10-TW high-contrast double CPA laser system for ion acceleration

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Abstract. We demonstrate an insertable pulse cleaning module (IPCM) that is connected to a commercial CPA Ti:sapphire laser system and reduces the background of amplified spontaneous emission (ASE), when the output energy and repetition rate of the original laser system is completely preserved. The ASE temporal contrast is suppressed by three orders of magnitude on the benefit of double saturable absorbers involved in the module. Our method can reform old conventional lasers into high-contrast advanced systems.

1. Introduction

Advances in the technology of ultraintense chirped-pulse-amplification (CPA) [1] lasers are propelling studies of the laser-driven particle acceleration to relativistic energies. Especially in the case of ion acceleration, a laser pulse with intensity well exceeding $10^{18}$ W/cm$^2$ irradiates a solid foil target, when the laser-solid interaction can be complicated by the presence of an amplified spontaneous emission (ASE) at a leading edge of the high-intensity laser pulse.

Several techniques have been developed to reduce the ASE of high-intensity laser pulses: saturable absorber (SA) [2, 3], double CPA laser system [4], optical parametric chirped pulse amplification (OPCPA) combined with SA [5], or cross polarized wave generation (XPW) [6, 7]. In these methods, the ASE suppression was accomplished by revising the laser system itself or developing a completely new laser. To enhance the temporal contrast in lasers of current architecture, plasma mirror [8, 9] can be installed after the final compressor of the system. This approach has the advantage that no further ASE can arise after the plasma mirror. However, it leads to energy losses that can no longer be compensated for. In addition, the plasma mirror is a fundamentally destructive device and thus is hard to accomplish with high-repetition-rate lasers. It was reported [9] that the total reflectivity of their double plasma mirror is around 50% and the total number of shots available was limited to 2000 with a maximum repetition rate of 1 Hz.

In the present work, we propose a novel method to enhance the temporal contrast of conventional laser systems, making NO change on the output energy, the repetition rate, and the current architecture of the laser: insertable pulse cleaning module (IPCM) with double SAs. In the IPCM beamline, a pulse compressor is placed upstream of a stretcher, in inverse with CPA lasers. Connecting IPCM to the intermediate stage of a single CPA laser, the system works
as a double CPA laser in whole, when SAs involved in IPCM are expected to suppress the ASE drastically. In previous works, SAs were used for a femtosecond (fs) pulses of 1-10 μJ [2, 5] or stretched pulses of 1 mJ [3]. The present work makes a first attempt to inject a few-10s-mJ laser into SA to filter the ASE without causing any damage on the devise. Thereby, the IPCM with SAs can be placed further downstream on the laser system line. This makes it possible to filter the ASE generated in the upstream components including a regenerative amplifier and a multi-pass amplifier, in our case. In addition, the IPCM has a multi-pass amplifier independently to compensate the energy of pulses decreased in the process of ASE-filtering with SAs. Therefore, the laser system completely preserves the final output energy after the installation of IPCM, although the laser contrast is enhanced.

2. Experimental setup
Development of IPCM has been performed at JAEA using JLITE-X [10], which was built based on a commercial Ti:sapphire fs laser system produced by Continuum in 2003. The setup is shown in Fig. 1. The front end consists of a Ti:sapphire oscillator that delivers 12-fs pulses and a pulse stretcher based on Öffner triplet [11]. The laser pulse stretched to ~1 ns with a positive chirp is injected into a regenerative amplifier and reaches ~2-mJ energy. Then, the pulse is amplified 4 times through a Ti:sapphire crystal pumped with a 532-nm Nd:YAG laser (Continuum, Surelite II-10) and obtains the energy of ~30 mJ. In the original JLITE-X system, the laser pulse is subsequently introduced into the final 4-pass amplifier, the crystal of which is pumped with two 600-mJ, 532-nm Nd:YAG lasers (Continuum, Powerlite 9010), and reaches ~500-mJ energy.

In this development, we connect the IPCM as a bypass line between the 4-pass preamplifier and the final 4-pass amplifier, mentioned above. The IPCM consists of the first SA, a grating compressor, the second SA, a stretcher and another 4-pass amplifier. The stretched pulse from the 4-pass preamplifier encounters the first SA (CVI Melles Griot, RG-850) having a thickness of 1 mm. Then, the ASE component lying prior to the 1-ns stretched pulse is expected to be absorbed. Consequently, the first SA works as a pulse cleaner in the time range farer than 0.5 ns from the pulse time center. A similar method is also seen in [5, 3]. Suppressing ASE in the ns range is crucially required by solid-target experiments, because the hydrodynamic expansion of preplasma can progress with a typical velocity of ~1-10 μm/ns [12], resulting in a serious deformation of the target in the ns time scale. The pulse is then temporally compressed to ~50 fs by the grating compressor and passes through the second SA (CVI Melles Griot, RG-850) of 2 mm in thickness, when the ASE pedestal lying just before the rising edge of the fs main pulse is absorbed. In other words, the second SA works up to the time range of picosecond (ps) prior to the main pulse peak.

The input beam energies for the first and the second SAs are ~30 mJ and ~10 mJ, respectively. In previous works [5, 2], SAs were used for fs pulses with the input energies of
1-10 μJ that is 10^4-times smaller than the present case. In our work, by setting the input energy fluence to be ~30 mJ/cm^2 and ~10 mJ/cm^2 for the first and second SAs, respectively, the laser pulse is transmitted without any damage. The energy transmittance observed is 70% and 40% for the first and the second SAs, respectively. In our knowledge, the present work is the first attempt to inject a few 10s mJ class laser pulses into SAs for the purpose of suppressing ASE.

The laser pulse cleaned by the double SAs is again stretched by the other Öffner-triple stretcher, when the beam diameter is set to be 5 mm in order to induce a laser pulse having a few mJ energy. The stretched laser undergoes 4-pass amplification to be compensated for the energy lost in the cleaning procedure. Therefore, the laser pulse completely recovers its energy at the entrance of the IPCM ~30 mJ, even though its ASE is drastically suppressed, and arrives at the final 4-pass amplifier.

3. Temporal profile measurements
Previous works [3, 5] reported that after passing through a saturable absorber laser pulses often suffer from spectral narrowing or reduction on the component having shorter wavelength. This unfavorable effect is attributed to the characteristics of the SA that the transmittance rapidly increases with the wavelength around 800 nm. It is known [5] that OPCPA pre-amplifier can compensate for the narrowed bandwidth by adjusting pulse timing and phase-matching conditions. In the present system, using no OPCPA, we have successfully minimize the spectral narrowing by decreasing the amplification on longer-wavelength component at the regenerative amplifier [13]. In JLITE-X system, a 5-μm-thick pellicle is used as an étalon and placed in the resonance cavity of the regenerative amplifier. The incidence angle of the intracavity beam is adjusted to attenuate the longer-wavelength component via Fresnel reflection effect on the both surface of the pellicle. Figure 2(a) shows the adjusted spectra obtained after the final amplifier. The bandwidth is 35 nm (FWHM), which is not suffering significant spectral narrowing in comparison with the case without the IPCM, 45 nm (FWHM), shown in Fig. 2(b).

To demonstrate the compressability of pulses undergoing the pulse cleaning with the IPCM, the temporal profile of the laser main pulse is measured after the final compressor with SHG-FROG spectrogram. Figure 3(a) shows a typical SHG-FROG result obtained with the IPCM, when the laser system is working at full power. The duration of the re-compressed pulse is determined to be 45.7 fs (FWHM) in average with a standard deviation of 6.8 fs, which is comparable with the result 40 fs [10] obtained without the IPCM.

The temporal profile including ASE is observed by a high dynamic range third-order cross correlator (Amplitude Technologies, Sequoia) having a temporal measurement range of 570 ps. The measurement is performed at full power mode with a repetition rate of 10 Hz. Figure 3(b) shows the trace of the pulse cleaned by the IPCM in a black line, where the leading edge of the main pulse is drastically suppressed in intensity. The contrast ratio between the intensities of the main pulse and ASE is determined to be 1 × 10^6 and 2.5 × 10^6 at 500 ps and 150 ps prior to the main-pulse arrival, respectively. It is worth noting that one cannot find any residual temporal
Figure 3. Temporal profiles measured at full power mode. (a) A temporal profile around the main peak acquired with SHG-FROG spectrogram. (b) Third-order cross correlation traces of the pulses from the final compressor obtained with (solid line) and without (dashed grey line) the IPCM.

distortion, including a prepulse having fs duration, at the leading edge ranging from -500 ps to -50 ps. This characteristics is clearly beneficial to realize preplasma-free interaction with a target. On the other hand, without the IPCM, the intensity contrast ratio is $5 \times 10^5$ at -150 ps. Evidently, our IPCM have achieved the ASE suppression with three-orders of magnitude. Here, we have to notice that the first SA works on the leading edge of the stretched laser pulse having 1-ns duration. Hence, the ASE suppression seen in the range closer than -500 ps is achieved predominantly with the second SA, which cleans the pulse up to the rising edge of the re-compressed pulse. Therefore, the contrast ratio is probably expected to be improved further more one or two orders of magnitude (resulting in $10^{10}$-$10^{11}$ contrast) at the range $< -500$ ps, not seen in Fig. 3(b), with the benefit of the first SA.

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