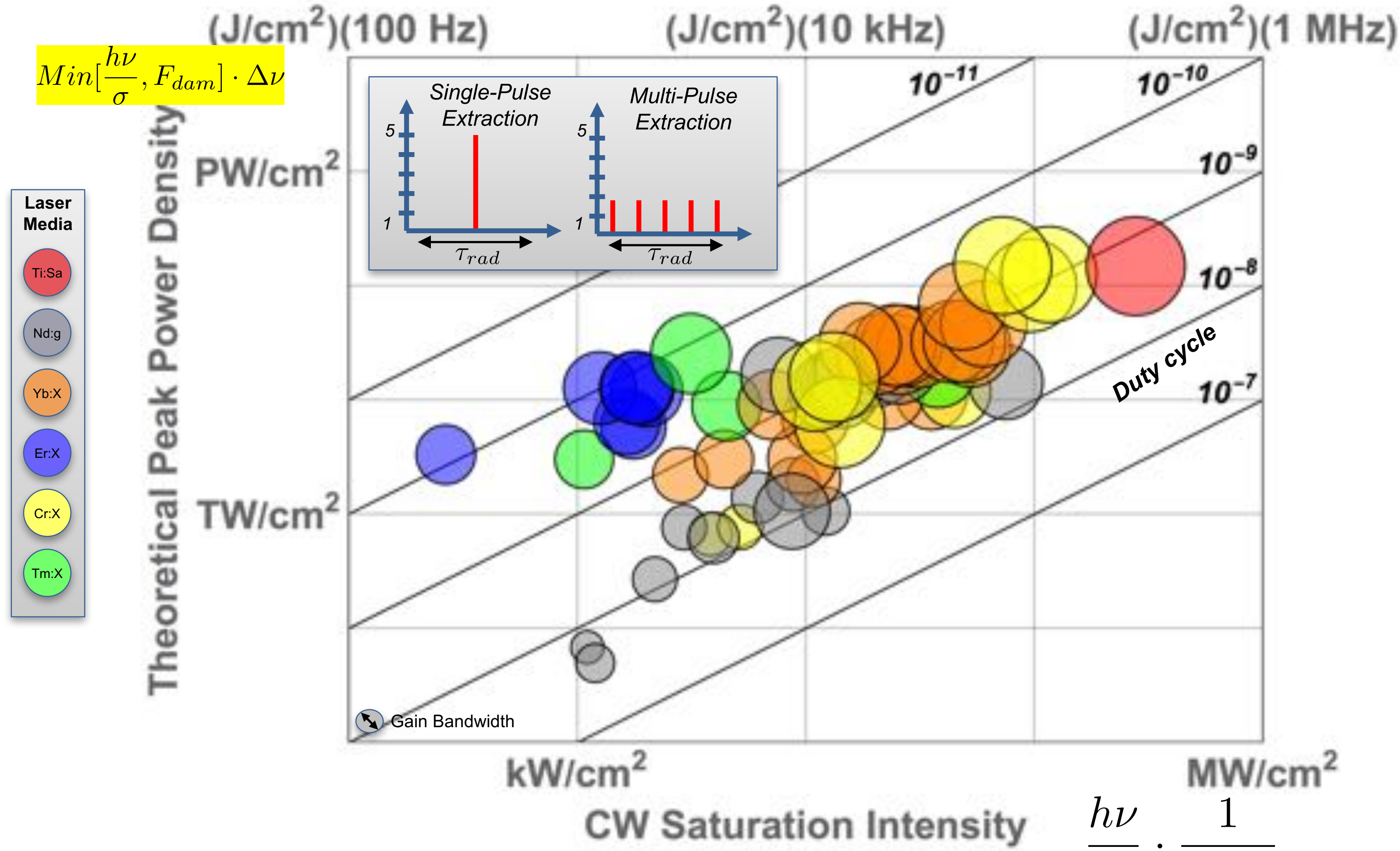


$$\frac{h\nu}{\sigma}$$

$$\frac{h\nu}{\sigma} \cdot \frac{1}{\tau_{gain}}$$

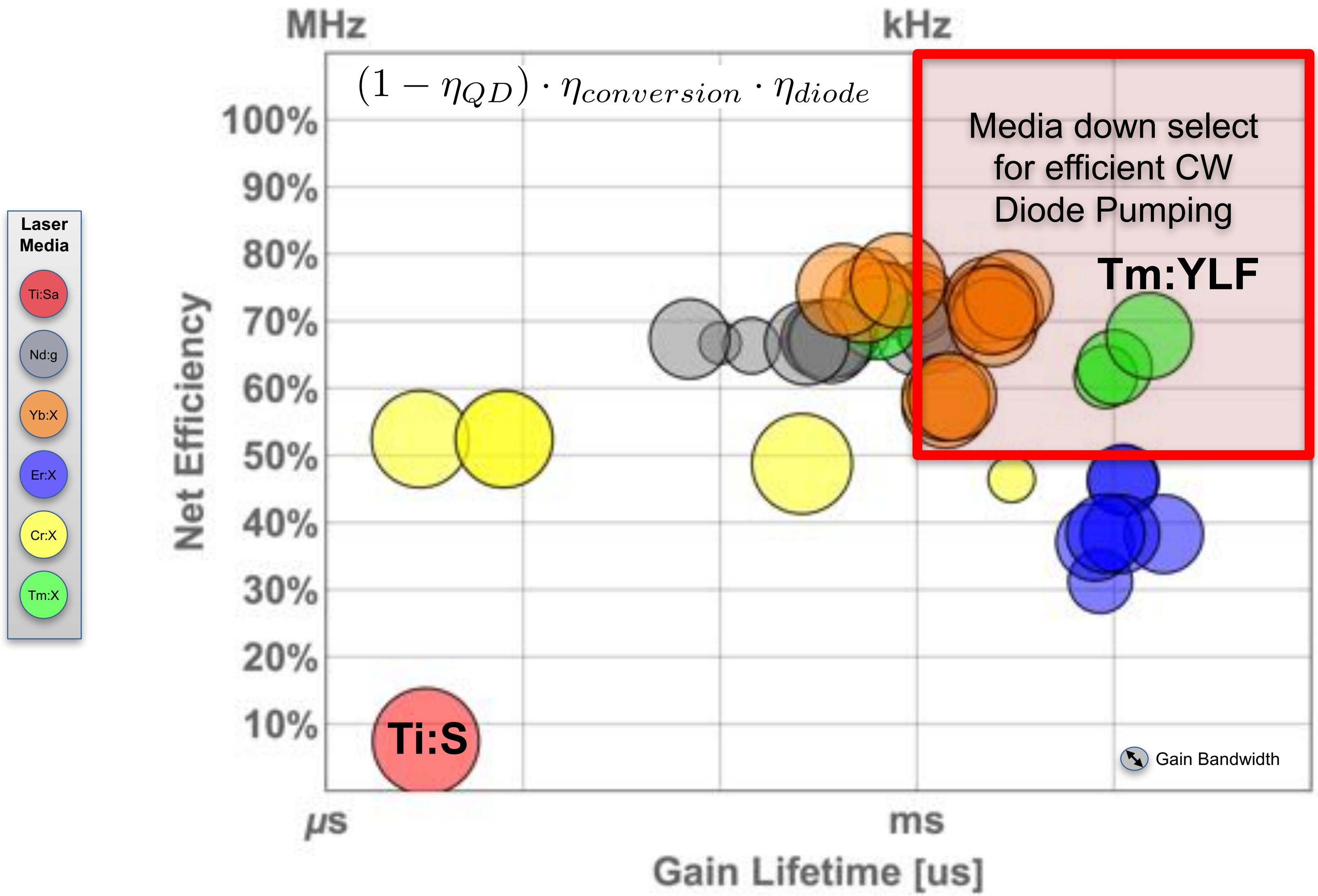
Power Scaling for Energy-Storage Laser Media:
Damage Limited Fluence and Multi-Pulse Extraction

$$Min[\frac{h\nu}{\sigma}, F_{dam}] \cdot \Delta\nu$$

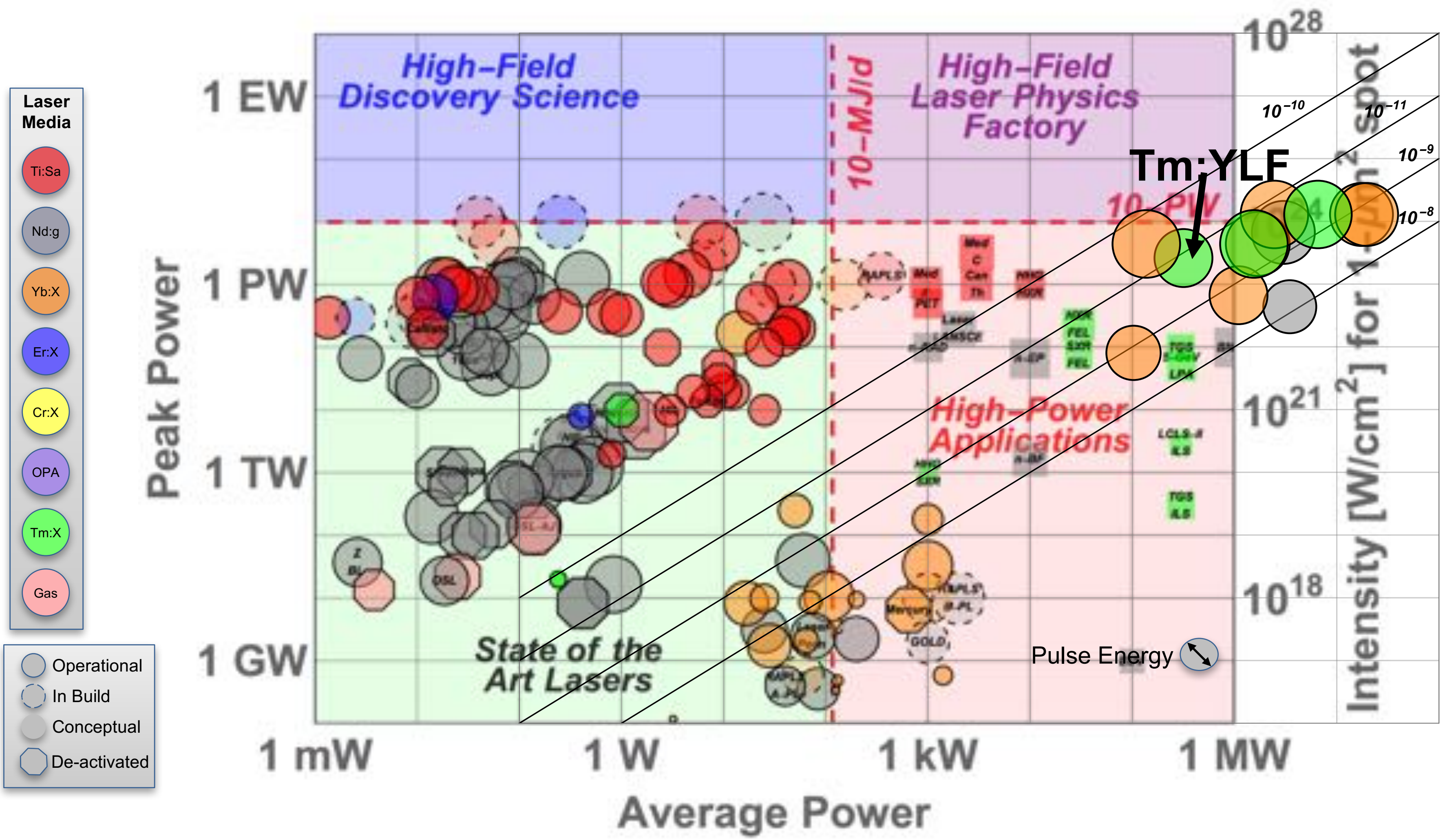


$$\frac{h\nu}{\sigma} \cdot \frac{1}{\tau_{gain}}$$

Quantum Defect and Gain Lifetime for Energy-Storage Laser Media

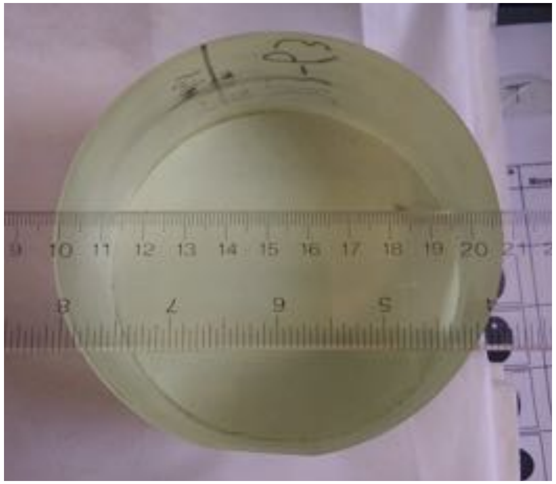


High-Power Single-Aperture Laser Beamline Performances



BAT: Big Aperture Thulium Laser. BAT is a high rep-rate PW-class architecture which scales to 300-kW average power

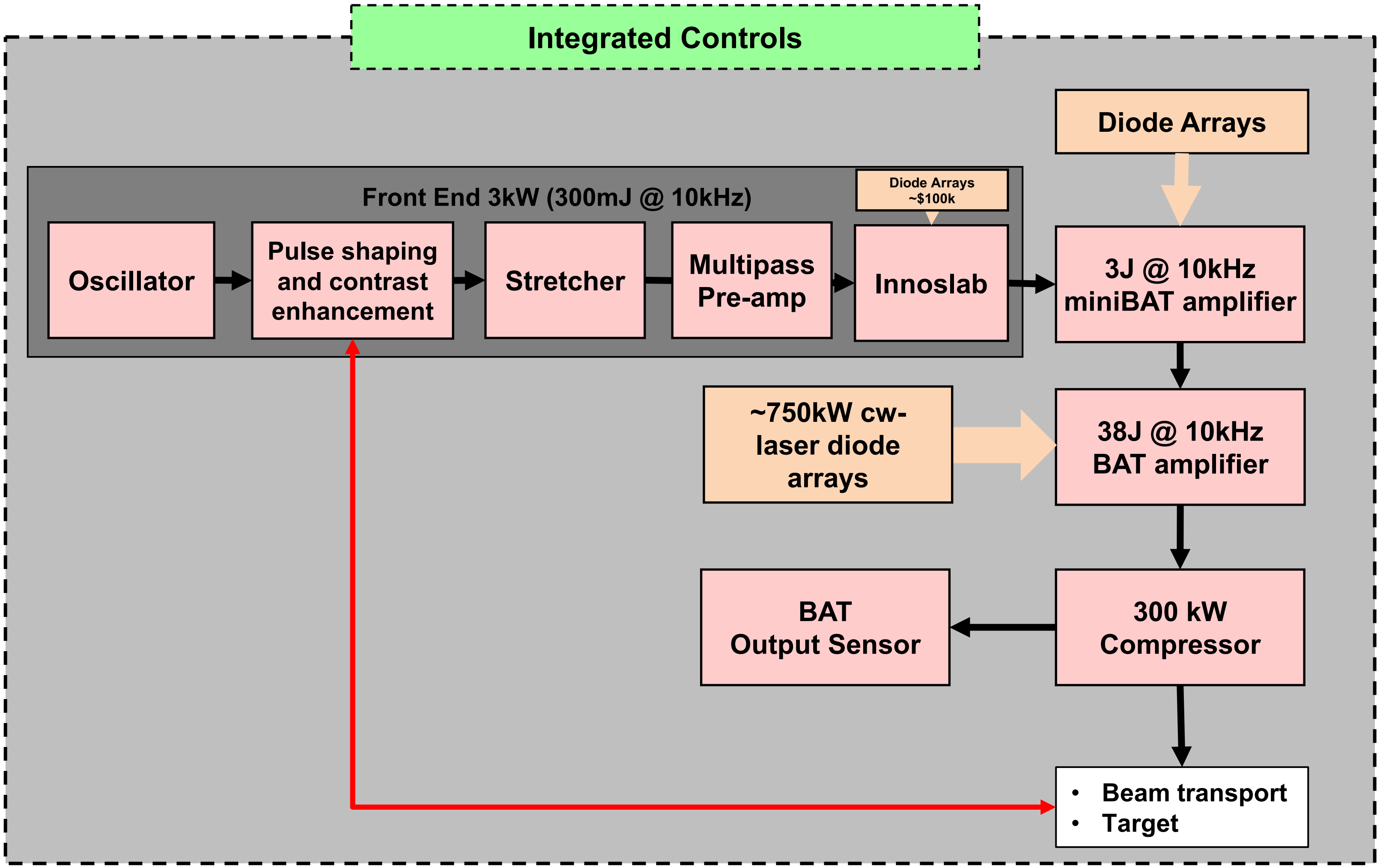
- Extension of HAPLS diode-pumped gas-cooled architecture
- Tm:YLF laser media (1.9um)
  - Commercially available in sizes for 300-kW
  - superior thermal wave front (-dn/dT vs thermal expansion)
  - anisotropic media - de-polarization not an issue
  - Pulse duration 40fs < t < 100fs TL
  - Two-for-one pumping by self-quenching in Tm enables low QD pump scheme
- True CW pumped:
  - Tm has long lifetime which when combined with the desired pulse repetition rates enables multi-pulse extraction and continuous pumping
  - Quasi-4-level losses are distributed among hundreds of pulses minimizing this effect
  - Efficient extraction at low fluence per pulse, low B, higher efficiency
  - ~40x lower diode cost compared to HAPLS; lower electronics cost due to simplicity over QCW
  - Efficient high-power pump diodes consistent with Tm pumping already on the market



Tm:YLF crystal recently procured by LLNL: Diameter ~10cm

We have purchased 300kW-equivalent size Tm:YLF boules, produced our first amplifier slabs and characterizing the material further for its suitability

Block diagram of BAT

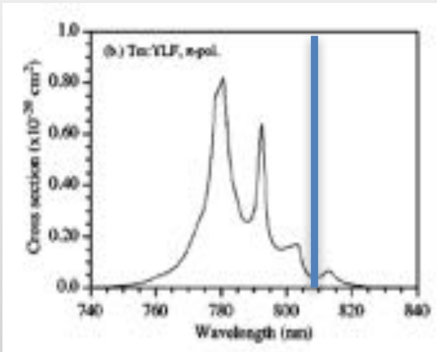


BAT emits 300kW from a single aperture

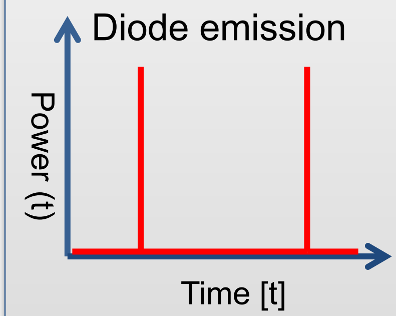
Characteristic	Value
Gain medium	Tm:YLF
Architecture	Multi-pass, multi-pulse gas cooled
Output energy	30 J
Repetition rate	10,000 Hz
Average output power	300 kW
Wavelength	~ 1.9 μm
Output fluence	0.7 J/cm^2
B integral (Poweramp)	< 0.1 radians (!!!)

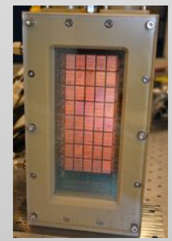
BAT laser diodes are always on!!!

Commercial pump cw-diode arrays are available (150W/bar) from multiple vendors



808 nm pump band matches Nd:YAG pump wavelengths





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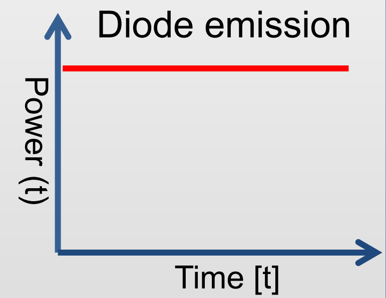
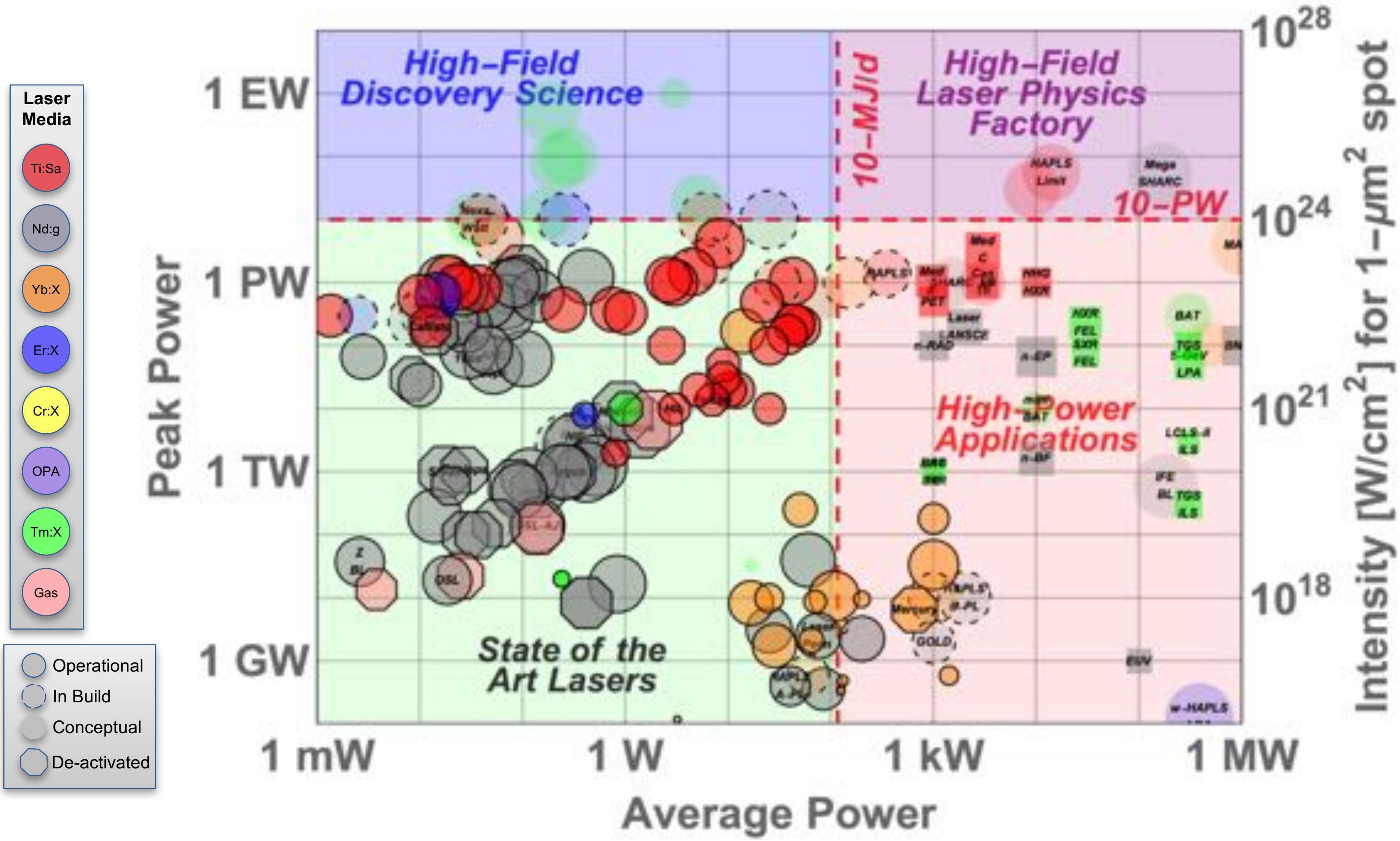


	HAPLS	BAT
Laser Average Power (kW)	0.3	300
# of arrays	4	4
Array Peak Power (kW)	800	188
Array Average Power (kW)	2.4	188
Emitting area (W x H cm^2)	5.6 x 13.4	6.6 x 28.4
Duty Cycle (%)	0.3	100
Relative Cost / array	1	1.9

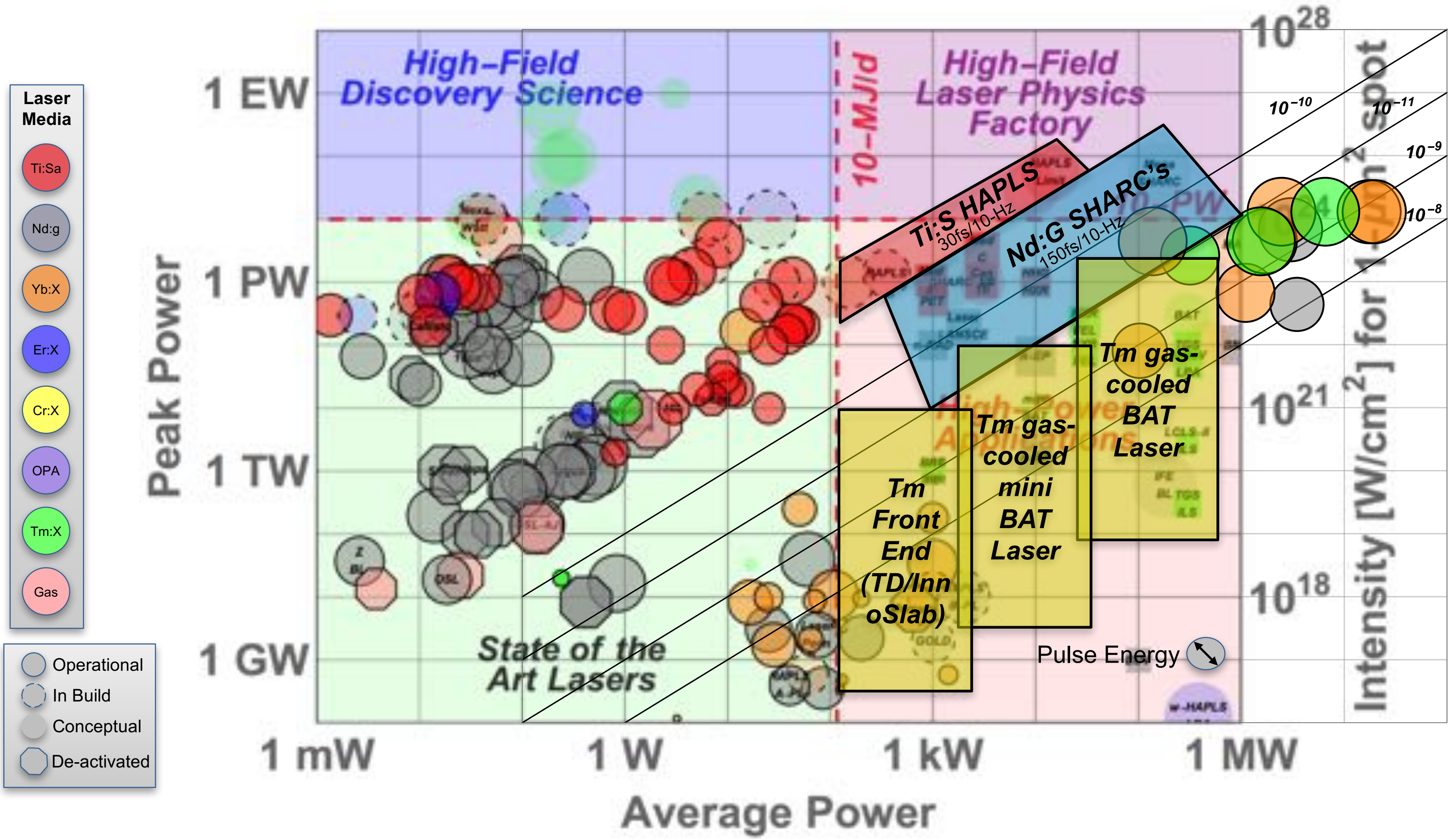
Diodes for a 300 kW class BAT system are only 1.9X the cost of the HAPLS arrays

High-Power Single-Aperture Laser Beamline Performances



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

High-Power Single-Aperture Laser Beamline Performances

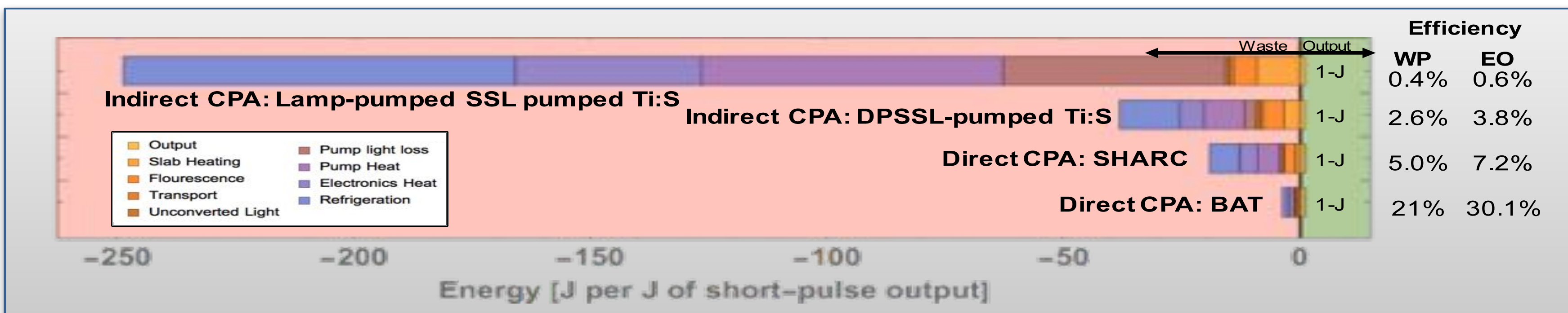


Pushing the frontiers of high-power applications and high-intensity science requires next-generation high repetition-rate high-energy solid state lasers.

Summary

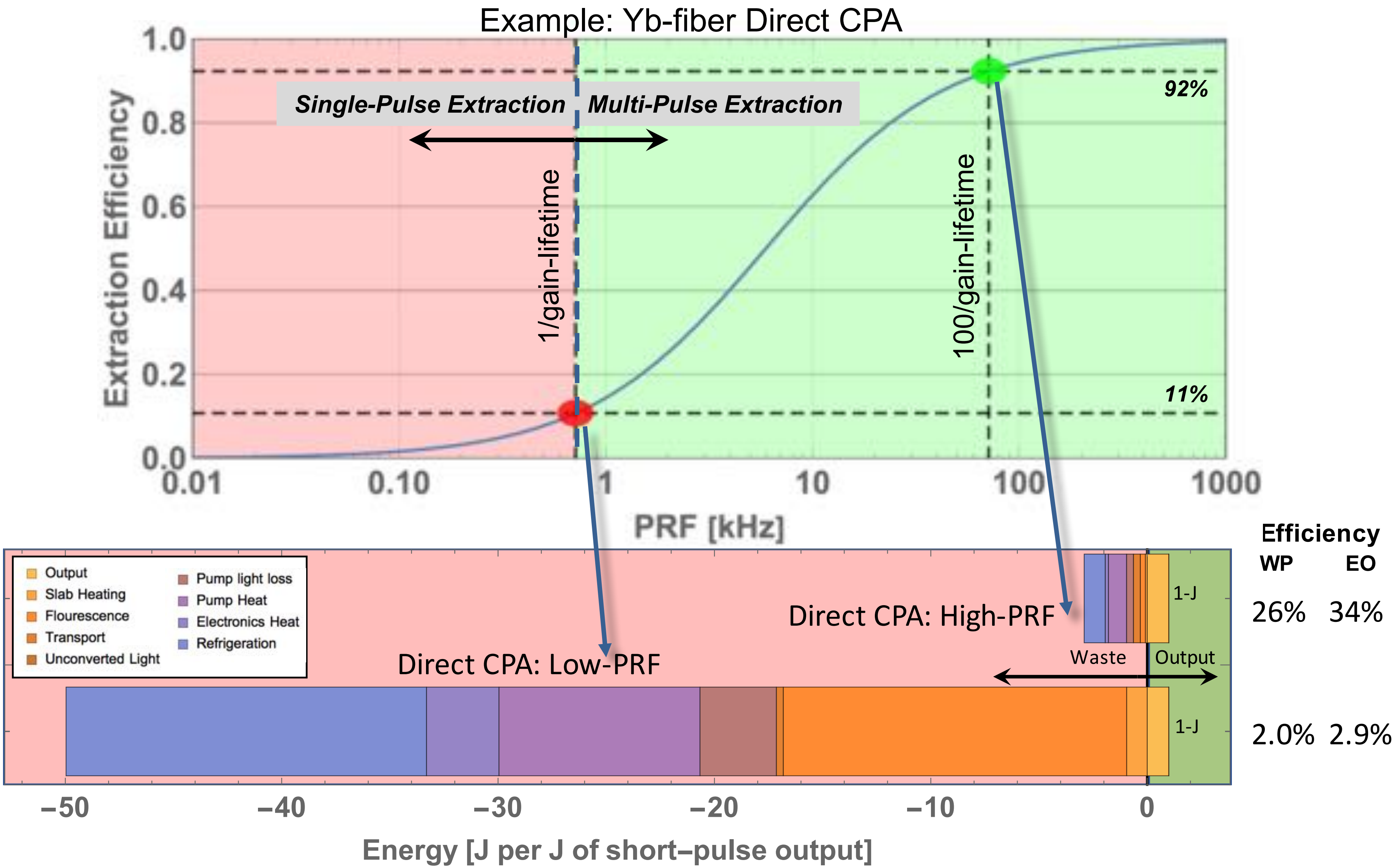
- LLNL is exploring avenues to break the kW barrier for high peak power lasers to drive high flux x-ray, ɣ-ray, and particle beams

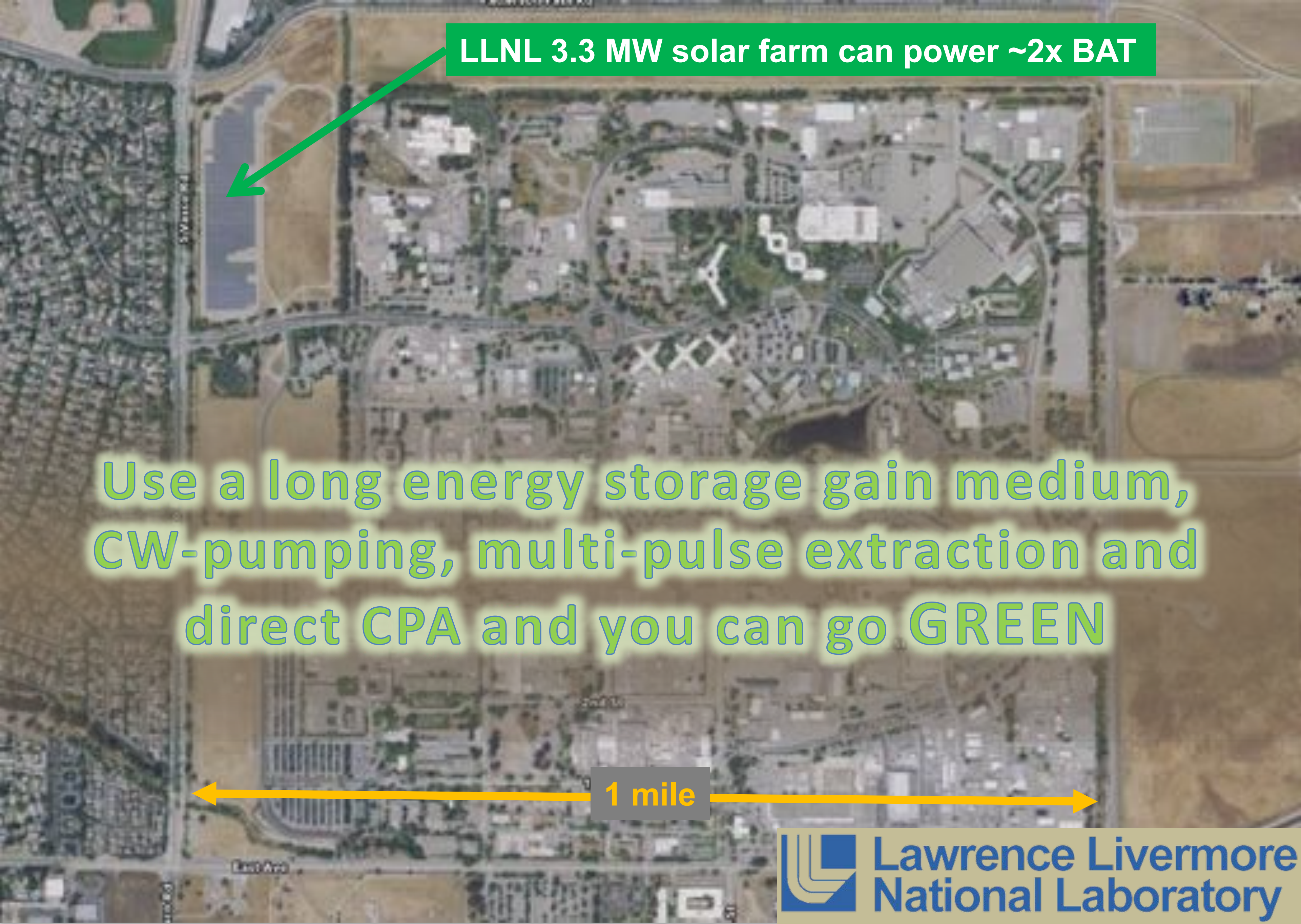
- Performed extensive architecture and material study. Crucially important for high average power lasers is high wall-plug efficiency: reduce heat (once heat is in it’s expensive and hard to pull it out) and heat effects (heating-cooling gradients cause beam deterioration, break stuff and limit average power)
  - Direct CPA increases dramatically the efficiency; beam quality and temporal pulse contrast require additional attention
  - Long radiative lifetime gain media become available through multi-pulse extraction at safe energy extraction fluencies
  - CW-pumping reduces massively the capital cost for high average power DPSSL



Diode pumping has a significant impact on system efficiencies, but direct CPA lasers with multi-pulse extraction and cw- pumping will have even greater impact on efficiency and system feasibility for laser-plasma accelerator applications

The repetition rate has a significant effect on the extraction and system efficiencies, depending on laser media




LLNL 3.3 MW solar farm can power ~2x BAT
Use a long energy storage gain medium, CW-pumping, multi-pulse extraction and direct CPA and you can go GREEN
1 mile
Lawrence Livermore National Laboratory

Summary

- We have developed a conceptual design for a single-aperture, 300 kW Thulium:YLF Petawatt-class laser **"BAT"** consistent with requirements for laser wakefield accelerators

- The underlying technology is a modest extension of established LLNL gas-cooling and rep rated Petawatt technologies

- BAT makes use of a highly simplified laser architecture, multi-pulse extraction of CW-diode pumped Tm:YLF and thus providing good wall-plug-efficiency

- We have developed a list of system TRLs and challenges that will inform the strategic plan for R&D and RTP efforts

System	Type	TRL Estimate	Integration Challenge	delivery horizon	E (J)	t (fs)	P_{av} (kW)	P_{peak}(PW)
HAPLS	DPSSL+TiS	7	Low	today	30	<30	0.3	1
SHARC	DP CPA Nd:Glass	6	Low	3yrs	150	150	1.5	1
Mini-BAT	DP CPA Tm:YLF	3-4	Medium	3-5yrs	3	40 or 100	3	.075
BAT	DP CPA Tm:YLF	3	Medium	5-7yrs	30	40 or 100	300	.75

NIF&PS

ADVANCED PHOTON TECHNOLOGIES

- Questions?
- Postdoc?
- Job?

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