Laser-driven proton acceleration from a near-critical density target

A. Yogo,1 H. Daido,1 S.V. Bulanov,1 T.Zh. Esirkepov,1 K. Nemoto,2 Y. Oishi,2 T. Nayuki,2 T. Fujii,2 K. Ogura,1 S. Orimo,1 A. Sagisaka,1 J.-L. Ma,1 M. Mori,1 M. Nishiuichi,1 A.S. Pirozhkov,1 S. Nakamura,3 A. Noda,3 and H. Nagatomo4

1Kansai Photon Science Institute, Japan Atomic Energy Agency (JAEA), Kyoto, Japan
2Central Research Institute of Electric Power Industry (CRIEPI), Kanagawa, Japan
3Institute for Chemical Research, Kyoto University, Kyoto, Japan
4Institute of Laser Engineering, Osaka University, Osaka, Japan

Abstract. The duration-controlled amplified spontaneous emission with intensity of $10^{13}$ W/cm$^2$ is used to convert a 7.5 µm thick polyimide foil into a near-critical plasma, in which the $p$-polarized, 45 fs, $10^{19}$ W/cm$^2$ laser pulse generates 3.8 MeV protons, emitted at some angle between the target normal and the laser propagation direction of 45°. The mechanism which explains the proton generation from the near-critical plasma cloud is discussed using the two-dimensional (2D) particle-in-cell (PIC) simulation.

1. Introduction
Recent progress in ultraintense lasers are propelling studies of the laser-ion acceleration [1]. When a laser pulse with an intensity well exceeding $10^{18}$ W/cm$^2$ is focused on a thin foil target, the laser-field-driven force accelerates electrons at the target up to relativistic velocity. A portion of the accelerated electrons passes through the target toward the rear side, resulting in generation of an electrostatic field, which accelerates ions at the target rear surface. The laser-target interaction can be complicated by the presence of an amplified spontaneous emission (ASE pedestal) at a leading edge of the high-intensity laser pulse. A nanosecond ASE pedestal with intensity of the order of $10^{12}$ W/cm$^2$ can heat the target causing its expansion and pre-plasma formation. As shown in experiments [2], the formation of a plasma corona at a rear side of a relatively thick target can hamper ion acceleration. In addition, the ASE pedestal can generate a shock wave which propagates through the target deforming its rear side thus changing the spatial distribution of the ion-accelerating electric field [3, 4]. On the other hand, Matsukado et al. [5] observed the protons accelerated from a thin-foil target, the laser-irradiated region of which was evaporated by the ASE pedestal with formation of near-critical density plasma profile. Willingale et al. [6] demonstrated an efficient ion acceleration with a gas target.

In this work, we use a nanosecond ASE pedestal as a tool for controlling the target parameters seen by the main (femtosecond) laser pulse. The ASE pedestal causes expansion of a thin foil target, thus reducing the target density to the order of the plasma critical density. A high-intensity femtosecond laser pulse can penetrate this modified target, accelerating electrons. Their current, together with the return current of bulk electrons, form long-living quasi-static...
2. Experiment

The experiment was performed with the Ti:sapphire laser system at CRIEPI [9]. The experimental setup is shown in Fig. 1(a). P-polarized laser pulse with the central wavelength of $\lambda = 800$ nm, the duration of 45 fs and the energy of 0.8 J is focused onto a 7.5 $\mu$m thick polyimide [(C$_{22}$H$_{10}$O$_4$N$_2$)$_n$] target at the incidence angle of 45$^\circ$ by a f/3.5 off-axis parabolic mirror. About 40% of the laser energy is contained in a 1/e$^2$ focal spot with 10-$\mu$m diameter, giving the peak intensity of $I = 1.5 \times 10^{19}$ W/cm$^2$. The measured main-pulse-to-ASE intensity contrast ratio is $2.5 \times 10^5$ starting from 10 ps before the main pulse. The duration of the ASE pedestal is controlled by adjusting Pockels cell in the range from 0.7 to 5 ns, monitored for each laser shot by a pin-photodiode detection system. The plasma cloud produced by the ASE pedestal is observed by the interferometer using a probe beam with the wavelength of 400 nm. The plasma image is taken at the time of 50 ps before the main-pulse arrival.

Protons are measured by two online TOF spectrometers placed behind the target at the angles of 0$^\circ$ (TOF-1) and of 22.5$^\circ$ (TOF-2) with respect to the direction of the target normal, Fig. 1. Each TOF spectrometer is equipped with a plastic scintillator (PS), as a detection medium, and a photomultiplier tube (PMT). Protons, generated in the laser-target interaction, arrive at the PS detector after passing a $L = 1.65$ m tube. The PS signal is amplified by the PMT and displayed on an oscilloscope as a TOF signal corresponding to a flight-time distribution of protons. A typical TOF signal is shown in Fig. 1(b). The TOF signal $V(t)$ (a function of time, $t$) is used to calculate the proton energy spectrum $F(E)$ [10], where $E \approx m_p v^2_p/2$. Here $m_p$ and $v_p = L/t$ are the proton mass and velocity. In addition, the spatial distribution of protons are also detected by the ion-track detector (CR-39) covered with a 13-$\mu$m-thick aluminum filter.

3. Results and Discussion

Typical proton energy spectra are shown in Fig. 2(a) for the target normal (TOF-1: solid line) and for the 22.5$^\circ$ (TOF-2: dotted line) directions. As a reference, we show the spectrum recorded by the TP analyzer in the 11.25$^\circ$ direction (TP: circles). These three spectra are obtained simultaneously in a single laser shot, where the ASE duration is $\tau_{ASE} = 0.7$ ns in (a) and $\tau_{ASE} = 2.7$ ns in (b). Protons emitted at the angles of 11.25$^\circ$ and 22.5$^\circ$ have higher energy than those emitted in the target normal direction. We note that the energy resolution for 3 MeV
protons is 0.2 MeV [10]. Figure 1(c) shows the spatial profile of the protons having energies above 1 MeV observed by the CR-39 detector. We see that the protons with higher energy are emitted at some specific angle between the target normal and the laser-propagation direction, so the fast proton beam direction turns out to be shifted from the target normal. The proton highest energy is 3.8 MeV, detected at the angle of 22.5°, as shown in Fig. 2(a). For protons with energy above 1 MeV, the laser-to-proton energy conversion efficiency is $f_{\text{eff}} \approx 0.3\%$. In Ref. [3], similar shifts were considered as a result of a bending of the target rear surface caused by an ASE-generated shock wave. In our case, as shown below, the ASE causes a significant expansion of the target at its rear side forming a gently sloping density profile, whose scale increases with the ASE duration, $\tau_{\text{ASE}}$, while the proton energy remains about the same level for $1 \text{ ns} < \tau_{\text{ASE}} < 3 \text{ ns}$.

The ASE pedestal with intensity $I_{\text{ASE}} \approx 6 \times 10^{13} \text{ W/cm}^2$ produces the ablation pressure of $p_a \approx 0.7 \text{ TPa}$ [11], for which recent Hugoniot data [12] give estimations of a shock-wave velocity $v_s \approx 22 \mu \text{m/n}\text{s}$ and a particle velocity $v_p \approx 17 \mu \text{m/n}\text{s}$, respectively. Thus, during the time period of $\tau_{\text{ASE}}$ before the arrival of the main pulse, the rear surface is expanded to the distance $l_{\text{ex}} \approx 2v_s(\tau_{\text{ASE}} - l_t/v_s)$, where $l_t = 7.5 \mu \text{m}$ is the target thickness. It gives $l_{\text{ex}} = 12 \mu \text{m}$ for $\tau_{\text{ASE}} = 0.7 \text{ ns}$ and $l_{\text{ex}} = 80 \mu \text{m}$ for $\tau_{\text{ASE}} = 2.7 \text{ ns}$ A significant breakout of the rear surface occurs even for the shortest ASE duration in this measurement, $\tau_{\text{ASE}} = 0.7 \text{ ns}$. We emphasize that the proton energy above 2.5 MeV is detected even for a relatively large ASE duration, 3 ns, in which case the ASE-irradiated region of the target is completely converted into a nearly underdense plasma.

We performed 2D HD simulations of the evolution of our polyimide target irradiated by the ASE pedestal with the help of the PINOCO code [13]. The result is shown in Fig. 3(a) for the ASE pedestal duration $\tau_{\text{ASE}} = 1.5 \text{ ns}$. As seen from the electron density profiles along the target normal, the rear surface loses its steep gradient before the main laser pulse arrives. The electron density maximum is reduced to $10^{22} \text{ cm}^{-3}$, which is somewhat two times higher than the critical density $n_{\text{cr}} \approx 4.9 \times 10^{21} \text{ cm}^{-3}$. The interferometry measurement is shown in Fig. 3(b). Although the second-harmonic radiation converted from the main laser pulse partially saturates the plasma image, we notice slight shifts of the fringes on the rear surface around the saturated region, which indicate the plasma density from $10^{18}$ to $10^{19} \text{ cm}^{-3}$, in agreement with the tails of the density profiles seen in the 2D HD simulation. This allows us to conclude that the detected proton acceleration occurred in a near-critical plasma cloud.

In order to reveal the mechanism of the proton acceleration in a near-critical plasma cloud, we performed 2D PIC simulations using the REMP code [14]. The $p$-polarized laser pulse with
duration of 45 fs and intensity of $1.5 \times 10^{19} \text{ W/cm}^2$ is focused at the $45^\circ$ incidence angle onto a hydrogen plasma. Initially, the plasma cloud has a smooth distribution of the electron density (the target is assumed to be exploded by the ASE pedestal), ranging from $0.5 n_{ce}$ to $2 n_{ce}$ with a thickness of 24 $\mu$m in the direction of the $x$-axis, which is normal to the initial target surface, shown in Fig. 4. The main laser pulse is almost completely absorbed in the plasma slab, forming a long-living channel seen in the ion density distribution at the time of 300 laser periods after the laser pulse entrance, as shown in Fig. 4(a). Inside the channel, the ion density filament is formed, [7]. The ion phase plane ($p_x$, $p_y$) in Fig. 4(b), where $p_x$ and $p_y$ are the $x$- and $y$-components of the ion momentum, shows that the accelerated ions form five beamlets, whose directions are marked by arrows; the same directions are shown in the frame (a). The beamlets (1) and (2) correspond to ions accelerated in the forward direction, (4) – in the backward direction; beamlets (3) and (5) consist of protons in the expanding channel walls. The highest energy proton beamlet, (1), is emitted at some angle between the target normal and the laser-propagation direction, in a qualitative agreement with the experimental results. The electrons accelerated along the laser pulse propagation direction, together with the return current of bulk electrons, form long-living quasi-static magnetic field. The electron vortices, associated with this magnetic field, move across the plasma density gradient, leave the channel and spread over the target rear interface. At the rear side, the magnetic pressure induces and sustains a charge separation electrostatic field. This field accelerates ions, [5, 7]. The proton energy spectrum in Fig. 4(c) exhibits a cutoff at the energy of 3.6 MeV, in agreement with the maximum energy observed in the experiment. The simulation shows that at the specified parameters the optimal conditions of the ion acceleration are met: a high absorption of the laser pulse, generation of a strong magnetic field and formation of the ion density filament in the laser pulse channel.

References
[1] M. Borghesi et al. 2006 Fusion Sci. Technol. 49 412
[2] J. Fuchs et al. 2007 Phys. Rev. Lett. 99 015002
[3] F. Lindau et al. 2005 Phys. Rev. Lett. 95 175002
[4] A.J. Mackinnon et al. 2002 Phys. Rev. Lett. 88 215006; M. Kaluza et al. 2004 Phys. Rev. Lett. 93 45003
[5] K. Matsukado et al. 2003 Phys. Rev. Lett. 91 215001
[6] L. Willingale et al. 2006 Phys. Rev. Lett. 96 245002
[7] A.V. Kuznetsov et al. 2001 Plasma Phys. Rep. 27 211; S.V. Bulanov et al. 2005 ibid. 31 369
[8] T. Esirkepov et al. 2006 Phys. Rev. Lett. 96 105001
[9] T. Nayuki et al. 2006 J. Appl. Phys. 100 043111; Oishi et al. 2005 Phys. Plasmas 12 73102
[10] S. Nakamura et al. 2006 Jpn. J. Appl. Phys. 45 L913; A. Yogo, et al. 2007 Phys. Plasmas 14 043104
[11] A. Benuzzi et al. 1996 Phys. Rev. E 54 2162
[12] K. Takamatsu et al. 2003 Phys. Rev. E 67 056406
[13] H. Nagatomo et al. 2007 Phys. Plasmas 14 056303
[14] T.Zh. Esirkepov 2001 Comp. Phys. Commun. 135 144