Supernova Remnant Relevant Laser-plasma Experiments

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Abstract. Laboratory astro-plasma physics experiments are being designed to advance both our astrophysics and plasma physics knowledge. With current laser technology, target design and diagnostics, it is now possible to reproduce and measure the conditions of temperature and pressure usually met in extreme stellar environments. Coupled with scaled plasma physics it is possible to simulate certain aspects of astrophysical phenomena in the laser laboratory. The focus is on experiments *designed* to address key aspects of the plasma physics occurring in supernova remnants. In this approach ideal magneto-hydrodynamics is applied to the supernova remnant and then scaled. Matching dimensionless parameters in a laboratory experiment enables the simulation of complex astro-plasma systems offering the advantage of repeated, detailed measurements and the flexibility to alter the input conditions. Work at York has centered on developing a collisionless plasma experiment. The experiment involves a magnetic field, and two laser-exploded plasmas to make possible a laboratory study of the interaction between a supernova remnant and the interstellar medium. These experiments and the analysis are discussed.

INTRODUCTION

High-power laser experiments are playing an increasingly important role in our understanding of astrophysical phenomena. A class of experiments is those that rely on scaling analysis [1]. In this approach dimensionless parameters derived from a model of an astrophysical object are matched in the experiment. A previous publication [2] described a collision-free laser-plasma experiment designed to create a scaled snapshot of the collisionless shock occurring in a young supernova remnant (SNR) approximately 100 years after the supernova explosion. Collision-free plasmas are distinguished by the typical particle mean-free-path (mfp), usually due to binary collisions, which exceeds the scale-lengths of interest. Collisionless plasmas are collision-free yet exhibit fluid-like behavior; the fluid-like behavior is induced by a magnetic field that reduces the appropriate scale length to the Larmor radius. In a SNR the thermal plasma pressure exceeds the magnetic pressure, yet the magnetic field results in shock formation on scale-lengths much shorter than the typical collision mean-free-path. Furthermore, cosmic ray acceleration is believed to be closely linked to the role of the magnetic field in these collisionless shocks [3]. In an experiment to simulate aspects of SNR collisionless shock formation, two supersonically expanding

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counter-streaming plasmas are designed to produce a collision-free interaction as they flow into each other. This collision-free interaction is studied without and with a scaled magnetic field. The effect of this magnetic field on the experiment is interpreted in terms of reducing the effective particle scale length to the Larmor radius.

SCALING

The description of plasma dynamics with ideal magneto-hydrodynamics (MHD) supposes that the plasma is collision-free, and that it behaves like an ideal fluid due to the magnetic field effectively reducing the particle scale length. In ideal MHD dissipative effects such as thermal conductivity and viscosity are negligible. This is the case if the Reynolds, R_e, (the ratio of the inertial to the viscous force) and Péclet, P_e, (the ratio of the heat convective to the heat conduction) numbers are very large. A SNR plasma can be described by ideal MHD as illustrated by the parameters in Table 1, the challenge is to reproduce similar parameters in the laboratory and thus achieve a similarity scaling.

The ideal MHD equations relate the density, velocity, pressure, magnetic field, and time of a magnetized plasma. A further assumption necessary for scaling between the SNR and laboratory is that the material equation of state is polytropic [1]. A polytropic equation of state implies that the plasma internal energy is proportional to its thermal pressure. This is the case for fully ionized plasmas. Generally, the electron and ion mfp in a fully ionized plasma are determined by binary collisions. In a SNR the collisionality parameter ζ, which is the ratio of the particle mean-free-path to a scale length L, is very large and the plasma is collision-free. However, the effective scalelengths are determined by the Larmor radius r_L and the localization parameter r_L/L is small, thus the SNR plasma behaves like a collisionless fluid.

TABLE 1. Comparison of the scaling parameters for the reverse shock in a young SNR [4] and the experimentally derived values measured at 500 ps.

Parameters	SNR: 100 yrs	Exp: 500 ps
R_e	10^{13}	10^{7}
P_e	10^{11}	10^{10}
ζ	10^{6}	3×10^{2}
r_L/L	10^{-9}	10^{-1}
Plasma β	$\beta = 5 \times 10^{2}$	$\beta^{*} = 4 \times 10^{2}$
Eu	18	21
M	16	12
M_A	3×10^{2}	20

As well as ensuring the experimental R_e, P_e, ζ are large and r_L/L is small, there are two further constraints that determine the magneto-hydrodynamic behavior of the plasmas. To ensure a laboratory simulation these two dimensionless constants, the plasma β and the Euler number Eu should be matched. The plasma β, which determines the role of the magnetic field, is the ratio of the plasma thermal pressure to magnetic pressure. This is approximately 500 indicating that the thermal pressure dominates the global fluid motion and not the magnetic field. Yet the magnetic field does introduce new physics by determining the effective scale length as the Larmor radius. The *Eu* determines the effective hydrodynamics exhibited by the plasmas [1]. In addition, in order to form a strong shock it is necessary for the sonic Mach number, M, and the Alfvén Mach number, M_A, to be greater than unity. In this case strong collisionless shock structures are expected to occur on scales of the order a Larmor radius.

The experiment uses two counter-streaming exploding plasmas to simulate the SNR. Clearly this experiment is not designed to follow the evolution of a SNR but to converge towards the parameter range that is relevant to SNR physics. In doing this we use a nonstandard definition of the experimental plasma β, called β^*. Plasma β^* is the plasma ram pressure normalized to the magnetic field pressure. Parameters identified with an asterisk are inferred from the flow kinetic energy rather than the thermal kinetic energy.

EXPERIMENT

The experimental setup consists of two thin low atomic number plastic foils (C_8H_8, thickness 0.1 μm) mounted face-parallel and separated by 1 mm. The non-opposing faces of the foils are simultaneously and uniformly irradiated over a 1 mm diameter focal spot as determined by phase-zone plates and shown in Figure 1. The laser spot size ensures a 1-dimensional expansion for at least 0.5 mm, to the midpoint between the foils. The irradiance is limited at 6×10^{13} W/cm^2 (± 10 %) in 80 ps pulse duration at 1.053 μm wavelength to prevent hot electron generation. Experiments are repeated without or with a 7.5 T magnetic field. For shots with a magnetic field, the foils are placed at the center of a pulsed electromagnet, which generates a uniform 7.5 T field

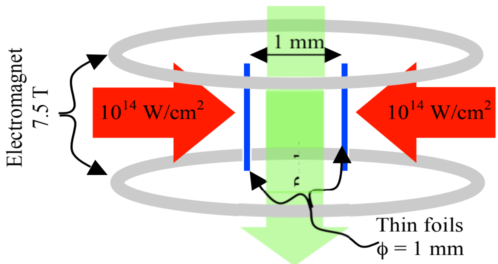

FIGURE 1. Diagram shows the experimental setup and the location of the two thin foil targets in the electromagnet. The magnetic field is oriented parallel to the probe, and perpendicular to the plasma expansion. The probe, 25 ps duration, is delayed relative to the peak of the drive laser pulses by between 250 – 750 ps.

for a duration of 1 ms over a region of approximately 10 mm. The magnetic field strength is chosen to match the SNR plasma β, although the highest possible field was 7.5 T. The field is oriented perpendicular to the direction of plasma flow. The plasma expansion is characterized using interferometry, using a 25 ps duration, frequency doubled (to wavelength 0.53 μm) laser probe. The delay of the probe beam with respect to the drive beams is changed between experiments to give a series of snapshots of the temporal evolution of the plasma expansion. From the fringe shifts in the resulting interferograms, the electron density is inferred across a 1 mm cord in the plasma. Further details can be found in Ref [5].

RESULTS

Each interferogram is a 25 ps snapshot, and these snapshots can be taken at between 250 – 750 ps after the peak of the drive laser pulse. An interferogram of a single expanding foil without a magnetic field is shown in Figure 2(a). This image was recorded at a probe delay of 750 ps with respect to the peak of the drive pulse. The initial foil position is at 0 on the horizontal axis, and the drive laser is incident from the left and centered on the position 0 on the vertical axis. The dark region, which can be seen immediately to the right of the initial foil position, is below the probe critical density, yet the density gradients in this region are sufficient to refract the beam out of the collection angle of the f/6 imaging system. From this and similar data, time

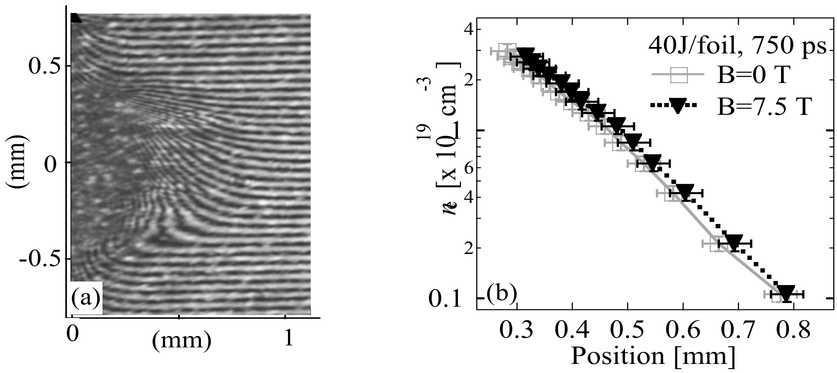

FIGURE 2. (a) An interferogram of a single exploding plastic foil taken at 750 ps. (b) the extracted single foil electron density profiles taken from a horizontal cross-section centered at the laser focal spot. Open squares data from a magnetic field free experiment are compared to solid triangles data from a 7.5 T experiment.[6]

resolved electron density (n_e) profiles, such as those shown in Fig. 2(b), are inferred along a 1 mm cord through the center of the plasma. The quoted laser energies have a ± 10 % accuracy. From measurements of n_e taken at a probe delay of 500 ps, the expansion speed of the leading edge of the plasma is estimated as 1.1×10^7 cm/s. By using thin plastic foil targets, the production of a rapidly expanding, low density, low atomic number plasma is obtained. This is important in order to achieve a collision-free interaction in the counter-streaming experiments.

Figure 2(b) compares the horizontal n_e measurements along the center of the plasma expansion, from two experiments and are recorded 750 ps after the peak of the drive pulse. The open squares (B = 0) represent the magnetic field-free expansion of the exploded foil, and the solid triangles (B = 7.5 T) show data taken in the presence of a 7.5 T transverse magnetic field. The energies on target are 42 J and 39 J respectively. The n_e profiles are identical within experimental accuracy. This indicates that up to relatively long times (750 ps), and distances comparable to the initial foil separation in the opposing-foil experiments (~ 1 mm) the presence of the magnetic field *does not* affect the hydrodynamics of the expanding plasma.

Figure 3(a) shows an interferogram taken from a counter-streaming plasma experiment with a 7.5 T magnetic field present. In these experiments two face-parallel foils are placed 1 mm apart, as shown in Fig. 1, and are simultaneously exploded. The initial foil positions are at – 0.5 mm and + 0.5 mm on the horizontal axis. The drive laser beams are incident from the left and the right, and centered at the position 0 on the vertical axis. Figure 3(b) shows the inferred n_e profiles from two similar counter-streaming experiments, one without (open circles) and one with a 7.5 T transverse magnetic field (solid triangles). The field-free n_e profile is parabolic in shape; this is consistent with the density profiles obtained from the free expansion of a single foil (both without and with a magnetic field), suggesting that the plasmas do interpenetrate. In comparison the profile with a 7.5 T magnetic field is characterized by a steepened density gradient close to initial foil positions, and an extended low-density plateau around 350 μm in width and with $n_e \sim 10^{18}$ cm^{-3}. This plateau is centered on the interaction point of the two plasmas at 0 mm. This result contrasts with the single foil results, where the magnetic field was found not to affect the evolution of the plasma

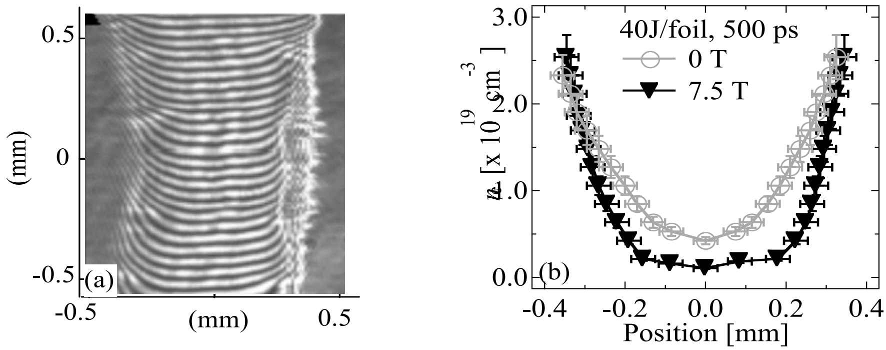

FIGURE 3. (a) An interferogram of a two opposing exploding plastic foil experiment taken at 500 ps. (b) the extracted opposing foil electron density profiles taken from a horizontal cross-section centered at the laser focal spot. Open circles data from a magnetic field free experiment are compared to solid triangles data from a 7.5 T experiment [6].

DISCUSSION

Experimental data enables the similarity scaling parameters to be estimated and compared to the SNR plasma. This comparison is shown in Table 1. The plasmas are formed from thin plastic foils at relatively high laser intensity and are highly ionized with large Reynolds R_e, and Péclet P_e numbers. A polytropic equation of state is assumed and dissipative effects are safely ignored. From experimentally inferred n_e

and expansion speed at 500 ps, the ion-ion mean free path is found to be larger than the system size; therefore collisions are not considered to be important at the time of the interaction. This is reinforced by the data shown in Figure 3(b). Here the open circles indicate the experimental n_e profile for two counter-streaming plasmas, at a time of 500 ps and with no magnetic field present. The collisionality parameter, ζ, is larger than one, a necessary condition for obtaining a collisionless plasma interaction. The ion localization parameter r_{Li}/L is less than unity and the ions may be considered weakly localized. However, r_{Li}/L is many orders of magnitude greater than a typical value for a SNR. The plasma β parameters and the Euler numbers are relatively close and indicate that the experimental magneto-hydrodynamics converges to the SNR at 500 ps. The hydrodynamic and Alfvén Mach numbers are sufficiently large that if the ions are sufficiently localized a strong shock may form. This indicates scaling between a laser-plasma experiment and a collisionless SNR plasma is achievable. We note nevertheless that no evidence of a collisionless shock is observed. A possible explanation is that the plasma scale lengths are not short enough, and that the parameter r_{Li}/L must be reduced below 10^{-2}.

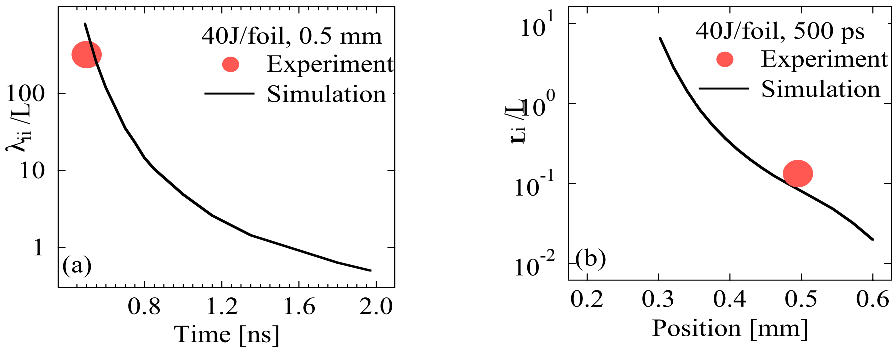

FIGURE 4. (a) The experimentally inferred collisionality parameter ($\zeta = \lambda_{\mathrm{ii}}/L$) at 500 ps compared to temporal variation of a numerical simulated ζ. (b) The ion localization (r_{Li}/L) at 500 ps compared to numerically simulated r_{Li}/L as a function of distance from the initial foil position.

In Fig. 4 the ion collisionality ζ and ion localization r_{L}/L parameters are compared to numerical simulation obtained using the one-dimensional hydrodynamic model Med103 [8]. The values inferred from experiment are indicated by the large dot. Figure 4(a) illustrates how the collisionality parameter, ζ, of two opposing plasmas without magnetic field varies with time. The experimental point and simulation agree with a $\zeta \sim 300$ at 500 ps at the mid-point between the foils (0.5 mm from each foil surface). However, numerical results indicate that the ζ decreases quickly with time and falls to unity 1.4 ns after the peak of the laser pulse. This indicates that the counter-streaming plasma interaction at around 500 ps delay is collision-free as suggested by the experimental data and plasma interpenetration should occur.

Figure 4(b) shows the ion localization as a function of position at 500 ps. This dimensionless parameter is most relevant to the role of the magnetic field, given plasma $\beta^* >> 1$. The results are based on a model of anomalous resistivity that enables rapid magnetic field penetration [5,7]. The r_{Li}/L are calculated using the thermal kinetic energy of the ions. The experimentally derived r_{Li}/L, 500 μm from the foil surface, is equal to 0.1. Numerical modeling illustrates how the r_{Li}/L may be expected to increase towards the initial foil location, and approaches unity around 350 μm, i.e. the magnetic field has penetrated up to 150 μm from the expanding edge of the plasma. The ion flow kinetic energy can be also used to estimate a $(r_{Li}/L)^*$, this is around unity, still smaller than the mfp, but would indicate the ions are not localized. The electrons, however with r_{Le}/L and $(r_{Le}/L)^*$ around 10^{-3} are localized. Electrostatic fields due to charge separation are then expected to keep the ions localized. This may offer some explanation for the observed density plateau that occurs on applying a 7.5 T magnetic field during the counter-propagation of the two plasmas.

Experimental results on applying this transverse magnetic field, see in Fig. 3(a) and the inferred n_e in Fig. 3(b), show a distinct change in the density profiles with steeper density gradients and a low-density plateau approximately 300 μm wide. Since plasma β^* is large, it is difficult to explain these results in terms of direct magnetic field pressure retarding the plasma flow. This is further illustrated by data shown in Fig. 2(b). Magnetic field compression is not expected, since the geometry of the experiment, (roughly, two opposing 1 mm diameter plasmas expanding approximately 0.5 mm) will allow the field to escape the interaction region. An alternative explanation is that the magnetic field penetrates the plasmas, and localizes the electrons and ions to the relevant Larmor radius. The Larmor radius is smaller than the collision mfp's and the system size. A simple model [5,7] based on anomalous resistivity suggests that at 500 ps, the magnetic field penetrates the plasma. A magnetic field will introduce new physics and new scale lengths, the Larmor radius, during the collision-free interaction. If the magnetic field is sufficiently strong that the shortest scale length is the Larmor radius, then this is the shortest scale at which fluid-like behavior may occur in a collision-free system. The model indicates that the magnetic field localizes the ions up to a distance of 150 μm (see Figure 4(b)) either side of the experimental mid-point and that the electrons if not the ions are localized with $r_{Le}/L<1$. This is consistent with the scale of the features seen in Fig. 3.

CONCLUSION

We have experimentally investigated the dynamics of single laser-exploded foils and the interaction of two counter-propagated laser-exploded foils with and without an applied magnetic field to establish an experimental simulation of a collisionless SNR plasma. Dimensionless parameters governing a collisionless SNR plasma are compared to those inferred from the experiment and from numerical simulation. These results show that the experimental parameters obtained 500 ps after laser irradiation converge on those believed typical of a reverse shock in a young SNR 100 years following the explosion of a supernova. This implies that a laser-plasma experiment can be used to simulate SNR plasma physics in the laboratory. Although a collisionless shock has not been observed, a 7.5 T magnetic field has been observed to effect a collision-free plasma interaction through the formation of an extended low-density plateau centered on the collision area. Experiment indicates that the magnetic field is not sufficiently strong to affect the plasma expansion dynamics directly. An explanation in terms of particle localization due to the magnetic field has been explored. It is found that the magnetic field penetration length is consistent with the width of the experimentally observed plateau and that the plasma electrons are magnetized and the ions are weakly magnetized. The weak localization of the ions possibly explains why shock formation was not observed. For shock formation it is suggested that r_{Li}/L, should be reduced to below 10^{-2}.

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