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Highly Resolved Spectroscopic Observations of Magnetic Field Penetration into an (almost) Collisionless Plasma

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Introduction

Classically, magnetic fields are expected to penetrate into high resistivity plasmas via diffusion, and to push low resistivity plasmas. However, it has long been known that in certain cases magnetic fields penetrate quickly into low resistivity plasmas. In these cases, the diffusion coefficient needed to account for the rapid penetration may by more than an order of magnitude larger than the measured one, even when the enhancement of the resistivity by electron interactions with waves in the plasma (anomalous collisions) is taken into account. An alternative, non diffusive model suggested for the penetration is the Hall penetration model. According to this model, in the presence of electron density or magnetic field inhomogeneities the Hall electric field acting on the electrons in the current channel enhances the penetration rate of the magnetic field into the plasma. The field penetration rate for the system discussed here was calculated by this model to be $\sim$ 60% of the measured one [1]. However, the current channel width seemed to be much wider than expected by the model, and there seemed to be no dependence of the penetration rate on the electron density gradient along the current, as is predicted by the model. It was suggested that the discrepancies between theory and experiment resulted from an insufficient spatial resolution of the observation [1]. The magnetic field may have small scale spatial structure, unobserved in the experiments, responsible for the apparent width. A reasonable lower limit for a physically important length scale for the penetration mechanism is the electron skin depth. It is not expected for the magnetic field to change significantly over distances shorter than this. However, the spatial resolution of earlier observations of the magnetic field front in the system discussed here was $\sim$ 15 mm, which is $\sim$ 50 times the electron skin depth. By implementing imaging spectroscopy with high accuracy doping techniques, combined with a new approach for the analysis of the spectroscopic data, we have significantly improved the spatial resolution and reached a spatial resolutions of a few times (3 -10) the electron skin depth. Observations at this high resolution, combined with previously measured data, reveal the spatial profile of the magnetic field across the shock front ("axial direction"). This profile agrees well with that predicted by a Hall-field induced magnetic field penetration model [2]. However, the new measurements also show an unexplained ion velocity distribution, possibly due to small scale structure of the magnetic field front in non axial directions.

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 μ seconds prior to the application of the generator current pulse. Details of the flash-board-plasma parameters are given in reference [3]. 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 ($n_p \sim 10^{13}\ cm^{-3}$) 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 $\sim 5\ eV$ [3]. The main observation tool applied is emission spectroscopy. The intensities of line emissions of elements in the plasma are recorded and analysed, yielding the plasma and field parameters. Radiation emitted from elements in the plasma is imaged on a spectrometer, converted to electric signal by Photo Multiplier Tubes (PMTs), and transferred to a series of digitizers. Since the imaging apparatus (having a high F-number) provides resolution only in the direction perpendicular to the line of sight, the resolution along the line of sight is accomplished through the controlled injection of chosen elements into the plasma. 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 penetrated by the magnetic field were used to determine the magnetic field profile, as explained in the next section. These velocities were measured through the Doppler shifts of the B II 3451.3 $\AA$ line. The technique used to introduce the doping is laser blow off. In this method a dopant is blown off a coated slide by a laser hitting the slide from its uncoated side. The material at the tip of the plume is dilute and well aligned, which makes it easily collimated by an iris. By optimizing the parameters of the laser blow off we have obtained plumes of a diameter smaller than 4 mm (containing 80% of the ions) for boron, and about 2 mm for magnesium.

Magnetic Field Determination

Direct measurement of the magnetic field by Zeeman splitting under the present plasma conditions is hampered by Doppler, Stark and instrumental broadening of the spectral lines, limiting the observation to magnetic fields larger than ~ 0.3 T. Moreover, since the measured splitting is an average over the doped region, the signal coming from a strong magnetic field localized in a small region of the observed plasma may be obscured by a weak magnetic field signal coming from a larger region. For a shock like magnetic field front propagating in a low beta plasma, when the electron density and magnetic field velocity are known, the above limitations may be lifted. Our new approach is based on deriving the magnetic field spatial profile from the velocities of ions accelerated in the magnetic field. Since for high field penetration rates ion velocities are much smaller than the magnetic field velocity, ion position change is neglected (in our case the ions travel $\sim 1\ mm$ during the field penetration). We start from the equation for the average force exerted by the magnetic field on ions of charge z_i, in perpendicular to the magnetic field direction. n_e is the electron density, $\mathbf{J}$ the current density, electron pressure is neglected:

$$\mathbf{F} = \frac{z_i}{cn_e}\mathbf{J}\times\mathbf{B} = \frac{z_i}{n_e}\frac{(\nabla\times\mathbf{B})\times\mathbf{B}}{4\pi} = \frac{z_i\nabla\mathbf{B}^2}{8\pi n_e} \tag{1}$$

From eq.(1), and using $B = B(x+vt)\hat{y}$ to switch to integration over time, we obtain the magnetic field's spatial profile. x, t_0 the observation position and time, v_B the magnetic field velocity, m_{ions} the ion mass:

$$\mathbf{B}^2(x,t_0) = \int_{-\infty}^{x}\nabla\mathbf{B}^2(x',t_0)dx' = \int_{-\infty}^{x}\frac{\nabla\mathbf{B}^2(x',t_0)}{n_e(x,t)}n_e(x,t)dx' = \frac{8\pi}{z_i}\int_{-\infty}^{t_0}n_e(x,t')\mathbf{F}(x,t')v_B dt'$$
$$= \frac{8\pi}{z_i}\int_0^{v_{ions}(t_0)}n_e(x,v_{ions}(x))\ v_B\ d(m_{ions}v_{ions}(x)) \tag{2}$$

Ion velocities are determined from the Doppler shifts of the line observed. However, the spectral line shape of the radiation emitted from ions accelerated by the magnetic field may be very complex, being affected by the profile of the magnetic field across the dopant plume as well as by atomic processes in the observed region. Thus a fit for the complete line shape is a daunting task. Our approach is, instead, to follow only the time evolution of the velocity of the fastest dopant ions, thereby following the evolution of the magnetic field front penetrating the edge of the dopant plume.

Results and Discussion

Previous measurements [1] show that for the time scales of the present observation the magnetic field is approximately of the form $B = B(x+vt)\hat{y}$, with a propagation velocity of $v_B \sim 3\times10^7\ cm/s$. Preliminary high resolution measurements of the electron density give $n_e = 3\pm1\times10^{14}\ cm^{-3}$ during the penetration. The magnetic field profile obtained, based on these measurements and the recorded ion velocities, is shown in Fig. (1).

The solid line is the fit to the magnetic field profile predicted by a Hall-field induced magnetic field penetration model [2]. The resistivity is the free parameter in the fit, and was determined to be $\eta = 6.7 \times 10^{-14}\ s$. This value agrees well with previous estimates for an anomalous resistivity [1], and is a few times (~ 5) higher than expected from Spitzer resistivity. The velocity distribution of dopant ions after the magnetic field penetration shows the presence of a significant nearly unaccelerated component (Fig. 2). Since no neutral boron atoms were observed in the plasma, the unaccelerated boron ions can not be neutral boron atoms (which are not accelerated by the magnetic field) which were ionised after the penetration. This suggests the existence of some small scale structure in the magnetic field's spatial structure. One possibility is that curvature of the field front may accelerate ions in various non axial directions. Another explanation may be the formation of "fingers" in the magnetic field front, where ions are accelerated at the tip of the fingers by a shock like front, but between fingers the penetration is by diffusion, with little acceleration of the dopant ions.

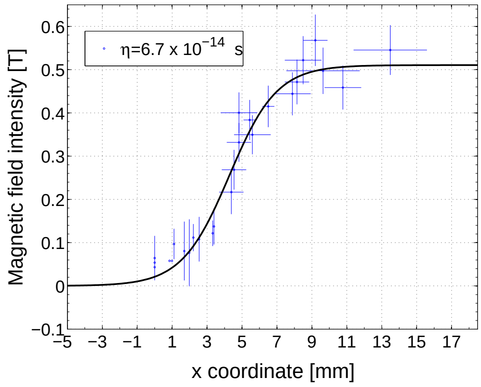

Figure 1: Magnetic field profile.

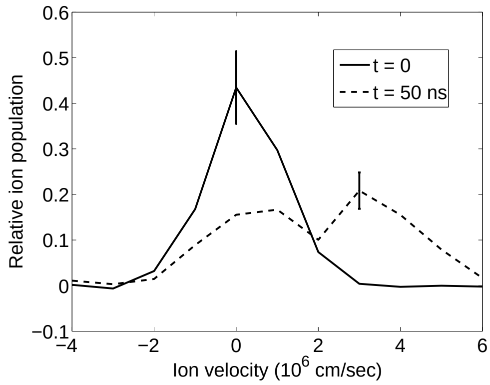

Figure 2: Ion velocity distribution before and after the magnetic field penetration.

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