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Experimental Studies of the Penetration of a Plasma Stream
Into a Transverse Magnetic Field*

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ABSTRACT

The interaction of a dense ($n \approx 3 \times 10^{13} \text{ cm}^{-3}$), fast ($v \approx 4 \times 10^7 \text{ cm/sec}$) plasma stream with a transverse magnetic field is studied experimentally by injecting a plasma from a coaxial gun perpendicular to the magnetic field of a pair of mirror coils. The experiments show that the stream from such a gun can penetrate magnetic fields up to $\sim 9 \text{ kG}$. A rapid field-plasma intermixing takes place and the injected stream crosses the magnetic field by electrically polarizing and producing an $\underline{E} \times \underline{B}$ drift. It was found that the forward motion of the stream can be stopped by draining the

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polarization charge by current flow along field lines to a shorting conductor located outside a magnetic mirror. Measurements of stream thickness normal to the magnetic field and the effectiveness of the depolarizing conductors have been made as a function of the strength of the transverse field. The exclusion of the plasma from high magnetic fields, and the variation of stream width with magnetic field intensity are due to plasma polarization effects rather than plasma diamagnetism. Observations on high energy electrons > 200 keV which are produced during the experiment are discussed.

I. INTRODUCTION

The penetration of a moving plasma into a region of strong, transverse magnetic field has in general been considered to take place in a way lying between the following two extremes: (1) The plasma is completely diamagnetic and has sufficient momentum flow rate ρv^2 to overcome the magnetic field pressure $B^2/2\mu_0$. The plasma then excludes the field from its interior as it penetrates and crosses the region of strong transverse field. Figuratively speaking the plasma pushes the field lines aside and passes between them. Such a mechanism of field penetration has been discussed by several authors.¹⁻³ (2) The plasma is considered as remaining nondiamagnetic as it enters the field region and crosses the field by means of an electric polarization and an $\vec{E} \times \vec{B}$ drift. The penetration and crossing of transverse fields by this mechanism has been discussed by numerous investigators.⁴⁻¹¹

The experiments to be discussed were an outgrowth of the results of experiments performed on the dense ($n = 10^{15} \text{ cm}^{-3}$), relatively slow ($v \approx 5 \times 10^6 \text{ cm/sec}$) plasma produced by a crossed field accelerator, the details of which are reported elsewhere.¹² The plasma stream from this accelerator was found to be limited in velocity by the release and ionization of large quantities of gas from its electrodes. The resulting stream, was observed to be well permeated by the strong applied transverse field and the stream crossed the field by means of electric polarization

(mechanism (2) above). It was found that the forward motion of the plasma was stopped when the stream was depolarized. The depolarization was accomplished by current flow to a conductor which connects magnetic field lines together at the side of the stream.^{12,13}

The present paper describes the results of experiments which extend the plasma stream observations above. For these experiments, the plasma from a coaxial gun¹⁴ is injected into the magnetic confining field of a mirror machine such that the plasma enters in a direction normal to the magnetic field. The plasma from the gun consists of a stream about a meter in length in contrast to the short plasmoids used in the cross field injection studies of previous investigations.^{15,16} Measurements are reported on the magnetic field penetration and polarization effects of the fast ($v \approx 4 \times 10^7$ cm/sec), dense ($n = 3 \times 10^{13}$ cm⁻³) plasma stream from the coaxial gun.

II. MODEL

We begin with a discussion of the usual model of a low pressure plasma stream crossing a magnetic field by means of an $\vec{E} \times \vec{B}$ drift as shown schematically in Fig. 1. The stream is assumed to be permeated by and moving normal to a strong, externally produced, uniform magnetic field $\vec{B}$. In such a model the effect of the Lorentz $\vec{v} \times \vec{B}$ force is cancelled by the action of an electric field produced by charge separation in the plasma. If for any reason such an appropriate $\vec{E}$ -field is not initially present, the $\vec{v} \times \vec{B}$ force acts on the charged particles of the stream causing a deflection of the ions and electrons in opposite directions (these

deflections are upward and downward respectively in Fig. 1). This action results in a production of a net positive charge on the upper boundary of the stream and an equal amount of negative charge on the lower boundary as shown in Fig. 1. Such a charge separation will continue until the resulting electric field is strong enough to cancel the deflecting effect of the magnetic field, i.e., until¹⁷

$$\underline{E} + \underline{v} \times \underline{B} = 0. \quad (1)$$

The plasma stream then continues to move across the magnetic field with the well known $\underline{E} \times \underline{B}$ drift

$$\underline{v} = \underline{E} \times \underline{B} / B^2. \quad (2)$$

This simple picture is subject to further refinements. For example, the particles in the charge layers will experience less electric force and consequently cannot keep up with the drift of the main stream, an effect which has been described by several authors.^{5,8,10,11} The "pooled off" charge which is left behind can provide a source of electric field for the succeeding components of the stream. A further effect is that the space charge repulsion in the charge layers will spread the polarization charge laterally along the magnetic field lines. If the field lines pass through an insulator as shown in part (a) of Fig. 1, the insulator will become charged, and the polarization charge will be redistributed such that the magnetic field lines become lines of equal electric potential. If, on the other hand, the magnetic field lines pass through a good conductor as shown in part (b) of Fig. 1, the polarization charge will be

neutralized by the shorting effect in the plate as fast as it is produced by the action of the unbalanced $\vec{v} \times \vec{B}$ force. Depolarizing currents will continue to flow in the conducting plate as long as the plasma stream has forward momentum.

The above model of a polarized plasma stream is useful in explaining many of the phenomena observed in the experiments to be described.

III. APPARATUS

The arrangement of the experiment is shown in Fig. 2. A pair of circular mirror coils, when energized by a quarter-megajoule capacitor bank, is capable of producing a 15-kG peak magnetic field on axis at the midplane. The coils are separated 25 cm and produce a mirror ratio of 1.3 on the axis. The field is a rectified sinusoidal pulse of time duration (2.5 msec) which is long compared to the time of plasma injection. The field coils are situated around a T-shaped Pyrex vacuum chamber (30-cm dia x 100-cm long) and produce a mirror-type confining field in its interior; typical magnetic flux lines are shown in Fig. 2. Near the time of peak field, a coaxial plasma gun¹⁴ operating with a 0.6-cc atm pulse of deuterium gas with its muzzle 40-cm from the axis of symmetry (15-cm outside magnetic field zero) injects plasma through the 20-cm diameter Pyrex inlet tube into the transverse field. Insulated end plates containing ports allow the insertion of electric and magnetic probes, shorting plates, and current measuring pickup loops. Pyrex end plates are used when photographic observations through the ends of the vacuum chamber are desired.

IV. INJECTION PHENOMENA

A. Electric and Magnetic Probe Measurements of the Injected Stream

It was established by magnetic probes that the injected stream from the coaxial gun penetrated into the magnetic field causing only a small disturbance of the vacuum field, $|\Delta B/B| < 0.1$. Thus the plasma is streaming through the magnetic field and polarization electric fields are to be expected.

The polarization electric field was measured by a pair of voltage probes separated 15 cm and spanning the injected plasma (one above and one below the stream). The probes showed that an appropriate E-field was present. A plot of the peak probe voltage, as a function of the applied transverse field B_0 is shown in Fig. 3.¹⁸ The polarization voltage rises linearly with B_0 up to $B_0 \approx 3$ kG, with a constant slope, corresponding to a fixed plasma drift velocity. This demonstrates that a low pressure plasma is entering the transverse field. Above 3 kG the voltage signals decrease drastically. For $B_0 > 5$ kG, no signals appear. As we show in the next section the latter effect results from the fact that at high fields the plasma is stopped in the fringing field in the inlet tube before reaching the electric probes. Measurements of the E-field with a multiple electric probe outside the magnetic mirror are described in detail in Section V.

B. Wall Depolarization Effects

To further investigate the cut-off of the plasma stream at high magnetic fields, magnetic probe data were taken across the inlet tube where it joins the main chamber. The probe arrangement in the chamber is

shown in Fig. 2. A plot of the maximum change of the axial (z) component of magnetic field during the time of injection is shown in Fig. 4. These data together with data taken at various stations outside the inlet tube are indicative of current paths as drawn in Fig. 5. Since magnetic field lines become lines of equal electric potential, surfaces which are cut by magnetic lines that pass through the moving plasma stream must support the polarization electric field. Evidently a Pyrex surface is not a good insulator under these conditions and the plasma stream depolarizes by conduction currents flowing at the glass wall of the inlet tube. At the higher magnetic fields this effect is so pronounced that the polarization charge is drained as fast as it is produced. Probe data indicate that wall currents flow even at very low values of magnetic field ($B_0 \sim 1$ kG) when the fringing field at the wall of the inlet tube is only a few hundred gauss.

The conductivity at the Pyrex wall is probably influenced by bombardment with both particles and photons. When a collimator is placed to shadow the inlet wall from direct bombardment by the injected stream the penetration of the plasma stream is greatly enhanced and the cut-off field is increased from 5 to 9 kG. The collimation is accomplished by placing two circular glass discs, separated 7-cm and containing 6-cm holes at their centers, 8-cm in front of the gun muzzle and oriented normal to the flow of the plasma beam (see Fig. 2). It is found that while there are currents present on the gun side of the collimators, there is little or no wall-current flowing in the inlet tube on the downstream side. This reduction

of the depolarization current for a given value of applied field is believed responsible for the increased value of cut-off field achieved with the collimated beam. These results give further evidence that the interaction of plasma with the wall of the glass inlet tube plays an important role in inhibiting the penetration of the plasma into high magnetic fields.

C. Depolarization Through a Magnetic Mirror

With collimators, an injected fast stream moving through magnetic fields up to 9 kG can be studied. Of great interest is the effect of depolarizing a plasma stream by conducting plates located outside the magnetic mirror as shown schematically in Fig. 6. A measurement of the depolarization current was made by a Rogowski loop around the conducting plate.¹⁹ An oscilloscope trace of a typical current signal in a shorting plate is displayed in Fig. 7. The first current peak which occurs at the time corresponding to the peak electric probe voltage (without a shorting plate) is a measure of the streaming energy density present in a fast component of plasma produced by the coaxial gun. The second current peak occurs at a time when the voltage signals are very small and is thus associated with a slow moving plasma.

The peak current in the conducting plate located 15-cm outside a mirror, as a function of applied magnetic field B_0 is shown by the curve in Fig. 8 (data points shown with circles). The second curve (x-points) of Fig. 8 shows the corresponding measurements obtained with the plasma beam collimated. As shown in the next section, the depolarization current is a measurement of the change in plasma momentum flow rate owing to depolarization in the plate.²⁰ Above 6 kG, without the collimator no plasma

reaches the region where field lines connect to the plate because of wall depolarization at the inlet tube. When the plasma stream is collimated, plasma is detected by the depolarizing plate up to 9 kG, thus demonstrating enhanced penetration at the higher values of magnetic field. The small depolarizing current at low B-fields corresponds to incomplete depolarization with a finite plate. As the field rises the plate draws larger depolarization current until the point is reached where the entire stream is stopped. Further discussion of this effect is in Section IV. Although there is considerable scatter owing to gun irreproducibility, the data suggest that the momentum transferred to the plate is approximately constant between 3 and 7 kG.

D. Plasma Momentum Measurement

A measurement of the depolarization current in the shorting plate under conditions for which the forward motion of the stream is completely stopped gives a new method of determining the flow rate of the plasma momentum. To demonstrate the method, assume for simplicity, the model of Fig. 1, namely, a polarized plasma beam of mass density ρ flowing with a velocity $\underline{v}$ across a uniform magnetic field $\underline{B}$ and having a rectangular cross section of width w and height h . Since each element of polarizing current in the plasma is matched by an equal but oppositely directed depolarizing current in the plate, the $\underline{J} \times \underline{B}$ decelerating force on each plasma current element gives an equal reactive force contribution to the plate. Thus the plasma momentum is transferred electromagnetically to the shorting plate. Equating the rate of change of plasma momentum to the force on the plate one obtains

$$(\rho w) v(hv) = I h, \quad (3)$$

where k is a factor which ranges between a value unity if the plasma is brought to rest to a value of two if the plasma is completely reflected. Expression (1) may be solved for the average momentum flow rate per unit area ρv^2 , or equivalently, the translational energy density $(1/2)\rho v^2$,

$$\frac{1}{2} \rho v^2 = IB/2wk. \quad (4)$$

Using Eq. (4), the number of ions per unit cross-sectional area (looking in the B-field direction) can be found from the measured values of depolarization current and stream velocity.²¹ With the value of peak current taken at 6 kG from Fig. 8 and the time-of-flight value of stream velocity (4×10^7 cm/sec) the cross-sectional density is $\rho w = 9 \times 10^{-10}$ gm/cm² corresponding to a number density of 3×10^{14} ions/cm² if one assumes the plasma is pure deuterium. Estimating a 10-cm width in the stream in the direction of $\underline{B}$, the deduced number density is $n \approx 3 \times 10^{13}$ deut/cm³.

IV. MAGNETIC FIELD DEPENDENCE OF THE SHORTING PROCESS

This section gives the results of an experimental investigation of the stopping power of a narrow shorting plate as a function of magnetic field. The set-up consisted of three shorting plates located outside one of the magnetic mirrors. The three plates, equipped with current measuring loops, were stationed at successive positions downstream (cf. Fig. 9(a)). The second plate was used to stop the portion of the stream that was not stopped by the narrow first plate. The third plate served as a detector to confirm that the stream was completely stopped by the first two.

In general, one finds that the depolarizing current in the shorting plates occurs in two peaks. We interpret these to be due to a fast

component of the plasma stream followed by a slower and denser component.

The results are shown in Fig. 9(b). The ratio of the current in the first narrow plate to the total depolarization current is plotted vs B_0 for the first and second current peaks. The data were taken with plasma collimators present. From the data it is apparent that the slower moving component is more readily stopped by a narrow plate than the fast one even though the total translational energy density is larger in the slow component (see Fig. 7). The observation that the slow plasma component can be stopped, while the fast component is admitted suggests the use of this property of shorting plates as a velocity filter for a plasma stream. The stopping ability of the narrow plate also increases with strength of the transverse magnetic field. It is believed that this property results from the fact that inductance limits the rapidity with which the depolarization current can be established. Since the plasma is decelerated by a $\underline{J} \times \underline{B}$ force, with larger fields, a smaller current is required to produce a given amount of deceleration to the plasma. In addition, the motional emf increases linearly with B so that, for a given inductance in the shorting current path, a more rapid increase of depolarization current is obtained at the higher field values.²² These effects should increase the effectiveness of the narrow plate in stopping a plasma during its transit time across the plate, as B increases. The action of a plasma stream encountering a region shorted by a narrow plate has been analyzed in the case of an ideal stream homogeneous in velocity and density. This analysis has been applied to the fast ($v = 4 \times 10^7$ cm/sec;

$n = 3 \times 10^{13} \text{ cm}^{-2}$) and the slow ($v = 5 \times 10^6 \text{ cm/sec}$; $n = 10^{15} \text{ cm}^{-2}$) components of the plasma stream and it was found that an inductance of a few tenths of a microhenry gives a good fit to the data plotted in Fig. 9 when one uses estimated values of the stream dimensions. This reasonable magnitude of the inductance thus deduced gives some confidence in the concept that the observed depolarization effects are to a large part inductance controlled.

V. MEASUREMENTS OF THE THICKNESS OF THE INJECTED PLASMA STREAM

A measurement of the polarization electric field distribution along a diameter of the vacuum chamber normal to both $\vec{B}$ and the stream velocity (i.e., in the y direction of Fig. 2) was made using multiple electric probes. The multiple probes consisted of a line of four pairs of tungsten elements (each pair measuring voltage across 1.5 cm) arranged in a linear fashion and located outside one of the magnetic mirrors. The voltage difference across a 300 Ω load connected between the elements of each pair was measured by inductive coupling to an oscilloscope. Each pair was thus allowed to float electrically. These data measured the spatial extent of the polarization electric field of the stream by coupling along the lines of magnetic force. In this way the thickness of the stream in the direction of the polarization E -field could be determined at the time the beam was traversing the point of maximum strength of the transverse magnetic field.

The probe signals typically rose in about 0.1 μsec and dropped in $\sim 1 \mu\text{sec}$. The results at the time of peak electric field are shown in

Fig. 10 for two values of applied B_0 . Plotted is the electric field (voltage between a pair of elements divided by their separation) for each of the four probes. The data show a broader distribution at the lower field value. At high B -fields the probes indicate a reversed electric field at the top and bottom of the stream. These reversed fields are believed to be outside the main penetrating component of the stream. If one defines the thickness h as the separation of the points where E goes through zero and plots $1/h$ vs B_0 as obtained from the probe data, the result is shown in Fig. 11. The data fit the relation $hB = \text{constant} = 22 \text{ kG-cm}$ fairly closely. It is interesting to note that this $hB = \text{constant}$ law can be obtained with a model behaving as follows: Each fluid element of the plasma enters (with a given thickness) and internizes with a fixed value ($\sim 2 \text{ kG}$) of fringing B -field (independent of the value of applied field for $B_0 > 2 \text{ kG}$), and then moves in across the remaining field region at constant forward velocity while remaining both pressureless and flux conserving.

A plot of the peak E -field in the stream deduced from the probe data as a function of B_0 is shown in Fig. 12. The electric field rises very nearly linearly with B_0 with a slope corresponding to E/B of 40 cm/uess , but departs from the linear rise above 5 kG , indicating a deceleration of the plasma at the higher fields.

VI. IONIZATION OF NEUTRAL GAS BY A POLARIZATION E-FIELD

The ability of the polarization electric field of a moving stream to ionize and accelerate an injected gas was investigated.

Deuterium gas was admitted by means of a fast acting valve outside one of the mirrors during the time of passage of the injected stream. Over a wide variety of conditions of gas pressures and magnetic field values, no ionization of the gas is detected by current loops or visually, although E-fields of more than 2 kV/cm are present. However, when a pair of metal plates is placed above and below the region where the gas is injected, ionization takes place and the ionized gas acquires momentum from the primary stream.

Evidently when no electrodes are present $\vec{E}$ and $\vec{B}$ are orthogonal and the electrons are not able to acquire more than the $40 \text{ cm}/\mu\text{sec}$ $\vec{E} \times \vec{B}$ drift velocity which is far below that required to produce ionization. Apparently the upsetting of the orthogonality of the fields and the flow of depolarization current from the primary stream to the electrodes allows the ionization to start.

It was noted that with this ionized gas "shorting conductor" the current was oscillatory in contrast with the unidirectional depolarizing currents when metallic plate is used. A possible explanation of this effect is that the plasma between the plates acts as a small hydromagnetic capacitance in series with the inductance of the current path resulting in an oscillating system. The frequency was 500 kc/sec at $B_0 = 6 \text{ kG}$ and varied linearly with magnetic field over the range of fields studied, $B_0 = 3$ to $B_0 = 7 \text{ kG}$.

VII. THE DEPOLARIZATION TRAPPING CONCEPT

The experiments have shown that (1) plasma is injected across magnetic fields up to $\sim 9 \text{ kG}$, (2) the plasma exhibits low pressure and traverses

The magnetic field by setting up a polarization electric field allowing an $\underline{E} \times \underline{B}$ drift, (3) the forward motion of the plasma can be stopped by means of a metallic conductor located outside a mirror, and (4) the inductance of the depolarization current path allows the plasma stream to penetrate well into the shorted volume before the forward motion is halted.

The above experimental observations serve to demonstrate that the forward motion of an injected plasma stream can be stopped inside a magnetic bottle by locating conductors outside the confining region. These results suggest the possibility of cross-field injection with subsequent depolarization as a scheme for trapping a plasma in a magnetic bottle. This scheme of "Depolarization Trapping" would be particularly useful if in addition, the original energy of the stream remains in the plasma so that a hot plasma is trapped.

The portion of the original translational energy of the stream that goes into heating the plasma inside the confining field is at present unknown.²³ It is suspected that much of the energy goes into heating the slower and denser plasma which enters the field after the high velocity component. The dense low energy component of plasma which is produced by the coaxial gun has prevented, to date, any definitive measurements of the possible depolarization trapping of energetic ions.

It should be noted that the observations reported in Section VI on the depolarization of a plasma by another initially stationary plasma suggest a mechanism for trapping of solar streams in the earth's magnetic field. The momentum of the solar stream could be transferred to the dense ionospheric plasma by the flow of depolarization current along field lines to the point where lines dip into the ionosphere in the pole region.

VIII. PLASMA INJECTION WITH THE PLASMA GUN MUZZLE IN A STRONG TRANSVERSE FIELD

The foregoing experiments were performed with the gun muzzle well outside the strong field region. This choice of gun location was dictated by the results of the following investigation.

The stainless steel outer electrode of the coaxial gun was equipped with a half-inch thick copper sleeve to prevent the pulsed transverse field from entering the gun barrel and affecting the gun operation. With the gun muzzle located in a transverse magnetic field, it was found that the plasma stream was bent sharply up or down depending on the direction of the applied transverse field. The plasma immediately collided with the wall rather than flowing in the desired direction into the vacuum chamber. It was found that the plasma deflected toward the $-\mathbf{v} \times \mathbf{B}$ direction where $\mathbf{v}$ is the initial stream direction. This deflection phenomenon may stem from the fact that the conducting gun muzzle prevents (by shorting) the establishment of a polarization $\mathbf{E}$ -field in the vertical direction required for an $\mathbf{E} \times \mathbf{B}$ drift in the desired direction into the vacuum chamber. It may be noted that the direction of the deflected beam is in the $\mathbf{E} \times \mathbf{B}$ direction where $\mathbf{E}$ is a charge separation electric field built up because the ions have a larger gyro radius and penetrate a greater distance into the transverse field than the electrons. It is quite possible that plasma could be injected along the vacuum chamber axis by directing the coaxial gun at nearly a right angle to the desired direction of injection. This possibility was not further investigated since a suitable injection port did not exist in the glass vacuum chamber.

IX. X-RAY OBSERVATIONS

Scintillation detectors (plastic scintillator-6810 photomultiplier combination) were located immediately outside the glass vacuum chamber. With the gun operating in the "high density mode" of the foregoing discussions (15-kV applied ~ 250 μ sec after opening the fast acting valve which admits 0.6-cc-atm of D_2) the detectors show signals indicating x rays which last as long as there is a small depolarizing current present in a plate located outside one of the mirrors (~ 75 μ sec). It appears that electrons are raised to high energies during interaction of the plasma with the magnetic field. These energetic electrons subsequently hit the walls of the vacuum chamber producing the observed x rays.

When the gun is run in a low density mode²⁴ the x-ray signals become sustained for a longer period. The signals display a characteristic narrow pulse followed by tail which persists for ~ 500 μ sec in a 7-kG field.²⁵ When no magnetic field is present the x rays consist of a single early short pulse only. Attenuation curves for aluminum and lead indicate x-ray energies up to ~ 60 keV for the first pulse and ≥ 200 keV for the long tail. The intensity of the x rays varies widely from shot to shot, indicating very erratic plasma gun behavior in the low density mode. The detectors show that the x-ray intensity does not vary by much more than a factor of two between any two stations located at different positions outside the glass vacuum chamber. Evidently the entire vacuum chamber wall is bombarded by the high energy electrons and serves as a target for the production of the energetic x rays.

The long tail of x rays is uncorrelated with presence of a metal shorting plate outside the magnetic mirror. If the sustained tail is produced by a depolarization trapping mechanism the required depolarization currents must flow at the interior surfaces of the walls of the vacuum chamber.²⁶

The long tail of x rays indicates either that high energy electrons are produced, trapped, and confined up to ~ 500 μ sec or that energetic electrons are continually produced over this period by an unknown plasma-magnetic field interaction.

X. CONCLUSION

These experiments have demonstrated that plasma streams from coaxial guns can enter and cross transverse fields up to 9 kG. In all cases the plasma which enters the field is observed to be only slightly diamagnetic and the motion of the plasma stream through the field is by means of an $E \times B$ drift resulting from self-polarization of the plasma stream.

At magnetic fields above which the plasma was stopped, it was found that large depolarizing currents were flowing at the surface of the inlet tube of the glass vacuum chamber. It appears that higher fields can be penetrated if the vacuum chamber and field configurations are such that no magnetic field lines which the stream must cross during injection intersect the walls. Studies with an experimental device having these properties are in progress.

Removal of the forward momentum of the plasma stream is possible through depolarization by conducting plates placed outside the magnetic mirror. A measurement of the depolarization current gave the portion of

momentum removed by the conductor as a function of magnetic field for the fast and slow components of the stream. For sufficiently high fields the forward momentum was completely stopped. From the data it is apparent that the depolarization process is controlled by the stream velocity and the inductance of the depolarization current path along magnetic field lines.

The polarization properties of the injected plasma stream suggest that plasma might be trapped in a mirror machine with conducting plates and that the mirror machine flute instability might be stabilized by shorting the electric field which accompanies this instability.

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REFERENCES

1. S. Chapman and V. C. A. Ferraro, Terr. Mag. (J. Geophys. Research), 36, 77 (1931).
2. J. L. Tuck, Phys. Rev. Letters, 3, 313 (1959).
3. D. J. Rose and M. C. Clark Jr., Plasmas and Controlled Fusion, M. I. T. Press and John Wiley and Sons, N. Y., 416 (1961).
4. S. Chapman, Proc. Cambridge Phil. Soc. 21, 577 (1923).
5. S. Chapman and V. C. A. Ferraro, Terr. Mag. (J. Geophys. Research), 36, 77 (1931).
6. D. J. Rose, Thermonuclear Project Semiannual Report July 31, 1959, Oak Ridge National Laboratory Report, ORNL-2802, 99 ().
7. G. Schmidt, Phys. Fluids, 3, 961 (1960).
8. W. H. Eastick, Proc. Symposium on Electromagnetics and Fluid Dynamics of Gaseous Plasmas, Polytechnic Institute of Brooklyn, Brooklyn, N. Y. 211 (1961).
9. Ref. 3, 395.
10. J. M. Deliquad, C. R. Acad. Sc. 256, No. 19, 3984 (1963).
11. J. M. Deliquad, C. R. Acad. Sc. 256, No. 20, 4170 (1963).
12. D. A. Baker and J. E. Hammel, Los Alamos Scientific Laboratory Report, LA (1964).
13. D. A. Baker, J. E. Hammel, Phys. Rev. Letters, 2, 157 (1962).
14. J. Marshall, Phys. Fluids, 3, 135 (1960).
15. W. H. Eastick, Phys. Rev. 104, 292 (1956).

16. K. D. Sinel'nikov, B. G. Safranov, V. A. Siderkin, and S. A. Trubchaninov, Motion of Plasmas Transversely to a Magnetic Field, ADC-tr-6726, (Transl. publication of Physico-Technical Institute of the Ukrainian Ac. of Sc., Khar'kov) (1960).
17. All numbered equations are in rationalized MKS units.
18. The applied magnetic field B_0 is measured on the axis of symmetry and midway between the field coils.
19. The plate consists of a 10-cm wide and 15-cm high sheet of stainless steel oriented at right angles to the magnetic field and is surrounded by a Rogowski current measuring loop. The plate is thin enough (0.15-cm thickness) to allow the pulsed magnetic field readily to penetrate it.
20. The fact that large current densities flow along the field lines to the shorting plate implies that there is plasma (which is probably of much lower number density than the plasma in the main stream) between the primary stream and the plate. If such a background plasma were not present, space charge effects would prevent such large currents from flowing.
21. This calculation ignores inductance effects and small corrections associated with the fact that the field is not uniform.
22. The initial rate of rise of the current in a loop with inductance L is given by $(dI/dt)_0 = (emf)_0 / L$.
23. The resistance of the shorting plate is too low to produce an appreciable dissipation by ohmic heating. Heating of the plate and plasma outside the mirror by losses in voltage sheath regions at the plate surfaces may occur, however.

24. This operating mode is obtained in either of two ways: (1) by shortening the delay between gas valve opening and voltage application to 100 μ sec, or less, or (2) by reducing the total gas admitted by the valve approximately a factor of ten.
25. It is not known whether the 500 μ sec is a natural decay time or is a result of the fact that the pulsed magnetic field begins decreasing significantly at this time.
26. Measurements of depolarization currents present on the surface of a glass plate located outside the magnetic mirrors in some cases show currents up to 1/5 that observed in a corresponding metal plate.

CAPTIONS

- Fig. 1. Simplified model of a low pressure plasma crossing a transverse magnetic field showing (a) the charging up effect of an insulating wall and (b) depolarizing effect of a conducting wall.
- Fig. 2. Schematic of the transverse injection apparatus. Key: (1) Pyrex vacuum chamber, (2) field coil, (3) coaxial plasma gun, (4) Pyrex collimating diaphragms, (5) Pyrex inlet tube, and (6) magnetic probe for measuring for wall currents (movable in z-direction). Typical field lines produced by the mirror coils are shown; the field zero is at the position of the collimator farthest from the gun. The directions of the x and z axes of a coordinate system referred to in the text are shown; the positive direction of the y axis is out of the paper.
- Fig. 3. Polarization voltage vs applied magnetic field as measured between a pair of electric probes spanning the injected plasma stream and located at the point of maximum transverse field. Probe separation = 15 cm.
- Fig. 4. Peak change in magnetic field during plasma injection as measured by a magnetic probe at various stations across the mouth of the inlet tube (see Fig. 2). The asymmetry in the distribution may be due to an asymmetry in the plasma leaving the coaxial gun.
- Fig. 5. Diagram showing a wall depolarizing currents which give rise to the field distribution of Fig. 4 (as viewed toward gun muzzle).
- Fig. 6. Diagram demonstrating the depolarization of a plasma stream by a conductor located outside a magnetic mirror. I_p is the small polarizing current required to setup the polarization electric

field allowing the observed $E \times B$ drift. I_0 is the much larger current that flows when the polarization charge is drained as fast as it is produced by current flow along field lines to the shorting plate.

Fig. 7. Oscilloscope record of current detected in the conducting sheet illustrated in Fig. 6. The current detector consists of two oppositely wound Rogowski loops in the same envelope, thus giving a means of discriminating between current signal and electrostatic pickup.

Fig. 8. A plot of peak depolarizing current in a conducting sheet outside one of the magnetic mirrors as a function of the applied transverse field B_0 . The circles represent data taken with an uncollimated beam while the x's are the corresponding data with collimating diaphragms present.

Fig. 9. (a) Arrangement of three shorting conductors located outside the magnetic mirror. The three plates replace the single plate shown in Fig. 6. (b) A plot of the ratio of the current in the first narrow plate to the total depolarizing current in the first two plates. Data points are shown only for those values of B_0 in which no current was detected in the third plate.

Fig. 10. Polarization electric field distribution in the direction normal to B (for two values of B_0) across an injected stream as obtained by multiple electric probes. The error bars show the separation of the pair of probes for which the corresponding field data point is deduced.

Fig. 11. Plot of the reciprocal of the width (defined by the separation of the points of zero polarization field) of the injected stream, at the point where it traverses the maximum value of magnetic field, vs B_0 .

Fig. 12. A plot of the maximum electric field as detected by multiple electric probes outside a magnetic mirror as a function of the applied transverse field.

FIG. 1

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FIG. 2

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FIG. 3

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FIG. 4

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FIG. 5

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FIG. 6

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6 KA/div

5 μ sec/div

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FIG. 8

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FIG. 9

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FIG. 10

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FIG. 11

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FIG. 12

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