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Two-dimensional simulations of ion acceleration by ultraintense femtosecond laser pulses

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1. INTRODUCTION

Generation of fast ion beams in the interaction of ultrashort relativistic laser pulses with plasma is a subject of interest for several applications, such as positron emission tomography (PET), proton cancer therapy, fast ignition in inertial confinement fusion, etc. To put them in practice, the ion beams have to satisfy very demanding criteria. For example, the treatment of deep-seated tumours requires monoenergetic proton beams with energies about 200 MeV. To produce practical radioisotope sources for PET, a large flux of protons with the energy about 10 MeV is required. The fast ignition scheme requires a proton source with a very small divergence.

It has been proposed to use small targets with dimensions less or comparable to the laser spot size, so-called mass limited targets (MLT), in order to enhance the efficiency of laser energy transformation into fast ions. As MLTs are of a near-solid density and of micron sizes comparable to the laser wavelength, a high laser absorption and intense laser-plasma interaction are expected to proceed without lateral losses from the interaction region. Recent experiments with heavy water microdroplets [1] have shown a possibility to control ion energy spectra and to generate quasi-monoenergetic fast deuteron beams with energies of several MeV.

Our objectives are to study the efficiency, energy spectrum and focusing of protons accelerated in homogenous multispecies MLTs of various shapes. An advantage of homogenous targets is in their well defined composition and in a possibility to compensate partially the effect of Coulomb repulsion of accelerated ions [2].

2. SIMULATION METHOD AND PARAMETERS

Numerical simulations have been performed with our newly developed two-dimensional (2D3V) relativistic colisionless particle-in-cell code [3]. The code is parallelized via OpenMP scheme, which enables us to compute on JUMP cluster in Juelich (Germany) on a node with 32 CPUs.

In order to investigate the role of target shape on the proton acceleration, fully ionized homogenous targets of three different shapes have been employed: (i) a disk with a diameter of 3λ, which serves as a model of a microdroplet in the 2D case; (ii) a flat foil section of a size $3\lambda \times 4\lambda$; (iii) a curved foil section [4] of a size $3\lambda \times 4\lambda$ with the radius of curvature 4λ at the rear side. The targets were containing two ion species (protons and "heavy" C^{4+} ions in a ratio 1:1) and they were irradiated at a normal incidence by a p-polarized laser pulse of the wavelength $\lambda = 800$ nm and intensity $I = 4.5 \cdot 10^{19}$ W $\cdot$ cm^{-2}. The pulse length was about 30 fs (12 laser cycles) with $\sin^2$ shape and with the beam width 3λ (a gaussian distribution) at the focal spot. The initial temperature was set to 1 keV and the initial electron density to 20 n_c (n_c is the critical density).

3. RESULTS AND DISCUSSION

Ion acceleration in multispecies homogenous targets has been theoretically described in [2]. The electrons accelerated and heated by a laser pulse on the front side of the target are entering the thermal plasma and are forming a population of hot electrons. These hot electrons are crossing the target and are expanding beyond its rear side. There, a sheath layer is formed and a strong electric field is accelerating ions. This is a so-called target normal sheath acceleration mechanism (TNSA) [5].

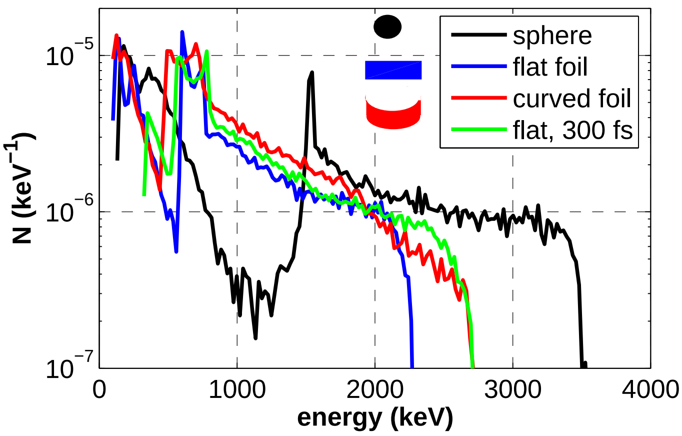

Figure 1: Proton energy spectra for three target shapes at the time of 200 fs after the interaction, and, for the flat foil section at the time of 300 fs (green line).

Initially, a small layer (a few nm or several tens of nm depending on the initial maximum target density and density profile) of protons at the rear surface of the target is accelerated by a strong electric field (with maxima values $\approx 10^{12} - 10^{13}$ V $\cdot$ m^{-1}). Heavy ions from this layer are accelereted somewhat later because of their inertia. They shield the sheath electric field for other protons from deeper layers and also interact with earlier accelerated protons.

Figure 1 shows the proton energy distribution of multispecies targets (beyond the rear side) of various shapes. The laser pulse has the same parameters in all cases. The fast protons are separated from the thermal particles by a deep dip, their spectrum consists of a high energy tail and a peak, which is caused by the presence of the second ion species (C^{4+} ions).

The initial separation of ion species occurs quickly during several tens of fs. The formation of the dip and the peak in proton energy spectrum takes at least 100 fs. Fast protons are accelerated by fast electrons and at the same time they explode in space due to the effect of Coulomb repulsion. This latter effect is compensated partially by the electric field of heavy ions, which serve as a piston. While the first part of fast protons is accelerated and forms the energetic tail in spectrum, the second part forms a peak under the electric field of expanding heavy ions. The peak in the proton energy spectrum corresponds to a plateau in the phase space, that is the protons of the same energy are spread in the coordinate space. As time goes on, the protons from behind overtake the others producing a fine structure of the peak. In the case of a disk, a high angular divergence of fast protons leads to their lower densities and the peak evolves more slowly.

Figure 1 demonstrates that the energy of accelerated ions can be enhanced in a microdroplet target compared to the flat foil. It has been observed that the position of the peak remains constant after its formation (on 100 fs time scale), in contrast to the cutoff energies, which still increase in time because of the Coulomb repulsion of ions. Moreover, the simulations show that the energy content of fast protons is defined by the position of the peak in their energy spectrum, not the cutoff energy, which contains only a relatively small portion of fast protons.

While the peak energy position for the spherical target is 1.5 MeV, the latter is lower for the flat foil and curved foil sections, about 600 and 450 keV, respectivelly. The peak position depends on two parameters: the cutoff energy of heavy ions and the spatial density of accelerated heavy ions and protons. In the cases where the spatial density of ions is higher, the Coulomb explosion is stronger and the bunch of fast protons follows more closely the position of the most energetic heavy ions, that is, the peak energy decreases at higher proton densities. The cutoff energies of heavy ions at the time of 200 fs after the interaction are about 400 keV for the flat foil and curved foil sections and about 800 keV for the disk. Cutoff energies of heavy ions depend mainly on the absorbed laser energy. A higher absorption of laser pulse energy in the disk case (i.e. 15% vs. 10% for the flat and 11% for the curved foil) can be explained by the presence of a curvature at the front side of a target. In this case, the laser pulse arrives on the target on larger angles giving rise to more efficient colisionless absorption and higher electron energies.

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 side target surface. In the case of a microdroplet, the ions are accelerated in all directions almost isotropically. On the contrary, the curved foil section seems to be very prospective, owing to a possibility to focus ion beam.

Figure 2 shows the angular distribution of protons for different target shapes at the time of 300 fs after the interaction.

For the curved foil, the beams of protons and heavy ions are focused at the distance about the radius of the rear side curvature. The beam width is estimated to be 2λ, compared to 5λ for the flat foil at the same time. After reaching their focal spot, the protons are spreaded due to the effect of Coulomb repulsion as well as in the case of flat foil since the beginning.

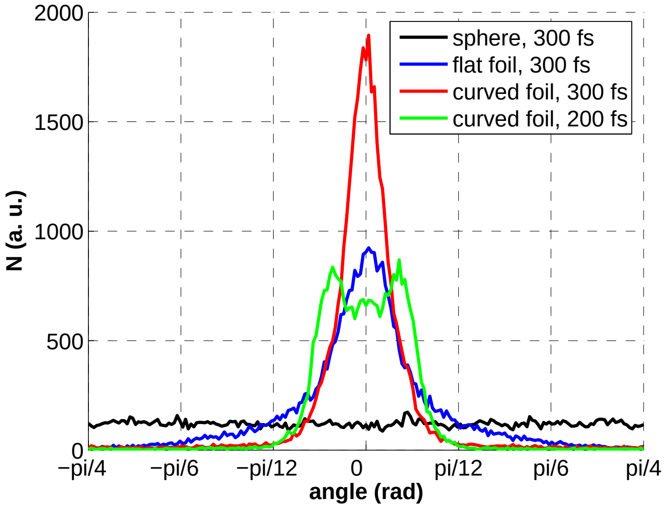

Figure 2: Direction of motion of fast protons for three different target shapes.

4. CONCLUSION

Possibilities to control the energy spectra and divergence of fast proton beams in multispecies targets are demonstrated by means of computer simulations using a 2D particle-in-cell code. The presence of heavy ions serving as a piston compensates partially the effect of Coulomb explosion and maintains for a long time a narrow proton energy spectrum. Various shapes of target were modeled and substantial differences, both in energies and in the divergence of generated proton beams, have been found. The employment of spherical targets enhances the proton energy, but produces an undesirable divergence of the beam, which leads to lower densities of fast ions. On the other hand, the employment of a curved foil section allows one to focus proton beam at a specific distance determined by the radius of curvature at the rear side of the target.

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