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PLASMA DIAGNOSTICS IN TFTR USING EMISSION OF CYCLOTRON RADIATION AT ARBITRARY FREQUENCIES

BY

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PRINCETON
PLASMA PHYSICS
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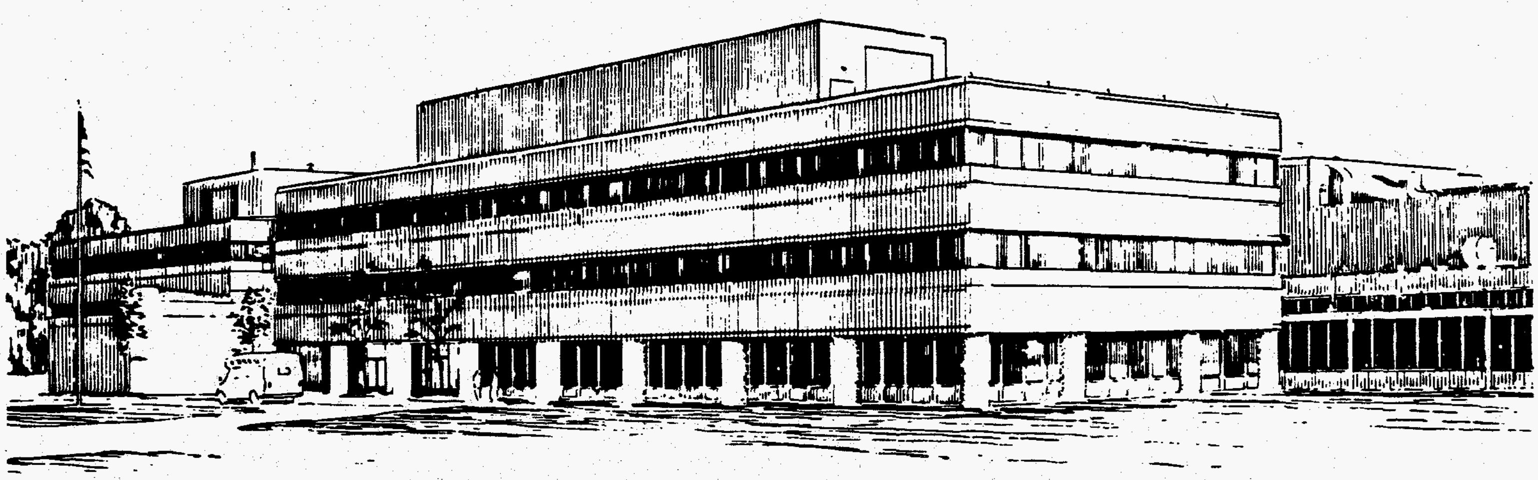

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PLASMA DIAGNOSTICS IN TFTR USING EMISSION OF CYCLOTRON RADIATION AT ARBITRARY FREQUENCIES

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Abstract

Emission of cyclotron radiation at arbitrary wave frequency for diagnostic purposes is discussed. It is shown that the radiation spectrum at arbitrary frequencies is more informative than the first few harmonics and it is suited for diagnosis of superthermal electrons without any "ad hoc" value of the wall reflection coefficient. Thermal radiation from TFTR is investigated and it is shown that the bulk and the tail of the electron momentum distribution during strong neutral beam injection is a Maxwellian with a single temperature in all ranges of electron energies.

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I. INTRODUCTION

Electron cyclotron emission (ECE) near the electron gyrofrequency ω_c and its first harmonic $\omega = 2\omega_c$, is routinely used for electron temperature measurements in tokamak plasmas. The advantage of this method is that in an inhomogeneous magnetic field, the region of emission is very close to the resonance points $\omega = n\omega_c$ and a local value of the temperature is obtained. The disadvantage of the method is that the energy of the emitting electrons is subthermal, i.e., $E < T_e$, and therefore ECE carries no information on the temperature of electrons with energy $E \geq T_e$. Of course for a Maxwellian distribution the two values of the electron temperature are expected to be the same. However, in view of the complexity of the actual plasma, deviations from the Maxwellian distribution can occur in the superthermal ($E > T_e$) range of energies and it is therefore desirable to enhance the validity of the ECE method by extending the range of the electron energy beyond T_e. Another motivation for the present work comes from the long standing systematic disagreement which has been reported between second harmonic ECE and Thomson scattering measurements of T_e on TFTR[1]. An example of this disagreement is shown in Fig. 1. T_e measured by second harmonic ECE (which is sensitive to subthermal electron energies) is up to 25% higher than temperatures measured by Thomson scattering (which is sensitive to electron energies $\sim T_e$). This observation raises the question of whether the electron velocity distribution is non-Maxwellian in high temperature TFTR plasmas. The aim of this paper is to investigate this problem by considering emission at arbitrary frequency. This concept has already been considered for electron temperature diagnostics in hot next step tokamaks[2,3] by using high frequency synchrotron radiation. From the emitted spectrum at arbitrary frequencies, it is possible to explore a wide range of energy of the emitting electrons and therefore to characterize the electron momentum distribution for subthermal, thermal, and superthermal electrons. It is worth noting that in contrast with low harmonic emission, the high frequency spectrum is not very sensitive to the precise value of local magnetic field. By analogy with electron cyclotron emission, the generalized method is here denoted as electron synchrotron emission (ESE).

The plan of this paper is as follows. In Sec. II, we present the theoretical framework of ESE, namely, the structure of the emitted spectrum versus frequency, the localization of the emitted radiation in the ordinary and momentum spaces, and the problem of the effective wall reflection coefficient. In Sec. III, we apply the theory to radiation measurements in TFTR and show the potential of the ESE method on present-day and next step tokamaks. The conclusion is given in Sec. IV.

II. THEORY OF ESE

We consider emission in the mid-plane normal to the magnetic field (x-direction). For an arbitrary isotropic momentum distribution f(p), the X-mode spectrum is given by

$$I(\omega) = \int_{-a}^{a} dx\eta(\omega,x)\exp[-\phi(\omega;x)] / \{1 - R_f(\omega)\exp[-\phi(\omega;-a)]\} \tag{1}$$

where a is the plasma radius,

$$\phi(\omega;x) = \int_{x}^{a} dy\alpha(\omega,y),$$

$R_f(\omega)$ is the effective reflection coefficient, and $\eta(\omega,x)$, $\alpha(\omega,x)$ are the emission and absorption coefficients, respectively. Following Ref 4, for $\omega \geq 2\omega_c$

$$\alpha(\omega,x) = \left(\frac{\omega}{cN_r}\right)\left[\varepsilon''_{22} + 2\varepsilon''_{12}\left(\frac{\varepsilon^0_{12}}{\varepsilon^0_{11}}\right) - \varepsilon''_{11}\left(\frac{\varepsilon^0_{12}}{\varepsilon^0_{11}}\right)^2\right], \tag{2}$$

where ε^o_{ij} and N_r are the dielectric tensor and the refractive index in the cold plasma approximation, and

$$\varepsilon''_{jl} = -\left(\frac{2\pi\omega_p}{\omega N_r}\right)^2 mc \sum_{n>n_o} \varepsilon''_{jl,n} Y_n^3 \left(\frac{Df}{Dp}\right)_{\gamma=Y_n}, \gamma = (1 + p^2/m^2c^2)^{1/2}.$$

The emission coefficient is given by the same expression as $\alpha(\omega,x)$ [Eq. (2)] but

$$\varepsilon^{\cdot}_{jl} = \left(\frac{2\pi\omega_p}{N_r}\right)^2 \frac{mc^2}{8\pi^3c^2} \sum_{n>n_o} \varepsilon^{\cdot}_{jl,n} Y_n^2 \left(Y_n^2 - 1\right)^{1/2} [f(p)]_{\gamma=Y_n},$$

where

$$\varepsilon''_{11,n} = \frac{\pi}{2\nu} g_n J^2_{n+1/2}(\nu)$$

$$\varepsilon''_{12,n} = -i\varepsilon''_{11,n} + i\frac{\pi}{2n} g_n J_{n+1/2}(v) J_{n+3/2}(v),$$

$$\varepsilon''_{22,n} = \varepsilon''_{11,n} + \frac{\pi}{4n^2(n+2)} g_n \{v(n+3)\left[J^2_{n+3/2}(v) - J^2_{n+1/2}(v)\right]$$

$$-(2n^2 - n - 9) J_{n+1/2}(v) J_{n+3/2}(v)\},$$

$$\varepsilon''_{13,n} = \varepsilon''_{23,n} = 0, \varepsilon''_{33,n} = \frac{s^2}{2}\left[\varepsilon''_{11,n} - \left(\frac{\pi}{2v}\right) g_n J_{n-1/2}(v) J_{n+3/2}(v)\right],$$

$$v = N_r \frac{\omega}{\omega_c}\left(Y_n^2 - 1\right)^{1/2}, s = N_r\left(\frac{\omega}{n\omega_c}\right)\left(Y_n^2 - 1\right)^{1/2}, Y_n = n\omega_c / \omega,$$

$$n_o = \omega / \omega_c, g_n = (2n+1)!!/2^n n!.$$

For a Maxwellian distribution

$$f(p) = f_m = \frac{\mu}{4\pi K_2(\mu)} \exp(-\mu\gamma),$$

$\mu = mc^2/T_e$, K_2 is the McDonald function, and $\eta(\omega) = (\omega^2 T_e / 8\pi^3 c^2)\alpha(\omega)$.

The radiation spectrum for a Maxwellian distribution represents the reference spectrum. By comparing the actual experimental spectrum with that of a Maxwellian distribution, the existence of non-Maxwellian features can be revealed. The thermal spectrum in general displays a number of maxima and minima at $\omega = \omega_i^*$ and is formed by two parts, the range of frequencies where the plasma is optically thick $(\exp[-\phi(\omega;-a)] \approx 0)$ and where the plasma is optically thin $(\exp[-\phi(\omega;-a)] \approx 1)$. In the optically thick range of frequencies, $I(\omega)$ is independent of R_f. The wall reflection coefficient is in general unknown, except in the case in which a radiation stopper[5] or a highly reflecting mirror[6] are installed in the viewing direction, and many authors have arbitrarily chosen "ad hoc" values of R_f to fit the experimental results. This arbitrary choice of R_f can be avoided using the following procedure[3]. At the maxima and minima, $dI(\omega)/d\omega = 0$, thus, assuming that $R_f(\omega)$ is a slowly varying function of ω, i.e.,

$$\left|dR_f(\omega)/R_f d\omega\right| << \left|d\exp(-\phi)/\exp(-\phi)d\omega\right|, \tag{3}$$

from Eq. (1), we obtain

$$R_f(\omega_i^*)\exp\left[-\phi\left(\omega_i^*;-a\right)\right] = \left[\frac{dV/d\omega}{dV/d\omega + V(\omega)d\phi(\omega;-a)/d\omega}\right]_{\omega=\omega_i^*}, \tag{4}$$

$$I(\omega_i^*) = \frac{V(\omega_i^*)}{1-\left[\frac{dV/d\omega}{dV/d\omega + V(\omega)d\phi(\omega;-a)/d\omega}\right]_{\omega=\omega_i^*}} \tag{5}$$

where

$$V(\omega) = \int_{-a}^{a} dx\eta(\omega,x)\exp[-\phi(\omega;x)].$$

Equation (5) relates the experimental values of $I(\omega_i^*)$ with the momentum distribution without any assumption on the value of R_f. If the electron momentum distribution f(p) contains parameters characterizing the deviation from a Maxwellian distribution they can in principle be determined using Eq. (5). Note that the inequality (3) is easily satisfied since in the optically thin range of frequencies $\exp(-\phi)$ tends rapidly to unity for increasing ω. We now consider the spatial distribution of the radiation source. This is given by the integrand of the numerator in Eq. (1). For a Maxwellian distribution the source of radiation is

$$G(\omega) = \alpha(\omega,x)\exp[-\phi(\omega;x)]. \tag{6}$$

We first consider emission at $\omega = 2\omega_c$. In this case

$$\alpha(\omega,x) = \frac{\pi\omega\omega_p^2\mu^2 N_r}{30c\omega_c^2 K_2(\mu)\exp(\mu)}\left[\left(\frac{2\omega_c}{\omega}\right)^2 - 1\right]^{5/2}\exp\left[-\mu\left(\frac{2\omega_c}{\omega}-1\right)\right],$$

$$= \frac{4\pi^{1/2} N_r \omega \omega_p^2}{15 c \omega_c^2} y^{5/2} \exp(-y), \qquad y = \mu \frac{x}{R_o}$$

where R_o is the tokamak major radius. Numerical computations of $G(\omega,x)$ show that the maximum of $G(\omega,x)$ occurs for $y<1$ and we then solve the equation $dG/dx = 0$ for $y<1$ and we obtain

$$\exp(-y) = \left(\frac{5}{2y} - 1\right) y^{-5/2} \left(\frac{\mu}{R_o} \frac{15 c \omega_c^2}{4\pi^{1/2} N_r \omega \omega_p^2}\right) = 1,$$

hence

$$y_m = \mu \frac{x_m}{R_o} = \left(\frac{\mu}{R_o} \frac{75 c \omega_c^2}{8\pi^{1/2} \omega \omega_p^2 N_r}\right)^{2/7}. \qquad (7)$$

For T_e = 10keV, $n_e = 10^{20}$ m^{-3}, B_o = 5T, R_o = 2.5m, we obtain $y_m = 1/2$, x_m = 2.5 cm. It appears that $G(\omega,x)$ is a δ-like function near $x = 0$ where $\omega = 2\omega_c$. The energy of the predominant emitting electron is given by

$$E = mc^2 \left(\frac{2\omega_c}{\omega} - 1\right) = mc^2 \left(\frac{2}{\omega / \omega_c(x_m)} - 1\right) = T_e / 2.$$

For arbitrary frequencies, $G(\omega,x)$ is computed numerically. Now the energies of the emitting electrons are given by

$$E_n = mc^2 \left(\frac{n}{n_o} - 1\right), n > n_o,$$

where n is an integer greater than n_o, but n_o is not necessarily an integer and depends on x, $n_o = \omega/\omega_c(x)$. In general, a few values of $n>n_o$ are really relevant.

III. ESE ON TFTR

The theory of Sec. II is now applied to emission at arbitrary frequencies for a R_o = 2.52 m, a_o = 0.87 m TFTR plasma, heated by approximately 31 MW of neutral beam injection. This plasma (shot#76771) is the one for which the temperature profile comparison was made in Fig. 1, it had an axial toroidal field of 5.08 T and a plasma current of 2.5 MA. The electron density profile was measured by multi-chord far-infrared interferometry and the electron temperature profile by second harmonic ECE, assuming a Maxwellian momentum distribution. Electron density and temperature profiles, flux surface mapped to major radius at 4 s, were used in the analysis and these profiles are shown in Fig. 2. As shown before, the measured electron temperature refers to subthermal electrons. We now wish to verify that the assumption of a Maxwellian distribution holds for arbitrary values of the electron energy $E > T_e$ using ESE. Shown in Fig. 3 (a, b) are the experimental (full) and theoretical (dashed) spectra and $t_r(f) = \exp[-\phi(\omega;-a)]$ versus $f = \omega/2\pi$ for the parameters of Fig. 2 (a, b). It appears from Fig. 3 (b) that for $f \leq 400$ GH_z, the emitted spectrum is optically thick. For f > 400GHz, $I(\omega)$ becomes optically thin and the minimum at f = 425 GHz and the maximum at f = 500 GHz are affected by wall reflection. At f = 500 GHz, the value of R_f obtained from Eq. (3) is $R_f = 0.7$. Since R_f is a slowly varying function of f near f = 500 GHz, the same value of R_f is used for f in the range 425 - 540 GHz. A smooth variation of the emitted spectrum with respect f is a signature of a slowly varying reflection coefficient. So far, the single temperature Maxwellian is a trial function. The following discussion will show that it is the only acceptable function to fit the full spectrum. We first discuss the energy selection of the emitting electrons at a given frequency. Shown in Figs. 4 are the source function $G(\omega,x)$ versus x for several values of f. Figure 4 (a) represents the source function for $f = 2f_c$. The value x_c where $f = 2f_c(x_c)$ is $x_c/a = -0.13$. The maximum of G is at $x = x_m = -0.15a$ = -13cm in agreement with Eq. (7). For increasing frequency, the contribution of higher harmonics gradually increases. It appears that $G(\omega,x)$ is a sensitive function of f and an appreciable change in the location of the radiation source will take place for a small variation of f. The energy of the emitting electrons follows the same pattern and therefore the radiation emitted in a small range of frequencies is generated by electrons in a wide range of energies. Shown in Table I are the relevant energies for the first relevant value of $n>n_o$ corresponding to the spatial distribution of the radiation source of Fig. 4 (a,..., e). For higher values of n, the contribution of the relevant electrons rapidly decreases since in general the corresponding resonant energies lie in the far tail of the electron distribution. In Table I, for each frequency we present the resonant energy corresponding to the maximum of $G(\omega,x)$, i.e., $E(x_m)$ and the values of the energies at the half-width Δx of $G(\omega,x)$, here denoted $E(x_f)$ where $x_f = x_m \pm \Delta x$, normalized at the corresponding temperature $T(x_m)$ and $T(x_f)$, respectively. It appears that, in contrast with second harmonic emission, ESE results from the contribution of a wide spectrum of energy from subthermal to superthermal. ESE is much more informative than second harmonic with respect to the energy dependence of the electron momentum distribution. For instance, for f = 280 GHz, the source of radiation is located near the plasma axis where second harmonic allows the determination of the central temperature of subthermal electrons. Emission at f = 480 - 520 GHz on the other hand, in addition to the subthermal temperature yields information on the superthermal momentum slope of the electron distribution. In our case, we have found that the experimental spectrum for any frequency agrees satisfactorily with the theoretical spectrum computed with a Maxwellian distribution with the temperature measured by second harmonic emission, that is with the bulk temperature and we conclude that subthermal and superthermal electrons are well described by a Maxwellian with the same temperature. The consistency of our results is not of course an absolute proof that a Maxwellian with a single temperature for all electron energies is the only solution. One can in principle imagine that there exists a variety of non-Maxwellian distributions which might be consistent with the experimental spectrum. However, the good agreement between theory and experiments obtained with the familiar single temperature Maxwellian represents an attractive and convincing choice. A Maxwellian-like distribution with two temperatures, a bulk temperature T_b and a tail temperature T_t is described by[7]

$$f = A\exp\{-\gamma_o(\mu_b-\mu_t)H(\gamma-\gamma_o)-\gamma[\mu_b-(\mu_b-\mu_t)H(\gamma-\gamma_o)]\}, \qquad (8)$$

where A is the normalization factor, $\mu_b = mc^2/T_b$, $\mu_t = mc^2/T_b$ and H(x) is the Heaviside function. Equation (8) represents a Maxwellian at temperature T_b for $\gamma<\gamma_o$ and a Maxwellian at temperature T_t for $\gamma>\gamma_o$. As shown in Ref. 7, a small deviation of T_t/T_b from unity at energy $mc^2(\gamma_o-1)$ = (2-3)T_b will result in an appreciable change in the emission and absorption coefficients and therefore on the emitted intensity. In the case of Fig. 3, the theoretical spectrum will fit satisfactorily the experimental one for all frequencies only for $\gamma_o \rightarrow \infty$.

We now consider the effect of using the Thomson scattering temperature profile obtained from Fig. 1. This lowers the maximum value of T_e from 11.5 keV to 8.5 keV. The Thomson scattering measured profile begins to deviate from ECE measured profile at ± 50cm from the magnetic axis at R = 2.7m. Shown in Fig. 5 are the experimental spectrum (full) and the computed spectrum (dashed) with the new temperature profile.. In the range of frequencies considered $t_r(f)\equiv o$ and the effect of the reflection coefficient can be neglected. It appears that the positions of the maxima and minima coincide with the experimental ECE spectrum but the magnitude of the computed radiation differs significantly (Fig. 5) and therefore we conclude that the experimental spectrum is consistent with the temperature profile of Fig. 2(b) for both subthermal and superthermal ($E>T_e$) electrons.

IV. CONCLUSION

We have presented a new method for investigating the electron momentum distribution in tokamak plasmas based on electron cyclotron emission at arbitrary frequencies. This is a natural generalization of the familiar method which utilizes low harmonic emission and it is aimed at obtaining information on the energy distribution of the superthermal electrons. Low harmonic radiation is emitted by localized electrons both in ordinary space and in momentum space. The ordinary space localization is simply given by the relation $\omega = n\omega_c(x)$ and the corresponding resonant energy is subthermal ($E \leq T_e$). Emission at high frequencies ($\omega > 2\omega_c$) is also somewhat localized in space but the rather broad spatial and momentum profiles of the radiation source depend on the electron momentum distribution. The high frequency spectrum is therefore more involved than that of low harmonics, but it turns out to be much more informative. The emitted spectrum has an optically thick range of frequencies where the wall reflection coefficient plays no role. On the other hand, the optically thin spectrum is affected by wall reflection. We avoid the arbitrary choice of the value of the reflection coefficient by investigating emission near the maxima and minima of the radiation spectrum $I(\omega)$ using the property that $dI/d\omega = 0$. This general procedure allows us to identify the existence of non-thermal features for electron energies resonating with the frequency where $I(\omega)$ is maximum (minimum). We have applied the method to emission from TFTR during neutral beam injection to verify that the bulk temperature ($E \leq T_e$) obtained from second harmonic emission is the same as that of superthermal electrons ($E > T_e$). The result obtained is consistent with the assumption that the electron momentum distribution is a Maxwellian with a single temperature for all electron energies. In conclusion, we wish to point out that spectra similar to that of TFTR are expected on next step tokamaks operating at high central temperatures, $T_{eo} \geq 20$ keV. Radiation spectra away from the plasma core will be similar to that considered here and the method presented in this paper will then be applicable to obtain information on the electron distribution at arbitrary electron energy.

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Figure Captions

Fig. 1 Electron temperature profiles versus major radius measured by ECE (solid line) and Thomson scattering (•) measured for a TFTR neutral-beam-heated, supershot, plasma.

Fig. 2 Electron density (a) and temperature (b) profiles versus major radius used to model the ECE spectrum of the plasma shown in Fig. 1. The electron density and temperature profiles were measured by multi-channel, far-infrared, interferometry and ECE, respectively.

Fig. 3 Radiation temperature (T_{rad}) (a) and optical depth ($t_r(f)$) (b) vs frequency for the parameters of Fig. 2.

Fig. 4 G(f,x) vs x for several values of f, a) f = 280 GHz, b) f = 380 GHz, c) f = 390 GHz, d) f = 410 GHz, e) f = 500 GHz.

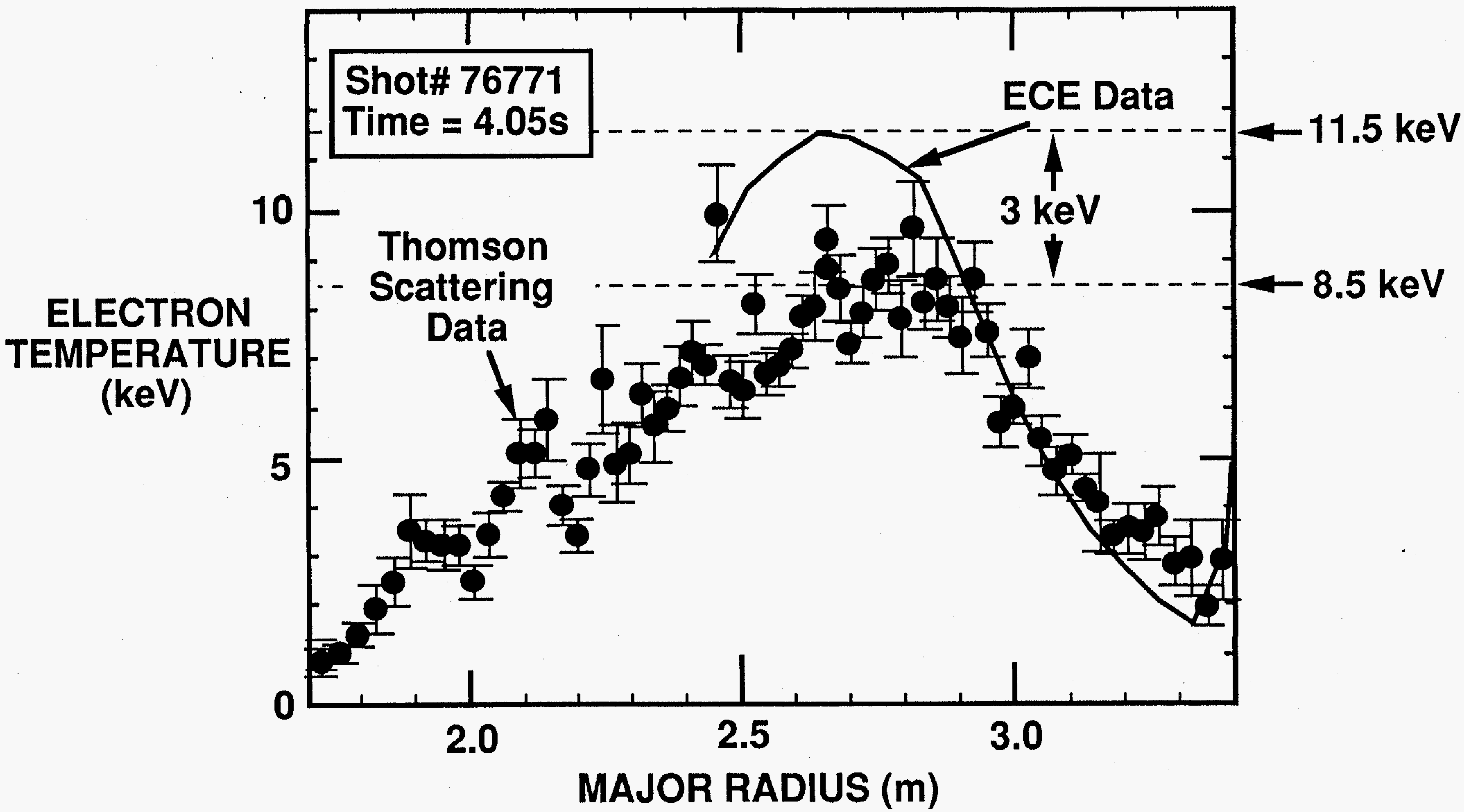
Fig. 5 T_{rad} (a) and t_r (f) (b) frequency using the temperature profile measured by Thomson scattering shown in Fig. 1.

Table Captions

Table I Resonant energies $E(x_m)$ and $E(x_m \pm \Delta x)$ for the conditions of Fig. 4.

f (GHz)	x_m (cm)	Δx (cm)	$E(x_m)/T_e(x_m)$	$E(x_m-\Delta x)/T_e(x_m-\Delta x)$	$E(x_m+\Delta x)/T_e(x_m+\Delta x)$
280	-13.0	1.06	0.528	0.750	0.312
300	-28.0	1.04	0.430	0.746	0.135
380	7.14	4.22	1.40	2.16	0.664
390	-0.290	4.04	1.53	2.30	0.796
410	-13.0	3.72	1.70	2.59	0.919
480	11.0	10.1	3.36	5.18	1.72
500	0.800	8.47	3.19	4.94	1.66
520	-8.36	7.50	3.14	5.01	1.64

Table I



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ECE Data
11.5 keV
3 keV
8.5 keV
Thomson
Scattering
Data
ELECTRON
TEMPERATURE
(keV)
10
5
0
2.0
2.5
3.0
MAJOR RADIUS (m)

Fig. 1

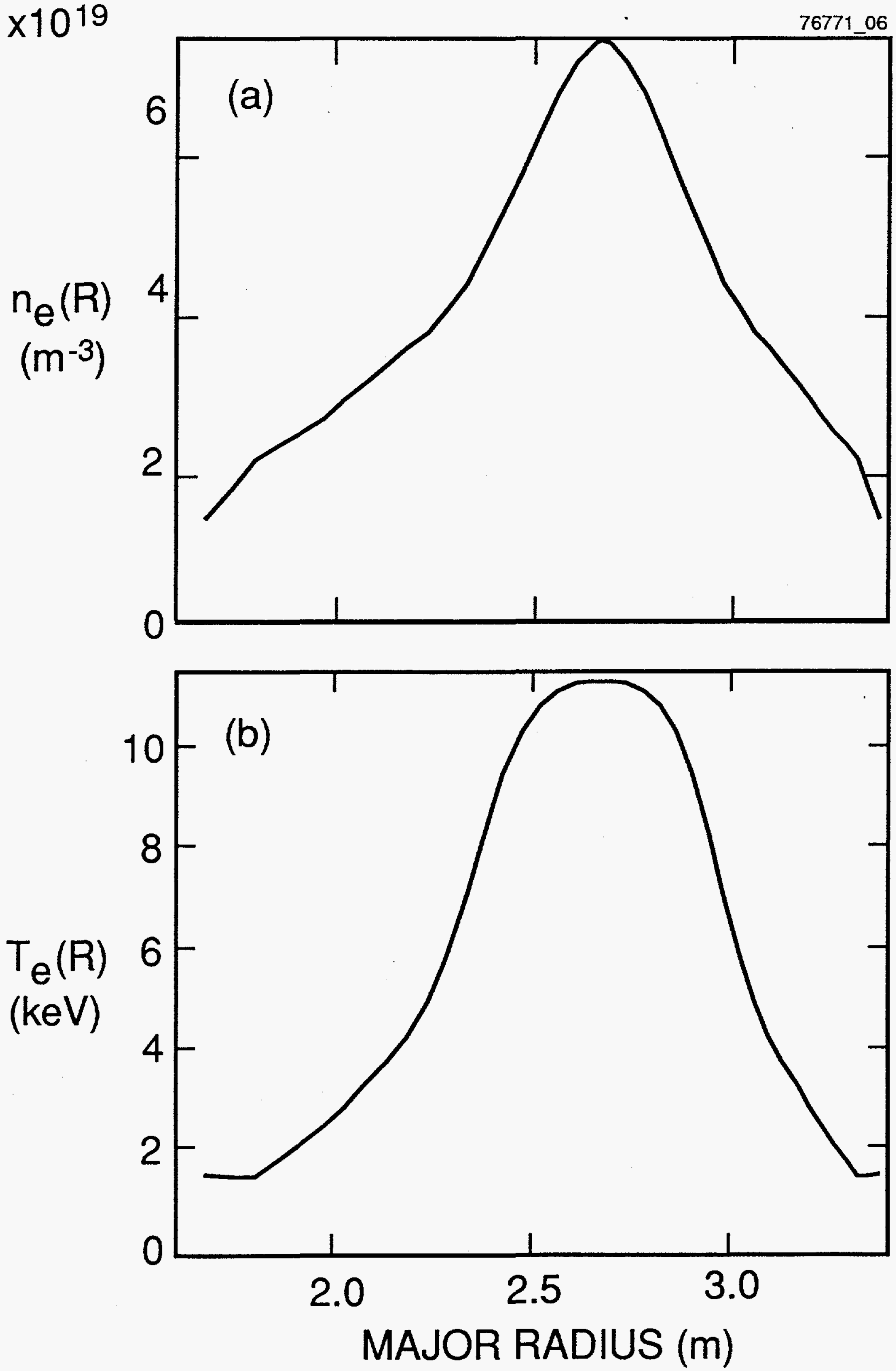
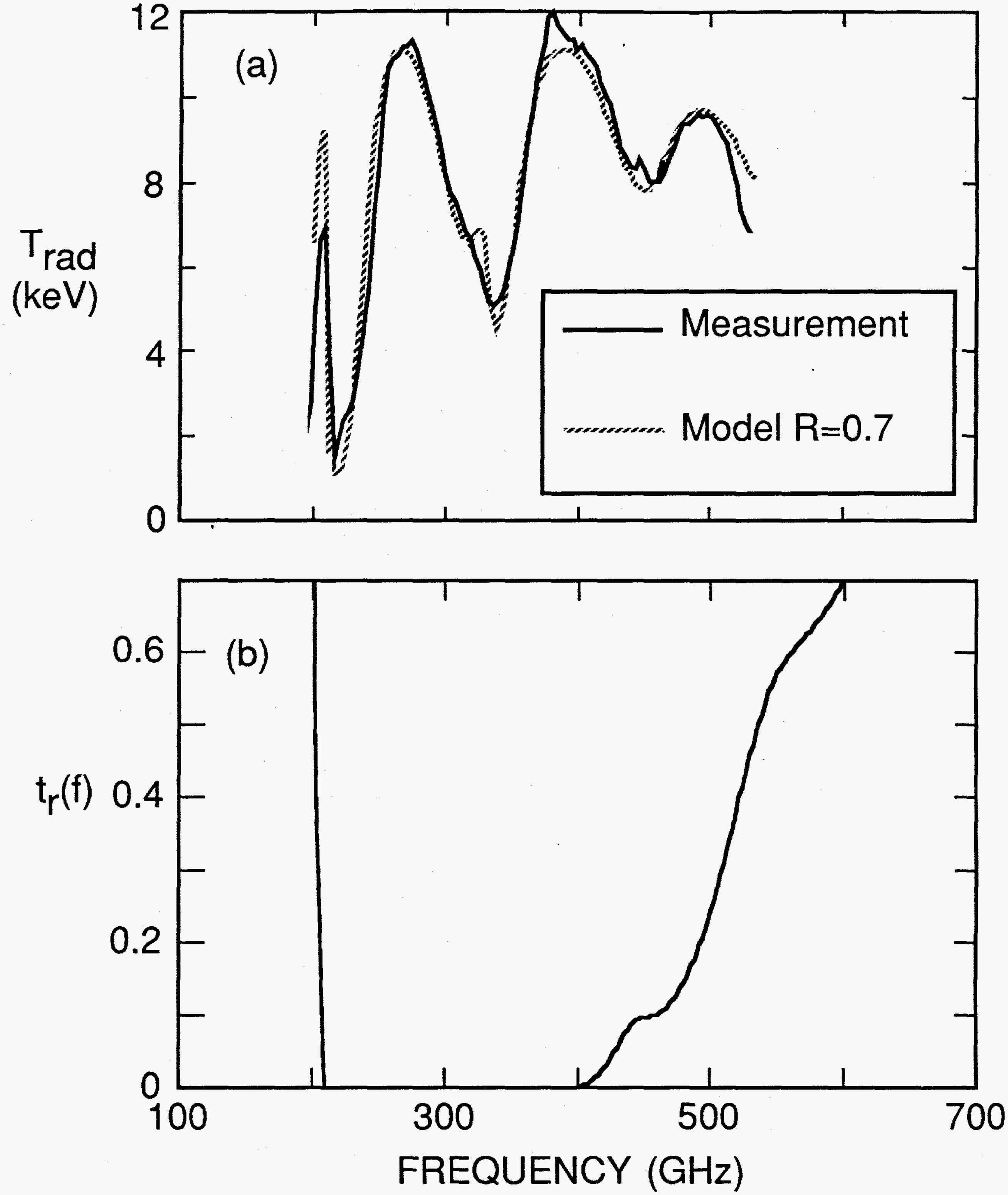

x10^19
76771_06
(a)
6
4
2
0
n_e(R)
(m^-3)
(b)
10
8
6
4
2
0
T_e(R)
(keV)
2.0
2.5
3.0
MAJOR RADIUS (m)

Fig. 2



12
8
4
0
(a)
T_{rad} (keV)
Measurement
Model R=0.7
0.6
0.4
0.2
0
(b)
$t_r(f)$
100
300
500
700
FREQUENCY (GHz)

Fig. 3

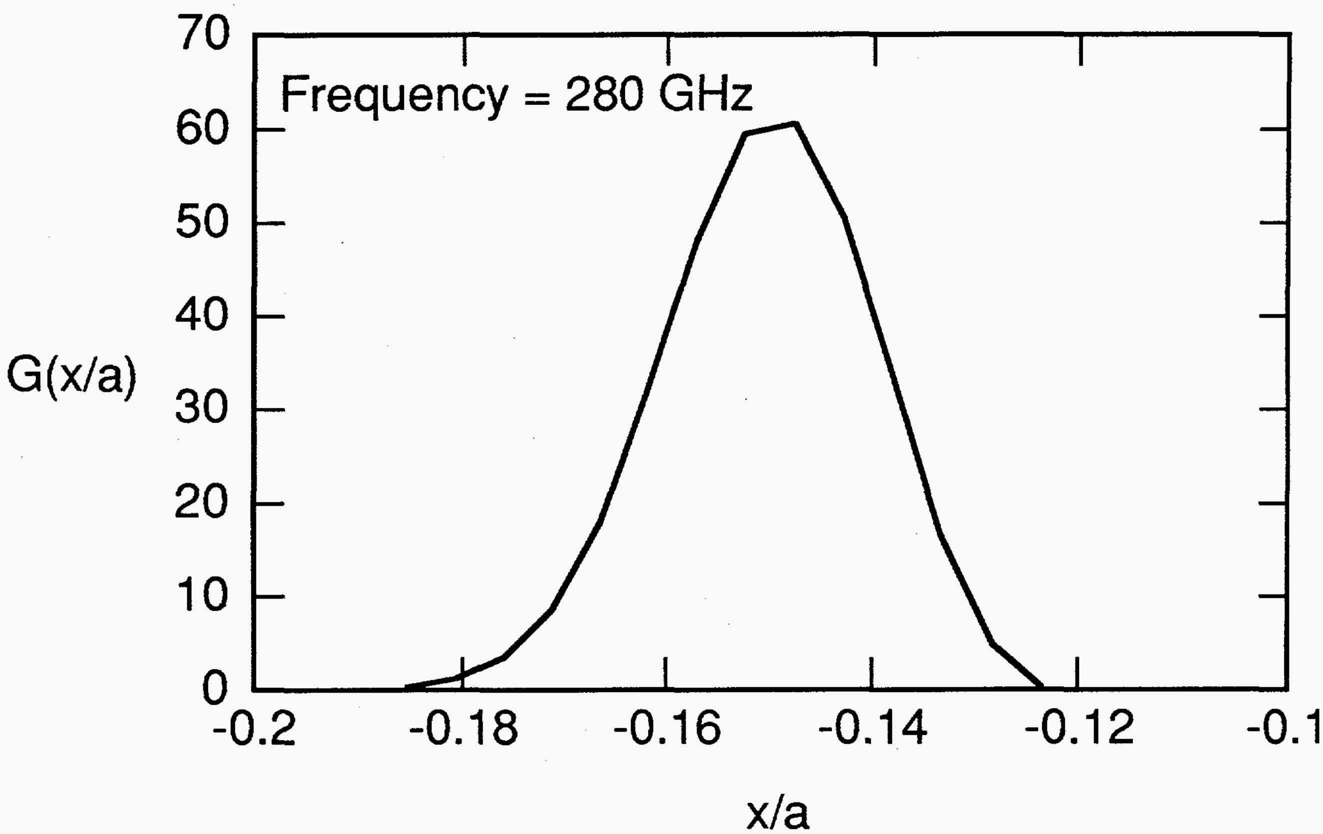
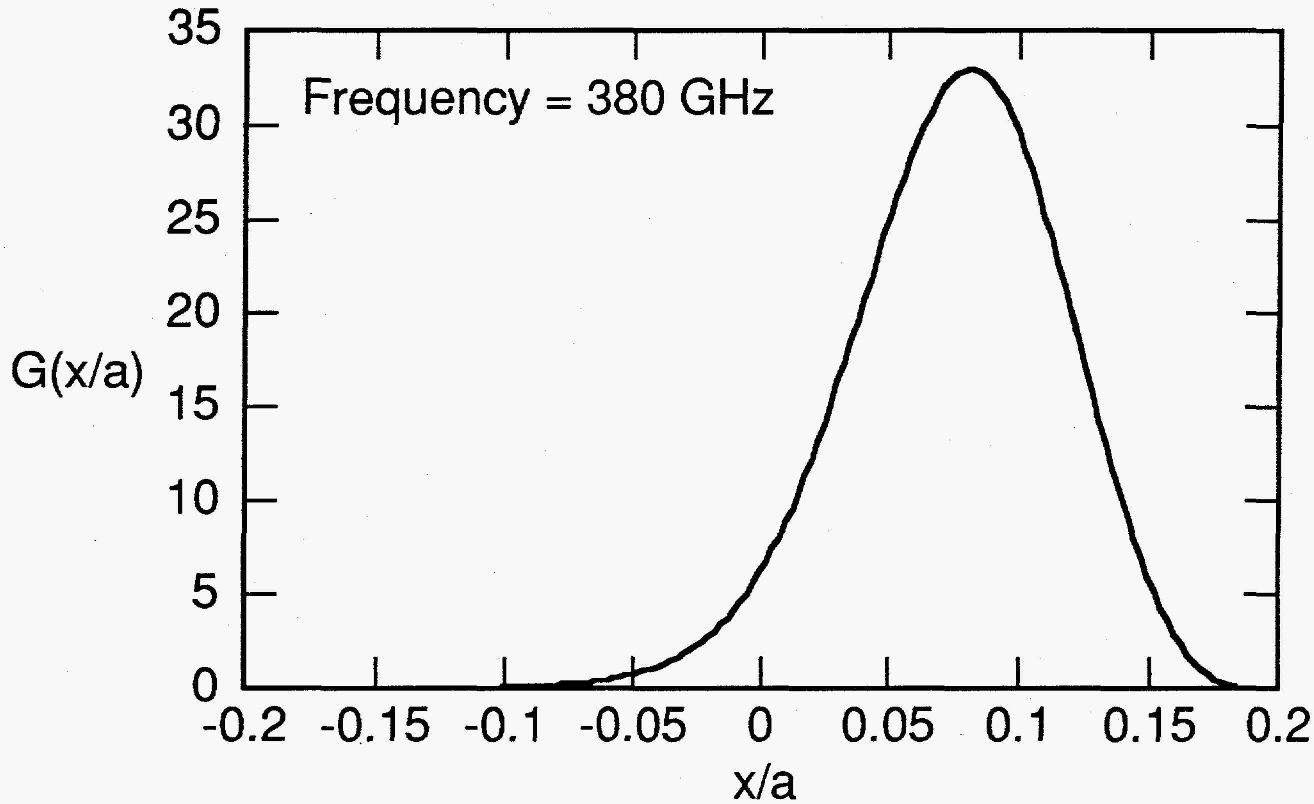

Frequency = 280 GHz
G(x/a)
x/a
0
10
20
30
40
50
60
70
-0.2
-0.18
-0.16
-0.14
-0.12
-0.1

Fig. 4(a)



Frequency = 380 GHz
G(x/a)
x/a
35
30
25
20
15
10
5
0
-0.2
-0.15
-0.1
-0.05
0
0.05
0.1
0.15
0.2

Fig. 4(b)

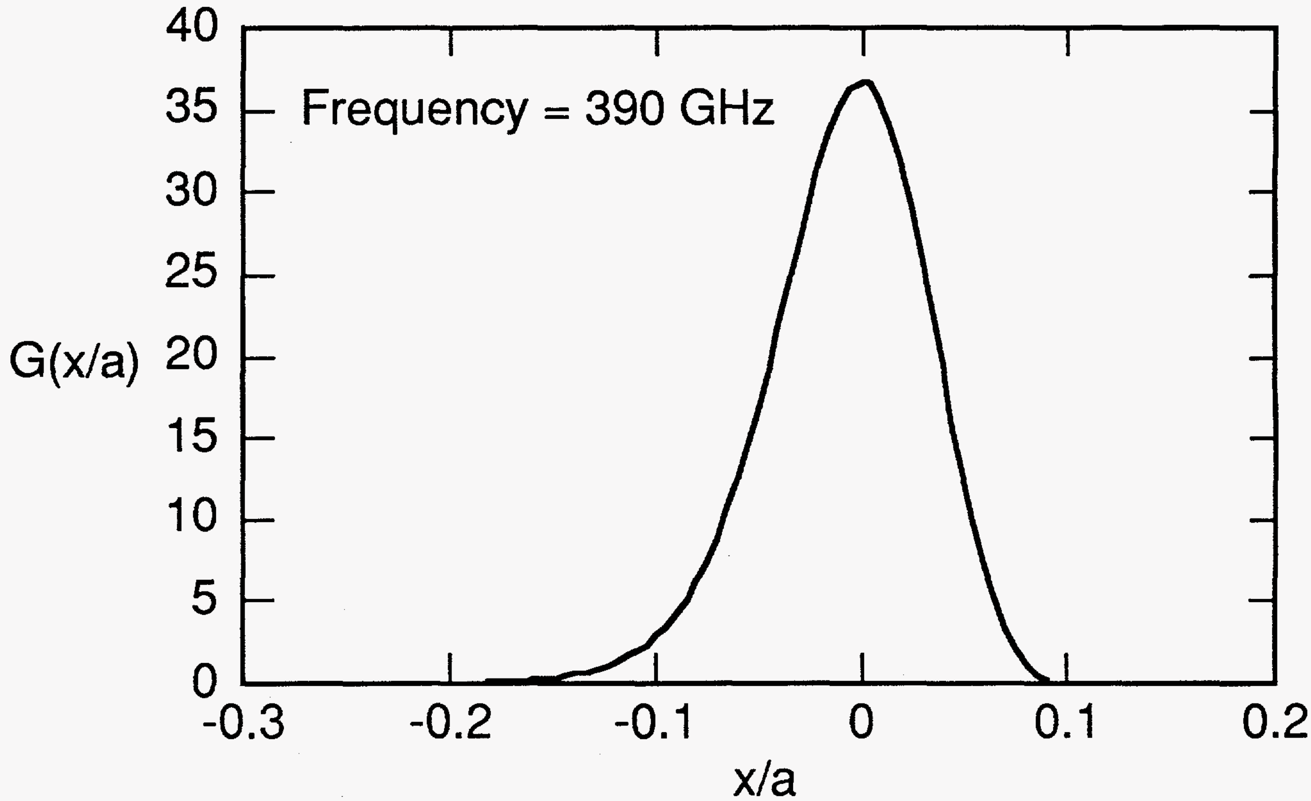
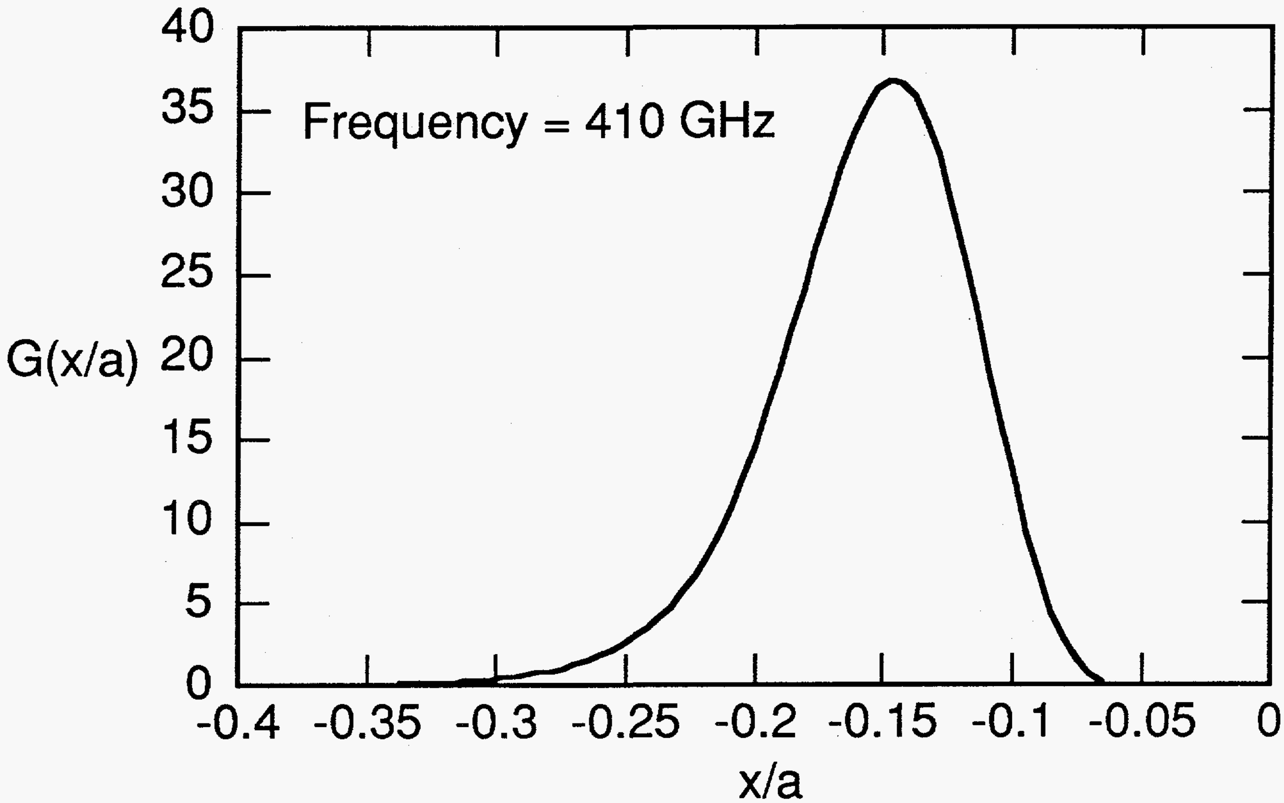


Fig. 4(c)


Frequency = 410 GHz
G(x/a)
x/a
40
35
30
25
20
15
10
5
0
-0.4
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-0.3
-0.25
-0.2
-0.15
-0.1
-0.05
0

Fig. 4(d)

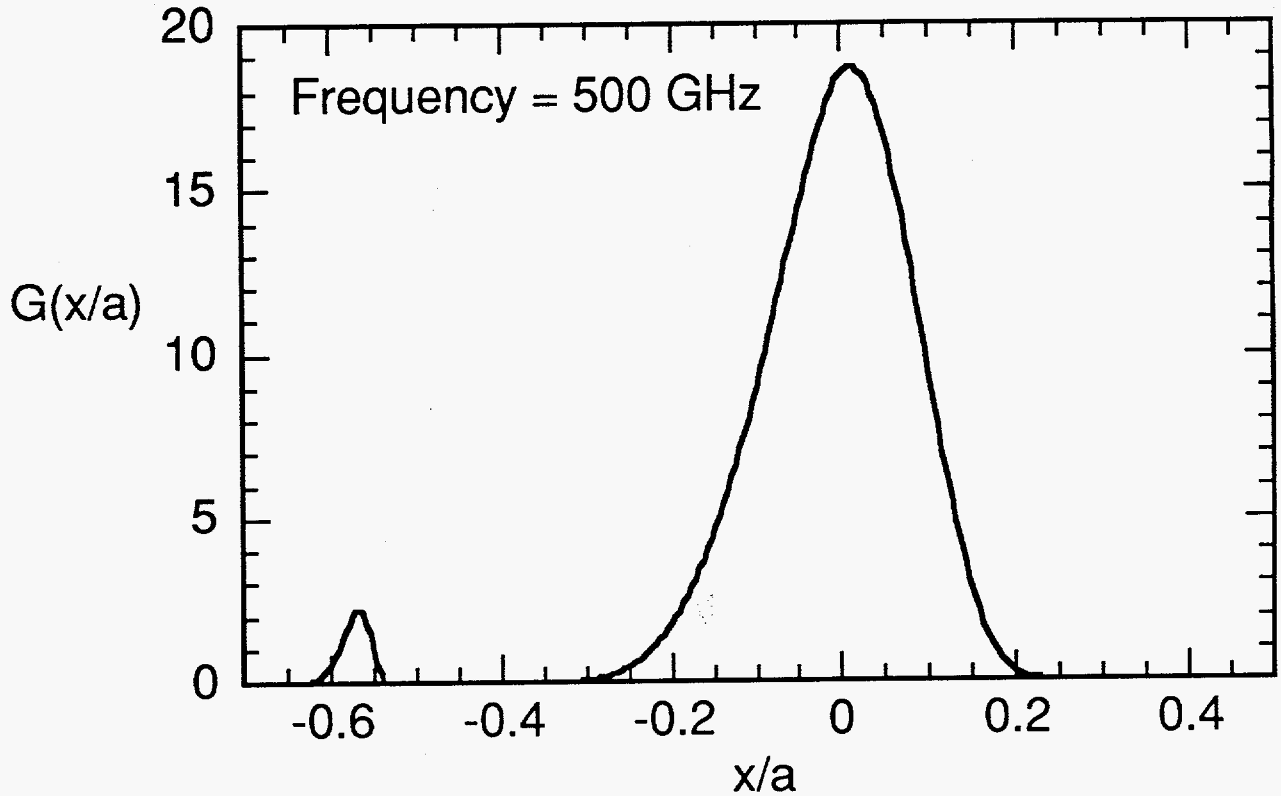
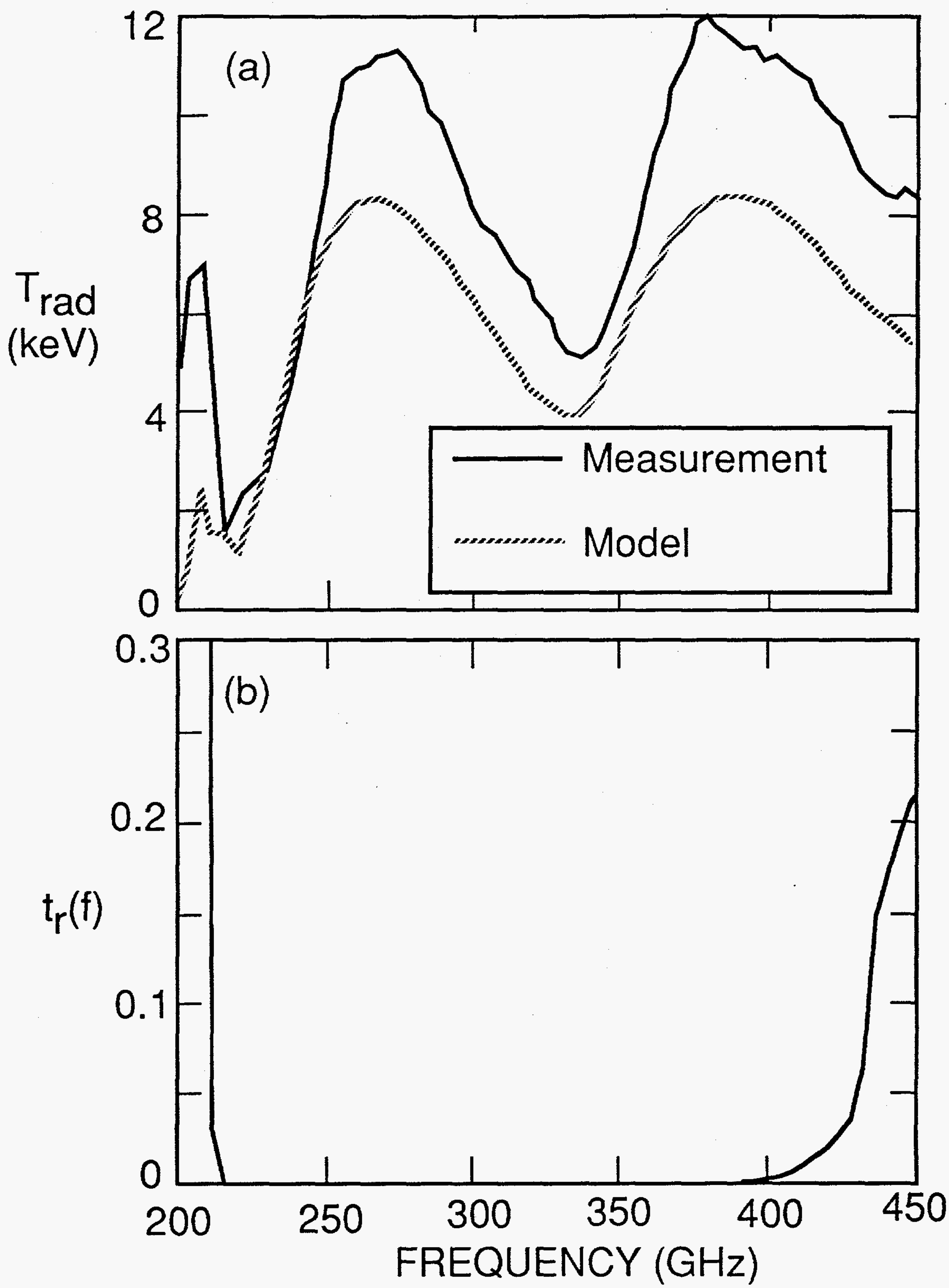


Fig. 4(e)



12
8
4
0
(a)
Trad
(keV)
Measurement
Model
0.3
0.2
0.1
0
(b)
tr(f)
200
250
300
350
400
450
FREQUENCY (GHz)

Fig. 5

EXTERNAL DISTRIBUTION IN ADDITION TO UC-420

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