Enhanced laser-ion acceleration in thin foils of reduced surface

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Abstract: Ion acceleration in the interaction of ultrashort intense laser pulses (~ 2×10^{19} W/cm^2, 10s-100s fs) with thin solid foils of limited transverse extend (~ 10s of µm) is measured experimentally and studied numerically (by PIC simulations). Reducing the target surface area allows hot electrons to be reflected from target edges during or shortly after the laser pulse. This transverse refluxing in such targets maintains hotter and denser electron sheath around the target for a longer time. Consequently, maximum proton energy and laser-to-proton energy conversion efficiency can be significantly increased.

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]. Here, we report an investigation of the influence of the target lateral dimensions on the dynamics of the hot electrons and the associated energetic proton production.

2. Results and discussion

2.1 Experiments

The experiments were performed using the 100 TW laser at LULI working in the Chirped Pulse Amplification regime. The main laser pulse was compressed down to 400 fs, then frequency-doubled and filtered at 529 nm in order to enhance its temporal contrast. This was done to avoid preplasma formation on the front surface that would hydrodynamically expand and damage the rear surface. The laser beam of the width ~ 6 µm (FWHM) was focused on the center of Au foils, at 45° incidence. The laser energy in this focal spot was $E_L \sim 7$ J which led to a peak intensity on target of I ~ 2×10^{19} W.cm^{-2}. The targets had constant thickness (2 µm), but variable surface area in order to explore the effect of transverse refluxing on proton acceleration. The diagnostic uses films (RCF) to resolve energy and angle of accelerated protons. More details about set-up of the experiment are described in Ref. [2].

The experiments show a clear improvement of proton beam characteristics (maximum proton energy ε_{max} and laser-to-proton energy conversion efficiency) when the target dimensions are reduced, as shown in Fig. 1, and as was suggested by several theoretical studies [3, 4]. Both the proton energy and conversion efficiency increase starting from target surface area of ~$3\text{-}4\times10^4$ µm². The proton dose is determined through absolute calibration of the deposited dose in the RCF as well as through nuclear activation measurements. Such an increase in dose is very promising for applications such as proton-isochoric heating of matter or radioisotope generation, where the laser-to-proton yield is the appropriate figure of merit.

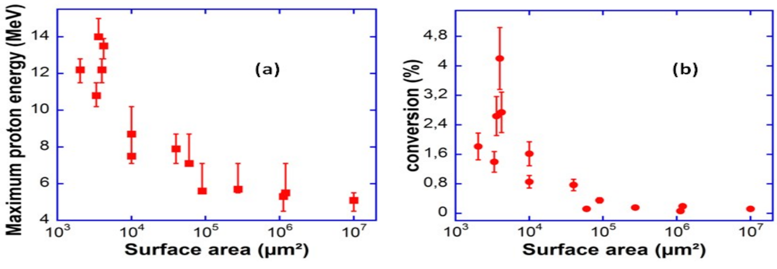

Fig. 1. Data from RCF give (a) maximum proton energy for 2 µm thick Au targets of various surface area and (b) laser-to-proton energy conversion efficiency (for protons with energy > 1.5 MeV) for the same targets.

2.2 Numerical simulations

To determine the mechanism leading to an increase of the proton energy and conversion efficiency, we performed two-dimensional (2D) particle-in-cell (PIC) simulations of laser-target interactions with the code described in Ref. [5]. Present-day computational limitations do not allow treating simulation boxes of several hundred microns across, therefore the laser and target parameters were rescaled in such a way that the ratio of target diameter, D_s, to laser pulse duration, τ_L, was kept the same as in the experiment. This parameter is key in determining whether or not the electrons reflux laterally during or shortly after τ_L, during ion acceleration time which is ~2-3 τ_L.

The simulations use τ_L = 80 fs, a p-polarized laser beam has a wavelength of λ = 600 nm and a supergaussian profile (n = 3) with a FWHM of 7λ. The incidence angle is 45°, and the maximum intensity is I = 2.4×10^{19} W/cm^2. "Small" foil of transverse size equal to 20λ and "medium" foil of the size equal to 80λ are 2λ thick and composed of protons and electrons with a step-like density profile of $n_e = 20n_c$ and an initial temperature of 2 keV. Simulation boxes are 76$\lambda\times$76λ, and 2λ thick absorption layers are added behind each side of the box and cell size is set to 12 nm. The electrons that reach the simulation box boundaries are frozen there. The simulations were run up to 3.5τ_L after the laser hits the foil.

We observed in the simulations that the hot electron spectra, time-integrated over ion acceleration time and measured at the target center, display higher temperatures T_h and higher numbers n_h for the small foil compared to medium (and large) ones. This is caused by hot electrons reflected back from the small foil edges towards the target center (by the local sheath field) where they overlap. The temporal evolution of electron energy spectra beyond the focal spot is shown in Fig. 2 for both the small (a) and medium (b) foils, the evolution of corresponding hot electron temperature component in the ion acceleration direction is displayed in Fig. 2 (c). Only the electrons with energies higher than 100 keV in a 10λ wide central strip are considered. In the small foil case, T_h decreases slowly throughout the proton acceleration (~2τ_L) due to the constant refluxing of hot electrons. On the contrary, in the medium foil case, T_{hot} drops dramatically after the laser pulse ends and the electrons return to the center later (at ~2.5τ_L), when the acceleration process terminates. Since the ion accelerating electric field is proportional to $(n_hT_h)^{1/2}$ [6], the enhancement of proton acceleration in the central region is observed in the small foil compared to the medium foil.

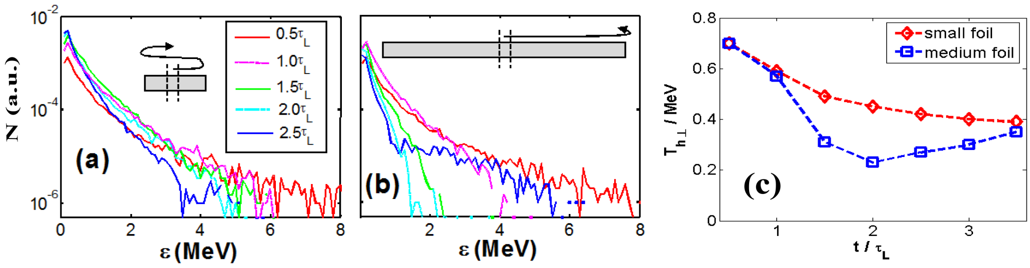

Fig. 2. Temporal evolution of electron energy spectra beyond the focal spot for (a) small and (b) medium foils; (c) corresponding hot electron temperature component in the direction perpendicular to the target surface for the foils. The schematic drawings inset represent, for each target at 1.5τ_L after having being launched at the target center, the path of a hot electron.

3. Conclusions and perspectives

Reducing the surface area of solid targets leads to an increase in the effective hot electron number and mean energy due to the lateral electron recirculation. This effect enhances the properties of laser-accelerated ions, in terms of energy and flux, as necessary for progress towards applications. Use of this simple mechanism for future experiments at higher intensity laser facilities requires laser pulses with high temporal contrast to avoid preplasma leakage to the target rear-surface. In addition, progress in target fabrication will offer targets that are not only of reduced lateral size, but also thinner as it is now found favourable for ion acceleration [1].

References

[1] 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).
[2] S. Buffechoux *et al.*, "Hot electrons transverse refluxing in ultra-intense laser-solid interactions", *submitted to* Phys. Rev. Lett. (2010).
[3] J. Psikal *et al.*, "Ion acceleration by femtosecond laser pulses in small multispecies targets", Phys. Plasmas **15**, 053102 (2008).
[4] J. Limpouch *et al.*, "Enhanced laser ion acceleration from mass-limited targets", Laser & Part. Beams **26**, 225 (2008).
[5] J. Psikal *et al.*, "PIC simulations of femtosecond interactions with mass-limited targets ", Czech. J. Phys. **56**, B515 (2006).
[6] P. Mora, "Plasma expansion into a vacuum", Phys. Rev. Lett. **90**, 185002 (2003).