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Collisionless interaction of an energetic laser produced plasma with a large magnetoplasma

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Abstract We have commissioned a high-energy glass-laser at the Large Plasma Device (LAPD) to study the interaction of a dense laser-produced plasma with a large (17 m) magnetized plasma. First experiments with an energy of the laser blow-off an order of magnitude higher than previous work (Gekelman et al. in *J. Geophys. Res.* 108(A7):1281, 2003) produced large amplitude Alfvén waves ($\delta B_{\perp}/B_0 \approx 15\%$). We will discuss the potential of this facility for collisionless laboratory astrophysics experiments.

Keywords Alfvén waves · Collisionless shocks

1 Introduction

High-power laser produced plasmas can model certain aspects of astrophysical phenomena in a controlled laboratory setting, by doing well-scaled physics despite orders-of-magnitude discrepancies in spatial and temporal scales (Ryutov et al. 2001; Remington et al. 2006). In combination with an ambient magnetized plasma, novel laser experiments can be devised (Drake 2000) that are relevant to collisionless processes, such as shocks (Sagdeev 1966), magnetic turbulence, magnetic reconnection, or wave-particle

interactions. These laboratory experiments are crucial to benchmarking the codes developed to model space physics and astrophysical phenomena of interest, such as planetary bow-shocks, coronal mass ejections, and supernova remnants.

2 Experimental arrangement and diagnostics

The experiments described here are performed at the Large Plasma Device (LAPD) at UCLA (Gekelman et al. 1991). The LAPD creates highly magnetized plasmas of unsurpassed dimensions (60 cm diameter, 17 m length). These experiments differ thus from previous work in that they allow studies of laser-plasma coupling to the ambient plasma over much larger length and time-scales. In addition, the surrounding plasma is large enough to support Alfvén waves. The long linear vacuum chamber is surrounded by a large solenoidal magnet array that creates a uniform axial dc-magnetic field between 300 and 2000 G. The discharge is initiated once per second in a variety of gases (He to Xe) using a pulsed cathode. The plasma is uniform, quiescent, current-free, and reproducible, with a typical density of $2 \times 10^{12} \text{ cm}^{-3}$, an electron temperature of 5 eV, and an ion temperature of ~ 1 eV. For most ions the ionization stage is $Z = 1$ and there are about 30% neutral atoms. The discharge reaches a steady regime of constant density after a few ms and lasts for 10 ms.

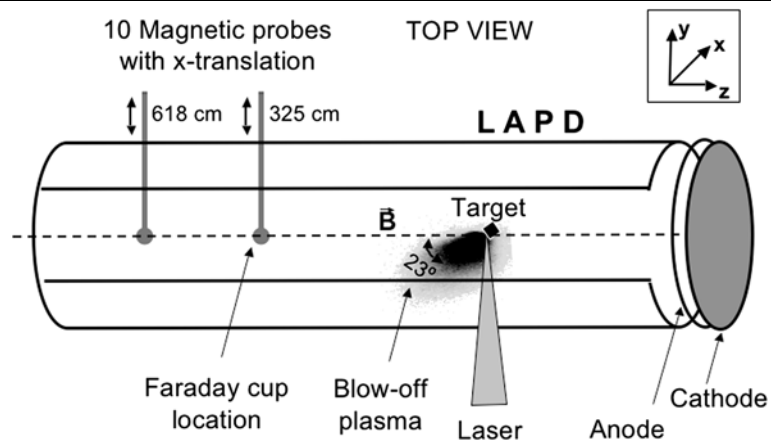
The unconverted beam from a flashlamp-pumped Nd:glass laser (20 J, 5 ns, 1064 nm, circularly polarized) entered the LAPD chamber (Fig. 1) from a side port, at the time when the LAPD plasma was operating in a steady regime. An $f/22$ lens created an elliptical laser focal spot of $200 \times 500 \mu\text{m}^2$ onto a thick graphite target. The resulting peak intensity was $3 \times 10^{12} \text{ W/cm}^2$. The target was mounted

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Fig. 1 Experimental setup showing the blow-off laser plasma emerging from a graphite target embedded in the LAPD plasma, and some of the diagnostics



from the top, 5 m away from the cathode, and the interaction region was >10 m in the opposite direction. The target normal was oriented at an angle of 23° relative to \vec{B} (quasi-parallel), while the laser beam was incident perpendicular to \vec{B} . The target surface was refreshed after each shot. A fast shutter camera was used to image the temporal evolution of the laser produced plasma from below, with several filters for CI to CIII emission. These images, together with time-of-flight measurements taken with a Faraday cup 3.3 m away from the target location provided information on the blow-off expansion velocity. Faraday cup measurements were taken during shots without background plasma. An array of 10 magnetic pickup coils (sensitive to $d\vec{B}/dt$ in each direction, x , y , and z) was distributed along the machine at distances Δz between 30 cm and 1000 cm to the target to measure the magnetohydrodynamic response of the background plasma to the laser blow-off. These probes were differentially wound on a 3 mm cube core (10 turn per axis) and were calibrated to frequencies up to 100 MHz. The probe signals were recorded for different transverse positions x using custom-built 200 MHz differential amplifiers coupled to 14 bit digitizers. The signals were numerically integrated using an algorithm that applies a frequency-dependent calibration for both amplitude and phase in the frequency domain.

3 Scaled laboratory experiments and first results

Creating collisionless shocks in the laboratory is a challenge (Drake 2000) because it requires facilities that can produce highly magnetized, high- β plasmas at densities sufficiently low to minimize collisions (where β is the ratio between the plasma pressure and the magnetic field pressure). Previous laboratory experiments used magnetic-pinch plasmas (e.g. Paul et al. 1967; Stamper and DeSilva 1968; Keilhacker et al. 1969; Martone and Segre 1970; Mourenas et al. 2003) or laser-produced plasmas (Tsuchimori et al. 1968; Borovsky et al. 1984; Ripin et al. 1987;

Dimonte and Wiley 1991; Ditmire et al. 2000), creating the first test beds where observations and models could be compared. Although limited in size and duration at scales that allow for a detailed study of shock formation and particle acceleration, these pioneering experiments made a valuable progress in understanding various aspects of collisionless shock physics (see reviews in Drake 2000 and Zakharov 2003).

Past laser experiments at the LAPD (VanZeeland et al. 2001; Gekelman et al. 2003) with low laser energies (~ 1 J) and intensities ($\sim 5 \times 10^{10}$ W/cm²) discovered that shear Alfvén waves are radiated from the laser-plasma. These experiments also studied the evolution of the laser plasma expansion in magnetized environments and the consequent formation of a diamagnetic cavity (VanZeeland and Gekelman 2004). Recently, interactions between colliding plasmas were also studied (Gekelman et al. 2007), but were limited to laser-plasma kinetic energies of $E_0 < 1$ J and blow-off velocities of $v_{lp}/v_A \leq 0.3$ (where v_A is the Alfvén speed). As a result, a small conversion efficiency of laser energy into Alfvén waves $E_A/E_0 \leq 1\%$ was observed, in agreement with numerical simulations.

Some of the first results that we obtained with increased laser energy and intensity, in a He plasma with a density of 2×10^{12} cm⁻³, are shown in Fig. 2. The velocity distribution of the blow-off plasma ions was measured by the 5 mm diameter Faraday cup, biased at -90 V. The velocity of C ions peaks at around 250 km/s, in agreement with fast shutter photographs obtained with filters for wavelength ranges around $\lambda = 460$ nm, specific to CIII emission. This is consistent with the on-target intensity and is below the Alfvén velocity in He ($v_A = 460$ km/s). Different velocities are attributed to different charge states of the blow-off ions. We observe Alfvén waves with amplitudes as large as 100 G ($\delta B_{\perp}/B_0 \approx 15\%$) emerging from the laser-produced plasma in the He-discharge at $B_0 = 600$ G (Fig. 2a and 2c). Van Campennolle et al. (2006) has shown that these waves are created through Cherenkov radiation by fast electrons.

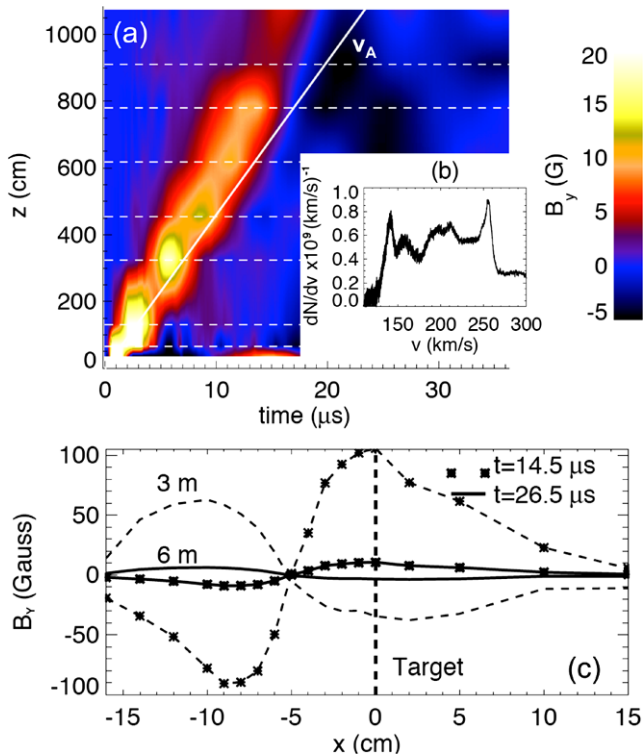


Fig. 2 (a) Evolution of a magnetic perturbation caused by a large amplitude Alfvén wave along the LAPD, at position $x = 2$ cm. (b) Velocity distribution of the carbon ions ejected by the laser plasma, as inferred from the Faraday cup measurements, 3 m away from the target. (c) Magnetic field signals measured 3 m (dashed line) and 6 m (solid line) away from the target in a He plasma, at $B = 600$ G. Two different times are shown

A typical Alfvén wave behavior, causing B_y field oscillation along the transverse direction x was measured with a Bdot-probe at a distance of $\Delta z = 6$ m from the target, as shown in Fig. 2c. The probe was moved to a new x position after 3 laser shots and the experiment was repeated with a laser energy stability better than 10%. The measured Alfvén frequency is 160 kHz (70% f_{ci} , where f_{ci} is the ion gyrofrequency), which is consistent with previous work (Gekelman et al. 2003), but an order of magnitude larger in amplitude. With the high-power laser now available, experiments could in principle drive shocks in plasmas that approach the collisionless regime. The laser-produced blow-off plasma acts as a piston upon the ambient plasma. Drake (2000) shows that a large ambient plasma size L is crucial to drive collisionless shocks in a laboratory experiment. A shock velocity v_s in excess of the Alfvén speed $v_A \sim B/\sqrt{mn}$ is required to ensure that the upstream magnetic turbulence does not escape the shock (Alfvénic Mach number $M_A = v_s/v_A \geq 1$). Here B is the external magnetic field, while m and n are the mass and the density of the ambient plasma-ions, respectively. The plasma $\beta \sim nT/B^2$ must be as large as possible so that the shock can affect the magnetic field, and yet the plasma must be highly magnetized (i.e. magnetiza-

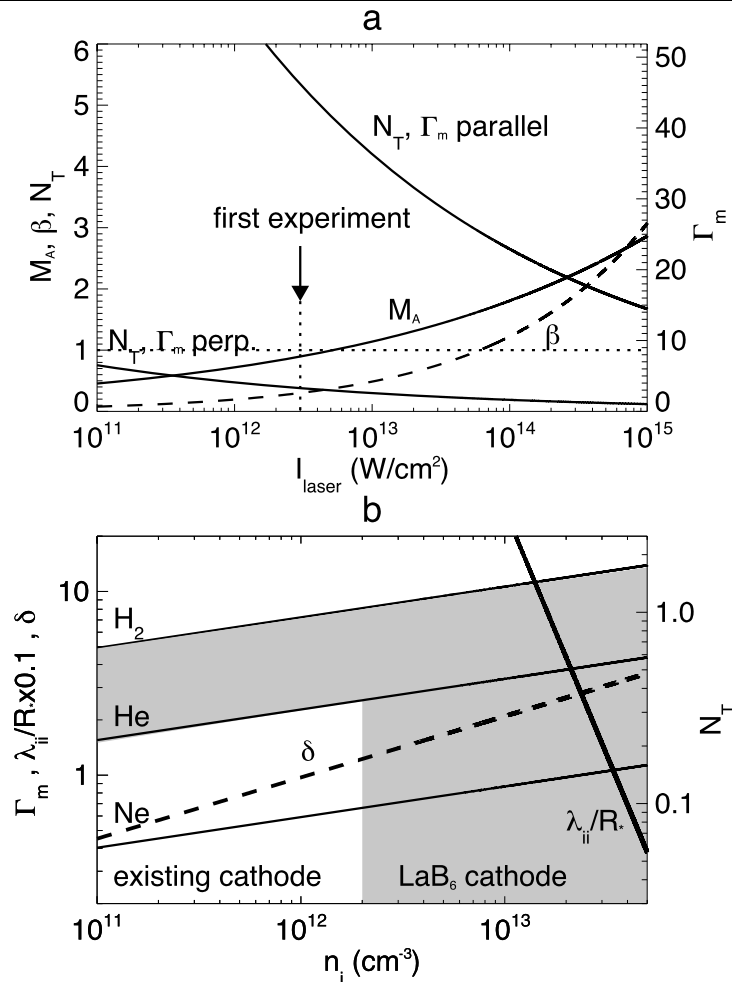
tion $\Gamma_m = d/r_{Li} \gg 1$, where d is the relevant background plasma size scale, and $r_{Li} \sim \sqrt{mT}/B$ is the ion Larmor radius). The parameter d will be determined in principle by the size of the expanding diamagnetic cavity formed by the laser plasma (see details in Bashurin et al. 1984). In the perpendicular case the cavity radius is given by the equal-charge radius: $R' = (3Z_i N_i / (4\pi Z n))^{1/3} \equiv (m Z_i / (m_i Z))^{1/3} R_*$, where Z , m , and Z_i , m_i are the ion charge state and the mass of laser-plasma and background plasma, respectively, $R_* = (3N_i m_i / (4\pi n m))^{1/3}$ is the equal-mass radius, with N_i the number of ions in the laser-plasma, and n the density of ions in the background plasma. In the parallel case, the laser cloud extends over larger distances, as indicated by our measurements (more than 3 m).

Another key parameter to be considered in the shock formation is the Larmor-coupling efficiency (Bashurin et al. 1984; Golubev et al. 1978; Winske and Gary 2007) that depends strongly on the magnetic laminar mechanism (MLM) criterion: $\delta = R'^2 / (R_L \cdot R_{L*})$ must be greater than 1, where R_L is the Larmor radius of the laser-plasma ions, which is proportional to the laser-plasma front speed v_{lp} , and R_{L*} is the directed Larmor radius of the background ions, also proportional to v_{lp} (Zakharov 2003).

In addition, the experiment must last long enough for the shock to form. In the quasi-perpendicular case ($\vec{v}_s \perp \vec{B}$ within $\pm 45^\circ$), the shock-formation takes a time of the order of the ion gyroperiod $T_{ci} \sim m/B$. In the quasi-parallel case ($\vec{v}_s \parallel \vec{B}$ within $\pm 45^\circ$), the shock formation time is believed to be much longer, of the order of the growth-rate of the firehose instability ($\sim 10T_{ci}$) (Draine 1993). This means that the number of gyroperiods per shock transit time $N_T = (L/v_s)/T_{ci}$ must be larger than 1 in the quasi-perpendicular case and larger than 10 in the quasi-parallel case. Therefore, even though the size is larger in the axial direction ($L_{\parallel} \geq 1000$ cm) compared to $L_{\perp} \sim 40$ cm in the transverse direction, creating collisionless shocks can prove more challenging due to the increased growth time of the shock formation and requires more laser energy.

Figure 3a shows that a high-power laser focused to moderate intensities around 10^{13} W/cm² could create conditions in the LAPD where M_A and Γ_m are above unity. We note that Fig. 3a shows a lower bound of β . The actual plasma pressure will be higher close to the laser target, since the blow-off density is initially orders of magnitude larger than the density of the ambient plasma. Here we use an empirical scaling law for the blow-off velocity $v_{lp} \equiv 3/4 v_s = 2.5 \times 10^7 I_{12}^{0.2}$ for 1064 nm laser light, where I_{12} is the intensity in units of 10^{12} W/cm² (Key et al. 1983; Meyer and Thiell 1984). While this regime is interesting in itself one can see that these conditions are not maintained long enough for a shock to form (i.e. $N_{T,\perp} < 1$ and $N_{T,\parallel} < 10$). A simple scaling analysis shows that a small ion mass is required for shock formation. Using the standard relation for the temperature of the shocked ions $T \sim m v_s^2$ we

Fig. 3 (a) Scaling of M_A , β , N_T , and Γ_m with laser intensity for a He-discharge in 600 G, with a density of $2 \times 10^{12} \text{ cm}^{-3}$, over distances $L_{\parallel} = 1000 \text{ cm}$, and $L_{\perp} \sim 40 \text{ cm}$. (b) Γ_m and N_T as a function of n_i for different gases at $M_A = 1$, in a perpendicular geometry. The bold line indicates the proton mean free path $\lambda_{ii} \sim 1/n_i$ in units of plasma size (scaled down by a factor of 10 in this plot), and the dashed bold line indicates the MLM parameter δ , calculated for a H background plasma, and blow-off velocities of 170 km/s, in a 600 G magnetic field. The shaded areas indicate the parameters accessible with the existing and with the new cathode



find that for a constant M_A shock ($v_s \sim B/\sqrt{mn}$) neither the magnetization Γ_m , nor N_T and the plasma β vary with the external magnetic field. The reduced gyroperiod at higher B is compensated by the shorter shock transit time, while the temperature of the shocked ions must increase with B keeping the gyro-radius constant. Furthermore, Γ_m and N_T have the same scaling dependence, and increase with plasma size and ion-density, but decrease with ion-mass. Thus, maximizing density while minimizing mass will create the best experimental conditions for shock formation. At the densities accessible by the LAPD the mean free path of the shocked ambient ions $\lambda_{ii} \sim v_{ip}^4/n$ is typically much larger than the ambient plasma size such that collisionless processes dominate (Fig. 3b). From the laser-driver point of view a lower B will require the smallest blow-off speeds and smallest laser intensities, maximizing the number of particles that can be energized by the limited laser energy absorbed.

4 Conclusion and outlook

A high-energy laser coupled to the LAPD provides a unique experimental capability to study the interaction between a

laser plasma and an ambient magnetized plasma at scale-lengths, time-scales, and energies previously inaccessible. First experiments with 20 J have created blow-off plasma speeds below the Alfvén velocity in He ($0.5v_A$), creating Alfvén waves with amplitudes an order of magnitude higher than in previous work. Experiments in the near future will take advantage of a new lanthanum-hexaboride cathode (LaB₆) that is chemically compatible with hydrogen and will also support higher densities (up to $5 \times 10^{13} \text{ cm}^{-3}$). In particular, scaling shows that collisionless shocks are possible in H-plasmas at these higher densities and magnetic fields of 300 G (as low as LAPD can support). $M_A \sim 1$ shocks with $N_T \geq 30$ in the quasi-parallel case, and $N_T \sim 2$ in the quasi-perpendicular case could then be produced. Here, the perpendicular case benefits from the compressed field ($B \approx 2B_0$ for $M_A = 1$). Gases heavier than He are not suitable for the formation of collisionless shocks in the LAPD. At laser intensities around 10^{11} W/cm^2 we expect to ablate around 10^{17} particles from the laser-target (Meyer and Thiell 1984). An energy of 25 J (more than 4 times the total energy in the ambient plasma) would be sufficient to maintain the required ion-temperatures for a $M_A = 1$

shock. The ions in the laser plasma are well magnetized in these conditions, since the Larmor radius decreases and the $R_* \sim 40$ cm increases, at blow off velocities of 170 km/s. The MLM interaction parameter δ is then around 1. These parameters show that conditions favorable for studying the Larmor coupling mechanism, the collisionless shock formation and propagation, as well as its interaction with the ambient magnetic field are possible and can be of great value for testing the existing models. Ultimately, strong ($M_A \geq 4$) shocks and studies of the associated particle acceleration thought to be caused by them can be then attempted at facilities providing laser energies at kilojoule levels, as discussed in Drake's and Zakharov's reviews.

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