Experimental Observation of a Wedge-Shaped Density Shock in a Plasma Opening Switch

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We present the first two-dimensional picture of the plasma electron density perturbation generated in a plasma opening switch by the current-driven magnetic field. A fast electron density increase propagates with different velocities both radially and axially, and has a clearly apparent wedgelike shape. The local plasma density drop at the load plasma edge lags behind the magnetic field exit to the downstream region. The experimental result can be attributed to a specific shock wave, where the Hall-effect-driven field penetration causes a 2D plasma density redistribution.

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The classical problem of the interaction of fast magnetic fields with a nonmagnetized plasma arises in all principal pulsed-plasma devices, such as high-current diodes, Z or Θ pinches, plasma focus, plasma accelerators, etc. (see theoretical reviews [1,2]). The plasma usually forms a short circuit between two high-voltage electrodes during a certain time t_c. The magnetic field, initially confined in a subregion, may further accelerate the plasma or penetrate into it. One specific geometry, the plasma opening switch configuration (POS), has acquired unexpected practical importance during the last decade [3]. In this configuration a low-density (10^{13}–10^{16} cm^{-3}) weakly collisional plasma abruptly increases its resistance after the time t_c, allowing a fast transfer of the current-generated magnetic field to the downstream region. An optimized POS in the long-conduction-time regime of operation ($t_c > 0.5$ μs) would allow efficient and compact pulse compression and power multiplication staging [4]. Some specific features of electromagnetic energy transport in this plasma object are of fundamental interest and have evoked an intense international study of the phenomenon [2–4]. In particular, experimentally observed anomalously fast penetration of the magnetic field into the switch plasma [5] immediately distinguished this plasma object from other magnetically accelerated plasmas and contributed to the development of a new branch of plasma theory, electron magnetohydrodynamics (EMH) [2].

Most existing models explain the opening effect by invoking the hypothesis of a local plasma density decrease. Spatially resolved plasma density measurements would help to discriminate between different theoretical approaches and lead to a physical picture of the process. The first measurements of electron density redistribution in the POS plasma were made along the plasma length [6], with limited resolution of the local density profile. Furthermore, important EMH effects (which occur at $a \ll c/\omega_{\mathrm{pi}}$, where a denotes characteristic size of the problem [2]) could hardly be seen with the sensitivity of plasma density measurements obtained in these experiments. In our experiment we used interferometry sensitive to these effects with the probe beam azimuthally. In this direction, the plasma thickness is subject to weak changes during the shot. In addition, this setup allowed temporal, radial, and longitudinal resolution of the density.

Experiments were performed on the MAG-1 inductive storage generator [7]. At 50 kV charging voltage, it provided a 300 kA upstream current in the storage inductance of 80 nH. The load was a short circuit with the inductance of 25 nH. Plasma was injected from the 15-cm-radius outer anode to the 10-cm-radius inner cathode by 16 Mendel-type plasma guns [8]. The guns were driven by six 0.6 μF capacitors charged to 20 kV, so that the current through each gun reached 12–15 kA. At this charging voltage the initial plasma density was higher than optimum for the best opening. However, this configuration allowed improved accuracy of the density measurements. The optimum delay between firing the guns and the MAG-1 generator resulted in 200–250 kA downstream current in the inductive load. Switched current was measured by a set of B probes located near the short circuit, 30 cm downstream of the plasma region. The local current amplitudes and rise times differed by less than 20% at different azimuths, a variation which falls within the experimental error. A magnetic probe B_p was installed, as shown in Fig. 1. Its response was proportional to the difference between the magnetic field of plasma and load current. The B_p timing served as an estimation of the magnetic field penetration time. Previous studies [9] showed that the plasma density has a rather steep initial profile in the gap which ranges from approximately 10^{14} cm^{-3} near the cathode surface up to 10^{16} cm^{-3} near the anode. The plasma composition included mainly single and double-charged carbon ions. The injected plasma had a velocity of 5–6 cm/μs, and its azimuthal length on the cathode was about 6 cm. The reproducibility of the plasma density from shot to shot was better than 30%.

The details of the interferometer, data treatment procedure, and experimental sensitivity are discussed elsewhere [9]. The interferometer probe beam scanned the plasma from shot to shot between the electrodes in both the radial and axial directions (Fig. 1). This technique allowed detection of a line integrated density as low as 10^{14} cm^{-2} with

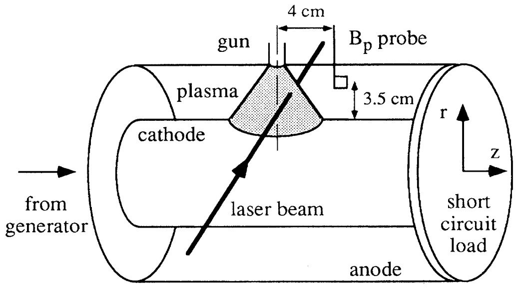

FIG. 1. A sketch of the experimental arrangement.

spatial resolution of 1–2 mm. Minor changes in the experimental setup, reported in Ref. [9], improved the time resolution to 40 ns. The possibility of nonplasma sources contributing to the measured phase shift during the discharge was excluded by test shots in which the probe beam was screened from the injected plasma. The influence of the nearest neighboring guns was also very small. Nevertheless, refraction on plasma gradients which increases the optical path length was not assumed to be negligible. The refraction effect was estimated for each beam position before the following shot with the interferometer. The phase shift introduced by the maximum plasma density gradient ($\langle \partial n_e/\partial r \rangle \sim 2 \times 10^{16}$ cm^{-4}) was less than one-tenth of that produced by the electron density.

A typical history of the line integrated density is shown in Fig. 2. This picture was obtained when the probe beam was located at the load side of the plasma (see also Fig. 1), 2.9 cm from the cathode surface. During the first 300 ns of the conduction phase, the line density evolution follows that measured when only the guns were fired. Then the density suddenly increases, and, after 100 to 200 ns, drops below the resolution limit. The downstream current begins before the plasma density drops back to the guns-only value.

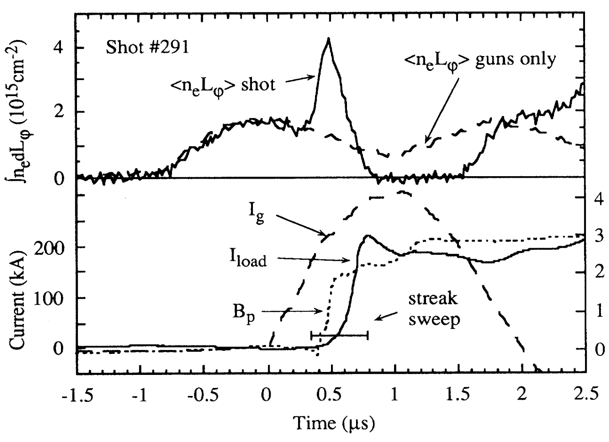

FIG. 2. Measured line integrated density for the position 2.9 cm from the cathode and 1.4 cm from the gun axis towards the load. L_φ denotes one plasma length (2.8 cm). Also shown are upstream (I_g) and downstream (I_{load}) currents, B_p monitor signal, and time position of the optical streak camera sweep.

Our main result, shown in Fig. 3, is that the density profile has a wedge-shaped, propagating shock structure. At the plasma axis, the density maximum first appears at the distance of $\Delta_r^* = 2.9$ cm from the inner electrode surface [Fig. 3(a)]. The further the point of measurement is from the position Δ_r^*, the later the maximum occurs. Moreover, the measured line density drops below the sensitivity level only at Δ_r^*. It is natural to assume that the main processes in the plasma leading to the current interruption occur at this plasma cross section. We effected similar measurements at other axial positions, where we observed the same drastic density drop at Δ_r^* and there alone [Fig. 3(b)]. Thus one can see that the perturbation propagates rapidly from the generator side of the plasma towards the local plasma edge.

Finally, Fig. 4(a) represents a qualitative picture of the line density maxima profile. The shock process has its origin at the generator plasma edge and propagates axially with a somewhat greater velocity than in the radial

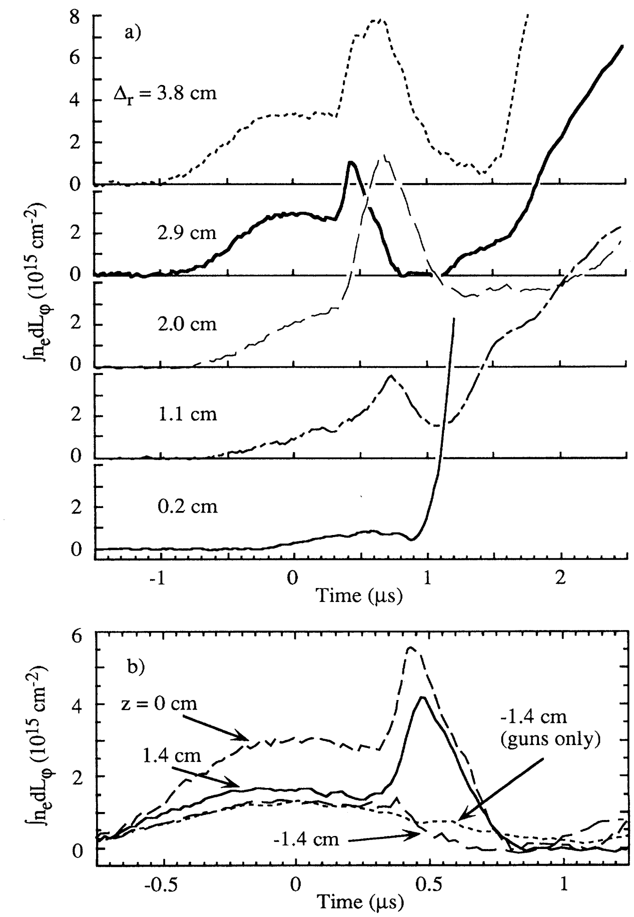

FIG. 3. (a) Line plasma density measured at different $\Delta_r = r - r_c$ along the gun axis. (b) Analogous measurements for different distances from the gun axis z at 2.9 cm from the cathode. The guns-only line density time behavior at $z = -1.4$ cm is also shown. Zero time corresponds to the upstream current beginning.

direction. This interpretation is supported by the optical streak camera image of the interelectrode region inside the wavelength range 300–700 nm [Fig. 4(b)]. The dark region on the film denotes either a decreased plasma density or a spectral shift to shorter wavelengths ($\lambda <$ 300 nm). This region also originates in the center of the gap and expands towards the electrodes during the opening. We improved analogous experiments [10,11] by additional collimation to suppress the intense light emission of both electrodes. This resulted in better resolution of the bulk plasma emission and allowed comparison with the interferometer measurements.

Previous experimental investigations of the magnetic field transport through the plasma switch [12,13] indicate that the opening begins after the current channel front propagates to the end of the switch region. This correlates with the earlier appearance of the B_p signal with respect to the load current in Fig. 2. In the Hawk experiment [6] the line-averaged plasma electron density was already much lower than its initial level by the time of opening. The authors of this work conclude that the magnetic field travels along the POS region by pushing the plasma boundary. The velocity of such motion is proportional to the Alfvén velocity v_A. The radial dependence of the Alfvén velocity (maximum of v_A occurs in the middle of the interelectrode spacing) results in a bending of the back plasma edge.

In MAG-1, the POS plasma density dynamics differs considerably from that described above. At the moment of opening, when the current has already penetrated the plasma channel (at least at Δ_r^*), the plasma density at the load plasma edge reaches its peak value. The back edge of the density perturbation arrives later, during the downstream current rise time (Fig. 2). This front propagates in a wedgelike fashion (Figs. 3 and 4), even though the initial plasma density distribution has a monotonic variation of the Alfvén velocity with the maximum at the cathode. This last point makes it difficult to explain the midgap plasma rarification by one-fluid hydrodynamic effects.

From our viewpoint, an alternate explanation should involve the fast magnetic field transport by the plasma Hall effect when ion velocities are much lower than electron velocities (EMH framework) [2,14,15]. The so-called Kingsep-Mokhov-Chukbar (KMC) shock [14] was the first example of this transport with a background of motionless ions. In reality, during such magnetic field propagation the ions can acquire velocities $u_i \approx v_A^2/2u_f$ [16,17] (where u_f denotes the magnetic field front velocity). Here one can distinguish three important cases.

(I) $u_f \gg v_A$ results in a "pure" EMH effect, where the magnetic field penetrates the plasma bulk with nonperturbed density [14]. (II) In the intermediate regime when $u_f/v_A > 1$, the ion motion can be appreciable. Yet the EMH approach still remains valid ($v_e > u_f \gg v_i$) and the density perturbation lags behind the magnetic field (as occurs in our case). (III) Another limit case, when $u_i \approx u_f$ (as realized in the Hawk experiment [6]) means a snowplow MHD plasma compression, $u_i = v_A/\sqrt{2}$. All three regimes are shown schematically in Fig. 5 for our experimental conditions. The solid line shows the radial profile

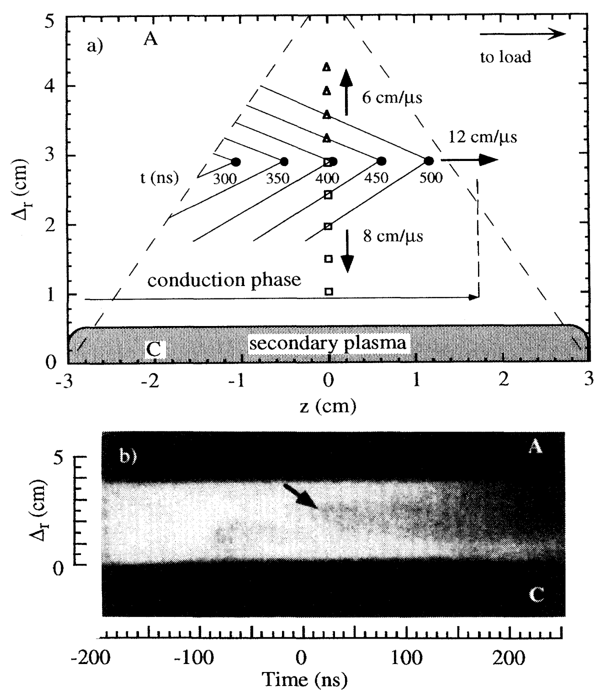

FIG. 4. (a) Reconstruction of the density maximum propagation through the plasma. Dashed lines indicate the initial plasma boundary. Moments of the peak maximum arrival are referred to the start of the upstream current. (b) Visible streak picture of the plasma (gun axis). The arrow points to the wedge front. Zero time corresponds to the 10% amplitude of the load current.

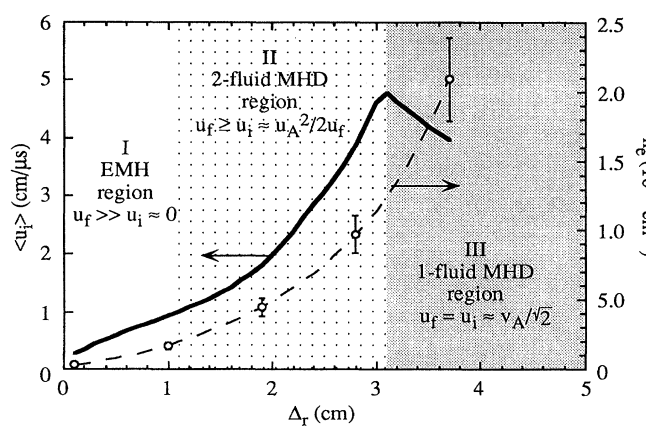

FIG. 5. Radial dependence of the function $\langle u_i(r)\rangle$ (see text) behind the KMC-type magnetic field shock (I, II) and due to the snow-plow plasma pushing (III). Electron density is calculated for the moment of the upstream current beginning as $n_e = \langle n_e L_p \rangle / L_p$, where $L_p(r)$ was obtained by scanning the plasma in axial direction [9].

of the ion velocity averaged over t_c, $\langle u_i(r) \rangle$. It is seen to have a maximum near the radius where the plasma density reaches its minimum value in Fig. 3(a).

The observed redistribution of plasma density inside the region II of Fig. 5 could be interpreted as a Hall shock wave in which the evolution of magnetic field is substantially faster than the ion motion, but in which the ion motion is responsible of the POS dynamics. Because of this shock process, quasineutrality could be violated in the locally rarified plasma. This could lead to further plasma erosion and the appearance of the corresponding resistance [18]. At the same time, EMH resistance could already appear at the plasma stage due to dissipation of the magnetic energy flux [15].

In this Letter, we report the first observations of 2D shock propagation accompanied by an abrupt local increase of plasma density in a plasma switch. The fastest axial perturbation propagation ($\sim 10^7$ cm/s) was found at the location where the density dropped to the lowest level. The back front of this shock lags behind the magnetic field. Penetration process and has a clearly marked wedgelike shape. These two last points are difficult to explain in terms of the snow-plow model suggested in Ref. [6]. We suggested that the observed plasma dynamics may be explained by a nonlinear skin effect, in which the perturbation of the plasma density depends on the degree of the ion acceleration at the magnetic field propagation front. Preliminary estimation for the KMC-type magnetic field shock yield a plasma profile close to the experimental one.

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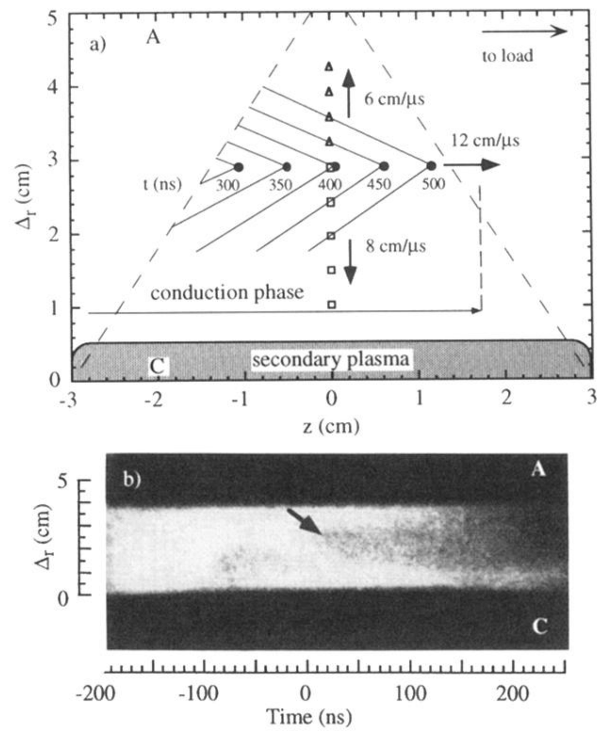

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