Ion beam control in laser plasma interaction

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Abstract. By a two-stage successive acceleration in laser ion acceleration, our 2.5-dimensional particle-in-cell simulations demonstrate a remarkable increase in ion energy by a few hundreds of MeV; the maximum proton energy reaches about 250 MeV. The ions are accelerated by the inductive continuous post-acceleration in a laser plasma interaction together with the target normal sheath acceleration and the breakout afterburner mechanism. An intense short-pulse laser generates a strong current by high-energy electrons accelerated, when an intense short-pulse laser illuminates a plasma target. The strong electric current creates a strong magnetic field along the high-energy electron current in the plasma. During the increase phase in the magnetic field strength, the moving longitudinal inductive electric field is induced by the Faraday law, and accelerates the forward-moving ions continuously. The multi-stage acceleration provides a unique controllability in the ion energy and its quality.

1. Introduction

Ion beam has been used in cancer treatment, ion beam inertial fusion, material sciences and other purposes, and has a unique preferable feature to deposit its main energy, for example, inside a human body, so that cancer cells could be killed by the ion beam [1, 2]. However, conventional ion accelerators tend to be huge in its size and its cost. In this paper a control of laser produced ion beam is discussed for a future compact intense-laser ion accelerator.

The issues in the laser ion accelerator include the energy efficiency from the laser to the ions, the ion beam collimation, the ion energy spectrum control, the ion beam bunching, the ion particle energy control, the intense-laser repetitive operation, the laser and target alignments, etc. The energy efficiency from the laser to ions was improved by using a solid target with a fine sub-wavelength structure [3] or by a near-critical density gas plasma [1, 2]. The ion beam collimation was realized by holes behind the solid target, and the ion beam bunching [2] was successfully realized by the target normal sheath acceleration (TNSA).

When an intense laser illuminates a target, electrons in the target are accelerated and leave from the target; temporarily a strong electric field is formed between the high-energy electrons and the target ions, and then the target ions are accelerated gradually. In this paper we discuss on the control of the ion energy spectrum and the ion particle energy based on a two-stage ion acceleration. A staged laser acceleration would provide a flexibility to control the ion beam quality.
2. Two-stage proton acceleration

Figure 1 presents our particle simulation model for the two-stage acceleration. In this specific case we employ the two identical plasma targets and the identical laser pulses. The Gaussian-laser pulse intensity is \(7.5 \times 10^{20} \text{W/cm}^2\), the pulse length is 30fs and the target density is \(0.7n_c\). The other parameter values are shown in Fig. 1.

When the intense laser pulse propagates through the plasma, it accelerates a part of electrons. The electrons form a high current and generate the azimuthal magnetic field around the laser axis. In the increase phase in the azimuthal magnetic field strength, the strong inductive electric field was generated by the Faraday law. The ions were accelerated by the inductive electric field inside the plasma, as well as the TNSA mechanism, the dipole vortex one \([4]\) and the breakout afterburner (BOA) one \([5]\).

Figure 2 shows the simulation results for the transverse magnetic field, the inductive acceleration field, the TNSA field and the magnetic vortex acceleration field at \(t=140\)fs and \(220\)fs for the first target illuminated by the first laser. At the later time, the BOA field or the charge-separation acceleration field appears as shown in Fig. 3. The phenomena in Figs. 2 and 3 are identical in the second target illuminated by the second laser. Figure 4 shows the history of the maximal proton energy in the two-stage acceleration. The proton energy reaches \(253\)MeV at \(t=3000\)fs.

In the first stage the TNSA, magnetic vortex and BOA accelerations contribute mainly to the proton acceleration in the first stage. In the second stage the inductive electric field inside the plasma target also contributes to the continuous proton acceleration. The TNSA and magnetic vortex acceleration fields also appear at the right side of the second target. In addition, the continuous BOA acceleration contributes to the further proton acceleration.

Figure 5 presents the energy spectra of the proton beam generated at the first target at \(t=1400\)fs and \(3000\)fs. At \(t=1400\)fs, the proton beam does not yet enter the second target, and then the beam protons are further accelerated in the second target. The energy spectrum at \(t=3000\)fs shows a preferable energy peak at around 250MeV.
3. Discussions and conclusions

In our work we employed the two targets and the two laser pulses for the staged laser ion acceleration. The staged acceleration provides a flexibility to control the ion beam quality, though the laser illumination timing and the second laser alignment with the proton beam generated by the first target should be taken care of.

In addition, the first laser should not give a serious influence to the second target. The target length was selected to optimize the proton acceleration efficiency and also to minimize the first laser ember effect to the second target. Actually in our simulations the first laser has successfully almost no effect to the second target. At the same time the first target debris should not affect seriously the second laser propagation. In this paper the distance between the two targets was selected in order to keep this effect small. During the second laser propagation, the first target debris was well removed. We have also checked these effects to obtain the effective post acceleration at the second target.

In order to realize a real laser ion accelerator for a daily use [2], the ion beam should be repetitively and stably generated, should be collimated [2, 6, 7], and also must be controlled well. The ion beam bunching [2] would be further required depending on the usage purpose. To this end, further studies are required [2, 8].

In this paper we have presented the two-stage laser ion acceleration and the remarkable ion energy increase as well as the mono-energetic spectrum. The present results shown in this paper would
demonstrate the flexibility of the multi-stage acceleration.

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