Wavefront correction to improve the focused intensity of 10 PW SULF Laser

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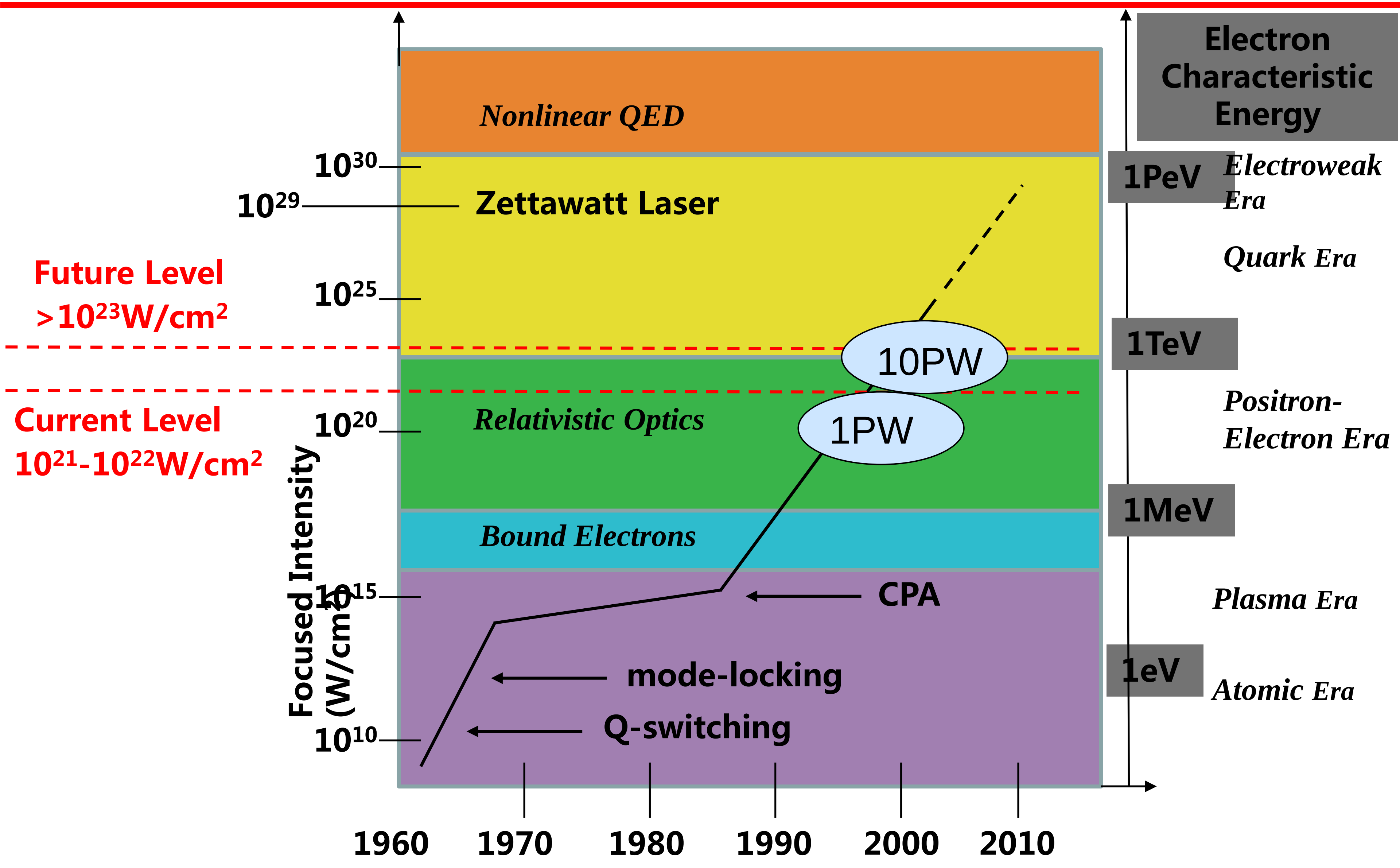
Shanghai Institute of Optics and Fine Mechanics , CAS

2020-12-01

Content

目录

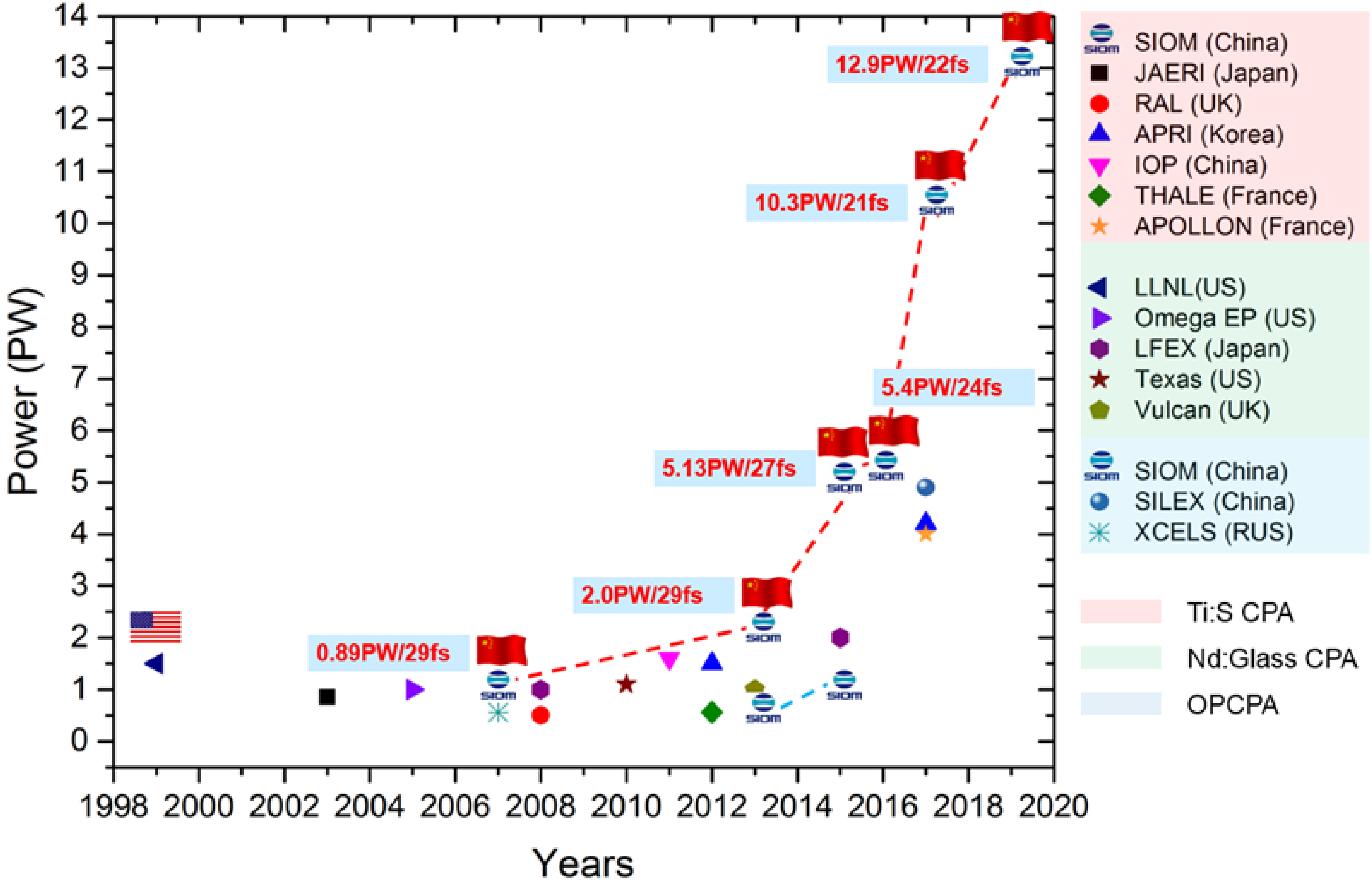
Background



G. A. Mourou, et al, Rev. Mod. Phys 78, 309 (2006).

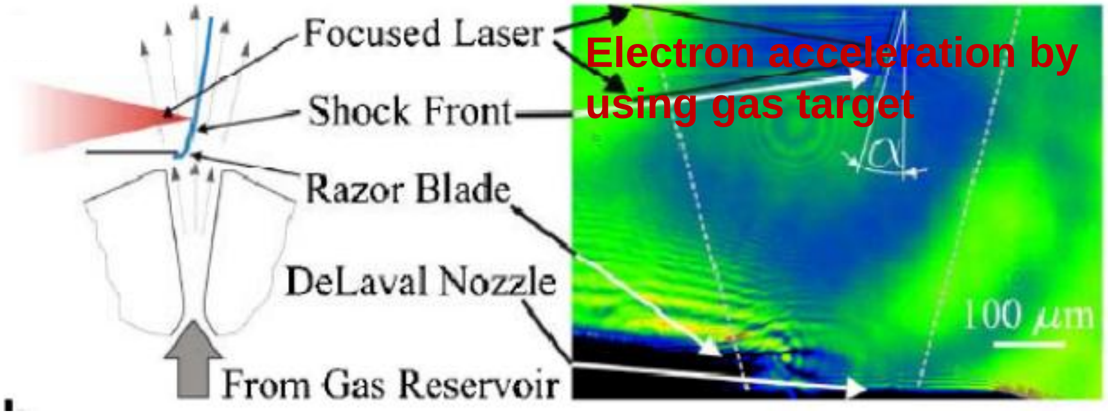
Background

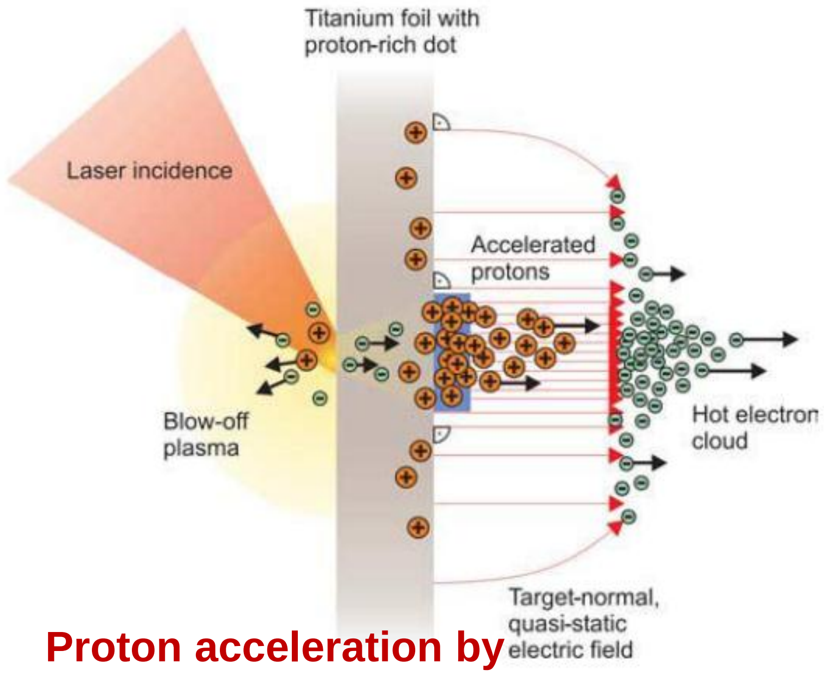
Development of Petawatt laser since the invention of CPA



Background

The focal intensity at the target plane is a critical parameter for high-field laser-matter interaction experiments.





Proton acceleration by using solid target

$$P_0 = E_0 / \tau_{\text{eff}} .$$

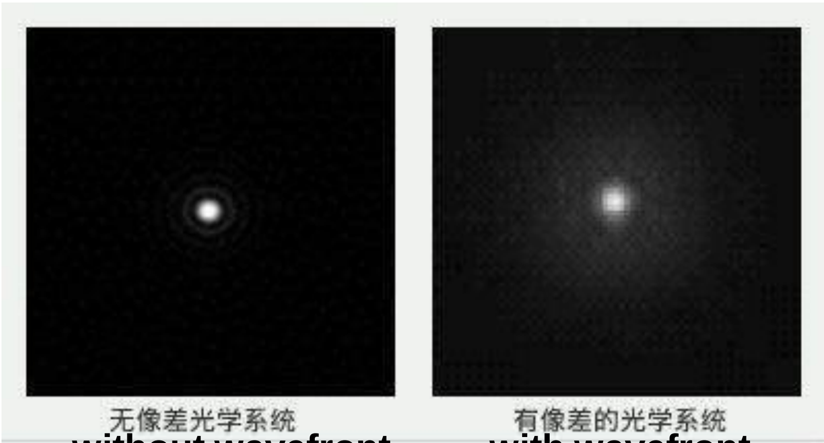
$$I_0 = \frac{E_0}{A_{\text{eff}} \tau_{\text{eff}}} = \frac{E_0}{\pi r_{\text{eff}}^2 \tau_{\text{eff}}} .$$

P_0: laser Power （PW）

I_0: Focal intensity

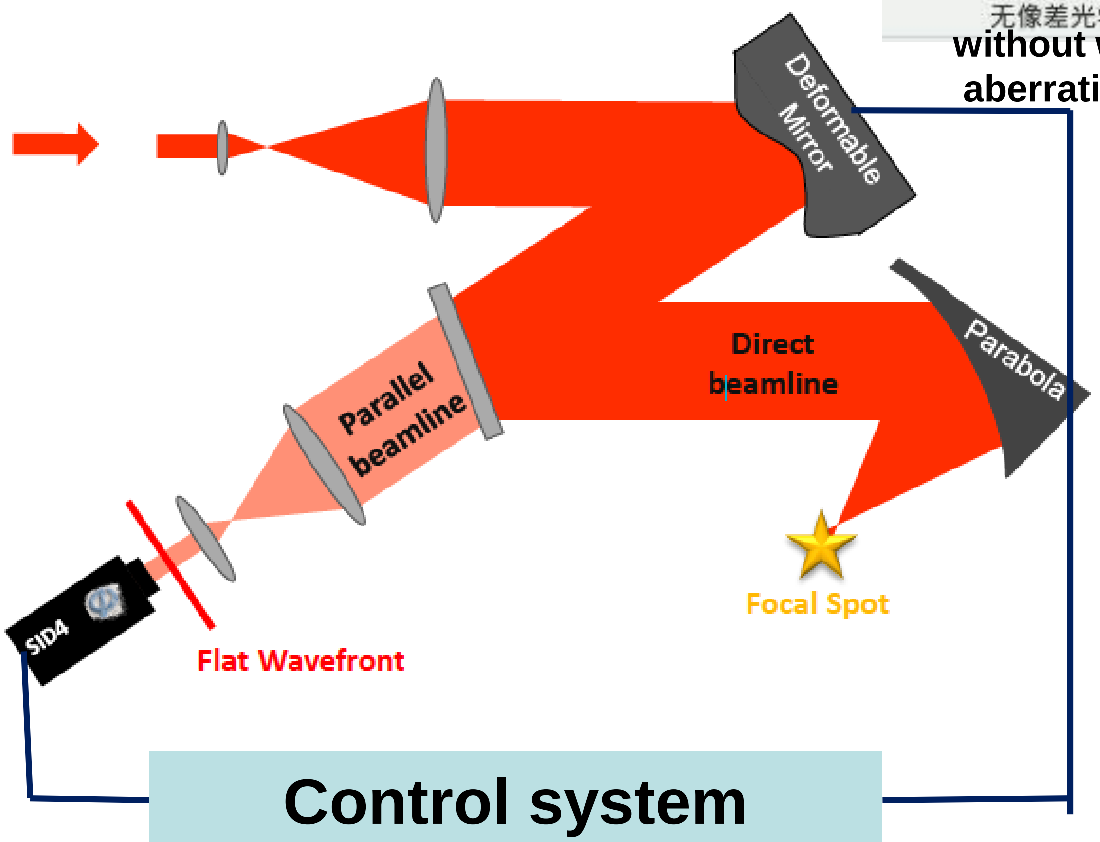
Background

Focal spot size is related to wavefront aberrations of laser pulse and the F number (f/D) of focus element.



without wavefront aberration

with wavefront aberration



AOS: Adaptive optical system

Background

Year	Facility/ Lab/Country	Output Power	AO system	F number of OAP	Focal spot size (FWHM)	Focal intensity
2004/ 2008	HERCULES laser/*University of Michigan team*/**USA**	45TW/ 300TW	1	F#0.6/ F#=1.3	0.8um/ 1.3 um	1×10^{22} W/cm^2 /2×10^{22} W/cm^2 *[1],[2]*
2017	J-KAREN-P laser facility / *Kansai Photon Science Institute*/**Japan**	300 TW	1	F#1.3	~ 1.3 μm	~10^{22} W/cm^2 *[3]*
2018	SULF/*SIOM*/**China**	5.4 PW	2	F#2.5	2.75×2.87 um^2	2×10^{22} W/cm^2 *[4]*
2019	Texas Petawatt Laser /*University of Texas at Austin*, **USA**	80-120J/ 150 ± 20fs	1	F#1	~1.32um	≥10^{22}W/cm^2 *[5]*
2019	multi-PW laser/ *Center for Relativistic Laser Science*/**South Korea**	4.2PW	2	F#1.6	~1.5×1.8 μm^2	5.5×10^{22} W/cm^2 *[6]*

[1].Opt. Lett. 29, 2837(2004); [2] Opt.Express 16, 2109 (2008); [3] Opt. Express 25, 20486 (2017);
[4] Opt.Express 26, 26776 (2018); [5] Opt. Lett. 44, 2764(2019) ; [6] Opt. Express 27, 20412 (2019);

Background

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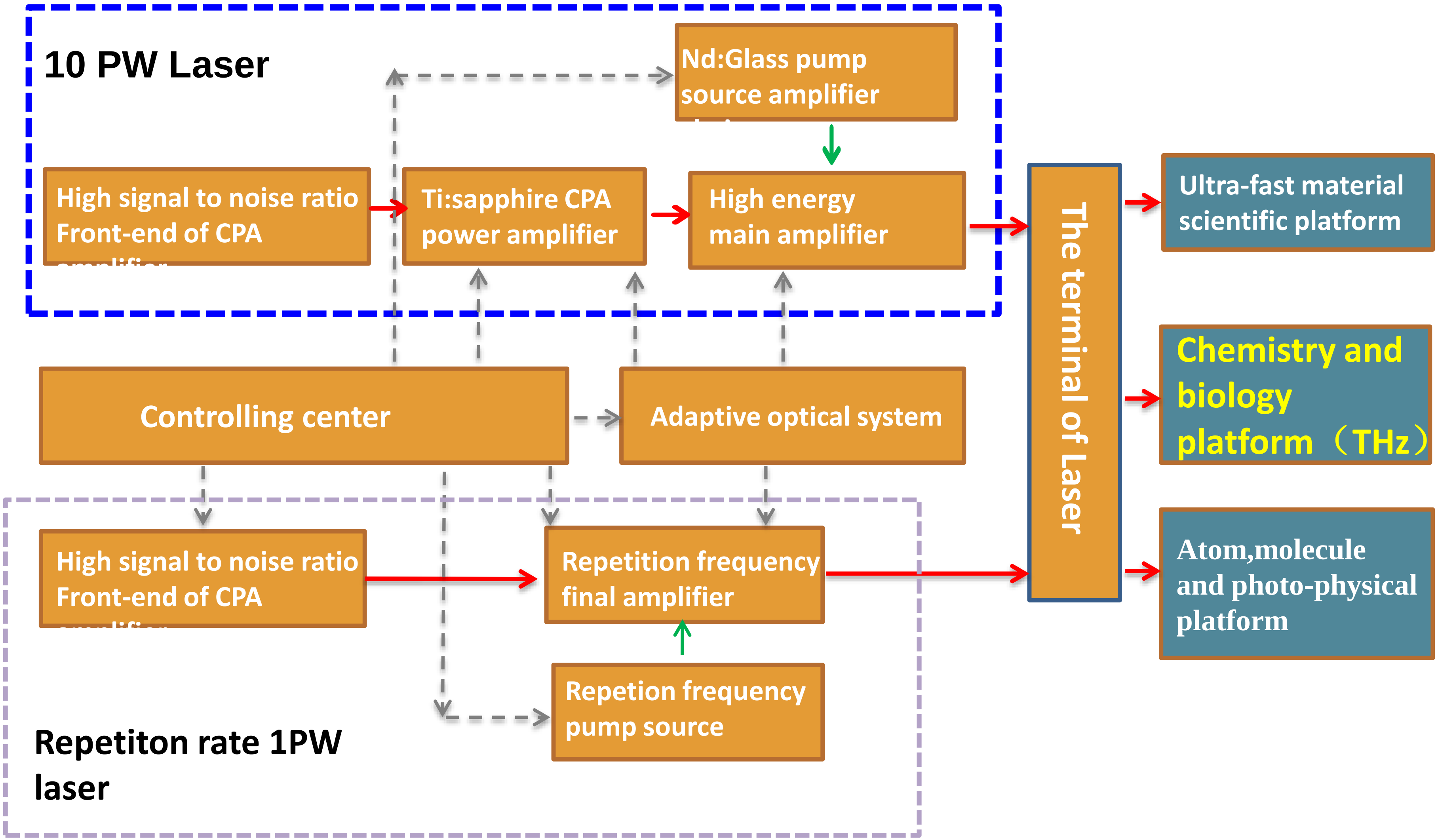
Content

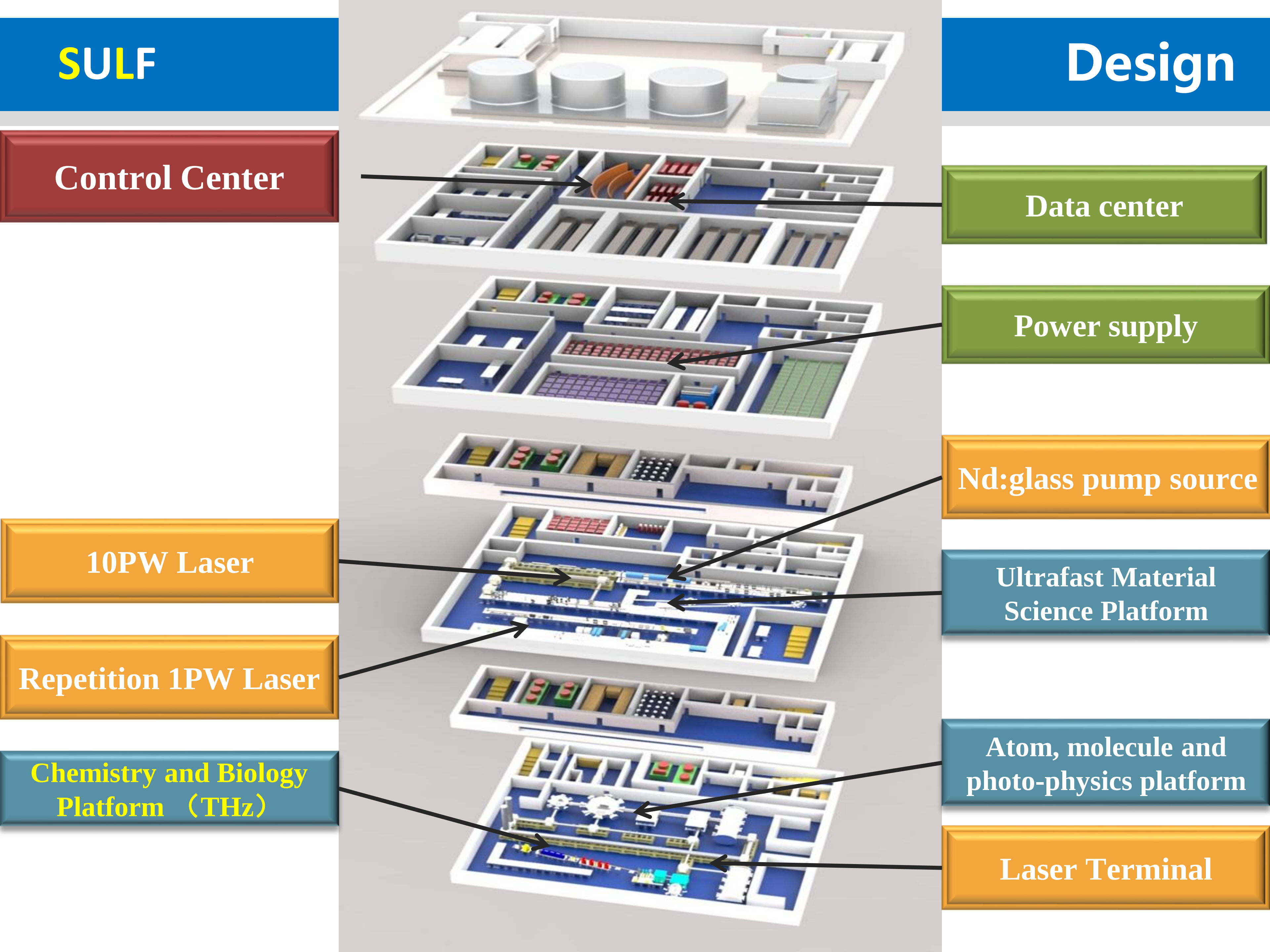
目录

SULF — 10PW

SULF Project

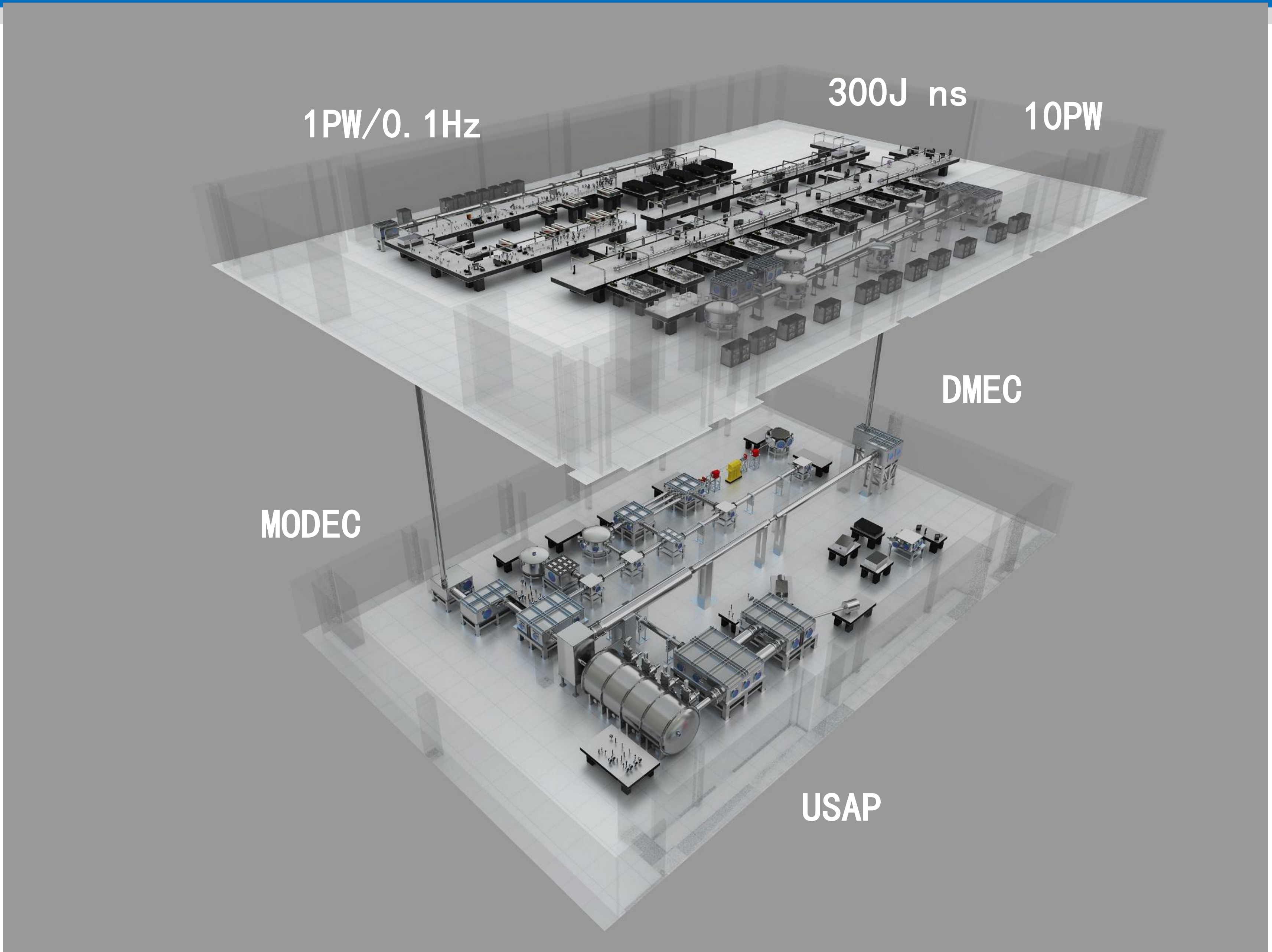


SULF Design

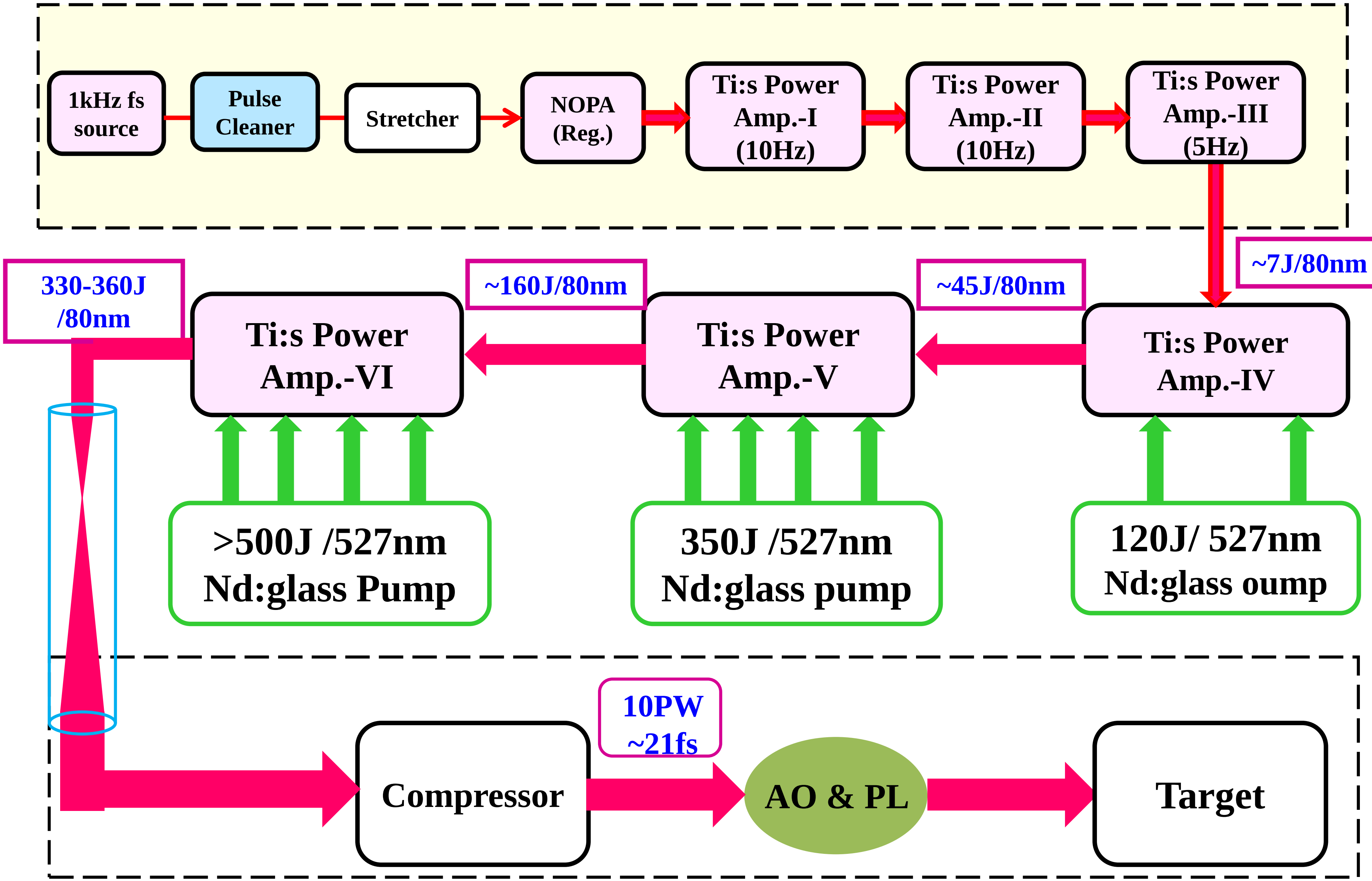


Control Center
Data center
Power supply
Nd:glass pump source
10PW Laser
Ultrafast Material Science Platform
Repetition 1PW Laser
Atom, molecule and photo-physics platform
Chemistry and Biology Platform （THz）
Laser Terminal

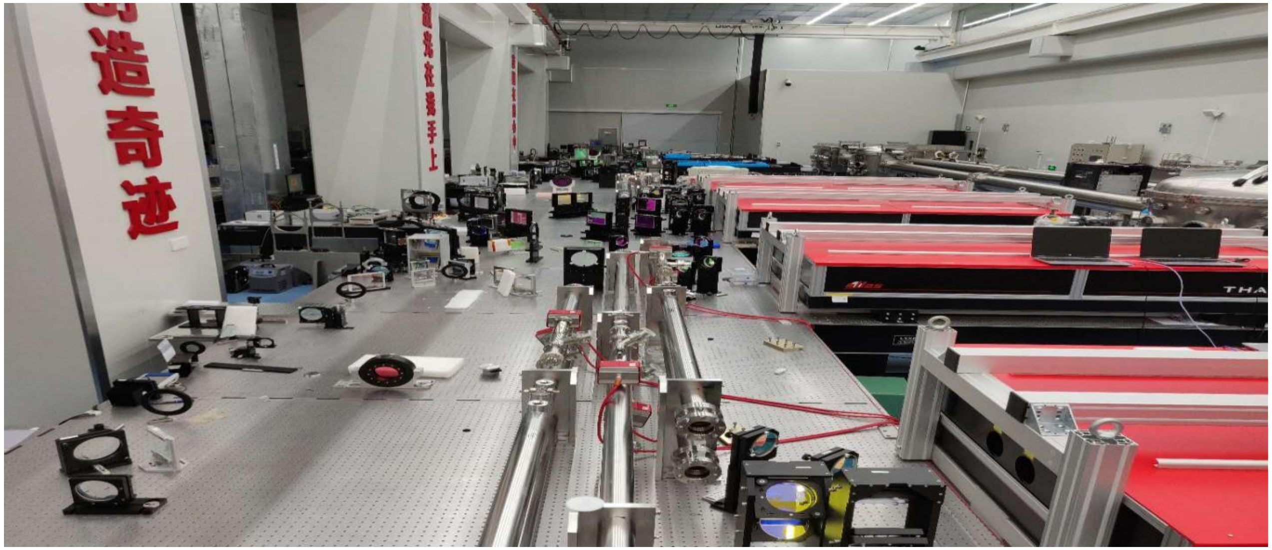
Layout of SULF 10PW



Design of 10PW CPA Laser



Ti:Sa Amplifiers of SULF 10PW



Output:

Amlified energy (avg.): 407.9J

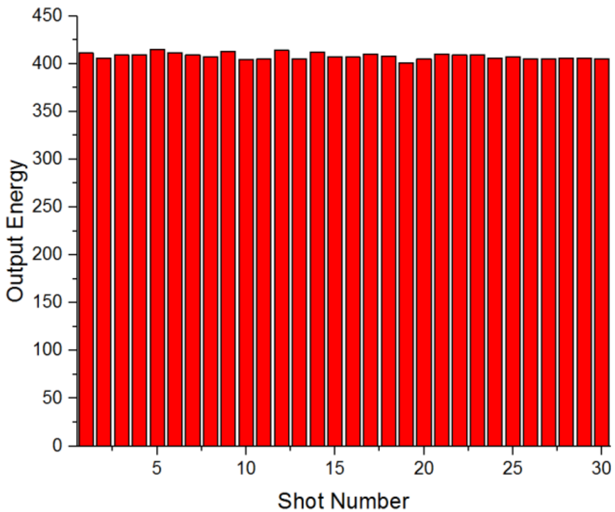
Pump energy (avg.): 529J

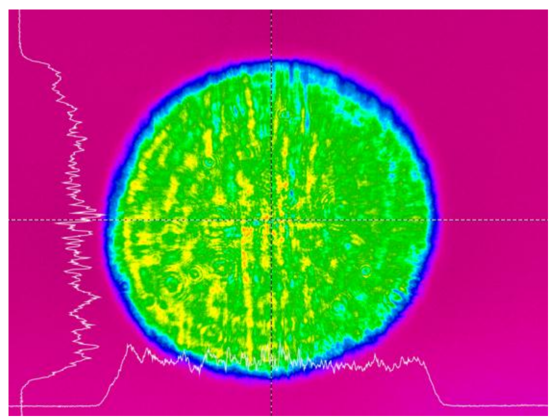
Conv. effi. of pump: 47%

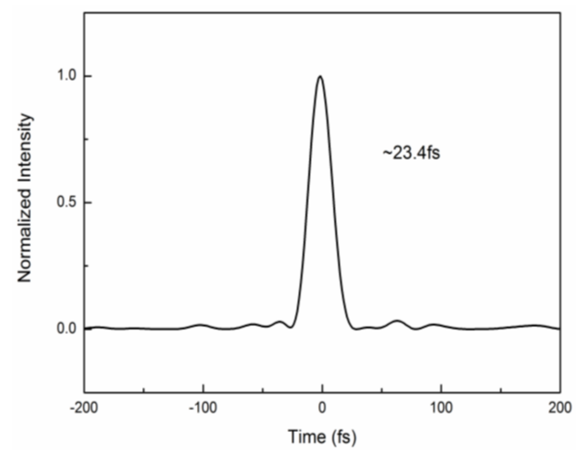
Energy stability: 0.8% (RMS)

Compressed duration: 23.4fs

Peak power (avg.): 11.7 PW

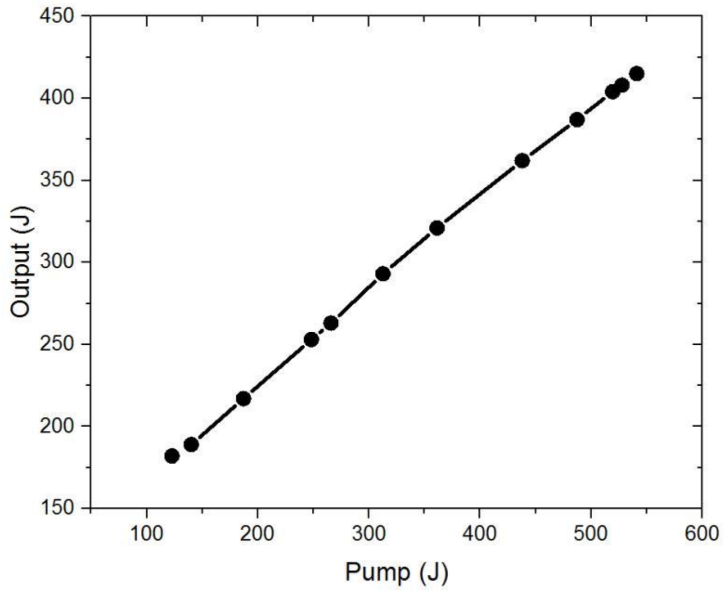




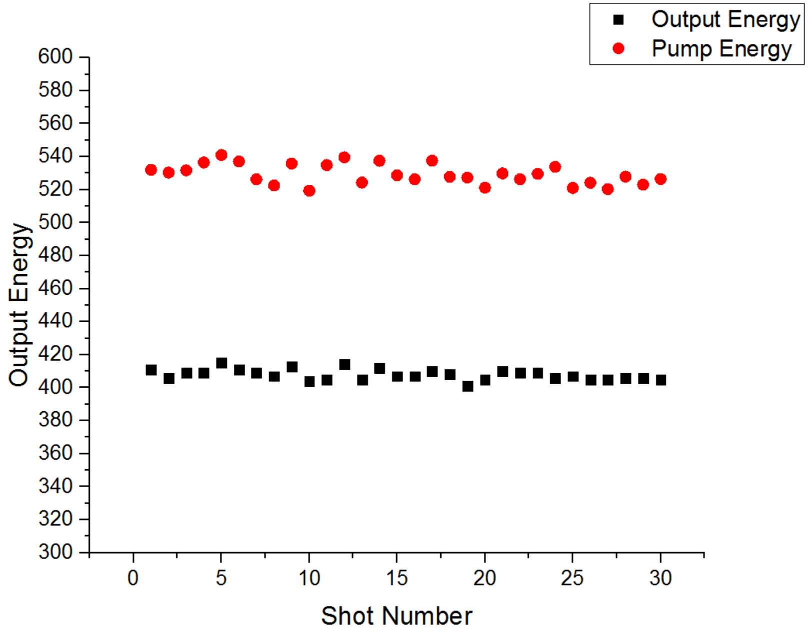


Amplified energy from final amplifier

Output energy vs Pump



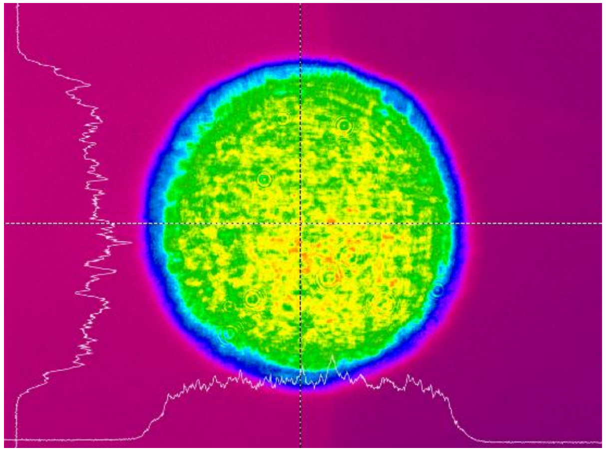
Stability of output energy



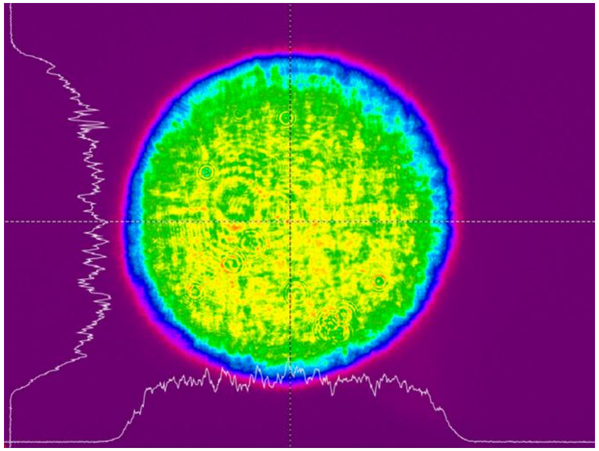
Pump energy: 540J
Injected energy: 160J
Amplified energy: 422J
Conversion efficiency: 43%

For 30 shots:
Evergy energy: ~408J
RMS: 0.8%

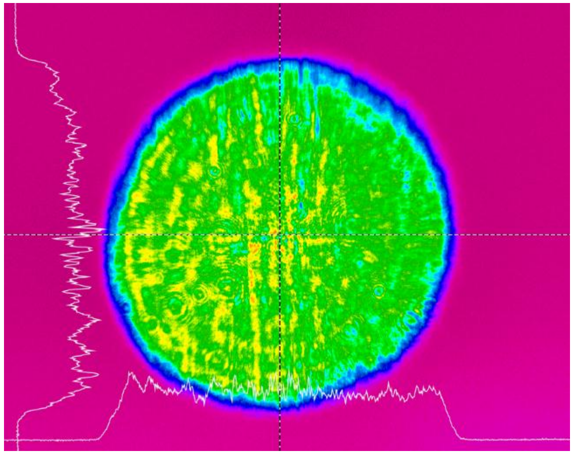
Beam Profile



Beam Profile at 50J from ϕ100 Ti:sapphire amp.

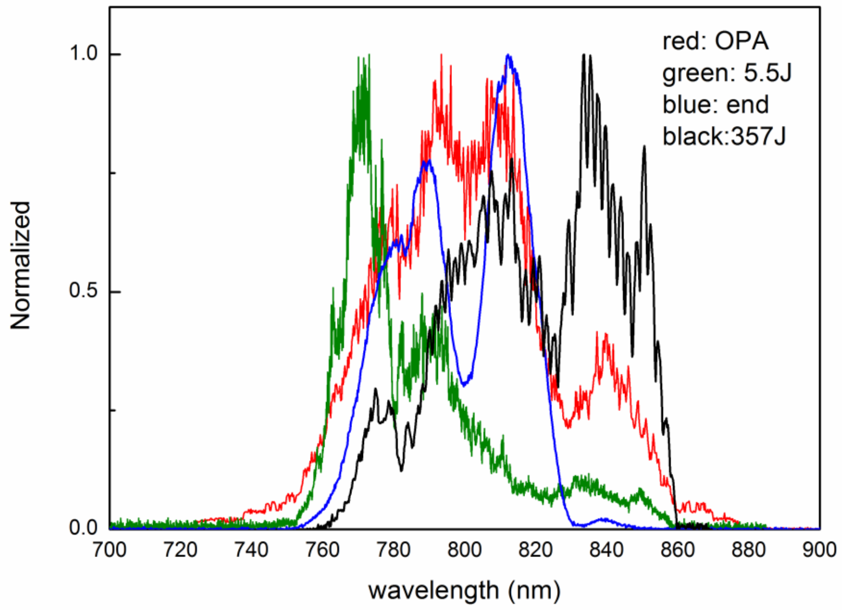


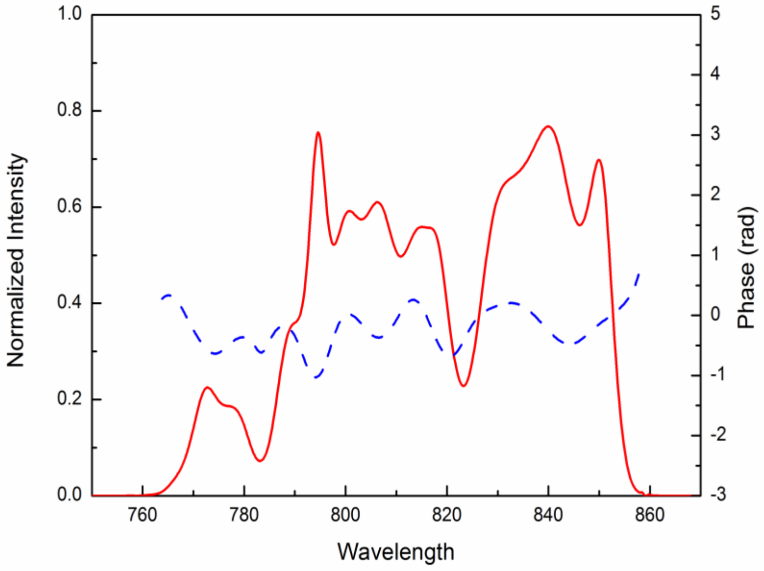
Beam Profile at 160J from ϕ150 Ti:sapphire amp.



Beam Profile at 410J from ϕ220 Ti:sapphire amp.

Spectrum and dispersion

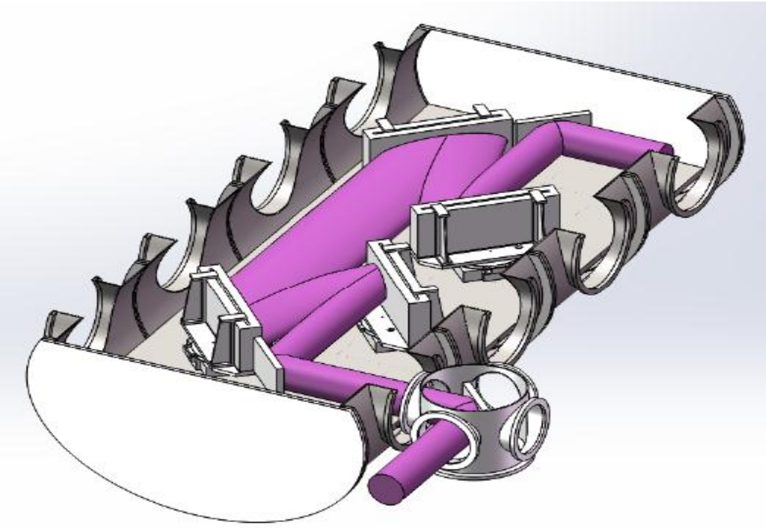


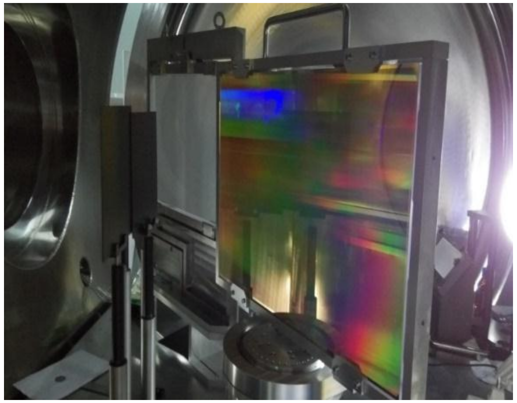


Full spectrum width at energy of 357J: 760nm—858nm

Active Compensation of dispersion by Dazzler

Pulse compression



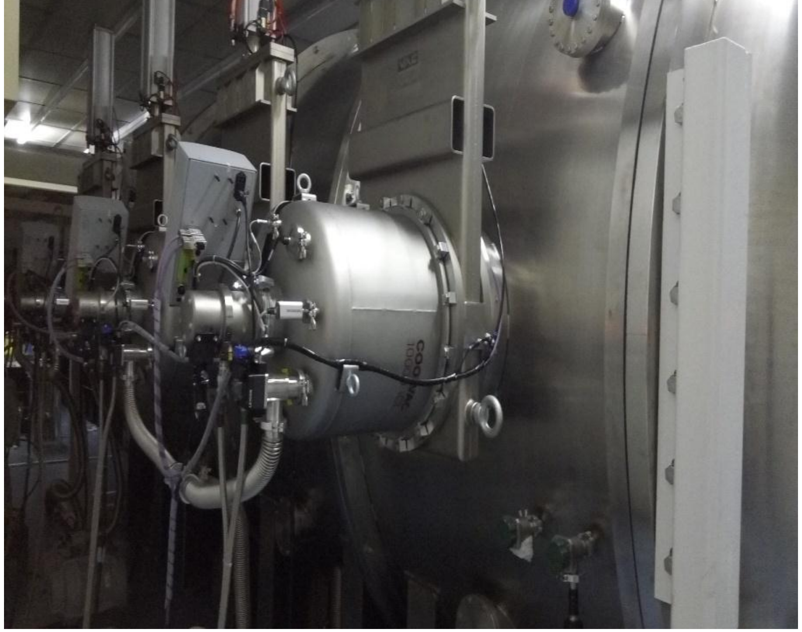


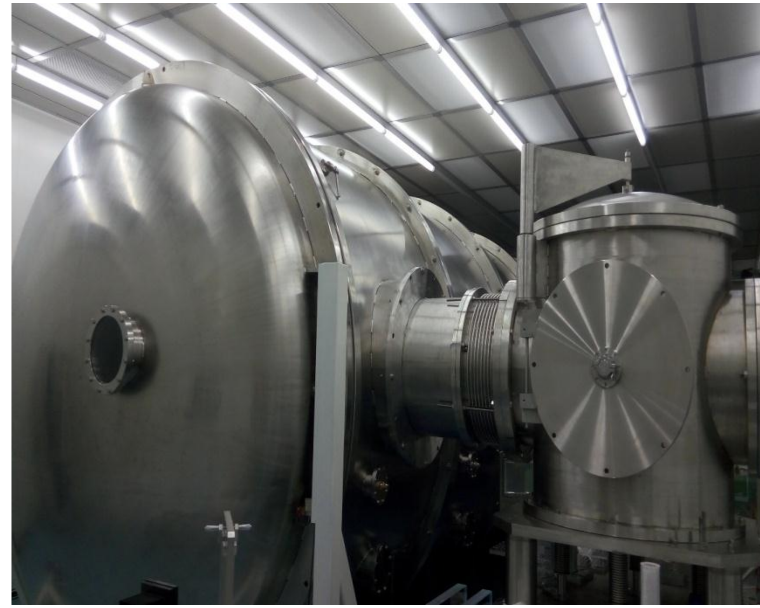
Grating size:
560×1100（mm）, 1480 lines/mm

Chamber size：ϕ2000×6000（mm）

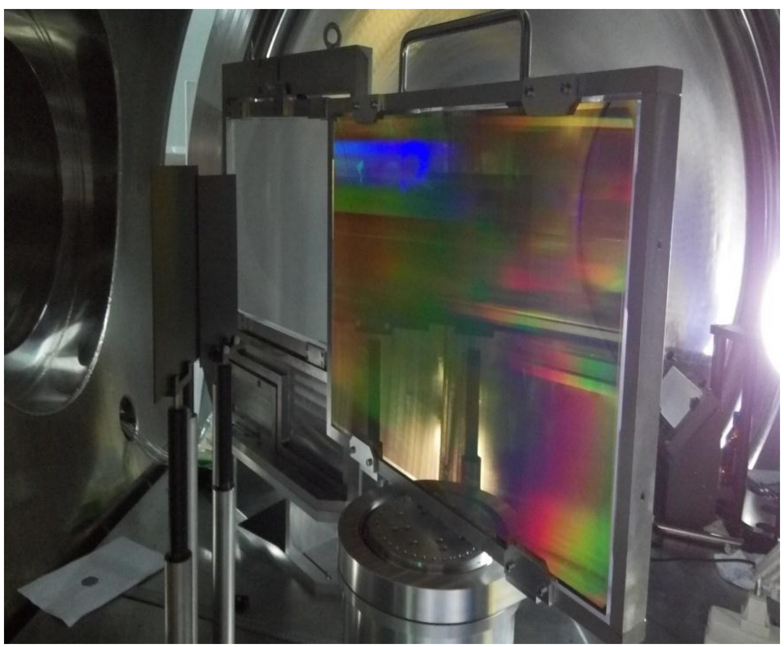
Beam size: ϕ500mm

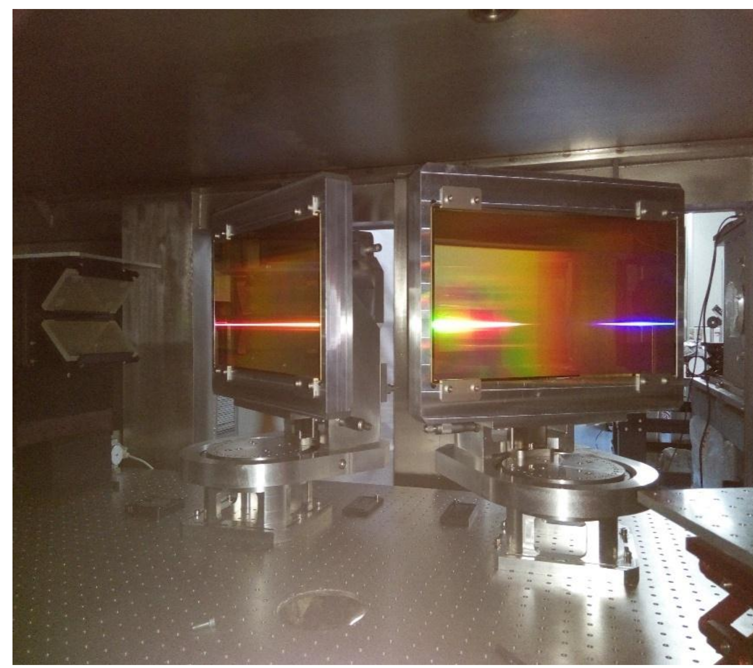
efficiency：~71.3%



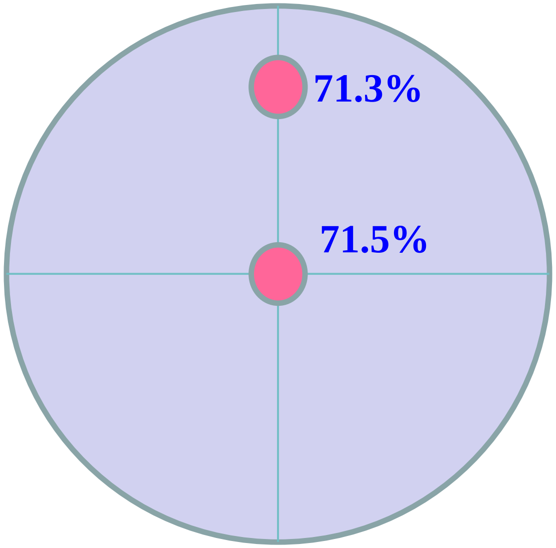


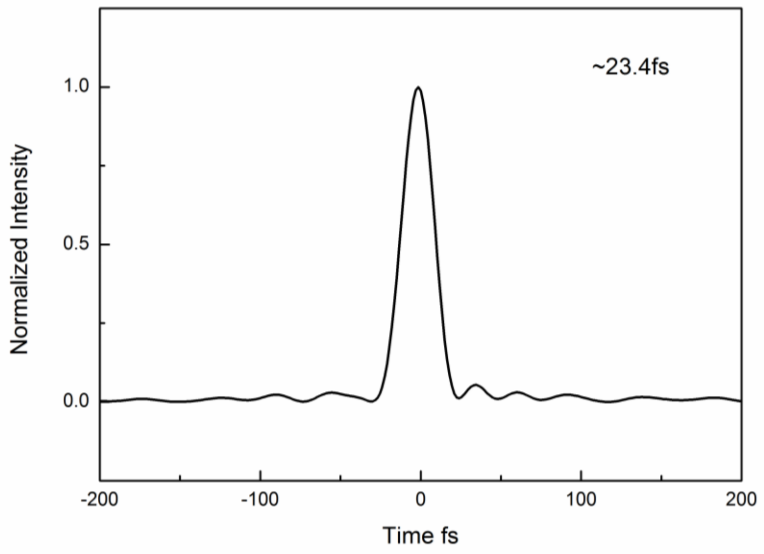
Gratings for 10PW: 1480g/mm, 560mm*1100mm





Pulse Width Measurement





Efficiency measure：71.3%

Pulse width：23.4fs

Peak power : ***422 J× 71.3% / 23.4 fs = 12.9 PW***


SULF-1PW


SULF-10PW
家国在我心中

Content

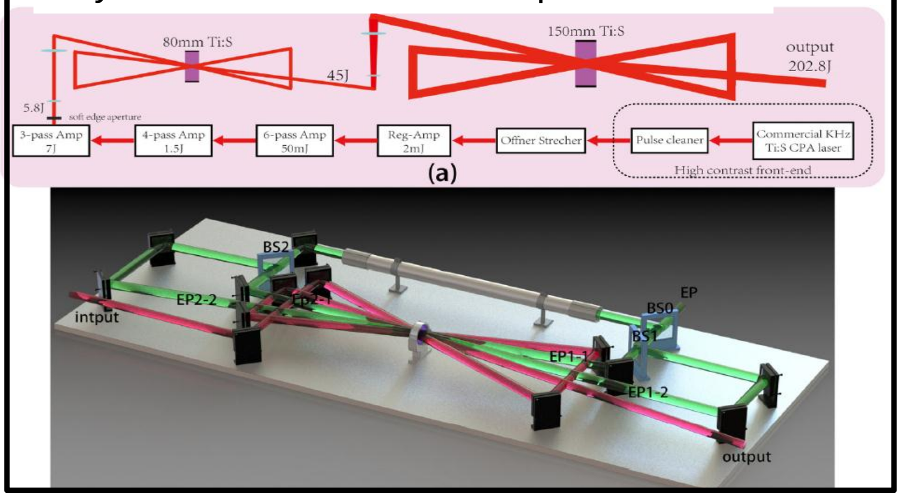
目录

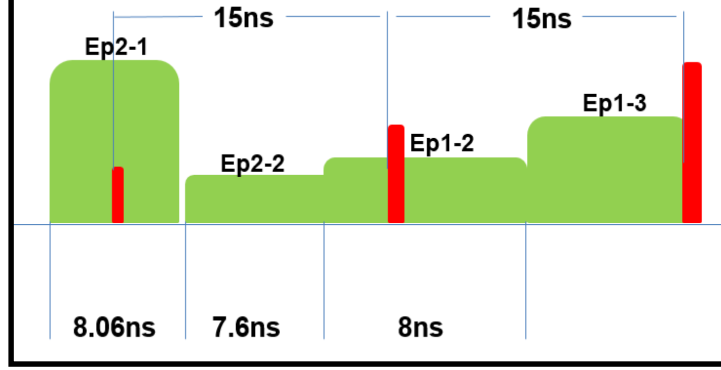
SULF

5.4 PW output

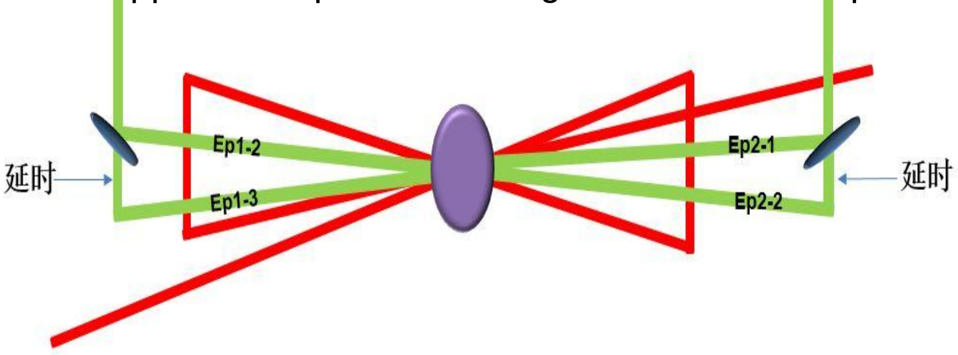
2016

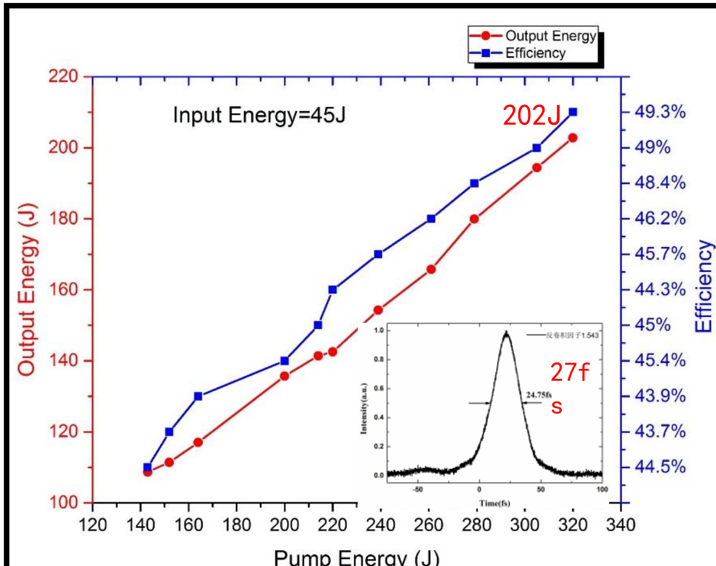
Layout of the CPA 5.4PW Amplifiers





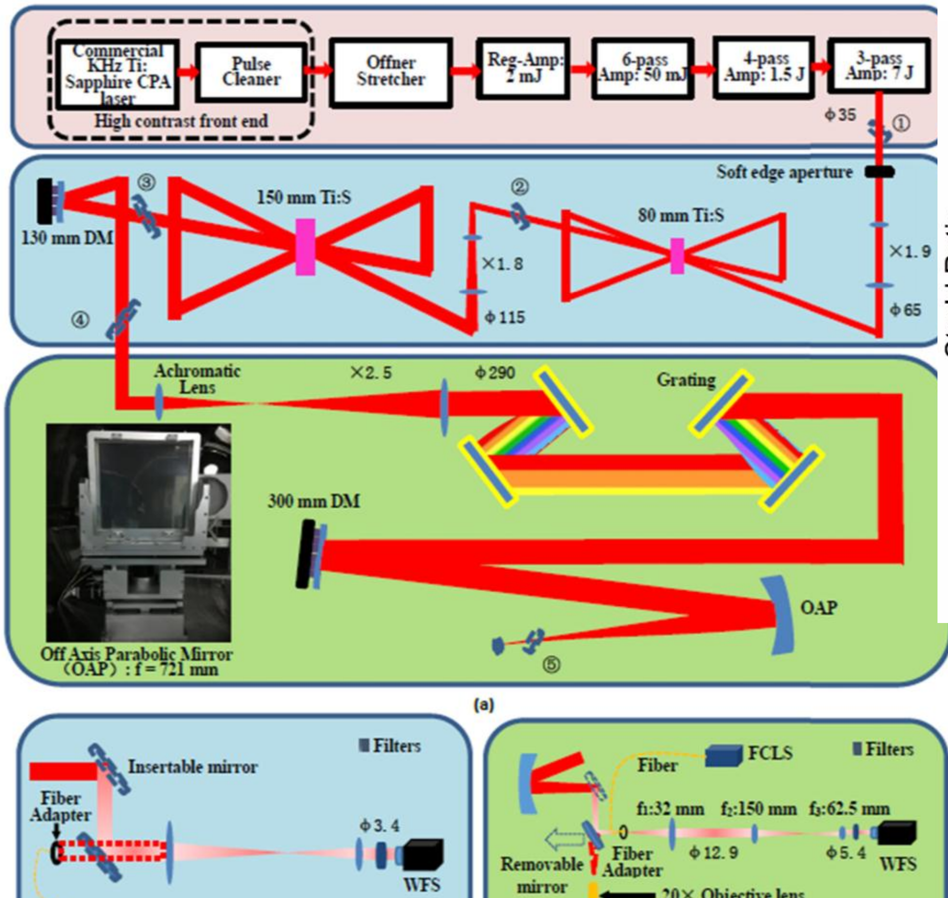
Temporal dual-pulse pumped technique to suppress the parasitic lasing of Ti:Sa main amplifier



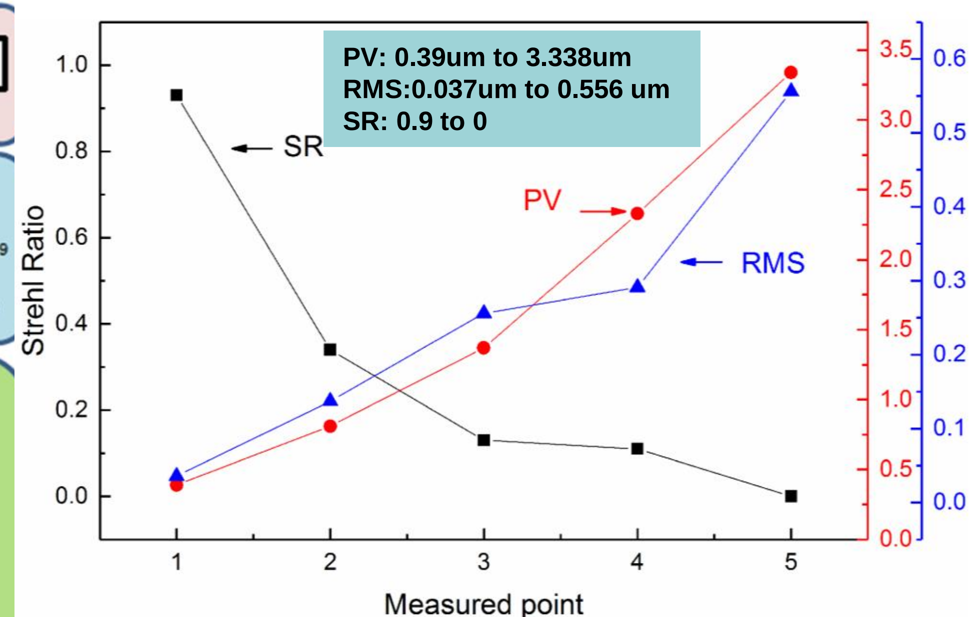


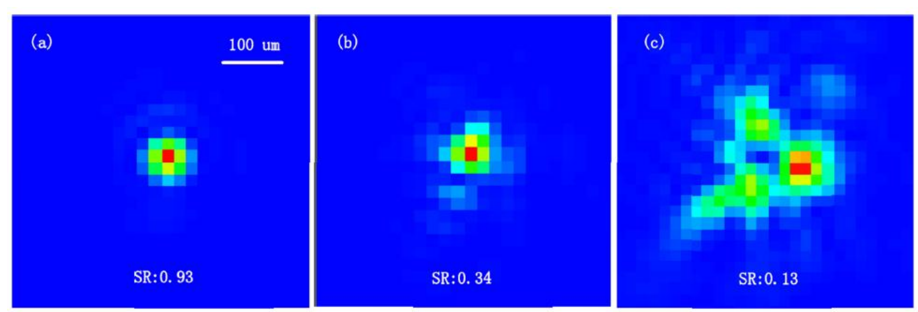
Zebiao Gan[†], Lianghong Yu[†], Shuai Li[†],Xiaoyan Liang*, Yuxin Leng*, Ruxin Li*, and Zhizhan Xu*,**et.** Opt. Express 25, 5169-5178 (2017)

Evolution of wavefront aberration



Layout of the 5.4 PW laser system





①- ⑤ : the measured points
(b) : The insertable sampling optical path for ①- ④;
(c): The sampling optical path for ⑤.

Calculated focal spots by the corresponding wavefront and intensity measured at point ①- ③

Deformable Mirror -1

Deformable mirror

Wavefront sensor

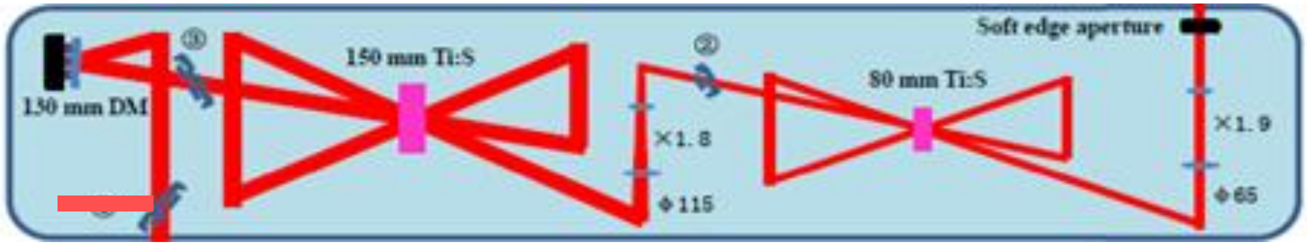
Main technical parameters of the bimorph mirror DM2-130-64

Flatness of the initial surface (P-V; RMS), µm	1.786; 0.355
Corrected mirror surface (P-V; RMS), no more than 20 % of control range of voltage applied, µm	0.061; 0.008
Number of control electrodes	64
Control voltage range, V	-300 ÷ +500
First resonance frequency, kHz	2.175
Operating frequency range, kHz	0 ÷1.0
Hysteresis, %	9
Reflecting coating	Multilayer dielectric
Maximal reflectivity (λ=800 nm), %	99.96
Reflectivity in the range from 800±50 nm, %	Not less than 99.82
Diameter of the substrate, mm	140
Optically used diameter, mm	130
Active aperture, mm	130
Substrate material	Glass LK-105
Thickness of the substrate, mm	4.0
Number of the piezo-discs	2
Diameter of the piezo-discs, mm	130
Thickness of the piezo-discs, mm	0.5
Dimensions of the holder (diameter x length), mm	∅155 x 64
Weight in the holder, kg	1.2

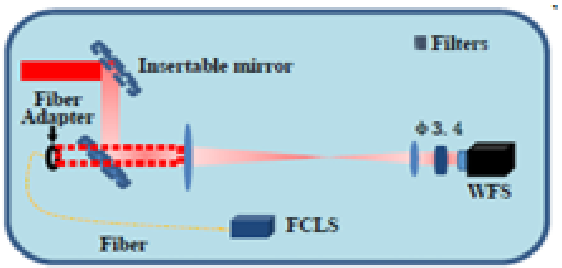
Active Optics NightN company, Russia

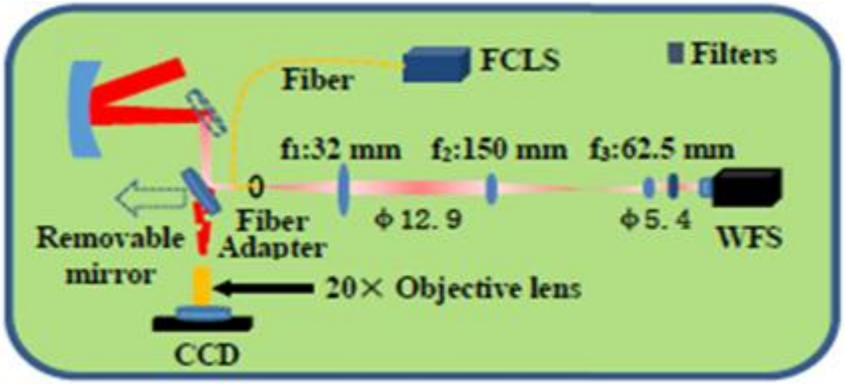
WFC in amplification Stage

The position of first DM and sampling beam



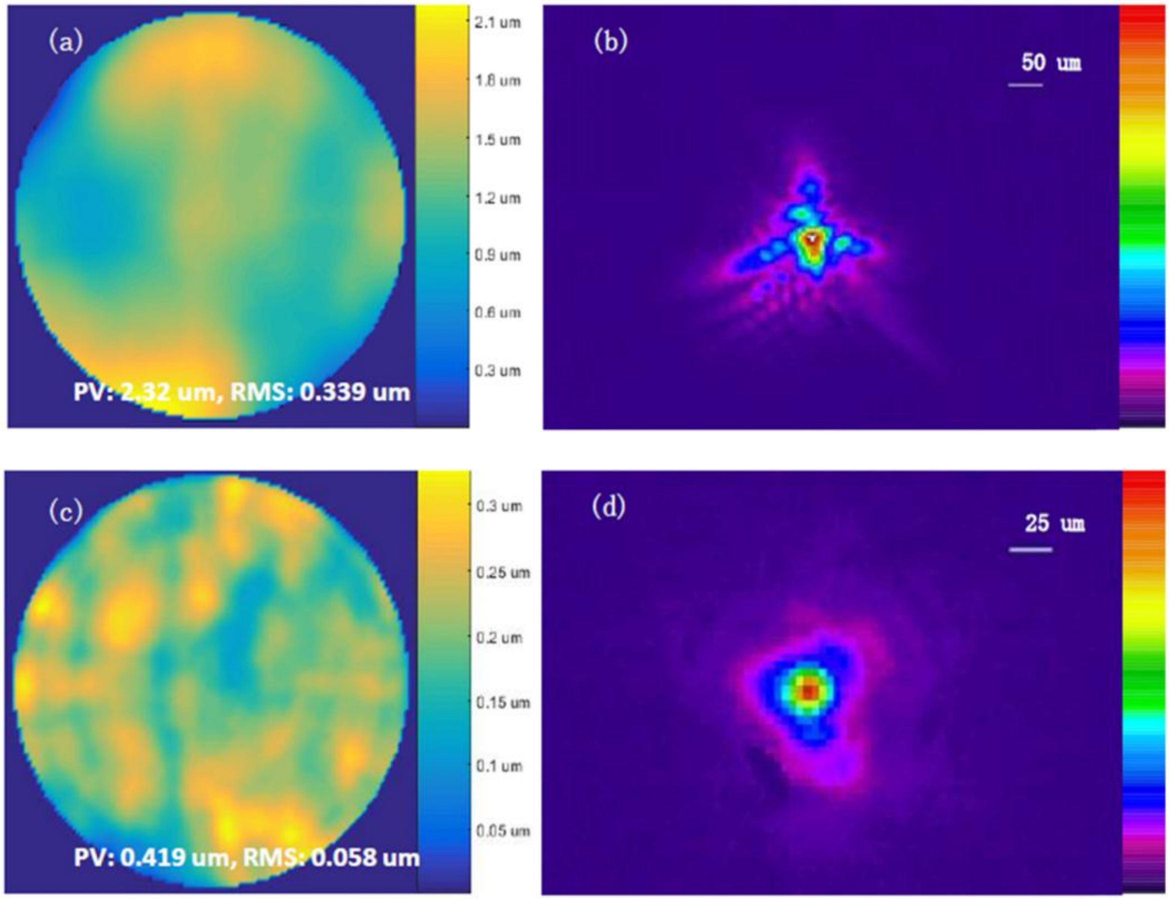
Measurement of wavefront and focus spot





FCLS: Fiber-Coupled Laser Source, an ideal point source was inserted in the focal position to measure and remove aberrations of the sampling optical path.

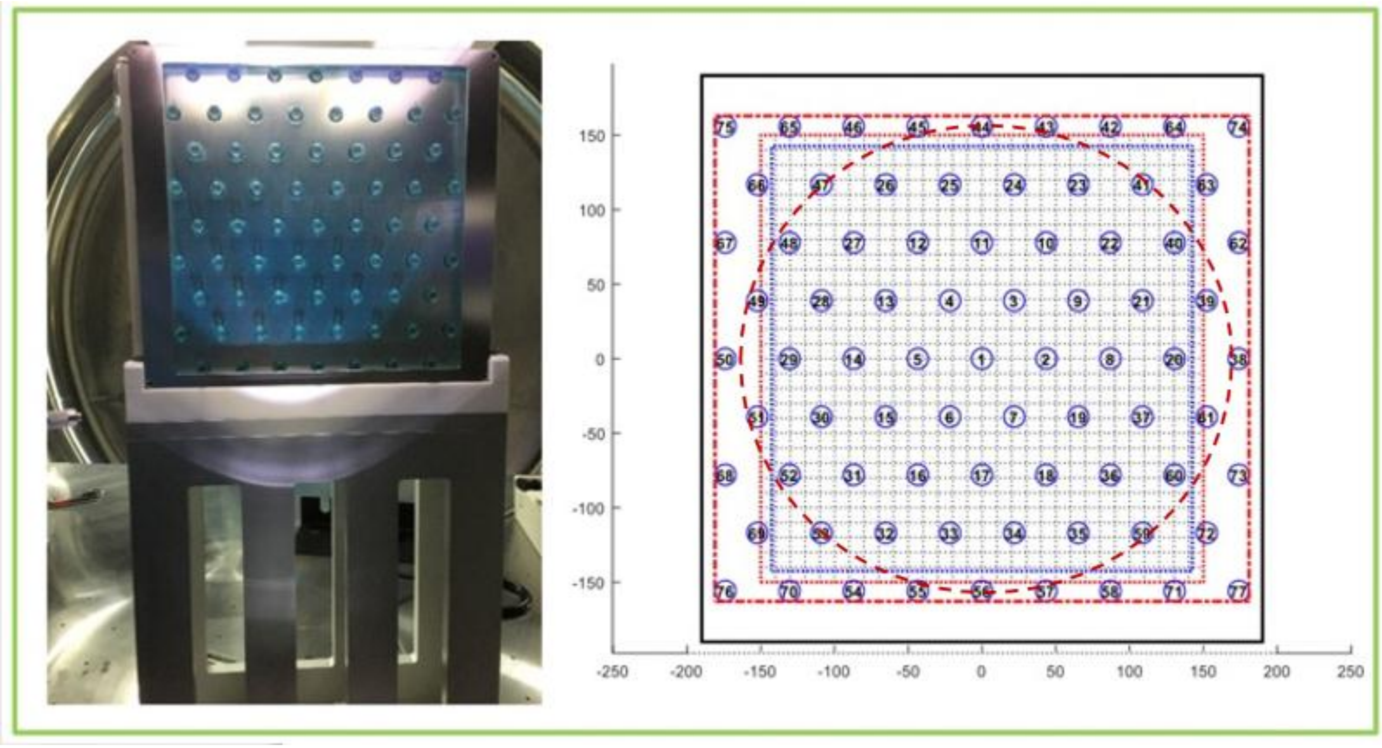
Results of WFC in amplification stage



The phase profiles of the laser beam (a) before and (c) after the correction; (b) and (d) the corresponding focal spots focused by the f4 = 2500 mm lens.

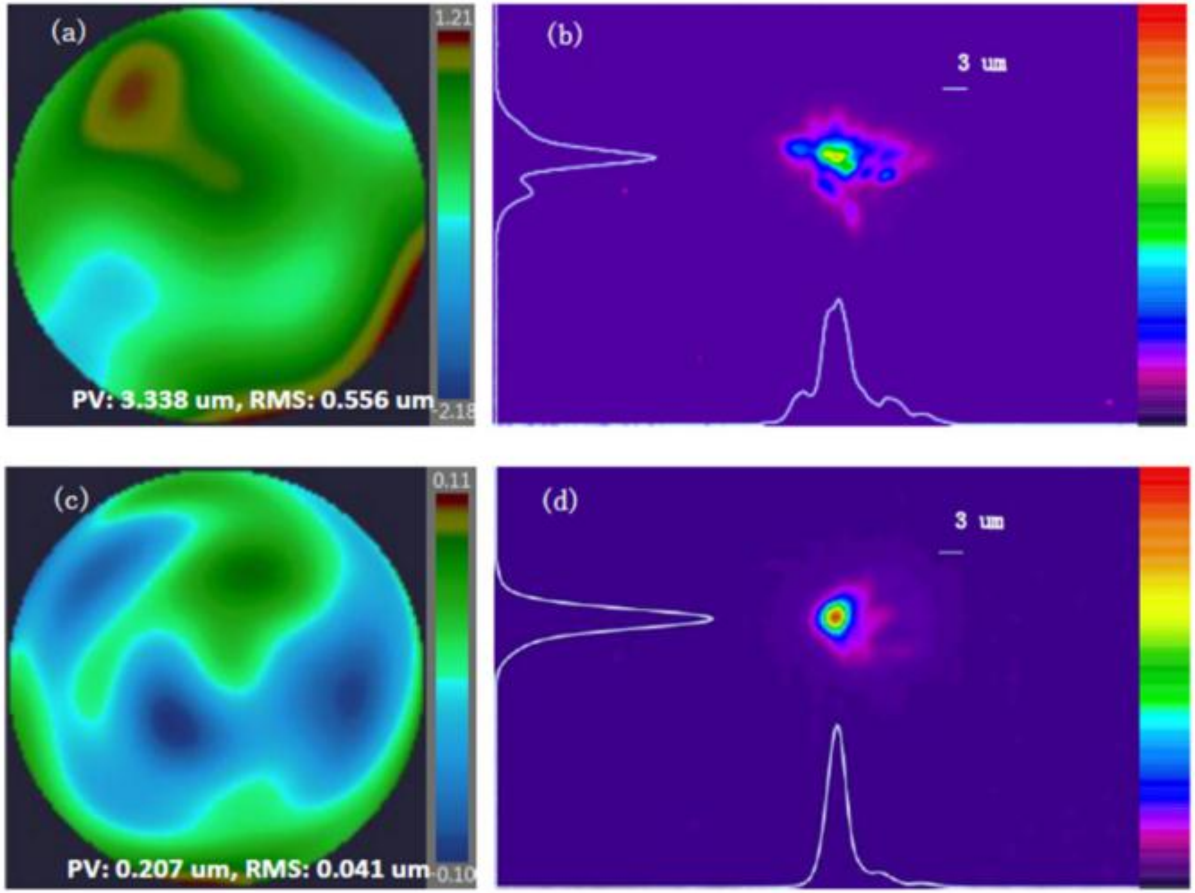
Correction: pv: 2.32μm → 0.419μm
RMS: 0.339μm → 0.058μm

Deformable mirror - 2



Effective aperture: 300mm*300mm
Number of control actuators: 77
Actuator type: Piezoelectric ceramics
Produced by Institute of Optics and Electronics (IOE),CAS

Results of WFC in terminal stage



The focal spot is enlarged by a 20X objective lens and measuered by a 12-bit CCD

RMS=0.556um

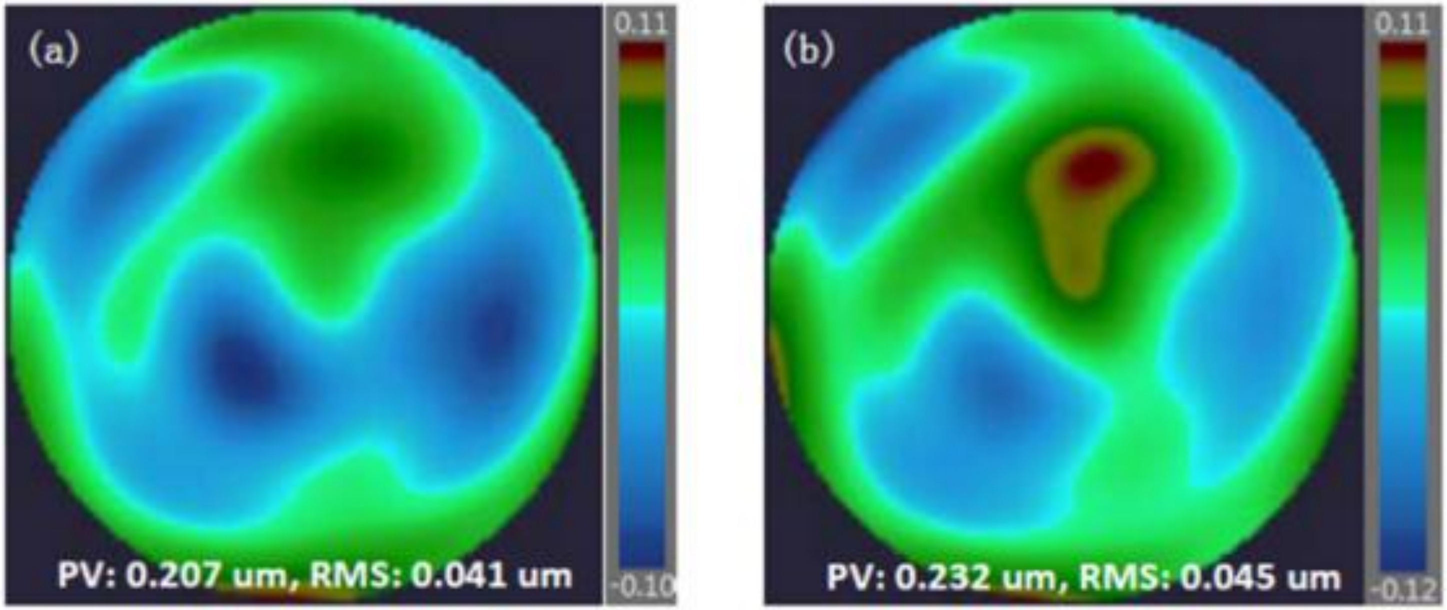
Experimental Schematic:

- **DM1: ϕ130mm, after the Amp.V;**
- **DM2: 300mm*300mm, after the compressor;**
- **OAP: F/2.5, 400mm*400mm, f=721mm, D_{beam}= 290mm; off-axis angle = 31°**

Correction: pv: 3.338μm ⟶ 0.207μm
RMS: 0.556μm ⟶ 0.041μm

⇨ **focus spot size: 2.75 × 2.87 um²**

Wavefront for single shot amplification

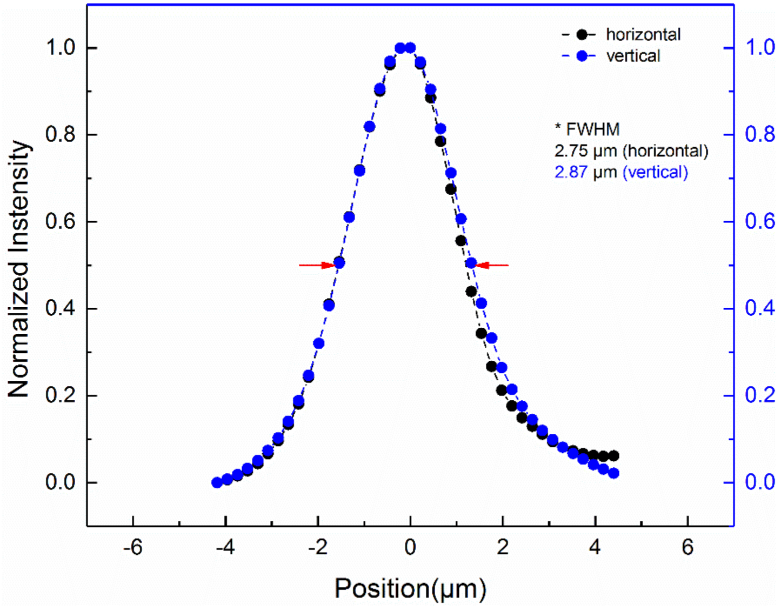


The phase profiles at point ⑤ : (a) measured at a frequency of 1 Hz; (b) measured at a single-shot amplified with an amplified energy of 40 J (after being attenuated by the high quality mirrors without coating).

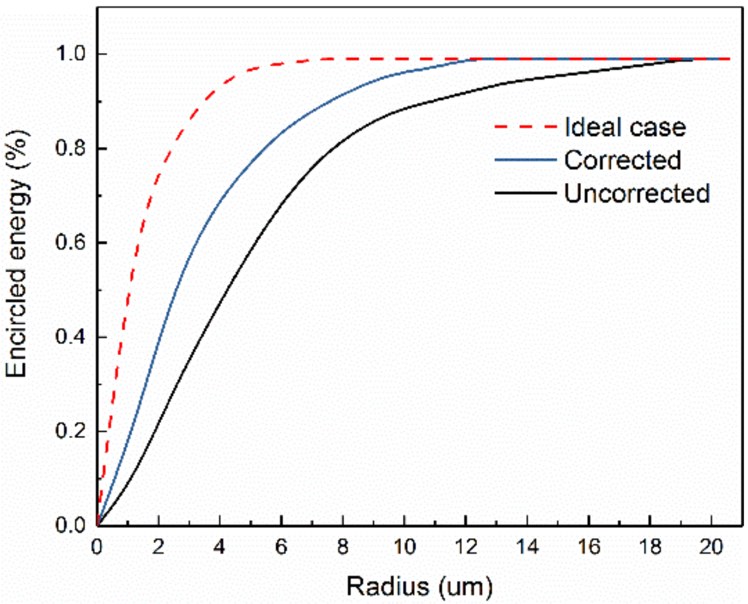
The RMS value of the single-shot amplified beam was 0.043– 0.05 µm, which was nearly the same as that measured in the frequency amplification.

Results of WFC in terminal stage

The distributions of the focal spot on the x and y-axes



The encircle energy curves

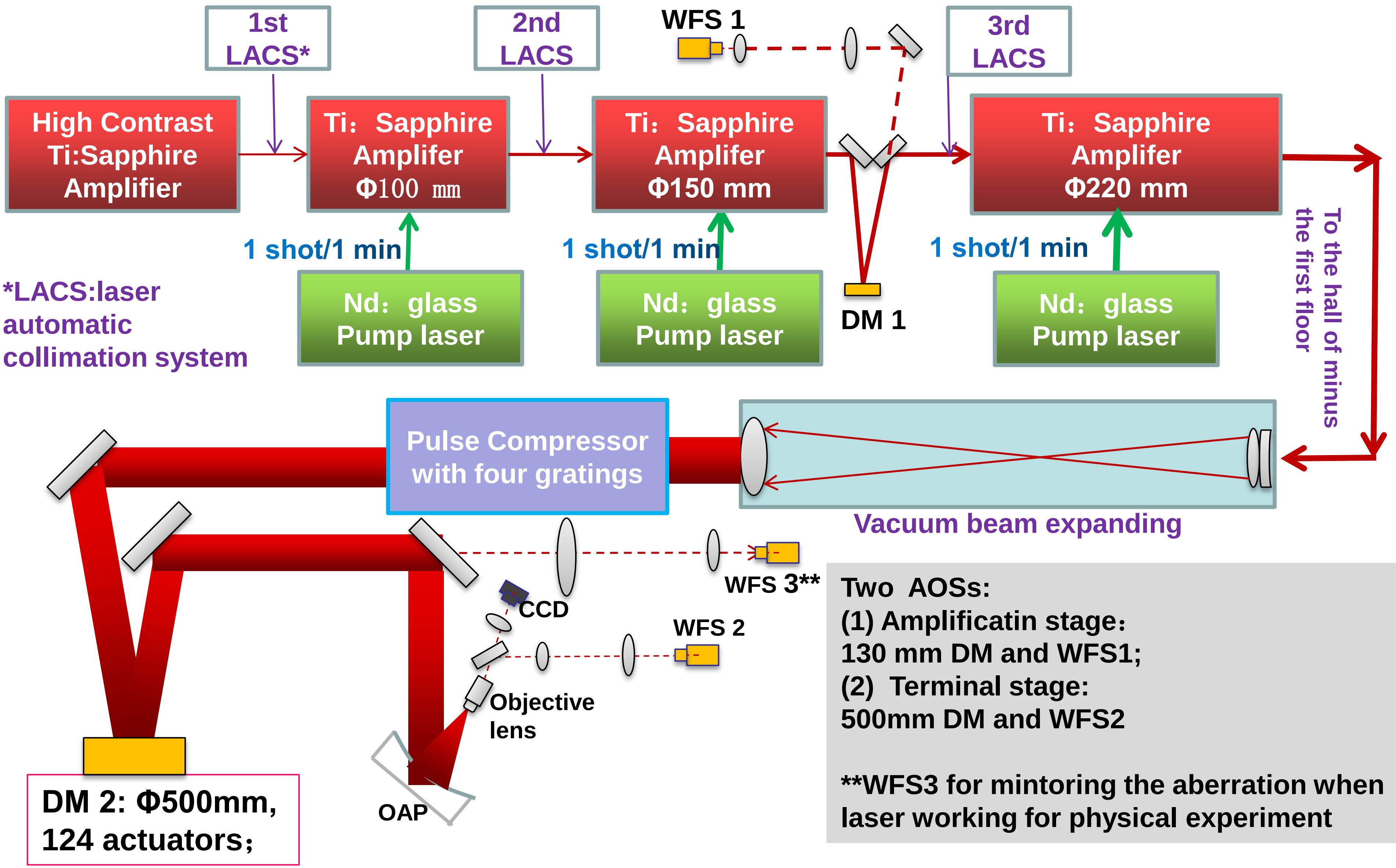


- The FWHM of the focal spot is 2.75×2.87 um
- The focal spot of the measured plane contained approximately 27.69% energy in the FWHM area and 59.43% energy in the e^2 area.
- And, the peak intensity exceeded to 2× 10^{22} W/cm^2 with working distance of 721 mm (length of OAP)

Content

目录

Diagram of SULF 10PW



Two AOSs:
(1) Amplificatin stage:
130 mm DM and WFS1;
(2) Terminal stage:
500mm DM and WFS2

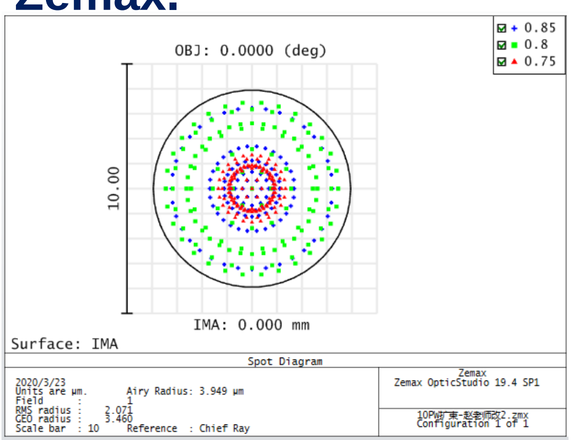
**WFS3 for mintoring the aberration when laser working for physical experiment

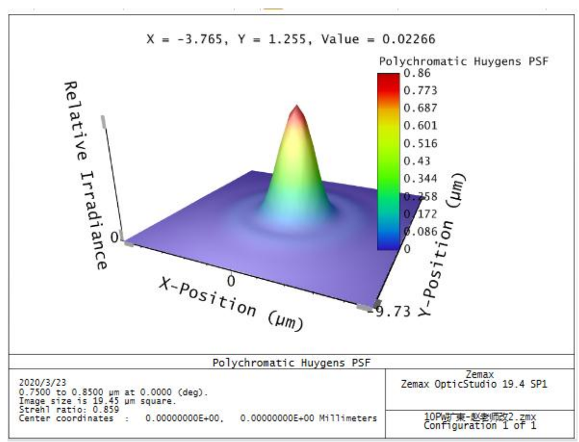
Beam Expanders of SULF 10 PW

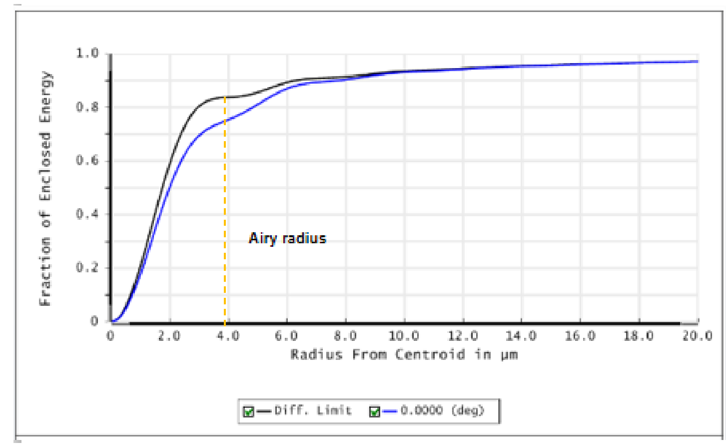
Four beam expanders based on achromatic lens were used to expand the beam size from 32 mm to 500 mm, and then into the 4-grating compressor. The expander were optimized design by Zemax.

Φ32mm Φ120mm Φ180mm Φ500mm

Optimization results: chromatic aberration causing by lens was optimized by Zemax.







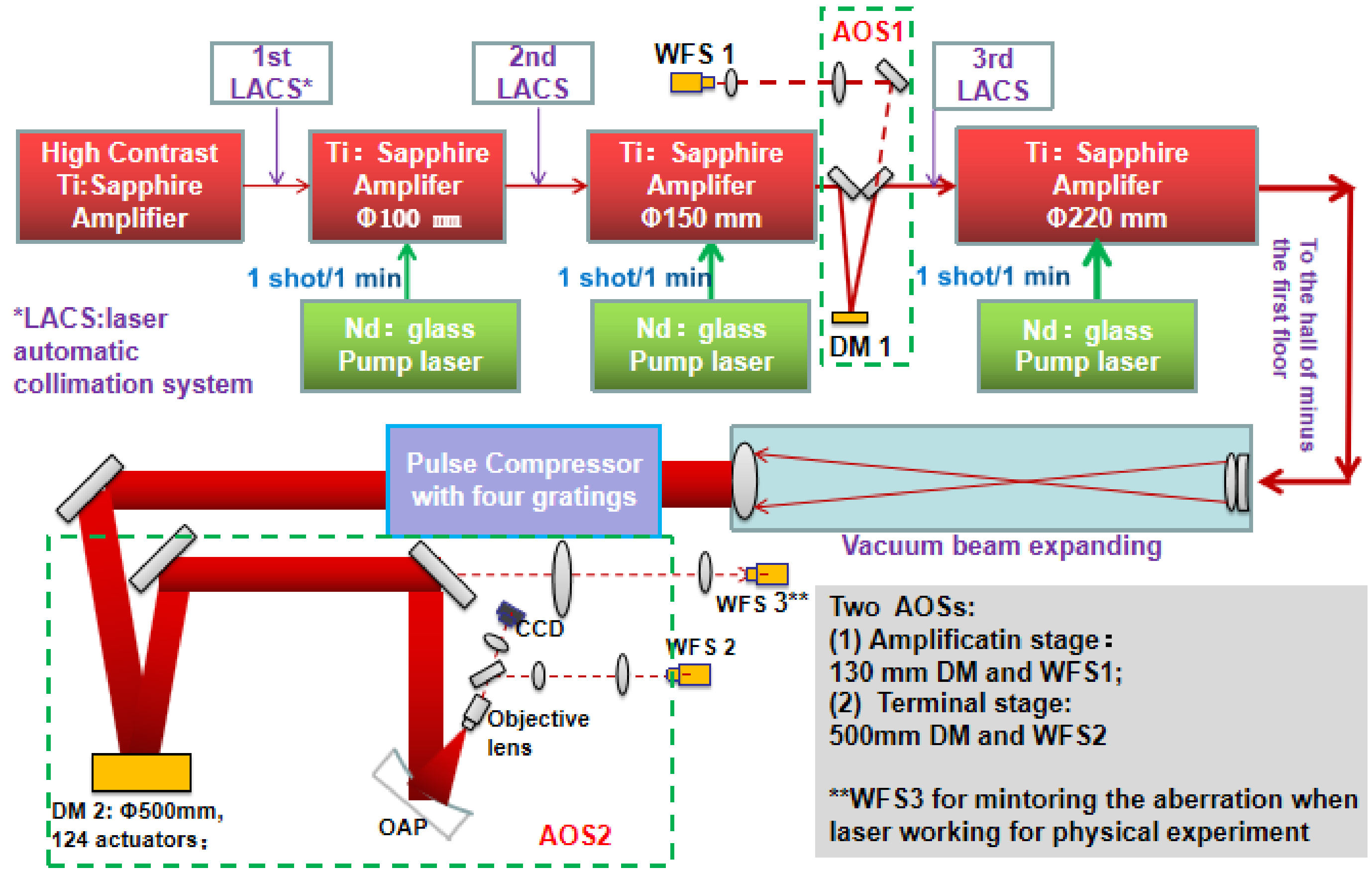
Spot Diagram:
Airy radius:3.949um
RMS radius: 2.071um
GEO radius: 3.460um

Huygens PSF:
Strehl rate: 0.859

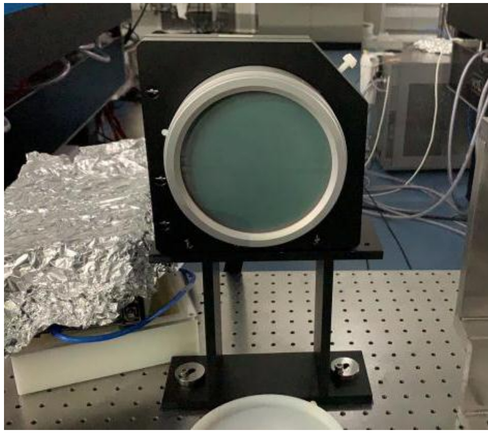
Fraction of encirled energy

WFC and focusility of 10PW

To improve the focusility of 10 PW laser pulse, two adaptive optics systems were used in SULF.



AOS1:130mm DM



AOS2:500mm DM

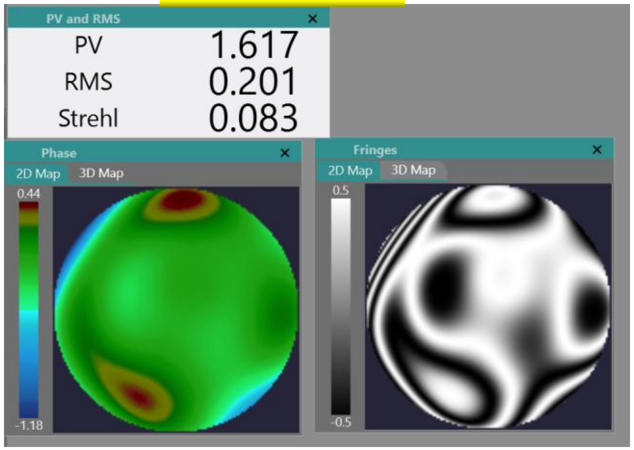
AOS in amplifier stage

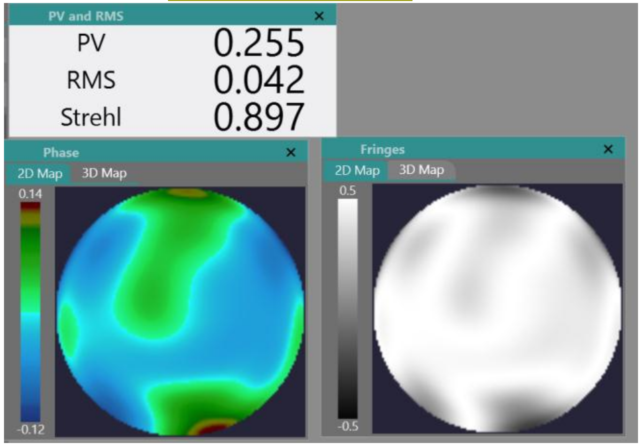
After correction of the first AOS in amplifier stage, the PV value was decreased from 1.6 um to o.2um and the RMS value from 0.255 um to 0.042um. The strehl ratio was increased to 0.89.

AOS off

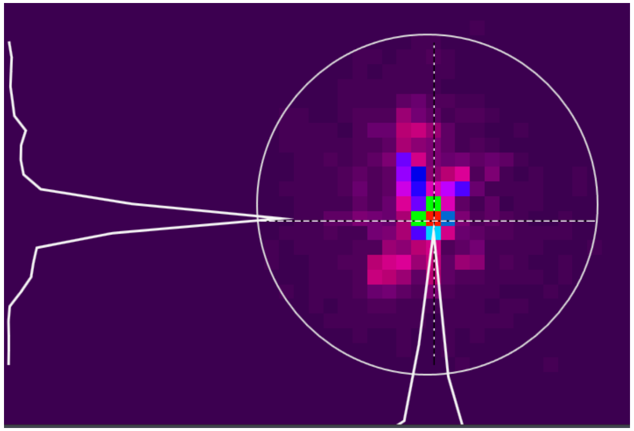
OAS on

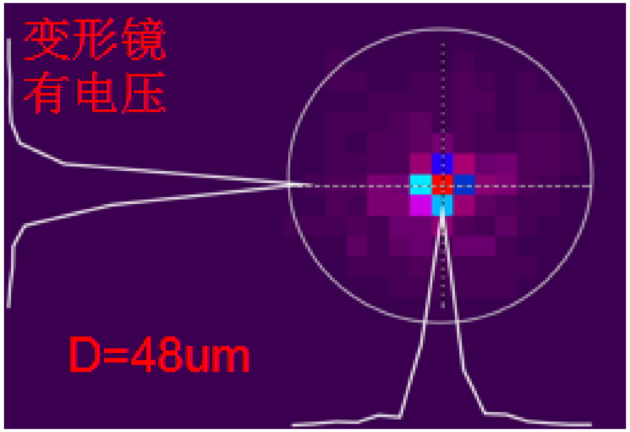
Wavefront map





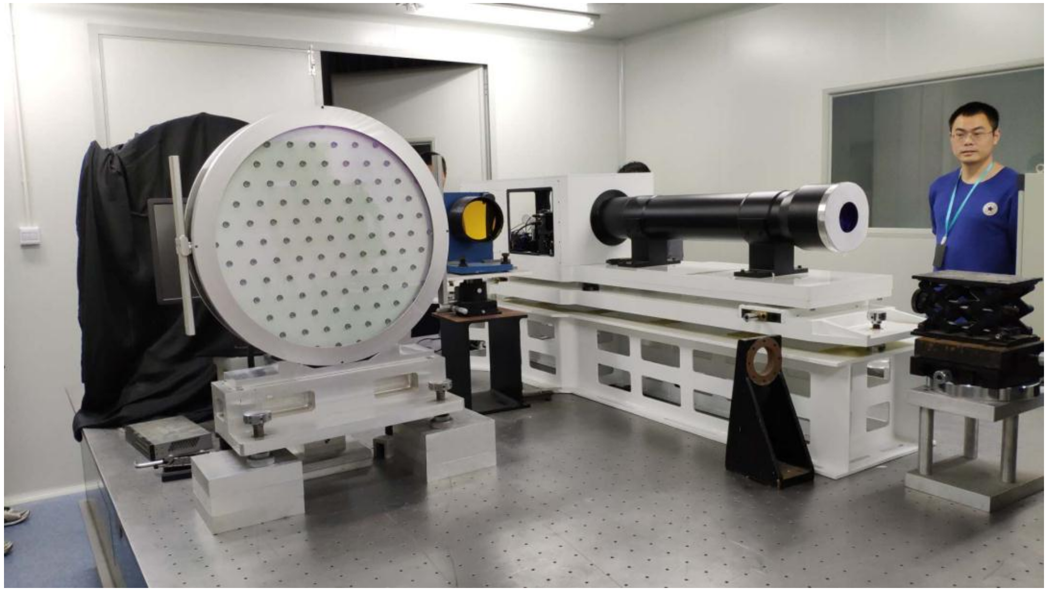
Focus spot



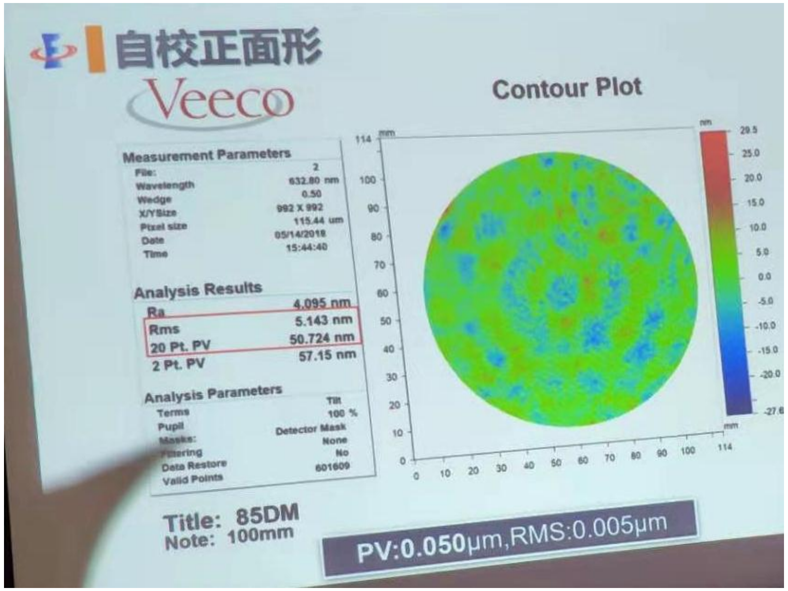


AOS in terminal stage

DM for terminal stage



Off-line measurement

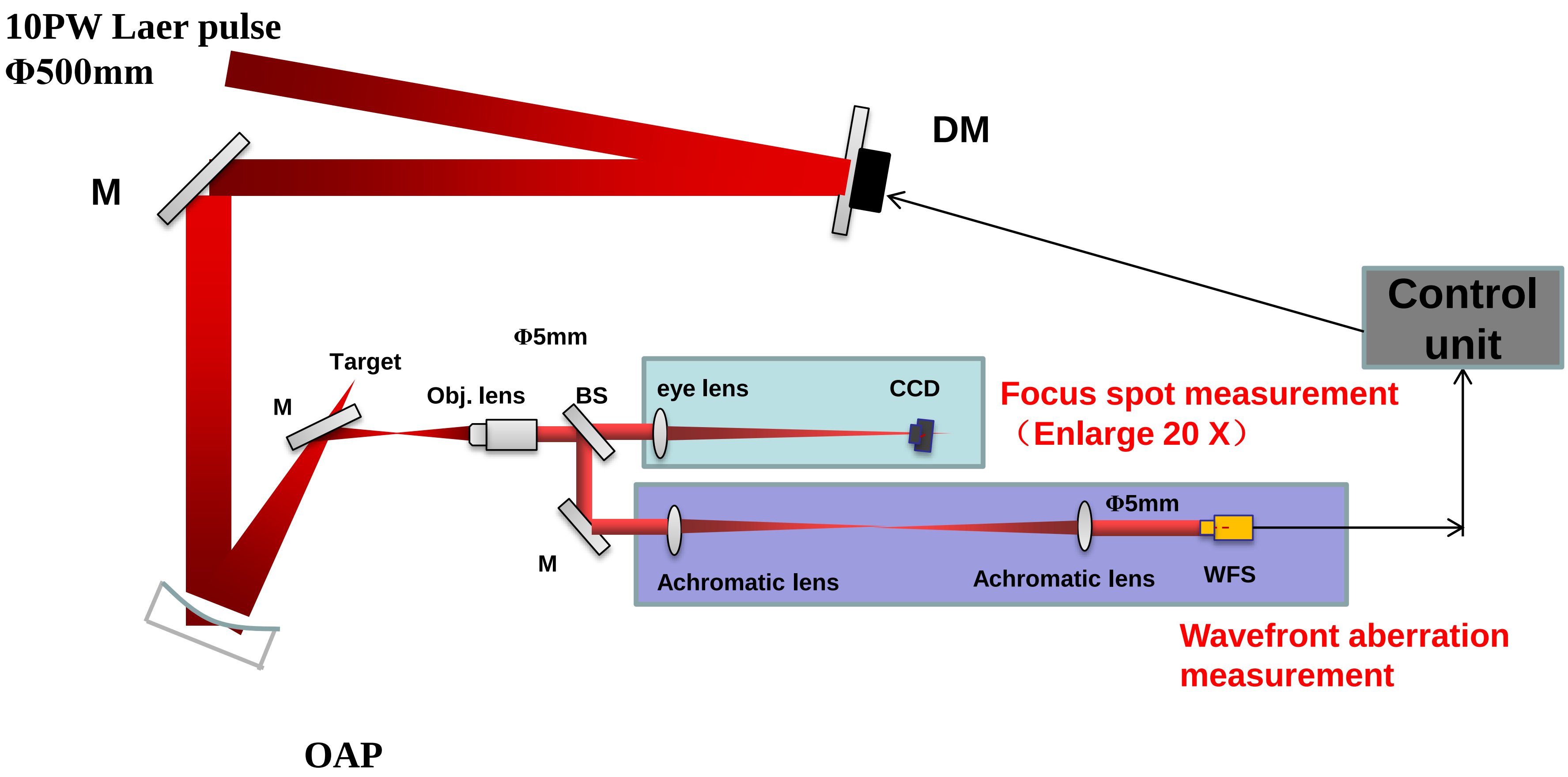


Result

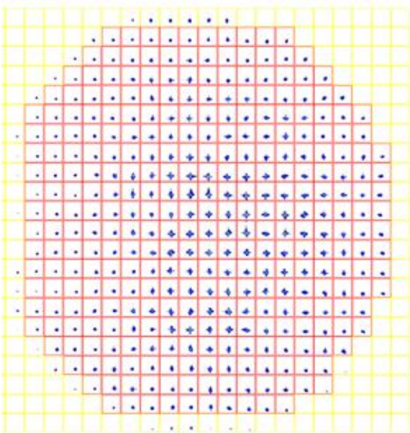
Clear aperture： Φ500mm
Number of actuators: 124
Range:±7.5um

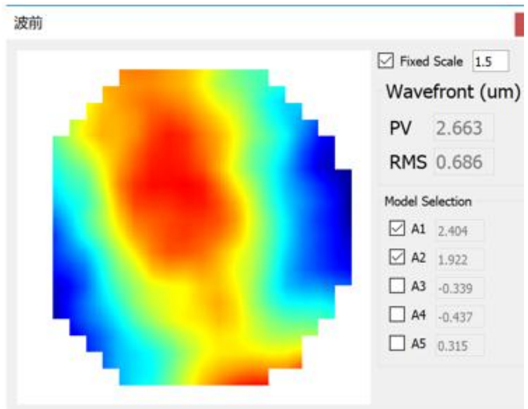
AOS in terminal stage

Optical path diagram of wavefront correction and focus measurement. It can measure the wavsfront map and focus spot (20 X) of laser pulse at the same time. The deformable mirror and Hartmann are imaged by two stage image system. The objective lens and eye lens can enlarge the orginal focus spot of OAP by 20 times.

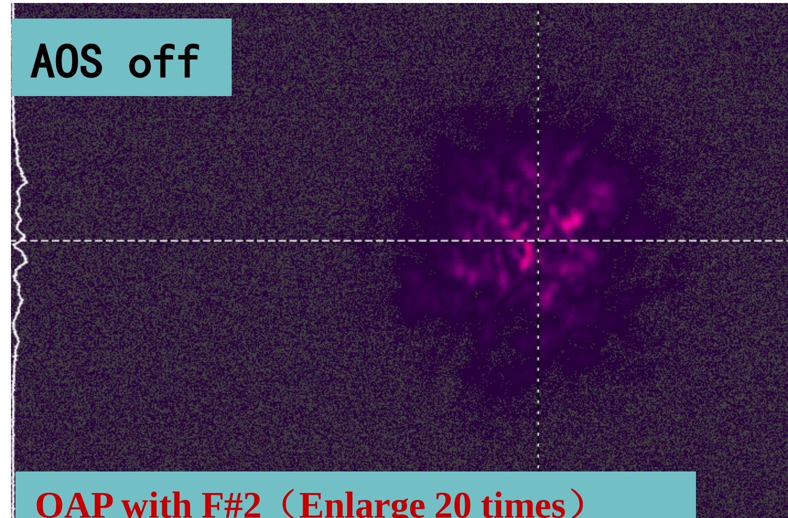


WFC and focusility of 10PW

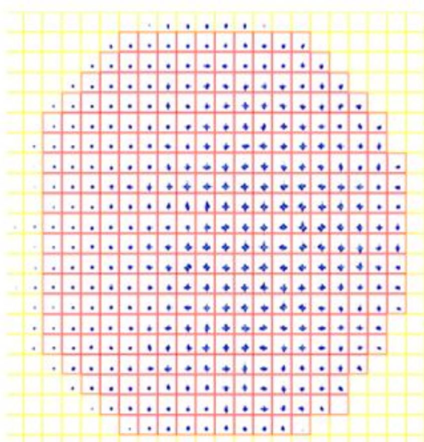


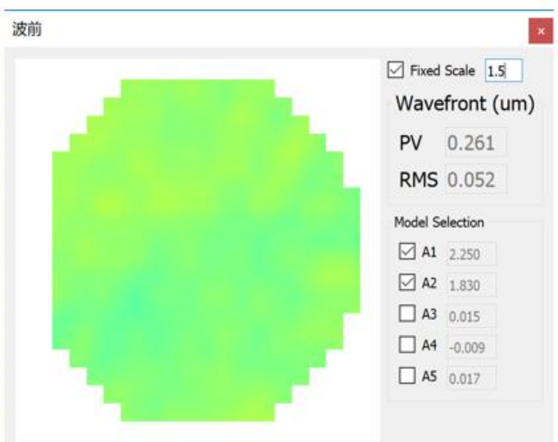


AOS off：PV=2.663um，RMS=0.686um

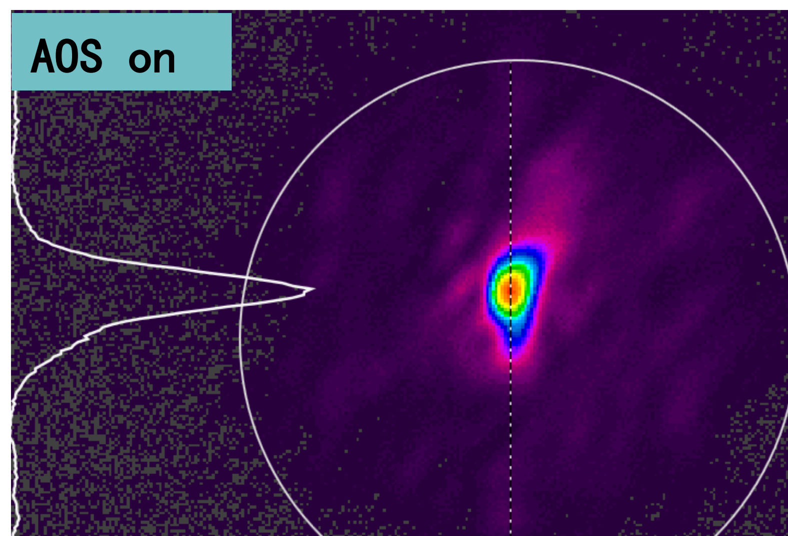


OAP with F#2（Enlarge 20 times）





AOS on：PV=0.261um，RMS=0.052um

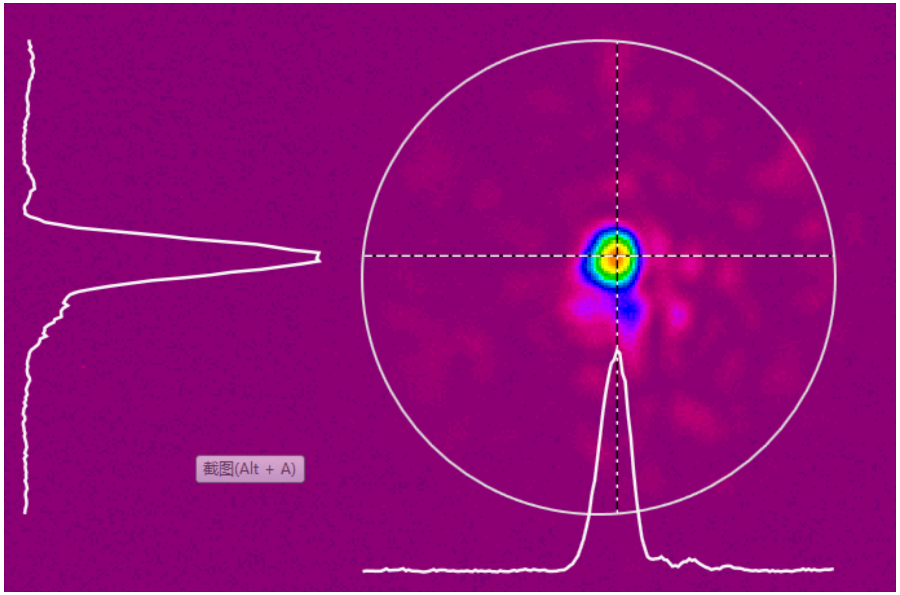


OAP with F#2: Spot size（20X）（FWHM）：2.4um×2.9um. Encirled energy in Φ4um 28.9%.

Focus Intensity ~2.3×10^{22}W/cm^2

Focus with narrow bandwidth filter

With 800nm±10nm filter



Beam size: 2.5um(FWHM),

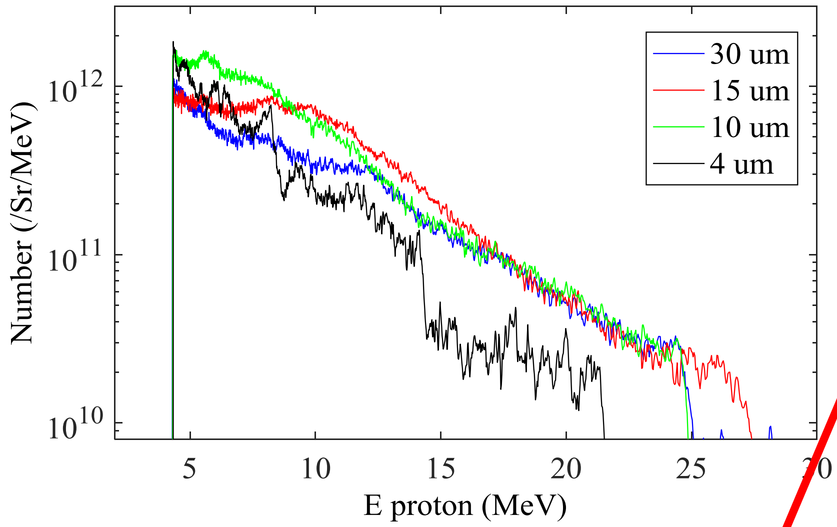
Encirled energy ~26.14%,

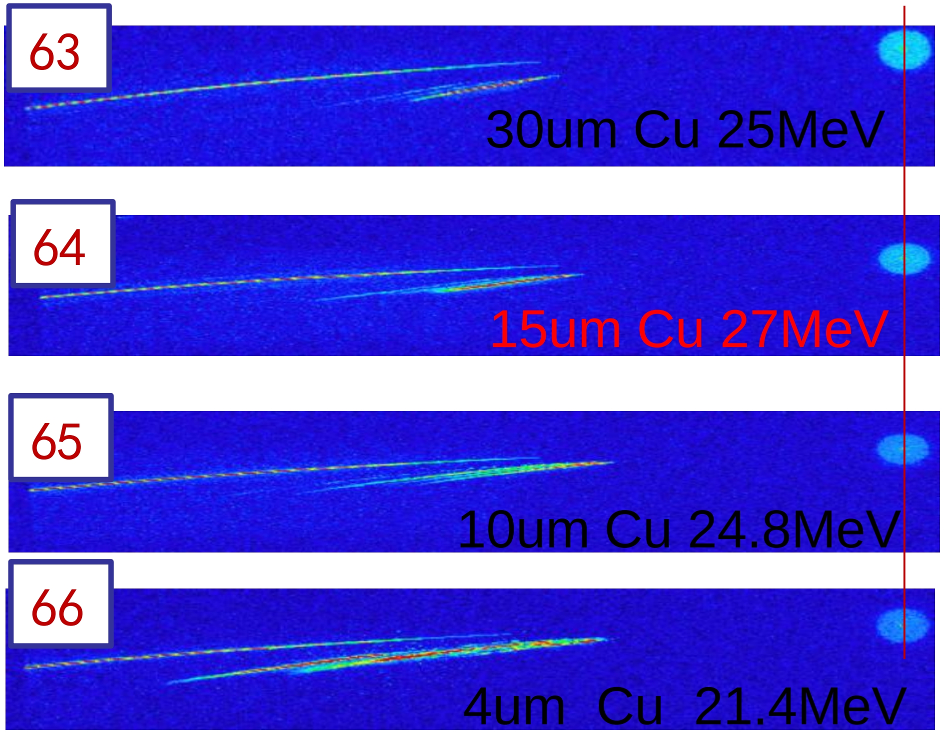
Encirled energy in 1/e^2>45%

Proton acceleration

Laser Parameters : 60 J/30 fs， 2PW
Target : 15 um-thickness Cu,

Proton Energy





Proton Numbers

Proton spectrum intergral

Energy interval	Number of Proton	Size of Proton source
10-20 MeV	1.8e+5	7um×10um

Content

目录

Summary

- **Two adaptive optics systems are used in SULF 10 PW laser facility to optimize the wavefront aberration and improve the focus intensity;**
- **The corrected beam is focused to 2.75×2.87 um^2 at FWHM with a long focal length OAP (f=721mm) in the year of 2018. A peak intensity of 2×10^{22} W/cm^2 is achieved at the output of 5.4 PW .**
- **In 10 PW laser facility, the focus spot size after correction is 2.4um×2.9um （F#2 OAP） and encirled energy is 28.9% in Φ4 um. The focus intensity is ~ 2.3×10^{22} W/cm^2 at present.**
- **In future, focus spot will be optimized (for example:angular chirp, chromatic aberration and measurement of focus, etc) and intensity will be up to 10^{23} W/cm^2 with OAP of F#2. And some interesting experiment will be carried out with intensity of 10^{22}~$10^{23}$$W/cm^2$**

Better laser, Better life　激光让生活更美好

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Shanghai Institute of Optics and Fine Mechanics , CAS

Thank you