Since 2000, a great research effort has been devoted to producing laser-driven ion beams which are oriented to vast promising applications including tumor therapy, proton imaging, nuclear fusion, neutron source generation, and high energy density science. And several ion acceleration mechanisms are proposed, such as target normal sheath acceleration (TNSA), radiation pressure acceleration (RPA), hole-boring acceleration (HBA), collisionless shock acceleration (CSA), magnetic vortex acceleration (MVA), etc.

By the most studied TNSA mechanism, the foil is irradiated by intense laser whose energy is delivered to the electrons with J×B heating. Then ions are accelerated in the sheath field created by those superthermal electrons at the rear of the foil. Some applications, such as proton imaging and neutron source generation, are achieved by this concept. While TNSA is proved experimentally robust, its ion beams are charactered with large divergence and exponential energy spectrum, which limiting its efficiency and uses in other applications. Also studied a lot is the RPA mechanism which employs circular polarized laser to directly push the electrons with light pressure. And the whole plasma foil is accelerated as a “light-sail”. RPA is theoretically much more efficient and can produce beams with narrow energy spread. However, rigorous requirement in both laser and target condition make it difficult to practically apply RPA.

In previous researches on CSA, shocks are considered in one- or quasi-one-dimensional configuration. Namely, either periodic boundaries or very large laser focal spots are used. However, this one-dimensional approximation is unfair in experiments, because small focal spot is required for high laser intensity. On the opposite, shock must propagate a long-distance for efficient ion acceleration. As shown in this paper, finite laser focal size has important impact on the CSA scheme, which may stand in the way of implementation of CSA experiments.

introduction

Since 2000, a great research effort has been devoted to producing laser-driven ion beams which are oriented to vast promising applications including tumor therapy, proton imaging, nuclear fusion, neutron source generation, and high energy density science. And several ion acceleration mechanisms are proposed, such as target normal sheath acceleration (TNSA), radiation pressure acceleration (RPA), hole-boring acceleration (HBA), collisionless shock acceleration (CSA), magnetic vortex acceleration (MVA), etc.

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Benefited by nowadays high intensity large energy lasers, as well as great advances in producing near-critical plasma, alternative ion acceleration concepts may have chance to be proved in experiments. Among them, CSA is a promising mechanism which produces high-flux quasi-monoenergetic ion beams. Theoretic and numeric studies show that CSA has several advantages over TNSA or RPA, for specific, ion energy scaling linearly with laser intensity, relax requirement on laser condition, and high repetition rate. For experimental study, quasi-monoenergetic 1 MeV ion beam has been achieved by CSA with CO2 laser facility which, however, limited by its low intensity. In CSA, the ponderomotive force of laser pushes near-critical plasma to pile up a high-density spike. When the density ratio of spike and unperturbed plasma exceeds specific threshold (2.56), a collisionless electrostatic shock is exited and propagates with a constant velocity vs. As the plasma density jumps abruptly, a strong charge separation field is established at the shock front where upstream ions are reflected and accelerated to 2vs.

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We find that multi-dimension effect the 1D scheme in three aspects. Firstly, the high density downstream region local within laser spot size is prone to extent to non-irradiated region, which lowers its density when shock propagates and finally extinguishes the shock. Secondly, the superthermal electrons, essential for heating upstream plasma, diverts to ambient region, which lead to lower temperature and consequently lower shock velocity. Thirdly, intense laser usually filaments when propagates in near-critical plasma. These filaments easily get through the peak of density spike and greatly perturb the upstream, which distort the shock front and spoil the quality of ion beams. To mitigate these effects, it’s necessary to couple the near-critical plasma to proper confinements. Here, we propose and demonstrate by PIC simulations that a metal tube as the confinement can far improve both shock and ion beam quality.

In this paper, we at first point out the effects that could undermine the acceleration process by two-dimensional PIC simulation. Following that, we propose the confined-configuration to mitigate those effects. And the advance of the confined- over open-configuration is discussed. Finally, a new easy method of controlling plasma density profile is displayed by simulation.

model

In the one-dimensional model, laser irradiated at the near-critical plasma is reflected at critical density surface. As a result, the ponderomotive force of laser pushes the critical surface forward at velocity vhb termed hole-boring velocity. As critical surface moves, it swaps plasma along the way and piles up a high-density spike. This process creates the essential condition for launching a collisionless shock, namely, a density jump between spike and unperturbed plasma. The threshold of shock formation is obtained by kinetic analysis, where density ratio to be 2.56. After shock launches, it propagates at constant velocity vsh, or equally Mach number M=vsh/cs, where cs= is the ion-acoustic velocity in upstream. The density jump at the shock front also generate strong electrostatic field which forms potential barrier. In the frame of shock, upstream ions moving relatively to the shock front are reflected by the potential barrier. Back to laboratory frame, those ions are accelerated to 2vs. Each gains energy of e=2\*mi\*vs^2. This ion acceleration progress continues until shock lost most of its energy which origin from laser. Therefore, so long as shock keeps propagating stably, CSA could efficiently produce quasi-monoenergetic ion beams.

, where $Z$ is ion charge, $m\backslash M$ is electron**\verb**|\|ion mass, $n\_c$

We here begin with the 1D hydro-model.

Simulation Results

Numeric simulations are carried out using 2D PIC code EPOCH. The simulation box is set to be 400\*80um with