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Optimization of laser parameters for proton acceleration using double laser pulses in TNSA mechanism

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Research Article

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Abstract

The energy of protons accelerated by ultra-intense lasers in the target normal sheath acceleration (TNSA) mechanism can be greatly enhanced by the laser parameter optimization. We propose to investigate the optimization of laser parameters for proton acceleration using double laser pulses in TNSA mechanism. The sheath field generation at the rear side of the target is significantly affected by the introduction of second laser pulse in TNSA mechanism, and consequently, the energy of the accelerated protons is also modified. The second laser pulse was introduced with different delays to study its impact on proton acceleration. Our study shows that the interplay of laser intensity and pulse duration of both laser pulses affects the proton acceleration. It was found that the proton maximum energy is the function of both laser intensity and pulse duration. A number of simulations have been performed to obtain maximum proton energy data under different combinations of laser intensity and pulse duration for the two laser pulses. The simulation results account for the underline physics for the proton bunch energy and the sheath field as a function of pulse intensity and pulse delay.

Introduction

The development of ultra-intense laser pulse gives an immense push to the field of ion or proton acceleration from laser-solid interaction (Daido *et al.*, 2012; Macchi *et al.*, 2013). The highly intense electrostatic field of order TV/m generates proton beams with tens of MeV energy on the micron scale (Wilks *et al.*, 2001). The accelerated proton bunch has good beam quality, such as low emittance, short duration, and high current, and can be a potential for a wide range of applications in the fields such as the nuclear physics (Bychenkov *et al.*, 1999), hadron therapy (Bulanov *et al.*, 2002), and fast ignition for inertial confinement (Roth *et al.*, 2001). Thus, presently, the field of proton acceleration from laser is widely explored, and there is a surge in various research and experimental work to reach toward a compact and controlled source of proton beam. The various physical mechanisms have been proposed and some of them has been reported experimentally and others through analytical and numerical simulations such as target normal sheath acceleration (TNSA) (Snavely *et al.*, 2000; Hegelich *et al.*, 2005), radiation pressure acceleration (RPA) (Robinson *et al.*, 2008), breakout after burner acceleration (BOA) (Yin *et al.*, 2007), and coulomb explosion (Tripathi *et al.*, 2009). Above all, the mechanism of TNSA has been widely accepted and a lot of parametric estimation (Mora, 2003; Passoni *et al.*, 2004) and scaling law (Fuchs *et al.*, 2006; Robson *et al.*, 2007) have been proposed.

The mechanism of TNSA is based on the effective heating of electrons interacting with laser. When a high-intense laser pulse incidents on a target of few micron length, the energetic electrons are generated at the front side of the target which move toward the rear side of the target. The plasma expansion takes place at the rear surface and an effective electrostatic field develops which is responsible for the acceleration of proton at the rear side. Initially, there is a debate regarding the generation of proton form the front or rear side of the target, but most of the experiment predicts the acceleration from the rear side. The protons from the front side are accelerated in the case of RPA in a higher intensity regime. As evident, the process of TNSA mechanism is simple, therefore, a lot of experimental works is focused on it. There are various laser and target parameters which dictate the energy spectrum of the proton beam such as target material (Fuchs *et al.*, 2003), target thickness (Mackinnon *et al.*, 2002), laser pulse asymmetry (Kumar *et al.*, 2019), and presence of preplasma (Sentoku *et al.*, 2002). Recently, Ferri *et al.* (2018) have used a successive ultra-intense laser pulse with different delays to study proton acceleration under the TNSA scheme experimentally as well as numerically.

The introduction of two laser pulses to study proton acceleration has been proposed earlier by Robinson *et al.* (2007). With the help of 1D simulation, it has been shown that the spectral peaks are obtained when two laser pulses incident on the target with a delay of 100 fs. However, there was no significant change in proton cut-off energy. Markey *et al.* (2010) show that the use of two laser pulses with same energy as that of single laser can enhance the proton energy. The increase in proton energy is associated with the enhanced laser absorption due to the expansion of plasma before the arrival of the main laser pulse. Brenner *et al.* (2014) also shows enhancement in coupling of laser energy to proton using two pulses. Scott *et al.* (2012) have used multiple pulse on plasma half cavity target to enhance laser energy absorption which ultimately give rise to more energetic proton beam. Thus, it turns out that the application of two successive laser pulses can be a good controlling parameter for proton acceleration from a solid target. In our work, we have taken a clue from the experimental work of Ferri *et al.* (2018) and have studied the effect of variable laser intensity and pulse duration on proton acceleration in the double pulse regime. The acceleration mechanism has dependence on laser intensity (Sentoku *et al.*, 2002) and laser pulse duration (Schreiber *et al.*, 2006). Several simulation (Carrí *et al.*, 2009) and experimental studies (Oishi *et al.*, 2005; Flacco *et al.*, 2010; Tayyab *et al.*, 2018) explore the TNSA scheme with variation in laser pulse duration over a wide range. In the earlier works with the double laser pulse, the laser pulse duration for the two successive pulse was chosen to the same, and the laser intensity was also equal for the second as well as the main laser pulse. With the help of two-dimensional (2D) PIC simulation, we explore and investigate the scope for generating more energetic proton beam and an additional controlling parameter along with a delay between the two laser pulses in a double-pulse interaction regime. The proton energy estimation and optimization by laser parameters have been investigated for the double pulse case. The laser energy absorption by plasma is usually dependent on the pulse length. Thus, the study of the effect of different pulse on proton acceleration is necessary to reach at an optimized condition with a successive laser pulse. We provide an optimization of laser parameters for enhanced proton acceleration in TNSA mechanism. The detail of PIC simulations is given in the "2D PIC simulation" section. The simulation results of proton acceleration are discussed in the "Results and discussion" section, and finally, the conclusions are underlined in the last section.

2D PIC simulation

We have used the 2D PIC simulation code EPOCH (Arber *et al.*, 2015) for doing the proposed simulation work. The two laser pulses are linearly polarized with wavelength $\lambda_L = 1\ \mu m$ and spot size $r_0 = 6\ \mu m$. The normalized laser strength parameters are $a_0 = 10$ and $a_0 = 7$, which corresponds to the laser intensity of 1.36×10^{20} and $6.8 \times 10^{19}\ W/cm^2$, respectively. A different pulse duration has been chosen for both laser pulses and are mentioned at different points in the "Discussion" section. A fully ionized plasma of thickness 3 μm is considered as a solid target with electron and proton density of 40 n_c, where n_c is the critical plasma density. The simulation box of size $50\ \mu m \times 40\ \mu m$ has been chosen for this case study extending from −25 to 25 μm in the x-direction and from −20 to 20 μm in the y-direction. The overdense plasma target is placed at − 5 μm and a long vacuum region has been left for the expansion of plasma at the rear side of the target. In order to resolve the simulation results, the grid size for present simulations has been chosen as $\Delta x = 50$ nm in the laser propagation direction (x-axis) and $\Delta y = 50$ nm transverse to laser propagation (y-axis). We have chosen 25 particles per cell for each plasma species (electrons and protons). The periodic boundary condition is chosen in the transverse direction and absorbing boundary conditions is chosen for the left and right boundary of the simulation box. In all the simulation in this paper, the delay between the two laser pulses are measured between the peak intensity of two laser pulses.

Results and discussion

We run the simulations with two ultra-intense laser pulses of the intensity parameter of $a_0 = 10$, which corresponds to the laser intensity of $1.36 \times 10^{20}\ W/cm^2$. The two laser pulses incident normally on the target with a delay of 50 fs between the peak of the two pulses. When the first laser pulse interacts with the 3 μm target, electron heating takes place at the front surface of the target. The heated electrons move to the rear side of the target and form the sheath field. The sheath field accelerates the proton from the rear side of the target. As the peak intensity of the second laser pulse reaches to the target after 50 fs, the plasma electrons are further heated by this laser pulse and it significantly contributes in the formation of the sheath field at the rear surface. The continuous flow of energetic electrons maintains the strength of sheath field for a longer duration of time. This effect can be confirmed by comparing the sheath field generated by the single laser pulse and the double laser pulse. For this comparison, we also run the simulations for a single laser pulse of same intensity as taken for the double pulse case. Figure 1 presents the sheath field for single and double laser pulses. Figure 1a and 1b represents the sheath electric field at different times after the laser peak interacts with the front of the target for single and double laser pulse cases, respectively. In the case of the double laser pulse, the sheath field remains above 0.4 TV/m for a longer period of time as compared to the single laser pulse. This stronger sheath field generation by two lasers is due to the efficient heating of the plasma electrons at the front. As a result, the energy gain in the double pulse case should be greater than the single pulse case. To estimate the proton energy, we show the proton energy spectrum corresponding to the sheath field shown in Figure 1 for the single and double laser pulse cases. Figure 2 shows the energy spectrum of proton for the two cases discussed above. The energy spectrum is shown for the time when the proton cut-off energy reaches to its saturation value. It is evident from Figure 2 that the proton maximum energy for the case of double pulse is around 10 MeV greater than that of the single laser pulse case. Thus, it shows that the application of double laser pulse with a proper delay leads to modify the proton energy spectrum. In order to observe the effect of pulse delay, we run simulations with different pulse delays of $\Delta t = 100$, 200, and 400 fs. The corresponding proton energy spectra for these three cases have been shown in Figure 3. The proton energy reduces as the delay between two pulses increases. And after a delay of 400 fs, the proton energy is almost same as that of the single laser pulse. Thus, the second laser pulse has no effect after a particular delay time. The sheath field no longer sufficiently gets boost from the second laser, and there is no further increment in proton energy. After the delay of 400 fs, the front and rear surface of the target get evolved that's why the second laser pulse is no longer effective. Thus, with the help of delay between two lasers, the proton energy spectra can be controlled.

In the above simulations, we have used two laser pulses of equal intensity and pulse duration. Surely, the results strengthen the effect and application of two laser pulses. However, there is scope for further investigating the double pulse regime with different laser intensity and pulse duration. Experimentally, the single laser pulse can be divided into two laser pulses with

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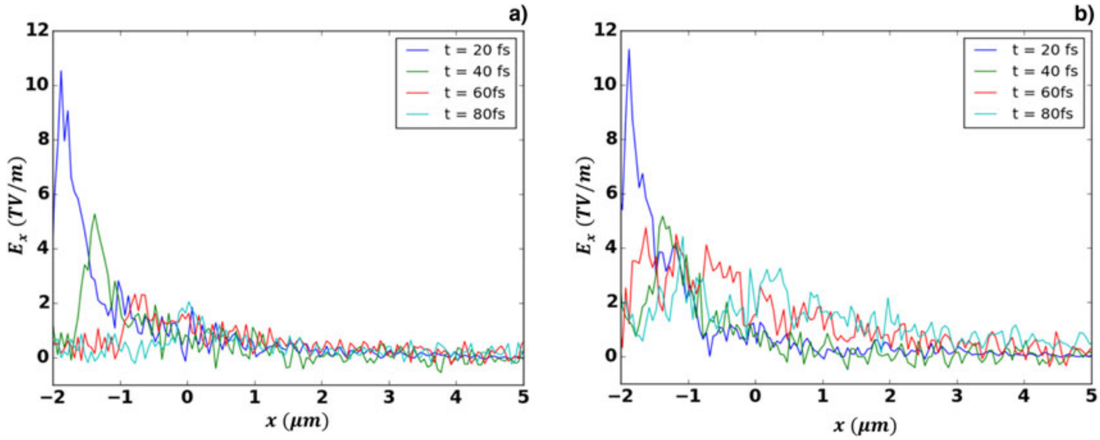

Fig. 1. Sheath field at different times after the laser peak interacts with the front surface of the target for (a) a single laser case and (b) a double laser case with a delay of 50 fs. The laser intensity parameter considered for these simulations is $a_0 = 10$.

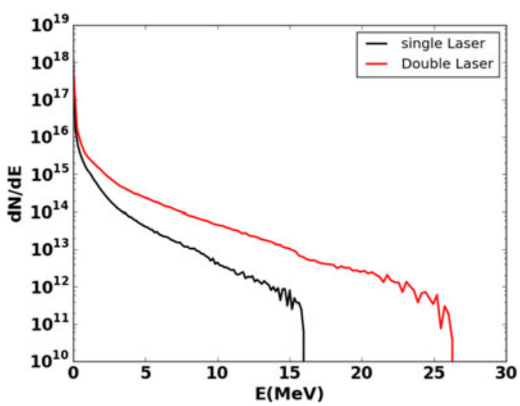

Fig. 2. Proton energy spectrum corresponding to the maximum proton energy achieved for a single laser pulse case (black curve) and a double laser pulse case (red curve).

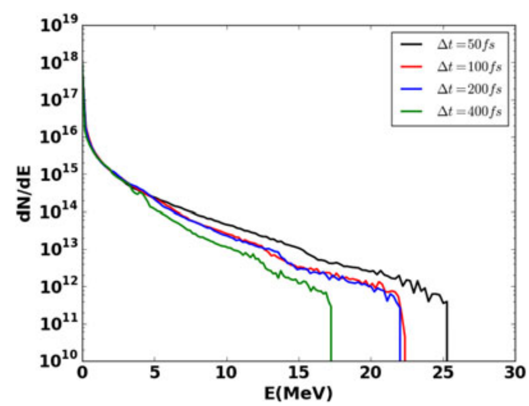

Fig. 3. Proton energy spectra for two laser pulses incident on the target with delays of $\Delta t = 50$, 100, 200, and 400 fs. The two laser pulses have equal pulse duration and intensity $a_0 = 10$ and $\tau = 40$ fs.

different pulse duration. Thus, the study of proton acceleration with different laser intensity and pulse duration is more realistic, and therefore, we have focused our simulation work to aforesaid condition. In the first case, the leading laser is taken to be of the pulse duration of 40 fs with $a_0 = 10$ and the trailing pulse duration is taken 100 fs with $a_0 = 7$. The second laser pulse intensity is chosen, such that its intensity is half that of the leading pulse. The two laser pulses incident on the target normally with delays of 50, 100, 200, and 400 fs, respectively. The proton energy spectra for these conditions is shown in Figure 4. As we can see from the energy plot that the energy gain of the protons in this case is greater than the case discussed in Figure 3. After the interaction of first laser pulse, the plasma gets expanded at the front of the target. It is know that the laser absorption increases with plasma expansion at the front (McKenna *et al.*, 2008; Carrí *et al.*, 2009). In order to see the plasma expansion at the front after the laser interacts with the target, we have plotted the density line profile at different times in Figure 5. That's why when the second laser pulse comes after a particular delay time, the laser absorption is enhanced and subsequently the proton acceleration. Although, the laser intensity is half as compared to the previous case, yet the absorption of laser energy enhances due to the longer pulse length. With a lower intensity of the second pulse and larger duration, the proton energy gain is sufficiently higher.

If the above situation is reversed, that is the first laser pulse has a pulse duration of 100 fs and intensity $a_0 = 7$ and the second laser pulse has duration 40 fs and intensity $a_0 = 10$. The proton energy spectra for this case is shown in Figure 6. The proton cut-off energy for different delays is greater than as compared to the case reported in Figure 3. However, if we compare the results of Figures 4 and 6, for a smaller pulse delay of 50 fs, the proton energy is higher for a longer pulse duration of the second pulse. For Figure 6, however, the leading pulse has a longer pulse duration, but there is no sufficient plasma expansion initially; hence, the proton cut-off energy is smaller. With the increase in pulse delay, the electron heating process in the expanding plasma increases, and it is well supported by higher intensity of the trailing pulse. Thus, proton energy for longer delay times of 100, 200 and 400 fs is higher for this case as compared to Figure 4. In totality, it can be inferred that the different pulse and different intensity of two laser pulse is more favorable for proton acceleration in the double pulse regime. As far as experimental works are concerned, there are few work reported with the double laser pulse as discussed in the "Introduction" section. As we compare our result with the experiment work of Ferri *et al.* (2018), the proton energy is higher in our case, this is because we have considered the simplest target of proton and electron. They have shown the maximum proton energy of around ∼8 MeV with the double

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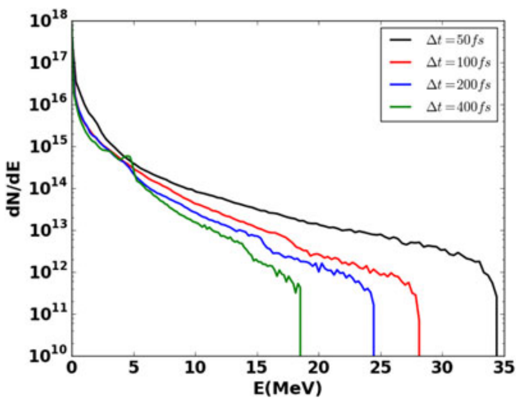

Fig. 4. Proton energy spectra for two laser pulses incident on the target with delays of Δt = 50, 100, 200, and 400 fs. The leading laser pulse has $a_0 = 10$ and $\tau_1 = 40$ fs, and the trailing laser pulse has $a_0 = 7$ and $\tau_2 = 100$ fs.

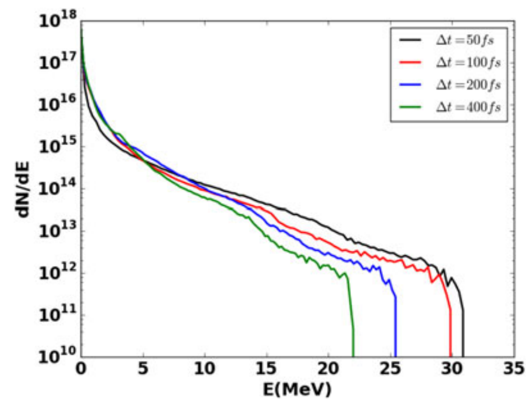

Fig. 6. Proton energy spectra for two laser pulses incident on the target with delays of Δt = 50, 100, 200, and 400 fs. The leading laser pulse has $a_0 = 7$ and $\tau_1 = 100$ fs, and the trailing laser pulse has $a_0 = 10$ and $\tau_2 = 40$ fs.

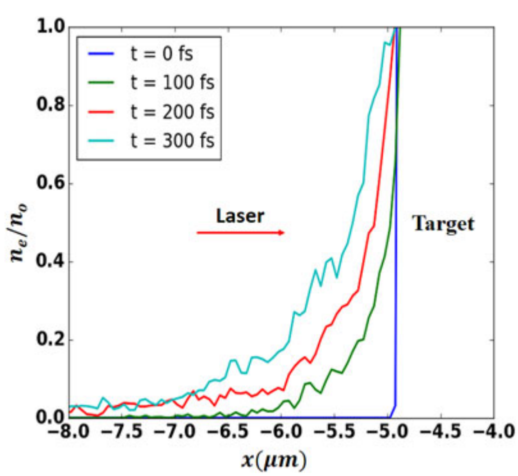

Fig. 5. Electron density line plot after a single laser peak interacts with the front of the target with laser parameter $a = 10$ and $\tau = 40$ fs, $t = 0$ represents the time when peak of the laser pulse interact with front of the target.

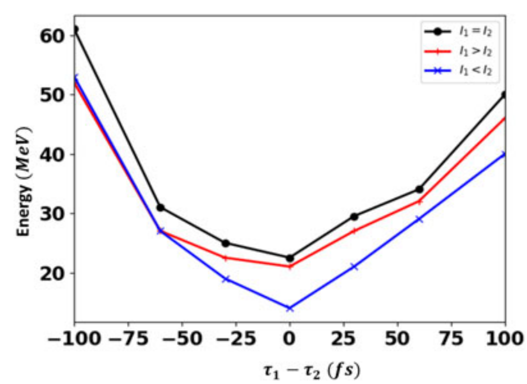

Fig. 7. Maximum proton energy with different combinations of laser pulse duration and intensity for two laser pulses with a delay of 100 fs between them.

laser case. In our case with equal pulse duration and intensity of two laser pulse, the maximum proton energy is around ~25 MeV and there is increment of around 10 MeV with varying laser pulse duration and intensity. However, experimental finding with exact laser and target parameters are not performed and its our simulation finding that pulse duration and intensity plays a significant role in the enhancement of proton energy.

In order to present the effect of different combinations of laser intensity and pulse duration for the two laser pulses, we have done a number of simulations with a delay of 100 fs between these two laser pulses. The duration of laser pulse is considered ranging from 200 to 50 fs for the two laser pulse, and the corresponding maximum proton energy achieved during acceleration is estimated. The sets of two laser pulses with different duration have been studied under three different regime of laser intensity. The first case where the two laser pulses have same intensity of $I_1 = I_2 = 1.36 \times 10^{20}$ W/cm^2, in the second case, the first laser pulse intensity is double as that of the second laser pulse, that is, $I_1 = 1.36 \times 10^{20}$ and $I_2 = 6.8 \times 10^{19}$ W/cm^2. Finally, in the third case, the first laser pulse has the half intensity as that of the delayed laser pulse (reverse of the second case). Figure 6 shows the maximum proton energy gained with different laser intensity and pulse duration for double laser pulse cases as described above. Other simulation parameters are same as discussed previously. From Figure 7, it can be inferred that the proton energy depends on the laser intensity of both laser pulses. The proton energy is maximum when both the laser pulses have equal intensity for all laser pulse duration. Also, the proton energy is higher when the long pulse duration is considered for two lasers. It has been seen that with the pulse duration of $\tau_1 = 100$ fs and $\tau_2 = 200$ fs (τ_1 and τ_2 represents the pulse duration for first and second laser pulses, respectively), the proton maximum energy is around 60 MeV for equal intensity of both laser pulses. On the other hand, for $I_1 > I_2$ and $I_1 < I_2$, the proton maximum energy is about 50 MeV for both cases. As we interchange the pulse duration of both laser pulses, the proton energy somewhat decreases for all the three cases described above. Thus, our simulation results predict that the long duration of trailing laser pulse is more effective for the maximum proton energy as compared with the long duration of leading laser pulse. This is because the trailing pulse interacts with expanded plasma for a longer duration of time. In the case of the short laser pulse duration for two laser pulses (i.e., around 70 fs), the proton energy is almost symmetrical with interchange in the pulse duration of two laser pulses. Thus, a combination of shorter and longer pulse duration for two laser pulses is more effective in generating more energetic proton beam.

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Conclusions

We have investigated the optimization of laser pulse parameters for proton acceleration from a solid target in TNSA mechanism under different possible combinations of two laser pulse. The proton energy is enhanced by employing two laser pulses interacting with a solid target. The increment in proton energy is associated with the increased laser absorption at the target front. It has been shown that the sheath field is enhanced with the arrival of the second laser pulse to the target. For proton acceleration under the action of the successive laser pulse, we found the importance of different pulse duration and laser intensity for the two laser pulses for better optimization. The proton energy increases with the introduction of the double laser pulse. However, the intensity of both laser pulses and the pulse delay play a crucial role in determining the proton energy during acceleration. As the effect of delay time is concerned, the proton energy reduces with the pulse delay between two laser pulses. The effect of delay time ranging from 50 to 400 fs has been estimated. It can be concluded that the delay between two laser pulses can act as a controlling parameter for maximum proton cut-off energy. With the help of various simulations, the combined effect of laser intensity and pulse duration has been estimated for pulse duration ranging from short pulse of 40 fs to long pulse of 200 fs. The proton energy is found to be more pronounced when the second laser pulse has a longer pulse duration. However, if both laser pulses have a shorter duration, the interchange of pulse duration has a negligible effect. Overall, it can be asserted that the double pulse scheme with optimized laser parameters is a useful tool for varying the proton beam energy over a wide range of spectrum.

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