Characteristics of a Microwave Plasma in a Toroidal Octupole*

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ABSTRACT

A 3 GHz magnetron produced a 10^9 cm^{-3} 10 eV electron temperature plasma in the Wisconsin toroidal octupole. This plasma resembled the usual gun injected plasma except that the ions were cold. The plasma was produced in the outer high field region where it is hydromagnetically unstable. Within 50 μsec the plasma collapsed inward to fill the toroid with a density distribution which depended on the magnitude of the magnetic field during breakdown. The plasma was created with azimuthal density variations of about a factor of two, but became azimuthally symmetrical in 500-1000 μsec. The density at a given azimuth decayed uniformly with an average lifetime of 900 μsec as compared with 700 μsec for the gun plasma. No appreciable fluctuations of density or potential were observed in $\oint \frac{d\ell}{B}$ stable region, except for a drift wave which appeared outside the separatrix in the regions of unfavorable curvature only in the presence of a very sharply peaked density distribution. Flute oscillations were observed in the unstable region near the walls but they decreased inside ψ_{crit} in a manner similar to that for the gun plasma.

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It is possible to produce a cold ion plasma in the Wisconsin toroidal octupole by filling the cavity with 10 kW of 3 GHz microwave power for 100 μsec with a background hydrogen gas pressure of 10^{-4} torr.[1] The plasma thus produced resembles the usual gun injected plasma[2,3] in that the density is about 10^9 cm^{-3} and the electron temperature is about 10 eV.

Figure 1 shows a magnetic flux plot in a cross sectional plane of the toroid. The light lines are magnetic field lines and are numbered from $\psi = -5$ at the hoops to $\psi = +5$ at the walls. The heavy lines are contours of constant magnetic field strength. When the rf pulse is applied, plasma is produced along that constant B surface which gives electron cyclotron resonance. By varying the magnetic field strength, the spatial distribution of plasma can be drastically changed. For example, the usual magnetic field gives resonance on the line labeled 1 in figure 1. This field gives two density peaks, one near the wall and one near the hoop with relatively little plasma on the separatrix. By decreasing the field by a factor of six, plasma can be produced in one peak near the separatrix. A distribution strongly peaked off the separatrix is unstable and is observed to collapse inward in about 50 μsec. In all cases, after a stable spatial distribution is achieved, the density is constant on a field line and decays exponentially with a lifetime of about 900 μsec.

There are three classes of fluctuations which I will discuss: 1) The first is a drift wave which occurs in a region of steep density gradient outside the separatrix but inside ψ_{crit}. This is a standing wave with a peak in the regions of unfavorable curvature and nodes in the regions of favorable curvature. 2) The second is a flute instability which occurs in the V'' unstable region near the walls. 3) The third is an unexplained oscillation which occurs when a very steep density gradient exists near the hoops.

Since the density is constant on a field line, it is convenient to plot density in ψ-space. Such a plot is shown in figure 2. The density is initially peaked off the separatrix toward the hoops and toward the wall in rough agreement with what is expected from volume considerations,[4] indicated by the dotted line labeled $\frac{R}{V'|\nabla B x \nabla \psi|}$ in Fig. 2. The best stability of such a system is obtained when the density is peaked on the separatrix and decreases monatonically outward. However, because of the finite pressure term in the energy principle, it is possible to support a slight inverted density gradient.[3,5] The maximum stable gradient is given by the slope of the function $1/V'^{\gamma}$ shown as a dotted line in figure 2 with $\gamma = 5/3$. Note that initially the density gradient exceeds the stability limit, but that within a short time, the density becomes nearly constant and then decays uniformly. The collapse inward is accompanied by 100 volt potential fluctuations.

At full magnetic field amplitude, no plasma is expected to be created between $\psi = -3$ and the hoops. In fact, the initial density distribution does drop sharply in this region, as shown in figure 2, but by 200 μsec the distribution has become nearly flat in spite of the fact that this gradient is expected to be stable. Large potential fluctuations are observed in this region, and persist for about 400 μsec -- long after the distribution has become flat.

Figure 3 shows some profiles of ion saturation current which can be achieved by varying the magnetic field. Triple probe measurements[6] show that the electron temperature is constant in space and so the ordinate of the curve is proportional to density. With high magnetic fields, the density profile is relatively flat, but as the field is decreased, the density peaks more and more sharply near the separatrix eventually becoming even steeper than the usual gun injected plasma.

When the density gradient becomes sufficiently large, fluctuations appear in the V'' stable region where the curvature is unfavorable as shown in figure 4. The amplitude of these fluctuations is maximum where the density gradient is maximum and amounts to about a 10% variation in density. The fluctuations occur only on the side of the peak toward the walls and have nodes in the regions of favorable curvature. This oscillation has a frequency of about 100 kHz in agreement with the theoretical prediction[7,8,9] of

$$\omega \approx 0.3 k_\perp \frac{kT_e}{eB} \frac{\nabla n}{n}$$

and a parallel wavelength $\frac{1}{2}$ as long as a closed field line. The wave propagates in the direction of the electron diamagnetic current and has a perpendicular wavelength of 3 cm in agreement with the prediction that

$$k_\perp^2 \rho i^2 \sim T_i/T_e .$$

To a close approximation the density and potential fluctuations are in phase implying no transport in agreement with the fact that the density gradient persists throughout the life of the plasma. The amplitude of the oscillations decreases in time presumably because the electron temperature is decaying. The addition of a toroidal magnetic field of about 100 gauss does not suppress the fluctuations. The parallel phase velocity of the wave is greater than the ion thermal speed and less than the electron thermal speed:

$$v_{Ti} < \frac{\omega}{k_{\parallel}} < v_{Te}$$

This wave is apparently identical to the collisionless ballooning mode observed by Meade and Yoshikawa[9] in a linear quadrupole.

Figure 5 shows the amplitude of density fluctuations near the critical ψ surface where $V'' = 0$. The fluctuations amount to about 40% in the unstable region and fall off rapidly inside ψ_{crit}. The oscillations are at a frequency of a few tens of kHz, and the profile resembles that for the gun injected plasma.[3] Density and potential fluctuations are very nearly 180° out of phase implying no transport. When a toroidal magnetic field of 180 gauss is added, the fluctuations decrease in the originally unstable region and increase in the originally stable region in a manner similar to that previously observed[3] for the gun plasma. These oscillations have $k_{\parallel} = 0$ and hence are rightly called flutes.

Figure 6 shows oscilloscope traces which summarize the behavior of the plasma. The top picture shows the density in the resonance region. No plasma is produced for the first 40 μsec, and then the density rises quickly to 10^{11} cm^{-3}. The time required for the density to increase is inversely proportional to the background pressure and is about equal to the electron-neutral collision time. The optimum background pressure for breakdown is about 10^{-4} torr giving a neutral density 1000 times the electron density. When the density reaches 10^{11} cm^{-3}, the electron plasma frequency equals the microwave frequency and the plasma no longer absorbs power.

The second picture shows the floating potential and circumferential electric field in the same region. The electric field $\vec{E} \times \vec{B}$ drifts plasma out toward the wall at this azimuth for the first 60 μsec, but as the density builds up, the electric field reverses. The magnitude is just sufficient to allow the plasma to collapse at the observed rate.

The third picture is a triple probe[6] trace on the zero field axis. The density decays uniformly with a lifetime of 900 μsec. Langmuir probes show a temperature of about 10 eV which decays about 40% over 1 msec, although there is reason to believe that the temperature might be considerably lower than this. Electrostatic energy analyzer[10] measurements place an upper limit of 1 eV on the ion temperature. After the first 200 μsec, the floating potential on the zero field axis shows no fluctuation.

Outside the critical ψ line, potential fluctuations of a few tenths of a volt and density fluctuations of about 40% are observed. Under special conditions a very steep density gradient can be produced in the V'' stable region near a hoop and fluctuations are observed to accompany a motion of plasma toward the hoops. Under other special conditions, a very sharply peaked distribution leads to a ballooning mode localized in the region of unfavorable curvature inside ψ_{crit}.

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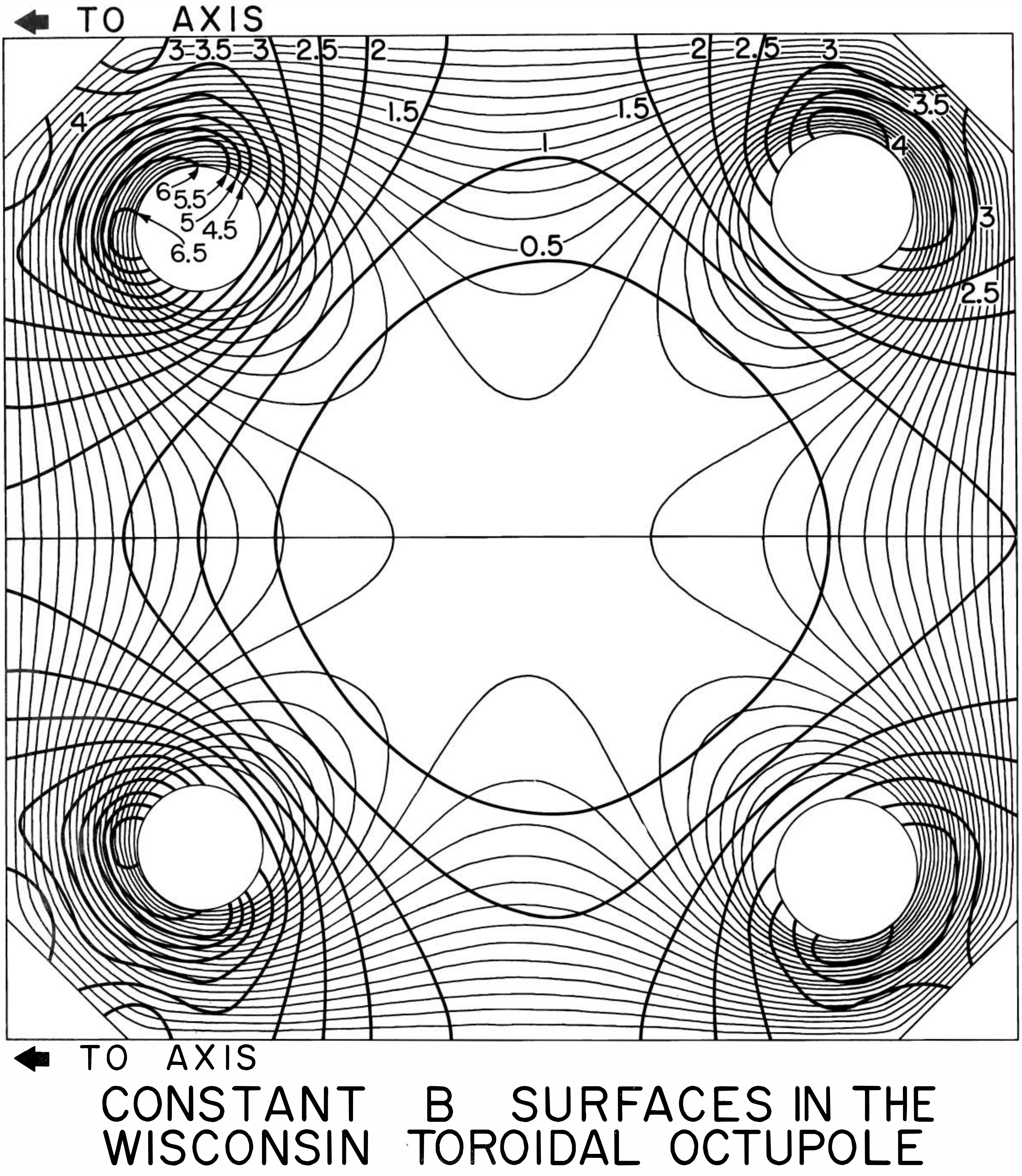
TO AXIS
3
3.5
3
2.5
2
2
2.5
3
4
1.5
1.5
3.5
4
1
6
5.5
5
4.5
6.5
0.5
3
2.5
TO AXIS
CONSTANT B SURFACES IN THE WISCONSIN TOROIDAL OCTUPOLE

Figure 1

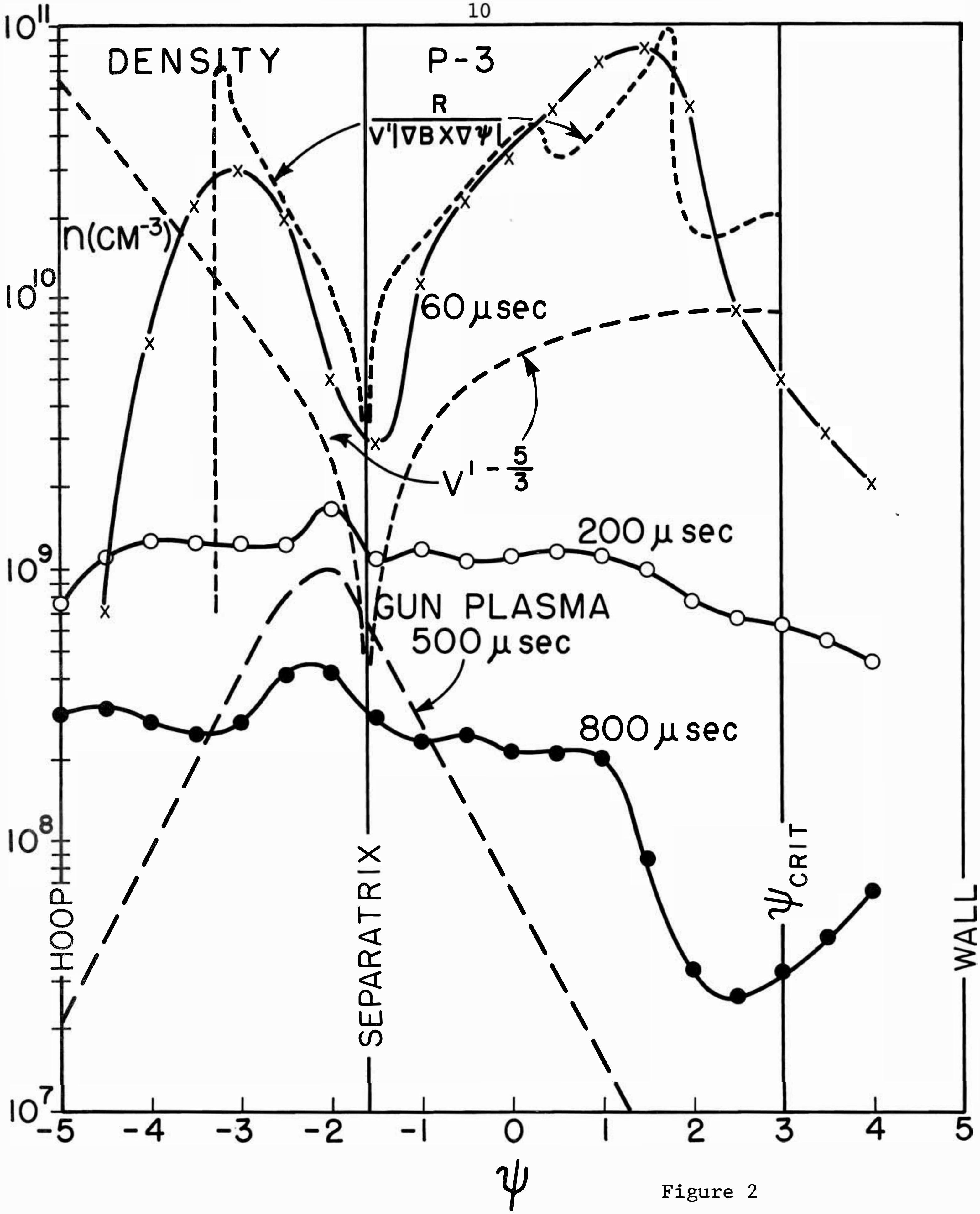
DENSITY
P-3
$n(\mathrm{CM}^{-3})$
$\frac{R}{V'|\nabla B \times \nabla \psi|}$
60 μsec
$V'^{-\frac{5}{3}}$
200 μ sec
GUN PLASMA
500 μ sec
800 μ sec
HOOP
SEPARATRIX
ψ_{CRIT}
WALL
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
-5
-4
-3
-2
-1
0
1
2
3
4
5
ψ

Figure 2

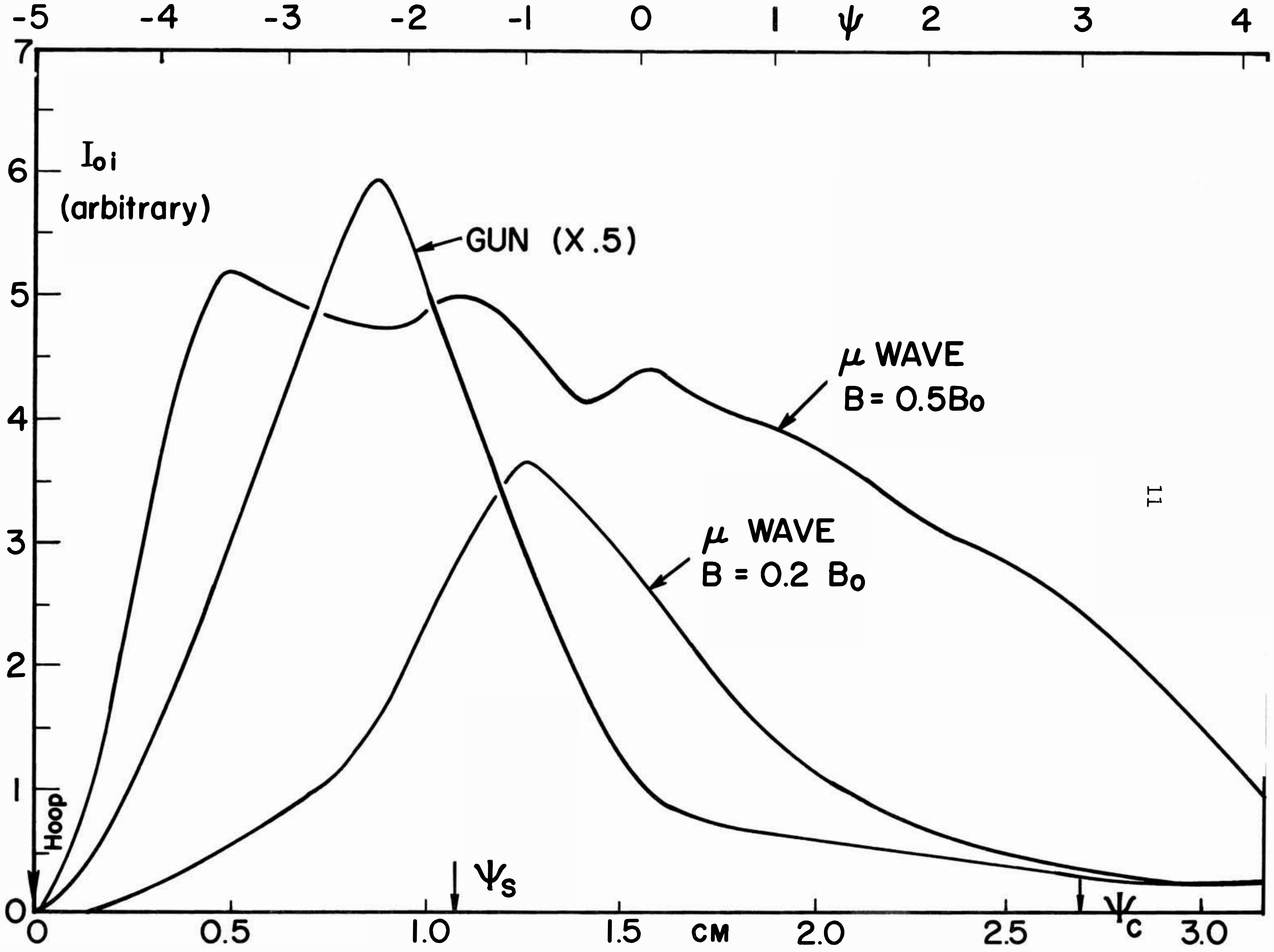
-5
-4
-3
-2
-1
0
1
ψ
2
3
4
7
6
5
4
3
2
1
0
I_{oi}
(arbitrary)
GUN (X .5)
μ WAVE
B = 0.5Bo
μ WAVE
B = 0.2 Bo
Hoop
Ψ_S
Ψ_C
0
0.5
1.0
1.5
CM
2.0
2.5
3.0

Figure 3

DENSITY PROFILE AT 500 μ sec

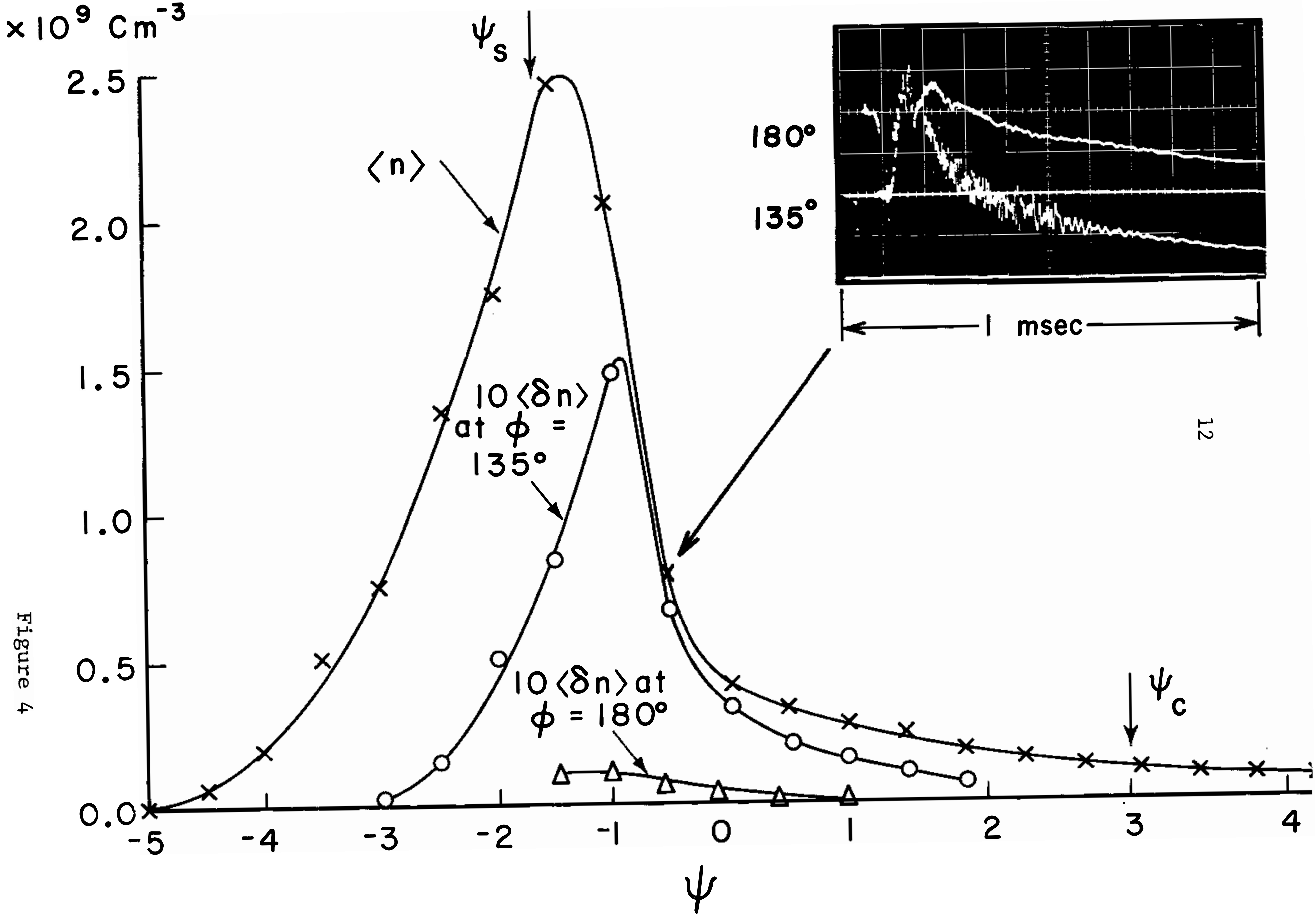

Figure 4

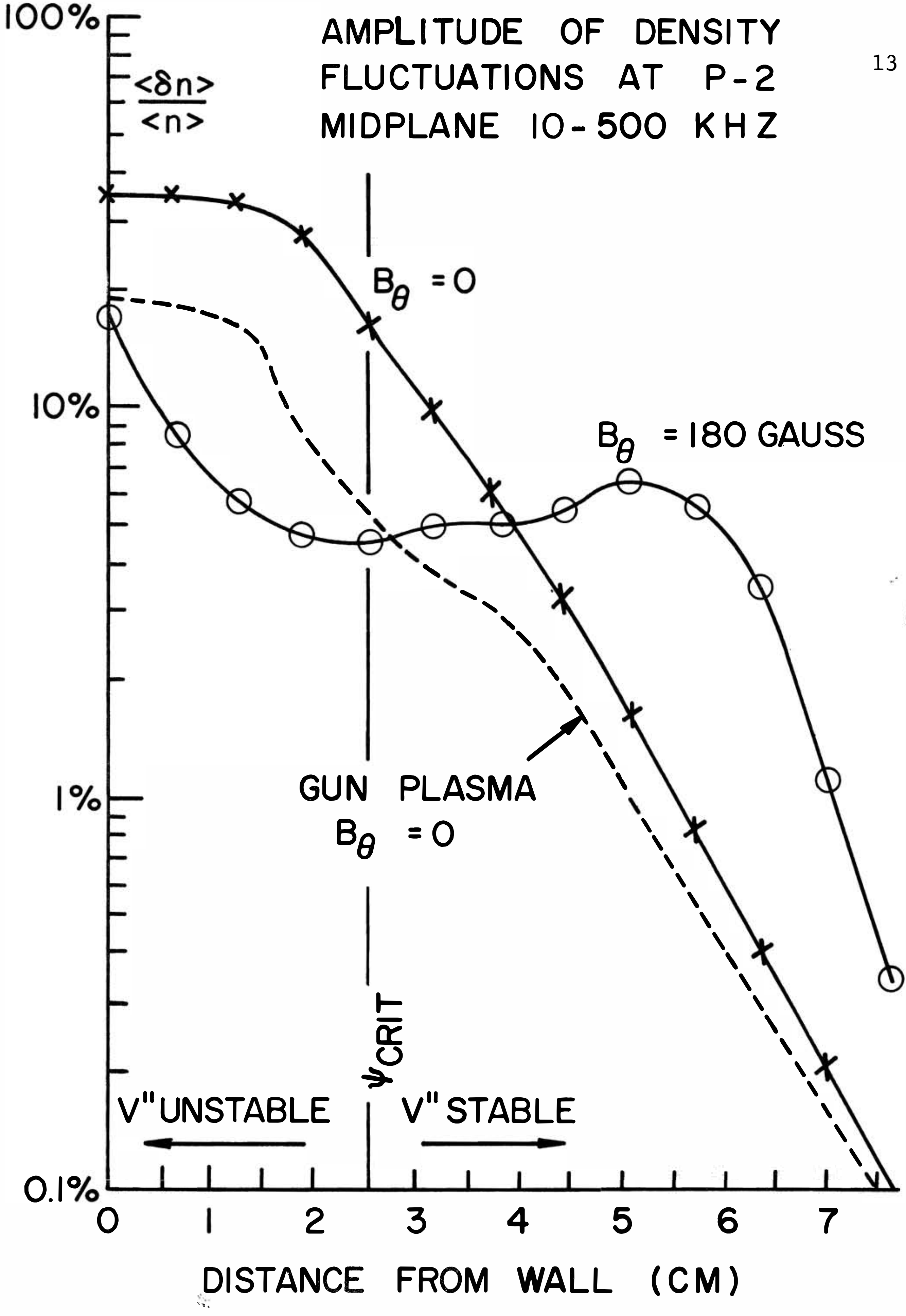
AMPLITUDE OF DENSITY FLUCTUATIONS AT P-2 MIDPLANE 10-500 KHZ
100%
$\frac{\langle\delta n\rangle}{\langle n\rangle}$
10%
1%
0.1%
B_θ =0
B_θ =180 GAUSS
GUN PLASMA
B_θ =0
ψ_{CRIT}
V" UNSTABLE
V" STABLE
0
1
2
3
4
5
6
7
DISTANCE FROM WALL (CM)

Figure 5

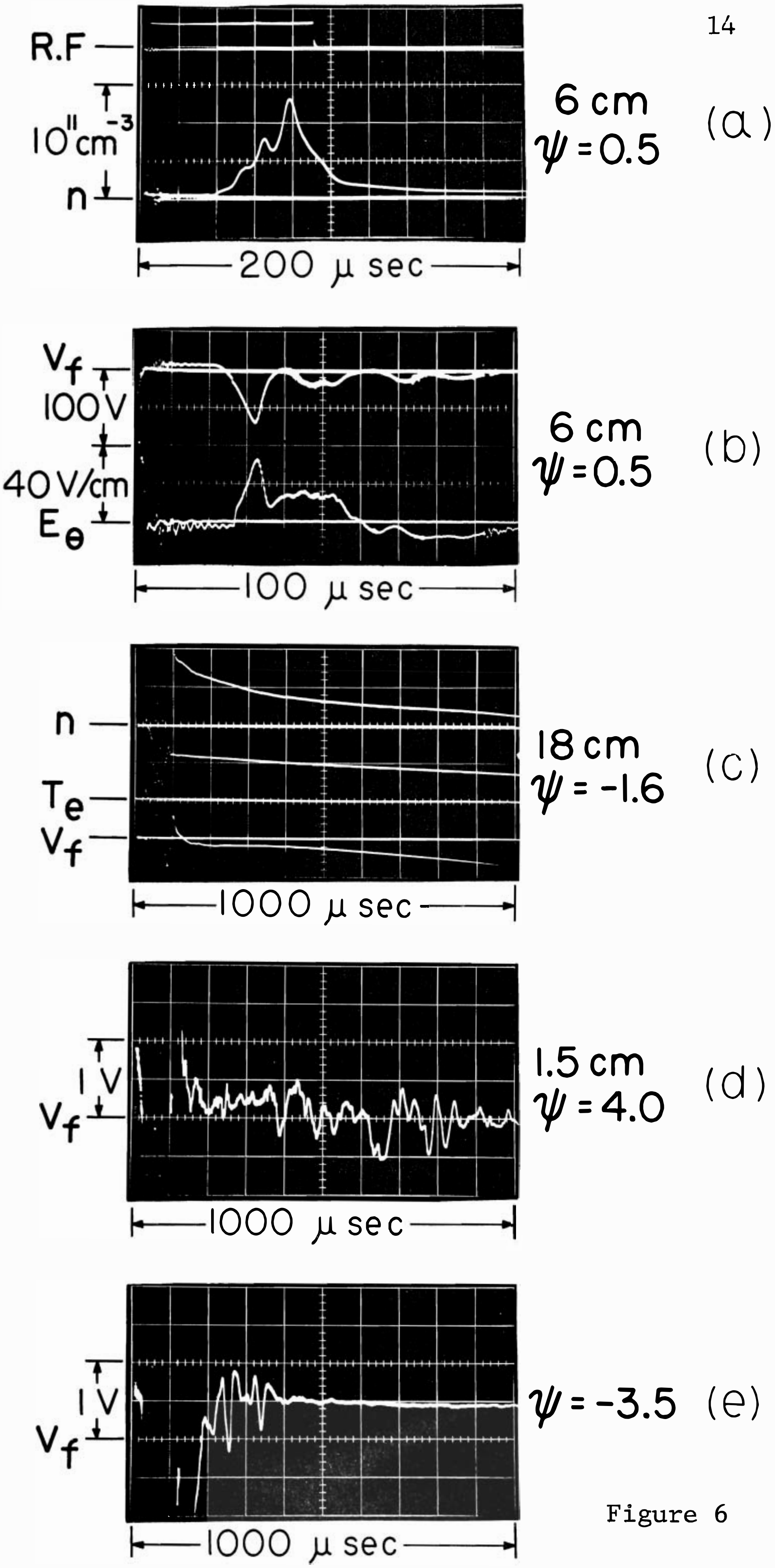
R.F
10¹¹cm⁻³
n
200 μ sec
6 cm
ψ = 0.5
(a)
V_f
100 V
40 V/cm
E_θ
100 μ sec
6 cm
ψ = 0.5
(b)
n
T_e
V_f
1000 μ sec
18 cm
ψ = -1.6
(c)
1 V
V_f
1000 μ sec
1.5 cm
ψ = 4.0
(d)
1 V
V_f
1000 μ sec
ψ = -3.5
(e)

Figure 6