RECENT PROGRESS OF PROTON ACCELERATION AT PEKING UNIVERSITY *

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Abstract

We study the enhanced laser ion acceleration using near critical density plasma lens attached to the front of a solid target. The laser quality is spontaneously improved by the plasma lens and energy density of hot electrons is greatly increased by the direct laser acceleration mechanism. Both factors will induce stronger sheath electric field at the rear surface of the target, which accelerates ions to a higher energy. Particle-in-cell simulations show that proton energy can be increased 2-3 times compared with single solid target. This result provides the opportunities for applications of laser plasma accelerator, such as cancer therapy. Further experiments will soon be carried out on 200 TW laser acceleration system at Peking University.

INTRODUCTION

The emission of highly energetic ions from solid targets irradiated by intense laser pulses has been extensively studied due to its wide potential applications. Several radiographic applications of laser driven protons have been reported and radiographs of objects for various size and thickness have been obtained [1]. One of the most challenging applications driving recent activities is laser-based proton and ion acceleration for medical application in cancer therapy [2], with advantages in terms of compactness and costs. The required proton energy ranges is between 60 and 250 MeV (which extends up to 400MeV/nucleon for carbon ions), depending on the location of the tumor. These energies are extremely difficult to achieve on existing laser system limited by the low energy laser conversion efficiency.

Most of the experimental studies on laser driven ion acceleration are based on solid density targets. Two major acceleration mechanisms have been identified: target normal sheath acceleration (TNSA) [3] and radiation pressure acceleration (RPA) [4]. In TNSA, the ions are accelerated by the electron sheath field formed on the target back surface. Due to the rapid dispersion of electrons, ions can only be accelerated to tens of MeV level with large energy spread. In RPA, in order to produce the radiation pressure at the front surface boosting the ion and electron layers synchronously, extremely high laser intensity, sharp rising front and ultrahigh laser contrast are required and the quality of ion beam is sensitive to the target parameters.

Recently, attentions have been paid on ion acceleration from near-critical density (NCD) targets, which are considered to have much higher laser-plasma energy coupling efficiency. Such NCD target has density between $0.1n_c$to $10n_c$and can be realized by either cluster [5] or gas jet [6]. Collimated ion beam have already demonstrated in these experiments. Ma et al [7] utilized ultrathin carbon nanotube foams (CNF) to precisely control the NCD density profile. The CNFs are highly homogeneous above um scale. The thickness of the foam is controlled by the deposition time and the growth rate of the foam. A two-layer target combining a critical density layer (CDL) with a solid density layer (SDL) was proposed by Wang to further enhance ion acceleration [8]. First, the laser pulse simultaneously experiences relativistic self-focusing, longitudinal profile steepening and non-relativistic pre-pulse absorption process in the CDL, which is called as plasma lens effect (see Fig. 1). Meanwhile, when the electron betatron oscillation frequency is close to its witnessed laser frequency, energetic electrons are efficiently accelerated by the direct laser acceleration (DLA) mechanism in the self-focused channel [9]. Both the two factors will extend the intensity and lifetime of the sheath field at the rear of SDL, consequently favorable for ion acceleration.

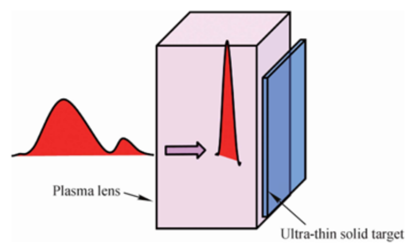

Figure 1: The sketch of laser plasma lens.

SIMULATION RESULTS

Fig. 2 is a 3D simulation of the laser pulse with a peak laser intensity of $7.46 \times 10^{20}\mathrm{W}/cm^{-2}$, propagating into a n=$2.4n_c$ uniform density CDL plasma, where the critical density $n_c = m_e\omega^2/4\pi e^2$,$m_e$, e, and ω are electron mass, charge, and laser angular frequency. As we can see, the laser intensity increased by a factor of 25. Meanwhile, the laser pulse developed a steep front and the pre-pulse was absorbed by the CDL, making it suitable for RPA acceleration mechanism.

Besides the laser sharping effects by plasma lens, high energetic electrons producing will also enhance ion acceleration. Figure3 shows the electron energy spectrum for all the electrons, the laser coupling efficiency is much higher in CDL than in SDL, which leads to both higher electron temperature and electrons number.

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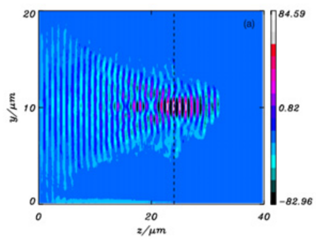

Figure 2: The incident beam first propagates through an unstable filamentary stage and then collapses into a single channel.

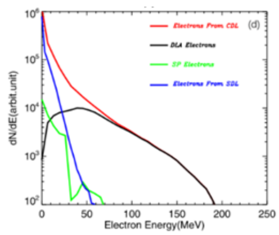

Figure 3: The electron energy spectrum for the electrons from CDL, include DLA electrons and SP electrons and electrons from SDL.

CDL can also be generated by laser inherent pre-pulse or a specially designed ablation pulse hundreds ps before the main pulse [10]. In this case, the CDL is induced by the pre-plasma expansion and has an exponential density profile $n_e = n_c[(x - x_c)/c_s t]$ for x < x_c, where c_s is the adiabatic sound velocity determined by the target material and electron temperature. This up-stream density distribution helps laser in self-focusing, as $\sqrt{an_c/n_e}\sim$ constant [8]. Fig.4 is the ablated plasma density profile of an aluminium foil target illuminated by a table envelope pulse with 200ps duration and 10^{12}W/cm^2, performed by hydrodynamic code MULTI. The pink bar is the initial target, the black and green dash curves are the 1D and 2D results. The ablated plasma length is about 40 um (from $0.01n_c$ to $1n_c$).

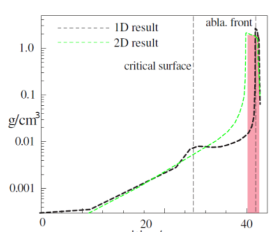

Figure 4: The plasma density distributions of MULTI 1D and 2D simulations.

Relativistic PIC simulation code KLAP 2D/3D is used to investigate the proton acceleration. The p-polarized Gaussian laser pulse with intensity I= 1.67×10^{20}W/cm^2 and duration 30T (FWHM). The target is loaded from the MULTI 1D simulation above, with 10nc 0.1 um H contamination layer at the rear surface. As shown in Fig. 5, the laser focusing starts at t = 20T, accompanied with the DLA electrons generation. The laser gets nearly exhausted at t = 120T when it is reaching the foil target, transferring as much energy to the electrons. Meanwhile the bunch structure electrons beam, which has always been focused in the channel, will get through the foil target and set up acceleration field at the rear surface.

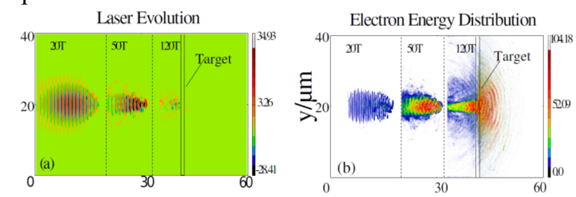

Figure 5: Snap shots of the laser electric field E_y and the corresponding electrons energy density in the pre-plasma.

Comparison of electron and proton energy spectrum for different ablation pulse durations: 200ps, 100ps, 280ps, (the corresponding ablated plasma length are 40, 20, 60 um), called “optimal”, “shorter”, “longer” respectively, as shown in Fig 6. The electrons spectra indicate that, the “optimal” and “longer” have more energetic electrons than the “shorter”. The proton spectrum show that energy enhancement is available in all three ablated cases compare the no ablation target, due to the generation high energy density DLA electrons. In the “optimal” case, the efficient enhancement is three folds energy improvement.

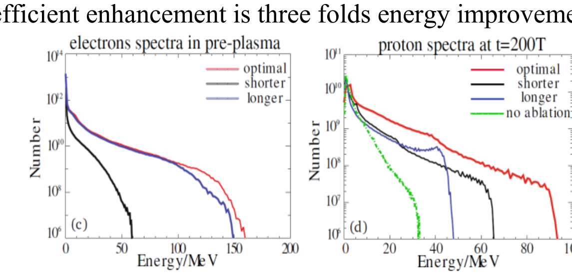

Figure 6: Electrons spectrum in pre-plasma and proton spectrum for the optimal, shorter, longer and the no ablation.

EXPERIMENT RESULTS

The critical plasma lens was realized recently in the experiments [9] by using two-layer targets (ultrathin carbon nanotube foam + diamond-like carbon foil), where the carbon energy was increased from 70MeV to 119MeV. Fig.7 shows the energies increase with increasing CNF thicknesses, and best performance is observed for the largest CNF thickness. Carbon acceleration benefits most with an increase in maximum energy of 2.7 times over an uncoated DLC foil and proton energies increased by a factor of only 1.5.

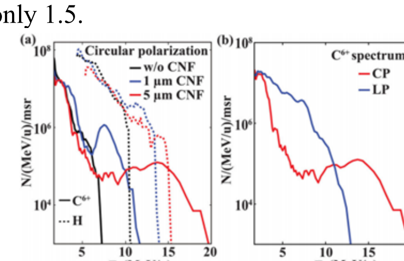

Figure 7: (a) Energy spectrums of C^{6+} ions (solid curves) and protons (dashed curves) registered from DLC foils combined with CNF targets of varying thicknesses irradi-

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ated by circularly polarized laser pulses. (b) C^{6+} ion spectrum under best conditions for CP (red) and LP (blue).

RECENT PROGRESS IN PEKING UNIVERSITY

The Peking University Compact LAser Plasma Accelerator (CLAPA) project has been approved by MOST (Ministry of Science and Technology) in 2013. CLAPA aims to build the first prototype of laser driven ion accelerator in China (1~15 MeV/1 Hz with less than 5% energy spread), based on the PSA (Phase-Stable-Acceleration) [11] mechanism and plasma lens. The sketch of the system is shown in Fig. 8.

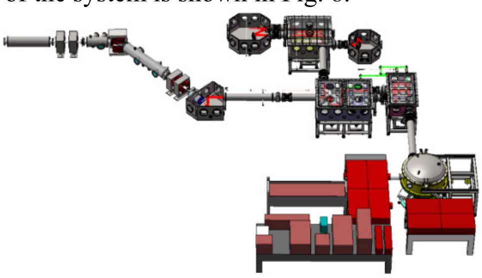

Figure 8: Compact LAser plasma proton Accelerator (CLAPA) at Peking University.

A 200 TW, 5 Hz Ti-Sapphire laser system based on the double Chirped Pulse Amplification (CPA) technology (see Fig. 9) has been installed. The laser system delivers pulses with 5 J energy, 25 fs duration and contrast of 10^{-10} at 100 ps and 10^{-9} at 20 ps. The target chamber is also ready to use (see Fig. 10), including OAP (off-axis parabolic mirror) controller, target controller, laser focusing monitors, plasma diagnosis and Thomson parabola spectrometers. A two stage shutter system has also been installed to actualize the single-shot laser model as well as protect gratings and crystal from over-heating effect.

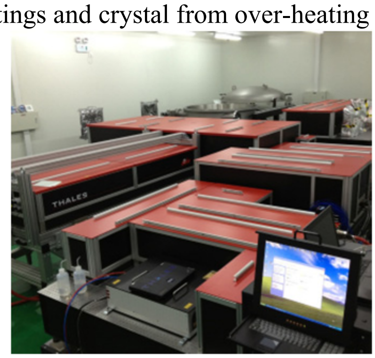

Figure 9: 200 TW Ti-Sapphire laser system.

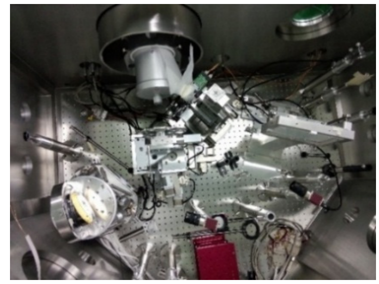

Figure 10: Target chamber for laser ion acceleration.

CONCLUSION

In conclusion, the enhanced laser ion acceleration via a near critical density plasma lens has been confirmed by both simulations and experiments. It is found that DLA electrons from pre-plasma is the essential factor for the enhancement in using laser ablation to realize NCD plasma. Both 2D/3D simulations show that two to three times of proton energy enhancement can be realized. The plasma lens can also be realized by CNF+DLC targets and the experiment shows that the ion energies increase with increasing CNF thicknesses.

A 200 TW laser system and ion acceleration experiment system have been built at Peking University. Based on the plasma lens technology, PSA acceleration mechanism and magnetic transmission system, we aim to generate high quality ion beam for multiple applications, such as ion radiograph and cancer therapy.

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