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TITLE CALCULATED NON-LINEAR MAGNETIC FIELD PENETRATION
OF PLASMA OPENING SWITCHES

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Calculated Non-linear Magnetic Field Penetration of Plasma Opening Switches

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Abstract. We examine magnetic field penetration in the Plasma Opening Switch, exploring, in particular, advective field penetration arising in conjunction with radial density gradients across the cathode anode gap. Our calculations have been completed with the implicit multi-fluid, ANTHEM code. We show favored penetration along a radial density jump, unstable plain wave penetration for a $1/(y - y_{a+})$ density dependence (with y measured from cathode to anode at y_a) in planar switches, and the penetration of finger-like magnetic field perturbations, when the fill plasma bears initial sinusoidal disturbances on its generator interface.

Recently, the Plasma Opening Switch (POS) has been under scrutiny at a fundamental level¹. The POS basically consists of a plasma injected between the anode and cathode of a bi-cylindrical transmission line. A pulse supplied at the generator side of the line is short circuited through plasma during the so-called "conduction time". Eventually, the plasma is disrupted, current passage through it is substantially reduced, and power passes down the transmission line to the load.

Numerical calculations with the ANTHEM implicit multi-fluid code² have shown that disruption of the plasma is associated with three main effects: (1) The formation of a plasma gap which propagates along the cathode, with fast opening ensuing as this gap reaches the load side of the plasma. (2) Magnetic insulation of the electrons along the anode, so that they return to the anode at progressively deeper points, and the formation of an associated anode gap as magnetic pressure pushes the plasma away from the anode. (3) Advective penetration, by which the streaming electrons transport B-field into the plasma. Here, we are concerned principally with the third effect.

Kingsep et al.³ showed some time ago that in the electrodynamic limit electron advection could result in non-linear magnetic field penetration of plasmas. In a dense collisionless plasma with fixed ions the electric field can reduce to

$$\mathbf{E} = -\mathbf{v}_e \times \mathbf{B}/c.$$

With Faraday's Law, cartesian geometry, and a single, B_z field component this yields

$$\partial B_z / \partial t = -\nabla \cdot (\mathbf{v}_e B_z),$$

which advects B_z with the electron velocity \mathbf{v}_e . Ref. 3 showed that, since the electron velocity is constrained to obey

$$\mathbf{v}_e \simeq -c/(4\pi en_e) \nabla \times \mathbf{B},$$

the full effect of this advective transport should be null, i.e. $\partial B_z / \partial t = 0$, if the cartesian plasma density is constant, because, then, $\nabla \cdot \nabla \times \mathbf{B} = 0$. More generally, the field will change according to

$$\partial B_z / \partial t = c/(8\pi c) \nabla(1/n) \times \nabla B_z^2$$

Accordingly, one dimensional plane wave propagation of magnetic field should be possible in a POS for a switch density rising as $1/(y - y_{a+e})$ from the cathode and to the anode at y_a . Magnetic field advecting with the electrons would be essentially "piled up," as the electrons are slowed upon entering the denser plasma. Even with a constant plasma density plasma, field should pile up at the anode, since its presence effectively represents a steep density rise. Also, radial factors in cylindrical geometry can allow the advective field penetration to proceed at constant density.

Chukbar and Yan'kov⁴ first associated such non-linear waves with POS opening, and Gordeev et al.⁵ have been particularly concerned with field accumulation at the anode.

We have examined such effects with the ANTHEM simulation model¹. Typical results for a short conduction time, bi-cylindrical switch with constant fill density are displayed in Fig. 1. The power is supplied from the left. The cathode and anode radii are 20 and 28 cm, respectively. The fill plasma is C^{++} at a density of 10^{13} electrons/cm³. It initially fills the region between $z = 2.6$ to 13.6 cm. Here, zero injection velocity is assumed. A constant drive voltage of 4 MV is applied, through an external inductance of 50 nH, so that by 50 ns the current would reach 4 MA for a magnetic field of 4 Tesla, if the the plasma remained a perfect conductor. Similar conditions have been encountered on the PBFA II accelerator at Sandia National Laboratories. Fig. 1(a) Shows the calculated magnetic field contours at $t = 20$ ns, while Fig. 1(b) gives the corresponding electron density profile.

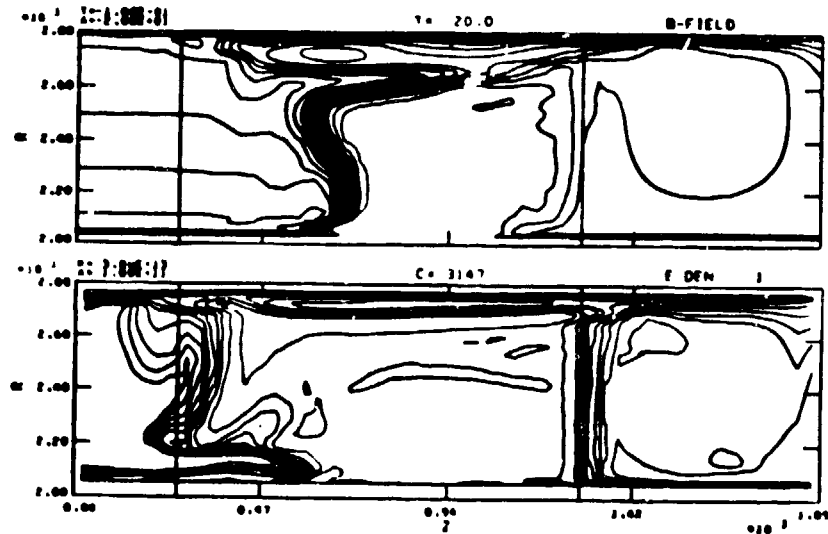


Fig. 1

The cathode and anode electrodes have been represented by the use a high density, massive ion, wall plasma 0.5 cm just above and below the simulation boundaries. Thus, electron emission can proceed either electrode. The developing cathode density gap is clearly evident, as is the density gap near the anode. A $1/r$ drop-off of magnetic field is apparent in the vacuum region near the generator. Near the anode the field contour appear to break into two pieces. The lowest level contours run to the right, the highest levels shift back toward the generator. At radii just below the breakup point, a finger of magnetic field lines has very nearly penetrated to the load region on the right. Many similar features have been noted in long time scale magnetic probe results recently reported by Bystritskii⁶ for the DOUBLE device at Tomsk.

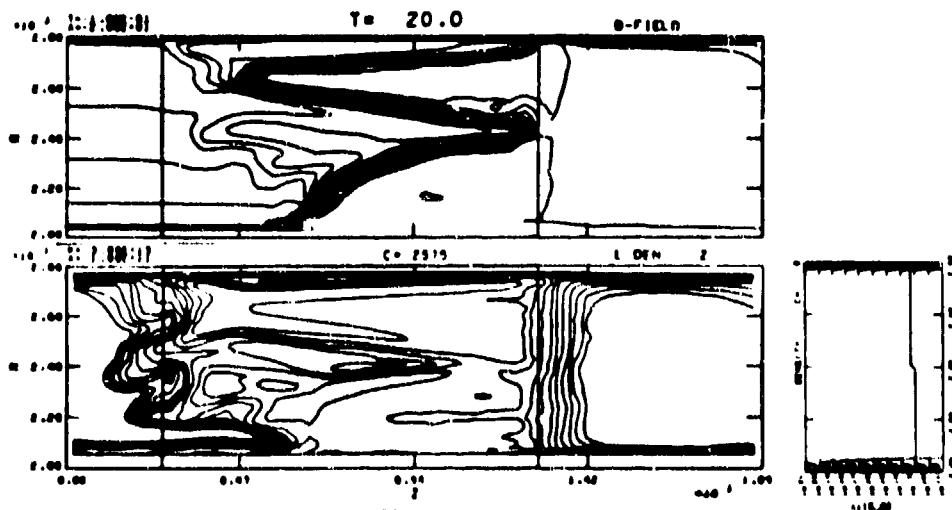


Fig. 2

When, for the sake of examination, we assume that the switch density jumps by a factor of two from 1 to 2×10^{13} electrons/cm³ along a line mid-way across the switch at $r = 24$ cm, as plotted in Fig. 2(c). The magnetic field rapidly penetrates across the density interface to the load. Thus, there is both anode penetration and mid-switch penetration by $t = 20$ ns [Fig. 2(a)]. Figure 2(b) shows contours of the concomitant electron density profile. The magnetic field front starts at the end of the electron density gap, passes across the 10^{13} density region, but then back nearly to the drive end of the switch in the 2×10^{13} plasma.

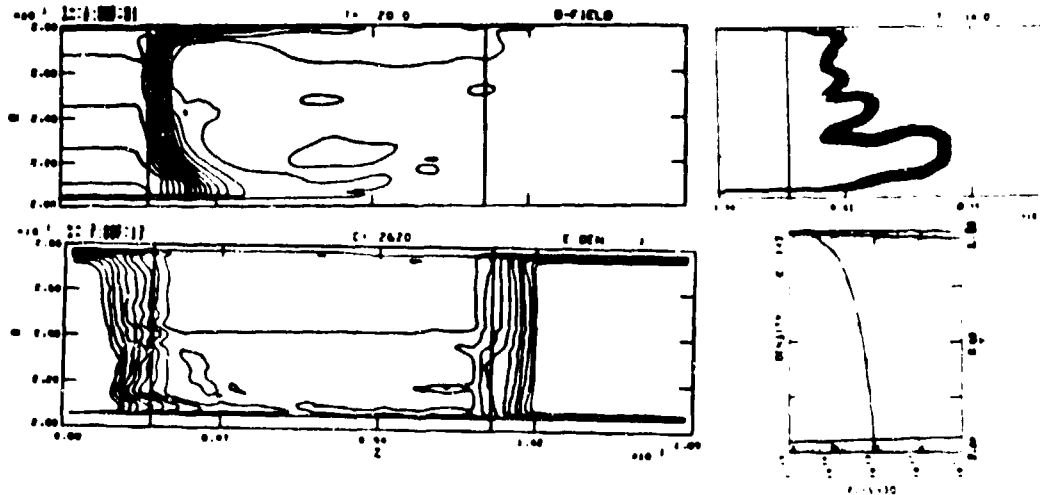


Fig. 3

Alternatively, when the $\nabla \times \mathbf{B}$ terms are suppressed in ANTHEM², the enhanced magnetic field penetration along the mid-radial density jump ceases, as evident from Fig. 3 [(a) B-contours and (b) electron density contours at $t = 20$ ns], so that the field is confined principally to within a skin depth of the fill plasma generator surface.

Figure 3(c) shows the field penetration result at $t = 14$, when the initial plasma density rises as $1/(n - n_{a+t})$ toward the anode at y_a , [Fig. 3 (d)]. From the Kingsep theory³ we expected to record a straight plane wave of penetrating magnetic field. But here we differ from the theoretical situation in that the ions can move. As a result, a gap forms along the cathode, favoring field penetration there. The increased plasma density near the anode certainly delays the field penetration there substantially. However, the anticipated plane wave appears to be unstable in two dimensions.

Finally, we examine the Chukbar-Van'kov⁴ suggestion that a periodically disturbed switch plasma would exhibit enhanced penetration. In our simulation we loaded in an 80% density disturbance along the first 1 cm of a 5 cm wide band of fill plasma. We allowed for five density maxima across the 8 cm wide switch.

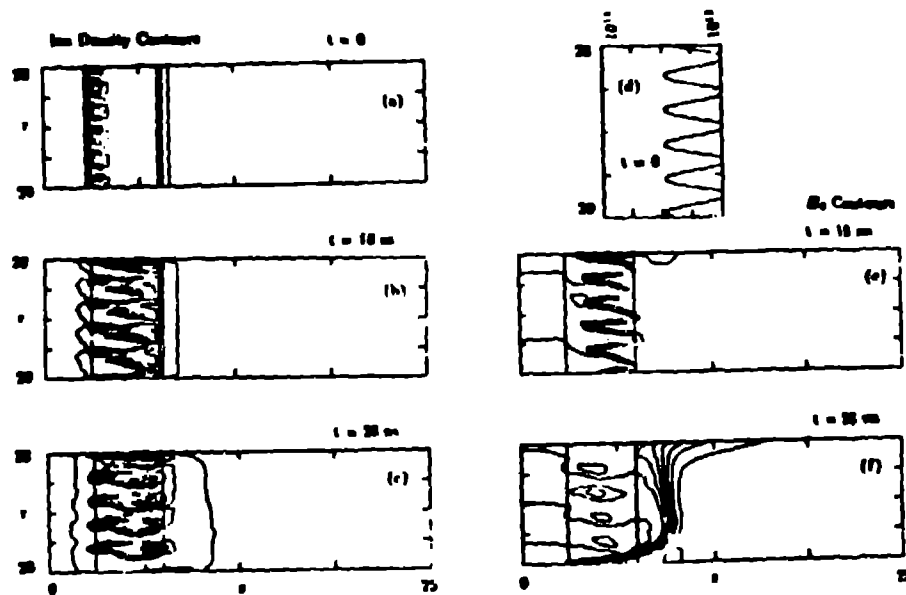


Fig. 4

Figure 4 collects our results. The sinusoidal character of the initial disturbance is shown in Fig. 4(d). Frames (a) to (b) show that by 18 ns under our standard input pulse the density disturbance has propagated to the back side of the plasma. There is an accompanying "snake-like" pattern in the B_z contours. By $t = 28$ ns, there is an array of axial density gaps across the full fill plasma, and current is running principally up the back side of the plasma, so that the switch is essentially open. The opening time has not been affected by the density perturbations, but the field history inside the switch plasma has been altered significantly.

We conclude that the advective field penetration mechanism does, indeed, favor magnetic penetration along density interfaces, as theoretically predicted³⁻⁵. Magnetic insulation at the anode, first noted by Waisman et al.⁷, is a by-product of the density dependence of the advective mechanism. In practice, magnetic pressure gradients from the currents in an opening switch will move the ion so that density gradients are established that further aid the self-consistent penetration of the magnetic fields in the POS. The fact that so many effects are in competition during typical operation of a POS certifies the need for global switch simulations, as provided by the ANTHEM code.

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