Measurement by a mirror probe method of the anisotropy of the electron distribution function of an afterglow plasma confined in a magnetic mirror field*

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The anisotropy of the electron distribution function of an afterglow plasma produced in a microwave discharge and confined in a magnetic mirror field is studied with the use of a mirror probe method. It is found that the observed distribution indicates the characteristics of the loss-cone distribution function.

I. INTRODUCTION

The anisotropy of the ion or electron velocity distribution function in a magnetized plasma is an important problem related to several microscopic instabilities,[1-6] especially in a magnetic mirror field. Some experiments to determine the anisotropy of ion or electron mean energy have been reported in relatively-high-temperature magnetized plasmas.[7-11]

Greene *et al.*[12] showed the possibility of estimating the anisotropy of the electron energy distribution in a magnetized plasma from the free-free bremsstrahlung. Moreover, Shohet and coworkers[13,14] found experimentally that the distribution function of high-energy electrons confined in a magnetic mirror field was just the loss-cone distribution function. This result may be reasonable for the following reasons: The electrostatic potential distribution in a high-electron-temperature plasma which includes the plasma vessel is formed mostly be the ions and the low-energy parts of electrons. Thus the high-energy part of an electron is scarcely affected by the electrostatic potential of the plasma system. Moreover, as the high-energy parts of electrons have longer collision times, the high-energy electrons may form the usual loss-cone distribution function which has been analyzed theoretically by several authors.[15-17]

On the other hand, it is not clear whether or not the low-energy parts of electrons confined in a magnetic mirror field form the loss-cone distribution function for the following reasons: Since the mean kinetic energy of the electrons may be comparable to the electrostatic potential energy of the plasma, each electron may be more or less affected by the electrostatic potential distribution in the plasma and also by the potential difference between the plasma space and the surface of the end wall.

Up to this time the experimental methods for measuring the anisotropy of the electron distribution have been restricted to the high-energy electrons. Furthermore, accurate space and time resolution of the anisotropy has been lacking. To take a measurement at one point in the plasma, and to make possible the measurement of the anisotropy even in a low-temperature plasma, a single simple measuring technique—the mirror probe method—has been developed.[18,19] With this method, $T_{e\parallel}$ and η $(=T_{e\perp}/T_{e\parallel})$ can be determined in almost the same way as by using the ordinary Langmuir probe.

In this paper we present an experimental study of the anisotropy of the velocity distribution function of low-energy electrons in an afterglow plasma produced by a microwave discharge at the electron cyclotron resonance and confined in a magnetic mirror field. The anisotropy of the velocity distribution function of the electrons is measured with the mirror probe, and the distribution is observed to have some characteristics of the loss-cone distribution function.[15-17]

II. EXPERIMENTAL DEVICES

A schematic diagram of the experimental apparatus is shown in Fig. 1. The 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 G for the electron cyclotron resonance, at a microwave power of 0.5 kW, operated in pulse with a duty factor 0.48 at 60 pulses/sec. The microwaves are fed through a rectangular waveguide to a glass horn window. An argon plasma is produced near the glass horn and diffuses into the magnetic mirror field. The magnetic field strength at the mirror center is held constant at 460 G and the mirror ratio can vary from 2.0 to 4.0.

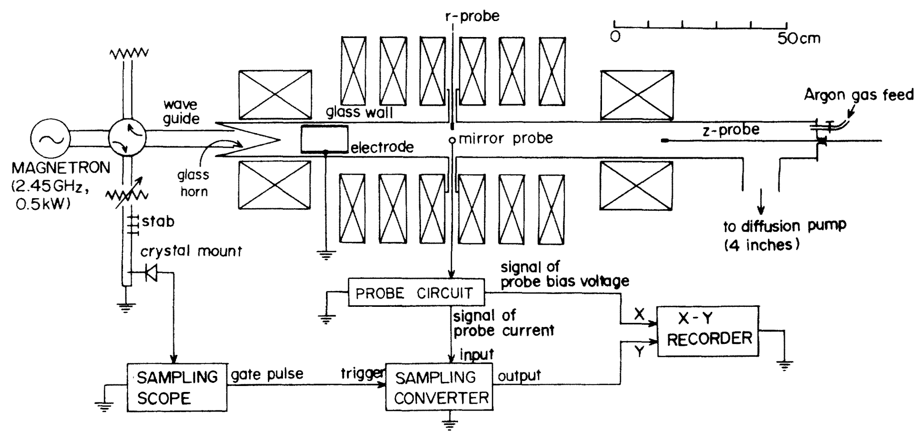

FIG. 1. Schematic structure of the experimental devices.

III. EXPERIMENTAL RESULTS

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 the *z* probe shown in Fig. 1) is inserted slightly into the region of the magnetic mirror field through the mirror throat, the plasma disappears within 0.1 msec, 8 msec after the turn on of microwave power (as indicated by curve b in Fig. 2). Without the obstacle, the afterglow plasma can remain much longer (as indicated by the solid curve a in Fig. 2).

The radial profiles of plasma density (on the order of 10^{10}–10^{11} cm^{-3}) and of electron temperature (about 10eV) are both observed to be flat at distances close to the wall. Their axial distribution is also observed to be uniform in the uniform magnetic field region.

8 msec after the microwave power is turned on, the microwave power input becomes so low that it cannot maintain discharges, although the microwaves remain 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 8.4 msec after the turn on of the microwave power, the electron temperature is almost constant at 0.4–0.7 eV. In this range the cross section between the electron and argon atoms is very small because of the Ramsauer effect. Thus the electron mean free path becomes about ten times larger than the longitudinal distance between the magnetic mirror points at a pressure of 10^{-4} Torr. However, plasma density decreases exponentially throughout the later afterglow at a time constant of about 2.0 msec.

The mirror probe is made of a ferromagnetic sphere 3 mm in diameter; one-half of a *local* magnetic mirror field forms around it, if it is situated in a externally applied magnetic field. Its structure and principle of operation are the same as described in Refs. 18 and 19. Variations in the electron currents collected through the window with different *local* mirror ratios over the window enable us to estimate the anisotropy of the electron temperature. In the case of a mirror probe, the *local* mirror ratio in the presence of the collecting surface is arbitrarily selected up to the value of 3.0 by varying the angle θ between the external applied magnetic field lines of force and the normal to the collecting surface. In this experiment, we choose two different *local* mirror ratios of 1.5 and 3.0 which correspond to $\theta = 60°$ and 0°, respectively. The experimental results (as discussed below) are similar in the case of selecting two different *local* mirror ratios also.

Typical current-voltage characteristics of the mirror probe are indicated in Fig. 3. From the characteristic curves of the mirror probe ob-

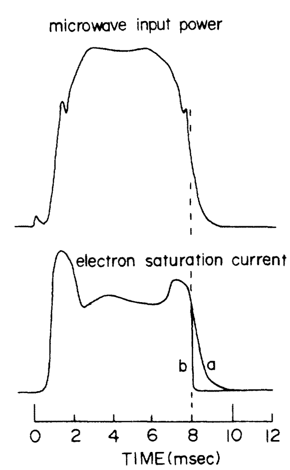

FIG. 2. Time displays of microwave input power and corresponding electron saturation current.

tained, we plot the ratio of $i_{ep}(60°)$ to $i_{ep}(0°)$ (the probe electron currents at θ) vs $eV_p/\kappa T_e$ in Figs. 4 (a) and 4 (b), where e is the electronic charge, V_p is the probe bias voltage measured from the space potential, $\frac{3}{2}\kappa T_e$ is the mean kinetic energy of electrons, and the parameters are the detecting times in the afterglow plasma. Theoretical curves in Fig. 4 are discussed in Sec. IV.

IV. DISCUSSION

We give the theoretical considerations that we use to explain the experimental results shown in Fig. 4. If the velocity distribution function of electron is a two-temperature Maxwellian whose two temperatures are parallel and perpendicular to magnetic field lines of force, the ratio $i_{ep}(0°)/i_{ep}(60°)$ must not depend on the probe bias voltage, according to the analyses of Refs. 18 and 19. However, the experimentally obtained ratios depend strongly on V_p.

Next we assume the velocity distribution of the electrons to be the simplest form of the loss-cone distribution.[16] The modified loss cone is expressed by the hyperboloid[20]

$$\sin\Theta = (1 + 2eV_M/m_e v^2)^{1/2}/R_M^{1/2}$$

in velocity space, where Θ is the angle between the magnetic field lines of force and the velocity vector, m_e is the mass of electron, v is the absolute value of the velocity vector, and R_M is the mirror ratio of the confined magnetic mirror field.

It is rather difficult to measure the potential difference (V_M) because of the experimental error and the unreliability for separating the space potential from the probe characteristics in the magnetic field, and because of the change of the condition of the afterglow plasma by setting a Langmuir probe at the mirror throat (as mentioned above). However, in other, similar experiments on the afterglow plasma confined in a magnetic mirror field[21] we obtained a value of $eV_M/\kappa T_e$ between −2 and 0 by the ordinary Langmuir probe method.

The assumption of the lack of electrons inside of the modified loss cone is reasonable for the following two reasons: In our experiment the electrostatic potential of the right-hand side of the metallic end wall of the cavity (as seen in Fig. 1) is not lower than V_M. Thus electrons which flee from the right-hand side of the mirror throat may be absorbed by the end wall if they do not collide, and will not come back into the mirror region. The second reason is that the electron mean free path is sufficiently long because of the

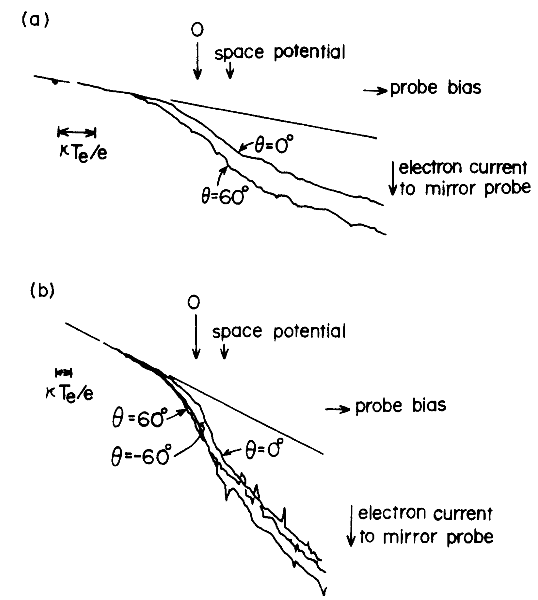

FIG. 3. Typical current-voltage characteristics of the mirror probe in the afterglow plasma (a) when the space potential is relatively low (on the order of $\kappa T_e/e$) and (b) when the space potential is relatively high (on the order of two times $\kappa T_e/e$).

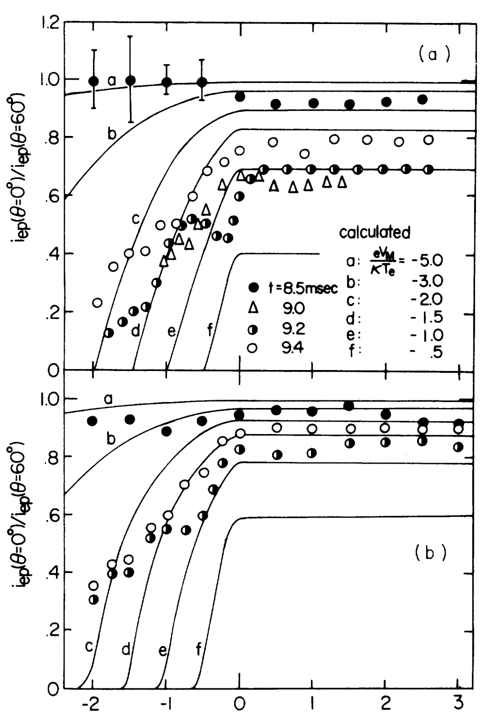

FIG. 4. $i_{ep}(\theta=0°)/i_{ep}(\theta=60°)$, the mirror probe electron current ratio of two different angles of θ vs normalized probe bias voltage at a pressure of 0.2 mTorr and at the mirror ratio of (a) 2.35 and (b) 3.15, respectively.

TABLE I. Calculation of the normalized electron current to a mirror probe $i_{ep}(\theta)/i_0$, where $i_0 = n_e e S_p (\kappa T_e/2\pi m_e)^{1/2}$, n_e is the electron density, S_p is the area of the collecting surface of the mirror probe, and $\gamma = 3\cos\theta/R_M$.

	$\gamma \leq 1$	$\gamma \geq 1$
$V_p \geq 0$	$1-\gamma\exp(eV_M/\kappa T_e)$	$1-\gamma\exp(eV_M/\kappa T_e)+(\gamma-1)\exp\{e(\gamma V_M - V_p)/[\kappa T_e(\gamma-1)]\}$
$0 \geq V_p \geq V_M$	$\exp(eV_p/\kappa T_e)-\gamma\exp(eV_M/\kappa T_e)$	$\exp(eV_p/\kappa T_e)-\gamma\exp(eV_M/\kappa T_e)+(\gamma-1)\exp\{e(\gamma V_M - V_p)/[\kappa T_e(\gamma-1)]\}$
$V_M \geq V_p$	$(1-\gamma)\exp\{e(V_p-\gamma V_M)/[\kappa T_e(1-\gamma)]\}$	0

Ramsauer effect, as described above. In accordance with these facts it can be concluded that the number of electrons which move from the outside to the inside of the loss cone by collisions and which stay in the inside of the loss cone or come back through the mirror throat from the outside of the magnetic mirror field is negligibly small.

If we calculate the electron current to the mirror probe, $i_{ep}(\theta)$,[14] with the use of the loss-cone distribution function as assumed above, we obtain the values of $i_{ep}(\theta)/i_0$ shown in Table I, where $i_0 = n_e e S_p(\kappa T_e/2\pi m_e)^{1/2}$, with the electron density n_e, the area of the collecting surface of the mirror probe S_p, and $\gamma = 3\cos\theta/R_M$. From these results we show the calculated curves (solid) in Figs. 4(a) and 4(b), which are drawn with the parameter V_M. Thus the ratio $i_{ep}(\theta=0°)/i_{ep}(\theta=60°)$, which is theoretically predicted, depends strongly on V_p. The theoretical curves explain the experimental results well and it can be said that the electrons almost obey the loss-cone distribution function.

For the loss-cone distribution function at the collisionless limit, $\frac{1}{2}\langle v_{e\perp}^2\rangle/\langle v_{e\parallel}^2\rangle > 1$ will hold, where $\frac{1}{2}m_e\langle v_{e\perp}^2\rangle$ is the perpendicular mean energy of the electrons and $\frac{1}{2}m_e\langle v_{e\perp}^2\rangle$ is the parallel mean energy of electrons. If we take the loss-cone distribution function given above, we obtain

$$\tfrac{1}{2}\langle v_{e\perp}^2\rangle/\langle v_{e\parallel}^2\rangle = \alpha/\beta, \qquad (1)$$

where

$$\alpha = \tfrac{1}{2}\pi^{1/2} - \mathrm{erfc}(\zeta^{1/2}) + \frac{\frac{1}{2}\zeta^{1/2}\exp(-\zeta)}{R_M} + (1-R_M^{-1})^{1/2}\left(1+\tfrac{1}{2}R_M^{-1} - \frac{\zeta}{R_M-1}\right)\exp\left(\frac{\zeta}{R_M-1}\right) \times \mathrm{erfc}\left(\frac{R_M\zeta}{R_M-1}\right)^{1/2},$$

$$\beta = \tfrac{1}{2}\pi^{1/2} - \mathrm{erfc}(\zeta^{1/2}) - \frac{\zeta^{1/2}\exp(-\zeta)}{R_M} + (1-R_M^{-1})^{3/2}\exp\left(\frac{\zeta}{R_M-1}\right)\mathrm{erfc}\left(\frac{R_M\zeta}{R_M-1}\right)^{1/2},$$

$$\zeta = -eV_M/\kappa T_e,$$

$$\mathrm{erfc}(x) = \int_x^\infty \exp(-t^2)\,dt.$$

The magnitude of this anisotropy is determined by the mirror ratio R_M and the normalized potential difference $eV_M/\kappa T_e$. Since the experimental value of the anisotropy of electron mean energy can be estimated from the mirror ratio and the normalized potential difference, which are read from Fig. 4, with Eq. (1), we can indicate the time dependence of this anisotropy as shown in Fig. 5(a). The characteristics of $\frac{1}{2}\langle v_{e\perp}^2\rangle/\langle v_{e\parallel}^2\rangle$ versus mirror ratio thus obtained are shown in Fig. 5(b).

As seen in Fig. 5(a), the electron energy distribution is rather isotropic both at the beginning and near the end of the late-afterglow plasma, and anisotropy is evident between them. This is interpreted as follows:

Because the microwave power still exists at the beginning of the afterglow plasma, it affects the energy distribution of confined electrons in such a way as to randomize the loss-cone distribution. After this effect ceases, the loss-cone distribution establishes as shown in Figs. 4(a) and 4(b) or

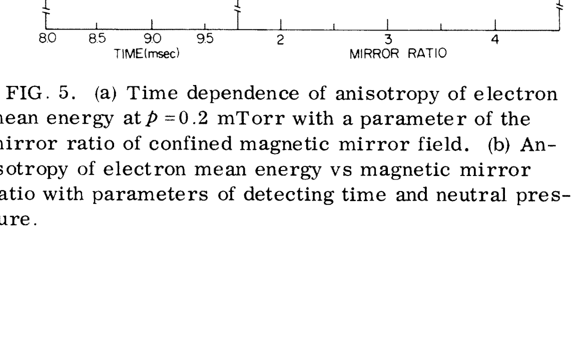

FIG. 5. (a) Time dependence of anisotropy of electron mean energy at $p = 0.2$ mTorr with a parameter of the mirror ratio of confined magnetic mirror field. (b) Anisotropy of electron mean energy vs magnetic mirror ratio with parameters of detecting time and neutral pressure.

Fig. 5 (a). However, because the negative potential at the throat is likely to grow quickly owing to the longer lifetime of ions compared with electrons and, moreover, owing to the cooling of ions (which results in the much longer lifetime of ions) in the lapse of afterglow, the escape of electrons from the throat will become more and more difficult towards the end of the afterglow because the negative potential difference V_M grows with time. This will affect the electrons so as to recover the isotropic energy distribution as indicated by calculated curves in Figs. 4(a) and 4(b).

At lower pressures (on the order of 10^{-5} Torr) and at mirror ratios slightly smaller than 2.2, the experimental results show rather isotropic energy distribution functions for the electrons, as seen in Fig. 5(b). In this case, the afterglow plasma is observed to be very noisy. The cause of the noise may be related to some loss-cone instabilities; furthermore, the presence of large fluctuating fields may tend to obscure the anisotropy to be detected by the present method.

As seen in Figs. 4(a) and 4(b) the experimental data gradually deviate from each of the presumed theoretical curves as the probe bias becomes deeper. This deviation tends to become large as the mirror ratio increases. It becomes clear by a simple theoretical estimation that its deviation cannot be explained only by the effect of the collisions neglected previously. Recent experimental results[21] show that the electrostatic potential of the end wall is not always higher than V_M and that as a result some electrons which flee from the mirror region are reflected at the end wall and come back again into the mirror region without collisions. This phenomenon can lead to such a deviation and will be almost negligible in the case of high-energy electrons, as described earlier.

V. CONCLUSION

It is experimentally found with the use of the mirror probe method that the low-energy electrons of an afterglow plasma confined in a magnetic mirror field almost obey the loss-cone distribution function. The velocity distribution of these electrons is rather isotropic, both at the beginning and near the end of the late-afterglow plasma, and is evidently anisotropic between them.

The experimental deviation from theory has been discussed, but is not yet well explained. However, it seems to be a phenomenon peculiar to low-energy electrons.

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