Observations of two-dimensional magnetic field evolution in a plasma opening switch

R. Shpitalnik, A. Weingarten, K. Gomberoff, Ya. Krasik, and Y. Maron
Faculty of Physics, Weizmann Institute of Science, Rehovot 76100, Israel

(Received 30 September 1997; accepted 8 December 1997)

The time dependent magnetic field distribution was studied in a coaxial 100-ns positive-polarity Plasma Opening Switch (POS) by observing the Zeeman effect in ionic line emission. Measurements local in three dimensions are obtained by doping the plasma using laser evaporation techniques. Fast magnetic field penetration with a relatively sharp magnetic field front ($\leqslant$1 cm) is observed at the early stages of the pulse ($t \lesssim 25$). Later in the pulse, the magnetic field is observed at the load-side edge of the plasma, leaving ''islands'' of low magnetic field at the plasma center that last for about 10 ns. The two-dimensional (2-D) structure of the magnetic field in the r,z plane is compared to the results of an analytical model based on electron-magneto-hydrodynamics, that utilizes the measured 2-D plasma density distribution and assumes fast magnetic field penetration along both POS electrodes. The model results provide quantitative explanation for the magnetic field evolution observed. © *1998 American Institute of Physics.* [S1070-664X(98)03403-X]

I. INTRODUCTION

Studying the interaction of magnetic field with short-duration plasmas is of major importance for understanding various phenomena in plasma discharges, thermonuclear-fusion research, and astrophysics, and for the progress towards various applications of pulsed-power systems, such as the generation of particle beams and the development of radiation sources. An example of such a system is the Plasma Opening Switch (POS) in which high current is conducted through a prefilled plasma (in a coaxial or planar geometry) before switching fast into a load. POS's have been used for prepulse suppression in high current accelerators,[1] for switching of inductively stored energy at currents up to 6 MA into various loads during 10–100 ns,[2] and for voltage and power multiplication in nanosecond[3] and microsecond[4] time-scale generators.

In Plasma Opening Switches, the characteristics of the current conduction through the plasma, the plasma flow, the plasma erosion, and the current switching to the load are decisively affected by the evolution of the magnetic field in the switch region.[5–7] The magnetic field in POS has been studied by magnetic probes inserted in the switch region. Measurements were carried out for POS of short ($\simeq$100 ns)[8] and long time scales ($\simeq$1 μs).[9] In these measurements it was found that the magnetic field penetrates the plasmas much faster than expected from estimates of its diffusion rates. In Ref. 5 the magnetic field was observed to penetrate into a 90-ns, 200-kA coaxial negative-polarity (i.e., the inner electrode is negatively charged) POS at a velocity $\simeq 4\times 10^8$ cm/s. In the 800-ns, 250-kA POS the magnetic field penetration velocity was observed to be $\simeq$10 times smaller. In both experiments, the current channel width in the plasma is $\simeq$30 times larger than the classical skin-layer thickness.

Earlier explanations of the relatively fast field penetration suggested that plasma instabilities may give rise to anomalous collisionality that enhance the magnetic field diffusion rate.[10] It was later argued[11] that this treatment is overestimating the collision frequency for the nanosecond POS. Later, theoretical treatments based on electron magnetohydrodynamics (EMHD),[12–15] showed that the field may penetrate fast in low-collisionality plasma. The field penetration due to the EMHD, where the Hall-field in the plasma plays a crucial role, is highly dependent on the two-dimensional (2-D) electron density distribution[12,13] and on the system geometry.[14] It has been shown recently[15] that the field penetration into the plasma is also dependent on the magnetic field penetration near the POS electrodes. Indeed, such a fast magnetic field penetration into non-neutral regions near the electrodes has been described earlier in a few studies.[1,13,16]

In a previous study[17] we reported on the determination of the time dependent magnetic field distribution in a coaxial positive-polarity POS plasma using a nonintrusive spectroscopic method, in which the ion acceleration (obtained from ionic-line-emission Doppler shifts) and the electron density (determined from the ionization rates) were used to give the magnetic field gradient in the plasma. Three-dimensional (3-D)-spatial resolution were achieved by doping the plasma with various ions using laser evaporation of material placed on the POS electrodes. In this paper, we present a time dependent 2-D mapping of the magnetic field in the r,z, plane obtained from measurements of the Zeeman splitting of ionic lines [here we assume azimuthal uniformity thus, $B = B_\theta(r,z)$]. Preliminary results of such measurements were described in Ref. 18.

The magnetic field was found to penetrate into the plasma at a velocity (10^8 cm/s) much higher than the expected field diffusion rate, with the current layer being significantly narrower ($\leqslant$1 cm) than the plasma axial length. Later in the pulse, when the field appears at the load-side edge of the plasma, a region of relatively low field near the plasma axial center is observed. A 2-D model based on

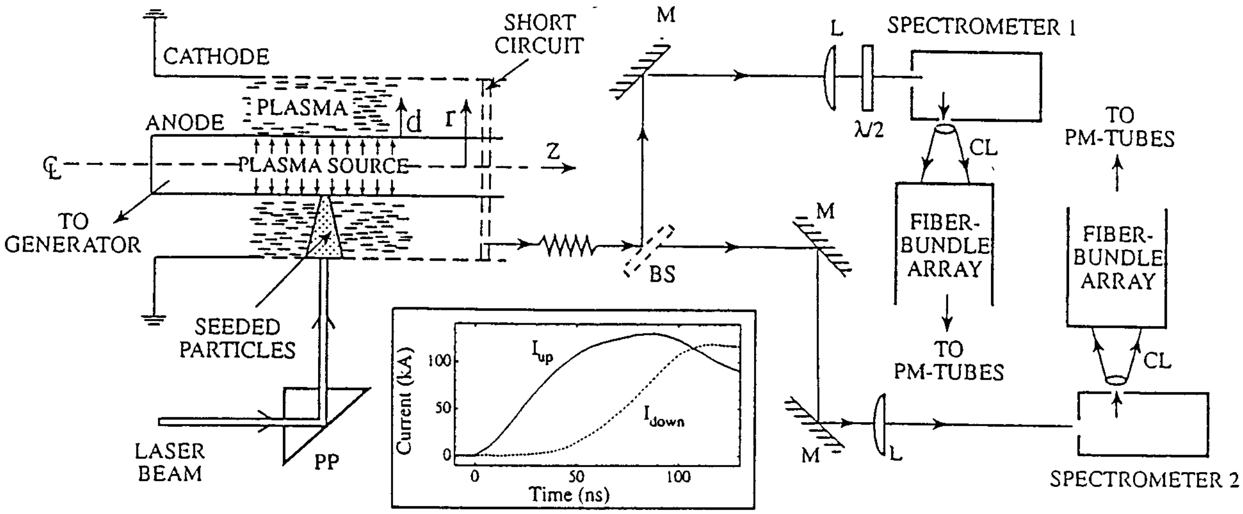


FIG. 1. The experimental setup: light emitted from the plasma is collected using the beam splitter (BS) and mirrors (M), and focused by the lenses (L) onto the spectrometers. The light from the spectrometers output is dispersed on the optical fibre bundles using cylindrical lenses (CL). The prism (PP) is used to displace the axial position of the evaporating laser beam. The selection of the polarization is made by the spectrometer grating which is seven times more efficient for the polarization normal to its grooves than the one parallel to them. The λ/2 plate is used to rotate the light polarization for efficient collection by the spectrometer. The upstream and downstream currents measured by Rogowski coils are shown in the insert.

EMHD was employed to describe the magnetic field evolution. Highly required for the application of such a model is knowledge of the electron density as a function of r and z, which was determined experimentally. In the model, it is assumed that instantaneous magnetic field penetration occurs along both POS electrodes. The model is found to provide a satisfactory quantitative explanation for the magnetic field distributions observed.

II. EXPERIMENTAL AND DIAGNOSTIC SYSTEMS

In our experiment we use the coaxial POS and spectroscopic system shown in Fig. 1. The POS consists of two coaxial aluminum tubes with inner and outer diameters of 5 cm and 10 cm, respectively. The load is short-circuit giving a downstream inductance of 25 nH, while the upstream inductance is 120 nH. A positive high voltage pulse is applied to the inner electrode, giving a peak current of 135 ± 10 kA with a quarter period of 90 ns. The POS current is delivered by an LC-Water-Line generator (4.1 kJ, 300 kV, 1 Ω). Two calibrated Rogowski coils and eight magnetic loops azimuthally separated by 90° are used to measure upstream and downstream currents, shown in the insert in Fig. 1.

The plasma is injected into the interelectrode gap at a velocity $\simeq 1.5\times10^6$ cm/s from a specially designed cylindrical gaseous plasma gun,[17] which is installed inside the inner POS electrode. The electron density was determined prior to the current pulse[17] from hydrogen line Stark broadening, giving a density decreasing with radius with a value of $(1.3\pm0.3)\times10^{14}$ cm^{-3} at a distance of 0.5 cm from the anode. The density distribution in the axial direction was determined using electrical probes, and the plasma axial length (where it decrease to half of the value at the POS axial center) was found to be $\simeq$4 cm near the anode, and $\simeq$6 cm near the cathode. This distribution was used in the electron MHD model described below since the electron density distribution was shown to change insignificantly during the pulse,[17] because of the low ionization rates and the slow plasma flow. The plasma consists of neutral hydrogen and carbon, protons, and up to four times ionized carbon ions. The azimuthal uniformity of the electron density, determined by electric probes, is $\pm15\%$. The electron temperature prior to the current pulse, determined from CII and CIII line intensities and collisional radiative calculations,[14] is (2 ± 1) eV. The reproducibility of these parameters was found to be $\pm20\%$.

For the spectroscopic observations we used two 1 m spectrometers equipped with 2400 grooves/mm gratings. The output of the spectrometers is coupled to an array of optical fiber bundles that transmit the light to a set of photomultiplier tubes (PMT). For the plasma doping in these experiments we used a 20-ns laser pulse to evaporate material initially deposited on the surface of the inner POS electrode (the anode in the present experiments). The laser pulse was applied 3–4 μs prior to the current pulse, producing a conical column of barium atoms and ions with diameters $\simeq$0.2 cm near the anode and $\simeq$1 cm in the middle of the $A-K$ gap.

It was verified that the column of the doped material injected into the switch plasma did not affect the plasma parameters at the time at which the current pulse was applied.[19] This was examined by measuring line intensities of carbon ions and hydrogen-line Stark broadening as a function of time after the injection of the dopant plasma, which showed that the latter thermalized with the prefilled plasma and insignificantly affect the plasma electron density and temperature.

A difficulty in measuring Zeeman splitting in high-current systems is that the line emission is much affected by the Doppler effect due to the ion motion under the magnetic field. It was shown in Ref. 17, however, that the ion velocities are lower for lower Z/M, where Z is the ion charge and M is the ion mass. Thus, to minimize the Doppler broadening in these measurements, the plasma was doped with BaII using evaporation of barium metal deposited on the POS anode. Furthermore, in order to discriminate the Zeeman splitting from the Doppler broadening, we observed the spectral profiles of the π and σ components of the line from the same volume element in a single discharge using the two spectrometers. In the present measurements we used the BaII $6p\ ^2P_{3/2} \rightarrow 5d\ ^2D_{5/2}$ transition (6142 Å).

In such plasma-doping experiments there is a need to know the position of the doped material during the pulse. To this end the Doppler shifts of the BaII line was observed, giving the BaII directed velocities. It was found that the BaII displacement in the axial direction during the pulse is $\simeq 0.1$ mm, which is much smaller than the BaII column width.

III. EXPERIMENTAL RESULTS

In this paper we present measurements for the period until $t = 60$ ns after the beginning of the current pulse. For later times, due to the BaII ionization,[17] the BaII line emission was too weak to allow for satisfactory measurements. The magnetic field mapping is performed for a single azimuth. The plasma regions observed are located at the radial distances 0.5, 1.0, and 1.5 cm from the anode, and at axial distances between -1.2 cm and $+1.2$ cm from the axial center of the plasma (defined as $z = 0$), where positive z is towards the load (see Fig. 1). The magnetic field is also measured at the plasma edge in the upstream side, $z = -2.4$ cm, and was found to be in agreement with the magnetic field obtained from the generator current. The line Doppler broadening at the load side edge of the plasma was larger than in the rest of the plasma (consistent with the results in Ref. 14), which hindered the Zeeman splitting observation for $z \geqslant 1.2$ cm. At radial distances from the cathode larger than 1.5 cm, the determination of the magnetic field was not possible because of the weak line intensities resulting from the low plasma density in this region.[17]

In Fig. 2 we present the magnetic field at $r = 3$ cm as a function of the axial distance from the POS center for 10 and 20 ns after the start of the upstream current. Each point represents an average of 3–6 discharges. The uncertainties shown mainly result from the photon statistics, the electrical noise, and the error in the relative timing of the spectral profiles of the π and σ components measured by the two spectroscopic systems. The shot-to-shot irreproducibilities are within the error bars shown. The relative error is larger at the early times, of the pulse when the magnetic field is low, being 50% at $t = 10$ ns and decreasing to 30% at $t = 20$ ns (as can be seen in Fig. 2). The latter is about our minimum uncertainty since the shot-to-shot irreproducibility in $B(r,z)$ is about 20%. It is seen in Fig. 2 that the magnetic field penetrates into the plasma significantly already at 10 ns, and it propagates at an axial velocity $\simeq 10^8$ cm/s.

The measured values of B in the r,z plane are used to obtain the current $I(r,z) = (c/2)Br$ that within a loop of radius r, assuming an azimuthal symmetry. The contour lines of constant $I(r,z)$ thus obtained give the direction of the

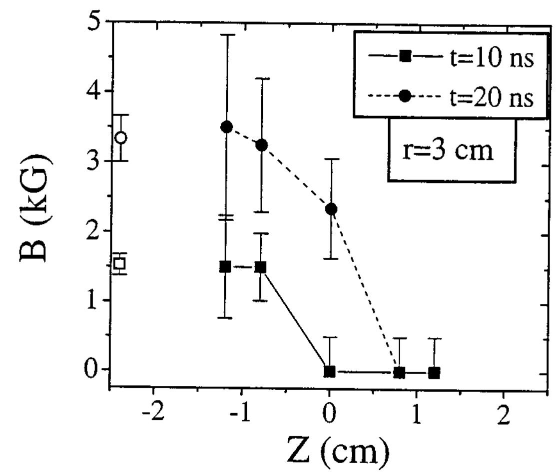


FIG. 2. The measured magnetic field as a function of the axial distance z for $r = 3$ cm, for $t = 10$ ns (solid line) and $t = 20$ ns (dashed line). Also shown are the values of the magnetic field obtained from the measured upstream current.

current flow. Such contours, computed from the data values using the Kriging correlation method,[20] are given in Fig. 3 for $t = 20$, 30, 35, 40, and 50 ns.

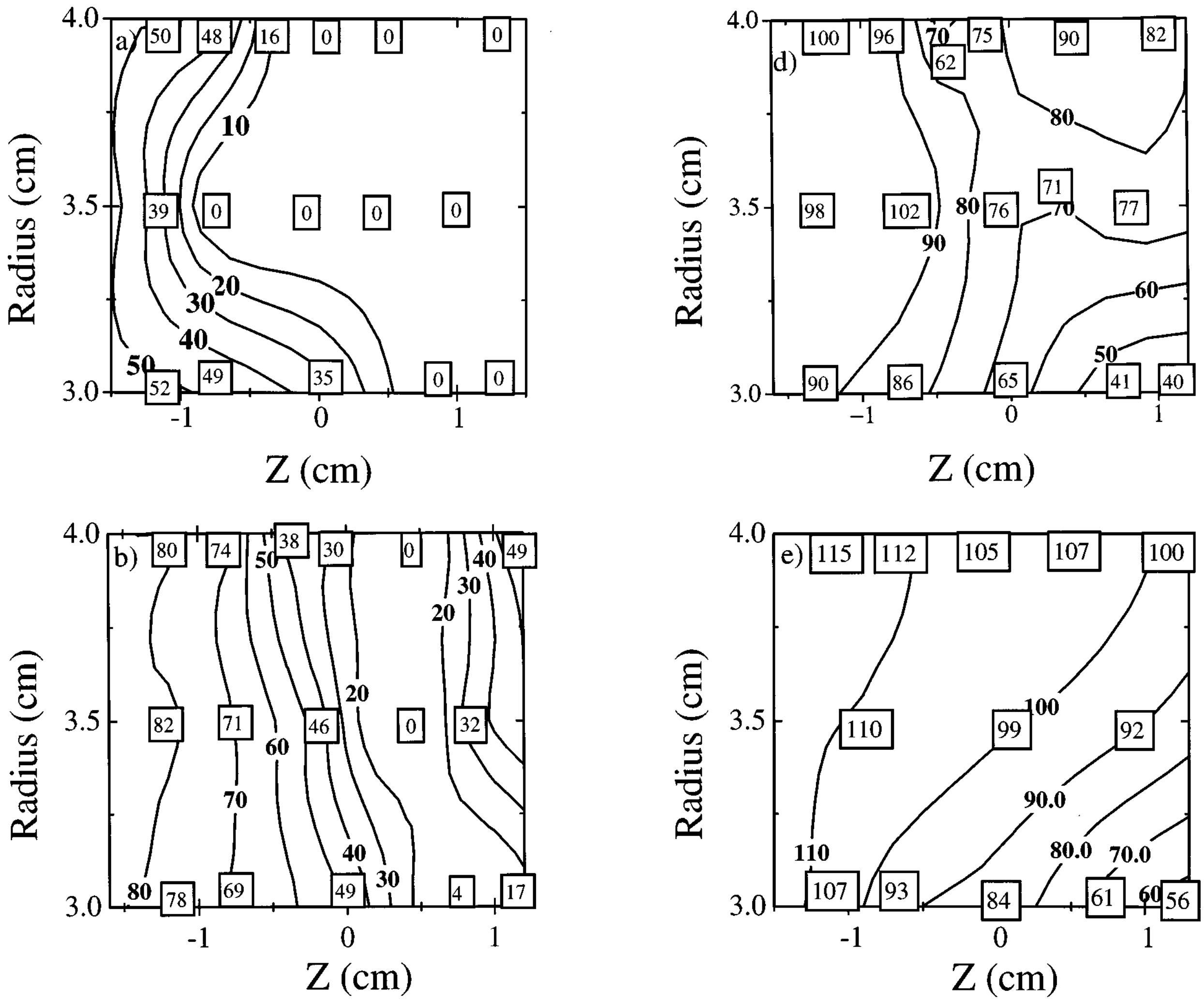
It is seen from Fig. 3(a) that at $t = 20$ ns the magnetic field penetrates up to about the axial center of the plasma. At this time most of the current appears to flow in a region $\lesssim 1$ cm wide in the axial direction. The true current channel width could even be smaller since the observed width it is comparable to the measurement spatial resolution. At 30 ns the magnetic field appears at the load-side edge of the observed region, as shown in Fig. 3(b), and a region of low field is seen at $z \simeq +0.5$ cm, a peculiar feature to be discussed in Sec. IV. This low field is still observed a $t = 35$ ns [Fig. 3(c)]. At $t = 40$ ns [Fig. 3(d)], a small low-field region is still observed at $z \simeq 0$ cm and $r = 4$ cm, while at smaller radii the field axial dependence is monotonic. Later in time, the low-field region vanishes entirely.

The current at the load-side edge of the plasma and downstream the POS region rises at $t \geqslant 40$ ns. At $t = 50$ ns it is found that a current of 30 ± 15 kA flow at the plasma region $z \leqslant 1.2$ cm [see Fig. 3(e)] and 24 kA are measured at the load. Since the generator current at this time is 115 kA, a current of 60 ± 15 kA flows through the load-side edge of the plasma ($1.2 < z \lesssim 2.5$ cm) and between the plasma and the load.

It is interesting to compare our presently measured 2-D magnetic field distribution to the magnetic field obtained from previous measurements of the ion acceleration under the magnetic field gradient.[11] In Ref. 11, the magnetic field at $z = 1.2$ cm, $r = 3.2$, $t = 50$ ns was determined to be 5.4 kG. The current within this radius (assuming azimuthal symmetry) is 86 kA, which is in satisfactory agreement with the 70 kA observed here [see Fig. 3(e)].

IV. THEORETICAL MODEL

We first note that the fast penetration of the magnetic field into the plasma is highly unlikely to result from mag-



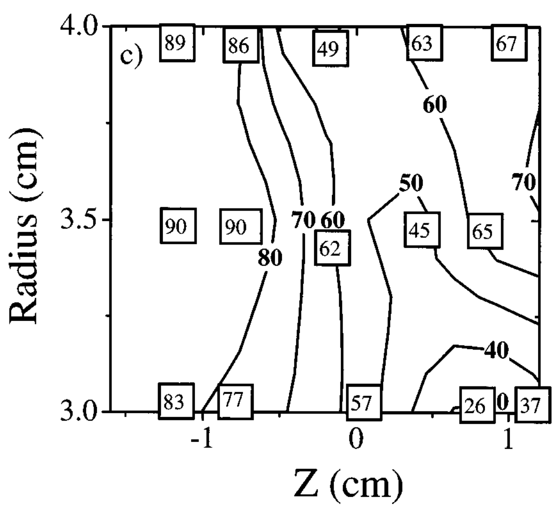


FIG. 3. Contours of constant current $I(r,z)$, given in kA by the numbers on the contour lines, obtained from $B(r,z)$ assuming azimuthal symmetry $I = \frac{c}{2}Br$ (see the text). The current values obtained from the magnetic field measured at each location are given in the boxes. (a) $t=20$ ns, (b) $t=30$ ns, and (c) $t=35$ ns, (d) $t=40$ ns, and (e) $t=50$ ns. The upstream current at these times is 52, 81, 88, 96, and 115 kA, respectively. The load current is 0, 8, 12, 16, and 24 kA, respectively.

netic field diffusion, since such a diffusion would require plasma resistivity that is anomalously higher by about 3 orders of magnitude than the classical (Spitzer) resistivity, demonstrated to be unlikely.[11] Here, we suggest that the magnetic field penetration occurs due to the Hall fields,[12] a mechanism that is dominant when the length scales of the density and geometrical gradients are less than the ion skin depth (in our experiment this condition is marginally fulfilled since the ion skin depth is about 2 cm). By this mechanism, the magnetic field may penetrate into a low-collisionality plasma as a shock wave, either due to density nonuniformity in planar geometry[12,13] or due to magnetic field curvature in cylindrical geometry.[14] In cylindrical geometry, for a density that is axially uniform, the magnetic field is expected to penetrate only in one of the switch polarities, depending on the sign of the radial density gradient, $(d/dr)(nr^2)$. If (d/dr)

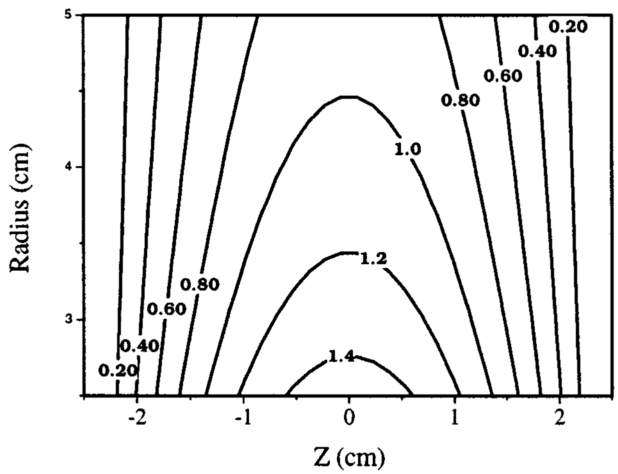


FIG. 4. The nr^2 contours used in the model. The radial dependence was measured experimentally, and the axial distribution was assumed to be parabolic.

$\times(nr^2)$ changes sign, penetration will occur for both polarities, but at a different region of the POS for each polarity.

The combined effect of nonhomogeneous plasma density and the cylindrical curvature on the Hall magnetic field penetration was studied in Ref. 15. In this 2-D model it is shown that the magnetic field penetrates as a shock along the constant nr^2 lines, in such a way that nr^2 increases along the electron flow. Therefore, the magnetic field evolution is dictated by the magnetic field behavior at the end point of each constant nr^2 line, while the direction of penetration of the magnetic field is determined by the sign of the gradients of nr^2 and the switch polarity.

In a realistic profile the density varies with both r and z. The nr^2 lines measured experimentally prior to the beginning of the current pulse[17] were used in the 2-D model, and are shown in Fig. 4. The plasma density is assumed to have a parabolic z dependence, peaking at $z=0$ and zeroing at $z=\pm 2.5$ cm, and to vary as $r^{-2.7}$. The axial length was taken as 5 cm, although the actual cross in the $r-z$ plane of the plasma is a trapezoid (Sec. II). It can be seen that some constant nr^2 lines intersect the electrodes, while others originate at the plasma–vacuum boundary at the generator or the load side. If the magnetic field penetrates fast along the electrodes, field penetration from the electrodes into the plasma may occur for both polarities. Thus, in order to calculate the magnetic field evolution in EMHD theory, the switch polarity, the 2-D electron density profile, the magnetic field at the plasma–vacuum boundary, and the magnetic field distribution along the electrodes should be considered.

Our spectroscopic measurements show that plasmas are formed near both POS electrodes early in the pulse, indicating early non-neutral-sheath formation.[17] Since theoretical studies predict fast magnetic field penetration along the anode[13,21] and the cathode[1,16,21] in such sheaths, we attempt to model the magnetic field evolution by assuming fast magnetic field penetration near the electrodes and by using our measured $n(r,z)$. The magnetic field $B_0(t)$ at the generator side is taken from the upstream current, and is approximated by a linear rise in time, i.e., $I_0[\mathrm{kA}]=2.7t[\mathrm{ns}]$, which is a good approximation for the first 50 ns. The assumption of fast penetration along the electrodes is implemented by assuming that at each instant the magnetic field along the electrodes decreases from $B_0(t)$ at the generator side ($z=-2.5$ cm) to zero at the load side of the plasma ($z=+2.5$ cm).) The functional decrease was selected to be

$$B(z,t)=B_0(t)\left[1-\left(\frac{z+z_0}{2z_0}\right)^{\alpha}\right],$$

where α is a free parameter.

Under these conditions the model yields magnetic field penetration into the plasma from the anode and from the cathode at the generator and load sides, respectively. It was found that the results are insensitive to the value of α at the anode for any $\alpha>0.5$, as long as the magnetic field is large enough at the anode near the generator side. This results from the fact that the magnetic field values in most of the plasma (mainly $z\leqslant 0$) are determined by the field values at the intersection points of the nr^2 lines with the anode close to the generator. In our calculations we used $\alpha=1$ for the anode. However, penetration into the plasma from the cathode is found to be highly affected by the magnetic field values at the cathode at $z>0$ (i.e., closer to the load side), which are very sensitive to the value of α. This is because the magnetic field values along the cathode close to the load side are rather small as they zero at the load side of the plasma. Therefore, the power α for the cathode was so chosen ($\alpha=2.5$) to obtain a best fit of the calculated values to the experimental magnetic field at the time when the latter was first seen near the load side of the plasma. The assumption of vanishing magnetic field at the plasma load-side edge is valid as long as the experimental downstream current remains low, as occurs for the times here discussed. Furthermore, since the magnetic field penetrates into the plasma with the electron flow along constant nr^2 lines, and since the constant nr^2 lines in our experiment originating at $z\geqslant 1.5$ cm do not enter the observation region, the values of the magnetic field at $z\gtrsim 1.5$ cm at the cathode were found to have no effect on the magnetic field in the plasma region studied. It is noteworthy that the decrease of nr^2 towards the cathode, occurring in this experiment, enhances the magnetic field penetration for the present positive-inner-electrode configuration.

Figure 5 shows the results of this analytical model for $t=20$, 30, and 50 ns. The dotted region shows the region for which data were obtained. At $t=20$ ns, the model predicts magnetic field penetration into this region only from the anode at the generator side, fitting reasonably well the experimental evolution of the magnetic field [see Fig. 3(a)]. The field distribution given by the model indicates the formation of a magnetic shock (as shown by the solid line in Fig. 5(a), which results from the assumption of almost collisionless plasma. In reality, it is possible that plasma turbulence, as observed in our experiment[22] may lead to higher collisionality[10] and broadening of the current channel.[12,23] The true width of the current channel could not be determined in the present measurements to within less than $\simeq 1$

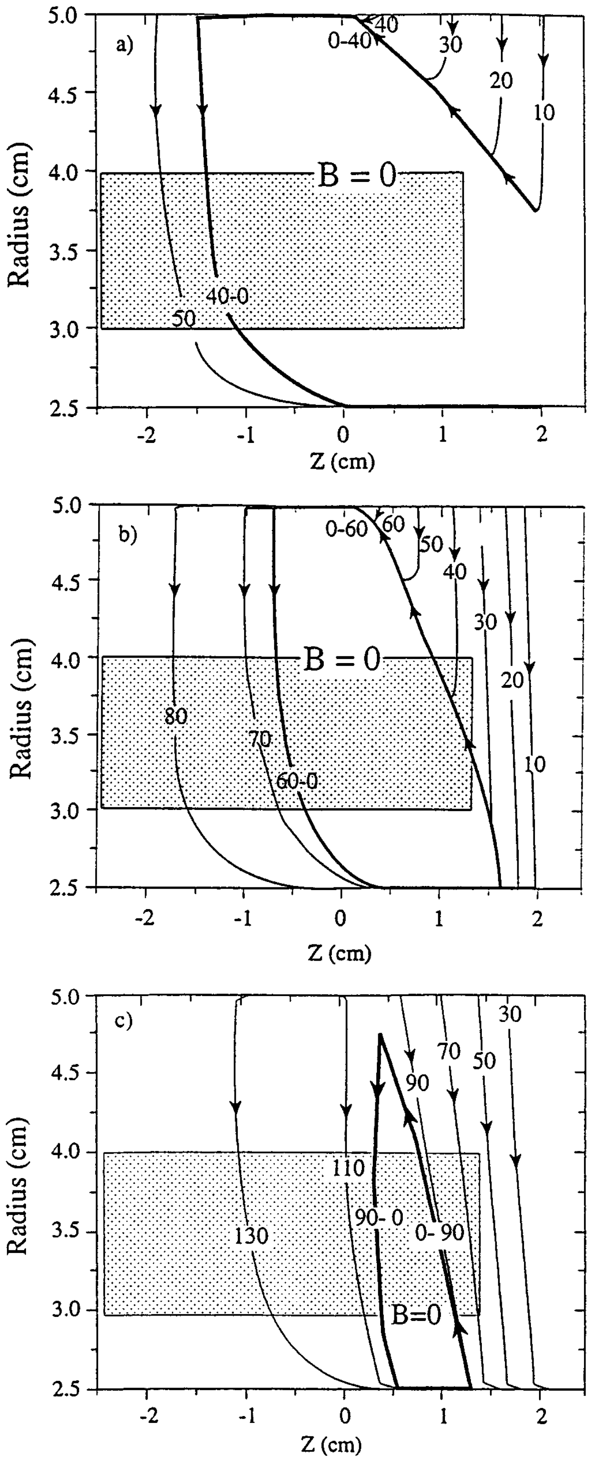


FIG. 5. Contour lines of constant current $I(r,z)$ over the entire plasma obtained from the model. (a) $t=20$ ns. The thick line marked by 40–0 represents a shock that penetrates from the generator side through which current of 40 kA is conducted towards the anode (all contours for current below 40 kA coincide with this line). The thick line marked 0–40 represents a shock, penetrating from the cathode side, along which the contours for current below 40 kA merge. Current of 40 kA flows from this line along the plasma–cathode boundary and then to the anode along the 40–0 line, as shown by the arrows. The magnetic field between the two shocks remains zero. The dotted region shows the region for which measurements were performed (see Fig. 3). (b) $t=30$ ns. The thick line marked 60 is a line along which 60 kA are flowing towards the anode. The thick line marked 0–60 is a line along which the contours of current below 60 kA merge, (c) $t=50$ ns, the region of low magnetic field is smaller than the experimental spatial resolution.

cm, because of the $\simeq 1$ cm spatial resolution resulting from the width of the Barium column used to dop the plasma.

At $t=30$ ns [Fig. 5(b)] the magnetic field also penetrates the region observed from the cathode side, leaving a region of zero magnetic field at the center. The modeling thus explains the peculiar feature of low magnetic field at $z=+0.5$ cm at $t=30-35$ ns observed in the experiment. Note that we adjusted the magnetic field contours at $t=30$ ns through the free parameter α. However, from this time on, not only the time evolution but also the magnetic field values agree with the experiment. The shock positions and the current values for both magnetized regions are consistent with the experimental results. At $t=50$ ns, [Fig. 5(c)] the model predicts that $\simeq 60$ kA flows at $Z \geqslant 1.2$ cm, which is in good agreement with the experiment [Fig. 3(c)]. At this time, the analytical contours, unlike the experimental ones, still show a region of low magnetic field. However, a region of this size is too small to be observed with the present measurement spatial resolution.

The details of the energy dissipation associated with the magnetic field penetration are not fully known to us as yet. The average energy dissipation per particle in the plasma due to the magnetic field penetration described here is estimated to be $\simeq 2$ keV. The nonprotonic ions in the plasma were found (from Doppler-line-shifts velocity measurements)[17] to carry a small fraction of the dissipated energy. The energy carried by the protons is, however, still uncertain (if the protons are accelerated to high velocities their motion may modify the magnetic field penetration[24]). A considerable fraction of the energy is probably dissipated by the electrons that are accelerated in the current layer and then convect their kinetic energy to the POS anode.[6,25]

V. CONCLUSIONS

In this study the 2-D evolution of the magnetic field was determined using a nonintrusive spectroscopic method. An analytical model based on electron magneto-hydrodynamics, that is based on the measured 2-D electron density, is found to provide a satisfactory quantitative explanation to both the fast field penetration observed and the somewhat peculiar nonmonotonic variation of the magnetic field at certain times along the axial POS dimension. Understanding the details of the energy dissipation during the magnetic field penetration requires further study.

The results of the model suggested are highly sensitive to the plasma electron density and density distribution (that in our experiment were determined from independent spectroscopic observations), the POS polarity, the POS geometry, the field evolution near the POS electrodes, and the timescale of the experiment, demonstrating the need to analyze these factors in detail in order to improve the understanding of the magnetic field evolution in various magnetic-field-plasma-interaction configurations in laboratory[7,26] and in space[27].

ACKNOWLEDGMENTS

The authors are very grateful to M. Sarfaty and R. Arad for their invaluable suggestions and to A. Fruchtman for the insight he provided. We are indebted to V. Fisher, B. Pereiaslavets, Yu. Ralchenko and S. Alexiou for their considerable help. We thank P. Meiri and Y. Macabi for their skilled technical assistance.

This work was supported by the Israeli Academy of Science and by the Minerva Foundation, Munich, Germany.

[1]C. W. Mendel, Jr. and S. A. Goldstein, J. Appl. Phys. **48**, 1004 (1977).
[2]Special Issue on Fast Opening Switches, IEEE Trans. Plasma Sci. **Ps-15** (1987).
[3]R. A. Meger, R. J. Commisso, G. E. Cooperstein, and S. A. Goldstein, Appl. Phys. Lett. **42**, 943 (1983).
[4]D. d. Hinshelwood, J. R. Boller, R. J. Commisso, G. Cooperstein, R. A. Megev, J. M. Neri, P. F. Ottinger, and B. V. Weber, Appl. Phys. Lett. **49**, 1635 (1986); B. M. Koval'chuk and G. A. Mesyats, Sov. Phys. Dokl. **30**, 879 (1986).
[5]B. V. Weber, R. J. Commisso, P. J. Goodrich, J. M. Grossmann, D. D. Hirshelwood, J. C. Kellogg, and P. F. Ottinger, IEEE Trans. Plasma Sci. **19**, 757 (1991).
[6]C. W. Mendel, Jr., M. E. Savage, D. M. Zagar, W. W. Simpson, T. W. Grasser, and J. P. Quintenz, J. Appl. Phys. **71**, 3731 (1992).
[7]A. V. Gordeev, A. S. Kingsep, and L. I. Rudakov, Phys. Rep. **243**, 215 (1994).
[8]B. V. Weber, R. J. Commisso, R. A. Meger, J. M. Neri, W. F. Oliphant, and P. F. Ottinger, Appl. Phys. Lett. **45**, 1043 (1984).
[9]V. M. Bystritskii, Ya. E. Krasik, I. V. Lisitsyn, and A. A. Sinebryukhov, IEEE Trans. Plasma Sci. **PS-19**, 607 (1991).
[10]R. M. Kulsrud, P. F. Ottinger, and J. M. Grossmann, Phys. Fluids **31**, 1741 (1988).
[11]L. I. Rudakov, C. E. Seyler, and R. N. Sudan, Comments Plasma Phys. Control. Fusion **14**, 171 (1991); C. K. Nr and R. N. Sudan, J. Appl. Phys. **69**, 137 (1991).
[12]A. S. Kingsep, Yu. V. Mochov, and K. V. Chukbar, Sov. J. Plasma Phys. **10**, 495 (1984); A. S. Kingsep, K. V. Chukbar, and V. V. Yankov, in *Reviews on Plasma Physics*, edited by B. Kadomtsev (Consultants Review, New York, 1990), Vol. 16, p. 243.
[13]A. V. Gordeev, A. V. Grechikha, Ya. L. Kalda, Sov. J. Plasma Phys. **16**, 95 (1990); A. V. Gordeev, A. V. Grechikha, A. V. Gulin, and O. M. Drozdova, *ibid.* **17**, 381 (1991).
[14]A. Fruchtman, Phys. Fluids B **3**, 1908 (1991); A. Fruchtman, Phys. Rev. A **45**, 3938 (1992).
[15]K. Gomberoff and A. Fruchtman, Phys. Fluids B **5**, 2841 (1993).
[16]P. F. Ottinger, S. A. Goldstein, and R. A. Meger, J. Appl. Phys. **56**, 774 (1984).
[17]M. Sarfaty, Y. Maron, Ya. Krasik, A. Weingarten, R. Arad, R. R. Shpitalnik, A. Fruchtman, and S. Alexiou, Phys. Plasmas **2**, 2122 (1995).
[18]M. Sarfaty, R. R. Shpitalnik, R. Arad, A. Weingarten, Ya. Krasik, A. Fruchtman, and Y. Maron, Phys. Plasmas **2**, 2583 (1995).
[19]B. Pereiaslavets, M.Sc. thesis, Weizmann Institute of Science, Israel, 1993.
[20]J. C. Davis, *Statistics and Data Analysis in Geology* (Wiley, New York, 1986), p. 383.
[21]J. M. Grossmann, S. B. Swanekamp, P. F. Ottinger, R. J. Commisso, D. D. Hinshelwood, and B. V. Weber, Phys. Plasmas **2**, 299 (1995).
[22]A. Weingarten, S. Alexiou, M. Sarfaty, Ya. E. Krasik, R. Arad, and Y. Maron, Bull. Am. Phys. Soc. **39**, 1691 (1994).
[23]J. M. Grossmann, R. Kulsrud, J. M. Neri, and P. F. Ottinger, J. Appl. Phys. **64**, 6646 (1988).
[24]A. Fruchtman and L. I. Rudakov, Phys. Rev. Lett. **69**, 2070 (1992).
[25]A. Fruchtman and L. I. Rudakov, Phys. Rev. E **50**, 2997 (1994).
[26]R. L. Stenzel and J. M. Urrutia, Phys. Plasmas **3**, 2589 (1996).
[27]J. D. Huba, Phys. Plasmas **2**, 2504 (1995).