Enhanced laser proton acceleration in mass-limited targets

J. Psikal[1,2], V. T. Tikhonchuk[2], E. D'Humieres[2], J. Limpouch[1], O. Klimo[1]

[1] *Faculty of Nucl. Sci. and Physical Engineering, Czech Technical University, Prague, Czechia*

[2] *Centre Lasers Intenses et Applications, CEA-CNRS-Université Bordeaux 1, Talence, France*

1. INTRODUCTION

Short-duration, multi-MeV ion beams, produced in the interaction of high-intensity laser pulses with solid targets, have opened up perspectives for important applications such as warm dense matter production, fast ignition of fusion targets, radiography of dense matter, radioisotopes and neutron production, hadrontherapy, etc. These beams are electrostatically accelerated, by the laser-generated hot electrons, from the target surfaces into vacuum, with the highest energy ions originating from contaminants on the laser non-irradiated (i.e. rear) target surface. These applications however, require improvements of the ion beam characteristics, particularly regarding the conversion efficiency, peak energy, monochromaticity, and collimation. These improvements are possible either by increasing the laser intensity on target, or by altering the target characteristics using presently available laser intensities.

It has been already demonstrated that the efficiency of ion acceleration can be enhanced by decreasing the target thickness due to hot electron recirculation [1]. Recent experiments [2] have shown enhanced energy, number and collimation of accelerated protons with reducing the surface of solid targets of the same thickness (2 μm thick Au foils). Here, these recently obtained experimental results are explained by multidimensional particle-in-cell simulations.

2. SIMULATION METHOD AND PARAMETERS

We employed mainly 2D PIC code described in Ref. [3] and, for additional simulations, 3D PICLS code described in Ref. [4]. These particle-in-cell (PIC) collisionless simulations were performed to study in more detail hot electron dynamics in foils of the same thickness, but various transverse sizes. Because of high computational demands, the laser and target parameters were rescaled in such a way that the key ratio of the target transverse size to the laser pulse length was kept the same as in experiment [2]. In two (2D) simulations discussed below we are considering two foils of the same thickness of 2 wavelengths (2λ), but different transverse sizes D_s of 12 μm (20λ), referred as "small-sized foil", and 48 μm (80λ), referred as "medium-sized foil", assuming the laser wavelength $\lambda = 600$ nm.

The duration τ_L=80 fs (= 40τ, i.e. laser cycles) of laser pulse consisting of a central plateau 60 fs long and of two linear ramps of duration 10 fs is chosen such that the ratio $D_s/(\tau_L c)$ is 0.5 for small-sized and 2.0 for medium-sized foil. The p-polarized laser beam has a supergaussian profile (n=3) with the beam width (FWHM) 7λ (4 μm) and the incidence angle is 45°. Targets are composed of protons and electrons of the density $20n_c$ with a step-like density profile and with the initial temperature of all particles 2 keV. The simulation box has size $76\lambda \times 76\lambda$ and the absorption layers of the thickness 2λ are added behind each side of the box in order to eliminate unphysical reflections from the simulation box boundaries. The electrons reaching the simulation box boundaries are frozen there. The cell size is set to 12 nm. The simulations were run up to 300 fs after laser interaction with the foil, at which time the acceleration of high-energy ions saturates.

3. RESULTS AND DISCUSSION

The temporal dependence of hot electron temperature and density on foil transverse sizes is responsible for differences in ion cutoff energies and laser-to-proton conversion efficiencies. Temporal evolutions of electron energy spectra beyond the focal spot are shown in Fig. 1a for the small-sized foil and in Fig. 1b for the medium-sized foil. (Only the electrons with energies higher than 100 keV and in the strip of the width of 10λ are considered). During laser-target interaction, hot electrons are recirculating in thin foil [1] and are drifting towards foil edges. At the foil edges, the electrons are reflected back towards interaction region. They are returning back to the center and enhancing accelerating electric field in this region.

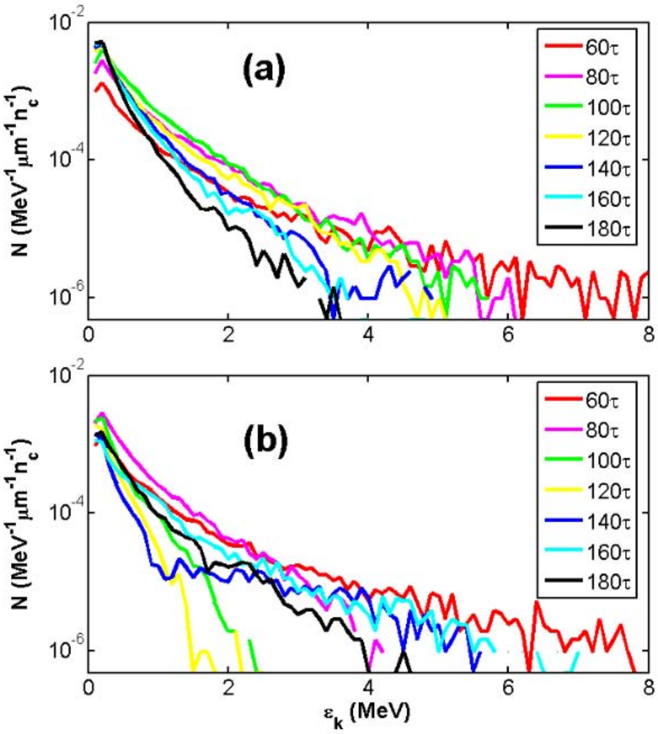

Figure 1: Simulated energy spectra of electrons beyond the laser focal spot in several time moments for the two cases of (a) small and (b) medium foils. Only electrons in the strip of 6 μm near the center are considered. The time is measured in laser periods τ = 2 fs.

When the laser pulse duration $\tau_L >> D_s/c$ (where c is speed of light, i.e. maximal velocity of electrons in the direction along the foil surface), hot electrons from the foil edges mix with newly heated electrons by still interacting laser pulse. In our case of the small-sized foil (Fig. 1a), $\tau_L \approx 2D_s/c$, and one can see an enhancement of hot electron density (from time moment 80τ), whereas no enhancement is possible for medium-sized foil as the first electrons reflected from the foil edges reach the interaction zone at the time of about 140τ (Fig. 1b). (The laser pulse interact with the foil from 35τ to 75τ in both cases.) Thus, we can roughly estimate the velocity of hot electrons along the foil surface about (2/3)c in the simulations, which is 0.2 μm/fs. The hot electron recirculation from foil edges explains also a narrower angular ion spread in small-sized targets as the electron sheath is more homogeneous along the target surface.

The temperature of hot electrons during the interaction time (60τ in Fig. 1) is approximatelly 0.95 MeV in the target center in both cases, which agrees well with the ponderomotive scaling ($T_{h,pond} = m_e c^2 (\sqrt{1 + a_0^2/2} - 1) \approx 1$ MeV). However, hot electron temperature decreases after the laser pulse end, more rapidly for the medium foil. This leads to different hot electron temperatures averaged over the ion acceleration time (from 60τ to 180τ). We obtain effective temperature 0.67 MeV for small and 0.59 MeV for medium foils. Also the averaged hot electron densities are different. The density is 2.3 times higher in the central part of the small foil, while the absorption of the laser pulse energy is the same for both cases - about 45%.

The 2D simulations demonstrate well increasing tendency of maximum proton energy with decreasing foil surface, in agreement with the experiment [2] - 12 MeV for small-sized and 10 MeV for medium-sized foil. However, the enhancement of the laser-to-proton conversion efficiency found in 2D simulations (6% for small vs. 4% for medium foil), is much smaller than observed in the experiments. This can be explained by the fact that the electrons cannot spread in the third spatial dimension in our 2D simulations. The conversion efficiency is proportional to the product $T_h n_h$ [5], and therefore is very sensitive to the electron density. On the contrary, the maximum ion energy depends on $T_h \ln^2(n_h)$ [6], which is much weaker function of the hot electron density n_h. Thus, 2D simulations can predict relative scaling of maximum energy well, but they overestimate conversion efficiency for larger targets. This is confirmed by our 3D simulations, where the simulation parameters were further downgraded (the transverse foil sizes, laser pulse duration and beam width are reduced about two times compared with 2D case) to get a reasonable calculation time. In those 3D simulations, the conversion efficiency for small-sized foil is almost 10 times higher than for medium-sized foil, whereas the decrease in the maximum energy agrees relatively well with 2D case (the decrease about 20%).

4. CONCLUSION

We have demonstrated by numerical simulations that reducing the surface of a thin foil results in an increase of the hot electrons number and mean energy, which is translated into more efficient proton acceleration. These results are in agreement with experimental observations [2] and explain them by the hot electron dynamics. When the spatial length of laser pulse is comparable with foil transverse dimensions, the hot electrons are reflected back from target edges and sustain a high accelerating electrostatic field for a longer time. When the laser pulse spatial length is larger than the foil transverse dimensions, the accelerating sheath is more uniform, which results in a lower angular divergence of the proton beam. 2D simulations seems to be sufficient for determination of a correct scaling of maximum proton energy on transverse foil sizes, whereas 3D approach is necessary to reproduce well the conversion efficiency.

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