Experimental study of subcritical laboratory magnetized collisionless shocks using a laser-driven magnetic piston

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Recent experiments at the University of California, Los Angeles have successfully generated subcritical magnetized collisionless shocks, allowing new laboratory studies of shock formation relevant to space shocks. The characteristics of these shocks are compared with new data in which no shock or a pre-shock formed. The results are consistent with theory and 2D hybrid simulations and indicate that the observed shock or shock-like structures can be organized into distinct regimes by coupling strength. With additional experiments on the early time parameters of the laser plasma utilizing Thomson scattering, spectroscopy, and fast-gate filtered imaging, these regimes are found to be in good agreement with theoretical shock formation criteria. © 2015 AIP Publishing LLC.

I. INTRODUCTION

Space and astrophysical collisionless shocks are rich and complex phenomena that occur in many environments, including the solar wind, coronal mass ejections, and supernova remnants. Unlike hydrodynamic shocks, collisionless shocks dissipate energy through collective electromagnetic effects that occur on length scales far shorter than the classical mean free path. These shocks form as a super-magnetosonic plasma flows through an ambient plasma and so can often be modeled as a magnetic piston interacting with a magnetized background plasma.

Besides their ubiquity in space environments, collisionless shocks are of general interest for several reasons. While these shocks have been studied remotely and in situ by spacecraft for decades, those systems are difficult to diagnose or largely steady-state, and so have focused on properties of pre-formed shocks (see Refs. 1 and 2 for reviews on terrestrial space and astrophysical shocks, respectively). As a result, the microphysics of shock formation has been largely left to theoretical efforts. With the recent discovery3 that Earth’s bow shock can reform, there has been renewed interest in understanding shock formation. Additionally, several physical effects are still not well understood, including the mechanism by which entropy is generated in the shock front4 and the process by which ions are accelerated to extremely high energies.5

By providing greater control over relevant parameters and reproducibility, appropriately scaled laboratory experiments can thus contribute to an understanding of collisionless shocks, despite orders of magnitude differences in scale.6,7 Moreover, experiments can help validate complex computational codes and complement spacecraft measurements. In the past five decades, much work has been done on collisionless shocks in the laboratory. Strictly perpendicular shocks were successfully created using \( \theta \)-pinches, but those shocks did not separate from the imploding magnetic field (e.g., piston).8–11 In contrast, work by Refs. 12–14 achieved some success in creating a shock-like structure that separated from the piston by combing a laser-produced plasma with a \( \theta \)-pinch. Much work has also been done on sub-Alfvénic laser-driven plasma in an external magnetic field,15–19 but these experiments cannot produce shocks. Given the difficulty of generating shocks with lasers, more recent works have utilized a Z-pinch20 or field-reversed configuration (FRC) plasma guns21 to study collisionless shocks.

Previous efforts22,23 have been unsuccessful in generating shocks because there are several criteria that must be simultaneously fulfilled by scaled laboratory shock experiments to be of relevance to space and astrophysical environments.24 The magnetic piston must drive a super-Alfvénic magnetic pulse through a magnetized ambient plasma long enough for instabilities to grow in the pulse front. This also implies that the system size must be large enough for a shocked ambient ion moving at the shock speed to complete one gyro-orbit. The mean-free-path of a shocked ambient ion must also be much larger than the system size to avoid classical collisions. To ensure sufficient coupling between the piston and ambient ions, hybrid simulations have predicted that the piston width must be larger than an ion inertial length25 and the piston radius must be larger than a piston ion directed gyroradius.26 Together, these criteria simultaneously require a high-energy piston (so that the pulse is super-Alfvénic) and a highly magnetized ambient plasma (so that the piston couples to the ambient plasma) while keeping the energy-density ratio \( \beta = E_{\text{piston}} \cdot (8\pi/B^2) > 1 \).

By using a high-energy laser to drive a magnetic piston through a large-scale magnetized ambient plasma, experiments at UCLA have recently demonstrated the formation of a quasi-perpendicular, magnetized collisionless shock.27,28 Because the flexibility of the laser allows non-perpendicular geometries, and because the piston is only temporarily tied to the shock, these experiments allow more control over

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shock formation and evolution than the original ones on $\theta$-pinches.

Building on the success of generating a collisionless shock, this paper is concerned with the general aspects and characteristics of forming a subcritical magnetized collisionless shock in the laboratory. New data taken in different formation environments and consistent with 2D hybrid simulations show the relationship of subcritical shocks to non-shocks and pre-shocks, allowing observed shock structures to be newly correlated with various experimental regimes. Additionally, measured features from shocks in various stages of formation allow a new analysis on how well theoretical shock formation criteria encapsulate shock formation physics. These shock criteria are also used to quantify the observed experimental regimes.

The paper is organized as follows. Section II provides additional background information on sub-critical shock formation. Section III describes the experimental setup. Section IV details the experimental results, which are then discussed in Section V. Section VI summarizes important findings.

II. BACKGROUND

A shock is created when a flow moving faster than the local sound speed encounters an obstacle. The obstacle serves to slow down the flow. Because the oncoming flow is faster than the sound speed, information about the obstacle cannot propagate quickly enough upstream to directly affect particles. To compensate, a region is established that acts to slow the incoming flow at the expense of increased entropy. In other words, the shock converts the high ram, low thermal pressure flow upstream (the region that shock has not reached) to a low ram, high thermal pressure flow downstream (the region the shock has passed). In a collisionless shock, the transition region (shock layer) is much smaller than the classical mean free path. For a comprehensive theoretical treatment of collisionless shocks, see Refs. 35–37.

Here, the relevant sound speed is the magnetosonic speed $c_{ms} = c_s^2 + c_A^2$—where $c_A$ is the Alfvén speed and $c_s$ is the sound speed—and, for the plasmas of interest, can usually be approximated as $c_{ms} \approx c_A$. The magnetosonic speed $c_{ms}(\theta_B)$ can be further written as a function of the shock wave propagation angle $\theta_B$ relative to the magnetic field. As a result, shocks can be classified by the angle $\theta_B$ as quasi-perpendicular ($\pi/4 < \theta_B \leq \pi/2$) or quasi-parallel ($0 \leq \theta_B < \pi/4$). The experiments detailed here then involve the formation of quasi-perpendicular, fast mode shocks.

Using the magnetohydrodynamic (MHD) equations for a single-fluid plasma, and assuming a planar shock, relationships between the upstream (ahead of the shock and denoted subscript 1) and downstream (behind the shock and denoted subscript 2) values of density $n$, velocity $v$, magnetic field $B$, and pressure $P$ can be derived. These are known as the Rankine-Hugoniot (RH) jump conditions, and describe the global (far from the shock layer) conservation of energy across the shock.

For a strictly perpendicular shock ($\theta_B = \pi/2$) and assuming an ideal gas equation of state, 37,38 the jump conditions show that the magnetic field and density downstream of the shock increase by the same amount as the velocity decreases. For the marginal $\beta \sim 1$, quasi-perpendicular, low-Mach number plasmas in the experiments, these compression ratios $(B_2/B_1, n_2/n_1, v_1/v_2)$ approximately scale as the Alfvénic Mach number $M_A$, as seen in Fig. 1.

Shocks can be further classified by their criticality, a measure of how well a shock can maintain itself through the anomalous (since there are no classical collisions) resistive dissipation. Criticality is expressed in terms of a critical Mach number $M_c$, where $M < M_c$ is subcritical and $M > M_c$ is supercritical. A supercritical shock is unable to maintain itself solely through resistive dissipation. $M_c$ depends on the plasma $\beta$ and $\theta_B$, but the largest possible value is $M_c \approx 2.76$ ($M_c$ increases as $\theta_B$ increases or $\beta$ decreases).36,39 For the experiments detailed here, the shocks are generally subcritical.

In addition to the expected shock features, the formation process places limits on the conditions under which a collisionless shock will form. In the shock frame, the upstream ions with flow $v_0$ must, of course, be super-Alfvénic ($M_A = v_0/v_A > 1$). The collisional mean free path between shocked ions must be larger than their gyroradii ($\lambda_{\text{ms}} > \rho_{\text{is},2}$), where $\rho_{\text{is},2} = v_s/\Omega_{\text{is},2}$, $\Omega_{\text{is},2} = Z_a e B_2/m_2 e$, $v_s \approx v_0/M_A$, and $B_2 \approx M_A B_0$ is the compressed magnetic field for low-Mach number shocks. In order to set up a cross-ramp potential, the shocked ions must be sufficiently magnetized, i.e., their gyroradii must be less than the system size ($\mu = D_0/\rho_{\text{as},2} > 1$). This is equivalent to the condition that the upstream ions have sufficient time to establish the cross-ramp potential $(T = D_0/v_s > \Omega_{\text{is},2}^{-1})$. The system size $D_0$ is defined as the distance from the target to the edge of the (suitable) ambient plasma.

Shocks can be further (though incompletely) characterized by a coupling parameter $\epsilon$ that helps distinguish when a shock will form. The parameter was originally derived by Bashurin et al.41 using the equal charge radius $R_\epsilon = (3N_e Z_a^2/4\pi Z_a e^2)^{1/3}$. An alternate, empirically motivated version using the equal mass radius is given by

$$\epsilon = R_h^2 \rho_d \rho_a = \left( \frac{R_M}{\rho_d} \right)^2 \left( \frac{m_d Z_a}{m_a Z_d} \right),$$

FIG. 1. Compression ratio (ratio of downstream to upstream value) versus Alfvénic Mach number $M_A$ for a strictly perpendicular ($\theta_B = \pi/2$) planar shock with lines of constant $\beta = 8\pi nT/B^2$. For $\beta \sim 1$, the compression ratio scales as the Mach number for $M_A \ll 3$. 

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where \( R_M = \left( \frac{3N_em_d}{4\pi m_en_0} \right)^{1/3} \), \( \rho_d = \frac{v_0 m_d}{(eZ_d B_0)} \), \( \rho_a = \frac{v_0 m_a}{(eZ_a B_0)} \), \( v_0 \) is the piston speed, and the subscripts refer to debris and ambient ions, respectively. Note that this parameter was derived strictly for large-Mach number shocks, so its application is approximate. Hybrid simulations suggest that \( \epsilon \approx 0.5 \) is necessary for shock formation.

### III. Experimental Design

The experiments were carried out on the Large Plasma Device (LAPD)\(^{29}\) using the Raptor high-energy laser\(^{30}\) at UCLA. The LAPD is a large scale (18 m long by \( \varnothing 1 \) m) facility that provides a well-characterized and highly reproducible magnetized ambient plasma. The plasma is steady-state (10 ms), quiescent and current-free, and customizable in both background magnetic field (0.2–1.8 kG) and ambient gas fill (H\(_2\), He, Ne, Ar). A BaO-coated Ni cathode generates the background magnetic field (0.2–1.8 kG) and ambient gas fill.

A typical experimental setup is shown in Fig. 2. A graphite or plastic (high-density polyethylene C\(_2\)H\(_4\)) target was embedded in a magnetized ambient H or He plasma 30 cm from the machine center axis. The target was translated and/or rotated every shot for a fresh surface. Since the laser-ablated plasma is always directed normal to the target surface, the target normal was oriented along \( \hat{x} \), resulting in a laser blow-off across the background magnetic field. The Raptor laser is a kJ-class laser (1053 nm, 25 ns) used to drive the magnetic piston.

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The evolution of the magnetic field was measured with a variety of differentially wound bdot probes.\(^{32}\) Single-axis bdots measured the \( \hat{z} \) component of the field up to 60 cm from the target along \( \hat{x} \). Individual probes were positioned in 1 cm increments with 1–3 shots taken per position, while a “5-tip” probe—containing 5 bdot cores spaced 1 cm apart—was incremented in 5 cm steps with generally 1 shot per position. Additional tri-axis bdots measured all three components of the field up to 10 m from the target along \( \hat{x} \). The probe signals were sent through custom-built 150 MHz differential amplifiers and coupled to fast (1.25 GHz) 10-bit digitizers.

Data characterizing the ablating and ambient plasma were measured with Thomson scattering, spectroscopy, and fast-gate filtered imaging, as detailed elsewhere.\(^{33}\)

### IV. Experimental Results

To illustrate the characteristics of subcritical shock formation in a laboratory setting, several representative experimental runs were carried out with a range of laser energies, intensities, background magnetic fields, and ambient plasma conditions. Since shock formation strongly depends on ambient density, ambient density profiles are also provided. In the following, the ion inertial

![Fig. 2. Schematic layout of an experiment on the LAPD. (a) Coordinate system of the experiment. (b) Cartoon cross-section of the LAPD plasma in a two-cathode configuration.](image-url)

| TABLE I. Summary of collisionless shock experiments. \( E_0 \) and \( I_0 \) are the average laser energy and intensity, respectively, for each run. \( n_a \) is the peak ambient ion density, \( \Omega_\perp \) is the ambient ion gyropoint, \( c/\Omega_\perp \) is the ion inertial length, \( \rho_d \) is the debris (laser-ablated) plasma ion gyroradius, and \( \rho_a \) is the Alfvén speed. Note that while Run 3 used a plastic (C\(_2\)H\(_4\)) target, measurements and simulations show no significant effect from the H debris. However, the plastic target allowed much higher laser intensities than a graphite (C) target. |
|---|---|---|
| Run 1 | Run 2 | Run 3 |
| \( E_0 \) (J) | 19 ± 1 | 90 ± 5 | 190 ± 10 |
| \( I_0 \) (10\(^11\) W/cm\(^2\)) | 5 | 1.4 | 12 |
| Target material | C | C | C\(_2\)H\(_4\) |
| Ambient plasma | He\(^{+1}\) | H\(^{+1}\) | H\(^{+1}\) |
| \( B_0 \) (G) | 275 | 200 | 300 |
| \( n_a \) (10\(^{12}\) cm\(^{-3}\)) | 5 ± 1 | 5 ± 1 | 12 ± 1 |
| \( \Omega_\perp \) (\( \mu s \)) | 1.5 | 0.5 | 0.3 |
| \( c/\Omega_\perp \) | 20 | 10 | 7 |
| \( \rho_d \) (cm) | 35 | 32 | 31 |
| \( \rho_a \) (cm/s) | 134 | 195 | 189 |
length $c/\omega_{pi}$ and ion gyro-frequency $\Omega_{ci}^{-1}$ are given in terms of ambient ion conditions as listed in Table I, and unless otherwise stated, distances are relative to the target and times are relative to laser ablation.

**A. Weak coupling regime**

Fig. 3 shows results from Run 1 (see Table I). In the figure, a diamagnetic cavity is seen expanding from the target, reaching a maximum size of $\sim 20$ cm at $\sim 0.9 \mu s$. Soon after, the cavity begins to collapse due to magnetic diffusion. Also seen is a magnetic compression initially moving at the same speed as the cavity ($v_0 \sim 330$ km/s, $M_A \sim 2.7$). Later, the magnetic pulses separate from the cavity as the cavity slows down.

This run lies in the weak coupling regime, in which the piston fails to transfer significant energy to the ambient plasma. While super-Alfvénic for most of its lifetime, the resulting magnetic field structures are very similar to the sub-Alfvénic features seen in Refs. 17, 18, and 34. As is typical in sub-Alfvénic cases, at early times ($t = 200$ ns or $\sim 0.1 \Omega_{ci}^{-1}$), the ramp of the compression is shallow and ends at the cavity edge (i.e., no pulse width, see Fig. 3(b)). This is due to the penetration into the ambient environment of magnetic field from the cavity, as well as the decoupling of faster debris ions that carry some magnetic compression with them. The magnetic pulse reaches a peak compression of $B/B_0 = 1.3 \pm 0.1$ at $t = 549$ ns ($\sim 0.4 \Omega_{ci}^{-1}$), but its leading edge remains shallow. The pulse also begins to broaden due to the difference in speeds between the cavity ($M_A = 2.7$) and leading ($M_A = 3.7$) edges. By $t = 800$ ns ($\sim 0.5 \Omega_{ci}^{-1}$), however, the compression remains broad but weakly compressed with a shallow ramp. Unlike the following runs, the ambient density remains largely uniform (though lower) throughout this run due to the use of just the larger-diameter BaO cathode.

**B. Moderate coupling regime**

Run 2 (Fig. 4) is typical of the moderate coupling regime. Like Run 1, Run 2 has at early times ($t = 500$ ns or $\sim 1.3 \Omega_{ci}^{-1}$) a compression with a shallow ramp ending at the cavity edge (see Fig. 4(b)). Unlike Run 1, however, the compression continues to grow until reaching a maximum value $B/B_0 = 1.7 \pm 0.1$ at $t = 1.1 \mu s$ ($\sim 1.9 \Omega_{ci}^{-1}$) at $x = 29$ cm ($0.9 \pm 0.1 \rho_d$). At this time, the compression is also moving at $M_A = 1.8 \pm 0.1$ (see Fig. 4(a)). Additionally, comparing

![FIG. 3. Results from shock experiment Run 1 (see Table I). (a) Contour streak plot of normalized magnetic field. Also shown are spatial and temporal lineouts (dashed). (b) Spatial lineouts from (a), including at maximum compression (solid). The ambient density profile is also shown (gray overlay). (c) Temporal lineouts from (a) containing maximum compression. The results indicate no shock or pre-shock is formed, consistent with a weak coupling regime.](image1)

![FIG. 4. Results from shock experiment Run 2 (see Table I). (a) Contour streak plot of normalized magnetic field. Also shown are spatial and temporal lineouts (dashed). (b) Spatial lineouts from (a), including at maximum compression (solid). The ambient density profile is also shown (gray overlay). (c) Temporal lineouts from (a) containing maximum compression and corresponding vacuum profile. The results indicate that a pre-shock formed but did not have sufficiently uniform ambient density to steepen and separate from the piston.](image2)
the magnetic field profile with and without an ambient plasma indicates a strong ambient effect (see Fig. 4(c)). The compression with ambient plasma is stronger and has a steeper temporal ramp (but comparable breadth). The compression’s leading edge also arrives faster, while its cavity edge is slower, indicating coupling with the ambient plasma. However, as the magnetic pulse reaches its maximum compression, the ambient density falls significantly (see Fig. 4(b)). This causes the local Alfvén speed to increase and the pulse to become sub-Alfvénic. As a result, the compression fails to further steepen or separate and instead dissipates.

C. Strong coupling regime

Results from Run 3 (Fig. 5) indicate a strong coupling regime. Like the previous run, Run 3 shows signs of moderate coupling at $t = 280$ ns ($\sim 0.6 \Omega_i^{-1}$), see Fig. 5(b)). The leading edge of the compression moves at $M_A = 1.5 \pm 0.1$ with a magnetic compression $B_z/B_0 = 1.6 \pm 0.1$, but has a shallow ramp. However, the compression continues to grow until reaching a maximum value at $t = 708$ ns ($\sim 1.9 \Omega_i^{-1}$) and $x = 29$ cm $(0.9 \pm 0.1 \rho_d)$, at which point the pulse has a considerably different structure. The compression has increased to $B_z/B_0 = 2.0 \pm 0.1$ and moves at $M_A = 2.1 \pm 0.1$. The ramp of the compression, though, has steepened to a width $\delta = 0.5 \pm 0.2 c/\omega_{pi}$. Furthermore, the width of the pulse has increased to $\Delta = 1.4 \pm 0.2 c/\omega_{pi}$, showing a significant separation of the front of the compression from the cavity edge. This can also be seen in the difference between the speeds of the front ($M_A = 2.1 \pm 0.1$) and back ($M_A = 1.6 \pm 0.1$) of the compression (see Fig. 5(a)).

Like the moderate coupling run, comparison to shots taken in vacuum under the same conditions indicates that the above features are tied to the ambient plasma (see Fig. 5(c)). At $x = 37$ cm $(1.2 \pm 0.1 \rho_d)$, the magnetic pulse in vacuum has a much shallower ramp. Though the width of the pulse in vacuum is broader than seen in previous runs, it is, nonetheless, much narrower than the corresponding pulse with ambient plasma. Furthermore, the cavity moves more slowly with an ambient plasma $(350 \text{ vs. } 390 \pm 20 \text{ km/s})$, consistent with energy being coupled to the ambient ions, while the leading magnetic compression moves more quickly $(530 \text{ vs. } 420 \pm 10 \text{ km/s})$, consistent with a pulse that is being carried by accelerated ambient ions.

Similar to Run 2, by $t = 940$ ns ($\sim 2.5 \Omega_i^{-1}$), the compression has entered a region of significantly reduced ambient density. This causes both the Alfvén speed and ion inertial length to increase, decreasing and smearing out the leading edge of the magnetic compression.

V. DISCUSSION

From the considerations of Section II and experimental conditions, a quasi-perpendicular, fast mode, low-Mach number, subcritical shock is expected with a shock layer thickness on the order of an ion inertial length and magnetic field compression similar to the Mach number. Fig. 6 shows a diagram of the process by which the shock is expected to form (in terms of the magnetic field, though the process should be similar for the ambient density). Initially, a diamagnetic cavity and compression at the cavity edge are formed by the piston. The compression moves super-Alfvénically, and the leading ramp of the compression is much larger than an ion inertial length due to faster ions slipping through. Later in time, a shock begins to form as piston-accelerated ambient ions overrun unperturbed ions. As the piston loses energy, a large compression width develops as the shock separates from the slowing cavity edge. The leading compression ramp also steepens. Late in time, the shock has separated from the piston, with a well-defined shock ramp and downstream region. Additional details on the shock formation process can be found in Ref. 27.

These features allow the various experimental regimes of Section IV to be related to shock formation. In the weakly coupled regime, no shock forms. Indeed, in Run 1, the magnetic compression ($B_z/B_0 = 1.3$) and Mach number ($M_A = 2.7 - 3.7$) are inconsistent with the RH conditions. Instead, the resulting magnetic pulses are most similar to the sub-Alfvénic regime.

In the moderately coupled regime, a pre-shock can form. A pre-shock has sufficient initial conditions to begin shock formation (unlike the weak coupling case), but fails to
fully steepen due to a lack of space, time, and/or sufficient ambient density (pre-shocks were also observed in Ref. 22). This is supported by Run 2, where the magnetic compression \((B_z/B_0 = 1.7)\) and Mach number \((M_A = 1.8)\) are consistent with the RH conditions for low-Mach number shocks, and the initial conditions suggest the beginning of shock formation. The lack of sufficient ambient density (due the sharp drop at the edge of the LaB6-generated plasma), however, causes the pulse to dissipate before a shock can form.

This is further supported by 2D hybrid simulations of Run 2 initialized to the same experimental conditions (see Fig. 7). The simulations utilize a 2D3V collisionless magnetostatic hybrid code in two Cartesian spatial dimensions with three-dimensional fields and velocities. Additional details can be found in Refs. 26 and 40. The simulations do not include the laser-target interaction, but focus on a plasma expanding out from a planar target perpendicular to a uniform magnetic field into an ambient plasma at experimental conditions. In the simulation, an ambient plasma with a Gaussian density distribution centered \(\sim 2.5 c/\omega_{pi}\) from the initial debris distribution is superimposed on a uniform low-density plasma covering the entire simulation domain. The debris plasma consisted of a cloud of C\(^{1+5}\) ions that expanded out conically at \(M_A \sim 1.8\). In Fig. 7(b), the simulation shows the formation of a magnetic compression consistent with the RH jump conditions. However, it also shows that the ambient density, while compressed from piston coupling, fails to remain tied to the magnetic compression due to insufficient magnetization. This is also seen in Fig. 7(c), where there are no reflected ambient ions in phase space at the leading edge of the magnetic pulse.

Finally, systems in the strongly coupled regime can support full shock formation, as seen in Run 3. The magnetic pulse seen in Run 3 is not only consistent with the RH conditions but also has a steep leading edge on the order of the ion inertial length that is beginning to separate from the cavity. This can also be seen in Fig. 8, in which key features of the magnetic pulse are tracked in time. As expected in shock formation, the magnetic pulse compression, steepness, and broadness increase in unison, reaching a maximum value at approximately the same time. For similar reasons as Run 2,
As can be seen in Figs. 9(a) and 9(b), the formation of a low-Mach number collisionless shock is also reproduced in the simulations. In particular, a magnetic and ambient density compression consistent with the RH jump conditions is seen in Fig. 9(b), while a small population of reflected ambient ions from the shock front is seen in Fig. 9(c). The simulations also show the dissipation of the shock as it leaves the high-density ambient plasma (see Fig. 9(a)), consistent with experimental observations.

It is of further interest to determine whether the shock criteria outlined in Section II can accurately capture the differences between these experimental regimes, which would indicate that these criteria are encapsulating the physics of laboratory shock formation. It would also allow the experimental regimes, previously defined by their dominant expansion speed, to be quantified by shock formation parameters.

In order to calculate the criteria, in particular, $\epsilon$, it is necessary to have information on the initial state of the laser plasma (piston). This is estimated from the results found in Ref. 33. Here, laser-target interactions were simulated using the 1D HELIOS radiation-magnetohydrodynamic code that provided a range of particle number and charge state values for various laser intensities. The simulation results were benchmarked by the measured density and temperature profiles and were found to be in good agreement after scaling to 3D. Additionally, the numerical results compared well to laser-based empirical scaling laws. The total number of ablated particles was then calculated from the experimental laser intensity, and, by using both the measured intensity and expansion speed, interpolated average ablated charge states for that speed were estimated. Together with the experimental ambient conditions, this allowed a calculation of the equal mass radius $R_M$, debris gyroradius $\rho_d$, and ambient gyroradius $\rho_a$, and hence $\epsilon$.

The shock formation criteria for the experimental results are summarized in Table II. As can be seen, only Run 3 satisfies all formation conditions, consistent with the measurements from Section IV C that indicate a collisionless shock formed. While a super-Alfvénic expansion, sufficient coupling, and high $\beta$ were achieved in most cases, the most...
TABLE II. Criteria necessary for shock formation for runs from Table I. $M_A = v_0/v_A$ is the Alfvénic Mach number, where $v_A$ is the shock speed (generally the piston expansion speed). $\epsilon = R_M^2/p_M /p_A$ is the coupling parameter, where $R_M = \left( \frac{3AM_{pA}^2}{4AM_{pA}^2} \right)^{1/3}$, $\rho_M = \frac{m_A}{m_p} c_A^2 /Z_A$, and $\rho_A = \frac{m_A}{m_p} c_A^2 /Z_A$. The magnetization parameter $\mu = D_M /p_{\text{sc}}$ is defined with respect to the shocked ambient ions, where $D_M$ is the system size, $p_{\text{sc}} = \rho_M /\Omega_{\text{ion}}$, $\Omega_{\text{ion}} = Z_A^2 B_0 /m_A c^{3} /\pi B_c^2$, and $n_{\text{sc}} = M_A n_A$.

<table>
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<th>Condition</th>
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<th>Run 3</th>
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<td>$\approx 1$</td>
<td>$\approx 1$</td>
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<tr>
<td>$\beta &gt; 1$</td>
<td>0.7</td>
<td>1.3</td>
<td>1.9</td>
</tr>
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VI. SUMMARY

Laboratory experiments combining a laser-driven magnetic piston with a large, pre-formed magnetized ambient plasma have allowed a unique investigation into collisionless shock formation not readily available to spacecraft. Magnetic field measurements indicate that a subcritical, quasi-perpendicular, magnetized collisionless shock was created, and was beginning to separate from the piston before dissipating in a low-density ambient plasma. The 2D hybrid simulations reproduced these features. In combination with the above result, additional shock experiments in which no shock or a pre-shock was formed were found to be consistent with theoretical predictions of collisionless shock formation and shock structure. Furthermore, these experiments could be organized by weak, moderate, or strong coupling according to their magnetic profiles: weak coupling corresponding to weakly compressed super-Alfvénic pulses; moderate coupling corresponding to well-compressed but un-steepened pulses; and strong coupling corresponding to fully formed shocks.

Multiple shock formation criteria were investigated, revealing that the most important criteria, in addition to being super-Alfvénic ($M_A > 1$), were the coupling $\epsilon > 0.5$ and magnetization $\mu > 1$ parameters. Within these parameters, the most important experimental consideration for shock formation was the amount of space ($D_0$) over which ambient conditions were relatively constant. Consistent with theory, shocks only formed in those experimental conditions that satisfied all shock formation criteria. Using the results of laser plasma characterization studies to calculate shock formation criteria, the experiments were found to lie in distinct regions of an $\epsilon-\mu$ parameter space, which agreed well with the observed shock formation regimes of weak coupling ($\epsilon < 0.5$, $\mu < 1$), moderate coupling ($\epsilon > 0.5$, $\mu < 1$), and strong coupling ($\epsilon > 0.5$, $\mu > 1$). This indicates that the $\epsilon$ and $\mu$ parameters are capturing most of the physics of laboratory shock formation. Future work will continue to characterize shock evolution, as well as transition to quasi-parallel shock geometries.

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