Towards a parallel collisionless shock in LAPD

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Abstract. Using a high-energy laser to produce a super-Alfvénic carbon-ion beam in a strongly magnetized helium plasma, we expect to be able to observe the formation of a collisionless parallel shock inside the Large Plasma Device. We compare early magnetic-field measurements of the resonant right-hand instability with analytical predictions and find excellent agreement. Hybrid simulations show that the carbon ions couple to the background plasma and compress it, although so far the background ions are mainly accelerated perpendicular to the mean-field direction.

1. Introduction
Collisionless shocks are a virtually ubiquitous phenomenon in space, from planetary bow shocks in our solar system [1, 2, 3, 4, 5] to the shocks occurring in supernova remnants [6, 7] and presumably the jets of active galactic nuclei [8]. Our understanding of the complex process of shock formation has greatly improved since Sagdeev’s seminal paper [9], thanks to both satellite observations [10, 11] and numerical simulations [12, 13]. Yet the complicated three-dimensional structure that one would predict for a parallel shock on theoretical grounds [14] is difficult to confirm, either because of the nature of one- or few-point satellite measurements or because three-dimensional kinetic simulations are computationally too expensive.

To avoid these particular difficulties, our group is working on producing a parallel collisionless shock in a laser-plasma experiment at the Large Plasma Device (LAPD) [15]. Simulations assuming a quasi-one-dimensional carbon front [16] showed that the available energy density is sufficient to observe the early stages of collisionless-shock formation. In this proceeding, we present measurements of the resonant right-hand instability in our experiment and compare them with predictions of shock-formation theory [17]. This research continues previous work on the generation and investigation of a perpendicular collisionless shock [18, 19].

2. Theory and definitions
For an externally magnetized plasma which consists of two ion species and charge-compensating electrons with a relative drift velocity along the magnetic-field direction much larger than either thermal velocity, the dispersion relation for parallel-propagating waves is [17]

$$\omega^2 - k^2 \omega^2_\perp = \omega^2_{p,0} \frac{\omega - k V_0}{\omega - k V_0 \pm \Omega_0} + \omega^2_{p,b} \frac{\omega - k V_b}{\omega - k V_b \pm \Omega_b} + \omega^2_{e,0} \frac{\omega - k v_0}{\omega - k v_0 \pm \Omega_e} + \omega^2_{e,b} \frac{\omega - k v_b}{\omega - k v_b \pm \Omega_e},$$

(1)
where $\omega$ and $k$ are frequency and wavenumber along the magnetic field, while $\omega_p$ and $\omega_e$ are the plasma frequencies of the proton and electron populations for background (subscript 0) and beam (subscript b) species. $V$ and $v$ denote the drift velocities of ions and electrons, respectively; $\Omega_0$, $\Omega_b$, and $\Omega_e$ are the positive gyrofrequencies of background ions, beam ions, and electrons.

We define right-handed circular polarization with respect to the magnetic field as having the same sense of rotation as the Larmor motion of electrons with no parallel velocity component in a given frame of reference. It follows that the upper signs in the denominators of eqn. (1) correspond to a right-hand circularly polarized wave, the lower signs to left-handed polarization.

The electron terms can be simplified if we assume that the frequency range of interest is much smaller than the Doppler-shifted electron gyrofrequency, $|\omega - kV_0/b| \ll \Omega_e$. Moreover, we will choose as our frame of reference a frame in which the net electron current vanishes, such that $\omega_{e,0}^2 v_0 + \omega_{e,b}^2 v_b = 0$, and define $\omega_e^2 = (\omega_{e,0}^2 + \omega_{e,b}^2) \Omega_0/\Omega_e$ to obtain

$$\omega^2 - k^2c^2 = \omega_{p,0}^2 \frac{\omega - kV_0}{\omega - kV_0 \pm \Omega_0} + \omega_{p,b}^2 \frac{\omega - kV_b}{\omega - kV_b \pm \Omega_b} - \omega_e^2 \frac{\omega}{\pm \Omega_0}. \quad (2)$$

Although this choice of frame simplifies the solution of the dispersion relation and saves us from having to consider the electric field created by a net current, this solution is only valid in the zero-current frame. In the experiment, on the other hand, wave measurements are taken in the lab frame in which the background ions are at rest; consequently, a Doppler shift becomes necessary for comparing the results.

![Figure 1](attachment:image1.png)

Figure 1: a) Schematic of turning mirror reflecting the laser beam on the polyethylene (CH$_2$) target inside LAPD. b) Cross section of LAPD with relative sizes of target, high-density helium plasma created by the LaB$_6$ cathode, debris/blow-off ion cloud, and lower-density helium plasma created by a BaO cathode. c) Cut along LAPD with positions of target, cathodes, and sample configuration of Bdot and Langmuir probes.
3. Experimental setup
The background plasma in our experiments is confined in the 17-metre-long LAPD. A discharge current is created with a lanthanum hexaboride (LaB$_6$) cathode and ionizes helium to He$^+$ with a density of $10^{13}$ cm$^{-3}$ at an ion temperature of $T_i = 1$ eV. In future experiments, significantly higher densities will be facilitated by a second LaB$_6$ cathode. Pancake magnets surrounding the plasma maintain a magnetic field of 300 gauss. Thus the nominal Alfvén velocity evaluates to $v_A = 106$ km s$^{-1}$, the gyroperiod of a singly charged helium ion is $\tau_{\text{He}^+} = 8.7 \mu$s. An overview of the experiment is shown in Figure 1.

In order to create the beam ions, the high-energy Raptor laser ($E \leq 250$ J, $\lambda = 1053$ nm) is focused on a high-density polyethylene target and various charge states of carbon are ablated at super-Alfvénic velocities, predominantly C$^{3+}$ and C$^{4+}$ [20]. By adjusting the alignment of the target, we control the angle between the bulk velocity of the blow-off ions and the external magnetic field. After a previous campaign of experiments at LAPD studied the generation of collisionless shocks perpendicular to the magnetic-field direction [21], we will focus in this report on our recent progress towards exciting a parallel collisionless shock.

4. Measurements
As the ablated carbon ions stream through LAPD, they cannot couple to the background plasma collisionally because their mean-free-path is far longer than the available distance. Creating a shock requires instead that the carbon ions excite electromagnetic waves of such an amplitude that the background plasma is accelerated and compressed efficiently by the steepening wave fronts which propagate along the external magnetic field.

We quantify the carbon ions free-streaming down the central axis of LAPD with two types of probes. Langmuir probes detect the carbon-ion saturation current at various distances from the target. In addition, a fibre probe positioned 30 centimetres from the target transmits light through a monochromator to an avalanche photodiode (APD) to measure the spontaneously emitted fluorescence of C$^{4+}$ ions. Time-of-flight analysis yields a bulk velocity of $v_C \approx 2.5 \ v_A$ after 2.0 metres that is slowed down to $2.0 \ v_A$ after another 4.0 metres, although some ions appear to stream ahead with a velocity of $4.5 \ v_A$. It is presumably these latter fast ‘vanguard’ ions that are the predominant cause of the observed magnetic instabilities.

All three components of the magnetic field on the central axis are measured with several

![Figure 2: Sample time trace of the radial magnetic-field component measured 7.5 metres from the target on the central axis of the plasma column](image)
magnetic-flux or ‘Bdot’ probes. The amplitude of the waves in the radial component decreases from 6 G after 1.5 metres to about 3 G after 11.5 metres. A sample time trace for the radial component, taken at a distance of 7.5 metres from the target, is shown in figure 2. As that plot demonstrates, the parallel-propagating waves excited by the carbon ions can be distinguished unambiguously into two groups: a fast high-frequency chirp propagating with a group velocity of about 550 km s$^{-1}$ or 5.2 $v_A$, and a larger-amplitude wave packet traveling at about the Alfvén velocity. The latter component is clearly dominated by modes with oscillation periods at least twice the gyroperiod of background ions.

To investigate the wave dispersion of the high-frequency chirp in closer detail, we show in figure 3 iso-intensity contours of a Morlet-wavelet transform of the signal measured 7.5 metres from the target. The highest frequencies at about $10^{1.5} f_0$ are picked up by the probe after about 15 seconds ($f_0 = \Omega_0/(2\pi)$), followed by a smooth transition towards lower frequencies all the way down to the sub-cyclotron range. During this chirp, the spectral intensity of the signal passes through two maxima, one at $10^{0.9} f_0$ after 24 seconds, the other one at $10^{0.5} f_0$ after 30 seconds. A closer look at the phase relation of the two perpendicular magnetic-field components shows that the waves during this period are almost exclusively right-hand polarized.

We can thus compare the timing of this signal to the dispersion that we expect for waves in the helium plasma on the fast-magnetosonic/whistler branch with right-hand polarization, which corresponds to taking the upper signs in the denominators of equation (1). We neglect the beam terms in the dispersion relation because the carbon is too dilute to affect the group velocity.
over most of the distance covered by the waves. Using the plasma frequency and Alfvén velocity given above, we calculate the group velocity, and thus the expected time of arrival (ETA) at the probe location, as a function of the Doppler-shifted frequency, plot the result over the measured intensity contours in figure 3, and find close to perfect agreement in the regime above $\Omega_0$. At lower frequencies, left-handed waves on the Alfvénic branch of the dispersion relation contribute more and more to the measured signal and arrive later than predicted for waves of right-handed polarization.

Close to the target, where the carbon ions excite the waves, the beam terms must be retained. Making several simplifying assumptions, such as neglecting the finite temperature of the beam and the presence of blow-off ions other than C$^{4+}$, we can derive an exact analytical expression for the growth rate $\gamma_{\text{RHI}}$ of the right-hand instability from the dispersion relation (2). Since this growth rate is far more sensitive to the beam velocity than to its density (at moderately super-Alfvénic velocities, [22]), we expect that the fastest ions detected by the Langmuir probe at 2 metres make the dominant contribution to the instability and assume a beam velocity of 4.2 $v_A$. At a relative number density $n_b/n_0 = 5.8 \%$, the growth rate as a function of frequency exhibits two easily separated peaks. The colour coding of the ETA line in figure 3, which represents that growth rate, shows that these two fastest growing modes are located extremely close to the maxima of the measured spectral intensity.

All these data are thus described by the cold-plasma dispersion relation to a surprisingly high level of accuracy. Determining the effect of the carbon-ion beam on the helium background, however, in particular the amount of compression and acceleration, requires numerical simulation.

5. 2D-hybrid simulations

In order to capture the important beam-resonant instabilities, we use a hybrid code that treats ions with the particle-in-cell method and approximates the electrons as an inertia-less magnetohydrodynamic fluid [23]. The magnetic field is computed on a two-dimensional grid 20 inertial lengths ($=20\delta_i$) wide and extending 256 inertial lengths along the mean-field direction, which is the $x$ axis. Resolutions in time and space are $0.001/\Omega_0$ and 0.125 $\delta_i$, respectively; each grid cell is initially populated with 100 background-ion quasiparticles.

We model the ablated carbon-ion beam as a 50:50 mixture of C$^{3+}$ and C$^{4+}$ of a total initial density 300 times the helium-ion density $n_0$, concentrated in a volume measuring $0.5 \times 0.03 \delta_i^2$ around the point $(x, y) = (2\delta_i, 10\delta_i)$. The angular distribution of velocity and density is proportional to $\cos^2 \varphi$ and to $\cos^4 \varphi$, respectively [24], such that the resulting mean $x$-velocity is $\langle v_x \rangle = 1.3 \ v_A$ for C$^{3+}$ and $3.9 \ v_A$ for C$^{4+}$. To match the Langmuir-probe measurements, we add an isotropic thermal-velocity component corresponding to $\beta = 10$. The resulting initial velocity distribution has a mean $\langle v_x \rangle = 2.6 \ v_A$ averaged over both carbon species, as in the experiment.

Qualitatively as well as quantitatively, we find strong agreement in both frequency and amplitude between the right-handed waves as they appear in time traces of the magnetic field in the simulation and the right-handed waves as measured by the Bdot probes (see figure 4). This strong agreement for the right-hand instability, which is mainly driven by the fastest beam ions, is to be expected as the fastest C$^{4+}$ quasiparticles in the simulation have a velocity of around $v_x \approx 5.0 \ v_A$, similar to the Langmuir-probe measurements of the experiment. A detailed comparison of the left-hand circularly polarized low-frequency pulse between simulation and experiment is currently in progress.

The effect of the propagating carbon ions on the background-plasma density is shown in figure 5. While the two clouds of ablated ions spread and re-converge because of their gyromotion in the magnetic field, the helium ions are compressed in a thin (about one inertial length in diameter) channel along the central axis of LAPD. Although the density in this channel
Figure 4: Comparison of Morlet-wavelet transforms of a magnetic-field time trace from the hybrid simulation (left) and the experimentally measured Bdot signal (right) 7.5 metres from the target (gyrofrequencies are $T_g^{-1} = 1.1 \cdot 10^5$ Hz for He$^+$ and $1.5 \cdot 10^5$ Hz for C$^{4+}$).

Figure 5: Simulated density of carbon beam ions (a–c) and helium background ions (d–f) as the beam, which consists of slow C$^{3+}$ and fast C$^{4+}$, propagates to the right.

doubles, this compression does not result in a shock since the acceleration of the helium ions is mainly perpendicular to the central axis. Energy transport in the parallel direction is too small to sustain the compression, which ceases after only about 50 inertial lengths from the target. Further work will focus on improving the collimation of blow-off ions and thus the conversion of beam energy into parallel kinetic energy of helium ions.

6. Summary
We have ablated carbon ions from a plastic target in a highly magnetized plasma with a high-energy laser. Measurements of the current have confirmed that the ions propagate at several Alfvén velocities, and we have shown that the waves that the ions produce as they propagate along the field direction are excited by the right-hand instability, one of the beam instabilities associated with the formation of the parallel bow shock.

However, the amplitude of the waves is not yet high enough to accelerate the background ions efficiently in the parallel direction. Instead, hybrid simulations suggest that the background
plasma within a distance of 4 metres from the target is compressed by a factor of 2 perpendicularly to the mean-field direction. In order to form a parallel collisionless shock, we are currently investigating methods to decrease the perpendicular spread of the carbon blow-off, which will result in improved coupling between the beam ions and the parallel velocity of the background ions.

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