Laser acceleration of ions in mass-limited multi-species targets

J Limpouch, J Psikal, V T Tikhonchuk, O Klimo, A V Brantov and A A Andreev

1 FNSPE, Czech Technical University in Prague, 115 19 Prague 1, Czech Republic
2 CELIA, Université Bordeaux 1-CNRS-CEA, Talence cedex, France
3 P. N. Lebedev Physics Institute, Russian Academy of Sciences, Moscow, Russia
4 ILP, S. I. Vavilov State Optical Institute, St. Petersburg, Russia

limpouch@ishtar.fjfi.cvut.cz

Abstract. Intense short laser pulses may accelerate ions in thin targets to energies of several MeV per nucleon and highly collimated ion beams may be formed. Quasi-monoenergetic ion beams were generated last year from foils with a specially treated rear surface and from the water droplets. Mass-limited targets such as water µm-sized spheres or small metal discs offer an advantage of reducing the absorbed laser energy spread in the transverse directions. Ion acceleration in targets irradiated by short ultra-intense laser pulses is studied here via two-dimensional in space and three-dimensional in velocities (2D3V) relativistic electromagnetic particle-in-cell code. Simulations were performed for plane and curved foil sections and cylindrical targets that serve as a two-dimensional model of spherical micro-droplets. Two ion species with different charge-to-mass ratios facilitate the formation of persistent peak in energy distribution of the lighter ions, while the heavier ions act like a piston.

1. Introduction

Generation of fast ion beams in the interaction of ultrashort relativistic laser pulses with plasma is subject of interest for many attractive potential applications, such as the proton radiography, isochoric heating of solid-density matter, isotope production, ion cancer therapy and surgery, and the fast ignition of inertial confinement fusion targets. However, laser generated ion beams have to fulfill very demanding conditions for their practical utilization. Recent experiments with thin foil targets [1] and microdroplets [2] have shown a possibility to control the ion energy spectra, and quasi-monoenergetic fast ion beams with energies of several MeV per nucleon have been generated.

Many experimental groups use thin metal or insulator foils as targets. Ions accelerated in such targets are mainly protons originating from low-Z water and hydrocarbon deposits on the surface. Targets consisting of a high-Z layer and a very thin low-Z layer at the rear side were proposed [3] to enhance the laser energy conversion into fast ions and to improve their energy spectrum. Mass-limited targets such as µm-sized spherical water microdroplets or small metal discs offer an advantage of reducing the absorbed laser energy spread in the transverse directions.

Here, results of our 2D3V PIC simulations of laser interaction with multi-species mass-limited targets are presented and optimum interaction regimes for generation of quasi-monoenergetic proton beams by transverse normal sheath acceleration (TNSA) are searched for.
Figure 1 Studied laser-target configurations: (a) cylinder that serves as a two-dimensional model of a droplet; (b) flat foil section; (c) curved foil section

2. Simulation method and parameters

We use our relativistic two-dimensional in space and three-dimensional in velocities (2D3V) PIC code [4] for simulations of interactions of intense femtosecond laser pulses with mass-limited targets. The code uses damping regions for the absorption of outgoing electromagnetic waves in order to eliminate spurious reflection from the simulation box boundaries. A zigzag scheme is implemented for the computation of current densities in order to guarantee the automatic compliance with the continuity equation. The code was parallelized via the OpenMP scheme.

In this paper we investigate laser interactions with C$^4+$H$^+$ targets of three geometrical shapes schematically displayed in Figure 1. A two-dimensional (2D) simulation geometry includes inherent assumption of uniformity along the axis normal to the displayed plane, and thus an infinite cylinder serves here as a model of a spherical droplet. The cylinder diameter is set to $3\lambda$, flat and curved foil sections are assumed $3\lambda$ thick and $4\lambda$ wide. In order to alleviate computational demands the assumed initial target electron density of $20n_c$ ($n_c$ is the critical density) is approximately 7 times lower than in the fully ionized solid density material. Our preliminary simulations show that an increase in the target density leads to a somewhat lower absorption efficiency and somewhat lower energies of the accelerated protons while the results do not differ qualitatively. Targets are irradiated at a normal incidence by the p-polarized laser pulse of the intensity $I = 4.5 \times 10^{19}$ W/cm$^2$ and wavelength $\lambda = 800$ nm. The full duration of the sin$^2$ shaped pulse is 30 fs (12 laser periods $\tau$) and the full width at half maximum (FWHM) of the Gaussian-shaped laser beam is $2.5\lambda$ at the focal spot. The initial temperature is set to 1 keV (for the cell size $\lambda/100 \times \lambda/100$) in order to avoid numerical heating. Such a relatively high initial temperature can be justified for mass-limited targets as our preliminary simulations have shown that the cold electron temperature increases in several femtoseconds up to several keV, when the target is irradiated by a laser beam of a relativistic intensity.

3. Results and discussions

Ion acceleration in multi-species homogenous targets has been described theoretically in paper [5]. A strong electric field in the sheath layer at the target rear side provides a spatial separation of fast protons and heavier ions. Mutual
interaction of the ion species affects the ion distribution functions and the acceleration efficiency significantly. The formation of the proton bunch is demonstrated in Figure 2, which shows the phase space \((x, v_x)\) of protons and \(\text{C}^{2+}\) ions beyond the rear side of flat foil section target at the time of 200 fs after the interaction. Initially, a proton layer of sub-nanometer thickness is accelerated at the rear side by a strong electric field \((\approx 10^{12} - 10^{13} \text{ V/m})\). Heavier ions follow protons with a certain inertia-induced delay and they shield the electric field. Thus, an access of protons from deeper layers in the target into the acceleration region is inhibited. In-flight interaction between protons and heavy ions compensates the effect of Coulomb repulsion partially and a stable peak in proton spectrum is formed spatially just ahead of the fastest heavier ions. One can also see protons accelerated at the front side, but our simulations indicate that the energy of these protons is reduced for higher target densities even when collisions are not taken into account. The dependence of the proton energy spectrum behind the target on the target shape is demonstrated in Figure 3, the laser parameters and the target thicknesses are unchanged. Due to the presence of \(\text{C}^{2+}\) ions, the fast protons are separated from the thermal ones by a deep dip and the spectrum above the dip consists of a peak and a high energy tail. The energy of accelerated ions is enhanced for a microdroplet (cylinder) target. The position of the peak remains constant after its formation, while the ion cutoff energies still increase in time due to Coulomb repulsion. Our simulations were stopped 300 fs after laser-target interaction. At this final moment, laser energy transformation into proton kinetic energy was 2.8%, 3.0% and 3.8% for flat and curved foil sections and the cylindrical target. For these respective targets, fast protons constituted 0.8%, 0.8%, 1.1% of all protons and they contained 1.7%, 2.2%, 2.6% of the laser energy, while 3.6%, 3.9%, 6.7% of the laser energy was transformed into the kinetic energy of carbon ions. The laser absorption was 15.8% for the cylindrical target and only 11.6% and 12.4% for the flat and curved foil sections, respectively.

The laser absorption efficiency can be controlled by the target density profile. The step-like profile was assumed at the onset of the previous simulations. However, the target starts to expand due to a non-zero initial temperature and the density scale lengths on the all target sides are approximately \(L = 0.05 \lambda\) during the laser target interaction. Such a density profile is labeled as “steep” in Figure 4, where the impact of the plasma density profile on fast proton spectrum is demonstrated for the flat foil section target. When the target is initiated with an exponential profile with the density scale length \(L = 0.2 \lambda\) (\(L = 0.25 \lambda\) during the laser target interaction) at the front side of the foil, laser absorption is increased to 26% and the energy of the proton spectral peak is enhanced more than 2 times. The laser energy transformation to the fast protons rises to 5.2% while the number of fast protons is practically unchanged (0.8%). When the same exponential profile is assumed also at the target rear side, the fast proton number is slightly enhanced (1.1%) but the energy of the spectral peak is reduced. The laser transformation efficiency to fast protons (5.2%) is equal to the previous case. These numerical results are in agreement with experimental results published by Kaluza et al. [6].

The quality of fast proton beam is characterized by the number of particles and the beam divergence. The latter is controlled by the shape of the rear target surface. The angular distribution of fast protons at the rear side of the target is displayed in Figure 5 for various target shapes at the time of 300 fs after the interaction. In the case of cylindrical target, the protons are accelerated into a very broad range of angles, though an anisotropy still exists and fast protons angular density in the direction
Figure 4 Proton energy spectra at the time of 200 fs after the interaction for the flat foil sections with different initial density profiles at the front and rear side. “Steep” stands for density scale length $L \approx 0.05 \lambda$, while “exp” stands for $L \approx 0.25 \lambda$.

Figure 5 Angular distribution of fast protons for various target shapes and a steep density profile. The increase in the angular density of fast protons for the times 200 - 300 fs for the curved foil section is due to ion focusing.

of the incident laser beam (angle 0°) is 2.5 times higher than in the direction opposite to the beam (angle 180°). On the contrary, a very narrow angular distribution is observed for the curved foil section and the maximum angular density grows due to ion focusing induced by the rear side shape.

4. Conclusions

A possibility to control the energy spectrum of protons accelerated by the TNSA mechanism in multi-species targets has been demonstrated in two-dimensional particle-in-cell simulations. Heavier ions serve as a piston, they compensate partially the Coulomb explosion and thus, a narrow peak in the proton energy spectrum is maintained for a long time.

The effect of the shape of mass-limited target has been studied. A spherical microdroplet target, modeled here in two-dimensions via an infinite cylinder, enhances the proton energy, but produces an undesirable divergence of the beam, which leads to lower densities of fast protons. On the other hand, a curved foil section has an advantage of proton beam focusing at a specific distance determined by the radius of curvature at the target rear side.

The laser energy transfer into fast protons may be enhanced by controlling the density profile scale length $L$ at the target front side, while the fast proton energy is reduced when the target rear side is expanded.

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References

[1] Hegelich B M, Albright B J, Cobble J et al. 2006 Nature 439 441
    Schooerter H, Pfotenhauer S, Jaeckel O et al. 2006 Nature 439 445
[2] Ter-Avetisyan S, Schnuerer M, Nickles P V et al. 2006 Phys. Rev. Lett. 96 145006
[3] Esirkepov T Z, Bulanov S V, Nishihara K et al. 2002 Phys. Rev. Lett. 89, 175003
[4] Psikal J, Limpouch J, Kawata S and Andreev A A 2006 Cz. J. Phys. 56, B515
[5] Brantov A, Tikhonchuk V T, Klimo O et al. 2006 Phys. Plasmas 13, 122705
[6] Kaluza M, Schreiber J, Santala M I K. et al. 2004 Phys. Rev. Lett. 93 045003