ENHANCED LASER ION ACCELERATION BASED ON NEAR-CRITICAL DENSITY PLASMA LENS

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Abstract

When a laser pulse propagating in a near critical density plasma, its quality can be spontaneously improved by this “plasma lens” through transverse self-focusing, longitudinal profile steepening and pre-pulse cleaning. High energetic density electrons can also be generated in this process, which is crucial for the high gradient acceleration field formation. Both effect can significantly enhance the ion acceleration efficiency. Such near critical density plasma lens can be generated in front of the solid target using a proper controlled pre-pulse, which is normally considered “harmful” for the laser acceleration. A 3 mJ Ti-Sapphire laser system has been build at Peking University in order to experimentally study the pre-pulse effect on a solid target. The plasma lens will be used in the CLAPA at Peking University next year.

INTRODUCTION

The generation of ion beams by an intense laser pulse irradiating on solid targets has been extensively studied due to its wide potential applications [1-3], most of which require high energy and low energy spread ion parameters. However, according to scaling law, the laser system has to be PW level or even higher to achieve hundred MeV proton beams [4]. Also the main laser pulse often accompanied by a pre-pulse, which may pre damage the solid target. So pre-pulse is consequently considered as a “harmful” effect for the ion acceleration in the previous research.

Recently, many novel plasma phenomena were discovered when ultra-intense laser pulse interacting with nearly critical dense (NCD) plasmas (0.1 $n_c < n_e < n_c$), such as relativistic self-focusing [5], pulse steepening [6] and resonant electron acceleration [7], which greatly improve the laser to particle energy transmission efficiency. Here, we propose to recycle the usually ’harmful’ prepulse as ’helpful’ target ablation source to generate the NCD plasma in front of a solid target. Simulation shows that hundreds MeV proton beam can be achieved by only hundred TW level laser.

PLASMA LENS MECHANISM

When an intense, short Gaussian laser pulse propagates in the near-critical plasma, strong currents of relativistic electrons can be generated, and it can magnetize the plasma. Self-focusing and relativistic self-phase modulation can change the transverse and axial profiles of laser pulse. The laser intensity is increased by one order of magnitude. Figure 1 is a 2D simulation of the laser pulse with n_0=16.5 propagating into a plasma with n=2.4n_c. The normalized electric field E_y increased more than 5 times. Meanwhile, the laser pulse rising edge can be steepened and the nonrelativistic pre-pulse can also be absorbed by the plasma lens, which can improve the laser contrast without affecting laser shaping of the main pulse [6].

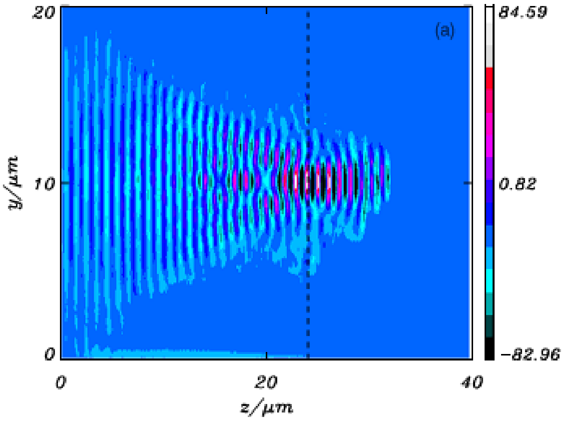

Figure 1: The condition of laser beam propagating in near critical plasma.

HIGH ENERGETIC DENSE ELECTRON GENERATION

When Inside the plasma channel, some energetic electron experiences transverse betatron oscillations. When the laser frequency experienced by these electrons matches their oscillation frequency, direct laser acceleration dominates, leading to electron bunches with temperature several times higher than ponderomotive heating [8]. Meanwhile these electron bunches are tightly focused by the quasi-static fields. If a solid target is put right behind the NCD plasma as shown in Fig. 2, such energetic dense electron bunches will form a long distance, high gradient acceleration field, which is the crucial effect for the enhancement of the ion acceleration.

Figure 3 shows the proton cutoff energy spectrum from a 2D simulation, in which the laser pulse intensity is a=1, and the double layer target is formed by a 20 μm, 0.125n_c NCD plasma and 1 μm, 90n_c solid target. Note that the proton cutoff energy from the double layer target is about 14 meV, which is 4 times higher compared to the classical TNSA.

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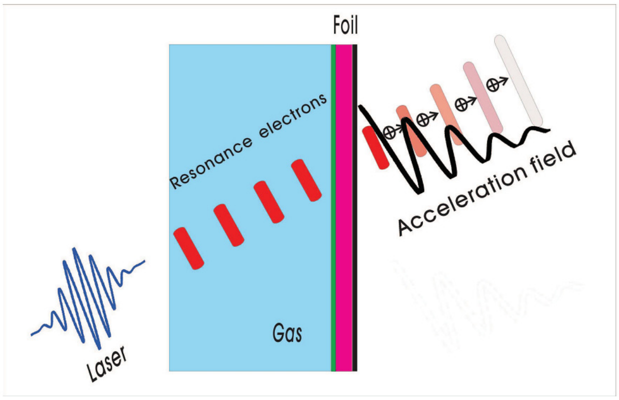

Figure 2: The sketch of laser ion acceleration based on NCD plasma lens+ solid target.

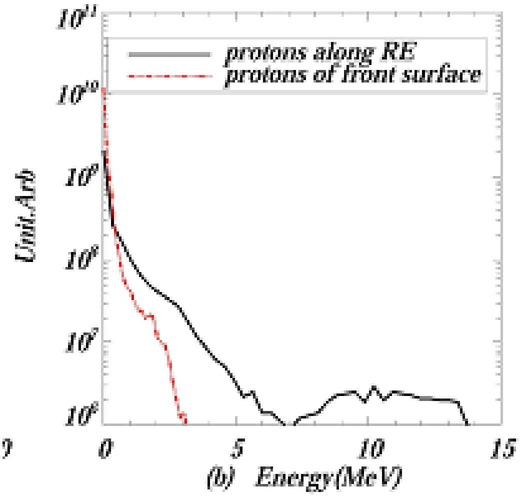

Figure 3: Energy spectrum of proton beams; the red line is for classical TNSA; black line is for the NCD plasma+solid target.

MEASUREMENT OF PLASMA DENSITY SYSTEM

The NCD plasma lens can be generated using the inherent prepulse of the main laser pulse. Prepulse is generally considered to be "harmful" because it causes damage of the target and complicates the interaction process. However, with proper chosen intensity, energy and delay parameters (<10^{13} W/cm^2, a few Joule, picoseconds duration), a pre-plasma with critical density and tens-µm scale length can be generated in the target front surface. Figure 4 is the pre-plasma density distribution in front of an aluminium target after irradiated by a 200 ps, 10^{12} W/cm^2 pre-pulse using 1D MULTI [9] simulation. The pink area represents the origin target, the black line for the ablated target. In this case, several tens micro plasma length is generated.

In order to experimentally implement this idea, a 3mJ Ti-Sapphire laser system (as shown in Fig. 5) and a plasma test system (as shown in Fig. 6) have been built at Peking University. The laser system is composed by an oscillator delivers 10 Hz pulses up to 3 mJ energy and 150 fs pulse duration. The laser pulse is perpendicularly focused onto the target with a RMS spot radius of 12 µm with Strel ratio 14%, corresponding to an intensity of 10^{15} W/cm^2. All the experimental units are mounted onto separate multiple-motorized-stages system to make sure the laser and target coupling position.

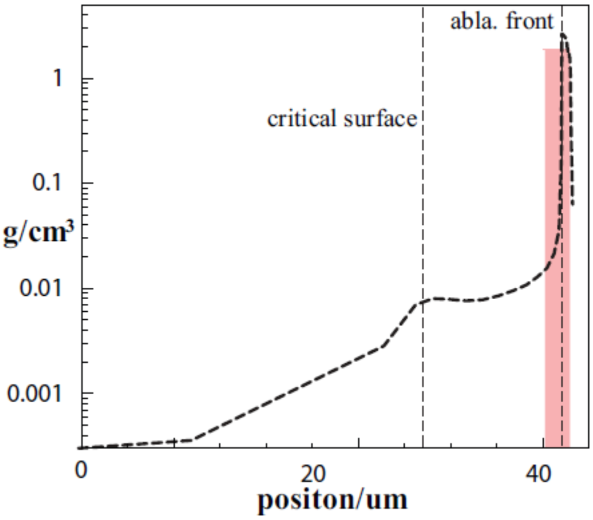

Figure 4: Plasma Density distribution after 200 ps.

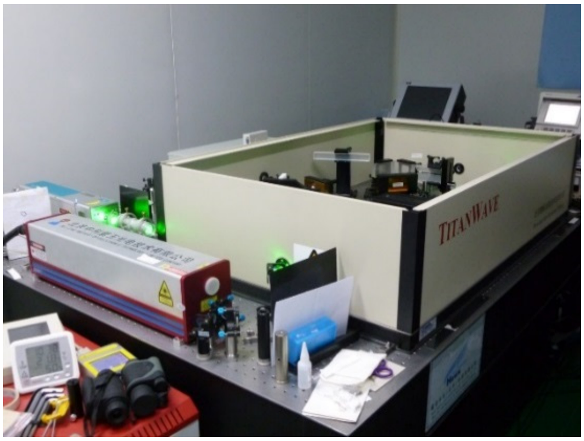

Figure 5: 3 mJ laser system.

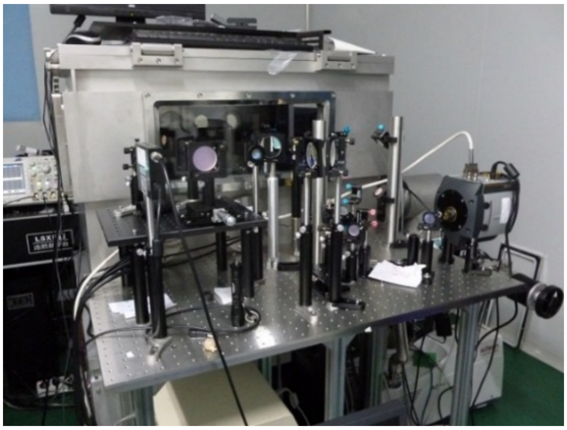

Figure 6: The plasma test system.

Primary experiments was done with 40 micron thickness aluminium foils. Figure 7 shows the shadow graph of the targets 10 ps after heated by one laser shot. The expand plasma can be clearly observed. The expanding velocity computed by the plasma length is about 2500 km/s. More systematic experiment still need to be done to totally understand the dependences between the pre-plasma evolution and the laser pulse parameters.

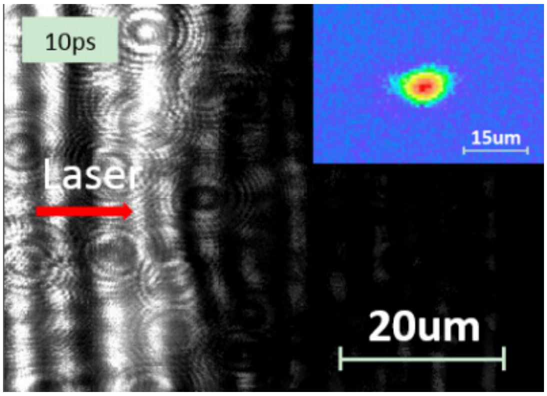

Figure 7: The shadow of target.

FUTURE WORK

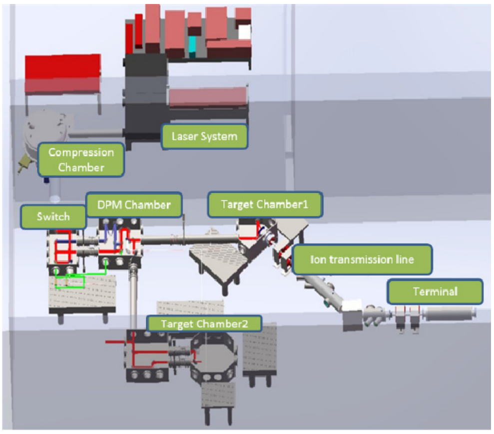

Figure 8: The shadow of target.

Figure 8 is the layout of CLAPA (Compact LAser Plasma Accelerator) project at Peking University, which has been under construction since the beginning of 2013. CLAPA is aimed to generated 1-15 MeV tunable energy proton beam with less than 5% energy spread based on the Phase-Stable-Acceleration (PAS) Mechanism [10]. With plasma lens technology, simulation shows that the proton energy can be increased to over 80 meV.

CONCLUSION

Transverse self-focusing, longitudinal profile steepening and prepluse cleaning can experience by a laser at the same time when it propagates in near critical density plasma due to plasma lens mechanism. Proton can also be more effectively accelerated for generation of high energetic dense electrons in near critical density plasma.

A 3 mJ Ti-Sapphire laser system and plasma test system have been build at Peking University in order to implement the plasma lens mechanism in experiment. The primary experimental result shows that this system can be used to carry on this research. In the next step, more systematic experiment will be done to totally study the dependences between the pre-plasma evolution and the laser pulse parameters.

REFERENCES

[1] M. Borghesi et al., Phys. Plasmas 9, 2214 (2002).
[2] S. V. Bulanov et al., Phys.Rev. A 299, 240 (2002).
[3] T. Zh. Esirkepov et al., Phys. Rev. Lett.89, 175003 (2002).
[4] J. Fuchs et al, Nature Phys. 2, 48 (2006).
[5] A. Pukhov, J. Meyer-ter-Vehn, Phys. Rev. Lett.76, 3975 (1996).
[6] H. Y. Wang, C. Lin, X. Q. Yan et al., Phys. Rev. Lett.107, 265002 (2011).
[7] B. Liu, X. Q. Yan et al., Phys. Rev. Lett.110, 045002 (2013).
[8] S. Zhao, C. Lin, X .Q .Yan et al., Submitted, Nuclear Instruments and Methods.
[9] R. Ramis, R. Schmalz, and J. Meyer-Ter-Vehn, Comput. Phys. Commun.49, 475 (1988).
[10] X. Q. Yan, C. Lin et al., Phys. Rev. Lett.100, 135003 (2008).