RADIATION PRESSURE ACCELERATION OF MULTI-ION THIN FOIL

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Abstract

Radiation pressure acceleration (RPA) is considered as an efficient way to produce quasi-monoenergetic ions, in which an ultra-thin foil is accelerated by high intensity circularly polarized laser. Our simulation study shows that an important factor limiting this acceleration process is the Rayleigh-Taylor instability, which results in the exponential growth of the foil density perturbation during the acceleration and hence the induced transparency of the foil and broadening of the particle energy spectrum. In this paper, we study RPA of multi-ion thin foil made of carbon and hydrogen and investigate the possibility of using abundant electrons supplied from carbon to delay the foil from becoming transparent, enhance the acceleration of protons and therefore improve the energy of quasi-monoenergetic proton beam. We show the dependence of the energy of quasi-monoenergetic proton and carbon beam on the concentration ratio of carbon and hydrogen in the foil for RPA.

INTRODUCTION

Compact laser-driven accelerators is an attractive alternative for high-quality mono-energetic proton and ion generation to conventional radio frequency accelerators because the electric fields for particle acceleration can reach the order of tens of GV per cm, which allows reduction of the system size and cost. With the advent of short pulse intense lasers with intensities as high as 10^{20} W/cm^2, laser hadron acceleration has become an active field of study. There are tremendous beneficial applications of high energy quasi-monoenergetic hadrons such as particle therapy for cancer treatment [1], fast ignition [2,3], and proton imaging methods [4]. In previous studies of generating highly energetic ion beams from laser-plasma interactions, foil targets with thicknesses ranging from a few to tens of laser wavelengths were used and the target normal sheath acceleration (TNSA) was the predominant mechanism leading to producing ion beams with energy of tens of MeV [5-10]. The resulting ion energy spectrum, however, is broad, and the energy conversion efficiency is also low, not suitable for applications requiring high quality beams of monoenergetic ions.

Laser radiation pressure acceleration (RPA) of an ultra-thin target, where a self-organized double layer plasma is accelerated by reflecting the laser, was considered an efficient way of obtaining quasi-monoenergetic ions [11-17]. The conversion efficiency with the RPA scheme is estimated to be more than 40 times higher than TNSA [9]. In experiment, using a 30 TW laser with a peak intensity of 5×10^{19} W/cm^2 irradiated on a diamond-like carbon (DLC) foil of thickness 5.3 nm, Henig *et al.* obtained a C^{6+} ion beam with a distinct peak energy of around 30 MeV and an energy spread of around 20 MeV by both 2D simulations and experiments [18].

Although with relatively high energy conversion efficiency, the time when the foil can be effectively accelerated with RPA scheme is largely limited by Rayleigh-Taylor instability (RTI) [19], which is one of the most important instabilities arising when a thin plasma foil is accelerated by the radiation pressure of an intense laser. The small perturbation in foil density grows exponentially and the laser beam then leaks from those low density region and ceases to accelerate the foil. To obtain ions with higher monoenergy without raising the input laser power, special design in foil or laser profile is required and now a field of active study. We show in this paper that using a foil with ions of different charge-to-mass ratio can suppress the instabilities, extend the accelerating time and further accelerate the foil with not only radiation pressure but also Coulomb repulsion.

In RPA, high intensity circularly polarized laser with high contrast ratio accelerates the ultra-thin foil by the ponderomotive force acting on the electrons [13]. The laser sweeps all electrons in the foil forward until the electrostatic force due to the ions left behind balances the ponderomotive force at a distance *D*. When the thickness of the target l_0 is equal to *D*, we obtain optimal thickness. In the limit of normalized laser amplitude $a_0 = e|E_0|/(m\omega_L c) >> 1$, this thickness is

$$l_0 \approx \frac{4\pi}{\lambda_L}\left(\frac{c}{\omega_p}\right)^2 a_0 = \frac{a_0}{\pi}\frac{n_c}{n_0}\lambda_L\,, \qquad (1)$$

where *m* and –*e* are the electron mass and charge, λ_L and ω_L are the laser wavelength and angular frequency, ω_p is the electron plasma frequency, n_0 is the target electron density, and $n_c = \varepsilon_0 m\omega_L^2/e^2$ is the critical density. In RPA, the ions are accelerated forward by the electric force of the electron layer, and the inertial force in the accelerating frame moving with the foil pulls them back. The balance of these two opposing forces forms a trap for the ions in real and phase spaces, and this self-organized double layer system is accelerated as a whole by the laser radiation pressure nearly mono-energetically

With multi-ion foil, there are two phases of acceleration: during the RPA phase, heavier (less charge-to-mass ratio) ions are less accelerated and left behind the lighter ions, forming a triple layer system. After the electron layer is mostly decomposed by RTI, it then enters

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to the Coulomb repulsion phase, where the lighter ion layer continues to be pushed by the heavier ion layer behind and further accelerated until the energy spectrum is broadened.

SIMULATION SETUP AND RESULTS

Simulation Setup

We here employ two-dimensional (2D) particle-in-cell (PIC) simulations to demonstrate the generation of quasi-monoenergetic ions by the RPA and Coulomb repulsion. For RPA dominated cases, the simulation domain is $-4 \le x/\lambda_L \le 12$; $-12 \le y/\lambda_L \le 12$ and is divided into 64 grids per wavelength. The boundary condition is periodic in y direction and out flow in x direction. The hydrogen foil is initially located at $0 \le x \le l_0$ with $l_0 = 0.2\lambda_L$ being the foil thickness and is resolved by 49 quasi-particles per grid of each species. The amplitude of the incident circularly polarized laser has a Gaussian profile in the transverse direction with the spot size being $8\lambda_L$ in radius and a time profile of $3T_L$ rising and a continuous waveform thereafter.

Hydrogen Target

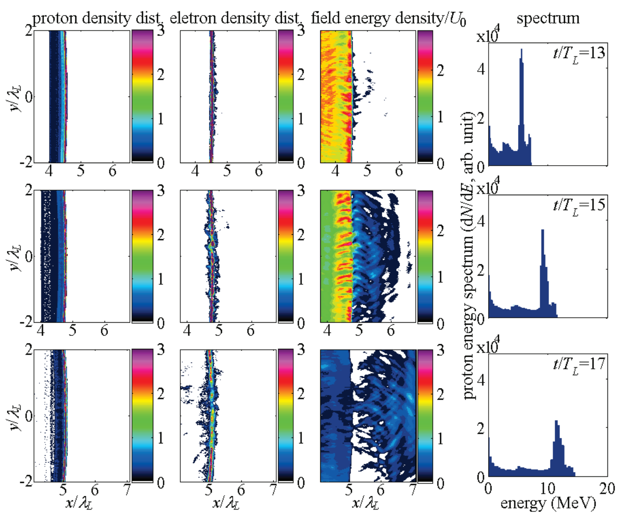

Figure 1: 2D PIC simulation results of the evolution of proton density map (the first column), electron density map (the second column), normalized electromagnetic field energy density over incident laser energy density (the third column) and energy spectrum of the protons within $|y| < \lambda_L$ (the fourth column) at three instants. Top, middle, and bottom rows are at $t = 13T_L$, $15T_L$, and $17T_L$, respectively.

Figure 1 shows 2D PIC simulation results of the RPA of a thin foil made of pre-ionized hydrogen only with a normalized incident laser amplitude $a_0 = 5$. The initial foil density is $n_0 = 8.3n_c$ and the thickness is $l_0 = 0.2\lambda_L$, corresponding to the optimal thickness as defined in Eq. (1). It shows that the RTI can destroy the electron layer and widen the energy spectrum of the ions in as fast as 17 wave period. Density perturbations form interleaving high density blobs and low density regions, as shown in Fig. 1. Once the density of the low density region of the foil falls below the critical value, the laser light can penetrate, after which the energy cannot be converted into foil acceleration efficiently, and the particle energy spread will be significantly increased. This leads to a leakage of radiation through the target by self-induced transparency. After this stage, the foil can no longer be accelerated efficiently and the energy spectrum starts to broaden dramatically and thus loses its monoenergetic property.

Carbon-Hydrogen Target

Using a foil made of both pre-ionized carbon and hydrogen with the same electron density and thickness, the acceleration time can be extended significantly. Figure 2 shows the same input laser parameters while the foil is now made of 1:1 carbon and hydrogen mixture. Although initially the acceleration is less than pure hydrogen foil due to a larger overall mass, the proton can stay mono-energetically for a longer time and Coulomb repulsion also helps to increase the proton energy as well. It can be seen in Fig. 2 that with the presence of carbon ion, the portion of protons which fall behind, both in density map and energy spectrum, is considerably suppressed.

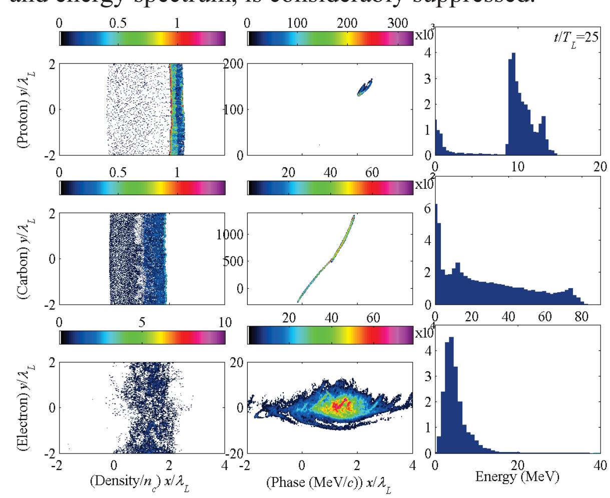

Figure 2: 2D PIC simulation results of the density map (the first column), phase map (the second column) and energy spectra of the different species within $|y| < \lambda_L$ (the fourth column). Top, middle, and bottom rows are the plots of protons, carbon ions and electrons, respectively.

Obtainable Quasi-Monoenergetic Proton Energy versus Concentration

While increasing the percentage of carbon ions, the portion of fall-behind protons decreases and the Coulomb repulsion from carbon ion becomes greater. Therefore, the proton layer can maintain being monoenergetic longer and be further accelerated, and the obtainable monoenergy is also largely increased. To explore the relationship between the concentration of carbon and the obtainable monoenergy, we perfume simulations by

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increasing the percentage of carbon in the foil by 10% in each simulation and the result is shown in Fig. 3. It can be seen that at 50%, the Coulomb repulsion is large enough to compensate the loss in RPA due to a heavier target foil.

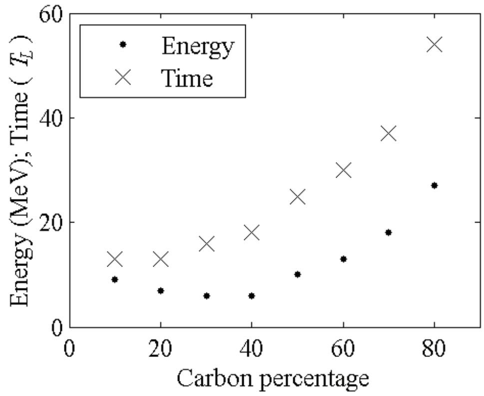

Figure 3: The obtainable energy and accelerating time with different carbon.

The obtainable energy from Coulomb force is proportional to the charge of carbon ion layer and proton layer, i.e. electric potential. Increasing the carbon concentration, although harder to be accelerated by RPA, can provide greater repulsive force and energy. It can be seen in Fig. 3 that in the region of small carbon percentage, the obtainable proton monoenergy is decreased with increasing carbon percentage. This is due to that the separation of carbon ion and proton with small carbon concentration is not significant so that the repulsion force from carbon is not enough to enhance the obtainable energy against the effect of foil being heavier. For higher carbon concentration, the proton layer is almost totally separated from the carbon ion layer during the RPA phase, and it thus maintains monoenergy for a longer time and accelerates more. With $a_0 = 5$, corresponding to the intensity of $7\times10^{19}\,\mathrm{W/cm^2}$ and the power of 70 TW, the obtainable proton quasi-monoenergy for 80% carbon and 20% hydrogen composite targetcan reach as high as 27 MeV, more than two times the energy obtainable from pure hydrogen targets.

DISCUSSIONS AND CONCLUSIONS

In RPA scheme, the acceleration is mainly decided by the intensity of the input laser and the charge-to-mass ratio of the ions in the foil. Therefore the acceleration with fixed laser intensity can be maximized with hydrogen foil. However, making thin foil out of pure hydrogen is difficult and impractical. In contrast, multi-ion foils made of both carbon-like ions (fully-ionized ions with the same charge-to-mass as carbon ions, like nitrogen ions or oxygen ions) and hydrogen can be easily found in organic compounds like methyl methacrylate resin (empirical formula $C_5O_2H_8$, carbon-like ion concentration 49%) or biaxially-oriented polyethylene terephthalate ($C_{10}O_4H_8$, concentration 66%). The feasibility of using multi-ion targets to get high energy monoenergetic protons is better than using pure hydrogen targets.

The number of protons within one wavelength radius, with initial conditions $n_0 = 8.3n_c$, $l_0 = 0.2\lambda_L$ and 80% carbon ions, is 2.3×10^8 (37 pC in charge), close to the requirement of medical applications.

In summary, we have reported that the RPA coupled with Coulomb repulsion scheme can increase the obtainable monoenergy of protons from 10 MeV to as much as 27 MeV with less than 100 TW input laser. The obtainable energy is mainly limited by the Coulomb explosion of the ions.

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