CLM-R 82

CLM-R 82

United Kingdom Atomic Energy Authority
RESEARCH GROUP
Report

# PLASMASCOPE OBSERVATIONS OF PLASMA IN A MAGNETIC FIELD

D. W. ATKINSON
J. A. PHILLIPS

Culham Laboratory
Abingdon Berkshire

1968

Available from H. M. Stationery Office
SIX SHILLINGS NET

U.D.C.
621.039.665.024
533.933
621.039.615.18.024

UNCLASSIFIED
(Approved for Sale)

CLM - R 82

# PLASMASCOPE OBSERVATIONS OF PLASMA IN A MAGNETIC FIELD

by

D.W. ATKINSON
J.A. PHILLIPS*

## ABSTRACT

A plasmascope is used to observe the behaviour of plasma particle density $\sim 10^{10} - 10^{11}$ cm$^{-3}$, and velocity $\sim 5 \times 10^{7}$ cm sec$^{-1}$, injected by a coaxial plasma gun into a longitudinal magnetic field of 780 gauss, also plasma of particle density $\sim 10^{14}$ cm$^{-3}$, and velocity $\sim 10^{8}$ cm sec$^{-1}$, injected and trapped in a magnetic mirror.

The transverse velocity of the ions is found to extend from close to zero to the maximum velocity whose Larmor orbit can be accommodated within the plasma jet. Many of the orbits do not enclose the magnetic field axis. No marked instabilities are observed at the boundaries of the plasma under normal conditions, although at times the energetic electrons have a characteristic spiral shape.

Plasmascope observations on the plasma of the MTSE I experiment show no evidence of instabilities at early times for the simple mirror or minimum B configurations.

*On leave from Los Alamos Scientific Laboratory, University of California, Los Alamos, New Mexico

U.K.A.E.A. Research Group,
Culham Laboratory,
Abingdon,
Berks.

March, 1968 (MEJ)

# CONTENTS

## 1. INTRODUCTION

The study of plasma when injected into magnetic fields of various geometries is fundamental in controlled thermonuclear research. Of particular interest is the simple case of a uniform longitudinal magnetic field along which plasma is directed into more complex configurations. When fast low density plasma (velocity $\sim 10^8$ cm sec$^{-1}$, and particle density $\sim 10^{11} - 10^{12}$ cm$^{-3}$) is launched axially into such a magnetic field it has been established by Ashby and Avis(1) that the electrons are confined mainly to the axis, whilst the ions due to their considerably larger Larmor-radii penetrate the magnetic field radially much further and consequently carry most of the transverse energy of the plasma. The space charge which results is neutralised by electron currents which flow across the surfaces of the vacuum chamber where these cross the magnetic field lines. If the space charge is not completely neutralised then electric fields must exist and may persist as the plasma flows along the field and so modify the velocity and or azimuthal drift of the particles.

The subsequent flow of plasma along a uniform magnetic field has been studied by a number of experimenters(2,3,4,5) and all report an increasing loss of transverse energy, although by differing amounts, with distance along the field. This loss of transverse energy is measured at known distances along the magnetic field by diamagnetic loops.

The validity of this method of measuring the change in transverse energy of the plasma with distance is not questioned but it may be observed that when comparing signals from successive loops it is assumed that the velocity of the ions is constant and this may not be so; also if the signal in a loop is considered as that due to coupling with the current helix formed by gyrating ions then leakage flux is not taken into account.

In view of the foregoing, the loss of transverse energy of plasma with distance along the magnetic field should be regarded as an apparent loss.

The authors have reported an attempt to measure the apparent loss of transverse energy using diamagnetic loops(3) and now describe observations made upon plasma which has travelled the same distance along a uniform magnetic field and is then examined with a plasmascope. The plasmascope displays on a fluorescent screen the spatial position of ions and electrons, with time resolution.

Finally, observations made on the plasma of the MTSE I experiment are reported, using a plasmascope placed so as to study the plasma before entering into the magnetic trap and then re-located to observe the plasma which escapes from the second mirror.

## 2. APPARATUS

The apparatus used in these experiments is described fully in a previous report(3), but in essentials comprised a vacuum vessel 350 cm in length, inside diameter 21 cm, in which a base pressure of $2 \times 10^{-5}$ torr is normally obtained. At one end of the tube a coaxial plasma gun injected hydrogen plasma of particle density $\sim 10^{10} - 10^{11}$ cm$^{-3}$, with velocity $\sim 5 \times 10^7$ cm sec$^{-1}$, into a uniform longitudinal magnetic field of strength $\sim 780$ gauss provided by coils mounted coaxial with the vacuum vessel. Plasma thus launched into the magnetic field was able to travel the length of the tube before being received by the plasmascope mounted at the other end. The purpose of the plasmascope (described later) is to detect differentially ions and electrons and display the spatial distribution of the particles in the cross-section plane of the tube. As the device is operative only for the time during which a voltage pulse is applied, then some time-varying properties of the plasma may be studied.

The plasmascope was originated by L.I. Elizarov and A.V. Zharinov(6) and B.C. Safranov et al.(7) and improved by F. Coensgen et al.(8) at Livermore. The principles have also been independently established by D.W. Mason(9) who designed an ion energy analyser. The device is shown in Fig.1(a) and comprises three components, a plasma attenuator 'A', an electron suppressor 'B' and a disc of phosphor 'C'. On the front face of the phosphor a thin layer of aluminium is evaporated which is opaque to light but permits 10 keV electrons to pass through with negligible absorption. In operation the plasmascope is placed so that the attenuator 'A' intercepts the plasma, reducing the particle density so that the transmitted fraction (electrons and ions) behave as single particles. The grid 'B' repels electrons with energy less than the applied potential (-40 to -1,000 volts), while the ions continue through. When a positive voltage pulse (+10 kV or +15 kV) of duration 0·3 µsec is applied to the aluminium coating on the phosphor the ions in the grid/phosphor space are decelerated and return to the grid 'B' where some of them on striking the grid wires release secondary electrons. The electrons are accelerated, pass through the aluminium layer and cause the phosphor to fluoresce. During the time when there is no voltage applied to the aluminium layer only electrons with energies higher than the negative bias will pass into the phosphor and be detected, and as these can readily be identified as explained below, the plasmascope is sensitive only when a positive voltage pulse is applied.

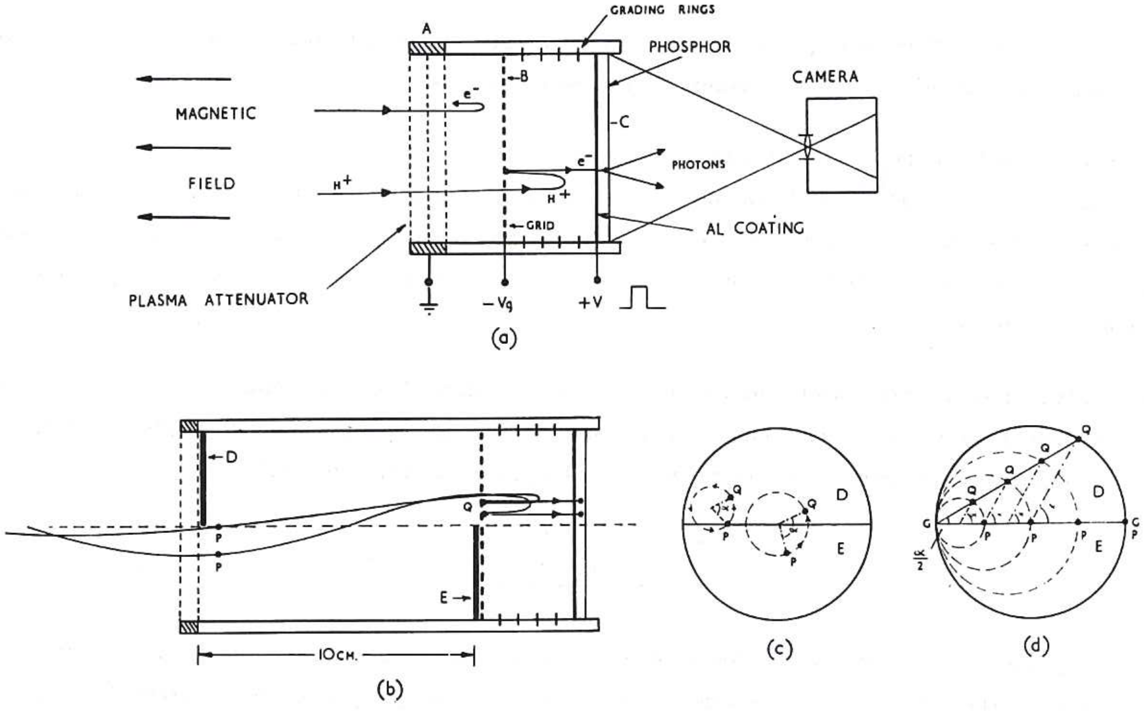


Fig.1 Schema of plasmascope (CLM-R82)

The attenuator 'A', following the example of Coensgen$^{(8)}$, comprised a number of perforated stainless-steel discs spaced 0·6 cm apart. Each disc, cut from masks used in colour television tubes$^{(10)}$, was 0·18 mm thick and had a regular pattern of round holes 0·23 mm in diameter. The transmission of each disc was about 30% and the number used varied with the experiment. The criterion which determined the total attenuation factor (the number of discs) in each experiment was that the particle density be reduced such that the Debye length be large compared with the spacing between the attenuator and the electron suppressor grid. The grid 'B' was made from stainless steel wire mesh, with wire of diameter 0·375 mm giving 8 meshes/cm and spaced 1·25 cm from the attenuator. The plastic phosphor disc 'C' (Type N.E.102) was 0·3 cm thick and coated with ~ 5,000 A.U. of aluminium and spaced 2·5 cm behind the grid 'B'. Four aluminium rings graded the potential at the edge of the phosphor disc. The plasmascope presented an aperture of 19 cm to the plasma with an overall diameter of ~ 20 cm and was located with the front face of the attenuator 304 cm from the gun. A camera with F 2·9 lens recorded the image formed on the phosphor which was marked with a circular scale of 1 cm spacing to identify spatial positions.

The device operated as expected with protons detected having energies ~ 100 eV, estimated from time of flight measurements. The choice of the coarse mesh for the electron suppressor grid made it possible to distinguish between electrons and ions. When this grid was at low negative potential, ~ 40 volts, electrons of higher energy were able to pass through the holes in the grid and be accelerated by the positive voltage pulse applied to the aluminium coating on the phosphor. These electrons gave a pattern of square bright spots on a dark background whereas the ions which are detected by the secondary electrons produced on the grid wires caused bright continuous lines, in effect an image of the grid mesh (see Fig.2). Where both electrons and ions are present together the pattern produced is easily distinguished from that due to either particle alone.

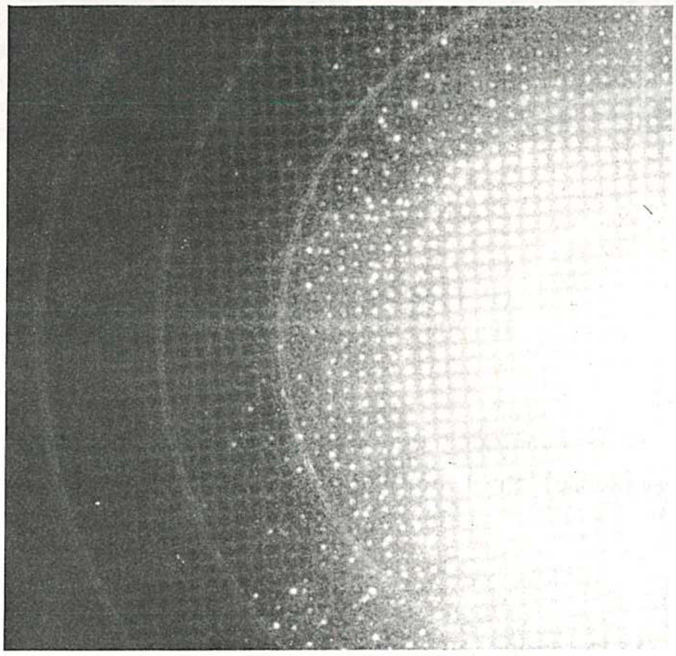
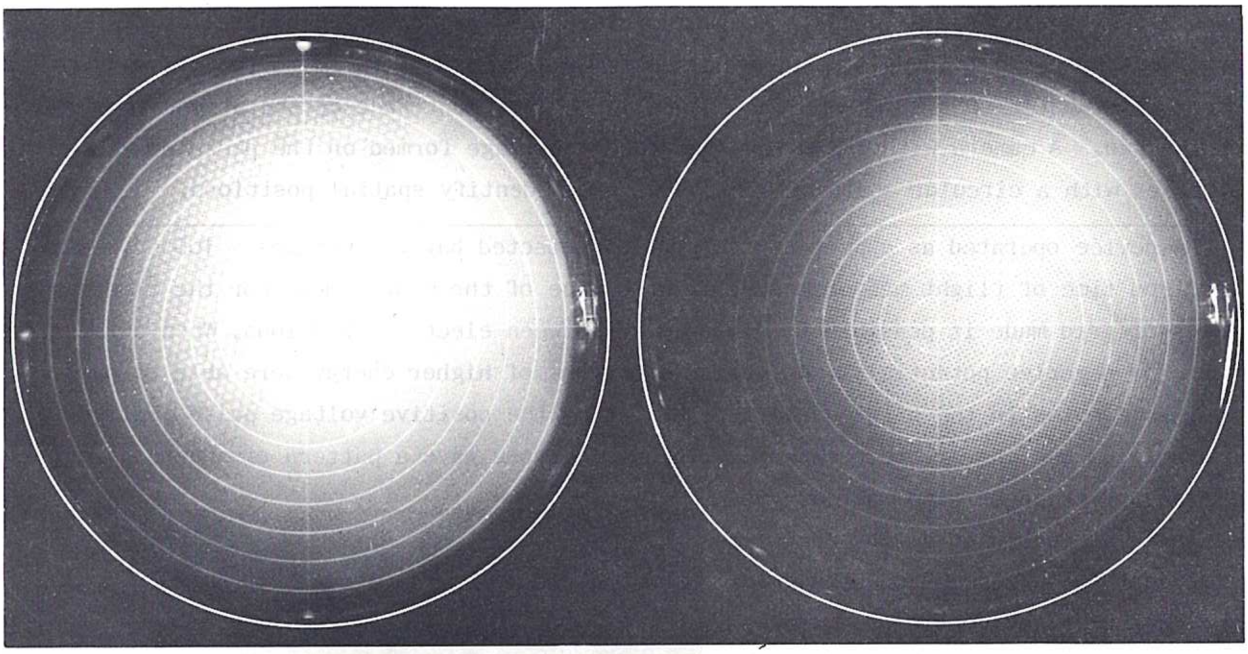


Fig. 2 (CLM-R82)
Ions and electrons produce distinctive patterns
(Left - ions; right - electrons)

The number of perforated discs used in the attenuator was typically three, which gave a geometric transmission of 2·7%. Reduction in particle density by a factor of ~ 37 was at first treated with some reserve as various processes which might modify the attenuation factor presented themselves. For example, plasma bombardment of the front face of the attenuator might release neutral gases in which ions may be lost by charge exchange. Additionally, the formation of a sheath on the disc could decrease the effective diameter of the holes. Both effects tend to increase the effective attenuation.

In order to test the possible effect of a sheath on the behaviour of the attenuator the following simple experiment was performed. The front disc was removed, cut across its diameter and replaced together with a piece of perforated copper sheet of similar shape and size but having holes 2·1 mm in diameter. The front face therefore, presented a full disc but with half its area having holes nearly ten times the normal size. Since the geometric transmission of each half was similar it was expected that the effect of a sheath would be to modify the transmission of the half with the larger holes less and that the difference would be seen in the pattern on the phosphor. Fig.3 shows the result, with 140 volts bias on the suppressor grid plasma electrons show clearly the demarcation of the two halves of the front disc, (the larger holes are quite distinct). When the grid is biased to -300 volts, however, ions predominate and no difference is observed between the two halves.



(a) -40 V

(b) -300 V

Fig. 3 (CLM-R 82)
(a) Electron pattern distinguishers half of attenuator disc with larger holes
(b) When electrons are excluded ion pattern shows attenuation unaffected

It is concluded that at the particle densities in this experiment ($10^9$ $cm^{-3}$ at the plasmascope) the behaviour of the attenuator is not very different from that calculated.

## 3. OBSERVATIONS WITH THE PLASMASCOPE

A series of photographs with the plasmascope triggered at different times with respect to the firing of the gun is shown in Fig.4. Here the positive voltage pulse to the phosphor coating was + 10 kV and duration 0·4 μsec. At very early times, ~ 0·5 μsec, the fast precursor of the plasma jet is seen over a small central region of the plasmascope. From an examination of the pattern on the phosphor this precursor is identified as a group of high energy electrons. At later times the main plasma jet arrives and the radial distribution of the ions is clearly seen. The spatial shape varies from shot to shot, on some almost filling the plasmascope aperture and on others being located over relatively small regions. The intensity of the plasmascope image has been found to correlate well with diamagnetic signals, the largest and brightest images having the largest amplitude signals.

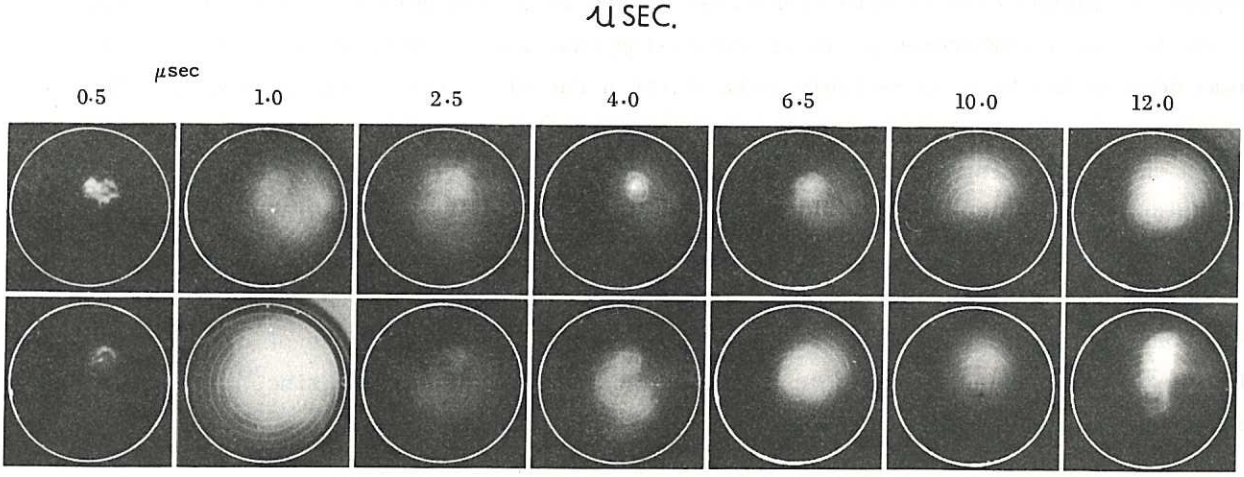


Fig. 4 (CLM-R82)
Photographs with the plasmascope triggered at different times with respect to the firing of the plasma gun

We have attempted to correlate the position of the plasma jet in the vacuum chamber with the loss of diamagnetic signal and find none. The loss appears not to depend on whether the plasma is centrally located on axis or is squeezed up close to the tube wall. From this result we must conclude that either 1) wall losses are small or 2) the plasma writhes about and strikes the tube wall as it flows along the magnetic field and the plasmascope shows only one of its many positions in the tube.

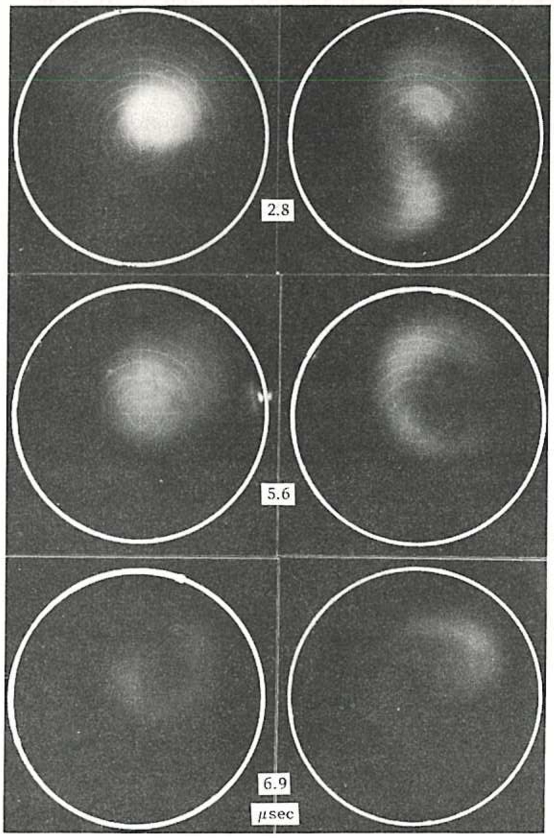


Fig. 5 (CLM-R82)
Occasionally spiral structure is seen in the plasma-jet

It will be noted in Fig.4 that the energetic electrons are displaced upward about 3 cm from the axis of the plasmascope. As these electrons presumably originate from the end of the inner electrode of the gun (charged negatively) the magnetic field lines passing through the gun apparently did not pass down the axis of the solenoid. Indeed it was found that the iron cases of the high voltage gun condensers, located on each side and below the gun, did pull magnetic lines downward. When iron was placed above the gun to balance that in the condensers, the electrons passed along the axis and were centred in the plasmascope. This centering of the plasma jet by 3 cm in the 10·5 cm radius tube did not noticeably alter the ratios of the diamagnetic signals with distance.

It will be seen in Fig.4 that there is no discernible structure in the plasma jet. When a glass plate with a 5 cm diameter aperture is placed ~ 40 cm downstream from the gun(3), however, we have in some cases seen structure in the plasma, Fig.5. Typically these are seen as spiral arms radiating outward from the central part of the plasma. These may indicate co-operative plasma effects with transverse motion of plasma across the magnetic field and possible wall bombardment. It is surprising that such structure is observed when the plasma density has been appreciably reduced (by a factor $\sim 10$) by the aperture. The explanation may be simply due, however, to the fact that the plasma density on passing through the restricting aperture in the glass plate is highly asymmetric about the axis. (An asymmetry of plasma bombardment on the front face of the glass plate has been observed by eye). The electric fields produced by space charge separation of these asymmetric plasma jets may lead to drifts as seen by the spiral arms. The growth of these spiral arms and their possible interaction with the wall could explain the larger loss of diamagnetic signal with the smaller apertures. We have not attempted a correlation since the number of plasmascope pictures showing definite spiral arms was small.

## MEASUREMENTS WITH THE PLASMASCOPE

In an attempt to obtain measurements of ion trajectories with the plasmascope the first two discs of the three in the attenuator were moved 10 cm ahead of the third (see Fig.1(b)). This 10 cm space between the discs allowed a drift space for the particles the purpose of which will be described below. Also two masks D and E were added; one (D) immediately behind the first two discs of the attenuator, and the other (E) in front of the third disc. Each of these masks cut out one half of the plasmascope aperture and were positioned so that the second mask cut out that which the first mask did not. The functions of these masks were as follows. The first mask allowed particles in one half of the tube to pass into the 10 cm drift space at some point P where they would execute a fraction of their Larmor orbit as indicated in Fig.1(c) and then be detected at Q by the plasmascope in the usual way. Since the longitudinal velocity $v_z$ of all the particles is known when the plasmascope is energised (from the time of flight and distance from gun to plasmascope) the angle $\alpha$ which the particles precess in this drift space can be calculated. (The Larmor gyration frequency is also known). From the resulting pattern on the phosphor information of the ion transverse energy is obtained. Consider for example the idealised case in which all the ions have their centres of gyration positioned along a diameter G-G′ (Fig.1(d) and have the maximum Larmor radius that could be contained in the vacuum chamber. If all the ions start at points P on this diameter, the points Q form a straight line displaced by an angle $\alpha/2$ with respect to the diameter in the direction of the orbiting ions. In practice,

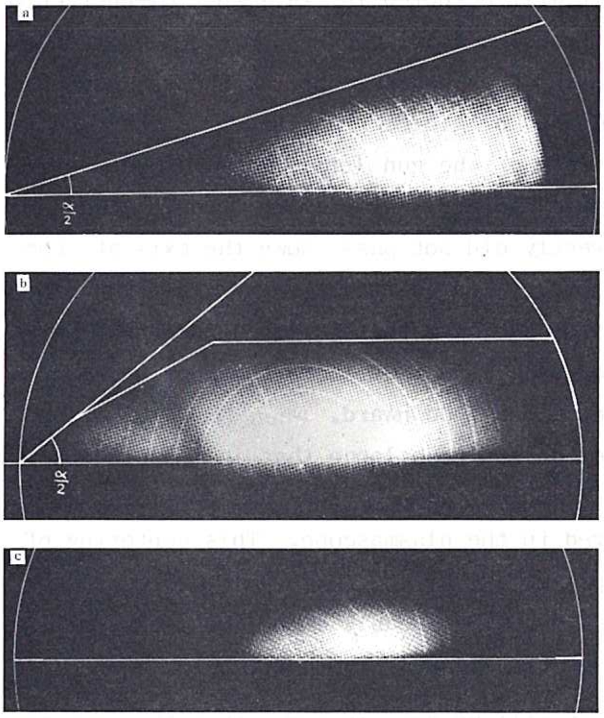


Fig.6 (CLM-R82)
Photographs of pattern with plasmascope modified to include a 10 cm drift space

however, the centres of gyration are randomly positioned about the tube and the region between the straight line pattern and the diameter would be filled in and a wedge would result. The intense bombardment of the region not covered by mask D (the gun was run flat out to make this measurement) raised the possibility that X-rays produced by the 15 keV electrons striking the aluminium surface would in turn release other electrons from the electron suppressor grid destroying the reproduction of the ion distribution. The second mask E was therefore added to remove the large flux of particles in this area.

Typical results are shown in Fig.6 with this arrangement of masks and drift space. In Fig.6(a) we have the expected wedge shaped pattern, although only part of the wedge is clearly seen. The plasmascope was triggered early with the calculated angle $\alpha$ from time of flight (plus the time for deceleration and acceleration in the region between the electron suppressor grid and aluminium surface to be $19{\cdot}0^{0}$). The measured angle $16{\cdot}5^{0}$ is smaller. Measurements from a series of such photographs, show that in all cases the measured $\alpha$ is smaller than that calculated. This may be explained by 1) the film (polaroid) not being sufficiently sensitive to the low light intensity in the outer regions and 2) the plasma did not contain many ions having the maximum permissible Larmor radii.

A second photograph taken at a later time (Fig.6(b)) with a calculated $\alpha$ of $42{\cdot}0^{0}$, the measured angle $38{\cdot}5^{0}$ shows that the majority of the ions have radii considerably smaller than the maximum. Note in the lower left quadrant the shadow of a small flag which was placed in the plane of mask E. This was inserted as a further check that X-rays were not important. Also note that on the right hand side of the centre there are some ions which have moved in behind the edge of the second mask. These ions just missed the second mask and in the deceleration region between the electron suppressor grid and phosphor executed part of a Larmor orbit.

To define further the ion trajectories the two masks D and E were replaced by one mask at the position formerly occupied by the first mask D. The new mask had two 1 cm diameter holes located on a diameter 1 cm and 6 cm from the geometric centre. The drift space of 10 cm was unchanged. Fig.7 shows three examples when the plasmascope was triggered at a) 5·5 μsec, b) 13·0 μsec and c) 16·0 μsec. In Fig.7(a) there is some structure in the spatial distribution of the ions as shown by the flares radiating outward from the holes. The majority of the ions which passed through the top hole had their centres of gyration below the hole, whereas ions passing through the lower hole were of two classes, one with their centres below and the other above the hole. Since all the ions in this photograph have the same longitudinal velocity their transverse velocities are proportional to the distances from the hole to their positions in the pattern. We see from the plasmascope picture that there is a spectrum of transverse velocities extending from zero out to high velocities. At later times, Fig.7(b), more random spatial velocities are seen. In the example shown in Fig.7(c) we have a rather uniform pattern around the two holes. These patterns which show structure must be due to plasma jets in which there are pronounced density variations: in particular if the hole is on the boundary of a high density region a flare will be produced in the direction of the boundary.

Some attempts have been made from these data to obtain transverse energy distributions for the ions. It has been found, however, that the reproducibility for successive discharges and the subjectiveness in reading the photographs (together with the sensitivity of

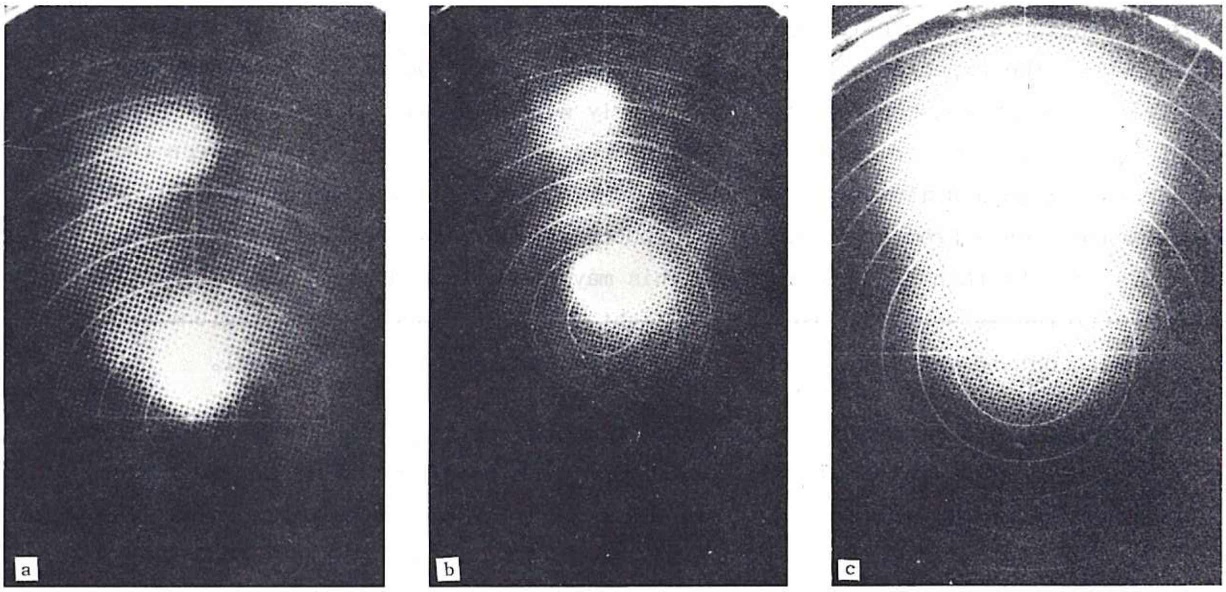


Fig. 7 (CLM-R 82)

Photographs with modified plasmascope. Attenuator covered by mask with two holes. Ion pattern spreads away from holes proportional to the transverse velocity distribution of the ions

(a) − 300 V (b) − 60 V

Fig. 8 (CLM-R 82)

Plasmascope used as an energy analyser. Electron and ion currents collected by the phosphor are measured for various grid potentials the photographic process) make the results uncertain. However, from these results from the plasmascope and the masks used with it we can make some general statements. For the plasma jets considered in this experiment the centres of gyration of the ions are rather uniformly distributed about the cross sectional area of the plasma and not grouped about the centre. Also for each value of the longitudinal velocity the ions have a broad spectrum of transverse velocities extending from zero to, in a very few cases, the maximum allowed by the size of the vacuum chamber. In general from an examination of a large number of photographs it can be said that for a plasma jet having an arbitrary cross sectional shape the largest Larmor orbits are those that will fit inside the plasma boundary and will therefore be found at the boundaries of the plasma. (We exclude here the very few cases inwhich there was some evidence of fluting inwhich the previous statement would not be true). That ions having the largest transverse energies are among those whose trajectories pass close to the plasma boundary helps to clarify the observation made by N.A. Khizhnyak(11) at Kharkov. Here a similar plasma was injected into a longitudinal magnetic field whose intensity increased with distance from the gun. It was found that the part of the plasma jet that was first reflected back towards the gun was that on the boundary of the plasma. This is what one would predict from the present plasmascope results since the ions having the largest ratio of perpendicular to longitudinal velocities would be at the boundary. (We assume that the magnetic moment is conserved).

The plasmascope structure as shown in Fig.1(a) has been also used as a detector to measure longitudinal energies of both electrons and ions. In the measurements of electron velocities the current to the aluminium surface on the phosphor was measured across a 100Ω resistor connected to ground. A variable negative D.C. bias voltage was applied to the electron suppressor grid. Typical curves for two values of this bias voltage are shown in Fig.8 together with the diamagnetic signal from the last loop. At a bias of -300 volts (see Fig.8(a)) there is at first the usual negative signal due to the high energy electron precursor. The energy of these electrons was higher than the maximum voltage, about 2 kV, that could be applied to the grid. This negative pulse is followed by a large positive signal which is predominantly due to the ions. Superimposed on this rather smooth positive pulse which closely follows the diamagnetic signal are bursts of electrons which occur at intervals of about 4 μsec. At a bias voltage of -60 volts these negative bursts are more pronounced Fig.8(b). These bursts have been correlated with the gun voltage which rings with a period of about 4 μsec. Each time the centre electrode swings negative, electrons are apparently accelerated along the magnetic field lines to the plasmascope which is grounded. The energies of these electrons have been determined by varying the bias potential on the electron suppressor grid and we find the energies are low, (~ 400 eV maximum on the first burst) and decrease on succeeding bursts. These electron currents to ground have also been detected with magnetic pick-up loops on the outside of the glass vacuum chamber. The amplitudes of these electron currents are small, about 50 mA.

The longitudinal velocity of the ions was measured by applying a positive bias to the aluminium surface on the phosphor. An ion current was collected on this surface as long as the longitudinal energy was greater than the applied positive potential, but dropped to zero when below. Good correlation with time of flight was found for energies below 1 keV but breakdown within the plasmascope prevented measurements with D.C. potentials greater than 1 kV.

One further observation with the plasmascope may be of interest. The masks D and E were removed while retaining the 10 cm drift space between the second and third discs in the attenuator. A mask having a 0·5 cm wide slit across its diameter was placed immediately behind the second disc. When the plasmascope was triggered at an early time the photograph shown in Fig.9 was obtained. The pattern, a mosaic of small squares, shows that fast electrons were detected. The electron current passing through the slit was small, about 10 mA, and the vacuum pressure before the plasma gun was fired was 10$^{-5}$ torr. We see evidence of turbulence in the electron beam with transport of electrons across the magnetic field.

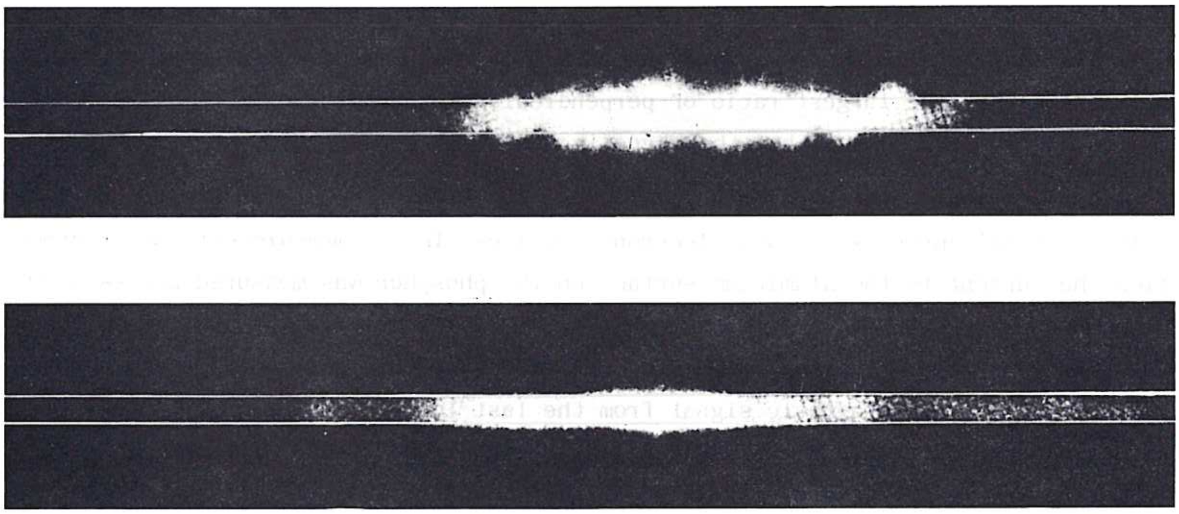


Fig. 9 (CLM-R82)

Photographs with modified plasmascope. Attenuator covered by mask with 0.5 cm slit shows some evidence of turbulence in the electron beam with transport of electrons across the magnetic field

## RADIAL ELECTRIC FIELD MEASUREMENTS

We have suggested that the potentials created by space charge separation as the plasma jet enters the magnetic field will accelerate parts of the plasma as it flows down the longitudinal magnetic field. These potentials will give rise to intense radial electric fields which together with the longitudinal magnetic field will lead to azimuthal particle drifts. There is some evidence for this azimuthal drift in the characteristic 'prawn' or spiral pattern of energetic plasma electrons observed with the plasmascope (see p.13). As the source distribution of these electrons is not known we wished to establish the existence of radial electric fields by measuring the azimuthal drift of a known beam of electrons. Consequently, we set up the following experiment.

A glass plate with a 5 cm diameter axial aperture located 40 cm from the plasma gun was used to support an assembly of ten small electron guns. The electron guns were mounted across the radius of the tube and the electron beams were directed down the magnetic field towards the plasmascope. Each gun consisted of a tungsten filament to which a 1 kV negative pulse of duration ~ 1·0 μsec was applied. An earthed wire mesh screen spaced 1·0 mm in front of the filaments acted as an anode and accelerated ~ 5 mA of current. The electron guns were pulsed at various times after firing the plasma gun and the plasmascope was triggered ~ 0·3 μsec after the electron guns to detect the beams of 1 keV electrons.

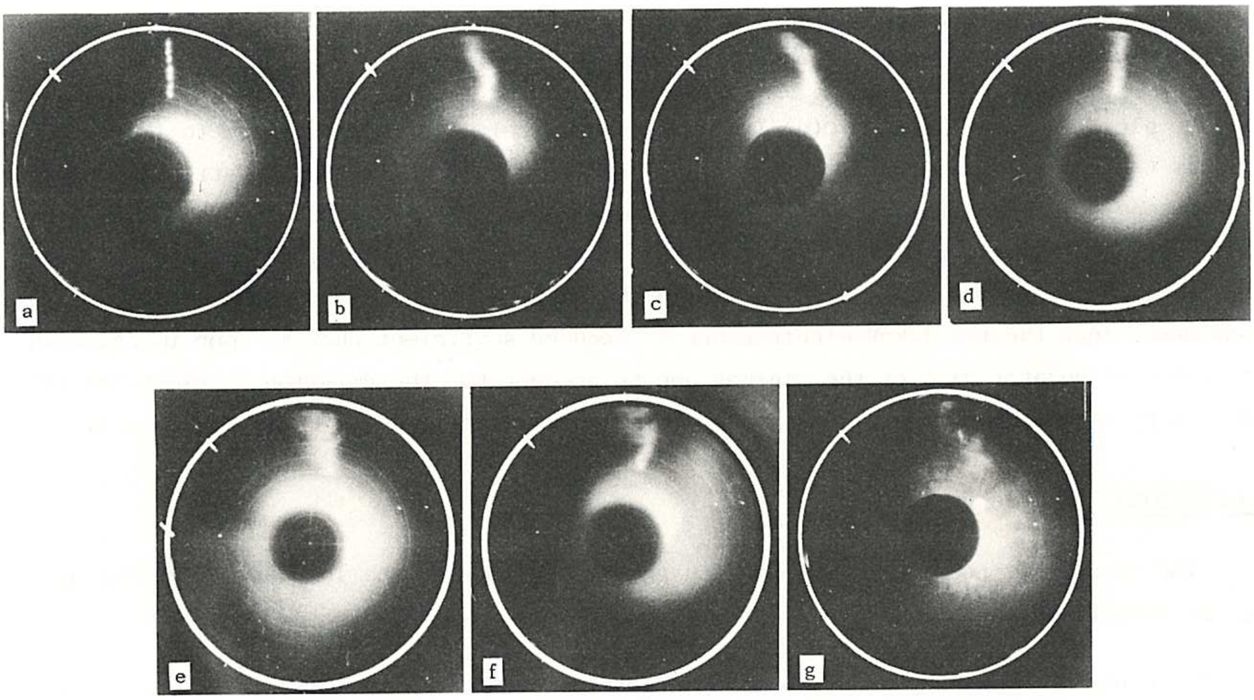


Fig.10 (CLM-R 82)
Pictures show electron beams deflected by radial electric fields

Examples of pictures taken by the plasmascope are shown in Fig.10(a)-(g) which correspond respectively to 2,3,4,5,6,7 and 8 μsec after firing the plasma gun. When the electron guns were pulsed early (Fig.10(a)) it is seen that the electron beams follow the magnetic field lines and produce a straight line pattern of bright spots on the plasmascope screen and when the electron guns were pulsed later but before the main plasma arrived at the plasmascope, the beams were rotated in the azimuthal direction. The images of each beam are diffuse but clearly displaced. The directions of displacements are a little surprising being clockwise for beams close to the tube axis and counter-clockwise for beams close to the tube walls. This will occur if the region half way out in radius was charged positive and that about the axis and the tube wall negative. The positive charge would be due to ions while the axis and the tube wall would be grounded.

From the observed drifts of the electron beams some estimates can be made of the magnitubes of the radial electric fields in this experiment. If it is assumed that this field is constant along the path of the electron beams, the observed azimuthal displacement of $\sim 1$ cm would result from a radial electric field of $\sim 60$ volts $\mathrm{cm}^{-1}$. However, since there is an axial expansion of the plasma as it flows down the magnetic field with a decrease in particle densities, the radial electric field should be greater than 60 volts $\mathrm{cm}^{-1}$ near to the plasma gun, falling to a lower value at the plasmascope position. Indeed this would be compatible with the loss of diamagnetic signal with distance, the loss rate being largest close to the plasma gun where the space-change separation is the largest.

This situation is complicated, however, in that if these radial electric fields lead to potentials which are comparable with the ion energies then the trajectories of individual ions will be modified and this simple explanation must fail. It is clear that more data must be obtained to understand this phenomenon completely.

The pictures shown in Fig.10(a)-(g) include a circular dark patch close to the centre. This is the shadow of a metal disc placed in contact with the first attenuation disc of the plasmascope. The need for this arose when it was found that each time the ten small electron guns were pulsed, a small current of high energy electrons originating at the centre electrode of the plasma gun caused damage to the aluminium coating on the screen. It is considered that the ten 1 keV electron beams produced sufficient photons upon impact with the outer attenuator disc of the plasmascope to account for the emission of electrons from the centre electrode of the plasma gun which was held standing at -10 keV to -15 keV.

## CONCLUSIONS

The results of these experiments with the plasmascope on the low density plasma jet may be summarised as follows.

1. Under normal operating conditions no definitive pattern on the cross sectional shape of the plasma jet has been observed which can be associated with an instability. On rare occasions there are some indications of a flute when the diameter of the plasma is limited by an aperture. It is possible that such instabilities are inhibited by the presence of the plasmascope, as for example, magnetic line tying by the conducting front face of the attenuator. However, since the ratios of the diamagnetic signals with distance did not noticeably change with the plasmascope in place we conclude that instabilities are not very important.

2. Only a small number of the energetic ions in the plasma jet have trajectories which encircle the magnetic axis.

3. The transverse velocity distribution of the ions is continuous from close to zero to that maximum velocity giving a Larmor orbit contained within the boundaries of the plasma jet. This maximum velocity may be considerably smaller than that determined by the size of the vacuum chamber.

4. No correlation has been found with the radial position of the plasma jet in the vacuum chamber and the loss of diamagnetic signal. If 'wriggling' of the plasma is small it must be concluded that loss of plasma to the walls is unimportant.

## 4. PLASMASCOPE OBSERVATIONS ON THE PLASMA OF MTSE I

With the success of the plasmascope on the gun facility we were encouraged to construct a special plasmascope to determine ions and electron density distributions in MTSE I(12).

In this experiment a coaxial electrode Marshall gun injects plasma, density ~ $10^{14}$ particles $cm^{-3}$, and velocity ~ $10^8$ cm $sec^{-1}$, into a longitudinal magnetic guide field which rises to ~ 4 kG in 300 cm. This quasi-d.c. magnetic field is uniform over a central region of length ~ 150 cm and then falls to zero in a further 300 cm. At one end of the central region remote from the plasma gun a pulsed mirror coil provides a magnetic field which rises to 8 kG giving a mirror ratio of 2. At the other end of the central region a mirror coil is pulsed to provide a magnetic field which rises to 16 kG giving a mirror ratio of 4. A divertor coil located 85 cm from the gun is energised 7·0 μsec after the gun is fired to divert away slow plasma. Also in the central region six longitudinal Ioffe bars give an $\ell = 3$ minimum B magnetic field configuration with the field at the glass vacuum chamber being 2·5 times that on the axis. The bars are energised 12·0 μsec after the gun and reach peak current at ~ 62 μsec i.e. 50 μsec rise time.

The plasmascope could be located on axis either 60 cm in front of the first mirror coil or 100 cm behind the second. In both cases a diffusion pump was removed and the plasmascope observed by a 45° mirror through the manifold opening. The plasmascope was essentially the same as that described above with a usable aperture of 18 cm. The attenuator consisted of three perforated stainless-steel discs 0·15 mm thick pierced with a regular pattern of round holes 0·3 mm diameter. The transmission of each disc was 12%.

These observations consisted of a number of pictures taken with the plasmascope sited 1) ahead of the first mirror to examine the plasma jet as it entered the magnetic mirror region, 2) located after the second mirror with (a) D.C. fields only, (b) D.C. fields and pulsed mirrors and (c) all fields including Ioffe bars.

### PLASMA INJECTED INTO MIRROR REGION

With the plasmascope ahead of the first mirror the photographs reproduced in Fig.11 were obtained. The plasmascope was operated under normal conditions, -300 volts on the electron suppression grid with the aluminium layer on the phosphor pulsed +10 kV for 0·3 μsec. An oscillogram is included showing the integrated signal from a diamagnetic loop located 2 metres from the gun, together with the relative times at which the plasmascope was triggered.

At early times (Fig.11(a)) the fast electron burst is seen as was found in the earlier work. In this experiment we see that the magnetic axis is quite close to the geometric axis as the electrons originating at the gun are centred in the plasmascope. At a later time (Fig.11(b)) the ions make their appearance and at still later times (Fig.11(c)) the plasma density is much reduced. It is apparent from these photographs and others that the ions have radial and azimuthal distributions which are quite smooth. There is no evidence for plasma fluting or jetting across the magnetic field. The electrons, on the other hand, show a characteristic spiral shape which we have called 'prawns'. These patterns are clearly due to energetic electrons in the plasma jet since they are composed of bright squares located between the image of the grid wires in the phosphor as explained before. These 'prawn' shapes have been reported by others(13).

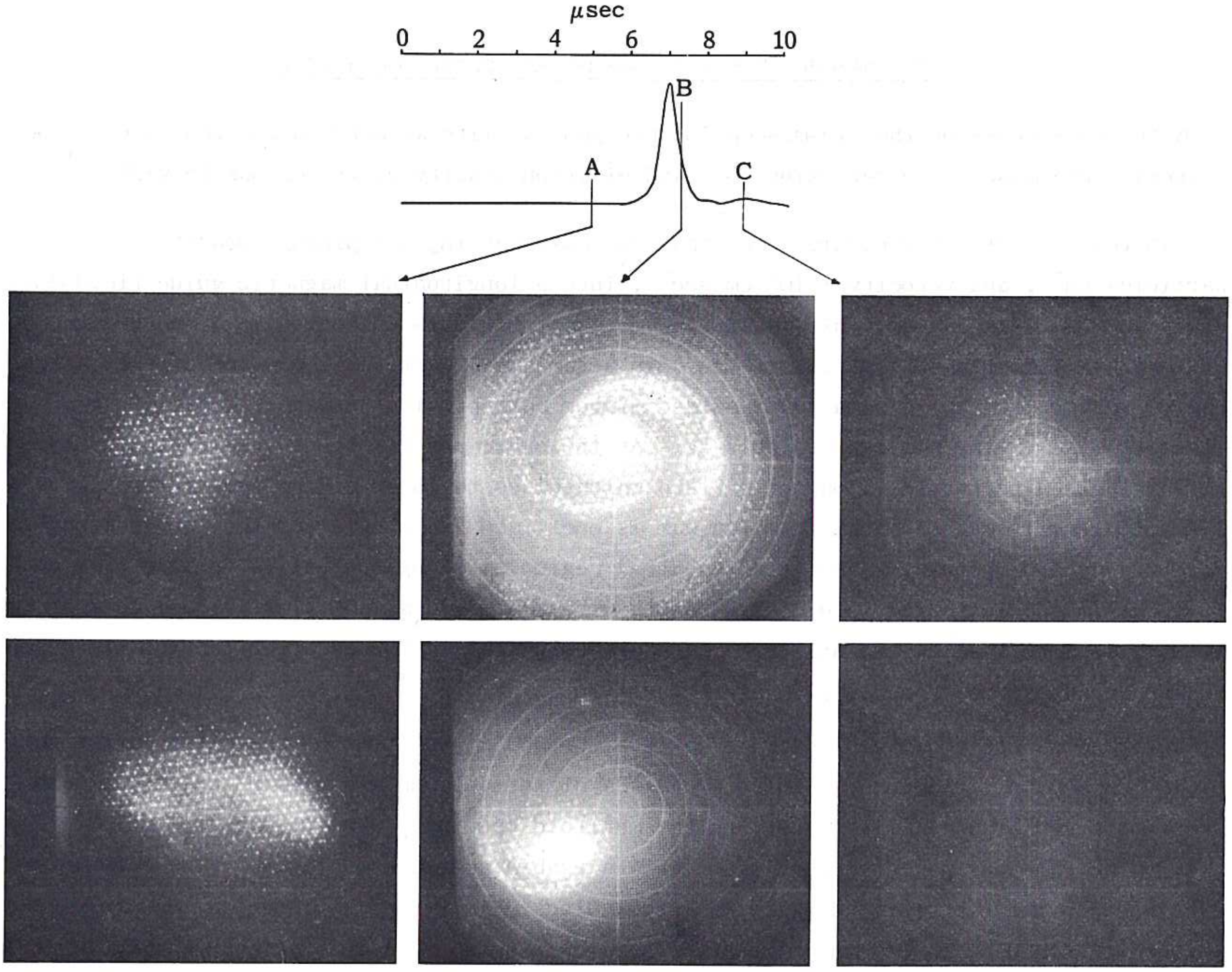


Fig. 11 (CLM-R82)
Plasmascope examines plasma entering the first mirror region of the MTSE I experiment

We suggest that this prawn shape of the electron distribution is due to the radial electric field in the plasma caused by space charge separation. It has been shown by Ashby that electron currents flow from the glass wall near the gun along magnetic fields to the orbiting ions as explained above. If the breakdown along the insulator is parallel to the axis we may then expect that a radial sheet of electron currents will move into the plasma. These electrons will undergo an azimuthal drift due to the crossed radial electric and magnetic fields If the electric field has a radial dependence falling off with radius (to be expected if the electrons are concentrated along the axis), then together with the reduced magnetic field due to plasma diamagnetism about the axis the electrons close to the axis will undergo larger azimuthal drift velocities than outer electrons, and the prawn shape will result. We have reported some observations on the radial electric field (see p. 10) which supports these conclusions.

### PLASMA ESCAPING OUT OF THE SECOND MIRROR

With the plasmascope located behind the second mirror the photographs shown in Fig. 12 and Fig. 13 were obtained. In Fig. 12 only the D.C. fields and divertor were energised and in Fig. 13 the two mirror and gate coils were added. In these examples and many others there is an almost complete absence of structure in the spatial distribution of the ions. Instead the distributions were rather uniform over most of the plasmascope aperture. Also the electron 'prawn' patterns discussed above were much less conspicuous. Probes had given evidence(12) for fluting of the plasma in this experiment with the simple mirror geometry and it was a surprise that flutes were not seen by the plasmascope.

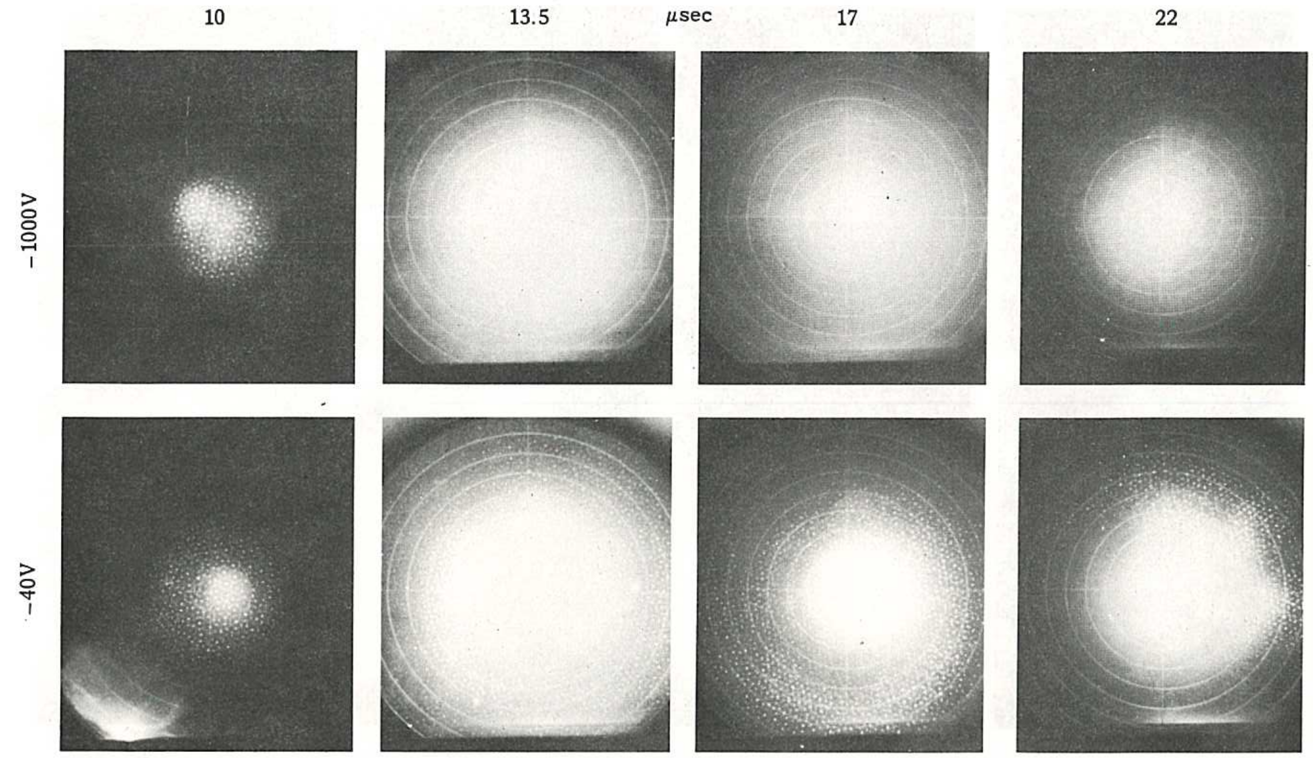


Fig. 12 (CLM-R 82)
Plasmascope examines plasma escaping from the second mirror. DC fields and divertor only

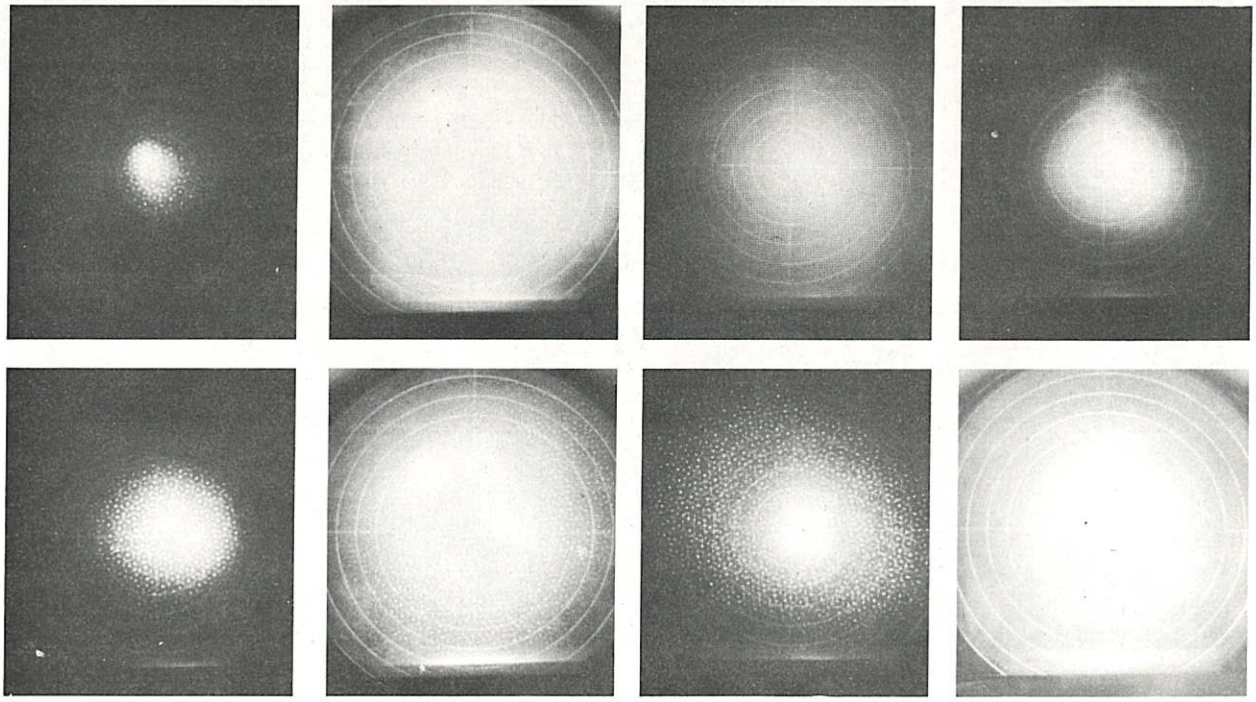


Fig. 13 As Fig. 12 but both mirror coils energised (CLM-R 82)

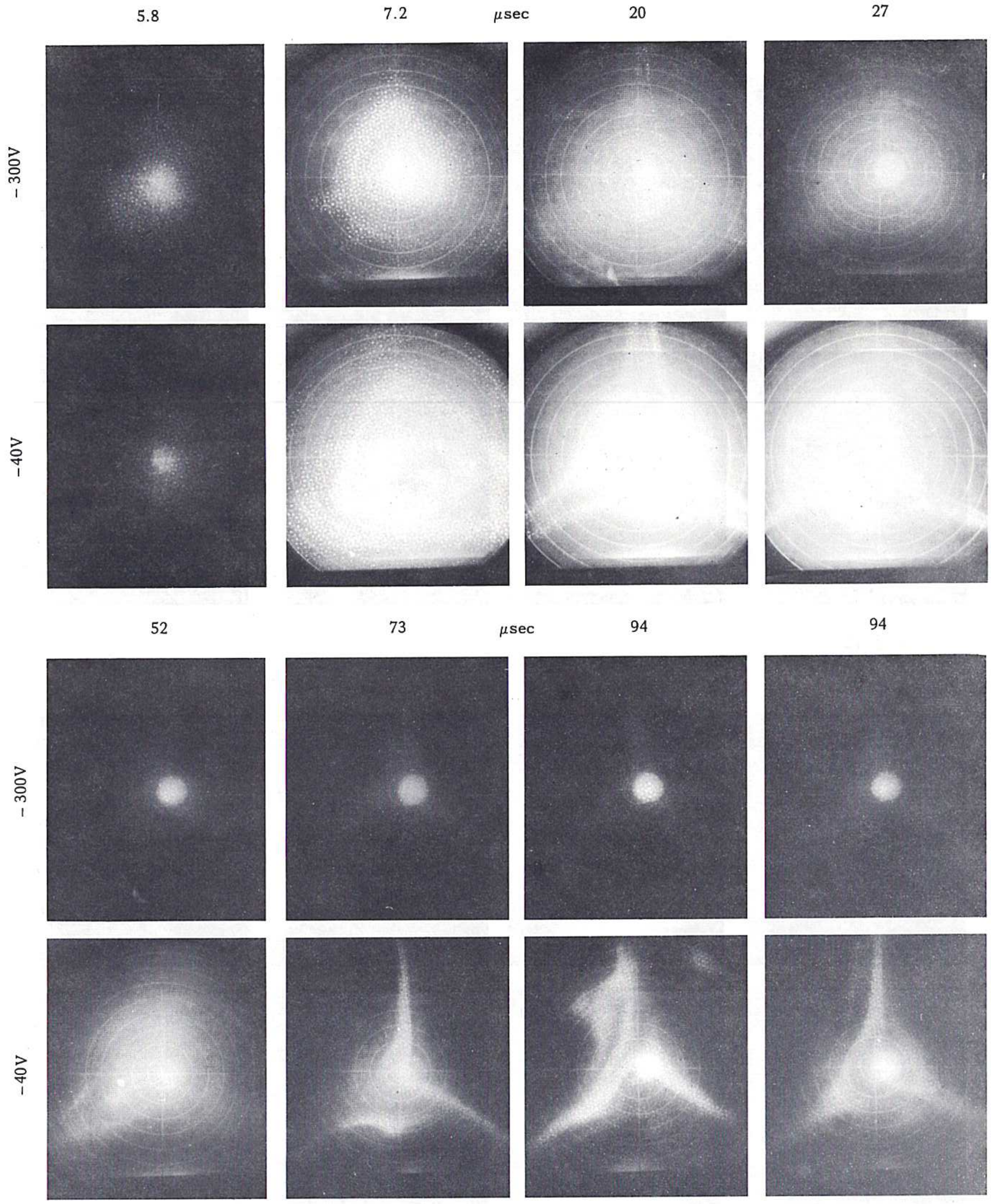


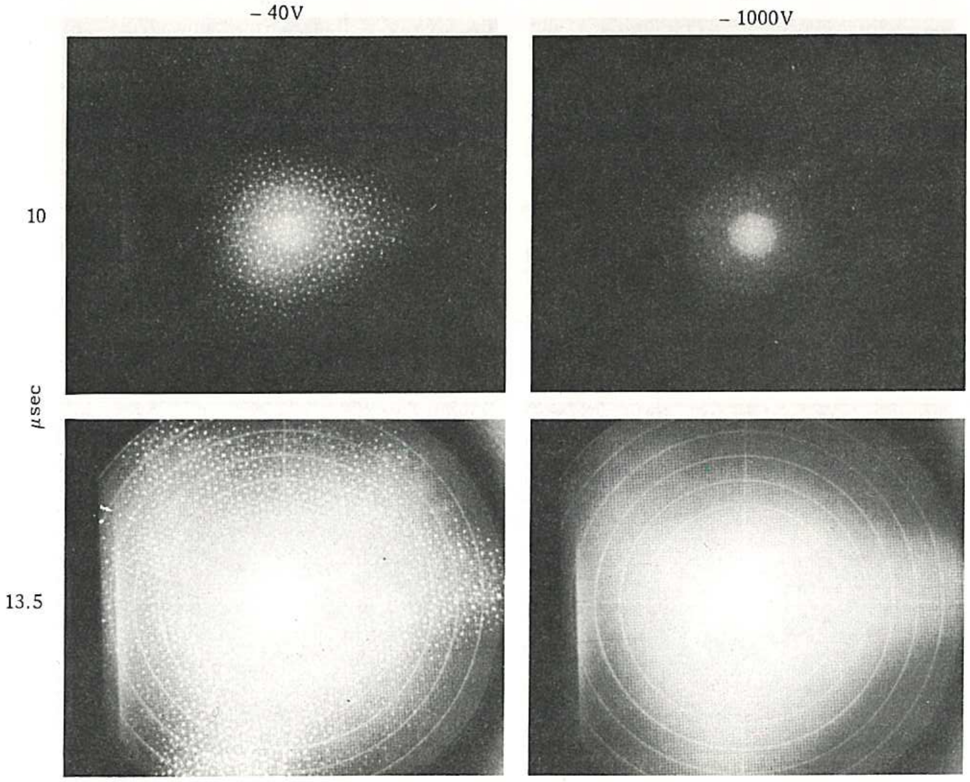
Fig. 14 (CLM-R82)
Plasma escaping from the second mirror with mirror coils and Ioffe bars energised
Grid Bias - 40 volts and -300 volts

However, there is a possible explanation for this lack of detail. The plasmascope may have inhibited the growth of flutes since the conducting surface of the first attenuator disc would tend to 'line tie' the magnetic field. For this reason perhaps only the results obtained at early times should be considered significant.

When the Ioffe bars were energised the results shown in Fig.14 and Fig.15 were obtained. These two figures show the effect of different values of electron suppression grid bias. We see in the pictures near the tube walls the early triangular pattern which with time penetrates further into the centre of the picture. The triangular pattern is most striking when with the bias at -40 volts energetic electrons are included, but is still quite distinct when with -1000 volts ions predominate. Again there is no clearly defined structure in the spatial distribution of the ions and from these photographs, bearing in mind the above reservations on the behaviour of the plasmascope, there does not appear to be any evidence for large scale instabilities.

## CONCLUSIONS

The photographs obtained show no striking evidence for gross instabilities in all cases examined. The plasma appears to flow along the longitudinal magnetic field into the magnetic trap in a well ordered way. As the plasma leaves the trap there is no evidence of instabilities for either a simple magnetic mirror or that with Ioffe bars. At early times energetic electrons give a characteristic spiral or 'prawn' shape pattern which may be due to azimuthal drifts caused by radial electric fields.



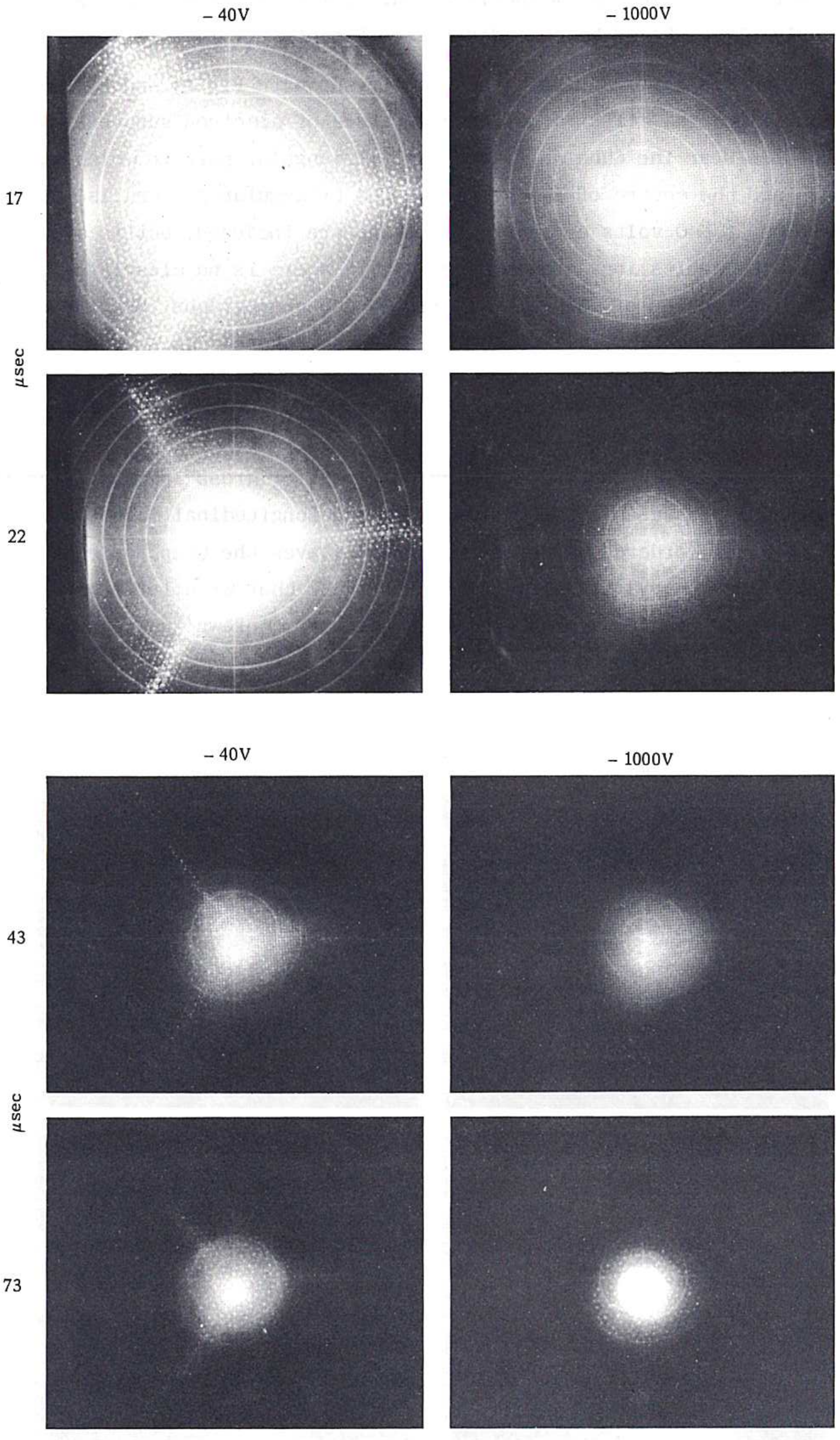


Fig. 15 (CLM-R 82)

Plasma escaping from the second mirror with mirror coils and Ioffe bars energised
Grid Bias - 40 volts and - 1000 volts

## 5. REFERENCES

1. ASHBY, D.E.T.F. and AVIS, B.E. The entry of a tenuous plasma into an axial magnetic field. Plasma Physics (Journal of Nuclear Energy Part C), vol.8, no.1, 1966, pp.1-9.
2. ASHBY, D.E.T.F. The flow of high energy plasma in a magnetic guide field. Presented at the VIth International Conference on Ionization Phenomena in Gases, Paris, July, 1963, vol. IV, pp.465-8.
3. ATKINSON, D.W. and PHILLIPS, J.A. Some observations on the flow of a tenuous plasma in a magnetic field. Culham Report, CLM - R 72, 1967.
4. VERON Dibier. Private communication.
5. MARSHALL, John. Private communication.
6. ELIZAROV, L.I. and ZHARINOV, A.V. Transverse motion of a plasma in a magnetic field. Plasma Physics and Controlled Nuclear Fusion Research, Conference Proceedings, Salzburg, 4-9 Sept. 1961, AEC-tr-5589, Book 1, pp.283-94.
7. SINEL'NIKOV, K.D., SAFRANOV , B.G., PADALKA, V.G. and DEMIDENKO, I.I. Visual study of plasma bursts. Zhurnal Technicheskoi Fiziki, vol.33, no.9, Sept.1963, pp.1055-8. English translation in Soviet Physics-Technical Physics, vol.8, no.9, March 1964, pp.786-9.
8. COENSGEN, F.H., CUMMINS, W.F., NEXSEN, W.E. and SHERMAN, A.E. Plasma camera. Review of Scientific Instruments, vol.35, Aug.1964, pp.1072-4. Also available as report, UCRL-7758.
9. MASON, D.W. An electrostatic ion-energy analyser. Plasma Physics (Journal of Nuclear Energy Part C), vol.6, no.6, 1964, pp.553-8.
10. Colour T.V. Masks: Buckbee Mears Co., St. Paul, Minnesota.
11. KHIZHNYAK, N.H. Private communication.
12. FRANCIS, G., MASON, D.W. and HILL, J.W. Containment of plasma in a magnetic mirror, with hexapole stabilizing fields. Nature, vol.203, no.4945, Aug.8, 1964, pp.623-4.
13. TRUBCHANINOV, S.A. and KALMYKOV, A.A. (Kharkov). Private communication.

Available from

HER MAJESTY'S STATIONERY OFFICE

49 High Holborn, London, W.C.1
423 Oxford Street, London W.1
13a Castle Street, Edinburgh 2
109 St. Mary Street, Cardiff CF1 1JW
Brazennose Street, Manchester 2
50 Fairfax Street, Bristol 1
258-259 Broad Street, Birmingham 1
7-11 Linenhall Street, Belfast BT2 8AY

or through any bookseller.

*Printed in England*

S.O. Code No. 91-3-22-28