

Ion Acceleration by Ultra-intense Laser Pulse Interacting with Double-layer Near-critical Density Plasma

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Abstract: A collimated ion beam is generated through the interaction between ultra-intense laser pulse and a double layer plasma. The maximum energy is above 1 GeV and the total charge of high energy protons is about several tens of nC/μm. The double layer plasma is combined with an underdense plasma and a thin overdense one. The wakefield traps and accelerates a bunch of electrons to high energy in the first underdense slab. When the well collimated electron beam accelerated by the wakefield penetrates through the second overdense slab, it enhances target normal sheath acceleration (TNSA) and breakout after-burner (BOA) regimes. The mechanism is simulated and analyzed by 2.5 dimensional Particle-in-cell code. Compared with single target TNSA or BOA, both the acceleration gradient and energy transfer efficiency are higher in the double layer regime.

1. Introduction

High energy ion beam has been used in cancer therapy [1], inertial confinement fusion [2], radiography of dense matter [3], fundamental particle physics [4] and other purposes. However, the size and cost of conventional accelerators are so huge that long term construction and international collaboration is required. With the development of laser technology, ultra-intense and ultra-short laser pulse are now available. Ion acceleration driven by laser-plasma interaction becomes an interesting and important topic and has been investigated intensively in these decades. Many mechanisms have been proposed including



target normal sheath acceleration (TNSA) [5], breakout after-burner (BOA) [6], radiation pressure regime [7], Coulomb explosions [8] and so on. In this paper, the enhanced BOA regime through a double layer near critical density plasma has been discussed by 2.5-dimensional particle-in-cell (PIC) simulations. The leading electrons in this regime is not the hot electrons but the laser-wakefield-accelerated (LWFA) electron beam which has good beam quality. The protons are accelerated for a long distance by the LWFA electron beam. The maximum ion energy exceed 1GeV and the accelerated ion bunch is also well collimated.

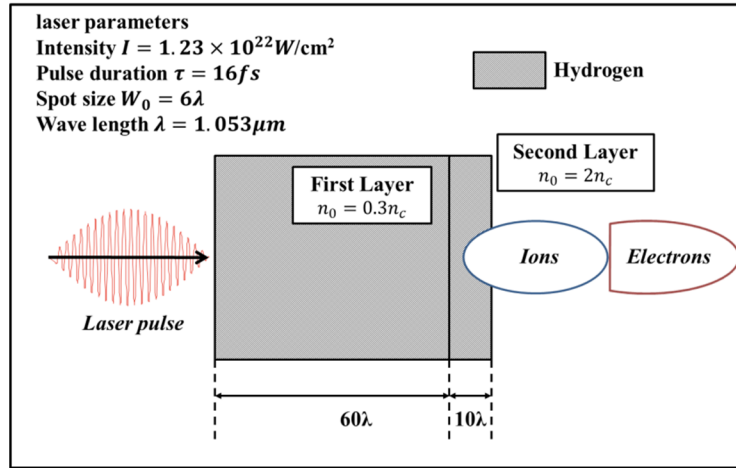


Figure 1. Schematic of the simulation model

2. Enhanced proton acceleration through the double layer target

The schematic of simulation model for double layer plasma acceleration is presented in Figure 1. The Gaussian pulse is focused at the left boundary of the target. The laser pulse is linearly polarized in y direction with intensity $I = 1.23 \times 10^{22} \text{ W/cm}^2$, pulse duration 16fs and radius $W_0 = 6\lambda$, here $\lambda = 1.053 \mu\text{m}$ is the pulse wavelength. The target is a hydrogen plasma which has two layers with different densities. The first layer is underdense with $0.3n_c$ locating from $20 \leq x(\lambda) \leq 80$, where $n_c = 1.005 \times 10^{21} \text{ cm}^{-3}$ is the non-relativistic plasma critical density. From 80λ to 90λ , there is the slightly overdense second layer with $2n_c$ as shown in Fig. 1. The simulations are based on the electromagnetic relativistic code “ZOHR”. Free boundary conditions are used for both particles and fields. The mesh size is $dx=dy=0.04\lambda$ and the total macro-particle number is about 7.3×10^8 .

The ultra-intense laser pulse induces a wakefield in the first layer underdense plasma when it is propagating through the target. The wakefield is strong enough to trap and accelerate a bunch of electrons to high energy in a short distance. In Fig. 2 (a), the wakefields at three moments (150fs, 225fs and 315fs) are plotted. One can find the maximum longitudinal electric field reaches 150GV/cm. The energy spectrums of the trapped electron beam at the corresponding time are depicted in Fig. 2 (b). In about 70λ , the trapped electrons have been accelerated to hundreds MeV. The effective acceleration gradient reaches about $6.8 \text{ MeV}/\mu\text{m}$. According to the angular spectrum, the electron beam is well collimated as shown in Fig. 2 (c)

with the transverse emittance of $(4/N) \sqrt{\sum_{i=1}^N (y_i - \langle y \rangle)^2} \times \sqrt{\sum_{i=1}^N (\theta_i - \langle \theta \rangle)^2} \approx 1.35 \text{ mm} \cdot \text{mrad}$.

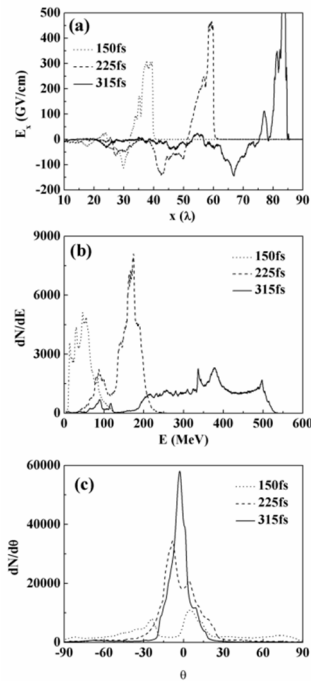


Figure 2. (a) The longitudinal electric field, (b) the energy spectrum and (c) the angular spectrum of LWFA electrons at 150fs, 225fs and 315fs are plotted with dotted line, dashed line and solid line, respectively.

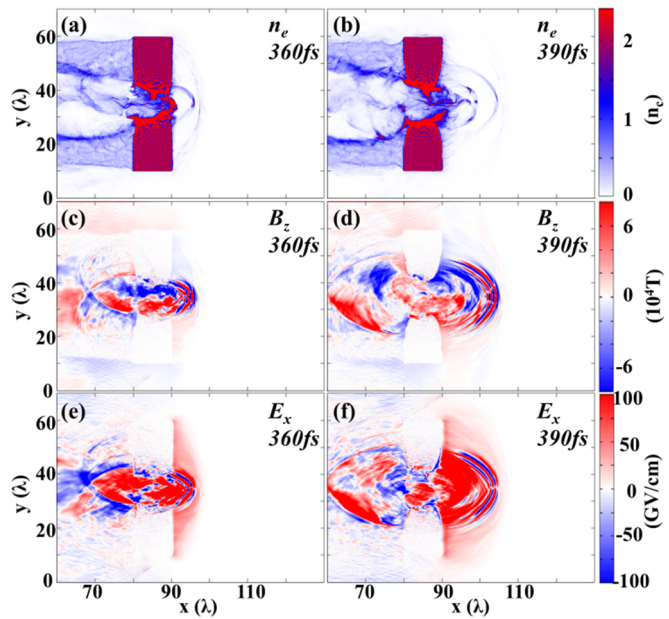


Figure 3. The distribution of (a, b) electron density, (c, d) z-component of magnetic field and (e, f) longitudinal electric field at 360fs and 390fs are plotted.

The accelerated electron beam induces a dipole magnetic field by its current. When the electron beam penetrates throughout the second layer target, the corresponding magnetic field expands quickly in vacuum. Figure 3 (a) and (b) show the electron density profile at 360fs and 390fs, respectively. During this period, the LWFA electron beam is propagating through the boundary of second target and ejecting into vacuum. The magnetic field (z-components) distributions at the corresponding moments are plotted in Fig. 3 (c) and (d), respectively. The expanding magnetic field structure is quite apparently by compared with the transverse size of B_z . With the expansion of magnetic field, a longitudinal electric field is induced near the boundary which accelerates the ions as shown in Fig. 3 (e) and (f). The longitudinal electric field expands with the magnetic field and reaches about hundreds GV/cm.

The longitudinal electric field along the second layer target boundary is plotted in Fig. 4 (a). Since the second layer density is overdense with $2n_c$, the field strength exceeds 600GV/cm. It also suggests the strong field is tightly localized near the center. The ions located near the boundary are accelerated violently to high energy with large gradient. The following ion acceleration stage is breakout after-burner (BOA) regime. From the distribution of electron density, ion density and transverse electric field at 811fs shown in Fig. 4 (b), one can find the steady BOA acceleration structure is already formed. The first electron density peak represents a bunch of electrons which is directly accelerated by the laser ponderomotive force. The second electron density peak is the LWFA electrons. Both of the two electron bunches accelerate the following ion beam. The accelerated ion bunch is also collimated since the

beam quality of the leading LWFA electrons. The electrons transfer their energy to the ions, while they are fed back through the pulse. This structure maintains for a long time and distance until the pulse energy is exhausted. In Fig. 4 (c) and (d), we present the proton energy spectrum and the energy angular related distribution at 946fs, respectively. The maximum proton energy is 1.03GeV. It's not the limit of the acceleration mechanism since the laser pulse still contains large energy at this moment. If the simulation area is enlarged, higher energy ions can be obtained. The proton bunch contains energy totally about $3.19\text{J}/\mu\text{m}$. The energy of the laser pulse in our simulation is about $10\text{J}/\mu\text{m}$, therefore the energy transfer efficiency from laser to the ions is about 31.9%, which is very effective. From Fig. 4 (d), one can also find most of the high energy protons are well collimated between $\pm 20^\circ$.

3. Discussions and conclusions

In our work, a high energy ion bunch is obtained with the interaction between a double layer near critical density hydrogen plasma and ultra-intense ultra-short laser pulse. The leading electron beam accelerates and collimates the following ion bunch in a long distance, while the energy is supplied to the electrons by the laser pulse. The steady structure maintains for a long time. Both the TNSA and BOA are enhanced through the double layer target. Higher energy and larger charge quantity are acquired compared with the single target regime [9, 10]. This kind of interaction is one of the promising mechanisms to obtain high energy ions.

Acknowledgements

This work was partly supported by NSFC (No. 11175048), Shanghai Nature Science Foundation (No. 11ZR1402700), and Shanghai Scientific research innovation key projects No. 12ZZ011. Support from Shanghai Leading Academic Discipline Project B107, the JSPS and MEXT Program, and CORE of Utsunomiya University, Japan are also acknowledged.

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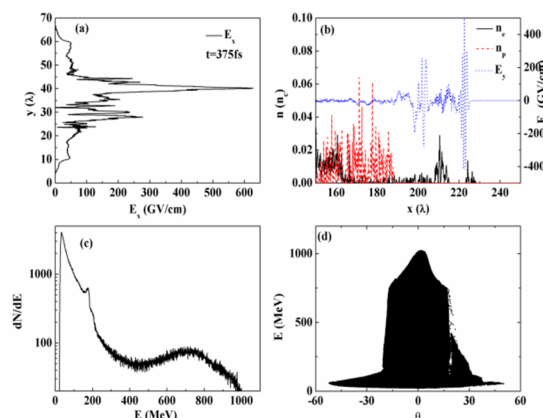


Figure 4. (a) The longitudinal electric field at 375fs along the target boundary. (b) The transverse electric field (blue dotted line), electron density (red dashed line) and proton density (black solid line) along $y=35\lambda$ at 811fs. (c) and (d) are the energy spectrum and energy-angular related distribution of the accelerated proton bunch at 946fs.