BEHAVIOR OF A COLD ION PLASMA IN A TOROIDAL OCTUPOLE

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ABSTRACT

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A 3 GHz magnetron supplied 10 kW of rf power for 100 μsec causing breakdown and electron cyclotron heating of hydrogen gas at a pressure of 5×10^{-5} torr in the Wisconsin toroidal octupole. The plasma was created in the outer high field region where it is expected to be hydromagnetically unstable inward. Azimuthal electric fields developed allowing the plasma to collapse inward toward the zero field locus along the toroid's minor axis. Within 50 μsec, a stable configuration was reached with the density approximately constant over most of the $\oint dl/B$ stable region. The density was about 10^{10} cm^{-3} and the electrons were Maxwellian with a temperature of about 10 eV. Triple probe measurements showed that the electron temperature was approximately constant in space and decayed slightly in time. The plasma was created with azimuthal density variations of about a factor of two, but became azimuthally symmetrical in 500 -

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1000 μsec. The density at a given azimuth decayed uniformly with an average lifetime of 900 μsec.

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The Wisconsin toroidal octupole is normally operated by injecting a 40 eV hydrogen plasma from an external conical pinch gun.[1,2] Recently a cold ion plasma has been produced within the octupole by a pulse of high intensity microwave radiation.

Figure 1 shows a magnetic flux plot in a cross sectional plane of the toroid. The magnetic field is purely poloidal and is produced by the induced currents in four copper hoops. RF power is produced by a 3250 MHz magnetron which supplies 10 KW in pulses as long as 100 μsec. The magnetic field pulse is a half cycle of a sine wave of 5 msec duration. The microwaves are pulsed on just before the magnetic field reaches its peak and the experiment is performed during the one millisecond when the field is nearly constant.

Because of the complicated geometry, no attempt was made to calculate the mode pattern of the toroidal cavity. However, we expect the plasma to be produced mostly in those regions where the magnetic field has the right magnitude to give electron cyclotron resonance. The cross hatched region in figure 1 shows where in the toroid the magnetic field is within 5% of the resonance value.

Note that some plasma is created on every field line except a few very close to the hoops.

By dividing the volume of the resonance region by the volume of the flux tubes which it intercepts, the initial density distribution can be estimated. Most of the plasma is deposited on the outer field lines where it is unstable inward. Within 50 μsec the plasma collapses inward to fill the volume uniformly out to the last stable field line Ψ_{crit}. Most of the data was taken in the horizontal midplane and along a diagonal line from the minor axis to an inner hoop. Since the density is constant along field lines it is possible to plot density as a function of Ψ, where Ψ is arbitrarily labeled -5 at the hoops and +5 at the walls.

Such a plot is shown in figure 2. The plasma is initially peaked off the separatrix toward the hoops and toward the wall in rough agreement with what is expected from volume considerations, indicated by the dotted line labeled $\frac{R}{V' \, |\nabla B \times \nabla\Psi|}$ in figure 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]

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 except for a slight peak just off the separatrix. This peak resembles the peak in the profile shown in figure 2 for the hot ion plasma injected from an external gun.[3] With the gun plasma, potential fluctuations are observed between the density peak and the separatrix,[3,4] but none were seen with the microwave plasma. Because of the finite pressure term in the stability condition, this inverted gradient is expected to be stable in accord with the fact that it persists throughout the lifetime of the plasma.

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 the distribution of density across the horizontal midplane. The plasma initially appears about 5 cm from the walls and builds up until the density at Ψ_{crit} reaches 10" cm^{-3} where the plasma frequency equals the microwave frequency and the microwaves do not penetrate the plasma. The collapse of the plasma inward is accompanied by 100 volt potential fluctuations, but by 200 μsec the plasma has evolved into a quiet state with the density approximately constant throughout the stable volume. Potential fluctuations inside Ψ_{crit} are generally less than 0.1 volt or 1% of kT_e/e. The density decays uniformly as particles are lost to the hoop supports. By 1600 μsec the magnetic field begins to decrease appreciably and the field lines move out toward the wall carrying the plasma with them[3,4] as shown in figure 3. This inverted density gradient is stable, and no potential fluctuations in this region are observed. In the flute unstable region outside Ψ_{crit}, fluctuations of up of 1 volt and frequencies between 5 and 100 kHZ are observed.

The electrons are maxwellian up to at least 4 times their mean energy. Triple probe measurements[5] show that the temperature is approximately 10 eV throughout the plasma and decays slightly in time. The decay rate increases with increasing background pressure.

The plasma is produced with considerable azimuthal density variations as figure 4 shows. By 800 μsec, the density is nearly the same at all azimuths. At a given azimuth the density on the zero field axis decays exponentially, and the average lifetime is about 900 μsec. The microwave antenna is located at port 4 and most of the measurements were made at port 3, 100° away.

Figure 5 compares the amplitude of the floating potential fluctuations for the two plasmas. The cold ion plasma generally fluctuates 1 to 2 orders of magnitude less than the hot ion plasma[4,6] in spite of the fact that the electron temperatures are comparable. When the background gas pressure is raised to 5×10^{-5} torr, the amplitude of the fluctuations with the hot ion plasma is considerably reduced as indicated by the dotted line in figure 5. The amplitude of the fluctuations is several orders of magnitude below the 10 eV electron temperature, and gives a diffusion coefficient much less than Bohm value.

Some tests have also been made with an added circumferential magnetic field of about 360 gauss[4], giving a topology similar to that of a stellarator. With both plasmas, the addition of this B_θ increases the amplitude of the fluctuations in the stable region. In all cases the fluctuations decrease rapidly inside the critical ψ line.

Figure 6 shows oscilloscope traces which summarize the behavior of the plasma. Figure 6 (a) shows the density in the resonance region. No plasma is produced for the first 40 μsec, and then the density rises quickly to $10''\ \mathrm{cm}^{-3}$. 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 the 100 μsec duration pulse is about 5×10^{-5} torr. By operating with a microwave pulse slightly longer than is necessary to obtain a density of $10''\ \mathrm{cm}^{-3}$, an extremely reproducible plasma results.

Figure 6 (b) 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.

Figure 6 (c) is a triple probe trace on the zero field axis. The density decays uniformly with a lifetime of 900 μsec. The electron temperature is about 10 eV and decays about 40% over 1 msec. After the first 100 μsec the floating potential shows no fluctuation.

Only two regions of the plasma show potential fluctuations. The first is in the unstable region outside Ψ_{crit} (figure 6 (d)) and the second is in the stable region near the hoops where a very steep density gradient exists when the plasma is first created (figure 6 (e)). The rest of the plasma is quiet with very small fluctuations and diffusion considerably less than the Bohm value.

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6. J.A. Schmidt and D.E. Lencioni (PLP 85), Bull. Am. Phys. Soc. 12, 790 (1967).

FIGURES

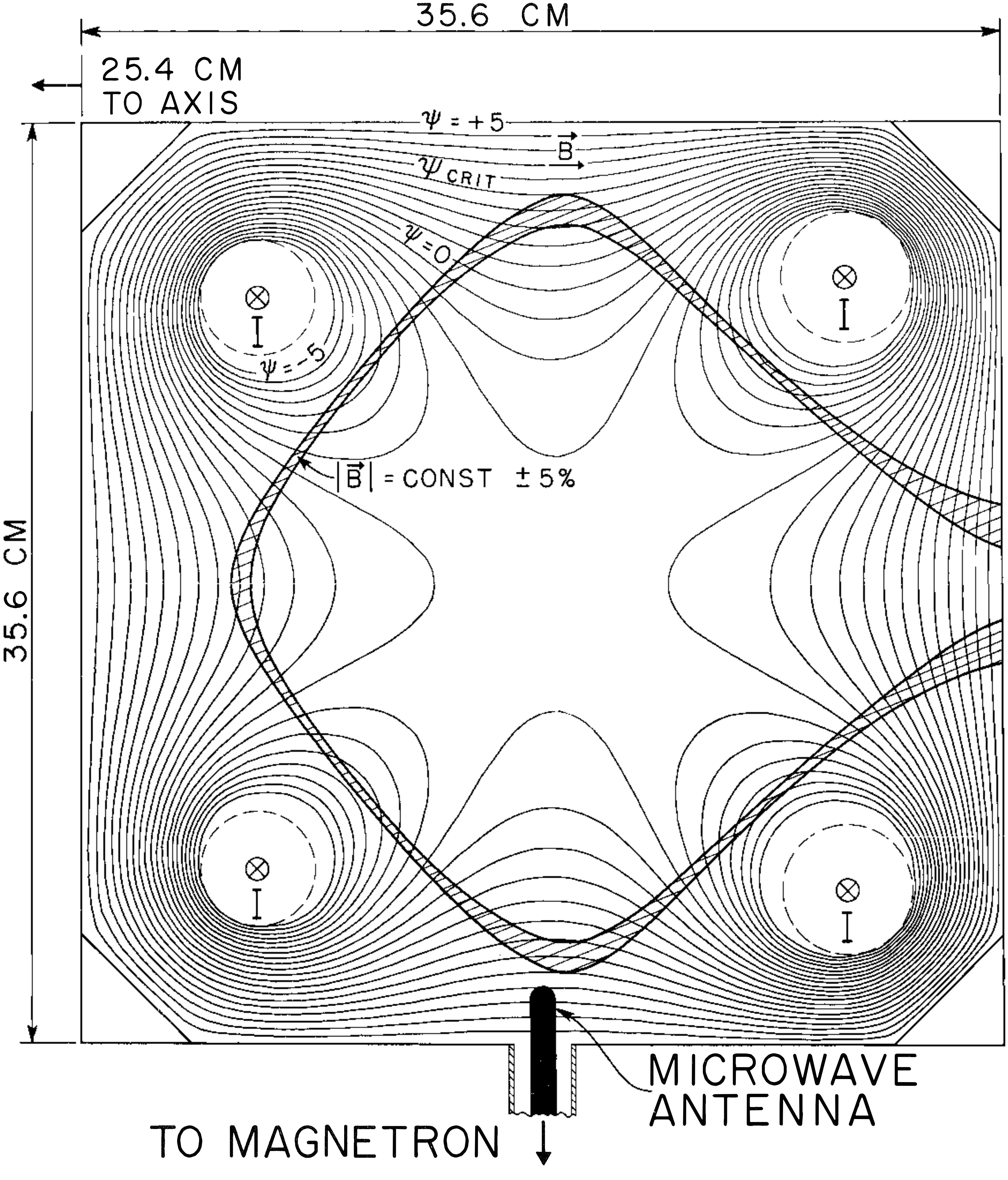

35.6 CM
25.4 CM
TO AXIS
ψ = +5
B
ψ CRIT
ψ=0
I
I
ψ=-5
|B| = CONST ±5%
35.6 CM
I
I
MICROWAVE
ANTENNA
TO MAGNETRON

Figure 1

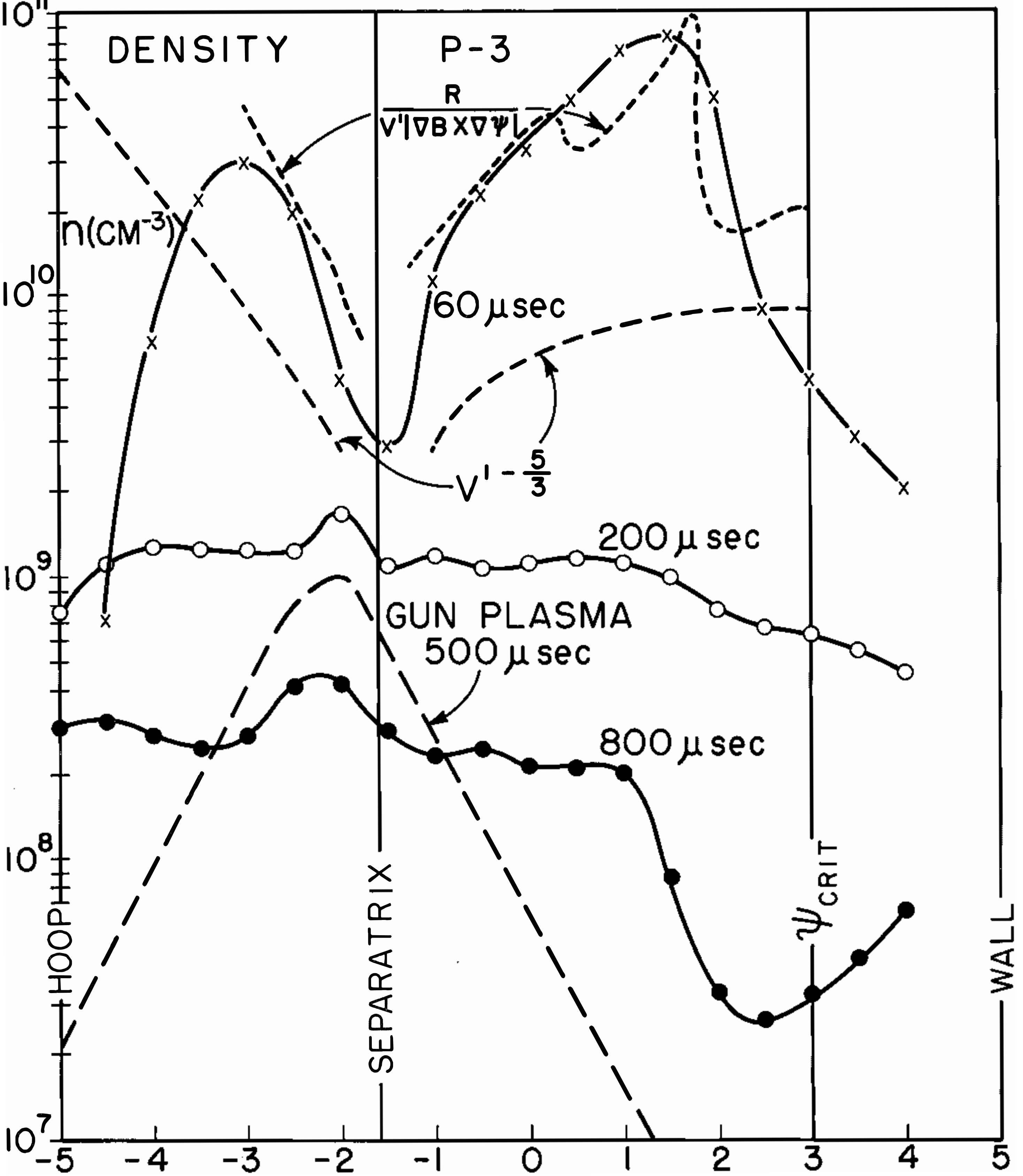

DENSITY
P-3
n(CM^{-3})
$\frac{R}{V'|\nabla B \times \nabla \psi|}$
60 μsec
$V'^{-\frac{5}{3}}$
200 μsec
GUN PLASMA
500 μsec
800 μsec
HOOP
SEPARATRIX
ψ_{CRIT}
WALL
10^{11}
10^{10}
10^{9}
10^{8}
10^{7}
-5
-4
-3
-2
-1
0
1
2
3
4
5
ψ

Figure 2

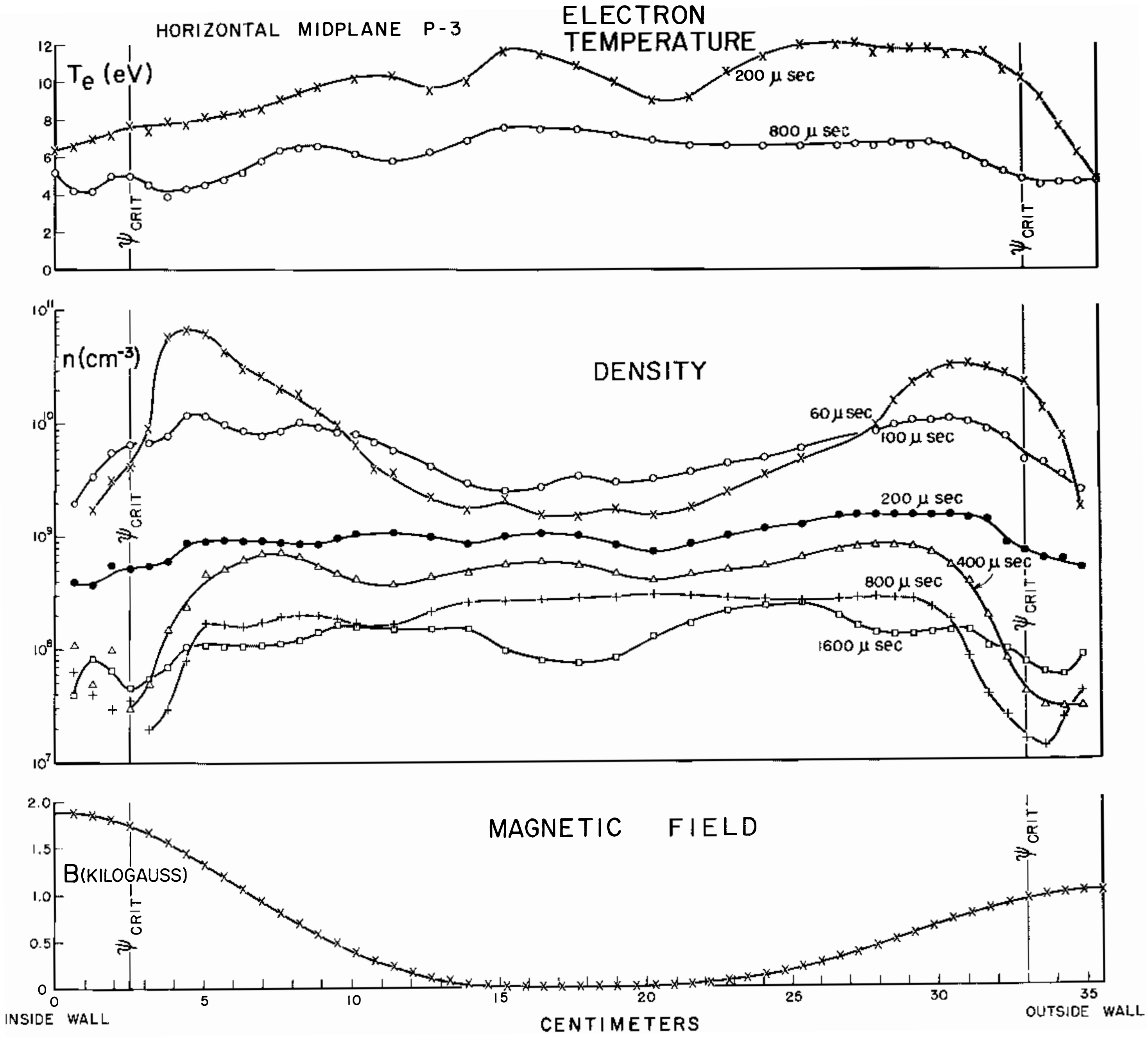

HORIZONTAL MIDPLANE P-3
ELECTRON TEMPERATURE
T_e (eV)
0
2
4
6
8
10
12
200 μ sec
800 μ sec
ψ_{CRIT}
ψ_{CRIT}
DENSITY
n(cm^{-3})
10^{7}
10^{8}
10^{9}
10^{10}
10^{11}
60 μ sec
100 μ sec
200 μ sec
400 μ sec
800 μ sec
1600 μ sec
ψ_{CRIT}
ψ_{CRIT}
MAGNETIC FIELD
B(KILOGAUSS)
0
0.5
1.0
1.5
2.0
ψ_{CRIT}
ψ_{CRIT}
0
5
10
15
20
25
30
35
INSIDE WALL
OUTSIDE WALL
CENTIMETERS

Figure 3

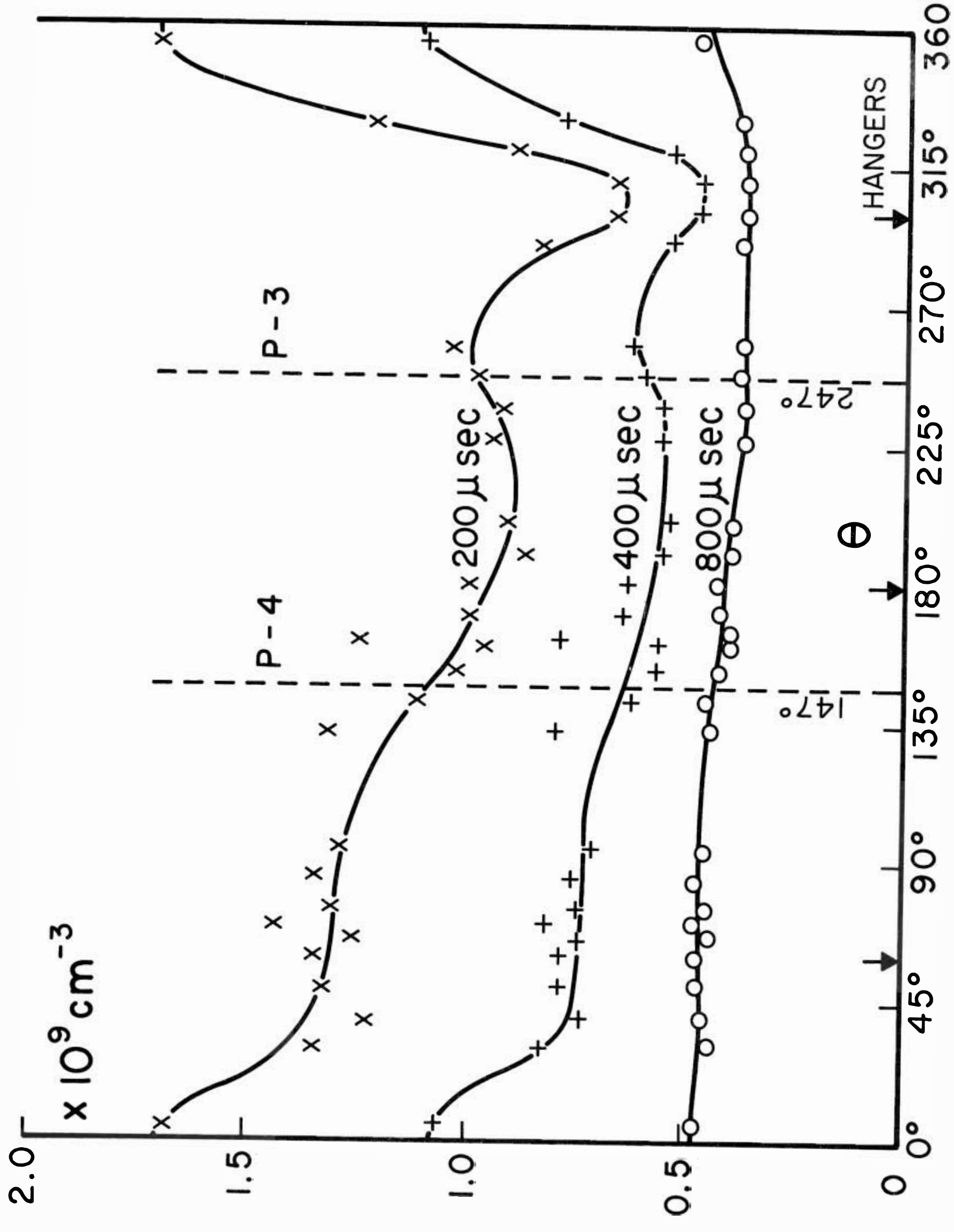

x 10^9 cm^{-3}
2.0
1.5
1.0
0.5
0
0°
45°
90°
135°
180°
225°
270°
315°
360°
θ
P - 4
P - 3
147°
247°
HANGERS
x 200 μ sec
+ 400 μ sec
800 μ sec

Figure 4

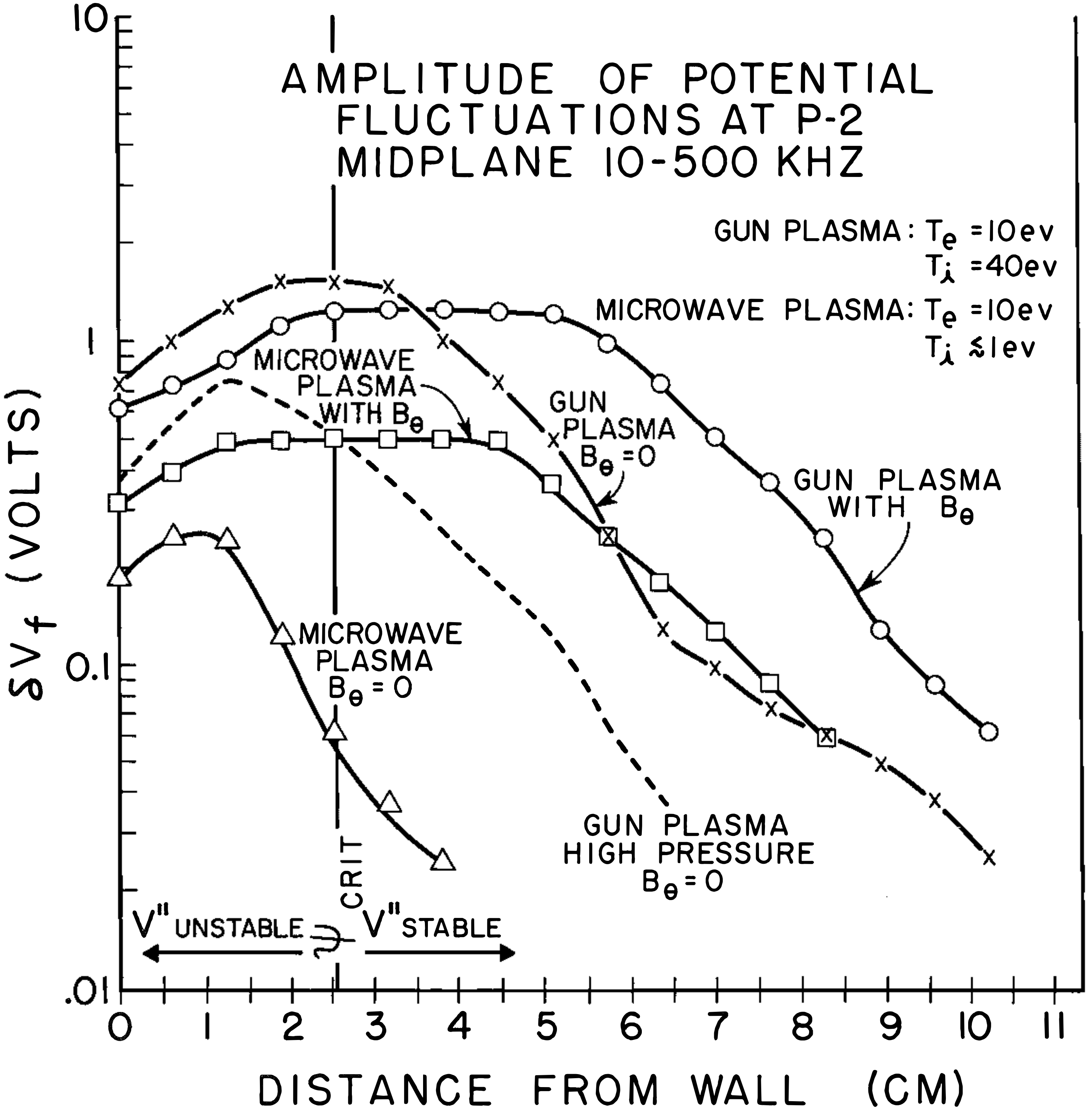
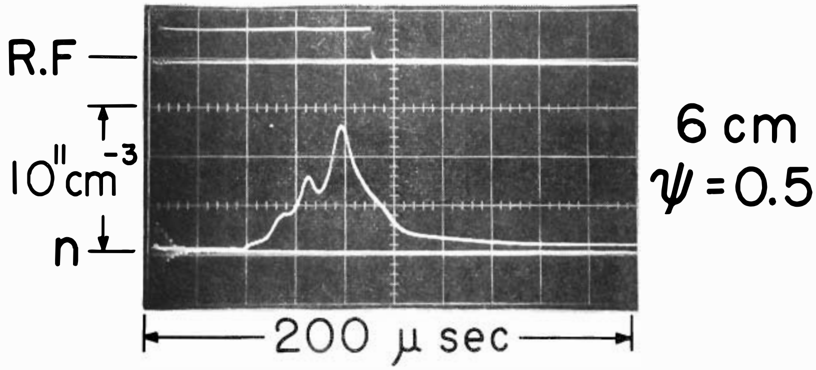
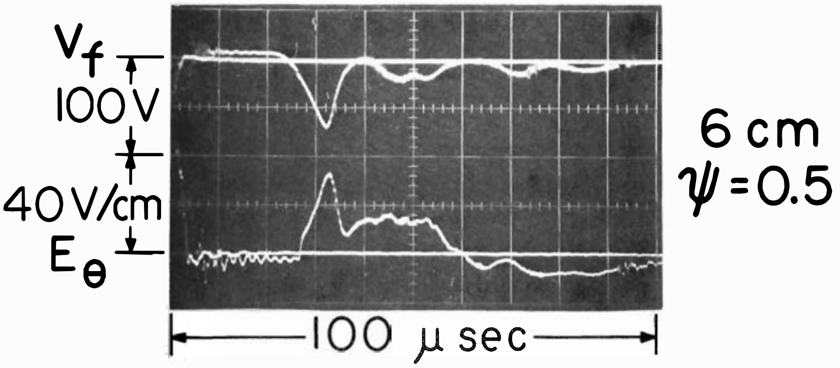

AMPLITUDE OF POTENTIAL FLUCTUATIONS AT P-2 MIDPLANE 10-500 KHZ
GUN PLASMA: T_e = 10 ev T_i = 40 ev
MICROWAVE PLASMA: T_e = 10 ev T_i ≲ 1 ev
MICROWAVE PLASMA WITH B_θ
GUN PLASMA B_θ = 0
GUN PLASMA WITH B_θ
MICROWAVE PLASMA B_θ = 0
GUN PLASMA HIGH PRESSURE B_θ = 0
ℓ CRIT
V'' UNSTABLE
V'' STABLE
δV_f (VOLTS)
10
1
0.1
.01
0
1
2
3
4
5
6
7
8
9
10
11
DISTANCE FROM WALL (CM)

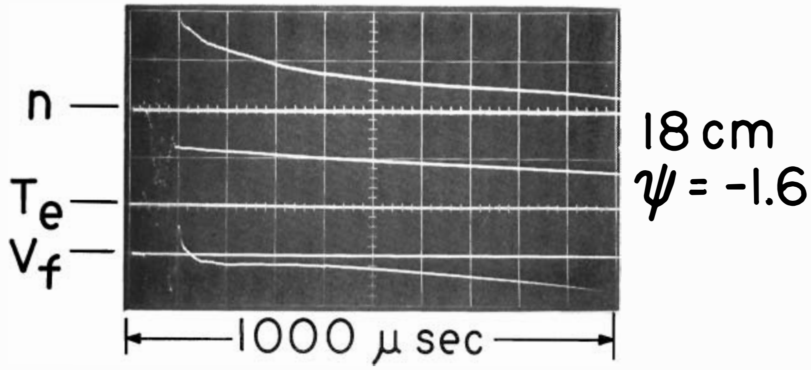
Figure 5


R.F
10^{11} cm^{-3}
n
200 μ sec
6 cm
ψ = 0.5

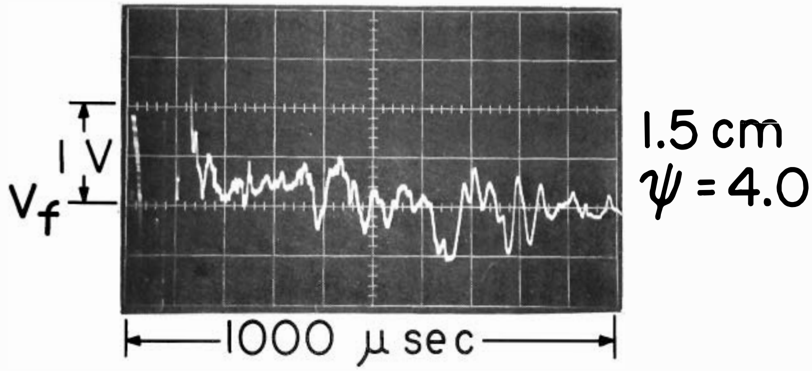
(a)


V_f
100 V
40 V/cm
E_θ
100 μ sec
6 cm
ψ = 0.5

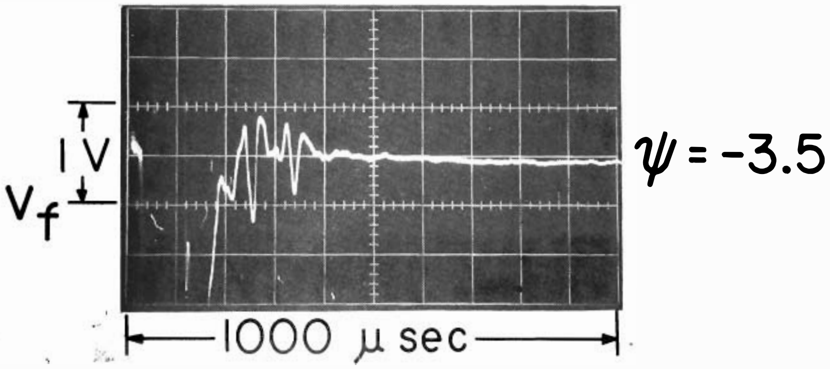
(b)


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)