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Plasma Fluctuation Measurements in ELMO Bumpy Torus

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CONTENTS

ABSTRACT

Spatially resolved density fluctuation measurements in the dc frequency range up to 500 kHz have been conducted on the ELMO Bumpy Torus (EBT-I) plasma using photodetectors and Langmuir probes. Plasma currents produced by microwave-heated hot electron annuli were found to reduce fluctuations of toroidal plasma to low levels. The mechanism of stabilization has been studied in detail. Large amplitude fluctuations that accompany the hot electron annuli that destroy a stable plasma confinement were observed at low neutral pressure.

1. INTRODUCTION

The ELMO Bumpy Torus (EBT)[1] is a steady-state toroidal confinement device of 24 canted mirror sections. The plasma, which consists of three components (a toroidal plasma; an annulus of high energy electrons; and an outer, poorly confined surface plasma), is produced and heated by microwaves that are applied at the electron cyclotron resonant frequencies. Toroidal equilibrium is established by the poloidal drifts that are due to the radial mirror field gradient and the radial electric field. The annulus of high energy electrons that is formed by the second harmonic electron cyclotron heating is predicted to have sufficient diamagnetic energy to modify the magnetic field and thus provide the stability to the toroidal plasma.

There are three distinct modes, depending on the microwave power and the background neutral pressure:[1] The C-mode is characterized by high electron line density and the absence of a hot electron annulus; the T-mode by a high-β, hot electron annulus and improved confinement with moderate electron line densities; and the M-mode by a very tenuous and unstable plasma. The previous fluctuation measurement performed by a microwave interferometer showed that the absolute fluctuation amplitude (0.01-30 kHz) in the T-mode is very small compared with the fluctuation in the C-mode.[1] However, the normalized fluctuation level is almost constant through both modes.[2] This result is very different from the one expected, i.e., that the normalized fluctuation level in the T-mode should be also much lower than the level in the C-mode.[1] Thus, detailed fluctuation measurements are required to accurately determine the role of hot electron annuli in stabilizing the EBT plasma.

This paper presents experimental results of studies of low frequency fluctuations (dc $\leq$ 500 kHz), with consideration of the spatial properties of the EBT plasma.

2. EXPERIMENTAL APPARATUS AND METHOD

The magnetic field and heating geometry is shown in Fig. 1. The magnetic field is chosen to be 5 kG at the midplane. The power available is 60 kW at 18 GHz and up to 30 kW at 10.6 GHz. The latter is used primarily to sustain the energetic electrons that produce the diamagnetic annuli.

Fluctuation measurements have been performed with silicon phototransistors and Langmuir probes. The phototransistor, which has a small viewing angle (~10°) and a dc frequency response up to ~400 kHz, is sensitive throughout the visible and near infrared spectral range; the most sensitive wavelength is about 0.83 μm with a FWHM of ~0.43 μm. The experimental geometry for the photodetectors is shown in Fig. 2. One detector has a fixed view along the horizontal midline and has produced all data shown in this paper except the spatial profiles. The spatial distributions have been measured by using the same optical system that was used to measure impurities and hydrogen neutrals,[3] although the detector is set inside the lead wall to increase the signal. This increase in signal was necessary to yield a sufficient number of photons during the short time period of a fluctuation. The spatial resolution is expected to be ~1.2 cm at the machine center in the horizontal midplane. No optical filter is used, again in order to increase the signal. However, the detector is expected to collect the H_{α} radiation because this is the dominant radiation in the visible spectrum. The H_{α} signal is related to the neutral and electron densities by

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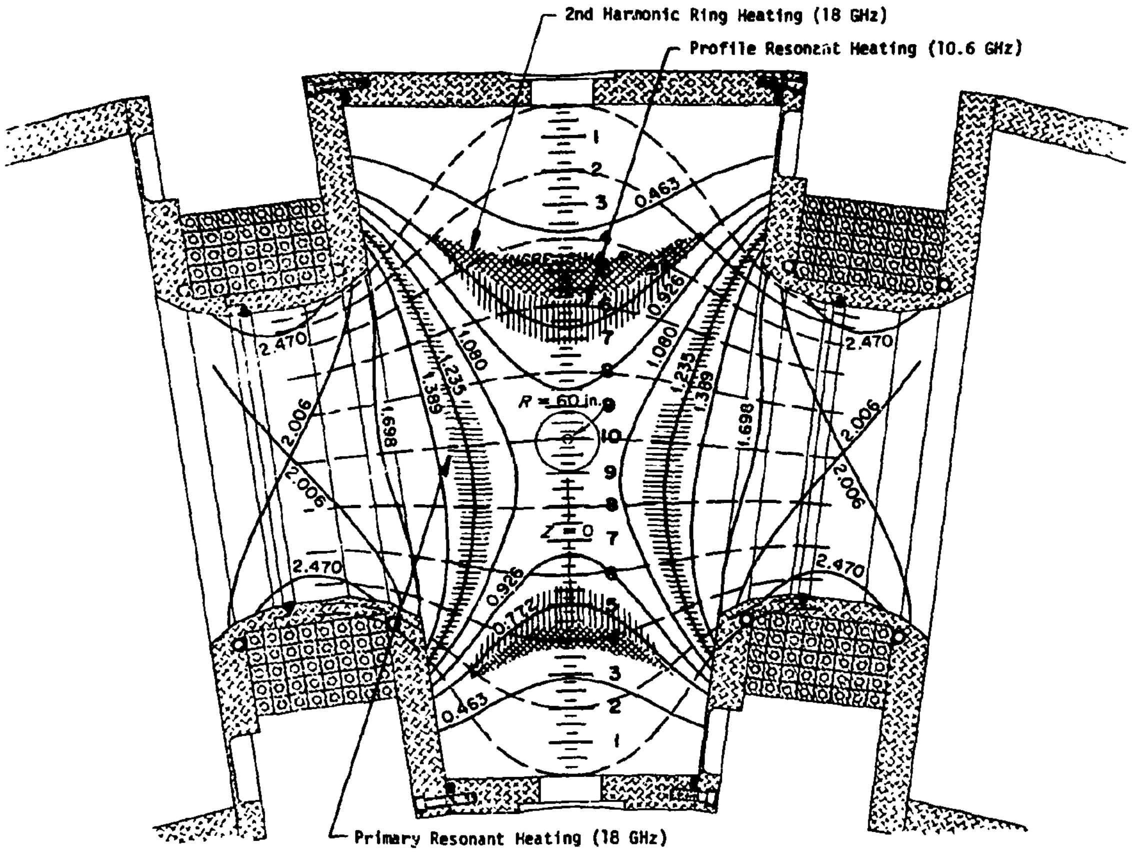

EBT Mod-B Contours (—), Flux Lines (---), and Heating Geometry (////), (⨯⨯⨯)

Fig. 1. Horizontal section through one of 24 cavities that make up the vacuum chamber of EBT. The solid lines are surfaces of B, the dotted lines are flux lines, and the shaded area shows resonance regions for primary heating power (18 GHz) and profile heating (10.6 GHz). The numbers on the surfaces of B are relative to the value at the cavity midpoint; radial dimensions are in inches.

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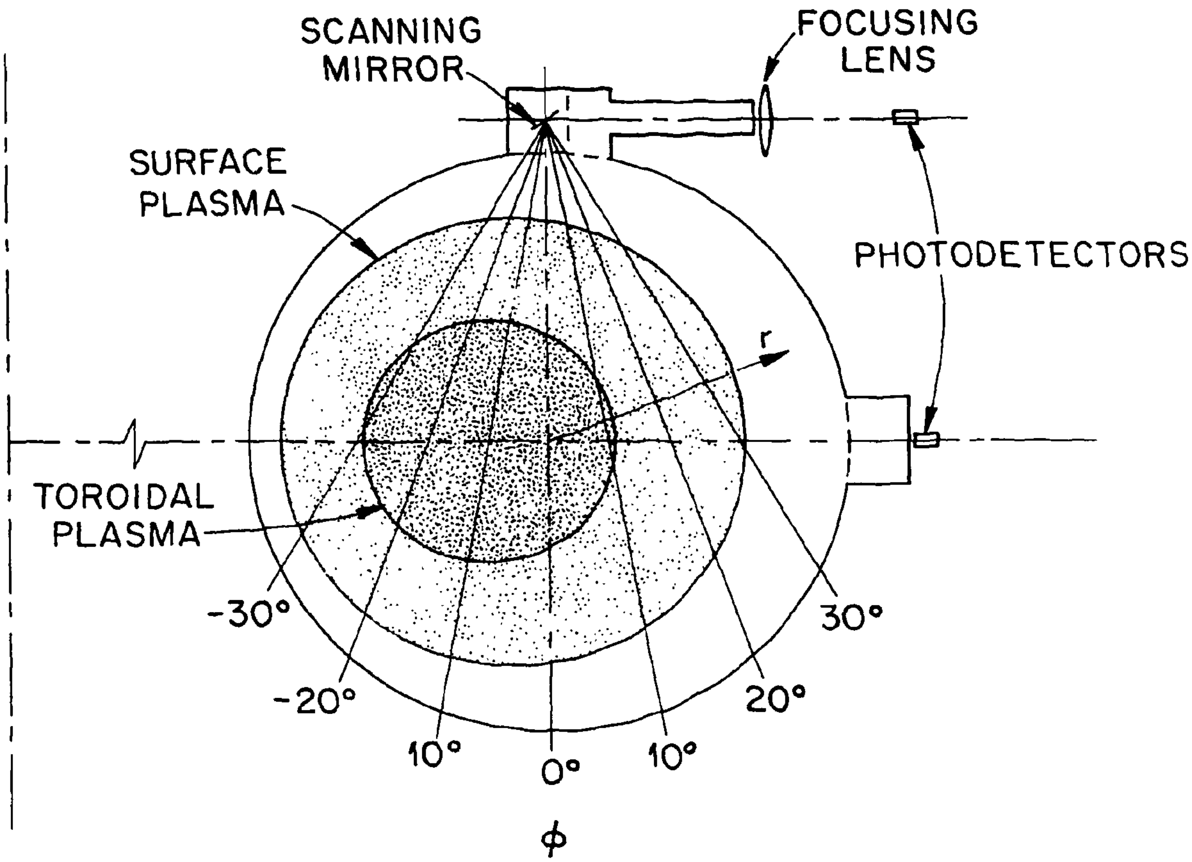

Fig. 2. Optical geometry for photodetectors. Two detectors are, in fact, situated at different mirror cells.

$$I \propto \int n_o n_e \langle\sigma v\rangle \Omega \, dV \propto \int n_o n_e \langle\sigma v\rangle \, d\ell \qquad (1)$$

where $\langle\sigma v\rangle$ is the excitation rate coefficient and a function of electron temperature, Ω is the solid angle subtended by the optical system, and the volume integral dV that is replaced by the line integral $d\ell$ is along the chord passing through the plasma that the optical system views. Because the electron temperature (except near the wall) is considered to be higher than 50 eV under our experimental conditions, $\langle\sigma v\rangle$ is expected to be nearly constant. Because $n_o(r)$ is also constant within 10-20%, I is, roughly speaking, replaced by

$$I \propto n_e \ell P , \qquad (2)$$

where P is the neutral pressure and $n_e \ell$ represents the electron line density. Thus, the value I will carry information about density fluctuations, but not about temperature fluctuations.

A single water-cooled Langmuir probe was used in the midplane of a mirror cavity, and microwave power feed to this one cavity was shut off. The probe can be inserted horizontally from the outside of the torus to approximately the machine center. Although the probe has a dc frequency response up to ~20 MHz, the measurements were performed in the range of frequencies lower than 500 kHz.

3. EXPERIMENTAL RESULTS AND DISCUSSIONS

At first, the fixed-view photodetector was used to study the neutral pressure dependencies of electron line density and fluctuation level at constant microwave power. In all of the experiments, the fluctuation amplitude was minimized by the error field correction.[1]

Figure 3 shows the dc components of I and $n_e \ell$ (as measured by the microwave interferometer) as a function of neutral pressure. It is easily recognized from the figure that the ratio of I_o to $n_e \ell P$ is almost constant throughout the neutral pressure region. This is the most important justification for the assumptions given in the derivation of Eq. (2) in Sect. 2. The modes are distinguished by $n_e \ell$: the regime of high neutral pressure ($P \gtrsim 1.8 \times 10^{-5}$ torr) is regarded as the C-mode, while the regime of medium neutral pressure (5×10^{-6} torr $\lesssim P \lesssim 1.8 \times 10^{-5}$ torr) is regarded as the T-mode. No measurements were made in the M-mode.

The peak fluctuation amplitude $\tilde{I}$, measured by an oscilloscope, is shown in Fig. 4, together with the normalized fluctuation level $\tilde{I}/I_o$. As the neutral pressure is reduced, $\tilde{I}$ is found to decrease gradually from 2.5×10^{-5} torr to $\sim 8 \times 10^{-6}$ torr, except for a small bump at $P = 1.8 \times 10^{-5}$ torr that is always observed at the C-T transition. However, the normalized fluctuation level increases slightly as the neutral pressure is reduced, because I_o decreases at a larger rate than $\tilde{I}$. This agrees with the result obtained by the microwave interferometer.[2] The large amplitude fluctuations whose normalized fluctuation level reaches ~30% are found at the low neutral pressure

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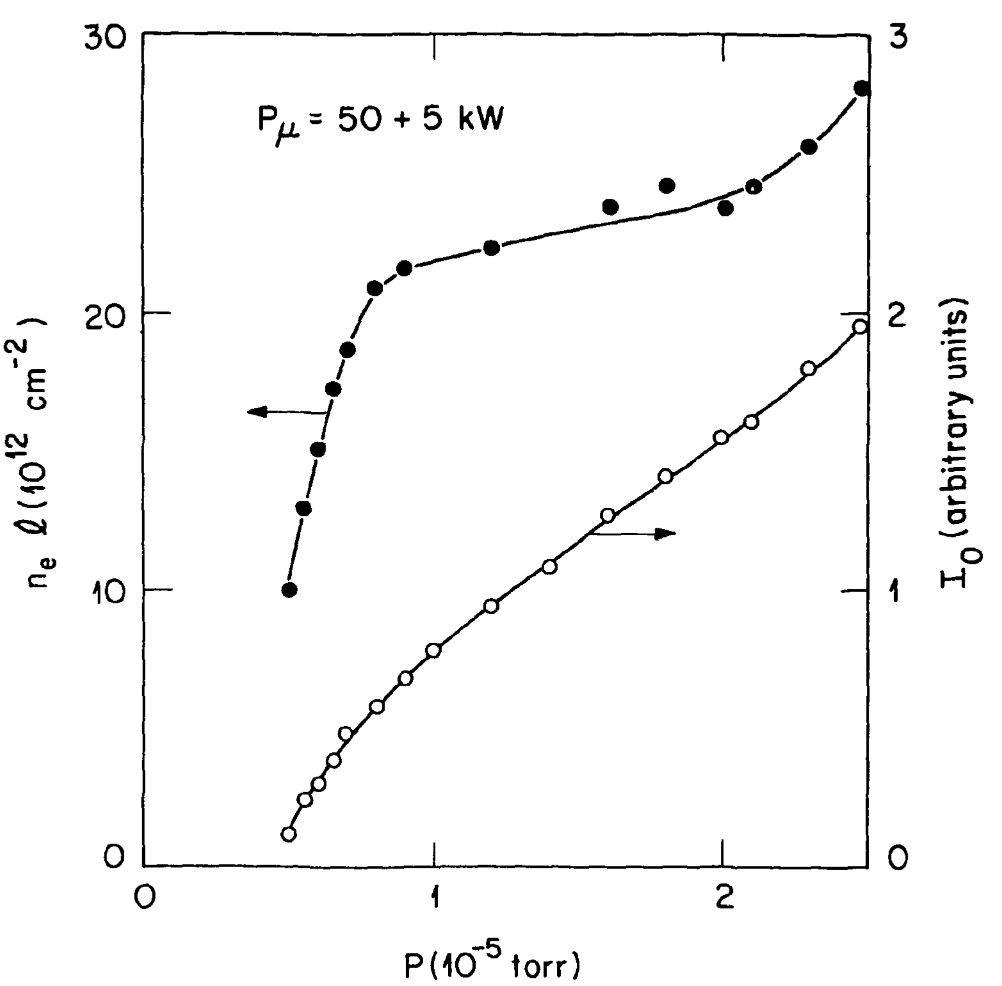

Fig. 3. Line density $n_e\ell$ measured by a microwave interferometer and photodetector signal I_0 as a function of neutral pressure P. The relation P_μ = 50 + 5 kW means that the microwave power at 18 GHz is 50 kW and the power at 10.6 GHz is 5 kW.

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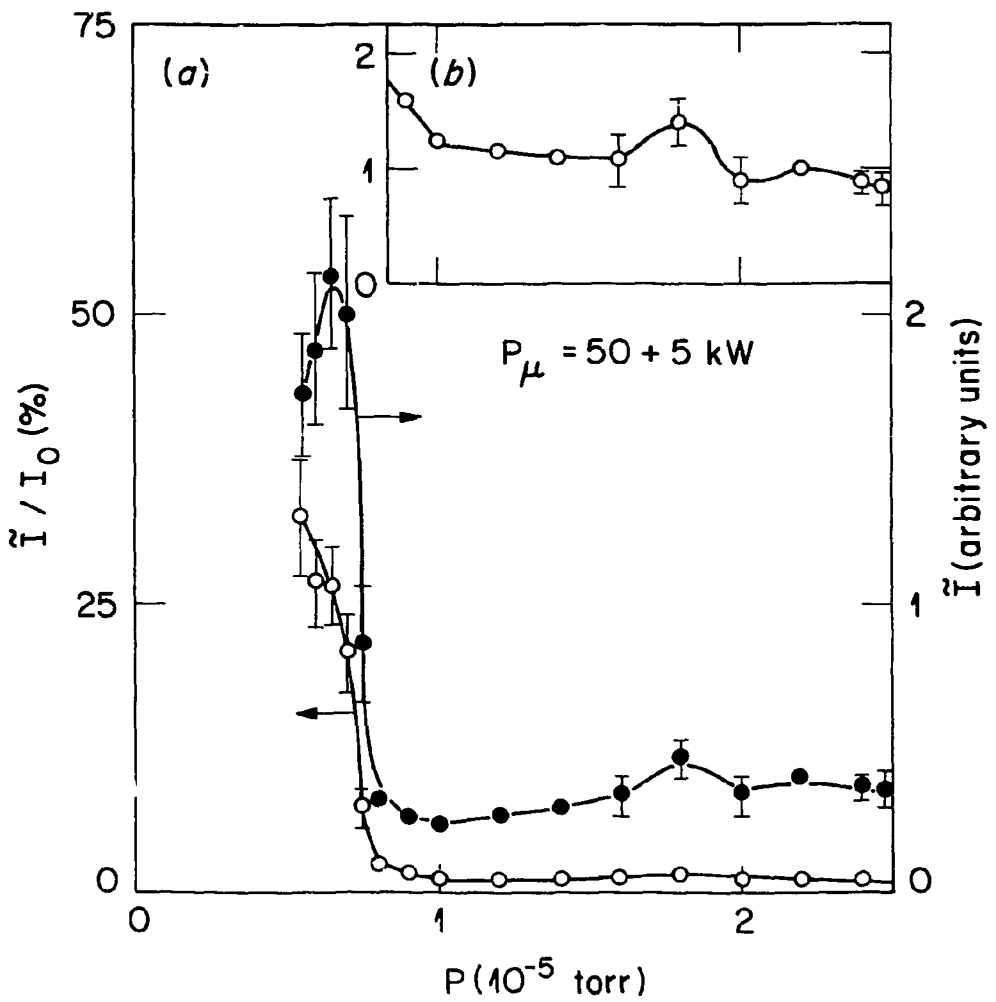

Fig. 4. (a) Fluctuation of I and normalized fluctuation level $\tilde{I}/I_o$ as a function of neutral pressure. (b) $\tilde{I}/I_o$ in the regime of high neutral pressure; the vertical scale is different from that of (a).

region ($P \lesssim 7.5 \times 10^{-6}$ torr). This excitation corresponds to the steep decrease of $n_e \ell$ seen in Fig. 3. It is clear that the fluctuations significantly influence the EBT plasma transport. This regime of operation is known as the T-M transition.

Similar results can be obtained even if the microwave power is changed. In Fig. 5, the bump of $\tilde{I}/I_0$ that is seen at the C-T transition is recognized at $P = 1.3 \times 10^{-5}$ torr, and the steep increase in $\tilde{I}/I_0$ is also observed in the low neutral pressure region. Apparently the higher microwave power yields the larger T-mode region. The large bump of $n_e \ell$ seen in the T-mode is clearly observed when the microwave power is low and only the 18-GHz microwave power is used.

Displayed on a spectrum analyzer, $\tilde{I}$ shows that the fluctuations consist of low frequency oscillations, as shown in Fig. 6. Although the coherent oscillation of ~20 kHz is recognized in the C-mode, both the amplitude and the frequency of this oscillation decrease and then disappear as the neutral pressure is reduced. Thus the fluctuations observed in the T-mode do not have a clear peak in the spectra. These fluctuations are found to be electrostatic. This characteristic spectrum of $\tilde{I}$ changes slightly near the T-M transition where a large amplitude coherent fluctuation is excited, accompanied by a magnetic fluctuation. This electromagnetic fluctuation is observed even in the T-mode, as shown in Fig. 7. Although the wave amplitude is small, the fluctuation is recognized at the T-mode before it increases sharply at the T-M transition. The frequency of this fluctuation increases as the neutral pressure is reduced. This is plotted as a function of neutral

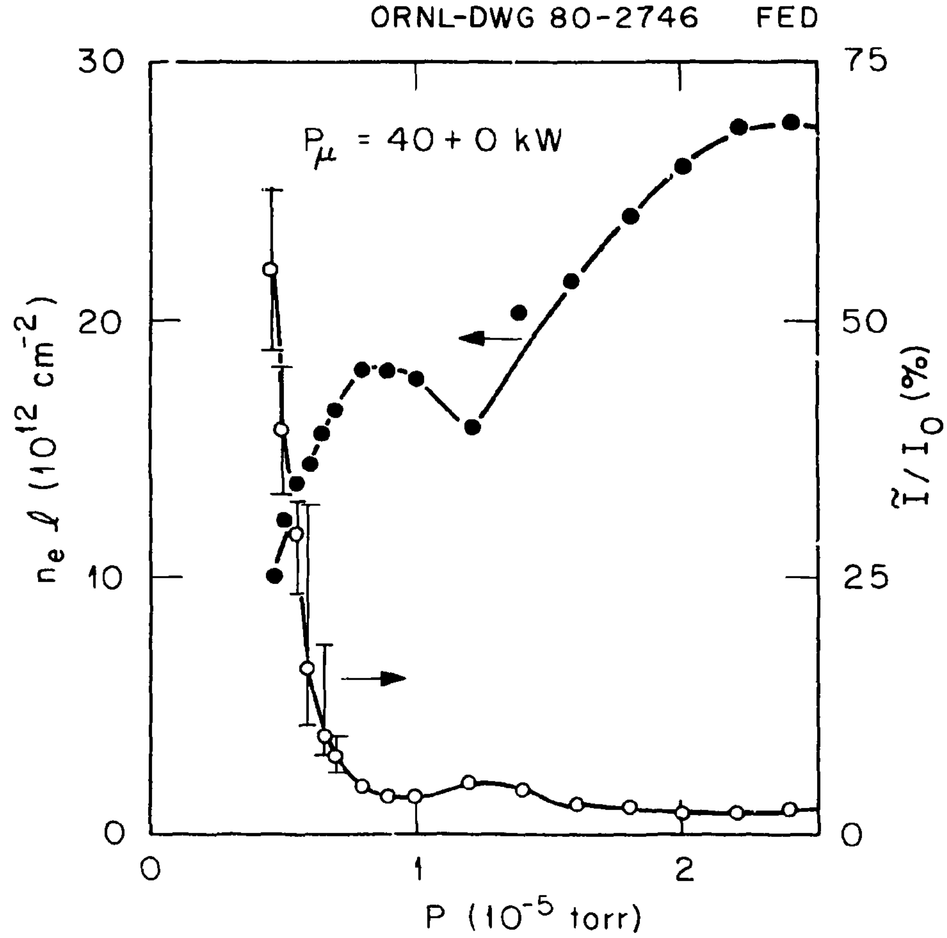

Fig. 5. Line density $n_e\ell$ and normalized fluctuation level $\tilde{I}/I_o$ measured at a low microwave power.

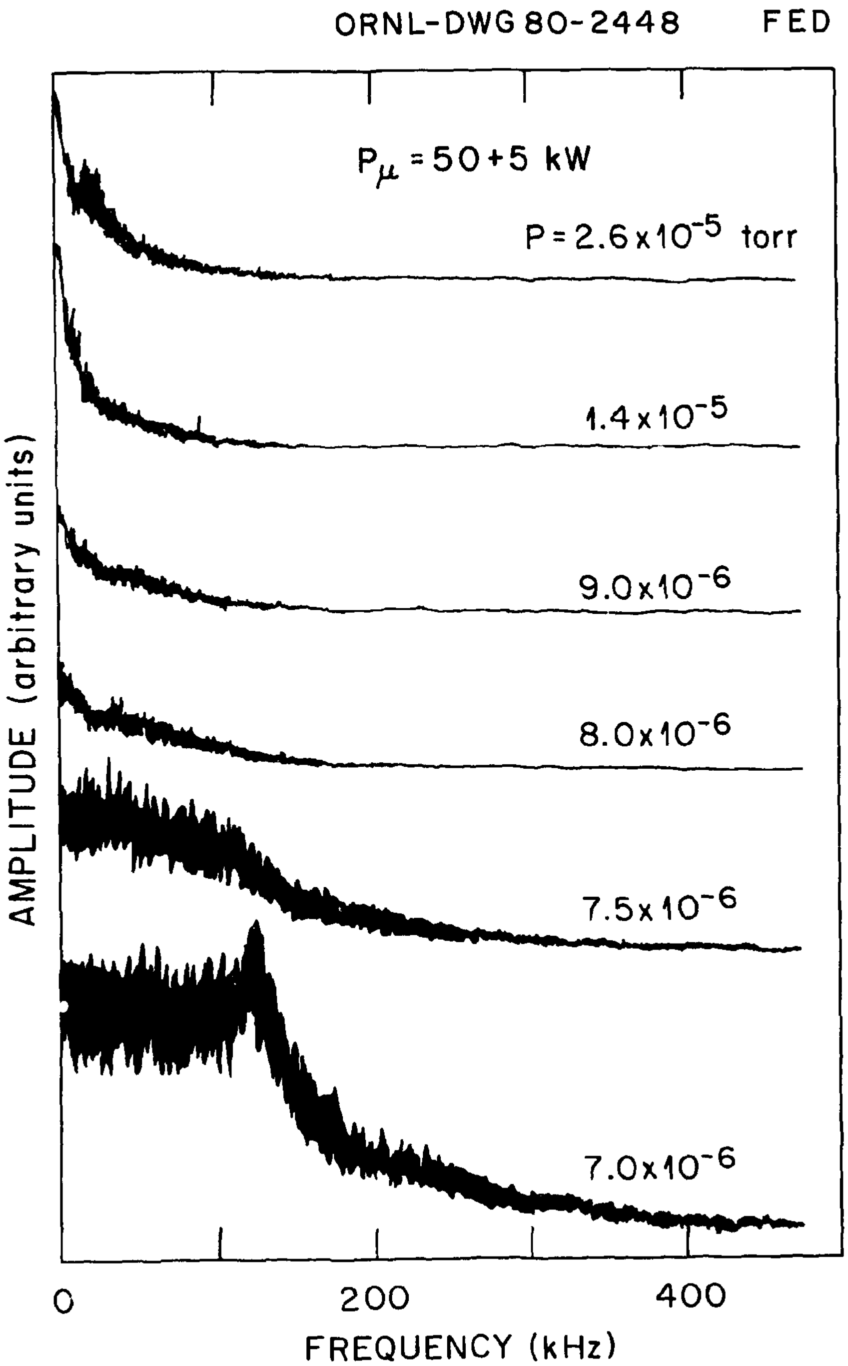

Fig. 6. Dependence of frequency spectra $\tilde{I}$ on neutral pressure. Upper two spectra are in the C-mode, middle two in the T-mode, and lower two at the T-M transition.

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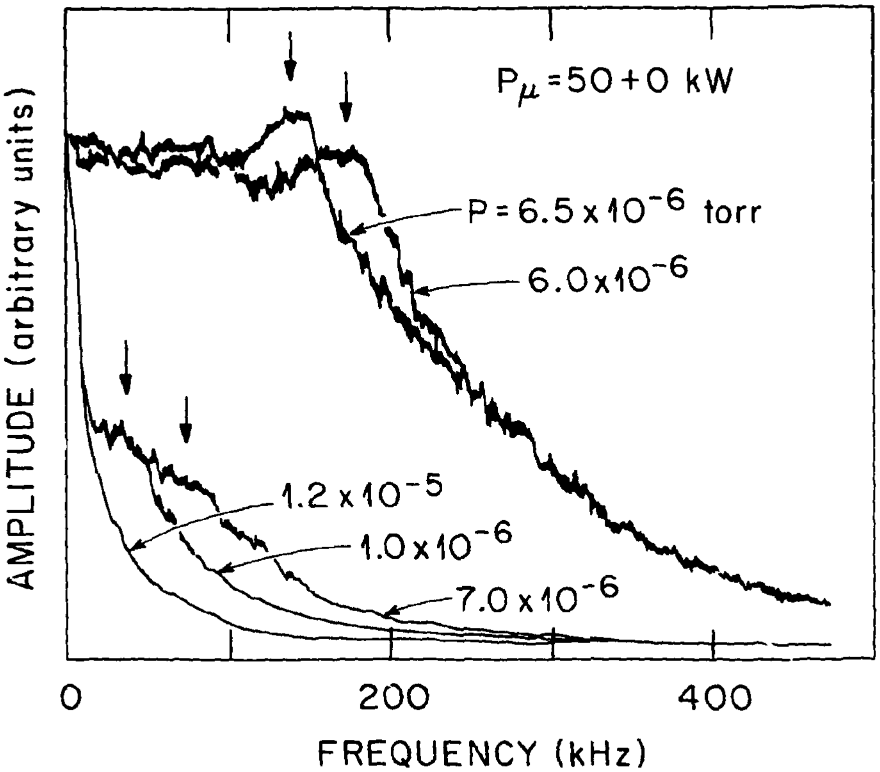

Fig. 7. Dependence of frequency spectra of $\tilde{I}$ on neutral pressure. Vertical arrows indicate the estimated peak frequency of the fluctuation concerned.

pressure in Fig. 8 by using the magnetic probe data, which show clear peaks in the spectr The spectra of the magnetic fluctuations are shown in Fig. 9, together with the spectrum of $\tilde{I}$. The toroidal and poloidal magnetic field fluctuations ($\dot{B}_z$ and $\dot{B}_\theta$, respectively) have been investigated by one-turn loop magnetic probes ~1 cm in diameter, which are set on the wall. In this figure, two peaks are found in $\tilde{I}$, and these two modes are observed to be polarized. The fluctuation of ~33 kHz is sometimes observed at the T-M transition, but not in the T-mode.

The spatial distributions of electrostatic fluctuations were obtained by the photodetector, which is convenient for the measurement of toroidal plasma fluctuations. Although Fig. 10 shows the spatial distributions of 2-kHz fluctuations, these profiles are characteristic of electrostatic fluctuations of the whole frequency range. Because many profiles have no axial symmetry, the simple Abel transform cannot be used. Thus, the profiles are represented as a function of the viewing angle ϕ, but they give important spatial information, especially about the toroidal plasma fluctuations. Using this method, it is difficult to get precise spatial distributions of the fluctuations excited near the wall. The profile obtained in the C-mode has two ridges near the hot electron annulus, and the minimum fluctuation amplitude is near the machine center. Thus, the fluctuations are expected to form the axially symmetric, hollow shape distribution. As the neutral pressure is lowered, the fluctuation amplitude inside the hot electron annulus, especially near the machine

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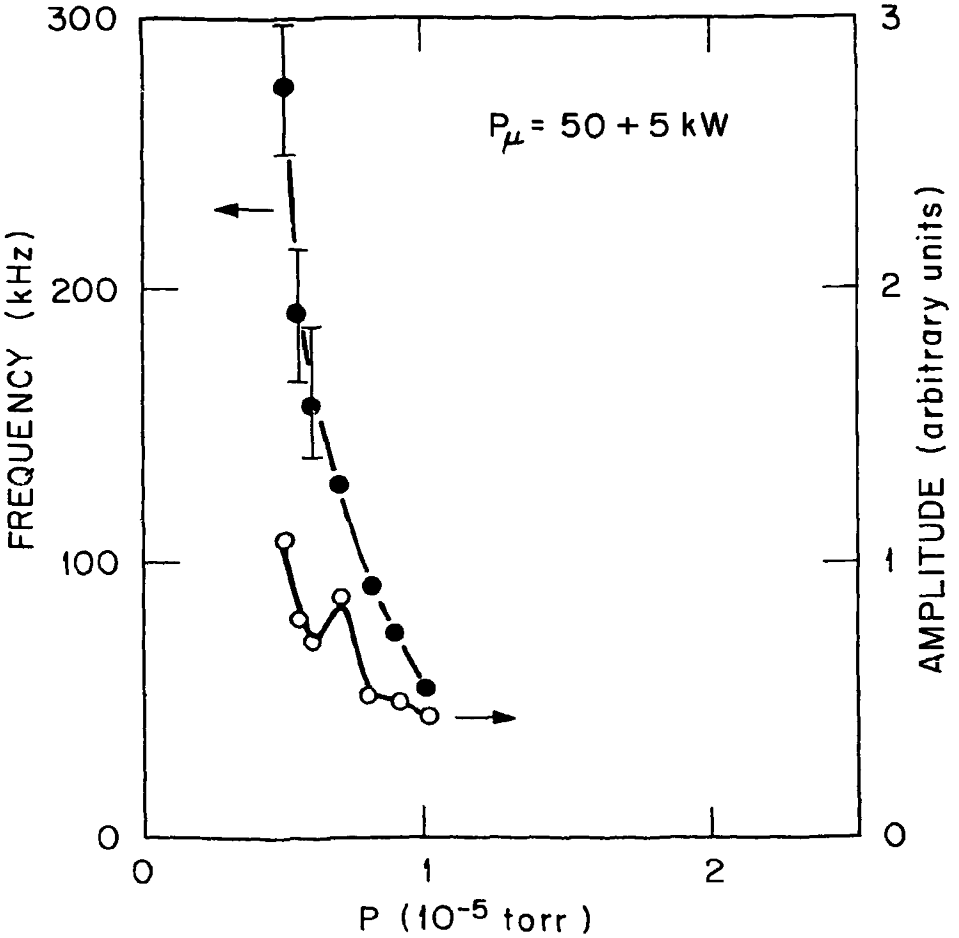

Fig. 8. Frequency and amplitude of the fluctuation observed by the magnetic probe as a function of neutral pressure. These are measured on the wall, so that the amplitude does not represent the maximum wave amplitude.

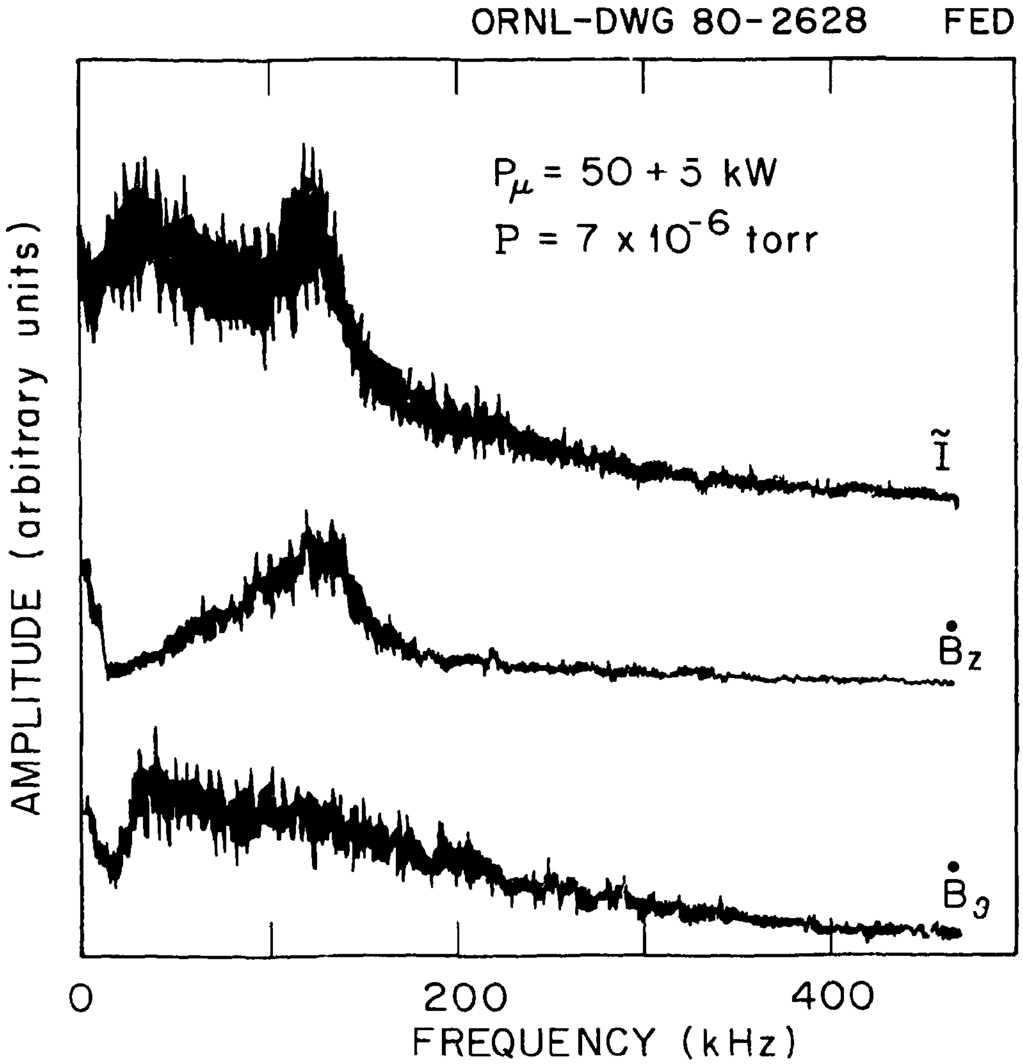

Fig. 9. Frequency spectra of $\tilde{I}$, $\dot{B}_z$, and $\dot{B}_\theta$ observed at the T-M transition.

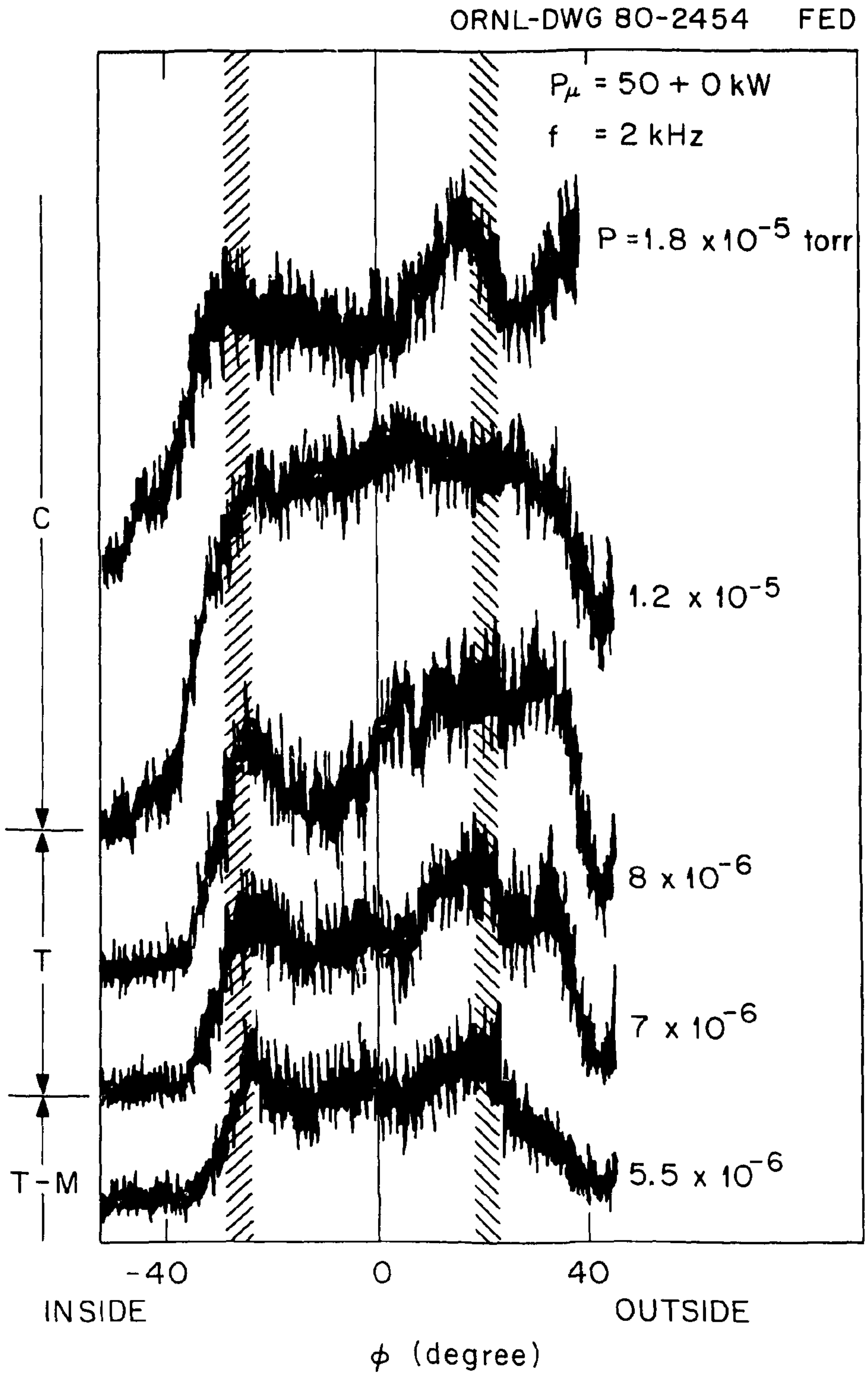

Fig. 10. Spatial distributions of $\tilde{I}$ with respect to 2-kHz fluctuations. Hatches represent locations of hot electron annuli on the equatorial plane.

center, increases ($P = 1.2 \times 10^{-5}$ torr). This corresponds to the bumps of $\tilde{I}/I_0$ observed at the C-T transition. In the T-mode, the fluctuation amplitude decreases, and the hollow shape distribution appears again; the location of the minimum, which corresponds to that of the plasma center,[1] is displaced about 10^o from the machine center. This fluctuation location is characteristic of the fluctuations observed in the T-mode. Because of these results, this electrostatic fluctuation is considered to be a drift instability. Thus, the profile obtained in the T-mode shows that the density or temperature gradient exists around the plasma center. Two small peaks ($\phi \sim 5^o$ and $\phi \sim -25^o$) recognized in the profile at the C-T transition are observed at the same spatial position as those in the T-mode, so that the spatial profile of $\tilde{I}$ is basically the same for both the T-mode and the C-T transition. The profile obtained at the T-M transition is somewhat similar to the profile obtained in the C-mode, but the shallow, hollow shape distribution around the plasma center can still be seen. The fluctuation location is found to move inward as the neutral pressure is lowered. It is expected from these fluctuation profiles that in the C-mode the particles cannot orbit their own drift surfaces due to collisions; this results in the axially symmetric fluctuation profiles. They do, however, complete drift surface orbits; in other words, they are well confined in the T-mode and at the C-T transition. Thus, it is meaningless to compare the fluctuation level observed in the T-mode with the level in the C-mode.

The electromagnetic fluctuation of 100-300 kHz observed at the T-M transition is localized outside the hot electron annulus, as shown in Fig. 11. This profile was measured by the Langmuir probe and represents the fluctuation amplitude of the ion saturation current. In addition to the fact that the wave amplitude in the T-mode is very small, the fluctuation is located at the same spatial position as it is when excited at the T-M transition, i.e., outside the hot electron annulus. Thus, in the T-mode the toroidal plasma transport is influenced more by the electrostatic fluctuations than by the electromagnetic fluctuations.

The Langmuir probe also gives good information about electrostatic fluctuations. Figure 12(a) is taken with the probe situated at r = 14 cm, just outside the hot electron annulus. Figure 12(b) is taken at r = 2.2 cm, the same position ($\phi \sim 5^{o}$) as that of the peak intensity of $\tilde{I}$ in the profile obtained at the C-T transition in Fig. 10. As the neutral pressure is reduced from 1.8×10^{-5} torr, the normalized fluctuation level at r = 14 cm decreases to a minimum at $P = 1 \times 10^{-5}$ torr and then increases steeply. This decrease of $\tilde{J}_s/J_{so}$ in the hot electron annulus region corresponds to the increase in the diamagnetic energy stored in the hot electron annulus.[1] On the contrary, the normalized fluctuation level at r = 2.2 cm increases and has a maximum at $P \approx 1.2 \times 10^{-5}$ torr as the neutral pressure is lowered. These results agree with those obtained with H_{α}, and they show the spatial variation of the fluctuations more clearly than the results shown in Fig. 10. The fluctuations of toroidal plasma contribute to the

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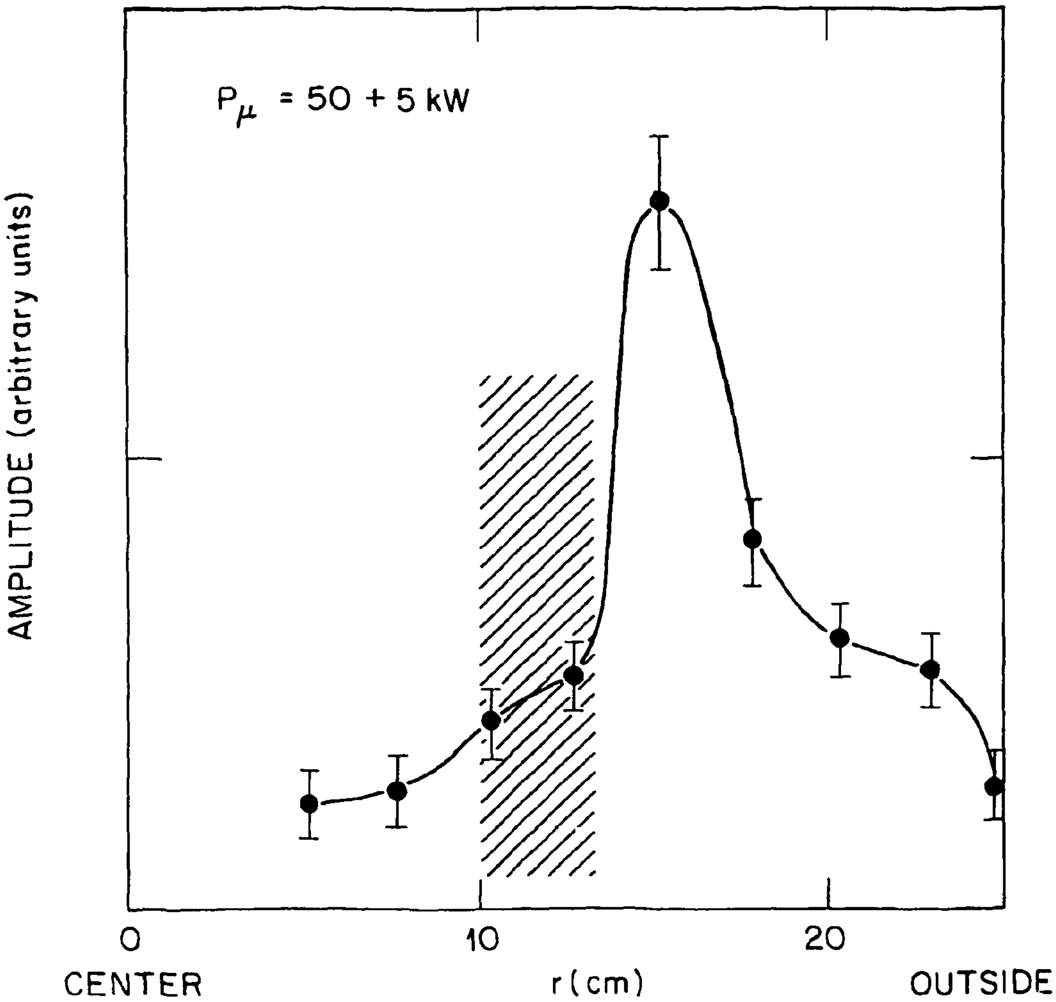

Fig. 11. Spatial distribution of the fluctuation amplitude of ∿150 kHz, observed at the T-M transition, as a function of r. This profile is taken by the Langmuir probe at P = 6 × 10^{-6} torr.

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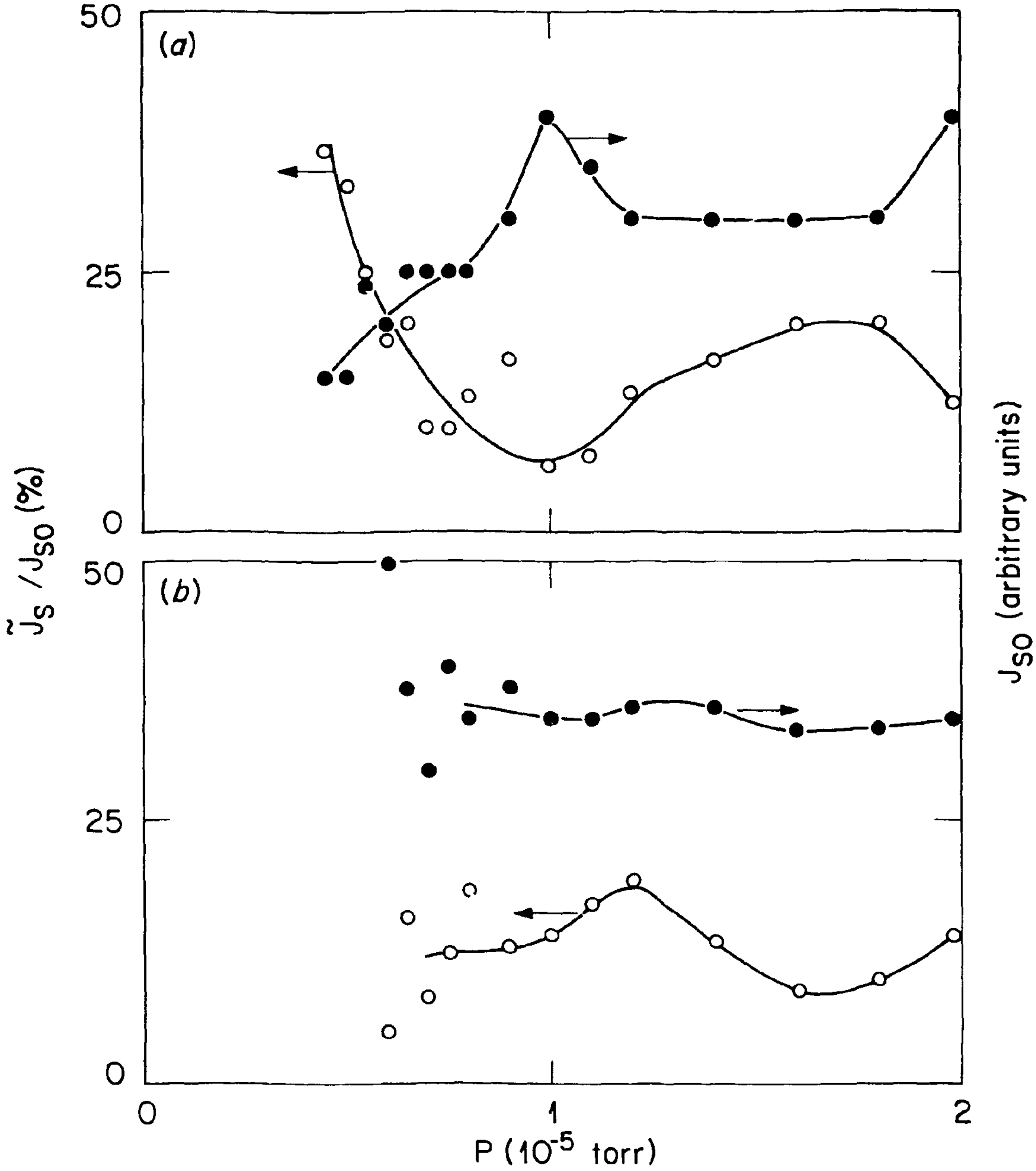

Fig. 12. Ion saturation current J_{so} and normalized fluctuation level $\tilde{J}_s/J_{so}$, collected by Langmuir probes; P_μ = 40 + 0 kW. (a) is taken at r ∿ 14 cm and (b) at r ∿ 2.2 cm.

increase of $\tilde{I}/I_o$ in the C-mode and the bump of $\tilde{I}/I_o$ at the C-T transition. It is clear that the hot electron annulus stabilizes the fluctuations excited near its location, but it does not stabilize the fluctuations in the toroidal plasma. The increase of $\tilde{J}_s/J_o$ in the toroidal plasma is caused by the steep density gradient accompanied by the improved particle confinement at the C-T transition. The curve of $\tilde{I}/I_o$ in the low pressure region ($P \lesssim 8 \times 10^{-6}$ torr), shown in Fig. 5, is very similar to that of the normalized fluctuation level shown in Fig. 12(a). However, it cannot be concluded that the increase of $\tilde{I}/I_o$ in this pressure regime is due to the fluctuations excited near the hot electron annulus, because the contribution of toroidal plasma fluctuations is unknown. The data on toroidal plasma in the low pressure regime ($P \lesssim 8 \times 10^{-6}$ torr) are not reliable, since the probe is found to disturb the plasma when it is inserted near the machine center.

The most important points shown in Fig. 12 are that the ion saturation current near the hot electron annulus has a maximum at the same neutral pressure at which the fluctuations have a minimum and that the ion saturation current at r = 2.2 cm does not increase. This demonstrates that the plasma diffused from near the plasma center due to fluctuations is stagnated around the hot electron annulus region because of the low fluctuation level, as water is stopped by a dam. Thus, a reduction in the toroidal plasma fluctuation level is expected because the density gradient is reduced. The normalized fluctuation level at r = 2.2 cm, shown in Fig. 12(b), is reduced, compared with that at $P = 1.2 \times 10^{-5}$ torr. So it is quite probable that the hot electron annulus can reduce the fluctuations in the toroidal plasma by the "dam" effect, although the annulus itself stabilizes only fluctuations excited near its location. This dam effect is not expected to occur at the C-T transition because of the high fluctuation level in the hot annulus region.

The change of density profiles at the beginning of T-mode is also recognized by the other diagnostics. The microwave interferometer measurement shows that the bump of $n_e \ell$ seen in Fig. 5 corresponds to the increase in the ion saturation current at r = 14 cm. In Fig. 13, the normalized spatial profile of H_α radiation taken in the T-mode ($P = 1.1 \times 10^{-5}$ torr) shows that the H_α radiation increases inside the hot electron annulus but decreases outside it, compared with the profile obtained in the C-mode ($P = 1.5 \times 10^{-5}$ torr). It is clear from these results that the data taken by the Langmuir probe are reliable and that the change in the ion saturation current is mainly caused by the density, since $n_e \ell$ and H_α carry information about density but not about temperature.

An important feature shown in Fig. 12 is that the change of $n_e \ell$ is due mainly to the change of the plasma diameter, although the density itself changes slightly.[4] In Figs. 12(a) and 12(b), the ion saturation currents are regarded as almost constant through the C-mode, although the $n_e \ell$ shown in Fig. 5 decreases greatly as the neutral pressure is reduced. Thus, the density of the surface plasma outside r = 14 cm is expected to change in this mode. In the regime of low neutral pressure

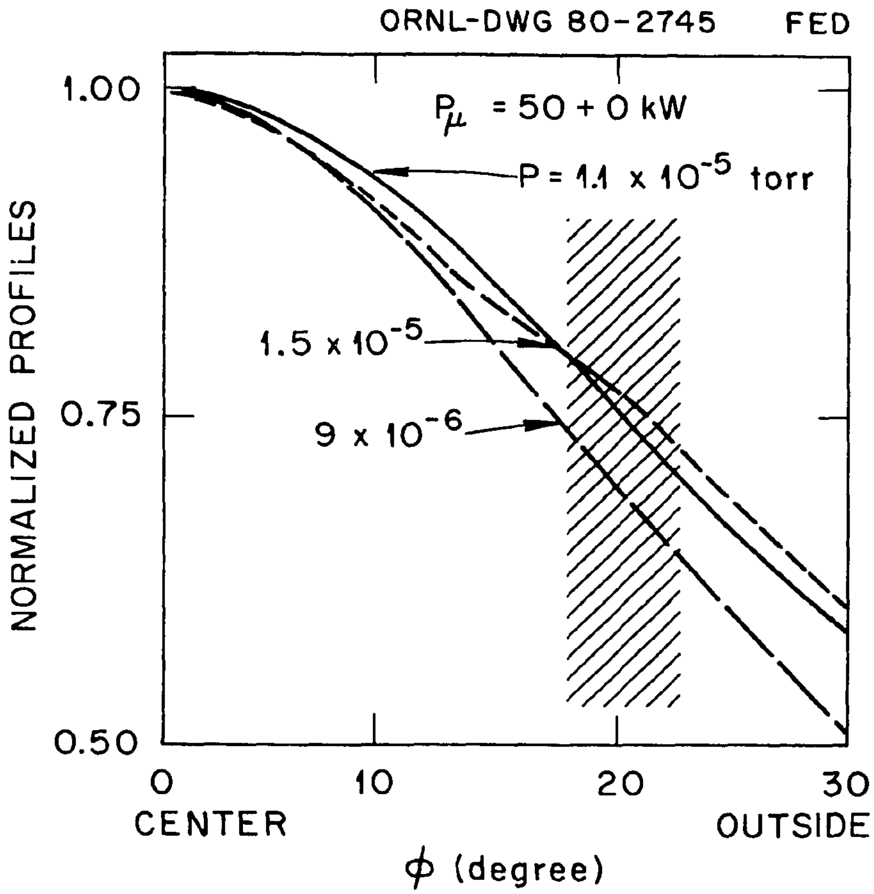

Fig. 13. Spatial profiles of H_α radiation as a function of viewing angle. Profiles are normalized by the maxima.

($P \lesssim 1.2 \times 10^{-5}$ torr), the ion saturation current at r = 14 cm changes in the same manner as the $n_e \ell$ shown in Fig. 5, so that the boundary of the plasma is considered to be moving around r = 14 cm. These results indicate that the plasma boundary in the T-mode is situated near the hot electron annulus. The plasma diameter and the toroidal plasma density are almost constant through the T-mode, so that $n_e \ell$ is found to be flat, as shown in Fig. 3. They begin to change again at the T-M transition. Thus, it is explainable that the normalized profiles shown in Fig. 13 tend to move toward the center as the neutral pressure is reduced. In this case, the T-mode region is so small that the plasma diameter decreases at $P = 9 \times 10^{-6}$ torr, a neutral pressure somewhat lower than that at which the well-confined plasma is obtained.

The well-confined plasma configuration is destroyed by the large amplitude electromagnetic fluctuation excited near the hot electron annulus. This fluctuation is considered to be the instability participating in the hot electron annulus because of its location. Recently, Spong[5] has theoretically shown that the hot electron annulus excites an instability in this frequency region. The change of frequency, as shown in Fig. 8, is considered to be due mainly to the change in electron temperature; according to soft x-ray measurement,[6] the electron temperature increases steeply at the T-M transition as the neutral pressure is reduced, while it is regarded as constant, or as a slightly decreasing function of neutral pressure, through the C- and T-modes. This is also true of the ion temperature.[1] It is possible that these steep increases in electron and ion temperatures at the T-M transition result from the fluctuation that is caused by the hot electron annuli; therefore, the fluctuation can transfer a large amount of energy from the hot electron annuli to the toroidal plasma. Since this fluctuation is observed through the T-mode, the plasma parameters are expected to have sufficient values to excite the fluctuation even at the beginning of the T-mode. The density profile in the T-mode has a steep gradient just outside the stabilizing layer where the plasma boundary lies, as shown in Fig. 12. Thus, a small part of the hot electron annulus, which also exists just outside the stabilizing layer, is considered to excite the fluctuation. However, the main part of the annulus, which produces the minimum-B field, prevents it from growing (i.e., from penetrating into the inside), depending on both the growth rate of the fluctuation and the amount of the stored energy contained in the annulus. The fluctuation of ~33 kHz seen in Fig. 9 is found to have very interesting spatial distributions, as shown in Fig. 14. The profiles were obtained by the photodetector as a function of viewing angle. This figure shows that the higher frequency fluctuation exists in the outer regions of the plasma. The apparent point is that this fluctuation greatly affects the plasma transport because it is associated with a substantial decrease in $n_e \ell$. However, this fluctuation does not take part in destroying the well-confined plasma configuration, because this fluctuation appears after it is destroyed.

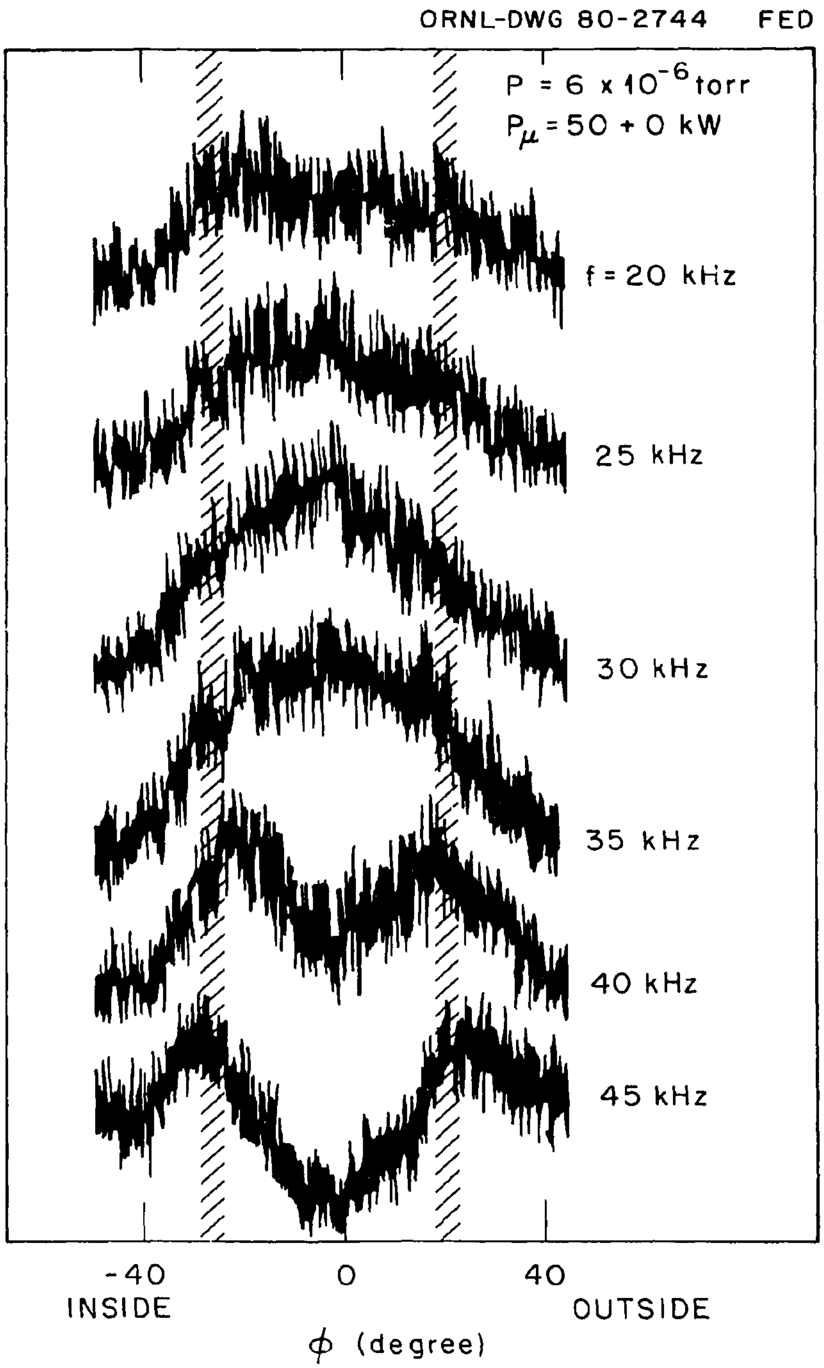

Fig. 14. Spatial profiles of $\tilde{I}$ of ∿33 kHz, observed at the T-M transition, as a function of viewing angle.

The high frequency fluctuations ($\gtrsim$500 kHz) have not been investigated here. Some theories[7] have predicted high frequency instabilities of 10-400 MHz, and these should be studied. However, the high frequency and small amplitude fluctuations[8] should not seriously affect the results obtained in this paper.

4. CONCLUSIONS

This study has shown that the hot electron annulus reduces the toroidal plasma fluctuations and has clarified the stabilizing mechanism in detail. While it could not be shown clearly that the toroidal plasma fluctuations are reduced to an extremely low level or to nearly zero, these conditions will be realized only if the total microwave power is increased with supplementary power to maintain the hot electron annulus. This will produce a strong hot electron annulus and increase the stabilizing layer. The probability of improved fluctuations is recognized in Fig. 4, which shows the large T-mode region (8×10^{-6} torr $< P < 1.6 \times 10^{-5}$ torr) and the low fluctuation level. The fluctuations that grow at the T-M transition were also studied in detail in relation to the plasma transport and were found to have very interesting and important features.

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