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MATTER AND RADIATION
AT EXTREMES

Matter and Radiation at Extremes xx (2018) 1–8

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

Research Article

Self-modulation and anomalous collective scattering of laser produced intense ion beam in plasmas

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Received 23 July 2017; revised 22 November 2017; accepted 11 December 2017
Available online ■ ■ ■

Abstract

The collective interaction between intense ion beams and plasmas is studied by simulations and experiments, where an intense proton beam produced by a short pulse laser is injected into a pre-ionized gas. It is found that, depending on its current density, collective effects can significantly alter the propagated ion beam and the stopping power. The quantitative agreement that is found between theories and experiments constitutes the first validation of the collective interaction theory. The effects in the interaction between intense ion beams and background gas plasmas are of importance for the design of laser fusion reactors as well as for beam physics.

PACS codes: 52.38.Kd; 29.27.Fh; 52.40.Kh; 52.70.Nc

Keywords: Two stream instabilities; Ultra intense short pulse laser; Proton beam; Wake field; Electron plasma wave; Laser plasma interaction

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1. Introduction

Proper understanding of collective interaction between ion beams and plasmas is of prime importance for various fields, including the alpha particle interaction with gases in a laser fusion reactor chamber [1], beam propagation in the ion driven fast ignition scheme of inertial confinement fusion [2], collision of plasma bursts from super-nova with inter-stellar gases and collisionless shock wave generation [3–7], and charged particle beam dumping or scattering by gases [8,9]. Theoretical and numerical works have been done to predict collective ion beam-plasma interactions such as the two stream instability and the Weibel instability [3–5].

There are various ion beam instabilities in un-magnetized plasmas. Their growth rates depend upon the beam velocity relative to the ion acoustic velocity, the electron thermal velocity, or the speed of light, the beam velocity spread, the beam density relative to the ambient plasma density, and so on. When the ion beam velocity is higher than the electron thermal velocity, the characteristics of the instabilities are different whether the beam velocity is (1) non-relativistic, or (2) relativistic. In case (1), the instability characteristics are divided into the following two cases: (1)-1 The longitudinal and oblique electron plasma waves are excited by the coupling of a beam mode and an electron plasma wave [10], if the beam velocity spread is smaller than the resonance width of the coupling. It is the so-called "cold beam two stream

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https://doi.org/10.1016/j.mre.2017.12.004

Please cite this article in press as: K. Mima, et al., Self-modulation and anomalous collective scattering of laser produced intense ion beam in plasmas, Matter and Radiation at Extremes (2018), https://doi.org/10.1016/j.mre.2017.12.004

instability" ; (1)-2 On the other hand, when the ion beam velocity spread is larger than the resonance width, namely, the warm beam case, the longitudinal or oblique electron plasma waves and the Weibel mode are excited by the wave particle resonance, namely the "inverse Landau damping". In case (2), when the beam velocity is finite relatively to the speed of light, namely, $\frac{v_b}{c}$ is finite, both electrostatic modes and transverse electromagnetic modes are excited [2–7,11]. The transverse electromagnetic mode is called the "Ion Weibel Instability" [3–7]. Case (2) is relevant to the generation of collisionless shock waves [3–7] where beam density n_b is comparable to plasma electron density n_e.

Although the plasma stopping power of the ion beam from accelerators has been investigated by experiments [12], collective interactions of intense ion beams with hot dense plasmas have not been well investigated experimentally. It is mostly due to the fact that the involved phenomena require extremely large current ion beams such as the alpha particle stream in burning plasmas, or ion streams in the vicinity of super-nova or other particle streams related to extreme events [6].

The generation of intense ion beam by intense short pulse laser (ISPL), however, offers now the unique possibility to explore such collective effects in laboratory. Various mechanisms for ion acceleration by ISPL have been demonstrated experimentally [13–19]. The ion beams emitted as a short pulse from the target source, have naturally a wide energy spectrum and a large number (10^{11}–10^{13}) of particles produced in a single short bunch (ps at the source). The propagation of the laser produced ion beam in vacuum has been investigated in order to characterize the beam emittance, laminarity, and focusability [17,20–22] and to explore its possible applications [19,22]. Its interaction with matter has been proposed as a way to produce hot dense matter [19]. However, no work has addressed the issue of collective interaction of the laser produced ion beams with plasmas.

Here, taking advantage of the unique characteristics of proton beam produced by ISPL, namely its short duration at the source and large number of particles per bunch, we provide the first experimental evidence for the importance of collective interaction effects. It is indeed found that, depending on the beam current density, the characteristics of an ISPL produced high current proton beam could be modified after passing through a plasma jet. The results are found to be in agreement with theoretical predictions based on collective instability theory. In Section 2, we will present the results of our simulations to give the readers a sense of the expected instability growth behavior and its effects on the propagation of the beam. Then, we will show the experimental results (in Sections 3 and 4) as well as an analytical description of the instability that we have observed (in Section 5).

2. Hybrid simulation of ion beam-plasma instabilities

The previous simulations by Kato et al. [3] and Silva et al. [4] investigated the two stream instability for counter-streaming plasmas. In their cases, the growth rate of the electro-magnetic transverse instability like ion Weibel instability is comparable to that of the electrostatic instabilities. In particular, in the nonlinear regime, the magnetic field fluctuations are dominant. On the other hand, in the present laboratory experiments, the proton beam is weakly relativistic, namely $\frac{v_b}{c} \sim 0.1$ and the beam density is much less than the ambient plasma density. In this case, the electrostatic or weak electromagnetic instabilities are dominant and the nonlinear behavior of the proton beam is different from the previous cases [3,4]. In order to investigate the linear and nonlinear developments of the beam instabilities, we carried out large scale hybrid simulations [23] and compared the results with the experimental ones.

In our instability analysis, the proton beam density varies from 10^{-1} to 10^{-5} of the ambient plasma electron density and the beam energy is 4–10 MeV for comparison with the experiments discussed in Section 3. For the same reason, we fix the ambient plasma electron density to be 4×10^{19} cm^{-3}. When the proton beam propagates from the laser irradiation target to the gas jet, the proton beam pulse spreads in space and time. In the beam spreading process, the local velocity spread of the beam is reduced to be $\frac{\Delta v_b}{v_b} \sim \frac{\Delta d}{d} \sim \frac{\Delta t}{t}$, where Δd is the acceleration distance ~10μm, d is the distance between the proton source and the gas plasma ~4 mm, Δt is the acceleration time ~0.1 ps [24,25], and t is the time-of-flight from the source to the gas plasma ~50 ps. Then, the beam temperature in the interaction region is estimated to be $M\frac{(\Delta v_b)^2}{2} \sim 10^{-5} M\frac{v_b^2}{2} < 100$ eV. This is the reason that we assume the beam temperature is 100 eV in the simulation and it is consistent with the experimental findings [26].

The linear dispersion relation for the ion beam instability reported in the works [3,27,28] is solved numerically to observe the longitudinal and oblique mode growth rates. The growth rates for the ion beam instability of various ion beam densities are shown in Fig. 1, where the ion beam velocity spread is assumed to be 0.35%. When the beam density is higher than 0.1% of the plasma electron density, the growth rate is proportional to the cubic root of the beam density as shown by a broken line in Fig. 1(a), which represents the cold beam instability. On the other hand, when the beam density is much smaller than 0.1% of the ambient plasma electron density, the instability is due to the inverse Landau damping and the growth rate is proportional to the beam density. We note here that when the Doppler shift frequency due to the beam velocity spread $k\Delta v_b$ is larger than the cold beam growth rate which is actually the resonance width of the beam mode coupling, the instability becomes kinetic, namely, the instability is due to the inverse Landau damping.

As shown in Fig. 1(a), the maximum growth rate is higher than $10^{-4}\omega_{pe}$ when $\frac{n_b}{n_e} > 10^{-5}$ and is finite. For the plasma density of 4×10^{19}cm^{-3}, the growth length $\frac{v_b}{\gamma_{max}} \sim 0.7$ mm. Therefore, the electron plasma waves could grow significantly, if the plasma length is longer than a few millimeters, which is the case in our experiment and will be discussed later. Fig. 1(b) shows that the transverse wave number of the

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