INSTITUTE OF PLASMA PHYSICS

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RESEARCH REPORT

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Anisotropy of Electron Distribution Function of After-Glow Plasma Generated by Electron Cyclotron Resonance Heating and Confined in Magnetic Mirror Field

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Abstract

Anisotropy of electron distribution function of after-glow plasma generated by electron cyclotron resonance heating and confined in a magnetic mirror field is studied with the use of a magnetic mirror probe method. It is found that the observed distribution indicates the characteristics of the loss-cone distribution function.

1. Introduction

Anisotropy of ion or electron velocity distribution function in a magnetized plasma is an important problem being related to several microscopic instabilities,[1-6] especially in a magnetic mirror field. Some experiments to determine anisotropy of ion or electron mean energy have been reported in relatively high temperature magnetized plasmas.[7,8,9] Green, et al.[10] showed the possibility to estimate the anisotropy of electron energy distribution in a magnetized plasma from the free-free Bremsstrahlung. For making a measurement at one point in the plasma, using a single simple measuring technique and making possible to measure the anisotropy even in a low temperature plasma, the magnetic mirror probe method has been developed[11,12] by which $T_{e//}$ and η $(=T_{e\perp}/T_{e//})$ can be determined in almost the same way as that of ordinary Langmuir probe method.

In this report, we make an experimental study of anisotropy of electron velocity distribution function in the after-glow plasma produced by microwave discharge at the electron cyclotron resonance and confined in a magnetic mirror field. Anisotropy of velocity distribution function of electron is measured by a magnetic mirror probe, and the distribution is observed to have some characteristics of the loss-cone distribution function[13-15] as discussed below.

2. Experiment

Schematic diagram of the experimental apparatus is shown in Fig. 1. Plasma is produced by microwave discharge at the electron cyclotron resonance. The microwave frequency is 2.45 GHz, associated with the magnetic field intensity of 875 Gauss for the electron cyclotron resonance, at the microwave power of 0.5 kW, operated in pulse with a duty factor 0.48 at 60 pps. The microwave is led to the glass horn window through retangular waveguide. Argon plasma is produced near the glass hone and diffuses into the magnetic mirror field. The magnetic field strength at the mirror center is held constant at 460 Gauss and the mirror ratio can vary from 2.0 to 4.0.

Oscilloscope traces of the input microwave power and electron saturation current are shown in Fig. 2. If a certain obstacle (for example, a metallic port of z-probe shown in Fig. 1) is slightly inserted into the region of magnetic mirror field through the mirror throat, the plasma disappears as quickly as within 0.1 msec at the time of 8 msec which is the time after turn-on of microwave power (solid curve of b in Fig. 2). Without the obstacle, the after-glow plasma can remain much longer (sold curve of a in Fig. 2). The radial profile of plasma density (in the order of 10^{10} to

10^{11} cm^{-3}) and that of electron temperature (about 10 eV) are both observed to be flat over the distance close to the wall. Their axial distribution is observed also to be uniform in the uniform magnetic field region. After 8 msec and later on from the turn-on of the microwave power, the power level of microwave input becomes so low that it cannot maintain discharges , though it remains for about 0.5 msec as seen in Fig. 2. In this time, the electron temperature rapidly decreases to 0.4-0.7 eV with a time constant of about 0.1 msec, and after 8.4 msec and later on from the turn-on of microwave power, the electron temperature is held almost constant keeping the temperature of 0.4-0.7 eV, in which the cross-section between the electron and argon atoms is minimum due to Ramsauer effect. In this case, the electron mean-free-path becomes about 10 times larger than the longitudinal distance between the magnetic mirror points at the pressure of 10^{-4} torr. However, plasma density decreases exponentially throughout the late after-glow at a time constant of about 2.0 msec.

The magnetic mirror probe used is made of a ferromagnetic shere of 3 mm in diameter. Its structure and principle of operation are just the same as described in ref. 11 and 12. Difference of the electron current collected through the window with different mirror ratios enables us to estimate the anisotropy of electron temperature. In case of a magnetic mirror probe, the local mirror ratio in the presence of the collecting surface is arbitrarily selected up to the value of 3.0 as varying θ , the angle between the external applied magnetic field line of force and the normal to the collecting surface. In our experiment, we choose two different local mirror ratios of 1.5 and 3.0 which are corresponding to $\theta = 60^\circ$ and 0° respectively. The local mirror ratio of 1.0 (corresponding to $\theta = 70.5^\circ$) is avoided because of tending to generate the relatively large error from the required mirror ratio as setting the mirror probe to the angle of $\theta = 70.5^\circ$. From the characteristic curves of the magnetic mirror probe obtained, we plot the ratio of $i_{ep}(\theta=0^\circ)$ to $i_{ep}(\theta=60^\circ)$, the probe electron currents at $\theta=0^\circ$ to that at $\theta=60^\circ$, versus $eV_p/(\kappa T_e)$ in Fig. 3(a)-(c), where V_p is the probe bias voltage measured from the space potential and the parameters are the detecting time in the after-glow plasma. If the velocity distribution function of electron is two=temperature Maxwellian, the ratio of $i_{ep}(\theta=0^\circ)/i_{ep}(\theta=60^\circ)$ must not depend on the probe bias voltage according to the analysis of ref. 11 and 12. However, the experimentally obtained ratios depends strongly on V_p. If we assume the velocity distribution of the electron to be the loss-cone distribution in the collisionless limit (this assumption will be reasonable because of long electron mean-free-path due to Ramsauer effect as described above), the ratio of $i_{ep}(\theta=0^{\circ})/i_{ep}(\theta=60^{\circ})$ strongly depends on V_p as shown by solid curves in Fig. 3(a)-(c), which are drawn with the parameter V_M, which is the potential difference of the plasma at the mirror throat and at the midplane on the axis. Comparing calculated curves with the experimental results, it is found that the electrons almost obey the loss-cone distribution function.

For the loss-cone distribution function at the collisionless limit, $\frac{1}{2}\langle u_{e\perp}^2\rangle/\langle u_{e//}^2\rangle > 1$ will hold, where $\frac{1}{2}m_e\langle u_{e\perp}^2\rangle$ is the perpendicular mean-energy of the electron and $\frac{1}{2}m_e\langle u_{e//}^2\rangle$ is its parallel mean-energy. The magnitude of this anisotropy is decided by the mirror ratio and the potential difference V_M. From the anisotropy of electron mean energy estimated from the mirror ratio and the potential difference V_M, we can get the time dependence of this anisotropy as shown in Fig. 4(a). The characterestics of $\frac{1}{2}\langle u_{e\perp}^2\rangle/\langle u_{e//}^2\rangle$ versus mirror ratio thus obtained are shown in Fig. 4(b).

3. Discussion

In Fig. 3(a)-(c) the theoretical curves well explain the experimental results, especially in the case of the small mirror ratio as seen in Fig. 3(a). As seen in Fig. 3(a)-(c) and Fig. 4(a), the electron energy distribution is rather isotropic both at the beginning and near the end of the late after-glow plasma, and anisotropy is evident between them. This is interpreted as follows.

Because the microwave power still remains at the beginning of the after-glow plasma, it affects the energy distribution of confined electrons to randomize the loss-cone distribution. After this effect ceases, the loss-cone distribution establishes as shown in Fig. 4(a) or Fig. 3(a)-(c). However, because the negative potential at the throat is likely to grow so quickly, owing to the longer life time of ions compared with electrons, and moreover, owing to the cooling of ions (which results in the much longer life time of ions) in the lapse of after-glow, the escape of electrons from the throat will become more and more difficult towards the end of after-glow due to the negative potential difference V_M growing with time. This will affect the electrons as to recover the isotropic energy distribution as shown in calculated curves of Fig. 3(a)-(c).

In the lower pressure (the order of 10^{-5} torr) and at the mirror ratio slightly smaller than 2.2 the experimental results show rather isotropic energy distribution functions for the electron. In this case, the after-glow plasma is observed to be very noisy. The cause of the noise may be related to some loss-cone instabilities, and furthermore the presence of large fluctuating field may tend to obscure the anisotropy to be detected by the present method.

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Figure captions

Fig. 1. Schematic structure of the experimental devices.

Fig. 2. Time displays of microwave input power and corresponding electron saturation current.

Fig. 3. $i_{ep}(\theta=0^\circ)/i_{ep}(\theta=60^\circ)$ the magnetic mirror probe electron current ratio of two different angles of θ versus normalized probe bias in the pressure of 0.2 mtorr and at the mirror ratio of (a) 2.35, (b) 3.15, (c) 3.95, respectively.

Fig. 4. (a) Time dependence of anisotropy of electron mean energy at p=0.2 mtorr with a parameter of mirror ratio.

(b) Anisotropy of electron mean energy versus magnetic mirror ratio with parameters of detecting time and neutral pressure.

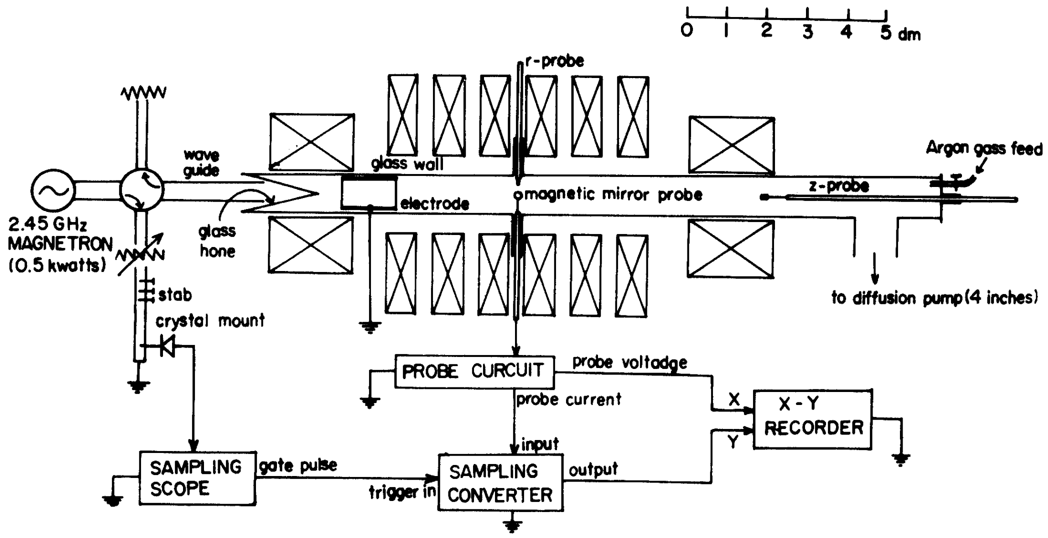

0 1 2 3 4 5 dm
r-probe
wave guide
glass wall
Argon gass feed
2.45 GHz
MAGNETRON
(0.5 kwatts)
glass hone
electrode
magnetic mirror probe
z-probe
stab
crystal mount
to diffusion pump (4 inches)
PROBE CURCUIT
probe voltadge
probe current
X
Y
X-Y RECORDER
input
SAMPLING SCOPE
gate pulse
trigger in
SAMPLING CONVERTER
output

Fig. 1.

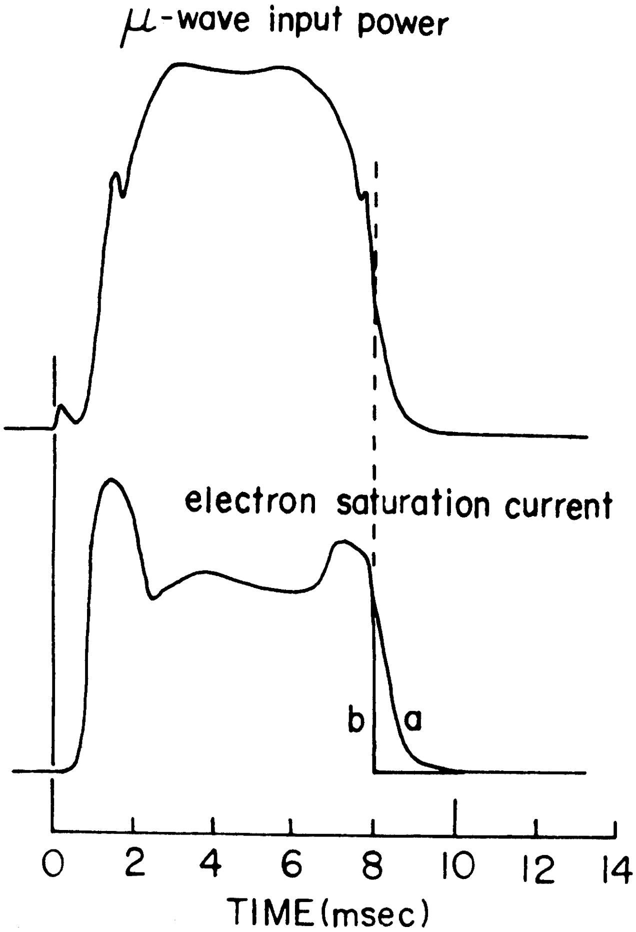
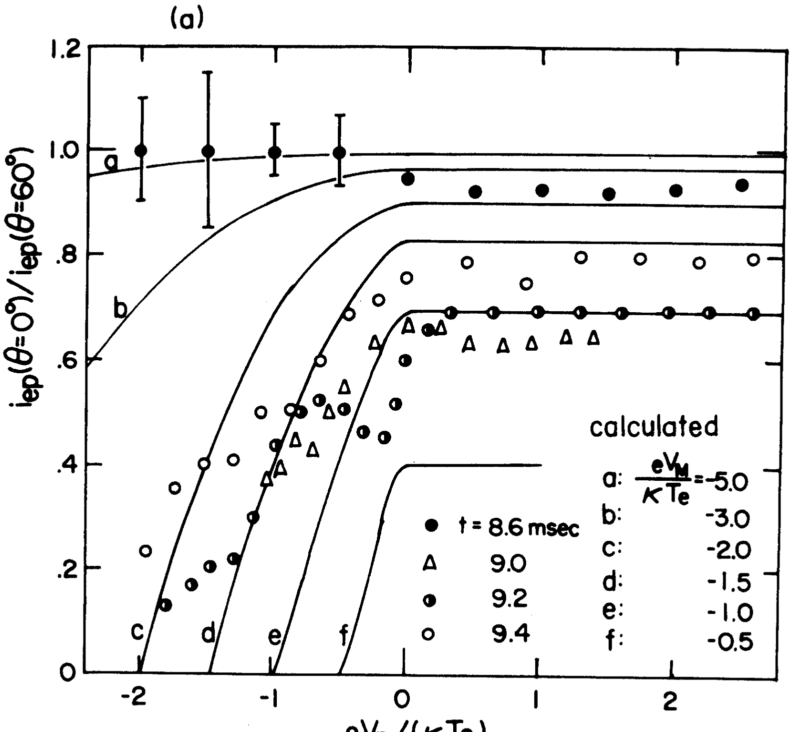
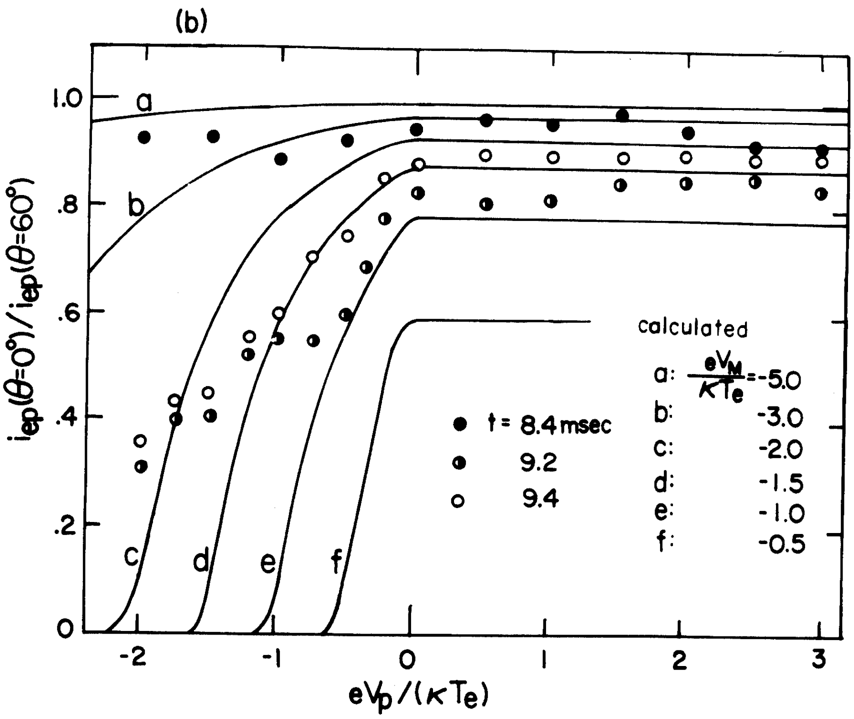

μ-wave input power
electron saturation current
b
a
0
2
4
6
8
10
12
14
TIME(msec)

Fig. 2.



(a)
1.2
1.0
.8
.6
.4
.2
0
-2
-1
0
1
2
eVp/(κTe)
iep(θ=0°)/iep(θ=60°)
a
b
c
d
e
f
calculated
a: eVM/κTe = -5.0
b: -3.0
c: -2.0
d: -1.5
e: -1.0
f: -0.5
t = 8.6 msec
9.0
9.2
9.4

Fig. 3(a)



(b)
1.0
.8
.6
.4
.2
0
a
b
c
d
e
f
-2
-1
0
1
2
3
$i_{ep}(\theta=0°)/i_{ep}(\theta=60°)$
$eV_p/(\kappa T_e)$
t = 8.4 msec
9.2
9.4
calculated
a: $\frac{eV_M}{\kappa T_e}$ = -5.0
b: -3.0
c: -2.0
d: -1.5
e: -1.0
f: -0.5

Fig. 3(b)

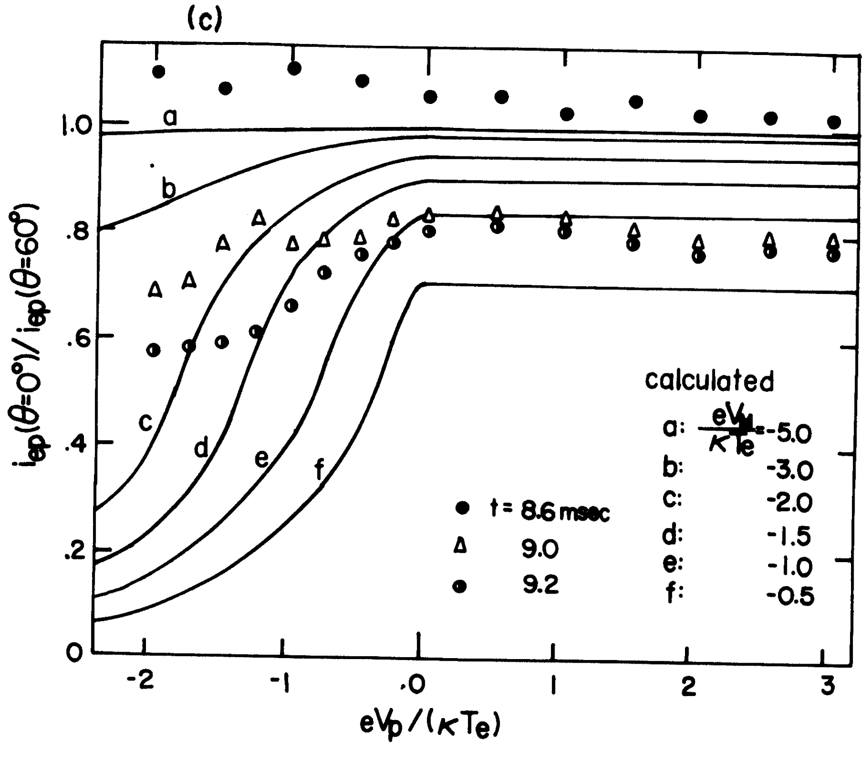

(c)
a
b
c
d
e
f
1.0
.8
.6
.4
.2
0
-2
-1
.0
1
2
3
$i_{ap}(\theta=0°)/i_{ap}(\theta=60°)$
$eV_p/(\kappa T_e)$
● t= 8.6 msec
Δ 9.0
⊙ 9.2
calculated
a: $\frac{eV_1}{\kappa T_e}$=-5.0
b: -3.0
c: -2.0
d: -1.5
e: -1.0
f: -0.5

Fig. 3(c)

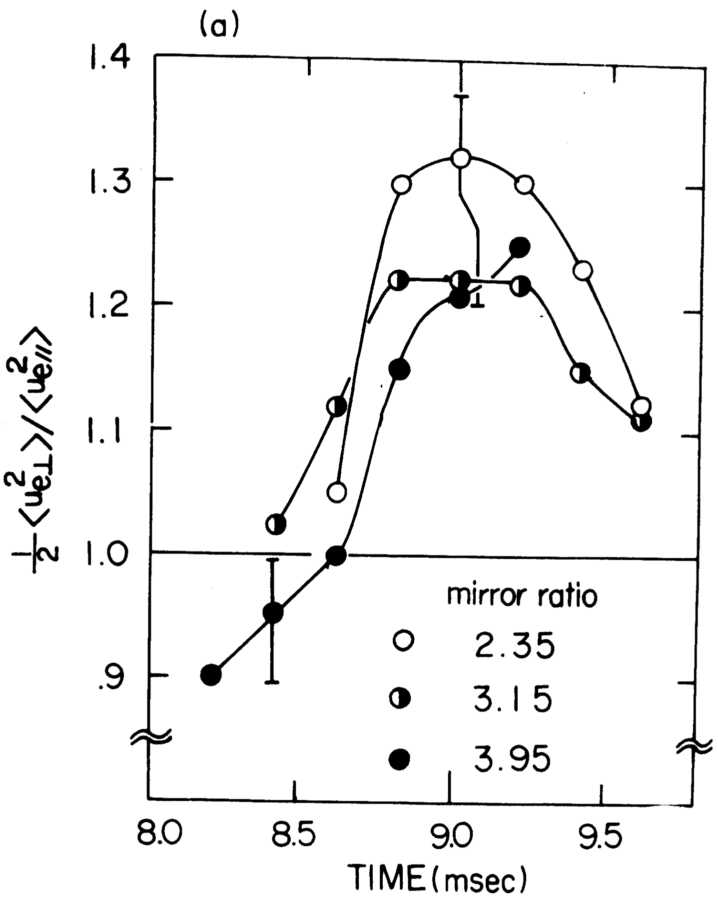

(a)
1.4
1.3
1.2
1.1
1.0
.9
$\frac{1}{2}\langle u_{e\perp}^2\rangle/\langle u_{e\parallel}^2\rangle$
mirror ratio
2.35
3.15
3.95
8.0
8.5
9.0
9.5
TIME(msec)

Fig. 4(a)

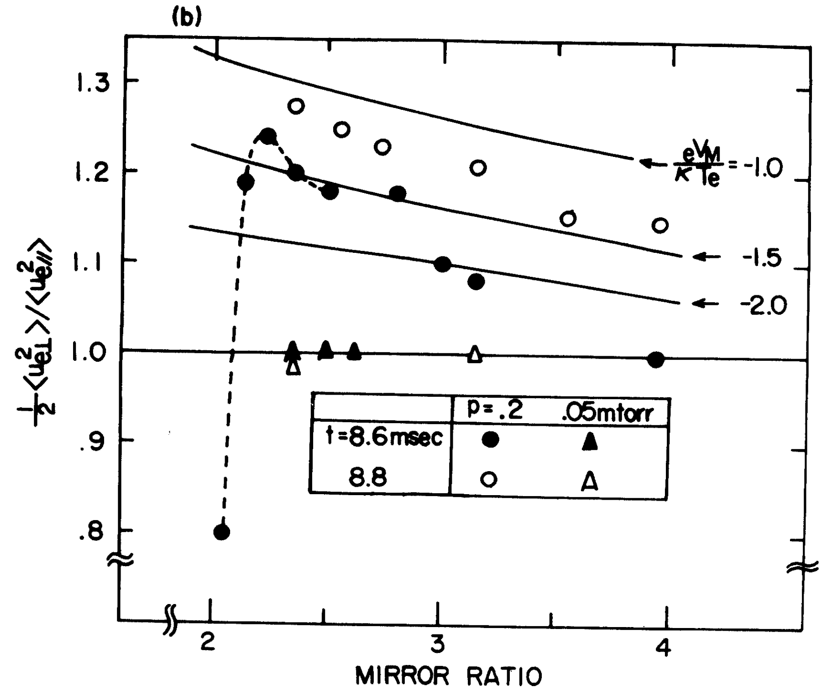

(b)
1.3
1.2
1.1
1.0
.9
.8
2
3
4
MIRROR RATIO
eV_M / κ Te = -1.0
-1.5
-2.0
p=.2
.05mtorr
t=8.6msec
8.8

Fig. 4(b)