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THE INJECTION OF TENUOUS PLASMA INTO A MAGNETIC GUIDE FIELD IN THE ABSENCE OF WALL-SHORTING

by

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A B S T R A C T

A burst of plasma from a thetatron gun is allowed to expand freely as it passes along a drift tube; an aperture limiter selects a central beam of plasma which then flows axially into the field of a solenoid. The ion energy is centred about 800 eV and the maximum ion density is about $3 \times 10^{11} cm^{-3}$. The solenoid is suspended in a large vacuum chamber so that the wall-shorting effect, described in connection with a similar experiment is inhibited. A removable conducting cylinder at the solenoid entrance enables a direct comparison to be made between the case when a radial space charge field exists in the plasma stream and when it is short-circuited. Measurements of azimuthal ion flux, electric field and current flow at the solenoid entrance, show that shorting can be prevented. The radius of the plasma stream is always comparable to twice the ion gyro-diameter $2 R_{ci}$; it is not reduced to $2 R_{ci} (m/M)^{\frac{1}{2}}$, as simple theory predicts, when 'shorting' is prevented.

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1. INTRODUCTION

A magnetically guided plasma stream can be formed by directing plasma from a plasma gun into the entrance of a long solenoid (e.g. COENSGEN et al, 1960; FRANCIS et al, 1964; AZOVSKII et al, 1966). If the plasma stream is sufficiently tenuous it does not exclude the magnetic field and β, the ratio of transverse plasma pressure to magnetic pressure, is small (typically 10^{-2}). At the same time, the radius of the stream is approximately twice the ion gyro-radius (R_{ci}) appropriate to the transverse ion pressure (ASHBY and AVIS 1966, LITTLE and AVIS 1966, ATKINSON and PHILLIPS 1967). Ashby and Avis explained this result by showing that a short-circuiting effect occurs which entails current flow to the wall near the solenoid entrance; this effect removes the gross radial electric space charge field in the plasma and consequently the ions tend to behave as single particles injected into the solenoid and pass through the magnetic axis on each gyration.

The experiment to be described was aimed at discovering what happens if wall-shorting is prevented and in particular whether the diameter of the plasma stream is reduced to substantially less than $2\ R_{ci}$.

2. THEORY

Consider the low - β plasma stream formed by injecting axially a plasma beam of finite radius into the magnetic field of a long solenoid (Fig.1). Initially, at $z = -\infty$, the plasma has zero temperature and a velocity V_o parallel to the z-axis. If no collisions occur and if $\frac{\partial}{\partial\theta}$ and $\frac{\partial}{\partial t}$ are zero then, at radius r in the plasma, the kinetic energy and canonical angular momentum of the ions and electrons satisfy the following equations:

$$\tfrac{1}{2} M (V_z^2 + V_r^2 + V_\theta^2) = \tfrac{1}{2} M V_o^2 - e\varphi \qquad \ldots (1),$$

$$p_{\theta i} = Mr V_\theta + er A_\theta = 0 \qquad \ldots (2),$$

$$\tfrac{1}{2} m (v_z^2 + v_r^2 + v_\theta^2) = \tfrac{1}{2} m V_o^2 + e\varphi \qquad \ldots (3),$$

$$p_{\theta e} = mr v_\theta - er A_\theta = 0 \qquad \ldots (4).$$

The electrostatic potential φ arises from charge separation caused by the magnetic field: A_θ is the magnetic vector potential: M and m are the ion and electron masses while V_z, V_r, V_θ and v_z, v_r, v_θ are the velocity components of the ions and electrons.

If $M \gg m$ and $\tfrac{1}{2} M V_z^2 \gg \tfrac{1}{2} m v_z^2$ then, near the edge of the stream where V_r and v_r tend to zero, equations (1) - (4) give

$$A_\theta^2 \simeq (Mm/e^2)\ (V_o^2 - V_z^2) \qquad \ldots (5).$$

Now

$$2\pi r\ A_\theta \simeq \pi r^2\ B_z \qquad \ldots (6),$$

hence equations (5) and (6) give the approximate radius of the plasma stream in the uniform region of the magnetic field namely:

$$r \simeq (2/\omega_{ci})\ (V_o^2 - V_z^2)^{\frac{1}{2}} (m/M)^{\frac{1}{2}} \qquad \ldots (7),$$

where $\omega_{ci} = eB_z/M$ is the ion gyro-frequency. If wall-shorting removes the radial space charge field so that $\varphi = 0$, then equations (1), (2) and (6) give

$$r \simeq (2/\omega_{ci})\,(V_o^2 - V_z^2)^{1/2} \quad \ldots (8);$$

in this case each electron in the plasma stream has a canonical angular momentum of $-erA_\theta$ (i.e. $v_\theta = 0$), as a result of the wall-shorting mechanism, and equations (3) and (4) are no longer valid.

At any point in the plasma stream $(M/2)(V_o^2 - V_z^2)$ is the energy associated with transverse motion. In equations (7) and (8) $(V_o^2 - V_z^2)^{1/2}/\omega_{ci}$ can be approximated to the ion gyroradius (R_{ci}) appropriate to the transverse energy in the plasma stream. Hence equations (7) and (8) show that when a space charge field develops the radius of the ideal plasma stream considered is approximately $2R_{ci}(m/M)^{1/2}$ compared with $2R_{ci}$ for the case of no radial electric field; this result depends critically on the assumptions made. If collisions or microinstabilities produce azimuthal forces on the particles so that they do not conserve their individual canonical angular momenta, the plasma will diffuse outwards and increase the radius of the stream.

The assumption that $\frac{\partial}{\partial\theta}$ and $\frac{\partial}{\partial t}$ are zero, so that the ions and electrons do conserve their individual canonical angular momenta, is commonly made in the analysis of plasma boundary problems; in particular it is made when calculating the escape rate of plasma through a magnetic cusp (e.g. FIRSOV 1959, BERKOWITZ et al. 1958) and the reflection of plasma from a collision-free current sheet (ROSENBLUTH 1957). The present experiment can be considered as a check on the validity of assuming that particles in a plasma conserve their individual canonical angular momentum for the case when the initial plasma temperature is low compared with the initial ion energy.

3. APPARATUS

The apparatus used is shown in Fig. 2. The thetatron gun was built and developed by Cruddace (CRUDDACE and HILL, 1966); it produced a burst of hydrogen plasma with a directed energy centred about 800 eV (i.e. a velocity of 4×10^7 cm sec^{-1}). The aperture limiter, at the end of the flight tube, was 5.5 cm in diameter and selected the central portion of plasma containing ions moving essentially parallel to the axis of the apparatus. The particle density near the solenoid was about 3×10^{11} cm^{-3} and the electron temperature was less than 1 eV. (ASHBY and PATON 1966).

The solenoid was pulsed and could produce flux densities up to 4 kG with a quarter period of 120 μsec; it was suspended in the middle of the vacuum tank so that most of the field lines containing plasma closed on themselves without intercepting the walls. The removable cylinder shown was made of thin stainless steel and offered negligible impedance to the pulsed field of the solenoid; it could be placed either at the entrance of the solenoid, where it intercepted most of the magnetic flux through the centre of the solenoid, or swung to one side. In this way it was possible to make a direct comparison between injection with and without wall-shorting.

The ion probe shown in Fig.3b measured the longitudinal and transverse ion flux. The electrodes were biased negatively so that they collected only ions. The longitudinal ion velocity was derived from transit time measurements thus the particle density and the transverse ion velocity could be determined from the ion currents to the two electrodes (ASHBY, 1963 and ASHBY and AVIS, 1966). The probe shown in Fig.3a compared directly the transverse ion flux from opposite directions. Both probes were clad in glass for most of their length and isolated from earth by chokes so that they could assume the plasma potential.

Fig.4 shows an electric probe used to measure the potential difference between the edge of the plasma stream and the axis; its output was fed to an oscilloscope via a balanced-to-unbalanced transformer.

All the probes were mounted as shown in Fig.2 and could be moved both radially and axially within the solenoid.

4. <u>EXPERIMENTAL RESULTS AND DISCUSSION</u>

Equations (7) and (8) show that when shorting is prevented the radius of the plasma stream should be reduced by the order of magnitude of $(m/M)^{\frac{1}{2}}$ unless, at the same time, the mean transverse energy per ion-electron pair increases by the order M/m. In practice a reduction in plasma radius was <u>not</u> observed when the conducting cylinder (see Fig.2) was moved from its position at the solenoid entrance although the transverse energy was essentially unchanged.

Fig. 5 compares the measured density profile of the stream with and without the cylinder in place. The measurements were made with an ion probe 35 cm from the solenoid entrance at a magnetic flux density of 2 kG. The size of the error bars indicates the degree of non-reproducibility of the plasma (standard errors of six measurements are shown at each point).

It can be argued that, with the cylinder removed, the radial electric field may still be shorted by currents which now flow to the tank walls, to plasma near the solenoid entrance or to the ion probe. Measurements of the azimuthal flux of ions will be described next which counter this argument and show that shorting is inhibited when the cylinder is removed.

At any point in the plasma the radial electromagnetic force confining the ions in a volume δV is

$$F_r = ne\ (E_r + v_\theta B_z)\delta V \qquad \ldots (9),$$

where v_θ now refers to the mean azimuthal velocity of the ions. If shorting occurs, so that $E_r = 0$, then $v_\theta \neq 0$ and the ions are confined by a diamagnetic current nev_θ. On the other hand if no shorting occurs the plasma as a whole cannot have angular momentum as long as $B^2 \ll 2\,\mu_0 nMc^2$ (HAINES, 1965). Equation (9) shows that when $v_\theta = 0$, a radial electric field E_r confines the ions. An experimental demonstration that $v_\theta = 0$ across the plasma stream is tantamount to showing that shorting has been prevented. The oscillograms in Fig. 6 illustrate that v_θ is in fact zero when the conducting cylinder is removed from the entrance to the solenoid.

Fig.6 shows oscillograms of the azimuthal ion flux with and without the cylinder in place; as before these measurements were made 35 cm from the solenoid entrance at a flux density of 2 kG. Each pair of oscillograms shows the two ion currents collected by the probe in Fig.3a when placed at various radii with the admittance holes set to receive azimuthal ion flux. With the cylinder in place the counter-clockwise ion flux exceeds considerably the clockwise flux, i.e. $v_\theta \neq 0$. (This effect is identical with that observed and described previously by ASHBY and AVIS (1966).) From the ion density given in Fig.5, it is apparent that the ion flux corresponds to an azimuthal plasma velocity of about 10^7 cm sec^{-1} and consequently a transverse ion energy of 50-100 eV. With the cylinder removed the two ion fluxes are roughly equal, therefore $v_\theta \simeq 0$ and, from the argument of the preceding paragraph, $E_r \neq 0$ and shorting has been inhibited; the magnitude of ion flux is unaltered so the transverse ion energy is still 50-100 eV and $\int Edl$ across the plasma radius should be of the order of 100 volts. The measured plasma diamagnetism is nearly the same with the cylinder removed as with it in place; in both cases the magnitude of the diamagnetism is consistent with a transverse ion energy of 50-100 eV.

Fig.7 shows the effect of the conducting cylinder on the radial electric field in the plasma stream and current flow at the solenoid entrance. In each column the first oscillogram is the output from the electric probe in Fig.4; the second is the longitudinal ion flux received by an ion probe and is a measure of plasma density; the third trace is the integrated output from a movable glass-clad Rogowski Loop placed in front of the solenoid where it measures 'shorting' current (see ASHBY and AVIS, 1966).

Consider the current measurement. With the cylinder in place a circulating current of 15 A flows to and from the cylinder as plasma enters the solenoid; the magnitude of this current is consistent with the plasma flux in the stream. With the cylinder removed no measurable current flows until 1 μsec after plasma enters the solenoid. The total charge which has passed through the Rogowski at the time the ion probe signal peaks is reduced by 80% when the conducting cylinder is removed; until this time at least little shorting can have occurred. The current which flows subsequently is not necessarily connected with shorting and plasma rotation. Moving the Rogowski axially shows that this current passes right through the solenoid and does not necessarily cross any flux lines whereas, with the cylinder in place, the current loops into the solenoid and out again crossing flux lines in the process.

The measurements of radial electric field were made with one electrode of the probe on the axis of the solenoid and the other near the edge of the plasma. The oscillograms in Fig.7 show that fluctuating electric potentials are detected as soon as plasma enters the solenoid irrespective of whether the cylinder is in place or not. However, with the cylinder removed the axis of the plasma becomes 100V negative with respect to the edge as the plasma density peaks; this sudden increase is absent when the cylinder is in place.

The experimental results show that although removing the cylinder stops shorting the associated reduction in plasma diameter, predicted by theory, does not occur. The essential assumption of this theory is that the injected particles individually conserve their canonical angular momentum; this assumption is invalid if collisions occur or if the flow is electrostatically unstable. Collisions, however are unlikely to play a major role in the present experiment as the ions should be collision-free because of their high energy (~800eV), while the electrons, although initially cold, should acquire a large transverse energy on entering the magnetic field; once their energy exceeds about 10eV they should be collision-free as well. It cannot be stated with certainty that an electrostatic instability causes the theory to fail but two points support this conjecture:

1. It has been shown elsewhere that a streaming instability is present when shorting does occur (ASHBY and PATON, 1967). It seems improbable that the stream will be more stable when shorting is prevented as the velocity anisotropy should increase.

2. The ion probe and electric probe measurements show fluctuations and shot-to-shot variations which is symptomatic of an unstable system rather than collisional diffusion.

5. CONCLUSION

It has been shown that wall-shorting can be prevented when tenuous plasma is injected axially into a long solenoid. The diameter of the resulting plasma stream is approximately $2R_{ci}$ whether or not shorting is stopped. In the absence of shorting the plasma radius is not reduced to $2R_{ci}(m/M)^{1/2}$ although this reduction would occur if the injected particles individually conserved their canonical angular momentum.

6. ACKNOWLEDGEMENTS

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REFERENCES

ASHBY, D.E.T.F. (1964) Proc. 6th Int. Conf. Ionization Phenomena in Gases, Paris, 1963. 4, 465.

ASHBY, D.E.T.F. and AVIS, B.E. (1966) J. Nucl. Energy Pt C, 8, 1.

ASHBY, D.E.T.F. and PATON, A. (1967) Culham Laboratory CLM-P 126. To be published in Plasma Physics.

ATKINSON, D.W. and PHILLIPS, J.A. (1967) Some Observations on the Flow of a Tenuous Plasma in a Magnetic Field. H.M.S.O., Report CLM-R 72, London.

AZOVSKII, Yu.S., GUZHOVSKII, I.T., MAZALOV, Yu.P. and PISTRYAK, V.M. (1966) Sov. Phys.-Tech. Phys., 10, 1092.

BERKOWITZ, J., FRIEDRICHS, K.O., GOERTZEL, H., GRAD, H., KILLEEN, J. and RUBIN, E. (1958) Proc. 2nd U.N. Int. Conf. on the Peaceful Uses of Atomic Energy, Geneva, 1968. 31, 171.

COENSGEN, F.H., SHERMAN, A.E., NEXSEN, W.E. and CUMMINS, W.F. (1960) Phys. Fluids, 3, 764.

CRUDDACE, R.G. and HILL, M. (1966) Mechanism of plasma acceleration in a conical thetatron gun. Culham Laboratory, 1966, CLM-M 52.

FIRSOV, O.B. (1959) Plasma Physics and the Problems of Controlled Thermonuclear Reactions. Pergamon. III, 386.

FRANCIS, G., MASON, D.W. and HILL, J.W. (1964) Nature, 203, 623.

HAINES, M.G. (1965) Advances in Phys. (Phil. Mag. Supp.) 14, no.54, 167.

LITTLE, P.F. and AVIS, B.E. (1966) J. Nucl. Energy Pt C, 8, 11.

ROSENBLUTH, M.N. (1957) Dynamics of a Pinched Gas. In: LANDSHOFF, R.K.M. (ed) (1963) Magnetohydrodynamics, Stanford University Press, and Chapter V, Elementary Plasma Physics by CONRAD L. LONGMIRE. Interscience Publishers.

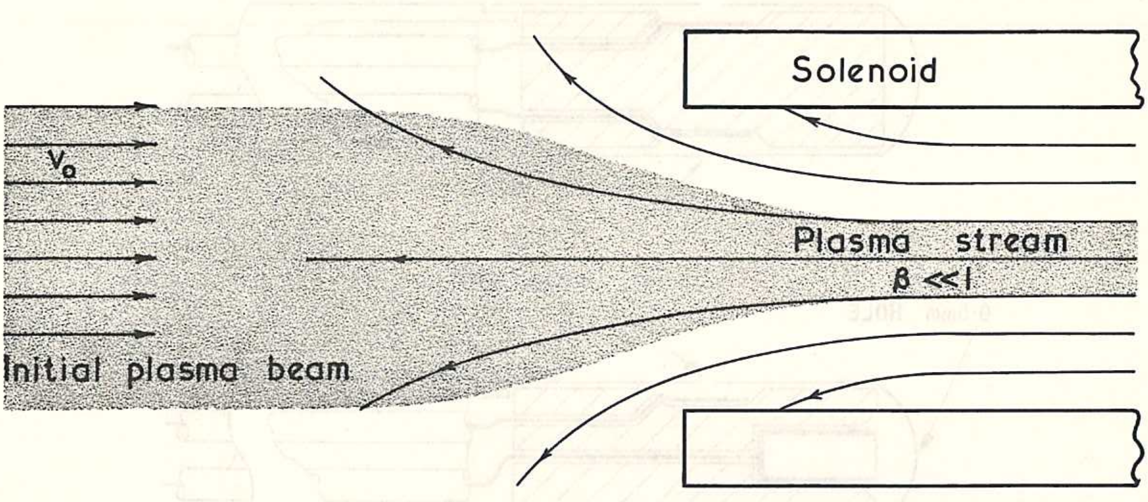

Fig.1 The theoretical model (CLM-P132)

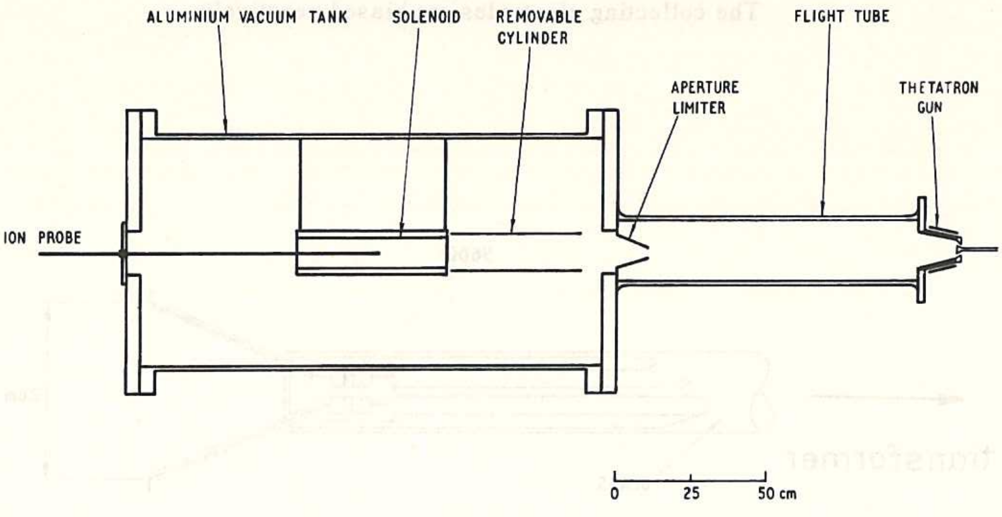

Fig.2 Schematic diagram of the apparatus (CLM-P132)

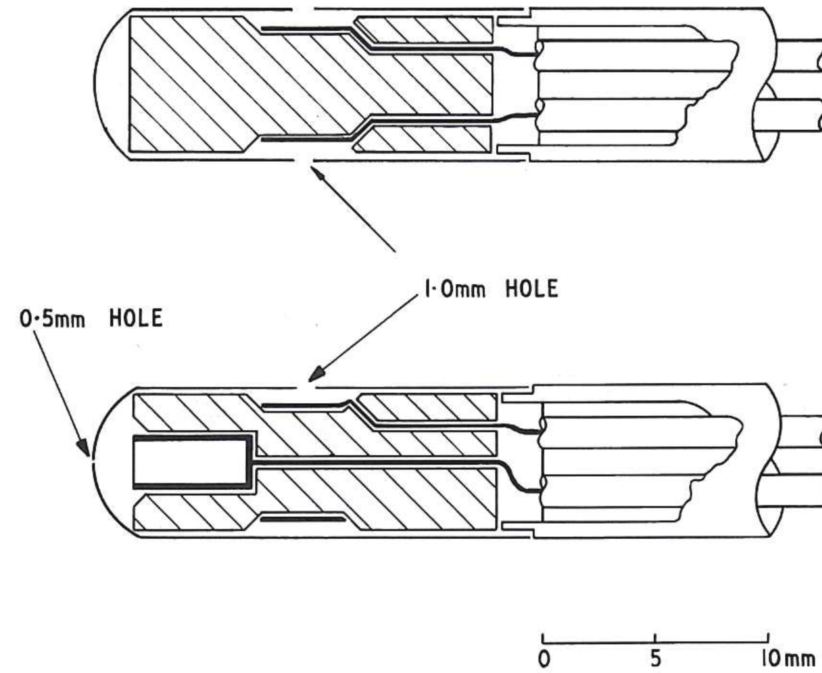

Fig.3 (CLM-P132)

(a) Ion probe used to compare the azimuthal ion flux from opposite directions

(b) Ion probe used for measuring ion flux and density. The collecting electrodes are biased negatively.

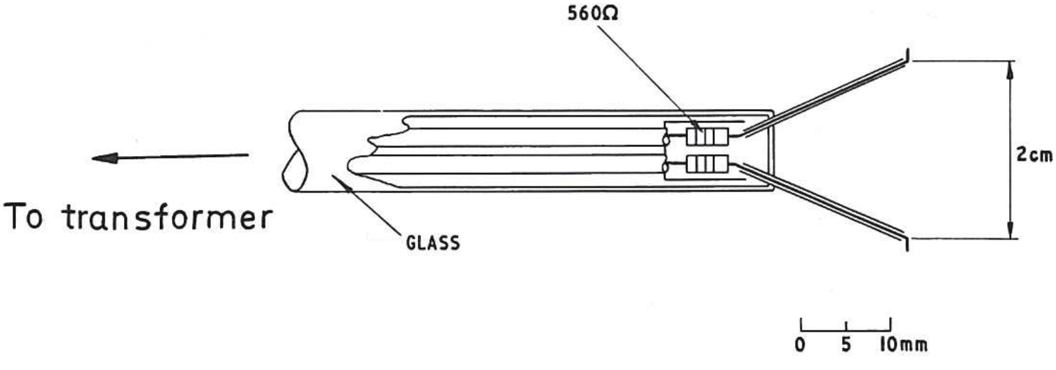

Fig.4 (CLM-P132)

Electric probe used to measure the potential difference across a radius of the plasma stream

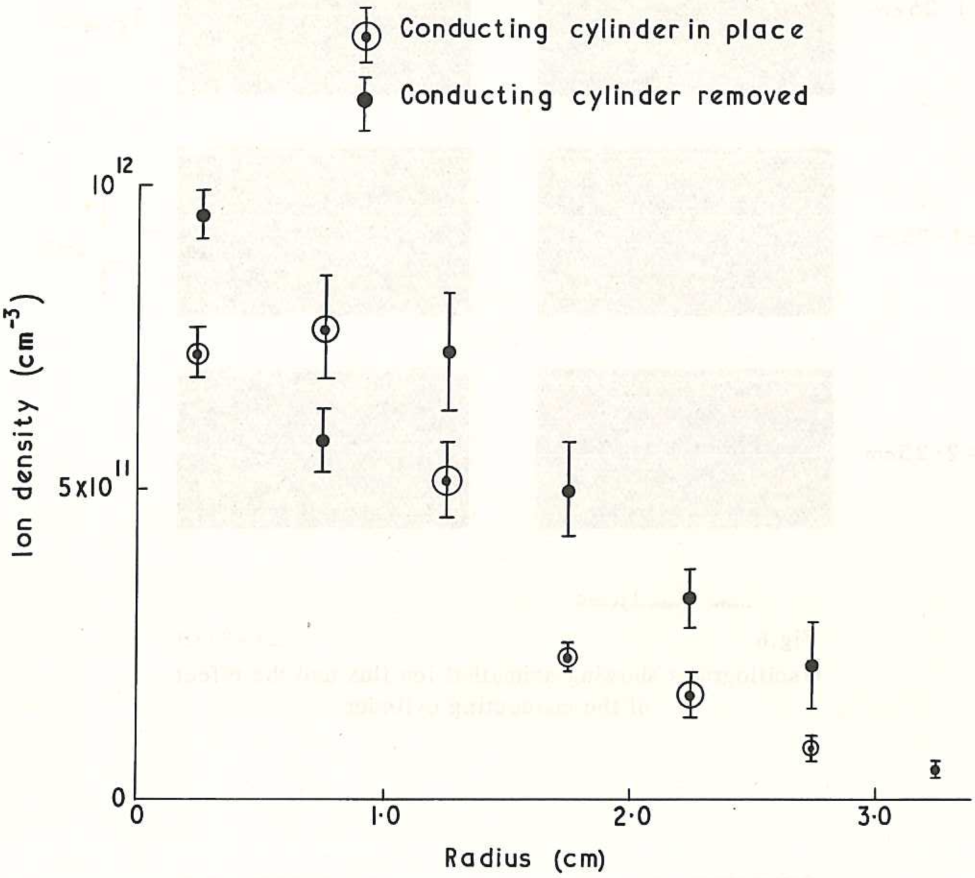

Fig.5 (CLM-P132)
The variation of plasma density with radius with the conducting cylinder in place and with it removed

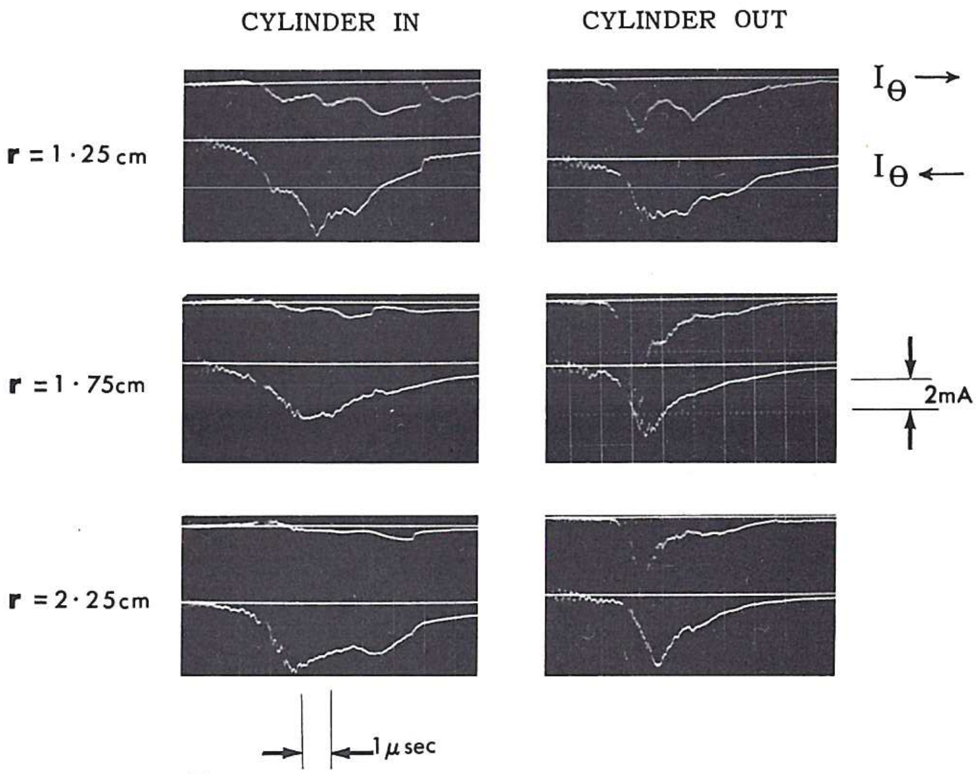

Fig.6 (CLM-P132)

Oscillograms showing azimuthal ion flux and the effect of the conducting cylinder

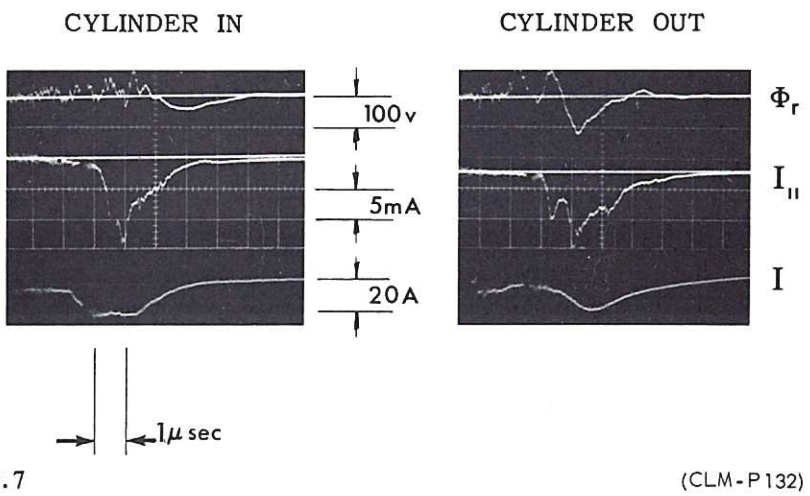

Fig.7 (CLM-P132)

Oscillograms showing the effect of the conducting cylinder on the radial electric field in the stream and of currents at the solenoid entrance