# Asymmetric electron cyclotron emission from superthermal electrons in the TFR tokamak

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Measurements of electron cyclotron radiation near the fundamental frequency on the high- and low-magnetic-field side of the TFR tokamak are reported. In the presence of a superthermal electron component the measured intensities are asymmetric. A theoretical explanation based on the combined effects of the electron relativistic mass variation and the $1/R$ variation of the tokamak magnetic field is discussed.

Emission of nonthermal cyclotron radiation from toroidal plasmas in the presence of fast superthermal electrons has often been observed.[1–3] Of special interest is the study of the emitted radiation from tokamak plasma with a small mildly superthermal component of electrons since the situation can commonly occur in present and future tokamaks during ohmic heating in weakly collisional plasmas or with rf heating and current generation via electron Landau damping. In this case for a given frequency the radiation intensities towards the high- and low-magnetic-field sides of the torus can be different. This asymmetry is predicted by the theory[4,5] and results from the combination of two effects, namely, the relativistic mass variation and the magnetic field inhomogeneity.

In this Communication we report the first observation of the asymmetric emission in the TFR tokamak. The radiated power at the electron cyclotron frequency has been collected by two high-gain microwave horns located opposite one another in the equatorial plane along the major radius. The external horn (30-dB gain) is oriented to receive ordinary polarized waves only, whereas a circular horn (22-dB gain) positioned in the high-magnetic-field side (internal side) collects both the ordinary and extraordinary (named $O$ and $X$, respectively) polarized waves.

The collection angle $2\Delta\theta$ is different for the two horns. For the external horn $\Delta\theta = 3°$ whereas for the internal we have $\Delta\theta = 6° 30'$. The spatial resolution $d$ in the direction parallel to the toroidal magnetic field is, however, the same in the two cases since the radius of the external horn with respect to the plasma axis is twice that of the internal one; i.e., $d = 5.5$ cm. Each horn is followed by a similar superheterodyne receiver tuned by the same local oscillator. A microwave polarimeter precedes the internal receiver to select the polarization to be measured.

For a fixed value of the magnetic field the emission profile is obtained on a shot to shot basis by changing the frequency of the local oscillator. The frequency resolution for the two receivers is set by the if amplifier bandwidth $\Delta f = 500$ MHz which gives a spatial resolution along the major radius $\Delta R \simeq 1$ cm.

By programming the gas admission (hydrogen), the time evolution of the electron density as shown in Fig. 2(c) is obtained. The high-density regime $[n(0) \simeq 10^{14}\ \text{cm}^{-3}]$ is achieved at $t = 150$ ms, and in Fig. 1 we present the corresponding temperature profile obtained by the radiated power in the $O$ mode from the outside of the torus. For comparison the temperature profile $T_e(r)$ obtained from Thomson scattering along a vertical diameter is also shown. As found previously[6] the emission profile is in a good agreement with Thomson scattering as expected for blackbody emission by a thermal plasma (region where the optical thickness $\tau > 1$). For $r > 13$ cm Thomson scattering measurements are not available

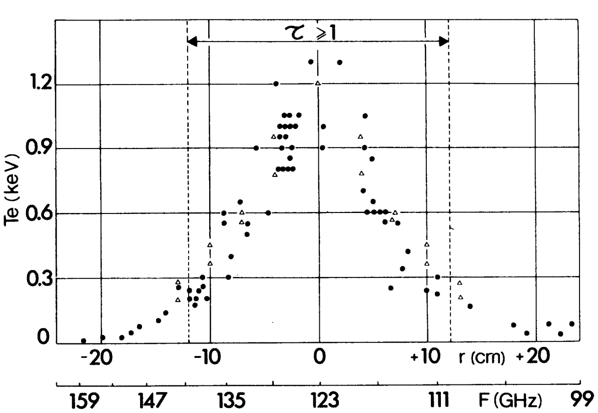


FIG. 1. The radiation temperature at the outside receiver in the $O$ mode as function of frequency (●) compared with the $T_e$ vertical profile by Thomson scattering (Δ) at $t = 150$ ms. The frequency-space correspondence is obtained by assuming $F = F_{ce0}R/(R \pm r)$, $F_{ce0} = 123$ GHz is the electron cyclotron frequency at the center, $R = 98$ cm. The receiver was previously calibrated by a standard noise tube.

but the smooth behavior of the emission going to a tens of eV, which is within the error bars 10–20 eV, suggests that the emission remains that of a blackbody. This is generally explained by the high reflectivity of the vacuum vessel, bringing the emission to the blackbody level. In this high-density regime blackbody emission yielding the local temperature has also been found for both the $O$ and $X$ mode[7] when viewed from the inside of the torus. Thus it is clear that at $t = 150$ ms the cyclotron emission from the plasma is thermal emission.

The emitted power measured by the outside horn ($O$ mode) and by the inside horn ($X$ mode) as a function of time for a frequency corresponding to a radial position $r = +6.5$ cm is shown in Figs. 2(a) and 2(b), respectively. It is clear that the rate of increase in the radiated power is larger for the inside receiver than for the outside one. Definitely an asymmetry with respect to the direction of propagation of the wave builds up as the density decreases.

In Fig. 3(a) the radiation temperature profile measured from the inside in the $X$ mode is shown at the time $t = 380$ ms corresponding to the end of the current plateau. This profile has to be compared with the corresponding $O$ mode radiation temperature profile measured by the outside receiver [Fig. 3(b)]. In both cases Thomson scattering $T_e$ profile is also shown. Enhanced emission with respect to the thermal level is observed from the inside. Subtantial emission is also measured for frequencies corresponding to the region in the limiter shadow (positive side) where an apparent temperature of >200 eV is obtained. The situation is markedly different for the $O$ mode measured from the outside where the enhanced emission is limited to the border region $r \geqslant 14$ cm where $\tau < 1$. The increase of the ordinary mode at the high-field plasma edge is not at present understood. A possible explanation is the overlaping with the second harmonic due to a large relativistic mass variation of fast electrons. For the $X$ mode, the overlaping with the second harmonic is prevented by the upper cutoff of the extraordinary mode.

Enhanced radiation in the $O$ mode from the inside with a behavior similar to that shown in Fig. 3(a) but with smaller amplitude has been also measured. In Fig. 4 the ratio of the emitted power of the $X$ and $O$

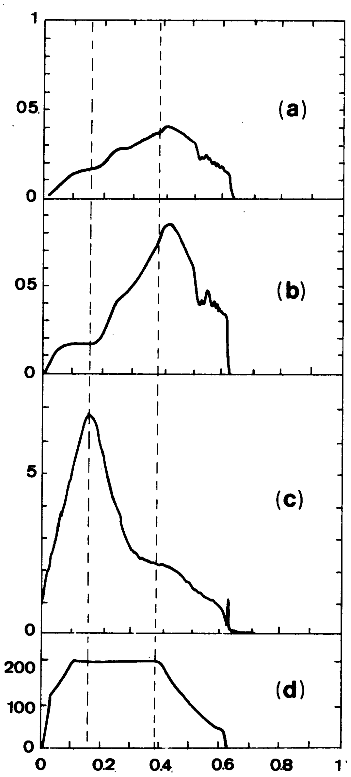


FIG. 2. (a) The radiated power in the $O$ mode at the outside receiver $P_+^O$; (b) the radiated power in the $X$ mode at the inside receiver $P_-^X$; (c) the average density $\bar{n}_e$; and (d) the plasma current $I_p$ as function of time.

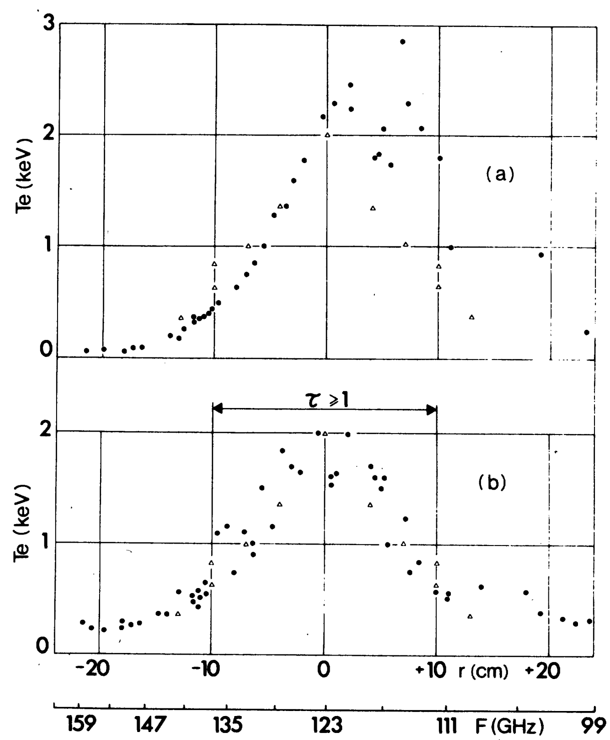


FIG. 3. (a) The radiation temperature measured at the inside receiver in the $X$ mode (●) and (b) the radiation temperature measured at the outside receiver in the $O$ mode (●) as a function of frequency-space at $T = 380$ ms. For comparison the $T_e$ vertical profile by Thomson scattering is also shown (Δ).

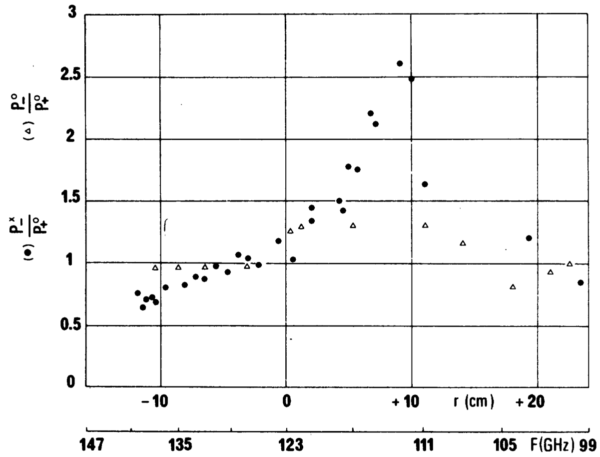


FIG. 4. The radiated power in the $X$ mode at the inside receiver normalized to the power in the $O$ mode at the outside receiver $P_-^X/P_+^O$ (●) and the radiated power in the $O$ mode at the inside receiver normalized to the power in the $O$ mode at the outside receiver $P_-^O/P_+^O$ (Δ) as a function of frequency space at $t = 380$ ms.

modes from the inside to the $O$ mode from the outside as a function of radius at $t = 380$ ms is presented. In both cases the enhancement appears only for positive values of $r$, but $X$ mode has a peak value of 2.6 at $r = 10$ cm whereas a broad maximum of 1.3 is observed for the $O$ mode.

These results seem consistent with the following model. In the high-density regime, the collision rate is high enough to avoid the creation of a superthermal tail in the electron distribution. The emission is that of a Maxwellian plasma at temperature $T_b$. At lower density a small superthermal tail of temperature $T_b$ is superimposed on the thermal background which affects the emitted radiation. The theory of the emission has been developed for both $X$ and $O$ modes in Refs. 4 and 5 and here we only give a brief qualitative description of the manner in which the asymmetry arises.

We describe the small fraction $\eta$ of the superthermal electrons by a Maxwellian with temperature $T_d$ and a drift velocity $v_d$.

For $\eta = 0$, and for a one-dimensional antenna the measured power is $P = T_b(1-e^{-\tau})\Delta\omega/2\pi(1-\gamma e^{-\tau})$, where $\Delta\omega$ is the bandwidth of the receiver. In our experiment the reflection coefficient $\gamma > 0.95$ therefore $P$ is always proportional to the local temperature even for $\tau < 1$ (see Fig. 1). For $\eta \neq 0$ $P_\omega(-a) \geqslant P_\omega(a)$. As shown in Refs. 4 and 5 this can be qualitatively understood by considering that in the region where $\tau > 1$ the enhanced emission due to the superthermal electrons when propagating towards the low-magnetic-field side is reabsorbed by the thermal electrons in the region $\omega = \omega_c(r)$ (the variable $x$ in the slab approximation corresponds to $r$ in the experiments). On the contrary, no reabsorbtion is expected in the propagation towards the high-magnetic-field side (see the asymmetry in Fig. 2). If we assume that the density of the superthermal electrons is maximum near the plasma axis, because the wave resonates with the electrons for large values of $\omega_c - \omega > 0$ the enhancement in the radiated power is generally maximum for positive value of $r$ as in Figs. 3(a) and 4. Moreover, for large values of the magnetic field the theory shows that the enhancement is generally much greater for the $X$ than for the $O$ mode (Fig. 4). Note that in the region where $\tau < 1$ the reabsorbtion of the nonthermal emission by thermal electrons is less effective and the enhanced radiation can be observed by both sides, as in Fig. 3. It is worth noting that the emission in the $X$ mode is the superposition of the radiated electromagnetic energy resulting from the gyration motion of the particles (thermal and superthermal) and that due to mode conversion of Bernstein modes at the upper hybrid resonance. This extra emission corresponds to a localized source of blackbody radiation.[7] Using the transfer equation, for the measured temperature we have $T_r = T_e(x_c)\exp(-\tau_X) + T_g$, where $\tau_X$ is the optical thickness of the $X$ mode evaluated from $-a$ to $x_c$, $T_g$ is the contribution due to the gyration motion of the electrons, and $x_c$ is defined from the relation $\omega = \omega_c(x_c)$. Note that $\tau_X$ results from the contribution of the thermal and superthermal electrons. For $x_c \lesssim 0$, the effect of the superthermal electrons is negligible and $\tau_X$ is determined by the thermal electrons only. As known,[8] in the case $\tau_X < 1$, and, correspondingly, $T_g = T_e(x_c) \times (1-e^{-\tau_X})$, thus, $T_r = T_e(x_c)$. For $x_c > 0$, the effect of the superthermal electrons is predominant and $\tau_X >> 1$, $T_g > T_e(x_0)$, and $T_r > T_e(x_c)$, as shown in Fig. 3(a). Note also that the emission (absorption) of the superthermal component is generally not a localized effect in space; therefore it is possible to observe radiation for $\omega$ for which the corresponding $x_c$ lies outside the plasma border (Fig. 3). Fair agreement between the theory and experiments is obtained for $\eta = 3\times10^{-2}$, $T_d = 6$ keV, and $v_d \approx (T_e/m_e)^{1/2}$. A quantitative analysis of the profile of the measured radiation temperature is not straightforward since it is sensitive to the profiles of $\eta$, $T_g$, and $v_d$. These parameters and their profiles should be evaluated from the kinetic theory of the plasma state. This problem is now under investigation.

In conclusion, we have presented the first experimental evidence that for low-density regimes in TFR the power radiated in the equatorial plane along the major radius at the electron cyclotron frequency displays a marked asymmetry when viewed from the inside or the outside of the torus. These results seem qualitatively consistent with the recent theory of the electron cyclotron radiation from hot plasma with a small superthermal electron population.

We wish to point out that simultaneous observation of the radiation from both sides of the torus may be a very simple and sensitive diagnostic to obtain useful information about the electron distribution during the rf or neutral injection auxiliary heating in tokamaks.

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