35th EPS Conference on Plasma Phys. Hersonissos, 9 - 13 June 2008 ECA Vol.**32D**, P-4.138 (2008)

Ultrathin foil irradiated by circularly polarized laser pulse as an efficient source of quasi-monoenergetic ions

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1. INTRODUCTION

Collimated beams of energetic ions accelerated from thin foil targets irradiated by short laser pulses are interesting for various applications, e.g. radiography, isotope production, isochoric heating. As most applications require a narrow energy spectrum of ions, it is desirable to produce quasi-monoenergetic ion beams efficiently. The beam energy distribution resulting from the TNSA process, which is responsible for acceleration of ions in most experiments, is usually exponential and tailoring its shape might be difficult and not really efficient. In this paper, an alternative and a fairly efficient mechanism capable of producing monoenergetic bunches of ions of varies species is presented and studied using one- and two-dimensional particle simulations.

2. DESCRIPTION OF THE ION ACCELERATION PROCESS, 1D PIC SIMULATION

The presented ion acceleration mechanism takes place in the radiation pressure dominant regime at the front side of the target and it can be described by the momentum transfer from the laser beam to ions. This momentum transfer is maximized when an ultrahigh contrast circularly polarized laser wave is normally incident on the surface of overdense foil, in which case most electron heating mechanisms (resonance absorption, vacuum heating, heating by the oscillating ponderomotive force) are inefficient and the laser beam is largely reflected. The laser pulse momentum is transferred to electrons via the ponderomotive force and subsequently to ions via the strong quasistatic electric field resulting from the space-charge separation. This is demonstrated in the ion phase space and the spatial electrostatic field profile in Fig. 1. The figure comes form 1D PIC simulation, in which 200 nm thick foil composed of C^{6+} ions with the density of 3.5×10^{22} cm^{-3} is irradiated by 80 fs long circularly polarized laser pulse with intensity of

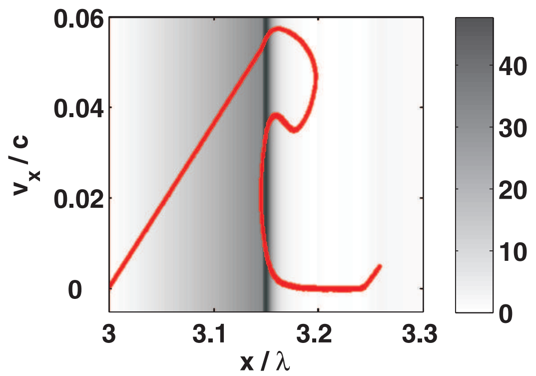

Figure 1: Ion phase space (red) and electrostatic field strength in TV/m (gray color transition in the background) in the early stage of ion acceleration. For 1D PIC simulation parameters, see the text.

3×10^{20} W/cm^2 and wavelength 800 nm. As the electron heating is inefficient, TNSA process is negligible in comparison with ion acceleration at the front side of the target (left side).

The acceleration process is accompanied by the ballistic evolution of the target itself. Accelerated ions cross the region of strong electrostatic field at the front side and propagate further with constant velocity. At the same time, electrons are pushed further into the target by the ponderomotive force and the process continues by acceleration of the next layer of still stationary ions. This process is repeated several times until the full thickness of the foil is accelerated.

Provided that the laser irradiation of the target still continues, the acceleration process proceeds further, but now it takes place in the frame moving with the average ion velocity. At the front side of the propagating ion bunch, ions are accelerated in the electrostatic field. Their velocity becomes higher than the velocity of the bunch and they propagate through the bunch to the back side. Meanwhile, the velocity of the bunch (the average velocity of ions) increases and the ions at the back side become slower than the bunch. These ions are overtaken by the bunch and they get to the front side, where they are again accelerated. This process is characterized by a series of loops in the ion phase space. During this ion acceleration stage the velocity spread of ions and the volume of the ion bunch are conserved but the average velocity of the bunch increases. The energy distribution of ions thus shows a relatively narrow peak at high energy at the end of the laser target interaction.

Moreover, the combination of front side acceleration and ballistic evolution naturally results in acceleration of the target composed of any sort of ions to a well defined macroscopic velocity just like in the case of a single species target. A higher charge to mass ratio of lighter ions is compensated by a shorter time of their presence in the acceleration layer which is con-

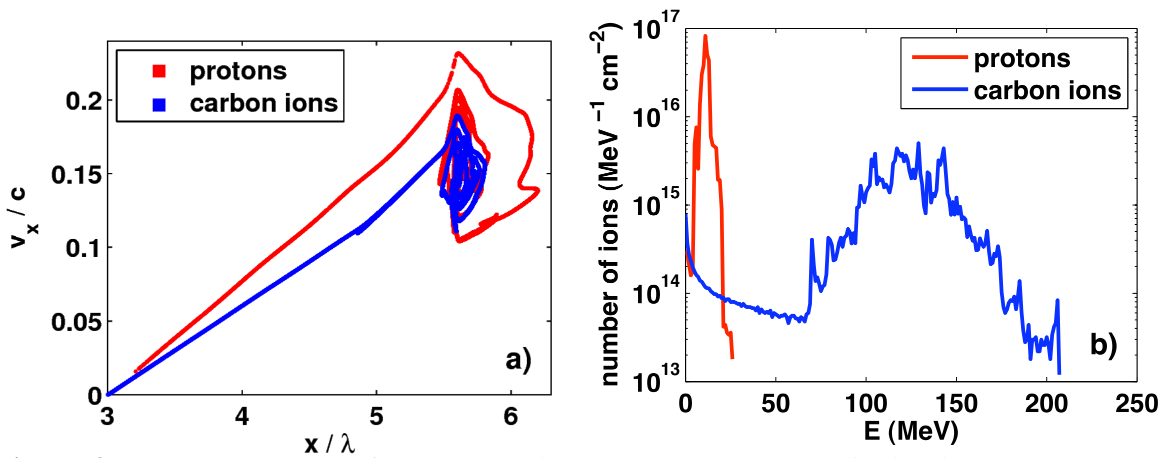

Figure 2: The phase space of accelerated ions a) and the energy distributions b) at the end of the acceleration process. The simulation parameters are same like in Fig. 1 with exception that the target is composed of CH_2 (with same mass density).

fined at the front side by the heavier ions. As all ions irrespective of their charge to mass ratio attain approximately the same velocity, the heavier ions attain much higher energy. Therefore, this acceleration mechanism is especially interesting for heavy ion acceleration even if the target surface is contaminated by lighter ions, the case where the other existing mechanisms are usually inefficient.

The phase space of ions and their energy distributions at the end of the acceleration process are demonstrated in Fig. 2. This figure results from 1D PIC simulation with 200 nm plastic foil and the same laser parameters like the simulation in Fig. 1. The density of C^{6+} ions of 7.5×10^{21} cm^{-3} and two times higher density of protons is used here.

3. 2D SIMULATIONS

The acceleration process gets more complex in multiple spatial dimensions. The front side electrostatic field (the ion acceleration force) depends on the local laser radiation pressure. To produce a quasi-monoenergetic beam of ions, a flat top or at least Super-Gaussian laser intensity profile in the focus is required. However, even with such intensity profile, acceleration of ions to very high velocities is complicated, as a long acceleration distance is required. Moreover, the radial dependence of the acceleration force results in hole boring (see Fig. 3 panel a) which is accompanied by efficient electron heating due to oblique laser incidence on the density profile in the hole. Efficient electron heating may cause rapid explosion of the target and widen the energy distribution of ions. Thus, the laser target interaction should be terminated before the hole in the target becomes too deep in order to preserve the narrow peak in the energy distribution of ions.

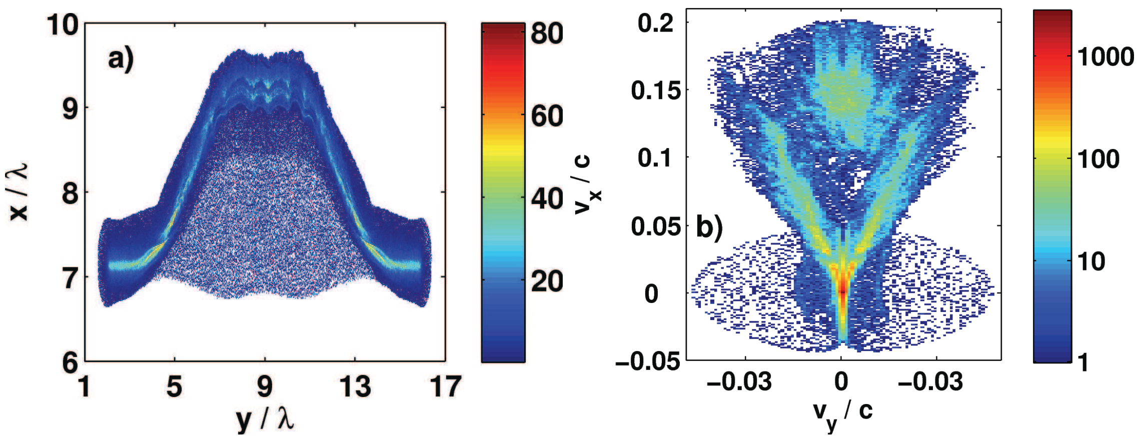

Figure 3: The density of carbon ions multiplied by the charge and normalized to critical density a), and the velocity distribution of carbon ions b) at the end of the acceleration process in 2D PIC simulation. The simulation parameters are the same like in Fig. 1.

Nevertheless, the ion acceleration process may work similarly like in one-dimensional geometry for a sufficiently long time at least in the focal region. This is demonstrated in the velocity distribution of ions at the end of 2D PIC simulation in Fig. 3 panel b). The simulation parameters are the same like in 1D simulations and the quasi-monoenergetic bunch of ions has average velocity of about $0.15c$. This bunch is relatively good collimated and the slower ions form a ring structure around it because they originate from the radially expanding borders of the hole.

4. CONCLUSIONS

In this paper, we study novel mechanism of monoenergetic ion beam generation based on the interaction of a short intense circularly polarized laser pulse with an ultrathin overdense foil. This mechanism may be suitable for acceleration of heavy ions where other existing mechnisms are inefficient. The formation of quasi-monoenergetic spectrum results from combination of ion acceleration in the electrostatic field at the front side of the foil and ballistic evolution of the target itself. Unwanted electron heating is suppressed by using circular polarization, high intensity contrast and normal incidence. All species of ions attain nearly the same velocity irrespective of their charge-to-mass ratio and contamination of target by light ions is not a hinderance for acceleartion of heavier ions. In multiple dimensions, the main obstacle is curving of the front surface of the foil under the radial profile of the laser pulse intensity. Presented ion acceleration mechanism has been recently independently proposed and studied in [1, 2, 3, 4].

Acknowledgments

This work was supported by the Czech Ministry of Education, Youth and Sports under project No. LC528. and by the Czech Science Foundation under project No. 202/06/0801. The authors are grateful to John von Neumann Institute in Juelich, Germany, for computational capabilities.

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