Intense Lasers: High Average Power talk II
Development of Ultra Intense, High Average Power Lasers

Advanced Summer School on "Laser Driven Sources of High Energy Particles and Radiation"
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LLNL-PRES-737007

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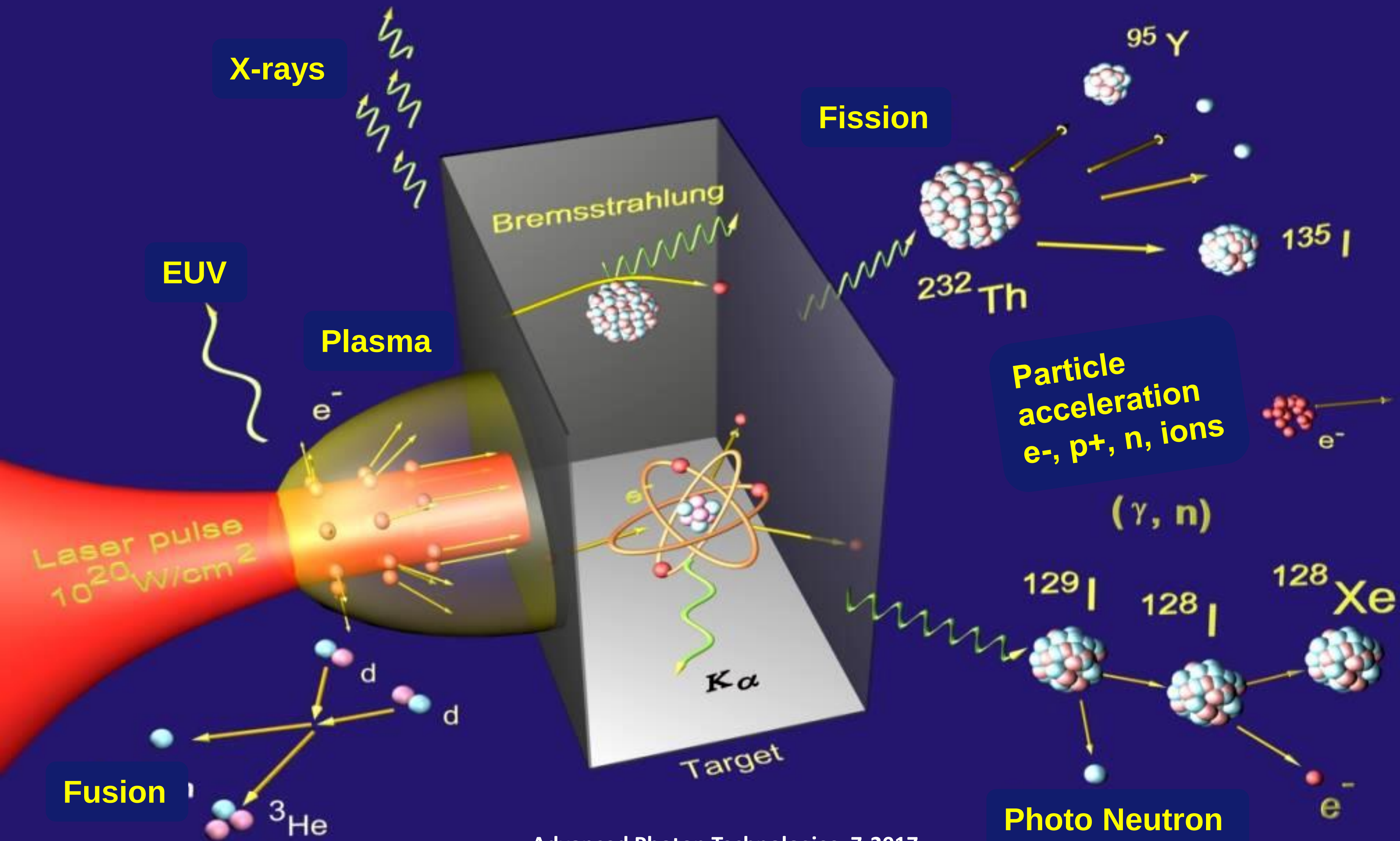
Amplification of Multiple Wavelengths (Broadband) typically needed for short pulse operation & secondary sources

Depiction of scientists who must amplify broadband radiation

Class #2

High intensity lasers operated at high average power are poised to have far reaching impact on industry, society, and science



X-rays

Fission

EUV

Plasma

Particle acceleration e-, p+, n, ions

Fusion

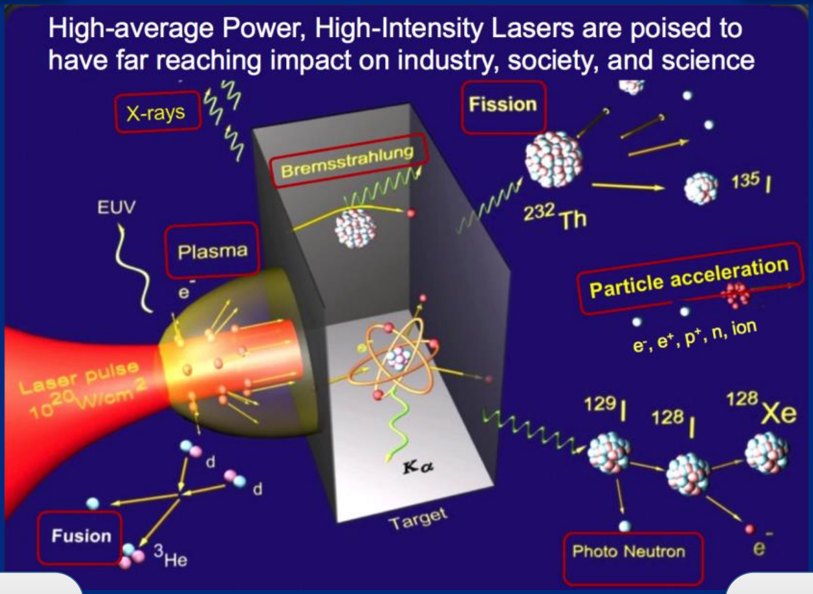
Photo Neutron

EUV Litography
Extending Moore’s Law

Medical
PET tracer, tomography

Inertial Fusion Energy
Enabling laser fusion power

HEDS / Materials Sci
Laboratory Astrophysics



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

SNM Detection
Nuclear Materials Security

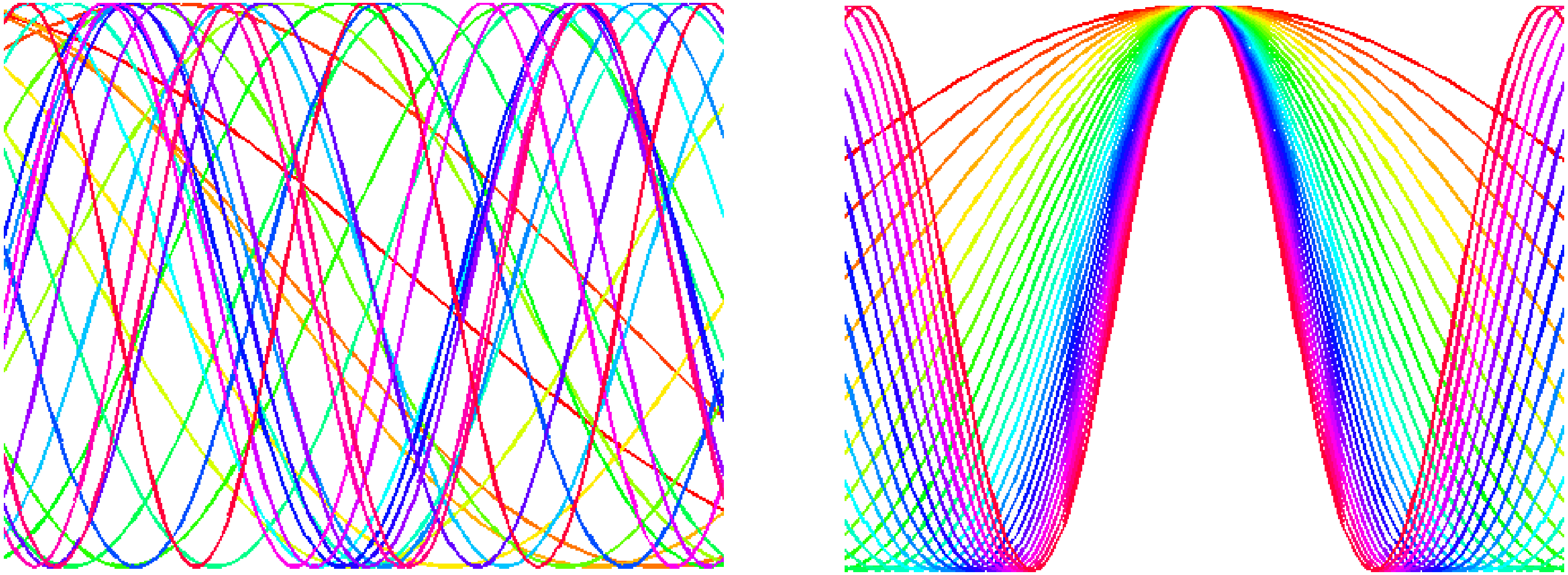
Accelerators
Compact laser based

Non-Destructive
Quality Assurance

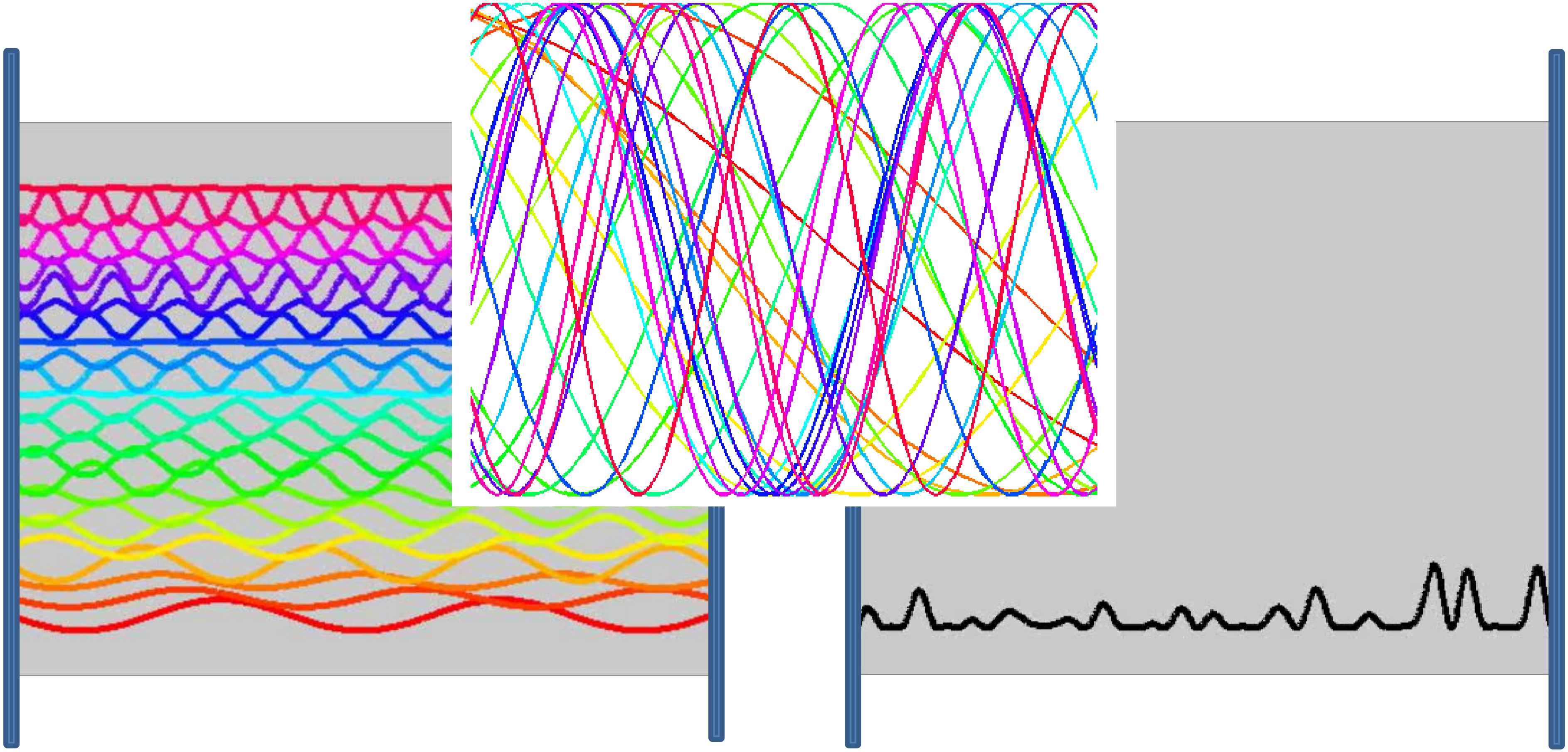
Industrial Processing
Taylor made properties

What do we need to make a short pulse?

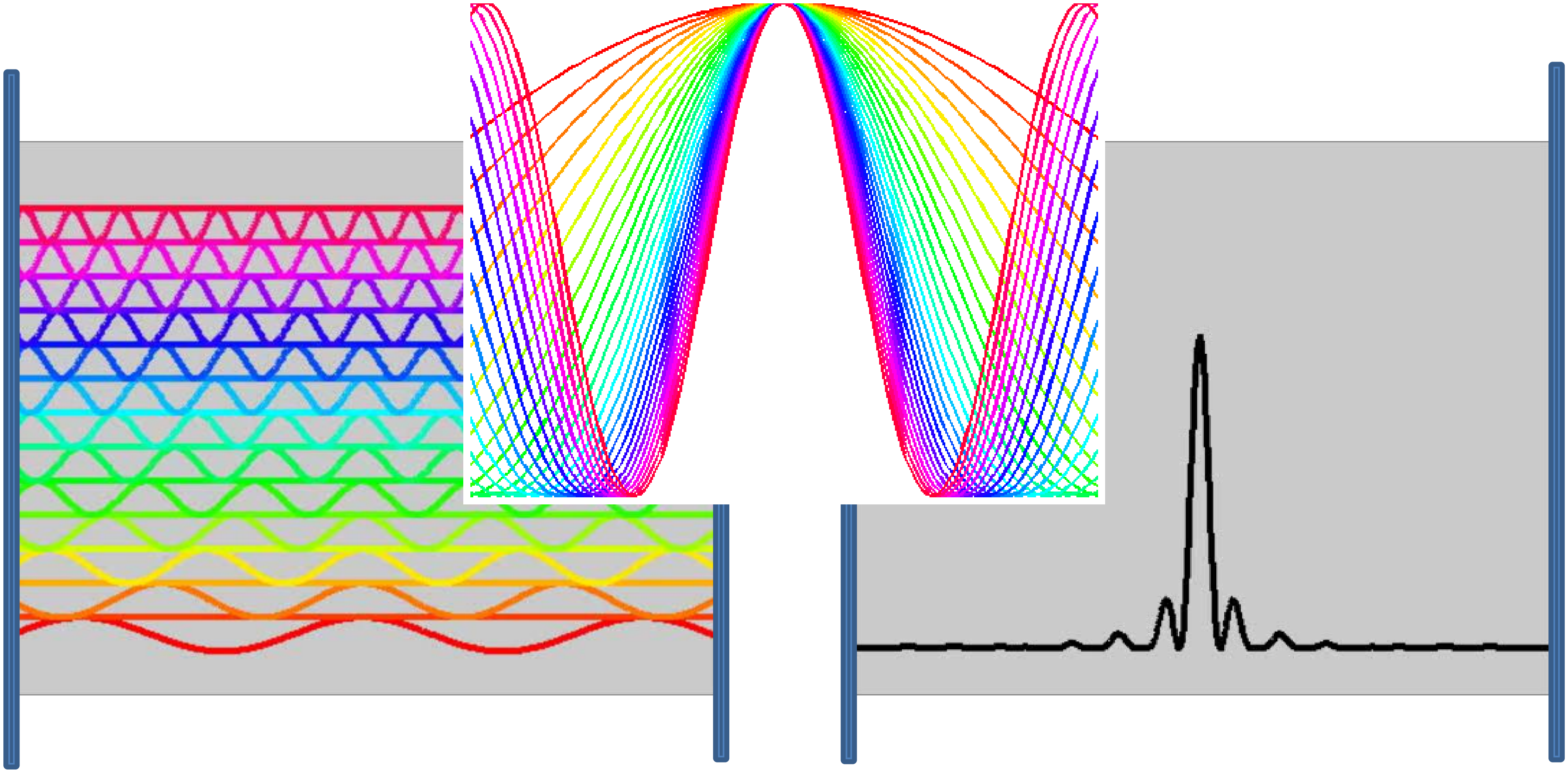
1. Broadband spectrum (many different colors of laser light)
2. Ability to “line up” all the waves



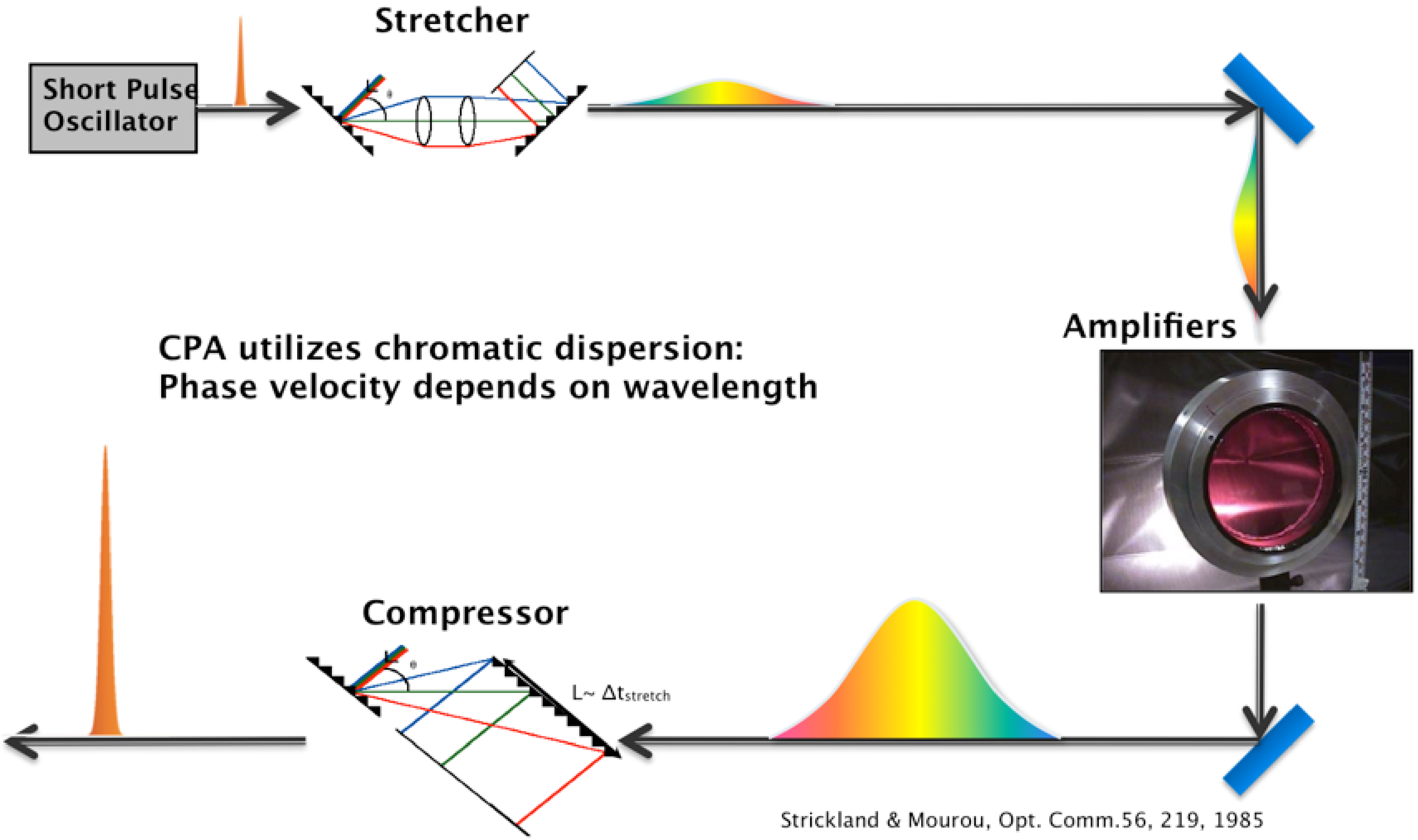
How does a free running broadband oscillator work with bandwidth?



How does a mode locked broadband oscillator work?



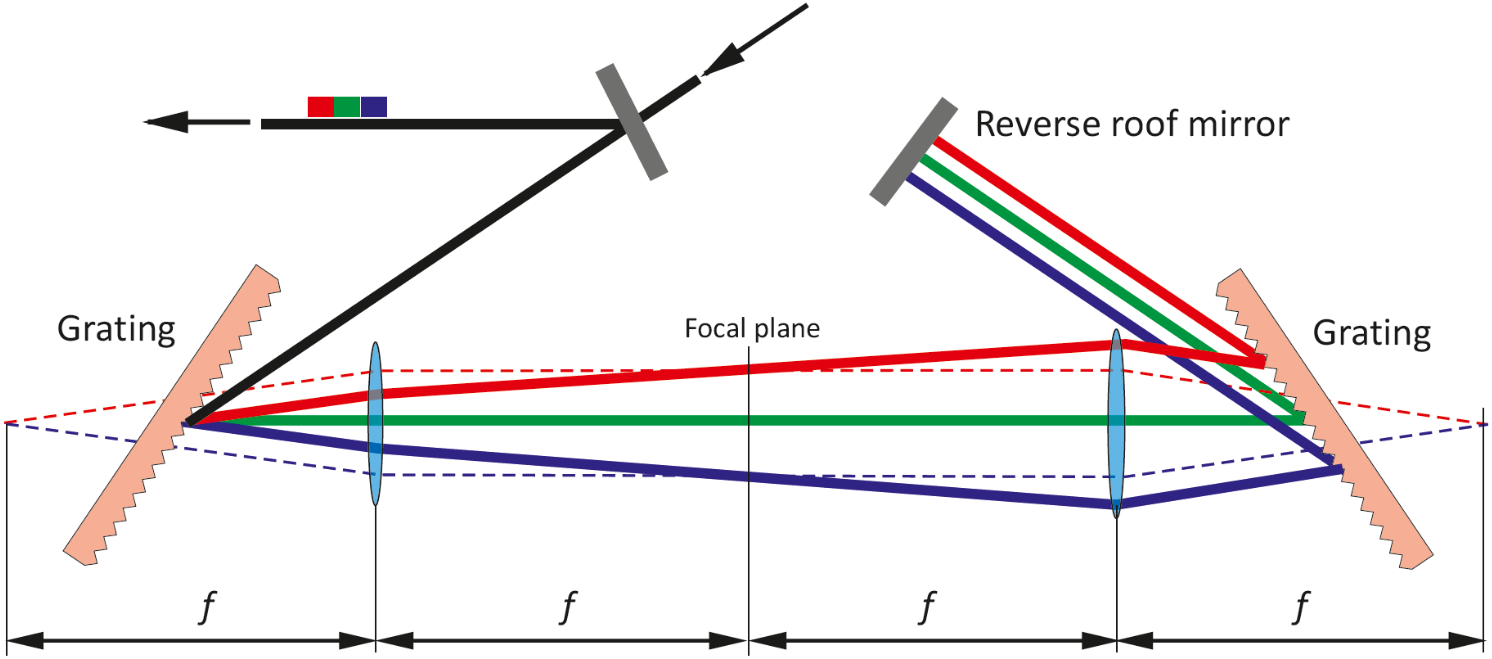
Amplifying Intense Ultrashort Laser Pulses



CPA utilizes chromatic dispersion:
Phase velocity depends on wavelength

Strickland & Mourou, Opt. Comm.56, 219, 1985

Nanosecond pulse stretcher - principle



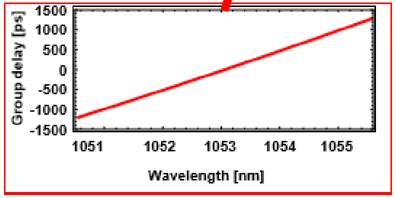
- **Telescope placed between compressor gratings effectively reverses the dispersion sign**
- **A number of stretcher designs developed: all-reflection solutions for pulses <50 fs**

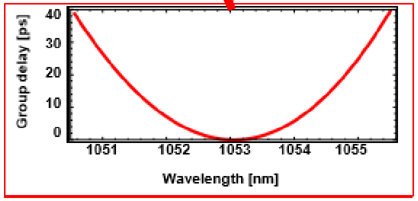
Group delay can be written as a Taylor Expansion of the spectral phase

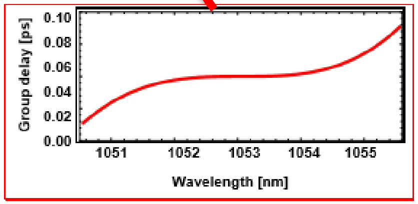
$$\tau(\lambda) = \frac{p \cdot Sec(\theta)}{1 + Cos\left(\theta - sin^{-1}\left(\frac{\lambda}{G} - Sin(\theta)\right)\right)}$$

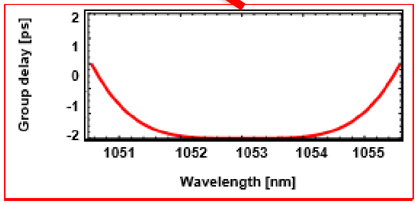
Group delay as a function of angle of incidence (θ), grating groove density (G), and grating distance (p), and ω= 2πc/λ

$$\tau(\omega) = \frac{\partial\varphi}{\partial\omega} + \overset{\text{GDD}}{\boxed{\frac{\partial^2\varphi}{\partial\omega^2}}}(\omega - \omega_0) + \frac{1}{2!}\overset{\text{TOD}}{\boxed{\frac{\partial^3\varphi}{\partial\omega^3}}}(\omega - \omega_0)^2 + \frac{1}{3!}\overset{\text{FOD}}{\boxed{\frac{\partial^4\varphi}{\partial\omega^4}}}(\omega - \omega_0)^3 + \frac{1}{4!}\overset{\text{QOD}}{\boxed{\frac{\partial^5\varphi}{\partial\omega^5}}}(\omega - \omega_0)^4$$









To obtain transform limited pulses the net group delay needs to cancel out over the laser bandwidth

$$\tau_{Stretcher} + \tau_{Compressor} + \tau_{PulseWidthController} + \tau_{Materialdispersion} = 0$$

Dispersion management in broadband laser systems

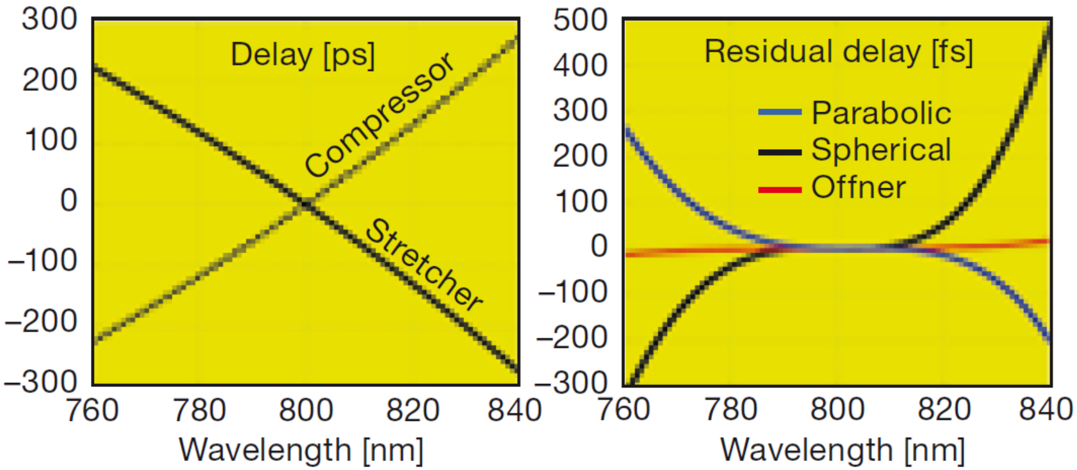
Goal:

Spectral dispersion introduced by Stretcher =

spectral dispersion by transmission optical elements +
spectral dispersion by reflective layers +
spectral dispersion by Compressor

Example:

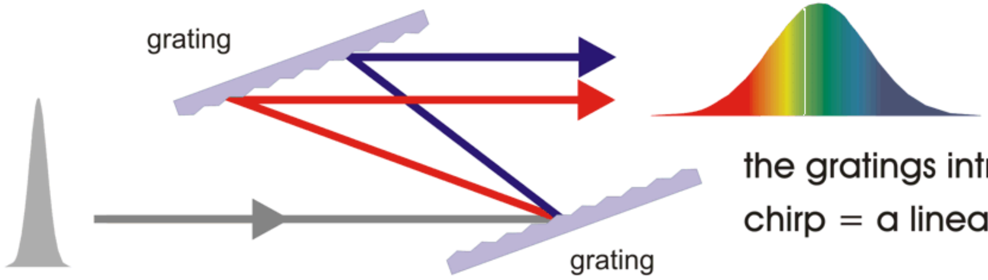
Delay introduced by one compressor and 3 different stretchers.



Residual delay from summing compressor + stretcher delays

from C.V. Filip, Computers at Work on Ultrafast Laser Design, Optics & Photonics News, May 2012

Grating compressor: ns to fs pulses

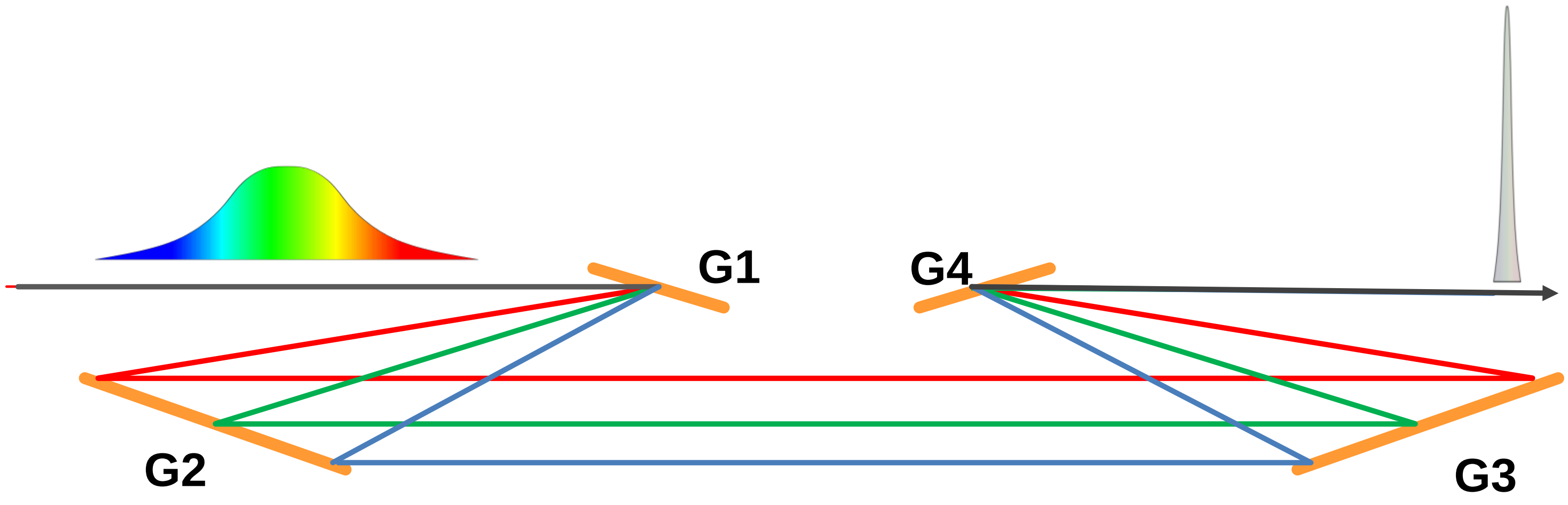


Carrier frequency:
$\omega=\omega_0+\beta t$

the gratings introduce a frequency dependent time delay

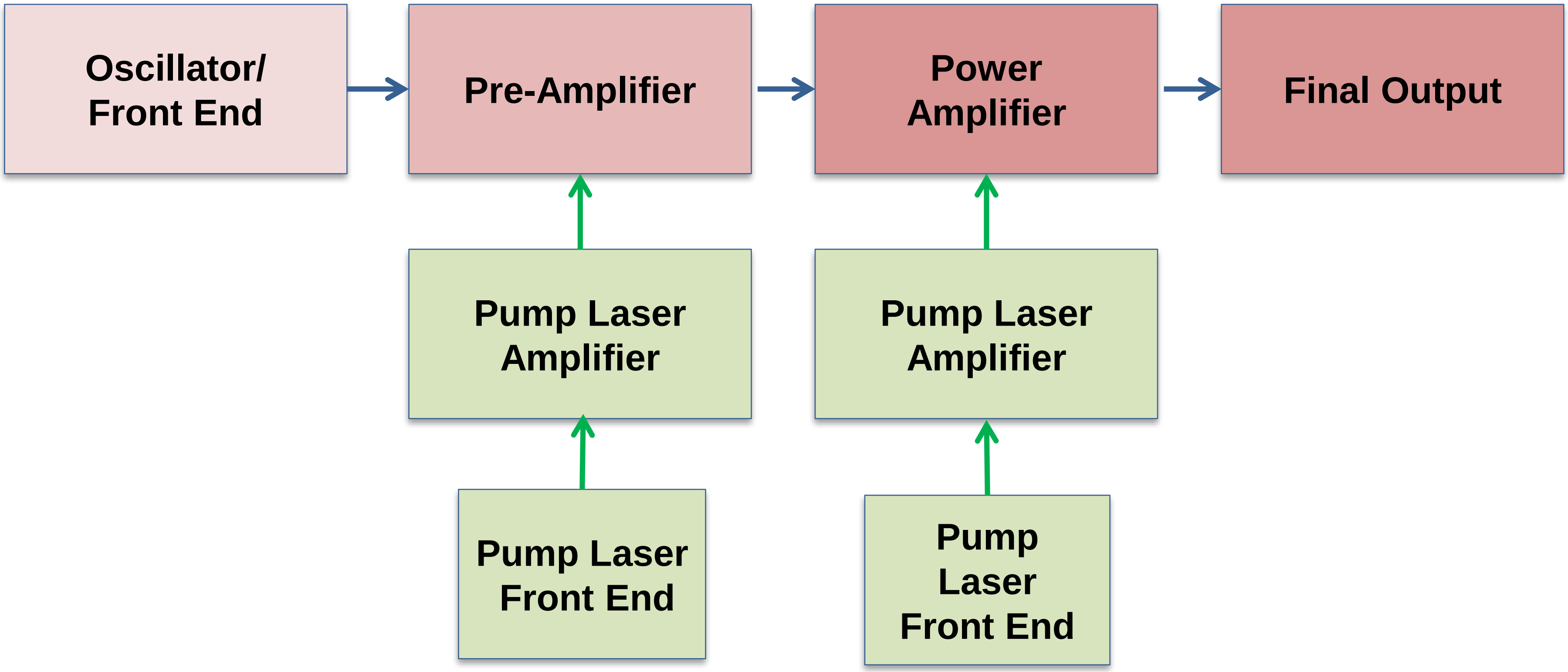
chirp = a linear frequency sweep, $d\omega/dt$

The "blue" frequency component appears ahead of the "red" component = NEGATIVE CHIRP



E.B. Treacy, Optical Pulse Compression With Diffraction Gratings, IEEE J. Quant. El., Vol QE-5, pp. 454-458 (1969)
O.E. Martinez, IEEE J. Quantum Electron. **QE-23**, 59 (1987)

A Typical Ultra-intense Laser Architecture



Oscillator/ Front End

Pre-Amplifier

Power Amplifier

Final Output

Pump Laser Amplifier

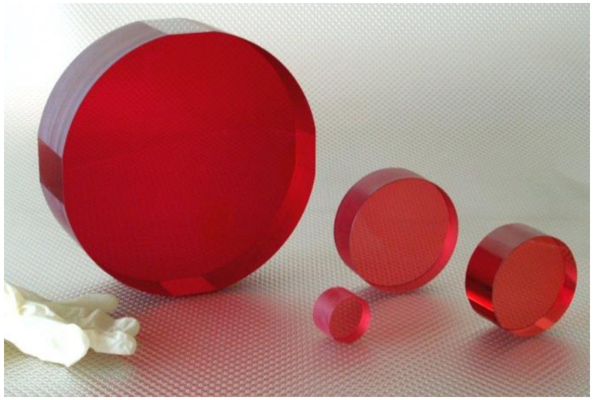
Pump Laser Amplifier

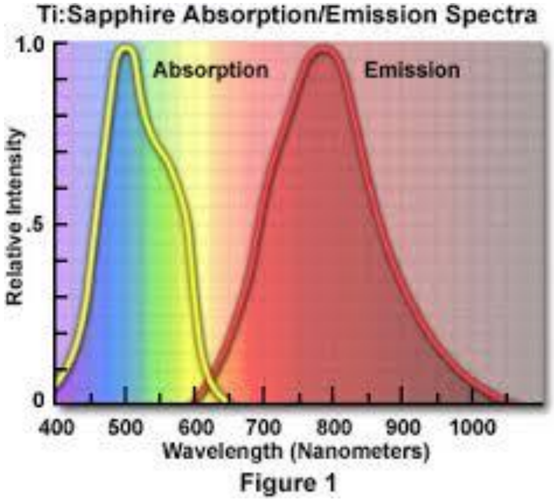
Pump Laser Front End

Pump Laser Front End

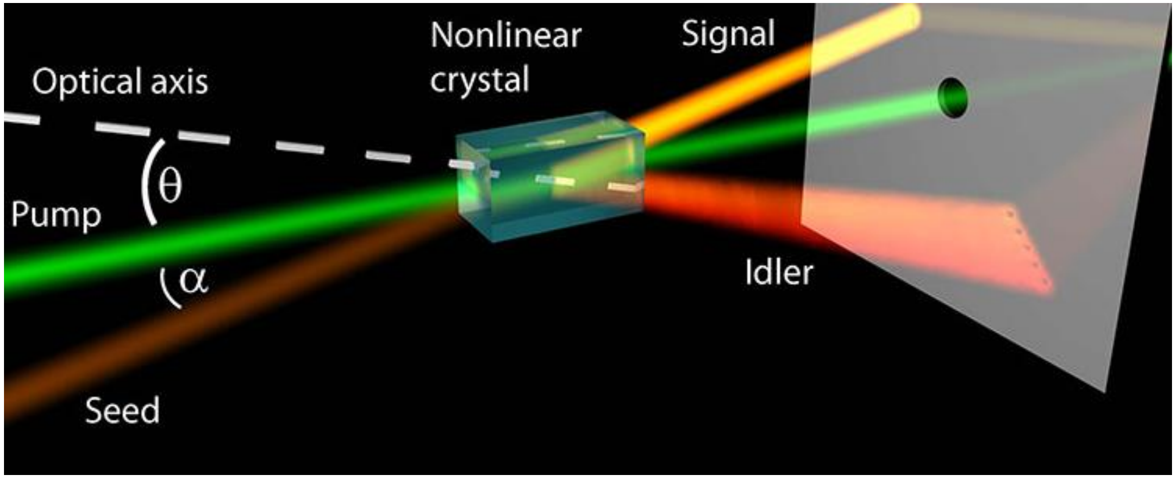
Broadband laser amplifiers

Ti:sapphire





OPCPA



Remember from talk 1: High-efficiency strategy – still applies with some adjustments

- Any energy that does not become laser light is ultimately heat that must be removed.
  - Even diode pumped laser systems which have high efficiency operate between 3-20% efficiency – that is still a lot of heat
- Minimize decay losses during the pumping process
  - Use cladding and smaller apertures smaller to reduce amplified spontaneous emission loss
- Use a pump profile with a high fill factor that gain-shapes the extracting beam
- Absorb nearly all the pump light
- Extract nearly all the available stored energy

  \- Operate at fluences well above the saturation fluence
- Multipass the extracting beam
- Keep passive optical losses low
- Relay the beam to the middle of each amplifier to minimize edge losses

New issues specific to short pulse require extremely detailed design and attention during commissioning to meet performance requirements

- **Contrast is important to deliver energy for secondary sources**

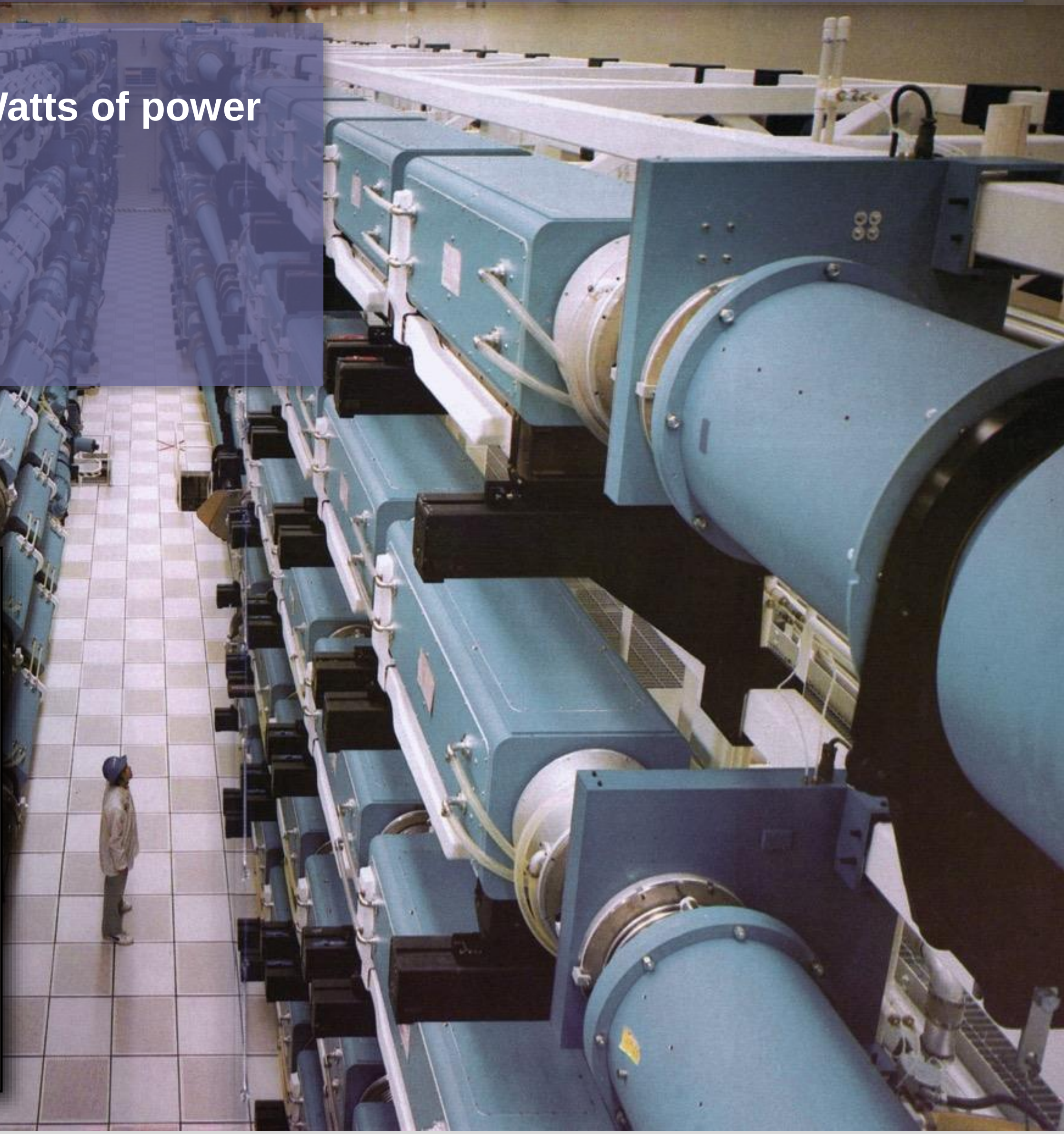
  Example: Assume you have a petawatt laser system which is easily capable of 10^21 W/cm2 for use in secondary source generation.
    - **A beam with 10^10:1 contrast (difficult) still has prepulse of 10^12 W/cm2 which is enough to vaporize solid targets.**
      - **Need > 10^11:1 – very difficult**
    - **Gratings, stretcher optics, transmissive optics, mirror surfaces, amplifier spontaneous emission, and even quantum noise sets the limit on background and prepulse contrast.**
    - **Every surface, material must be carefully managed to avoid these problems**

- **Nonlinear phase accumulation or B-integral:**
  - **Long pulse limit was ~2 rad.**
  - **Short pulse system limits more like ~1 radian.**
  - **Issue is nonlinear phase shifts colors around within the pulse messing up the chirp.**
  - **Since B is intensity dependent any intensity spatial nonuniformity will result in spatially non uniform chirp which is not correctable**
  - **B integral also transfers energy from post pulse to pre-pulse where it becomes a contrast issue.**

1996: LLNL Demonstrates First Petawatt Laser: 600 J, >1 PW

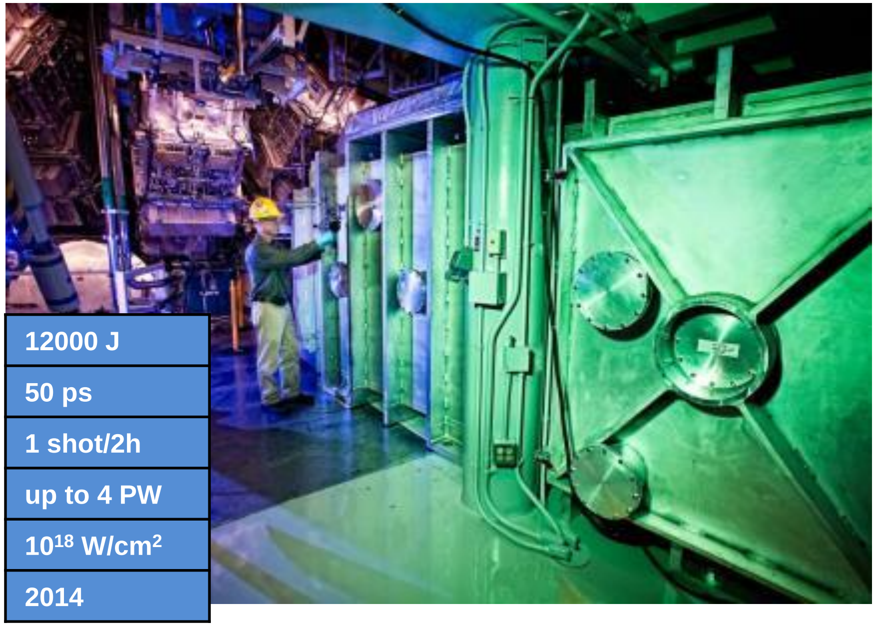
Petawatt discoveries:

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



Two major high intensity petawatt laser projects at LLNL

Advanced Radiographic Capability (ARC)

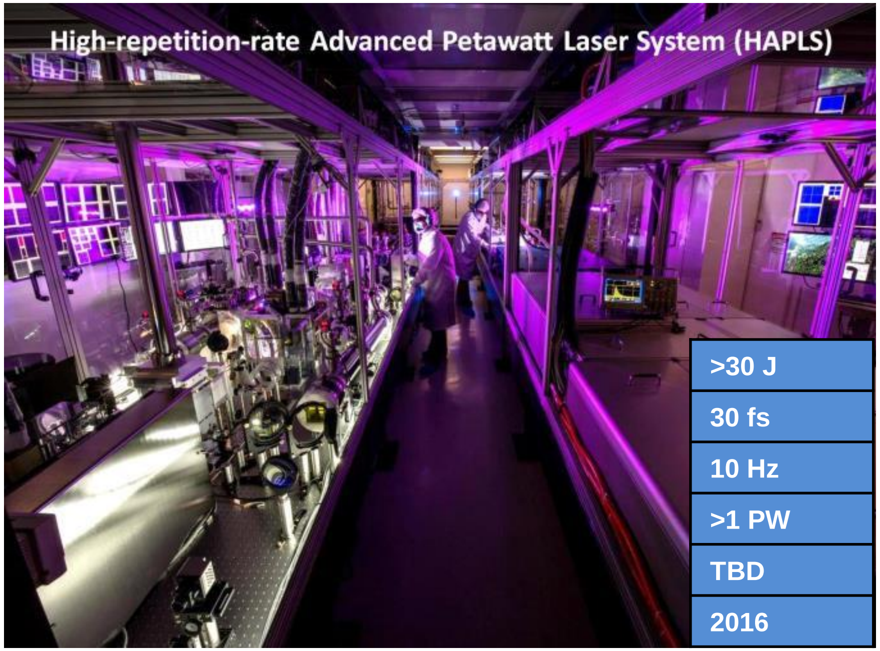


- 12000 J
- 50 ps
- 1 shot/2h
- up to 4 PW
- 10^{18} W/cm^2
- 2014

World's most energetic Petawatt laser

12,000 J in 10 ps, 1 shot/2 hours

High repetition-rate Advanced Petawatt Laser System (HAPLS)



- >30 J
- 30 fs
- 10 Hz
- >1 PW
- TBD
- 2016

World's highest rep-rate Petawatt laser (10 Hz)

30 J in 30 fs, 10 shots/second

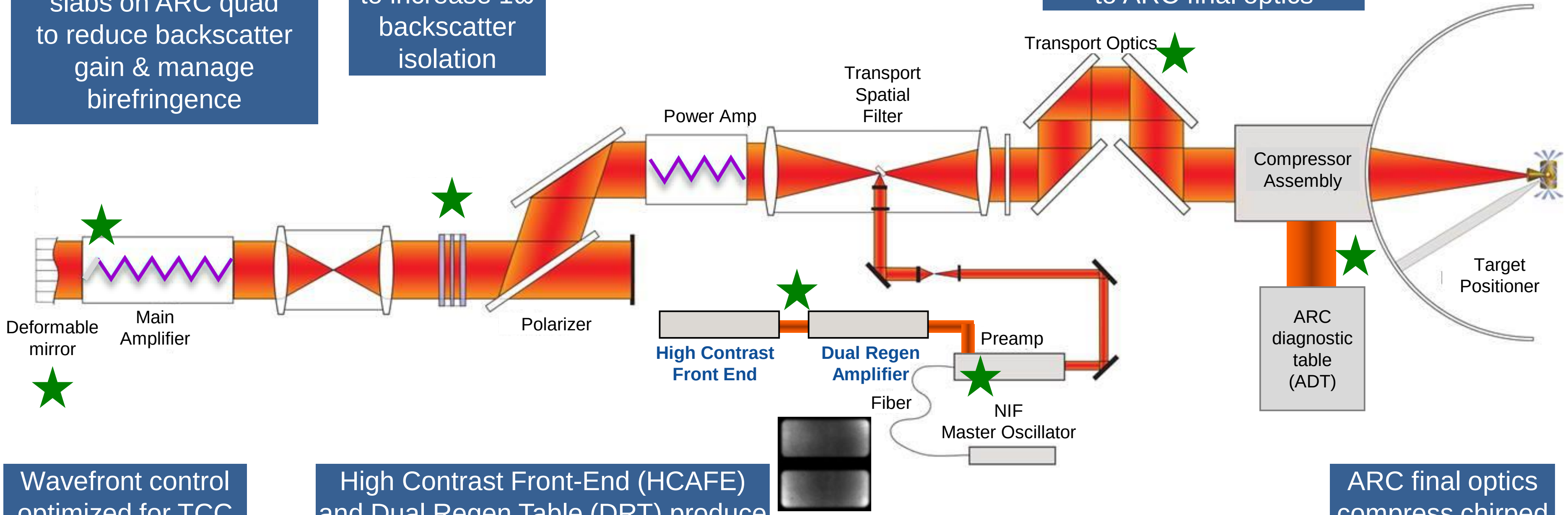
1 Petawatt = 10^{15} Watts = 1,000,000,000,000,000 Watts

Modifications to the NIF quad (Q35T) are required to protect NIF & ARC components, optimize ARC performance and permit changing from NIF to ARC during automated shots

Replace Nd slab with polarizer reduces # of slabs on ARC quad to reduce backscatter gain & manage birefringence

Triple pulse PEPC to increase 1ω backscatter isolation

ARC/NIF pick-off mirror switches beams from NIF to ARC final optics



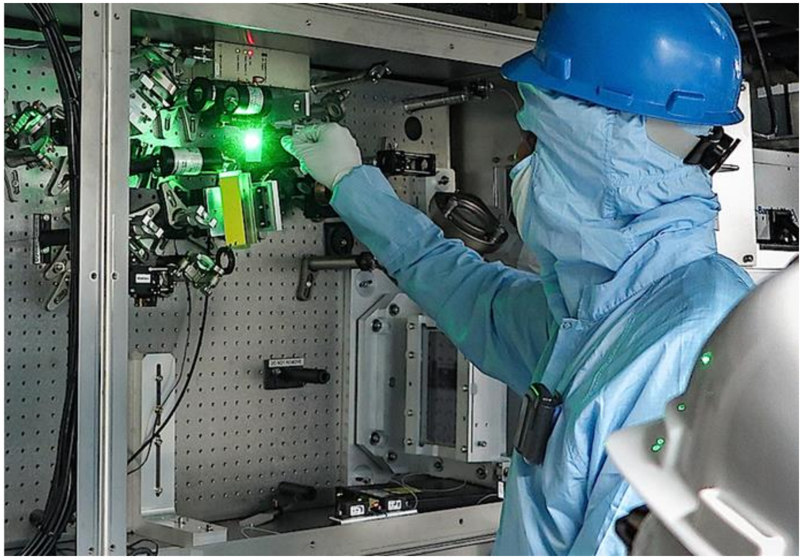
Wavefront control optimized for TCC focus using target in the loop (TIL) software

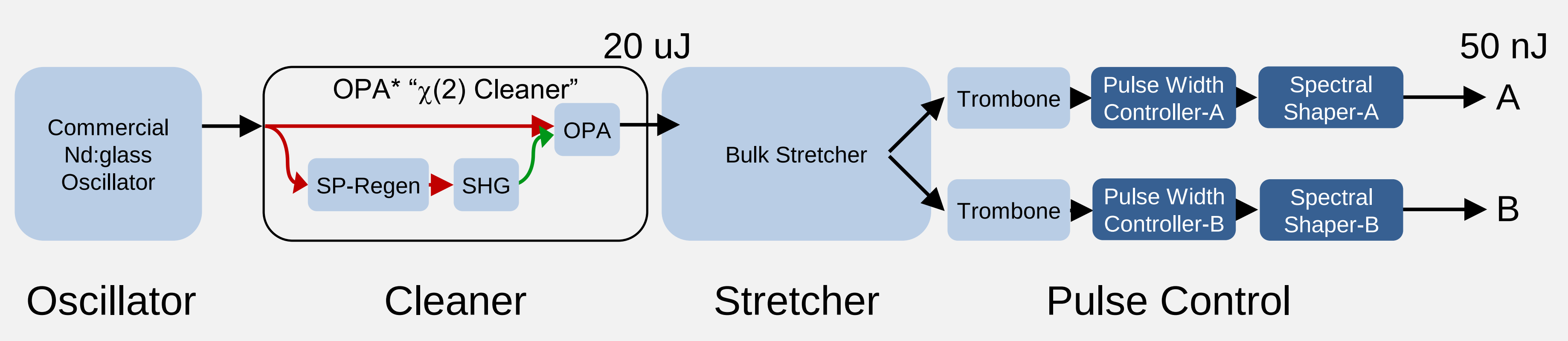
High Contrast Front-End (HCAFE) and Dual Regen Table (DRT) produce 2 beamlets that can be independently timed and each match the group delay of the 2 different compressors

A half waveplate in the preamp is inserted/removed to switch between ARC & NIF

ARC final optics compress chirped pulses and focuses beamlets to TCC

The High Contrast ARC Front End (HCAFE) uses short pulse OPA technology* to produce high temporal contrast





20 uJ

50 nJ

Commercial Nd:glass Oscillator

OPA* “χ(2) Cleaner”

OPA

SP-Regen

SHG

Bulk Stretcher

Trombone

Pulse Width Controller-A

Spectral Shaper-A

A

Trombone

Pulse Width Controller-B

Spectral Shaper-B

B

Oscillator

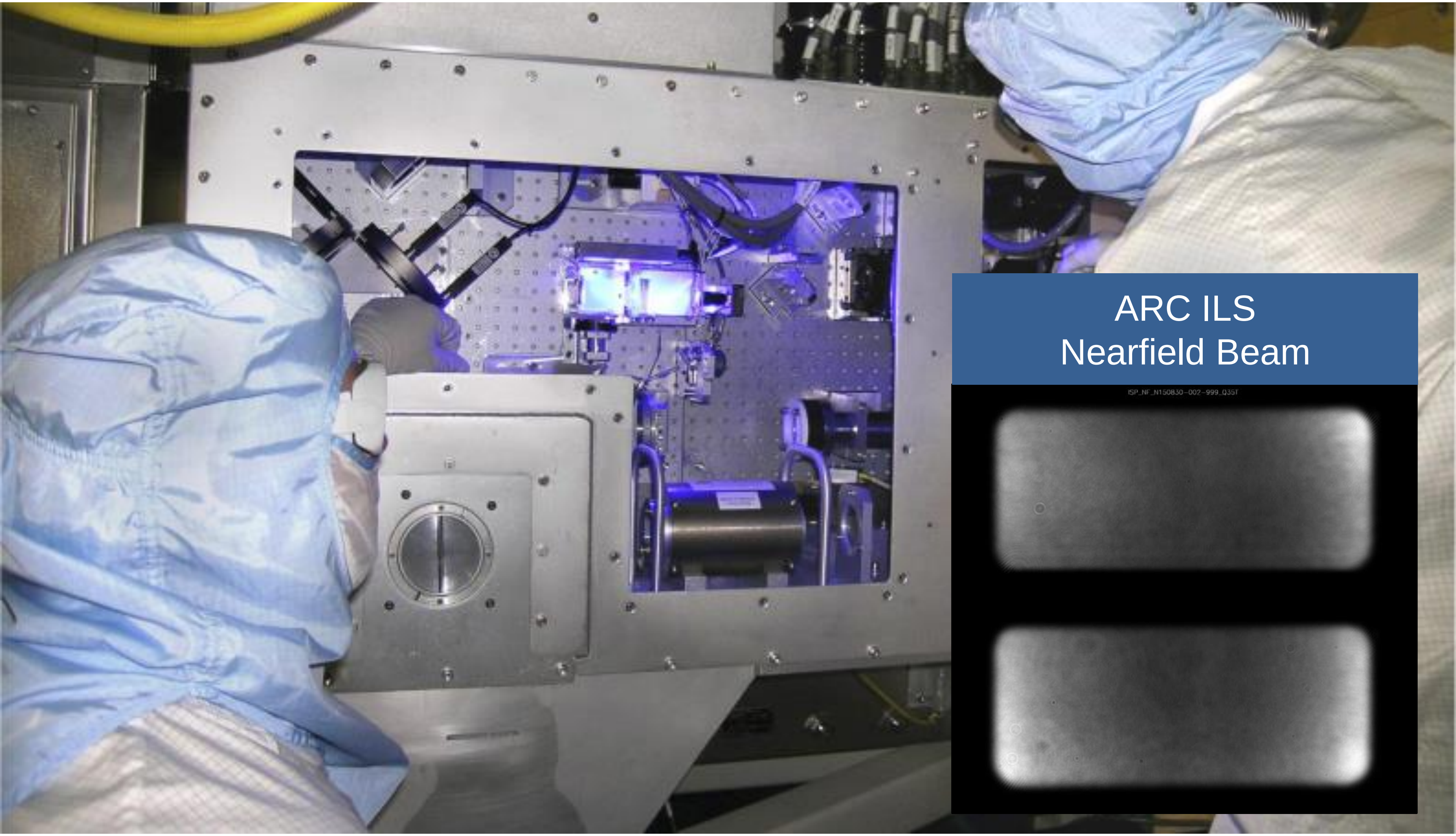
Cleaner

Stretcher

Pulse Control

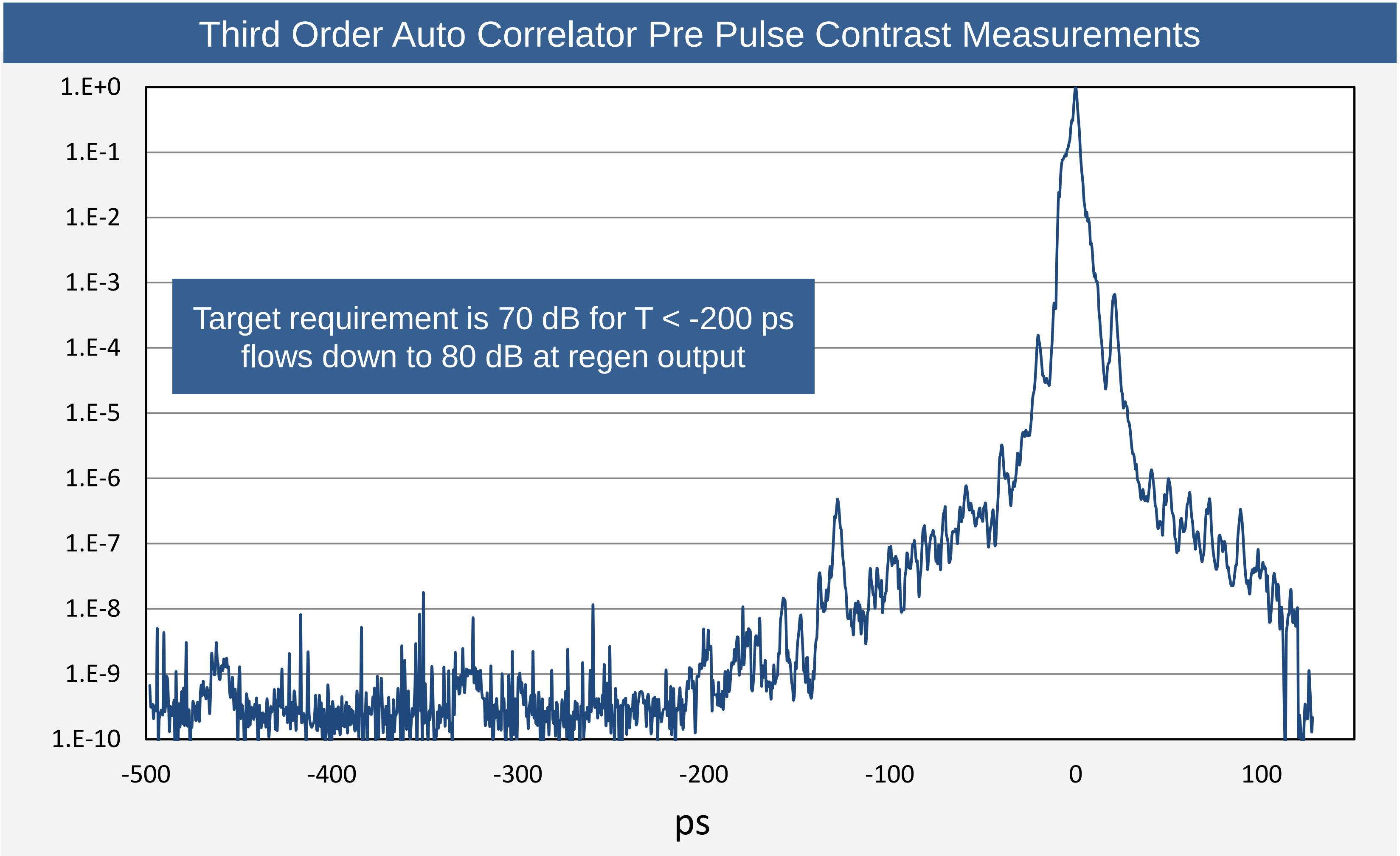
***Based on LLE Omega EP front-end OPA (C. Dorrer, et al., CLEO 2011)**

The dual regens (DRT) & split beam injection (SBI) produce 2 beamlets that can be independently timed



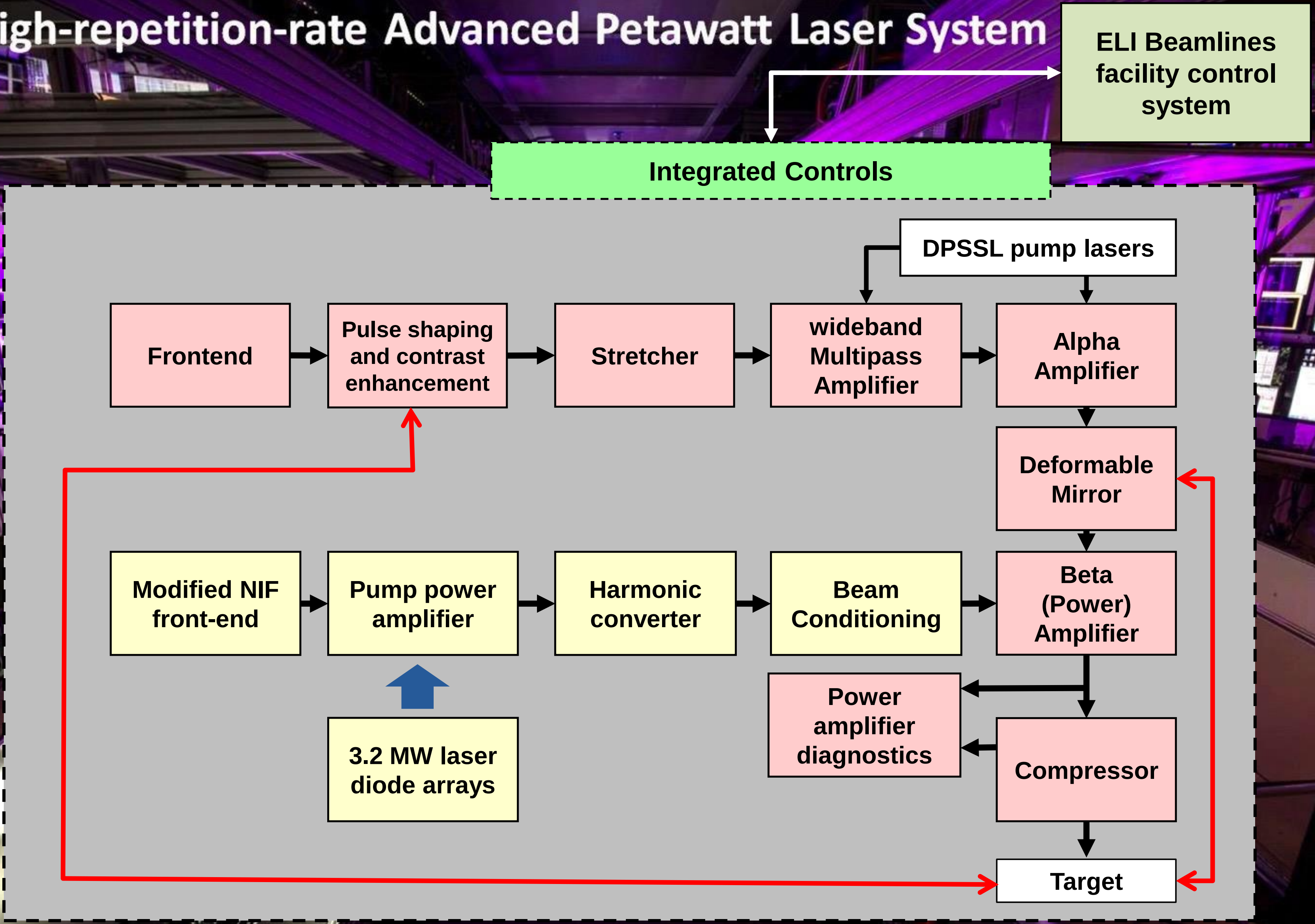
ARC ILS
Nearfield Beam

The High Contrast Front End output meets prepulse contrast requirement of 80 dB for t < -200 ps



Target requirement is 70 dB for T < -200 ps flows down to 80 dB at regen output

High-repetition-rate Advanced Petawatt Laser System


ELI Beamlines facility control system

Integrated Controls

DPSSL pump lasers

Frontend

Pulse shaping and contrast enhancement

Stretcher

wideband Multipass Amplifier

Alpha Amplifier

Deformable Mirror

Modified NIF front-end

Pump power amplifier

Harmonic converter

Beam Conditioning

Beta (Power) Amplifier

3.2 MW laser diode arrays

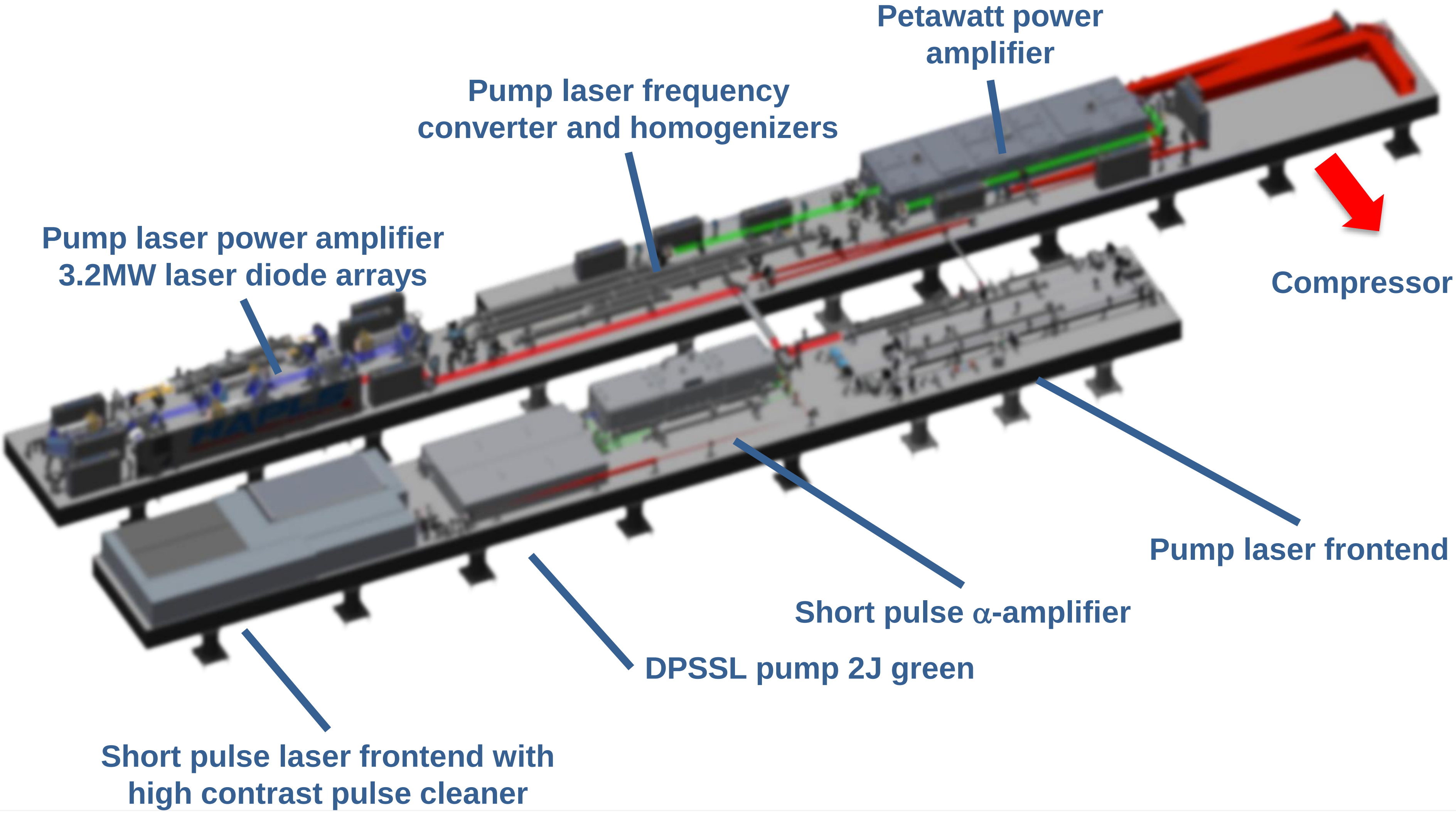
Power amplifier diagnostics

Compressor

Target

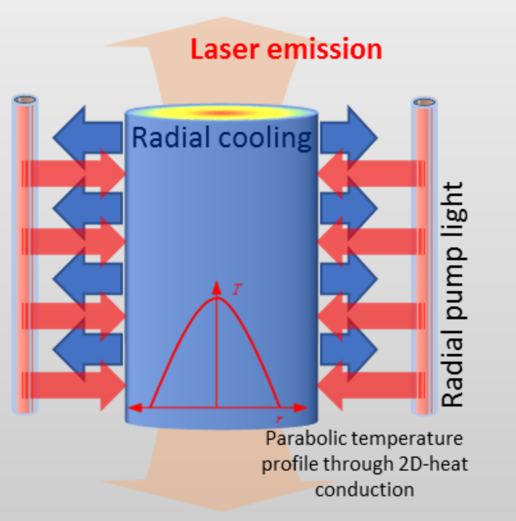
10 Hz rep rate allows adaptive feedback enabling highest intensities

HAPLS Petawatt System is compact and has a 17m x 4.6 m footprint



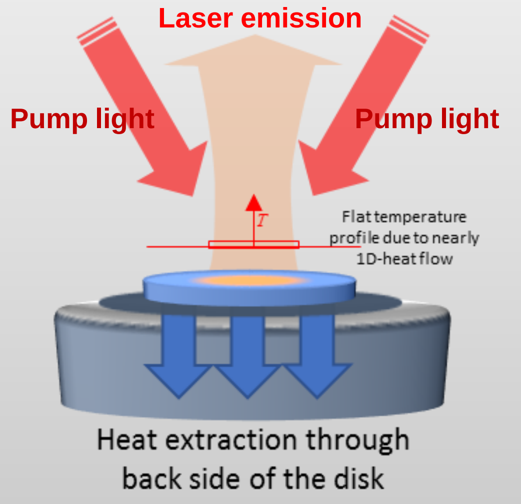
Heat can be extracted through the “edge” or the “face”

Rod amplifiers



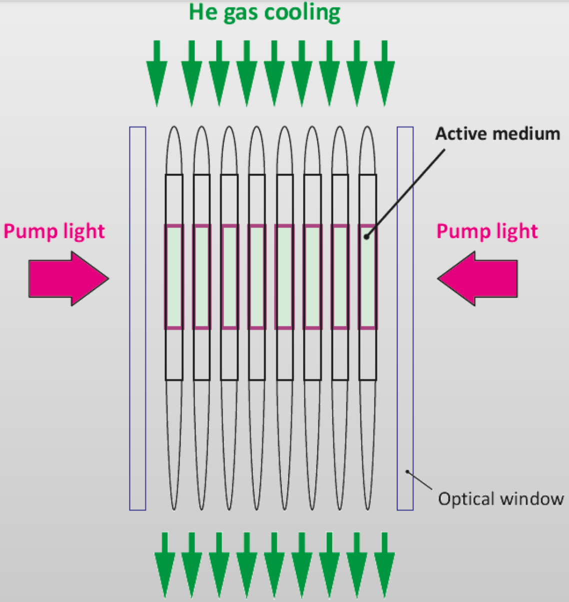
- Conductive cooling through edges
- Stress orthogonal to laser beam
- High energy storage

THIN DISK: “active mirror”



- Conductive cooling through back side
- Stress parallel to laser beam
- Low energy storage

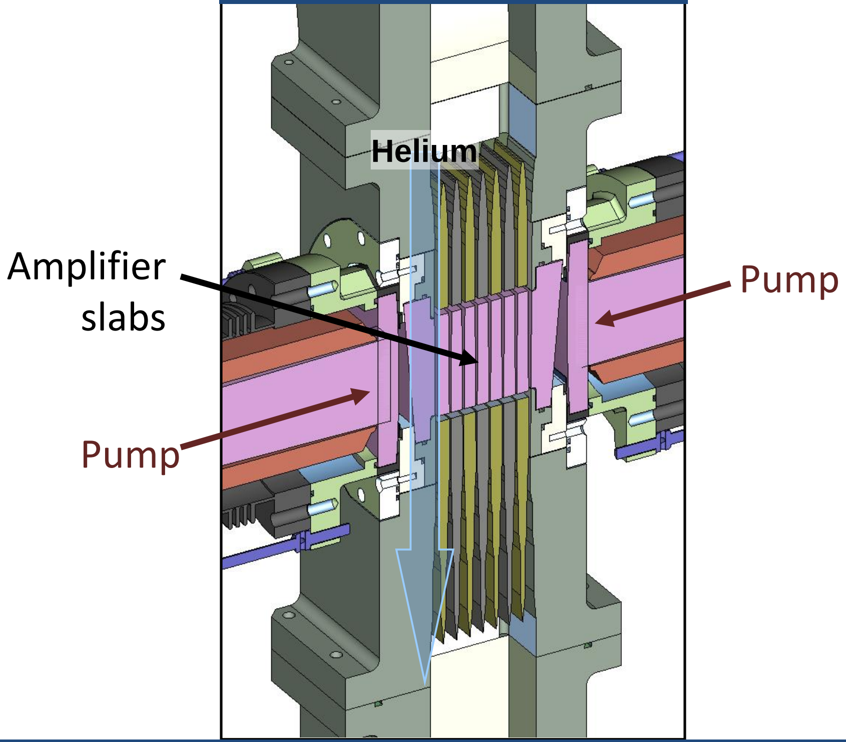
multislab-face-cooling



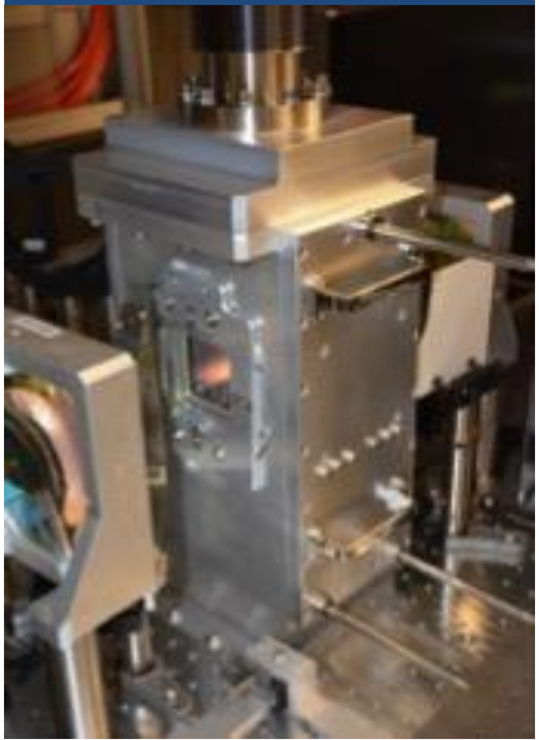
- Conductive/convective cooling with liquid (National Energetics) or Helium gas (LLNL, RAL)
- Stress parallel to laser beam
- High energy storage

LLNL’s HAPLS Laser slabs are cooled by rapidly flowing, room temperature He-gas

Gas-cooled amplifier prototype



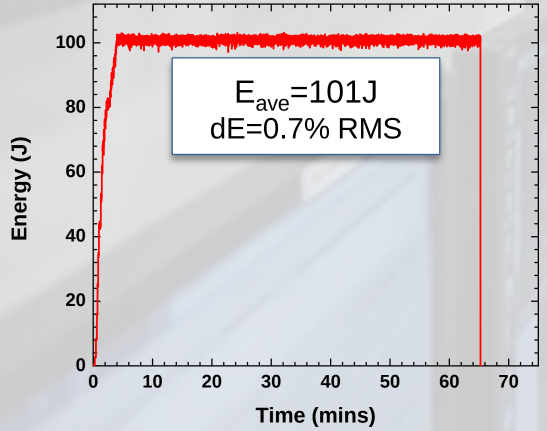
HAPLS production Amplifier Assembly



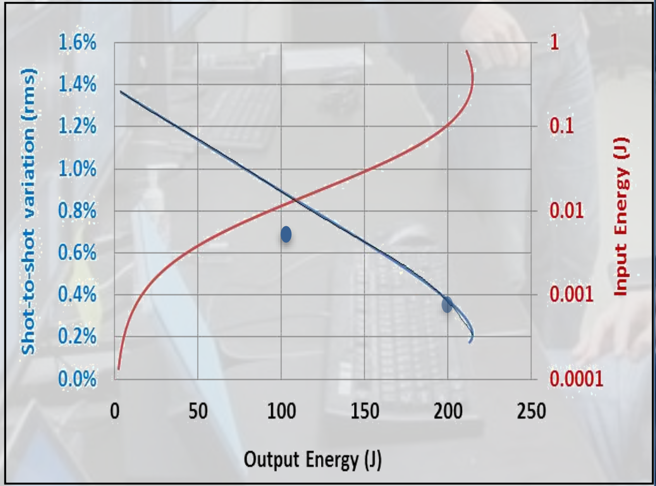
- Face cooled Nd:Glass slabs
- Room temperature Helium gas coolant
- Gas acceleration vanes Mach 0.1
- Cooled ASE Edge claddings

Today the HAPLS pump laser delivers continuously >100J at 3.3Hz, energy stability 0.7%RMS, and no optical damage

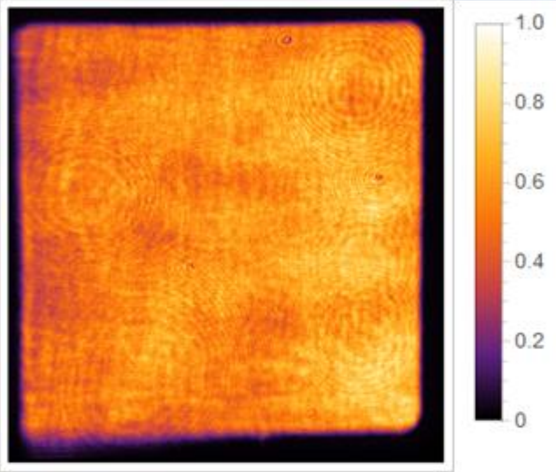
Continuous 1hr run delivering 100Joule pulses at 340W



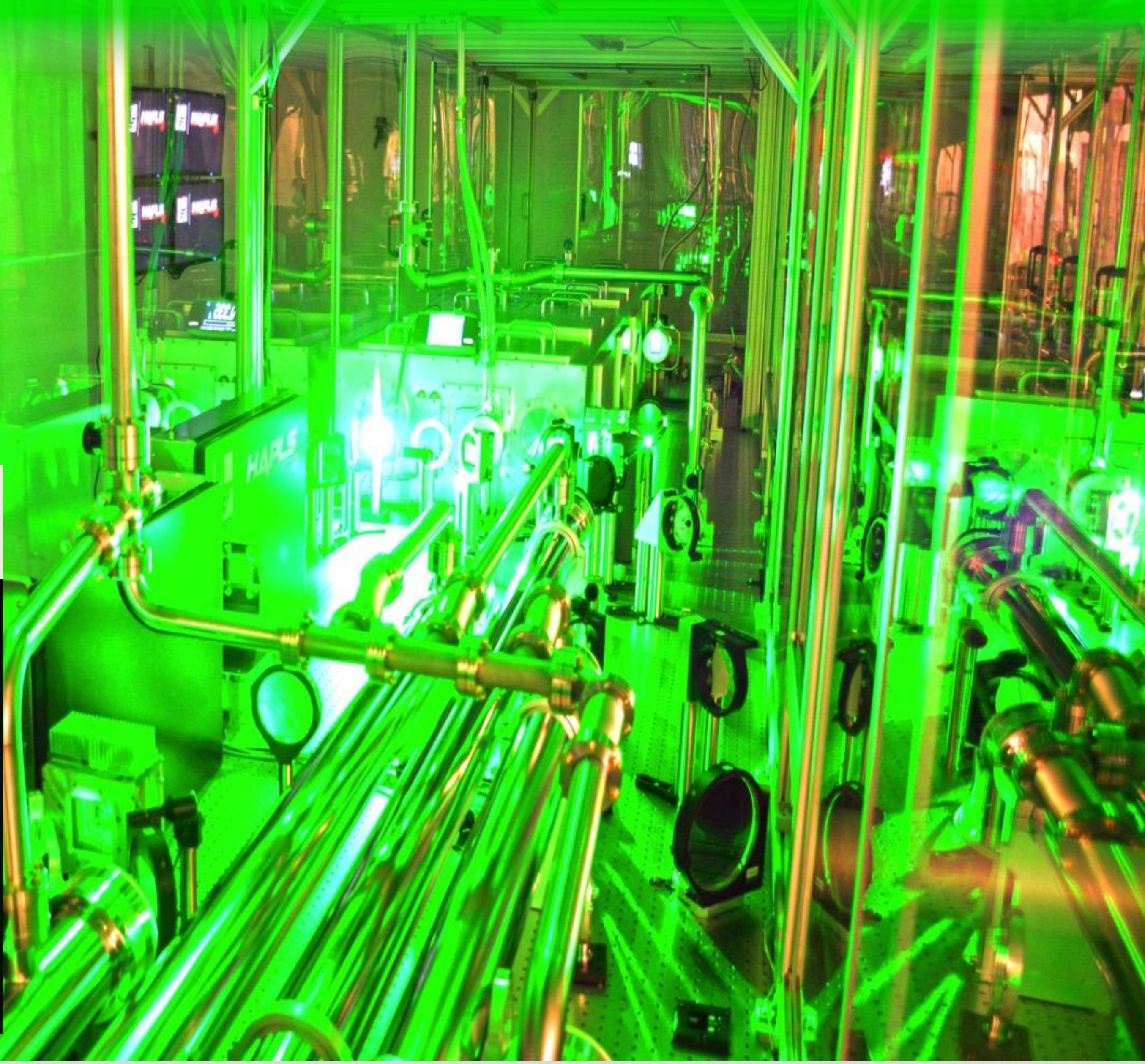
Energy stability scales with output energy. Predicted <0.35% @ 200J



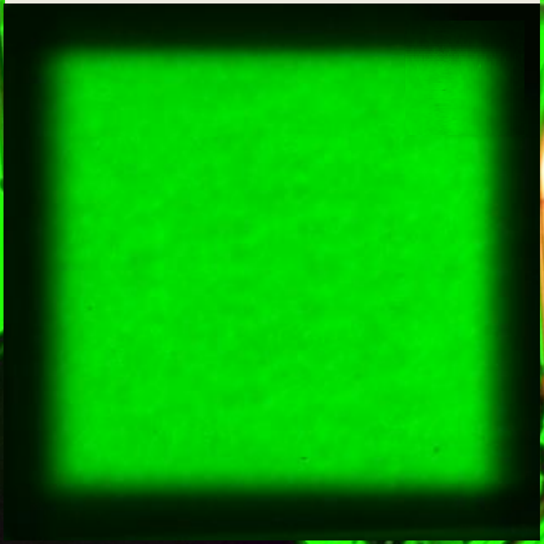
Output beam profile



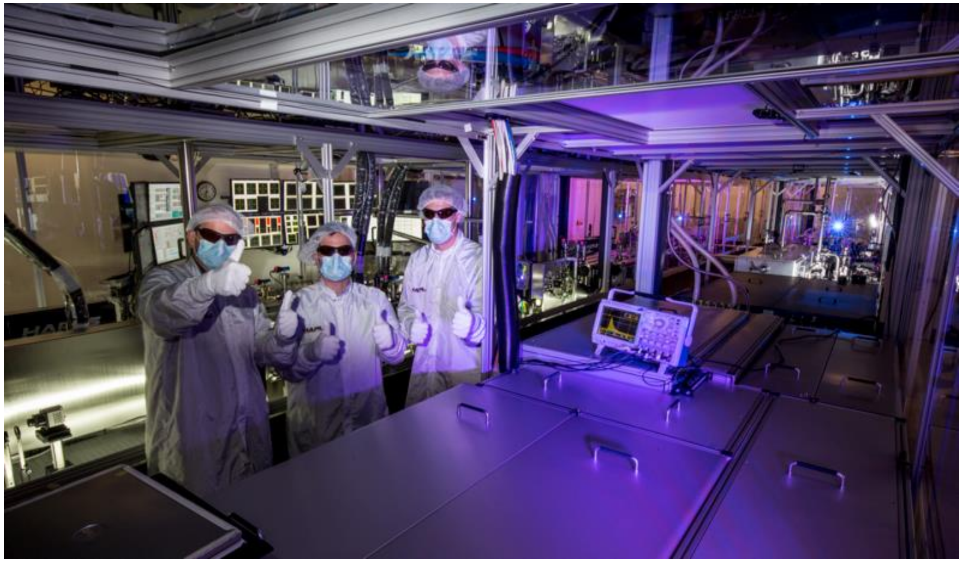
Today HAPLS delivers 80J of second harmonic light



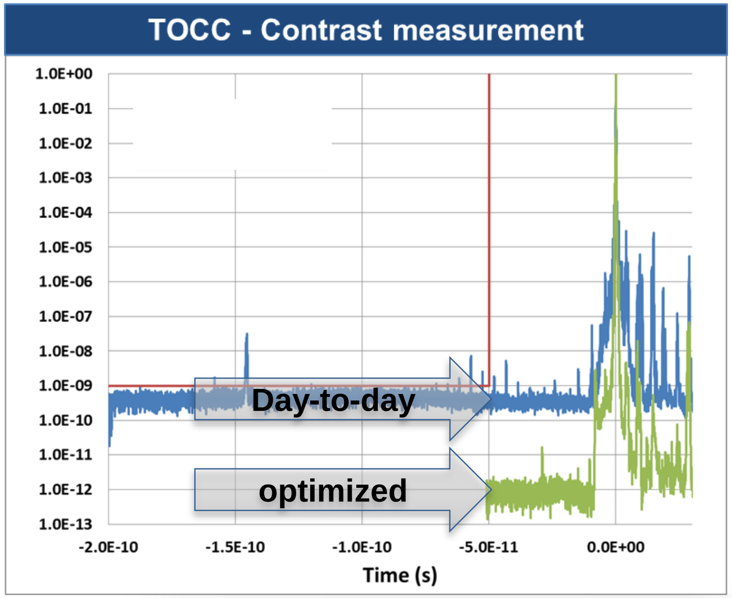
Pump Profile at Beta Amplifier



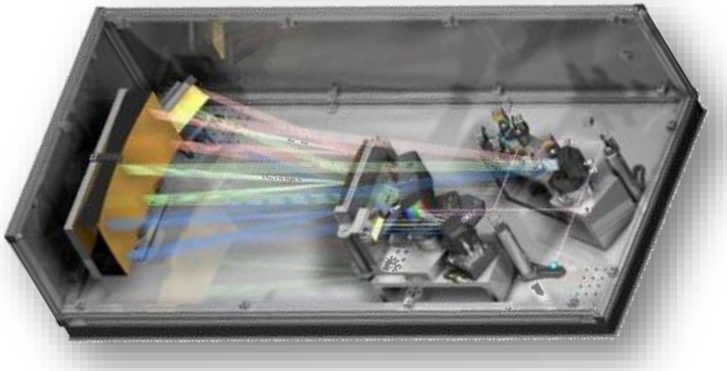
The commercial short pulse front end provides a robust, turn-key stretched-pulse seed to HAPLS short pulse beamline



The last time the SPFE system required manual alignment was >12months ago

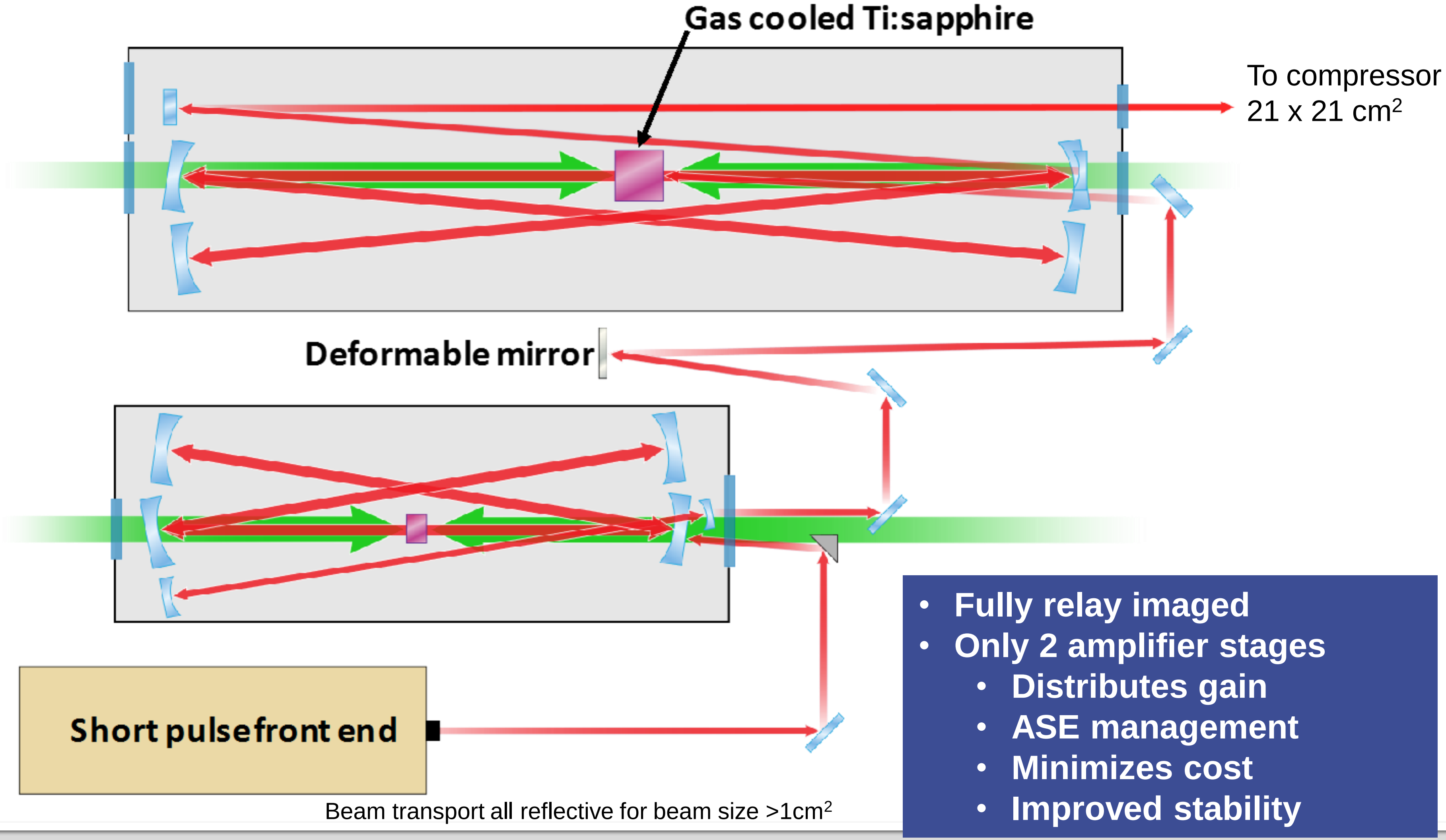


Robust XPW Pulse Cleaner enables achieving reliably ~10^9 temporal contrast and 10^{11} (5ps) in optimized configuration



Includes an LLNL-built Offner-triplet stretcher with a 20,000:1 stretch factor

The short pulse laser architecture utilizes dual amplifier zero propagation architecture to achieve high mode-fill and stability



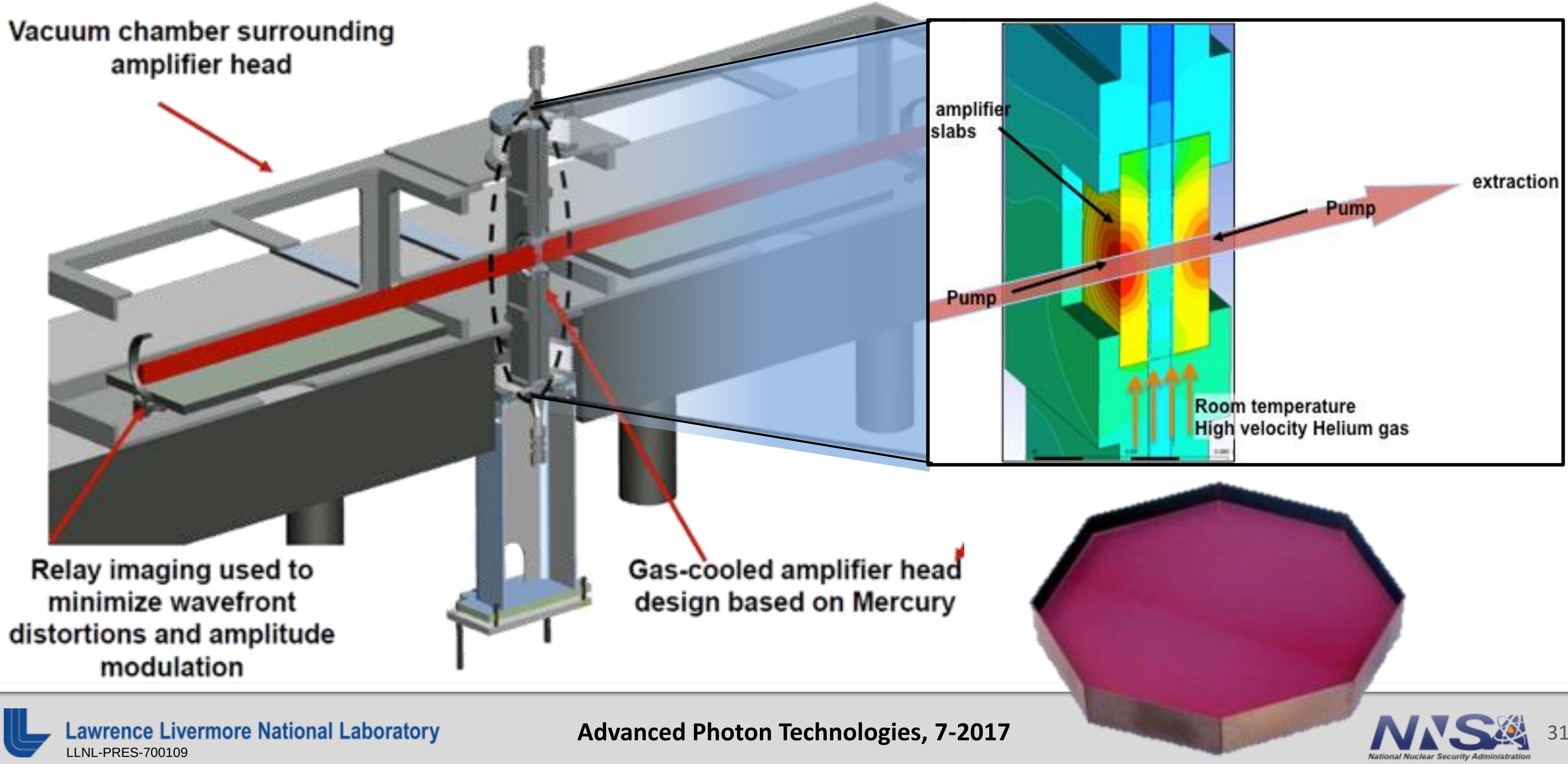
Beam size 5x5 cm^2

Beam transport all reflective for beam size >1cm^2

- **Fully relay imaged**
- **Only 2 amplifier stages**
  - **Distributes gain**
  - **ASE management**
  - **Minimizes cost**
  - **Improved stability**

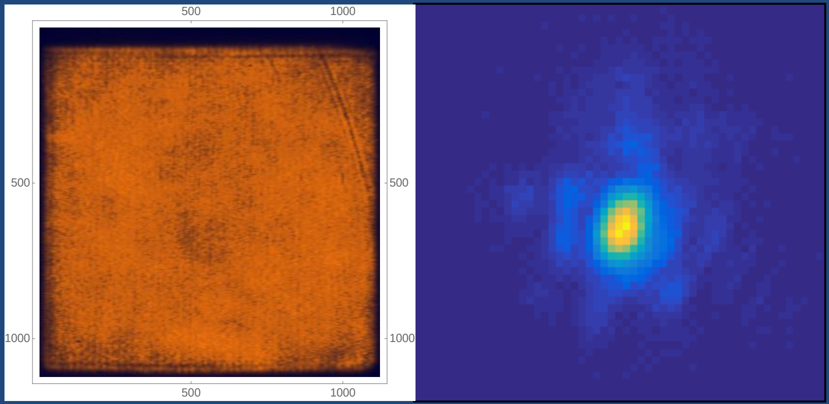
The Ti:Sa short pulse power amplifier is pumped with ~1 kW 2ω and utilizes the same gas-cooling concept

- **Approx. 50% of the pump incident to Ti:sapphire dissipated into heat**
- **~heat load doubles when unextracted**
- **High-speed flow of helium gas between Ti:sapphire slabs removes heat**
- **HAPLS uses solid state edge claddings**



Today, the HAPLS delivers 16J of broadband laser pulses at 3.3 Hz and pulse duration 28fs.

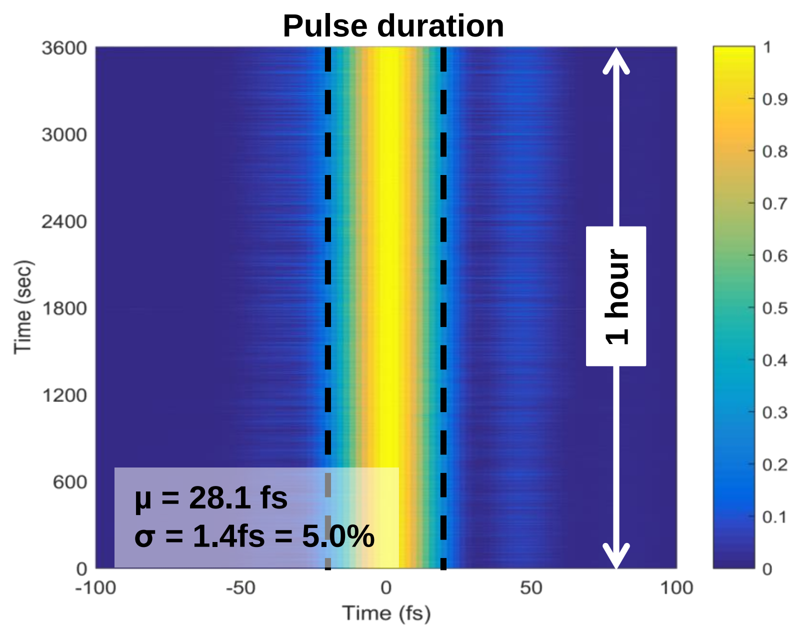
NF and FF Profiles at energy
(first results, adaptive mirror not active)



HAPLS output NF

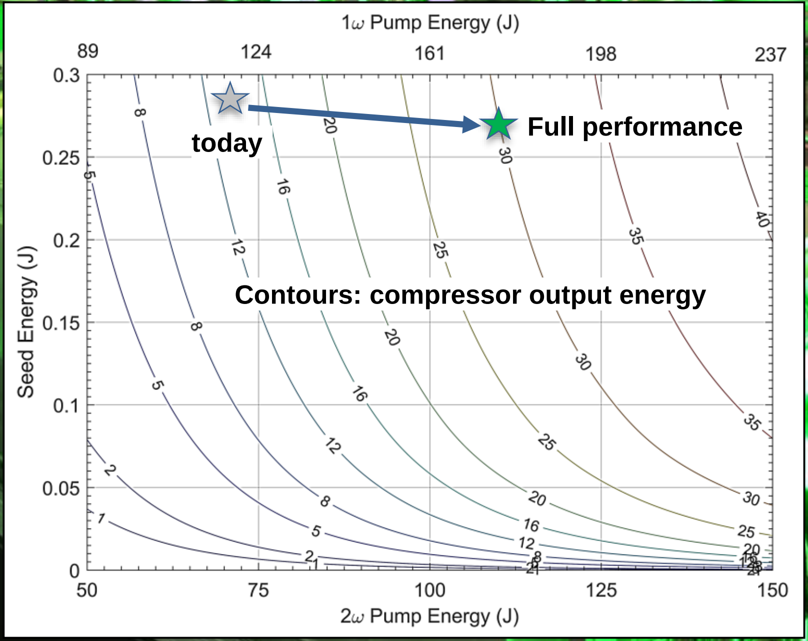
Encircled energy in DL spot = ~0.5

Today, the HAPLS delivers 16J of broadband laser pulses at 3.3 Hz and pulse duration 28fs.



Advanced Photon Technologies, 7-2017

The HAPLS final amplifier can deliver up to 45J of pulse energy

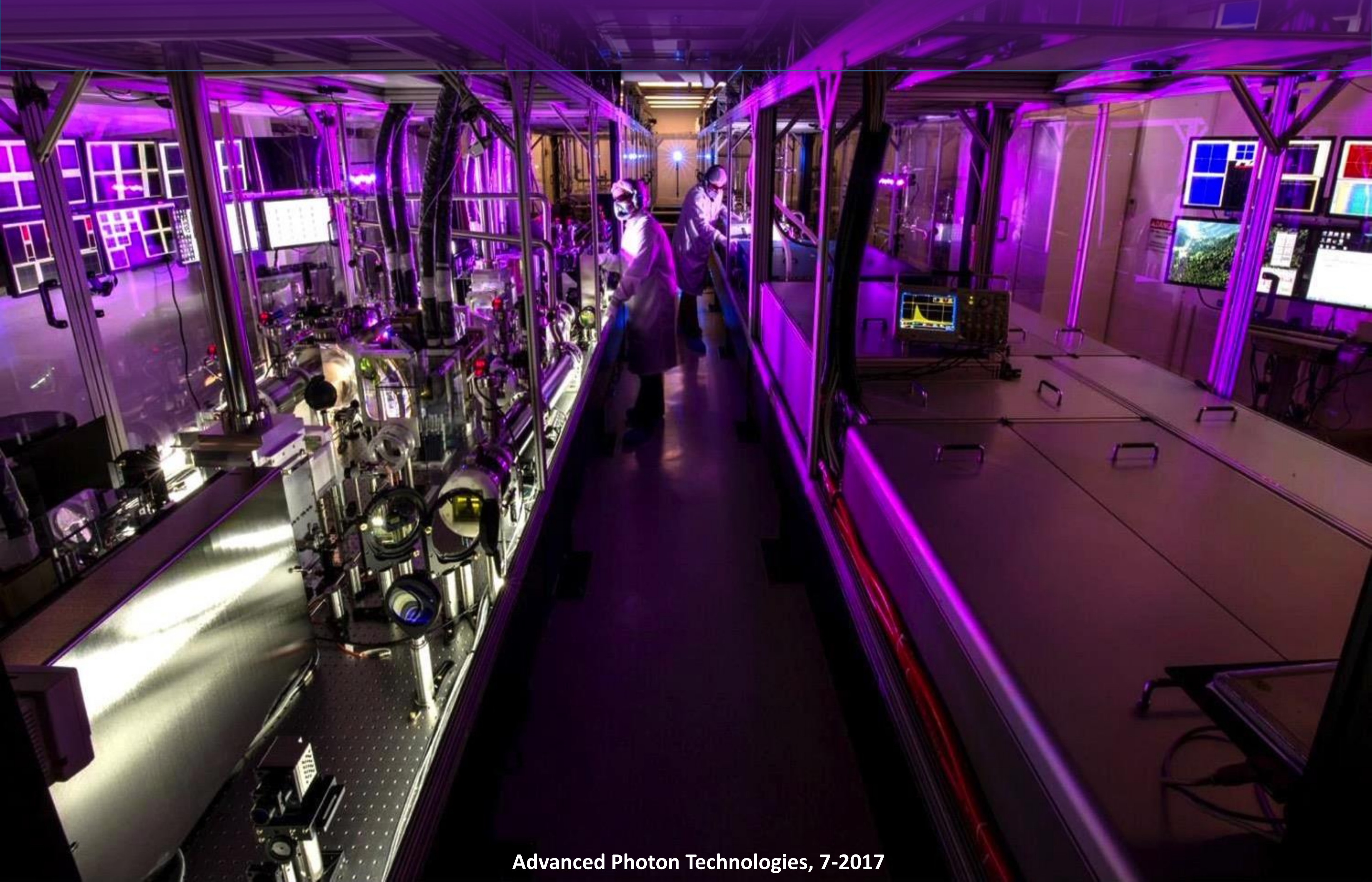


today

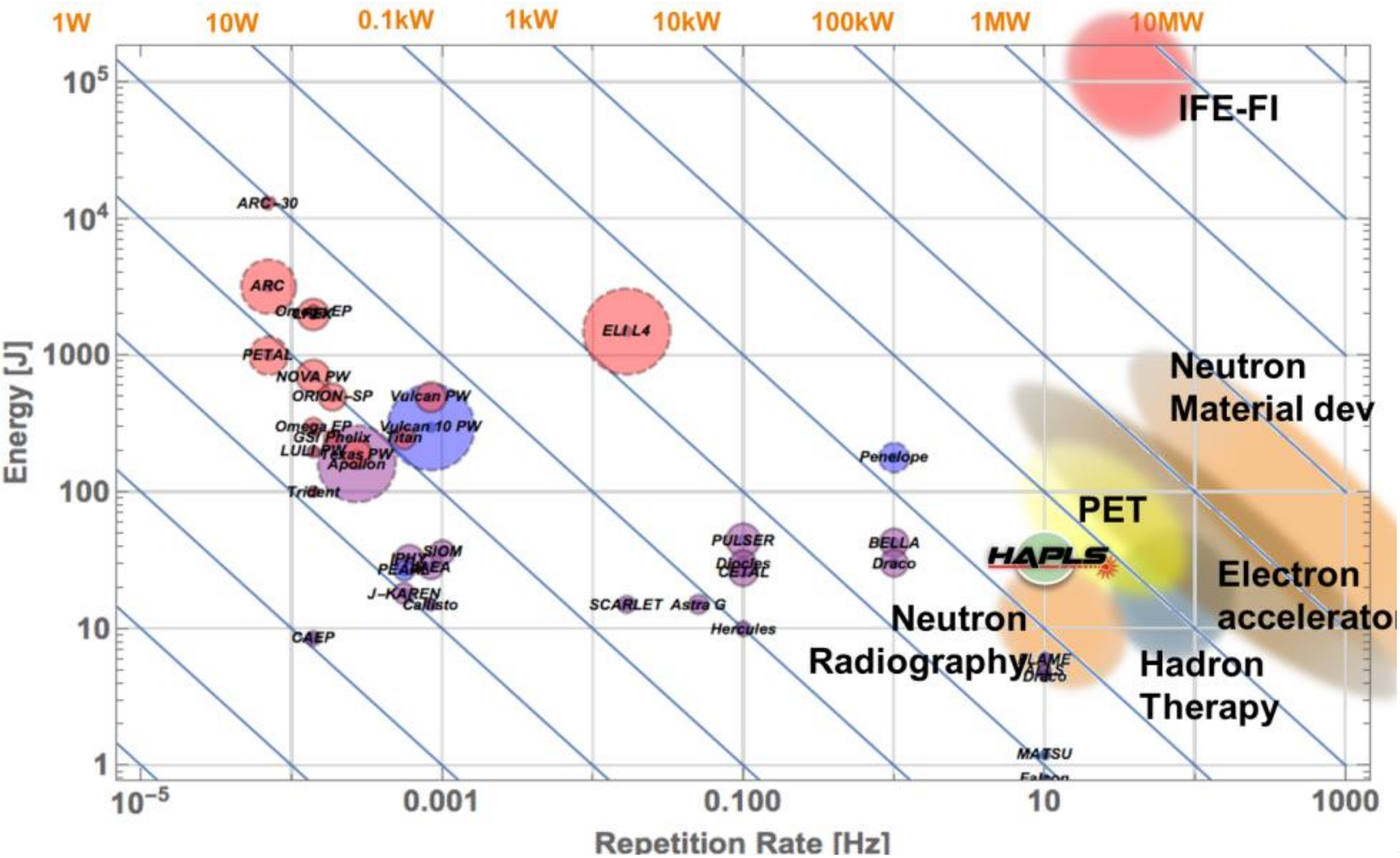
Full performance

Contours: compressor output energy

The HAPLS laser runs 200,000 times faster than both ARC and the original 1996 Petawatt



HAPLS is the first laser system that approaches a performance level consistent with real applications



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