Efficient laser acceleration of deuteron ions through optimization of pre-plasma formation for neutron source development

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Abstract
With the objective to develop a compact neutron source with laser accelerated ions, optimization of pre-formed plasmas for efficient target normal sheath acceleration (TNSA) of deuteron ions is investigated using two-dimensional radiation hydrodynamic and particle in cell (PIC) simulation codes. The plasma profile of a foil target irradiated with a pre-pulse of ns duration at the intensity of $10^{11} - 10^{13}$ W cm\textsuperscript{-2} is obtained with the radiation hydrodynamic simulation code. In addition to the formation of a long scale length pre-formed plasma at the front of the target foil, decrease of the plasma scale length at rear side is observed during temporal evolution of the preformed plasma. The two-dimensional PIC simulation on ultra-high intensity laser irradiation shows that the pre-formed plasma profiles at both sides of the target can be optimized for efficient TNSA acceleration, leading to generation of deuteron ions, collimated in the forward direction, with a larger amount and higher energy. The number of neutrons generated by deuteron-beryllium reaction increases by an order of magnitude in comparison to the laser irradiation without a pre-pulse.

Keywords: TNSA, radiation hydrodynamics, PIC simulation, neutron source

(Some figures may appear in colour only in the online journal)

1. Introduction

The laser-acceleration of ions is being investigated extensively to develop laser-driven bright neutron sources for applications in science, industry and medicine [1–6]. The development of laser technologies based on chirped pulse amplification [7] has realized generating ultra-high intensity irradiation field, exceeding the relativistic intensity of $10^{18}$ W cm\textsuperscript{-2}, with tabletop high repetition lasers. Electrons and ions with their kinetic energies beyond MeV have been accelerated with such ultra-high intensity lasers [8–12]. With the forward-directed fast ions, it is possible to generate the forward-directed neutrons by nuclear reaction of the laser accelerated ions generated in the first target (‘pitcher’) with nuclei in the second target (‘catcher’). Compact and directional neutron sources could be realized, based on the laser ion acceleration with the ‘pitcher-catcher type’ targets [13–17]. Because of its mobility and compactness, the laser-driven neutron source has potential for application in
many fields, such as boron neutron capture therapy [18], imaging [19, 20], nondestructive inspection of materials [21, 22] and infrastructures [23, 24], as with the accelerator-based compact neutron sources [25].

The target normal sheath acceleration (TNSA) of ions [26, 27], has been applied for the laser intensity range of $10^{18}$–$10^{20}$ W cm$^{-2}$ [28–34]. When the ultra high intensity laser irradiates a foil target, the fast electrons with the kinetic energy of the order of MeV are generated and the energetic fast electron cloud spreads from the laser-irradiated spot. The spatial charge separation between the fast electrons and the ions generates an electric field around the foil target. In the laser-irradiated front side of the target, the electric field is nearly neutralized by laser-produced plasmas expanding from the target foil. However, in the rear side of the foil, the intense electric field is generated in the Debye length over the time duration until the plasma expands and neutralizes the electric field [29]. This is because the expansion speed of the lower-temperature plasmas in the rear side is slower than that of the ablated plasma in the front side. This electric field can accelerate ions to multi-MeV kinetic energy in the direction normal to the target at the rear side of the foil. When the laser intensity increases beyond $10^{21}$ W cm$^{-2}$, the radiation pressure acceleration becomes the dominant acceleration mechanism of ions [35–39]. Currently, lasers with such extremely high intensities are available only at several laser facilities [40–43].

In typical cases of neutron generation with the pitcher-catcher configuration based on Be(d,n), Be(p,n), Li(d,n) and Li(p,n) reactions, the energies of the deuterons and protons required for neutron generation is less than $\sim$10 MeV. In these cases, we could generate these particles and thus neutrons with relatively compact lasers which can be operated repetitively over long time. In order to investigate the possibility of developing a compact laser-driven neutron source, we have started a preliminary experiment with the pitcher-catcher target using a short pulse laser with the pulse duration of $\sim$100 fs and the peak power of less than 100 TW. We have found in this preliminary experiment that the neutron yield increases when the laser pulse is accompanied with small pre-pulses. In this paper, we investigate the possibility of increasing the number of ions generated by TNSA by optimizing the profiles of low-density preformed plasmas by controlling the laser pre-pulses.

In general, the high intensity laser pulses are accompanied with pre-pulses, as shown schematically in figure 1. The pre-pulse is typically composed of a foot pulse of low intensity and ns-duration, as well as a pedestal close to the main pulse with pulse duration of the order of 100 ps. The contrast ratio is defined as the ratio of the intensity of pre-pulse to that of the main pulse. If a long scale pre-formed plasma (pre-plasma) on the surface of the target is irradiated with an ultra-intense laser, the kinetic energy of generated fast electrons increases to higher than 10 MeV at the intensity of $10^{19}$ W cm$^{-2}$ [44].

Although the presence of the pre-plasma is undesirable in general, it may work positively for TNSA laser acceleration, because not only the hot electron slope temperature is higher, but also because the pre-plasma increases the laser absorption. When there is no pre-plasma, the laser absorption fraction for the normal incidence is usually 10%–30% in the intensity range from $10^{18}$–$10^{19}$ W cm$^{-2}$ [45, 46], whereas the presence of pre-plasma can increase the absorption fraction [47, 48], and leads to enhancing hot electron generation. On the other hand, the increase of the average energy of the accelerated electrons by the pre-pulse have been reported by the LFEX experiments [49]. The electric field $E$ generated by the fast electron cloud in the rear side of the target foil is estimated as;

$$eE \sim \frac{k_BT_e}{\text{max}(L_{pr}, \lambda_{De})}. \quad (1)$$

Here, $k_BT_e$, $e$ and $L_{pr}$ are the kinetic energy of the fast electrons, the electron charge and the rear side plasma scale length, respectively. $\lambda_{De}$ is the Debye length of the fast electron cloud, estimated as

$$\lambda_{De} = \left( \frac{k_BT_e}{4\pi n_{he}e^2} \right)^{1/2}, \quad (2)$$

where $n_{he}$ is the hot electron density. Assuming that $k_BT_e$ is 10 MeV, and $n_{he}$ is the critical density ($n_{cr}$) for 0.8 $\mu$m laser wavelength, $n_{cr} = 1.7 \times 10^{21}$ cm$^{-3}$, the Debye length is of the order of 0.57 $\mu$m. If we assume the hot electron density to be 0.1$n_{cr}$, then the Debye length is 1.7 $\mu$m and TNSA acceleration decreases since the electric field weakens. Therefore, in order to accelerate fast ions efficiently, not only the Debye length should be shorter, namely the hot electron density should be higher, but also the plasma scale length $L_{pr}$ in the rear side of the target should be comparable to or less than the Debye length, i.e. $L_{pr} \leq \lambda_{De}$. If the laser pulse is accompanied with an intense pre-pulse, ablation plasma is generated and its radiation preheats the rear side of the target. Also, a strong shock wave is driven into the foil target, which generates an expanding pre-plasma in the rear side of the foil. These effects weaken the ion accelerating electric field in the

![Figure 1. Schematic of a laser pulse accompanied with a pre-pulse, which is typically composed of a long-duration foot pulse and a shorter duration pedestal before the main pulse.](image-url)
rear side. However, the multiple shocks are generated in the foil by the ablation pressure and compress the pre-plasma in the rear side to steepen the density scale length. Therefore, the efficient TNSA acceleration could be achieved by simultaneously optimizing the pre-plasma conditions at both the front and the rear sides of the target foil.

Although generation of $10^{10} \text{n/sr}$ neutrons has been achieved with a 50 J, ps-laser by laser by Roth et al. [4], further investigation is needed for realizing efficient neutron sources. In this paper, we focus on controlling the pre-pulse and the target thickness to achieve the optimum condition for ion acceleration with TNSA. Section 2 describes the radiation hydrodynamic simulation of the pre-plasma formation. Section 3 presents the results of particle in cell (PIC) simulations of the ion acceleration. The conclusion is given in section 4.

2. Pre-plasma formation

2.1. Method of hydrodynamic simulation

The ablation and deformation of plastic foil targets due to the foot laser pulse was analyzed with STAR2D, a two-dimensional radiation hydrodynamic code [51] in cylindrical coordinate. The code adopts two-temperature one-fluid model, where Euler equations are solved by the HLLC [52] for conserved variables of mass density, momentum, and total energy. The Constrained Interpolation Profile [53] scheme is used for solving ion and electron temperature equations. A deuterated plastic (CD) foil is studied to generate fast deuterion ions $D^+$. In the hydrodynamic code, we used the plastic CH SESAME table [54] as the equation of state (EOS) instead of CD, because EOS of CD and CH are similar except for their solid densities and the SESAME table for CH is considered to be more accurate. The electron thermal conduction coefficient is given by Spitzer–Härm [55], and the electron transport is solved by the flux-limited diffusion model [56] with flux-limiter of 0.1. The ion conduction coefficient is given by Braginskii [57] and the electron-ion relaxation coefficient is given by Spitzer [58]. For the radiation transport, we use the flux-limited multi-group approximation [59], with the emissivity and the opacity calculated by the averaged ion model in the collisional radiative steady state (CRSS) [60]. The radiation group ranging from 0 to 5keV of photon energy was divided into 40 bins. The laser is absorbed by inverse-bremsstrahlung [61] with 1D ray tracing along the laser axis. The ionization degree is also given by the CRSS. The laser beam of 0.8 $\mu$m wavelength is incident on the target in normal direction. The laser spot diameter is 10 $\mu$m (FWHM) with Gaussian spatial profile. The temporal profile of the pre-pulse is modeled by a flat-top foot pulse. This simplified model of the pre-pulse is valid when the pre-plasma generated by the ns-duration foot pulse is irradiated by $\sim 100$ ps pedestal, because the electron density scale length of the front side pre-plasma is not much affected by the increase of the ionization degree due to the pedestal heating. We note also that the low-Z materials such as a plastics are easily fully-ionized by irradiation of the ns-duration foot pulse and the ionization degree of the front side pre-plasma saturates. We carried out the radiation hydrodynamics simulation up to 5 ns for the intensities of $10^{11}$, $10^{12}$ and $10^{13}$ W cm$^{-2}$ for the target thickness of 1, 2, 5, and 10 $\mu$m. The simulation size is 1000 × 600 $\mu$m, with 500 × 150 Euler meshes of varied intervals, to decompose the spatial resolution of foil and ablation regions.

2.2. Hydrodynamic simulation results

Figures 2(a)–(h) show the temporal evolution of the spatial distributions of the mass density and the electron density for a 10 $\mu$m thick target irradiated with a foot pulse of $1 \times 10^{12}$ W cm$^{-2}$ intensity. After the start of laser-irradiation at $t = 0$, the front surface of the target (left-hand side in these figures) is heated and pre-plasma is formed by laser ablation. Then, the shock wave, launched by the ablation pressure, propagates through the foil (figure 2(a)). Simultaneously the radiation from the ablated plasma heats the target, leading to expansion of the rear side of the target due to radiation heating at $t = 0.8$ ns (figure 2(b)). The expanded region becomes the pre-plasma at the rear side of the target, where we define the pre-plasma as the plasma with the electron density $n_e$ below the critical density $(n_c < n_e)$. The shock wave from the front surface reaches the rear side at $t = 1.4$ ns (figure 2(c)), at which the pre-plasma starts to expand at the rear side (figure 2(d)), and the rarefaction wave goes back to the front side. The central part of the target starts accelerating after arrival of the rarefaction wave, and then the high ablation pressure launches the second shock wave into the target (figure 2(e)). The target density, decreased after arrival of the rarefaction wave, increases again by the second shock wave at $t = 2.8$ ns (figure 2(f)), leading to the large density gradient of the backside pre-plasma at the shock front around $t = 3.0$ ns (figure 2(g)). At this moment, the foil target shows large deformation around the laser spot. After the second shock wave has passed, the rear side pre-plasma starts to be decompressed again due to the rarefaction wave. However, the peak density of the foil at the laser spot still remains overdense $(n_e > n_c)$ around $t = 4.0$ ns (figure 2(h)), and is maintained up to $t = 4.9$ ns. After this time, the target along the laser axis is decompressed to below the critical density.

In order to investigate the temporal evolution of the electron density at the rear and front sides of the target, we measured the scale length $L_p$ between the critical density $(n_c)$ and 0.1$n_c$ for both sides at the foot pulse intensity of $10^{12}$ W cm$^{-2}$ and the target thickness of 1, 2, 5, and 10 $\mu$m, respectively. The electron density scale length $L_p$ defined as $L_p = n_e / \langle \nabla n_e \rangle$ along the laser axis, is plotted for the rear side in figure 3(a) and for the front side in figure 3(b), up to the time where the target is decompressed to below the critical density.

Referring to figure 3(a), rear side density scale length $L_{pr}$ in general, increases linearly with time after some delay from the start of laser irradiation. Then $L_{pr}$ suddenly decreases, and increases again after some time interval. This time interval corresponds to the time gap between...
compression by the second shock wave and decompression by the rarefaction wave. This dip in $L_{pr}$ leads to the efficient TNSA acceleration, where the $L_{pr}$ could be smaller than the Debye length $\lambda_{De}$. The dip in $L_{pr}$ indicates a possibility to optimize the timing of the main pulse irradiation for efficient TNSA ion acceleration. The rear side pre-plasma scale length $L_{pr}$ at the dip is 0.05 $\mu$m or less for all the thicknesses we have studied.

In figure 3(b), we show the time evolution of the front-side $L_{pf}$ for the foot pulse intensity of $10^{12}$ W cm$^{-2}$. The scale length increases rapidly just after the foot pulse irradiation, due to rapid increase of the plasma temperature. Then the expanding plasma becomes isothermal, and the scale length grows proportionally with time until the foil starts to accelerate. After the start of acceleration, the front side $L_{pf}$ begins to increase rapidly because of the large target deformation due to target acceleration. At this time, the ablated blow-off plasma is geometrically confined near the laser axis in the region surrounded by bubble-like deformed target (as described later with figure 8), and consequently the front-side $L_{pf}$ rapidly increases.

Since the break-through of the first shock wave at the rear side is delayed in time as the target thickness increases, the start of target acceleration is delayed as the thickness increases. Therefore, a thicker target has a longer $L_{pr}$ in the front side. The increase of $L_{pf}$ can be an advantageous in TNSA, since interaction of the ultra-intense laser with a longer scale pre-plasma will increase the relative amount of high-energy fast electrons. Thus, the longer $L_{pf}$ and the shorter $L_{pr}$ help in TNSA acceleration. At the time of the bottom of the dip of $L_{pr}$, $L_{pf}$ is 8 $\mu$m, 12 $\mu$m, 13 $\mu$m and 17 $\mu$m for the targets of 1 $\mu$m, 2 $\mu$m, 5 $\mu$m and 10 $\mu$m thickness, respectively. Therefore the 10 $\mu$m thick foil is most preferred among the simulated targets for the foot pulse.
intensity of $10^{12}$ W cm$^{-2}$. However, hot electron expansion in the large scale front side pre-plasma may degrade the TNSA. So, the PIC simulations should be referred to optimize the target thickness.

The temporal evolution of $L_{pr}$ and $L_{pf}$ for the foot pulse intensity of $10^{13}$ W cm$^{-2}$ for various target thicknesses are shown in figures 4(a) and (b), respectively. Unlike the case of $10^{12}$ W cm$^{-2}$ (see figure 3(a)), the thinner foil target shows the larger increase rate of $L_{pr}$ as seen in figure 4(a). Due to radiation preheating from the ablation plasma on the front surface, the backside of the thinner target is more easily heated above the boiling temperature, leading to a faster increase of $L_{pr}$ before the first shock wave breaks through the target.

Similar to the case of figure 3(a) for the laser intensity of $10^{12}$ W cm$^{-2}$, the rear side $L_{pr}$ shows the dip due to the compression effect of the second shock wave (see figure 4(a)). However, compared with figure 3(a), the temporal change of $L_{pr}$ at the dip is moderate, and the depth of the dip is shallower as the target becomes thinner. At the dip, the local minimum value of $L_{pr}$ is 0.7 μm, 0.5 μm, 0.3 μm, and 0.05 μm for the targets of 1 μm, 2 μm, 5 μm and 10 μm thickness, respectively. Since these values are comparable or slightly shorter than the Debye length, efficient TNSA acceleration is not expected except for the 10 μm thick target. In figure 4(b), $L_{pf}$ shows faster increase compared to the case in figure 3(b). At the bottom of the dip, $L_{pf}$ is 21 μm for the 10 μm thick target, which is larger than that in figure 3(b). Since the radiative preheating increases the optimum thickness of the target, there is room for optimizing the conditions for efficient TNSA for the foot pulse intensity of $10^{13}$ W cm$^{-2}$.

The temporal evolution of $L_{pr}$ and $L_{pf}$ for the foot pulse intensity of $10^{11}$ W cm$^{-2}$ for various target thicknesses are shown in figures 4(c) and (d), respectively. Compared with the foot pulse intensity of $10^{12}$ W cm$^{-2}$, the temporal evolutions of $L_{p}$ at both sides are delayed. $L_{pr}$ are smaller and the dips are more pronounced with longer durations, especially for the 2 μm thick target. $L_{pr}$ at the bottom of the dip is 0.02 μm or less for all target thicknesses. These $L_{pr}$ values are much less than the Debye length driven by 10 MeV electrons. However, $L_{pf}$ is 5 μm and 6 μm for the targets of 1 μm and for 2 μm thicknesses, respectively at the bottom of the dip of $L_{pr}$. These values are smaller than those for $10^{12}$ W cm$^{-2}$ (see figure 3). This comparison indicates that thicker target as 10 μm still gives longer $L_{pf}$ at the dip bottom of $L_{pr}$ even in
the foot-pulse intensity of $10^{11}$ W cm$^{-2}$. As the foot pulse intensity increases, the scale length of the backside pre-plasma tends to increase due to radiant heating, and the dip becomes shallow. On the contrary, as the foot pulse intensity decreases, the change of the scale length of the backside pre-plasma in dip caused by shock wave compression increases. Therefore, the irradiation timing of the main pulse may significantly affect the acceleration performance.

3. Ion acceleration

3.1. Method of PIC simulation

In order to confirm the validity of simultaneous optimization of the pre-plasma at the rear and front sides of the foil for efficient TNSA deuteron acceleration, we carried out the 2D3V PIC simulations using the results of the electron density profiles $n_e$ obtained by the radiation hydrodynamic simulations described in section 2. We used the PICLS code for PIC simulations [62]. The calculation size is 280 $\mu$m with 14,000 cells in the $x$-direction and 204.8 $\mu$m with 10,240 cells in the $y$-direction, respectively, where $x$ is in the target normal direction. Each cell includes super-particles comprised of 10 electrons, 10 fully-ionized carbon ions and 10 ionized deuterons to satisfy the charge neutrality and to fit the initial pre-plasma density $n_e$ by changing the weight $w_{ij}$ per super-particle in the particle conditioning. The pulse duration of the ultra-intense pulse is 50 fs (FWHM) with Gaussian profile. We set that the laser peak arrives the target surface of $x = 100 \mu$m at 430 fs, and conducted the simulation up to 2.67 ps. The laser wavelength, and the laser spot size are 0.8 $\mu$m, and 10 $\mu$m, respectively. The laser incidence angle is normal to target surface. We used the initial condition of the electron density profile corresponding to the foot pulse duration of 1.8 ns for the 2 $\mu$m thick target, irradiated at the foot pulse intensity of $10^{12}$ W cm$^{-2}$. The maximum and minimum electron densities are set to 10 $n_{cr}$ and 0.05 $n_{cr}$ respectively. The hydrodynamically calculated profile shows a considerably deformed profile of the target foil. The pre-plasma scale $L_p$ in the front side of the target is 26 $\mu$m as shown in figure 3(b). We note that this condition is not optimum for TNSA, because the rear side pre-plasma scale length is over 1.4 $\mu$m as shown in figure 3(a), which is almost comparable to the Debye length at $0.1 \times n_{cr}$ for 10 MeV electron cloud, as described in section 1.

3.2. PIC simulation results

Using these initial conditions optimized only for the front side, we carried PIC simulation at two different intensities of $2.8 \times 10^{18}$ and $9.4 \times 10^{18}$ W cm$^{-2}$. The kinetic energy spectra of the accelerated electrons near the boundary of the calculation domain at $t = 600$ fs are shown in figure 5. Also, as a reference case of high-contrast limit, we carried out PIC simulation for a 2 $\mu$m thick CD foil with no pre-plasmas, both at the rear and the front sides of the target, for the irradiation intensity of $9.4 \times 10^{18}$ W cm$^{-2}$. In figure 5, we see that the reference-case (c) shows a smaller number of accelerated relativistic fast electrons (>0.5 MeV) compared to other cases with pre-plasmas. Compared to the reference-case (c), case (b) gives a large amount of relativistic fast electrons for the same $9.4 \times 10^{18}$ W cm$^{-2}$ intensity of ultra-intense laser, confirming that the acceleration of relativistic fast electrons is enhanced by increasing the scale length of the pre-plasma conditions in the front side of the target. Comparing different laser intensities of cases (a) and (b), we see that the amount of the relativistic electrons increases significantly as the laser intensity increases. Even in the case (a), the lowest laser intensity of $2.8 \times 10^{18}$ W cm$^{-2}$, the amount of the relativistic electrons is larger than in the reference-case (c). The small amount of the relativistic accelerated electrons in (c) is ascribed to smaller laser absorption fraction of the ultra-intense laser pulse due to shorter scale length in the front side of the target. As described earlier, without a pre-plasma, the laser absorption fraction is not high when the intensity is less than $10^{20}$ W cm$^{-2}$. The laser absorption fraction is 26% for the reference-case(c), whereas in other cases of (a) and (b), the laser absorption fraction is (a) 86% and (b) 91%, respectively. In figure 5(d), we also show the electron spectrum for the optimum condition for the foot-pulse described in the previous section; i.e. a 10 $\mu$m thick CD foil is irradiated by a main laser pulse at $9.4 \times 10^{18}$ W cm$^{-2}$, which is accompanied with a foot pulse of 3.0 ns duration and intensity of $10^{12}$ W cm$^{-2}$. The (d) shows a smaller amount of relativistic electrons and larger numbers of non-relativistic electrons compared to those of (b), although case (d) gives the laser absorption fraction of 92% similar to (b). This implies that the longer scale length front pre-plasma is more preferable to generate larger amount of relativistic electrons.

In figure 6 we show energy spectra of the forward-accelerated deuterons, corresponding to the cases (a)-(d) in figure 5, near the boundary of the calculation region at 2.67 ps. These simulation results confirm that the TNSA
acceleration can be optimized by controlling the pre-plasma conditions of the target. The smallest amount of the accelerated deuteron in the reference-case (c) is due to the smaller amount of relativistic electrons shown in figure 5. Comparing the case (b) with the reference-case (c) for the same laser intensity in figure 6, we see that the case (b), which has longer scale length front side pre-plasma, gives the accelerated deuteron ions with significantly larger amount and higher maximum energy of over 10 MeV. In comparison, the highest energy of the deuterons is around 3–7 MeV in (c).

This difference of the maximum energy is critical for the efficient neutron generation through the nuclear reaction. In order to generate neutrons, we assume the nuclear reaction using the accelerated deuteron ions as:

\[ ^9\text{Be} + d \rightarrow ^{10}\text{B} + n + 4.35 \text{ MeV}, \tag{3} \]

where Be, B, d and n are beryllium, boron, deuteron and neutron, respectively. The neutron yield in this \( ^{10}\text{Be} - d \) reaction increases as \( E_dy \), where \( E_dy \) is the bombarding deuteron energy of \( d \) to Be, with the exponent \( \beta > 1 \) in MeV region of \( E_d \) \[63\]. Comparing the different intensities (a) \( 2.8 \times 10^{18} \text{ W cm}^{-2} \) and (b) \( 9.4 \times 10^{18} \text{ W cm}^{-2} \), the amount and maximum energy of accelerated deuteron ions increase as the intensity of ultra intense laser increases. This is consistent with the corresponding electron spectra in figure 5.

Now we consider the effect of the plasma scale length at the back-side of the target. Comparison of case (b) for the 2 \( \mu \text{m} \) thick target and (d) for the 10 \( \mu \text{m} \) thick target in figure 6 shows that (d) gives larger amount and maximum energy of the accelerated deuterons than those in (b), although (b) gives a larger amount of relativistic electrons than that of (d) as seen in figure 5. The case (b) has a long scale length pre-plasma of 26 \( \mu \text{m} \) at the front side, but the scale length of the rear side pre-plasma is of the order of 1.5 \( \mu \text{m} \), which is not optimized as described in the previous section. On the other hand, case (d) has the optimum pre-plasma condition at both sides for the foot-pulse intensity of \( 10^{12} \text{ W cm}^{-2} \). In this case although the front-side pre-plasma scale length of 17 \( \mu \text{m} \) is slightly smaller than in (b), but the rear side pre-plasma scale length of 0.05 \( \mu \text{m} \) is much less than 1.5 \( \mu \text{m} \) in (b). The larger amount of the accelerated deuterons seen in (d) is ascribed to the condition that TNSA driving electric field stays longer in space as the rear side pre-plasma becomes shorter. This comparison shows that optimization for the efficient TNSA is possible by preparing the optimum pre-plasma condition at both sides of the target at the same time, through choosing appropriate target thickness and proper timing for target irradiation by an ultra-intense laser with a moderate pre-pulse. Also, the case (d) shows the increased amount of forward-accelerated MeV deuterons by several orders in comparison with the no pre-pulse case of (c). This implies that if we optimize the pre-plasmas at both sides of the target, significantly higher neutron yields can be obtained with the \( ^{10}\text{Be} - d \) nuclear reaction.

Figure 7 shows the calculated angular dependences of the accelerated deuterons with >1 MeV energy, corresponding to the cases in figures 6(a)–(d). The reference-case (c) shows the collimation within the half divergence angle of 5°. In the other cases of (a), (b), and (d) where the target has large deformation, we also see the sharply collimated component within the half divergence angle of 5°. Especially, in case (d), the optimized condition, we see the sharp collimation within 3°. Although there are secondary peaks at around 40°–90° caused by TNSA on the deformed portion of the foil target, the collimated components have larger amount than those with large divergence angles. This result shows that optimization of pre-plasma is effective not only for increasing the amount of the accelerated deuterons but also for improving its divergence angle. Such high collimation seen above shows the potential for producing the collimated neutron beam with small divergence angle.

In order to study the spatial distributions of the accelerated deuterons, we show the initial electron density \( n_{cr} \) normalized by \( n_{cr} \), used for the initial condition of PIC simulation in figure 8(a), the energy of the accelerated deuterons at 2.5 ps in figure 8(b), and the weight of the super-particle in figure 8(c), corresponding to the case (b) of figure 7, where a 2 \( \mu \text{m} \) thick foil target is pre-irradiated by a foot pulse of 1.8 ns
duration at $10^{12}$ W cm$^{-2}$. Also, we present the normalized initial electron density $\tilde{n}_e^0$ in figure 8(d), energy of the accelerated deuterons at 2.5 ps in figure 8(d), and the weight of the super-particle in figure 8(f), corresponding to the case (d) of figure 7, where a 10 $\mu$m thick target is pre-irradiated by a foot pulse of 3.0 ns duration at $10^{12}$ W cm$^{-2}$. The intensity of the ultra-intense laser is $9.4 \times 10^{18}$ W cm$^{-2}$ for both cases. In the PIC simulation, super-particles are weighted to fit the electron density at their initial position as $\tilde{n}_e^0 = \frac{7}{3} w_d$. Therefore, it is possible to find the initial electron density, from which the super-particle of weight $w_d$ is accelerated.

In figure 8(b), we see that the forward-accelerated deuterons are composed of three components; one is the deuterons from the tip of the largest deformed part of the target, shown in orange. It is almost overlaid by the second component, shown in light-deep blue, that is emitted radially from the less deformed region. The third component is deuterons from the relatively un-deformed flat part of the foil around the previous regions of the first and second components. The spatial acceleration characteristics of the respective components are significantly different. From the deformed parts, the first and the second components are accelerated with semi-hemispherical shape reflecting the shape of the deformed density profile of the target, and its leading part on the laser axis is accelerated most up to 14 MeV for the first component. On the other hand, the maximum energy of the accelerated deuterons from the flat part (the third component) is up to 5 MeV. These three components explain the angular distribution of the accelerated deuterons as shown in figure 7, in which the highly collimated part is given by first and the third components, and the secondary part with the large divergence angle corresponds to the second component in figure 8(b). In figure 8(b), we also see the directly accelerated deuterons from the inside of deformed part of the target due to the ponderomotive force of the laser. However, this component has small amount compared to others. Also, looking at the particle weight of figure 8(c), the leading edge of the accelerated deuterons shows the weight $w_d \sim 0.1$, which corresponds to the initial electron density of $n_e^0 = 0.23 n_{cr}$. This confirms that most accelerated deuterons come from the sub-critical regime of the rear side pre-plasma. Although the accelerated deuterons from the relatively flat part of the target (the third component) partially show a relatively high particle

Figure 8. (a) and (d) normalized initial electron density $\tilde{n}_e^0$, (b) and (d) accelerated deuteron energy $E_d$ (MeV), and (c) and (f) weighting factor of deuteron particle $w_d$ in 2D PIC, respectively. The irradiation condition in (a)–(c) correspond to the case (b) of figure 6, and (d), (e) and (f) correspond to the case (d) of figure 6, respectively. Spatial scale is normalized by the laser wavelength. The color scales of $\tilde{n}_e^0$, $E_d$, and $w_d$ are shown at the right-hand sides of these figures. The white regions in (b)–(f) have the values smaller than the smallest shown by the dark colors.
weight of $w_d \sim 1$, corresponding to $n_e^0 \sim 2.3 n_{cr}$ above the critical density, the accelerated energy of this part is limited to 5 MeV.

In contrast to figure 8(a) corresponding to figures 7(b), 8(d) corresponding to figure 7(d) shows a relatively high-density sharp surface at the rear side of the target, since the pre-plasmas at both sides are optimized in case (d). In figure 8(e), the first and the second components show the increase of the accelerated energetic deuterons with >8 MeV compared to the case of figure 8(b). This explains the difference of the deuteron spectrum between case (b) and case (d) in figure 6. Also, in figure 8(e), we clearly see that the first component of the deuterons is accelerated forwards from the tip of the most deformed part into the half angle of 20°, up to 16 MeV. These energetic deuterons partially show a relatively high particle weight of $w_d \sim 1$ in figure 8(f), corresponding to the initial electron density of $n_e^0 = 2.3 n_{cr}$ above the critical density. This represents that the energetic and collimated deuterons are accelerated from the sharp boundary at the rear side of the deformed part compressed by the second shock wave, as described in section 2. From these comparisons, it is confirmed that optimization of pre-plasmas at both sides of the target can lead to efficient acceleration of the deuteron ions with higher energy and sharper collimation angle, compared to the case optimized only for the front pre-plasmas.

4. Conclusion

In order to optimize the pre-plasmas for improving the efficiency of ion acceleration by TNSA for efficient neutron generation, we have carried out 2D radiation hydrodynamic and 2D PIC simulations for foil targets. Radiation hydrodynamic simulations show large deformation of the target caused by foot pulse irradiation, resulting in the long scale length pre-plasma at the front side of the target by geometrically confining the blow-off plasma. We also observe dips of the plasma scale length in the temporal evolution of the backside pre-plasma arising from the shock compression of the pre-plasma. The plasma profiles of the 1–10 μm thick foils are optimized for the foot pulse intensity of $10^{11}$–$10^{13}$ W cm$^{-2}$, which correspond to moderate contrast levels of currently available ultra-intense lasers. We also conducted 2D3V PIC simulations for the set of initial conditions selected from the hydrodynamic simulations. It is shown that optimization of the pre-plasma condition for efficient TNSA of deuteron ions is possible by optimizing the target thickness, laser contrast ratio and injection timing of ultra-high intensity laser. By optimizing the pre-formed plasma condition at the front side and the rear sides of the target simultaneously, we can achieve efficient TNSA deuteron ion acceleration. When the 50 fs pulse of $8.9 \times 10^{18}$ W cm$^{-2}$ peak intensity is injected on the 10 μm thick CD target irradiated by the 3.0 ns duration foot pulse of $10^{12}$ W cm$^{-2}$ intensity, 2D PIC simulation shows larger amount of forward-accelerated MeV deuterons within 3° collimation in comparison with the no pre-pulse case. Thus the number of neutrons from the beryllium–deuteron reactions can be increased by orders of magnitude in comparison with the no pre-pulse case. Further enhancement and improvement are possible through additional optimizations of the system parameters.

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