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SOME OBSERVATIONS ON THE FLOW OF A TENUOUS PLASMA IN A MAGNETIC FIELD

by

D.W. ATKINSON
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ABSTRACT

A coaxial gun is used to inject plasma, particle density $\sim 10^{10} - 10^{11}/\mathrm{cm}^3$ and velocity $\sim 5 \times 10^7$ cm/sec into a longitudinal magnetic field of 780 gauss. Properties of the plasma as it flows down the magnetic field are examined by diamagnetic loops.

It is suggested that an apparent loss of transverse energy is not real, but that parts of the plasma jet are accelerated by electric fields produced by the space charge separation of ions and electrons.

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C O N T E N T S

1. INTRODUCTION

The interaction of high velocity plasma jets with magnetic fields of various geometries has been the subject of many investigations in controlled thermonuclear research. The main interest lies in the possibility of filling magnetic bottles with a high temperature plasma by the injection and trapping of the jets with randomization of directed energy into thermal energy. A number of papers have therefore been concerned with the entrance of plasma into axial magnetic fields and its subsequent flow along the magnetic field. By this means plasma might be channelled from a plasma accelerator or gun to the magnetic bottle.

The present understanding of the entrance of fast low density plasma (velocity $\approx 10^8$ cm sec^{-1}, particle density $\approx 10^{11} - 10^{12}$ cm^{-3}) into axial magnetic fields is in large part due to the work of Ashby[1]. It has been established that on entering the magnetic field the ions by their large Larmor radius penetrate the magnetic field radially outwards further than the electrons which are confined along the axis. The resulting separation of charge is relieved by electron currents flowing along magnetic field lines and shorting across conductors or insulating glass walls. The currents have been detected and measured and it has been established that most of the transverse energy of the plasma resides with the ions. In the present work we have found no contradiction with this picture.

However, there is an apparent loss of transverse energy as the plasma flows down the magnetic field. The transverse energy is normally determined by diamagnetic loops around the glass vacuum chamber which measure the perturbations in the magnetic field caused by the plasma. The integral over time of the flux change is found to decrease with axial distance. At high densities it has been established[2] that the longitudinal and transverse energies of the plasma are coupled by collisions so that as the plasma expands longitudinally the transverse energy decreases. In the present experiments this cannot occur as the densities are too low. Ashby[3] has concluded that this loss cannot be accounted for by particle loss nor by radiation. Veron[4], on the other hand, because of the large transverse energy of the ions in his experiment believes that particle loss to the vacuum chamber wall is important. Again, Marshall[5] has suggested that particles might be reflected backward by the magnetic mirror created at the front of the plasma jet by its own diamagnetism.

Some observations on the transverse energies of plasma jets are reported and a possible explanation for the apparent loss is presented.

2. APPARATUS

In these experiments the plasma gun, Fig.1, was coaxial in design as developed by Marshall[6] with 10 cm diameter outer electrode and 5 cm diameter inner electrode energized by a 2.1 μF condenser charged to 12 – 15 kV. Hydrogen gas was admitted by a fast acting valve ~ 350 μsec before three trigger electrodes located over the gas inlet ports were energized. There were no switches in the high voltage circuit. The plasma jet had a particle density of $\sim 10^{12}$ cm^{-3} as measured 60 cm from the gun, with a most probable axial velocity of $\sim 5 \times 10^7$ cm/sec. This apparatus had been used to test plasma guns for the MTSE-I experiment[7].

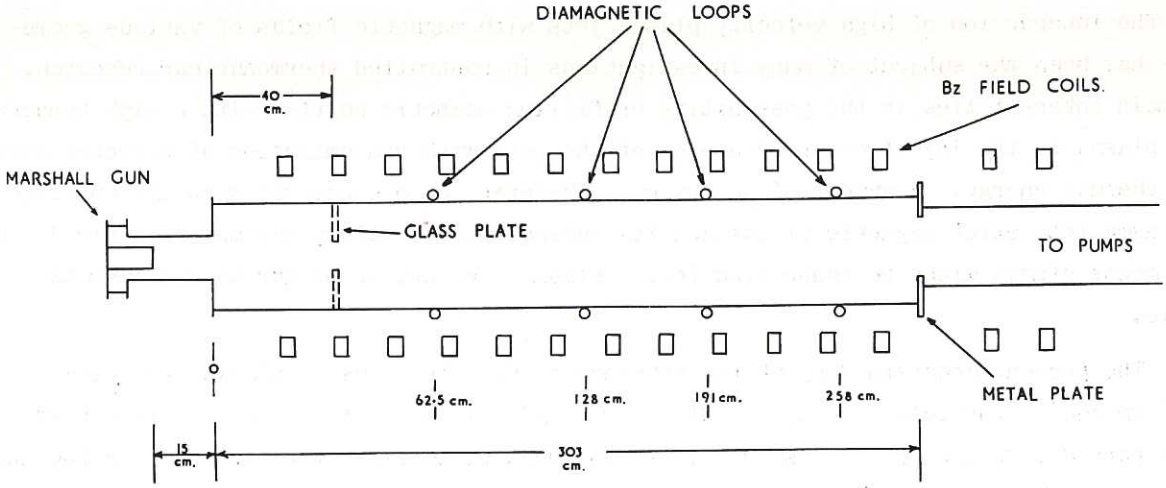

Fig. 1 Schema of apparatus (CLM-R72)

The solenoid, length ~ 350 cm, which produced the magnetic guide field consisted of a series of coils, spacing 18 cm energized by a d.c. power supply switched on ~ 1 sec before the gun was fired. Across each coil ~ 250 μF capacitors effectively prevented rapid fluctuations in the current through the coils due to the passing plasma. A current of 1,200 amperes gave a magnetic field of 780 gauss. The gun was located in front of the first coil where the fringing field was estimated to be ~ 200 gauss at the end of the centre electrode. The vacuum chamber was of pyrex glass, inside diameter ~ 21 cm; base pressures of ~ 2×10^{-5} torr were normally obtained.

LOSS OF TRANSVERSE ENERGY

A measurement of the transverse energy of the plasma was made in the usual way by the diamagnetic loops shown in Fig.1. These loops detect the decrease in magnetic flux within each loop as the passing plasma excludes a fraction of the magnetic flux. With the assumption of pressure balance we have

$$p_\perp = \frac{B_e^2 - B_i^2}{8\pi} = \frac{\Delta B\,(B_e + B_i)}{8\pi}$$

where $p_\perp$ is the transverse pressure, and B_e and B_i are the external and internal field intensities respectively. In this experiment, as ΔB is $\lesssim 5$ gauss and B_e is 780 gauss, we may take $B_e + B_i \simeq 2\,B_e$, and

$$p_\perp = \frac{1}{4\pi}\,(\Delta B)\,B_e\ .$$

If $\Delta\Phi$ be the total flux change in a loop about the plasma we have

$$\int \Delta\Phi\,dt = \int \frac{\Delta B}{v_z}\,dV = \frac{4\pi}{B_e}\int \frac{p_\perp}{v_z}\,dV$$

where v_z is the axial velocity and dV is an element of volume of the plasma. The total transverse energy of the plasma may then be calculated from the area under the observed diamagnetic signal, $\int \Delta\Phi\,dt$. Changes in transverse energy as plasma flows along the magnetic field can be determined by comparing these areas from successive loops.

The above analysis should be treated with some caution. The calculation is dependent on a detailed knowledge of axial velocity. In particular, if parts of the plasma are accelerated or decelerated during its passage along the field then clearly $\int \Delta\Phi \, dt$ from successive loops need not be a constant even if there is no change in the total transverse energy of the plasma. Also in the calculation it has been assumed that the diamagnetic loop measures all the magnetic flux change due to the plasma and there is no flux leakage between plasma and diamagnetic loop. This in general will not be strictly true since the plasma diameter is smaller than the diameter of the diamagnetic loop with a finite axial length of the plasma. Again the coupling between the plasma and diamagnetic loop is a function of the position of the plasma inside the loop, the coupling is larger the closer the plasma is to the loop. Thus if there be radial motion or 'wriggling' of the plasma then there will be variations in $\int \Delta\Phi \, dt$.

<u>Integrators and Diamagnetic Loops</u>

The voltage signals from the diamagnetic loops were integrated to give directly flux changes on oscilloscopes. The required time constant and frequency response of the integrator were determined as follows. The integrated signal was in general triangular in shape with the maximum flux changes in the last loop occurring about 5 μsec after the plasma left the gun. A time constant of ~100 μsec was therefore considered necessary to introduce an error smaller than 5% in the signal from the last loop. A necessary frequency response may be determined as follows. Consider a part of the passing plasma to be a current loop which is concentric with a diamagnetic loop. The mutual inductance between these loops is a measure of the flux linkage between these two loops and varies with axial separation. If the diameter of the plasma loop is one half that of the diamagnetic loop (~ 22 cm) the flux linkage when the axial separation is 14.2 cm is only one half the linkage when the two loops are coplanar. Thus for a thin plasma loop with an axial velocity of 5×10^7 cm/sec, the flux change measured by a diamagnetic loop will be peaked with a full width at half maximum amplitude of ~ 0.28 μsec. It thus appears that the integrator in this case should have a flat frequency response up to about 20 mc/s. This requirement may be too stringent since fluctuations in axial density are not expected to be as large as assumed in this approximation.

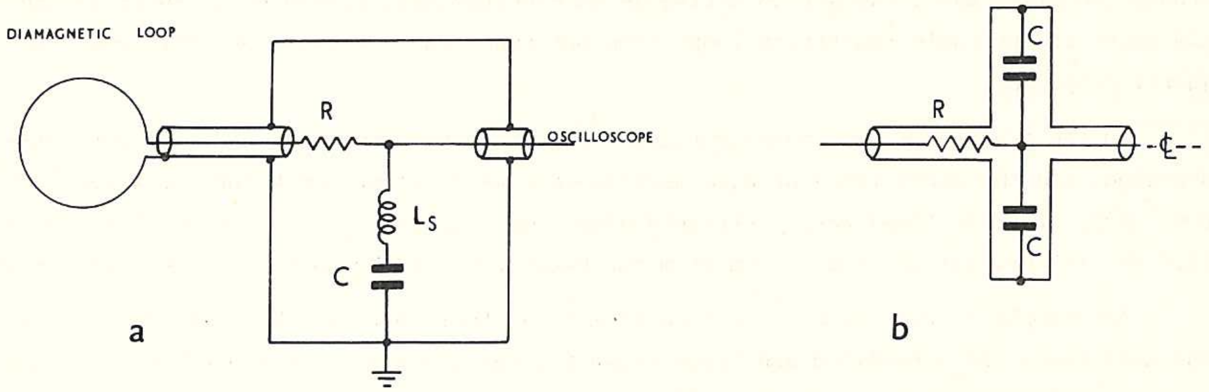

Fig.2 Integrator circuit. (CLM-R72)

A simple integrator, Fig.2a, using standard resistors and condensers in a shielded case was found to have a totally unacceptable frequency response curve (Fig.3). The fault was clearly in the stray inductance of the condenser which can be reduced by connecting in parallel a number of condensers in a coaxial array (Fig.2b). This arrangement gave the

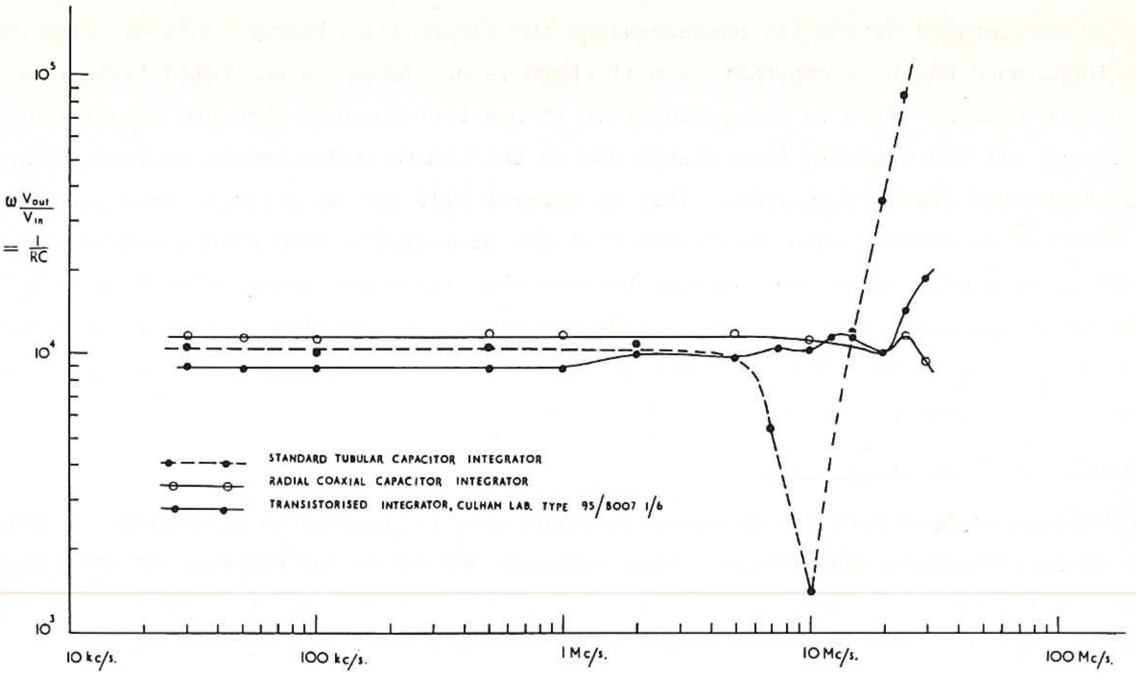

Fig.3 Frequency responses of integrators. (CLM-R72)

best frequency response that we measured (Fig.3). However, as the total flux change was small ($\Delta B \lesssim 5$ gauss) we finally chose a transistorized integrator [(8)] which gave a signal amplitude normally associated with a 10 μsec integration time constant, but with an integration time constant of 100 μsec. In the testing of the frequency response a 10 kc/s to 30 Mc/s oscillator was used with one Tektronix Type L amplifier, a Tektronix 555 oscilloscope and precision attenuators. The attenuators were used to measure the ratio of input to output voltages of the integrator as no two amplifiers were found to have similar responses over this frequency interval.

Each diamagnetic loop used consisted of a single turn of coaxial cable wrapped around the glass tube, the screen acting as an electrostatic shield being split as the mid point of the cable (multiturn loops were not practicable because of their poor frequency response).

In the experiment the transistorized integrators were matched, the time constants measured, and the sweep times of each oscilloscope were calibrated before or after each run. Four of these loops were positioned along the magnetic guide field and located at 62.5 cm, 128 cm, 191 cm, and 258 cm from the front face of the outer electrode of the gun.

An example of the signals received from these four loops is shown in Fig.4, where the amplitudes are normalised and lines drawn through the times corresponding to 50% maximum amplitude increasing, maximum amplitude, and 50% maximum amplitude decreasing, proved to be straight lines of constant velocity, with a nearly common intersection point, which gives the position in the gun assembly and the time at which the plasma was initially accelerated. In the present experiment plasma acceleration was usually found to have occurred within ± 5 cm in front of the centre electrode. This is in general agreement with the performance of other guns having similar parameters. The time of plasma acceleration is in some doubt as there was no distinguishing feature on total gun current (which

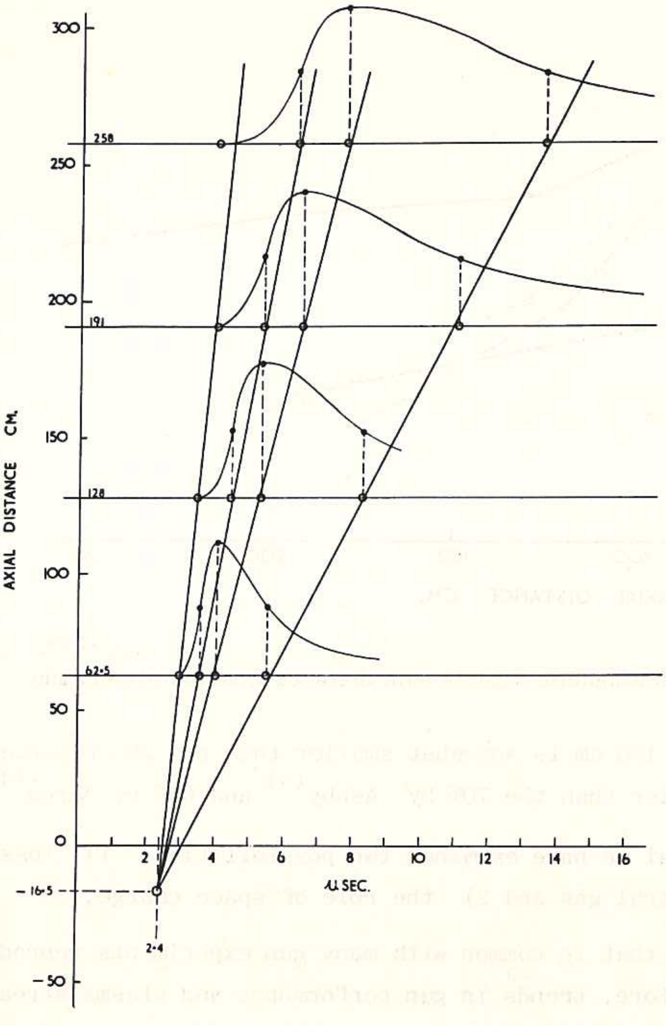

Fig. 4 (CLM-R72)
Integrated diamagnetic signals as a function of time after plasma acceleration

rang through many cycles with a decay of peak amplitude by 1/e in three periods) to indicate plasma acceleration. However, flow lines of constant velocity intersected generally within 0.2 μsec.

Fig.5 shows these same diamagnetic signals normalised in time (i.e. with the time to maximum and 50% maximum amplitude the same for each) but with their measured amplitudes. The shape is clearly almost the same for each, but the amplitude decreases with distance from the gun.

In most of the analysis reported here we have used only peak amplitudes and assumed that the plasma originated at the centre electrode.

A decrease of transverse energy with distance is obvious from Fig.6, others having reported similar results. The measured loss of 24% in passing

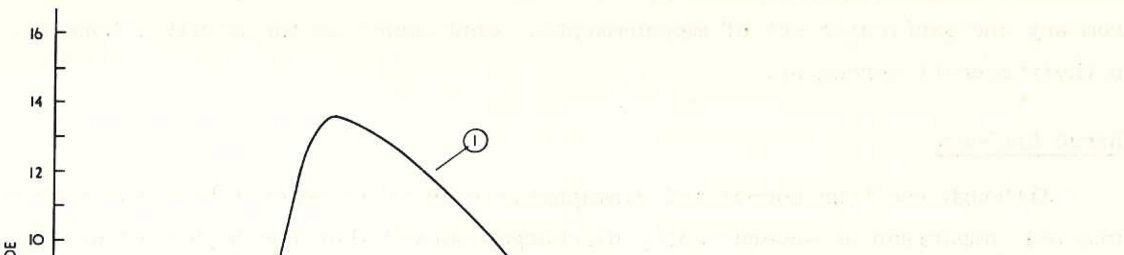

Fig. 5 (CLM-R72)
Integrated diamagnetic signals as a function of distance from the plasma gun.

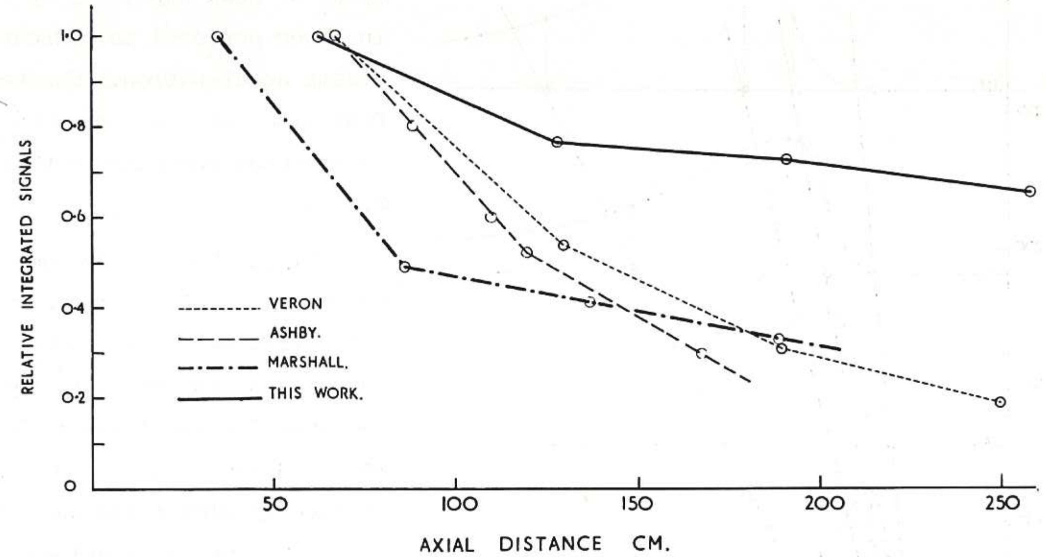

Fig. 6 (CLM-R 72)
Comparison of results - integrated diamagnetic signals with distance from the plasma gun

from an axial position of 70 cm to 170 cm is somewhat smaller than the 36% reported by Marshall[5], but considerably smaller than the 70% by Ashby[3] and 63% by Veron[4].

To explain this loss of signal we have examined two possibilities: 1) loss of plasma by charge exchange with neutral gas and 2) the role of space charge.

It should be emphasized here that in common with many gun experiments reproducibility from shot to shot was poor. Therefore, trends in gun performance and plasma streaming have to be inferred from averaging over a large number of shots. It was also found that there was a small run to run variation caused by unknown factors. In these cases only by repeating complete runs under many conditions would a definitive trend be established. Therefore the data reported here are the result of much averaging and may differ widely from any one particular set of measurements. Confidence in the results, however, rests in their overall agreement.

Charge Exchange

Although the four normalized diamagnetic signals in general have the same shape, a detailed comparison on several early discharges showed that the higher velocity ions were preferentially being lost over the slower. A mechanism with this velocity dependence in the energy interval with which we are concerned is charge exchange with neutral nitrogen gas. On analysing one particular set of traces an almost perfect fit was obtained with the charge exchange cross-section over the interval 1000-7000 eV. To account for the measured loss of transverse energy between the first and second diamagnetic loops a pressure of 10^{-4} torr was required, whereas the pressure measured in this region before the gun fired was 10^{-5} torr or less. A source of additional gas may be that injected into the gun before it is fired. However a considerable fraction of this gas would then have to have an axial velocity of $\sim 3 \times 10^5$ cm sec^{-1}.

With this possibility in mind the gas pressure was measured as a function of time after the gas was injected (the gun was not fired). A fast ion gauge[9] was located on the axis of the magnetic field 94 cm from the gun (approximately half way between the first and second diamagnetic loops). The pressure increased to 10^{-4} torr in 2.6 milliseconds after the valve admitting hydrogen gas to the gun was operated. Thus when the gun is fired, normally at ~ 350 μsec after the gas valve is operated the pressure is too low by almost a factor of ten to explain the loss by charge exchange with the volume of gas admitted into the gun. There does remain, however, the possibility that gas is removed from the glass walls of the vacuum chamber by plasma bombardment, but the radial velocities required to move distances of 5 to 10 cm in under 2 μsec, make this seem unlikely.

Additionally, if the pressure in the vacuum chamber is deliberately raised to high values, ~ 10^{-4} torr, by admitting air, a further loss of transverse energy with distance is observed consistent with that assuming simple charge exchange. This observation supports the assumption that most of the transverse energy in these plasmas is carried by the ions.

Space Charge

The process of plasma injection into a longitudinal magnetic field has been clarified to a large extent by Ashby[1]. It appears that the positive space charge of the ions which penetrate radially outwards from the axis due to their large Larmor radii is neutralized by electrons which flow along field lines and across an insulator. There is some evidence that the neutralization is not complete. Marshall[5] and others have measured voltages of several kilovolts induced by capacitive coupling on plates placed near the vacuum tube wall. Clearly the existence of large electric fields would influence the trajectories of individual particles as the plasma flowed down the field and would modify the signals seen by the diamagnetic loops. The possibility that separate groups of particles may be accelerated has been pointed out by V.S. Komelkov and B.G. Safranov[10].

In an attempt to understand the role of space charge, glass plates with central round apertures were placed across the tube 40 cm downstream from the gun (Fig.1). It was considered that these plates would have at least three effects: (a) they would reduce the density of the passing plasma, (b) reduce somewhat the diameter of the plasma column, and (c) make it more difficult for any space charge to be neutralized. The electrons are limited closely to those magnetic field lines which pass through the round aperture. On the other hand the ions with large Larmor radii may move to large radial distances from the axis after passing through the aperture. The resulting separation of charge forces electrons to flow radially across the back side of the glass aperture, and this surface is not under the intense plasma bombardment as is the insulator close to the plasma gun under normal operating conditions. It was expected therefore, that the flow of electrons would be impeded and a higher space charge be allowed to exist. Consequently, a smaller apparent loss of transverse energy was expected. The results from the diamagnetic loops when glass plates with apertures of 7.5 cm and 5 cm diameter were fitted are shown in Fig.7. It is seen that as the diameter of the aperture is reduced the apparent percentage loss of transverse energy with distance is increased.

A further modification was to replace the glass plates with a large copper ring across which was stretched a square mesh grid of copper wires of spacing 1 cm. This structure was not connected to any potential. The results with this grid assembly, Fig.7, gave the smallest loss of transverse energy that was measured.

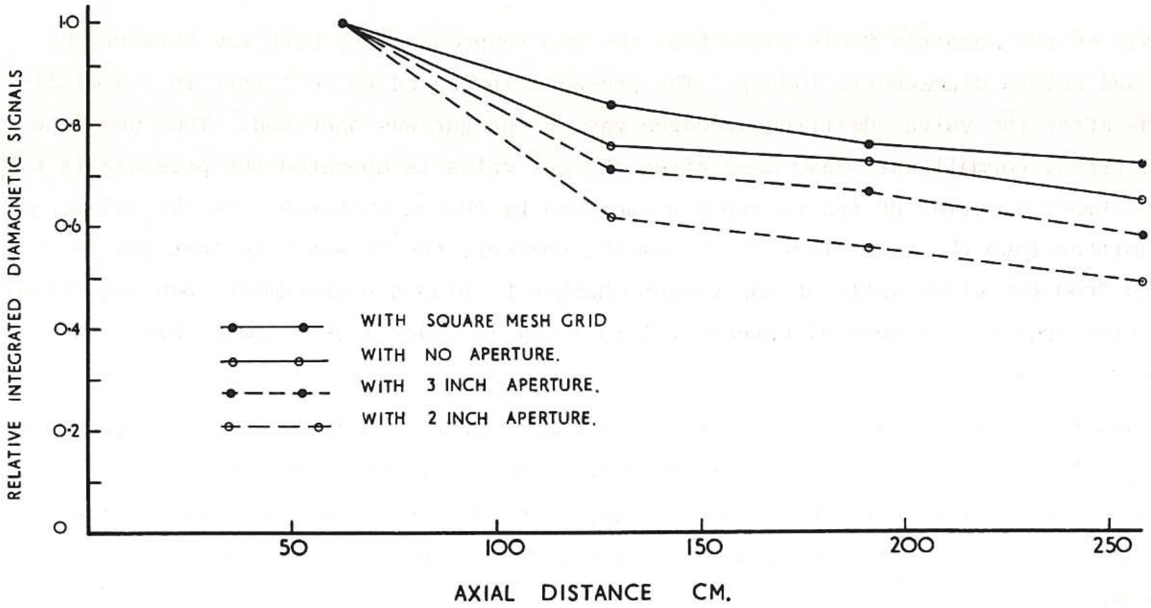

Fig.7 (CLM-R72)
Loss of diamagnetic signal increases as aperture is reduced.

A possible explanation of these results with the glass plates and wire grid is as follows. A relatively large fraction of the plasma may stagnate at the entrance to the magnetic field and by mutual coupling give a large contribution to the signal from the first diamagnetic loop. When the transmitted plasma is then reduced by glass apertures the signal from the first loop does not fall proportionately and the ratio of transverse energies of the second to first loop is too small. With the wire grid, however, the copper ring and wires may shield out signals from the stagnant plasma and then the first loop would only be influenced by plasma passing through it. To examine this possibility, the experiment was repeated with 3 mm thick copper plates placed immediately behind the glass plates (on the side facing the gun) with holes 0.6 cm larger in diameter than those in the glass plates. The results were essentially unchanged and we must conclude that coupling of stagnating plasma with the first loop was unimportant.

This apparent increase in loss of transverse energy with narrower apertures suggests that loss of plasma to the walls of the vacuum chamber is not important in agreement with Ashby's findings.

The results from the diamagnetic loops may also be explained as follows. Space charge produced by the separation of the ions from the axial electrons produces electric fields which 'blow-up' the ion cloud in a longitudinal direction. If ions are accelerated in their flight down the tube by these electric fields then their contribution to the integrated signal of successive loops will become smaller. If now this space charge is increased by introducing glass plates which make it more difficult for neutralizing electrons to flow, ion acceleration will be the larger and the effective loss in transverse energy the greater. Alternatively, wire grid, being a conducting mesh of wires and under intense plasma bombardment may more easily be able to provide the electrons necessary to neutralize the space charge and reduce the ion acceleration.

To test directly the effect of an electric field on the ion cloud a voltage was applied between the anode of the gun (which was earthed) and a metal plate having a round aperture 12.5 cm in diameter which was located at the far end of the vacuum chamber and served to connect the latter to a pumping section (Fig.1). The electric field was thus longitudinal and in the same direction as the magnetic field. The plate was supplied with a variable voltage and a condenser of 1 μF connected to earth to maintain a steady potential in the event of considerable charge being collected. This voltage was monitored and was found to change by not more than 10% during the first 50 μsec after the gun fired. A glass plate having a 5 cm central hole was fitted as before, 40 cm from the gun and this served to prevent a short circuit along the magnetic field line joining the metal plate to the gun.

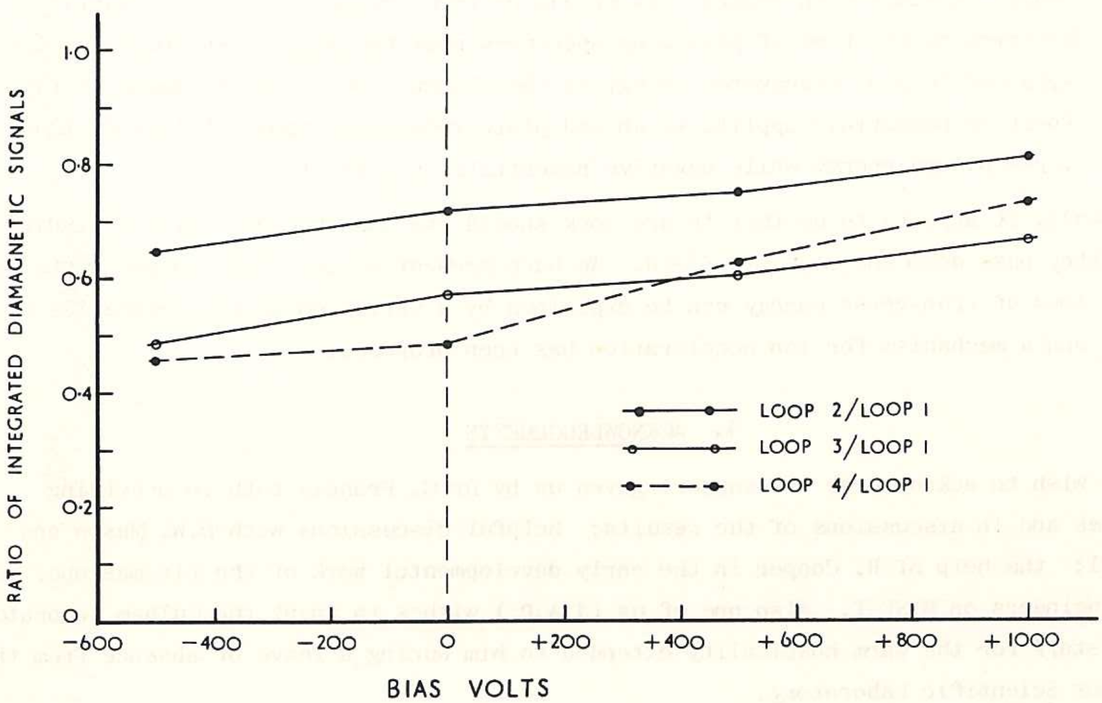

Fig.8 (CLM-R72)
Diamagnetic signal ratios vary with longitudinal electric field.

As the voltage on this plate was raised positively (Fig.8) the signals from the second, third and fourth diamagnetic loops increased, whereas with negative voltages they decreased.

Thus the diamagnetic signals vary with voltage on the plate and hence with electric field in the expected manner. As the voltage is made positive ions are slowed down on approaching the plate with a resulting increase in their contribution to the integral of the diamagnetic signal and vice versa. It was somewhat surprising to us that the electric field penetrated so far into the plasma and changed the diamagnetic signals from loops midway along the tube. Apparently at the highest voltages applied (+ 1000 volts) the electric field was not uniform along the tube as the integral from the fourth loop in some cases was <u>larger</u> than that from the third loop.

An obvious objection to this explanation of the loss of diamagnetic signal is the relatively high voltages required to accelerate the ions. If the signals from the fourth loop are to be reduced by ~ 35% by this mechanism the energy gained by the ion in passing from the first to fourth loop must be roughly equal to the initial energy of the ion. These voltages ($\lesssim$ 5 kV) would give rise to large radial electric fields (the axial magnetic field lines being shorted to ground by the flow of electrons) which would drastically modify the ion trajectories on entrance to the magnetic field. An attempt to measure this radial electric field is described in a separate report[11].

3. CONCLUSIONS

These results do not answer completely the question of the apparent loss of transverse energy as plasmas flow down a magnetic field. However, some observations can be made on the plasma used in this experiment.

(1) Charge exchange with neutral gas streaming from the gun is not important.

(2) Restricting the flow of plasma by apertures near the plasma gun increases the apparent loss of transverse energy as the plasma flows down the magnetic field.

(3) Positive potentials applied to an end plate reduce the apparent loss of transverse plasma energy while negative potentials increase the loss.

Finally it appears to us that future work should examine the velocities of individual ions as they pass down the magnetic field. We have presented data which suggests that the apparent loss of transverse energy can be explained by a variation in the velocities of the ions and a mechanism for ion acceleration has been proposed.

4. ACKNOWLEDGEMENTS

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