Spectral control in quasi-monoenergetic proton generation with double foil target

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Abstract. Quasi-monoenergetic protons are generated from double foil target irradiated by two ultra-short intense laser pulses in one-dimensional particle-in-cell (PIC) simulations. This approach uses the second laser pulse on the second foil to generate an electrostatic field to modulate exponential energy spectrum of protons generated by the first laser pulse onto the first foil. The peak energy of the quasi-monoenergetic protons can be tuned by the delay time of the second pulse to the first pulse. Simulation results show that when the second laser is incident earlier, the quasi-monoenergetic protons have higher energy.

1. Introduction
Nowadays, generation of quasi-monoenergetic ion beam is one of the critical issues in the laser produced high energy ion generation [1-6]. High-energy (>Mev) ions have been observed in the experiments and numerical simulations. Those energetic ions with very low emittance and high brightness are very attractive characteristics for possible applications in hadron therapy [7], nuclear physics [8], fast ignition [9], and so on.

Previous theoretical works and experiments have shown that energetic ions can be accelerated on solid foil target’s front and back surfaces by electro-static fields generated by the expansion of electrons generated by the intense laser plasma interaction, which is called target normal sheath acceleration (TNSA) [10, 11]. Many approaches have been proposed to reduce the emittance and energy spread of ion beam, by using the microstructured or deformed targets [2-4], or using ultrafast laser-driven microlens [5].

In this paper, we propose to improve the monoenergetic feature in the proton spectrum using a double foil target and two incident lasers. Figure 1 shows the schematic diagram of the simulation model. Stage 1: The first ultra-short intense laser irradiates on a high density foil target to generate hot electrons on one surface, some of which pass through the plasma slab and expand into the vacuum from the target back surface opposite to the first laser irradiated surface. The charge separation result in generation of strong electrostatic fields, which accelerate protons in the foil back surfaces. These energetic protons accelerated on the back side propagate to the second foil target. Their energy spectrum is exponential on the rear surface of the first foil. Stage 2: After some delay time, the second ultra-short intense laser irradiates on the second foil target. Hot electrons generated on the second foil...
surface induce electrostatic fields on both surfaces of the second foil, just as it happened on the first foil surface. The energetic protons, which were generated on the first foil surface are accelerated by the positive electrostatic filed on the back surface of the second foil, to get more energy. On the other hand, the energetic ions are decelerated by the negative electrostatic field on the other surface of the second foil. So the proton energy spectrum is modulated and the quasi-monoenergetic protons can be obtained. By changing intensity, delay time of the second laser, and distance between the two foils, we can get quasi-monoenergetic protons with different peak energy.

Figure 1. Schematic diagram of the double-foil target to generate quasi-monoenergetic ions. The red curve lines around the foils indicate the electrostatic fields resulting from the charge separation. The black arrows indicate the particles motion direction.

2. Simulation results

In one-dimensional (1D) particle-in-cell (PIC) simulations, the two ultra-short intense lasers have sine-square profile \(a_l=\frac{a_0}{2}\sin^2(\pi(x-c)/d_l)\) for \(0 \leq (x-c) \leq d_l\). Here, the laser peak amplitude \(a_0\) is related to the peak laser intensity through \(I\lambda^2=1.37\times10^{18}\text{W/cm}^2\mu\text{m}^2\cdot\mu\text{m}^{-2}\), where \(\lambda\) is the laser wavelength in vacuum. The both laser pulse durations are same and 30\(\tau\), where \(\tau\) is the laser period. They are incident perpendicularly onto the first foil front surface and the second foil back surface separately at different time.

Figure 2. The evolutions of electric field \(E_z\) of single-foil without the second laser (a), double-foil without the second laser (b), and with the second laser (c). The proton distributions in the phase space (momentum \(p\) — position \(x\)) (d), the energy spectra of protons which penetrate the second foil at \(t=62\tau\) (e), and the energy spectra in stable states (f). The four vertical lines in (a-d) represent the two foil front and back surfaces respectively.

In order to see the effects of the second foil and second laser pulse, we compare the evolution of electrostatic field \(E_z\) (Figure 2(a-c)), the proton distribution in phase space (Figure 2(d)), and energy spectra (Figure 2(e-f)) in the cases with single or double foils and with or without the second laser. In the two double-foil cases, the distance of the two foils is fixed at 1\(\lambda\). The first foil density is 12\(n_c\) and the thickness is 2\(\lambda\) with a preplasma whose density increases from 0.2\(n_c\) to 1\(n_c\) in 2\(\lambda\), where \(n_c\) is the
plasma critical density. The second foil density is 12n₀ and the thickness is 1λ without preplasma. The two foils are assumed fully ionized. The two laser peak amplitudes are same, namely a₁=a₃=5. We define the irradiation delay time of two laser pulses by the difference between the times when the first laser arrives at the first foil front surface and when the second laser arrives at the second foil back surface. The delay time is denoted by dt. Here we take dt as 20τ.

From the blue and red lines in Figure 2(d-f), we can see that the protons are blocked by the second foil and the protons penetrating through the second foil have less energy and 100% energy spread. In Figure 2(c), we can see the additional electrostatic field around the second foil, which is generated by the second laser irradiation. When protons originating from the first foil propagate to the second foil’s surfaces, the electrostatic fields decelerate protons in the left hand side of the second foil and accelerate protons in the right hand side of the foil, so that the proton energy spectrum is modulated. The red and black lines in Figures 2(d) show the compare of the proton distributions in the phase space (momentum pᵢ— position x) with and without the 2nd laser. The red and black lines in Figures 2(e) show the compare of the energy spectra of protons that pass through the second foil at the time t=62τ. Here t=0 corresponds to the time when the front of the first laser pulse arrives at the front surface of the first foil. The proton accelerated and decelerated at the second foil as shown in the Figure 2(d) forms the monoenergetic peak around 0.005mₚc² which is shown by the black line in Figure 2(e). Afterwards, those quasi-monoenergetic protons are accelerated further. The energy of the quasi-monoenergetic peak increases, although the quasi-monoenergetic proton number decreases. At the same time, many low-energy protons pass the second foil. But they are too late too be accelerated by the positive electric field on the second foil’s rear surface. After the disappearance of the electric field near the second foil, the proton energy spectrum reaches a stable state. In the stable state, we get an 8.1×10⁻³mₚc² (7.6MeV) monoenergetic peak as shown in Figure 2(f).

Figure 2(f) shows that the proton max energy with the second laser (black line) reaches 21×10⁻³mₚc² (19.7MeV) which is much larger than that without the second laser (red line) 12×10⁻³mₚc² (11.3MeV). The higher energy can be obtained by optimizing the second laser delay time.

From above analyse, we can see that this new approach to generate quasi-monoenergetic ion consists of two stages: energetic protons beam generation and the beam energy spectrum tailoring to form quasi-monoenergetic proton peak. The key process to generate the quasi-monoenergetic protons is in the second stage. The state of monoenergetic peak is related to many parameters, like the distance between the two foils, the parameters of the second foil and the second laser.

![Figure 2(f) shows that the proton max energy with the second laser (black line) reaches 21×10⁻³mₚc² (19.7MeV) which is much larger than that without the second laser (red line) 12×10⁻³mₚc² (11.3MeV). The higher energy can be obtained by optimizing the second laser delay time.](image)

Figure 3. The quasi-monoenergetic ions’ peak energy at different second laser delay time for different distance between the two foils.

Figure 3 shows the relation of monoenergetic ion peak spectrum to the second laser delay time for different distance between the two foils. The second foil is 2λ thick. The two laser peak amplitudes are same, namely a₁=a₃=5. All lines in these figures show that the earlier the second laser is the higher mono-energy can be obtained. The higher-energy protons which came out of the first foil pass through the second foil earlier. So, if the second laser is incident earlier, the electric field around the second foil is formed earlier, which act on the higher-energy protons. It results in obtaining the quasi-monoenergetic protons with higher peak energy. But if the electrostatic field around the second foil is formed too early, the highest-energy protons are in the left hand side of the second foil and are decelerated by the electrostatic field on the front surface of the second foil target. Since the protons
pass the second foil in later time, they are too late to be modulated because the electrostatic field on the second foil back surface has disappeared. So the quasi-monoenergetic protons can be no longer obtained. If the second laser is too late, there have been a lot of electrons and protons which came out of the first foil around the second foil, which preheat the second foil and influence the second foil badly. The electrostatic field around the second foil can not be formed strongly. The quasi-monoenergetic protons can neither be obtained. So the lines in Figure 3 are all finite and in a certain delay time duration.

Figure 3 also shows that when the distance between the two foils is larger and allows the proton get more energy on the back surface of the first foil, the monoenergetic proton energy can be higher if the distance between the two foils and the delay time of the second laser are optimized. On the other hand, for the larger distance, the larger second laser delay time is needed. Because the protons have a longer way to run from the first foil to the second foil. In our simulations, the monoenergetic peaks are very small when the separation distance is 6λ. Because, when the separation distance increases, the quasi-monoenergetic proton number decreases exponentially, and the full width at half maximum of the monoenergetic peak increases.

3. Conlusion
Tunable quasi-monoenergetic protons can be generated from double-foil target irradiated by two ultrashort intense laser pulses. This approach uses the second laser pulse on the second foil to generate an electrostatic field to modulate energy spectrum of protons generated by the first laser pulse onto the first foil. This approach decouples the proton beam tailoring stage from the acceleration stage and allow for their independent optimization, which leads to a system with high flexibility and easier for experiment setup.

Target parameters and laser parameters can be adjusted to get different quasi-monoenergetic protons. There are two methods to change the ion energy of the monoenergetic peak. One method is to change the proton energy during the acceleration stage, like changing the parameters of the first laser and the first foil or the distance between the two foils which influence the proton acceleration effect. The second main method is to adjust the state of the second laser or the second foil in the tailoring stage, which result in the change of the electrostatic field around the second foil to modulate the proton energy spectrum, when the protons come out of the first foil and run to the second foil.

In this paper, we change the second laser incident time to change the second electrostatic field generation time. Simulation results show that the earlier the second laser incident, the higher quasi-monoenergetic protons can be got. The influence of the other parameters to the property of the quasi-monoenergetic protons will be discussed.

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