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MATTER AND RADIATION
AT EXTREMES

Matter and Radiation at Extremes xx (2017) 1–12

www.journals.elsevier.com/matter-and-radiation-at-extremes

Review Article

Optimization of hole-boring radiation pressure acceleration of ion beams for fusion ignition

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Received 30 April 2017; revised 8 September 2017; accepted 11 September 2017
Available online ■ ■ ■

Abstract

In contrast to ion beams produced by conventional accelerators, ion beams accelerated by ultrashort intense laser pulses have advantages of ultrashort bunch duration and ultrahigh density, which are achieved in compact size. However, it is still challenging to simultaneously enhance their quality and yield for practical applications such as fast ion ignition of inertial confinement fusion. Compared with other mechanisms of laser-driven ion acceleration, the hole-boring radiation pressure acceleration has a special advantage in generating high-fluence ion beams suitable for the creation of high energy density state of matters. In this paper, we present a review on some theoretical and numerical studies of the hole-boring radiation pressure acceleration. First we discuss the typical field structure associated with this mechanism, its intrinsic feature of oscillations, and the underling physics. Then we will review some recently proposed schemes to enhance the beam quality and the efficiency in the hole-boring radiation pressure acceleration, such as matching laser intensity profile with target density profile, and using two-ion-species targets. Based on this, we propose an integrated scheme for efficient high-quality hole-boring radiation pressure acceleration, in which the longitudinal density profile of a composite target as well as the laser transverse intensity profile are tailored according to the matching condition.

PACS codes: 52.38.Kd; 52.57.-z; 41.75.Jv; 52.65.Rr; 52.72.+v

Keywords: Laser-driven ion acceleration; Radiation pressure acceleration; Fast ignition; Inertial confinement fusion; High energy density; Hole boring

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1. Introduction

Efficient ion beam generation in the interactions of intense laser pulses with matters has attracted increasing attention during the last few decades due to their broad applications in fundamental science, medicine, and industry [1,2]. In contrast to conventional accelerators driven by radio frequency fields, laser-driven ion acceleration can afford an accelerating gradient as high as a few hundreds of GV/m. Profiting from this, future laser-driven ion accelerators shall have the advantages of more compact size, shorter bunch duration, higher particle density of the produced beams over the conventional

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Peer review under responsibility of Science and Technology Information Center, China Academy of Engineering Physics.

https://doi.org/10.1016/j.mre.2017.09.002

Please cite this article in press as: S.M. Weng, et al., Optimization of hole-boring radiation pressure acceleration of ion beams for fusion ignition, Matter and Radiation at Extremes (2017), https://doi.org/10.1016/j.mre.2017.09.002

accelerators [3,4]. These advantages are of particular importance to many applications, such as radiography and radiotherapy [5–7], high energy density physics [8,9], fast ion ignition [10] of inertial confinement fusion (ICF) and so on.

In particular, fast ion ignition [10] is an attractive variant of fast ignition of ICF [11] which may greatly save the driver energy and simplify the target fabrication for a future high gain fusion reactor [12]. However, a high-quality high-fluence ion beam is critically required for the fast heating of a precompressed high-density fuel target to a sufficiently high temperature [13]. First, the ion beam should have an energy fluence as high as 1.5 GJ cm^{-2} when arrives at the hotspot [14]. Secondly, the ion beam should have a narrow energy spread (usually $\Delta E/E \leq 20\%$) in the stopping power range (usually a few tens of MeV/u) of the precompressed fuel target in order to suppress the time-of-flight spread and deposit the majority of ion energy into the hotspot [15]. Thirdly, a high laser-to-ion energy conversion efficiency ($\geq$10%) is critically required for economic reasons [10]. Therefore, to date the efficient generation of such a high-quality high-fluence ion beam remains a key challenge.

Stimulated by these prospective applications, a variety of novel schemes have been proposed and refined for laser-driven ion acceleration over the past decades. Most of these schemes can be classified into the following main mechanisms: target normal sheath acceleration (TNSA) [16,17], acceleration at relativistic-induced transparency [18] or break-out-afterburner (BOA) ion acceleration [19], collisionless electrostatic shock acceleration [20–22], Coulomb explosion [23,24], radiation pressure acceleration (RPA) [25–35]. Among these schemes, the TNSA is the most studied mechanism in the experiments, and the proton cut-off energy of 85 MeV with high particle numbers has been recorded in a recent experiment [36]. However, the energy spectra of the accelerated ions in the TNSA usually have quasi-exponential profiles. To get quasi-monoenergetic ion beams, the RPA has been proposed [25–35]. In the RPA, the electrons of a solid target can be coherently pushed forward by the ponderomotive force of an intense circularly polarized (CP) laser pulse, which results in a strong charge-separation field for ion acceleration. According to the thickness of irradiated solid targets, the RPA appears in two distinct modes. If the target is an ultrathin foil, then the ions of this foil can be accelerated continuously as a sail since they move together with the charge-separation field. Theoretically, the ions can be accelerated up to GeV by this light-sail mode of the RPA [25–30]. If the target is a thick enough solid target, then the hole-boring mode of the RPA develops [31–35]. At first, the hole-boring process was extensively investigated as an approach to fast ignition since it allowed the laser pulse penetrating deeper into a precompressed fuel target in the ICF [11,37]. Later, a lot of numerical simulations demonstrated that fast ions can be efficiently produced in the hole-boring process of a CP laser pulse penetration into a thick dense target [31–35].

Compared with other laser-driven ion acceleration schemes, the hole-boring RPA has great potential to generate high-fluence ion beams for fast ion ignition of ICF and even for heavy-ion fusion [10,38–42]. The laser-driven ion acceleration is usually realized via a charge-separation field. In general, the fast electrons generated in laser-plasma interactions will create a double layer [43,44], in which a strong electric field is induced due to the charge separation. If the pulse duration is long enough, the double layer can act as a piston and accelerate the whole micro-foil to a high velocity [45]. The accelerated micro-foil, as a plasma block, is particularly interesting for innovative ignition schemes for ICF, such as block ignition and impact fast ignition [44,46]. With an ultrashort laser pulse and a relatively thick dense target, however, the ion acceleration mainly happens in an extremely narrow charge-separation layer with a thickness of a few microns. Consequently, only the ions at a specific layer can be accelerated. For instance, the ions can be accelerated at the rear surface of a solid target in the TNSA [16,17]. In the hole-boring RPA, however, the ions of a thick solid target can be accelerated layer by layer, and finally a kind of volume acceleration is achieved [47]. Theoretically, such a layer-by-layer acceleration can continuously go on, thus there is no limitation upon the accelerated ion number if the laser pulse and the target are long enough. However, there are still many unsolved issues with regard to the hole-boring RPA. For instance, it is still hard to control the intrinsic oscillation of the accelerating field [34,35], which may deteriorate the quality of the accelerated ion beam or even terminate the acceleration.

In this paper, we present an overview of the hole-boring RPA studies in theory and simulation. First, we will show the underlying physics of the hole-boring RPA. Then we will discuss the schemes proposed recently improving the quality of the accelerated ion beam in the hole-boring RPA in detail. In addition, we will propose an integrated scheme for the efficient high-quality hole-boring RPA under the laser and target conditions available soon. Finally we will present a summary and further discussions.

2. Mechanism of hole-boring radiation pressure acceleration

The mechanism of the hole-boring RPA can be explained by a 1D quasi-stationary laser piston model [35], which is verified by the particle-in-cell (PIC) simulation as shown in Fig. 1. At first, the ponderomotive force of a laser pulse (black curve) will push electrons (green curve) forward from ions. Then a strong longitudinal electric field (red curve) will be formed in the charge-separation layer between the electrons and the ions. Finally, the ions (blue curve) can be accelerated by this charge-separation field.

For simplicity, we first analyze the hole-boring RPA in the interaction of a CP laser pulse of a constant intensity I with a uniform cold plasma. In this case, a quasi-constant hole-boring velocity (the velocity of the laser-plasma interface) v_b can be expected. In the boosted frame moving with the laser-plasma interface, the radiation pressure delivered by the laser pulse to the laser-plasma surface can be estimated as [34].

$$P_\mathrm{L} = \frac{2I}{c}\frac{1-v_\mathrm{b}/c}{1+v_\mathrm{b}/c}, \tag{1}$$

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