Proton acceleration from nanostructured targets by 0.1-1 PW lasers

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Advanced nanostructured thin foils have been used in order to enhance the laser-driven proton acceleration mechanism in TNSA regime. In particular, the presence of a monolayer of polystyrene nanospheres on the target front-side has drastically enhanced the absorption of the incident laser beam, leading to a consequent increase in the maximum proton beam energy and total charge. The experimental measurements have been carried out at the 100 TW laser systems available at the APRI-GIST facility. This is the first experimental demonstration of such advanced target geometry which was previously presented through particle-in-cell numerical simulation. Experimental results and comparison with theory are discussed.

1. Introduction

Currently the laser acceleration mechanism investigated experimentally is the so-called Target Normal Sheath Acceleration (TNSA) when ions are accelerated at the rear-side of a thin target in a quasi-electrostatic sheath created by fast electrons propagating from the target front-side [1]. Although the dramatic increase in attainable laser intensity by means of high power femtosecond lasers has generated a fast evolution of laser driven proton sources, the laser energy transformation into high energy protons has to be substantially raised for the majority of practical applications. Laser absorption may be boosted by the presence of sub-micrometer-scale structures on the laser-irradiated target surface, as demonstrated by experiments aimed to enhance the laser energy transformation into x-ray emission [2]. Recent PIC simulations have shown that the presence of a monolayer of polystyrene microspheres with a diameter of the order of the laser wavelength on a thin plastic foil front-side may significantly increase the energy and the total number of ions emerging from its rear-side, assuming a sufficiently high laser contrast [3].

2. Materials and Methods

The nanostructured target geometry is depicted in Fig.1. A monolayer of polystyrene (PS) nanospheres is located at the front-surface of a 1 μm thick mylar (PET) foil. Several targets having different sphere diameters, such as 266 nm, 535 and 920 nm, have been used in our experimental campaign.

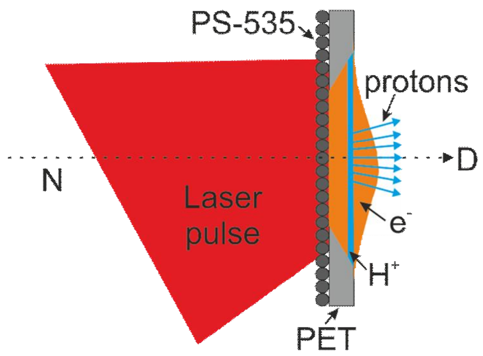

Figure 1. Target geometry (side view). The laser beam (p-polarized) is absorbed at the nanospheres-vacuum interface with an incidence angle of 22.5 degrees (*N* denotes the target normal). The hot electrons (generated at the target front-side) propagate forward and accelerate protons at the rear-side. The proton/ion diagnostics (*D*) is placed along the *N* direction.

The experiment has been performed with the 10 Hz, 100 TW Ti:sapphire laser system at the Advanced Photonics Research Institute (APRI) in Gwangju, which is based on the chirped pulse amplification (CPA) technique. The laser pulse duration and energy after compression were about 30 fs and 2 J, respectively. The laser beam was focused onto the target surface by an f/3 off-axis parabolic mirror, which allowed to reach a focal spot of about 5 µm in diameter (FWHM). The laser beam was p-polarized on target. The intensity level of the laser ns amplified spontaneous emission (ASE) is a crucial parameter when using such advanced targets since the nanostructured surface must be preserved to ensure a genuine interaction (no pre-plasma formation) with femtosecond high-intensity pulses. In fact, we have experimentally estimated the ablation-threshold intensity in the ns-regime for the irradiated targets [4], which is about 10^9 W/cm^2. Thus, the use of a double plasma mirror, which allowed to achieve a laser contrast of about $5x10^{11}$ up to 10 ps prior to the main pulse, was mandatory. On the other hand, the laser pulse energy was reduced by a factor of 50% (about 1 J) on target at the expense of the laser intensity which finally was about $5x10^{19}$ W/cm^2. The standard real-time ion diagnostics used consists of a Thomson Parabola (TP) spectrometer and a time-of-flight (TOF) detector fully described in literature [5].

3. Results

The proton energy distributions were compared to numerical results coming out from 2½-dimensional Particle-In-Cell (PIC) simulations. The simulations assumed the same laser pulse intensity, wavelength, duration, polarization and incidence angle used in the experiment. The target geometry was also the same and the target consisted of 1:1 mixture of

C^{4+} ions and protons with electron density 40 times the critical density (1.72×10^{21} cm^{-3} for 800 nm wavelength of Ti:sapphire laser).

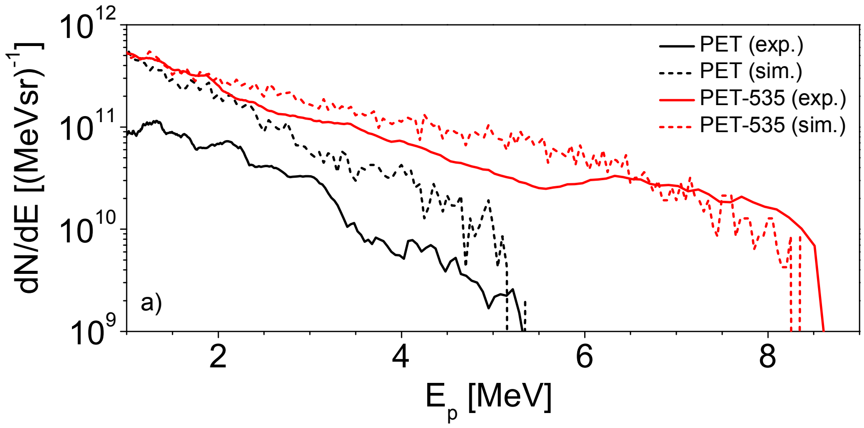

Figure 2. Proton energy distributions from analysis of TP experimental spectra (exp.) and PIC simulations (sim.) for a flat target (PET) and a foil structured with 535 nm spheres on the front-side (PET-535).

The comparison for the irradiated targets without (PET) and with 535 nm PS spheres (PET-535) on the front-surface is reported in Fig.2. The maximum proton energy achieved with the PET-535 target was about 8.6 MeV, showing a perfect agreement with the predicted PIC simulations. The cut-off energy measured for the planar target (PET) was about 5.3 MeV, also showing a very good agreement with the simulation results. In general, the PIC calculations show a trend for different target geometries which is in agreement with the experimental results. An accurate statistics has been performed in the experimental campaign for different nanosphere diameters. Both experimental results and numerical simulations show that under optimal experimentally achievable acceleration conditions optimal proton maximum energy as well as total proton beam energy can be obtained when targets with 535 nm diameter spheres are used. Also the total ion energy (estimated from TOF spectra) shows a similar trend. The average proton cut-off energy (measured by the TP spectrometer) was about 7.5 MeV and 4.7 MeV for PET-535 (nanostructured target) and PET (planar target), respectively. Results obtained with 535 nm diameter spheres showed a total proton beam energy and ion beam energy which was increased by 6.3 and 3.9 times, respectively, in comparison to the planar target geometry.

4. Discussions and Conclusions

The experimental results presented here clearly demonstrate that the use of nanostructured thin plastic foils on the target front-side can strongly enhance the laser-driven proton beam acceleration mechanism. In fact, the maximum proton energy was increased by a factor of 1.6 (~60% increment) for the optimal spheres' diameter of 535 nm in comparison to the planar foil. The total number of protons (with energies exceeding 1 MeV) was increased about 5 times. This valuable experimental result implies a substantial increase in the laser-driven proton acceleration efficiency (about 6 times) that is mainly related to the enhancement of the laser absorption efficiency at the target front-surface and to the subsequent increase of the hot electron population, which in turn is responsible for the proton acceleration mechanism [3].

A number of different effects may contribute to higher absorption for the used nanostructured targets. In fact, the nanosphere layer on the target front-side implies an effective larger surface area, i.e. a higher number of particles can interact with the laser field. Moreover, the nanosphere screens the incident laser wave but the accelerated electrons can propagate through it and consequently be easily out of the laser wave phase, thus gaining energy more efficiently along the longitudinal direction. This absorption process can be associated with the multipass stochastic heating in case of laser interaction with clusters [6]. PIC simulations showed that both the laser absorption and the proton acceleration efficiency are not particularly sensitive to the laser incidence angle [3]. However, along the experiment the laser incidence angle was not normal (with respect to the target surface), thus vacuum heating and resonance absorption mechanisms might have played a role. Such enhanced photo-proton sources may be considered as a compact alternative to low energy large conventional accelerators with a possible use for cancer therapy or other applications. In fact our simulations show that a maximum proton energy of about 60 MeV (requested energy for eye melanoma treatment) can be reached when using a PW-class laser beam with an intensity of about 2×10^{21} W/cm^2 (nominally 0.5 PW on target and 5 μm focal spot diameter) on the investigated nanostructured samples. The PIC simulations show that the maximum proton energy is also increased in this laser intensity regime (about 20%) with respect to the planar target.

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