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Collisionless shock experiments using large-scale laser systems
大型レーザーを用いた無衝突衝撃波生成実験

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A collisionless Weibel-instability mediated shock (Weibel shock) in a self-generated magnetic field is investigated using large-scale laser systems. It is predicted in two-dimensional particle-in-cell simulation that the generation of the Weibel shock requires to use hundreds of kJ high-power laser system. On OMEGA laser experiments with CH double-plane target, plasma parameters of counter-streaming flows are measured by collective Thomson scattering, and Weibel filaments are observed by D^3-He fusion produced proton radiography. On the National Ignition Facility, with CD double-plane target, DD neutrons at 7.1 ns after the laser turned off and strong x-ray emission from the hot plasmas in the middle of the two planes are observed. These results indicate that neutrons are produced in a shock.

1. Introduction

Collisionless shocks, in which coulomb mean-free-path is longer than the shock-front thickness, are often observed in space and astrophysical plasmas. It is believed that collisionless shocks are sources of high-energy particles or cosmic rays. In such collisionless plasmas, wave-particle interactions and collective effects play an essential role in the shock formation. However, there are significant uncertainties in the physics of particle acceleration by collisionless shocks. In addition to local observations of spaces plasmas by spacecraft and global emission measurements of astrophysical plasmas, a laboratory experiments can be an alternative approach to study the formation of collisionless shocks.

In this paper, we investigate the formation of Weibel-instability mediated collisionless shocks (Wiebel shock) in counter-streaming plasmas produced by large-scale laser systems.

Kato and Takabe investigated the collisionless Weibel shock in two-dimensional particle-in-cell (PIC) simulation using the injection method [1]. A scaling-law derived in the simulation revealed that high-density (electron density ~ 10^{20} cm^{-3}), high-flow velocity (~1000 km/s), and large volume (plasma length > 3 mm) plasmas are required to produce the collisionless Weibel shock [2,3]. In order to achieve these plasma parameters, a high-power laser system with energy of larger than hundreds of kJ or the word largest laser, the National Ignition Facility (NIF) laser (LLNL, USA), is required. We applied to the NIF facility time with “Collisionless shock generation mediated by Weibel instability in counter-streaming ablation plasmas by NIF (PI: Y. Sakawa)” in 2010, and it was approved. Before starting the NIF experiment, we conducted OMEGA laser (Rochester U., USA) experiment and measured plasma parameters such as electron and ion temperatures, electron density, and flow velocity of counter-streaming plasmas with collective Thomson scattering (CTS), and filamentary structure produced by the Weibel instability with proton radiography.

2. OMEGA experiment

Figure 1 shows the experimental configuration. 8 laser beams (351 nm (3ω), 1 ns, 4 kJ) were focused on each plane of CH double-plane target with 8-mm separation. It was observed using CTS measurements that electron density of $n_e \sim 5\times10^{18}$ cm^{-3} and flow velocity of v ~ 1000 km/s from each plane and electron and ion temperatures of $T_e \sim T_i \sim 1$ keV at 4 mm from the target (middle of the two CH planes) at 5 ns from the laser timing [4]. The presence of magnetic fields was detected using proton radiography as shown in Fig. 2(a). A proton source is generated by implosion of a SiO_2 capsule filled with D-^{3}He with 18 beams (~9 kJ total, 1 ns) producing 14.7 MeV proton [5]. Filamentary structures produced by Weibel instability are clearly seen parallel to the plasma flow direction. Planes of extended magnetic fields are also observed above and below the midplane as a result of the large-scale Biermann battery fields generated in the laser ablation process [6]. Figure 2(b) shows synthetic 14.7 MeV proton tracing from 3D PIC simulation [5]. The size of the Weibel filament spacing is nearly equal for the measured and simulated images. In OMEGA, we observed the Weibel instability filaments; the initial stage of Weibel shock formation. We need NIF to create fully formed collisionless shocks.

3. NIF experiment

We used 28 NIF beams (351 nm (3ω), 5 ns) to deliver 150 kJ to each plane of CD double-plane target (doped with 0.1% Fe/Ni, 6-mm separation). Neutron-yield diagnostics and x-ray spectral and imaging diagnostics were employed to evaluate the interaction region of the two interpenetrating plasma flows. We observed 3.7×10^{10} of 2.45 MeV DD neutrons at 7.1 ns after the laser turned off and strong x-ray emission from the hot plasmas in the middle of the two planes. These results indicate that delayed neutrons are produced in a shock. Proton backlight measurement was not conducted, since NIF has not operated this diagnostics yet. A mini-campaign for D-^{3}He proton backlight development has been discussed.

We continue the experiment one more year, and are applying for next call for proposals (FY2016-2017) with "Generation of collisionless shocks and magnetic fields on the NIF (PI: Y. Sakawa)".

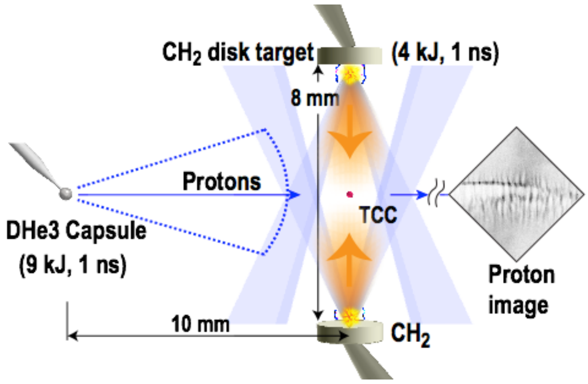

Fig.1. Schematic of OMEGA experimental setup.

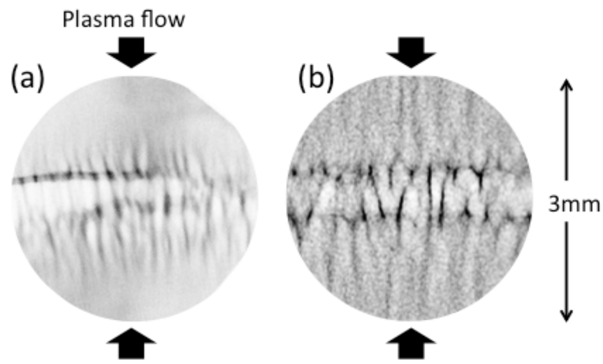

Fig.2. (a) Experimental and (b) simulated 14.7 MeV D-^{3}He proton images at 4.2 ns. The plasma flows enter the frame from the top and bottom [5].

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