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Ion beam propagation in a transverse magnetic field and in a magnetized plasma

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Propagation of a charge-neutralized ion beam, in a transverse magnetic field ($B_z < 400$ G) and in a magnetized plasma, has been studied. Measurements indicate that the beam propagation mechanism is due to the $\mathbf{E}\times\mathbf{B}$ drift in the region of high β ($1 < \beta < 400$), where β is the ratio of beam kinetic energy to transverse magnetic field energy. Diamagnetic measurements, both internal and external to the propagating beam, confirm the fast diffusion of B_z into the beam on a time scale much shorter than the beam rise time of 10^{-7} s. When the beam is injected into a magnetized plasma the electric field is shorted to a degree that increases with increasing background plasma density. When the plasma density reaches $10^{13}/\text{cm}^3$ ($\sim 200\times$ the beam density) complete shorting occurs and the beam is deflected by the transverse magnetic field.

I. INTRODUCTION

The propagation of a neutralized ion beam transverse to a magnetic field has important implications[1-5] for fundamental plasma physics, space physics, and fusion research. This problem has been studied at UCI for numerous years both theoretically and experimentally.[6-11] Most of our previous work has studied beam propagation in a vacuum transverse magnetic field. In this paper we report our most recent results of beam propagation in a magnetized background plasma. The results show that the induced polarization electric field is shorted significantly with increasing background plasma density and the beam fails to propagate by the $\mathbf{E}\times\mathbf{B}$ drift when the plasma density reaches $10^{13}/\text{cm}^3$, compared to the ion beam density of $4.4\times 10^{10}/\text{cm}^3$. The results of in-beam diamagnetic measurements have revealed the existence of fast penetration of the magnetic field into the beam, confirming earlier measurements reported by Li, *et al.*[11] which were made external to the beam.

In the next section the experimental arrangement is described. Results and discussion are presented in Secs. III and IV, respectively. The reader is referred to earlier publications[7-11] for the theory of $\mathbf{E}\times\mathbf{B}$ propagation and fast diffusion of the magnetic field into the beam.

II. EXPERIMENTAL ARRANGEMENT

The experimental arrangement is shown schematically in Fig. 1. The Marx generator consists of six stages of 50-kV, 0.7-μF capacitors and generates an output voltage in the range of 120–210 kV. The ion beam is produced by a magnetically insulated annular diode which is connected directly to the output of the Marx generator. The anode surface is covered with polyethylene sheet of approximately 0.8-mm thickness; stainless-steel pins embedded into the polyethylene sheet enhance surface flashover and ion production. The annular cathode is fabricated from graphite and supports the diode-magnetic-field coils with an inner and outer diameter of 11.5 and 15 cm, respectively. The magnetic insulation field is about 3.5 kG. The *A-K* gap spacing is 13 mm. The application of a 150-kV diode voltage produces a pulsed-ion beam of 4-kA total current and ~ 1-μs pulse duration; the beam composition is primarily protons and includes a small component of higher Z ions such as C^+, etc. Sections of 0.5-m-long lucite tubes with diameters of 26 cm were used as the beam drift tube. Vacuum was $\sim 10^{-5}$ Torr.

To produce the background plasma we used the plasma gun array illustrated schematically in Fig. 2 comprised of 15 small circular plasma guns connected in parallel. The design of these guns are similar to ones developed previously in our laboratory which have an annular gap filled with TiH_4 (Ref. 12); the inner and outer diameters of the annular gap are 9 and 19 mm, respectively. The plasma gun array was mount-

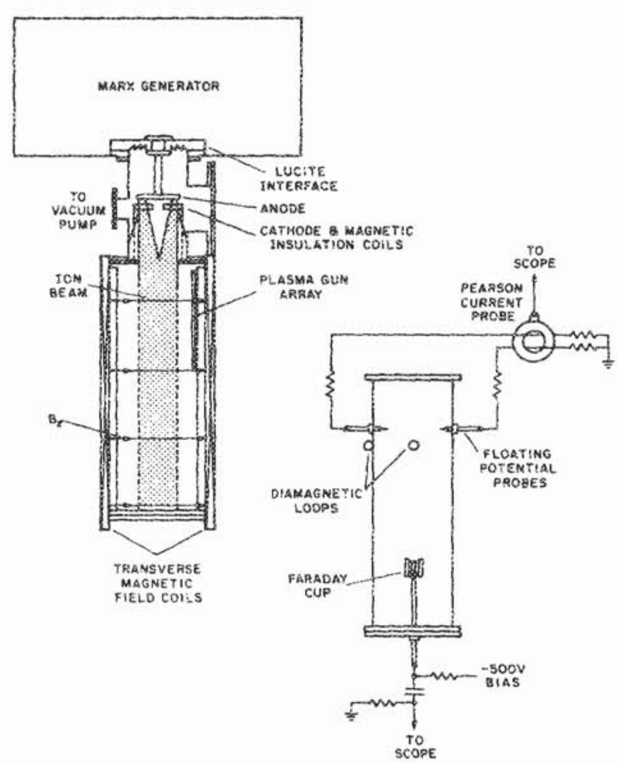

FIG. 1. Schematic diagram of experimental apparatus.

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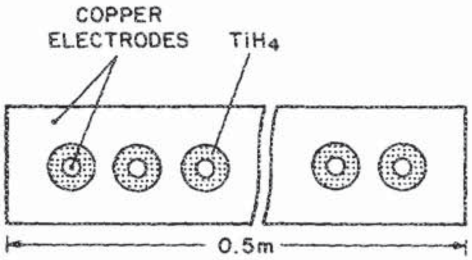

FIG. 2. Schematic diagram of the plasma-gun array.

ed against the inner wall of the beam drift tube, with its leading edge 27 cm downstream from the anode, and gave a uniform plasma distribution along the drift tube. The density of the gun plasma was measured by a 60-GHz microwave interferometer, and increased approximately linearly with increasing plasma gun discharge voltage, V_{PG}; when $V_{PG} = 4$ kV the peak plasma density was about 4×10^{13} /cm^3.

The transverse magnetic field B_z was produced by a pair of field coils with dimensions 115 cm$\times$50 cm and 5 turns; the long dimension of each coil was parallel to the direction of beam propagation with its leading edge located 30 cm downstream from the anode. The spacing between the two field coils was 51 cm. The field coils were driven by a 3-kV, 4×580-μF capacitor bank. Magnetic fields up to 460 G could be produced with a rise time of 0.7 ms, as measured by a $\dot{B}$ loop with a 47-ms integration time constant.

For the diamagnetic signal measurements, we used two search coils. One is located in vacuum 45 cm downstream from the anode, coaxial with the ion beam and drift tube. The other coil is located outside the drift tube, at the same distance from anode as the inner one, but at an off-axis radial distance of 15 cm. Both coils have a diameter of 27 mm and use an 11.2-μs time constant integrator to prevent the slower B_z magnetic field from being recorded. The sensitivities are 0.11 V/G and 0.20 V/G, respectively.

A pair of floating potential Langmuir probes were used to infer the polarization electric field E_y. These high impedance probes, fabricated from rigid coaxial cable with the central conductor exposed about 5 cm, were inserted into the drift tube through Wilson seals 40 cm downstream from the anode and allowed measurement of the potential difference over a known probe separation distance. Signals from these probes were electronically added with a Pearson current probe as shown in Fig. 1.

To measure the beam deflection we used red cellulose acetate film as witness plates located a distance of 100 cm downstream from the anode. The witness plate changes color and surface texture when bombarded by the ion beam. The ion beam current density was measured with a biased Faraday cup ($\sim$500-V bias) which had small permanent magnets to suppress secondary electron emission. The entrance aperture to the Faraday cup was located normally 100 cm downstream from the anode.

III. RESULTS

Most experiments were performed at a Marx generator peak output voltage of 160 kV. However, the peak ion energy was slightly lower, ≈120 keV, due to inductive voltage division in the output transmission line. The ion beam current density was measured to be approximately 3.4 A/cm^2, 45 cm downstream from the anode. Therefore, the velocity and particle density of the proton beam are $v_0 = 4.8\times10^8$ cm/s and $n_i = 4.4\times10^{10}$/cm^3, respectively. Related experimental parameters[7-11] of plasma beta β, ion gyroradius ρ_i, and plasma dielectric constant $\epsilon = 1 + \omega_{pi}^2/\Omega_{ci}^2$ are shown in Table I.

TABLE I. Experimental parameters. Transverse magnetic field B_z, plasma beta β, ion gyroradius ρ_i, and plasma dielectric constant, $\epsilon = 1 + \omega_{pi}^2/\Omega_{ci}^2$.

B_z (G)	23	46	115	231	346
β	402	101	16.1	3.99	1.78
ρ_i (cm)	1536	768	307	153	102
ϵ ($\times10^4$)	158.4	39.6	6.34	1.57	0.70

Typical data for beam propagation into a transverse, vacuum magnetic field are displayed in Fig. 3 which shows waveforms for the Marx voltage V_m, ion beam current density J_i, polarization electric field E_y, and inner and outer diamagnetic signals, ΔB_i and ΔB_0, respectively. Note that this data has been corrected for the beam propagation delay resulting from the downstream location of the diagnostics relative to the ion diode. As shown, the Marx voltage (accelerator pulse) rises in 150 ns, declines gradually 550 ns into the pulse, then declines more rapidly due to closure of the ion diode acceleration gap. Thus, during the pulse the ion energy is a gradually decreasing function of time.

The polarization electric field has a time dependence similar to that of the Marx voltage pulse. This electric field arises from the opposite deflection of ions and electrons in the transverse magnetic field and results in excess polarization charge at the surface of the beam, in a manner previously described as a plasma capacitor.[2,8] This electric field is necessary for undeflected beam propagation by the $\mathbf{E}\times\mathbf{B}$ drift and its magnitude is given by $E_y = v_0 B_z$. Thus, the

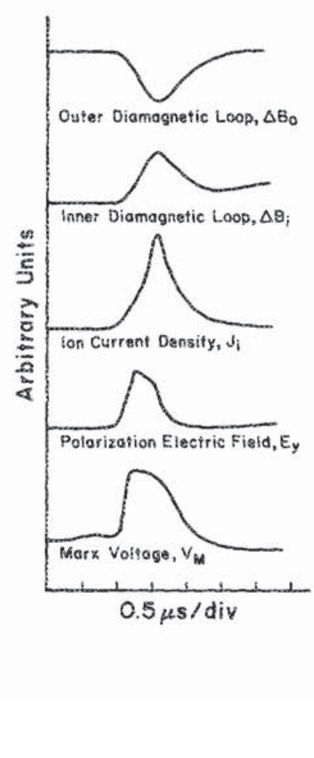

FIG. 3. Signal waveforms for a high beta ion beam in a transverse, magnetic field: $V_M = 160$ kV, $V_{PG} = 0$, $B_z = 115$ G, $\beta \approx 16$.

initial decline in E_y is a result of declining beam velocity caused by decreasing Marx voltage. The more rapid decline in E_y which occurs after 650 ns is attributed to diode shorting or, especially at high electric field stress, charge leakage to the walls of the lucite drift tube.

During the time when the electric field is high, the ion current density continually increases, reaching its peak value as the electric field begins to decline rapidly. The ion current rate of rise is independent of the electric field strength and is governed by the particular characteristics of the ion generation/acceleration process. The decline in J_i, coincident with E_y, is explained by the fact that the magnetic field of 115 G was sufficient to prevent single particle ion trajectories from reaching the Faraday cup. Thus, during the interval of rapidly declining electric field, E_y is insufficient to propagate the beam undeflected.

Figure 3 also displays signals for the inner and outer diamagnetic probes. As shown, these signals are of opposite polarity, indicating that the magnetic flux decreases internal to the beam and increases external to the beam. At this juncture we note that the measured diamagnetism, $\Delta B_i/B_z$ and $\Delta B_o/B_z$, is much less than unity even though beta is much greater; for this case, $\beta = 4\pi n_i m_i (v_0 B_z)^2 \approx 16$. Thus, beam propagation by diamagnetic flux exclusion is not observed.

Figure 4 displays polarization electric field measurements obtained for beam injection into a transversely magnetized plasma as a function of increasing background plasma density (i.e., increasing plasma gun voltage V_{PG}). The solid line shown for $V_{PG} = 0$ demonstrates that E_y is linear with B_z for $B_z < 100$ G. Higher values of B_z produce a larger divergence from this curve presumably due to beam-wall shorting at high electric-field stress. The remaining data for $V_{PG} > 0$ clearly shows that increasing plasma density enhances E-field shorting; at a plasma density of $n_p \sim 4\times10^{13}/\text{cm}^3$ ($V_{PG} = 4$ kV), complete shorting occurs.

Field shorting by this method prevents undeflected beam propagation as shown in the damage patterns of Fig. 5. As indicated, for beam injection into a vacuum field with no background plasma, $V_{PG} = 0$, the beam damage is centrally located on the witness plate. Whereas, for beam injection into a magnetized plasma, $V_{PG} = 3$ kV, the damage pattern is located near the upper region of the witness plate indicating that the beam has been deflected. The beam center de-

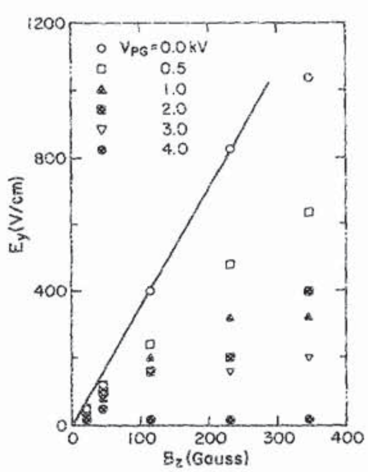

FIG. 4. Polarization electric field E_y vs transverse magnetic field B_z at various plasma gun voltages.

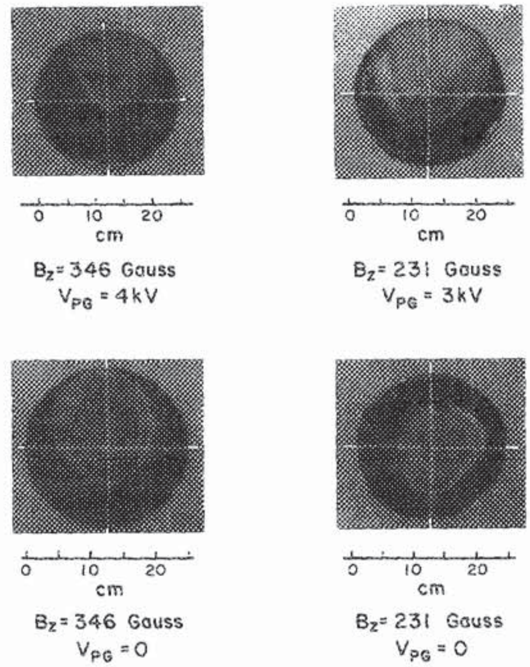

FIG. 5. Witness plate damage patterns, with and without shorting plasma.

flection due to the Lorentz force is calculated according to formula,

$$h_{cal} = \rho_i - \sqrt{\rho_i^2 - l_{eff}^2},$$

where ρ_i is the ion gyroradius and l_{eff} is the effective interaction length between the ion beam and the transverse magnetic field. For the "shorted field" conditions shown here, the measured beam deflection h_{exp} agrees quite well with the calculated value h_{cal} indicating the beam does indeed follow single particle trajectories.

The results of diamagnetic measurements with and without a background plasma are shown in Fig. 6; typical error bars, displayed only for the $V_{PG} = 0$ shots, were approximately $\pm 15\%$ of the signal value. Generally, on-axis diamagnetism was greater than that measured external to the beam. In the vacuum propagation case, the largest value of diamagnetism was of the order of 10%–15%, while the value of beam beta was $\beta \approx 400$. Thus, even in this high beta limit we conclude that the magnetic field diffuses rapidly into the propagating ion beam, on a time scale much shorter than the beam rise time and that beam propagation does not occur by diamagnetic exclusion of the transverse magnetic field. Indeed, for the vacuum propagation experiments the existence of the polarization field confirms this.

IV. DISCUSSION

In our earlier vacuum propagation experiments[11] we observed rapid diffusion of the transverse magnetic field into the beam and $\mathbf{E}\times\mathbf{B}$ propagation for a high beta beam. This behavior was accounted for by a classical theory which suggests that the field diffusion time decreases $[1 + (\Omega_c \tau_{ei})^2]^{-1}$, where $\Omega_c \tau_{ei}$ is large. For beam injection into a magnetized plasma this theory predicts similar fast diffusion accompanied by beam deflection when $E_y = 0$.

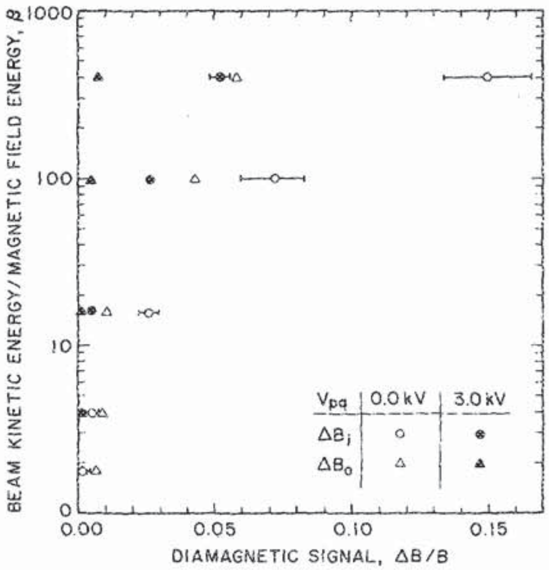

FIG. 6. Beam diamagnetism vs beta, with and without shorting plasma.

The present experiments confirm this behavior. Indeed, for all cases examined here the magnetic field diffuses rapidly into the beam accompanied by small diamagnetism even though the plasma beta is in the range of $\beta = 100$–400. When the polarization electric field is shorted the beam is deflected as if the ions follow single particle trajectories.

Recent rocket-born experiments have also reported fast diffusion of the magnetic field for a high density, heavy ion beam (xenon) propagating nearly perpendicular to the Earth's magnetic field in the presence of the ambient space plasma.[3,13] However, these experiments observed an initial diamagnetic cavity, where the ions where unmagnetized, followed by a region in which the magnetic field had practically totally penetrated the beam. In this case the length of the diamagnetic cavity was too short to be accounted for by the dynamical beam pressure and was instead attributed to thermal beam pressure. Furthermore, the rapid field diffusion was attributed to anomalous diffusion produced by lower-hybrid waves.

Significant differences exist between these space experiments and the experiments reported here so that direct comparisons are difficult to make. Nevertheless, our experiments are continuing to address these differences in order to obtain better convergence of these results.

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