A compact 355TW femtosecond Ti:sapphire laser facility and trend to high contrast ratio

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Abstract. A Ti:sapphire laser facility is established based on the chirped pulse amplification technology. For the first time we generate laser peak power of multi-100TW with three stages of amplifiers. In the final amplifier a 100J frequency-doubled Nd:glass laser is used as the pump source. To suppress the parasitic lasing (PL), we design the Ti:sapphire crystal with V groove cutting shape and use polymer thermoplastic cladding to absorb the reflection at the Ti:sapphire interface. With the optimized alignment under 60J pump energy, laser peak power of 355TW is obtained at 31fs average pulse duration. The repetition rate is about 20mHz between two shots. Although the multi-100TW laser will enable us to open new applications on ultra-intense physics, the contrast ratio play more important role for the laser-matter interaction. To pursue a higher contrast ratio, new design on doubled CPA and ring regenerative amplifier are introduced. By further improving the amplification efficiency, our analysis shows that it should be possible to obtain peak power of high than 500TW with contrast ratio of about $10^{10}$.

1. Introduction
The invention of chirped-pulse amplification (CPA) technique has greatly pushed the progress of ultra-intense laser physics and technology. In the last decade, with the development of large size optics, such as Ti:sapphire crystal and compression grating etc, multi-TW laser systems on table top scale were widely researched. Peak power of more than 100TW have been successfully obtained from Ti:sapphire laser amplifier in some groups[1~4], which enable us to carry out the advanced extreme physics research such as the generation of ultrafast x-ray radiation, ultrahigh-order harmonics, particle acceleration, optical fields ionization etc. In general, for such high power laser, more than four stages of amplifiers are necessary to boost the single laser pulse to a considerable energy. However, more stages mean more pump lasers, more transmission materials and longer propagate distance, which may lead to larger B-integral and uncompleted dispersion compensation, and further limit the recompressed pulse duration and beam quality.

It is demonstrated that optimizing the mode match and energy flux can reduce the stages of

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amplifiers. 20TW peak power is generated with only two stages of Ti:sapphire amplifiers including a regenerative amplifier and a multi-pass amplifier[5]. In this paper, we report a 355TW Ti:sapphire laser facility with three stages of amplifiers and the chirped laser pulse is boosted to energy of 21J. By injecting the laser pulse into a vacuum compression chamber, average laser pulse duration as short as 31fs is obtained with energy of about 11J. For the first time, we demonstrate a feasible way to generate hundreds of TW laser with an even more economic technique and a compact space.

2. System design

A typical CPA laser system consists of the femtosecond laser oscillator, the pulse stretcher, the energy amplifiers and the pulse compressor. To aim the peak power of hundreds of terawatt, we design the amplifier with three stages. Figure 1 shows the layout of the whole system. A home-made Ti:sapphire oscillator is used to generate the seed pulse. Pumped with 5W 532nm laser (Millenia, Spectra-Physics Inc.), it can put out stable mode-locking laser of sub-20fs at a repetition rate of 82MHz. To reduce the gain narrowing effect, we set an acoustic-optical modulator (DAZZLER™ WB-800, Fastlite Inc.) to pre-shape the laser spectrum. After stretching the laser pulse to around 600ps with an Öffner stretcher [6], the chirped laser is firstly amplified with a regenerative amplifier which is pumped by a single frequency Nd:YAG laser (Lab-170, Spectra-Physics Inc.) at a repetition rate of 10Hz. The second stage is a multi-pass amplifier which is pumped by a frequency-doubled Nd:YAG laser at 1Hz repetition rate (Beamtech Inc.), which is capable of single pulse energy of 3J at 532nm. An electrical frequency divider is designed to synchronize it with the regenerative amplifier. To obtain higher efficiency under safe pump, referring to our previous work [5], we enlarge the laser beam to 14mm in diameter, corresponding to the energy flux of about 2J/cm². Due to the limited pump energy from available commercial lasers, we further use a Nd:glass laser to pump the third stage of amplifier. The pump laser is customized design with dual beams output, energy of each beam is 50J at 527nm. Considering that the total energy can reach up to 100J, we further enlarge the beam diameter to 60mm in the third stage of amplifier so that the pump energy flux is limited below 3.5J/cm². Finally, the amplified laser pulse from this stage is enlarged to 120mm in diameter and injected into the vacuum compressor to restore the original pulse duration. A single shot autocorrelator is used to measure the compressed pulse.

3. Experiment and discussion

Compare to our previous research on 20TW facilities, the main progress is that we added a third stage of amplifier. Because the third stage of amplifier runs at single shot mode, we set the second amplifier at the repetition rate of 1Hz, so that not only easy the pulse picking up, but also feasible the pump laser at high energy, good beam pattern and low cost. Pumped the second stage with energy of 2.6J at 532nm, the optimized output energy is about 700mJ, corresponding to the efficiency of 27%. For the main amplifier, to pursue the output energy as high as possible, we use a disk Ti:sapphire crystal with size of 85mm in diameter and 20mm in thickness (Shanghai Institute of Optics and Precision Mechanics), which is the largest size available domestically. Considering the damage threshold and the saturable energy flux, it allows a pump energy of higher than 100J for such large aperture, so that we use a customized Nd:glass laser as the pump source. A quasi-single frequency Nd:YLF laser at 1053nm is used as the seed pulse. After one stage of amplification with a flash-pumped
Nd:YLF laser, the laser is divided into two beams and further boosts to 100J in each beam with three-stage Nd:glass amplifiers. The Gaussian reflection technique is used in this laser so that the beam distribution with top-tap mode. Figure 2 is a typical beam profile with modulation is less than 10% which is acceptable for pumping the Ti:sapphire laser. Frequency Doubling both beams is achieved with two KD*P crystals and laser energy of higher than 50 J is obtained at 527 nm for each beam, corresponding to the efficiency of larger than 50%. In table I we list typical energy of three shots within 1 hour, the average fluctuations are less than 10% for both beam A and B. For the large disk Ti:sapphire crystal, the parasitic lasing (PL) will be a serious problem under the high pump flux, which will greatly depress the available laser energy during amplification. To suppress the PL, one feasible technique is to clad the Ti:sapphire crystal by filling the material with matching refraction index where Fresnel reflection can be well depressed. The polymer thermoplastic is successfully used as the typical material to absorb the fluorescence from the Ti:sapphire interface[2]. However, the glutinous chemical material is easy to pollute the crystal surface and weaken the effect after a period. Thinking about the mechanics of PL, we design the crystal with V groove cutting shape so that the inner reflection can be suppressed. Figure 3(a) shows the section shape along the axis direction. We can easily understand that lasing will not be easy to occur inside the inner surface because of the non-parallel plane. Figure 3(b) is the photo of the crystal. Together with the polymer thermoplastic for refractive index matching, amplified energy of 20.9J is obtained in preliminary experiment under the pump energy of 60J, corresponding to an efficiency of about 26%. We measure the stability to be less than 1% within one hour. Although the pump energy flux is about 2.8J/cm², the amplification efficiency is much lower than the simulation prediction [2]. We believe that the main reason is the uncompleted absorption of the Ti:sapphire crystal for pump laser because of the 18mm thickness of the crystal. We measure the absorbptivity at 527nm is only 80% so that an excellent Ti:sapphire crystal with higher absorption is necessary for enhancement the amplification efficiency. To compress the amplified laser pulse, we first enlarge the beam to 120mm with a vacuum telescope which is also as an image relay system to restore the beam quality. The compressor consists of four gold coated holographic gratings (Jobin-Yvon) of which the size of the first and fourth gratings are 230 mm in length and 180mm in height, and the second and third ones are 460mm in length and 210 in height, respectively. All the gratings have the same groove density of 1480line/mm. Because of the large beam size, we set the gratings in the same plane with the standard Treacy’s configuration. To hold these heavy gratings stably, we design and manufacture four special holders to fix them and they perform very good robustness and can well eliminate the distortion by stress. The optimized parameters of the compressor are simulated by calculating all the material dispersions in three stages of amplifiers and the dispersion in the stretcher [6]. Based on the simulation, we set the separation

| Shot | Beam A(J) | Beam B(J) |
|------|-----------|-----------|
| 1    | 54.69     | 54.70     |
| 2    | 49.54     | 53.04     |
| 3    | 52.43     | 50.15     |

Table 1. SHG energy of beam A and B for three shots

![Figure 3 (a) The crystal shape in section plane.](image)

![Figure 3 (b) Photo of Ti:sapphire crystal cut with the design.](image)

![Figure 4 Calibration and measurement of laser pulse. Insets show the autocorrelation trace in beam pattern with the delay.](image)
between the two parallel grating as 380mm and the incident angle at 22°. The accurate adjustment for grating position and the incident angle is realized by electrically controlled step-motors. A single shot autocorrelator is used to measure the pulse duration after the compressor. Figure 4 shows the calibration for the single shot autocorrelator and the preliminary measurement. We can easily get the compressed pulse of about 50fs. Although the diffractive efficiency of each grating is more than 90%, we measure the transmissivity of the compressor is 52.3% (corresponding to compressed energy of 11J) because of the loss arising from the gold mirrors in the system.

After the fine alignment, we measure the pulse duration for many shots in the optimized situation. The average result is 31fs but fluctuates from 27.6fs to 34.7fs. The difference of each shot may be due to the energy fluctuation and the slip of the beam-pointing which can lead to change of self-phase modulation and the beam position in the autocorrelation, resulting in the error of measurement. Considering the average pulse duration, we can infer that the peak power is about 355TW which represents the highest result by using only three stages of amplifiers.

4. Route to high contrast ratio.

As the increase of peak power, the contrast ratio of laser pulse will be a very important factor for the experiment of high field physics. The conventional CPA technology is only capable of $10^{5-7}$, which will lead to a considerable pre-plasma and shield the process of main physics phenomena with hundreds of TW power. We have measured the current contrast ratio of our 355 TW laser system which is $10^7$ in nanosecond time scale and $10^4$ in ten picosecond time scale. Several new techniques, such as optical parametric CPA (OPCPA) [7], doubled CPA (DCPA) [8] and cross-polarized wave generation [9] are proposed to increase the contrast ratio. New results up to $10^{10-11}$ have been reported in sub-TW scale laser. However, realizing such high contrast ratio in PW scale laser is still a challenging work. To pursue the higher contrast ratio of the 350TW laser facility, we design a DCPA scheme. In the first CPA, the energy is boosted to 2.4mJ with a ring regenerative amplifier [10]. There has been demonstrated a contrast ratio of $10^3$ with this kind of amplifier [11]. After compression the pulse to sub-30fs and further elimination the ASE with a pockels cell, we then inject the pulse into the 350TW system from the stretcher. Following the second stretcher, the stretched pulse will be directly input the first multi-pass amplifier pumped with the 3J 532nm Nd:YAG laser at 1Hz repetition rate. Before the final amplifier pumped with the 100J Nd:glass laser at 527nm, we use another pockels cell to eliminate the ASE again. By using a new 80mm disk Ti:sapphire crystal with thickness of 40mm and optimizing the efficiency, it should be possible to upgrade the laser power to more than 500TW with a contrast ratio of $10^{10}$ after the vacuum compressor.

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