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Report

PLASMA PRODUCTION IN A GAS JET BY MICROWAVE IONIZATION

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PLASMA PRODUCTION IN A GAS JET BY MICROWAVE IONIZATION

by

J. HUGILL

ABSTRACT

An experiment is described in which cold, neutral gas issuing from a nozzle is ionized by a 2400 MHz alternating electric field. In the steady state the electron temperature in argon is 3.4 eV, and ions are accelerated by electron pressure gradients near the nozzle. When the gas flow is pulsed the degree of ionization can be up to 2.9% and this does not represent the limit of the technique. Application to the filling of a closed magnetic trap is discussed.

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1. INTRODUCTION

In order to estimate the containment time of a low-β magnetic trap, the loss time due to charge exchange collisions between plasma ions and background neutral molecules must be long compared with the measured plasma decay time. Generally this implies that a very good vacuum must be maintained, so that ionization of neutral gas in the trap, which is a common method of filling high-β devices, is not practicable. Plasma must be introduced from outside the confinement region. The usual methods are to inject plasma into the trap from a plasma gun, or to inject neutrals and ionize them within it.

The following describes some preliminary experiments to test a variation of the latter technique. Cold neutral gas issuing from a nozzle, which could be placed just outside the confinement region, is ionized by strong microwave fields. The ions produced just within the confinement region are accelerated along field lines by electron pressure gradients, which in turn arise from the high density gradients of neutral gas near the nozzle. The electron energy may be increased by electron cyclotron heating if the microwave frequency is properly chosen.

2. APPARATUS

A diagram of the apparatus is shown in Fig.1. An aluminium vacuum box, a, is placed above an oil diffusion pump, type F603, with baffle valve. The pumping speed is 230 litres sec^{-1} and the evacuated volume is 14 litres. The microwave supply is a 2400 MHz magnetron giving an output of 200 watts continuous. The microwave signal is introduced into the vacuum box through the coaxial connection c, shown in more detail in Fig.2. Initially the gas nozzle, d, was at the end of a λ/4 antenna, e, connected coaxially with the microwave input. The centre conductor, f, of the system is drilled to provide access to the nozzle. The whole microwave connection is mounted on a baseplate which can be positioned on top of the vacuum box or at the side. In experiments with a pulsed gas supply the gas is admitted through a separate valve, shown in Figs.3 and 4. When used this is mounted on top of the vacuum box with the microwave connection at the side, the two being coupled by a copper strip and T junction, g-g in Fig.1, to ensure that the voltage at the nozzle is as large as possible. Diagnostic probes, vacuum gauges or additional gas supply tubes can be introduced through the ports h .....n. Another port is positioned in the microwave supply baseplate, o, to allow probe movement along the axis of the vacuum box.

3. STEADY GAS FLOW

DENSITY DISTRIBUTION OF NEUTRAL GAS

The first experiments were done with a steady gas flow through the nozzle, whose tip was a tantalum tube with internal diameter 0.08 cm. The gas flow rate was controlled by a needle valve in the supply tube. Generally, the background pressure in the vacuum chamber was 3 to 4 $\times 10^{-3}$ torr, and the gas flow rate 1 litre-torr per second. At this flow rate the pressure just inside the nozzle is approximately 15 torr. The gas flows away from the tip in all directions, and is in free molecular flow at a very small distance from it. A calculation of the neutral gas density on the axis is shown in Fig.5. The density of the gas flowing from the nozzle falls to the same value as that of the background gas at a distance of about 1 cm. Unless otherwise stated, the following results were obtained with argon.

DISCHARGE PARAMETERS

A microwave discharge was obtained with a nominal magnetron power output between 50 W and 200 W. It usually required 'starting' with a tesla coil. The appearance was of a nearly uniform glow filling the vacuum chamber; more intense near the nozzle and especially just at the tip. Fig.6 is a photograph of the discharge near the nozzle. Estimates of E/p from the pressure given in Fig.5 and the known voltage on the magnetron supply line, yield values from 100 to 1000 volts/cm-torr within 1 cm of the nozzle. Similar values occur in the background gas. However, since the excursion of a free electron in the microwave field is typically 10^{-3} cm, conditions for breakdown are best near the nozzle, where the collision frequency is comparable with the microwave frequency. No discharge occurs at the same background pressure if the gas flow from the nozzle is stopped.

The electron density distribution was found by moving a probe along the axis and taking a measurement of the ion saturation current at intervals. The results are shown in Fig.7 for two values of the gas flow rate, giving background pressures of 2.6×10^{-3} torr and 1.1×10^{-3} torr for curves 1 and 2 respectively. Langmuir probe current v voltage curves taken at two points 1.4 cm and 7.4 cm from the nozzle gave values for kTe of 3.9 ± 0.2 eV and 3.4 ± 0.2 eV. These results suggest the presence of an axial electric field of approximately 0.43 volts per cm, balancing the electron pressure gradient, and this was verified by measuring the floating potential of the Langmuir probe as a function of distance from the nozzle. Plasma ions are accelerated in this electric field towards the walls of the vacuum chamber. Measurements of ion flux were made at port ℓ, using a small circular probe and guard ring coplanar with the vacuum chamber wall. These gave values of about 50×10^{-6} A cm^{-2} with an electron density of 2.2×10^{9} cm^{-3} near the wall. This implies an ion velocity of 1.4×10^{5} cm sec^{-1}, or an ion energy equivalent to 0.4 eV. The reason why the ion energy is so low is the small value of the mean free path for ion-neutral collisions. With a much smaller background pressure this will be increased substantially. The total ion current to the walls of the chamber was 0.2 A, measured by biassing the plasma positive with a spiral wire electrode surrounding the nozzle at + 24 V. The corresponding flux of neutrals through the nozzle was equivalent to 3.2 A: that is, 6.2% of the neutrals are singly ionized. However, most of this figure can be accounted for by ionization in the background gas, which would not be present in an actual machine.

MICROWAVE POWER REQUIREMENTS

The power absorbed from the magnetron, by the ionization of the gas, is very difficult to estimate. The vacuum chamber acts like a cavity and the standing wave pattern inside it is very complicated. The standing wave ratio on the line leading to the antenna was measured with a series of diodes weakly coupled to the line as shown at p-p in Fig.2. In the absence of plasma the voltage standing wave ratio was 4:1; when the microwave discharge was started this increased to more than 20:1, that is, more than 81% of the magnetron power is reflected; and the effective length of the $\lambda/4$ antenna was reduced by $\lambda/60$. These results show that in the presence of plasma the wavelength on the antenna is increased. This can only occur when the plasma frequency in the neighbourhood of the antenna is of the same order as, or greater than, the magnetron frequency.

VARIOUS GASES

Similar results were obtained with gases other than argon: air, helium and hydrogen. In helium and hydrogen the magnetron power was just sufficient to maintain the discharge under the most favourable conditions, that is, at the highest gas flow rate which the pump would handle. In helium the tip of the nozzle became red hot after about one minute; probably due to ion bombardment. To test this hypothesis argon was introduced through a stainless steel tube, at port ℓ Fig.1, which was electrically insulated from the vacuum chamber. It was sufficiently well coupled to the microwave antenna for a discharge to form at the tip of the tube. At zero bias the current to the tube was + 60 mA, and at zero current the tube biassed to + 18 V, showing that the plasma surrounding the tip is appreciably positive with respect to the vacuum chamber walls.

DISCHARGE NEAR TO THE NOZZLE

In Fig.6 an oval region with enhanced brightness can be seen surrounding the nozzle. It was not possible to obtain probe measurements of electron density in this region, because strong microwave fields near the tip affected probe characteristics strongly. (For example, the floating potential of a small probe varied from near zero to -60 V and back again as the bright region was traversed.) The electron density could only be found by extrapolation, giving a value of approximately 1.4×10^{10} cm^{-3}. The size of the region of enhanced brightness depended on the magnetron output and its shape was affected by the presence of a magnet nearby. It may be produced by a plasma resonance effect; the plasma frequency is approximately 1000 MHz. The phenomena which occur near the nozzle are important for the operation of this device. When the gas flow is pulsed, so that the background gas pressure is very low, nearly all the ionization will be produced within a small volume near the nozzle. For this reason, it may be important to examine the properties of this region in the steady state discharge in further experiments.

EFFECT OF MAGNETIC FIELD

The effect of a magnetic field was tested by placing a permanent magnet in the vacuum chamber, with a field strength of 960 oersteds in the median plane between the poles. Electrons are then resonant with the microwave signal somewhere near the pole pieces. A steady-state discharge was obtained over a very wide range of background pressure. At the lower pressures the discharge occurred between the magnet poles, and X-rays were detected outside the vacuum chamber, indicating strong electron cyclotron heating. No quantitative measurements were taken, but the experiment indicated no special problems in operating the discharge in a magnetic field.

4. PULSED GAS FLOW

PULSED GAS VALVE

In the following experiments both the gas flow and the magnetron were pulsed. The latter was not necessary, but provided a larger magnetron output, up to 1 kW, for a short time. The gas valve shown in Figs.3 and 4 operated as follows. The plenum between the nozzle, r, and O-ring, s, was filled with gas through the tube, t, to a pressure determined from outside the valve. At a signal from a trigger unit a solenoid accelerated the hammer, u, against the anvil, v, and raised the teflon seating, w, from the nozzle, allowing gas to escape. The time for which the valve was open was determined by the anvil-hammer distance, and the spring tension; and the amount of gas let through the valve could be varied by adjusting the plenum pressure. The calculated volume of the plenum was 0.065 cc, but it was always in connection with the gas supply, so that more gas was admitted during the pulse. Fig.8 shows the circuits used to drive the solenoid, pulse the magnetron, and trigger the 'scope. Measurements of total electron charge produced during a pulse were made by integrating the current from a stainless steel electrode, q, in Fig.1, biassed to + 120 V.

TRIGGER ELECTRODE

It was found necessary to provide some ionization in the 'neutral' gas pulse to start the microwave discharge. This was done by applying the magnetron supply direct voltage simultaneously to a trigger electrode, x, in the gas valve. A d.c. discharge occurs in the relatively high pressure gas near this electrode, and the gas issuing from the nozzle is sufficiently ionized to start the microwave discharge.

IONIZATION EFFICIENCY

Measurements were made of the electron current and electron charge to the positively biassed electrode for various values of the gas valve plenum pressure in the range 10 to 100 torr. Generally, the magnetron pulse was timed to start a fraction of a millisecond after the gas valve opened. The time variation of the neutral gas flow was not measured, but the current flow through the trigger electrode showed that the neutral gas pulse lasted between 5 ms and 10 ms, depending on the setting of the valve spring etc. The total amount of gas admitted during the pulse was found by measuring the subsequent pressure rise in the vacuum chamber, with the diffusion pump baffle valve closed.

The degree of ionization of the gas pulse is shown for various values of plenum pressure in Table 1. This is the ratio of total number of electrons collected to total number of neutrals admitted, and it increases as the plenum pressure is reduced. Calculation of the amount of gas recycled, assuming that the region where ionization occurs is confined to a sphere 1 cm in diameter near the nozzle, gives 1% of the total, and this is neglected in Table 1. Note that the figures in Table 1 are average values. Since the duration of the discharge is less than that of the neutral gas pulse, the maximum degree of ionization could be approximately four times larger than the values in Table 1. Also, the peak magnetron power output, measured by a diode in the microwave supply line, is only a factor of two larger than the power required to maintain the discharge. Fig.9 shows data taken during typical pulses.

No measurements were made in the presence of a magnetic field.

TABLE 1

Gas valve plenum pressure, torr	Background pressure rise after neutral gas pulses, torr	Total electron charge collected, coulombs	Duration of electron current pulse, milliseconds	Ionization efficiency, %
100	1.2×10^{-3}	5.84×10^{-4}	5.0	0.61
100	0.8×10^{-3}	5.92×10^{-4}	4.5	0.93
40	3.5×10^{-4}	2.72×10^{-4}	2.0	0.98
30	2.2×10^{-4}	2.08×10^{-4}	1.8	1.09
20	1.15×10^{-4}	1.76×10^{-4}	2.0	1.93
10	6.7×10^{-5}	1.52×10^{-4}	1.8	2.86
10	6.7×10^{-5}	1.04×10^{-4}	1.2	1.96

5. CONCLUSIONS

It is possible to ionize neutral gas issuing from a nozzle into a vacuum using microwave fields. In the steady state ions are accelerated by electron pressure gradients away from the nozzle. The fraction of neutral atoms ionized increases as the gas flow rate is reduced, and, at the lowest flow rate measured, 2.9% of a neutral gas pulse of 3.3×10^{16} atoms was ionized. Further, the maximum rate of ionization could be four times larger than this. With a larger magnetron power, better matching, a lower plenum pressure and a shorter gas pulse duration it is anticipated that the degree of ionization might be increased to about 25%. The effect of a magnetic field on these results was not tested. However, with a steady flow through the nozzle, the discharge was obtained just as easily with or without a magnetic field. In addition electron cyclotron heating was observed.

Further work on this system should test the effect of a magnetic field on the operation of the trigger electrode, use a gas more suitable than argon for containment experiments, and use a higher magnetron power. Some attention must be given to the problem of removing neutrals especially if a large degree of ionization cannot be achieved.

Parameters to be aimed at in a containment experiment might be:

Number of neutrals in gas pulse	2×10^{15}
Degree of ionization	25%
Number of ions produced	5×10^{14}
Pulse duration	0.5 ms
Magnetron power	1 - 5 kW pulsed
Volume of containment system	3×10^{4} cc
Volume of magnetic trap	10^{4} cc
Initial electron density	5×10^{10} cc^{-1}
Neutral pressure without pumping	10^{-6} torr
Charge exchange time for $\sigma = 10^{-15}$ cm^2, $v_i = 5 \times 10^6$ cm sec^{-1}	0.56 ms

The charge exchange time could be increased to 5.6 ms by pumping out 90% of the neutrals. This might involve surrounding the vicinity of the gas nozzle with a neutral-absorbing surface, and does not seem difficult to achieve.

6. ACKNOWLEDGEMENTS

This work was suggested by P.C. Thonemann, with whom valuable discussions were held throughout. The assistance of J.A. Daniel and R. Slough in setting up the experimental equipment is gratefully acknowledged. The pulsed gas valve was kindly supplied by D.E.T.F. Ashby.

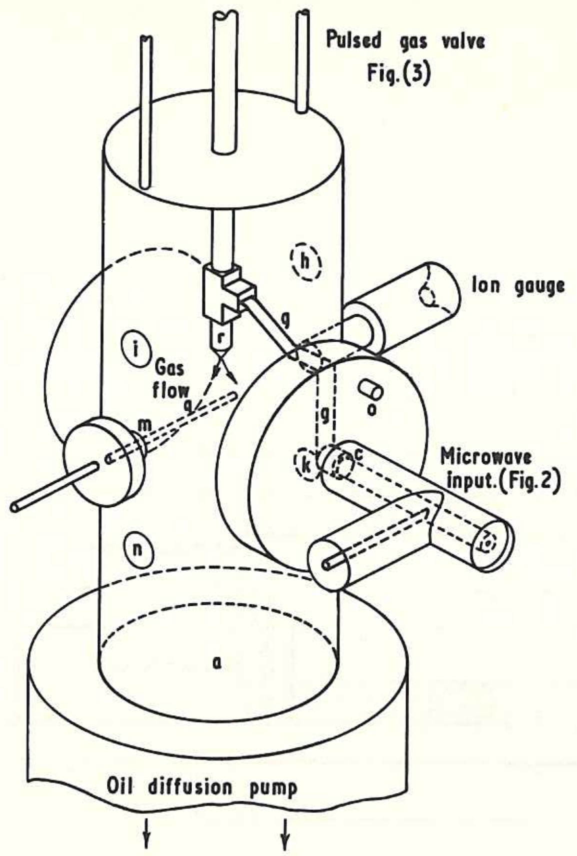


Fig. 1 (CLM-R80)
Vacuum chamber, showing relative positions of pulsed gas valve, microwave connection and probe.

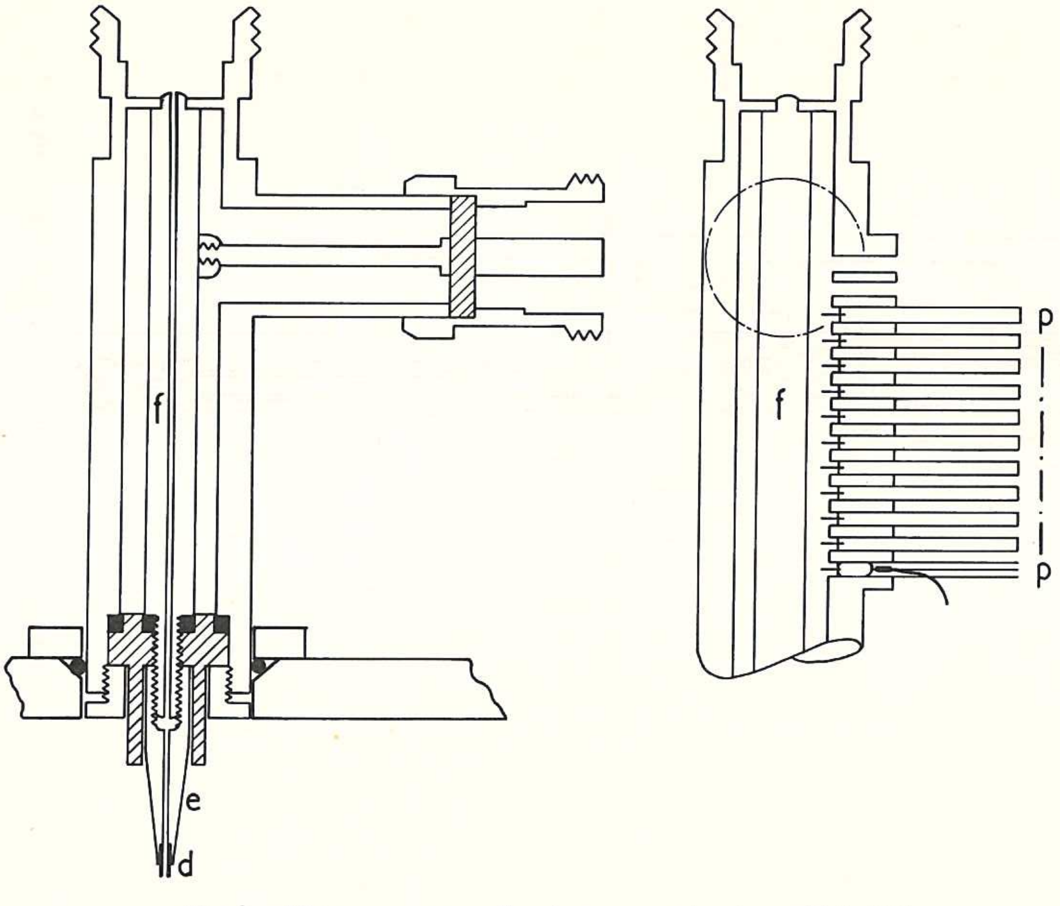


Fig. 2 Microwave connection to vacuum chamber. (CLM-R80)

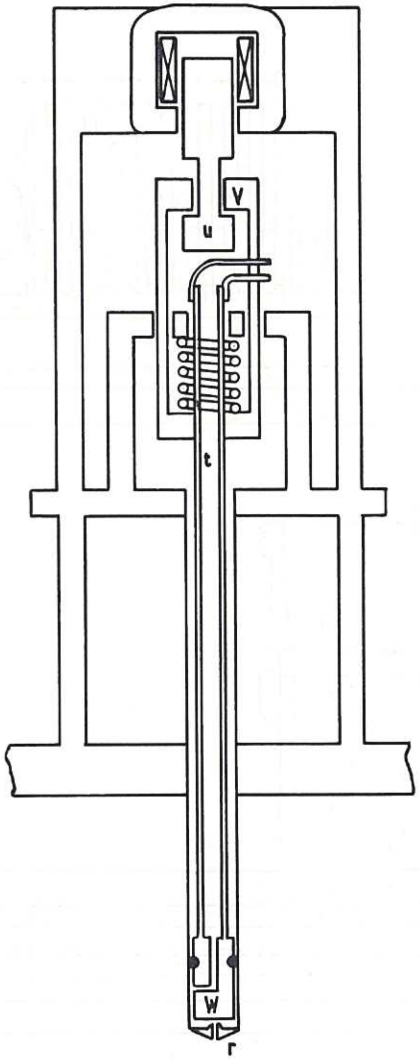


Fig.3 Simplified drawing of pulsed gas valve.

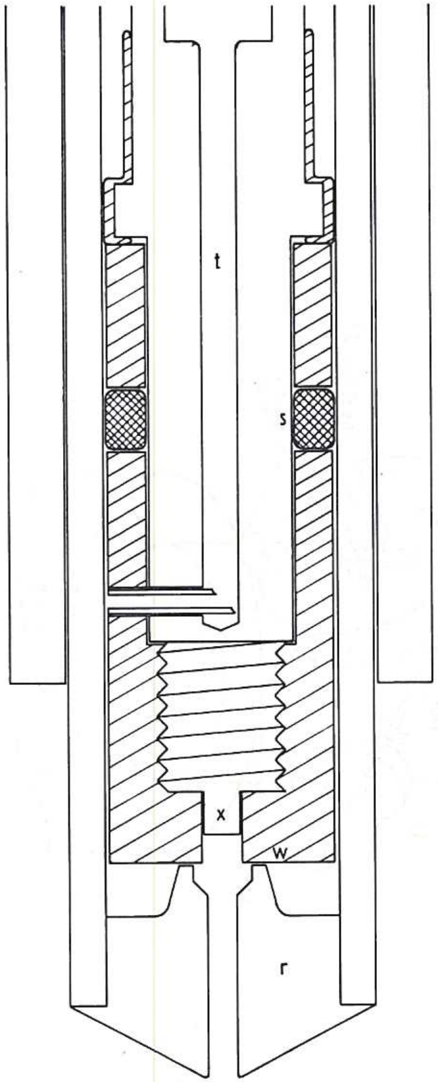


Fig.4 (CLM- R80)
Detail of pulsed gas valve, showing plenum, and nozzle.

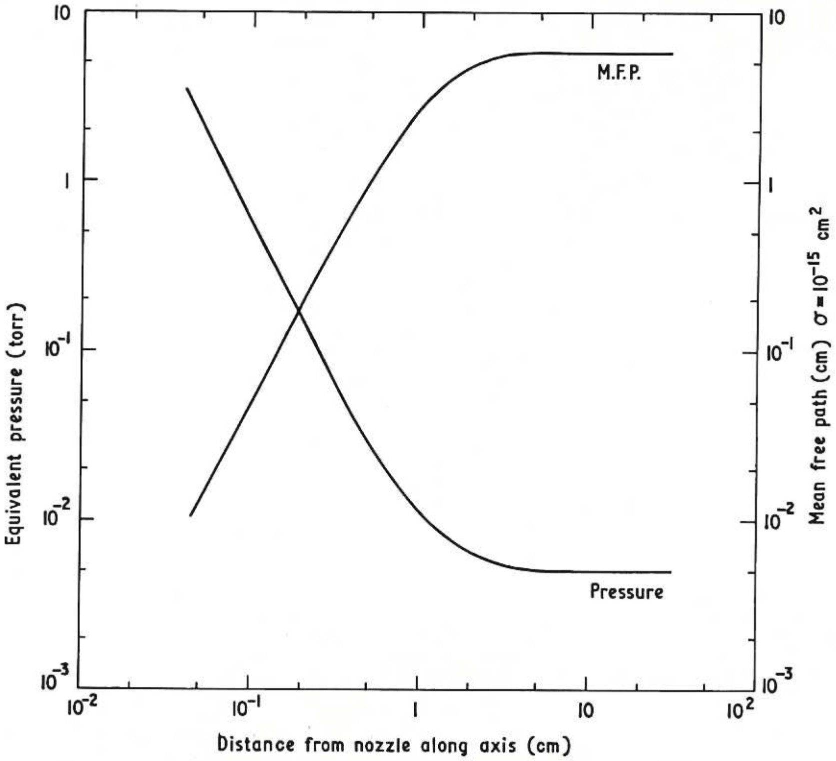


Fig. 5 (CLM-R80)
Calculated density profile of neutral gas flow from nozzle.

Fig. 6 (CLM-R80)
Photograph of steady-state microwave discharge near the nozzle. Gas: argon, background pressure: 3.8×10^{-3} torr, gas flow rate: 0.88 ℓ torr s^{-1}, magnetron output: 200W.

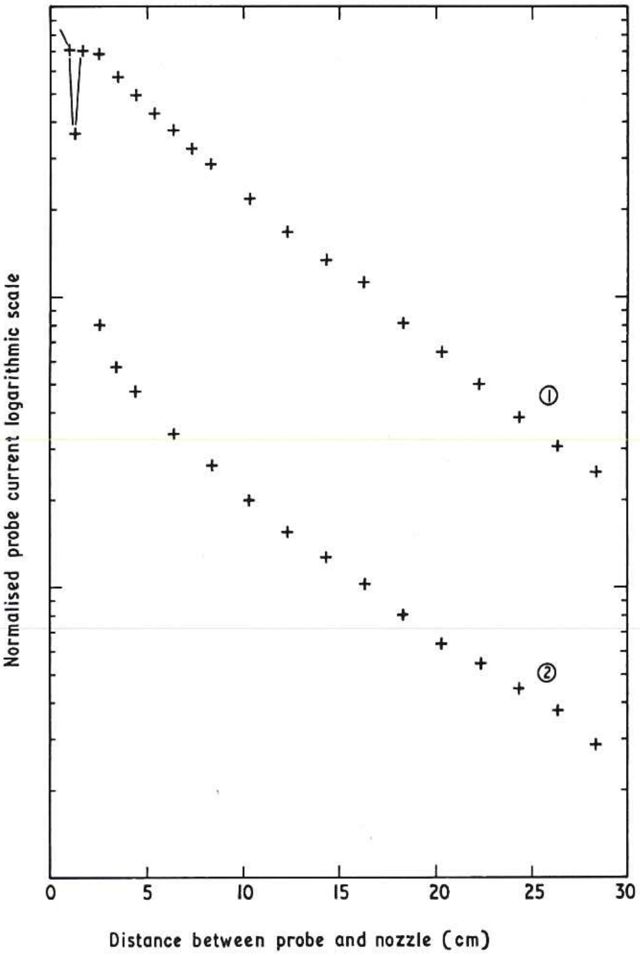


Fig. 7 (CLM-R80)
Electron density profiles on the axis of the nozzle. Background pressure curve (1): 2.6×10^{-3} torr, curve (2): 1.1×10^{-3} torr.

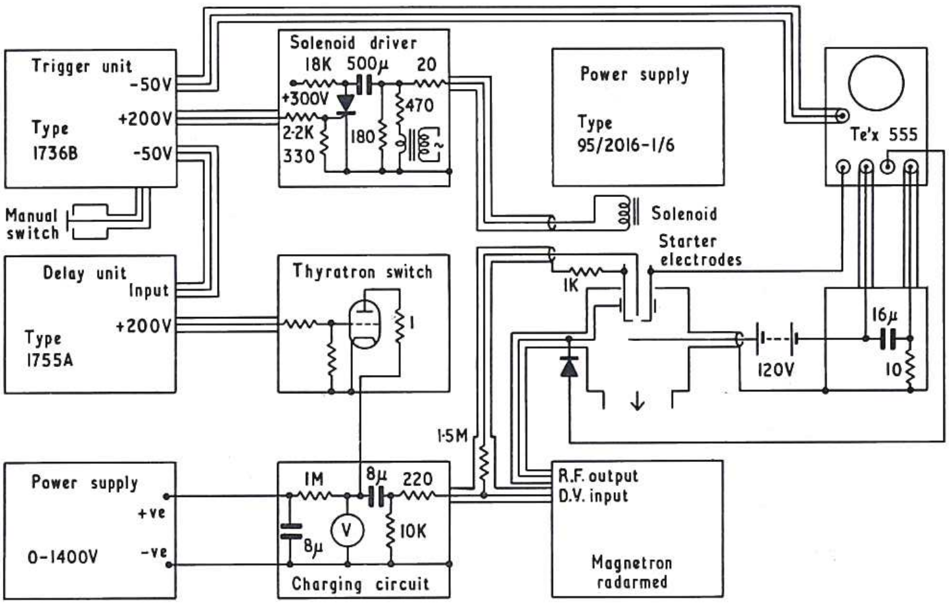
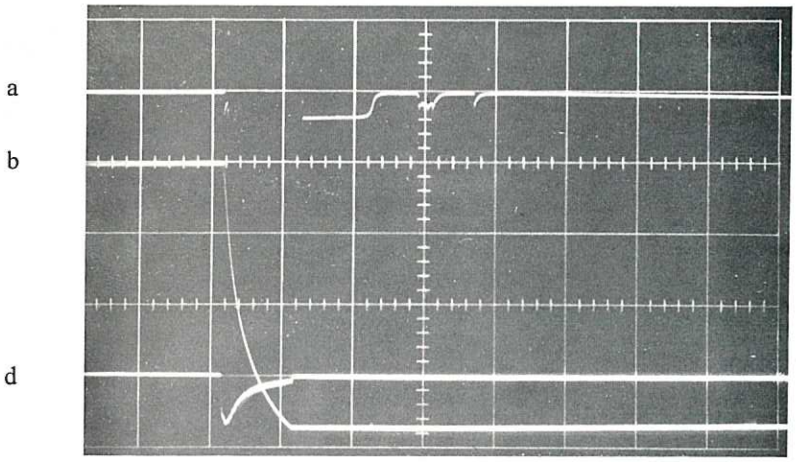
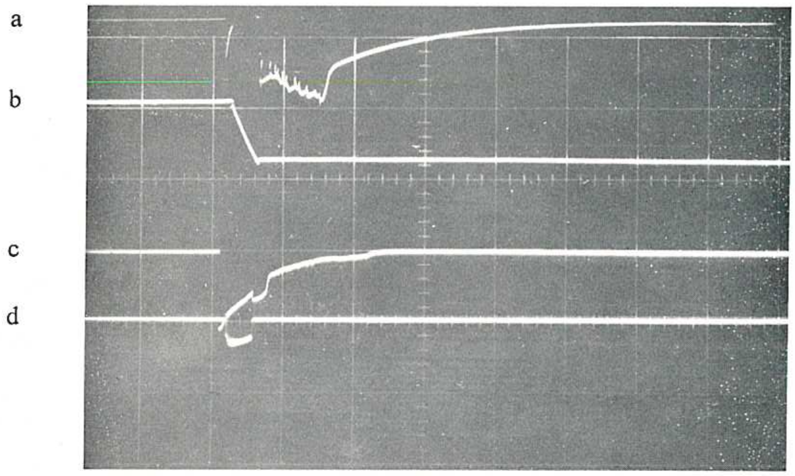


Fig. 8 Circuits for pulsed operation. (CLM-R80)



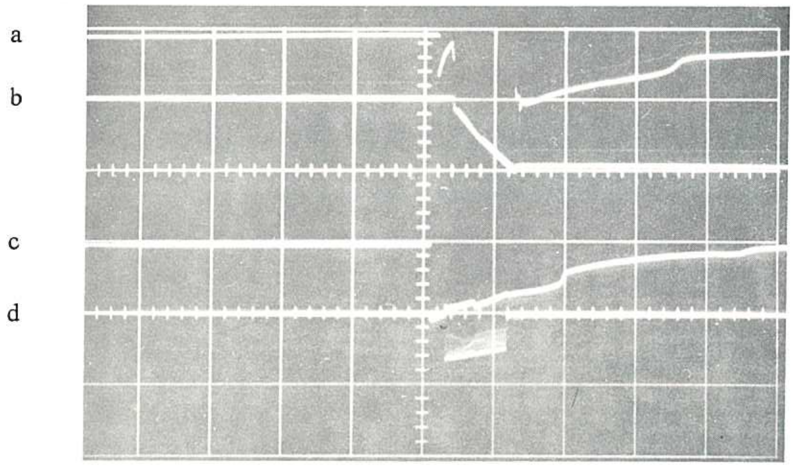
5 mS/ cm
a 2 mA/ cm
b 160 μcoulombs/ cm
d 0.5 A/ cm

Plenum pressure 100 torr



5 mS/ cm
a 1 mA/ cm
b 320 μcoulombs/ cm
c $\approx$1 kW/ cm
d 0.5 A/ cm

Plenum pressure 40 torr



2 mS/ cm
a 1 mA/ cm
b 160 μcoulombs/ cm
c $\approx$1 kW/ cm
d 0.2 A/ cm

Plenum pressure 10 torr

Fig.9 Photographs of typical data (CLM-R80)
Trace: a Trigger electrode current. c Magnetron output
b Integrated electron charge. d Electron current

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