Particle-in-cell simulations of laser-driven, ion-scale magnetospheres in laboratory plasmas

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Abstract

We present particle-in-cell (PIC) simulations of ion-scale magnetospheres that reproduce recent laboratory experiments performed on the Large Plasma Device (LAPD) at UCLA. In the PIC simulations, a super-Alfvénic driver plasma flows against a dipole magnetic field that is embedded in a uniform magnetized background plasma. The simulations replicate the main magnetospheric structures observed in the experiments and establish the conditions for their observation. Additionally, we develop a semi-analytical model of the parameters that characterize the coupling between the driver and background plasmas.

Introduction

Planetary-sized magnetospheres have typically tens of thousands of kilometers. However, magnetospheres with a few hundreds of kilometers are also observed in space environments such as the lunar surface. Although the Moon does not have a global magnetic field like Earth, it does have small localized regions of crustal magnetic field, of 10-100 nT over distances of 100-1000 km [1]. When the magnetic obstacle size is smaller or of the order of the ion kinetic scales of the plasma, the interaction with the solar wind results in ion-scale magnetospheres, or mini magnetospheres.

To complement these observations and study these systems in highly controlled configurations, multiple experiments attempted to replicate mini magnetospheres in laboratory environments. Such experiments were recently performed at the Large Plasma Device (LAPD), in UCLA, where fast collisionless plasma flows generated by high-repetition-rate lasers were collided with the magnetized ambient plasma provided by the LAPD and with a dipolar magnetic field obstacle, leading to the formation of mini magnetospheres [2]. Using motorized probes, high spatial and temporal resolution measurements of the magnetic field allowed the characterization of 2D magnetic field and current density structures. The experiments detected a reflection of the magnetic compression and a two current structure.

Particle-in-cell (PIC) simulations are often included to these studies as they capture important microphysical processes of mini magnetospheres [3]. In this work, we use PIC simulations of ion-scale magnetospheres driven by super-Alfvénic plasma flows to interpret the results of the recent LAPD experiments. Apart from validating the experiments, the simulations explore multiple parameter scans to investigate the formation of the magnetospheric properties [4].

Laboratory ion-scale magnetospheres

We performed 2D simulations of ion-scale magnetospheres with OSIRIS, a massively parallel and fully relativistic PIC code [5]. In the simulations, a driver plasma moves against a background plasma permeated by a uniform magnetic field $\mathbf{B_0}$ and a dipolar magnetic field $\mathbf{B_{dip}}$, both oriented along the z direction and transverse to plasma flow in the y direction [4]. The spatial scales are normalized to the ion skin depth $d_i = \sqrt{m_{i,0}c^2/4\pi n_0 e^2}$, where $m_{i,0}$ is the mass of the background ions, c is the speed of light in vacuum, n_0 is the background density, and e is the electron charge. The temporal scales are normalized to $1/\omega_{ci}$, where $\omega_{ci} = eB_0/m_{i,0}c$ is the ion cyclotron frequency of the background plasma ions. The simulation box is a 12 d_i $\times$ 12 d_i area with periodic and open boundary conditions in the x and y directions, respectively, and considered 25 particles per cell per species and 10 grid cells per electron skin depth $d_e = d_i\sqrt{m_e/m_{i,0}}$, where m_e is the electron mass.

The driver plasma has a $L_y = 2\ d_i$ length, infinite width, uniform density $n_d = 2\ n_0$, and flow velocity $v_0 = 0.1\ c$. The background plasma is an 8 d_i length and infinite width plasma and it has uniform density n_0. The driver and background ion masses are $m_{i,d}$ and $m_{i,0}$, respectively, with $m_{i,d} = m_{i,0} = 100\ m_e$. The internal uniform magnetic field $\mathbf{B_0}$, is such that $M_A = 1.5$, where $M_A \equiv v_0/v_A = v_0\sqrt{4\pi n_0 m_{i,0}}/B_0$ is the Alfénic Mach number. $\mathbf{B_{dip}}$ is externally imposed, with $B_{\text{dip}} = M/r^3$, where M is the dipolar magnetic moment and r is the distance to the dipole's origin. M was chosen such that the expected standoff, obtained from the equilibrium between the driver ram pressure with the magnetic pressure, is $L_0 = 1.8\ d_i$.

To compare the numerical results with the experimental data, synthetic diagnostics were obtained. Fig. 1 shows the variation of the magnetic field ΔB_z and the current density J_x at $x = 0$.

Fig. 1 is consistent with the experimental results. We see in Fig. 1 a) that, as the driver flows against the background, it expels the magnetic field, leading to an upstream magnetic cavity and a downstream magnetic compression. The driver experiences increasingly higher magnetic fields until the magnetic pressure is enough to reflect the driver, at $t\omega_{ci} \approx 3$. The magnetic cavity and the compression are also reflected. A background magnetic decompression is seen after $t\omega_{ci} = 5$.

In Fig. 1 b), we can observe the diamagnetic current that creates the magnetic cavity. This

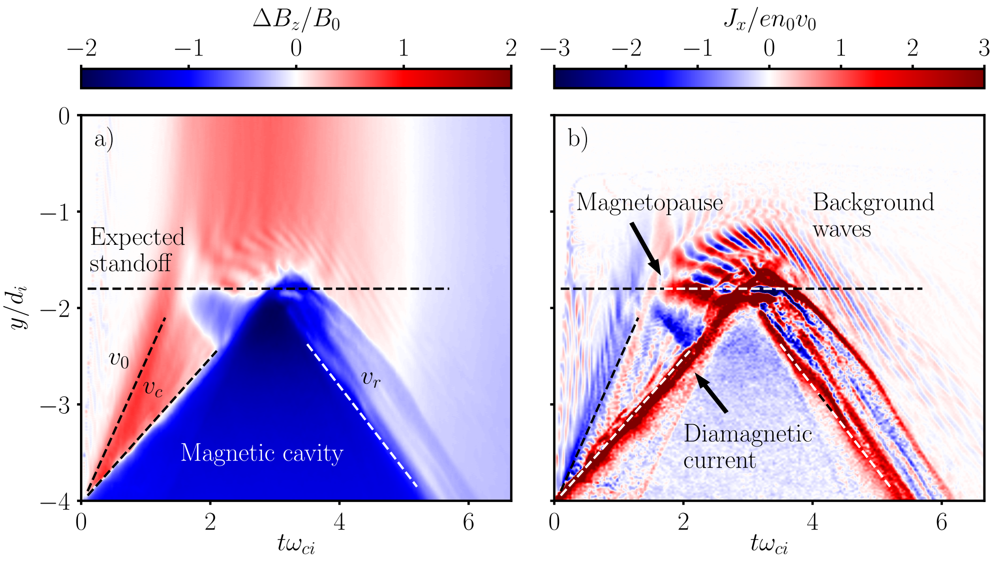

Figure 1: Temporal evolution of a) ΔB_z and b) J_x, at $x = 0$. The dashed lines have slopes that match the flow velocity v_0, the coupling velocity v_c and the reflection velocity v_r.

structure is reflected near the expected standoff $y_0 = -L_0$. Between $t\omega_{ci} \approx 2$ and $t\omega_{ci} \approx 3$, a second current structure is present in the background region. It is associated with the magnetopause of the system and arises from the interaction of the background ions with the dipole.

To determine the importance of each system parameter on the magnetospheric properties and find the parameters that best replicate the experimental results, we performed multiple parameter scans with the simulations. We observed that the driver length bounds the reflection of the magnetic compression, and for lower magnetic moments, the magnetopause is easier to identify. From the parameter scans, a driver with a density $n_d = 2\ n_0$ and a length of $2\ d_i$ best recreated the experimental results [4].

Coupling between a driver plasma and a magnetized background plasma

To fully understand the formation of ion-scale magnetospheres in the LAPD setup, we need first to understand the interaction of the driver with the background, before interacting with the dipole. This can be done by studying the coupling, *i.e.*, the efficiency in momentum and energy transfer between the plasmas.

We consider as coupling parameters the coupling velocity v_c and the stopping distance L_{stop}, *i.e.* the velocity and distance that the magnetic cavity travels through the background, in a no dipole case, respectively. The coupling velocity is always $0 < v_c < v_0$, and approaches v_0 in the high coupling regime. L_{stop} also increases for higher coupling. By defining $R_n \equiv 0.5\left(n_0 m_{i,0}/n_d m_{i,d}\right)^{1/2}$, we can obtain from the mass, momentum, and energy conservation laws across the discontinuities, that the coupling parameters are described by

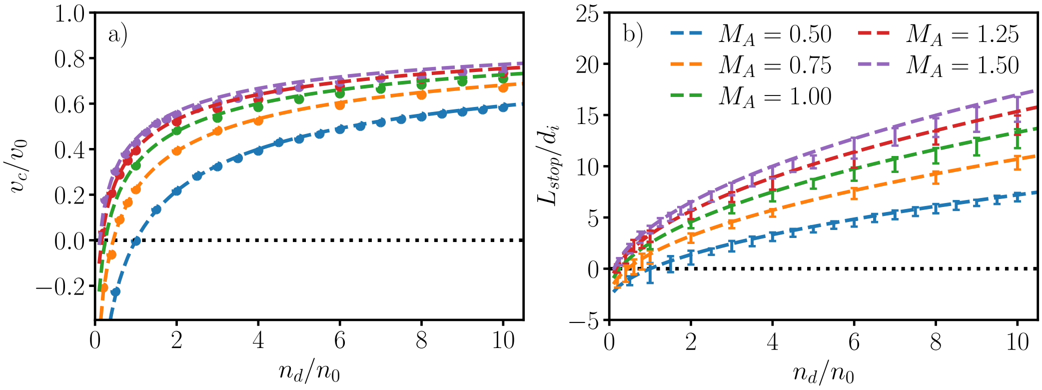

Figure 2: Comparison between a) the coupling velocity v_c measured in the simulations with Eq. (1), and b) the stopping distance L_{stop} with Eq. (2), for different Mach numbers M_A and driver densities n_d. The measured values are represented by dots, and the analytical expressions by dashed lines.

$$\frac{v_c}{v_0} = \frac{1}{M_A}\frac{M_A - R_n}{1 + R_n} \qquad (1) \qquad\qquad L_{stop} = L_y \frac{M_A - R_n}{R_n(1+M_A)} \;. \qquad (2)$$

To validate Eqs. (1) and (2), we performed additional 1D simulations, under a similar setup to the 2D runs, but where there is no dipole and the driver has a $L_y = 5\ d_i$ length and the background a 20 d_i. Fig. 2 compares the measured values of v_c and L_{stop} in the simulations with the equations, for different driver densities n_d and Mach numbers M_A. We can see that the equations are consistent with the simulations.

Conclusions

With this work, we successfully validated the formation of ion-scale magnetospheres in the LAPD. We observed the formation of a magnetic cavity upstream and the formation of a magnetic compression downstream, followed by their reflection after reaching the dipole. From multiple parameters scans, we observed that the driver length bonds the reflection of the magnetic compression, and lower magnetic moments lead to more visible magnetopauses. Additionally, we also show a model for the coupling between the driver and the background plasma, for $M_A \sim 1$. Work supported by the European Research Council (ERC-2015-AdG Grant 695088). Experiments supported by the NSF (Award PHY-2010248).

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