Petawatt Laser System for Fast Ignitor Studies at ILE, Osaka University

Y. Izawa1), Y. Kitagawa 1), H. Fujita 1), T. Jitsuno 1), T. Kanabe 2), R. Kodama 1), K. Mima 1), N. Miyanaga 1), H. Nishimura 1), S. Sakabe 2), K. Shigemori 1), K. A. Tanaka 2), H. Yoshida 1), and T. Yamanaka 1)

1) Institute of Laser Engineering, Osaka University, Suita, Osaka, 565-0871 Japan
2) Faculty of Engineering, Osaka University, Suita, Osaka, 565-0871 Japan

e-mail contact of main author: izawa@ile.osaka-u.ac.jp

Abstract. A petawatt laser system has been developed for the fast ignitor studies. Three new technologies were introduced; an optical parametric chirped pulse amplifier (OPCPA) in the front end for suppression of prepulse below 10^{-8} the main pulase, a deformable mirror for correction of wave front distortion and the chirped pulse amplification in the GEKKO-XII. The system delivered successfully the output energy of 420 J in 470 fs on target, which corresponds to the focal intensity of more than 10^{20} W/cm^2. By using the PW laser, the heating experiments of the high density plasma imploded by GEKKO-XII started.

1. Introduction

At ILE, Osaka University, the GEKKO-MII short pulse laser (25 J/0.4 ps/ 60 TW) [1], and the petawatt module (PWM) laser (70 J/ 0.7 ps/ 0.1 PW) [2] have been constructed, and the extensive studies on a fast ignitor laser fusion have been carried out. The PWM laser has been upgraded to 1 PW output with 500 J in 0.5 ps [3]. One of key issues to obtain a highly intense short pulse in Nd:glass system is to suppress gain narrowing in the main amplifier chain. For this purpose the amplifier chain has to be operated in the low-gain mode, and, therefore, a high output power from the front-end system is required. The Ti:sapphire regenerative amplifier in the front-end of PWM laser was replaced by the optical parametric chirped pulse amplifier (OPCPA) [4]. The OPCPA is an ideal pre-amplifier for the PW Nd:glass system, because of broadband and high single-pass gain, low levels of pre-pulses and amplified spontaneous emission, small gain length, and less thermal influence. The OPCPA produced the output energy of 65 mJ with prepulse ratio smaller than 1.5 x 10^{-8}. In order to obtain the focused intensity of more than 10^{20} W/cm^2, a large diameter deformable mirror was introduced to compensate for the wave front distortion. In the fast ignitor concept, the precise synchronization between two lasers for the compression and the heating is highly important. A weak pulse, which is split out from the front-end, was introduced into the GEKKO-XII compression laser.

2. PW Laser System

Figure 1 shows the block diagram of the PW laser configuration. The system consists of a front-end, a Nd:glass amplifier chain, a beam transport optics, a pulse compressor and a focusing optics. The front-end system consists of a passively mode-locked Nd:glass laser oscillator, two pulse stretchers, and two stages of OPCPA [3]. Also we have equipped the pulse monitoring compressor, which uses the same groove line grating as the main compressor. The main amplifier chain contains Nd:glass rod amplifiers and a booster amplifier. The booster amplifier is a Cassegrain-type three-pass disk system having 350 mm clear aperture. A serrated aperture was inserted into the entrance of the amplifier chain to smooth the beam edges out, which improved the beam filling factor up to 0.62. The output energy of 1.1 kJ was successfully obtained from the booster amplifier by chirped pulse

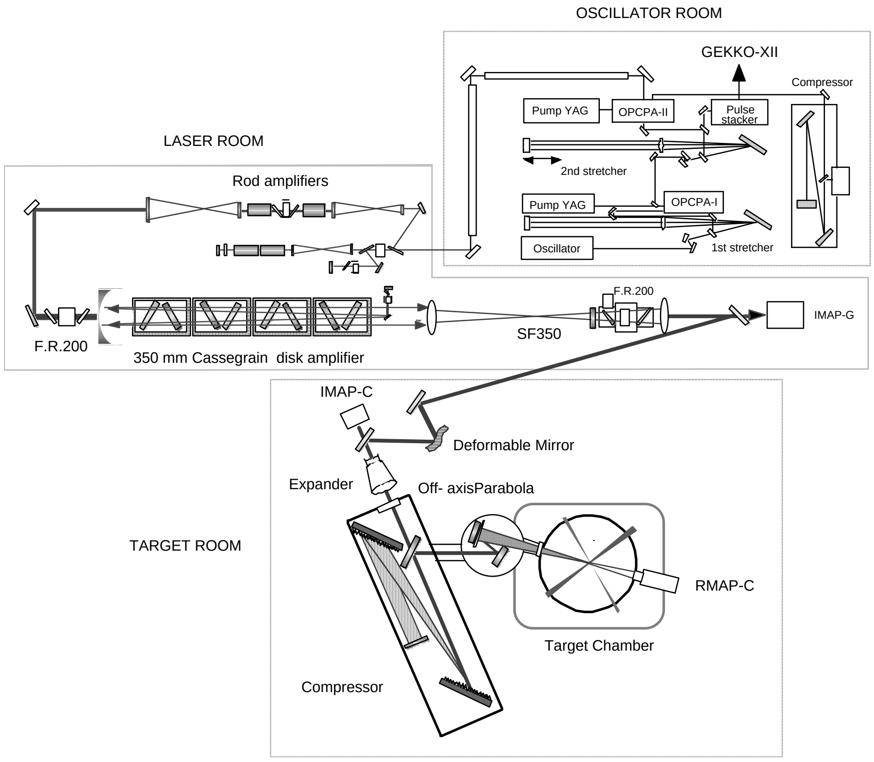

FIG. 1. Diagram of the PW laser configuration.

amplification (CPA) with the spectral width of 3.7 nm, which corresponds to 0.5 ps or less in Fourier transform limited pulse duration.

In the beam transport optics, a large aperture deformable mirror (DFM) was newly introduced to compensate for the spatial phase distortion mainly caused in the booster amplifier. A silica plate with 7 mm in thickness and 400 mm in diameter is driven by 37 actuators. It was confirmed that low order mode wave front distortions are corrected to 0.36λ in rms. The beam is expanded to 500 mm in diameter and transferred to the compressor. In the vacuum compressor chamber a pair of diffraction gratings with 900 mm in diameter are placed in double path configuration. Each grating has a gold-coated surface, grooved at 1480 lines/mm. The spacing of two gratings is 9.7 m. A part of the compressed beam is transported to the incident beam monitor and alignment package for the compressed one (IMAP-C).

The focusing system consists of two plane mirrors and an off-axial parabolic mirror of 3.8 m focal length, which concentrates the beam energy into the 20 μm spot area on target, providing the intensity of 10^{20} W/cm^2 or more. The system is installed in a vacuum chamber and is connected through a gate valve to the GEKKO-XII target chamber. On the counter port of the target chamber is set the focused beam monitoring and alignment package (RMAP-C). To protect the parabolic mirror from the target debris, a blast shield plate with 1.5 mm in thickness and 600 mm in diameter is put on the mirror. It is important to synchronize the PW laser with the GEKKO-XII. A weak pulse is split out from the front-end, sliced to 1 ns pulse width and then injected into the GEKKO-XII preamplifier chain. The timing jitter between two lasers is less than 10 ps.

3. PW Laser Front End

The optical layout of the front end system is shown in Fig. 2. The front end consists of a

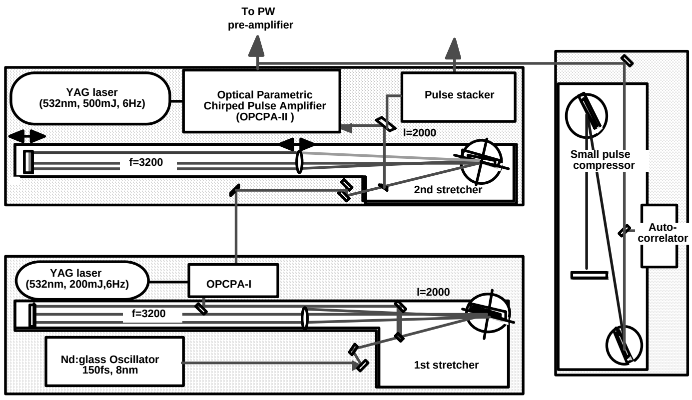

FIG. 2. Optical arrangement of front end system.

mode-locked cw Nd:glass oscillator, the first pulse stretcher, the OPCPA-I, the second stretcher and the OPCPA-II. The glass oscillator delivers the output power of 100 mW at the center wavelength of 1054 nm and the pulse width of 150 fs. The spectral width is 8.5 nm (FWHM). One of the fs pulses from the oscillator is selected by a Pockels cell and is temporally stretched from 150 fs to 1.5 ns (FWHM) by the first pulse stretcher, which is a telescopic stretcher formed by a 1480 lines/mm diffraction grating and a plane mirror separated by 3.2 m. The system produces a group velocity dispersion of about 250 ps/nm, which reduces the bandwidth from 8.5 ns to 6 nm by a spectral clipping through the telescopic lens and the grating. After the amplification by OPCPA-I, the laser pulse width is stretched again from 1.5 ns to 3ns (FWHM) by the second stretcher. The pulse is amplified by OPCPA-II and is injected into the main amplifier chain. Each OPCPA, operated in type-I angular phase matching, consists of two BBO crystals in series configuration. The optical layout of OPCPA-II is shown in Fig. 3. Pump pulse is a frequency doubled Nd:YAG Q-switched laser pulse operated in a single transverse mode to ensure the temporally smooth pulse profile, which prevents the spectral modulation of chirped pulse. Diameters of pump beam for OPCPA-I and OPCPA-II are 2 mm and 5 mm, respectively. The seed pulse energy and pulse duration for OPCPA-I are 0.5 nJ and 1.5 ns, respectively. The gains of 1×10^3 and 1×10^4 have been obtained for the first and second BBO crystals in OPCPA-I. The maximum output energy was 0.6 mJ. The spectral bandwidth of amplified pulse was 6 nm, which is the same as the seed pulse.

In the OPCPA-II, a small signal gain through two-stages BBO was more than 7000, and a saturated gain of 500 was obtained at a pump intensity of 550 MW/cm^2. Figure 4 shows the output energy of OPCPA-II. Maximum energy of 65 mJ was obtained at the incident energy

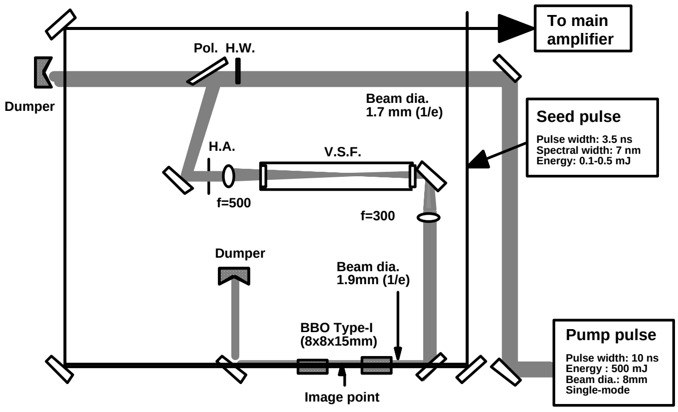

FIG. 3. Optical layout of OPCPA-II.

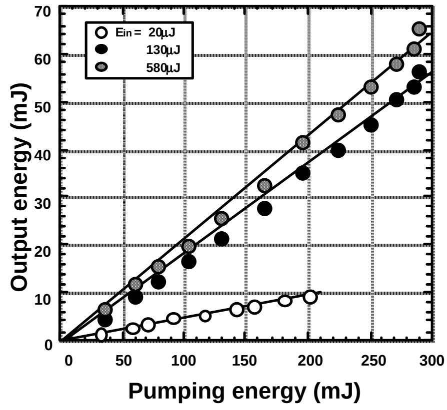

FIG. 4. Output energy of OPCPA-II

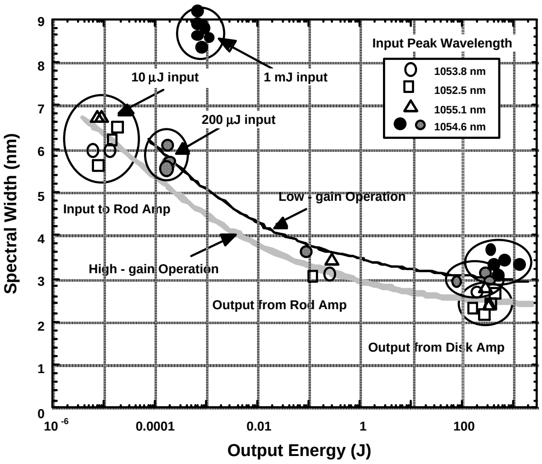

FIG. 5. Experimental results on gain narrowing.

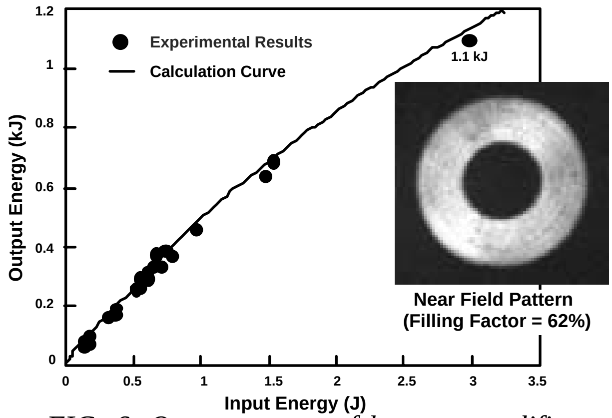

FIG. 6. Output energy of booster amplifier. Near field pattern is inserted.

of 0.6 mJ by single pass of 30 mm crystal in length. The pump-to-signal conversion efficiency was 23 %, which is almost a theoretical limit. In the saturation region, the temporal and spectral profiles of the amplified pulse become flat-top, and the maximum spectral bandwidth was 16 nm (FWHM). The prepulse ratio (the prepulse intensity divided by the main pulse intensity) was less than 1.5 x 10^{-8}, which is much better compared with the value of 8 x 10^{-3} for the regenerative amplifier. Shot-to-shot pulse energy stability was better than 8 %. This value can be minimized by the improvements of energy stability and temporal jitter of pump pulse.

4. Nd:glass Amplifier Chain

In order to suppress the gain narrowing and to make the B integral low in the amplifier chain, the rod and disk amplifier were operated in the low and high gain mode, respectively. Changes in the spectral width were measured using the full amplifier of the PW system. Experimental results are shown in Fig. 5, where the closed circles and the open marks are obtained by the operation of low and high gain mode, respectively. The data in the left hand side, the middle and the right hand side correspond to the spectral widths of the input pulse into the amplifier chain, the output pulse of the rod amplifier, and that of the booster amplifier, respectively. Due to gain narrowing, the spectral width of about 6 nm at the input decreases to 3 - 3.5 nm after the rod amplifier, and then decreases to 2.5 – 3 nm after the disk amplifier. However the low gain operation of rod amplifier improved the spectral bandwidth from 2.5 to 3 nm. When the input energy to the amplifier chain was increased to 1 mJ, the spectral width of 3.5 nm was obtained at the exit of booster amplifier.

One of the challenging issues in the main amplifier chain is to extract laser energy as high as possible without the damage of optics. In addition to the insertion of a serrated aperture at the entrance of amplifier chain, the radial gain distribution in the rod amplifier was improved. The output energy of the disk amplifier is plotted in Fig. 6, as a function of the input energy. Near field pattern of the output is inserted in Fig. 6. The maximum output of 1.1 kJ was obtained with the filling factor of 0.62. The B integral which is a measure of beam breakup is estimated to be 1.4.

5. Pulse Compression and Focusing

After the booster amplifier the laser beam is expanded from 350 mm to 500 mm in diameter

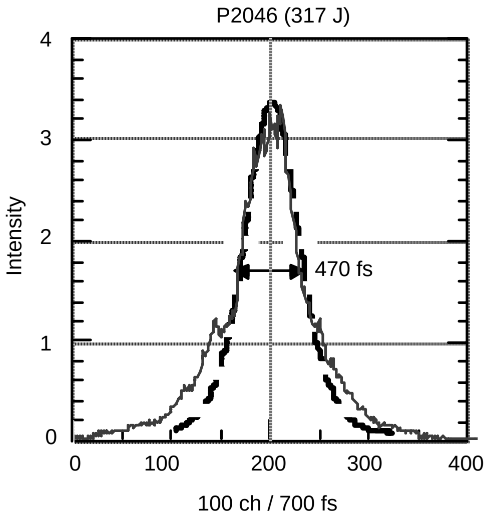

FIG. 7. Compressed pulse shape measured by the second order autocorrelator.

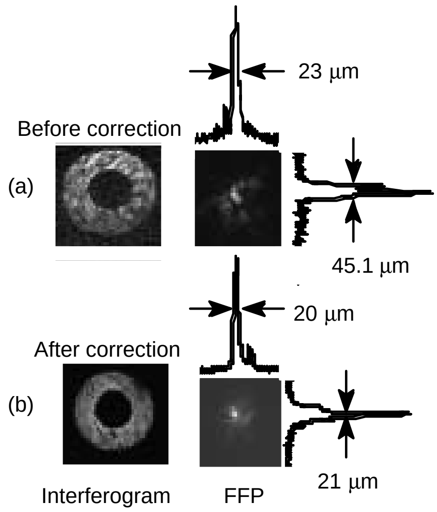

FIG. 8. Far field patterns of the compressed pulse before (a) and after (b) the correction of wave front distortion.

by a Galileo type beam expander and then injected into the pulse compressor. Maximum output energy from the compressor is evaluated to be 500 J using the damage threshold of 0.56 J/cm^2 for the gold-coated grating. The total efficiency of the compressor is estimated to be approximately 70 %, since the diffraction efficiency for each grating is 92 % averaged over the surface. So the input energy of 750 J is required to obtain the output energy of 500 J.

Laser energy, pulse width, far and near field patterns, and wave front distortion are monitored by IMAP-C. Figure 7 shows the pulse shape of the compressed pulse measured by a second-order autocorrelator, where the best fitted sech^2 shape given by the dashed line shows the pulse width of 470 fs. Figure 8 shows the interferograms and the far field patterns of the compressed pulse before (a) and after (b) the correction of wave front distortion by the deformable mirror. The focusing of 21 µm x 20 µm is obtained by the use of the deformable mirror. The spot diameter of an X-ray pinhole image was 30 µm in diameter at FWHM, when a plane target was irradiated by a 420 J laser. The focused intensity estimated from the encircled energy in the focal spot (30 µm) on target exceeds 10^{20} W/cm^2.

6. Summary

We have developed the PW laser system for fast ignitor research.
1) OPCPA was introduced in the PW front end, which produced 65 mJ output with 16.5 nm in spectral width, 23 % in conversion efficiency, and 1.5 x 10^{-8} of prepulse ratio.
2) The maximum pulse energy of 1.1 kJ was obtained by CPA with the spectral width of 3.7 nm.
3) After pulse compression, 420 J in 470 fs was achieved on target. The maximum intensity is higher than 10^{20} W/cm^2.

References

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