Resonant Microwave Heating

of a Gun Plasma in a Toroidal Octupole

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ABSTRACT*

Experiments are described in which a gun injected plasma with $n \sim 10^9$ cm^{-3}, $kT_i \sim 40$ eV and $kT_e \sim 5$ eV was heated by 144 μsec pulse of microwave power in a toroidal octupole magnetic field. Frequencies from 700 - 9000 MHz and powers up to 100 kW were used. Scintillator probes indicate large electron energy densities during the heating pulse in regions where $\nabla_{\parallel} B = 0$ at resonance. When the field strength and microwave frequency are adjusted so that the resonances occur near the hoops or walls, a large x-ray flux is emitted from these regions. Energy analyzer measurements show that the energy distribution is non-Maxwellian and consists of a cold component with $kT_e \sim 10$ eV and a hot component with a temperature of typically 1-10keV. With low background pressure ($\sim 10^{-6}$ Torr) and high microwave power, the hot component comprises an appreciable fraction of the total density, but the density of hot electrons decreases with increasing pressure and decreasing power. After the heating pulse, the hot component decays in about 1 - 10 μsec in agreement with calculated thermal flow to hoop supports and probes.

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Plasma confinement devices typically consist of an inhomogeneous magnetic field in a vacuum cavity with conducting walls. An example of such a device is the Wisconsin toroidal octupole, shown in Fig. 1. The octupole field is produced by the induced currents in four copper hoops which encircle the major axis. The light lines in Fig. 1 are magnetic field lines, and the heavy lines are surfaces of constant magnetic field strength.

Previous experiments[1,2] have shown that a cold ion plasma can be produced in the field by raising the background gas pressure to about 10^{-4} torr and injecting microwave power at a frequency such that electron cyclotron resonance occurs somewhere within the cavity. At low background pressure, no microwave power is absorbed, unless preionization is provided, in which case the electrons are heated. At low background pressure, the electron density remains relatively constant, since the ionization time is long.

In this experiment, preionization is provided by injecting a hot ion plasma from a conical pinch gun. After 500 μsec, when the gun plasma has filled the toroid, the microwaves are turned on. Before the microwaves are turned on, the density is about $10^9 cm^{-3}$, and the electrons are Maxwellian with a temperature of about 5 eV. Microwave frequencies of 700 - 9000 MHz and powers up to 100 kW are used.

The density and energy distribution of the electrons during and immediately after the microwave pulse were measured using scintillator probes and electrostatic energy analyzers. The energy analyzers consist of a set of slits and curved plates biased to accept electrons of a given energy. Electrons can be extracted from the field through a high permeability hypernik tube, or analyzed in situ by means of a miniature shielded analyzer placed near the zero field axis. The scintillator probes consist of small cylinders of plastic scintillator covered with various thicknesses of copper and aluminum foil and coupled through a flexible light guide to a photomultiplier tube outside the vacuum. For a Maxwellian electron distribution, the ratio of signals from two scintillators covered with different foil thicknesses gives a measure of the electron temperature, and the magnitude of the signals gives the density. The scintillator probes were used primarily to determine the spatial distribution of energetic electrons. The energy analyzers were used to measure the distribution function on the zero field axis.

If the magnetic field strength and microwave frequency are adjusted so that electron cyclotron resonance occurs, for example, on the surface $B_0 = 1$, we expect strong heating at places where the magnetic field lines are tangent to the heating surface, since electrons would tend to be mirror confined in the resonance regions.[2,3] A scintillator probe scan was made of the upper inside quadrant during the heating pulse, and Fig.2 shows the result. The diagonal lines show where the probe scans were made. The contours are surfaces of constant scintillator probe output signal. The heating is strongly localized in the resonance regions, as expected, but there is some tendency for the energetic electrons to flow along the magnetic field. The variation parallel to $\vec{B}$ suggests a velocity anisotropy, and other measurements show that this anisotropy is largest at high energies. The small signals in the midplane near the inner wall are caused by the fact that the probe crosses the resonance region and obstructs the heating. This can be demonstrated by observing the signal in the resonance region with a scintillator probe and inserting another $\frac{1}{4}$" diameter probe across the midplane at another port. When the probe crosses the resonance region, the scintillator probe signal drops by two orders of magnitude. This confirms the presence of large azimuthal ∇B drifts as expected.

If the magnetic field strength is reduced, the resonances move out near the walls and hoops, and we expect to see x-rays produced by energetic electrons striking the walls and hoops. Figure 3 shows the x-ray signal detected by a scintillator embedded in the vacuum tank wall. As the voltage on the capacitor bank used to excite the magnetic field is varied, the x-ray signal shows three prominent peaks. These peaks correspond respectively to resonance at the surface of the inner hoops, outer hoops, and wall. A collimated scintillation detector, which could be pointed at the hoops and wall, was used to verify the origin of the peaks. The position of the peaks also scales with microwave frequency in the expected manner as shown in Fig. 3.

Figure 4 shows a typical distribution function on the zero field axis during the heating pulse. The energy density is smaller on the zero field axis than in the resonance regions, but the volume of the resonance regions is so small that the total energy distribution is closely approximated by the distribution on the zero field axis. The high energy electrons observed on the zero field axis are presumably formed in the resonance region and diffuse to the center by some process not well understood. The distribution function is non-Maxwellian and can be approximated by the function $f(w) = \frac{3n}{\bar{w}} e^{-\sqrt{6w/\bar{w}}}$ over a wide range of energies. The high energy tail of the distribution is approximately Maxwellian with a temperature of a few keV. The density n and average energy $\bar{w}$ calculated from the distribution function are $1.35 \times 10^{9}cm^{-3}$ and 160 eV. At earlier times in the microwave pulse, the energy density is higher giving an efficiency approaching 100% and indicating the presence of a strong loss mechanism.

Higher power microwaves produce distribution functions with a similar shape but somewhat higher densities and average energies. For example, Fig. 5 shows the density and temperature measured by a scintillator probe on the zero field axis using the highest power available. Since the distribution is non-Maxwellian, the numerical values in Fig. 5 should not be taken too seriously, although the energy analyzer at 30 μsec gives a density of $6 \times 10^{9}cm^{-3}$ and an average energy of 700 eV. The density during the heating can apparently exceed the density before the heating, presumably as a result of ionization and secondary emission. When the r.f. is switched off, the density of energetic electrons decays in a few μsec. The temperature (or, more precisely, the slope of the distribution at high energies) remains unchanged. These observations are consistent with losses caused by the thermal flow of electrons to obstacles in the plasma.

The energy analyzer shows a similar decay after the microwaves are switched off as indicated in Fig. 6. The lifetime of electrons of a given energy is plotted vs. energy. The loss is consistent with a decay rate that is proportional to velocity, as expected for thermal flow to obstacles. The calculated cross section for electron loss is about 90 cm^2, and this is in reasonable agreement with the geometrical area of the probes, analyzers, and hoops supports. Additional obstacles inserted into the plasma increase the decay rate. Within about 100 μsec after the microwaves are off, the distribution returns to a Maxwellian with a temperature only slightly greater than that of the initial gun injected plasma.

Fig. 7 shows the density and temperature during the r.f. pulse as measured by a scintillator probe as a function of background gas pressure. All previous data were at a pressure of 10^{-6} torr. As the pressure is increased, the density of energetic electrons decreases sharply. Note that the measured density is not the total density, which presumably increases at higher pressure, but is in some sense the density of the hot electron component, which at high pressures comprises a small fraction of the total.

In summary, we have shown that a gun injected plasma in a toroidal octupole with an initial electron temperature of 5 eV can be strongly heated in local regions of cyclotron resonance by a pulse of r.f. power. The resulting distribution during the heating is non-Maxwellian with an average energy of a few hundred eV. After the heating pulse, the energetic electrons decay in a few μsec as a result of the thermal flow of electrons to obstacles in the plasma.

REFERENCES

1. J. C. Sprott, Bull. Am. Phys. Soc. 13, 266 (1968).

2. J. C. Sprott, University of Wisconsin Ph.D. Thesis (1969).

3. J. C. Sprott, Bull. Am. Phys. Soc. 13, 1508 (1968).

Figure 1

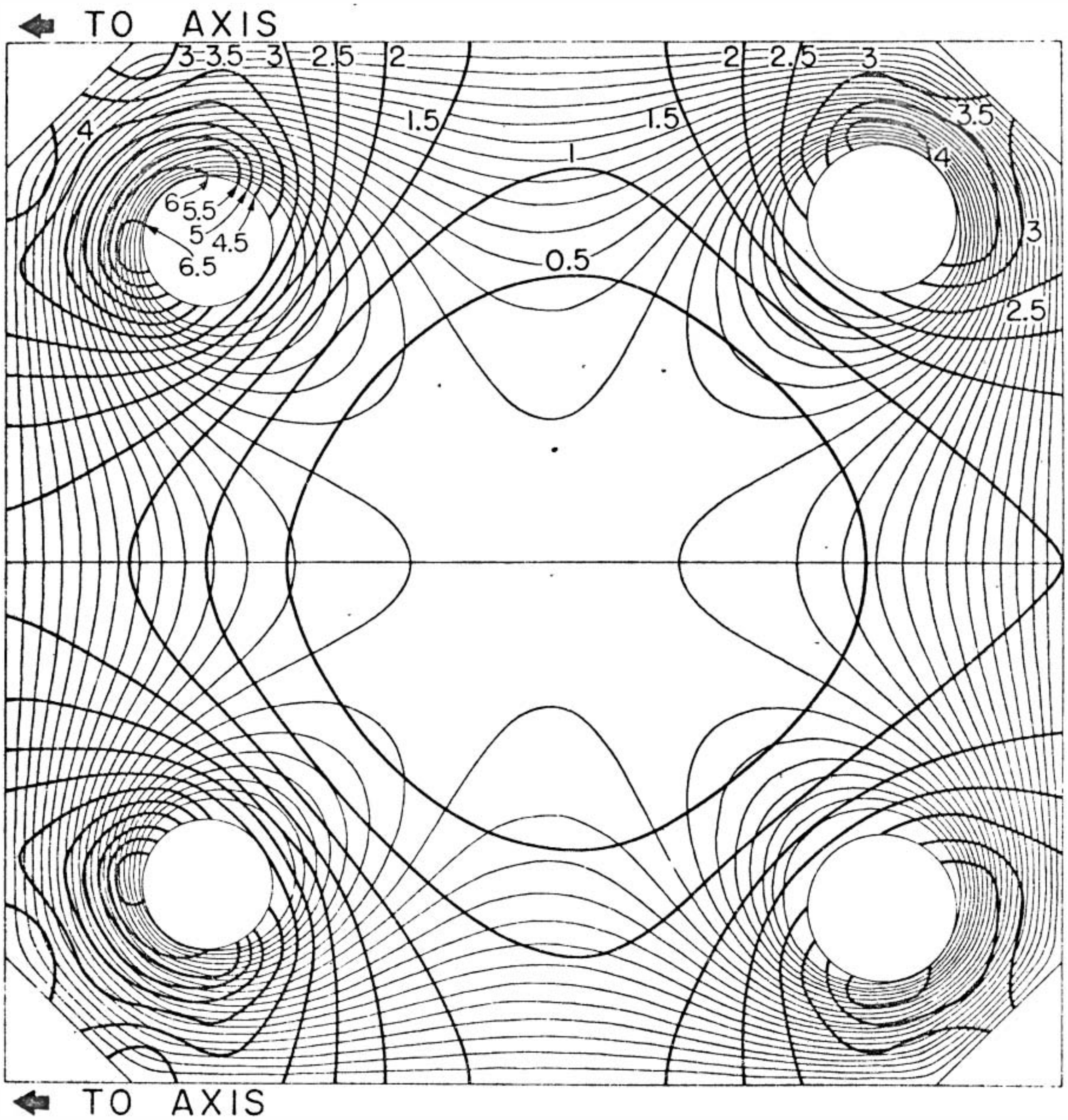


Figure 2

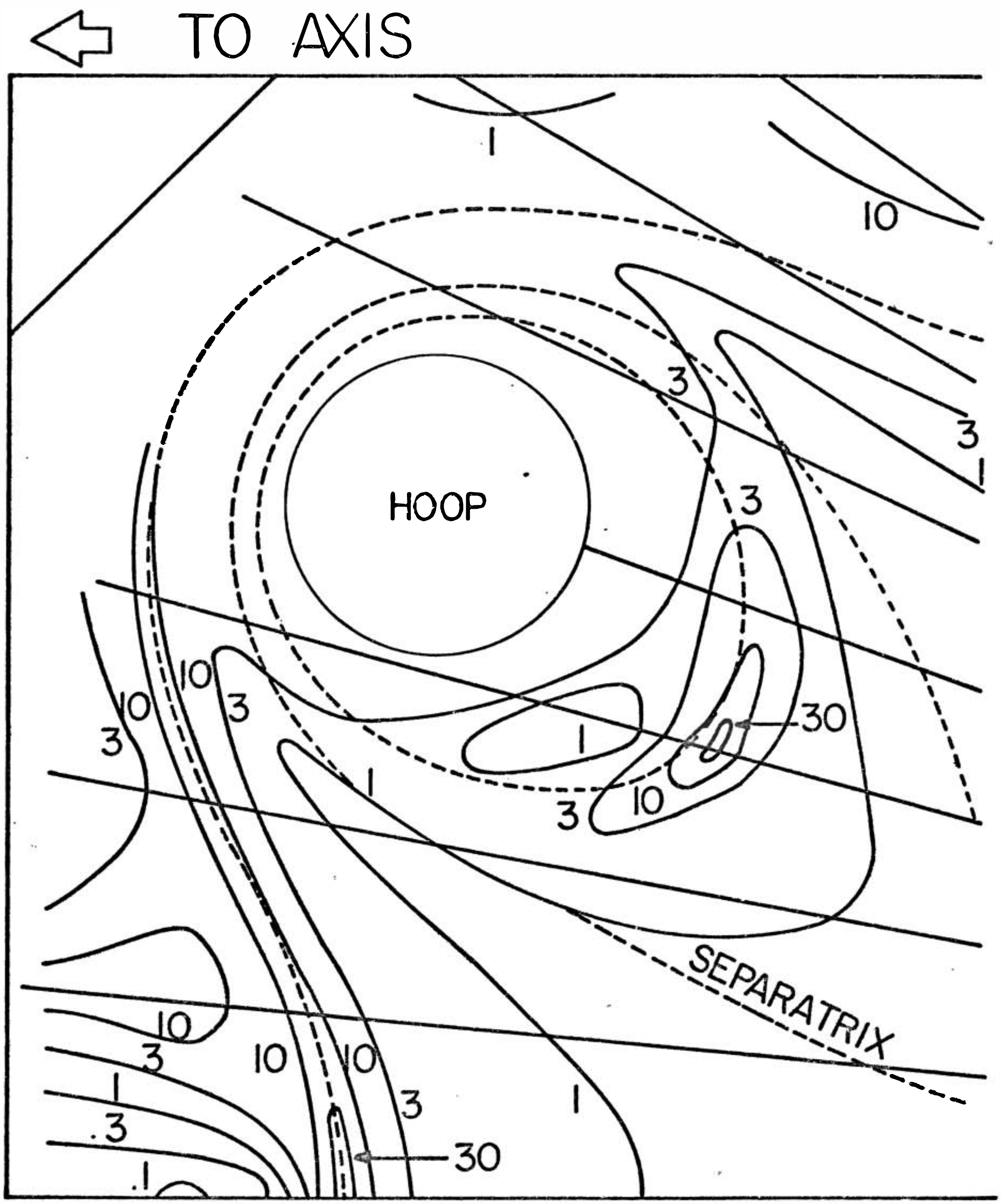

TO AXIS
HOOP
SEPARATRIX
1
10
3
3
1
3
10
3
10
10
3
1
30
1
3
10
10
3
1
.3
.1
10
10
3
1
30

Figure 3

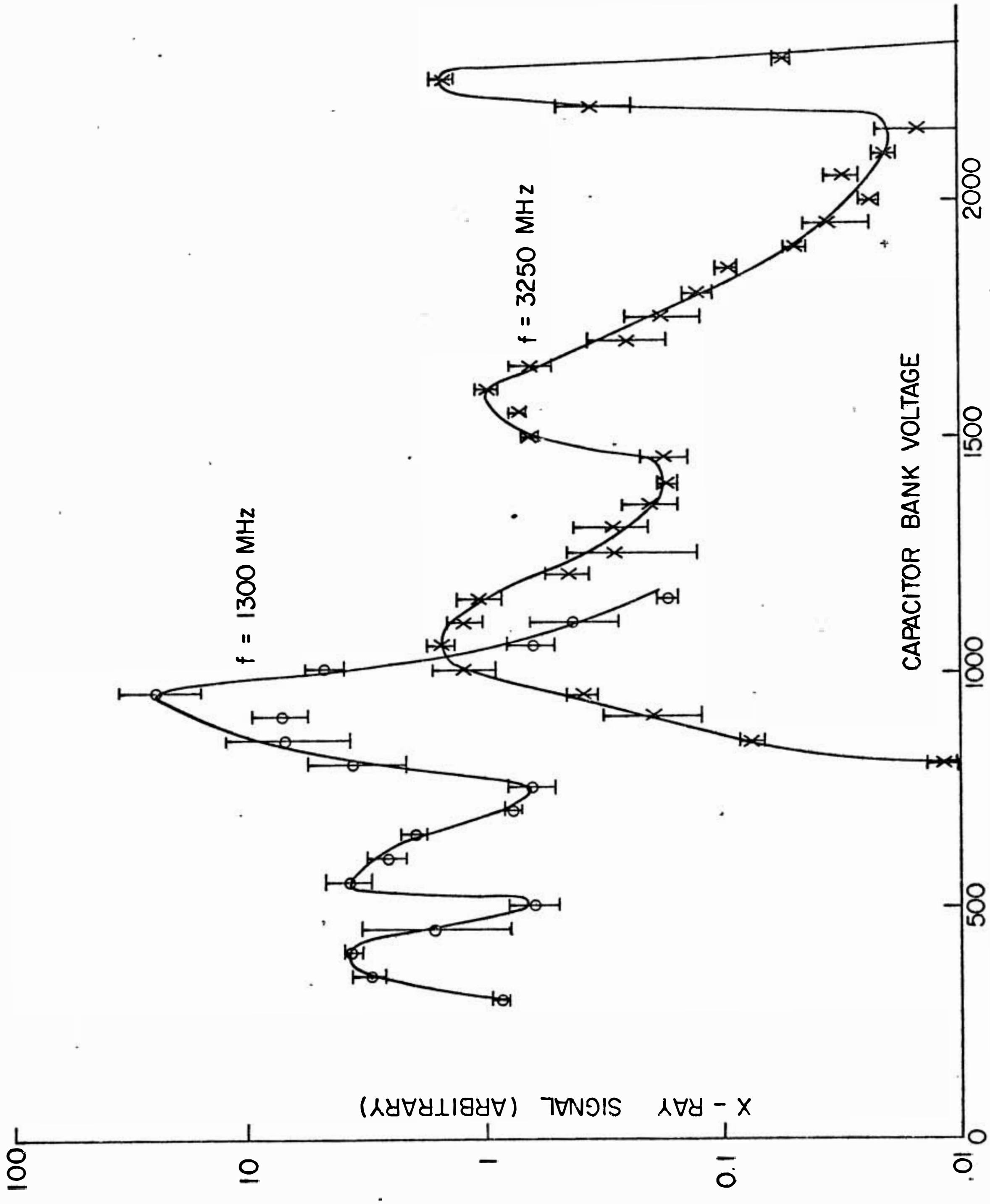
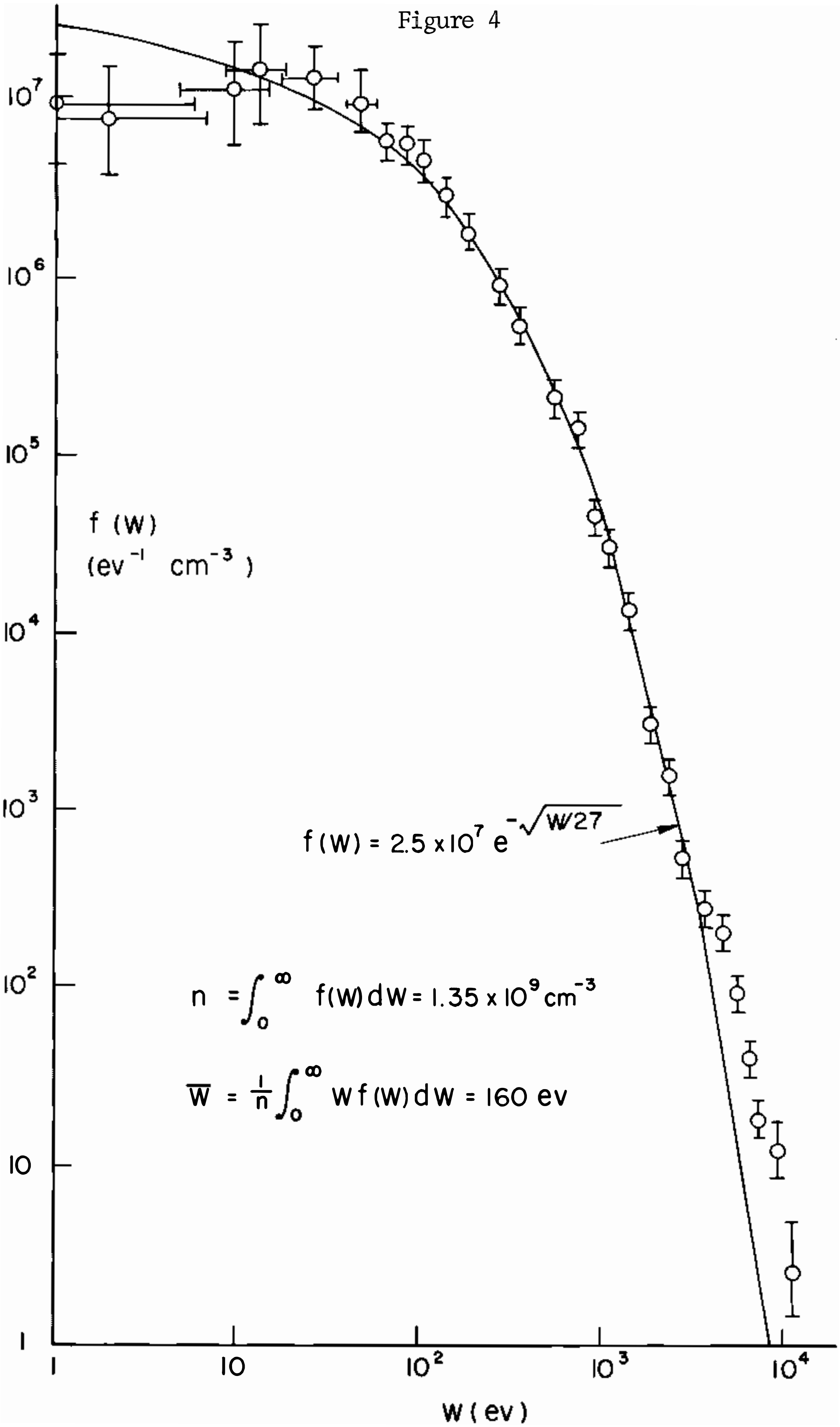

f = 1300 MHz
f = 3250 MHz
CAPACITOR BANK VOLTAGE
X - RAY SIGNAL (ARBITRARY)
0
500
1000
1500
2000
100
10
1
0.1
.01

Figure 4



f (W)
(ev⁻¹ cm⁻³)
$f(W) = 2.5 \times 10^7 e^{-\sqrt{W/27}}$
$n = \int_0^\infty f(W)\,dW = 1.35 \times 10^9 \text{ cm}^{-3}$
$\overline{W} = \frac{1}{n}\int_0^\infty W f(W)\,dW = 160 \text{ ev}$
W (ev)
1
10
10^2
10^3
10^4
10^5
10^6
10^7

Figure 5

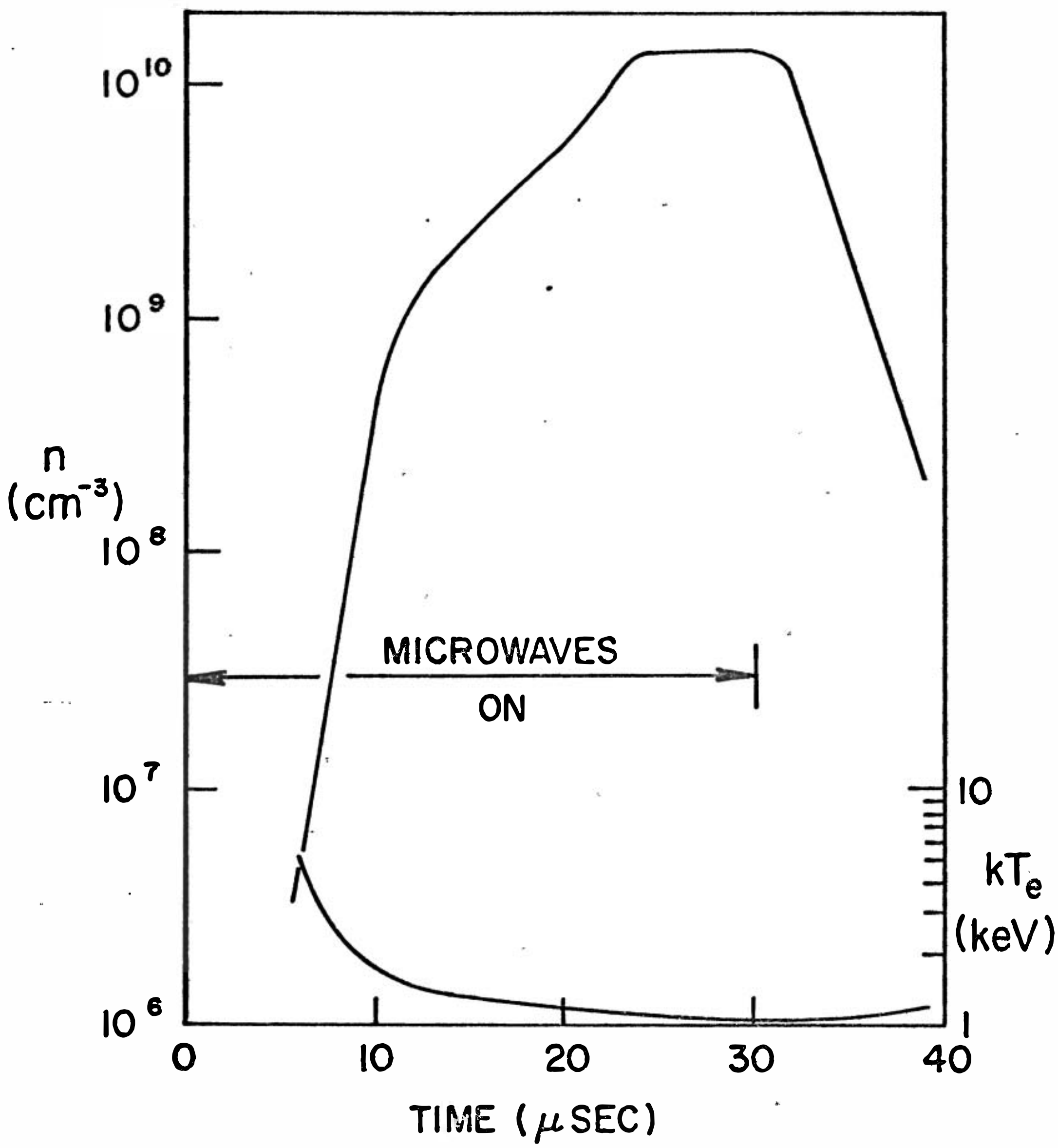

10^10
10^9
10^8
10^7
10^6
n
(cm^-3)
MICROWAVES
ON
10
kT_e
(keV)
1
0
10
20
30
40
TIME (μ SEC)

Figure 6

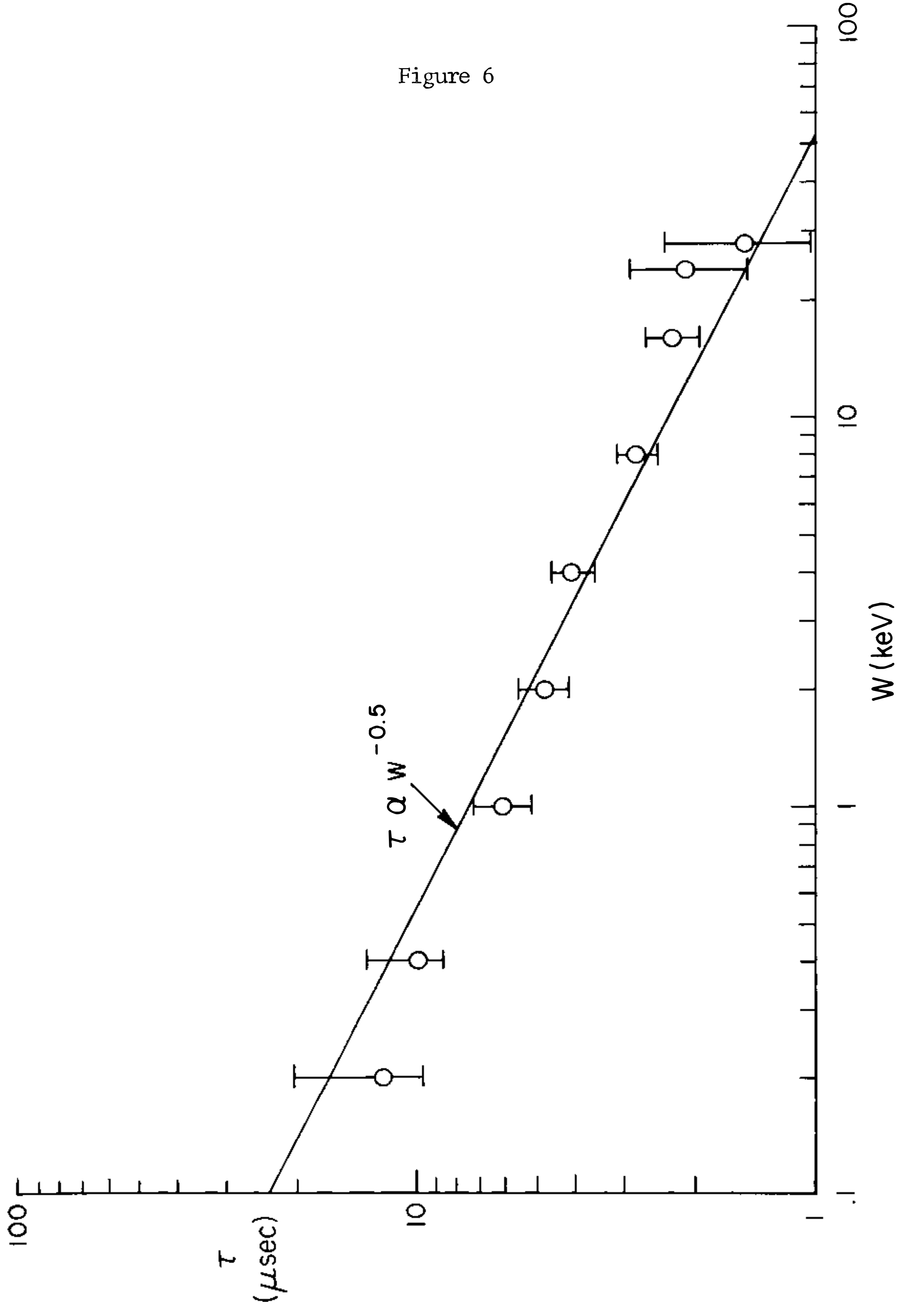
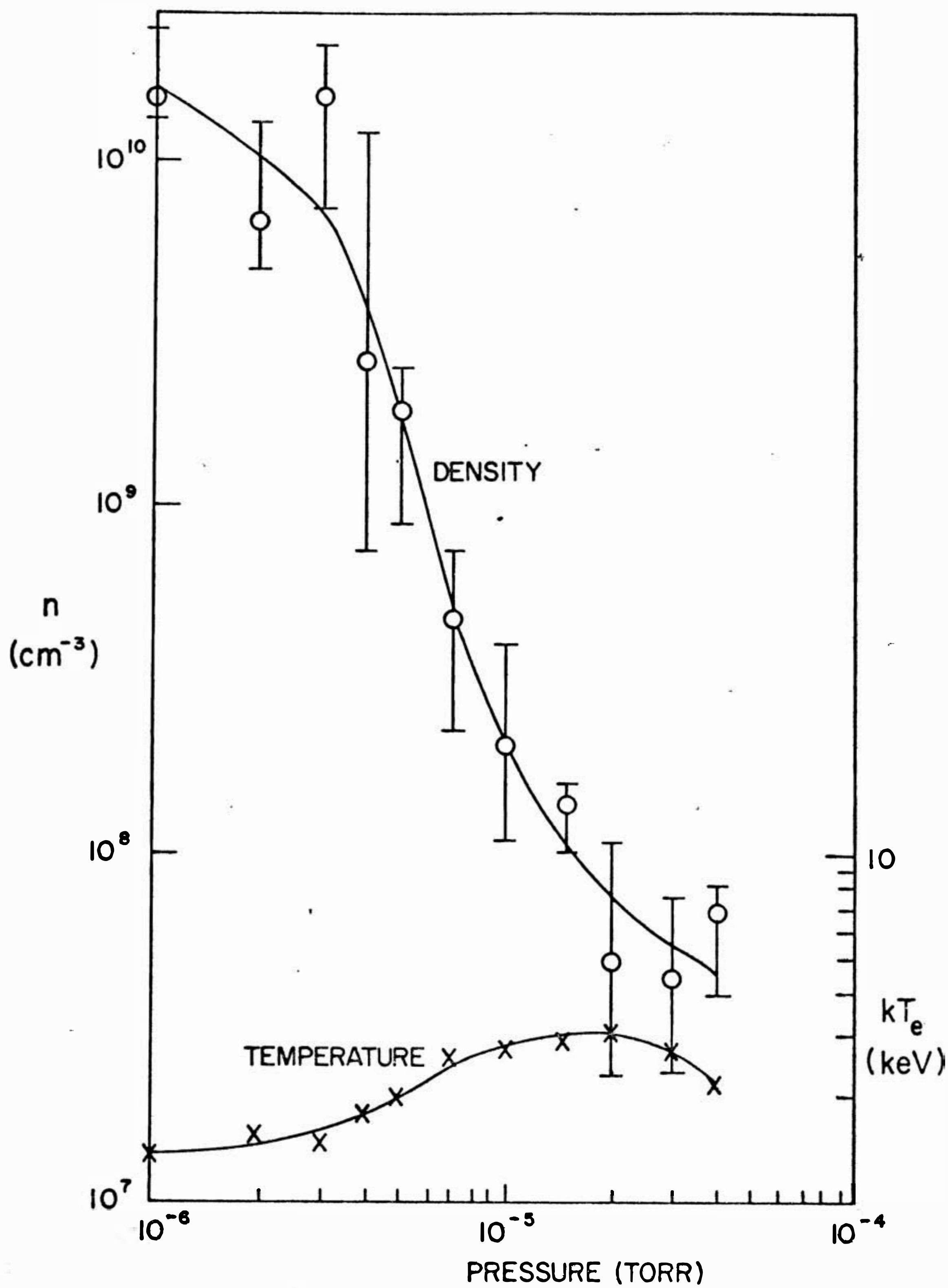


Figure 7


DENSITY
TEMPERATURE
n
(cm^{-3})
10^{10}
10^{9}
10^{8}
10^{7}
10
kT_e
(keV)
10^{-6}
10^{-5}
10^{-4}
PRESSURE (TORR)