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Ion velocity distribution in a low resistivity plasma traversed by a pulsed magnetic field

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Introduction

We present a study of the evolution of the velocities of ions in a nearly collisionless plasma penetrated by a pulsed magnetic field [1]. The plasma discussed has a low resistivity, and is composed mainly of protons, which are reflected by the magnetic field, and carbon ions, which penetrate into the field. The magnetic field penetrates the carbon component of the plasma rapidly in a non-diffusive manner, and has a well defined penetration front propagating through the plasma. The magnetic field penetration mechanism is not fully understood yet, but the penetration may be attributed, arguably, to the Hall electric field formed in the plasma during the field penetration [2]. As the magnetic field traverses through the plasma it accelerates its ions. Since the magnetic field has a smooth penetration front and the plasma has a low ion collision rate, it may be naively expected that following the penetration the ion velocity distribution will shift (due to the magnetic field pressure) but will not broaden significantly. However, measurements show that the ion velocity distribution broadens significantly. We show that the significant velocity broadening occurs after the reflection of the light ions (protons) by the magnetic field. This is in accord with a MHD simulation of our system, suggesting instabilities formed behind the penetration-front may be responsible for the velocity broadening [3].

The Experimental System

The experiment consist of producing a plasma between two electrodes, followed by driving a current between the electrodes, thereby creating the magnetic field interacting with the plasma. The plasma is produced by two surface-flash-over (flash-board) plasma sources, mounted 4 cm above a wire-anode and operated 1.2 μs prior to the application of the generator current pulse. Details of the flash-board-plasma parameters are given in Ref. [4]. The current forming the magnetic field is applied between two planar electrodes. The electrodes are 14 cm wide, 8 cm long, and separated by a 2.5 cm gap. The data is collected between the electrodes, 6 mm above the cathode. The plasma at that point consists primarily of protons ($n_p \sim 10^{14}\ cm^{-3}$) and carbon ions ($n_c \sim 10^{14}\ cm^{-3}$). The electron density during the field penetration is roughly $3 \times 10^{14}\ cm^{-3}$ and the initial electron temperature was estimated to be $\sim 6\ eV$ [4]. The main observation tool

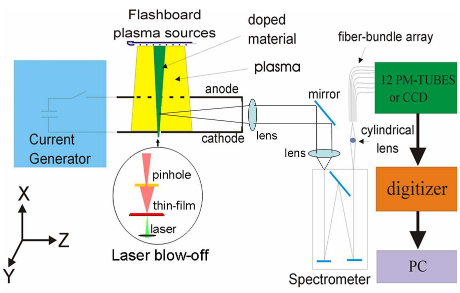

Figure 1: The experimental system.

applied is emission spectroscopy. To acquire 3D spatial resolution we combine imaging spectroscopy with a controlled injection of chosen elements into the plasma (dopants). Radiation from these elements is distinguished from the ambient plasma by its distinct emission lines. The dopants used in this study were magnesium and boron. The magnesium was used to measure electron density, using the population ratio of the levels $1s^2 2p^6 3p$ and $1s^2 2p^6 3d$. The velocities of the boron ions accelerated by the magnetic field were used to determine the magnetic field profile. The magnetic field was extracted from the electron density and ion velocities using Eq. (1), where n_e is the electron density, v_B is the magnetic field propagation velocity and z_i is the ion charge. Details of the derivation are given in Ref. [5].

$$\mathbf{B}^2(x,t_0) = \frac{8\pi m_{ion}}{z_i} \int_0^{v_{ions}(t_0)} n_e(x, v_{ions}(x))\, v_B\, d(v_{ions}(x)) \qquad (1)$$

Results and Discussion

The time evolution of the velocity distribution, of trace elements (B II) accelerated by the magnetic field traversing the plasma is shown in Fig. 3(a). At the start of the penetration the ion distribution broadens, due to the spatial extent of the dopant plume and the magnetic field profile. However, once the penetration front has passed the dopant ions, it is expected that the velocity distribution of the ions will narrow approximately to its initial width. The expected time evolution of the ion velocities, based on the measured electron densities and magnetic field profile (Fig. 2) is shown in Fig. 3(b). As can be seen by comparing Fig. 3(a) and Fig. 3(b), the calculated and measured evolutions agree during the first 25 *ns* of the penetration. However, from then on the calculated and the measured ion velocity evolutions differ, and the measured ion velocity distribution shows a significant broadening. Since the ion-ion collision rate in the plasma allows for less than 1% of the ions to collide during the ~ 35 *ns* it takes the magnetic field front to pass them, a simple process of collisions cannot account for this broadening. A possible explanation for the ion velocity broadening lays in the formation of a density peak when the

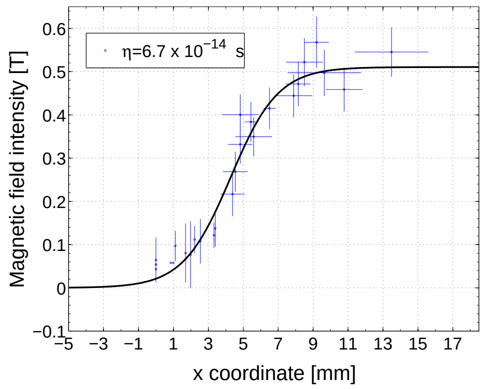

Figure 2: Magnetic field profile inferred from the ion velocities.

protons are reflected by the magnetic field, roughly 20 *ns* into the penetration (when the magnetic field reaches $\sim 0.4\ T$). Due to the density peak, a density gradient opposite to the magnetic field gradient forms, and Rayleigh - Taylor type instabilities may develop in the plasma. A simulation of our system [3] indeed shows that at late times in the penetration, Rayleigh - Taylor type instabilities may form behind the penetration front of the magnetic field.

Acknowledgements

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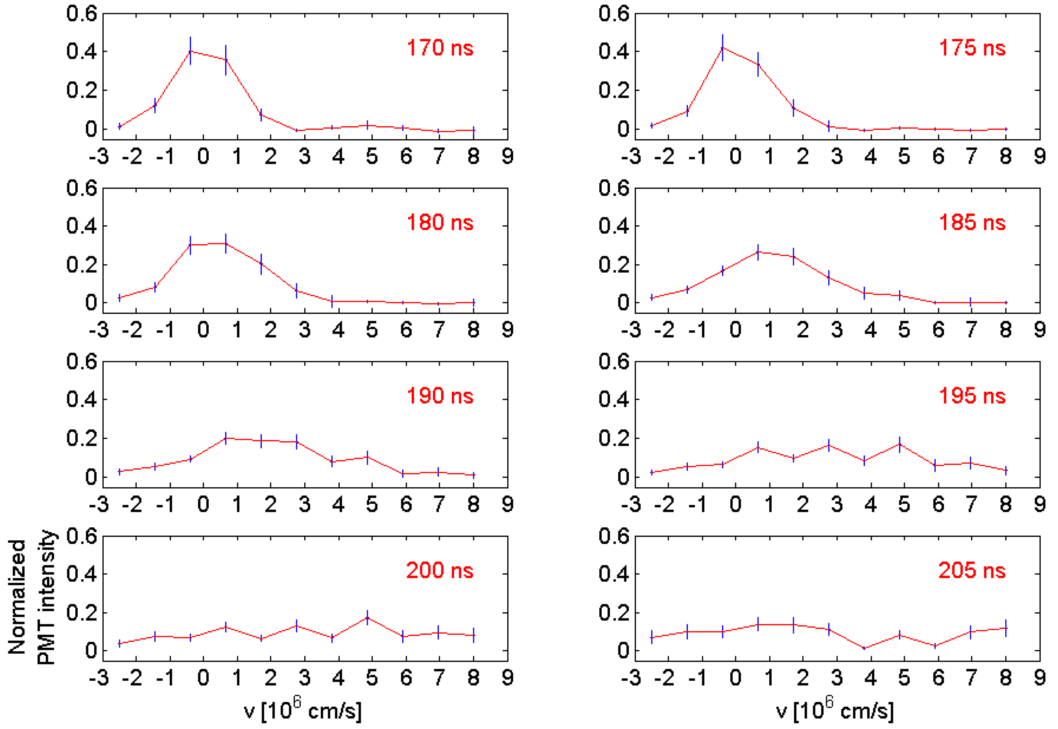
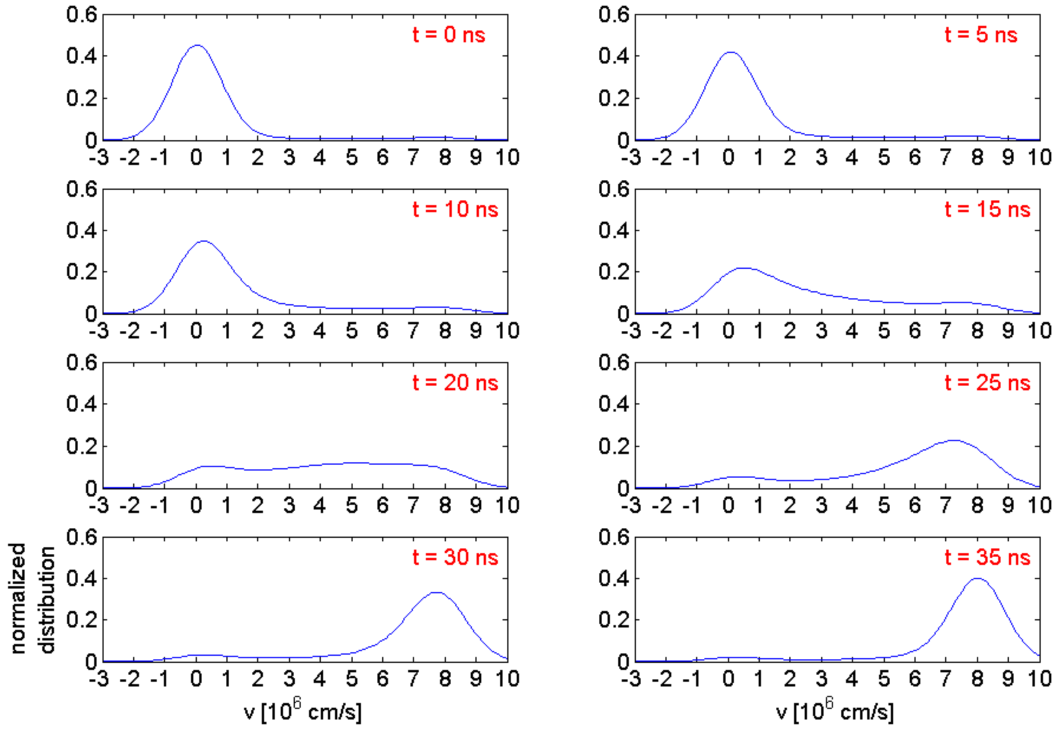


(a) Measured ion velocity distribution



(b) Ion velocity distribution expected for the measured 1D magnetic field front

Figure 3: Experimental and theoretical ion velocity distribution.