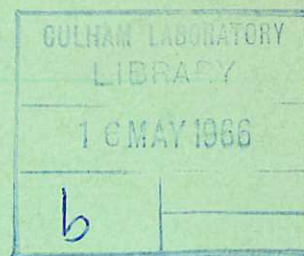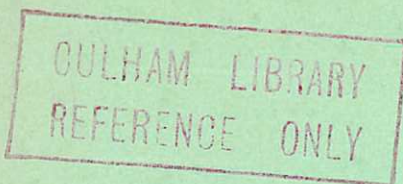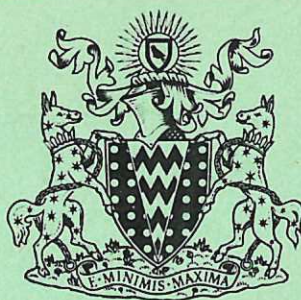United Kingdom Atomic Energy Authority

RESEARCH GROUP

Report

CURRENT INDUCED PUMP-OUT

E. S. HOTSTON
D. J. H. WORT

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by

E.S. HOTSTON
D.J.H. WORT

A B S T R A C T

Afterglow plasmas in hydrogen and deuterium produced in a toroidal device have been shown to be quiescent. A typical afterglow had an electron density of 4×10^{13} cm^{-3} near the bore centre, with the electron and ion temperatures substantially equal at 3200°K in this region. Near the torus wall the ion temperature fell to approximately one half of the electron temperature. This plasma was produced in an axial magnetic field of 150-500 gauss, and decayed by classical diffusion and recombination processes with a lifetime of 200 μsec.

An instability was induced in this plasma by causing a current of 1-2 A cm^{-2} to flow in it. This instability caused a rapid loss of plasma ("pump-out"), and was outwardly very similar to the pump-out induced in the Stellarator, reported by Motley[1]. The same criterion for the current required to cause pump out was applicable, but it was found that this criterion is incorrect, as the seat of the instability lies in the tenuous post pump-out rather than the pre-pump out plasma.

The correct criterion is given by Jackson[2], and it was found that this criterion was obeyed within a factor of five. There is no difficulty with the apparent absence of ion Landau damping which Motley required for his drift criterion to be valid.

The instability, after starting in the low density plasma near the inner wall of the torus, propagated outwards, creating a low density plasma suitable for its own maintenance as it proceeded.

C O N T E N T S

1. INTRODUCTION

The object of the experiments described below was to confirm and extend results repor-
ted by Motley[1], who had found a form of enhanced diffusion of plasma perpendicular to
the magnetic field in the Stellarator. A similar form of enhanced diffusion also occurred
in the ZETA assembly at Harwell[3].

The criterion proposed by Motley for the onset of the enhanced diffusion was that the
electron drift velocity due to the electric current which drove the diffusion was equal to
the electroacoustic speed. This is the condition for the initiation of an electrostatic
ion wave in a plasma of cold ions and hot electrons[4,5] but the stellarator plasma should
have been stable against this instability as the ions were not cold. Confirmation or re-
jection of Motley's results was important from the theoretical standpoint, since it would
throw light on the validity of ion Landau damping.

The experiments reported here were carried out with the small Mk.IV torus at Harwell,
and it was found that enhanced diffusion could be induced in a quiescent afterglow in this
torus by passing a pulse of electric current through the plasma. The diffusion was detec-
ted by measuring the plasma density with a microwave interferometer and a Langmuir probe.

It was found that the criterion for the onset of the instability appeared to be similar
to that proposed by Motley: however, more detailed examination showed that this interpre-
tation of the results was wrong.

2. THE APPARATUS

The Mk.IV torus was arranged with its major diameter in a horizontal plane (see Fig.1).
The torus was equipped with coils capable of giving an azimuthal magnetic field of several
hundred gauss. An R.F. preionizer provided a tenuous plasma in which a current pulse was
induced by the ignitron-controlled discharge of a 378 μF, 8 kV capacitor bank through the
primary windings of an ion cored pulse transformer. This current pulse, some tens of kilo-
amps in magnitude, ionized and heated the plasma and under suitable conditions left an
afterglow when the main current pulse had decayed to a low level (200 amps or less). The
total duration of the current pulse was some 500 μsec , and of the afterglow some milli-
seconds.

A few hundred microseconds after the initiation of the main discharge (an interval
determined empirically) the capacitor bank could be partially recharged from a second

similar capacitor bank via a one ohm resistor. As the ignitron discharging the main capacitor bank had not deionized by this time an additional current flowed in the primary windings and hence in the plasma. The magnitude of this current was controlled by the charging voltage of the second capacitor bank.

Two different Langmuir probes were used at different times, both being conventional double probes with platinum electrodes of equal area. The probe voltages were not swept but the characteristic curves were obtained from successive shots using different fixed bias voltages; the afterglow gave results sufficiently reproducible ($\pm$ 5% in probe current) for this to be acceptable.

The microwave interferometer worked in the 4 mm band using oversize waveguide. It was set up so that it looked vertically across a minor diameter of the torus at one of the window blocks.

3. PROCEDURE

The experiments fell into two separate groups separated in time by an interval of over a year. Since it was not possible to assembly the apparatus in exactly the same way each time some minor discrepancies appear between the observations of the two groups of experiments; the groups are designated as group A and group B and the appropriate group indicated for each observation. The results of the two groups of experiments are however the same within the limits of experimental error.

One difference between the two groups of experiments was that in group A the Langmuir probe was situated at the window block, generally placed along a horizontal minor diameter. For group B it was placed at an observation port let into the torus 135° in azimuth from the window block.

The gases used in the torus were either hydrogen or deuterium, and the results unless otherwise stated are for hydrogen with the plasma current anticlockwise looking down at the torus from above, and the azimuthal magnetic field clockwise. The pump-out was found to be unaffected by the directions of the magnetic field and plasma current.

The time origin has been chosen to coincide with the start of the disturbing current pulse.

4. THE AFTERGLOW PLASMA

It was first necessary to establish the properties of the afterglow plasma and to show that it was quiescent.

(a) THE PLASMA DENSITY

Fig.2 shows the saturated Langmuir probe current with the probe at the window block 2 cm outside the line of sight of the interferometer aerials, and also the microwave interferometer output as the plasma decayed. The interferometer fringes in Fig.2 lack symmetry, but this is typical of a system in which the amplitude of the microwave beam transmitted through the plasma was initially much less than the amplitude of the reference beam but became much greater as the plasma decayed. Fig.3 shows a typical characteristic curve of the Langmuir probe, from which the electron temperature can be seen to be 4500 ± 1000 $^{\circ}$K.

The microwave interferometer yields a line integral of the plasma density along the line of sight of the aerials and the density can only be determined absolutely if the density distribution is known. The Langmuir probe yields good relative density measurements and the results of traversing the probe both vertically and horizontally across the window block are shown in Fig.4.

The interpretation of the microwave results is facilitated if the density distribution is assumed parabolic and cylindrically symmetrical[6], the density given as a function of radius r by

$$n = K \, n_c \left(1 - \frac{r^2}{r_o^2} \right) ,$$

where   n   = electron density

n_c = the critical density for the microwave beam (6.3×10^{13} cm^{-3})

K   = a dimensionless parameter giving the central density

r_o = a parameter giving the size of the distribution.

This distribution agrees with the observed distribution at the window point (Fig.4) with r_o equal to the minor radius of the torus. Figs.5 and 12 show the density distribution at the 135° port, and it is evident that the inclusion of the window block in the torus caused some perturbation in the density distribution.

Using the parabolic distribution, K has been calculated as a function of time to an accuracy of 5% from the interferometer trace of Fig.2, using the theory given by Wort[6], the result being shown in Fig.6. It should be noted that the central density required for a parabolic distribution to give the same line of sight density as the measured distribution, is 16% higher than the true central density, for K ∼ 0.5. In what follows the parabolic density distribution will be assumed.

The saturation current density collected by the Langmuir probe is for a hydrogenous

plasma
$$\alpha \, n_e \, e \sqrt{\frac{kT_e}{M_i}}$$

where e is the electronic charge, k Boltzmann's constant, T_e the electron tempera-
ture, M_i the ionic mass, and α a dimensionless constant. The expression is usually
derived assuming the mean free paths of the particles in the plasma are larger than the
dimensions of the probe[7] but this is not the case for the afterglow plasma. Waymouth[8]
has calculated the saturation ion current for a spherical electrode in a plasma similar to
the afterglow, and found that when the ion and electron temperatures are equal, which is
the case here (see below), then the current is still given by the above expression with
$\alpha \sim 0.5$ if the probe radius is in the range 0.1 to 3 mm. It was also found that the pre-
sence of the probe perturbs the density of the plasma in the region of the probe over dis-
tances comparable with the probe radius.

Fig.5 shows the value of K deduced from the saturated Langmuir probe current assum-
ing a value of $\alpha = 1.00$. The probe density is consistently less than the microwave den-
sity by between 10% and 18% in accordance with the estimated systematic error of the
microwave determination. From this it is seen that the Langmuir probe can be used to
measure densities if it is first calibrated against the microwave interferometer.

(b) THE ELECTRON TEMPERATURE

The electron temperature has been measured by three methods:

(1) From the Langmuir probe characteristic. This method has been illustrated above;
it is open to the objection that it is sensitive to the tail of the Maxwellian energy
distribution of the electrons.

(2) From the attenuation of a microwave beam crossing the discharge. Wort[6] has
calculated the attenuation of the beam crossing a plasma of parabolic density distribu-
tion. The temperature of the afterglow can be calculated from the amplitude of the
interferometer fringes, but departure from the parabolic density distribution limits the
accuracy to $\pm$ 20%.

(3) From the low frequency resistivity of the plasma. The low frequency resistivity
η of an hydrogenous plasma is related to its temperature by $\eta = 2.64 \times 10^4 \, T_e^{-3/2}$
ohm-cm[9] the numerical factor being a slowly varying function of temperature and
density. To obtain the resistivity a current pulse of small magnitude was sent
through the plasma and the volts/turn around the torus measured at peak current. The
method is liable to a systematic error as the current pulse applied had sufficient
energy to heat the plasma, and might in addition have caused a current driven insta-
bility in the plasma. The shot-to-shot repeatability was 7%.

Fig.7 shows the variation of the electron temperature with time, the electron-ion collision frequency used in the reduction of the microwave results being that given by Heald and Wharton[9]. The agreement between the microwave results and that calculated from the resistivity is good.

(c) THE ION TEMPERATURE

The ion temperature was not measured directly, but was found to be within 20% of the electron temperature by considering the chain of collision processes transferring energy from the electrons (energy source) to the torus wall (energy sink). There are four processes of importance:

  (a) Electron-ion collisions, heating the ions.

  (b) Ion-molecule collisions, cooling the ions but heating molecules.

  (c) Electron-molecule collisions, heating the molecules.

  (d) Molecule-wall collisions, cooling the molecules.

In equilibrium "a" balances "b" and "b" and "c" together balance "d".

It is necessary to make an assumption regarding the neutral molecule concentration n_m. The initial gas pressure (3.8 mTorr) corresponds to an n_m of 1.4×10^{14} cm^{-3}. However, outgassing of the torus wall during the pulse probably occurred, so an alternative value for n_m of 7×10^{14} cm^{-3} is also used, corresponding to the evaporation of 3.3 monomolecular layers of absorbed gas[10].

The ion-neutral collision frequency is calculated from the assumed neutral densities and the ionic mobility given by Von Engel[11], having divided the published values by $\sqrt{3}$ to allow for the quasi-equality of ionic and molecular temperatures. It appears that the effect of error in the assumed mobility is very slight when the values of ionic and molecular temperatures are ultimately obtained.

Calculated values for the temperatures are given in Table 1 for various initial conditions in hydrogen. These results are specifically valid in the centre regions of the torus, embracing some 75% of the charged particles

<u>Table 1</u>

Time μsec	0	0	100
n_m cm^{-3}	1.4×10^{14}	7×10^{14}	7×10^{14}
T_e °K	3200	3200	2100
T_i °K	3100	2700	1900 ⎫
T_m °K	1750	1650	900 ⎬ ± 200°K

Thus it appears permissible to take the ion temperature to be substantially equal to the electron temperature in the hydrogen afterglow, and a similar result is obtained for deuterium.

Near the torus wall, however, this equality no longer holds. The electron density is much lower (2×10^{12} cm^{-3} at time zero and 5 cms from the inner torus wall) so the energy transfer to the ions is reduced, whilst the molecular temperature will also be lower. The calculated ion temperature for hydrogen, with a T_e of 3200°K and an n_e of 2×10^{12} cm^{-3}, and assuming a molecular temperature of 1000°K, becomes 1440°K. Thus it is concluded that near the torus wall the ions are considerably cooler than the electrons, a conclusion which is of some importance when the mechanism of pump-out is discussed (see section 7(b)).

(d) THE DECAY OF THE AFTERGLOW PLASMA

If the decay of the plasma can be shown to be governed by classical processes, there can be little doubt that it is quiescent.

A plasma decaying partly by diffusion and partly by recombination will have a density time relation given by

$$-\frac{dn}{dt} = a\,n + b\,n^2$$

where the coefficient a may be related to the diffusion coefficient, whilst b refers to the rate of recombination. The values of a and b deduced from the observed behaviour of the density (Fig.6) are:

Hydrogen $a = 2240$ sec^{-1} $b = 2.7 \times 10^{-11}$ cm^3 sec^{-1}

Deuterium $a = 1790$ $b = 6.6 \times 10^{-11}$ cm^3 sec^{-1}

Comparison between the observed density-time curve and the curve predicted by the a and b coefficients for hydrogen is made in Fig.8.

Bates[12] has calculated the recombination coefficient b, obtaining a value of 7.1×10^{-11} cm^3 sec^{-1} for a plasma of density 3.5×10^{13} cm^3 sec^{-1} at a temperature of 3000°K, falling to 1.6×10^{-11} cm^3 sec^{-1} if the temperature is reduced to 2500°K. These values are in reasonable agreement with the experimental quantities.

The ambipolar diffusion coefficient may be calculated from the plasma parameters assuming the diffusion to be taking place in a straight cylindrical tube: the correction for toroidal drift is found to be about 10%, and may be neglected. It is not, however, permissible to neglect ion-molecule collisions, and the Spitzer formula for diffusion across a magnetic field ($D = \eta \beta$ where η is resistivity and β the plasma-to-magnetic pressure

ratio) is inapplicable. Again the ionic mobility is required to calculate the ion-molecule collision frequency: as before, Von Engel's[11] values are used, divided by $\sqrt{3}$, and the effect of errors in the mobility is small. The calculated diffusion coefficients are given in Table II below.

Table II

Gas	n_m	$\omega_e\tau_e$	$\omega_i\tau_i$	D_c cm^2 sec^{-1}
H$_2$	1.4×10^{14}	0.33	0.52	9.9×10^4
	4.2×10^{14}	0.33	0.34	8.6×10^4
	7×10^{14}	0.33	0.19	6.4×10^4
D$_2$	1.4×10^{14}	0.46	0.39	8.8×10^4
	4.2×10^{14}	0.46	0.21	6.7×10^4
	7×10^{14}	0.46	0.10	5.2×10^4

The observed diffusion coefficient D_o is obtained from the a coefficient in the decay equation above:

$$D_o = a (0.416 R_1)^2$$

yielding values for D_o of 8×10^4 cm^{2}sec^{-1} for hydrogen and 6×10^4 cm^2 sec^{-1} for deuterium, the experimental error being of the order of $\pm 10\%$.

Thus there is good agreement between theory and observation for the decay of the plasma.

5. QUIESCENCE

The properties of the afterglow plasma described above show that it was decaying classically and was quiescent, so that it was a suitable medium in which to induce instabilities.

To recapitulate, these properties were:

(a) The close agreement between the microwave and Langmuir probe methods of measuring density (Fig.5).

(b) The close agreement between the decay rate of the plasma and the relation expected theoretically (Fig.8).

(c) The good agreement of the observed recombination and diffusion coefficients with the theoretical values.

(d) The steady variation of the microwave transmission of the plasma with time.

(e) Also the insertion of electrostatic probes into the afterglow failed to detect any fluctuating electric fields.

6. OBSERVATIONS ON PUMP-OUT

(a) THE EFFECTS OF A CURRENT PULSE

A current pulse was passed through the afterglow plasma. The current waveform and Langmuir probe traces were displayed or a double beam oscilloscope, the probe being inserted at the 135° port with its electrodes at the region of maximum density. Fig.9 shows a typical set of oscillograms, including the output of the microwave interferometer located at the window block, whilst Fig.5 shows the density distribution across the torus bore at the 135° position.

The probe current is not saturated during the first hundred microseconds of the trace, since the electron temperature was not negligible compared with the potential between the probe electrodes. However, during the duration of the disturbing current pulse the density and temperature of the plasma were such that the Langmuir probe current was within 5% of the saturation value.

The probe current in Fig.9b is less concave than that of Fig.9a showing that a disturbing current pulse of 1.04 kA caused some reionization of the residual gas in the torus. Increasing the current by a few hundred amps resulted in a sudden fall in probe current which is interpreted as a sudden fall in plasma density (Fig.9c). Fig.9d shows the effect of the disturbing current being increased to 1.9 kA; the sudden fall in density is still seen but there is now some trace of reionization of the background gas at a time of 320 μsec after the initiation of the disturbing current.

A similar sudden fall in probe current is seen with the Langmuir probe at the window block. Fig.10 taken in the same geometry as Fig.2 shows the sudden fall in probe current with the passage of a disturbing current pulse.

It is this sudden fall in density with the passage of the disturbing current pulse that is termed pump-out. Pump-out was found to set in when the peak value of the disturbing current pulse reached or exceeded a critical value which for the experiments of Fig.9 was 1.2 ± 0.1 kA.

The critical current did not appear to be affected by reversing the direction of the azimuthal magnetic field. Pump-out could be obtained with fields of strength between 125 and 500 gauss.

Pump-out only occurred if the plasma was clean, and after letting the torus up to air it was necessary to run for some eight hours at a rate of 1 shot every 4 sec before

repeatable results could be obtained.

Microwave interferometer fringes can be seen before and after the start of the disturbing current pulse, Fig.10. The fringes disappear 50 µsec before the sudden fall in plasma density recorded by the Langmuir probe, but reappear immediately afterwards, when one fringe is seen, showing the central plasma density had fallen to $\leqslant 2 \times 10^{12}$ cm^{-3}. The loss of fringes was due to the plasma ceasing to transmit the microwave beam of the interferometer, as shown by disconnecting the reference arm of the interferometer and measuring the transmission across the plasma. Fig.11 shows the results, the transmission returning from zero after the critical density cut off produced by the main current pulse, but falling to a low level (< 5%) for some 50 µsec at the time when the Langmuir probe indicated pump-out, returning again rapidly after pump-out. The fluctuations are due in part to an interferometer effect arising from reflections from the metal walls of the torus. Possible causes of the lack of transmission are discussed in section 6(d).

The value of the critical current was not, however, such a well defined quantity as the results of Fig.9 indicate. Fig.12 shows results obtained with a high gas pressure in the torus (7.8 mTorr). The density distribution across the torus bore obtained by traversing the Langmuir probe across the bore at the 135° port is also shown. Pump-out was found to occur near the inner wall of the torus for currents less than that required for pump-out near the centre of the torus bore, but at these low currents pump-out started at the inner wall and moved outwards to a point determined by the magnitude of the current pulse and then stopped. In Fig.12 the pump-out was monitored by placing the Langmuir probe at different points along a horizontal minor diameter. With the probe at the point of maximum density of the afterglow the current for the onset of pump-out was 1.5 kA. With the probe 11 cm from the inner wall, pump-out was found at currents of 750 amp or less. At a distance of 4 cm from the outer wall pump-out did not occur for currents up to 3.3 kA (the highest current used), although this current caused sufficient ionization of the background gas in the torus for two pump-out steps to appear near the inner wall of the torus.

For the lower gas pressures of Fig.9 (3.8 mTorr), pump-out was observed with the probe 1.4 cm from the outer wall for disturbing currents of 1.4 kA (the critical current was not measured). The pump-out of Fig.10 also extended to within 2 cm of the outer wall of the torus.

For these reasons critical current will be defined as the disturbing current sufficient to cause pump-out as indicated by the Langmuir probe when at the point of maximum density of the undisturbed afterglow.

The output of the microwave interferometer in Fig.12 is difficult to interpret as the disturbing currents used were either much less than the critical current for the line of sight, in which case no pump-out occurred, or much greater, in which case pump-out occurred together with a substantial degree of reionization of the residual gas in the torus.

(b) THE PUMP-OUT STEP

Fig.12 shows that the pump-out started near the inner wall of the torus and moved outwards, and thus consisted of a moving step in the density with an approximately 20-fold decrease in density across it.   The velocity of the step was measured by traversing the Langmuir probe across a minor diameter of the torus and timing the arrival of the step at the probe, and is given in Table III.

Table III
Velocity of pump-out step

Gas	Axial field gauss	Velocity of step cm/sec ± 20%	Position of probe	Series of Experiments
H_2	250	10^5	window block	A
H_2	300	$8 \cdot 10^4$	135° port	B

The time taken for the step to pass the end of the probe was 20-40 μsec (sometimes less) so that its width was 2-4 cm.

(c) THE DIRECTION OF PLASMA MOTION

Two types of motion could account for the movement of the step. Either the plasma moved outwards bodily or the plasma diffused down the density gradient at the step to the inner wall of the torus. If the latter explanation were correct the equation of continity predicts that the transverse drift velocity of the post pump-out plasma would be some 20 times that of the step i.e. $1.6 - 2 \times 10^6$ cm sec^{-1}.   In section 7(c) a theoretical estimate of this velocity is made, yielding a value of $2.2 \ 10^6$ cm sec^{-1}.

The plasma motion was investigated by placing an electrostatic probe on a vertical minor diameter at the window block, with the electrodes symmetrically placed with respect to the axis of the tube.   The electrode separation was either 10 or 25 cm, and the output of the probe was displayed on an oscilloscope with a balanced amplifier.   Pump-out was obtained with somewhat greater difficulty than before possibly due to contamination of the discharge by the electrodes.

Fig.13 shows a series of oscillograms of the voltage induced between the electrodes and the corresponding Langmuir probe signals.

In Fig.13a, the disturbing current was too low to cause pump-out; during the first 100 μsec of the trace, whilst the tail of the main current pulse was still flowing, the potential induced across the probe corresponded to an outward movement of the plasma; this movement decreased as the main current pulse died away, but revived during the duration of the disturbing current pulse. Fig.13b and 13c show the results of increasing the disturbing current pulse to a level sufficient to cause pump-out. The probe signals now show a reversed voltage corresponding to an inward movement of the plasma which lasted for 120-150 μsec.

The plasma flow at pump-out was found to be independent of both the direction of the axial magnetic field and the direction of the plasma current.

The time taken for the step in density to reach the outer wall of the torus after passing the probe was about 150 μsec which agrees well with the duration of the inward motion of the plasma deduced from the oscillograms with 10 cm electrode separation. The Langmuir probe was not situated at the window block so there was a time lag between the inward movement registered by the electrostatic probe and the pump-out registered by the Langmuir probe. Subsidiary measurements using a beam of microwaves as a probe showed that the electrostatic probe registered the inward movement at, or slightly before (10 μsec), the step in density arrived at the electrodes, that is during the time the microwave transmission was cut off.

(d) THE MICROWAVE TRANSMISSION OF THE PLASMA

The loss of microwave transmission noted in section 6A might be due to

(a) Collisional absorption in the plasma

(b) Refraction of the beam due to sharp density gradients

(c) Scattering of the radiation by a turbulent region in the plasma.

If the reason were (a), high absorption would, by Kirchoff's law, imply high emission. An attempt was made to detect any emission at pump-out using a radiometer of sufficient sensitivity to detect a radiation temperature of 1800°K. No emission was seen although the plasma temperature was estimated to be in excess of 3000°K, implying the lack of transmission was not due to an absorption of energy.

If the lack of transmission were due to refraction at a moving density gradient it is unlikely that the cut off would last for as long as 50 μsec, since the discontinuity in density would have crossed the line of sight of the aerials in 20 μsec (see section 9). It is also noticeable from Fig.12 that the cut-off appeared before the fall in density, so that the high density plasma 3 cm in advance of the moving discontinuity had become opaque, whereas the plasma behind the discontinuity was transparent. Attempts to detect refracted microwave power by moving the receiving aerial failed, because of stray reflection of power from the metal wall of the torus.

An alternative explanation to refraction of the beam is (c): it is suggested that the plasma ahead of the discontinuity was driven into a turbulent state by the passage of the disturbing current, causing variations in refractive index which scattered power out of the microwave beam. It may be shown that if the plasma were turbulent with density fluctuations of 10%, and with a correlation length of 1 cm, the transmission would be less than 5%[13].

It was not possible to decide between (b) and (c).

(e) OSCILLATING ELECTRIC FIELDS

During the A group of experiments the Langmuir probe, inserted at the window block, was used without bias as an electrostatic probe. A typical oscilloscope picture is shown in Fig.14, together with the interferometer output. It can be seen that after the inter-ferometer indicates pump-out the electrostatic probe shows erratic high-frequency "hash", with frequencies up to about 1 Mc/s. The appearance of these fields was rather unpredict-able, and their duration brief, making frequency analysis difficult: the lowest frequency seen to occur strongly was about 400 kc/s, which is just about the ion cyclotron frequency of 380 kc/s at the location of the probe electrodes

For the group B experiments the electrostatic probe described in section 6(C) was in-serted at the window block, the electrodes being 10 cm apart horizontally and spaced symmetrically about the bore centre. During the undisturbed afterglow decay the outer electrode became slightly negative (less than 1.5 volts) with respect to the inner one, but when a disturbing current sufficient to cause pump-out was passed the outer electrode be-came positive. This polarity was irrespective of the direction of the plasma current or axial magnetic field, and the potential difference amounted to some 10-20 volts, with vio-lent fluctuations.

During some shots the probe picked up a high frequency voltage, which was examined by passing the signal through a high-pass filter with a cut-off frequency of about 100 kc/s.

The filtered signal was displayed on a dual-trace oscilloscope, and Fig.15 shows a typical result. The lower trace shows the electrostatic probe output, with evidence for an electric field oscillating at about 360 kc/s with a strength of some 50 mV/cm. This frequency is about 0.8 of the ion cyclotron frequency for the hydrogen ion at the bore centre. When the experiment was repeated in a deuterium discharge the oscillation frequency fell to about 180 kc/s, so the oscillating fields would appear to be intimately related to the ion cyclotron frequency.

These fields only appeared if the disturbing current was sufficient to cause pump-out, and it may be noteworthy that they were considerably easier to detect with the "B" experimental arrangement.

(f) THE EFFECT OF A VERTICAL MAGNETIC FIELD

A vertical magnetic field was applied which interacted with the axial current flowing in the plasma, causing a radial displacement of the plasma. Some combinations of current and field directions destroyed the afterglow, others stopped the pump out which was monitored by the Langmuir probe placed at the position of maximum density of the undisturbed afterglow. Table IV lists the results, which are independent of the direction of the axial magnetic field. The combinations of field and current which destroyed or reduced the duration of the afterglow were those in which the B × I force was directed outwards; it was thought that the plasma at the end of the main current pulse was brought into contact with the outer wall of the torus.

The difference in the fields of 7 gauss needed in one case to remove the afterglow and the 10 gauss needed in the other was attributed to the presence of a stray magnetic field of 1 or 2 gauss vertically upwards.

<u>Table IV</u>

Effect of a vertical magnetic field on the pump-out

Vertical field / Plasma Current	Upwards	Downwards
Clockwise	Pump-out stopped by a field ⩽ 6 gauss	Afterglow lifetime greatly reduced by field of 10 gauss.
Anticlockwise	7 gauss removed afterglow	Pump-out stopped by a field of 3 gauss.

The suppression of pump out by a vertical field of small magnitude is consistent with the pump out being caused by a critical drift velocity of the charged particles in the plasma being exceeded when the current pulse was applied. To demonstrate this, the density distribution of the afterglow was measured by traversing the Langmuir probe across a minor diameter of the torus at the 135° port, with the direction of plasma current anticlockwise, both with and without a field of 6 gauss vertically downwards. The effect of the vertical field was to alter the distribution of the plasma in the torus, in particular it pushed the position of the density maximum towards the axis of the torus by 6 cm, so that it was 2 cm out from the axis of the torus. By keeping the plasma away from the walls the magnetic field increased the line density by 70%, and the plasma density 6.5 cm from the inner wall of the torus by a factor of 3. So that the critical current for pump out would be increased by a factor of 1.7, if the electron drift velocity in the centre of the plasma were the important parameter, or by a factor greater than 3 if the drift velocity at the inner wall were the important factor. This estimate requires that the current pulse produced no re-ionization of the background molecules, or any increase in electron temperature, which theory predicts should increase the critical velocity (see section 8). When these effects have been taken into account it is estimated that the critical currents should be raised by at least several tens of per cent on the values given above.

7. DISCUSSION OF THE OBSERVATIONS

(a) THE PUMP-OUT STEP AND THE DIFFUSION COEFFICIENTS

It has been shown in section 6(b) that the pump-out involved a density step some 2-4 cm thick, which moved outwards across the torus to about 10^5 cm sec^{-1}. The plasma density fell from 4×10^{13} cm^{-3} to 2×10^{12} cm^{-3} as the step passed, and the plasma motion was directed towards the inner wall of the torus bore.

The thickness of this density step was some ten times the ion mean free path, and it is thus permissible to calculate the diffusion coefficient appropriate to the flow of plasma down the step. This coefficient is about 2×10^5 cm^2 sec^{-1}, sufficiently close to the value of 8×10^4 cm^2 sec^{-1} measured in the undisturbed afterglow for the diffusion to be classical. On the other hand, the diffusion coefficient for the tenuous post pump-out plasma would be about 3×10^7 cm^2 sec^{-1}, some 400 times the classical coefficient.

(b)   THE MAINTENANCE OF PUMP-OUT AND SOME PROPERTIES
      OF THE POST PUMP-OUT PLASMA

The instability causing pump-out could lie in one or more of three regions of the
plasma:

  (a) The dense pre-pump-out plasma

  (b) The density step

  (c) The post-pump-out plasma

If the instability occurred in regions (a) or (b) it is difficult to see why the plasma
diffusion coefficient in these regions is essentially unaltered, whereas the diffusion co-
efficient in the post-pump-out plasma is increased by some 400 times. On the other hand,
if the instability occurred in region (c), and itself gave rise to the high diffusion co-
efficient, the step would be formed naturally as plasma diffused into the instability-
rarefied plasma with the classical diffusion coefficient.

Furthermore, the ion-molecule mean free path is short, so that collisions would soon
destroy the motion of the ions in the post-pump-out plasma unless some positive driving
force existed there. These collisions would give the molecules an overall directed motion
towards the torus wall, and hence increase the rate of cooling of the molecules. Conversely,
the return flux of cold molecules from the wall would tend to cool the ions rapidly, so that
in the post-pump-out plasma the ion temperature would be appreciably lower than the electron
temperature - the electron-ion mean free path is sufficiently long for there to be very
little rehating of the ions.

The electron temperature in the post-pump-out plasma cannot be very different from that
in the pre-pump-out plasma, for there are no discontinuities in either the current pulse
(Fig.9) or a volts-per-turn trace when pump-out occurs, indicating no perceptible change
in resistivity. The resistance measurements are slightly dependent on the magnitude of the
disturbing current, a current of 1.08 kA indicating an electron temperature of 3600°K where-
as a current of 1.30 kA gave a temperature of 4000°K. The temperature at the corresponding
time in the undisturbed afterglow was 3200°K.

Thus the post-pump-out plasma properties are reasonably well determined: the electron
density is about 2×10^{12} cm^{-3} and the electron temperature is about 3600°K. The molecule
temperature is probably low, and the ion temperature is close to the molecule temperature.

This plasma may be compared with the plasma close to the inner wall of the torus
(section 4(c), which has comparable electron density and temperature, and which has been

shown to have an ion temperature considerably lower than the electron temperature even in the absence of any enhanced cooling of the molecules produced by directed motion to the wall. The fundamental cause of the different ion-electron temperature ratios in the dense and rarefied plasmas is the decrease, whereas the ion-molecule collision rate is substantially the same.

The similarity of the post pump-out plasma and the initial plasma close to the torus wall suggests that if the post-pump-out plasma could support the instability, so could the plasma near the wall. In particular, if the instability arose from the electron drift velocity it would be expected to start at the region of maximum current density, close to the inner wall of the torus bore.

It is therefore postulated that an instability started near the inner wall and propagated outwards across the torus, creating a suitable plasma for its own existence as it went.

(c) THE TRANSVERSE DRIFT VELOCITY OF THE PLASMA

In section 6(c) it is shown that the plasma left the low density side of the step with a transverse drift velocity of some 2×10^6 cm·sec^{-1}. The kinetic energy imparted to the plasma presumably originated as work done by the expansion of the plasma as it passed through the density step, suffering a twenty-fold decrease in density. During this process the electron gas expanded isothermally but the ion gas was cooled, so the electrons supplied a rather larger fraction of the total energy than the ions. However, for the purposes of an order of magnitude calculation the electron and ion contributions will be assumed equal. Thus equating the work done on expansion to the kinetic energy imparted to the plasma:

$$2k\ T_e\ N\ \log_e\ 20 = \tfrac{1}{2}\ N\ (M_e + M_i)\ V^2\ ,$$

the transverse drift velocity V is found to be for hydrogen 2.2×10^6 cm sec^{-1} when T_e is 3600°K. The agreement of this figure with the drift velocity previously deduced supports the hypothesis that there are no non-classical processes occurring in the density step itself.

(d) THE ENERGY INPUT

The energy supplied to the torus by a disturbing current pulse of 1.08 kA peak up to the time at which pump-out occurred was 3.9J. Of this, some 1.3J was used in maintaining the plasma density more or less constant (arresting the decay of the afterglow), and about 0.1J stored in magnetic field. The energy required to heat the plasma by some 400°K (section 7(b))

and the energy lost by thermal conduction were negligible.

The velocity with which the plasma left the step was derived from the work done by the plasma expansion (section 7(c)). However, a continual input of energy to the ions in the post-pump-out plasma was required, otherwise they would have rapidly thermalised against the background molecules, so preventing the rapid pump-out diffusion. This continual input of energy would result in the molecules being heated, and also they would be given a mass motion towards the torus wall.

Elementary conservation of momentum would suggest that the energy transferred to the molecules amounted to 0.7J. However, this is a serious underestimate as it has not allowed for the continual driving of the ions which maintains their average velocity constant. A somehwat more realistic calculation in terms of the ion-molecule mean free path suggests that the ions could lose 3.1J in passing through the gas, but further refinement of this figure is impossible without any knowledge of the detailed flow pattern of the molecules. Nevertheless, it seems entirely reasonable to suggest that the 2.5J of energy unaccounted for in the first paragraph is used to impart kinetic energy (in the form of directed motion) to the molecules.

(e) FAILURE TO COMPLETE PUMP-OUT

Fig.12 shows that under some conditions the pump-out step did move right across the torus bore. For Fig.12 the initial gas pressure was twice that for Fig.5 (although the afterglow plasma density differed by less than 20%), and it would appear that the higher neutral particle density quenches the pump-out by destroying the energy balance described above. In mechanistic terms the molecules obstructed the flow of ions to such an extent that the plasma density on the low density side of the step increased until the instability was extinguished.

The quenching of the pump-out with the sub-critical current of 750 A at the low (3.8 mTorr) initial pressure may either be due to a similar energy shortage, or alternatively to the decrease in electron drift velocity as the step moved into a higher density region of the afterglow: the density immediately behind the step steadily increases as the step moves farther from the torus wall,as the overall density gradient must remain constant to maintain the diffusive process.

In complete pump-out at large currents, greater than 2.3 kA, probably results from the considerable (> 40%) reionization which takes place in the post-pump-out plasma, which

destroys the conditions necessary for the continued existence of the instability - possibly by reducing the electron drift velocity.

(F) THE ELECTRON DRIFT VELOCITY

Motley's interpretation of the Stellerator pump-out experiments[1] suggested that pump-out occurred when the electron drift velocity u exceeded the electro-acoustic velocity

$$ c = \sqrt{\frac{kT_e}{M_i}} \quad . $$

The electron drift velocity on the high density side of the pump-out step may be obtained from the saturated Langmuir probe current, assuming uniform plasma resistivity to determine the current distribution. Using this technique it was found that the ratio u/c lay between 0.35 and 0.47 for all conditions under which pump-out was observed, in either hydrogen or deuterium. Thus these results offer an immediate confirmation of Motley's observation.

However, this would suggest that the instability causing pump-out occurred in the dense pre-pump-out plasma, which does not appear to be supported by any of the experimental evidence (see section 7(b)). The relevant drift velocity ratio would be that for the post-pump-out plasma, and it is readily verified that in this plasma the ratio u/c is about 8. [$u = 4.5 \ 10^6$ cm sec^{-1}, $c = 5.5 \ 10^5$ cm sec^{-1} for hydrogen.]

8. A THEORY OF INSTABILITY

Motley[1] suggested that the electron drift through the plasma excited ion acoustic waves, which were somehow responsible for the enhanced diffusion. He pointed out however that the criterion $u/c \geqslant 1$ for the onset of instability only applied to a plasma in which the ions were cold: in a plasma with hot ions and ion Landau damping makes it necessary to increase the drift velocity by[5] a factor $\sim \left(\frac{M_i}{M_e}\right)^{\frac{1}{2}}$. Thus the $u/c \geqslant 1$ criterion should neither apply in the original Stellerator experiments nor the Mk.IV torus work reported here, and it would appear to be coincidental that both experiments lead to a comparable conclusion.

There appeared to be no way to resolve the theoretical difficulty surrounding the apparent absence of Landau damping: indeed, Stix[14], possibly influenced by Motley's result, comments that the theory of drift instabilities in a plasma whose ion and electron temperatures are equal appears to be seriously inadequate.

However, the instability in the Mk. IV torus has been located in a low density plasma

in which the ion temperature is considerably lower than the electron temperature, although the ratio $\frac{T_i}{T_e}$ can hardly be less than 1/10, otherwise the ions would be colder than room temperature. Thus the drift instability theory must take account of non-zero ion temperature, and such a theory has been published by Buneman[5] and Jackson[2]. Jackson in particular calculates the critical electron drift velocity ratio u/c as a function of the temperature ratio $\frac{T_i}{T_e}$. In the post pump out plasma in the Mk.IV torus the drift velocity ratio has a value around 8: according to Jackson's theory this is the critical drift velocity ratio for a plasma in which $\frac{T_i}{T_e} \sim \frac{1}{6}$. As the electron temperature in the post pump out plasma is about 3600°K, Jackson's theory implies an ion temperature of some 600°K, which although it cannot be verified is quite consistent with the processes believed to occur in this plasma (section 7(b)).

Table I shows that the neutral particle temperature, and hence the ion temperature, of the post pump out plasma should have been less than 2000°K. As the ion temperature must have been greater than 300°K, Jackson's theory predicts the critical drift velocity for the onset of instability in hydrogen to lie between $2.0\ 10^7$ and $1.3\ 10^6$ cm sec^{-1}. The observed critical drift velocity ($4.5\ 10^6$ cm sec^{-1}) is then in agreement with theory to within a factor of five.

It thus appears that Motley's original interpretation of pump-out being due to drift-excited ion wave instabilities is substantially correct, for although it is not certain that the Stellarator and Mk.IV torus phenomena are identical it seems likely that so similar a phenomenon could be excited by two different mechanisms. Furthermore, the Mk.IV results appear to be in agreement with theory, and there seems to be no difficulty with ion Landau damping.

Some support for the hypothesis that ion acoustic waves are involved may be derived from the oscillating electric fields detected during pump-out (section 6(e)). Ion acoustic waves have a frequency strictly limited to be below the ion cyclotron frequency, and the oscillating electric fields found during the B group of experiments suggest that this frequency limitation is obeyed. The fields found during the A group experiments are in direct contradiction however, but it should be noted that these fields were only rarely found, and that the B group probe sampled fields in the outward direction, whereas the A group probe sampled upward or axial fields. This it is possible that the B group results represent the true situation of ion acoustic waves travelling largely along a major radius of the torus.

If this were so, the observed pump-out rate could be attributed to a random-walk drift diffusion set up by the electric field of the acoustic wave; however, it is not possible to obtain any semblance of a quantitative agreement between the observed electric fields and the observed pump-out diffusion coefficient.

9. DISCUSSION AND CONCLUSION

This experiment has fallen into two parts. In the first part an afterglow plasma was shown to be quiescent, and found to decay by classical diffusion and recombination processes. Because of the high collision frequency questions of toroidal equilibrium did not arise, toroidal drift for example being a relatively small effect. In this afterglow the ions and electrons were at substantially the same temperature in the bulk of the plasma, although the ion temperature was shown to be lower near the torus wall.

In the second part of the experiment a current was passed through the afterglow plasma, which was thereby caused to become unstable. This instability arose near the inner wall of the torus, and as its main effect was to cause some form of enhanced diffusion and plasma loss, a density step moved across the torus bore causing the plasma to pump-out. The behaviour of the plasma before the step arrived, and on the step itself, appeared to be entirely classical.

Pump-out only occurred if the disturbing current exceeded some critical value, and this value appeared to be such that the drift velocity of the electrons in the undisturbed afterglow was approximately equal to the electro-acoustic speed. Inasmuch as Motely[1] made a very similar observation the initial aim of the experiment, to confirm Motley's results in a rather different geometry, had been achieved. However, the recognition of the tenuous post-pump-out plasma as the seat of the instability has disposed of the theoretical difficulties mentioned by Motley, who pointed out that the equality of drift velocity and electro-acoustic speed implied that ion Landau damping was somehow ineffective. The drift velocity criterion to be applied in the post-pump-out plasma takes account of the lower but non-zero ion temperature, and the experimental measurements themselves suggest a value for the ion temperature which appears to be not unreasonable.

It has not been possible to confirm the hypothesis that ion acoustic waves were responsible for the pump-out, although some evidence for the existence of these waves was provided by the electrostatic probe.

The suggestion advanced by Stodiek[15], that enhanced diffusion was due solely to a sharp increase in electron temperature, received no support in the Mk.IV experiments,

however valid it may be in the Stellarator. There was no indication of any significant change in the electron temperature produced by the disturbing current.

The evidence thus appears to be in favour of Motley's interpretation; however, the pantheon of instabilities possible in the geometrically rather complex system has been considerably enriched since these experiments were first considered, and it is possible that alternative explanations for the pump-out can be found. These alternatives will be discussed elsewhere; the purpose of this report is to outline the experimental evidence, and to make the point that the pump-out phenomenon is not peculiar to the Stellarator.

10. ACKNOWLEDGEMENTS

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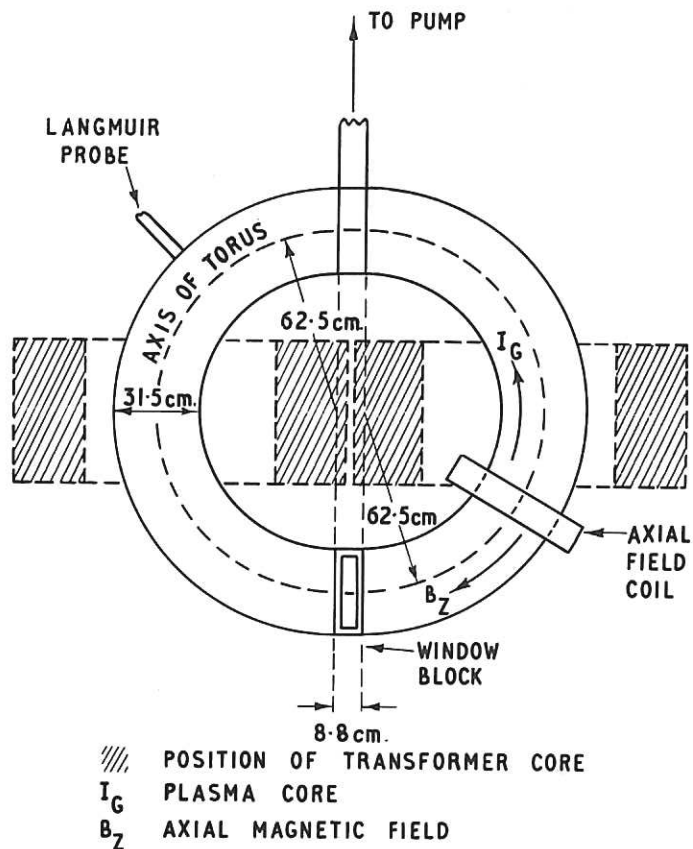
LANGMUIR
PROBE

TO PUMP

AXIS OF TORUS

62·5 cm.

31·5 cm.

I_G

62·5 cm

B_Z

AXIAL
FIELD
COIL

WINDOW
BLOCK

8·8 cm.

///, POSITION OF TRANSFORMER CORE

I_G PLASMA CORE

B_Z AXIAL MAGNETIC FIELD

Fig. 1   (CLM-R 55)

Diagram of MK IV Torus viewed from above, with transformer core removed. Only one of the coils producing the axial magnetic field is shown. The direction of the axial field and the plasma current are those which were used in the majority of the experiments.
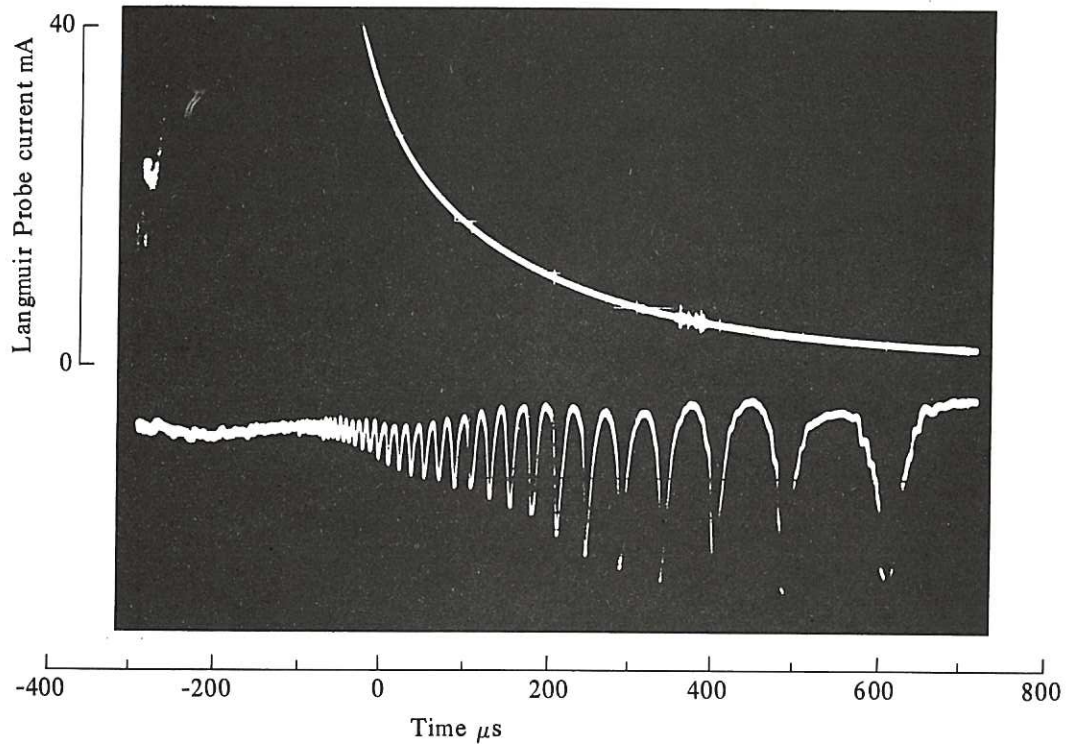
Fig. 2   (CLM-R 55)

Oscillograms of saturated Langmuir probe current (upper trace), and fringe system of the microwave interferometer (lower trace). Gas H_2, group of experiments A. The start of the trace is the start of the main current pulse. The duration of the sweep was 1 msec. For this figure the line of sight of the interferometer was 3 cm outside the centre line of the torus, so that it was at the maximum of density of the afterglow plasma. The Langmuir probe was 2 cm outside the line of sight of the interferometer.
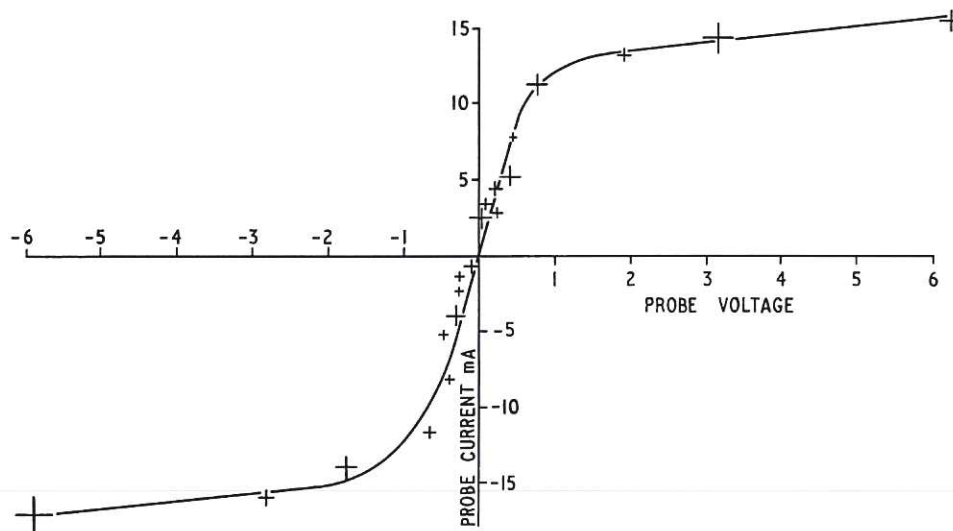
Fig. 3   (CLM-R 55)
Langmuir probe current as a function of voltage between the probes,
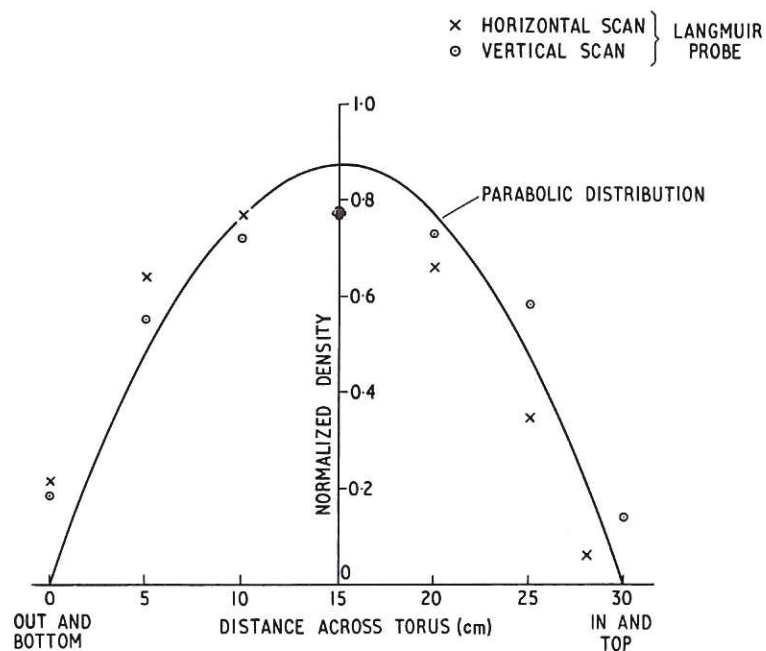for an experiment of group B. The error bars are mean deviations.

Fig. 4   (CLM-R 55)
Density distribution across the Torus at the window
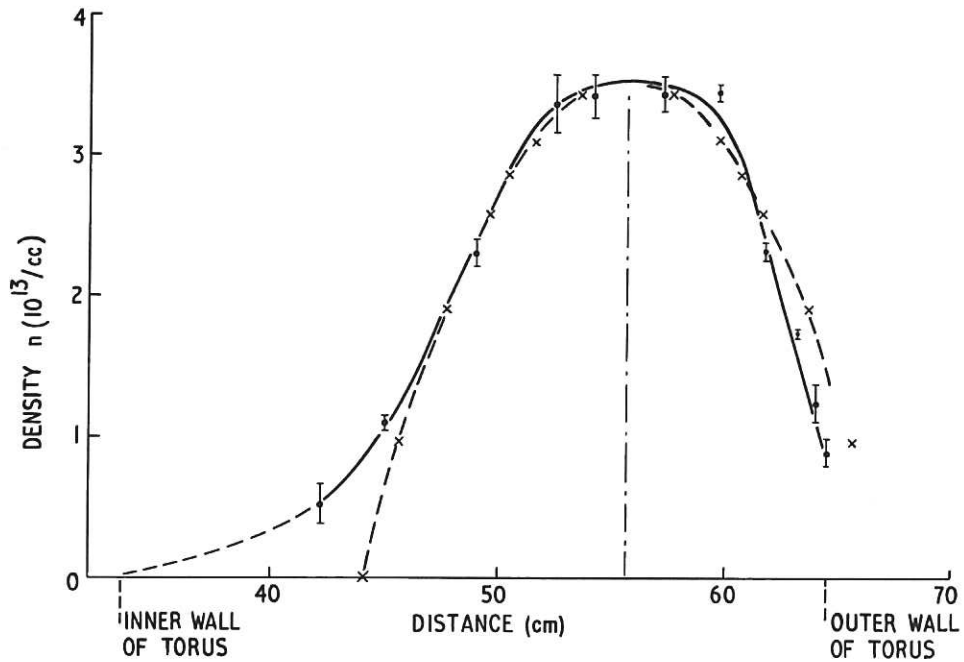block for an experiment of group A. The accuracy
of the determination is 5%.

Fig. 5   (CLM-R 55)

Density distribution of the afterglow across the Torus bore for an experiment
of group B. The dashed line has the equation $n = 3.5 \times 10^{13} [1 - (\frac{r}{11.7})^2]$
where r is measured from the position of maximum density.
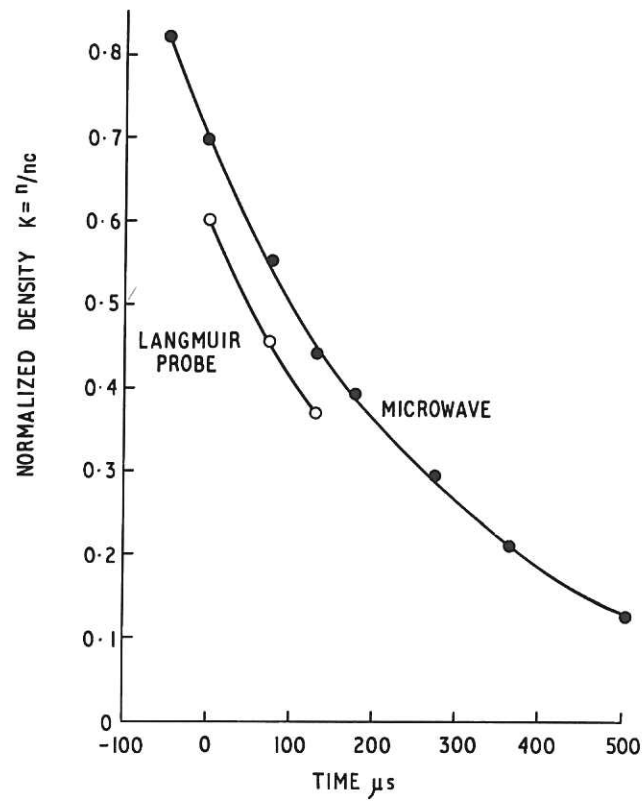
Fig.6   (CLM-R 55)

Variation of density of the afterglow with time for an experiment of group A.
The upper curve is obtained from the microwave results assuming a parabolic
density distribution, the lower from the saturated Langmuir probe current.
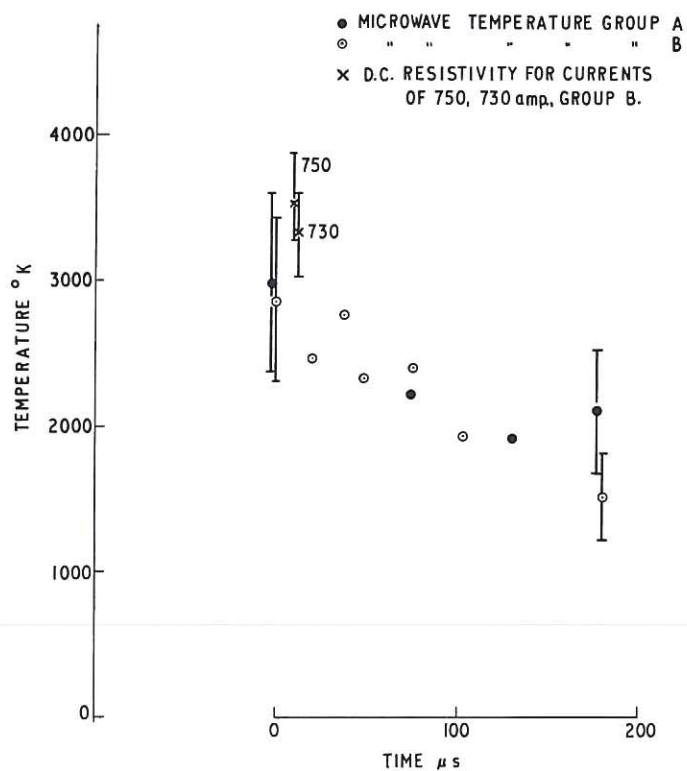The accuracy of the determination of each point is 5% or better.

● MICROWAVE TEMPERATURE GROUP A
⊙ " " " " " B
× D.C. RESISTIVITY FOR CURRENTS
OF 750, 730 amp, GROUP B.

750
730

TEMPERATURE °K

4000
3000
2000
1000
0

0   100   200

TIME μs

Fig. 7   (CLM - R 55)
The variation of electron temperature of the afterglow with time.

DENSITY n (10¹³/cc)

5·0
2·5
0

0   100   200   300   400   500   600

TIME μs
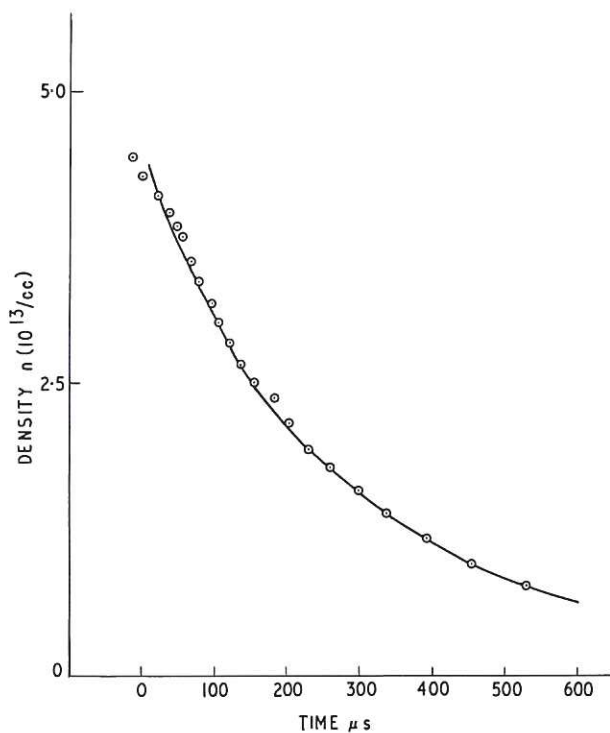
Fig. 8   (CLM - R 55)
The variation of plasma density with time for an experiment of
group B. The experimental points were calculated from the
readings of the microwave interferometer (accuracy 5%). The
solid curve has been calculated by integration of the equation
$-\frac{dn}{dt} = 2728\,n + (3.1 \times 10^{-11}\,n^2)$ and fitting the constant of integra-
tion to the observed points.

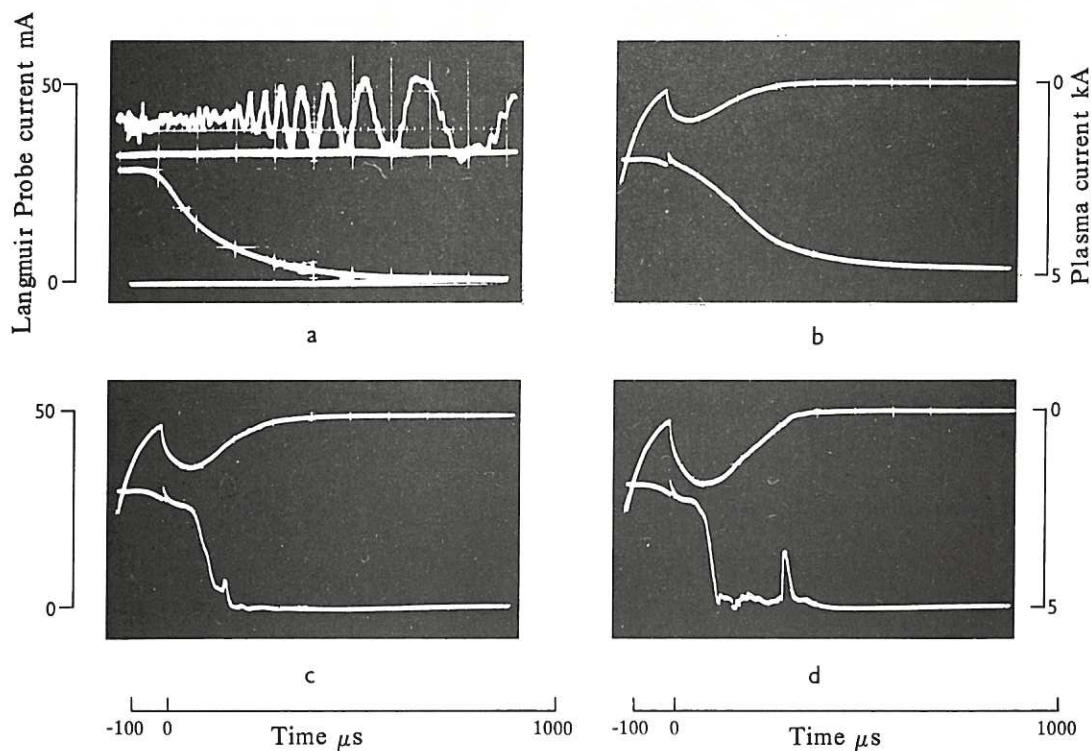Fig. 9   (CLM-R 55)
The onset of pump out (experiments of group B). The upper trace of figure (a)
shows the microwave interferometer fringes and the lower trace the Langmuir
probe current. For figures (b) (c) (d), the upper trace is the current flowing in
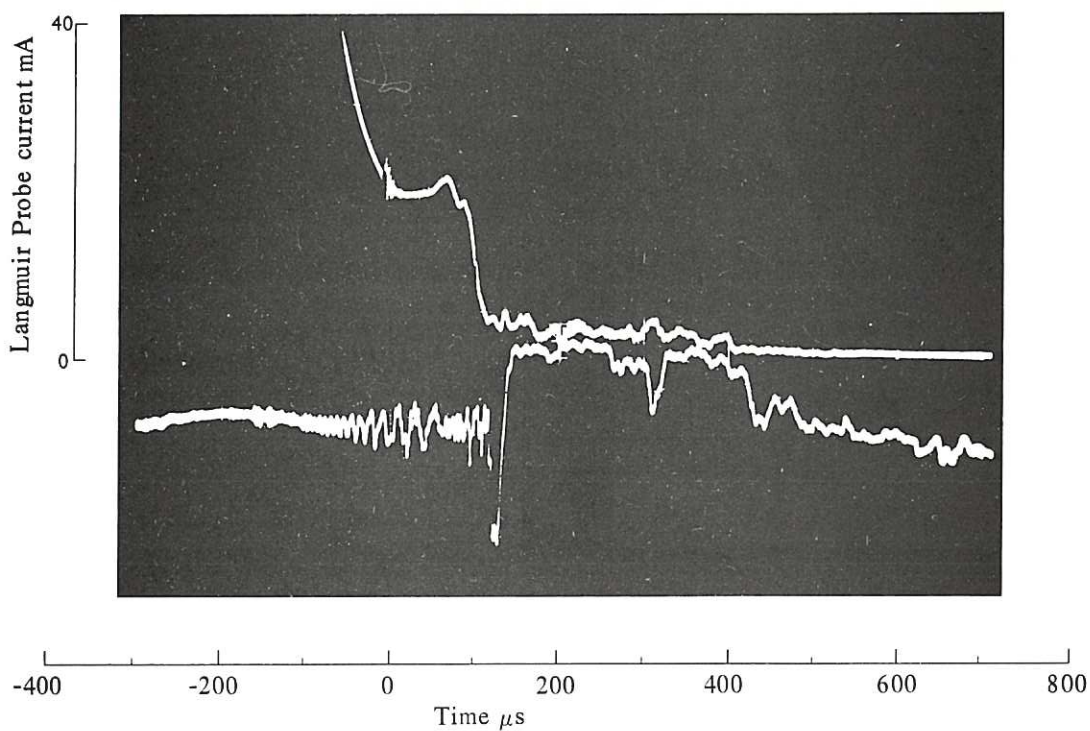the plasma, and the lower the Langmuir probe current.

Fig. 10   (CLM-R 55)
Oscillogram of Langmuir probe current (upper trace), and microwave interfero-
meter (lower trace), showing pump out obtained in an experiment of group A.
The oscilloscope settings and sensitivities are the same as those in Fig. 2, and
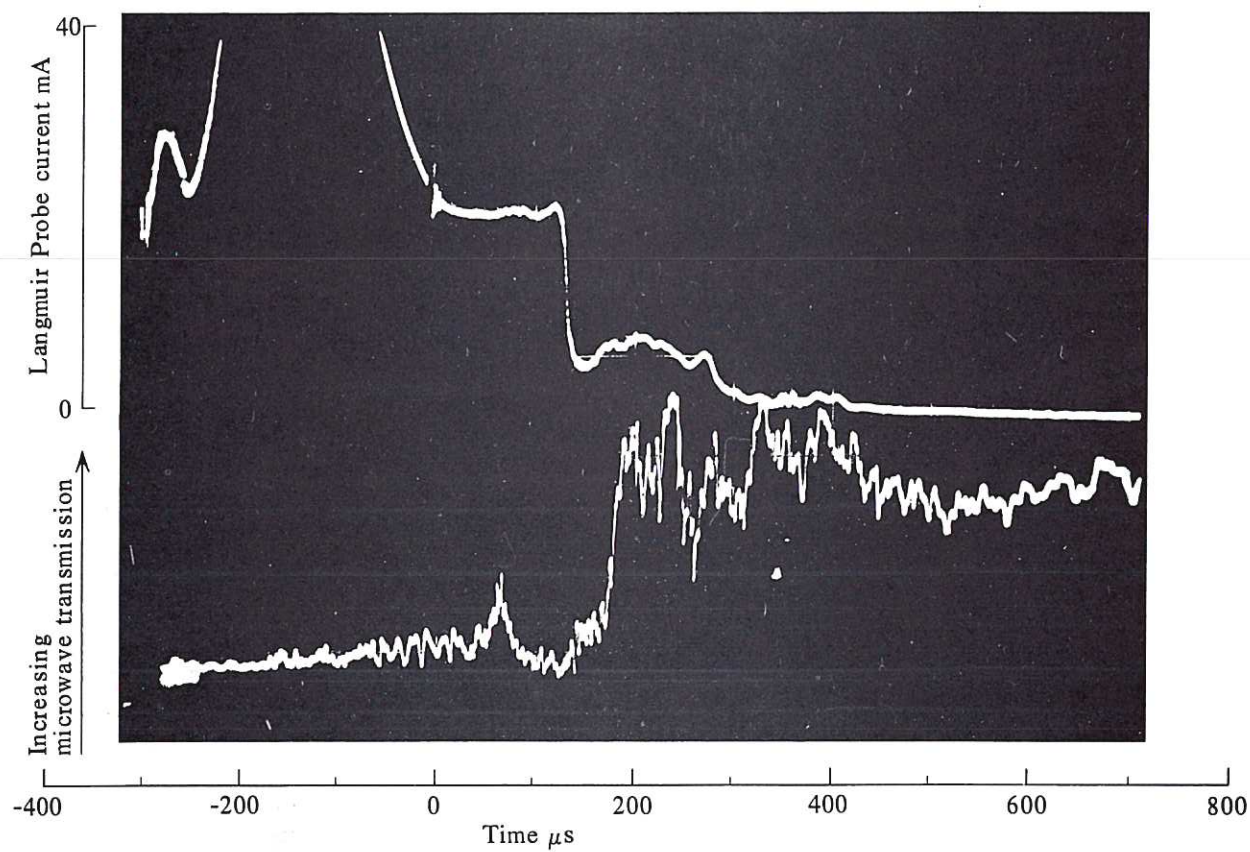comparison should be made with that figure.

Fig. 11   (CLM - R 55)

Oscillogram of Langmuir probe current (upper trace) and microwave transmission across plasma (lower trace) showing the cut off in transmission at pump out. The sensitivity of the oscilloscope is the same as for figures 2 and 10.
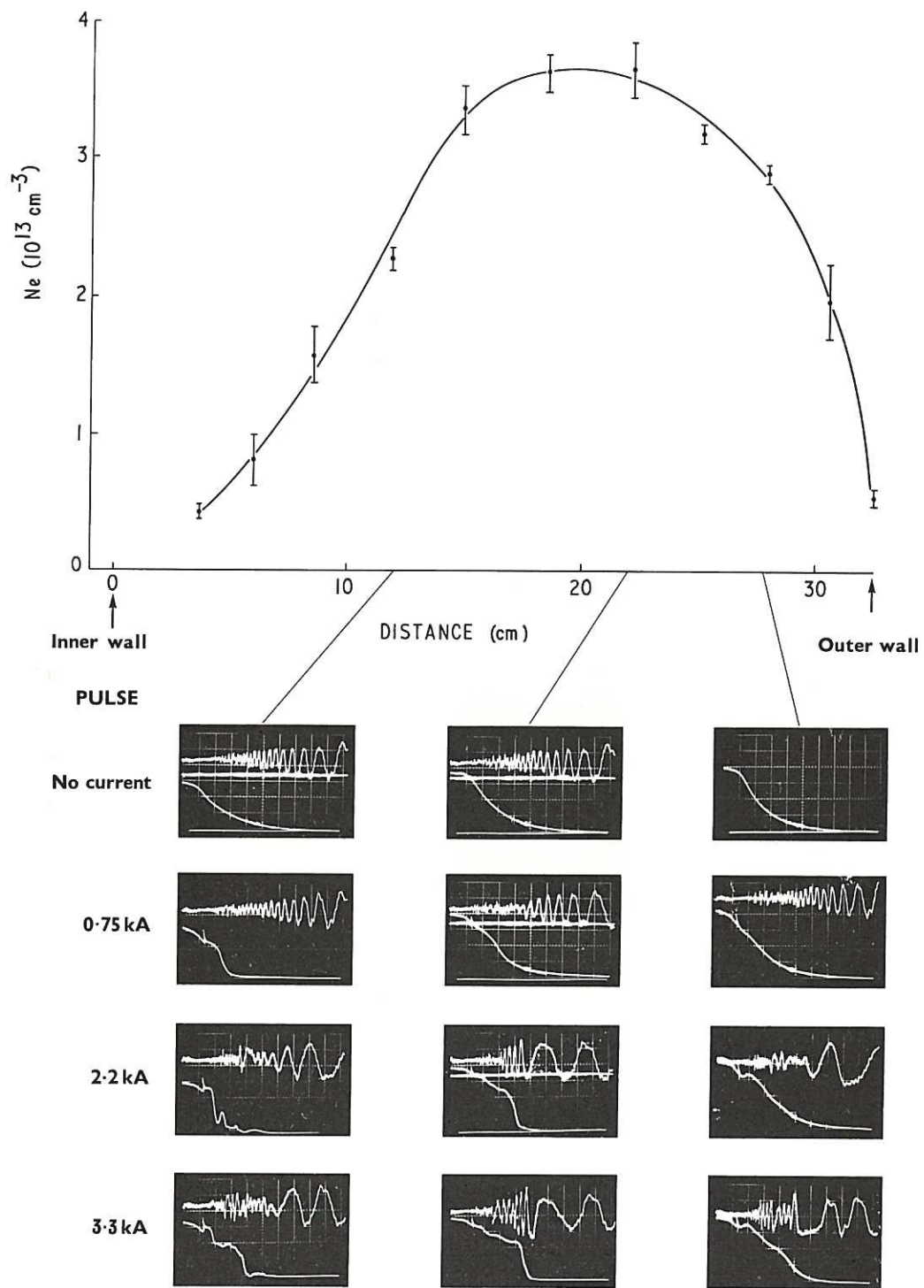
Fig. 12   (CLM- R 55)
Density distribution of the afterglow across the tube in a horizontal plane for
an experiment of group B. Also shown are the fringes from the interferometer
situated at the window block, and the Langmuir probe current for various values
of the disturbing current pulse. The Langmuir probe was situated 11.8 cm,
22 cm and 27.8 cm from the inner wall of the Torus. Time base 100 μsec/division

GRATICULE DIVISIONS
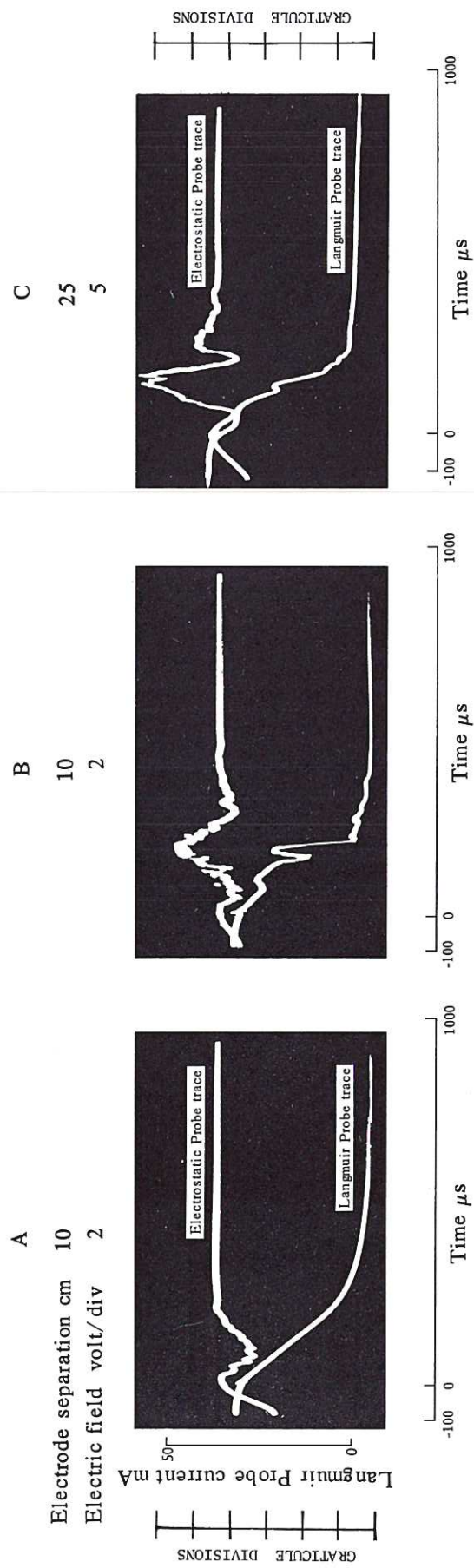
Electrostatic Probe trace

Langmuir Probe trace

Time μs

-100   0   1000

C

Electrode separation cm   25

Electric field volt/div   5

Electrostatic Probe trace

Langmuir Probe trace

Time μs

-100   0   1000

B

10

2

Electrostatic Probe trace

Langmuir Probe trace

Time μs

-100   0   1000

A

Electrode separation cm   10

Electric field volt/div   2

50

0

Langmuir Probe current mA

GRATICULE DIVISIONS

(CLM-R 55)

Fig. 13

The voltages induced between two electrodes placed vertically at the window block (upper trace) and the Langmuir probe current (lower trace); (experiments of group B). Gas current anticlockwise, azimuthal field clockwise. Time scale 100 μsec/division.

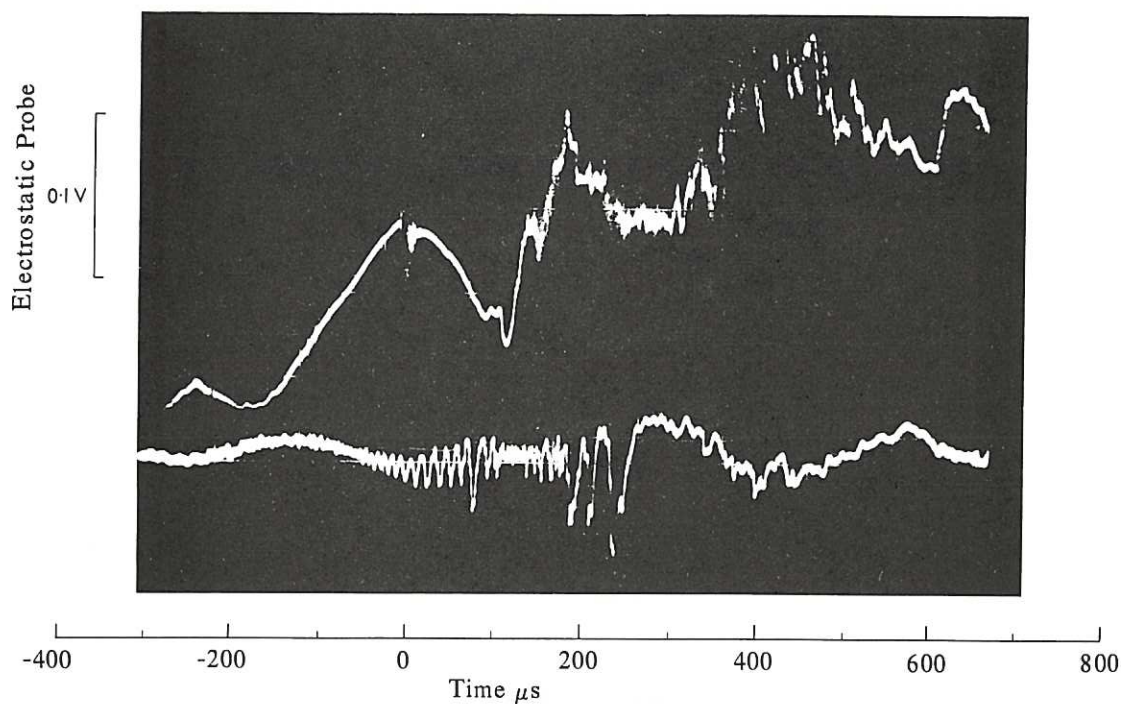Fig. 14   (CLM - R 55)

The output of the Langmuir probe used as an electrostatic probe (upper trace)
with microwave interferometer fringes (lower trace). Duration of sweep 1 msec,
sensitivity of probe trace .05 V/graticule division.   Arrangement of apparatus
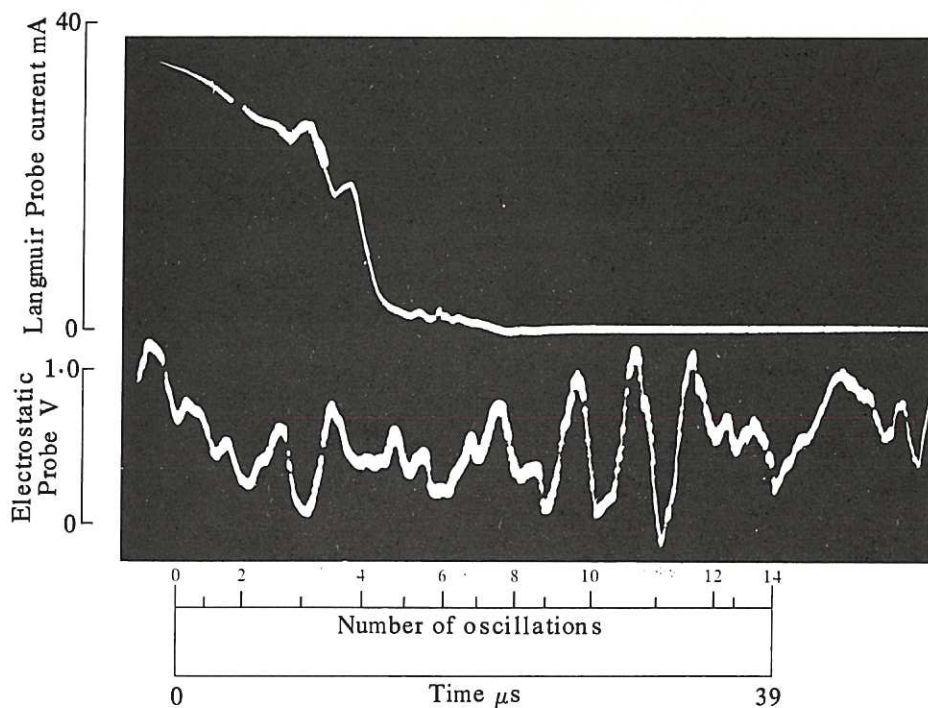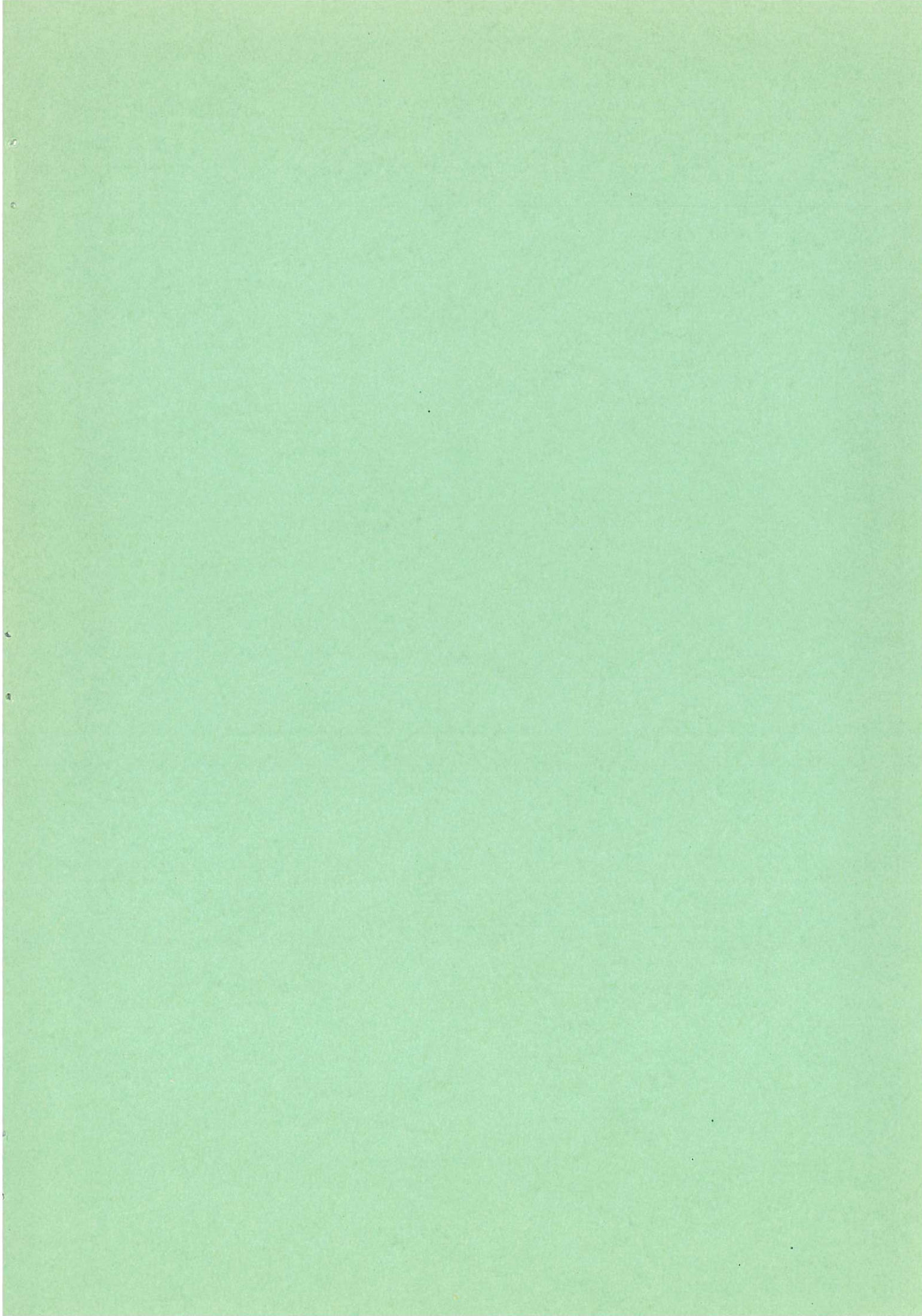as for figure 2.

Fig. 15   (CLM - R 55)

Oscillograph of saturated Langmuir probe current (upper trace) and electrostatic probe
(lower trace). The lower trace shows evidence of oscillating electric fields at a
frequency of 360 kc/s. Duration of upper trace 1000 μsec, of lower trace 50 μsec.
Experiments of group B. Lower trace sensitivity 0.5 V/graticule division.