SPECTROSCOPIC STUDY OF THE MAGNETIC FIELD, ION DYNAMICS AND ELECTRON DENSITY EVOLUTION IN A PLASMA OPENING SWITCH

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Abstract Spatially resolved measurements in a planar microsecond POS, using spectroscopy of dopants in the plasma together with charge-exchange spectroscopy, are presented. Measurements of the axial ion velocities together with the B-field and the plasma density evolution show pushing of the protons ahead of the magnetic field together with field penetration into the carbon plasma. A plasma density drop, which leads to the switch opening, was observed during the field penetration into the carbon plasma. The pushing of protons causes plasma flow into the vacuum region between the POS and the load and influences the energy coupling to the load. These results demonstrate the great importance of the effects associated with a multicomponet plasma and makes the plasma composition an important parameters influencing the POS operation. Measurements with a reversed polarity of the POS do not show any significant difference in the magnetic field and the electron density evolution, as predicted by the electron magnetohydrodynamic theory, implying the field penetration is not dominated by Hall penetration. Alternatively, the observed penetration could also be associated with an anomalous collisionality, which would also explain the observed broad current channel. However, so far, no mechanism predicting such a high collisionality has been demonstrated.

Keywords opening switch, charge transfer, model, diagnostics

I. Introduction

Pulsed power generators that use inductive energy storage techniques offer potential benefits for producing TW and higher electrical power pulses[1)]. Applications for such generators include inertial confinement fusion and the production of intense x-ray pulses. A plasma-opening switch (POS) allows the use of vacuum inductive storage for the generation of such high power pulses. A POS consists of a plasma injected between two conductors in vacuum, through which current flows, storing magnetic energy in the circuit. At some point, depending on the details of the POS and the driving current, this conduction phase ends and the switch opens rapidly, transferring energy to a load. Over the past years much attention has been directed toward microsecond conduction-time POS development. However still, there are many open questions relating to the mechanisms responsible for the opening of the switch. Also, significant losses in coupling the POS to various loads were found[2)].

The aim of this research is to seek a better understanding of the physical phenomena that are dominant in the POS operation. The interaction between the plasma and the magnetic field generated by the current may manifests itself in a variety of ways. A few competing processes can lead to either fast magnetic field penetration into the plasma with relatively low ion velocities, or on the other hand, if the field does not penetrate into the plasma bulk, it is expected to accelerate the plasma at the edge to velocities on the order of the Alfven velocity. These two extreme cases are expected to result in different opening mechanisms of the POS and, thus, understanding this interaction is essential for the optimization of the switch operation and its coupling to various loads.

II. Experimental setup

A 40-kV capacitor bank drives a current of 150 kA through our planar POS, which conduct the current for 400 ns before opening to an inductive load within ≈80 ns. Flashboards[3)] are used to produce the plasma. The flashboard plasma parameters, such as plasma density and composition, electron temperature and ion velocities were determined prior to the POS operation. The electron density was found to vary from 3×10^{14} cm^{-3} near the cathode to 7×10^{14} cm^{-3} near the anode. At 1 cm from the cathode the plasma is composed of protons ($1\pm0.3\times10^{14}$ cm^{-3}) and carbon ions ($1.3\pm0.3\times10^{14}$ cm^{-3}) with an effective charge ~3.

The main problem in these investigations is the need for time-dependent, non-intrusive, spatially resolved and unambiguous diagnostic methods. Visible and UV spectroscopy is employed. The light emitted from the plasma is collected by optical systems into 1-meter spectrometers, allowing spectral resolution down to 0.06 Å. The spectrometers are equipped with photomultiplier arrays. Thus, we obtain a time dependent line profile in a single discharge with a temporal resolution of 8 ns. The systems are absolutely calibrated.

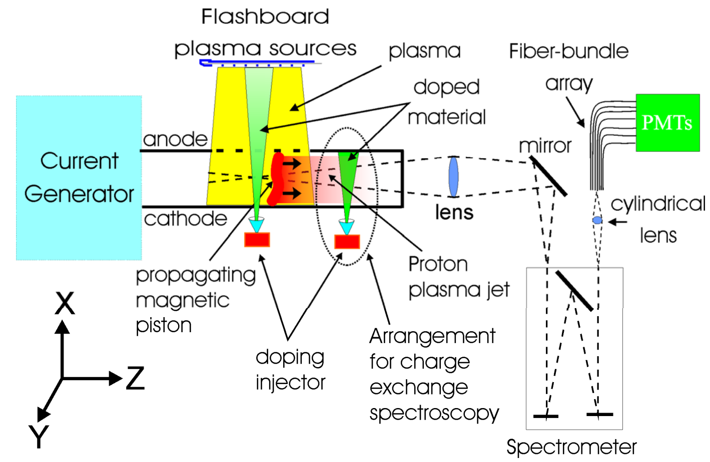

Figure 1 The setup and diagnostic system of the planar POS.

To obtain 3D spatially resolved measurements, we locally dope the plasma with various species whose emission is studied. Two doping techniques based on gas injection and surface flashover are employed[3,4].

III. Results

The evolution of the magnetic field is measured from Zeeman splitting of the $3d(^1D)$-$2p(^1P^0)$ transition (λ=6678 Å) of doped helium atoms. The accuracy of the magnetic field determination is ±0.15 T for B<0.5 T, when the Zeeman splitting is not resolved, and ±0.07 T for B>0.5 T for, which the two peaks of the Zeeman pattern are clearly resolved. Measurements at different axial positions (along Z) allow us to construct a 1D map of the magnetic field as a function of the axial position for different times, as shown on Figure 2. The magnetic field gradient (the region where the current is significant) is found to span over an axial distance of 2-3 cm. At x=1 cm the value of B=0.4 T propagates axially at a velocity of 3.6×10^7 cm/s.

Such measurements were performed also at different distances from the cathode and a 2D map of the magnetic field was constructed[6]. The front of the B-field is found to be approximately one-dimensional, however at higher value of B the propagation near the electrodes is slower (especially near the anode) resulting in a wedge-shaped structure. Both the 1D and the 2D map show a broad (2-3 cm) current channel at all times and positions.

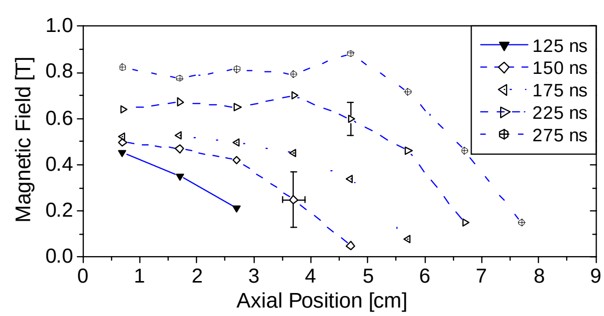

Figure 2 The magnetic field distribution as a function of the axial position at different times 1 cm from the cathode at the center of the electrodes along Y.

The electron density evolution is studied from line intensity measurements of the BIII 2066 Å spectral line. This spectral line intensity is proportional to the population of the 2p level that is only 6 eV above the ground state, which makes it insensitive to variations in the electron temperatures found here. Then, using data from different axial (along z) and radial (along x) positions in the anode cathode gap we constructed a 2-D map of n_e at different times. The electron density drops everywhere in the A-K gap at the end of the conduction phase and reaches a value below 2×10^{14} cm^{-3} near the cathode while near the anode the drop is less pronounced and a density of $3\text{-}4\times10^{14}$ cm^{-3} remains. The drop must result from radial (along X, see Figure 1) plasma flow since there is no buildup of plasma on the load-side edge of the POS region.

To determine the axial velocities of different ions we observed spectral lines of various species along the z-direction. The line-integrated measurements of axial velocity of CIII and CIV ions show the acceleration of the ions only to velocity of 1.3×10^{7} cm/s at the end of the current conduction. Local measurements of the axial velocities of HeII, LiII, BII, ArIII using the doping technique show linear Z/M velocity scaling between 7×10^{5} and 1.3×10^{7} cm/s. The observed velocities of these ions are lower than B-field propagation velocity, indicating the magnetic field penetration into the carbon plasma.

To study the axial proton velocity we employed charge exchange spectroscopy, in which fast protons undergo resonant charge exchange with doped hydrogen gas (see Figure 1) and thus are observable as Doppler shifts of the H_{α} spectral line. Measurements were performed by scanning the blue tail of the H_{α} line in three consecutive shots so that the array of photomultipliers monitored 36 points corresponding to velocities between $0\text{-}9\times10^{7}$ cm/s with a resolution of 3×10^{6} cm/s. To estimate the absolute density of the observed fast protons we compared the intensity of the shifted tail to the unshifted H_{α} line, which yielded the ratio between the doped hydrogen atoms and the density of protons that underwent charge exchange. Figure 3 shows spectral profiles of the H_{α} line at different times demonstrating clearly the presence of fast protons with velocities varying from $4\pm1\times10^{7}$ cm/s to $7\pm1\times10^{7}$ cm/s. The density of fastest protons (t=300 ns) is $7\pm2\times10^{13}$ cm^{-3}, later (at t=350 ns) the density increases to $1.2\pm0.3\times10^{14}$ cm^{-3}, both are comparable to the initial proton density in the plasma.

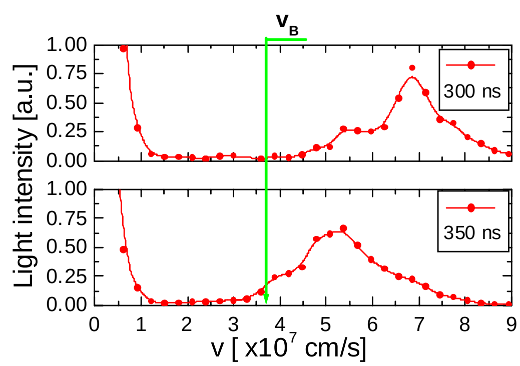

Figure 3 The proton velocities determined by the charge-exchange spectroscopy. Horizontal axis represents the Doppler shift from the central component in velocity units; vertical axis reflects the particle population. $\mathbf{v_B}$ is the propagation velocity of the current channel.

The proton velocity at early times ($7\pm1\times10^{7}$ cm/s) is exactly twice the propagation velocity of the current channel (3.6×10^{7}cm/s), suggesting that some protons are specularly reflected from the current channel. The observed axial velocity of protons decreases. This fact is addressed to either change of the direction of propagation of the proton plasma jet due to 2D structure of the magnetic field, or to effects associated with the broadening of the current channel.

IV. Discussion

As presented in Figure 3, protons are accelerated to a velocity that is up to twice the magnetic piston velocity. The heavy (carbon) ions attain peak velocities that are significantly lower than the piston velocity. Hence, making a distinction based on the relative ion and piston velocities one could say that the magnetic piston reflects the protons and penetrates into the carbon plasma.

In order to understand the field penetration let us look at the details of the evolution of the magnetic field and the electron density. Figure 4 shows the evolution of these parameters in the middle of the POS volume. The electron density increases during the rise of the magnetic field to a value of 0.5 T resulting in field penetration into the plasma. This is followed by a drop of the electron density, at the same time as B rises to its peak value.

One could ask by which mechanism the magnetic field penetrates into the plasma. Measurements with a reversed polarity of the POS do not show any significant difference in the observed results, as expected by the electron magnetohydrodynamic theory (through the dependence on the density-gradient direction), implying the field penetration cannot be explained by the Hall model[5]. However, the field penetration could be associated with anomalous collisionality (≈100 times Spitzer), which would also explain the observed broad current channel, nevertheless, for the POS conditions no mechanism resulting is such a high collisionality has yet been demonstrated. The broad current channel could also result from spatial integration over a complex 2D (or even 3D) magnetic configuration, which could form as a result of MHD turbulence. Indeed the small-scale turbulence-induced density gradients could enable field penetration due to the Hall term.

The proton pushing by the front of the magnetic field does not significantly alter the electron density due to relatively small fraction of the protons[3]. As the magnetic field exceeds 0.5 T and the protons have been pushed out, the electron density drops due to the motion of the carbon ions. The density drop results from radial (towards the electrodes) motion since the axial translation of the carbon ions is much less than the plasma extent. Due to the 2D structure of the B-field[6] a force component, accelerating the ions towards the electrodes exists. Based on the 2D magnetic field map the radial velocity of the carbon ions is expected to be approximately equal to axial velocity.

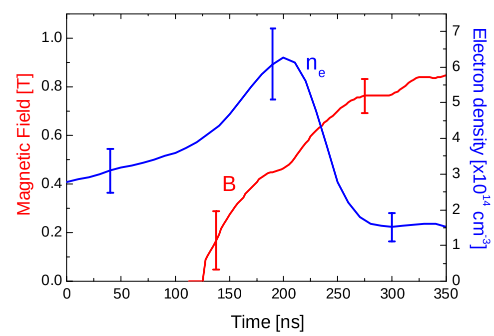

Figure 4 The evolution of the magnetic field and the temporal behavior of the electron density.

Most existing theoretical models of the POS treat the problem of the field penetration or plasma pushing under the assumption of a single ion species. However, as has been shown, in a multicomponent plasma one species may be reflected by the magnetic piston while the B-field penetrates into the slowly moving second species. Such energetic charged-particle flow (presumably protons) between the POS and the load have been observed at NRL and Maxwell Laboratories[7,8] resulting in significant energy losses and inefficient coupling of POSs to the load. Our experiments thus may explain the source of this ion flow, allowing for further optimization of the POS operation and its coupling to the load.

V. Acknowledgments

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