Collisionless shock generation by a high-power laser

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Abstract. We report the experimental generation of an electrostatic collisionless shock in counter-streaming plasmas without an external magnetic field. The collisionless counter-streaming plasmas were created by a high-power laser. The expansion of plasmas was measured with interferometry and shadowgraphy. Large density jump was observed in both diagnostics. The density jump is the collisionless shock because the width of this jump is much shorter than the ion-ion mean-free-path calculated from flow velocities and densities. Particle-in-cell simulations suggest the formation of the electrostatic collisionless shock in the counter-streaming plasmas. In our experiment, considering the shock width, the observed shock is the electrostatic shock.

1. Introduction
Collisionless shocks have been studied for many years[1, 2]. The collisionless shock is an important subject in not only plasma physics but also astrophysics. Cosmic rays whose energy is less than $10^{15}$ eV are speculated to be accelerated around the collisionless shock surface in supernova remnants in our galaxy. There is, however, no experimental evidence with a model experiment even for the formation scenario of the collisionless shock and resultant particle acceleration. It is demonstrated that in the situation where counter-streaming plasmas are produced, collisionless shocks can be produced two different kinds of collisionless shocks can be produced. One is essentially one-dimensional and electrostatic shock[3, 4], and the other is collisionless shock based essentially on the multi-dimensional physics, namely mediated by nonlinearity of Weibel instability[5, 6].

In this paper, we present the experimental observation of the electrostatic collisionless shock generated in the counter-streaming plasmas without an external magnetic field using a high-power laser.
2. Experimental setup

The experiment was performed with Shengguang-II laser facility (Shanghai, China). There are eight main beams in which the energy is about 260 J/beam in 351 nm (3ω) and pulse width is 1 ns. Probe laser is a short pulse laser with the width of 70 ps in 527 nm (2ω). Figure 1 shows the top view of the experimental setup. Our targets consist of two thin CH foils. The size of each foil is 2 mm × 2 mm × 100 µm, and two foils are separated by 4.5 mm. Four beams were focused on the surface of one side of the CH foil with the incident angle of 60 degrees from the target normal direction with 150 µm diameter at intensity ≈ 6 × 10^{15} W/cm^2. In the optical path for Nomarski interferometry, a Wollaston prism was placed near the focal spot of the probe laser. This prism can split incident light into two orthogonal linearly polarized beams. Two polarizer were placed before the target chamber and after the Wollaston prism so that the two beams interfere at the photoelectric surface of an ICCD camera. In the shadowgraphy, the incident probe beam passed through the plasmas was directly detected by the other ICCD camera. In our experiment, four beams were used to ablate only one of the CH foils (first CH). The plasma from the other CH foil (second CH) was created by the radiation and/or the plasma from the first CH. In this way counter-streaming plasma flows are created between two foils and interact near the surface of the second CH. Interferometry and shadowgraphy were taken at same region and timing, and hence, the information of density profile and derivative of density gradient can be compared.

3. Result

Phase difference δθ between two rays (one passes through plasmas and the other passes through vacuum) is expressed by optical path length l as δθ = ω/(2n_ec) ∫ ne(l) dl[7], where ω is the frequency of the probe beam, c is the speed of light, n_c is the critical density and n_e is the electron density. Assuming that plasmas are created axially symmetrically, n_e can be calculated by Abel inversion method. Abel inversion is calculated with Bockasten’s method[8]. The range of n_e which can be calculated from interferometry is about 1 × 10^{18} – 5 × 10^{19} cm^{-3}.

Figures 2(a) and 2(b) show the interferogram and shadowgraph respectively, measured at 9 ns after the peak of the main laser (t = 9 ns). The horizontal axis x represents the distance from the surface of the first CH. In Fig. 2(a), the interference fringes suddenly shift and a large density jump exists near the second CH. Sudden brightness changes are observed in the shadowgraph at the same position where the density jump exits. The arrows in Fig. 2(a) and 2(b) indicate the x position of sudden brightness changes. The density profile calculated from Fig. 2(a) is shown in Fig. 2(c). Figure 2(d) shows the density profile at y = 3.5 mm in Fig. 2(c). A large density jump is observed at x ≈ 3.1 mm. The width of this jump is about 100 µm. Figure 3 shows the density profile (Fig. 3(a)) and the shadowgraph (Fig. 3(b)) measured at t = 5ns. Some fine structures vertical to the flow direction are observed near the second CH in Fig. 3(b) at x ≈ 3.6 mm. This means that there is a very large density gradient. The arrows in Fig. 3(a) and 3(b) show the horizontal position of the large density gradients. Assuming that the plasma from the second CH is created by the radiation and both plasma flows start moving at t = 0 with a constant velocity, flow velocity v_{first} of the plasma with
Figure 2. (a) The interferogram and (b) shadowgraph measured at $t = 9$ ns. $x = 0$ and 4.5 mm are the surface of the first and second CH foils, respectively. Four beams were focused on the first CH at $x = 0$ and $y = 2.5$ mm. (c) The density profile calculated from (a). (d) The density profile measured at $y = 3.5$ mm.

$n_e \simeq 2 \times 10^{18}$ cm$^{-3}$ from first CH is roughly estimated as $v_{\text{first}} = \Delta x / \Delta t \simeq 2.0$ mm/3.0 ns $\simeq 830$ km/s, and the velocity from the second CH ($n_e \simeq 2 \times 10^{18}$ cm$^{-3}$) is $v_{\text{second}} \simeq 0.7$ mm/3.0 ns $\simeq 230$ km/s from the data at $t = 3$ ns (not shown). The ion-ion mean-free-path $\lambda_{ii}$ is expressed as $\lambda_{ii} = m_i^2 v_i^4 / (8 \pi n_i Z_i^2 e^4 \ln \Lambda)$\cite{9}, where coulomb logarithm is calculated with following formula with reduced mass $m_\text{r} = (1/m_\text{first} + 1/m_\text{second})^{-1} = m_i/2$, $\ln \Lambda = \ln (4 \pi \epsilon_0 \lambda_D m_i v_i^2 / (Z_i^2 e^2))$, where $m_\text{first}$ and $m_\text{second}$ are the ion masses coming from the first and second CH, respectively, and $\lambda_D$ is the Debye length. From the values of relative velocity $\simeq 1060$ km/s and the electron density $n_e = 8 \times 10^{18}$ cm$^{-3}$, $\lambda_{ii}$ is calculated as $\lambda_{ii} = 35$ mm for the electron temperature $T_e = 1$ eV and 25 mm for $T_e = 1000$ eV. It is difficult to estimate $T_e$ in our diagnostics, however $\lambda_{ii}$ does not strongly depend on $T_e$. Since the width of the measured density jump at $t = 9$ ns ($\simeq 100 \mu$m) is much shorter than $\lambda_{ii}$, the counter-streaming plasmas created in our experiment is collisionless and this density jump is the collisionless shock.

4. Discussion and conclusion

Particle-in-cell simulations show two possibilities for generation of collisionless shock in counter-streaming plasma. One is electrostatic shock\cite{3, 4} and the other is “Weibel-mediated” shock\cite{5, 6}. In latter case, the dissipation mechanism is provided by the magnetic field generated by the Weibel instability. The width of density transition region is evaluated as $W \simeq 100 c/\omega_{pi}$ where $\omega_{pi}$ is the ion plasma frequency. In the experiment, $c/\omega_{pi}$ is evaluated as $\simeq 110 \mu$m for $n_e \simeq 8 \times 10^{18}$ cm$^{-3}$, and $W \simeq 11$ mm which is much larger than the observed structure. In the case of electrostatic shock, the width of transition region is evaluated as $0.5 c/\omega_{pe}$\cite{3}. The electron inertial length evaluated from the experiment is $\simeq 2 \mu$m in $n_e \simeq 8 \times 10^{18}$ cm$^{-3}$. The width of shock structure is larger than this electron inertial length, but this is due to the resolution of experimental instruments. From the narrowest fringe in interferogram, the resolution of interferogram is about 50 $\mu$m. As a result, the width of shock structure $\simeq 100 \mu$m
is reasonably regarded as the electrostatic collisionless shock.

In summary, counter-streaming collisionless plasma flows were created with Shenguang-II laser facility. The large density gradient was observed in both the interferogram and shadowgraph at the same position. The width of the density jump was less than 100 µm, which is much shorter than the ion-ion mean-free-path, and the jump is the collisionless shock.

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