Beam quality improvement and focused peak intensity measurement of an intense femtosecond Ti:sapphire laser system

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Micro-lens arrays were adopted to homogenize the beam profile of 532-nm pumping laser for the main amplifier of an intense femtosecond, chirped pulse amplification (CPA) Ti:sapphire laser. Experimental measurements showed a great improvement of the near-field pattern of the CPA beam after the main amplifier and the size of the focal spot was improved from 2.7 times diffraction limitation (DL) to 1.6 DL. The spot size focused by an $f/4$ off-axis parabola (OAP) in the target chamber was measured to be 5.8 μm (full-width at half-maximum (FWHM)), and a peak intensity of 2.6×10^{20} W/cm^2 was obtained at the output power of 120 TW. Peak intensity exceeding 10^{21} W/cm^2 or even 10^{22} W/cm^2 can be expected with smaller f-number focusing configuration and wavefront correction.

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Femtosecond, terrawatt to petawatt level chirped pulse amplification (CPA)[1] lasers are widely used to investigate high field laser-matter interactions. The focused peak intensity of the laser is a key parameter in most experiments or applications. At the intensity level above 10^{18} W/cm^2, the relativistic effects dominate the interaction of laser and matter. Relativistic response of electrons or plasmas to the optical field yields a variety of research and application areas, such as high order harmonic generation in plasma[2], electron acceleration[3], proton/ion acceleration[4], "fast ignition" concept[5] for inertial confined fusion. At even higher intensities, new physical phenomena, such as quantum electrodynamics effects, may be experimentally investigated[6]. In general, with the increase of the laser intensity, new fields both in fundamental physics and in the frontier of applications will be uncovered.

The most direct way to increase the intensity is to increase the output power of the laser system, i.e., to increase the energy of the laser pulse or to reduce the pulse duration. So there are several petawatt level CPA laser systems built or being built around the world. However, the obtained peak intensity rises just linearly with the increase of the power. Because of the cost and complexity of high power pumping source, the difficulty of achieving shorter pulse durations from gain-narrowing and nonlinear dispersion in standard CPA chain, the peak power of laser system cannot be easily increased. Another important parameter which limits the peak intensity is the spot size of the focus. As the peak intensity is proportional to the reciprocal of the square of the spot size, reducing of the spot size can greatly increase the intensity.

There are two ways to obtain the available smallest focal spot-size. One is to use a high quality, small f-number focusing lens or mirror. The other is to improve the quality of the output beam, i.e., to minimize the aberration caused by the optical elements of the laser system and the inhomogeneous profile of the beam caused by the non-uniformity of the amplifying media or the pump beam, and to correct the wavefront using adaptive optical (AO) systems. Recently, it is reported that a diffraction-limitation (DL), 0.8 μm (full-width at half-maximum (FWHM)) focal spot was obtained with an $f/0.6$ off-axis parabola (OAP) and AO wavefront correction on a 45-TW laser system[7]. Thus they claimed a record peak intensity of 0.7×10^{22} W/cm^2. In this letter, we demonstrated a good quality laser beam based on a 120-TW, 36-fs CPA laser system[8]. By using the micro-lens arrays to homogenize the pump beam for the main amplifier, a good quality beam with the far field divergence angle of 1.6 DL was obtained. With an $f/4$ OAP, a focal spot of 5.8 μm (FWHM) was obtained in the target chamber, which is, to our knowledge, the best result for systems without AO wavefront correction.

The laser system is a standard high power CPA Ti:sapphire system[8,9], which can deliver pulses with peak power of 23 TW and pulse duration of 33.9 fs at 10-Hz operation. 120 TW can be achieved by adding an amplifier pumped by a single-shot operated, frequency-doubled Nd:glass laser system. At 10-Hz operation, two commercially available frequency-doubled Nd:YAG lasers are adopted as the pump source for the multi-pass main amplifier. Each of them delivers 1.2-J, 7-ns, 532-nm pulses at a repetition rate of 10 Hz. The non-uniformity of the pump beams originates from the unstable cavity configuration of the oscillator, and results in inhomogeneity of the amplified CPA laser beam (Fig. 1(a)). The near-field pattern of the CPA beam contains circled structure and several distinct hotspots. This defective energy distribution easily causes damage to the optical elements when the system is operated at high power level, as well as induces poor focusing ability. Applying spatial filter to either the pump beam or the CPA beam will improve the beam quality, but a lot of energies shall

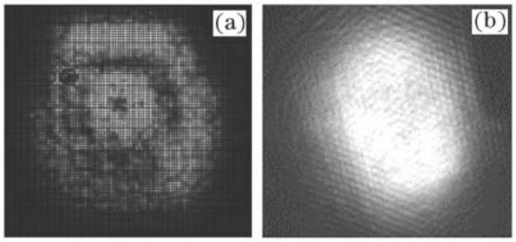

Fig. 1. Cross-section energy distribution pattern of the laser beam output from the main-amplifier without (a) and with (b) adopting the micro-lens arrays to homogenize the pump beam for the main amplifier.

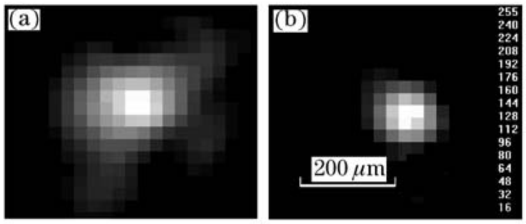

Fig. 2. Far-field intensity distributions before (a) and after (b) the pump beam homogenizing. The measured diameters of the waist of the $f/100$ focal spot are 270 μm (a) and 160 μm (b), respectively. The least resolution of CCD is 0.16 μm.

be lost. To overcome this situation two micro-lens arrays were added to generate two flat-top-distributed pump beams for the multi-pass main amplifier.

The technique of using micro-lens array to homogenize the pump beam for a CPA laser is firstly introduced by Dichiara *et al.*[10]. They obtained Gaussian near-field distribution of a 4-TW CPA beam by correcting the pump beam with micro-lens array. Considering the profile of the input beam to the main amplifier is already Gaussian-like, in our experiment we adopted flat-top-generators, i.e., micro-lens arrays that can correct inhomogeneous beam distribution to flat-top energy distribution. The micro-lens arrays were commercially available[11. Each array has a 15 × 15 (mm) dimension, densely packed with hexagonal negative micro-lens pixels. Each pixel has the diameter of 1 mm and the curvature radius of 91 mm. The array is placed between the output of the pump laser and the gain media, about 1300 mm from the center of the gain media. It can generate a flat-top distribution at the target plane with the energy density fluctuation less than 15%. At the same time the diameter of pump beam is enlarged from 10 to 15 mm to fit the size of the CPA beam, and the beam shape is changed from round to hexagon.

For inspecting the effect of using the homogenizing technique, the output CPA beam of the multi-pass main amplifier was shrunk by a telescope and directed onto an 8-bit scientific charge coupled device (CCD). The recorded images without and with the homogenizing technique are shown in Figs. 1(a) and (b), respectively. It can be clearly seen that the near field energy distribution was greatly improved. From Fig. 1(b) we can see some periodical structure in the energy distribution, which is caused by the structure of the micro-lens array. More smooth energy distribution will be obtained by adding another micro-lens array for the pump beam, at the expense of the cost and the complexity.

To measure the focusing ability of the 23-TW CPA beam an $f/100$ focusing optics was adopted. Since output pulse is a broad-band laser pulse, to avoid the chromatic aberration of single lens, a long focal length spherical mirror was used. Figures 2(a) and (b) show the focal spots before and after the pump beam homogenizing. The definition of laser beam quality β-factor is the diffraction limited multiple factor β. It is defined as the ratio of the size of measured focal spot to the diffraction limit. The diffraction limit $\Delta y = 1.22\lambda/2\sin\theta = 1.22\lambda \cdot f/d = 1.22 \times 800$ nm$\times 5000$ mm/80 mm$\approx$ 100 μm. The focal length f of concave mirror is 5 m, and the diameter of laser beam is 80 mm.

The results indicate that the far-field focusing ability was greatly improved by using pump beam homogenizing technique. According to the measured spot size, the far-field divergence angle trailed off. And the definition of laser beam quality β-factor became from 2.7 to 1.6.

The focal spot in the interaction target chamber was characterized to fully investigate the achievable peak intensity. The alignment of the focusing and measuring system is depicted in Fig. 3. The beam was focused by an $f/4$ OAP, and a 10×, NA=0.25 objective lens was used to image the focal spot to the CCD. While

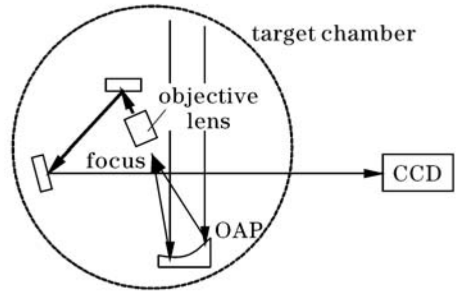

Fig. 3. Diagram of the method to characterize the focal spot in the target chamber.

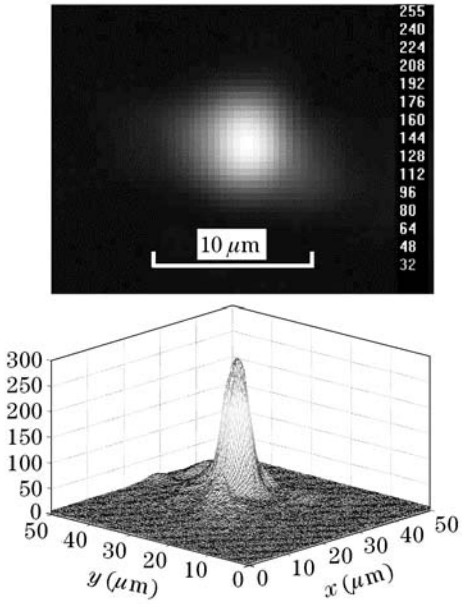

Fig. 4. Intensity distribution pattern and its three-dimensional profile of the focal spot.

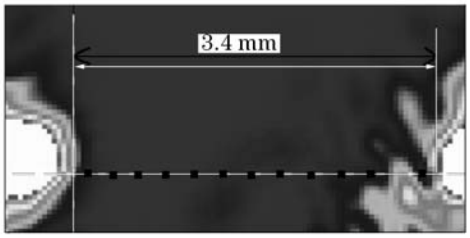

Fig. 5. A 30-μm diameter thread was placed superposed to the focal spot. The magnification is about 110.

adjusting the imaging system, a 30-μm diameter thread was placed, which superposed to the focal spot to scale the magnification (Fig. 5). The CPA laser system was fully pumped and the beam was attenuated by a polarization attenuator placed before the compressor. With the attenuated beam there is no air breakdown at the focus, enabling direct measurement of the spot size. Figure 4 shows the measured spot-size and intensity profile of the laser focus. The measured spot size at the focus is 5.8 μm (FWHM), and 40% of the totally measured energy is distributed in the FWHM range. The measured peak intensity is 1.35 times of the averaged intensity in the FWHM area. With all these characteristics of the focal spot we can deduce the peak intensity is 4.8×10^{19} W/cm^2 at 23-TW output and a peak intensity of 2.6×10^{20} W/cm^2 will be achieved at 120-TW output with an $f/4$ focusing optics.

Obviously using tighter focusing configuration, i.e., adopting smaller f-number OAP, higher peak intensity shall be achieved since for ideal focusing, the spot size is proportional to the f-number. For example, using commercially available $f/2$ parabola the expected peak intensity will reach 1.9×10^{20} W/cm^2 for 23 TW and 9.8×10^{20} W/cm^2 for 120-TW laser power. However, smaller f-number mirrors mean difficulty in manufacturing and alignment. In Ref. [7], an $f/0.6$ OAP was used to obtain a focal spot with diameter of 0.8 μm. Ideally, under the same situation the beam of our laser system will be focused to a size of 0.87 μm, yielding a peak intensity of 2.1×10^{21} W/cm^2 for 23-TW laser and 1.2×10^{22} W/cm^2 for 120-TW laser. Of cause, as is demonstrated in Ref. [7], adaptive optical system should be applied to correct the aberration of the focusing mirror and the beam itself.

In conclusion, we have obtained a high quality intense femtosecond laser beam by homogenizing the beam of the pump source for the main amplifier. Both the near-field cross-section energy distribution pattern and the far-field focusing ability were improved significantly. Optical measurement showed a 5.8-μm diameter (FWHM) focal spot in the target chamber with $f/4$ focusing configuration. By characterizing the focal spot, peak intensity of 4.8×10^{19} W/cm^2 was achieved at 23-TW power level and a peak intensity of 2.6×10^{20} W/cm^2 could be obtained at the output power of 120 TW.

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