High Energy Density Physics 23 (2017) 207–211

Contents lists available at ScienceDirect

High Energy Density Physics

journal homepage: www.elsevier.com/locate/hedp

Generation of counter-streaming plasmas for collisionless shock experiment

Y. Sakawa*,[a], T. Ide[a], T. Morita[b], K. Tomita[b], K. Uchino[b], Y. Kuramitsu[c], N. Ohnishi[d], H. Takabe[e]

[a] Institute of Laser Engineering, Osaka University, Suita, Japan
[b] Interdisciplinary Graduate School of Engineering and Science, Kyushu University, Kasuga, Japan
[c] Department of Physics, National Central University, Taoyuan, Taiwan
[d] Graduate School of Engineering, Tohoku University, Sendai, Japan
[e] Helmholtz-Zentrum Dresden-Rossendrof, Dresden, Germany

ARTICLE INFO

Article History:
Received 31 October 2016
Revised 28 April 2017
Accepted 29 April 2017
Available online 8 May 2017

Keywords:
Collisionless shock
Counter-streaming plasmas
Collective Thomson scattering
Double-plane target

ABSTRACT

The generation mechanism of counter-streaming plasmas, by irradiating an inner-surface of the 1st-plane of double-plane target, is investigated experimentally using optical imaging and collective Thomson scattering (CTS) ion-term measurement. The CTS measurement reveals that counter-streaming plasmas exist at the same time at the same position, which is the evidence for the collisionless interaction between the counter-streaming plasmas. The generation of the 2nd-plane plasma is in two steps: First, the 2nd-plane is ablated nearly at the laser timing by radiation from the 1st-plane plasma. Then $\simeq 5-7$ ns later, when the plasma from the 1st-plane reaches the 2ns-plane, it induces higher-density plasma generation.

1. Introduction

The physics of cosmic ray acceleration is one of the unsolved problems in astrophysics. It is believed that cosmic rays whose energy is less than $10^{15.5}$ eV are accelerated at collisionless shock in supernova remnants in our galaxy according to the observation of X-ray emission [1,2]. Therefore, collisionless shocks are important topic in astrophysics, and they have been investigated via observation, theoretically/numerically, and experimentally.

In collisionless shocks, the thickness of shock front is significantly shorter than ion-ion Coulomb mean-free-path. We can distinguish collisionless shock in three categories [3]: Magnetized or magneto-hydrodynamic shock (MHD shock) under an external magnetic field, electromagnetic turbulence sustaining shock (EM shock), and electrostatic shock (ES shock). MHD shock is ubiquitous in the space and astrophysical plasmas. EM shock is predicted to be mediated by self-generated turbulent electromagnetic field such as in gamma-ray bursts after glows [4]. The Weibel instability is a leading candidate for the generation mechanism of turbulent electromagnetic field and shocks [5]. ES shock is rare in the Universe. It may occur even with an external magnetic field under special conditions, such as in the auroral zones [6].

Experimental [7–9] and numerical/computational [10] studies on relatively low Mach-number ($M < 2$) collisionless ES shock using double-plasma device were conducted in 1970's. Experiments on ion acceleration in the radial direction to the incident high-intensity laser beam by a radial collisionless ES shock in an underdense plasma have been reported [11] in 2000's. Recently, numerical simulation has revealed ion acceleration at a relativistic ES shock generated in an overdense plasma due to reflection of ions in the upstream region by the shock front [12], and mono-energetic proton acceleration by ES shock has been investigated experimentally [13].

Basic physics of collisionless ES shock has been studied experimentally using high-energy laser systems, and two schemes for the generation of collisionless ES shock have been investigated: One is an interaction between laser-produced high-density ablating plasma and a low-density ambient plasma [14,15], and the other is an interaction between laser-ablated counter-streaming plasmas using double-plane target (DPT) [16–19]. Sorasio et al. have revealed a possibility of high Mach-number collisionless ES shock formation in counter-streaming plasmas in which temperatures and densities are largely different [20]. Motivated by the prediction [20], the generation of collisionless ES shock in counter-streaming plasmas using DPT and one-directional high-energy laser systems has been investigated [16–19].

In these experiments, the laser beams were irradiated only an inner surface of the 1st-plane of DPT, and counter-streaming

* Corresponding author.
E-mail address: sakawa-y@ile.osaka-u.ac.jp (Y. Sakawa).

http://dx.doi.org/10.1016/j.hedp.2017.04.007
1574-1818/

plasmas were generated. The plasma from the1st-plane is generated by laser ablation. However, the generation mechanism of the plasma from the 2nd-plane is not understood well and is of great interest. In this paper, we reveal the two-step generation of the 2nd-plane plasma using Collective Thomson scattering (CTS) measurement in addition to optical imaging. First, the 2nd-plane is ablated nearly at the laser timing by radiation from the 1st-plane plasma. Then when the plasma from the 1st-plane reaches the 2nd-plane at $\simeq 5-7$ ns later, it induces higher-density plasma generation.

2. Experiment

The experiment was performed using Gekko XII HIPER laser system (Nd: Glass) at Institute of Laser Engineering, Osaka University. Fig. 1 shows schematic view of the experiment setup. Two polypropylene (C_8H_8) planes (3 mm $\times$ 3 mm, $\sim$ 200 μm in thickness) were placed in parallel with a separation of 4.6 mm. One of the HIPER laser beams was focused on an inner surface of the 1st-plane with 300 μm in diameter with an incident angle of 45° . The laser delivered a 500-ps Gaussian pulse with an energy of $\sim$ 120 J at a wavelength of 351 μm, which results in the laser intensity of $\sim 3 \times 10^{14}$ W/ cm^2. A frequency-doubled Nd:YAG laser (532 nm, $\sim$ 10 ns, $\sim$ 300 mJ) was used for optical diagnostics from the perpendicular direction to the axis of the main laser (Optical probe). We obtained two-dimensional (2D) information of plasma density by shadowgraphy (SG) with intensified charge coupled device (ICCD) cameras with 200-ps gate duration and Nomarski interferometry (IF) with a 250-ps gated ICCD camera, and one-dimensional (1D) time-evolution of plasma density by streaked interferometry. We obtained 2D image of self-emission using an ICCD camera (GOI) with 1.6 ns gate width, and 1D time-evolution using streaked optical pyrometer (SOP). The silt of the streak camera was rotated 45° to measure the plasma dynamics normal to the target surface. The self-emission was filtered with a 450 nm interference filter.

A second frequency-doubled Nd: YAG laser beam (532 nm, $\sim$ 10 ns, $\sim$ 300 mJ) was used for CTS ion-term measurement (TS probe) [18]. It was focused to the center of the two target planes with a $\sim$ 100 μm focal-spot diameter using an $f = 1000$ mm lens. An incident angle of the TS probe with respect to the main laser was 45° , and the scattered light was detected at 90° from the TS probe by using a triple-grating spectrometer and an ICCD camera with 2-ns gate. As shown in Fig. 1, k-vector $\boldsymbol{k}$ is expressed in the following equation, $\boldsymbol{k} = \boldsymbol{k_s} - \boldsymbol{k_0}$, where $\boldsymbol{k_s}$ is the wave vector of the scattered light and $\boldsymbol{k_0}$ is the wave vector of the incident TS probe. The direction of $\boldsymbol{k}$ is parallel to the axis of the main laser.

3. Experimental results

Fig. 2 shows an SOP image. The surfaces of the 1st- and 2nd-planes are at $x = 0$ and 4.6 mm, respectively. The main laser pulse is irradiated at $t = 0$. At the laser timing, strong emission from the plasma is observed near the 1st-plane and lasts for $\sim$ 5 ns. A streaked interferogram was taken for the same shot as Fig. 2 (not shown). From the timing and shift of each fringe, we found that ablation of the 1st-plane started from $t \sim 0$, and flow velocity was $\sim$ 1000 km/s. Assuming the length of the plasma along the line of sight $L \sim 1$ mm, the density of the fast ablation-plasma was $\sim 2 \times 10^{18}$ cm^{-3}. In contrast to streaked interferometry, the SOP measurement did not detect a fast plasma flow of $\sim$ 1000 km/s from the 1st-plane, because the plasma density was too low to detect self-emission of the fast plasma.

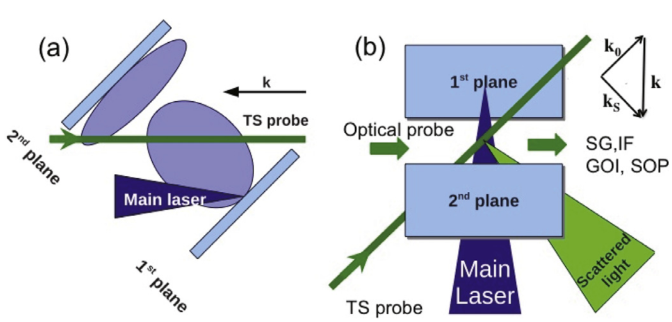

Fig. 1. The schematic of (a) side and (b) top views of DPT, main laser, Optical probe, TS probe, and diagnostics.

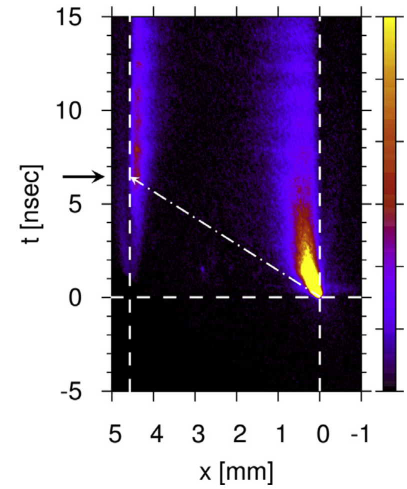

Fig. 2. An SOP image at the wavelength of 450 nm. $t = 0$ corresponds to the main laser timing, and the surfaces of the 1st- and 2nd-planes are at $x = 0$ and 4.6 mm, respectively. Horizontal allow at $t \sim 5.5$ ns indicates the timing when the emission intensity from the 2nd-plane plasma becomes maximum. Dot-dashed line is a guide for the eyes.

In Fig. 2, whereas the laser beam was irradiated only on the 1st-plane, weak self-emission from the 2nd-plane is also observed nearly at the laser timing. We also find that the emission from the 2nd-plane plasma becomes stronger at $t > 5$ ns. Assuming that the plasma from the 1st-plane ablates the 2nd-plane, the velocity of the 1st-plane plasma should be $\sim$ 900 km/s. It is comparable to the velocity estimated from the streaked interferometry.

Fig. 3 shows the temporal evolution of the CTS ion-term spectra along the scattering length y shown in Fig. 1. The middle of the 1st- and 2nd-planes is $y = 0$, and $y > 0$ ($y < 0$) corresponds to the 2nd- (1st-) plane side. The plasma flow velocity v_d is derived from the Doppler-shift of the scattered light from the wavelength of the TS probe laser $\lambda_0 = 532$ nm, using the relation $v_d = c\Delta\lambda/\lambda_0$, where c is the speed of light in vacuum and $\Delta\lambda$ is the wavelength shift of the peak.

Fig. 4 shows the temporal evolution of line profiles at $y = 2$ mm in Fig. 3. There are two peaks for $t = 10$ and 15 ns, for example, a stronger peak at $\Delta\lambda \sim -0.57$ nm (blue shift) and a relatively weak one at $\Delta\lambda \sim 0.30$ nm (red shift) for $t = 10$ ns. These blue- and red-shifted components correspond to the CTS ion-terms from the 1st- and 2nd-plane plasmas, respectively. The existence of counter-streaming plasma flows at the same time at the same position for $t = 10$ and 15 ns is clearly shown. The derived flow velocities v_d of the 1st-plane plasma are 590, 320, and 154 km/s at $t = 5$, 10, and 15 ns, respectively. On the other hands, v_d of the 2nd-plane plasma are derived to be 250 and 160 km/s at $t = 10$ and 15 ns, respectively. No red-shift components are observed at $t = 5$ ns.

4. Discussions

A 2D radiation hydrodynamic (RHD) simulation is performed using PheNiX [21] code to investigate the generation and