Simulation studies on laser ion acceleration in micro-structured targets and larger multispecies clusters

J. Psikal[1], O. Klimo[1], J. Limpouch[1]

[1] *Faculty of Nuclear Sciences and Physical Engineering, Czech Technical University, Prague, Czech Republic*

1. INTRODUCTION

When ultrashort intense laser pulse interacts with ionized solid or liquid targets, ions can be accelerated to high energies (in MeVs or even GeVs) on a very short distance of several microns. On the path towards possible applications of ions accelerated by femtosecond laser pulses, the energy and number of the ions have to be enhanced and their energy spectra have to be optimized.

In our recent numerical studies, we have proposed to enhance the laser absorption by microscopic structures on the front surface of thin foil targets, which results in higher ion acceleration efficiency and maximum ion energy [1]. We have also investigated interactions of femtosecond laser beam with larger multispecies clusters, which could be useful for the generation of quasimonoenergetic ion beams [2]. Both these results are briefly summarized in this contribution.

2. SIMULATION METHOD AND PARAMETERS

The results were obtained by our 2D PIC code described in Ref. [3]. For the studies with microstructured targets, 0.5 μm thick plasma layer of density 40 n_{ec} (where n_{ec} is the electron critical density) containing mixture of protons and C^4+ ions was employed. The laser pulse duration was 40 fs and the maximum intensity was set to 9×10^{18} W/cm^2. The incidence angle of laser beam onto the ionized foil surface was either 10° or 45°. On the front (laser-irradiated) surface of the foil, spherical periodic structure is attached. Three simulation runs are compared - foil irradiated without front structure and with the structure containing spheres of diameter 0.5λ or 1λ, where $\lambda = 800$ nm is the wavelength of p-polarized laser beam.

For the studies of laser interaction with submicron water droplets, field ionization of ions has been implemented into the code as the influence of various degree of ionization of oxygen ions was discussed in several previous studies. The droplet diameter varied from 75 nm to 600 nm, the laser pulse duration from 40 fs to 120 fs, and the laser pulse intensity from 5×10^{17} W/cm^2 to 5×10^{19} W/cm^2 in order to find optimal parameters for the generation of quasimonoenergetic protons. The droplet plasma was initially at density of water for step-like density profile, containing protons and slightly ionized oxygen ions ($Z = 1$). We also investigate the prepulse impact by using exponential profiles of various scale lengths L and the maximum plasma density is less than critical for a relatively large L.

3. RESULTS AND DISCUSSION

a) microstructured targets During laser-target interaction, the laser energy is absorbed by electrons and a part of the absorbed energy is transferred into kinetic energy of ions through induced quasistatic electric field on the plasma-vacuum boundary (TNSA mechanism). The laser energy absorption reaches almost 60% when the microspheres of diameter about the laser wavelength are present on the foil surface. For flat foils, the laser energy absorption is less than 20%.

We further compare the efficiency of conversion of laser energy into fast protons accelerated by TNSA mechanism and the proton energy spectra. The conversion efficiency shows similar trends to the laser pulse absorption. The calculated conversion efficiency reaches up to 2% in the case of targets with periodic structure on the front surface, whereas it is below 1% for flat foils (only protons with energy higher than 1 MeV are taken into account).

Energy distributions of fast protons are depicted in Fig. 1. In general, all of the distributions are exponential with a high energy cut-off. The slopes of exponential distributions for the targets with microspheres are similar to each other; only the numbers of accelerated protons and the cut-off energy differ. The highest cutoff energy is obtained for the incidence angle of 10° and the sphere size of λ. This is consistent with the highest absorption and conversion efficiencies. Similar results were observed for other regular structures on the foil surface - rectangular or triangular, and also for somewhat irregular structure - microspheres with random diameter in the range from 0.25λ to 1.0λ.

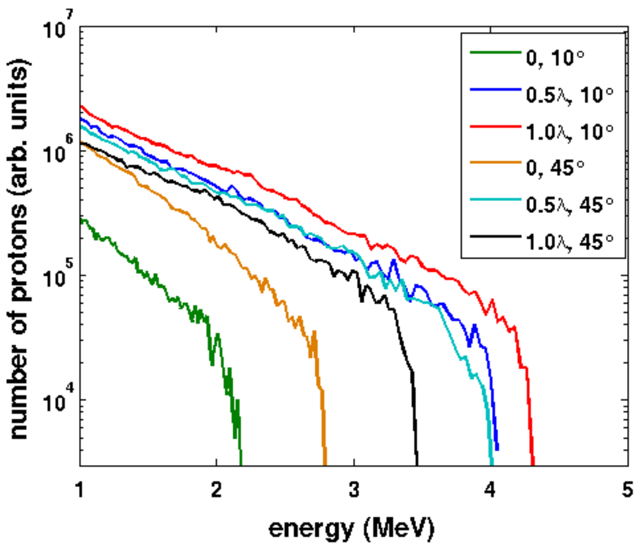

Figure 1: Energy distributions of fast protons accelerated by the TNSA process at the target rear sides. The first parameter stands for the diameter of microspheres on the target front surface, the second parameter stands for the incidence angle of the laser pulse.

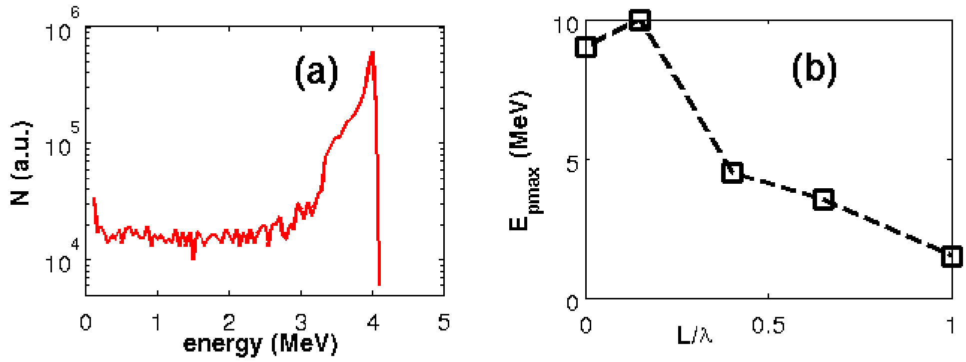

Figure 2: (a) Proton energy distribution function for submicron water droplet with exponential profile with density scale length $L = 0.65\lambda$; (b) Dependence of maximum proton energy on the initial density scale length L.

b) submicron water droplets In this case, the dependence of proton acceleration in water droplet of submicron diameter (regarded as larger cluster and produced in recent experiments [4]) was studied. Here, the proton acceleration is driven both by thermal expansion (as TNSA mechanism) and by Coulomb explosion (as in small clusters of nm sizes where all electrons are expelled from the cluster by laser wave). Fig. 2 shows an example of proton energy spectra for the droplet with initial density profile with scale length $L = 0.65\lambda$ (see below) and the dependence of maximum proton energy on the initial target density profile (the profile can be formed due to insufficient laser pulse contrast). The density profiles are calculated in the form $n_{max} \exp(-r/L)$, where n_{max} is the maximum density in the target center, r is the distance from the cluster center, and L is the density scale length. The maximum density is determined so that the number of particles in all cases is the same as for initially overdense cluster of step-like density profile and of a diameter of 150 nm - initial maximum densities are $n_{max} =$ 18.75 n_{ec}, 4 n_{ec}, 0.6 n_{ec}, 0.3 n_{ec}, 0.15 n_{ec} for the scale lengths $L = 0$, 0.15λ, 0.4λ, 0.65λ, or 1.0λ, respectively. The initial maximum densities are calculated for the initial charge of oxygen ions $Z = 1$.

Generally, the absorption of laser pulse in an underdense cluster is relatively low. Thus, the ion acceleration is less efficient for clusters with larger density scale length. On the contrary, the absorption and ion acceleration efficiency is enhanced for a relatively low scale length ($L = 0.15\lambda$) when the cluster center remains overdense before the interaction with peak of the laser pulse. Similar results were found when the influence of laser pulse duration or cluster diameter was investigated. The laser pulse absorption and the efficiency of ion acceleration are reduced when the cluster starts to be underdense before the end of laser-cluster interaction, i.e., when the laser pulse is too long or the cluster size is too small. On the other hand, too short laser pulse leads to lower maximum proton energy and too large cluster size eliminates quasimonoenergetic peak from the proton energy spectrum at maximum energy. However, the peak in the spectrum can be also observed for smaller, initially underdense clusters (see Fig. 2). For the laser pulse intensity 2×10^{19} W/cm^2 used in the experiment with the waterspray target [4], the cluster size about 150 nm, small density scale length of $L = 0.1\lambda$ and pulse duration between 40 fs and 80 fs are three preferential.

4. CONCLUSIONS AND PERSPECTIVES

Thin foil targets with microstructures on their front surface enable to enhance energy and number of accelerated protons due to improved laser pulse energy absorption. Our numerical results may be verified in experiments prepared in cooperation with experimental group from PALS laboratory in Prague (D. Margarone *et al.*) and with Gwangju Institute of Science and Technology in Korea. The targets for the experiment (polystyrene microspheres of diameter from 200 nm to 900 nm on the foil surface) are fabricated by J. Proska *et al.* at Department of Physical Electronics, FNSPE CTU in Prague [1].

Quasimonoenergetic proton beams can be produced by the interaction of femtosecond laser pulse with submicron water droplets. In this case, the laser pulse contrast is fundamental parameter for the interaction as laser pedestals or prepulses can completely evaporate the cluster before the interaction with the main laser pulse. In the future, initially underdense clusters will be analyzed in more detail and more realistic 3D simulations of laser-cluster interactions will be performed in order to imitate interaction conditions in previous experiments [4] properly.

Acknowledgments

Partial support by Project LC528 of the Ministry of Education, Youth and Sports, by Project No. 205/11/1165 of the Czech Science Foundation, and by Barrande project No. MEB021029 of the Association of Innovative Entrepreneurship of the Czech Republic is gratefully acknowledged.

References

[1] O. Klimo *et al.*, New Journal of Physics **13**, 053028 (2011)

[2] J. Psikal *et al.*, Proceedings SPIE **8079**, 807912 (2011)

[3] J. Psikal *et al.*, Czechoslovak Journal of Physics **56**, B515 (2006)

[4] S. Ter-Avetisyan *et al.*, Physics of Plasmas **15**, 083106 (2008)