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Generating monoenergetic proton beam by using circularly polarized laser*

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Abstract The interaction of ultrashort intense circularly polarized laser with ultra thin overdense foil is studied by particle-in-cell simulation and analytic model. It is found that with the balance between pondermotive force and electrostatic force, highly quasi-monoenergetic proton beam can be generated by Phase Stable Acceleration (PSA) process. As in conventional accelerators, ion will be accelerated and bunched up in the longitudinal direction at the same time.

Key words monoenergetic ions, ultra-short ultra-intense laser, phase stable acceleration

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Benefiting from the high accelerating field, ions generated in laser-solid interaction could gain high energy over micron length scale and hence construction of ultra compact accelerator becomes possible. These future accelerators have many potential applications, like Fast Ignition Inertial Confinement Fusion (ICF)[1], radiotherapy for treatment of tumours[2]. In recent years, many acceleration models for laser-plasma interactions have been presented, i.e. Coulomb explosion model, TNSA model, and Shock wave acceleration model[3]. But the nearly 100% energy spread of the output beams in these models extremely limits their applications. In this article, we will present a new laser-solid interaction model “Phase Stable Acceleration (PSA)”, which is similar to the acceleration method in conventional accelerators and can generate a quasi-monoenergetic ion beam.

Before detailing PSA model, we will investigate the electron heating effect in different polarizations. For linear polarization pulse, Kruer and Estabrook have demonstrated that due to the oscillation part in ponderomotive force electrons will be heated by $J\times B$ heating mechanism[4]. Considering a circular polarization wave with electric field amplitude $E=E_0(x)(\cos\omega t\hat{y}+\sin\omega t\hat{z})$, we derived the ponderomotive force $F_{\rm p}$ of this field in the usual way:

$$F_{\rm p}=-\frac{e^2}{2m_{\rm e}\omega^2}\frac{\partial}{\partial x}E_0^2(x)\hat{x}\,, \tag{1}$$

where $m_{\rm e}$ is the electron mass, and ω is the laser frequency. For simplicity we neglected the thermal and relativistic effect. Compared with the linearly polarized case[4], the ponderomotive force of a circular polarization wave does not depend on time, in other words, it has no oscillation part, so that the $J\times B$ heating[4] is not efficient and electrons can keep low temperature (Fig. 1(a)). When a CP pulse irradiates an ultra thin foil, electrons with low thermal velocity can pile up in the wavefront. Then two layers are

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formed[5]. One is the compressed electron layer composed of ions and compressed electrons, the other one is the electron depletion layer composed only of ions (Fig. 2). Then both the ponderomotive force and the electrostatic force exert on the compressed electron layer. If they come to balance, the compressed electron layer will be kept in quasi-equilibirum and the ions will be accelerated by the charge separation field. The electrostatic field in the compressed electron layer decreases with x, this provides a longitudinal restoring force for the ions in the compressed electron layer. Just like PSA in the conventional RF linac, the ion beams are oscillated around the reference particle and bunched up in the phase space (Fig. 1(b)), so that the energy spread can be efficiently decreased.

In order to reach balance between the two forces, the laser intensity, plasma density and foil thickness should satisfy the following equation[6]

$$(1+\eta)^{\frac{1}{2}} a \sim \frac{n_0}{n_{\rm c}} \frac{D}{\lambda}, \qquad (2)$$

where a is the normalized peak amplitude of laser pulse, which satisfies $I\lambda^2 = 2.74\times10^{18}(\mathrm{W/cm})^2\,\mu\mathrm{m}^2\times a^2$, η is the reflecting efficiency, n_0 is the plasma density, $n_{\rm c}$ is the critical density of the incident laser pulse, D is the foil thickness, and λ is the laser wavelength in vacuum.

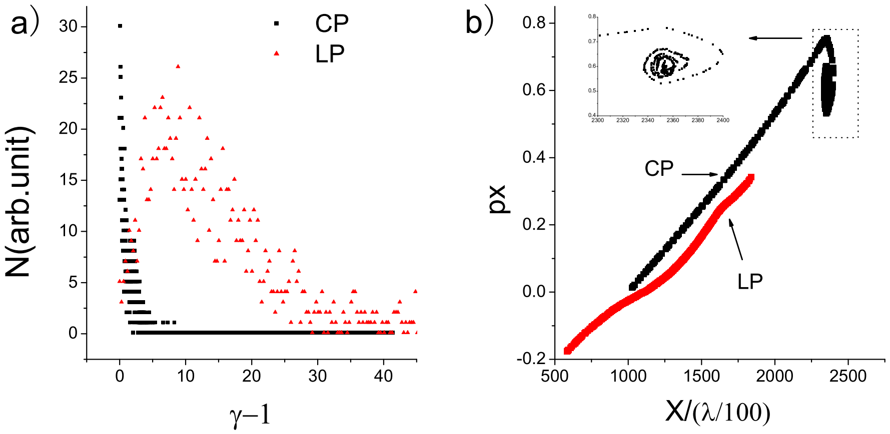

Fig. 1. (a) The electrons temperature in circularly polarized pulse (CP) and in linearly polarized pulse (LP) (b) phase space distribution in CP and LP; all of these data were taken at $t = 50$ T.

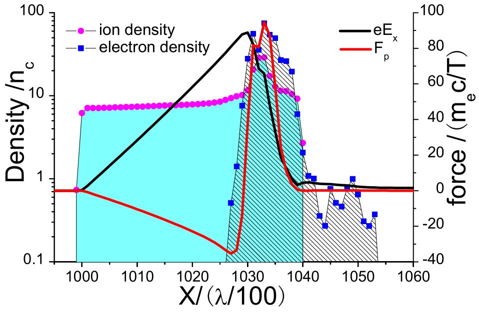

Fig. 2. Ions (magenta point) and electrons (blue point) density were plotted at t = 12 T. Ponderomotive force (red line) compared with electrostatic force (black line) was drawn to the check force distribution relative to particles densities at the same time.

We have performed one-dimensional (1D) PIC simulation by using KLAP code developed by the group of high field physics, institute of physics, Chinese Academy of Sciences. The simulation system is 100λ long in x direction and the incoming laser light launches from the left boundary. In our simulation we consider a laser pulse with peak intensity $a = 10$ normally incident onto a cold solid target with density $n = 10\ n_{\rm c}$, $D = 0.4\lambda$ overdense plasma slab composed of protons and electrons.

Figure 1(a) shows the phase space distribution of protons in $t = 50T$. When the pulse is circularly polarized, protons with large momentum bunch up and form spiral structure, which agrees with our analysis. In contrary, protons generated by linearly polarized pulse disperse in the phase space as a line and have lower max velocity. Fig. 1(b) compares the electron temperatures of different polarizations. As we mention above, with less efficiency of $J\times B$ heating, electrons keep low temperature in circularly polarized pulse.

In Fig. 2 we plot the density distribution at two laser cycles after interaction began. As it shows, Ions almost hold their positions and form an ion layer, while most electrons are pushed into a compressed electron layer ($\sim 0.15\lambda$). Due to vacuum expansion, some electrons expand out of the target and form a region with underdense plasma. We also show ponderomotive force and electrostatic force in Fig. 2. In such a case, the two forces are balanced in the front of the compressed electrons layer, which is in accordance with the model assumption. Fig. 3 displays the energy spectrum of protons at $t=150$ T. The energy of protons reaches ~500 MeV and the energy spread is less than 5%. The number of protons is calculated in arbitrary unit.

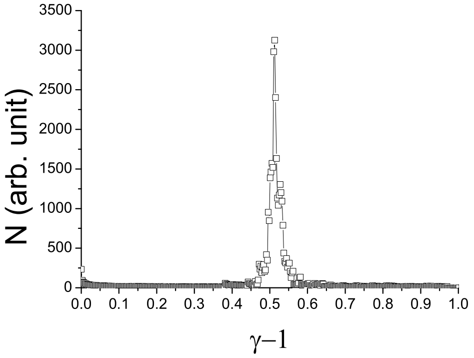

Fig. 3. Energy spectrum at $t=150$ T.

In order to analyze the Phase-Stable Acceleration further, we consider the motion of a foil moved by light pressure[7]

$$\frac{\mathrm{d}p}{\mathrm{d}t}=\frac{E_{\mathrm{L}}^2[t-x(t)/c]}{2\pi n_{\mathrm{e}}l}\,\frac{\sqrt{m_{\mathrm{i}}^2c^2+p^2}-p}{\sqrt{m_{\mathrm{i}}^2c^2+p^2}+p}\,, \tag{3}$$

where E_{L} is the peak amplitude of laser, n_{e} is the electron density, l is the target thickness, m_{i} is the ion mass, and p is the momentum of standard particle. For simplicity we take the reflection coefficient equal to 1. Suppose E_{L} is constant, the initial condition is $p(t=0)=0$, we have

$$p=m_{\mathrm{i}}c\left[\sinh u-\frac{1}{4}\mathrm{csch}u\right], \tag{4}$$

where

$$u=\frac{1}{3}\mathrm{arcsinh}(\varOmega t+2), \qquad \varOmega=\frac{3E_{\mathrm{L}}^2}{2\pi n_{\mathrm{e}}lm_{\mathrm{i}}c}\,.$$

We find the PSA model coincides with classic theory perfectly. It shows that the laser momentum is efficiently transported to the ion population.

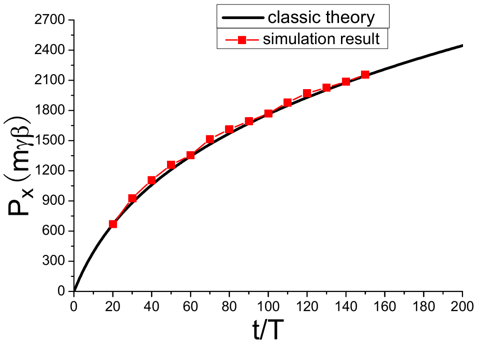

Fig. 4. Comparison of semi-analytic model (black line) to peak proton momentum in the simulation (red point).

By means of 1D KLAP PIC program, we simulate the interaction of ultra thin foil with ultra short intense circularly polarized laser. When the laser intensity, plasma density and foil thickness satisfy Eq. (2), Phase Stable Acceleration is realized. In this quasi-steady state, the separated electrostatic field synchronously accelerates and bunches the ion beam in longitudinal direction, so that quasi-monoenergetic ion beam is generated. Furthermore, we found the analytic model agrees extremely well with the PIC simulation results. Though 1D simulation shows the energy spread is able to be controlled less than 5%, in fact, the light intensity distribution in transverse direction leads to surface bending of the plasma. As a result, the energy spread will increase in multi-dimension case. Additional, instability will also affect the acceleration process.

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