Collisionless shockwaves formed by counter-streaming laser-produced plasmas

X Liu¹, Y T Li¹,⁹, Y Zhang¹, J Y Zhong², W D Zheng³, Q L Dong¹, M Chen¹, G Zhao², Y Sakawa⁴, T Morita⁴, Y Kuramitsu⁴, T N Kato⁴, L M Chen¹, X Lu¹, J L Ma¹, W M Wang¹, Z M Sheng¹,⁵, H Takabe⁴, Y-J Rhee⁶, Y K Ding⁷, S E Jiang⁷, S Y Liu⁷, J Q Zhu⁸ and J Zhang¹,⁵,⁹

¹ Beijing National Laboratory for Condensed Matter Physics, Institute of Physics, Chinese Academy of Sciences, Beijing 100190, China
² National Astronomical Observatories, Chinese Academy of Sciences, Beijing 100012, China
³ Institute of Applied Physics and Computational Mathematics, Beijing 100094, China
⁴ Institute of Laser Engineering, Osaka University, 2-6 Yamada-oka, Suita, Osaka 5650871, Japan
⁵ Key Laboratory for Laser Plasmas (Ministry of Education) and Department of Physics, Shanghai Jiao Tong University, Shanghai 200240, China
⁶ Laboratory for Quantum Optics, Korea Atomic Energy Research Institute, 1045 Daedeok Street Yuseong-gu, Daejon 305353, Korea
⁷ Research Center for Laser Fusion, China Academy of Engineering Physics, Mianyang 621900, China
⁸ National Laboratory on High Power Lasers and Physics, Shanghai 201800, China
E-mail: ytli@aphy.iphy.ac.cn and jzhang@aphy.iphy.ac.cn

New Journal of Physics 13 (2011) 093001 (8pp)
Received 17 February 2011
Published 1 September 2011
Online at http://www.njp.org/
doi:10.1088/1367-2630/13/9/093001

Abstract. The interaction between two counter-streaming laser-produced plasmas is investigated using the high-power Shenguang II laser facility. The shockwaves observed in our experiment are believed to be excited by collisionless mechanisms. The dimensionless parameters calculated with the results suggest that it is possible to scale the observation to the supernova remnants using transformation and similarity criteria.

¹ Authors to whom any correspondence should be addressed.
1. Introduction

The collisionless shockwave is one of the important phenomena in astrophysical plasmas (Ness et al 1964, McKee and Draine 1991, Sagdeev and Kennel 1991) such as solar winds and supernova remnants (SNRs) (Aharonian et al 2004, Chen et al 2007, He et al 2007, Uchiyama et al 2007, Romagnani et al 2008). It is believed that the dissipation process of the forward and the reverse shockwaves in SNRs is one of the mechanisms for generating high-energy charged particles and cosmic rays (e.g. Krymsky 1977, Bell 1978, Blandford and Ostriker 1978, Axford et al 1982). Those shocks are generally collisionless because the shock transition occurs on a length scale that is much shorter than particle mean free paths; that is, Coulomb collisions between particles are not important for the shock formation.

Collisionless shockwaves can also be generated with high-power lasers in the laboratory. Although the space and time scales of laser-produced plasmas are very different from the astrophysical, a comparison of the hydrodynamic and radiative properties of them can throw light on the astrophysical processes through transformation and similarity criteria proposed by Ryutov et al (1999), so that laboratory plasmas have been applied to understand such astrophysical phenomena (Remington et al 2006, Takabe et al 2008, Wei et al 2008). Drake (2000) has theoretically studied the formation of collisionless shocks in the laboratory relevant to such cosmic shocks, and discussed the constraints that must be met by experiments. Bouquet et al (2004) studied the laser-driven supercritical radiative shock precursors, and measured the temperature and electron density of shocks (Koenig et al 2005, Vinci et al 2006). Romagnani et al (2008) have observed collisionless shockwaves propagating in ambient low-density gas. Courtois et al (2004) have tried to demonstrate the shocks of SNRs by adding a magnetic field in counter-streaming laser-produced plasmas. Recent simulations also show that collisionless shockwaves can be formed in the unmagnetized counter-streaming plasmas (Sorasio et al 2006, Kato and Takabe 2008, Takabe et al 2008). However, no experimental evidence has been observed.

In this paper, we present our experimental studies of the interactions of two counter-streaming plasmas produced by high-power laser pulses without external magnetic fields. By carefully choosing the laser energy, the thickness of the targets and the distance between the targets, collisionless shockwaves have been observed. Numerical simulations reveal that electrostatic (ES) instability is responsible for the observation.

2. Experimental setup

The experiments were carried out in the Shenguang II (SG II) laser facility at the National Laboratory on High Power Lasers and Physics, which can deliver a total energy of 2.0 kJ in...
3. Experimental results and discussion

The interferograms taken at delay times of 1, 2 and 3 ns are shown in figures 2(a)–(c), respectively. The delay is defined as the time separation between the falling edges of the probe and the main pulses. The original target foils are marked by blue boxes. Two identical laser bunches, each of which consists of four laser pulses, shine on the facing surfaces of the foils, respectively. The dark regions correspond to the targets irradiated by lasers. This results in
Figure 2. Panels (a)–(c) are the interferograms obtained at 1, 2 and 3 ns, respectively. The blue boxes in (a)–(c) indicate the original position of the CH target. The four dark green arrows in (a) represent the laser pulses. The orange dashed box in (b) indicates the region of density jump. (d) Experimental and simulated electron density distributions along the target normal for the single target foil at 2 ns. (e) Comparison of measured density profiles along the cyan line in (a) at 1 ns and the blue line in (b) at 2 ns with the overlapping calculated density profile.

two counter-streaming plasmas, which interact with each other around the center of the targets. At 1 ns, the fringes between the targets are shifted, indicating that the two plasmas have met each other. At 2 ns, a clear density jump is observed at the middle region. The density jump, corresponding to abrupt fringe discontinuities, is clearly distributed from the bottom to the top at the two-plasma collision region. At 3 ns, the density jump becomes weaker, and the fringe shift becomes smoother.

The expansion velocity and electron density of the plasmas before the collision were calculated by irradiating only a target foil with one of the laser bunches of four laser pulses. The density profile of the plasma was deduced using Abel inversion (Li et al 2007) of the measured interferogram. The measured electron density distribution along the target normal direction is shown in figure 2(d). The flow velocity of the plasma is calculated using the density distributions at different delay times, which is estimated as the ratio of the propagating distance of $\sim 10^{19}$ cm$^{-3}$ isopycnic surface to the delay time. Hence, the average flow velocity of the plasma generated from one target is about $\sim 1.1 \times 10^8$ cm s$^{-1}$. A 2D radiation-hydrodynamics
code using the Arbitrary Lagrange and Euler method in the non-LTE (local thermal equilibrium) condition, XRL2D, was also used to simulate the single-plasma expansion (Zheng and Zhang 2008). The same laser and target parameters as the experimental ones were used in the simulations, including the incident angle of lasers of \( \sim 60^\circ \), the diameter of focal spots of \( \sim 150–200 \mu m \), the power density of \( \sim 10^{15} \) W cm\(^{-2} \), the pulse shape of \( \sim 1 \) ns square wave and the distance between the two targets of \( \sim 4.5 \) mm. The simulated density distribution is also shown in figure 2(d), which is in agreement with the experimental one. We can see that the hydrodynamic simulations can reproduce the expansion of a single plasma well.

Figure 2(e) shows a comparison of the observed density profile at 1 and 2 ns. The densities in the regions near the two target foils, i.e. \(< 1650 \) and \( > 2950 \mu m \), are slightly higher at 2 ns than those at 1 ns. This is because more target materials are ablated out from the target at 2 ns, resulting in higher electron densities. But in the regions near the middle plane, i.e. from 1650 to 2100 \( \mu m \) and from 2700 to 2950 \( \mu m \), the density profile at 2 ns is similar to that at 1 ns, which indicates the deceleration of the plasma flow. In the middle plane of two target foils, there is an obvious density jump at 2 ns, which does not exist at 1 ns. This abrupt density change indicates the formation of a shock. The density jump observed at 2 ns has an increase from \( 1.6 \times 10^{19} \) to \( 2.5 \times 10^{19} \) cm\(^{-3} \). The density increase is about 60% related to the base density \( 1.6 \times 10^{19} \) cm\(^{-3} \), which is quite large.

The overlapping calculated density profile is also shown in figure 2(e), which is obtained by flipping the experimental profile of figure 2(d) from left to right and adding to the original one. From left to right, the flipped–overlapped electron density drops, reaches the bottom in the middle position and then rises. No density peak is formed. This is much different from the experimental distribution in figure 2(b), which shows an obvious density peak with a width of \( \sim 350 \mu m \) in the middle region. The large deficit between the calculated and the measured density indicates that the two counter-streaming plasma interaction cannot be assumed to be a simple interpenetration of two plasmas. When the two plasmas interact with each other, the two plasmas cannot propagate freely, acting as a simple density overlap. Therefore, from the features of the deceleration of the plasma flow, the 60% density increase and the comparison of the measured and the overlapped calculated density profile, it is believed that the density jump observed at 2 ns indicates a shock generation, rather than a simple interpenetration of the two plasmas.

Using the formula for the ion–ion mean free path, \( \lambda_{ii} \) (Popovics et al 1997),

\[
\lambda_{ii} = \frac{m_i^2 v_{12}^4}{4 \pi e^4 Z^4 n Ln \Lambda_{12}},
\]

where \( n \) is the ion density in the plasma, \( v_{12} \) is the relative plasma expanding velocity, \( Z \) is the ionization state of the plasma, \( m_i \) is the ion mass, \( e \) is the elementary electric charge and \( Ln \Lambda_{12} \) is the so-called ‘Coulomb logarithm’ (Sivukhin 1966). In the case of identical laser pulses, when \( n \sim 10^{19} \) cm\(^{-3} \), \( v_{12} = 2.2 \times 10^8 \) cm s\(^{-1} \) (\( v_1 = 1.1 \times 10^8 \) cm s\(^{-1} \) and \( v_2 = -1.1 \times 10^8 \) cm s\(^{-1} \)), \( Z = 6 \) (taking \( Z \) as the maximum), \( m_i = 20.04 \times 10^{-27} \) kg, \( e = 1.6 \times 10^{-19} \) C and \( Ln \Lambda_{12} = 6 \), the low limit of \( \lambda_{ii} \) is estimated to be \( \sim 1100 \) mm. The width of the measured density jump in figure 2(b) is about 350 \( \mu m \). Since the width of the measured density jump is much shorter than \( \lambda_{ii} \), the interaction between the two counter-streaming plasmas observed in our experiment is collisionless.

The generation of collisionless shockwaves has been studied in our work (Kato and Takabe 2008; Takabe et al 2008) and other groups’ previous work (Forslund and Shonk 1970, 1997; Takabe et al 2008).
Figure 3. (a) The distribution of the electron to ion temperature ratio at 2.5 ns, obtained with the hydrodynamics code. The X-axis represents the position from the target surface, and the Y-axis represents the position along the target surface. (b) The linear growth rates of the ES ion–ion instability.

Mason 1972) with particle-in-cell simulations. The results show that two types of instabilities can generate collisionless shockwaves in counter-streaming plasmas. One is the ES instability, which is driven by the large difference between the electron temperature and ion temperature, and the other is electromagnetic (EM) Weibel-type instability.

Figure 3(a) shows the distribution of the ratio of the electron temperature to ion temperature at 2.5 ns, simulated by our hydrodynamics code with the same conditions as the experimental ones. The X-axis represents the position from the target surface, and the Y-axis represents the position along the target surface. The values are the ratio of the electron temperature to the ion temperature. We can see clearly that the electron temperature is much higher than the ion temperature on the front position, which is due to the two-temperature model used in our simulations. By using the parameters obtained from our experiments and hydrodynamical simulations, the linear dispersion relations of the ES instability are solved (Kato and Takabe 2010). The linear growth rate of the instability is shown in figure 3(b), when \( T_e/T_i \) is equal to 100. The results show that the ES instability can grow up rapidly and play a major role at the beginning of the counter-streaming plasma interaction. Therefore, the features of the temperature ratio and the linear growth of ES instability indicate that the collisionless shockwaves observed at 2 ns in our experiment are probably excited by ES instability.

Our experimental results and theoretical analysis show that it is possible to generate the collisionless shocks in low-density non-relativistic plasmas, the conditions in which are similar to the environment of supernovae and SNRs. A similarity principle that allows a direct scaling between the laboratory plasmas and the astrophysical objects such as SNRs has been proposed by Ryutov et al (1999). To do this, both the astrophysical and laboratory systems must behave like an ideal fluid, which is characterized by three parameters, namely the Reynolds number, \( Re \), the Peclet number, \( Pe \), and collisionality, \( \zeta \). Note that \( \zeta \) is defined as the ratio of the mean free path to the system size. It must be larger than 1 in order that the plasmas are collisionless.
Table 1. Comparison of the dimensionless parameters of the shock in an SNR (Decourchelle et al 2000) with experimental ones at 2 ns.

| Parameters       | SNR    | Expt  |
|------------------|--------|-------|
| Collisionality, $\zeta$ | 2E6    | 4E2   |
| Euler number, $Eu$ | 18     | 28    |
| Mach number, $M$  | 16     | 14    |
| Reynolds number, $Re$ | 1E13   | 2.5E6 |
| Peclet number, $Pe$ | 1E11   | 4.5E3 |

The Reynolds number and Peclet number, which force the plasmas to behave like a fluid and provide a dissipative effect, are also important. To make the Euler equations valid and usable, $Pe$ and $Re$ are required to be much larger than 1, i.e.

$$Pe = \frac{\nu L}{\chi} \gg 1, \quad Re = \frac{\nu L}{\chi_h} \gg 1,$$

where $\nu$ is the characteristic fluid speed, $L$ is the system size, $\chi$ is the thermal diffusivity and $\chi_h$ is the viscosity. If the three conditions for $\zeta$, $Re$ and $Pe$ are satisfied, the similarity of the laboratory system to the astrophysical objects is comparable by the Euler number, $Eu$, and the Mach number, $M$. The Euler number provides that the Euler equations are invariant under Euler transformation. The Mach number provides that a shock is formed. They can be obtained with the equations $Eu = \nu (\rho / p)^{1/2}$ and $M = U_f (\rho / p)^{1/2}$, where $p$ is the plasma pressure, $\rho$ the mass density and $U_f$ the bulk fluid speed (Courtois et al 2004). Table 1 gives the parameters of our experiment at 2 ns and a young SNR (Decourchelle et al 2000). We use the plasma parameters in the density jump regions where collisionless shockwaves occurred, as shown in figure 2(b), to calculate those parameters in table 1. One can see that $\zeta$, $Re$ and $Pe$ are all much larger than 1. This indicates that scaling of the collisionless interaction in our experiments to the SNR is possible.

4. Conclusion

The counter-streaming plasmas are generated by shining eight laser pulses on two facing CH targets. In our experiment, the collisionless shockwaves were observed. Numerical simulations were used to analyze the experiment results, which indicate that the collisionless shockwaves may be excited by ES instability. The comparison of the dimensionless parameters of our experiment with those of SNR indicates that it is feasible to scale our measurements to the astrophysical objects.

Acknowledgments

This work was supported by the National Science Foundation of China (grant nos 10925421, 10720101075, 10734130 and 11135012) and National Basic Research Program of China (973 Program) (grant no 2007CB815101). The authors thank the staff at the Shenguang II laser facility in Shanghai.
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