CW Microwave Heating in the Small Octupole

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We report here tests made using CW microwave sources to produce plasmas in the small (supported) toroidal octupole. The following sources have been used:

#	frequency	output power	pulse length
1	2600 MHZ	~100 W	CW
2	9600 MHZ	~100 W	CW
3	75 MHZ	~5 kW	10-100 msec

Using source #1 with a $\frac{1''}{8} \times \frac{1''}{8}$ cylindrical Langmuir probe on the B = 0 axis, the ion saturation current was measured when the magnetic field was pulsed on. The result is shown in Fig. 1 for various values of magnetic field. No plasma is observed until the magnetic field builds up to a value at which a region of electron cyclotron resonance appears in the machine. The ion saturation current then rises rapidly and remains relatively constant until the field starts to decay. Two shots were taken at each value of B to indicate the reproducibility of the plasma. The traces in Fig. 1 are for a background hydrogen gas pressure of $\sim 10^{-4}$ torr. At lower pressures, the rise of ion saturation current is less rapid and below $\sim 10^{-5}$ torr the peak ion saturation current occurs well after the peak magnetic field, indicating that the density has not had adequate time to build up.

In order to examine the pressure dependence in more detail, the magnetic field was run at the normal value (2 kV) and the peak ion saturation current was plotted vs gas pressure in Fig. 2 for several values of microwave power. The ion saturation current is roughly proportional to microwave power in this range and has a weak maximum at $\sim 10^{-5}$ torr. At low pressure, the decrease is presumably due to the small ionization rate, and at high pressure, neutral cooling is important. At 100 watts, the peak ion saturation current at $\sim 10^{-5}$ torr is an order of magnitude greater than the ion saturation current for the gun injected plasma one millisecond after injection, suggesting that the maximum density is $\sim 10^{10}$ cm^{-3}.

The spatial distribution of the plasma is similar to that of the plasma produced by pulsed microwaves of the same frequency. Large fluctuations are observed at the boundaries of the plasma near the hoops and wall, and small low frequency fluctuations are observed on the B = 0 axis (see Fig. 1). The floating potential on the B = 0 axis is fairly constant, small (~10 volts), and negative for all cases observed. Preionization from a gun injected plasma somewhat increases the ion saturation current. Several tests were made using source #2, and the results are practically identical to the previous results, provided the magnetic field is increased by the appropriate factor (3.7).

The rest of this note will be concerned with measurements on plasma created by source #3.

The rf pulse (40 msec) was turned on about 10 msec before the multipole fires. Fig. 3-a shows a sample of the reflected power from the octupole (lower trace). The upper trace is the ion saturation current measured at the B = 0 axis.

With no breakdown, most of the power available at the incidence is reflected back; that case was achieved by reducing the pressure to 7×10^{-7} torr (or lowering the magnetic field of the multipole).

The pressure was increased gradually until breakdown occurred. The presence of ion saturation current is accompanied by an evident decrease in reflected power. As a conclusion, the power available is consumed in the breakdown rather than the joule type losses in the walls of the octupole. A sweep of 5 msec/cm was used in Fig. 3. That shows the magnetic field is turned on while the rf power is almost constant.

The ion saturation current at the B = 0 axis was measured as the pressure was varied from 1×10^{-6} to 4×10^{-5} torr.

Figure 4 shows a trace of the ion saturation current with the pressure maintained at 6×10^{-6} torr.

The peak ion saturation current is plotted vs pressure in Fig. 5, the corresponding value for the gun plasma 1 msec after injection is shown for comparison.

Comparing this result with Fig. 2 we see that we are getting higher density plasmas (frequency of the rf field is different).

Comparing the particle density with the plasma density from the gun we see with microwave plasmas we can get higher densities than with the gun. To be more accurate, such a comparison is incomplete unless the electron temperature is included. We will refer to that later.

A look at the different ion saturation current traces vs pressure shows that the breakdown does not occur at the same time. Figure 6 shows the breakdown time vs pressure. The higher the pressure, the earlier the breakdown occurs.

To explain this, a microwave breakdown will occur in zones where the magnetic field B equals B_c defined by

$$B_c = \frac{m\omega_{ce}}{e} .$$

We will call these zones the resonance zones.

If we start with an idea that the electric field is uniformly distributed in the octupole, we should expect that breakdown will occur as soon as a resonance zone appears in the octupole, but from the magnetic field configuration (Fig. 7) we see that the resonance zone appears behind the inner hoops where the electric field is small and as time goes on, these resonance zones move in regions where the electric field is high enough for a breakdown to occur.

Two kinds of measurements were taken to prove this idea, but we will take that after discussing the shape of Fig. 4. As we know, the breakdown threshold decreases as the pressure increases and from what we said in the preceding paragraph, we can see that for a high background gas pressure a breakdown is likely to happen in zones where E is small or in other words breakdown occurs at earlier times than if the gas pressure is reduced.

To explain the shape of the ion saturation current, we should start by considering a simple case where both E and B are constant in time; in this case, a steady state will develop in which the rate of ionization is equal to the loss rate.

Now returning to our case, as time goes on, once breakdown is created the resonance zone is moved toward the B = 0 axis. In this case, we expect that other zones near the outer hoops will share in the production and, consequently, we expect the ion saturation current to increase in the first half of the magnetic field cycle. After that, it stays almost constant for a certain time, then decreases because the production zones are getting less.

This is an oversimplified picture of the situation because it does not explain breakdown at low pressures. We may expect, in this case, the breakdown time is comparable to the half period of the magnetic field.[1] Future investigation of this point will be carried on to add some light to it.

At t = 3.8 msec a peak in the ion saturation current on the B = 0 axis is present for the whole range of pressure investigated. A way to explain that is the following. At t = 3.8 msec, the resonance zone is behind the inner hoops. These regions do not participate in the plasma production during the first half cycle because there is not enough field to cause a breakdown, but in the second half due to the presence of ionized particles, the breakdown threshold is reduced. We assume that the rise in the ion saturation current is due to ionization in these regions.

Another remark to be pointed out here: The ion saturation current starts to decay at t = 4.2 msec. That time corresponds to the disappearance of a resonance zone inside the octupole. The behavior of the ion saturation current will be determined by the loss mechanism only.

The electron temperature was measured in different places in the octupole, using the admittance probe technique.[1] The result shows that kT_e varies between 2-5 eV.

To see the dependence of T_e on pressure, the electron temperature was measured on the B = 0 axis for different pressures (1×10^{-6} - 4×10^{-5} torr). The results are plotted in Fig. 8.

Figure 9 shows the ion saturation current measured behind the upper outer hoop at $\frac{3''}{8}$, $\frac{5''}{8}$, and $\frac{7''}{8}$ from the hoop (lower trace). The upper trace is the ion saturation current on the B = 0 axis.

The time lag between the appearance of the two currents led us to measure the ion saturation current vs position between the hoop and wall.

Figure 10 shows the spatial distribution of ion saturation current for different times (measured from the beginning of the multipole field pulse).

A look at the current behind the hoop shows that it goes from a small value near the hoop, increases at $\frac{1''}{2}$ from the hoop and then decreases again as we go towards the wall. This type of behavior is not expected if we believe that the electric field intensity is uniform in the octupole.

The electric field behind the upper outer hoop was measured by inserting a $\lambda/4$ stub type dipole. Figure 11 shows the results of measurements with such a dipole that gives a average of the electric field over a distance of $\lambda/4$.

Anyway, the results of such measurements explain why a breakdown is likely to happen $\frac{1''}{2}$ from the hoop and that corresponds to the region where the ion saturation current increases sharply.

The same type of measurement was made behind the bottom outer hoop. The same type of behavior was noticed.

The electric field in the midplane was plotted vs position. The results are shown in Fig. 12. That type of behavior is expected because it is a result of the interference of rays from the horn after being reflected by the walls.

Now we can give an explanation of why the ion saturation current behind the hoop appears later than in the midplane. Looking at Fig. 7, as the magnetic field is turned on, the resonance zone appears first in the octupole behind the inner hoops but the electric field is not high enough to create a breakdown. Then, as time goes on, these zones move to regions which have higher electric field, resulting in a breakdown. As soon as that happens, the plasma is pushed outwards toward the low field region (the magnetic field is decreasing radially outward at the breakdown regions). This time is still earlier for a resonance to appear behind the outer hoops. As time goes on further, a greater resonance zone is created and that contributes to the progressive increase in the plasma density in the midplane. Once a resonance region occurs behind the outer hoops, breakdown will occur and the density will increase at a faster range. That may be due to the presence of some ionized particles at the moment of breakdown.

A rough calculation of particle density of the microwave plasma shows that a density of 3×10^{10} is maintained. These calculations were based on a comparison of the ion saturation current of the gun plasma with that of the microwave plasma. The temperature of electrons and ions were taken into consideration. In such a case, an ionization percentage of 15% is calculated.

Our aim in this program is to get a better idea of the time sequence of plasma creation by microwave breakdown and to learn how to produce highly ionized plasma in pulsed toroidal multipoles.

References

1. J. C. Sprott Thesis, "Behavior of r.f. Heated Plasmas in a Toroidal Octupole Magnetic Field", May, 1969.

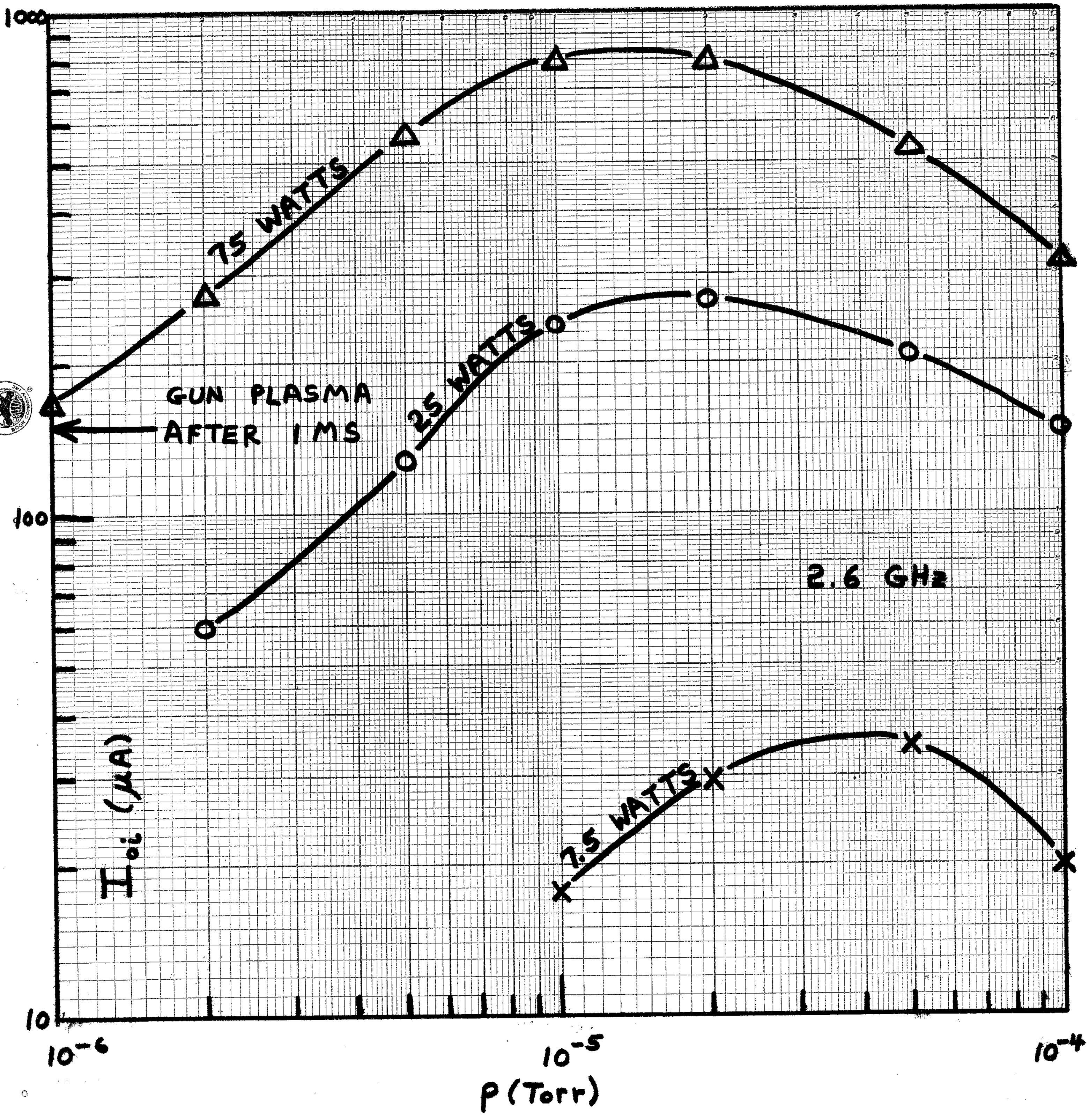

1000
100
10
10^{-6}
10^{-5}
10^{-4}
P (Torr)
I_{oi} (μA)
75 WATTS
25 WATTS
7.5 WATTS
GUN PLASMA
AFTER 1 MS
2.6 GHz

Fig. 2

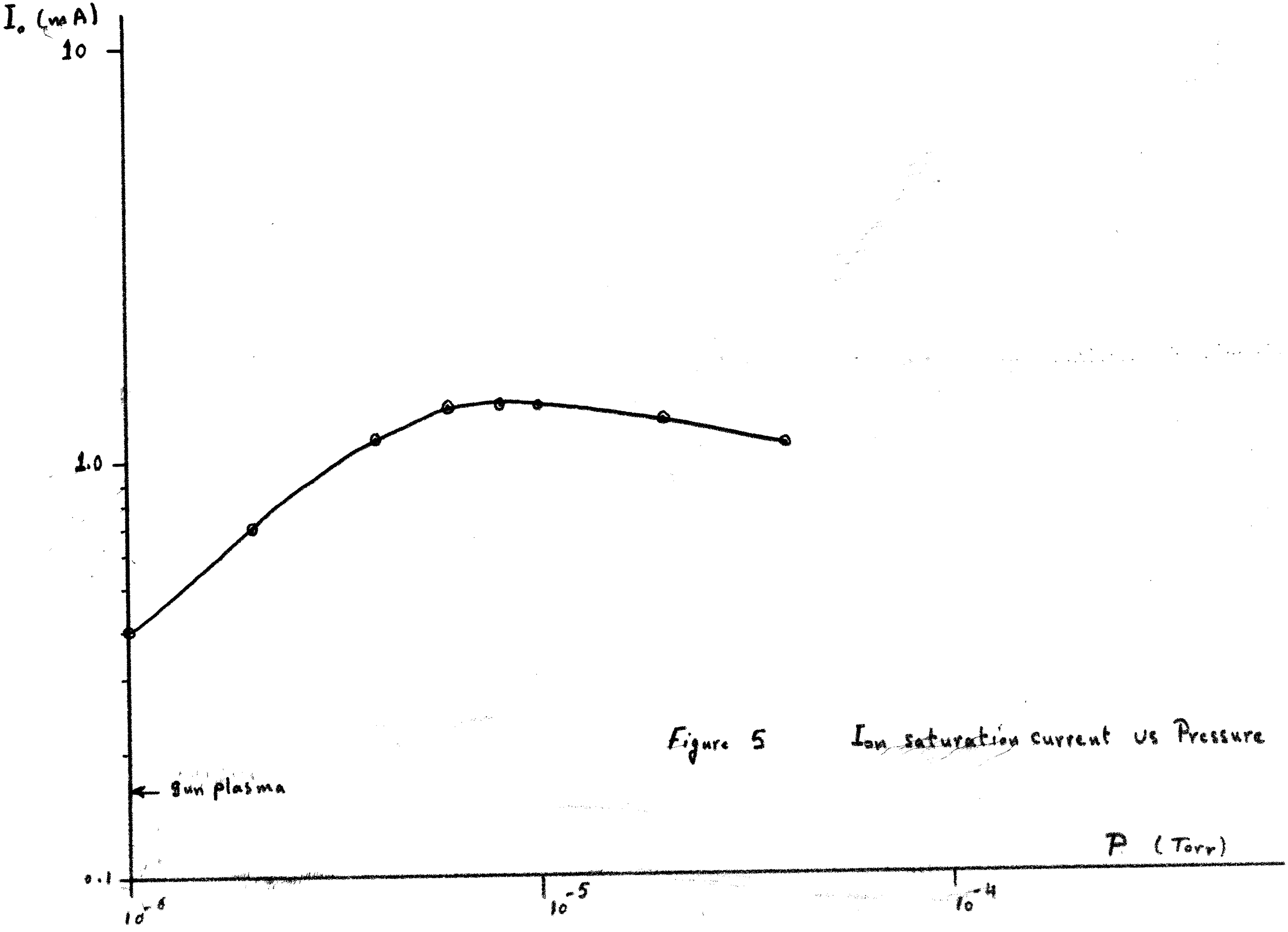


Figure 5 Ion saturation current vs Pressure

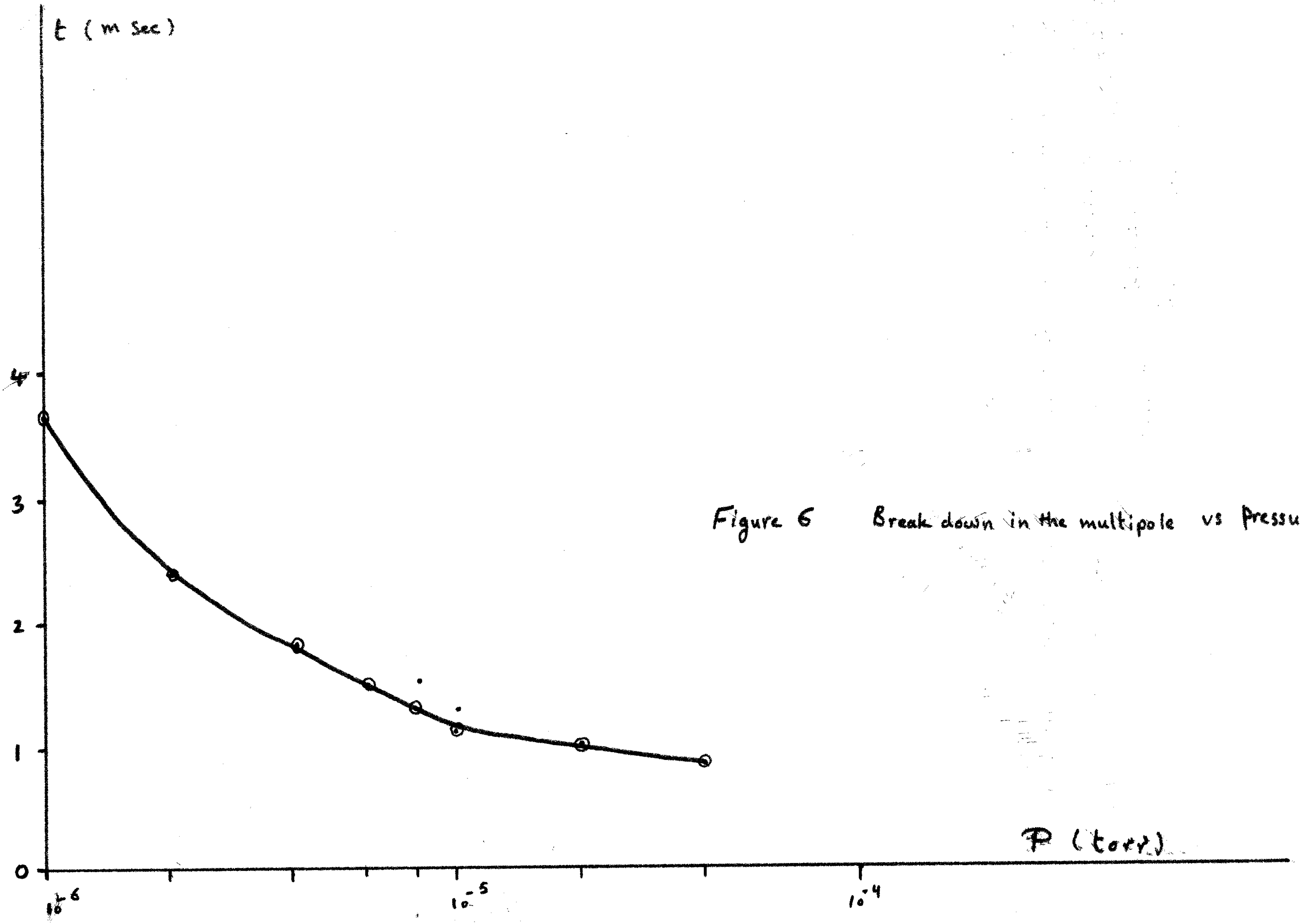
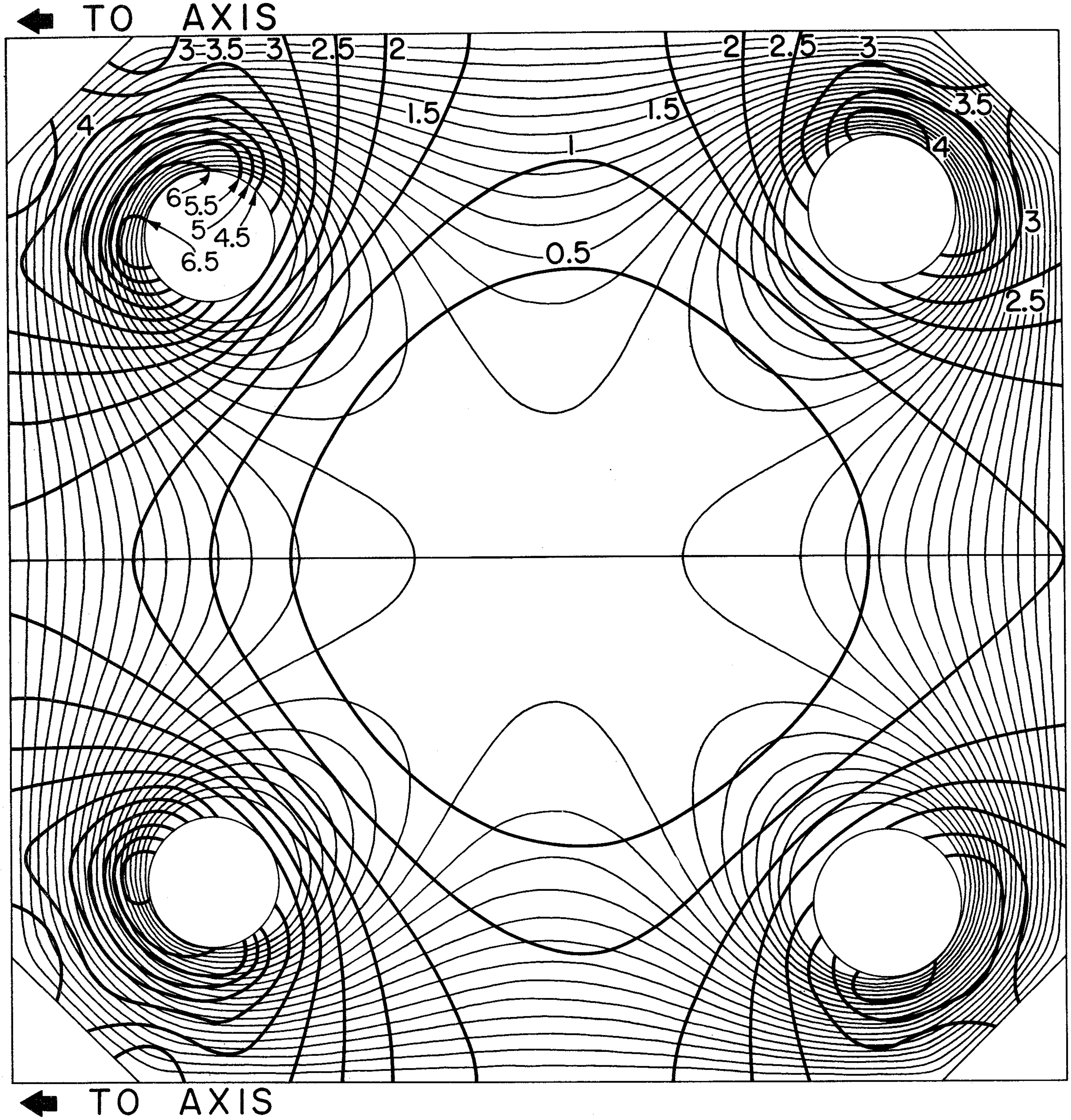


Figure 6 Break down in the multipole vs Pressure



CONSTANT B SURFACES IN THE WISCONSIN TOROIDAL OCTUPOLE

Figure 7

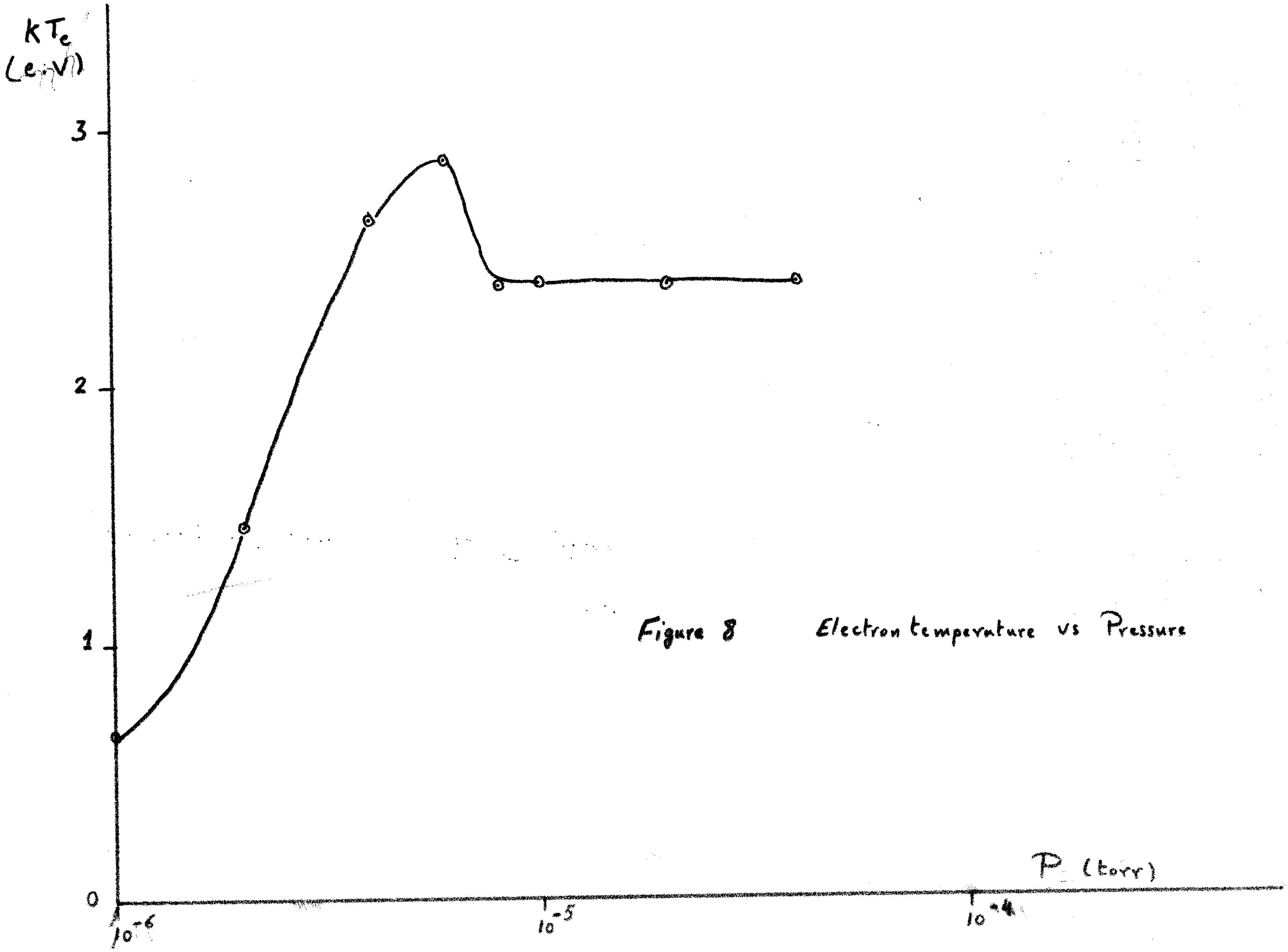


Figure 8   Electron temperature vs Pressure

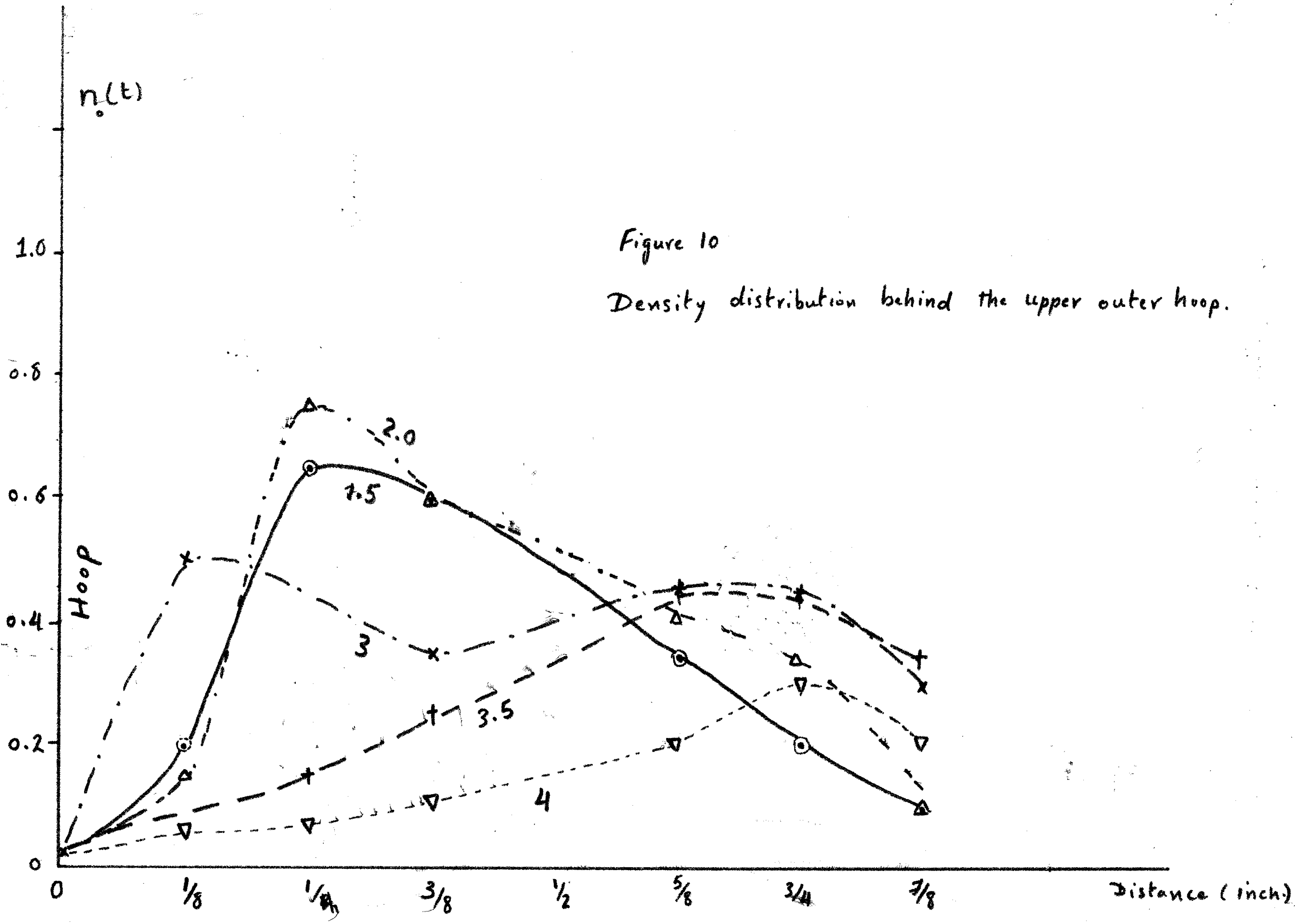


Figure 10

Density distribution behind the upper outer hoop.

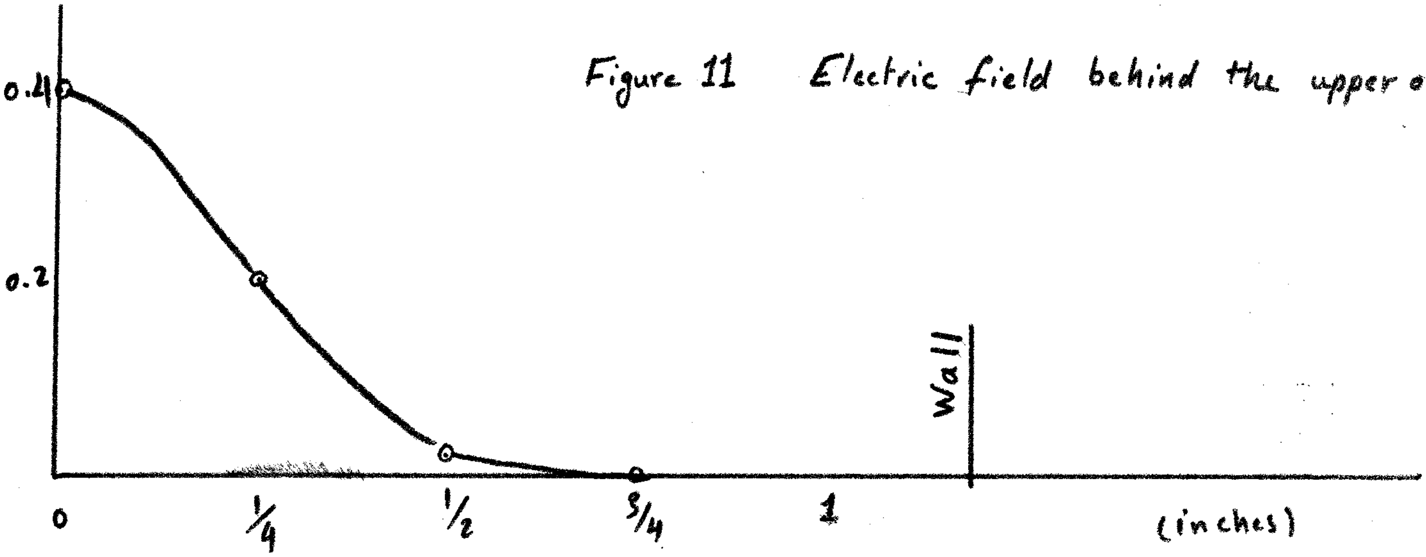


Figure 11 Electric field behind the upper outer hoop

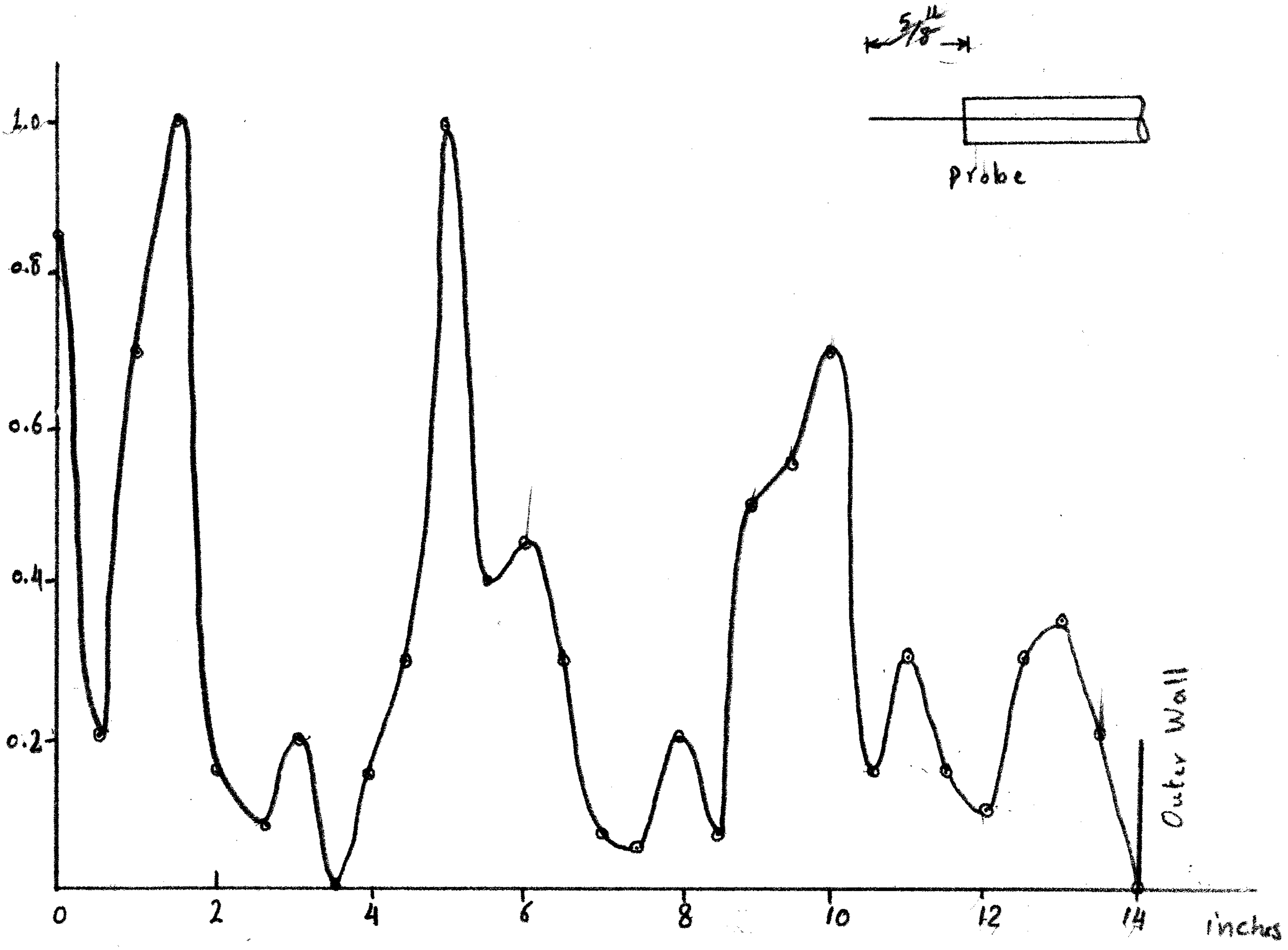


Figure 12 Electric field Across Midplane.