OPTIMIZATION OF LASER RADIATION PRESSURE ACCELERATOR FOR ION GENERATION

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Abstract

Compact laser-driven accelerators are an attractive alternative for monoenergetic proton and ion generation in conventional RF accelerator because the particle acceleration electric fields can reach tens GV/cm, which allows reduction of the system size. The scheme for generating quasi-monoenergetic proton with Radiation Pressure Acceleration (RPA) has the potential of leading to table-top accelerators as sources for producing 50-250 MeV protons. Theoretical and computational studies of ion energy scaling of RPA are presented. 2D and 3D PIC simulations are performed to study limitations of energy gain due to Rayleigh-Taylor instability and how is the Rayleigh-Taylor instability suppressed by density fluctuations or inhomogeneities of targets. Energy transfer efficiencies and qualities of accelerated proton beams are discussed.

INTRODUCTION

One of the most attractive applications of ultra-short superintense laser pulses is connected with the development of new methods of accelerating charged particles. The generation of high energy particles, both electrons and ions, when strong electromagnetic radiation interacts with a plasma is a well known phenomenon. However it is necessary to find the plasma and radiation parameters that optimize this process. Thick targets with thicknesses ranging from a few to tens of laser wavelengths were employed in early studies of ion acceleration. and the target normal sheath acceleration (TNSA) was the predominant mechanism leading to the production of multi-tens MeV ion beams but with wide energy spectra [1, 2]. Recently, the scheme of laser radiation pressure acceleration (RPA) of ultra-thin target shows promising aspect of efficient quasi-monoenergetic proton generation [3-5]. In the RPA scheme, a circularly polarized, high power, short pulse laser is focused on a suitable ultra-thin foil, which leads to the acceleration of the whole foil. The RPA focuses on increasing the efficiency of acceleration and producing monoenergetic protons. The scheme for generating quasi-monoenergetic proton with RPA has the potential of leading to table-top accelerators as sources for producing monoenergetic 50 - 250 MeV protons suitable for widespread dissemination for cancer therapy and other applications such as fast ignition in laser fusion. In comparison to the conventional TNSA-scheme, the conversion efficiency with the RPA scheme is estimated to be more than 40 times higher. During the RPA of a ultra-thin foil, the laser ponderomotive force sweeps all electrons in the foil forward until the electrostatic force on the electrons due to the ions left behind balances the ponderomotive force on electrons at a distance *D*. These electrons form a charged layer and their electrostatic force now accelerates the ions left behind. When the thickness of the target, Δ, is equal to this distance of maximum charge separation, we obtain optimal thickness $D=\Delta$, at which the electrons are pushed to the rear end of the target and the space charge force balances the ponderomotive force $eE=F_p(\Delta)$ on the electrons. In the limit of the normalized laser amplitude $a_0 = e|E|/(m\omega c) >> 1$, we obtain the thickness as

$$\Delta \cong \frac{4\pi}{\lambda_L}\left(\frac{c}{\omega_p}\right)^2 a_0 = \frac{\lambda_L}{\pi}\left(\frac{\omega}{\omega_p}\right)^2 a_0 \qquad (1)$$

where m and e are the electron mass and charge, λ and ω are the laser wavelength and angular frequency, ω_p is the electron plasma frequency, E is the electric field amplitude, a_0 is the dimensionless laser amplitude. To minimize the wave tunneling through the target, $\Delta > c/\omega_p$ should be satisfied.

In RPA, high intensity circularly polarized laser light with a high contrast ratio accelerates the ultra-thin foil with radiation pressure, and the foil has a definite, optimal thickness. It must be sufficiently thin so that

- The ponderomotive force of the laser radiation accelerating the electrons in the foil is balanced by the electric force due to ions at the outer edge of the thin foil.
- The mass of the thin foil must be sufficiently light so that the whole foil is accelerated by the laser radiation pressure in the short duration of the order of ion plasma period. In this case, protons are subject to both the electric force of the electron layer accelerating them forward, and the inertial force pulling them back in an accelerated frame. The balance of these two opposing forces forms a trap for the ions in real and phase spaces.
- These stably trapped protons and electron layers form a self-organized double layer. The laser radiation pressure accelerates this double layer as a whole, with protons trapped in it.

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However, the time for monoenergetic ion acceleration with RPA is limited by the duration in which the double layer can maintain its overdense properties, which can be lost due to the development of the Rayleigh-Taylor instability (RTI), which is one of the most important instabilities arising when a thin plasma foil is accelerated by the radiation pressure of an intense laser [6]. It poses a limit on the time a foil can be accelerated before it loses its monoenergetic properties.

Recent experiments and simulations have demonstrated effective CO_2 laser acceleration of quasi-monoenergetic protons from thick gaseous hydrogen target (of thickness tens of laser wavelength) via hole boring and shock accelerations [6]. Laser pulse can compress the target to form a shock and accelerate it as a whole, in the light-sail fashion, with the protons trapped in it. The proton acceleration is thus a combination of the RPA and the shock acceleration, with the RPA being the dominant acceleration mechanism at the later stage.

In this paper, we present the results of computer simulation of ion acceleration based on RPA scheme for generating quasi-monoenergetic protons, potentially suitable for medical applications such as particle therapy, and present recent advances in the studies of energy scaling of RPA. We propose a scheme of combining the laser radiation pressure acceleration (RPA) with the shock acceleration by irradiating lasers on thin gaseous targets, with thin gas targets thickness of a few laser wavelengths. Laser can compress it to form a shock and to accelerate it as a whole, in the light-sail fashion, with the protons trapped in it. Thus proton acceleration is a combination of radiation pressure acceleration and shock acceleration, with the RPA being the dominant acceleration mechanism at later stage. Ion acceleration is examined on the base of 2D and 3D, relativistic, electromagnetic, particle-in-cell (PIC) codes UMKA2D3V and MANDOR. These codes are massively parallel and designed for achieve high performance on modern supercomputers.

SIMULATION SETUP AND RESULTS

To demonstrate the proposed acceleration scheme, we performed a series of PIC simulations with CO_2 laser irradiated on a thin gas target with the dimensionless laser amplitude a_0=5-10.The incident laser is a circularly polarized plane wave with a longitudinal profile of $10T_L$ rising time, $280T_L$ flat top, and $10T_L$ falling time, where T_L is the laser period. The rising and falling time slope is of sine-quared shape. Target thickness varying from 1.5 λ to 15 λ. The target density n_0 varies from $5n_c$ to $40n_c$ where n_c is the critical density.

The light pressure may compress plasma and generate shock waves that lead to acceleration of ions due to reflection by shock front (monoenergetic component in ion spectra are produced). Snapshots of proton density distribution and the proton energy spectra are shown in Figure 1. During the first 40 T_L--70 T_L, the compression in shock formation is observed, and a compressed electron-proton layer is formed with enhanced density as high as 180 n_c within a region of sub-wavelength scale. The laser radiation pressure is able to accelerate this thin electron-proton layer formed around the over a distance of 3λ during 40 T_L and to generate the quasi-monoenergetic protons with energy gain of about 4 MeV and acceleration gradient of 1.3 GeV/cm. The quasi-monoenergetic proton beam is finally destroyed due to RTI, and the target becomes broadened and transparent with laser light leaking through the low density region.

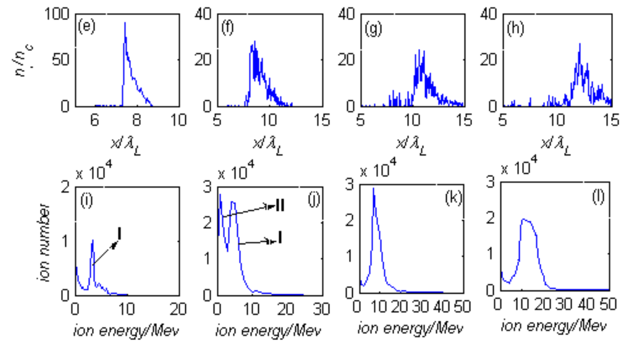

Figure 1: 2D PIC simulation results of the proton density distribution (the upper row) and the proton energy spectra (the lower row) with the normalized incident laser intensity a_0=10, the maximum plasma density n =30 n_c, and the plasma thickness l_s = 2.5 λ. From the left column on, the snapshots are at the times t = $30T_L$, $50T_L$, $70T_L$, and $80T_L$, respectively. Part I is the shock reflected protons, part II is the shock front I.

The usual nonlinear development of the RTI is to generate fingers of high and low densities at the most unstable mode with wavelength comparable to the laser wavelength (Figure 2). During the growth of the RTI, small ripples on the surface of foil grow exponentially and these fine structures in the transverse direction perpendicular to laser propagation will be converted to large amplitude perturbations with wider transverse periodical structure, i.e. density blobs. During the development of the RTI, the filamentation of the plasma density will produce regions of low density plasma, transparent to laser radiation. The laser can no longer be reflected effectively by the plasma mirror, and the acceleration stops.

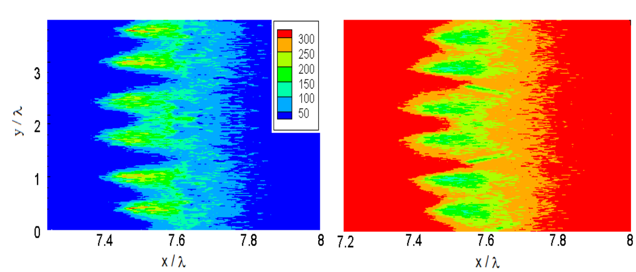

Figure 2: Ion (left) and electron density distribution in the stage of RT instability.

A direct consequence of RTI-induced transparency and the proton energy spectra broadening is the limitation on the achievable quasi-monoenergetic proton energy or brightness of the particle beam for a given laser power.

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By defining quasi-monoenergetic particle as particles having energy spread of half maximum particle flux within 20 percent of the energy of peak flux, we studied the scaling of quasi-monoenergetic proton energy vs. normalized incident laser amplitude (Figure 3). In this study, the foil density changes linearly with incident laser amplitude and the foil thickness was chosen to be optimal thickness (Eq. (1)). In the non-relativistic limit, the attainable quasi-monoenergetic ion energy is

$$E_{non-rel} \approx 2(\pi \frac{m_e}{m_i} \frac{a_0 t_s}{T_L})^2 m_i c^2 \qquad (2)$$

where t_s is the occurrence time of maximum quasi-monoenergetic ion energy. The scaling indicates that with flat ultra-thin targets of optimal thickness, the quasi-monoenergetic proton energy can be ~ 250 MeV for normalized incident laser amplitude a_0=25, corresponding to 2 PetaWatt laser power. Also, the quasi-monoenergetic proton energy is adjustable by changing the incident laser power.

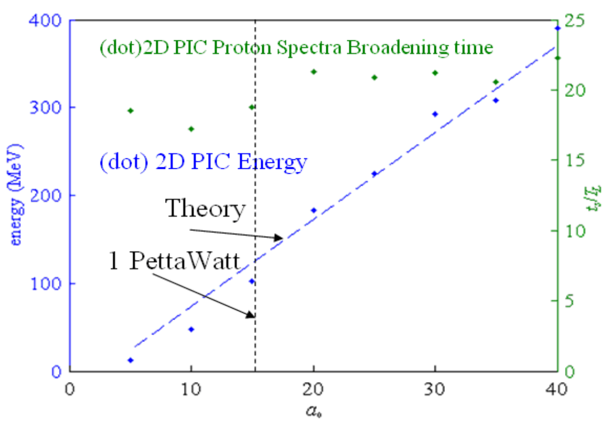

Figure 3: Scaling of quasi-monoenergetic proton energy vs. normalized incident laser amplitude as obtained from PIC simulation (blue dot) and theory (blue dashed curve). Green dots indicate the time when the proton spectra start to broaden and deviate from our definition of quasi-monoenergetic (a_0=15).

On the other hand, this scaling is still theoretical since in real applications, it is hard to have solid target made of pure hydrogen; particle energy spread being less than 10 percent of the peak flux energy is more desirable; and using sub-PetaWatt laser is more practical for commercialization and maintaining high repetition rate. Therefore, there are needs for research on laser proton accelerator using practical target and suppressing and remediate the RTI needs for research on laser proton accelerator using practical target and suppressing and remediate the RTI.

Figure 4 shows the dependence of the energy of quasi-monoenergetic protons on the gas target peak density and the incident laser energy in laser-thin gas target acceleration. The simulations use the same spatial profile of gas target density as that in Figure 1 with different peak gas target density and laser power.

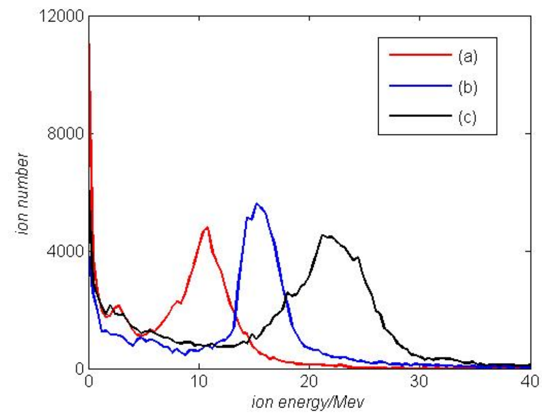

Figure 4: The proton energy spectrum obtained with different incident laser and plasma parameters. The simulation parameter of line (a) is normalized laser amplitude $a_0 = 5$, gas target thickness $l_s = 2.5\ \lambda_L$, peak gas target density $n_0 = 20\ n_c$, line (b) is $a_0 = 10$, $l_s = 2.5\ \lambda_L$, $n_0 = 20\ n_c$, and line (c) is $a_0 = 10$, $l_s = 2.5\ \lambda_L$, $n_0 = 30\ n_c$.

Changing the incident laser amplitude from $a_0 = 5$ to $a_0 = 10$ increases the energy of quasi-monoenergetic proton from ~ 10 MeV to 16 MeV. Further increase of peak gas density from $n_0 = 20\ n_c$ to $n_0 = 30\ n_c$ also helps further increases the energy of quasi-monoenergetic proton to 22 MeV.

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