Optimization of contrast ratio and focusable intensity in 700TW femtosecond Ti:sapphire laser facility

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Abstract. In this presentation, we report an improvement technique in our 700TW Ti:sapphire laser facility. In order to improve the contrast ratio, we designed a long cavity ring pre-amplifier. With careful alignment in each dimension of grating, we got a good focal spot after compressor. The size of focal spot was about 25 μm with an f/10 off-axis-parabolic mirror (OAP). Using an f/3 OAP to focus the laser beam in experiment, we expect the laser intensity of 10^{21} W/cm^2 could be realized on the target.

1. Introduction
In recent years remarkable progresses have been made on the ultrahigh intensity laser with peak power of multi-100TW[1,2], a new facility of ELI toward 200PW is being planned in Europe. In those facilities, the contrast ratio and beam quality will be the most important specifications for the laser matter interaction. In general, the contrast ratio was mainly related with the pre-amplifier, the conventional CPA scheme is only capable of 10^5-6, which will lead to a considerable pre-plasma and shield the process of the physics phenomena. Although high contrast ratio as 10^{11} was demonstrated in the front stage with new technique, still it is a challenge work to realize such a contrast ratio in PW scale laser. In other side, the focus ability of laser beam is tightly related with the wave-front, laser beam without phase distortion can be well focused into a diffractive limit and support a high focusable intensity. In this presentation, we will report the optimized experiments on the contrast ratio and beam quality in our 700TW Ti:sapphire laser facility (eXtreme Light III, XL-III). By using a filter based on cross-polarized wave (XPW) generation in BaF$_2$ crystal, the contrast ratio in front stage was greatly improved. Observation on laser beam also showed the focus ability with compressor alignment.

2. System description
Our laser system is made of femtosecond laser oscillator, pulse stretcher, energy amplifier and pulse compressor. A Ti:sapphire oscillator was pumped with 5W 532nm laser, which generated stable mode-locking laser of sub-20fs at repetition rate of 80MHz. To reduce the gain narrow effect, we set an acoustic-optical modulator (DAZZLER™) to pre-shape the laser spectrum, and the bandwidth of spectrum was broadened from 28nm to 36nm. After stretching the laser to about 600ps with an Öffner stretcher, the chirped laser pulse was firstly amplified by a regenerative amplifier which was pumped by a Nd:YAG laser at repetition rate of 10Hz. The second stage was a multi-pass amplifier which was pumped by a doubled frequency Nd:YAG laser at 1Hz repetition rate, which is capable of single pulse energy of 3J at 532nm. The pump laser was customized design with dual beams output, energy of each
beam was 50J at 527nm. Considered the total energy can reach 100J, we further enlarge the beam diameter to 60mm in third stage amplifier. In this stage, the chirped laser pulse was boosted to energy of 43.5J. Finally, the amplified laser pulse was enlarged to 120mm and injected into the vacuum compressor. The compressor was consisted of four gold coated holographic gratings (Jobin-Yvon Inc.) with groove of 1480 lines/mm, the size of grating 1 and 4 was 230x180x30mm, one of grating 2 and grating 3 was 460x210x50mm. Pulse duration as short as 31fs was obtained with energy of about 22.5J, corresponding to the peak power more than 700TW.

3. Contrast enhanced design

In the original design, the pre-amplifier was a traditional regen-amplifier. The contrast of ASE from the cavity was just $10^{-6}$. In order to improve the contrast to $10^9$, a double-CPA (D CPA) with XPW design was expected in our laser system[3,4]. Fig.1 is the layout of the XPW technique used in our laser system. The energy of laser pulses from the 1kHz Ti:sapphire system was about 450 $\mu$J. It passed through two pieces of cross-polarized Glan-Taylor prism, and was focused on the BaF$_2$ crystal with a 800mm focal lens. The length of BaF$_2$ crystal was 2mm. Using two pieces of BaF$_2$ crystals, the clean laser pulse with 40 $\mu$J was obtained from XPW device. Then it was injected into second stage CPA system. In the second stage, we designed a long cavity ring regen-amplifier, which cavity was about 12m, using two pieces of crystals in the cavity (Shown as in Fig.2). The Ti:sapphire crystals were pumped by a frequency doubled Nd:YAG green laser operating at 10Hz. Two concave mirrors with curvature radius of 4-m were positioned in the cavity to satisfy the stable-cavity criterion. We used two focal lens to focus the pump laser to the spot size of 2mm on the crystals. Two Ti:sapphire crystals were used to reduce the heat effect of a single one. All optical components were positioned far from the cavity beam waist which existed between the two concave mirrors. One of the crystals was near the concave mirror in order to allow the beam to double pass the gain medium. The two pockels cells were used in the cavity for the seed injection and amplified laser pulses ejection. With the pump energy of 160mJ, the energy of 20mJ was obtained.

4. The alignment of compressor gratings

We performed simulation using commercial optical design software ZEMAX to study the influence of relative misalignment angles between grating pair on the output beam far-field pattern. Fig. 4 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. The size of grating 1 and 4 was 230 mm × 180 mm × 30mm, and the size of grating 2 and 3 was 460mm × 210mm × 50mm. The grating groove densities of the four grating are 1480 lines/mm. A laser beam with diameter of 120 mm and incident angle of 20.5° onto grating 1 propagates through the compressor. Seven wavelengths range from 750 nm to 850 nm were used in the simulation. The output beam was focused by a lens with focal length of 1000 mm. The spatial profiles of the laser beam in the focal plane (in x-y plane) are investigated. The focus spots when grating 4 is added by a small angle deviation from its perfectly aligned orientation (shown as in fig.4). The rotation of the grating surface around x-axis ( =1 mrad) results in focal spot elongation along y-axis in the diffraction plane as shown in fig 3 (a). The rotation of the grating surface around z-axis ( =1 mrad) results in focal spot elongation along x-axis in the plane perpendicular to the diffraction plane in fig 3(b). The effect of rotation of the grating groove around y-axis is similar. When the grating surface has deviation around x-axis and z-axis simultaneously ( =1 mrad, =1 mrad), a tilt and elongated focal spot will be observed in fig 3(c). When grating groove rotation around y-axis is added further ( =1 mrad; =1 mrad; =1 mrad), the different spectrum components will no longer be in a line but curved as presented in fig 3(d). It is worthy to mention that this phenomenon can be used as a criterion of whether there are both alignment errors of grating surface rotation around z-axis and groove rotation around y-axis, which can not be determined easily by other devices because of only one dimensional diagnostics [5, 6] or two wavelengths used.

Fig. 3 Focal plane view when gratings 4 have a small angle deviation from its perfectly aligned orientation: (a) α=1 mrad, (b) γ=1 mrad, (c) α=1 mrad, and γ=1 mrad, (d) α=1 mrad; β=1 mrad; γ=1 mrad. The image size is 500 μm × 500μm. The spots corresponding to different wavelengths are due to spectral decomposition in the focal plane.

The gratings were installed on the geometrical position and pre-aligned using the usual method. The oscillator output pulses with beam size being expanded to about 120 mm diameter are injected into the compressor and with the designed incident angle of 20.5° onto the first grating. After propagation through the compressor, the pulses are focused onto a CCD camera to view the far-field pattern. Grating 2 is assumed to have a misalignment error in the dispersion plane with a slight angle around x-axis. The laser beam with incident angle =20.5° into compressor will have angular chirp when pass through the unparallel grating pair. The output angular difference between wavelength λ1 and λ2 is given by = (cos γ1 - cos γ2)/cos i, where γ1 and γ2 is the diffraction angle corresponding to wavelength λ1 and λ2 respectively [5]. 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. 4(c). The focal spots displacement is given by y = f 2 , where f =500 mm is the focal length of the lens. The displacement should be less than half of the focal spot diameter of D=20 μm as shown in fig. 4(d). So we obtain f 2 < 1/2 D, which results in < D cos i /(4f (cos γ1 - cos γ2)). For the laser beam from our oscillator with spectrum range from 750nm to 850 nm, we estimate the alignment error to be < 40 μrad. Using the formulas given in [5], the alignment error in other two orientations are estimated to be < 67 μrad; and < 38 μrad respectively.
Fig. 4 Example 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.

5. Summary
In this presentation, we report an improvement technique in our 700TW Ti:sapphire laser facility. With a DCPA design, the contrast ratio of laser was improved from the original $10^5$ to $10^8$ (shown as in fig.5). With careful optimization, we want to realize 700TW laser output with contrast of $10^9$. With careful alignment in each dimension of grating, we got a good focal spot after compressor. The size of focal spot was about 25 μm with a f/10 OAP(fig.5). Using an f/3 OAP to focus the laser beam in experiment, we expect the laser intensity of $10^{21}$ W/cm$^2$ could be realized on the target.

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