Laser Review

Route to High Contrast and Focusable Intensity in PW-Class Femtosecond Ti:sapphire Laser Facility

Cheng LIU, Zhaohua WANG, Feng LIU, Weichang LI, and Zhiyi WEI[†]

Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China

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This paper report the recent progresses on the XL-III facility by using a new front-end and optimizing the energy output from the final amplifier. To increase the contrast ratio, some novel techniques such as ring regenerative amplifier with ultra-long cavity length, double chirped pulse amplification (DCPA) and cross-polarized wave generation (XPW) were carried out. Contrast ratio of higher than 10^7 was demonstrated with combination of DCPA and XPW. The output energy from last stage was boosted to 45 J pumped with laser energy of 120 J at 527 nm. With the preliminary measurement of pulse duration of 31 fs, it supports the peak power nearly 1 PW.

Key Words: Petawatt, Contrast ratio, Beam quality, Ti:sapphire laser, CPA

1. Introduction

In the researches of femtosecond ultrahigh intensity laser and applications, it is a great challenge work to push the laser power to a petawatt (PW) scale with good beam quality and excellent pulse contrast. Although some petawatt facilities based on the Chirped-Pulse Amplification (CPA) technology have been built in recent years,1–8) it still remains some complicated techniques to reach an intensity of 10^{23} W/cm^2 with contrast ratio about 10^{10} to background noise.9) Generation of ultrafast laser pulse with relativistic intensity and high contrast ratio is an interesting work. In this paper, we present the recent progress on our XL-III laser facility with double-CPA (DCPA)10) and optimization of output energy from the final amplifier. By replacing the former short-cavity regenerative amplifier with a small CPA system and a cross-polarized wave (XPW) generation11) between the two CPA systems, the pulse contrast between the main pulse and the amplified spontaneous emission (ASE) researched to 10^{-8} in tens picoseconds scale. The final amplifier was optimized by using a thicker Ti:sapphire crystal with decreasing the parasitic lasing, the output energy was boosted to 45 J under the pump energy of 120 J at 527 nm before compressor. After compressor, the energy was 30 J. With the preliminary measurement of 31-fs pulse duration, it corresponds to a peak power nearly 1 PW.

2. The Description of XL-III Laser Facility

In order to increase the pulse contrast ratio, we improved the design of the XL-III (eXtreme Light) laser facility with a doubled CPA scheme by inserting a pulse cleaning filter between two CPA systems. The compressed pulse from the first CPA was injected into (XPW) filter to suppress the ASE and pre-pulses. Then the cleaned pulsed was injected into the second CPA system for further amplification. Figure 1 shows the schematic layout of whole system.

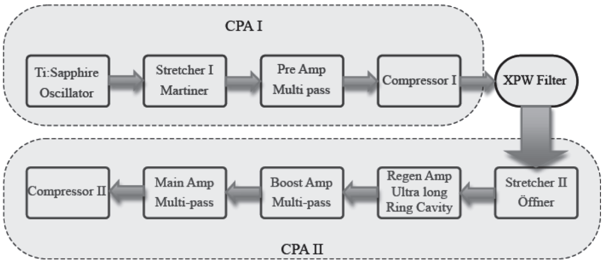

Fig. 1 Schematic layout of the doubled CPA with XPW filter.

A homemade femtosecond Ti:sapphire oscillator was used to generate the seeding pulse, which was designed with prism controlled dispersion compensation scheme. Under 4 W pump power, stable mode-locking laser pulses of 20 fs were obtained with average power of about 500 mW. Then a Martinz stretcher (stretcher I) was used to extend the seeding pulse to 200 ps for amplification. The first amplifier (Pre Amp) is designed with a con-focal focused configuration in ten passes.12) Pumped by a 10 Hz green Nd:YAG laser at 532 nm (PR-170, Spectral Physics Inc), the seeding pulse was amplified to about 3 mJ under the pump energy of 50 mJ. After the standard gratings compressor I, the pulses were compressed to 30 fs with energy of 1.6 mJ. Further inject the laser pulses into the XPW device to clean the pre-pulse, we measured the energy of clean pulse was about 0.2 mJ, corresponding to the efficiency of about 12 %. Finally, the cleaning pulse after XPW was injected into the second stretcher as a new seeding pulse for next CPA.

In the second stage CPA, the clean pulse was firstly re-extended to about 600 ps by an Öffner-type stretcher (stretcher

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II). Considered the ring cavity and long laser cavity support a higher contrast ratio,[13] we designed a novel ring regenerative amplifier with cavity length to 12.6 m as the first amplifier in the second CPA (Regen Amp with ultra long ring cavity). Figure 2 shows the layout of the ring regenerative amplifier, the cavity was composed of two curve mirrors with radii of concave (ROC) of 4 meters, and two pieces of Ti:sapphire crystals was placed in the cavity. With the pump energy of 150 mJ at wavelength of 532 nm, the energy of amplified laser pulse reached to about 20 mJ. Further, the chirped laser pulse was injected into the third stage amplifier which was designed with a six-pass configuration (Boost Amp). A 2.6 J doubled frequency Nd:YAG laser at repetition rate of 1 Hz (Beamtech Inc) was used as the pump source. Laser energy up to 700 mJ was obtained after the stage. In the last-stage amplifier (Main Amp), a custom designed Nd:glass laser was used to pump a Ti:sapphire rod with 80 mm diameter to realize a high energy output. To optimize the amplified energy, we enlarge the beam diameter to 70 mm to fit the energy flux of pump laser, which is about 3.1 J/cm^2 in total with both sides pump. With the total pump energy of 120 J at 527 nm, the laser energy of 45 J was obtained by further eliminate the parasitic lasing and the spontaneous amplified emission. Finally, the amplified laser pulse was enlarged to 140 mm in diameter by a vacuum image-transferred tube and sent into the vacuum grating-pair compressor (Compressor II). The compressor consisted of four large gold-coated holographic gratings (Jobin-Yvon Inc.) with groove of 1480 lines/mm, size of the larger gratings are 460 mm × 210 mm × 50 mm and the size of smaller gratings are 210 mm × 180 mm × 50 mm. The transmit efficiency of compressor was about 66 %, corresponding the energy of compressed pulse was about 30 J. The spectrum of output laser is shown in Fig 3 (a), and the bandwidth of the spectrum was about 31 nm. To safety optimize the dispersion compensation for pulse recompression, we stopped the main pump laser and only allowed about 20 mJ amplified laser through the final stage amplifier for compressor alignment in the preliminary measurement. By fine adjust the distance and origination of gratings in the compressor, we measured the optimized autocorrelation trace as Fig. 3 (b), it corresponds to the 31 fs pulse duration with sech square assumption.

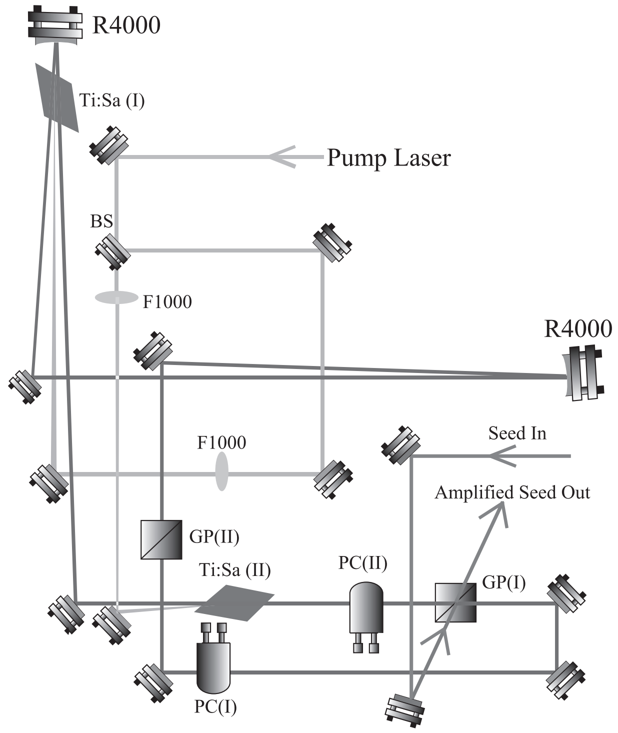

Fig. 2 Layout of the ring regenerative amplifier with 12.6 m cavity length.

3. Contrast and Focusable Intensity Enhancement of XL-III Laser Facility

In our original design, the pre-amplifier was a standard regenerative amplifier,[4] the contrast of ASE from the cavity was only 10^{5-6}. For many emerging applications, this contrast ratio will be a problem because of the per-plasma generation. In order to increase the contrast ratio for ultrahigh intense laser physics, such as laser wake field acceleration, ultrafast coherent X ray generation *etc*,[14] we re-designed the system with a DCPA scheme, a XPW filter was used between two CPA systems, which was installed inside a vacuum chamber and shown as Fig. 4. After increasing the polarization by a polarizer, the compressed laser pulse from the first CPA was focused at the point behind the BaF$_2$ crystal by a lens with 800 mm focal-length, it can efficiently increase the light intensity inside the BaF$_2$ crystal but avoid the damage. The BaF$_2$ crystal is 2 mm in thickness and cut along the direction of 110. Because of the nonlinear effect, laser polarization will be rotated as the laser intensity inside the crystal, so that after the analyzer (second polarizer), the lower intensity laser will suffer from a larger loss in temporal domain, result in a clean pulse with increased contrast ratio. In our experiment, two BaF$_2$ crystals were used to enhance the effect, and another sil-

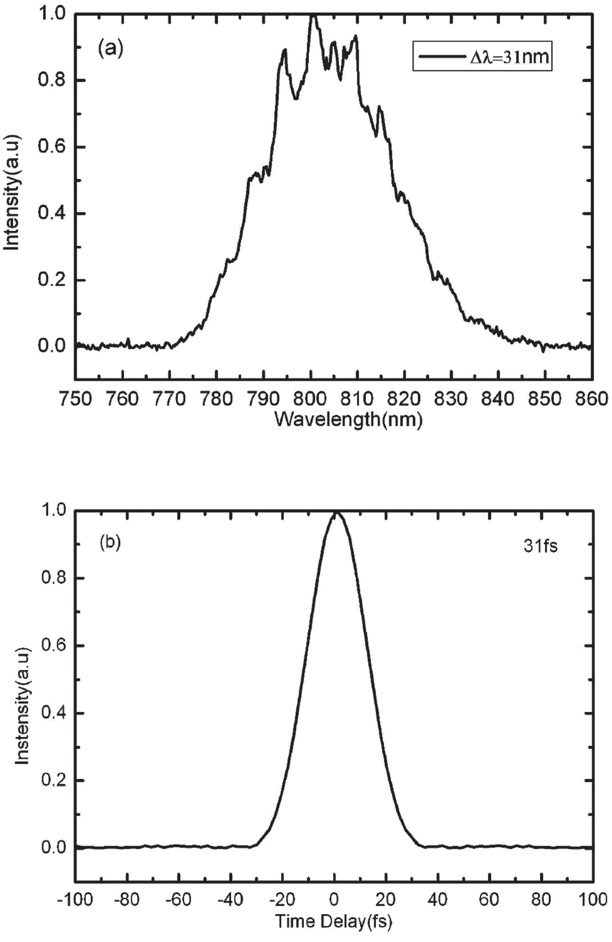

Fig. 3 The spectrum and the autocorrelation trace after the compressor II.

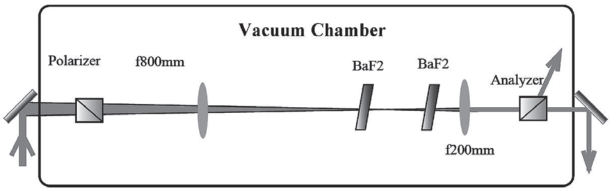

Fig. 4 Schematic diagram of XPW device. The amplified laser from the first CPA passed through a cross-polarized polarizer, was focused into two pieces of BaF_2 crystals using a f = 800 mm lens, and collimated by a f = 200 mm lens.

ica fused lens with 200 mm focal-length was used to collimate the laser beam. With the fine alignment and further amplification after second CPA, we measured the contrast ratio of amplified laser pulse was increased to higher than 10^7 with a commercial third-order autocorrelator. Figure 5 shows the typical result, compare to the previous result (black line) from our original system, the contrast ratio was obviously enhanced.

In order to get good focus ability, we used a novel method to align the gratings for optimizing the compressor under the incident energy of 20 mJ. Figure 6 shows a sketch of a single pass four-grating compressor which was equivalent to a double pass grating pair compressor with a retro-reflecting mirror. All the four gratings were installed on the geometrical position and pre-aligned using the usual method. The laser pulses with beam size about 140 mm diameter were injected into the compressor and with the designed incident angle of 20.5 ° onto the first grating. After propagates through the compressor, the pulses were focused onto a CCD camera to view the far-field pattern. Grating 2 was assumed to have a misalignment error in the dispersion plane with a slight angle α around x-axis. The laser beam with incident angle $\theta = 20.5$ ° onto compressor will have angular chirp when pass through the unparallel grating pair. The output angular difference between wavelength λ_1 and λ_2 is given by $\delta\phi = \alpha\ (\cos\theta_1 - \cos\theta_2)/\cos\theta_i$, where θ_1 and θ_2 are the diffraction angle corresponding to wavelength λ_1 and λ_2 respectively.[15,16] The double pass of the beam through the grating pair will double the angle difference. When the output beam is focused, the angular chirp will result in a decomposition of different spectral component in the focal plane as shown in Fig. 6 (c). In order to distinguish each element of spectrum, we set a mask between each pair of gratings and use a CCD to monitor the far-field. The detail information was shown as in Fig. 6. With careful alignment in each dimension of grating, we got an ideal beam spot for 20 mJ incident energy after the compressor. The size of focal spot was about 25 μm with a f/10 off axis parabola (OAP) (Fig. 7).

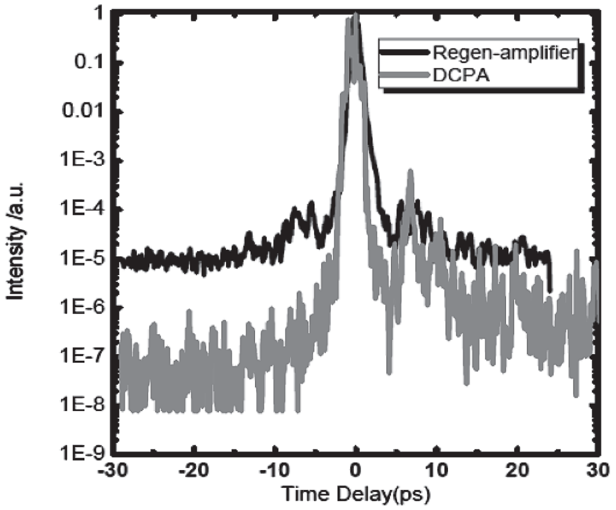

Fig. 5 Comparison of contrast ratio with original system and new DCPA system.

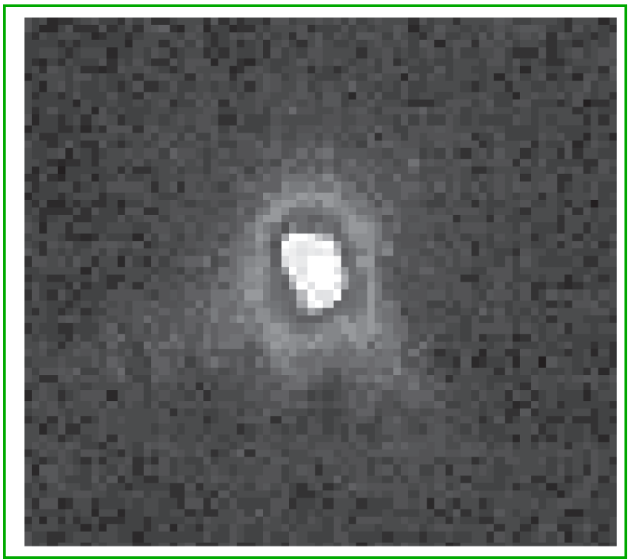

Fig. 7 The focal spot with f/10 OAP.

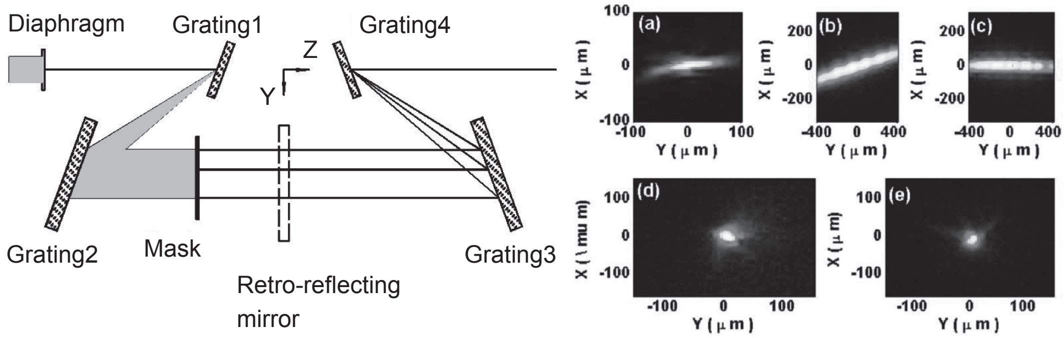

Fig. 6 Diagram of compression grating parallelism alignment procedure by far-field monitoring: (a) focal spot obtained after the gratings have been aligned by the usual method. (b) adjust the groove rotation around y-axis until the focal spots formed by different wavelength components are in a line instead of a curve. (c) adjust the surface rotation around z-axis until the focal spots are in a horizontal line. (d) the output far-field of beam double passing well aligned 2-grating pair and (e) the output far-field of beam single passing well aligned 4-grating compressor.

4. Conclusion

In conclusion, we reported our recent progresses on the XL-III facility with a new DCPA scheme. By using techniques such as cross-polarized wave generation (XPW), ring regenerative amplifier with long cavity length *etc*, the contrast ratio of amplified laser pulse was increased to higher than 10^7. Optimizing the boosting energy from the final amplifier stage enable us an output energy up to 45 J under the pump energy of 120 J at 527 nm. Although our preliminary measurement was carried out with 20 mJ energy of splitting from the main amplified laser, the 31 fs pulse duration promises a potential to peak power nearly 1 PW for full energy incidence. With a novel alignment method for compressor in each dimension of gratings, we obtained an ideal beam spot of which can be focused in the size of about 25 μm with a f/10 OAP. If an f/3 OAP will be used to focus the laser beam with full energy in the experiment, we expect that the laser intensity on the target could be reach to 10^{21} W/cm^2.

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