Observation of Preformed Plasma Generated from a Thin-Foil Target for Laser-Driven Proton Acceleration

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We have measured the proton yield from thin-foil targets irradiated with a high-intensity Ti:sapphire laser. The longitudinal extent of the preformed plasma protruding from the front surface of the target is reduced by decreasing the duration of the amplified spontaneous emission (ASE) before the main pulse. The maximum proton energy in the target normal direction increases when the size of the preformed plasma is controlled.

Key Words: High-intensity laser, Proton, Preformed plasma

1. Introduction

Electrons and ions are accelerated to high energies during the high-intensity laser-plasma interaction and a broad spectrum of electromagnetic waves, from x-rays to terahertz, is also typically emitted. A preformed plasma induced by a prepulse is a critical component in optimizing the generation of high-energy charged particles and electromagnetic wave radiation. It plays an important role in the absorption of the main pulse energy. In addition, its presence affects ion acceleration. Kaluza et al. investigated the dependence of the proton yield from laser irradiated thin-foil targets on the amplified spontaneous emission (ASE) duration. The prepulse that typically accompanies ultrashort intense laser pulses is primarily attributed to ASE in the laser system. Measuring the preformed plasma and controlling the longitudinal extent of the preformed plasma by changing the ASE duration are important for the optimization of the ion acceleration process.

We report here on an experimental investigation of the proton energy dependence on the extent of preformed plasma. The maximum proton energy in the target normal direction increases when the size of the preformed plasma is controlled.

2. Experimental setup

We use the J-KAREN Ti:sapphire laser system at JAERA. The laser pulse duration [full width at half maximum (FWHM)] is ~40 femtoseconds. The ASE level is suppressed by using optical parametric chirped-pulse amplification (OPCPA) and double chirped-pulse amplification (CPA) techniques. Figure 1 shows the schematic view of the experimental setup. A p-polarized laser beam is focused by an off-axis parabolic mirror with a focal length of 322 mm and directed on the target at an angle of 45°. The spot size of the focused laser pulse is 8 μm (FWHM) × 4 μm (FWHM). The estimated peak intensity on target is ~5 × 10^19 W/cm² with a pulse energy of ~2.5 J. The probe beam is extracted by an optical-grade pellicle beam splitter and passes through an optical delay line. A linear translation stage varies the time delay between the main and probe beams. The plasma image is magnified by a factor of 10 and detected by a CCD camera. Neutral density filters vary the probe intensity to comply with the dynamic range of the camera. An interference filter at 800 nm is placed in front of the CCD camera to reduce unwanted plasma emission. An interferogram is obtained from a Fresnel biprism ~50 ps prior to the arrival time of the main beam. Protons accelerated during the main laser pulse interaction with the target are detected with a time of flight (TOF) ion analyzer in the direction target normal. The TOF spectrometry provides on-line real-time information about the proton energy distribution.
3. Experimental results

Figure 2 shows typical interferograms of preformed plasmas on the front surface of a 2.5 μm thick stainless-steel target acquired with the fundamental wavelength probe. The white broken lines indicate the original target plane and the black arrows show the direction of laser pulse propagation. For these shots, the estimated peak laser intensity on target is $\sim 2 \times 10^{19}$ W/cm$^2$ by decreasing the laser energy. The Pockels cell voltage is off in the interferogram of Fig. 2 (a) and the ASE duration is greater than 1 nanosecond prior to the main pulse with the contrast level of less than $10^{-10}$. Consequently we observe that the longitudinal extent of the preformed plasma at the front target surface is significant. Fig. 2 (b) displays the interferogram where fast Pockels cell voltage is on and the ASE duration is reduced to ~700 ps before the main pulse (controlled by the Pockels cell trigger timing in the laser system). The rise time of the Pockels cell is ~130 ps. The contrast level is $\sim 10^{-12}$ before ~700 ps. In this case no preformed plasma is observed within an accuracy of ~30 μm which is the combination of uncertainties of target position and fringe separation. The electron density distribution of Fig. 2(a) in front of the target is shown in Fig. 3. This distribution is calculated from phase shifts as determined from fringe shifts in the interferogram. Assuming axial symmetry of the preformed plasma after the plasma expansion, the electron density distribution can be estimated from the phase shift distribution (by Abel inversion) with the techniques of smoothing and interpolation. The error bars on the data points are derived from the minimum density increment of $\sim 3 \times 10^{18}$ cm$^{-3}$ and the fringe thickness ($\sim 8$ μm), though the uncertainty of the target position is $\sim 15$ μm. The longitudinal extent of preformed plasma is $\sim 90$ μm at an electron density of $\sim 4 \times 10^{18}$ cm$^{-3}$. The extent of preformed plasma can therefore be changed by adjusting the ASE duration. In Figs. 2 (a) and 2 (b), the rear side of preformed plasma cannot be observed with our technique because of small size.

Figure 4 illustrates proton spectra in the target normal direction for the same shots used to acquire the interferograms of Fig. 2. The preformed plasma condition of Figs. 4 (a) and 4 (b) correspond to the cases shown in Figs. 2 (a) and 2 (b). The maximum proton energy increases to ~3.4 MeV as a result of reducing the preformed plasma by reducing ASE duration. The number of protons is also increased. These trends in the proton spectra and interferogram are observed in different shots. Shock wave generation by ASE-driven front surface ablation induces a density gradient at the target rear surface and makes the proton acceleration less efficient. The rear side deformation also deflects the proton beam. Preformed plasma control is therefore necessary for efficient and stable proton acceleration.

Figure 5 illustrates the interferogram obtained at a laser intensity of $\sim 5 \times 10^{19}$ W/cm$^2$ with a stainless-steel target of 2.5 μm thickness and the fast Pockels cell voltage on to limit the ASE duration to ~700 ps before main pulse. As in Fig. 2

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**Fig. 2** Interferograms of preformed plasmas on 2.5 μm thick stainless steel targets obtained ~50 picoseconds before the main pulse with fast Pockels cell voltage off (a) and on (b). The laser intensity is $\sim 2 \times 10^{19}$ W/cm$^2$. Dashed lines show the original target plane.

**Fig. 3** Electron density distribution as a function of distance from the foil target front surface in Fig. 2 (a).

**Fig. 4** Proton energy distributions measured by TOF spectrometry with a laser intensity of $\sim 2 \times 10^{19}$ W/cm$^2$. The preformed plasma conditions of (a) and (b) correspond to those shown in Figs. 2 (a) and 2 (b).

**Fig. 5** Interferogram for the 2.5 μm thick stainless steel target obtained ~50 picoseconds before the main pulse with the fast Pockels cell on. The laser intensity is $\sim 5 \times 10^{19}$ W/cm$^2$. 

Special Issue
to acceleration.
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the target normal direction increases when the extent of the
ASE prior to the main pulse. The maximum proton energy in
preformed plasma is reduced by decreasing the duration of the
thin-foil targets are measured. The longitudinal extent of the
spectrum of protons accelerated in laser interaction with
is attractive for irradiating thin-foil targets to ef
the target normal direction recorded for the same s hot is
~30 μm) at this higher laser intensity. The proton spectrum in
Fig. 6. The preformed plasma condition corresponds to

4. Summary

The spectra of protons accelerated in laser interaction with
thin-foil targets are measured. The longitudinal extent of the
preformed plasma is reduced by decreasing the duration of the
ASE prior to the main pulse. The maximum proton energy in
the target normal direction increases when the extent of the
preformed plasma is controlled. A high-contrast laser pulse
reduces the preformed plasma level and allows efficient pro-
ton acceleration.

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