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The College of Optics & Photonics

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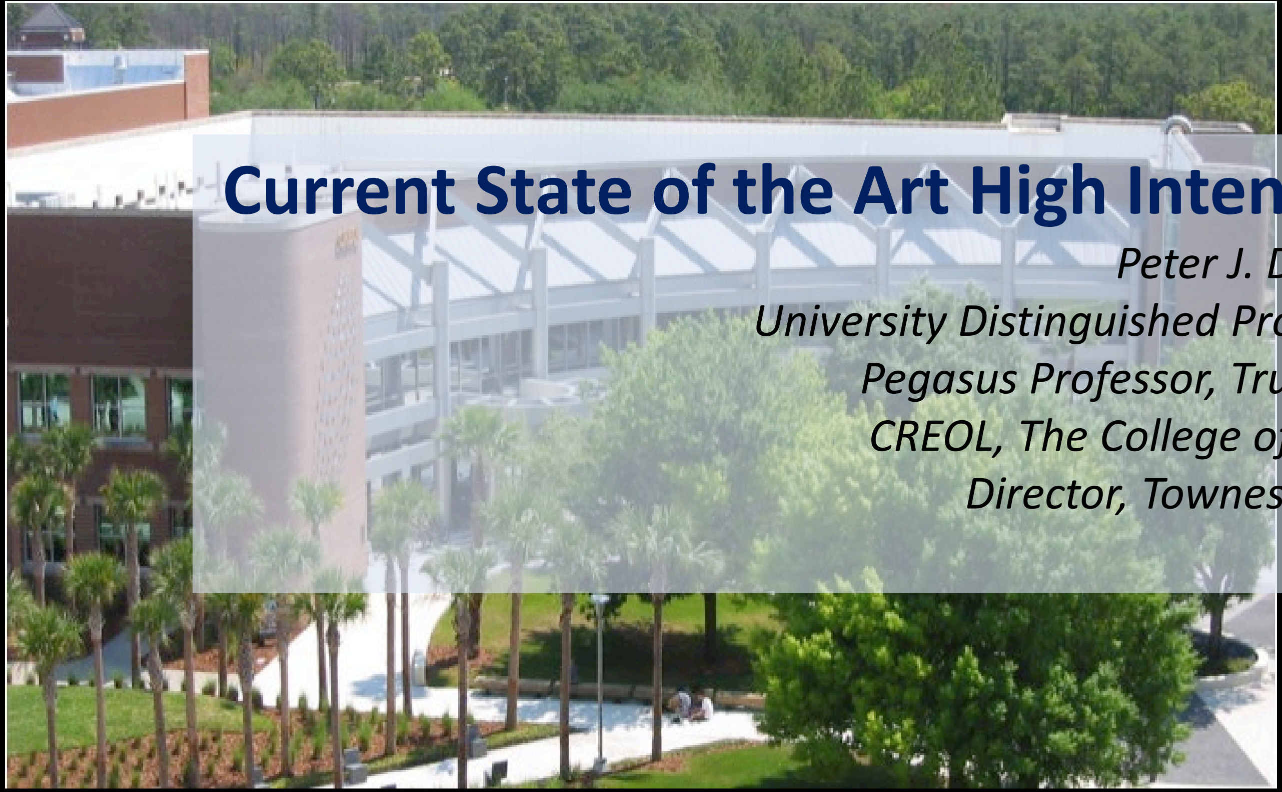
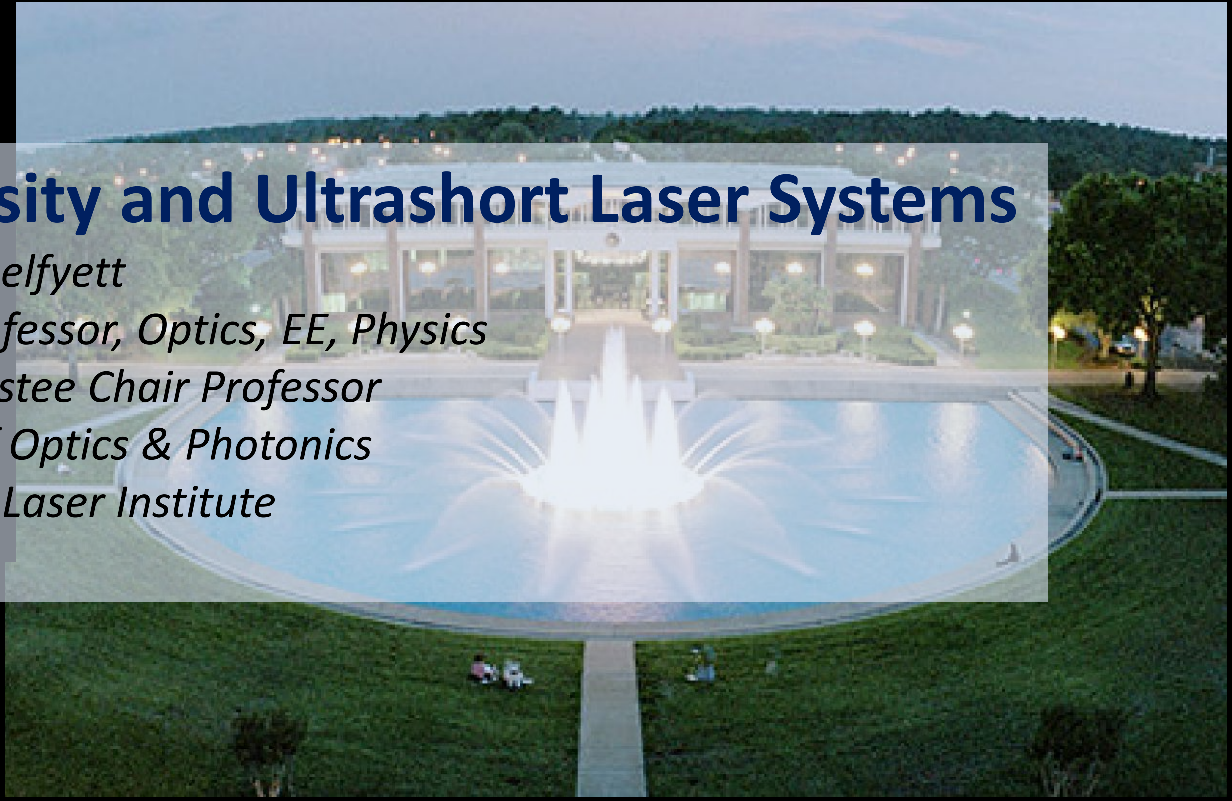

Current State of the Art High Intensity and Ultrashort Laser Systems

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CREOL, The College of Optics & Photonics

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Outline

- Introduction – What's State of the Art?
    - High Power Ultrafast Lasers for Accelerators
  - Typical Techniques –
    - Pulse Generation via Mode-locking
      - Stabilization for Single Cycle Generation
    - Amplification Techniques
      - Chirped Pulse Amplification
        - Regenerative or Optical Parametric Amplification
  - High Average Power Systems
- National Facilities – LaserNetUS
- Summary

What's "State of the Art"

Extreme Light Infrastructure

- **ELI– 10 PW (22fsec @1.1 um spot→ 10^{24} W/cm^2)**
- **1.2 urad pointing**

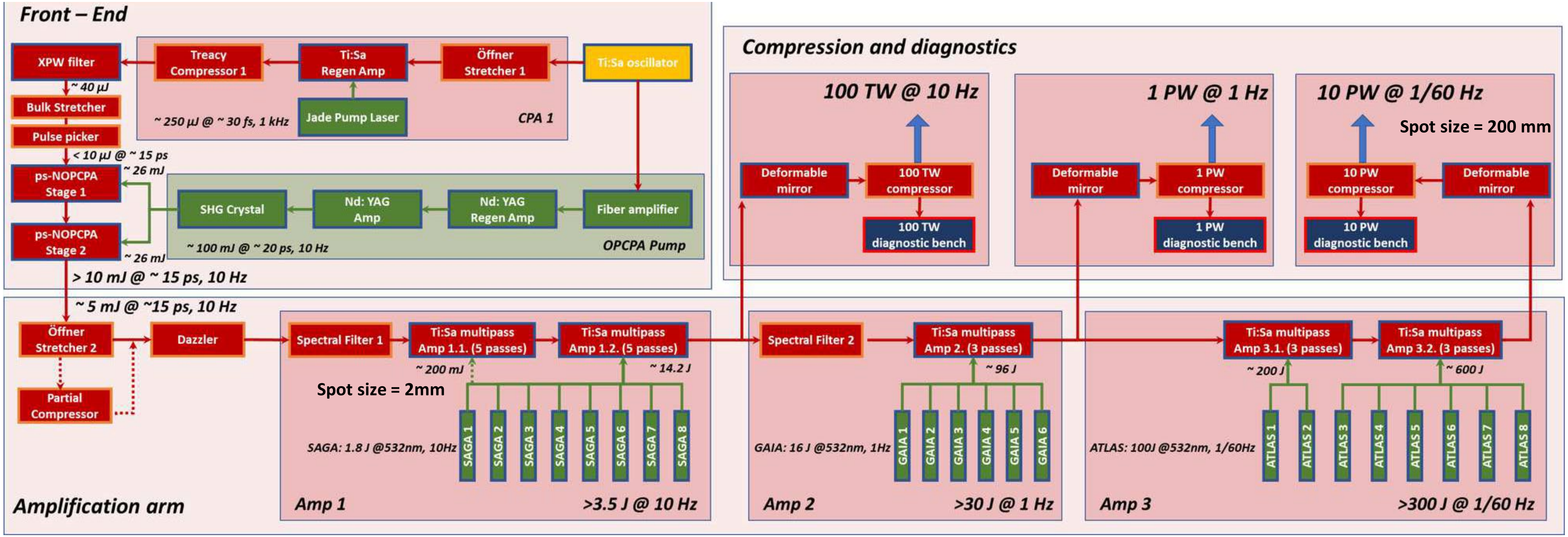
(use wavefront correction and stabilization)

What’s “State of the Art”

Center for Relativistic Laser Science

- **CoReLS –4 PW (10^{24} W/cm^2) 1.7 urad pointing (use wavefront correction and stabilization)**

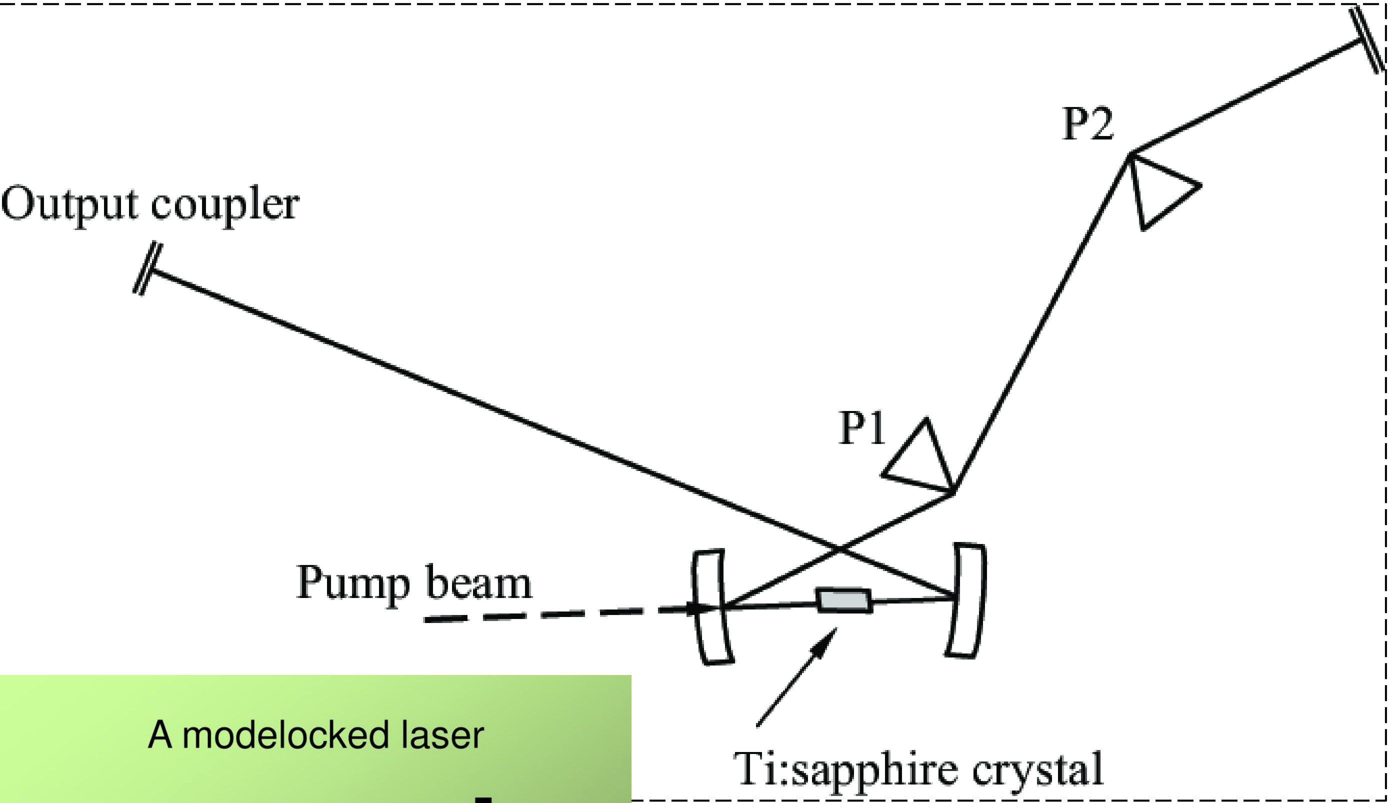
"State of the Art" – ELI



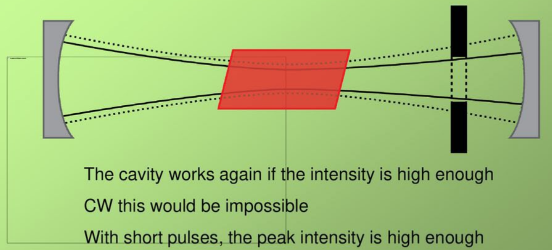
Block diagram of FE and one amplification arm with the three corresponding outputs:
100 TW at 10 Hz, 1 PW at 1 Hz, and 10 PW at 1 shot/min repetition rate.
Pulsewidth 20 fsec; spot size ~ 1 um, focused intensity – 10^{24} W/cm^2
Next: → 100 PW (50 cm xtal w/ NOPCPA)

How is it done?

The Technology – Mode-locked Laser Oscillator - KLM



A modelocked laser

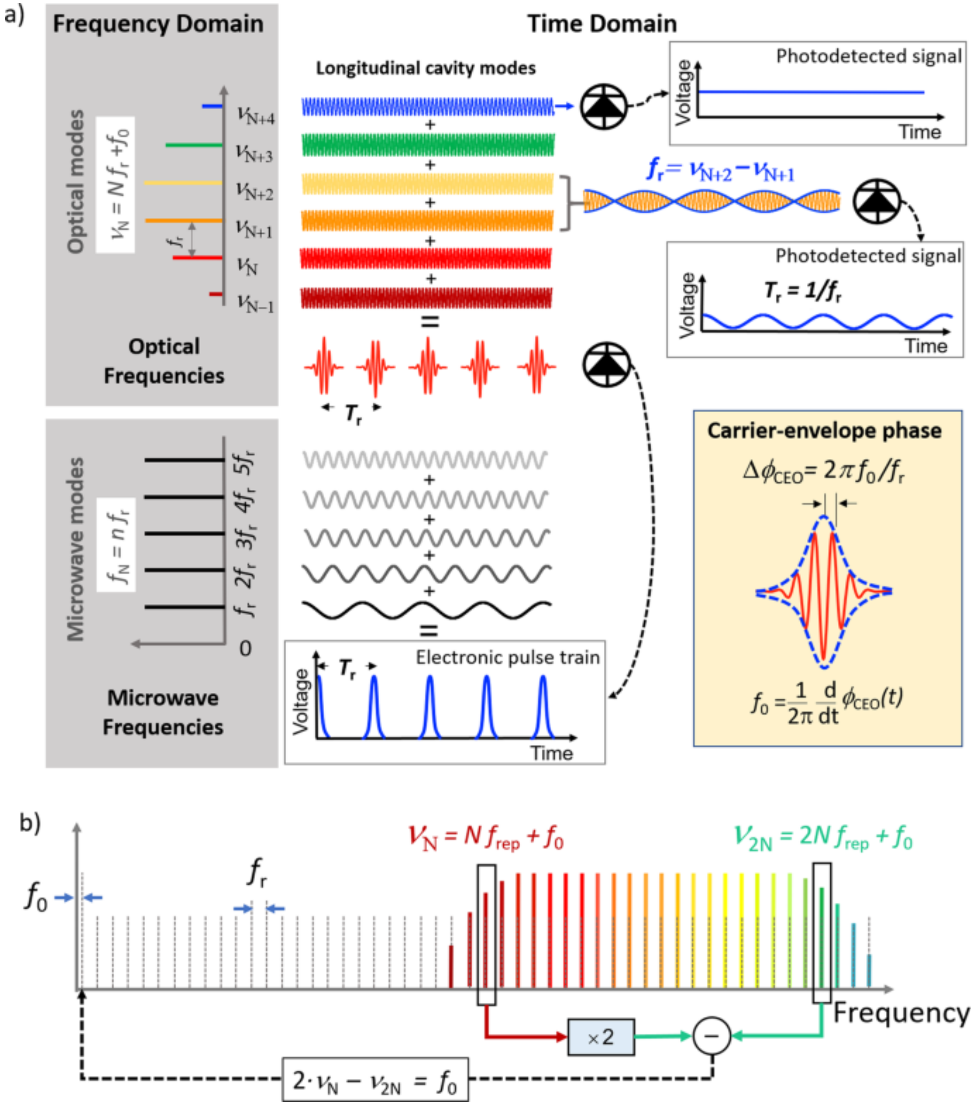


The cavity works again if the intensity is high enough

CW this would be impossible

With short pulses, the peak intensity is high enough

Kerr lens modelocking



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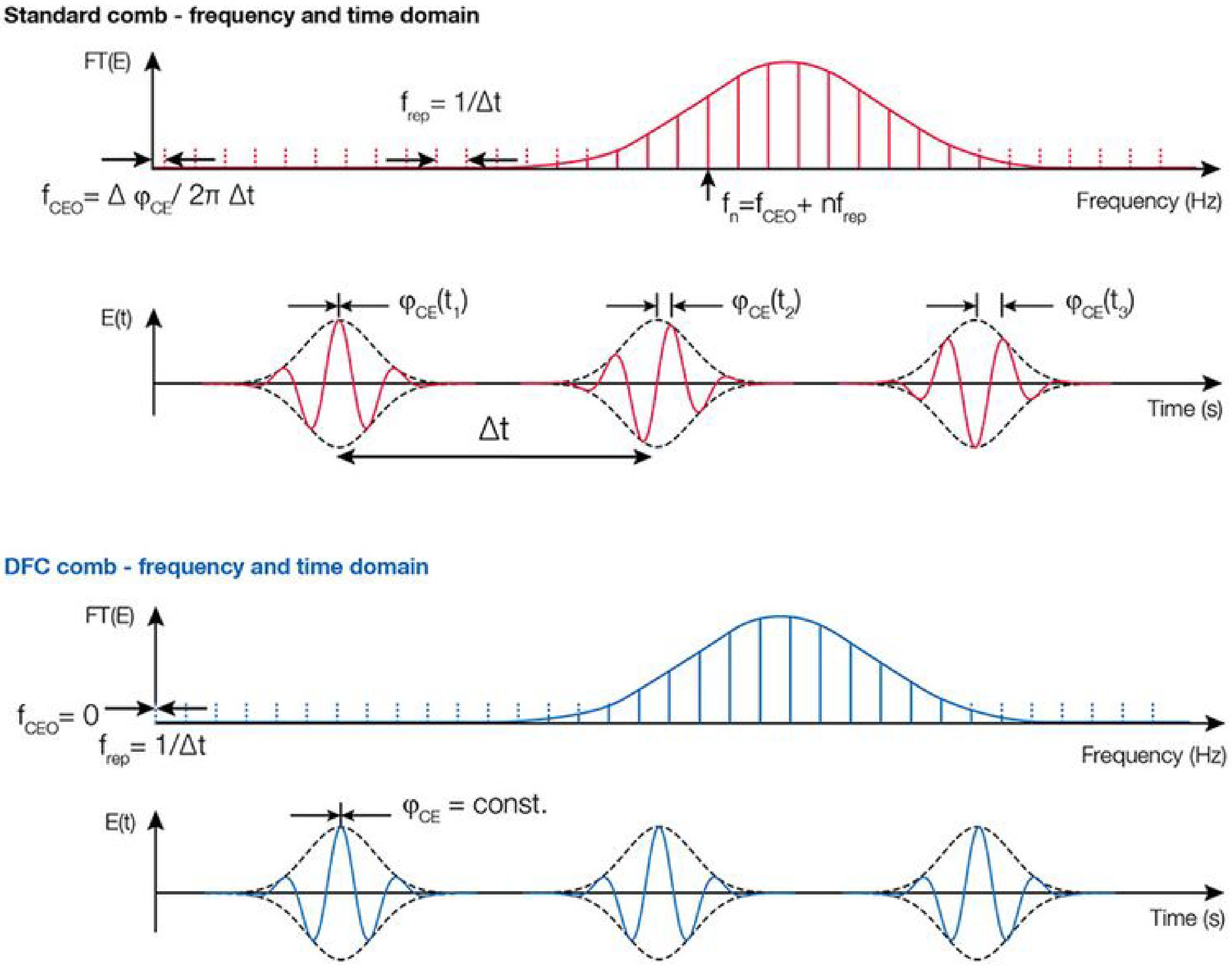
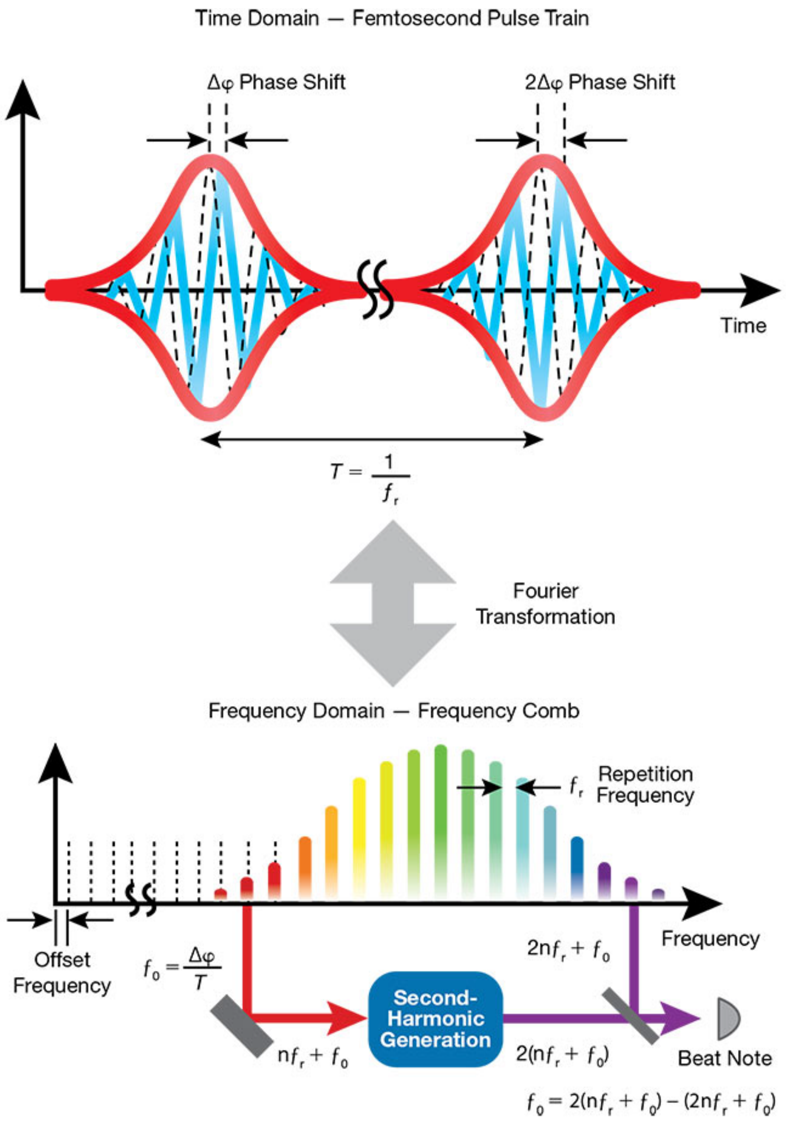
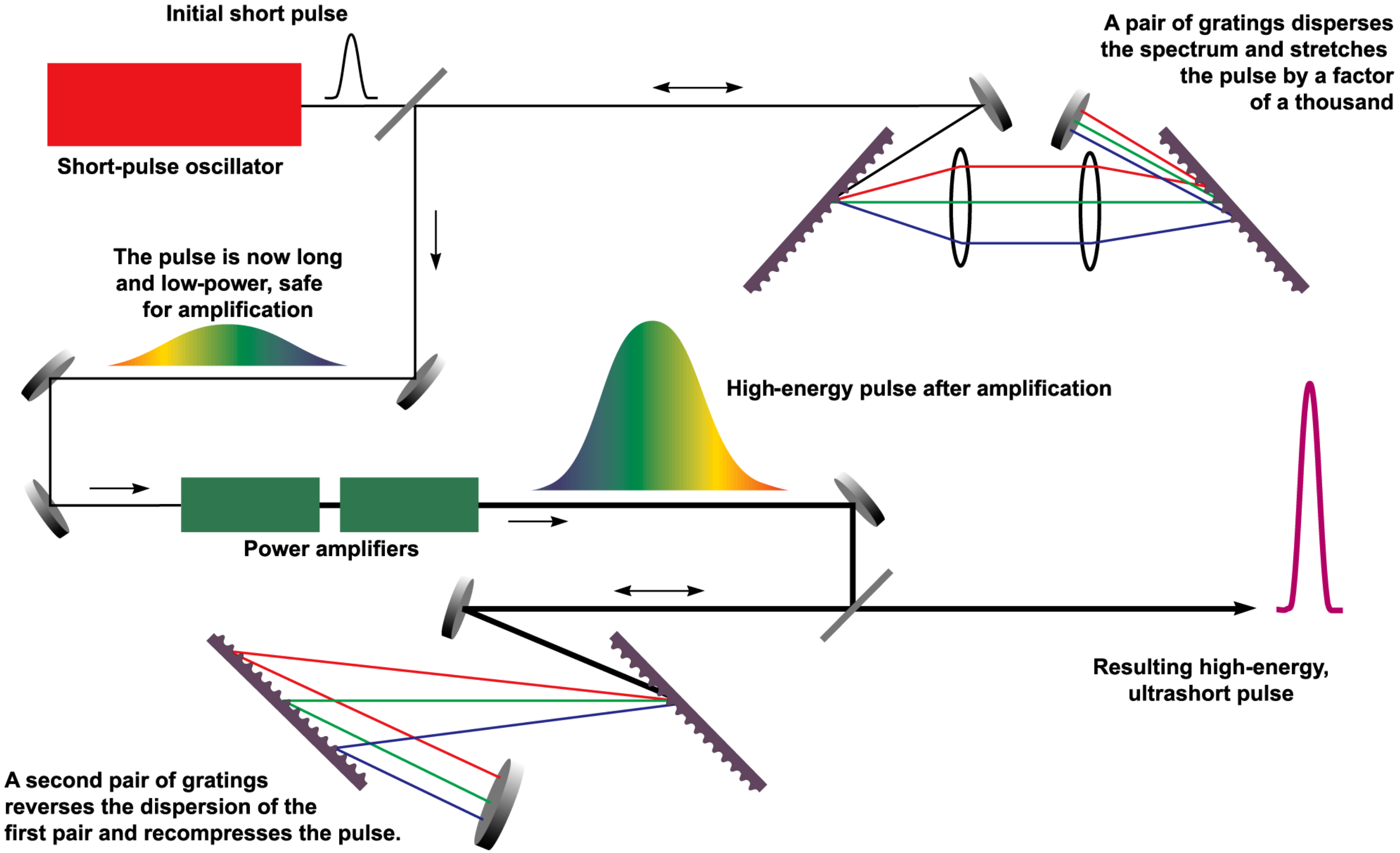
How is it done?
The Technology – Stabilizing the Carrier Envelope Offset (2005 Nobel)



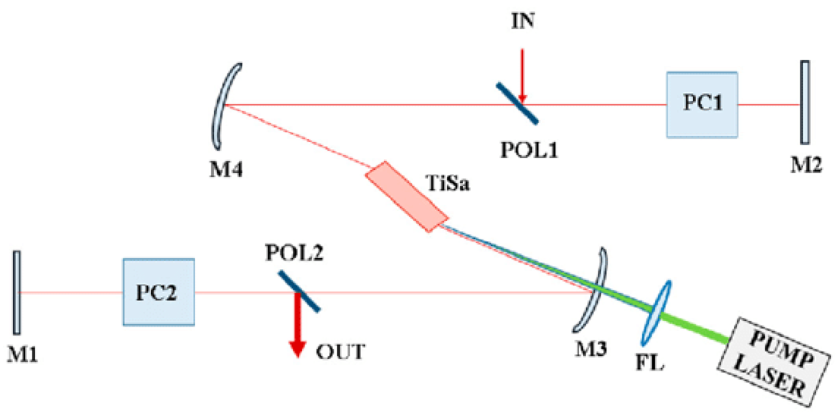


How is it done?
The Technology – Chirped Pulse Amplification (2018 Nobel)

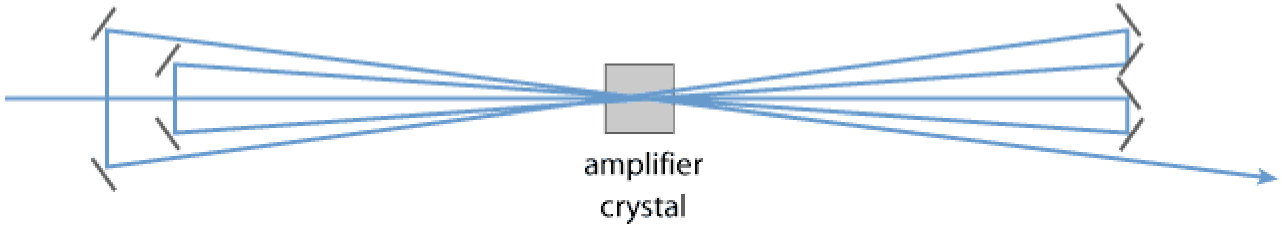


How is it done?

The Technology – Regenerative vs. Multi-pass Amplification



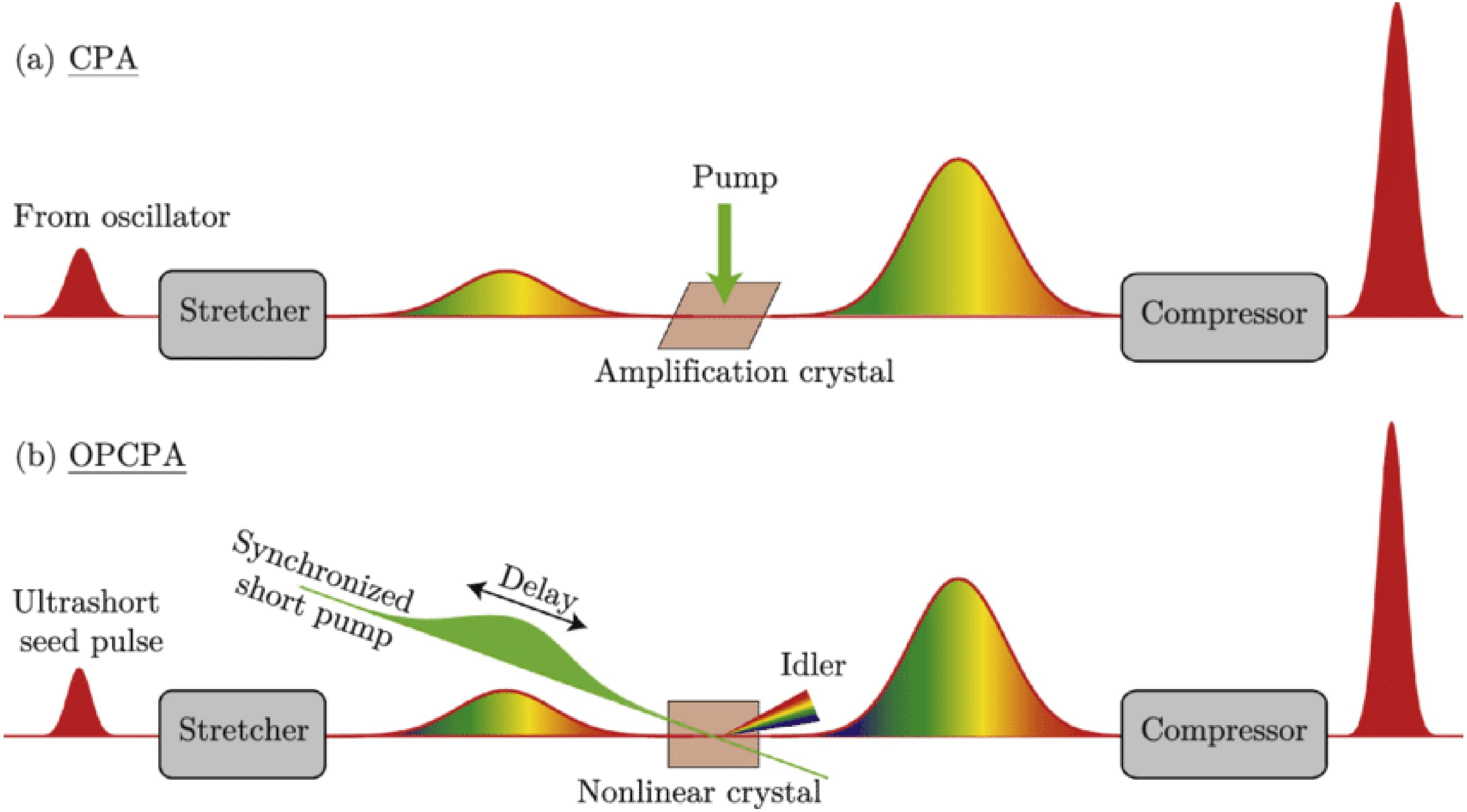
TiSa, Brewster angle cut Ti:sapphire crystal
M1-M4, high reflectance mirrors at 800 nm
PC1, injection Pockels Cell
PC2, extraction Pockels Cell
POL 1, POL 2, Polarizers
FL, Focusing lens



Typically uses many passes for high gain
Maintains mode size, but adds dispersion

Typically for maximum energy extraction
Fewer passes, complication alignment for many passes
Lower long term alignment stability

How is it done?
The Technology – Conventional vs Parametric Amplification



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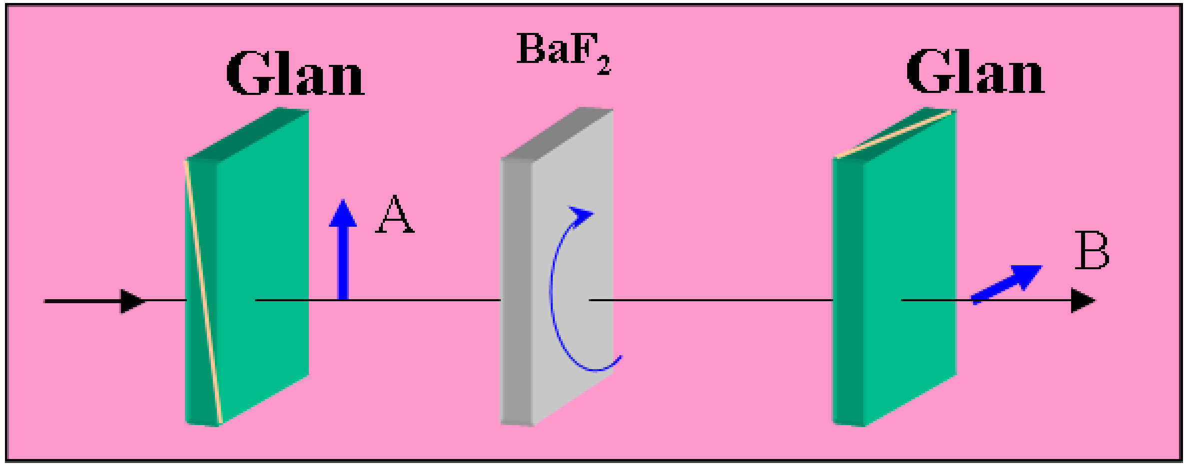
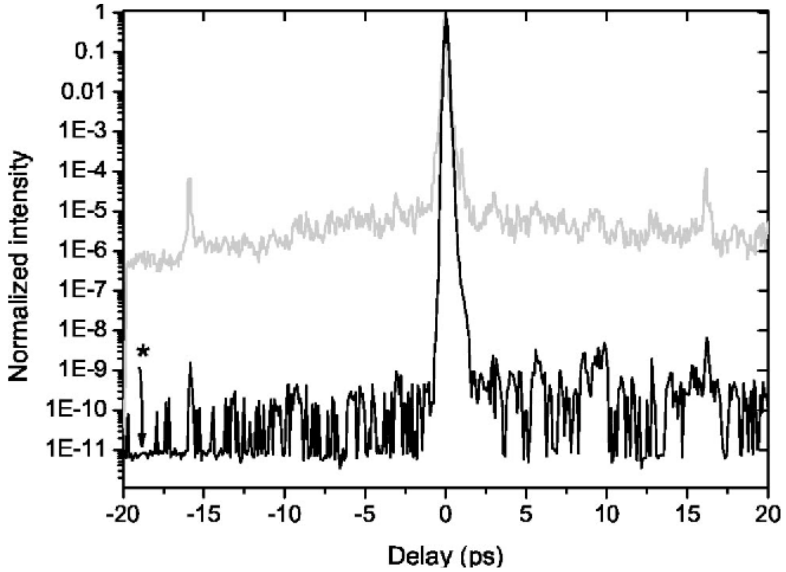
How is it done?
The Technology – Nonlinear Polarization Rotation

Cross Wave Polarization Filter (XPW) to ***Improve Pulse Contrast***

~10^{12} , 30% conversion efficiency

(nonlinear polarization rotation)





Intensity Autocorrelation showing Improved Pulse Contrast

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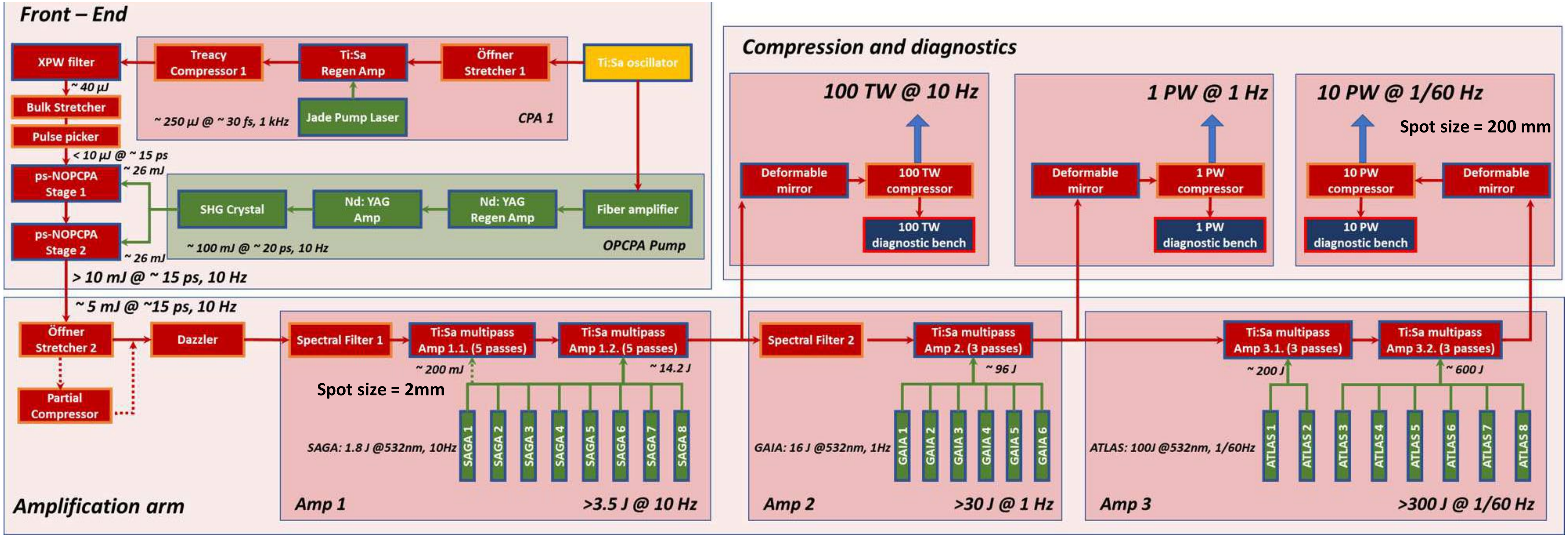
"State of the Art" – ELI and CoReLS



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Commercially Available State of the Art

Pulsar PW

Ultra intense ultrafast laser

State-of-the-art Ultra Intense Ultrafast Lasers

Pulsar PW is the ultimate light source dedicated to high field science, offering the best-in-class performance and bringing industrial-grade reliability to Science. Drawing on our large portfolio of pump lasers and solutions for effective thermal management, the Pulsar PW systems are designed for low (1 shot/min to 0.1 Hz) or high (1-5 Hz) repetition rates. This laser family has been designed to ensure the highest temporal quality at both femtosecond and picosecond timescales with optimized beam quality. Pulsar PW reaches the highest intensities with unsurpassed energy and pointing stabilities.

Pulsar PW comes with an embedded, flexible and user friendly monitoring and control software to further enhance the user experience and long term reliability.

The system versatility is augmented by a large offer of instrumentation and options for user specific needs.

Applications

Medical:
> X-Ray Imaging
> Protontherapy

Science:
> Accelerators

Key Features

> Up to 25 J
> Highest contrast ratio better than 10^{10} : 1
> Up to 5 Hz repetition rate
> Ultra-short sub-20 fs pulses
> Advanced Monitoring System

Amplitude

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Commercially Available State of the Art

Specifications	Pulsar 500	Pulsar 500 HR	Pulsar 1000	Pulsar 1000 HR
Repetition Rate (Hz)	1 shot / mn 0,1	1 to 5	1 shot / mn 0,1	1
Peak Power (PW)[1]	> 0,5		> 1	
Energy Per Pulse (J)	> 12,5		> 25	
Central Wavelength (nm)	800 ± 10			
Pulse Width (fs FWHM)[2]	< 25			
Pulse To Pulse Energy Stability (% RMS)	< 1.0			
Nanosecond Contrast	$> 10^8 : 1$			
Picosecond Contrast	$> 10^3$:1 beyond 1 ps			
	$> 10^6$:1 beyond 5 ps			
	$> 10^8$:1 beyond 10 ps			
ASE Contrast	$> 10^{10}$:1 beyond 100 ps			
Strehl Ratio[3]	> 0.85			
Pointing Stability (µrad RMS)[4]	< 5			

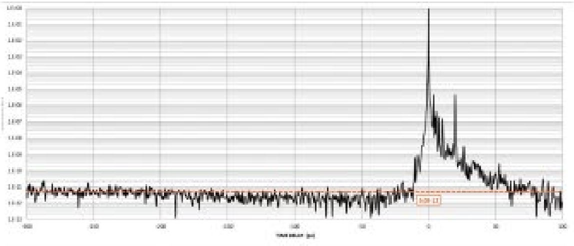
System dimensions

Pulsar 500	Pulsar 500 HR	32 m^2	344 ft^2
Pulsar 1000	Pulsar 1000	38 m^2	410 ft^2

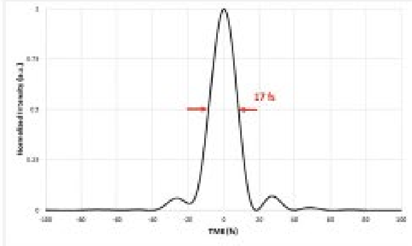
Others

Max Total Electrical Power[5]	20 to 40 kW
Max Water Cooling Capacity[5]	12 to 20 kW
Laboratory Temperature Range	18 - 23 °C
Laboratory Temperature Stability	+/- 1 °C

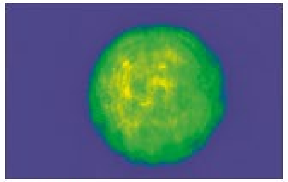
[1] Calculated at 25 fs pulsewidth
[2] Sub- 20 fs Ultra short pulse option available
[3] With Deformable mirror (in Option)
[4] Under stable controlled environment
[5] Depends on model



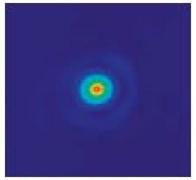
Pulsar 500 HR Sequoia HD contrast measurement



Pulsar 1000 HR typical pulse width measurement (with ultra short pulse option)



Pulsar 500 HR typical Near Field beam profile



Pulsar 1000 HR typical Far Field beam profile

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USPL High Average Power - State of the Art

10.4 kW
250 fsec
80 MHz
1045 nm
130 uJ
0.5 GW

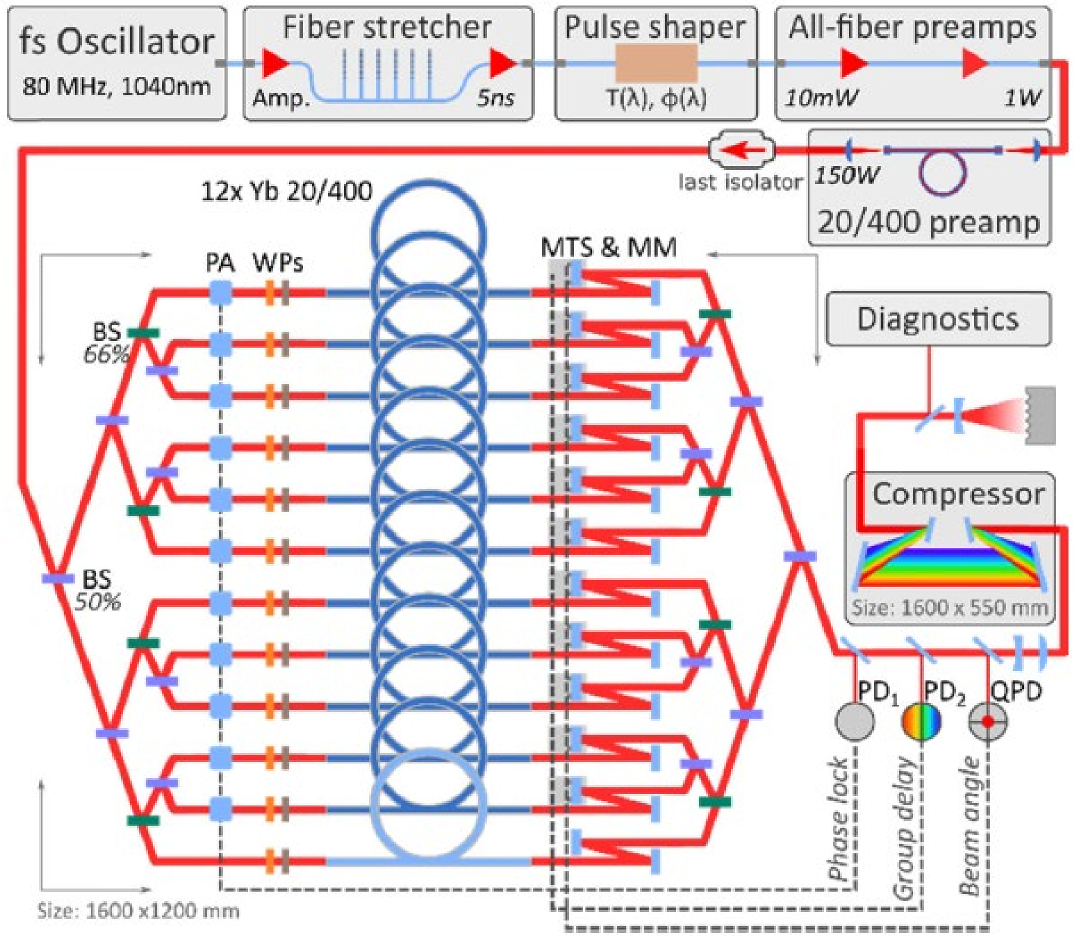
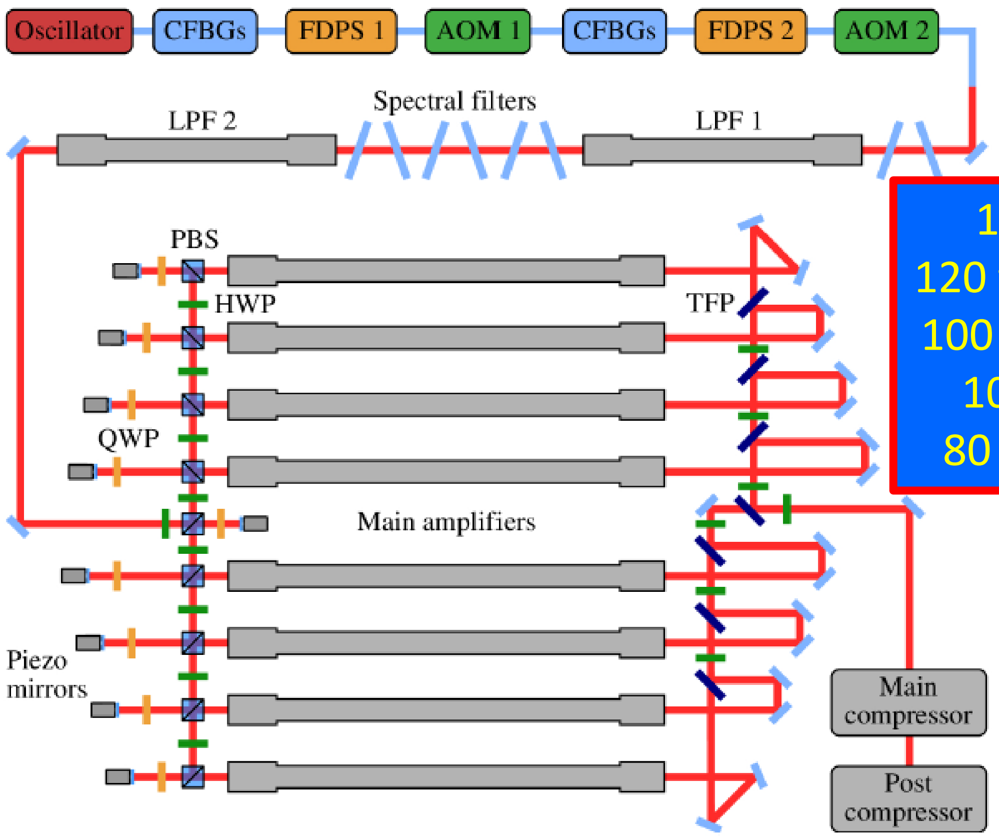


Fig. 1. Schematic setup of the laser system. BS, beam splitter; WP, quarter-/half-wave plate; MTS, motorized translation stage; MM, motorized mirror; (Q)PD, (quadrant) photodiode.



1 kW
120 fsec
100 kHz
10 mJ
80 GW

Fig. 1. Schematic of the setup. For clarity, only the lower level of the main amplifier stage is depicted. However, the upper level looks similar. CFBG, chirped fiber Bragg gratings; FDPS, Fourier-domain pulse shaper; AOM, acousto-optic modulator; LPF, large-pitch fiber; QWP, quarter-wave plate; HWP, half-wave plate; PBS, polarizing beam splitter; TFP, thin-film polarizer.


LaserNetUS
Creating a
Brighter World,
Together

LaserNetUS

Mission is to advance and promote intense ultrafast laser science and applications by:

•Advancing the frontiers of laser-science research;
•Providing students and scientists with broad access to unique facilities and enabling technologies;
•Fostering collaboration among researchers and networks from around the world

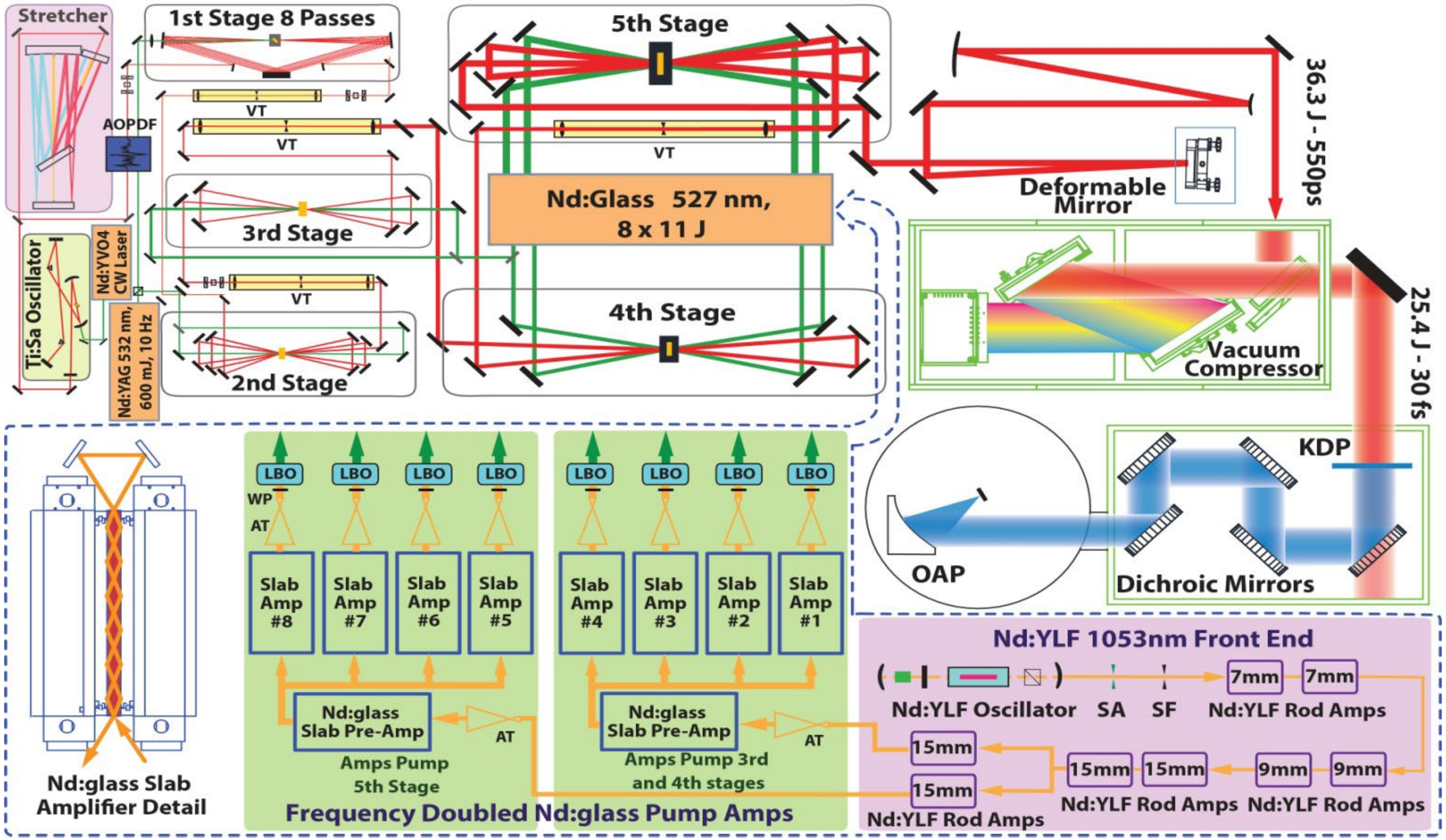
LaserNetUS supports students
The network allows graduate and undergraduate students access to laser facilities. The experiments at these facilities provide data for students' Ph.D. theses and students' publications. In 2019 alone, 80 students, 36 postdocs, and 86 staff scientists from users groups participated in LaserNetUS experiments.

Join the ecosystem as a:
User Facility Member
•Research Group Member
•Single Investigator Member
•Private Sector Partner

Member Institutions

Colorado State University
University of Michigan
University of Nebraska-Lincoln
Ohio State University
University of Texas at Austin
University of Rochester
Institut National de la Recherche Scientifique
University of Central Florida
Lawrence Berkeley National Laboratory
Lawrence Livermore National Laboratory
SLAC National Accelerator Laboratory.

Colorado State University - Aleph



Colorado State University - Aleph

ALEPH 400 nm

Parameter	Value	Unit	Additional Information			
Center Wavelength	400	nm				
Pulse duration (I FWHM)	45	fs				
Max energy on target	10	J				
Shot energy stability	10	%	r.m.s.			
Focal spot at target						
F/number	f/2					
intensity FWHM	1.2	µm				
Strehl ratio						
Energy containment	65	%	within	1/e		radius
F/number	f/25					
focal spot FWHM	20	µm				
Strehl ratio						
Energy containment	70	%	within			
Pointing Stability	2	µrad				
Pre-pulse contrast						
ps scale	10^{-12}		@ >25 ps			
Repetition Rate	3.3					

ALEPH 800 nm

Parameter	Value	Unit	Additional Information			
Center Wavelength	800	nm				
Pulse duration (I FWHM)	30	fs				
Max energy on target	26	J				
Shot energy stability	1.7	%	r.m.s.			
Focal spot at target						
F/number	f/2					
intensity FWHM	2.4	µm				
Strehl ratio						
Energy containment	65	%	within		µm	radius
F/number	f/25					
focal spot FWHM	40	µm				
Strehl ratio						
Energy containment	70	%	within			
Pointing Stability	2	µrad				
Pre-pulse contrast						
ps scale	5×10^{-6}		@ > 25 ps			
Repetition Rate	3.3	Hz		burst mode		

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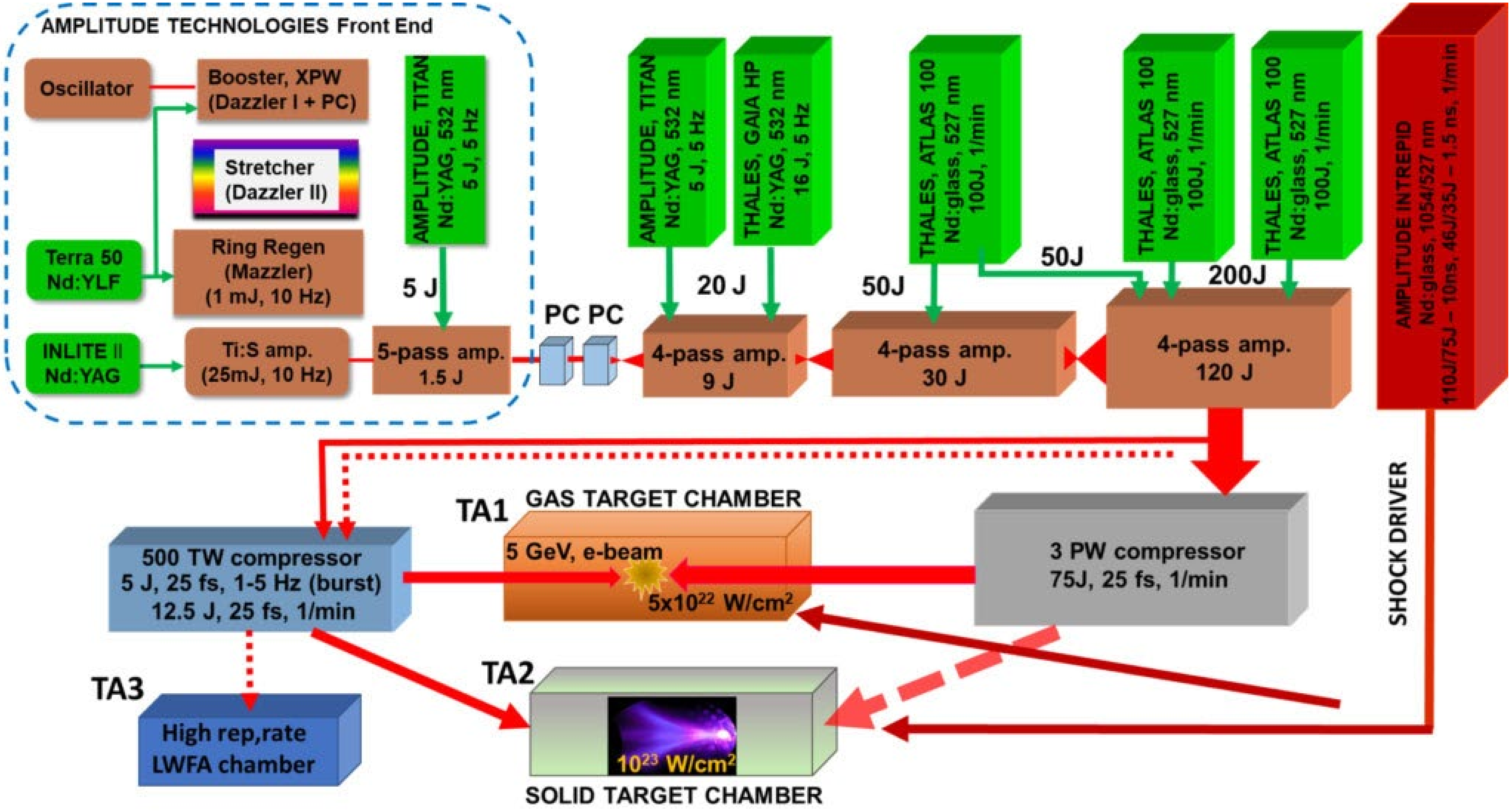
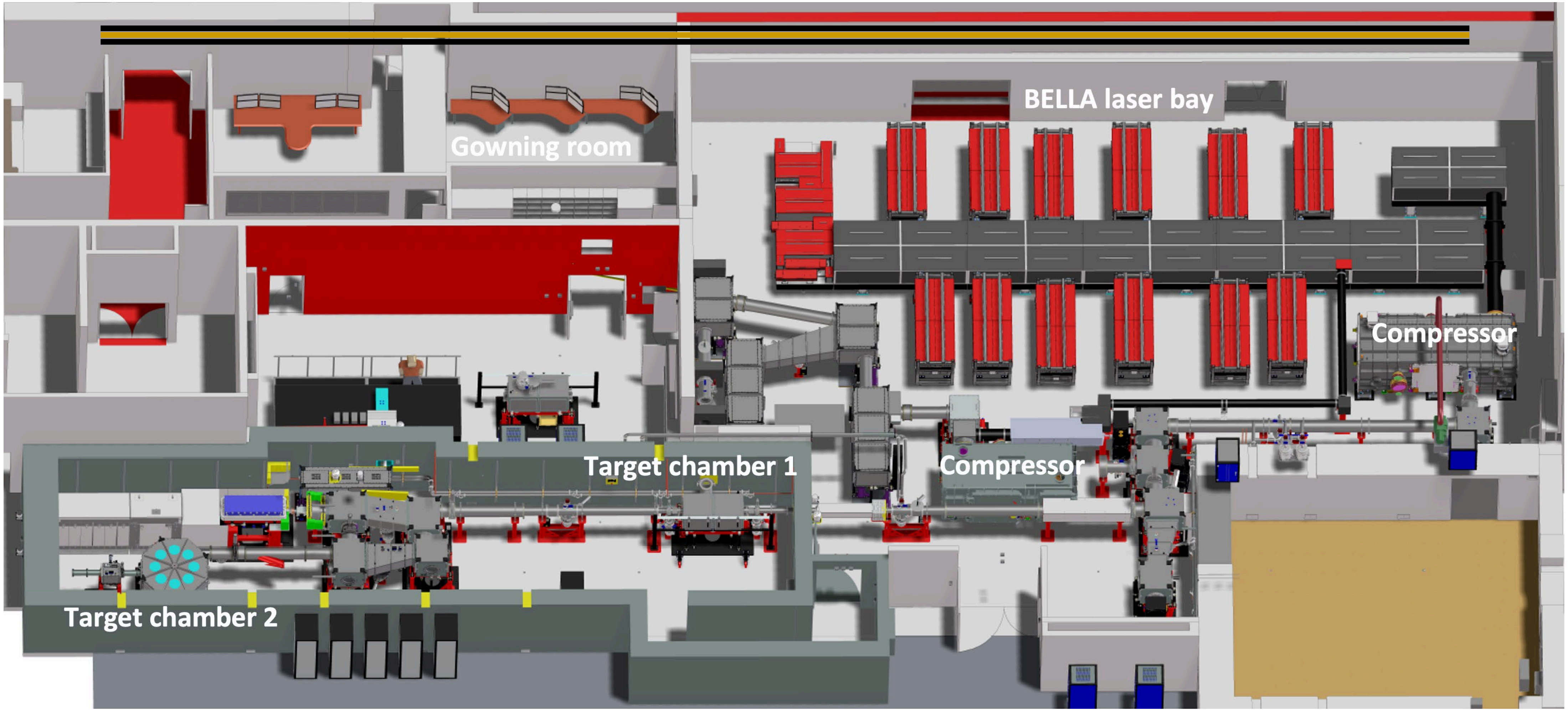
University of Michigan – Zeus

(Highest intensity in US)

Commercially Available



BELLA @ LBNL


BELLA laser bay
Gowning room
Compressor
Target chamber 1
Compressor
Target chamber 2

BELLA @ LBNL

1 PW Laser

Parameter	Value	Unit	Additional Information			
Center Wavelength	815	nm				
Pulse duration (FWHM)	30	fs				
Max energy on target	40	J				
Shot energy stability	2.5	%	r.m.s.			
Focal spot at target						
F/number	65					
intensity FWHM	65	µm				
Strehl ratio	>0.9					
Energy containment	75	%	within	67	µm	radius
F/number	f/2.5					
focal spot FWHM	2.7	µm				
Strehl ratio	0.7					
Energy containment	70	%	within	3	µm	radius
Pointing Stability	1.3	µrad	r.m.s.			
Pre-pulse contrast						
ns scale	10^{-9}		@	1	ns	
ps scale	10^{-6}		@	5	ps	
Repetition Rate	1 Hz					

Hundred TW Laser

Parameter	Primary beam	Secondary beam	Unit	Additional Information
Center Wavelength	800	800	nm	
Pulse duration (FWHM)	40	40 or 300,000	fs	
Max energy on target	>2	>0.5	J	
Shot energy stability	1.5	2.5	%	r.m.s.
Repetition rate	1 or 5	1 or 5	Hz	
Focal spot at target				
F/number	f/20	f/20		
Intensity FWHM	20	20	µm	
Strehl ratio	>0.8	>0.8		
Energy containment	80	80	%	
Pointing Stability	5	5	µm	r.m.s.
Pre-pulse contrast				
ns scale	10^{-7} (ns pedestal)	10-7 (ns pedestal) <10^{-5} (pre-pulse at ~10 ns from the front-end)		Ask facility for up to date information.
ps scale	10^{-6}	10^{-6}		

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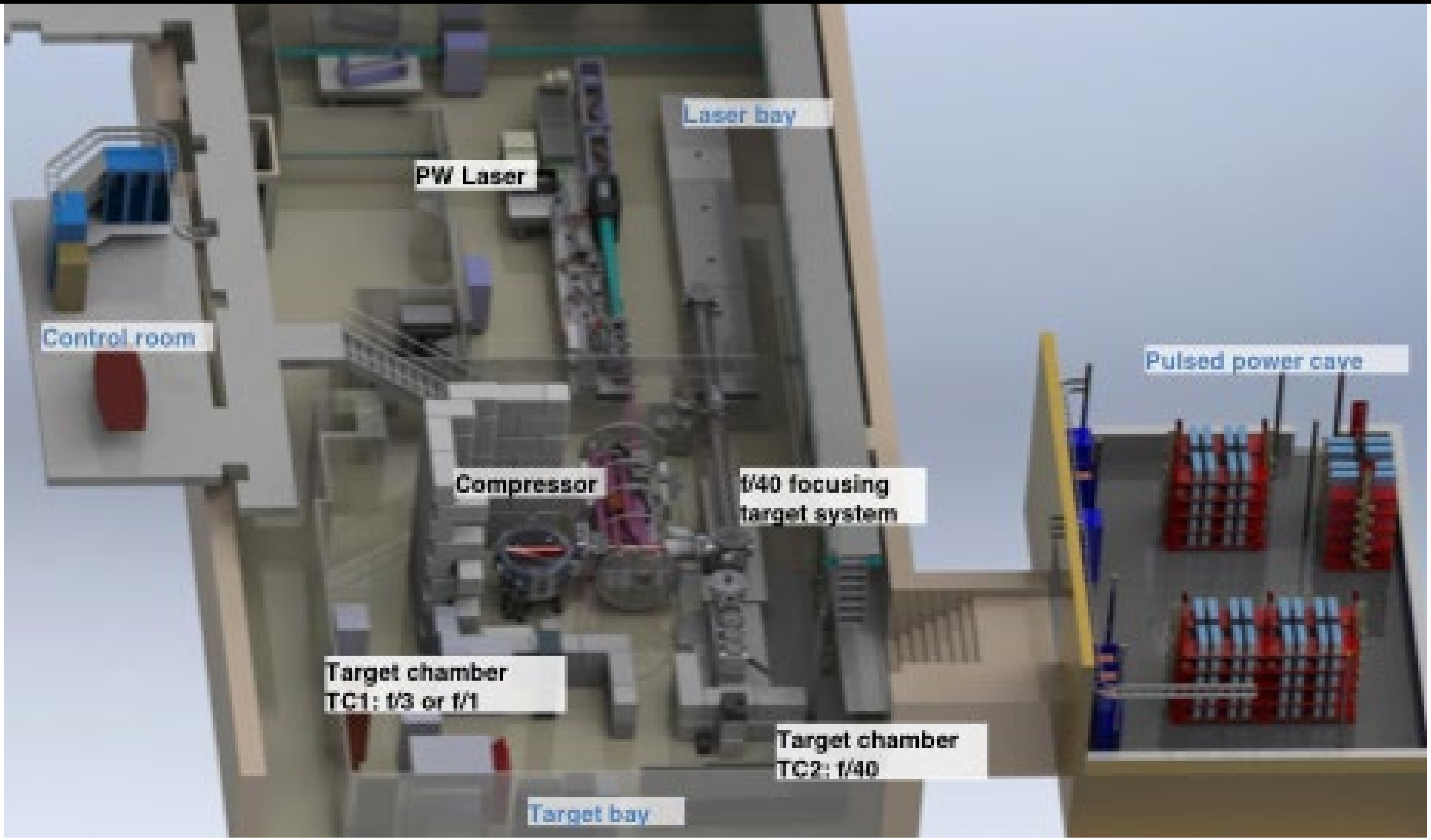
Texas Peta-Watt @ UTA



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      - Chirped Pulse Amplification
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  - High Average Power Systems
- National Facilities – LaserNetUS
- Summary → High Peak Intensity Laser are Ubiquitous