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Ion acceleration by relativistically intense laser pulses incident on target at large angles

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1. INTRODUCTION

Recent theoretical analysis, numerical simulations and experiments [1] - [3] have revealed a fast electron current along the target surface layer when a short laser pulse with a relativistic intensity ($I\lambda^2 \approx 10^{19}$ Wcm$^{-2}\mu$m^2) incidences on a plane target at a large angle ($\theta \approx 70°$). In this case, strong quasi-static magnetic and electric fields are generated at the surface layer. They confine the electrons in a potential well near the target surface and the electrons are resonantly accelerated by wiggling inside the static fields and laser fields [4].

While application of this effect has been reported for fast ignition by electrons [5], the influence of the surface current on ion acceleration has not been studied in detail yet. Moreover, in the case of a conical target considered in Ref. [5], the laser light focusing by the conical surface and the hot electron focusing induced by their currents to the tip of the cone cannot be well distinguished.

Previous papers related to a flat foil, such as Refs. [1] - [3], were concentrated entirely on a transport of electrons along the target surface, whereas our objective is to investigate the effect of the surface guiding of electron current on a fast ion emission in the foil by using 2D PIC simulations.

2. SIMULATION METHOD AND PARAMETERS

To asses the effect of the surface electron guiding on ion acceleration, two simulation setups were chosen. Our relativistic colisionless particle-in-cell code in two spatial directions and with three velocity components is described in Ref. [6]. The first simulation corresponds to the large angle of incidence of the laser pulse to a foil of 75°, the second to a smaller angle of 30°. Other simulation parameters are similar for both runs. A fully ionized foil of size $77.27\lambda \times 2\lambda$, consists of electrons and protons of the initial density 20 n_c. Additionally, to enhance the absorption of laser energy, a density ramp has been introduced with the exponential profile on the front side of the target with the density scale length $L = 0.1\lambda$. Note that a longer density scale length would destroy electron guiding along the target surface, because the dominant absorption mechanism would change from $J \times B$ heating, necessary for forming of the electron surface current, to resonance absorption [3].

The initial plasma temperature is 1 keV and the cell size is set to 20 nm. Absorbing boundaries for fields are applied [6]. Electrons reaching the simulation box boundaries are frozen there. The simulation box have to be sufficiently large to avoid protons reaching the simulation box boundaries and the formation of a high accelerating electric field by the frozen electrons. A p-polarized laser pulse at the wavelength $\lambda = 1.0\ \mu$m has a super-Gaussian profile in the perpendicular plane with the beam width 10λ at half maximum. The temporal laser pulse profile has a trapezoidal shape with a constant maximum intensity 3.4×10^{19} W/cm^2 (the dimensionless amplitude $a_0 = 5.0$) of duration 20τ (in laser periods, 67 fs), and two linear ramps of duration 5τ (17 fs) at the beginning and at the end of the pulse.

3. RESULTS AND DISCUSSION

It is widely accepted now that the ions are accelerated in the electrostatic sheath formed on the rear target side. The strength of the electrostatic field formed by hot electrons can be estimated as $E_{ac} \simeq \sqrt{n_h T_h/\varepsilon_0}$ (here n_h and T_h stand for the density and average kinetic energy of hot electrons). It is often considered that the hot electron temperature cannot exceed the ponderomotive energy, i.e. $T_h \approx m_e c^2(\sqrt{1+a_0^2} - 1)$ [7], and the hot electron density cannot exceed the critical density. However, these parameters could be controlled by choosing the target shape and interaction conditions. The electrons confined at the front surface layer may interact with laser fields many times, which would result in a temperature higher then the ponderomotive energy. Moreover, the hot electron density n_h can be enhanced by target geometry. Thus, with increasing T_h and n_h, higher sheath electric fields are expected, which will be translated in higher energies of accelerated ions.

To confirm these qualitative considerations, we compare simulations with two different laser beam incidence angles. The proton energy spectra at the time of about 250 fs after the interaction of the laser pulse with the center of target are shown in Fig. 1. The spectra are measured in the rectangular area of width 1.75λ perpendicular to the surface in the center of foil on its front, rear sides, and on lateral sides.

In Fig. 1b, a very high cutoff energy of protons (27 MeV) on a lateral side of the foil compared to the cutoff energies on the front and rear foil sides (8 MeV and 5 MeV, respectively) indicates a high accelerating electric field formed by hot electrons and, thus, confirms the existence of an intensive lateral electron transport from the interaction region to the foil edge. A significant part of hot electrons is transported along the surface between the foil front and laser specular direction as proved also experimentally [2]. Our simulation reveals that some energetic electrons cross the foil and are guided along the rear surface layer. However this effect is much weaker than the front foil side guiding, which is in agreement with very recent experimental results [8].

Also a very strong right-left asymmetry is found. The ions are accelerated very efficiently from the right lateral face, while there is no protons with energy larger than 1 MeV emitted from the left lateral face.

There is also a strong front-rear asymmetry. As a result of an efficient electron confinement, proton acceleration is inhibited from the rear side, see Fig. 1b. This is a signature of a very weak transport of hot electrons across the foil. The proton acceleration from the front side is strongly suppressed by ponderomotive force pushing electrons inside target. Nevertheless, protons are more efficiently accelerated at the front side than at the rear side, which is opposite to what usually observed at small incidence angles.

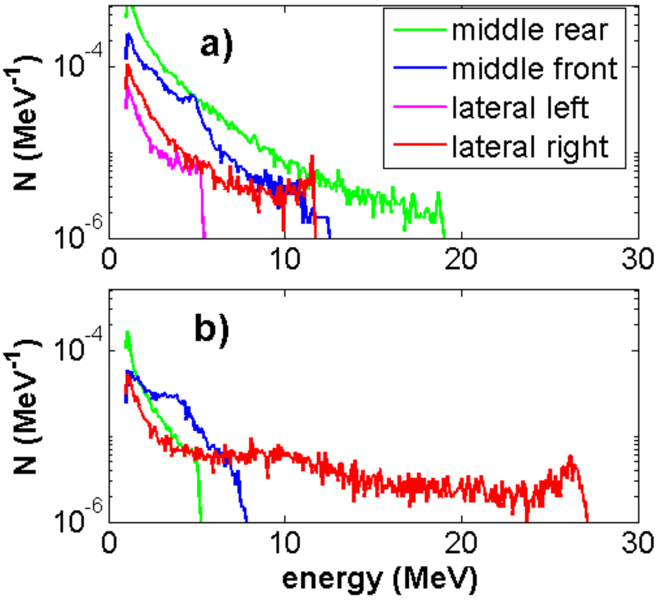

Figure 1: Proton energy spectra for angles of incidence a) 30°, b) 75°. Only protons with energy higher then 1 MeV are taken into account. In the case b), lateral proton emission from the left side is very weak and the cutoff energy of protons is about 0.7 MeV there. Lateral right side is in the direction of the laser wave vector projection onto the front target surface.

The proton spectra obtained for the oblique incidence at small angle are shown in Fig. 1a. These spectra are qualitatively the same as in many experiments. A strong proton acceleration is observed from the rear side of the foil (cutoff energy 19 MeV) compared to the front side (13 MeV) and lateral sides (12 MeV on the right and 6 MeV on the left) where is less asymmetric than for larger incidence angle. Fluence of accelerated protons with kinetic energy greater than 1 MeV is more than two times higher on the rear foil side than on the front and more than two times higher on the lateral right side than on the left. The fluence is seven times higher on the rear side, three times higher on the front side, and similar on the right lateral side for smaller than for larger angle. For lateral sides, proton energy flux is evidently higher (almost three times) in the case of larger angle. The energy flux is two times higher on the rear side for smaller angle than on the right lateral side for larger angle.

The simulations reveal that a lateral electron transport also takes place for a smaller angle of incidence, but a fraction of confined electrons decreases with the angle as well as it has been already investigated in Ref. [2]. On the other hand, electrons can be also transported towards lateral sides due to hot electron recirculation in a thin foil [7]. Hot electrons passed through the target are reflected in the expanding Debye sheath, which means a reduction of the axial component of electron velocity while the transverse velocity is largely unaltered. Then, a strong electrostatic fields formed by expanding electrons lead to ionization and ion acceleration even outside the focal spot (including lateral sides of the foil) as measured experimentally [9].

4. CONCLUSIONS

An effective ion acceleration is demonstrated from the edge of a foil in the direction of the laser wave vector projection onto the front target surface for the case of a large incidence angle of an intense femtosecond laser pulse on a foil. Two 2D PIC simulations were performed, the first with the angle of incidence equal to 30°, the second with the angle 75°, other parameters are the same for both runs. Comparing proton energy spectra on the foil front, rear, and lateral sides, substantial differences have been found. For the first case with the angle of incidence typical for many previous experiments, the ion acceleration is the most efficient on the rear side of the foil in agreement with observations. In the second case, a strong electron current is guided along the foil front surface and also a somewhat weaker current is guided along the rear surface. A large fraction of hot electrons is confined at the target surface and hot electron recirculation through the foil is strongly inhibited. This results in an additional resonant acceleration of confined electrons by laser pulse and their efficient transport to the foil edge. Consequently, a higher sheath electrostatic field is formed which results in a higher cutoff energy of protons emitted from the lateral side of the foil.

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References

[1] T. Nakamura, S. Kato, H. Nagatomo, and K. Mima, Phys. Rev. Lett. **93**, 265002 (2004)

[2] Y. T. Li, X. H. Yuan, M. H. Xu *et al.*, Phys. Rev. Lett. **96**, 165003 (2006)

[3] Y. Y. Ma, Z. M. Sheng, Y. T. Li *et al.*, J. Plas. Phys. **72**, 1269 (2006)

[4] T. Nakamura, K. Mima, H. Sakagami, and T. Johzaki, Phys. Plasmas **14**, 053112 (2007)

[5] Y. Sentoku, K. Mima, H. Ruhl *et al.*, Phys. Plasmas **11**, 3083 (2004)

[6] J. Psikal, J. Limpouch, S. Kawata, and A. Andreev, Cz. J. Phys. **56**, B515 (2006)

[7] Y. Sentoku, T. E. Cowan, A. Kemp, and H. Ruhl, Phys. Plasmas **10**, 2009 (2003)

[8] X. H. Yuan, Y. T. Li, M. H. Xu *et al.*, Opt. Express **16**, 81 (2008)

[9] P. McKenna, D. C. Caroll, R. J. Clarke *et al.*, Phys. Rev. Lett. **98**, 145001 (2007)