Laboratory Experiment to Study Collisionless Shock

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Abstract. We report the experimental results of collisionless shock formation in counterstreaming plasmas produced by a high-power laser system. The experiment was performed with Gekko XII HIPER laser system at the Institute of Laser Engineering. In order to model collisionless shocks in the universe, supersonic counterstreaming plasma flows were generated using a CH double-plane target. By using the self-emission measurements, we observed the emission increase toward the shock through the downstream. We also observed the density jump associated with the emission increase. The width of the transition region is shorter than the ion-ion mean-free-path calculated from the measured plasma velocity and density.

1. Introduction

Collisionless shocks are abundant in space and astrophysical plasmas, e.g., the Earth’s bow shock, interplanetary traveling shocks, and supernova remnants. It is considered that the first order Fermi acceleration or the diffusive shock acceleration (DSA) is a standard theory for nonthermal acceleration of energetic particles or cosmic rays in the universe. In many circumstances, space and astrophysical plasmas are collisionless, where the particle transport and relaxation are caused by wave-particle interactions. In space plasmas the electric and magnetic field, and plasma distribution functions, those are essential to understand the acceleration processes, are directly obtained by \textit{in situ} observations. The exponential growth of the proton and electron fluxes toward the interplanetary shock was observed \textit{in situ} \cite{1}. This is predicted by the DSA, and the above observation is recognized as an evidence of the DSA. On the other hand, in astrophysical plasmas there is no way to directly measure the key quantities to discuss the particle acceleration. Recently, the X-ray images of SN1006 showed the filamentary structures with the profiles of exponential growth \cite{2}. This indicates that the DSA can produce the nonthermal cosmic acceleration. However, there are many unknown parameters to prove the scenario of the DSA. A laboratory experiment can be an alternative approach to study the collisionless shocks and the particle acceleration. In this paper we report experimental
results of collisionless shock formations in counterstreaming plasmas produced by a high-power laser system, Gekko XII (GXII). Irradiating double CH (plastic) plane targets, we produced counterstreaming plasmas in order to excite a collisionless shock. By using gated optical imager and streaked optical pyrometry, the self-emission increase was observed during the two plasmas interactions. Furthermore, by using shadowgraphy a filamentary structure, which corresponds to a sudden density change, was simultaneously observed at the same timing and position of the self-emission increase. The mean-free-paths of the ions, estimated from the plasma density and the counterstreaming relative velocity, were larger than the shock transitions. These results strongly indicate the collisionless shock formation in the laboratory plasmas.

2. Experiment
The experiment was performed by GXII laser at the Institute of Laser Engineering at the Osaka university. The laser conditions were; the wavelength was 351 nm, the pulse length was 500 ps, the focal spot diameter was 300 µm, the pulse energy was ∼ 100 J. To produce counterstreaming plasmas, a CH double-plane target was irradiated with the laser. Figure 1 shows schematic drawing of the configuration of the laser and the double plane target. The both plane were 60 µm thick and the distance between the planes were 4.5 mm. The target normal is aligned 30 degrees from the laser propagation axis, so that the laser shot the right plane first then produced the ablation plasma at the front side of the right plane. The left plane is also ionized by the plasma, radiations and reflected light from the left plane.

The counterstreaming plasmas were observed by the transverse diagnostics with the probe laser and with the self-emission. The optical probe conditions were; the wavelength was 532 nm, and the pulse length was ∼ 14 ns. With the probe laser we obtained the density information of the two-dimensional snapshot by interferometry and shadowgraphy (250 ps gate width). We also measured the time evolution of the central plasma by streaked interferometry. Using 450 nm interference filters the self-emission was gated at the wavelength. We obtained the two-dimensional snapshot of the self-emission by gated optical imager (GOI) (1.6 ns gate width) and of the time evolution by self-emission streaked optical pyrometer (SOP). The slits of the streak cameras were also rotated in order to measure the time evolutions of the central plasmas.
3. Results

The two counterstreaming plasmas were seen in streaked interferogram (not shown). The density of the plasmas, obtained from interferogram before the plasmas occupied the hole field of view, $t \lesssim 5$ ns, was from $\sim 1 \times 10^{18}$ at the tip of the plasma to $\gtrsim 1 \times 10^{19}$ at the opaque region to the probe light. The plasma density is considered to decrease as the plasmas expand. Figure 2 (a) shows an SOP image where $t = 0$ is the main laser timing and the vertical dotted lines corresponds to the nominal target positions. The dashed arrows represent the fast plasma velocities estimated from the streaked interferogram taken on the same shot as Fig. 2 (a). In Fig. 2 (a) the fast plasma seen in streaked interferogram was not seen, but the plasma from the left plane went through the plasma from the right plane since the mean-free-paths of the fast counterstreaming ions are estimated as the order of meters, and then started to interact with the plasma staying around the right plane at $t \sim 12$ ns. The two stream interaction enhanced the self-emission at the interaction front and the sharp structure or shock propagated from right to left at 40 km/s. Figure 2 (b) shows the line profiles of 2 (a) at $t = 7, 13, 19,$ and 23 ns. At $t = 7$ ns the profile shows the emission increase gradually toward the right plane since there was no two stream interaction. At $t = 13$ ns, after the two plasmas interacted, a structure was formed at $x = 3.4$ mm. As time passed, the profiles became steeper and steeper, clearly showing the shocked structure. The shock transition width was typically $\sim 100\mu$m. The mean-free-path of ions is written as $\lambda_{ii} = 2\pi\varepsilon_0^2m_i^2\langle v_i \rangle^2/(n_iZ_i^2e^4\ln\Lambda)$, where $\varepsilon_0$ is the vacuum dielectric constant, $m_i$ is the ion mass, $\langle v_i \rangle$ is the average ion velocity, $n_i$ is the ion density, $Ze$ is the ion charge, $\ln\Lambda = \ln(\lambda_D^4\pi\varepsilon_0m_i\langle v_i \rangle^2/Z_i^2e^2)$, and $\lambda_D$ is the Debye length [3]. Using the relative velocities of the counterstreaming ions $165$ km/s $\leq \langle v_i \rangle \leq 340$ km/s, the mean-free-path for the counterstreaming flow is estimated as $0.4$ mm $\leq \lambda_{ii} \leq 4$ mm with $Z = 3.5$, a mass number $A = 6.5$, averaged values for a proton-carbon ion plasma, $n_e = Zn_i = 10^{18}$ cm$^{-3}$, and $T_e = 100$ eV. These are larger than the shock transition width.

Figures 3 (a) and 3 (b)–3 (d) show the snapshots of the shock structures by self-emission GOI.
Figure 3. (a) GOI snap shot at $t = 25$ ns. (b)–(d) Shadowgraphs at $t = 23, 25, 27$ ns taken on the same shot as Fig. 2 (a), and by shadowgraphy at $t = 23, 25, 27$ ns taken on different shots from Fig. 2 (a), respectively. In Fig. 3 (a) one can clearly see a filamentary emission increase or a bow-shock like structure in front of the right plane (marked by the circle). Besides the shocked self-emission structure, we observed thin structures correspond to the sudden density change in shadowgraphs in three different timing $t = 23, 25, 27$ ns in Figs. 3 (b)–3 (d) (marked by the circles). Furthermore, the thin structures in shadowgraphs moved toward the left at about the same velocity as the shock velocity observed in SOP of Fig. 2 (a). The self-emission increase observed by GOI and SOP associated with the large density change.

4. Conclusions
Two counterstreaming plasmas were created by irradiating the double-CH targets by GXII laser. The self-emission measurements showed the steepened structures as the counterstreaming interactions evolved. The shadowgraphs showed the thin structures corresponding to the large second derivative of the electron density. The position and the propagation speed of the thin structures were represented by the structure observed by self-emission, indicating the shock transition. The shock transition width is less than the mean-free-path of the counterstreaming ions. Our results strongly indicate the collisionless shock formation in counterstreaming laboratory plasmas.

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