3D simulation of hole-boring radiation pressure acceleration

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Introduction

Ultra-intense laser-plasma interactions are a well-known method to generate multi-MeV protons and ions. High quality ion bunches in the 100–1000 MeV range are motivated by a number of possible applications such as medical hadron therapy. Outstanding challenges include the generation of high-energy ion bunches with narrow-energy spread[1].

In the past few years, hole-boring radiation pressure acceleration (HB-RPA)[2-6] has generated great interest as method to generate high quality proton bunches with lower requirements on laser and target parameters as compared with radiation pressure acceleration (RPA) and sheath acceleration[7,8]. Theoretical studies have been reported confirming the effectiveness of this mechanism and enhancing our understanding of the HB-RPA mechanism[2-6].

Only 3D simulations model the transverse effects required to fully validate the results. However no 3D simulation work on HB-RPA proton acceleration has been reported up to now. In this report we present the generation of high quality GeV proton bunch from HB-RPA using, for the first time, three-dimensional simulation with the Particle-in-Cell code EPOCH[9]. It is found that the energy spectrum of the proton bunch has a sharp spike at more than 1.3 GeV with energy spread less than 28% for a laser pulse of peak intensity 4.0×10^{22} W/cm^2. The proton bunch contains 6.5 nC charge within a spot size of 2.9 micron full-width half maximum (FWHM), thickness of 0.8 micron and angular spread of 9.2 degree half-width half maximum (HWHM). The protons can thus be considered to originate from a point source.

Simulation conditions

The simulation window size was $X_w \times Y_w \times Z_w = 45\lambda \times 20\lambda \times 20\lambda$ with cell size $dX \times dY \times dZ = 0.04\lambda \times 0.05\lambda \times 0.05\lambda$, where $\lambda = 1$ µm was the laser pulse wavelength. A circularly polarised laser pulse with gaussian transverse and $\sin^2$ temporal profile with energy 170 J, pulse duration of 15 fs (FWHM) and focal spot of 2.5 micron (FWHM) was introduced along the laser-axis from the left of simulation window. The corresponding peak laser intensity was 4.0×10^{22} W/cm^2. The plasma was initialised as fully ionised hydrogen. The initial density of the plasma was $15n_c$. The targets were 20 micron thick (longitudinal direction) and 19 micron wide (transverse direction). 16 Macro-particles per species per cell were used. The initial temperature of both plasma electrons and protons was 10 eV.

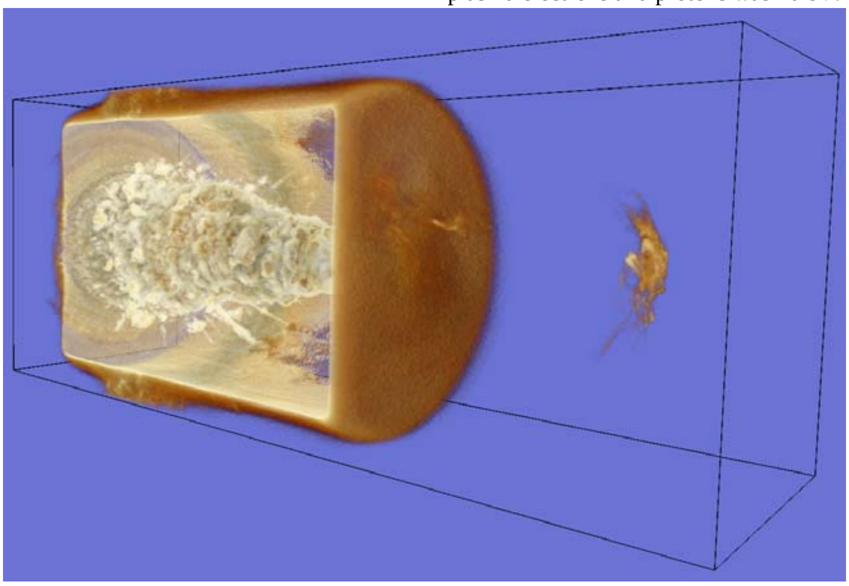

Figure 1. Three-dimensional proton density distribution at 150 fs into the simulation. Protons reflected off the hole-boring shock front are clearly seen exiting the plasma. The spot size of the proton bunch was 2.9 micron (FWHM) with thickness of 0.8 micron (FWHM).

High quality proton beam

Figure 1 shows the proton density distribution at a time of 150 fs after the laser pulse first enters the simulation box, well after the end of the laser plasma interaction. From this image, one can see that there is a hole-boring structure inside the target and a proton bunch of ultra-small size that has been accelerated and has already left the target. The spot size of the proton bunch was 2.9 micron (FWHM) similar to laser spot size with thickness of 0.8 micron (FWHM) and the total number of protons is 4.06×10^{10}. Figure 2 shows the spectrum and angular a proton bunch outside of the target at the same time. The proton bunch consists of upstream ions that have been reflected off the hole-boring shock. It is found that the peak energy is 1.32 GeV with energy spread less than 28% and the angular spread is 9.2 degrees (HWHM), which was calculated using $\theta = \tan^{-1}\left(\sqrt{v_y^2 + v_z^2} / v_x\right)$. Cattani's energy scaling[8] gives a proton bunch energy 590 MeV for the same plasma density and laser intensity used here, which is less than half of that from the simulation. The reason for the discrepancy will be pursued in further work.

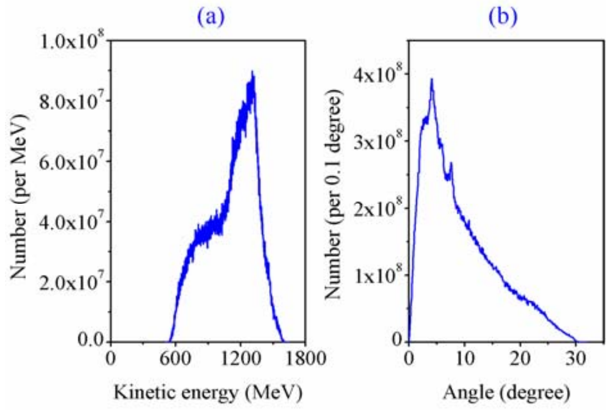

Figure 2. (a) Spectrum of the proton bunch, the peak energy is 1.32 GeV with energy spread less than 28%; (b) angular distribution of the proton bunch, showing an angular spread of 9.2 degree.

Figure 3 shows the phase space v_x-x of that proton bunch at regular intervals of 10 fs up to 150 fs. Only protons of kinetic energy above 90 MeV have been shown in this figure. From the figure one can see that the proton bunch is accelerated in an ultra-short time (on the order of 40-50 fs) from when the laser first hits the target (at around t = 20 fs). A stable proton bunch is thus generated after 70 fs.

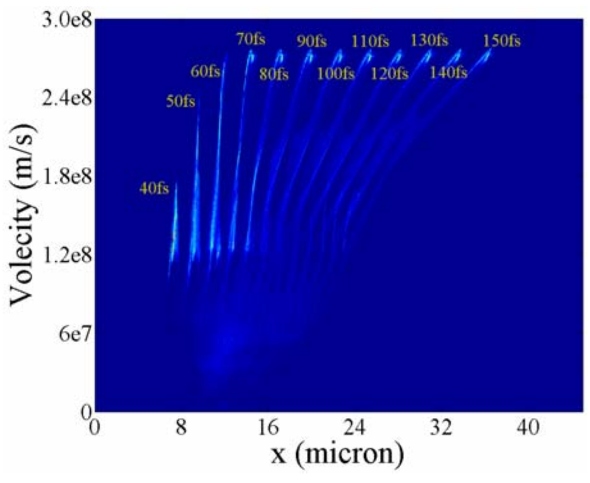

Figure 3. Proton phase space v_x-x at 10 fs intervals up to 150 fs into the simulation.

Conclusions

We have studied proton acceleration from an ultra-intense laser pulse interacting with near-critical density targets using 3D-PIC simulation. Proton bunches of more than 1.3 GeV with energy spread less than 28% can be accelerated by a laser pulse of 4.0×10^{22} W/cm^2 intensity. Also the proton bunch is high collimated with an angular spread less than 9.5 degree (HWHM). These small spot size and low emittance are ideal for numerous applications such as proton beam radiography of dense materials, or potentially injection into high-energy accelerator. Hence, this work motivates experimental work designed to generate high quality energy proton bunches by the hole-boring mechanism.

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