Center for Relativistic Laser Science

Onassis Science Lecture Jul. 5, 2023

Ultrahigh Intensity Multi-PW CPA Laser

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Overview

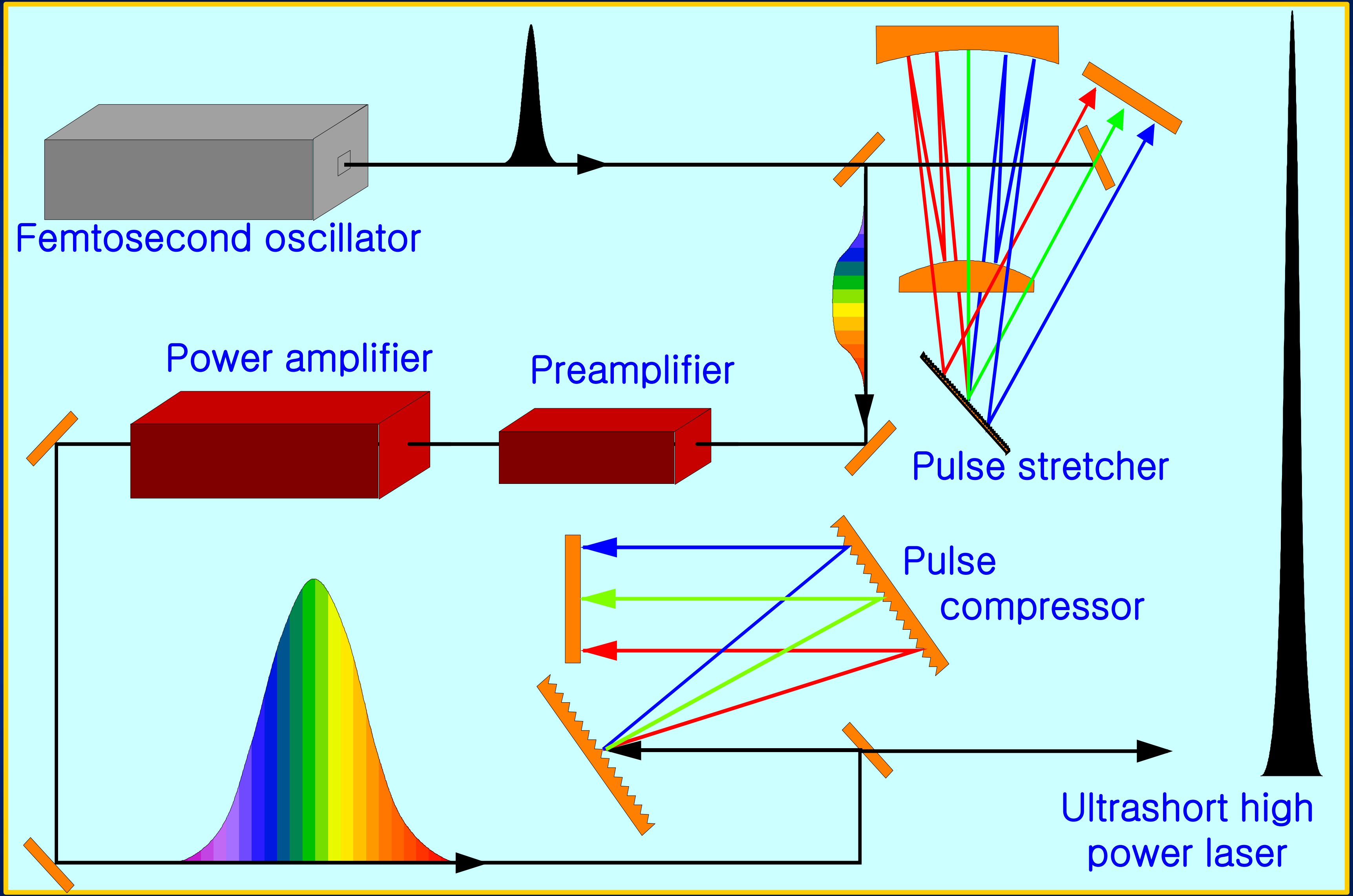
1. Ultrahigh power laser

A. Chirped pulse amplification (CPA)
B. 4 PW Laser @ 20 fs
C. Record-breaking laser intensity

2. Strong field QED research

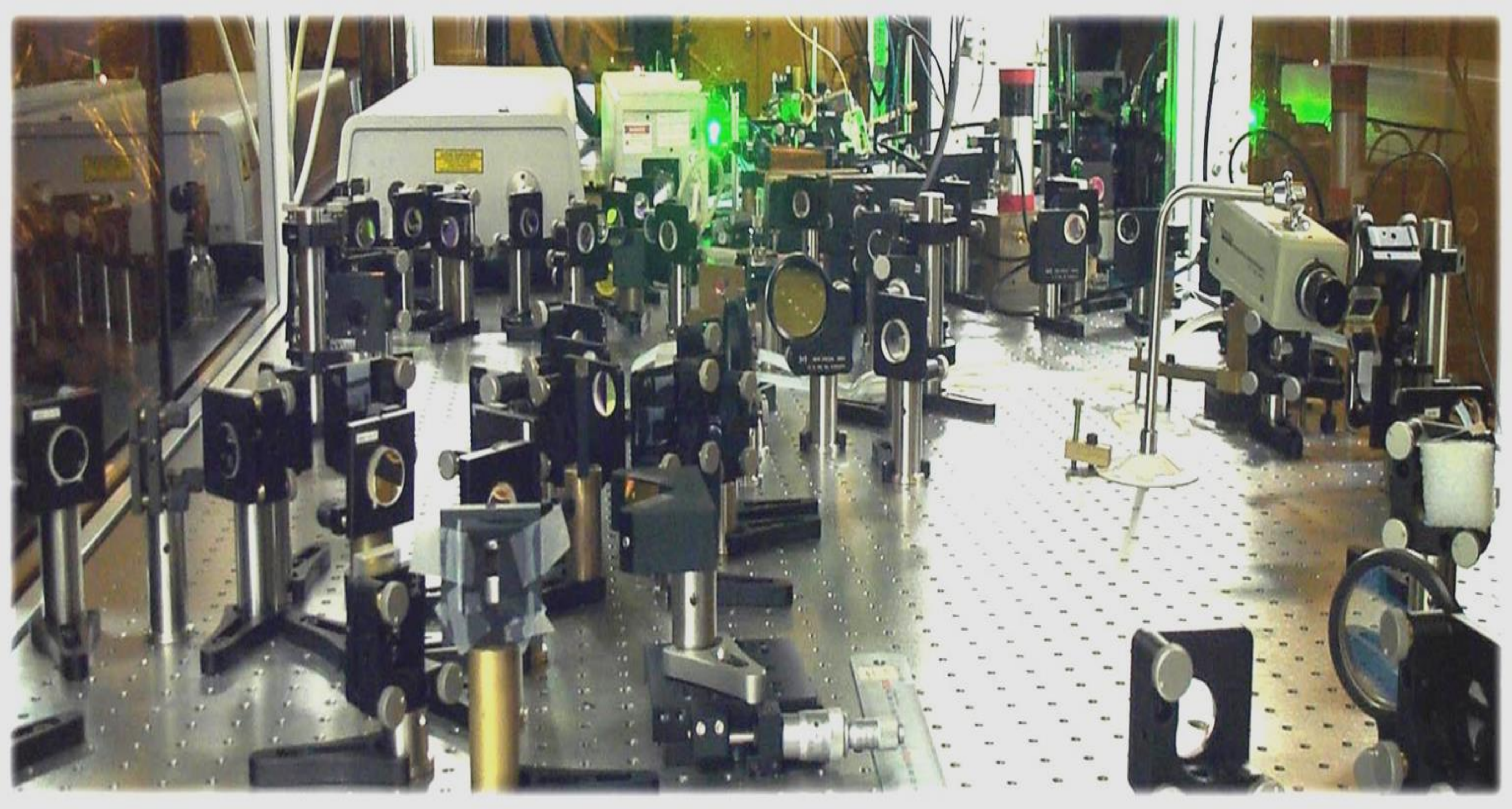
A. Laser-driven electron acceleration
B. Nonlinear Compton scattering

Chirped-Pulse Amplification (CPA) Technique



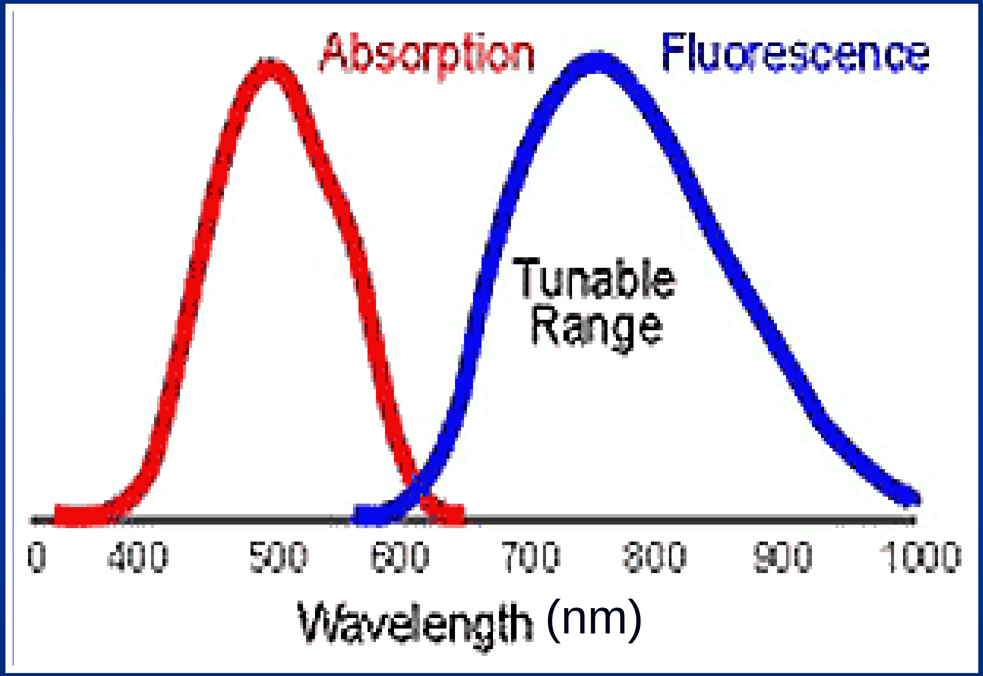
D. Strickland and G. Mourou, Opt. Comm. (1985)

20 fs, 3 TW Ti:Sapphire Laser at 10 Hz (KAIST, 1998)



Properties of Titanium Sapphire

Absorption and emission spectra of Ti:Sapphire



Ti:Sapphire lases from ~700 nm to ~1000 nm.

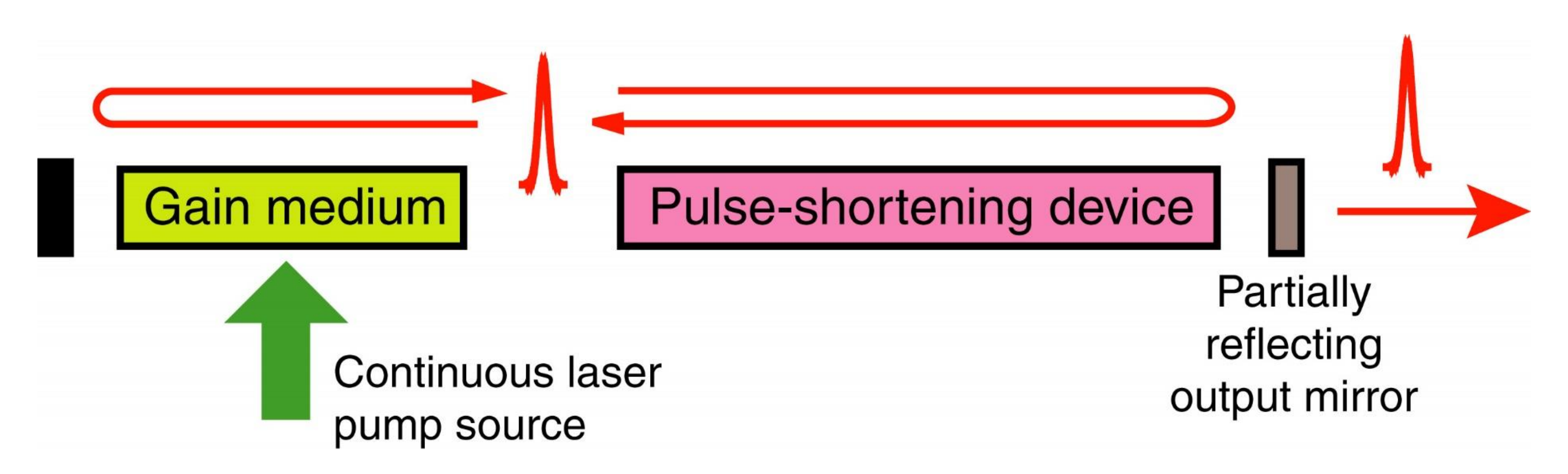
Upper level lifetime: 3.2 μsec

Broad absorption and gain bandwidths due to strong coupling between vibrational modes of ground and excited states, inducing strong homogeneous broadening.

It can be pumped with a (continuous) Argon ion laser (450-515 nm) or a doubled-Nd laser (~532 nm).

General structure of an ultrashort-pulse laser

An ultrashort pulse laser has a broadband gain medium and a pulse-shortening device.



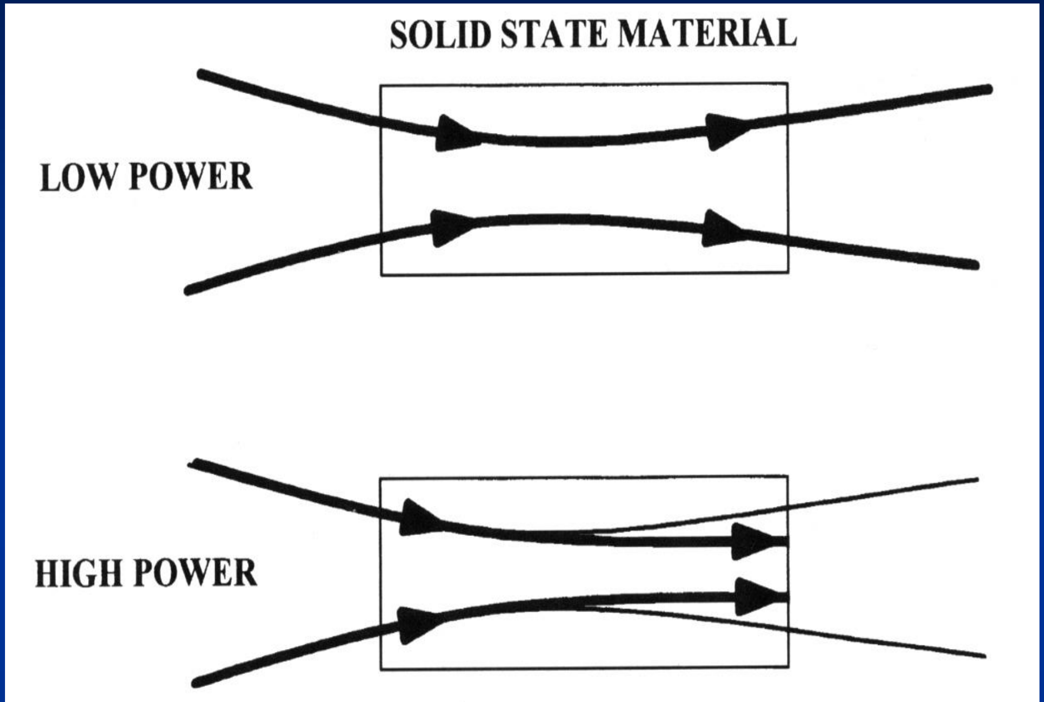
Pulse-shortening devices include: Saturable absorbers
Phase modulators
Optical Kerr media
Dispersion compensators

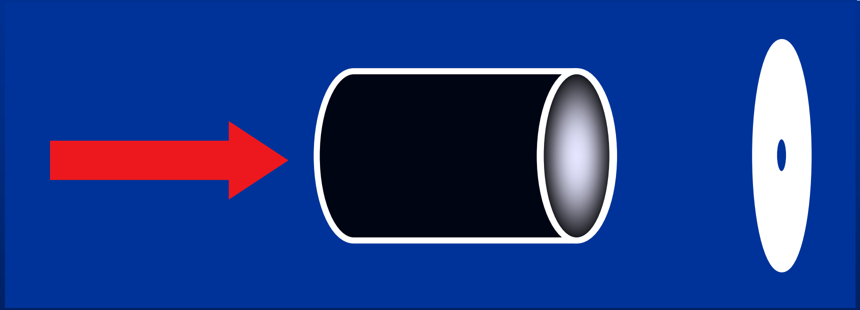
Kerr-lens mode-locking (KLM)

- Intensity-dependent refractive index of a medium:

  $n(I) = n_0 + n_2 I$

- If the pulse is more intense in the center, a lens-like refractive index profile is formed.
- Placing an aperture at the focus favors the propagation of a short (intense) pulse.

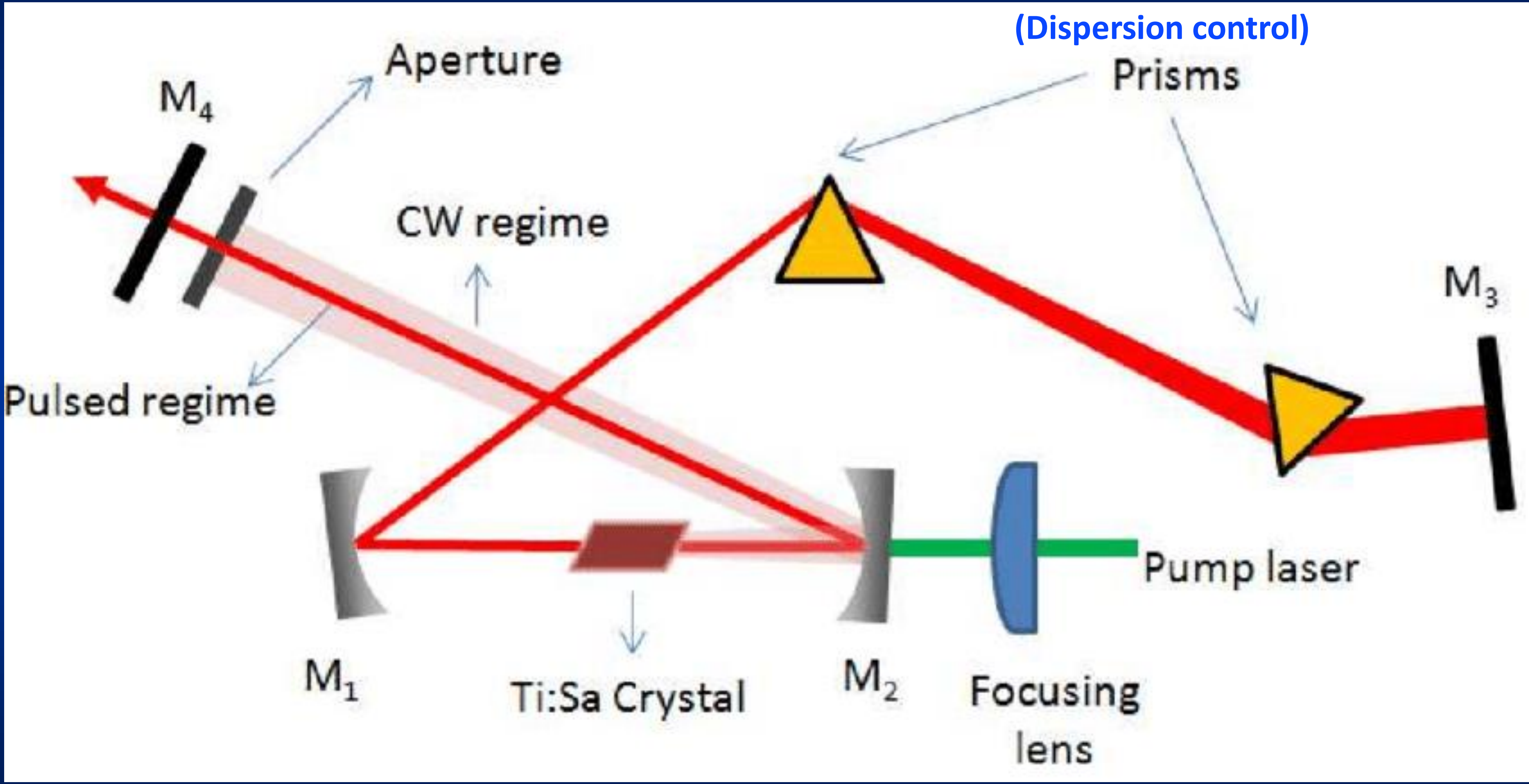




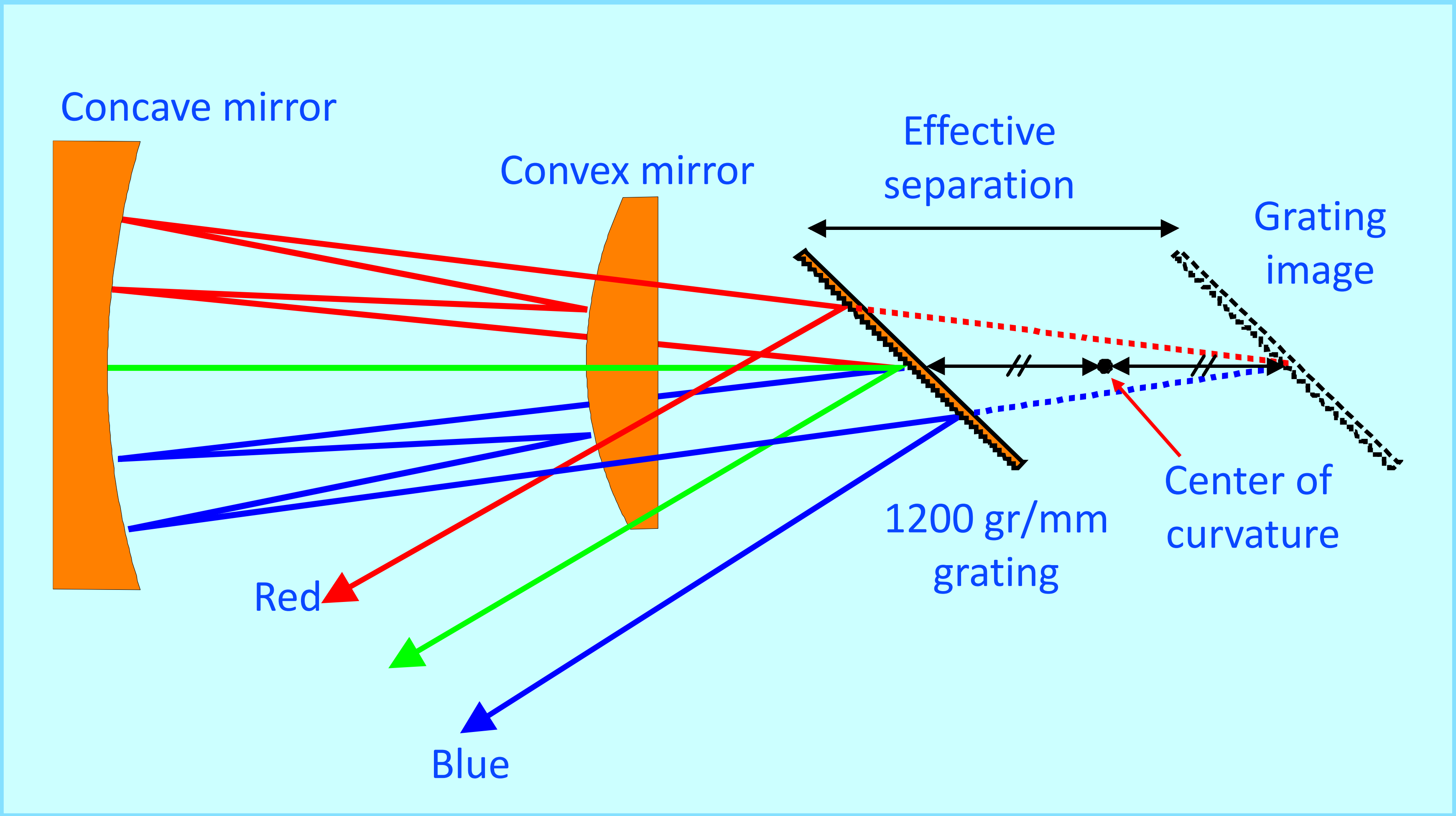
Losses are too high for a low-intensity mode to lase, but not for high-intensity fs pulse.

Kerr-lensing is the mode-locking mechanism of a Ti:Sapphire laser.

Optical setup of a KLM Ti:Sapphire laser

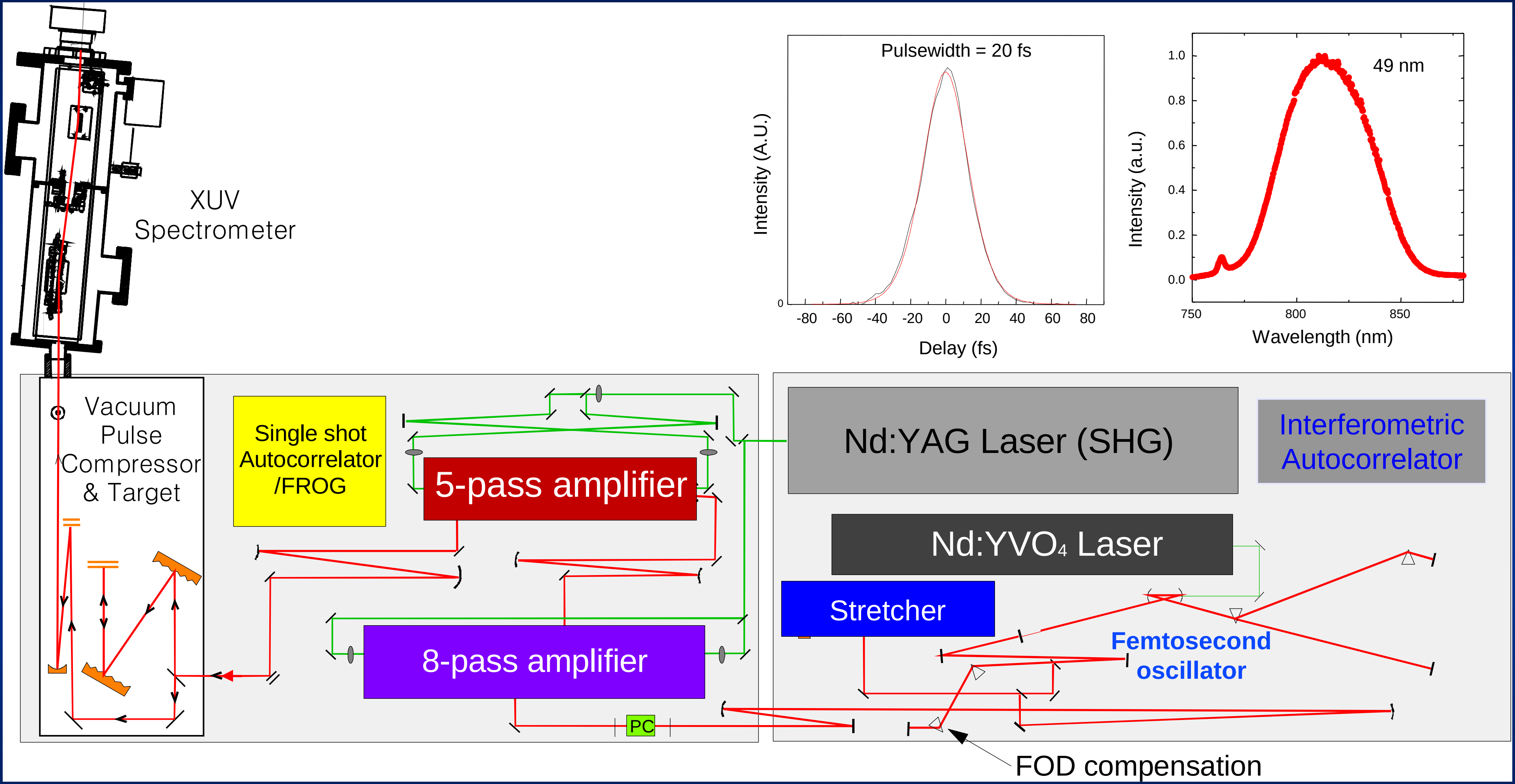


Four-pass Pulse Stretcher



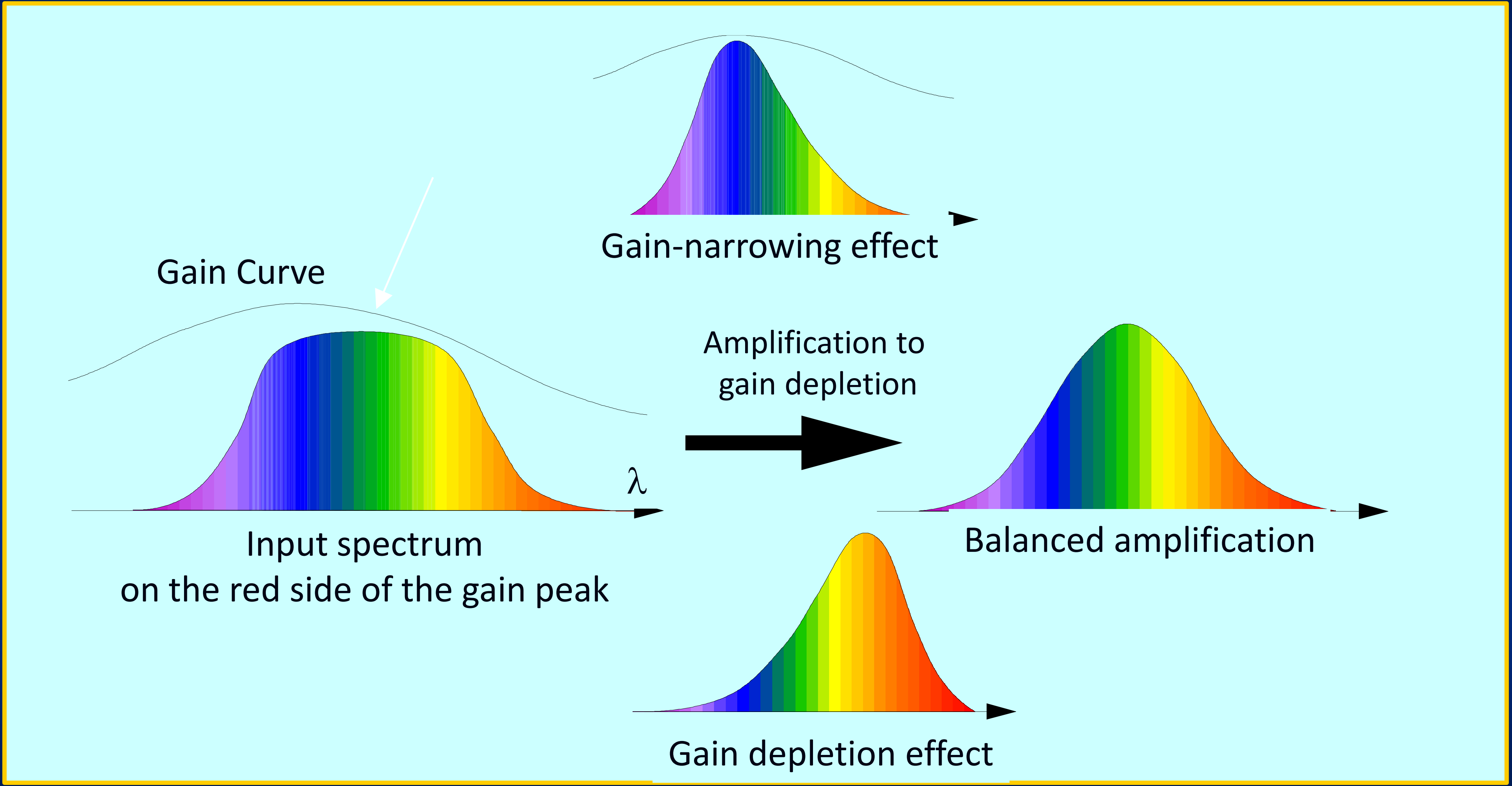
- Öffner-triplet type: minimization of spherical aberration
- All reflective type: minimization of GVD

20-fs, 3-TW Ti:Sapphire Laser at 10 Hz

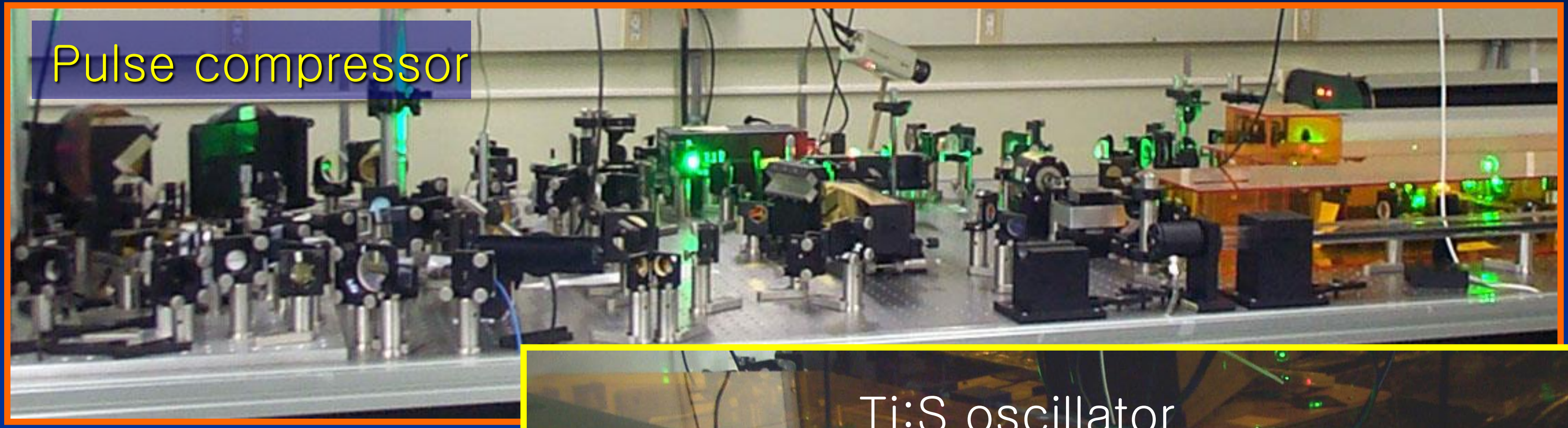


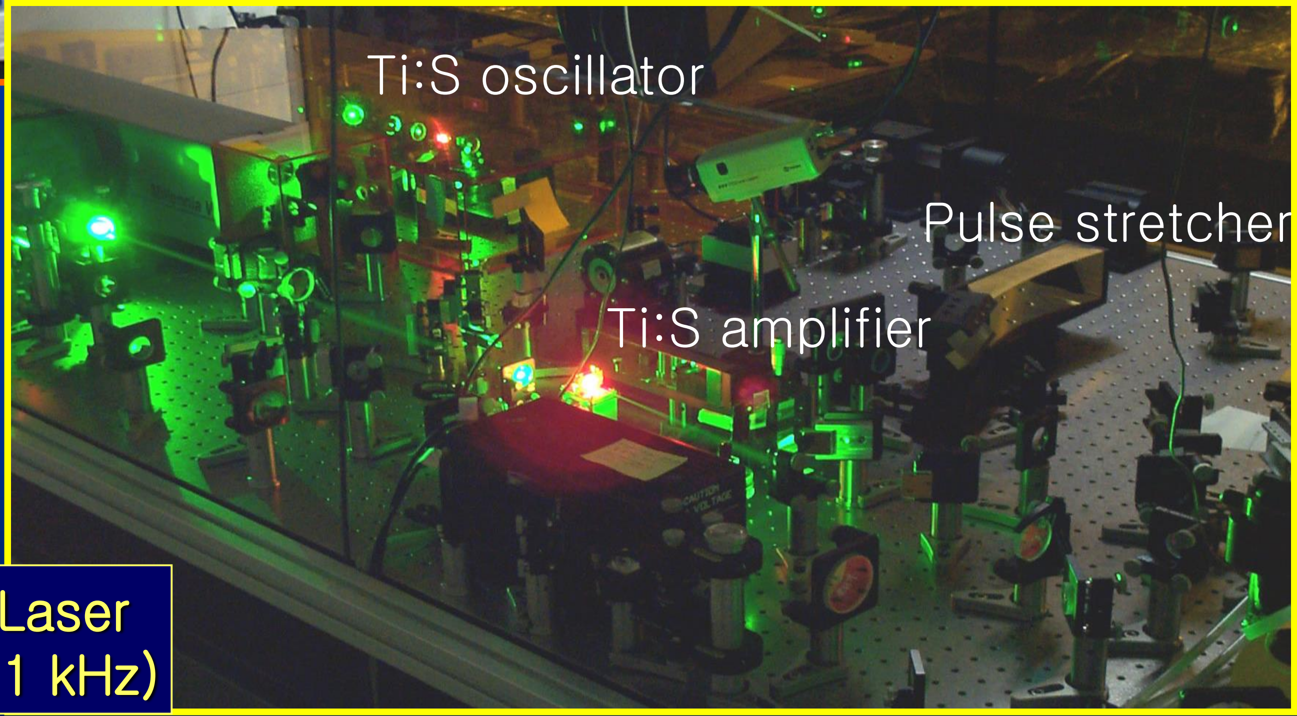
Long wavelength injection; J. Opt. Soc. Am. B 16, 1220 ('99)

Gain narrowing issue tackled with the long wavelength injection method



High Power Femtosecond Laser at KAIST





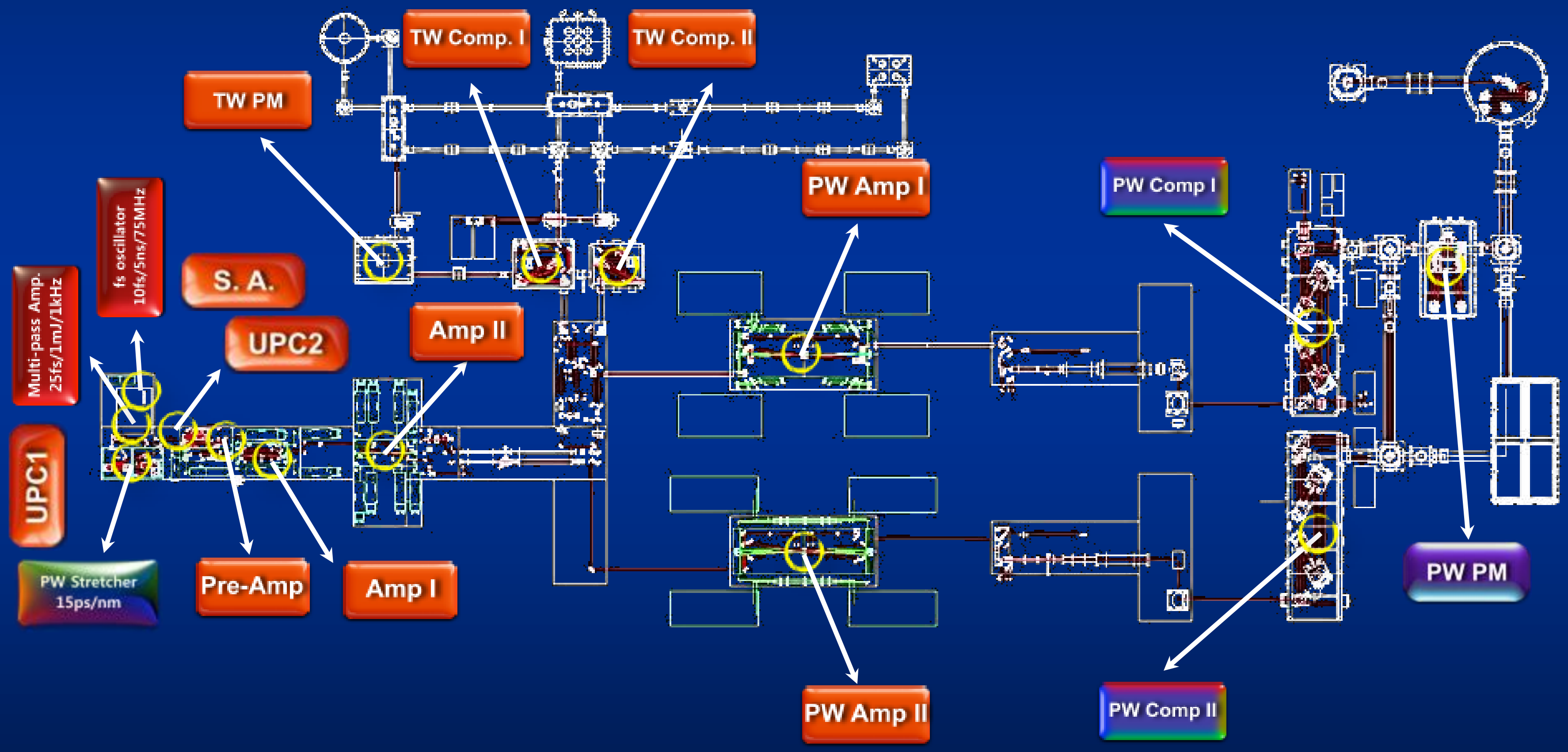
kHz Ti:Sapphire Laser
(25 fs, 0.2 TW @ 1 kHz)

Ultrashort Quantum Beam Facility (2003 - 2012) (PI: J. Lee)

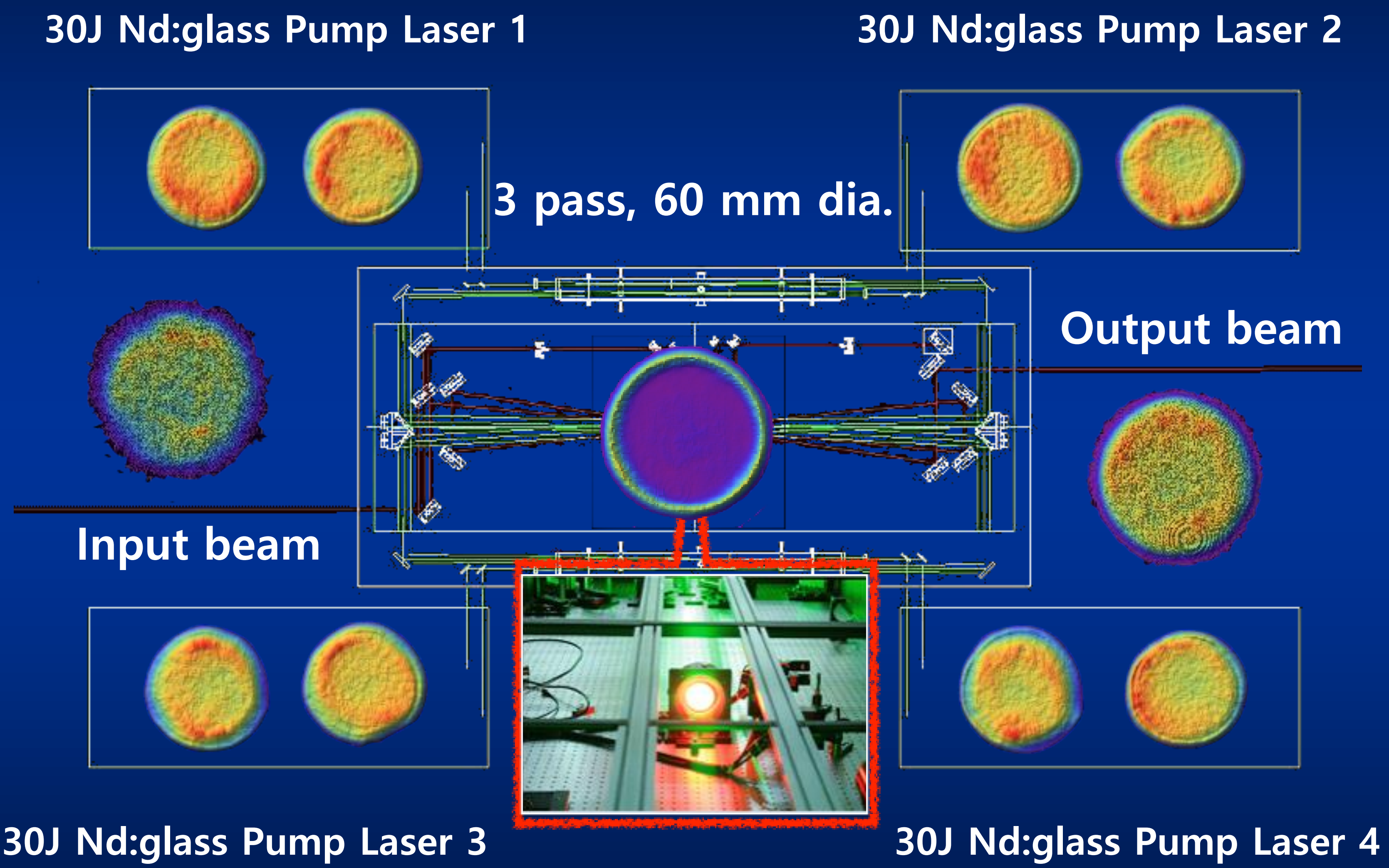
Completion of UQBF Building (2008.11)

PW Laser Beamline I & II

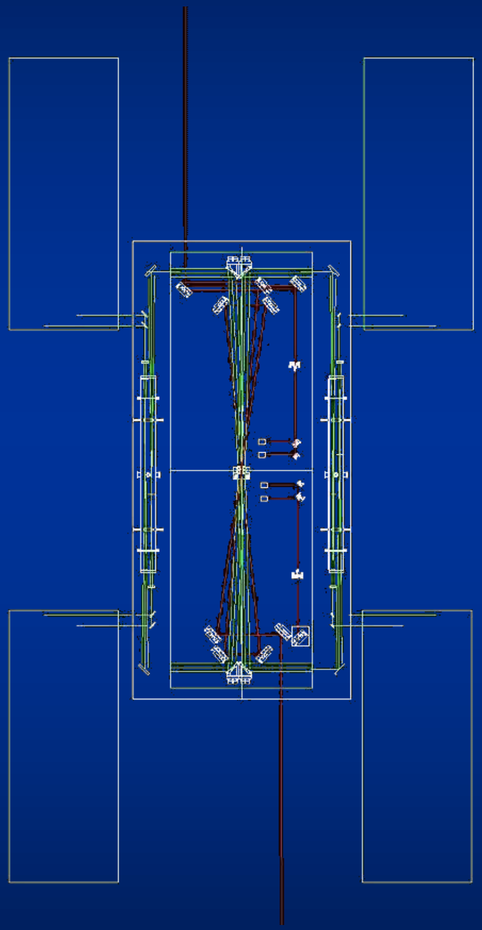
2009
2012

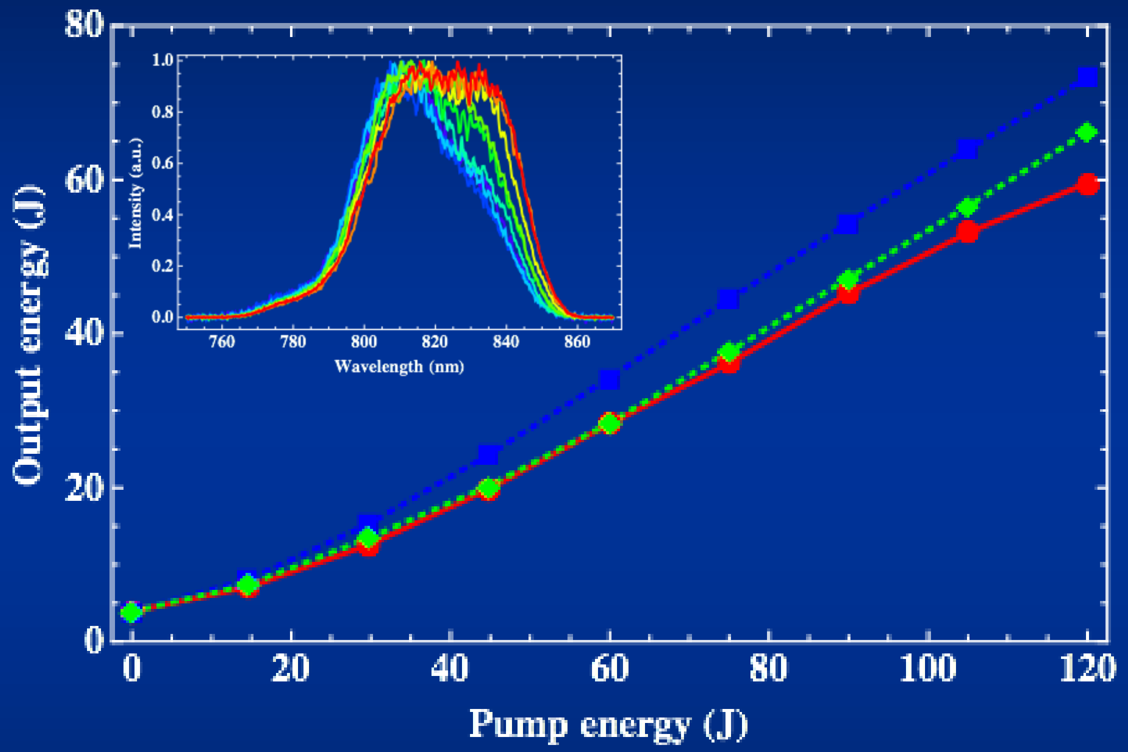


Beam Uniformity in PW Amplifier II



PW Amplifier II: Output Energy vs Pumping energy





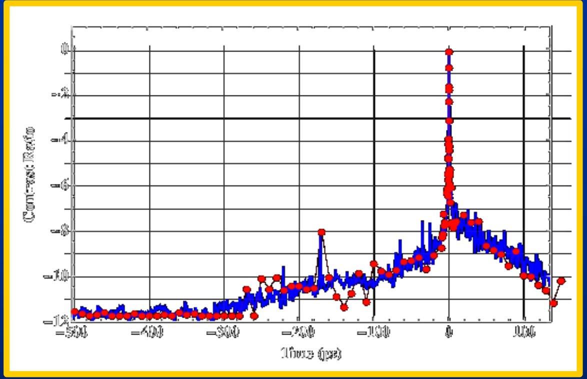
Measured output energy

2D F-N simulation

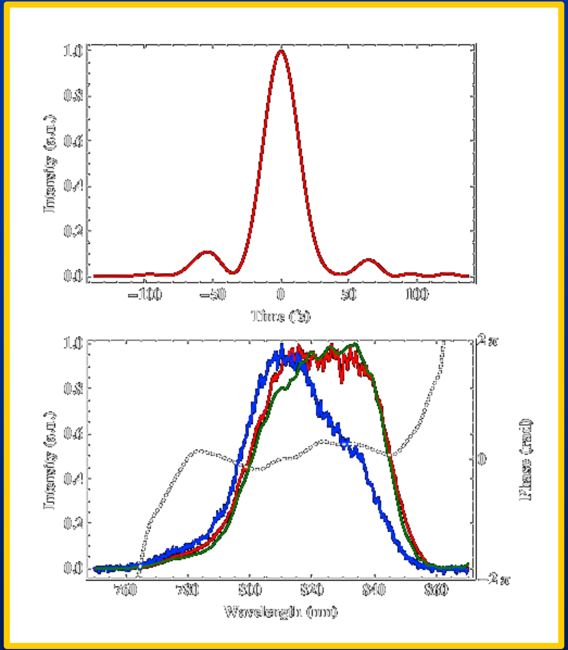
1D F-N simulation

High contrast, 30 fs, 1.5 PW Laser

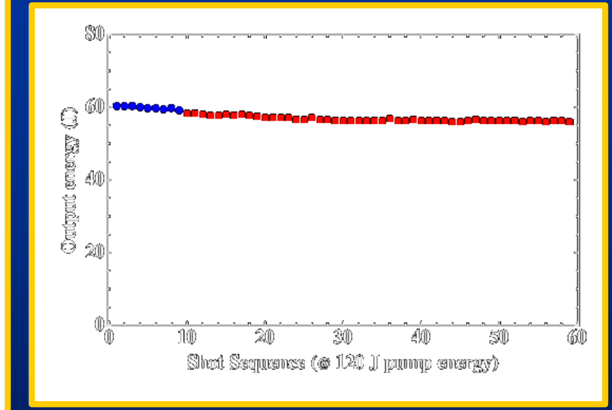
High contrast



30 fs



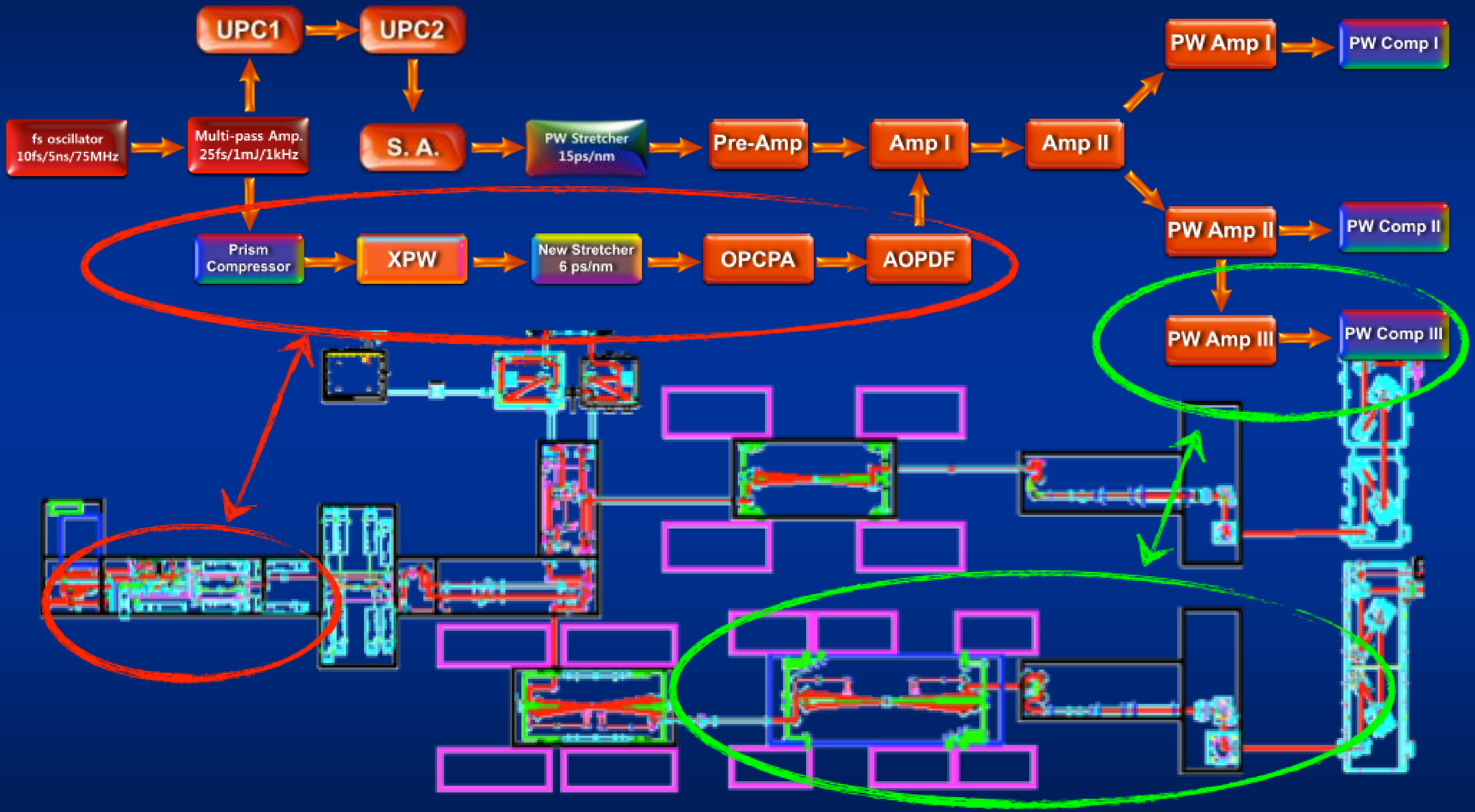
1.5 PW



IBS Center for Relativistic Laser Science since 2012

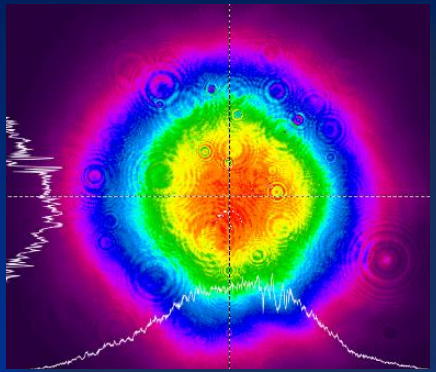
- PW Ti:Sapphire Laser
  - (1) Beamline I: 20 fs, 1 PW @ 0.1 Hz
  - (2) Beamline II: 20 fs, 4 PW @ 0.1 Hz
- 150-TW Laser: Δt = 25 fs @ 5 Hz

Upgrade: High Contrast, 20 fs, 4 PW Laser

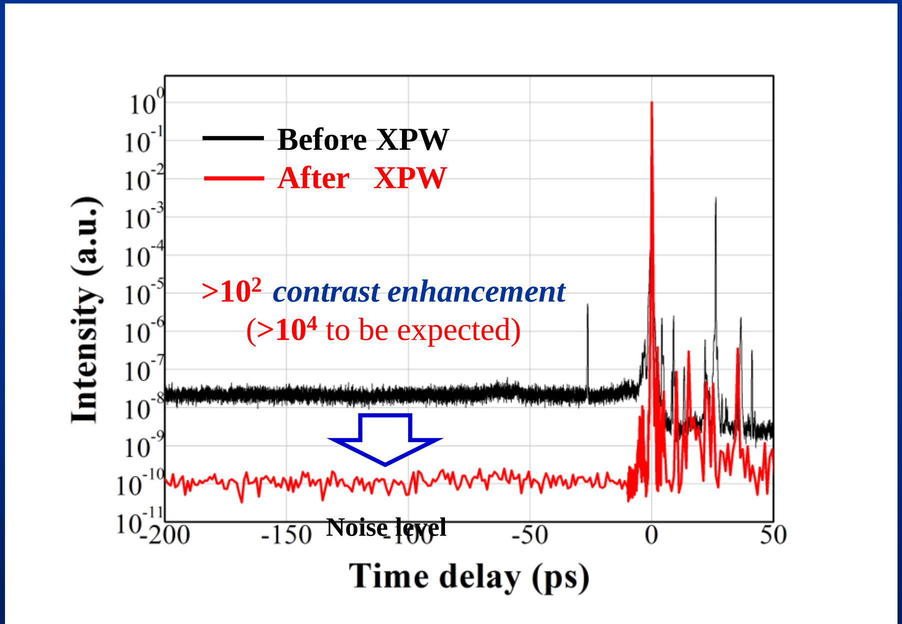


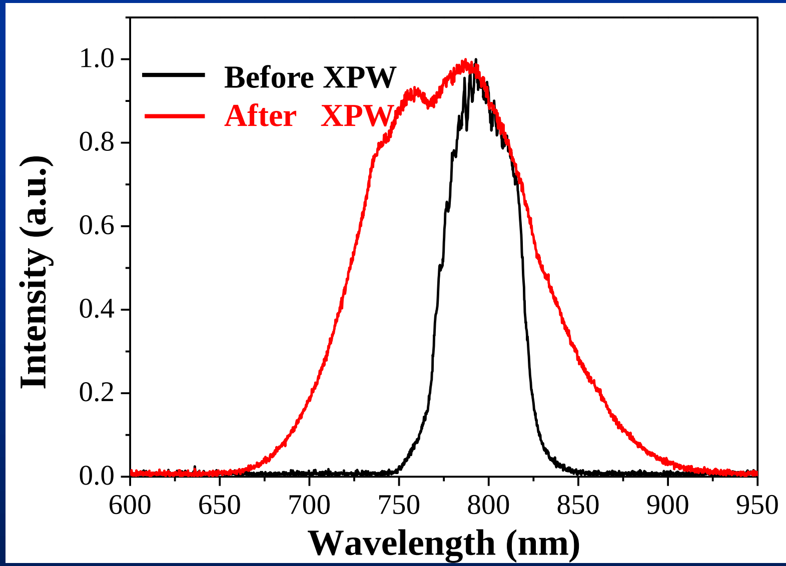
High contrast, broadband seed pulse with XPW

- Input pulse: 3 mJ, 25 fs
- Hollow fiber: 250-µm core, 20-cm long
- Energy after BaF_2 XPW: 500 µJ (16 %)



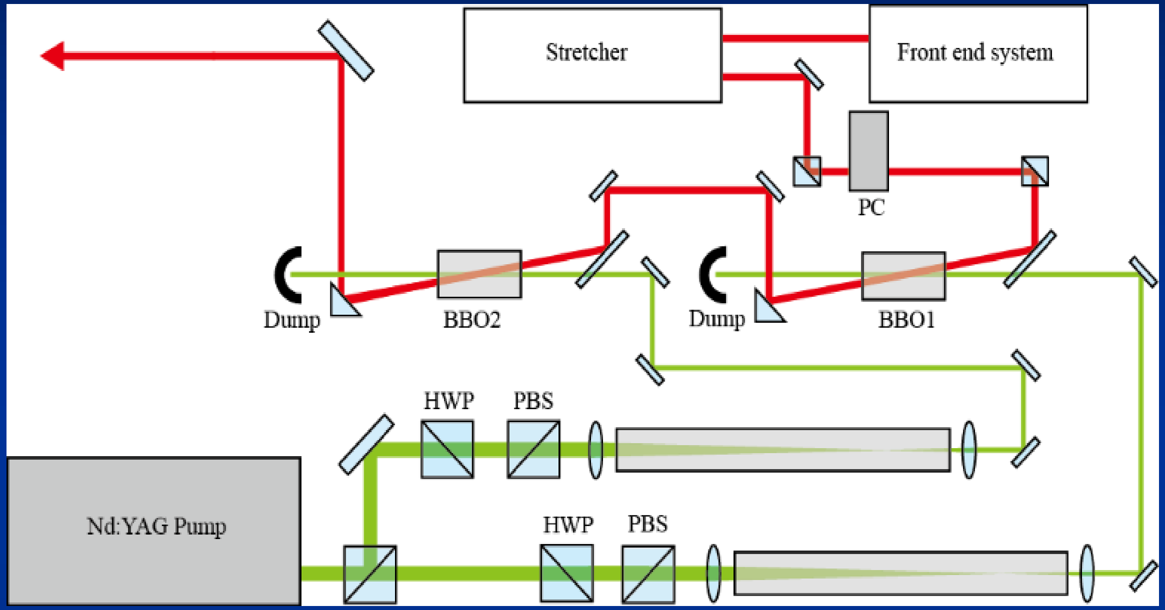
Beam profile after XPW

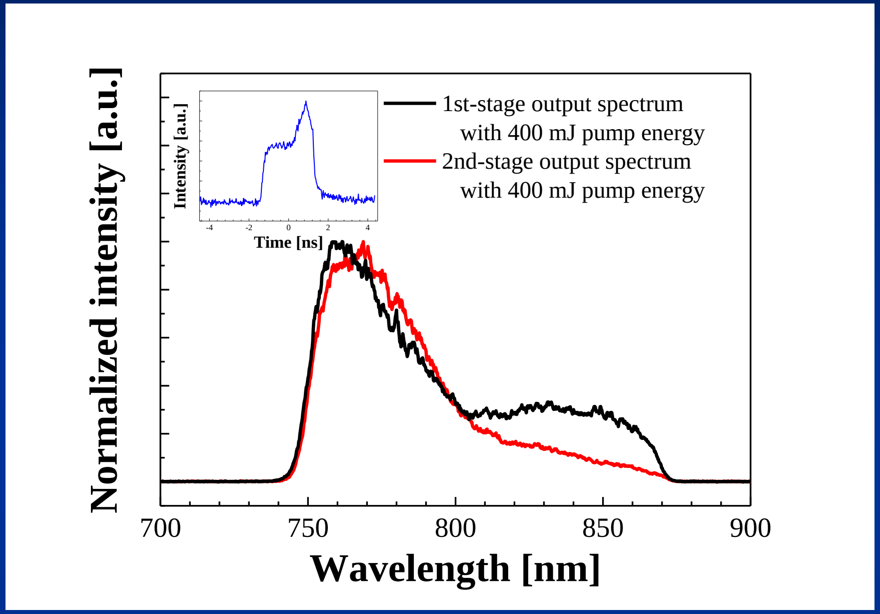




Two-stage OPCPA pre-amplifier

Two-stage OPCPA amplifier with a temporally shaped pump laser

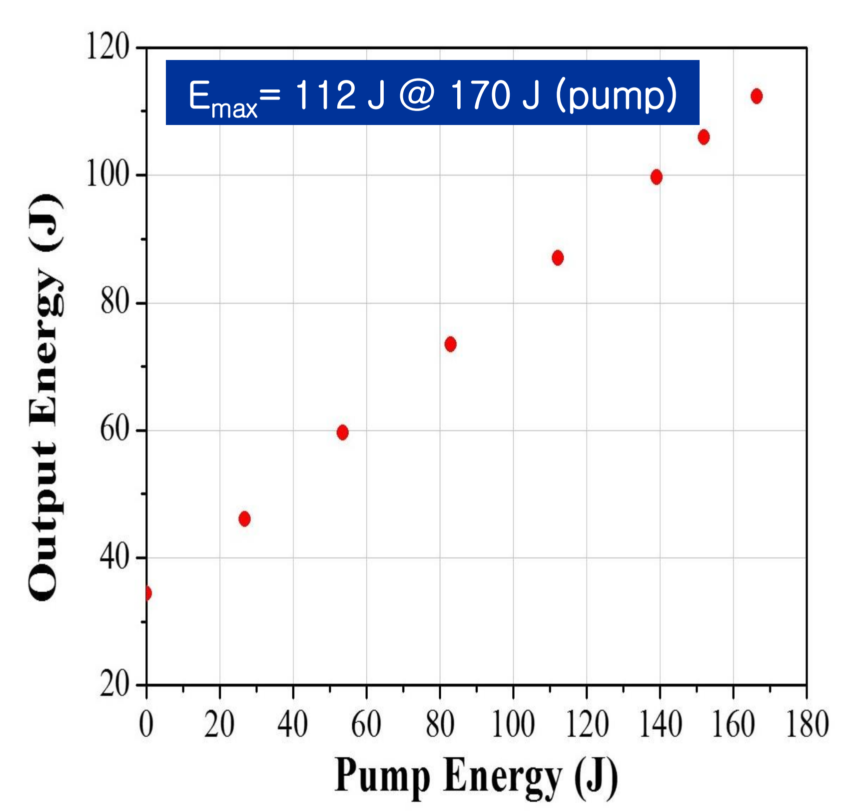


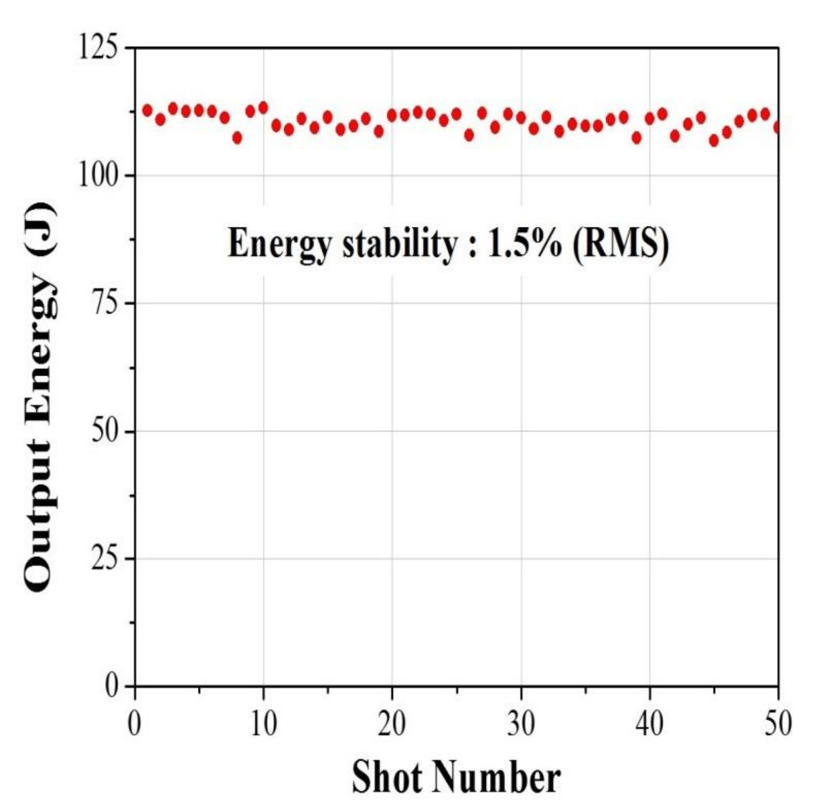


Max output energy: 240 mJ
Total efficiency: 30%

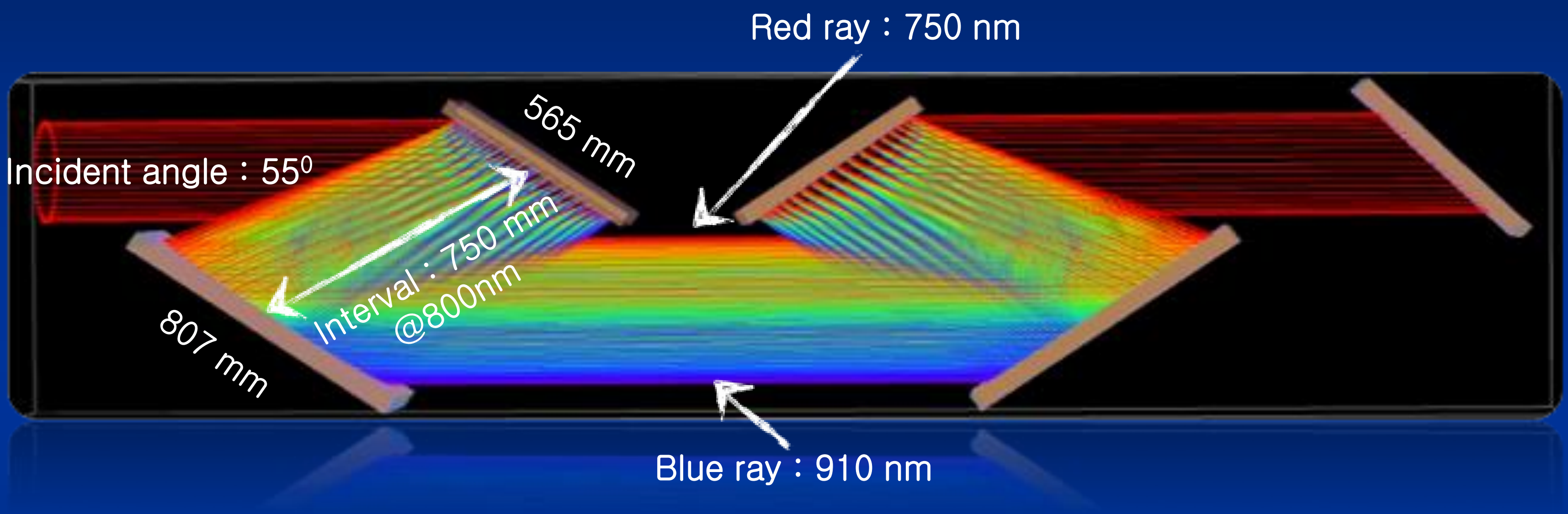
A spectrally shaped OPCPA pre-amplifier was employed to realize a high-contrast, 20 fs, 4 PW laser.

Energy and Stability of Final Booster Amplifier



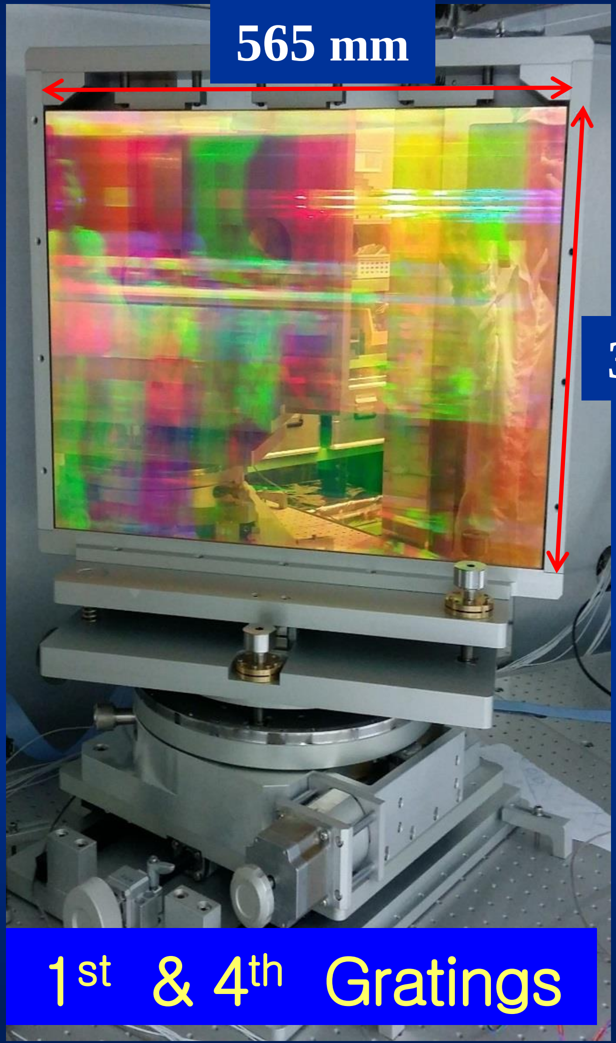


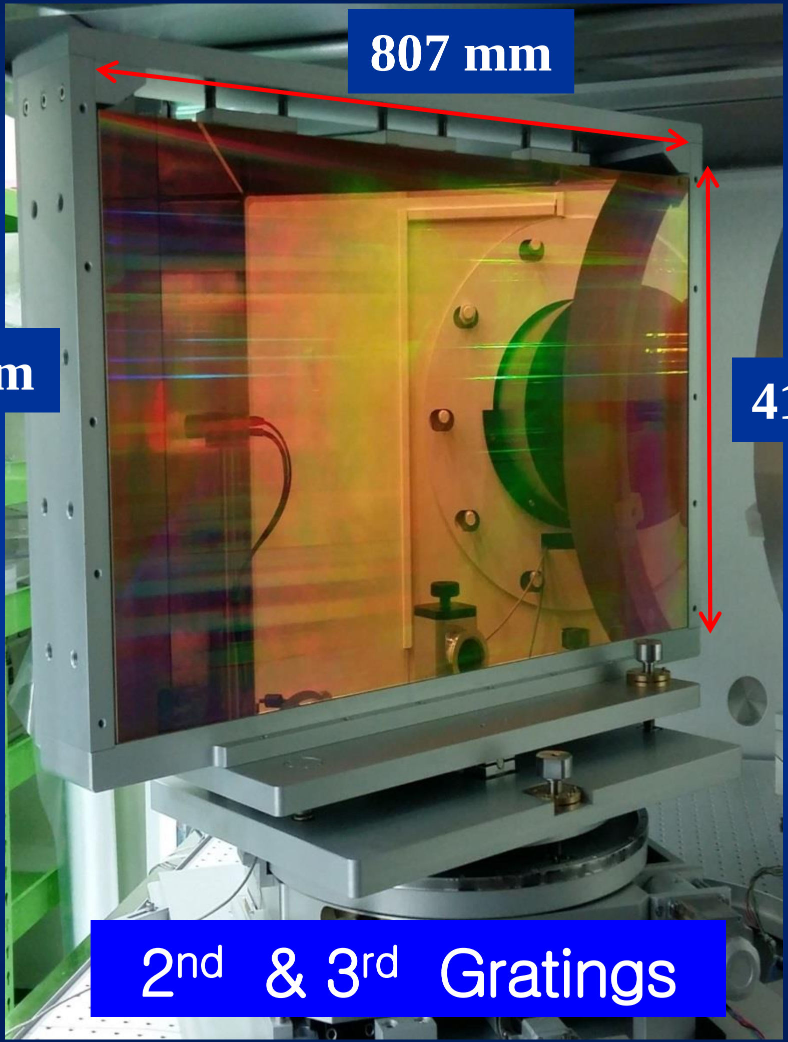
Pulse compressor



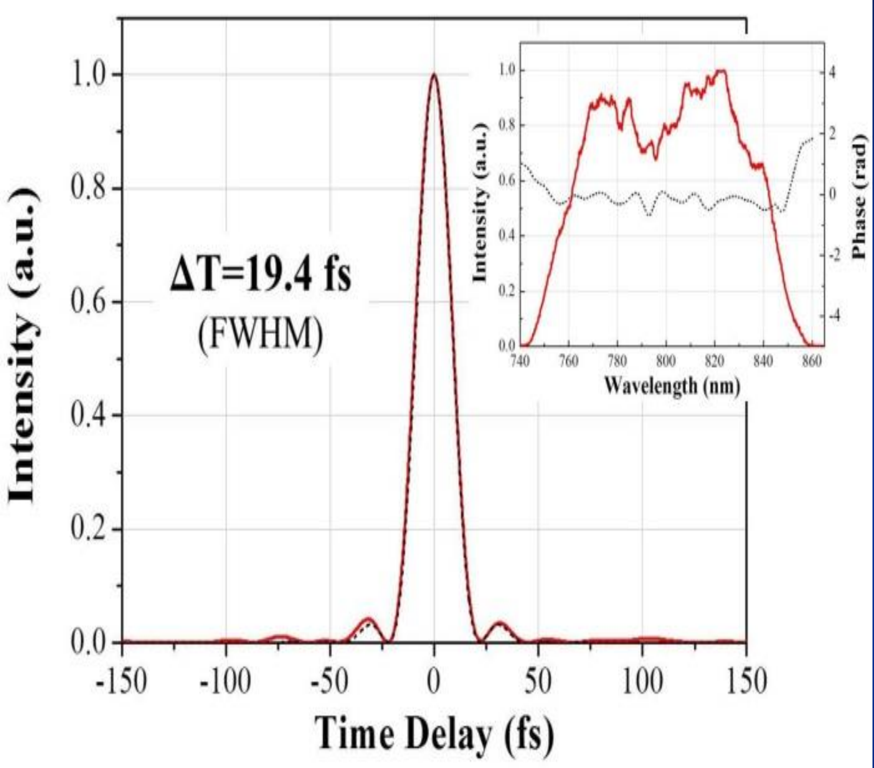
Optical Ray Tracing for 4 PW Pulse Compressor

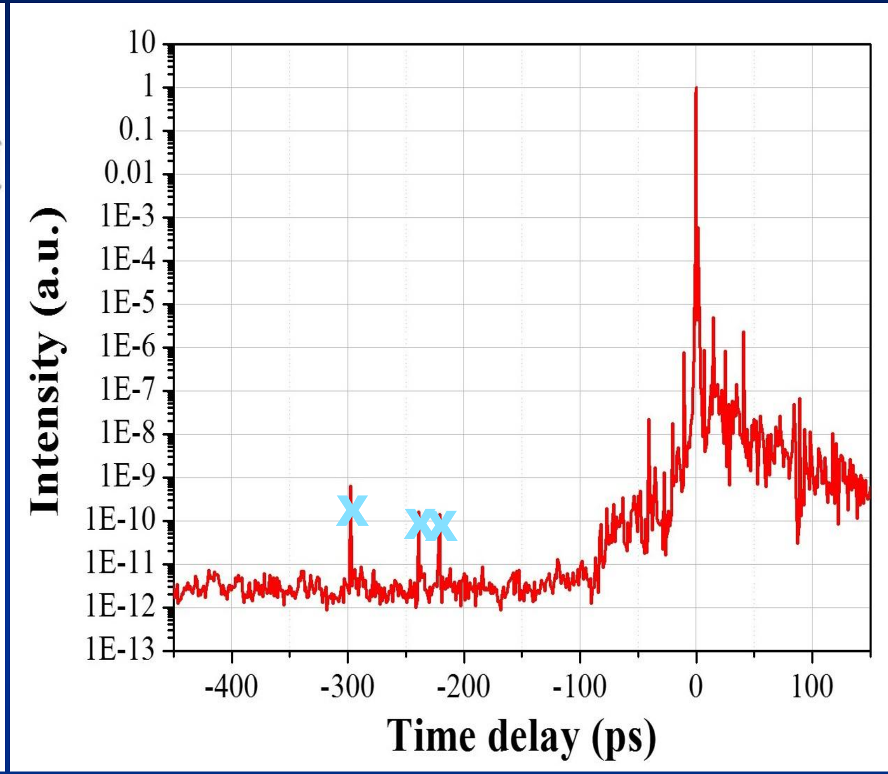
Pulse Compression Gratings





Temporal Profile and Contrast of 4 PW Laser





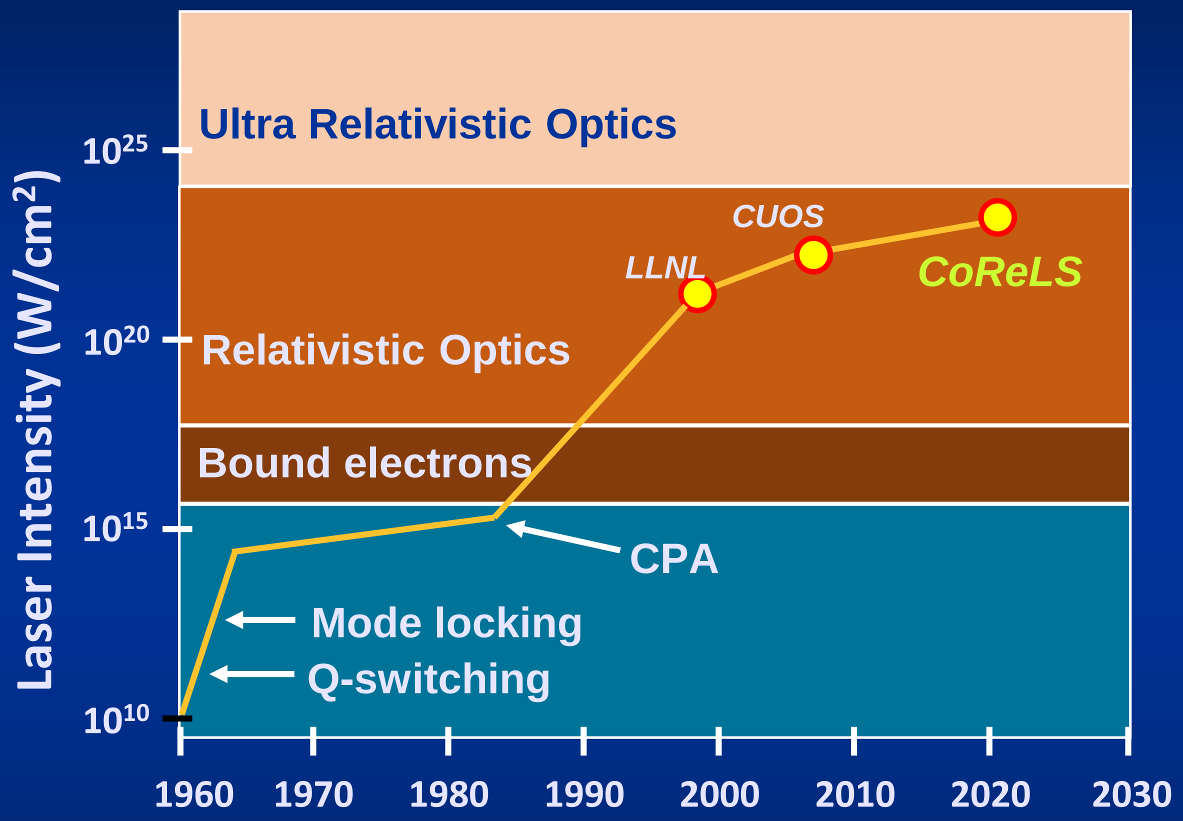
83J, 19.4fs, 4.2PW!

Sung et al., Opt. Lett. (2017)

CoReLS PW laser: 1 PW + 4 PW Beamlines

JH Sung, Opt. Lett. (2017)

Ultrahigh intensity over 10^{23} W/cm^2

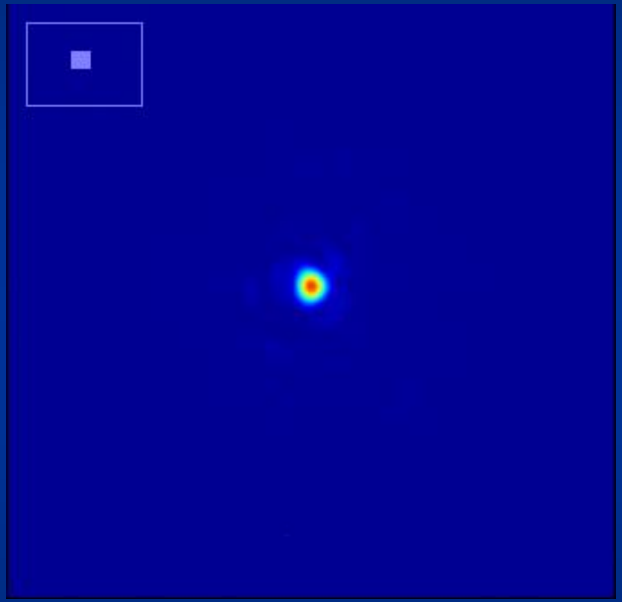


Evolution of laser intensity

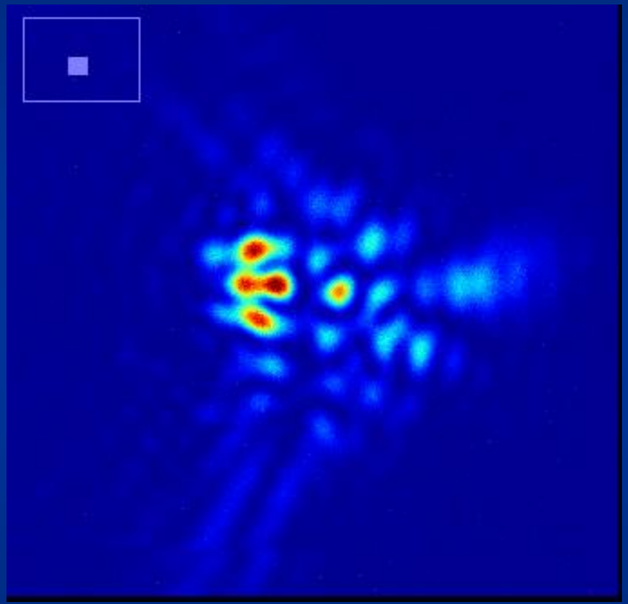
- Nova laser (**1.3 PW**) @ LLNL
  → 7×10^{20} W/cm^2 (1999)
- CUOS HERCULES laser (**300 TW**)@ Univ. of Michigan
  → 2×10^{22} W/cm^2 (2008)
- J-KAREN-P laser (**1 PW**) @ KPSI, QST
  → 1×10^{22} W/cm^2 @ 0.3 PW (2017)
- SULF laser (**5 PW**) @ SIOM
  → 2×10^{22} W/cm^2 (2018)
- Texas Petawatt Laser (**1 PW**) @ Univ. of Texas
  → 2×10^{22} W/cm^2 (2019)
- CoReLS PW laser @ IBS (**4 PW**)
  → 5.5×10^{22} W/cm^2 @ 3.0 PW (2019)
  → 1.1×10^{23} W/cm^2 @ 2.7 PW (2021)

Focal spot and laser intensity

In order to achieve the highest intensity, the focal spot should be a **single spot with the smallest size.**



Focal spot w/o wavefront distortion

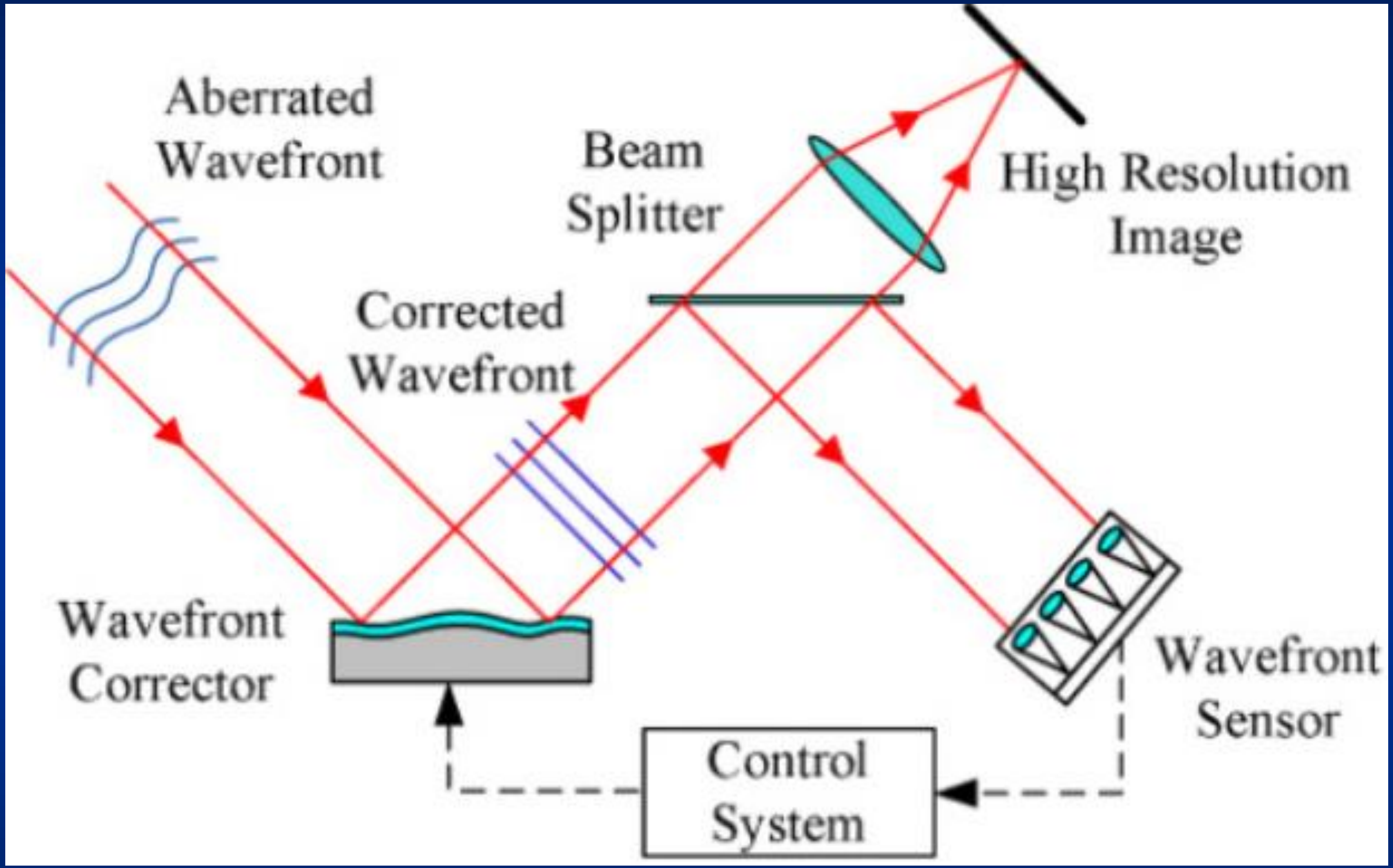


Focal spot with distorted wavefront

- Wavefront distortion in a high power laser
- Inhomogeneities in amplifying media
- Thermal loading
- Distortions from optical components

→ **An adaptive Optics system**

Adaptive Optics System

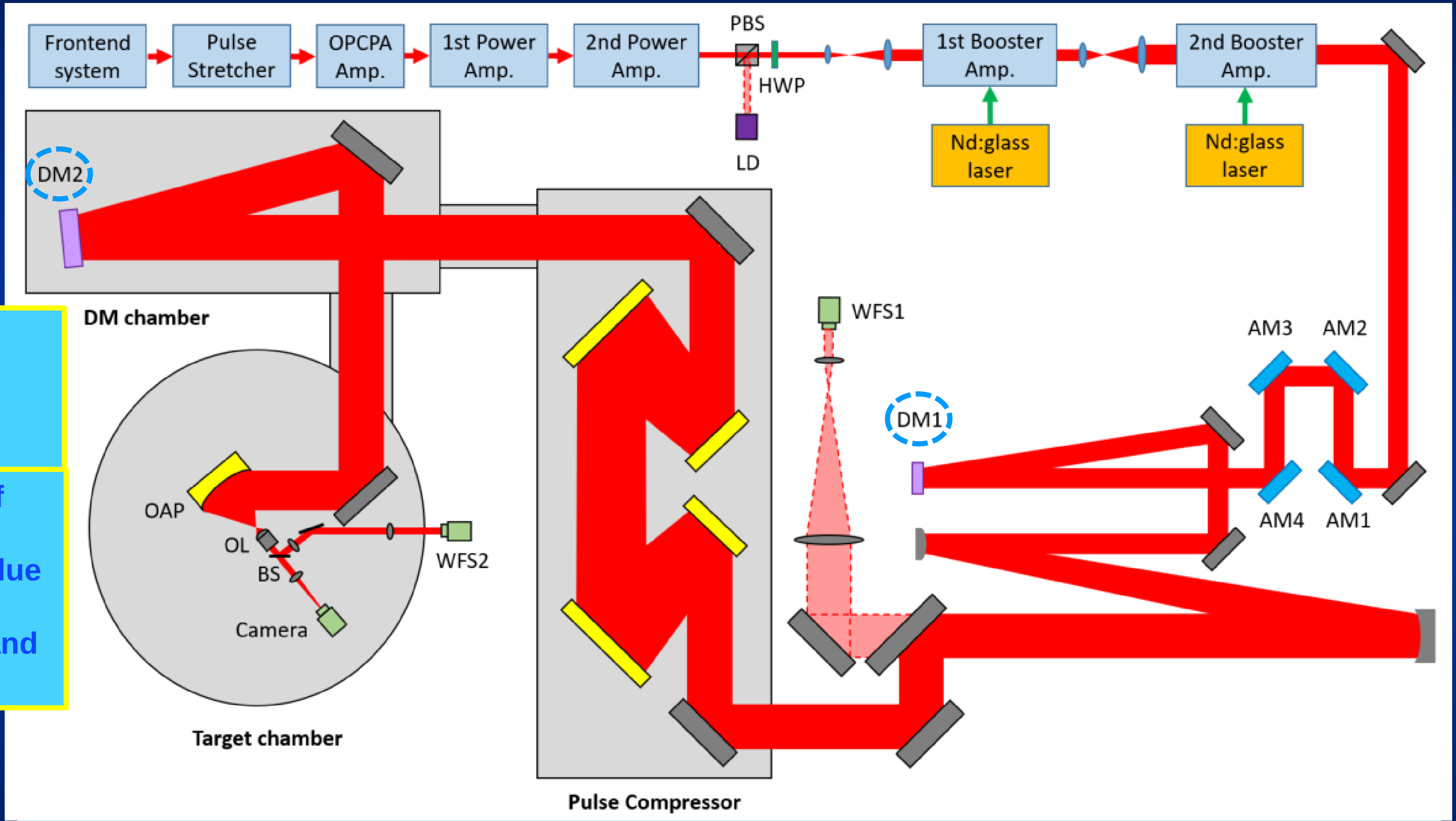


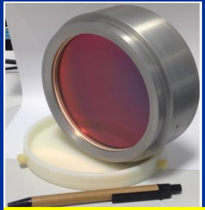
Principle of Adaptive Optics System

Optical layout of the 4 PW laser

- DM2
- Bimorph type
- 300 mm dia.
- 127 actuators

Compensation of the residual wavefront error due to the large aperture optics and focusing optics





- DM1
- Bimorph type
- 100 mm dia.
- 48 actuators

Wavefront correction of an amplified beam before the pulse compressor

wavefront correction with a two-stage adaptive optics system

Bimorph Deformable Mirror 1 (DM1)

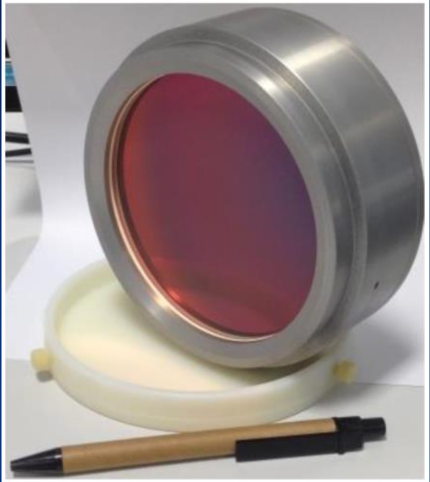
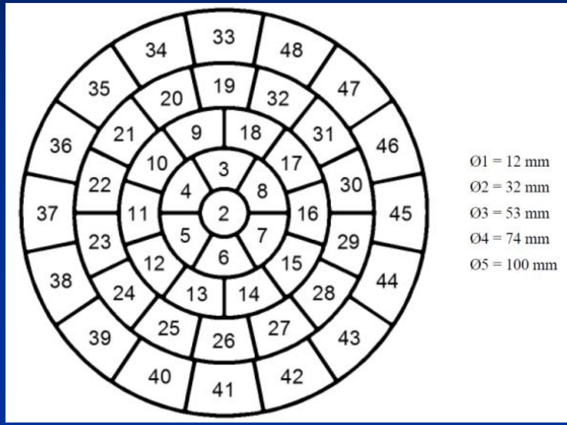
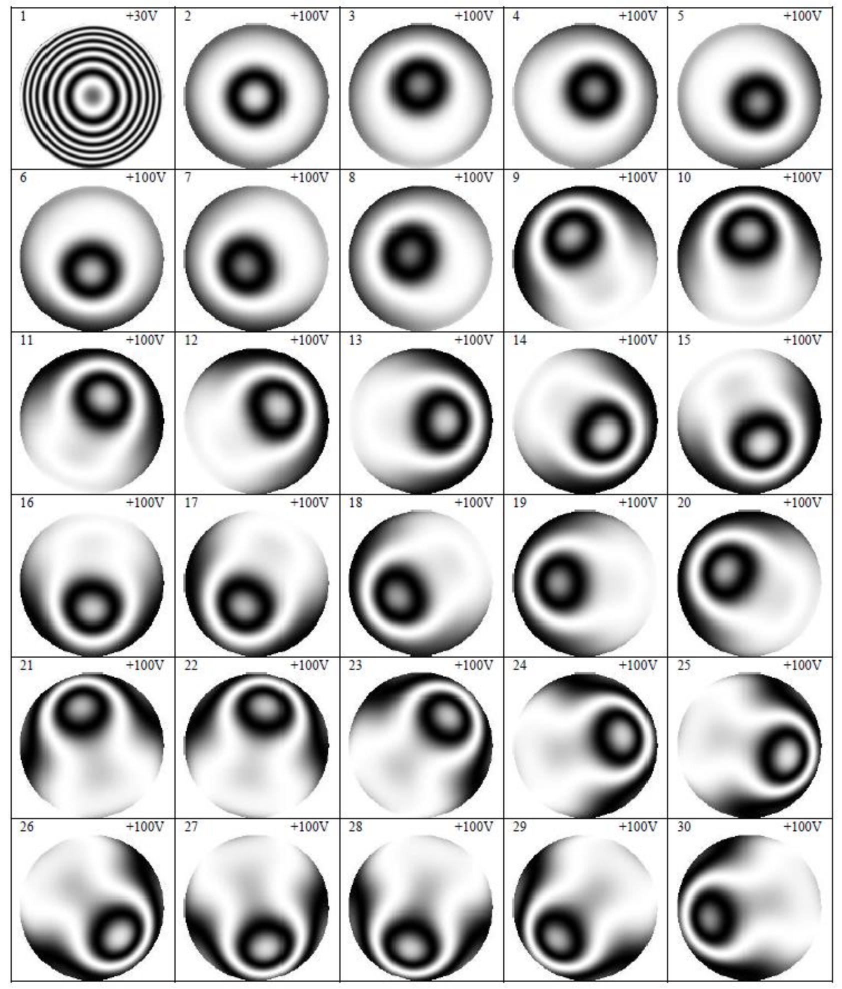


Photo of DM1
(bimorph type; AKA optics)



Scheme of electrode configuration

- Active diameter: 100 mm
- # of electrodes: 48
- Reflectivity: 99.9% (750 - 850 nm)
- Max. defocus stroke: ±10 μm



Interferograms of the mirror response functions

Large Aperture Deformable Mirror (DM2)

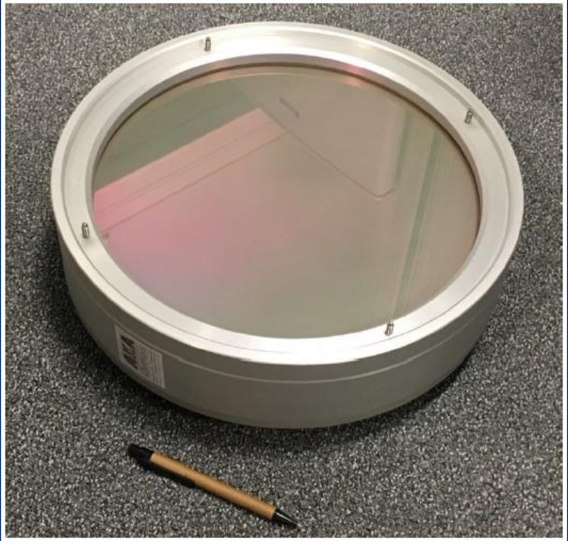
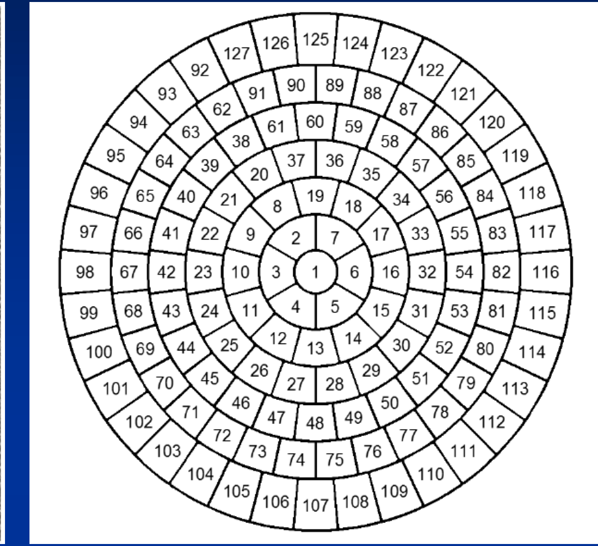
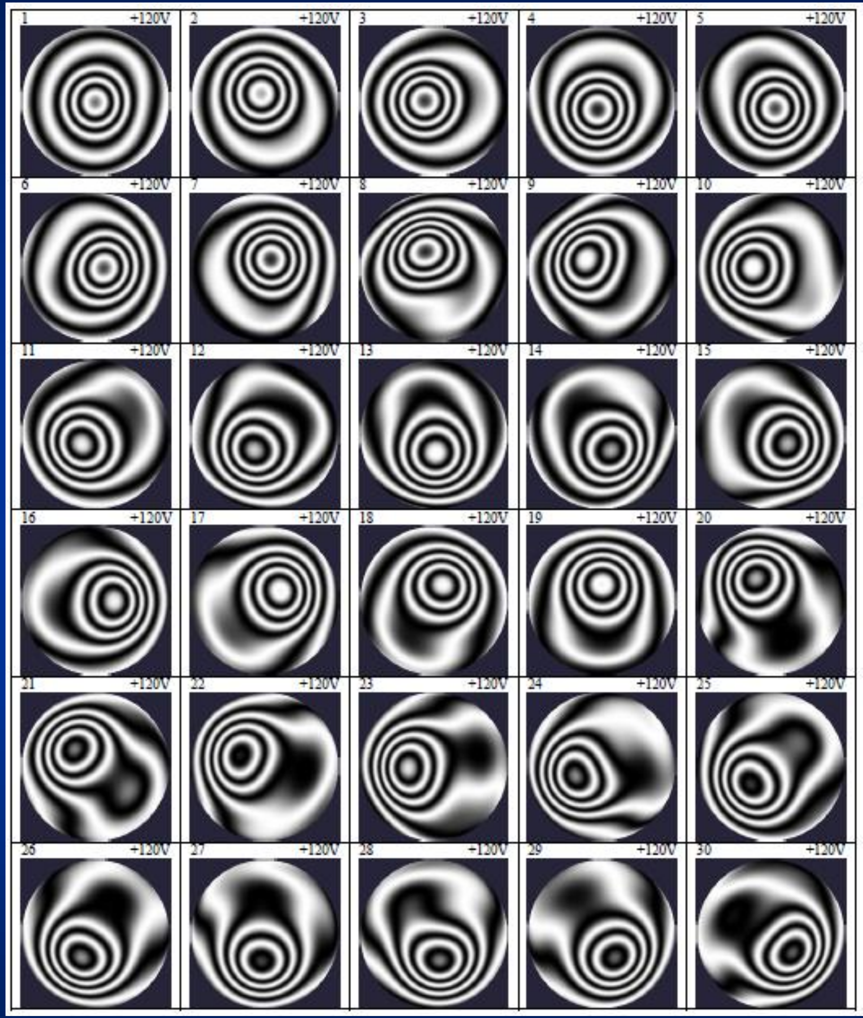


Photo of DM2
(bimorph type)



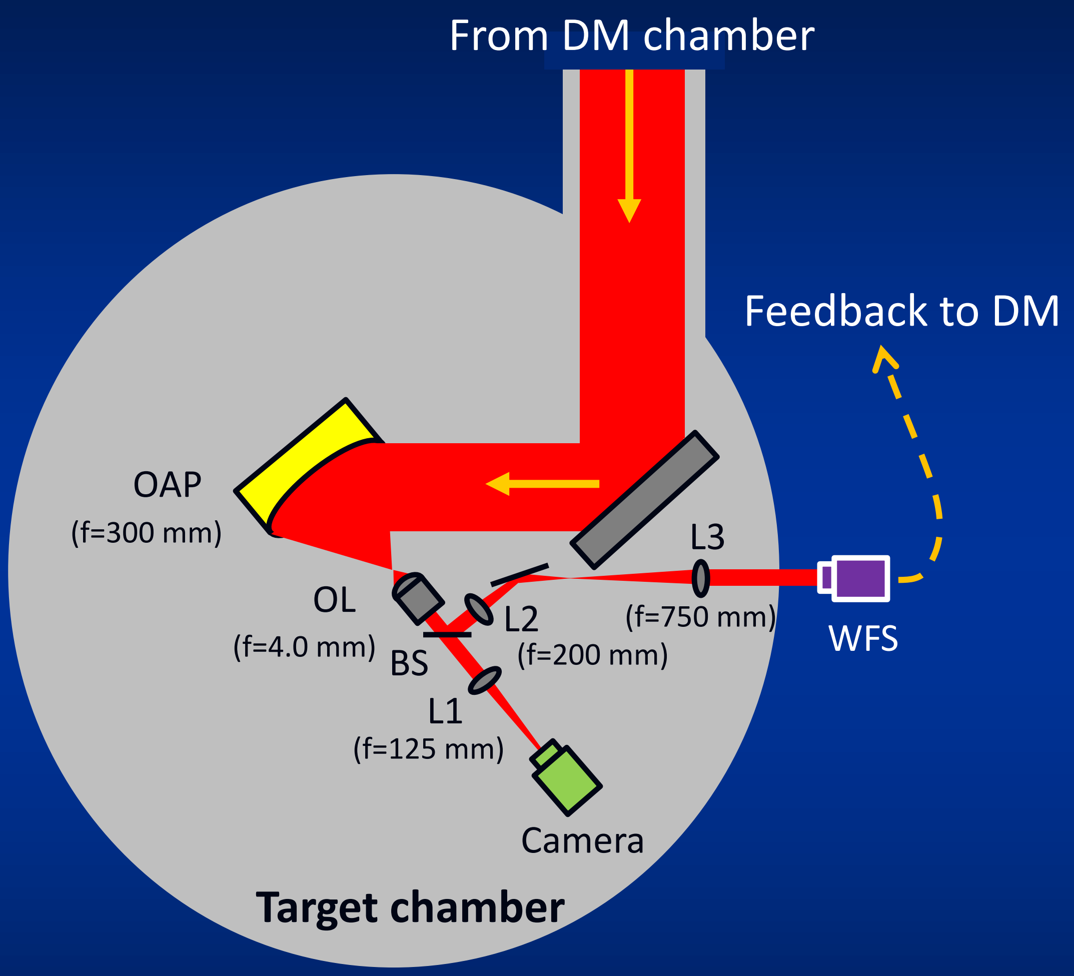
Scheme of electrode configuration



Interferograms of the mirror response functions

Active diameter: 300 mm
# of electrodes: 127
Reflectivity: 99.9% (750 - 850 nm)

Measurement of wavefront and focal spot



Experimental setup for wavefront and focal spot measurement
(OL, Objective lens; L1~3, Lenses; BS, Beam splitter; WFS, Wavefront sensor)

- **Collimation of the focused beam**

The focused laser beam is collimated by an objective lens (OL; f = 4.0 mm) and divided into two beam by a BS.

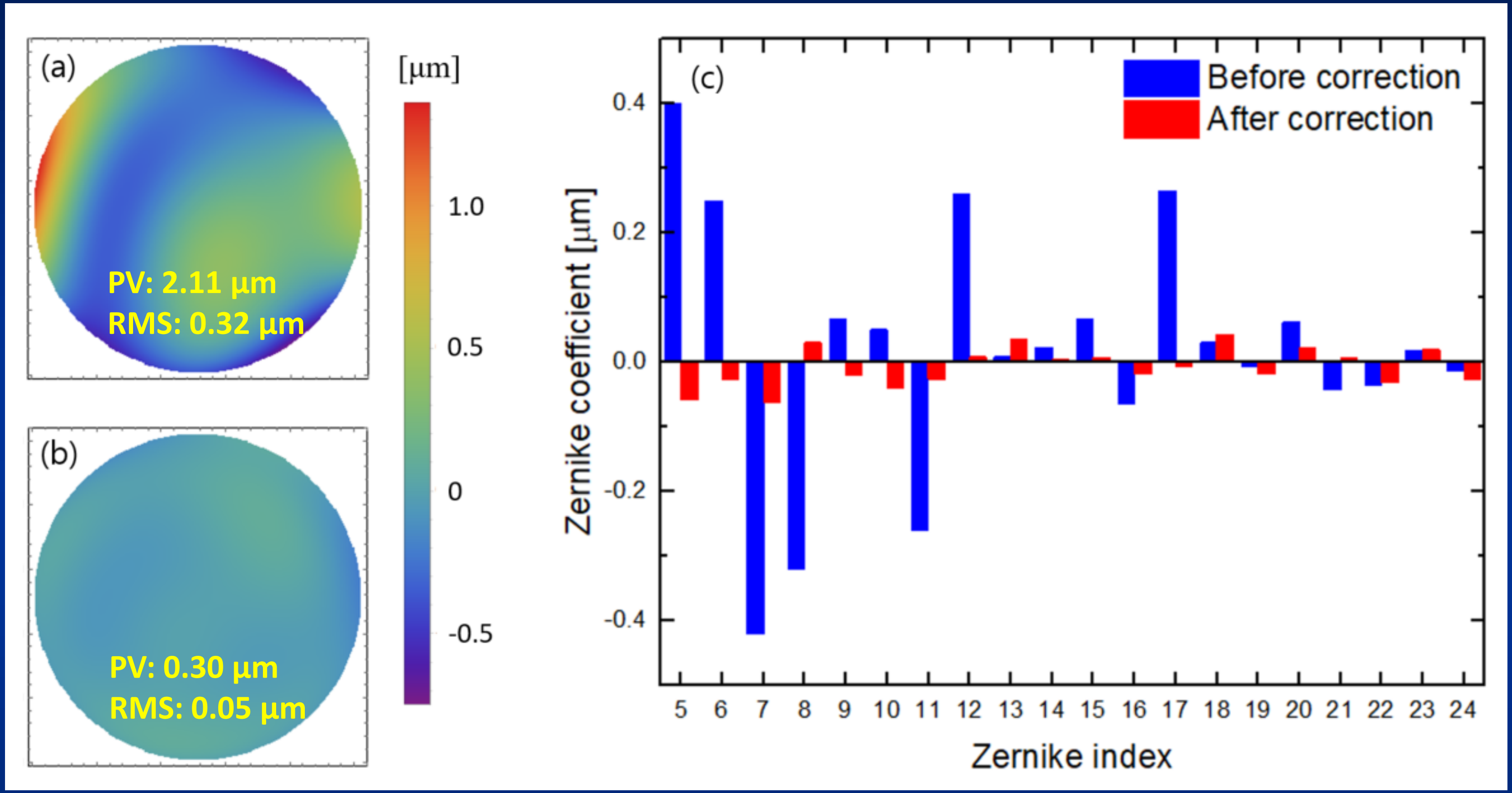
- **Wavefront measurement**

The reflected beam from the BS is relay-imaged onto a Shack Hartmann WFS with L2 and L3 (f=200 mm and f=750 mm).
Measured wavefront information is fed back to the DM control to correct the wavefront error.

- **Focal spot measurement**

Transmitted beam is focused by L1 (f=125 mm) and the focused beam image is measured by a camera.

Wavefront correction @ target area



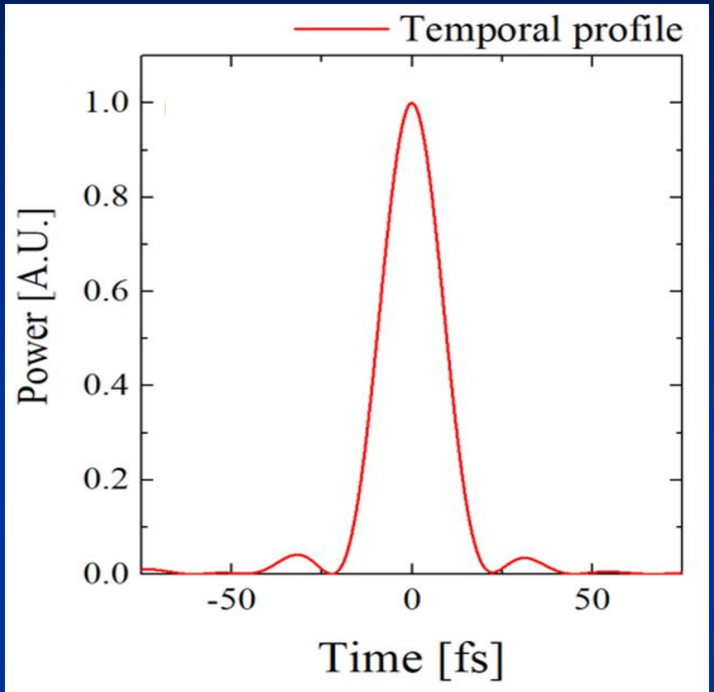
Zernike index	Aberration (Low order)
1	Piston
2	X Tilt
3	Y Tilt
4	Defocus
5	0° Astig
6	45° Astig
7	X Coma
8	Y Coma
9	Spherical
10	0° Trefoil
11	45° Trefoil

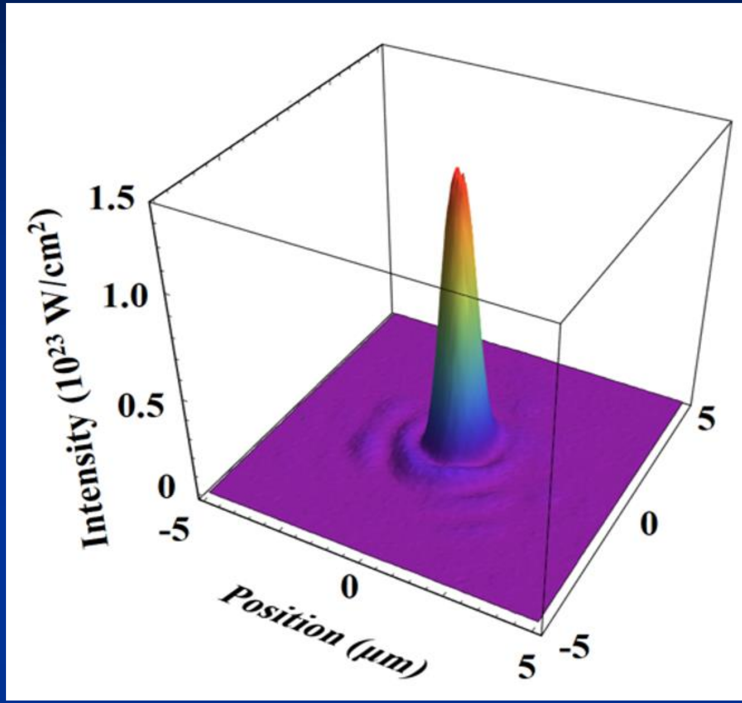
Wavefront maps measured at the target area (a) before the wavefront correction, (b) after the wavefront correction, and (c) the comparison of the Zernike coefficients before and after the wavefront correction

Measurement of Peak Laser Intensity

$$I_0 = \frac{E_0}{\tau_{eff} A_{eff}}$$

$$= P_0 / A_{eff}$$





$$P_0 = E_0/\tau_{eff} = E_0 / \int p(t)dt$$

τ_{eff}: effective pulse width
$p(t)$: normalized optical power
E_0 = 55.6±1.2 J

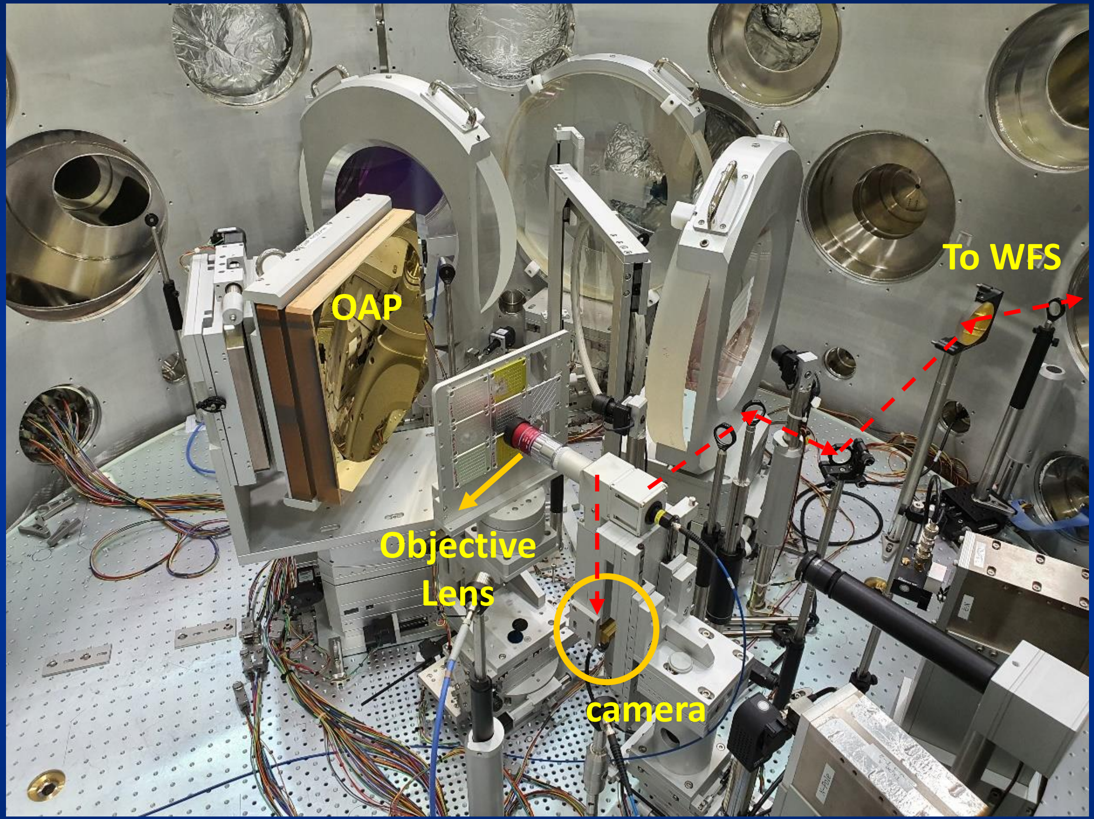
→ $P_0 = 2.7\ PW$

$$I_0 = E_0/(\tau_{eff} A_{eff}) = P_0/A_{eff} = P_0 / \int i(x,y)\, dxdy$$

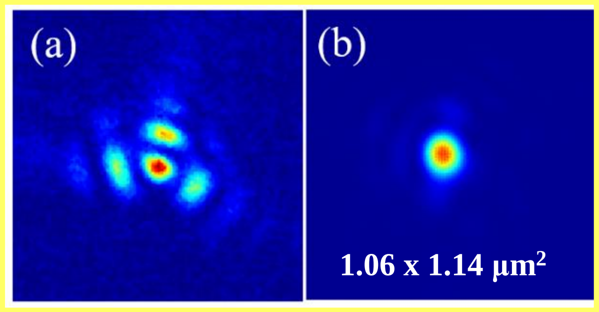
A_{eff}: effective spot area
$i(x,y)$: normalized intensity distribution

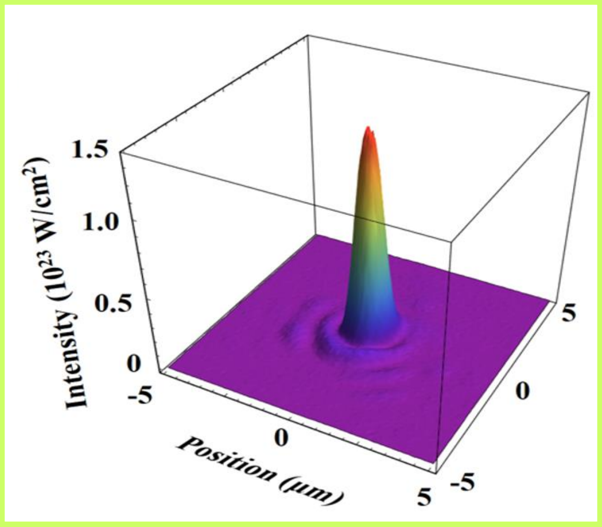
→ I_0 = 1.4 x 10^{23} W/cm^2

Record-breaking laser intensity > 10^{23} W/cm^2



Target chamber with f/1.1 OAP and imaging optics





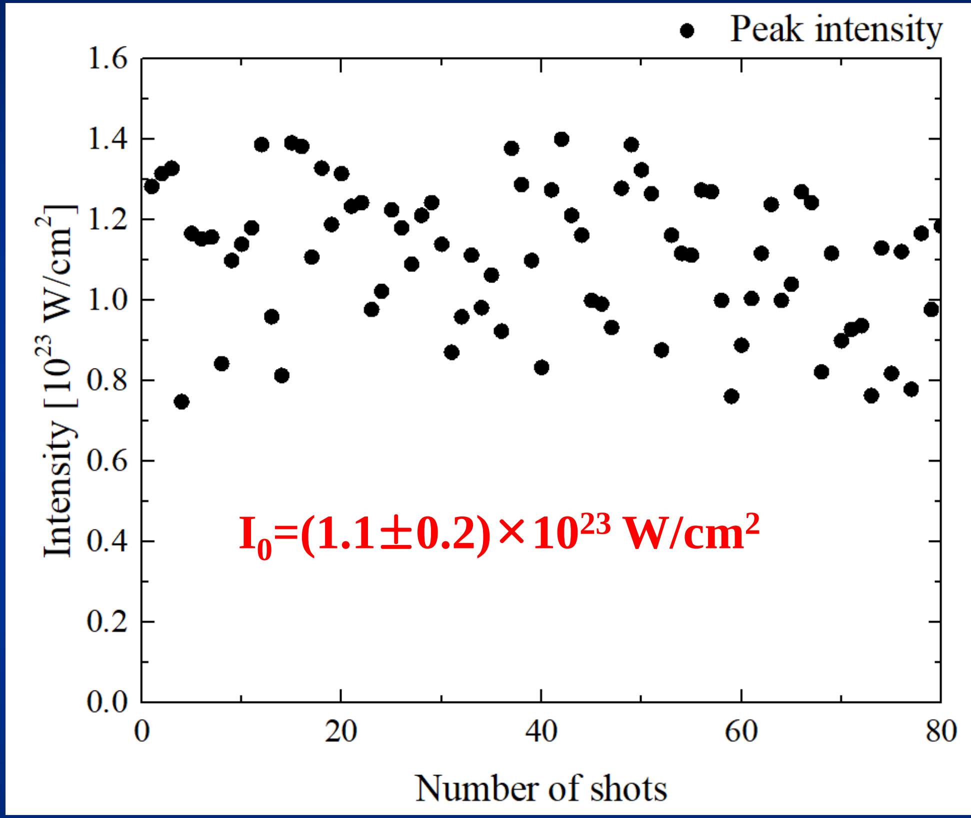
(a) before (b) after wavefront correction

Focusing with f/1.1 off-axis parabolic mirror after wavefront correction of 2.7 PW pulses,

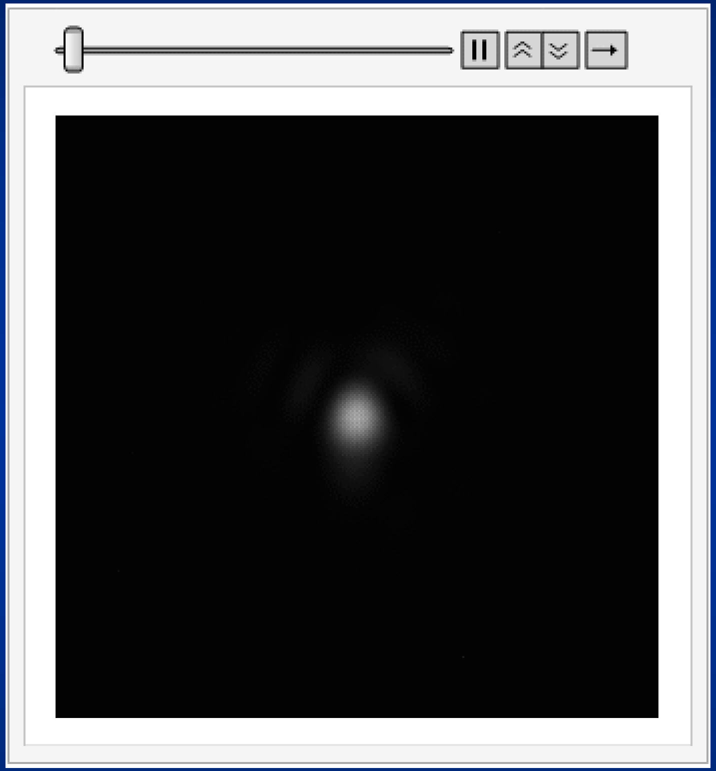
$$I = (1.1 \pm 0.2) \times 10^{23}\ \mathrm{W/cm^2}$$

JW Yoon, Optica (2021)

Stability of the focal spot and laser intensity



Measured peak intensity of the PW laser



Focal spot images
(80 consecutive shots)

Summary

1. The invention of the CPA method has prompted the development of ultrahigh power lasers.
2. CoReLS of IBS has been running the 20 fs, 4-PW laser since 2017 for the research on strong field physics.
3. The record-breaking laser intensity of $(1.1\pm0.2)\times10^{23}$ W/cm^2 was obtained by focusing wavefront-corrected 2.7 PW pulses with an f/1.1 OAP in 2021.
4. Ultrahigh power lasers open up new challenging research areas in strong field physics. The multi-PW laser has been applied to the exploration of laser-driven charged particle acceleration and strong field QED research as well as fundamental relativistic plasma physics.