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Control of proton energy in ultra-high intensity laser-matter interaction

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Abstract. Recent breakthroughs in short pulse laser technology resulted in (i) generation of ultra-high intensity ($2x10^{22}$ W/cm^2) and (ii) ultra-high contrast (10^{-11}) short pulses at the Hercules facility of the University of Michigan, which has created the possibility of exploring a new regime of ion acceleration – the regime of Directed Coulomb Explosion (DCE). In this regime of sufficiently high laser intensities and target thicknesses approaching the relativistic plasma skin depth it is possible to expel electrons from the target focal volume by the laser's ponderomotive force allowing for direct laser ion acceleration combined with a Coulomb explosion. That results in greater than 100 MeV protons with a quasi-monoenergetic energy spectrum. The utilization of beam shaping, namely, the use of flat-top beams, leads to more efficient proton acceleration due to the increase of the longitudinal field. According to the results of 2D PIC simulations a 500 TW laser pulse with a super-Gaussian beam profile interacting with 0.1 micron aluminium-hydrogen foil is able to produce monoenergetic protons with the energy up to 240 MeV.

1. Introduction

With the development of short-pulse high-intensity lasers it has become possible to generate beams of energetic particles from laser plasma interactions such as relativistic electrons and multi-MeV ions [1]. These beams of ions have a wide array of applications such as a compact source of radioactive isotopes [2], a table-top fission source [3] and as a ion injector source [4]. Beams of energetic protons can be used to generate quasi-homogeneous warm dense matter by the isochoric heating of solid density foils [5] or can be used as a radiography source to detect and study the evolution of electric fields in laser-matter interactions [6]. The possibilities to use beams of laser driven ions for hadron radiation therapy [7], for the fast ignitor research [8] and even for generation of exotic particles [9] have also been discussed.

Most proton beam applications require repetitive and controllable quasi-monoenergetic beams with energies that are an order of magnitude above current laser accelerated protons. In the majority of the experiments to date, protons from laser-solid interactions were produced in the target normal sheath acceleration (TNSA) regime [10] from foils with thicknesses orders of magnitude greater than the plasma skin depth. This generates proton beams with energies up to several to tens of

MeV but with an exponential energy spectrum in the number of accelerated protons followed by a cutoff.

Here we propose to explore a new regime of ion acceleration using the interaction of ultra-relativistic, ultra-short and ultra-clean laser pulses with ultra-thin membranes at focused intensities ~10^{22} W/cm^2 to achieve controllable quasi-monoenergetic beams of protons with energies in the 100-200 MeV range in the Directed Coulomb Explosion regime [11,12].

2. Directed Coulomb Explosion Regime

When an intense, prepulse-free, ultra-short laser pulse, I~10^{22} W/cm^2, directly interacts with an ultra-thin foil, it ionizes the target in a few femtoseconds maintaining the integrity of overdense plasma. It is reasonable to assume that under the action of the intense laser pulse, the electrons are evacuated from the foil region with transverse dimensions of the order of the focal spot diameter. If the laser field is much stronger than the Coulomb attraction field, the ions cannot retain electrons near the backside of the target, which leads to ion acceleration in the so-called Coulomb explosion regime [13]. In order to expel all the electrons and achieve Coulomb Explosion the following condition on laser electromagnetic vector-potential, a = 0.85 (I [W/cm^2] λ^2[μm] 10^{-18})$^{1/2}$ and foil thickness l must be satisfied

$$a > \pi \frac{N_e}{n_{cr}} \frac{l}{\lambda} \qquad (1)$$

Here, N_e is the electron density, n_{cr} is the plasma critical density, and λ is the laser wavelength. In order to estimate the typical energy of the accelerated ions in the Coulomb explosion regime, we assume that all the electrons produced by the ionization in the focal spot region are forced to leave the foil. In this case, the electric field near the positively charged layer is, $E_0 = 2\pi N_i Z_i el$, where N_i is the heavy ion density in the foil, and Z_i is the heavy ion electric charge. The size of the region where this estimation for E_0 is valid is of the order of the focal spot size, d, in both transverse and longitudinal directions providing a one-dimensional regime of ion acceleration. When the ions leave this region, the Coulomb explosion regime becomes three-dimensional, leading to an immediate drop in ion acceleration efficiency [14]. Thus the maximum energy of the protons can be estimated as

$$E_{\max} = \pi N_i Z_i e^2 ld \ . \qquad (2)$$

It follows from Eq. (2) that $E_{\max}$ increases linearly with foil thickness. However, the foil thickness, l, in equation (2) must satisfy the Coulomb explosion regime condition, $l/\lambda < an_{cr}/\pi N_e$. Correspondingly, one may conclude that for a given laser intensity and plasma density there is an optimum foil thickness for which the accelerated ions reach maximum possible energy. This was confirmed in 2D PIC simulations [11] (see Fig. 1a). Further increasing of foil thickness does not provide an ion energy increase.

For very thin targets laser light just transmits through a foil without pushing it. The transparency condition has the form $l/\lambda < \pi a N_e / n_{cr}$, that coincides with the Coulomb explosion condition (1). When a foil is thicker, laser light reflects and accelerates foil by radiation pressure [16]. In this case the laser field acts as a piston driving a flow of heavy ions tearing across the foil. Thus the regime described here is an efficient combination of the radiation pressure and Coulomb explosion effects and we call it a Directed Coulomb Explosion regime (DCE).

We used the 2D PIC code REMP [17] to numerically study the acceleration of ions in high-intensity laser interactions with an ultra-thin two-layer aluminum-hydrogen foil. In the simulations presented here, the uniform grid mesh size is λ/200. The pulse is linearly polarized along the z-axis. The temporal and spatial profiles of the pulse are Gaussian if not stated otherwise. The following parameters were used in the simulations: laser power of 150-500 TW, pulse duration of 30 fs, and a spot size of 1.0λ (FWHM). The aluminum layer thickness was varied from l=0.0125λ to l=0.2λ. The electron density of the foil is $400n_{cr}$, where n_{cr} is the critical density of the plasma. The hydrogen layer thickness was 0.05λ with an electron density of $10n_{cr}$.

The calculated spectrum of the accelerated protons is shown in Fig. 1b. The spectrum has quasi-monoenergetic features and is peaked at 140 MeV, with FWHM of 10 MeV or with the energy spread $\Delta E/E_{peak}$ = 6%. The width of the peak is mainly due to the Coulomb repulsion of protons and can be varied by changing the thickness of hydrogen layer, giving an additional parameter that controls the acceleration of protons in laser-foil interactions. Proton spectra at lower power exhibit similar features but the peaks are positioned at lower energies, i.e. at 45 MeV for 250 TW pulse and at 20 MeV for 150 TW. We estimated than ~4.10^8 protons are contained in the monoenergetic peak at 500 TW.

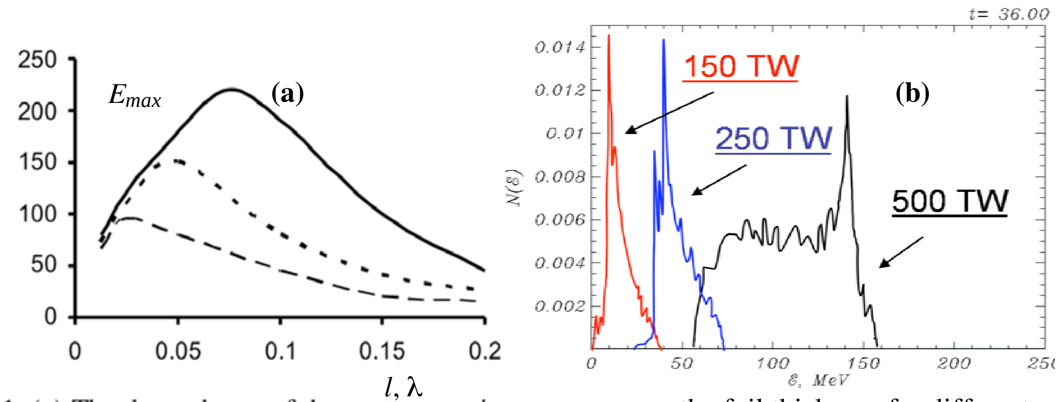

Fig. 1. (a) The dependence of the proton maximum energy on the foil thickness for different values of the laser pulse power: 150 TW (dashed curve), 300 TW (dotted curve), 500 TW (solid curve). (b) The spectra of protons accelerated from the double layer foil for 150 TW, 250 TW and 500 TW Gaussian pulses.

3. Proton Acceleration in DCE regime with Super-Gaussian Beams

Since proton acceleration is mainly due to the charge separation electric field, an increase in the acceleration effectiveness can be achieved by the enhancement of this field effect. Further optimization of low Z ion beam quality (maximum energy increase and energy spread decrease) can be achieved by employing the shaping of laser beams.

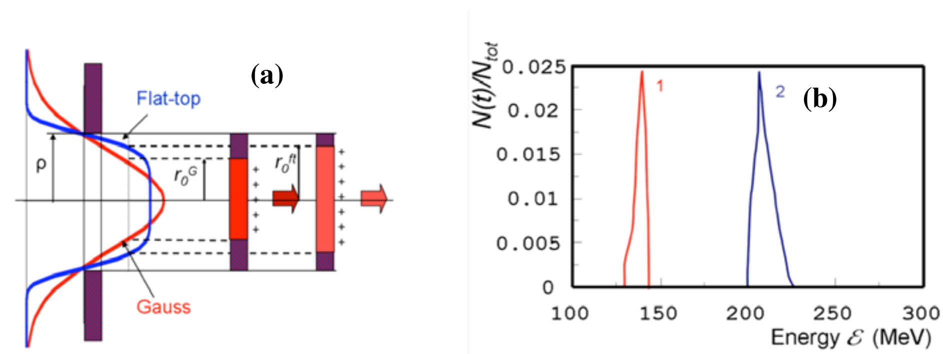

Fig.2. a) Principal scheme of foil fraction acceleration by Gaussian (radius of the area with all electrons expelled is r_0^G) and flat-top beams (radius of the area with all electrons expelled is r_0^{ft}); b) Spectra of protons that are accelerated inside an angle of 10 degrees to the target normal by Gaussian (1) and flat-top (2) beams (a 500 TW laser pulse interacts with a 0.1λ thick aluminium foil with a 50 nm second layer of hydrogen).

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The utilization of flat-top (super-Gaussian) beams enhances the longitudinal field for the same laser power, leading to maximum energy increases up to 45 % above the value generated by the conventional Gaussian beams for low Z ions according to the theoretical estimates [17]. This effect is due to the fact that flat-top beams evacuate electrons from a larger area on the foil, thus generating a stronger longitudinal electric field, as well as more effectively preventing the electrons from returning to the evacuated region due to a higher ponderomotive force (see Fig. 2a).

Our 2D PIC simulations show that the resulting proton spectrum demonstrates the same peaked structure as in the Gaussian beam case (Fig. 2b), but the maximum energy is increased by 45 % up to 250 MeV for 500 TW laser pulses, as it was predicted by the theoretical estimate of the effect [17]. Another advantage of using super-Gaussian beams is that the relative width of the high-energy peak in proton spectrum is smaller. This is mainly due to larger maximum energy, since the Coulomb explosion of the moving proton layer determines the absolute value of the energy spread in proton spectrum. This fact gives us one more parameter of laser-foil interaction that controls the energy spread: the initial thickness of the hydrogen layer.

5. Summary

We suggested accelerating protons to energies greater than 100 MeV with quasi-monoenergetic spectral features in the regime of Directed Coulomb Explosion using prepulse free interactions of a ultra-relativistic laser with ultra-thin membranes. The repetitive Ti:Sapphire Hercules laser at the University of Michigan recently set the world record for the highest focused intensity of $2\text{x}10^{22}$ W/cm^2 [17] and ASE intensity contract of 10^{-11} [18] and is capable to demonstrate this new regime of ion acceleration.

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