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High-power laser experiments to study collisionless shock generation

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Abstract. A collisionless Weibel-instability mediated shock in a self-generated magnetic field is studied using two-dimensional particle-in-cell simulation [Kato and Takabe, Astophys. J. Lett. 681, L93 (2008)]. It is predicted that the generation of the Weibel shock requires to use NIF-class high-power laser system. Collisionless electrostatic shocks are produced in counter-streaming plasmas using Gekko XII laser system [Kuramitsu et al., Phys. Rev. Lett. 106, 175002 (2011)]. A NIF facility time proposal is approved to study the formation of the collisionless Weibel shock. OMEGA and OMEGA EP experiments have been started to study the plasma conditions of counter-streaming plasmas required for the NIF experiment using Thomson scattering and to develop proton radiography diagnostics.

1. INTRODUCTION

Collisionless shocks are observed in astrophysical plasmas. For example in a shock wave observed in a supernova remnant, a Coulomb mean-free-path is much longer than the shock-front thickness. Large amplitude turbulent waves and energetic particles are also observed in the shock environments. Diffusive shock acceleration is considered to be a standard model for non-thermal acceleration of energetic particles or cosmic rays in the universe. On the other hand, in astrophysical plasmas, there is no way to directly measure the key quantities to investigate the shock dynamics and the particle acceleration. One

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can observe the X-ray emission from the vicinity of the shock-front; however, there are significant uncertainties in the physics surrounding particle acceleration by collisionless shocks. A laboratory experiment can be an alternative approach to study collisionless shocks and particle acceleration.

In this paper, we investigate results of particle-in-cell (PIC) simulation and laboratory experiments using high-power laser systems to study collisionless shock generation in counter-streaming plasmas.

2. NUMERICAL STUDIES

Recent numerical and PIC simulation studies show that there are two possible collisionless shocks in unmagnetized plasmas: One is an electrostatic (ES) shock [1, 2], and the other is a Weibel-instability mediated shock in self-generated magnetic field [3, 4].

Kato and Takabe investigated the collisionless Weibel shock in two-dimensional (2D) PIC simulation using the injection method [3]. Both electrons and ions are located in the region between the two rigid walls at the left- and right-sides of the simulation box with the bulk flow-velocity of V in the +x direction (towards the right-wall) and reflected at the right-wall. Figure 1(a) shows the ion density normalized by the upstream (left-side) electron density n_i/n_{e0} at $\omega_{pe}t = 2100$ for $V = 0.45\,c$ (c is the speed of light) and ion-to-electron mass ratio of $m_i/m_e = 20$. Here, we take ω_{pe}^{-1} (ω_{pe} is the electron plasma frequency) as the unit of time and the electron skin depth $\lambda_e = c\omega_{pe}^{-1}$ as the unit of length. The upstream plasma flows from the left to the right and goes through the transition region, which has a filamentary structure, and then reaches the almost uniform downstream state at $x/\lambda_e > 1900$. Figure 1(b) shows the time evolution of n_i/n_{e0}. The transition region or shock front is visible as a steep increase in the ion density after $\omega_{pe}t \sim 500$. Figures 1(c) and 1(d) represent V dependence of x-profiles of n_i/n_{e0} and the energy densities of magnetic fields normalized by the upstream bulk kinetic-energy density U_B/U_{KE}, respectively. Here, $U_{KE} = n_{e0}\,(m_i + m_e)V^2/2$. As the unit of length we define the ion inertial length $\lambda_i = (m_i/m_e)^{0.5}\lambda_e$ in Figs. 1(c) and 1(d). We see that n_i/n_{e0} [Fig. 1(c)] profiles are almost independent of V, and U_B/U_{KE} [Fig. 1(d)] profiles show small variation with V. The widths of the shock transition region are W – 100λ_i in all cases. A strong magnetic field is generated at the shock transition region, and U_B/U_{KE} reaches 1 – 2%. This strong magnetic field provides an effective dissipation mechanism for this collisionless shock.

A scaling-law derived by changing V/c (= 0.1, 0.2 and 0.45) and m_i/m_e (= 20, 50, 100) in simulation revealed that high-density (electron density $\sim 10^{20}\,\mathrm{cm}^{-3}$), high-flow velocity ($\sim$1000 km/s), and large volume (plasma length $\sim$30 mm) CH plasmas (average mass number $A = 7.5$ and charge $Z = 3.5$) are required to produce the collisionless Weibel shock. In order to achieve these plasma parameters, NIF class high-power laser system is required. Using kJ-class laser system, only the collisionless ES shocks can be generated.

3. EXPERIMENT

Under international collaborations, we have performed several series of experiments on the high-mach number collisionless ES shock formations using Shenguang II laser system in China [5] and Gekkko XII HIPER laser system in Japan [6].

In Shenguang II experiment, in order to produce collisionless counter-streaming plasmas, a plastic (CH) double-plane target (100 μm in thickness and 4.5 mm in separation) was used, and 4 beams [352 nm (3ω), 1 ns, $\sim$260 J/beam × 4 beams, 150 μm in spot diameter, laser intensity $\sim 6 \times 10^{15}\,\mathrm{W/cm^2}$] were focused on the inner-surface of the 1st CH plane. A laser-ablated plasma is formed at the 1st CH plane, and the 2nd CH plasma is created by radiation and the plasma from the 1st CH plane. The interferograms and shadowgraphs were taken transverse to the main laser propagation direction using a probe laser [Nd: YAG laser, 527 nm (2ω), 70 ps] with ICCD cameras. As a result, a

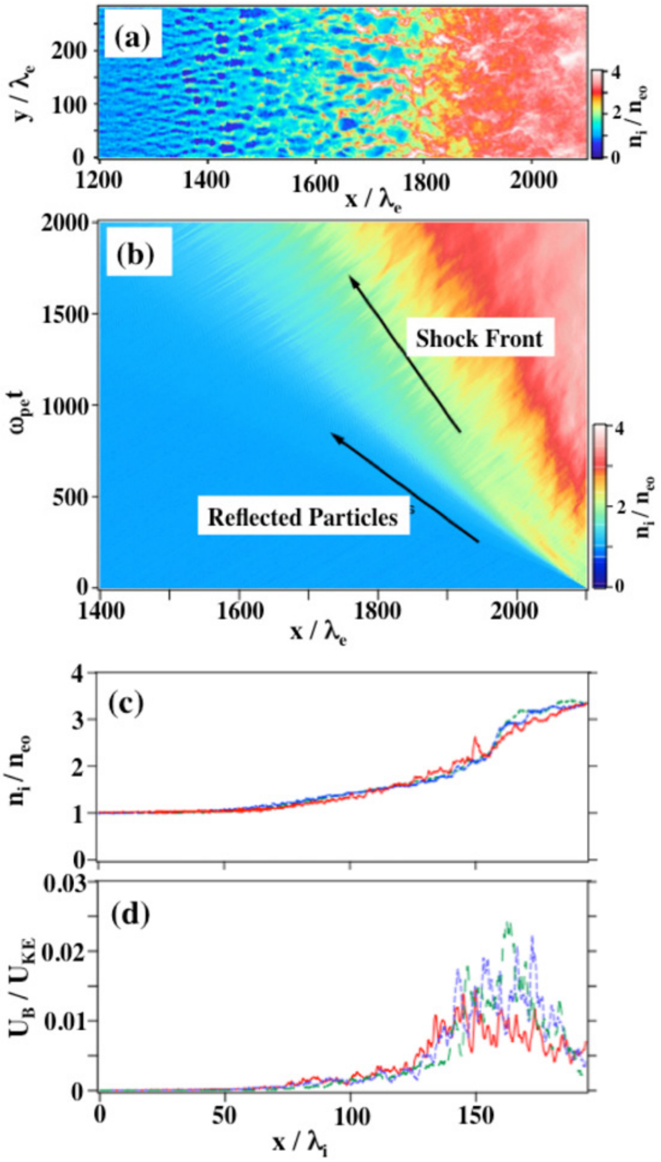

Figure 1. (a) Ion density profile at ω_{pe} t = 2100. (b) Time evolution of the ion density. The ion density is averaged over the y-direction. Profiles of (c) n_i/n_{e0} and (d) U_B/U_{KE} for V = 0.45 c (red solid curves), 0.2c (blue short-dashed curves), and 0.1c (green long - dashed curves) [3].

large density-jump with downstream- to upstream-density ratio of $n_1/n_0{\sim}3.9$ was observed at an ES shock, indicating a high Mach-number shock [5].

In Gekko XII experiment [352 nm (3ω), 500 ps, ∼100 J, 300 μm in spot diameter, laser intensity $\sim 3 \times 10^{14}$ W/cm^2], a CH double-plane target (60 μm in thickness and 4.5 mm in separation) was irradiated by a laser beam onto the inner-surface of the 1st CH plane as shown in Fig. 2(a) [6]. The plasmas and shocks were diagnosed transverse to the main laser propagation direction; shadowgraphy and interferometry using a probe laser [Nd: YAG laser, 527 nm (2ω), ∼10 ns] with ICCD and

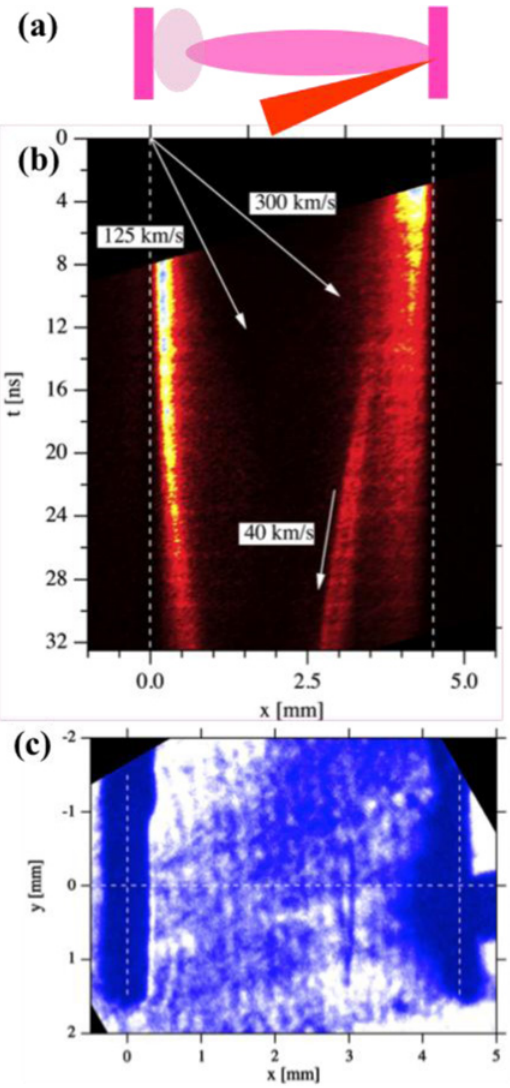

Figure 2. (a) Schematic of the double-plane target. Laser axis is 30° from the target normal. (b) SOP image. (c) Shadowgraphy snapshot at t = 25 ns [6].

streak cameras, and visible (450 nm) self-emission measurements with ICCD and streak cameras. Figure 2(b) shows streaked self-emission optical pyrometer (SOP) image. Counter-streaming plasmas were produced, and we successfully observed time evolution of an ES shock structure, which is clear at $x\sim 3$ mm by shadowgraphy [Fig. 2(c)] and self-emission measurement (not shown) [6].

In order to demonstrate the formation of collisionless shocks through the self-generated magnetic fields due to the nonlinearity in the growth of the Weibel instability, we have applied to the NIF facility time proposal 2010, “Collisionless shock generation mediated by Weibel instability in counter-streaming ablation plasmas by NIF” (PI: Y. Sakawa). It was approved as a combined experiment with “Laboratory simulation of cosmological magnetic fields and cosmic ray generation (PI: G. Gregori) as a three-year experiment, and the experiment will be conducted from ∼2013 when the required diagnostics, for example optical interferometry, are constructed.

We started OMEGA and OMEGA EP experiments [PI: H.-S. Park (LLNL) and PI: A. Spitkovski (Princeton Univ.)] to study the plasma parameters of counter-streaming plasmas required for the NIF experiment using Thomson scattering, and to develop proton-radiography diagnostics for the current filaments produced by the Weibel instability, self-generated magnetic field, and shock-structure measurements. In the OMEGA experiment, 10 laser beams (1 ns, 500 J/beam, $\sim 10^{16}$ W/cm^2) were focused on each plane of CH double-plane target with 8-mm separation. It was demonstrated using Thomson scattering measurements that a plasma with an electron density $\sim 10^{19}$ cm^{-3} and flow velocity $\sim$1000 km/s was created at 4 mm from the target (middle of the two CH planes) at $\sim$5 ns form the laser timing. Proton radiography using OMEGA EP laser with two long-pulse beams for counter-streaming plasma production [352 nm (3ω, 3 ns, $\sim$2.2 kJ/beam) and two short-pulse beams for two-channel proton radiography [1.05 μm(ω), 10 ps, 250 J/beam] showed interesting filamentary and shock-like structures.

4. SUMMARY

The collisionless Weibel-instability mediated shock in self-generated magnetic field is studied using 2D PIC simulation, and it is predicted that the generation of the Weibel shock requires NIF class high-power laser system. Collisionless ES shocks are produced in counter-streaming plasmas using lower-power laser systems: Shenguang II [5] and Gekko XII [6]. A NIF facility time proposal is approved to study the formation of the collisionless Weibel skock as a three-year experiment. OMEGA and OMEGA EP experiments have started to study the plasma conditions of counter-streaming plasmas using Thomson scattering and to develop proton-radiography diagnostics.

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