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Production of collimated high-current ion beams using skin-layer ponderomotive acceleration at relativistic laser intensities

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Abstract

Generation of fast proton beams by laser-induced skin-layer ponderomotive acceleration (SLPA) has been studied using a 2D two-fluid relativistic computer code and the time-of-flight measurements. It is found that the key parameter determining the spatial structure and angular divergence of the proton beam is the ratio d_L/L_n, where d_L is the laser beam diameter and L_n is the plasma density gradient scale length. When $d_L >> L_n$ and $d_L \geq 5\lambda_L$, a dense highly collimated MA proton beam with a proton current density approaching TA/cm^2 can be generated by SLPA even with a tabletop sub-picosecond laser. The possibility of focusing of a proton beam by curving the front target surface is demonstrated.

1. Introduction

Fast ion beams emitted from plasmas produced by the interaction of intense laser pulses with solid targets are currently a subject of growing interest due to the possibility of unique applications in various areas of science, technology and medicine. Some of the applications (e.g. high energy-density physics, fast ignition of inertial fusion, ion implantation or radioisotope production for PET) require ion beams of very high ion currents or/and current densities. A promising method of production of such ion beams is Skin-Layer Ponderomotive Acceleration (SLPA) [1, 2]. Our recent experiments [1, 2] have demonstrated that even at subrelativistic laser intensities SLPA can produce proton beams of the proton current density higher than those produced by Target Normal Sheath Acceleration (TNSA) [3 – 5] at relativistic intensities. However, for majority of high-ion-current applications, ion energies of tens or hundreds keV/amu, attainable at subrelativistic laser intensities are insufficient, and MeV ions are demanded. To produce such ions, relativistic laser intensities are necessary. In this paper, the possibility of generation of high-current collimated proton beams by SLPA at relativistic laser intensities is investigated using a 2D hydrodynamic relativistic code.

2. Results

In our model, the equations for a relativistic electron fluid and a non-relativistic ion fluid (i.e. continuity equations and energy-momentum equations) [6] are coupled to the equations for an electromagnetic wave in plasma given by the Faraday and Ampere laws. The interaction between the electron and ion fluids occurs through collisions and through the electric field induced by separation of the fluids. According to the basic SLPA scheme [1, 2], we numerically simulated the interaction of a sub-ps 1μm laser pulse, with a Gaussian shape in space (along the y-axis) and time, with an inhomogeneous, fully ionized hydrogen preplasma. The influence of the laser beam intensity I_L (range: $10^{16} – 10^{19}$W/cm^2) and diameter d_L (FWHM) as well as preplasma density-gradient scale length $L_n = n^o_{ec} \left(\partial n_e / \partial x\right)^{-1}_{x=x_c}$ on characteristics of the ion beam produced in front of the target was examined.

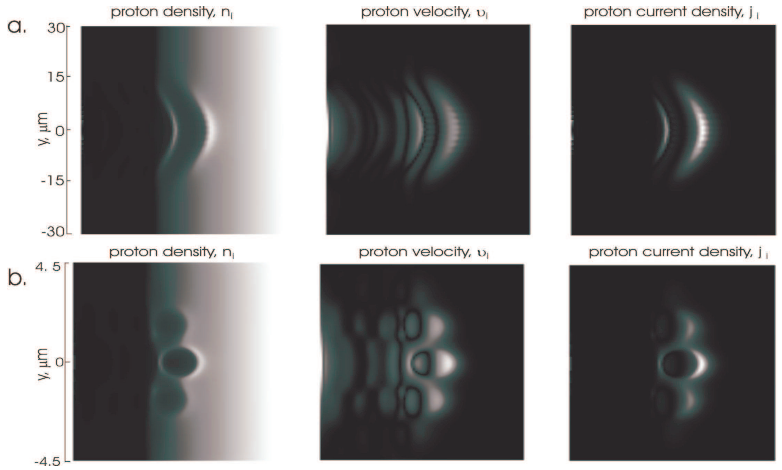

Fig. 1. Distributions of proton densities, proton velocities and proton current densities in the (x, y) plane at the final stage (t = 196fs) of the proton beam formation, for $d_L = 20$μm (a) and $d_L = 3$μm (b). $I_L = 3 \times 10^{18}$ W/cm^2, $\tau_L = 0.25$ps, $L_n = 0.75\lambda_L$.

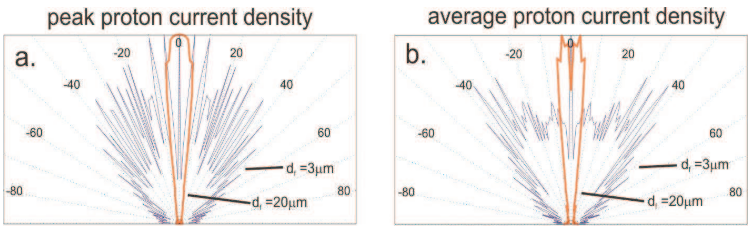

Fig. 2. Angular distributions of proton current densities at t = 196fs for $d_L = 3$μm and $d_L = 20$μm. The remaining parameters as in Fig. 1

Figs. 1 and 2 presents distributions of proton densities, proton velocities and proton current densities in the (x, y) plane as well as angular distributions of maximum and average proton current densities, at the final stage of the proton beam formation, for two values of the ratio d_L/L_n. It can be seen that in the case of high value of this ratio, $(d_L/L_n) \approx 27$ (large-aperture beam of $d_L = 20$ μm), the proton beam of low angular divergence and a Gaussian-like shape in the (x, y) plane is generated. However, when this ratio is small, i.e. $(d_L/L_n) = 4$ (the case of small-aperture beam of $d_L = 3$ μm), we observe a multi-bubble structure of the proton beam (bubble size ~ λ_L) and the angular divergence of the beam is large. This strongly inhomogeneous ion beam structure results from a fairly complex spatial distribution of the laser field near the critical surface. Since the laser beam aperture is small, this surface is significantly deformed by the laser beam and the overdense plasma surface of small radius of curvature (~ a few λ_L) is produced due to the hole boring effect. This curved surface reflects the laser light in various angles and the interference of the reflected waves with the incident wave creates a “two-dimensional” standing wave. Since $L_n \sim \lambda_L$, there is enough room in the plasma near the surface to accommodate at least one period of the standing wave in the plasma. The plasma is expelled by the ponderomotive force from the points where the laser field is close to maximum to the points where the field is close to minimum. As a result, a strongly inhomogeneous spatial distribution of plasma density, following roughly the (inverse) laser field distribution, is formed. In the case of large-aperture laser beam ($d_L >> \lambda_L$), the radius of the overdense plasma surface reflecting the laser light is large, so the reflection along the x axis dominates. As a consequence, ions are accelerated mostly in the x direction (both forward and backward). Such a quasi-planar acceleration takes place provided that the plasma density gradient scale length is sufficiently small, i.e. $L_n << d_L$, $L_n < \lambda_L$.

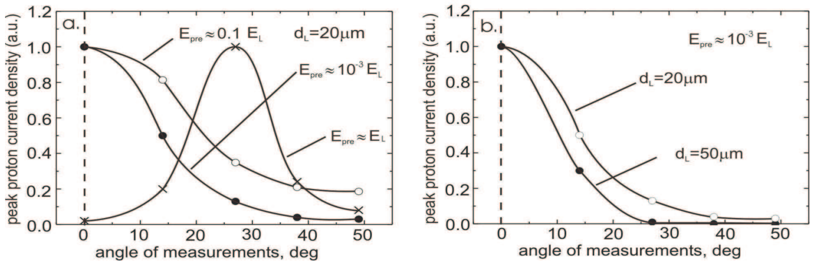

Fig. 3. Angular distributions of current density of protons emitted (backward) from Au target irradiated by laser beams of various prepulse energies E_{pre} (a) and various diameters d_L (b). $I_L \approx 0.6 \times 10^{17}$ W/cm^2, $\tau_L = 1$ps.

The importance of the d_L/L_n ratio in formation of collimated ion beams was confirmed by our time-of-flight measurements performed with the use of 1-ps laser pulse of subrelativistic intensity interacting with Au target – Fig. 3. One can see in the figure that an increase in both the laser pulse contrast ratio and the laser beam diameter results in a decrease of the proton beam angular divergence, in accordance with the hydrodynamic simulations.

Our simulations revealed that the proton current density (j_i) of large-aperture beam almost linearly increases with laser intensity in the range $10^{16} - 10^{19}$W/cm^2, and $j_i \approx$ TA/cm^2 at $I_L \approx 10^{19}$W/cm^2. Such laser intensity can be attained by focusing of 100 TW laser pulse (produced e.g. by a commercial tabletop laser) on the spot of diameter $d_L \sim 30 - 40$ μm. The total proton current in this case is equal $i_i \approx (\pi/4) d_L^2 j_i \sim 5 - 10$ MA.