Laser-driven proton acceleration enhancement by structured foils (simulations and experiments)

J. Psikal[1], O. Klimo[1], J.Limpouch[1], J. Proska[1], L. Stolcova[1], F. Novotny[1], D. Margarone[2], J. Prokupek[2], T. Mocek[2], G. Korn[2], I. J. Kim[3], T. M. Jeong[3], H. T. Kim[3], K. H. Nam[3], I. W. Choi[3], S. K. Lee[3], J. H. Sung[3], T. J. Yu[3]

1 Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University in Prague, Czech Republic
2 Institute of Physics, Academy of Sciences, Prague, Czech Republic
3 Advanced Photonic Research Institute, GIST, Gwangju, Republic of Korea
Corresponding Author e-mail address: jan.psikal@fjfi.cvut.cz

Abstract: The interaction of ultrashort intense laser pulses with thin foils is accompanied by the acceleration of ions from the target surface. In order to increase the efficiency of ion acceleration, microscopic structures on the target surface have been employed. 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 number of accelerated protons.

1. Introduction

Most of experiments use TNSA (target normal sheath acceleration) mechanism 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 efficiency into high energy protons has to be substantially raised for the majority of practical applications.

It has been already demonstrated that the efficiency of ion acceleration can be enhanced by decreasing the target thickness due to hot electron recirculation [2]. The maximum ion energy and laser energy transformation efficiency into fast ions can be further increased by reducing target lateral dimensions [3]. Here, we report on the third possible mechanism of the enhancement of ion acceleration efficiency - introducing of surface structures of characteristic width comparable to laser wavelength on the foil front side in order to enhance laser energy coupling.

2. Results and discussion

Firstly, we have studied the interaction of femtosecond laser pulses with thin foils with/without structures on the front surface by means of two-dimensional particle-in-cell simulations [4]. The structure on the front surface may significantly boost the energy absorption of intense laser pulses with ultra-high contrast and increase the hot electron temperature and density. This leads to higher ion acceleration efficiency and maximum ion energy in the case of thin foil targets, which may benefit from hot electron recirculation. The laser absorption process depends on the shape and size of the structure on the surface. The maximum laser pulse absorption is obtained when the characteristic size of the surface structure is comparable to the laser wavelength.

For experiments, we propose to use a target with a monolayer of closely packed polystyrene microspheres. A target covered by a layer of microspheres is quite simple for theoretical, numerical, and experimental studies. Polystyrene microspheres with different diameters in the range of 100-1000 nm are commercially accessible and their deposition on the target surface is quite straightforward. Self-assembly at the interface of water/air results in the creation of a compact monolayer of close packed microspheres. A thin plastic (flat) foil is submerged under the monolayer and then lifted up slowly so that the monolayer remains on its upper side. The result is a piecewise homogeneous monolayer of closely packed microspheres attached to the target surface. We found by numerical simulations that the optimum size of polystyrene microspheres favorable for ion acceleration is in the range of 0.5-1λ, where λ is the laser wavelength.

The experiment has been performed with the 10 Hz, 100 TW Ti:sapphire laser system at the Advanced Photonics Research Institute (APRI) in Gwangju, Korea. The laser pulse duration and energy after compression were about 30 fs and 2 J, respectively. The laser beam was p-polarized on target, with focal spot of about 5 μm in diameter (FWHM). In order to be below the ablation-threshold intensity in the ns-regime for the irradiated targets, which is about 10^9 W/cm^2, the use of a double plasma mirror was mandatory. Then, the laser pulse energy was reduced by a factor of 50% (about 1 J) on target and the laser intensity finally was about 5×10^{19} W/cm^2. The incidence angle of laser beam on 1 μm thick mylar foil was 22°. The real-time ion diagnostics used consists of Thomson parabola spectrometer and time-of-flight detector.

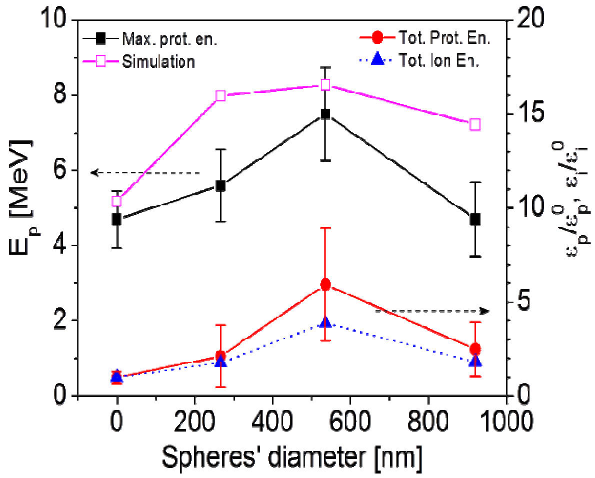

Fig. 1. Maximum proton energy (left axis, experiment – black, simulations – violet) and laser energy transformation (right axis) to protons with energy over 1 MeV (experiment - red).

The experimental results are quite well in agreement with our numerical simulations and clearly demonstrate that the use of nanostructures on the front-side of thin plastic foils can strongly enhance the laser-driven proton beam acceleration mechanism. In fact, the maximum proton energy was increased by a factor of 1.6 for the optimal sphere 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.

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.

3. Conclusions

Target normal sheath acceleration of ions from thin foil targets with a flat or structured front surface is studied in this contribution numerically and experimentally. The structure on the front surface may significantly boost the energy absorption of intense laser pulses with ultra-high contrast and increase the hot electron temperature and density. This leads to higher ion acceleration efficiency and maximum ion energy in the case of thin foil targets, which may benefit from hot electron recirculation. In the experiment, thin plastic foils covered by polystyrene microspheres of various sizes were used. We observed the enhancement of maximum proton energy about 60 per cent and 6-fold increase of laser to proton energy transformation efficiency compared with flat foil (for optimal microsphere size of 535 nm).

References

[1] S. P. Hatchett *et al.*, "Electron, photon, and ion beams from the relativistic interaction of Petawatt laser pulses with solid targets", Phys. Plasmas **7**, 2076 (2000).

[2] A. J. Mackinnon *et al.*, "Enhancement of proton acceleration by hot-electron recirculation in thin foils irradiated by ultraintense laser pulses", Phys. Rev. Lett. **88**, 215006 (2002).

[3] S. Buffechoux *et al.*, "Hot electrons transverse refluxing in ultra-intense laser-solid interactions", Phys. Rev. Lett. **105**, 015005 (2010).

[4] O. Klimo *et al.*, "Short pulse laser interaction with micro-structured targets: simulations of laser absorption and ion acceleration", New J. Phys. **13**, 053028 (2011).