**Title:** Propagation of Neutralized Ion Beams  
**Authors:** Drs. Amnon Fisher & Norman Rostoker

**Abstract:**
Propagation of plasmoids (neutralized beams) in a vacuum transverse magnetic field has been studied in the UCI laboratory for several years. The most recent experiments are aimed at studying the plasmoid propagation dynamics and losses in the presence of a background, magnetized plasma which is intended to short the induced polarization electric field and stop the beam. Preliminary results indicate that the beam propagation losses increase with the background plasma density. Principal diagnostics include: magnetically insulated Faraday cups, floating potential probes, calorimeters, microwave interferometer, and thermal-witness paper. Experiments in the near future will use an improved accelerator and transverse-field coil system which allows higher energy, 500 keV, higher current density plasmoids to be studied; this generator will improve the beam uniformity and angular divergence to allow beam propagation for up to five meters and permit study of losses from surface erosion.
FINAL TECHNICAL REPORT

for

PROPAGATION OF NEUTRALIZED ION BEAMS

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH
Contract No. F49620-86-K-0004
October 1, 1985 - December 31, 1987

Principal Investigators
Amnon Fisher
Norman Rostoker

Department of Physics
University of California
Irvine, California 92717

Accession For
NTIS GRA&I
DTIC TAH
Unannounced
Justification

Distribution/Availability Codes
Avail and/or
Special

88 2 28 126
PLASMOID PROPAGATION IN A TRANSVERSE-MAGNETIC FIELD AND IN A MAGNETIZED PLASMA

F. J. Wessel, R. Hong, J. Song, A. Fisher, N. Rostoker, A. Ron, R. Li, and P. Y. Fan

University of California, Department of Physics
Irvine, California 92717

ABSTRACT

The propagation of plasmoids (neutralized ion beams) in a vacuum transverse magnetic field has been studied in the UCI laboratory for several years. These experiments have confirmed that the plasmoid propagates by the LA drift in a low \( \beta \) and high \( \beta \) plasmoid beam (0.01 < \( \beta \) < 300), where \( \beta \) is the ratio of beam kinetic energy to magnetic field energy. The polarization electric field, \( \mathbf{E} \), arises from the opposite deflection of the plasmoid ions and electrons, due to the Lorentz force, and allows the plasmoid to propagate undeflected at essentially the initial plasmoid velocity. In these experiments we used plasmoids (150 keV, 5 kA, 50-100 A/cm², 1 \( \mu \)s) injected into transverse fields of \( B_t = 0-400 \) G. Anomalously fast penetration of the transverse magnetic field has been observed as in the "Porcupine" experiments.

Our most recent experiments are aimed at studying the plasmoid propagation dynamics and losses in the presence of a background, magnetized plasma which is intended to short the induced polarization electric field and stop the beam. Background plasma was generated by TiH₃ plasma guns fired along \( B \) to produce a plasma density, \( n_p = 10^{12} - 10^{14} \) cm⁻³. Preliminary results indicate that the beam propagation losses increase with the background plasma density; compared to vacuum propagation, roughly a 50% reduction in ion current density was noted 70 cm downstream from the anode for \( n_p = 10^{13} \) cm⁻³. Principal diagnostics include: magnetically insulated Faraday cups, floating potential probes, calorimeters, microwave interferometers, and thermal-witness paper. Experiments in the near future will use an improved accelerator and transverse-field coil system which allows higher energy, 500 keV, higher current density plasmoids to be studied; this generator will improve the beam uniformity and angular divergence to allow beam propagation for up to 5 meters and permit the study of losses from surface erosion.

1. INTRODUCTION

The first paper on plasmoid motion across a transverse magnetic field was published in 1931. The subject is fundamental to plasma physics and has applications to geomagnetic storms and solar wind penetration into the geomagnetic field, injection of a plasmoid into a magnetic containment device and the dynamics of pinches. The present work is concerned with the propagation of a neutralized ion beam (plasmoid) in and above the ionosphere in a background magnetic field and a low density partially ionized plasma. We define \( \beta = \frac{4\pi n M V^2}{B^2} \) as the ratio of the beam kinetic energy density to the magnetic field energy density. \( V \) is the beam velocity, \( M \) is the ion mass, \( n \) is the beam ion density, and \( B \) is the background magnetic field. Only the case \( \beta \gg 1 \) is considered. Three phases of propagation are illustrated in Fig. 1. The idealization of the diamagnetic phase to a perfect conductor suggests that the exclusion of the field should result in simple ballis-
tic propagation. After the magnetic field has penetrated the beam propagation would be expected by means of self-polarization and $E\times B$-drift as observed for low $\beta$-beams.  

A series of rocket experiments launched the "Porcupine plasma jet". Nearly undeflected propagation of the dense ($n_{\text{beam}} \gg n_{\text{plasma}}$) and fast heavy ion beam ($v = 1.7 \times 10^4 \text{ m/s}$; $M = 131 \text{ m}$/s) was observed in the magnetized ionospheric plasma. The beam passed from phase I to phase III of Fig. 1 in a time much shorter than that expected from classical diffusion. Propagation was dominated by phase III. This was attributed to anomalous diffusion caused by an instability driven by the diamagnetic current. On the other hand, in recent computer simulation studies of this problem the diamagnetic phase was dominant and the background plasma and magnetic field were diverted around the beam. We seek to understand these apparently contradictory conclusions by doing laboratory experiments where much more detailed measurements are possible, and analytic theory and computer simulation guided by the experimental results.

2. CROSS-FIELD PROPAGATION IN VACUUM

2.1. Description of Experiment

The experiment is illustrated in Fig. 2. The Marx generator consists of six stages of 50 kV, 0.7 $\mu$F capacitors and delivers an output voltage in the range 100-200 kV. The Marx output is connected to a magnetically insulated ion diode as illustrated in Fig. 3. It is an annular diode with an anode-cathode spacing of 13 mm. The magnetic insulation field is 2-2.5 kG with a field risetime of 40 $\mu$s. At 150 kV the diode produces a 4 kA beam of ions - 50 A/cm$^2$ and 1 $\mu$sec duration. Ions are produced by surface flashover of a 0.8 mm polyethylene sheet with stainless steel pins mounted on the anode electrode. The approximate ion composition in the beam is 75% H$^+$, 15% C$^+$, 10% CH$_n$+.

Two pairs of field coils were used to generate $B$, with dimensions: 2.3 m x 0.5 m with 5 turns and 1.15 m x 0.5 m with 5 turns. Each pair of coils had a spacing of 0.4 m and was driven by a 3 kV, 4 x 580 $\mu$F capacitor bank. The field strengths were 121 G/kV for the longer coil and 190 Gauss/kV for the shorter coil with risetime of 0.7 $\mu$s. Lucite drift tubes were used to study the beam propagation over the 2 m transverse field region. The tube diameters were nominally 26 cm and were installed in 0.5-m length sections or a single 2-m length section. Vacuum was 10$^{-5}$ Torr.

Several diagnostics were used in the experiments. The ion current density was measured using biased Faraday cups (-500 V bias) with small magnets to suppress secondary electron
A Rogowski loop with a 12 ms integration time was used to measure the $B_z$ field. The diamagnetic signal induced by the beam as it entered the field was measured by a pair of fast B-loops with a 11.2 μs integration time constant to prevent the slower $B_z$ field from being recorded. These diamagnetic loops have a diameter of 27 mm, 20 turns each, with a sensitivity of 0.2 V/Gauss. Both probes were wrapped in conductive cloth to shield the electrical noise. One coil was located in vacuum 45 cm downstream from the anode coaxial with the ion beam and the drift tube. The other coil was located outside the beam. A pair of floating potential Langmuir probes were used to measure the polarization electric field $E_x$. These probes were made of rigid coaxial cables with the center conductor exposed about 5 cm and inserted into the drift tube through Wilson seals. This allowed measurement of the potential difference $\Delta \phi$ over a known probe separation distance. Signals from these probes were sent to a differential amplifier and recorded. The existence of $E_x$ was verified by several tests: $\Delta \phi$ changes sign if the sign of $B_z$ is changed, $\Delta \phi = 0$ if the probes' tips are touching and linearly increases with probe tip separation, and $\Delta \phi = 0$ if $B_z = 0$. Thermal graphic paper was used as a witness plate to trace the beam location and radial profile and to estimate the beam divergence and beam energy. The paper shows a distinct and noticeable color change in the range of 1-5 Joules/cm²; beyond which no color change occurs.

2.2 Experimental Results

Net current measurements with a Rogowski loop and floating probe measurements verified that the ion beam in the drift tube was charge and current neutralized. Damage patterns on thermal paper located 40 cm and 70 cm downstream showed that the beam divergence was 3-4° when the diode voltage was above 100 kV. Some experimental parameters are given in Table I. $\rho_i$ is the ion gyroradius based on the beam velocity $v_0$. $\epsilon = 4\pi n_i m_e c^2/B^2$ is the dielectric constant.

<table>
<thead>
<tr>
<th>TABLE I</th>
<th>RELEVANT EXPERIMENTAL PARAMETERS</th>
</tr>
</thead>
<tbody>
<tr>
<td>$L = 50 - 200$ cm, $r = 10$ cm, $v_0 = 4.4 \times 10^8$ cm/sec (for 100 keV beam), $n_i = 1.42 \times 10^{11}$ cm⁻³ (for $J = 10$ A/cm²).</td>
<td></td>
</tr>
<tr>
<td>$B_z$ (Gauss)</td>
<td>50</td>
</tr>
<tr>
<td>$\rho_i$ (cm)</td>
<td>920</td>
</tr>
<tr>
<td>$\epsilon$ ($\times 10^4$)</td>
<td>107</td>
</tr>
</tbody>
</table>

Beam propagation across the transverse magnetic field was evaluated with Faraday cups. Figure 4 shows results. Although the angular spread of the beam leads to a significant decrease of current density with propagation distance, there is very little decrease in current density as the magnetic field is changed over a few orders of magnitude and $B_z$ changed from .01 to 300. The magnetic field $B_z$ does not significantly change beam propagation.

Diamagnetic signals $\Delta B$, were measured at 50 cm downstream from the diode and are shown in Fig. 5. The value of $\beta$ was changed by holding the diode voltage fixed at 150 kV and changing the magnetic field $B_z$. $\Delta B$ is the largest change in magnetic field just outside the beam at $r = 10$ cm. The magnetic field change was also measured by a similar $B$-probe on the beam axis. The polarity of $\Delta B$ was opposite to $\Delta B$, indicating that the field decreases inside the beam and increases outside. $\Delta B/B_z \ll 1$ and $\Delta B/B \ll 1$; with signals increase with increasing $\beta$ but the above inequalities are preserved for $\beta$ up to a value of 400.
These facts confirm that the magnetic field penetrates the plasma in a time that is small compared to the current rise time which is about 0.5 μsec so that only a slight perturbation of the magnetic field is ever observed although the beam is a good conductor.

![Graph of Faraday Cup Position vs. Vd](image)

**Figure 4.** Beam propagation across the transverse magnetic field with the annular diode. The values of beta are indicated in parentheses.

![Graphs of Diode Voltage, Current Density and Diamagnetic Field](image)

**Figure 5.** Measurements of diode voltage, current density and diamagnetic field at 50 cm from the anode; β is changed by changing the magnetic field.

Measurements of the polarization electric field, \( E_y \), 40 cm downstream from the anode, are displayed in Fig. 6 for fixed \( V_d \) and varying values of \( B_z \). These data show that the value of \( E_y \) increases linearly with \( B_z \). The peak value of \( E_y \) is compared to the theoretical value computed from, \( E_y = V_d B_z/c \). In these data the probe tip separation was 2 cm and we used a beam velocity corresponding to \( V_d = 150 \, \text{kV} \). Good agreement is observed over the range of parameters studied. This is consistent with the fast penetration of the magnetic field.
field and propagation by means of the ExB-drift.

**Figure 6.** Measurements of diode voltage, current density and polarization electric field at 40 cm from the anode for the annular diode

### 3. CLASSICAL AND ANOMALOUS DIFFUSION

Consider the idealization of a perfectly conducting cylinder in a transverse magnetic field as illustrated in Fig. 7. The magnetic field is given by $B = V \Phi$ where $V \Phi > 0$ subject to the boundary conditions

$$\lim_{r \to b} V = B_0 r \cos \theta$$

$$\frac{\partial V}{\partial t} = 0 \text{ for } r = a$$

The solution is $V = B_0 \left[ a^2/r \right] \cos \theta$. If $\theta = -\pi/2$

$$B_\theta = B_\phi = B_0 \left[ 1 + (a^2/r) \right]$$

At the surface of the beam $B_\phi = 2 B_0$ and at $r = 2a$ $B_\phi = 1.25 B_0$. In Table II we compare values of the calculated diamagnetic signal $\Delta B = B_0$ just outside the beam with the experi-
mentally measured diamagnetic signal $\Delta B_m$.

**TABLE II**

| $B_0$ (Gauss) | 50 | 89 | 149 | 194 | 239 | 284 | 328 |
| $\Delta B_m$ (Gauss) | 2.8 | 2.7 | 2.2 | 1.7 | 1.7 | .8 | .7 |
| $100 \Delta B_m/B_0$ | 5.6 | 3.04 | 1.48 | .88 | .72 | .28 | .2 |
| $\delta$ | 252 | 45 | 37 | 14 | 11.4 | 3.7 | 3.3 |

For a perfect conductor as in Fig. 7 the current should be localized on the surface, i.e.

$$J_x = J_x(a, \theta) \delta(r-a)$$

where

$$J_x = (c/4\pi) B_0 = - (c/2\pi) B_0 \sin \theta$$

For a finite classical conductivity magnetic diffusion should take place on a time scale given by

$$(\Delta \tau)^2 = D \Delta T$$

where

$$D = \left(\frac{c}{\omega_p^2}\right)^2 \left(\frac{1}{\tau_{ei}}\right)$$

$\omega_p^2 = 4\pi ne^2/m, n$ is the electron density, $\Delta r$ is the depth of penetration of the magnetic field or the current density after time $\Delta t$, $\tau_{ei} = 3 \times 10^4 (T^2/n)$ sec is the electron-ion collision time and $T$ is the electron temperature in electron volts. (For a vacuum of $10^{-5}$ torr only Coulomb collisions need be considered). The electron temperature has not been measured; we assume $T = 10$ ev, $\Delta r = 10$ cm and $n = 3 \times 10^{23} \text{ cm}^{-3}$; then $c/\omega_p = 1 \text{ cm}$, $\tau_{ei} = 10^{-6}$ sec, and $\Delta t = 100$ usec. The observed time is much less than $1 \text{ usec}$, and the electron temperature is probably more like $10-100$ ev. We conclude that the diffusion time is certainly much less than this classical estimate.

A similar conclusion was reached in the analysis of data from the "Porcupine" experiments. This conclusion is distinct from the computer simulations of Mankofsky et al. Ilishin, et al have explained the fast diffusion as an anomalous process attributed to a transverse electron drift current-driven electrostatic instability excited by the diamagnetic current. Initially this current is concentrated near the surface of the beam and linear instability criteria are easily satisfied. After some diffusion has taken place, the current density becomes too small for most instabilities. In any case, a satisfactory theory must explain the difference between the fast diffusion for a plasmoid and the slow diffusion for pinches. If the diffusion rate were as fast for pinches, the phenomena would not be observed and the current densities in pinches are usually much larger than for the present plasmoid experiments.

For further consideration we simplify the geometry and consider a one-dimensional problem as illustrated in Fig. 8. The magnetic field is assumed to be $\vec{B} = (0, 0, B_z)$ where $B_z = B_z(x, t)$ and at $t = 0$

$$\frac{\partial B_z}{\partial t} = \frac{e}{m} j_x$$

Maxwell's equations for the problem are
If there exists a relation of the form \( j_y = \sigma E_y \) and \( 4\pi \sigma \gg \left| \left[ \frac{\partial E_y}{\partial t} / E_y \right] \right| \), then Eqs. (8) and (9) combine to give a diffusion equation:

\[
\frac{\partial E_y}{\partial t} + \frac{1}{c} \frac{\partial B_z}{\partial x} = \frac{1}{c} \frac{\partial \sigma}{\partial t}
\]

(5)

\[
- \frac{\partial B_z}{\partial x} = \frac{4\pi}{c} j_y + \frac{1}{c} \frac{\partial E_y}{\partial t}
\]

(6)

where

\[
D = c^2 / 4\pi \sigma
\]

(10)

To determine \( \sigma \), we consider the generalized form of Ohms law:

\[
(m/n_e^2) \left( \frac{\partial j}{\partial t} / c \right) + j / \sigma_o + \left( j \times B \right) / n_e c = E + \left( V \times B / c \right) + \nabla P_e / n_e
\]

(12)

\( \sigma_o = (n e^2 / m) \tau_e \), \( V \) is the plasmoid velocity viewed from the laboratory frame and \( P_e \) is the electron pressure, \( P_e = eB_z / m_c \) is the electron cyclotron frequency. The last term \( \nabla P_e / n_e \) can be neglected. \( \tau_e \) is the collision frequency which we assume is \( \tau_e \) from classical Coulomb collisions. (According to Mishin et al it is \( \tau_e = (Q_o Q_0)^{-1/2} \) due to turbulence; in any case \( 2\tau_e \gg 1 \)). The appropriate form for the generalized Ohms law is

\[
\frac{\partial j}{\partial t} + \frac{1}{\tau_e} j = \sigma \left( \nabla \times E \right)
\]

(13)
\[
\frac{\partial j_x}{\partial t} + \frac{j_x}{\tau_e} + Q_e j_x = E_y'(\sigma_0/\tau_e)
\]

(14)

\[E_x' = E_x + \frac{1}{c} V_y B_z, \quad \text{and} \quad E_y' = E_y - \frac{V_x}{c} B_z\]

are the electric fields in the moving frame. If \(E_x', E_y', Q_e\) change little during a cyclotron period, the solution averaged over a cyclotron period is

\[j_x = \sigma_0 \frac{E_x' - Q_e \tau_e E_y'}{1 + (Q_e \tau_e)^2}
\]

(15)

\[j_y = \sigma_0 \frac{Q_e \tau_e E_x' + E_y'}{1 + (Q_e \tau_e)^2}
\]

(16)

The problem illustrated in Fig. 8a corresponds to a pinch. Since electrons and ions move together in the x-direction \(j_x = 0, V_x \neq 0\) and \(V_y = 0\); from Eqs. (15) and 16,

\[E_x = Q_e \tau_e j_y/\sigma_0 \quad \text{and} \]

\[j_y = \sigma_0 E_y' = \sigma_0 (E_y - \frac{V_x}{c} B_z)
\]

(17)

Diffusion in the moving frame is determined by the diffusion coefficient \(D = \frac{c^2}{4 \pi \sigma_0}\). Unless the collision time \(\tau_e\) is determined by turbulence, the diffusion would be very slow. Turbulence would be expected near \(t=0\) when the current density is very high, but after a short time the current density would drop and collision time \(\tau_e\) should be classical. This agrees with the observed behavior of pinches.

The problem illustrated in Fig. 8b corresponds to plasmoid or beam propagation. In order to propagate the beam must polarize in the x-direction so that \(E_x = E_x + (V_y B_z/c) = 0\), and \(V_x = 0\). Eqs. (15) and (16) then reduce to

\[j_y = \frac{\sigma_0 E_y}{1 + (Q_e \tau_e)^2}
\]

(18)

\[j_x = - (Q_e \tau_e) j_y
\]

The conductivity \(\sigma = \sigma_0[1 + (Q_e \tau_e)^2]\) is greatly reduced compared to \(\sigma_0\) because \(Q_e \tau_e \gg 1\). The diffusion equation becomes nonlinear with

\[D = \frac{c^2}{4 \pi \sigma_0} \left[1 + (Q_e \tau_e)^2\right]
\]

(19)

The diffusion equation (10) is nonlinear. An estimate of the penetration time is that it is reduced by the factor \((Q_e \tau_e)^2\) compared to the previous estimate of 100 \(\mu\)sec based on Eqs. (6) and (7). For the same assumed data and \(B_0 = 100\) gauss, \((Q_e \tau_e)^2 \approx 3 \times 10^6\) and

\[\Delta t = \frac{\Delta \tau_e}{c} \approx 0.3 \text{ nsec}
\]

(20)
If we assume with Mischin et al that $t_\text{coll} \sim (Q \tau)_{\text{pinch}}^{-1/2} \sim 23.5$ nsec $(Q \tau)^2 \sim M/m = 1.8 \times 10^3$ and $\Delta t \approx 1.3$ nsec. It is somewhat of a curiosity that decreasing the collision time increases the diffusion time. The difference between a pinch and a plasmoid propagating across a magnetic field is the factor $(Q \tau)_{\text{pinch}}^{-1/2} > 1$ whether or not the plasma is turbulent. We have thus accounted for the short penetration time and the very small plasmoid magnetic signal. The present experimental data is insufficient to come to a conclusion about turbulence.

The nonlinear diffusion equation with $D$ given by Eq. (19), has previously been studied by Felber et al in connection with a plasma switch application. Detailed solutions are given for the problems in plane geometry. In this paper ion conductivity is also included so that

$$D = ne^2 \left[ \frac{\tau_e/m}{1 + (Q \tau_e)^2} + \frac{\tau_i/M}{1 + (Q \tau_i)^2} \right]$$

If $Q \tau > (M/m)^{1/2}$ the ion conductivity becomes dominant. The calculation of Eq. (26) should accordingly be multiplied by the factor $(M/m)^{1/2}$ to give a classical estimate of $\Delta t = 0.2$ \mu sec.

Computer simulation studies of this problem have been carried out by T. Tajima and his collaborators. For $a/L < 100$ the magnetic field penetration is anomalously fast and for $a/L < 10$ the penetration is much slower. The computer model involves slab geometry; $L$ is the slab thickness and $a = V_\Omega /Q$ is the ion gyroradius. In the experiments $a/L >> 1$ in all cases observed; the penetration time was too short to observe in all cases when $a/L$ was varied over a factor of 5. There is some evidence for slower penetration when the plasmoid is produced by a plasma gun where $a/L < 1$.

4. CROSS FIELD PROPAGATION IN PLASMA

To produce the background plasma we used 15 small circular plasma guns connected in parallel. Each one has an annular gap filled with $\text{TiH}_4$. The density of the plasma produced by the plasma gun was measured by a 60 GHz microwave interferometer. The plasma density in the drift tube increased approximately linearly with increasing plasma gun voltage $V_{PG}$. When $V_{PG} = 4$ kV the average plasma density was about $10^{13}$/cm$^3$.

The electric polarization was measured for various magnetic fields and values of $V_{PG}$ (plasma density). The results are shown in Fig. 9. It is apparent that the plasma reduces the polarization electric field and it becomes negligible at about $10^{13}$ cm$^{-3}$. For a density of the order of the beam density or less there is little effect.

```
Figure 9. Polarization electric field vs. transverse magnetic field at various plasma gun voltage.

The beam deflection was also measured with red cellulose witness plates. When $V_{PG} = 3-4$ kV the beam deflection agrees quite well with a simple calculation based on the Lorentz...
```
force which is consistent with the vanishing of the polarization electric field. For plasma density less than the beam density, or no plasma density no deflection was observed.

In-beam diamagnetic measurements showed fast penetration on a time scale too large to allow with or without a background plasma. If we consider Eqs. (15) and (16), the appropriate conditions with a dense background plasma are $V_x = 0$ and $V_y = 0$ instead of $B_x + (V_y B_y/c) = 0$. Therefore

$$J_y \approx \frac{\sigma E_y}{1 + (2 e T_e)^2} \cdot n_e V_y$$

This leads to a modified diffusion equation

$$\frac{\partial}{\partial x} (D \frac{\partial n}{\partial x}) + 2 V_y (2 e T_e) \frac{\partial n}{\partial x} \approx \frac{34}{8} \frac{\partial^2 n}{\partial t^2}$$

with $D$ given by Eq. (19). The first term dominates if

$$\left| \frac{1}{B_x} \frac{\partial B_x}{\partial x} \right| > 2 V_y \frac{\partial}{\partial x} \left( \frac{E_y}{e} \right)$$

The solution of the nonlinear equation is more like a wave, and Eq. (24) would be satisfied at the front of the "magneto-resistive" wave so that Eq. (23) should produce fast diffusion similar to Eq. (10).

5. 500 KV PULSED BEAM ACCELERATOR

In order to investigate propagation over about 5 cm and in particular to investigate beam losses, a 500 KV Marx generator system has been assembled and characterized. An improved magnetically insulated annular diode has also been constructed. It produces an ion beam current density up to 170 A/cm² - 4 cm downstream from the anode. This is 20 times higher than the Child-Langmuir limit. The beam divergence is much smaller than it was for the previous system. The divergence determined by witness plates at various distances was previously about 5° for the low energy part of the beam. This is to be compared with 10° for the present system. For particle energy > 250 KV the beam divergence is now 1.1°. Propagation data from Faraday cup measurements is shown in Fig. 16. These results indicate

![Figure 16. Ion beam current density](image)

that a beam where all particles have an energy greater than 250 KV will expand by about 1 cm over a 5 m propagation distance due to angular divergence. Thus we can propagate a 5 cm beam 5 m and still have an equivalent current density of ions of at least 10 A/cm².
6. CONCLUSIONS

It has been established that a high β plasmoid propagates across a transverse magnetic field without significant deflection. The mechanism is not diamagnetic flux exclusion and ballistic propagation as first anticipated, but it is instead electric polarization of the plasmoid and ExB drift as in a low β-plasmoid. The magnetic field penetrates the plasmoid so rapidly that no significant diamagnetic effect can be observed. Essentially, the unperturbed magnetic field is present inside the plasmoid at all observable times. This behavior of a plasmoid is completely different from the behavior of a metallic conducting projectile. It is also completely different from a 2- or 0-pinch. Indeed, if the field slipped across the particles as fast in a pinch, a pinch would never be observed. We have explained the difference physically by the fact that the polarization for the pinch is longitudinal (electric field parallel to the motion) and transverse for the propagating plasmoid. The question of turbulence as proposed to explain the Porcupine experiments has not been resolved. Although there may be turbulence it is not essential to explain the fast penetration of the magnetic field.

With ExB propagation, the electric field near the plasmoid surface must be different than in the interior. Therefore, the surface must erode and this is the mechanism of beam loss that has been observed in computer simulations but not yet in the laboratory. In the laboratory losses have been observed by expansion of the beam from angular divergence in a small radius drift tube. A new system has been developed that involves a much smaller angular divergence of the plasmoid and a larger drift tube to study the erosion losses.

7. ACKNOWLEDGEMENTS

This research was supported by AFOSR/SDI.

8. REFERENCES


+ Institute of Atomic Energy, P.O. Box 275, Beijing, People's Republic of China.
++ Physics Department, Technion, Haifa, Israel.
* Changsha Institute of Technology, Changsha, Hunan, People's Republic of China.
END
DATE
FILMED
5-88
DTIC