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CYCLOTRON RESONANCE ABSORPTION AND
EMISSION IN THE PRINCETON LARGE

TORUS

BY

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ORDINARY-MODE FUNDAMENTAL ELECTRON CYCLOTRON RESONANCE
ABSORPTION AND EMISSION IN THE PRINCETON LARGE TORUS

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ABSTRACT

Fundamental electron cyclotron resonance damping for 4 mm waves with ordinary polarization is measured for propagation along the major radius traversing the midplane of the plasma in the Princeton Large Torus (PLT). Optical depths obtained from the data are in good agreement with those predicted by the relativistic hot plasma theory. Near blackbody emission over much of the plasma midplane is obtained and, in conjunction with the damping measurements, indicates that the vessel reflectivity is high. The practical use of ordinary mode fundamental electron cyclotron resonance heating (ECRH) in existing and future toroidal devices is supported by these results.

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In fusion research there is considerable interest in understanding and utilizing both the ordinary and the extraordinary mode wave absorption and emission near the electron cyclotron frequency, f_{ce} , and its harmonics.^{1,2,3} In the Model C Stellarator, the extraordinary mode absorption measurements near $2f_{ce}$ were successfully used, not only to measure T_e but also to study the details of the electron velocity distribution function.¹ However, the recent development of powerful millimeter microwave sources (i.e., gyrotrons) has stimulated considerable interest in wave absorption near f_{ce} since a clear understanding of the absorption process can prescribe the proper conditions for efficient application of electron cyclotron resonance (ECR) heating in tokamaks. The primary schemes for ECR heating of tokamak plasmas are (1) as a general method of heating the bulk electrons, and (2) as a specific method of controlling the T_e profile with spatially localized heating with beneficial consequences including, for example, the suppression of magnetohydrodynamic (MHD) instabilities. For ECR heating of tokamaks the attractive feature of the f_{ce} -ordinary mode is that the wave can be launched from the low magnetic field (B) side of the torus, simplifying the transmission of high powers to the plasma.

In this letter, we present the first direct measurements of ordinary-mode wave absorption at the fundamental electron cyclotron frequency, f_{ce} , along with the corresponding emission scans over the midplane of a hot tokamak plasma in PLT. The ordinary-mode f_{ce} -wave absorption measurements are found to be in good agreement with the predictions of the relativistic hot plasma theory

of Fidone, Granata, Ramponi, and Meyer⁵ as well as the full-wave absorption calculations of Antonsen and Manheimer.⁶ We then present the experimental evidence which demonstrates that in PLT discharges, with a sufficiently low runaway population, the ordinary mode emission near f_{ce} , when viewed from the outside of the torus, is essentially at the blackbody level. This emission from the cyclotron layer [$f \approx f_{ce}(R)$ where R is the major radius of the emitting layer], results either from an optically thick emitting layer (blackbody) or the combination of an optically thin layer with sufficient wave reflection from the vessel (multipass blackbody).

Figure 1 is a schematic block diagram of the experimental arrangement. The incident 4 mm microwave power, P_0 , is supplied by a klystron transmitter at a fixed frequency of 71 GHz. The orientations of both the transmitter and the receiver horns are such that their electric vectors, $\vec{E}$, are parallel to $\vec{B}$ and their axes are perpendicular to $\vec{B}$. The microwave power transmitted through the PLT plasma is collected by the receiver horn and is mixed with a fixed amount of reference signal from a local oscillator. The resultant radio-frequency (r.f.) output is amplified (by an amplifier of bandwidth $\Delta f \approx 90$ MHz) and is then detected with an rf detector. The signal from the output of the detector, displayed on an oscilloscope is proportional to the transmitted power, P_T . The local oscillator is swept repetitively from 70 to 72 GHz in 10 msec. With this sweeping technique any small frequency drifts of the transmitter relative to the local oscillator do not affect the absorption measurements and the

frequency integrated absorption over the f_{ce} -resonance is obtained for a direct comparison with the predictions of the relativistic hot plasma theory of Refs. 5 and 6. Finally, both the transmitter and the local oscillator power are stabilized by self-contained power-levelling feedback loops (Hughes 44764 II), described elsewhere.⁷ For emission measurements we turn off the transmitter klystron and increase the amplifier bandwidth to $\Delta f = 400$ MHz. Then, radial profiles of $T_e(r)$ are obtained by repetitively sweeping the local oscillator from 60 to 90 GHz in 10 msec throughout the duration of the discharge.

The fractional microwave power (P_T/P_O) transmitted through the plasma may be written $(P_T/P_O) = \exp(-\tau)$ where $\tau = \int_{R_O-a}^{R_O+a} 2\text{Im}(k_z) dr$ is the optical depth, P_O and P_T are the incident and transmitted powers, respectively, Im signifies the imaginary part, $a = 40$ cm is the minor radius of the plasma, $R = R_O + r$, $R_O = 132$ cm being the nominal major radius at the center of the PLT plasma. According to the relativistic hot plasma theories of Fidone et al.⁵ and Antonsen et al.,⁶ the expression for the optical depth τ appropriate for perpendicular propagation of the ordinary mode radiation of frequency $f = f_{ce}$ may be written

$$\tau \approx \frac{\pi^2 R}{c} \frac{f_{pe}^2}{f_{ce}^2} \left(1 - \frac{f_{pe}^2}{f_{ce}^2} \right)^{1/2} \left(\frac{kT_e}{m_e c^2} \right) \quad (1)$$

where f_{pe} is the electron plasma frequency, f_{ce} is the electron cyclotron frequency, k is the Boltzmann constant, m_e is the rest mass of the electron, and c is the velocity of light. It should be pointed out that the result of Eq. (1) is valid only when

$(2k_{\perp}/2 - f_{ce}) \leq (2T_e/m_e c^2)^{1/2} \cdot (f_{pe}^2/f_{ce}^2) - 1$. Here $\perp$ and $\parallel$ refer to directions perpendicular and parallel, respectively, to the magnetic field, $\vec{B}$. In arriving at the result of Eq. (1), finite Larmor radius terms and the relativistic correction of the electron mass play a dominant role.

Since in tokamaks $B \propto R^{-1}$, the absorbing cyclotron layer $f \approx f_{ce}(R)$ can be placed at the desired R or r by choosing the appropriate magnetic field level $B(R_0)$ for the fixed transmitter frequency, $f = 71$ GHz. Laser Thomson scattering measurements give both the density, $n_e(r)$ and temperature, $T_e(r)$ profiles. Thus by changing $B(R_0)$ we can measure the optical depth $\tau(r) = [n_e(r), T_e(r)]$ as a function of r , or equivalently, as a function of pairs of values of n_e and T_e . In Table 1 we summarize our f_{ce} -ordinary mode absorption results for two different experimental runs. The experimental values of the optical depth, τ_{exp} , have been obtained from the measured values of (P_T/P_0) and the relation $(P_T/P_0) = \exp(-\tau)$. In P_0 , the refraction losses have been experimentally taken into account by measuring the transmitted power for the same central density and density profile for reduced $B(R_0) = 16.8$ kG for which there is no cyclotron layer anywhere in the plasma (i.e., for the range $R_0 - 40 \leq R \leq R_0 + 40$ cm) and thus, $\tau = 0$. For plasma discharges where the absorption is measured, the same density profile is maintained. Typically, the refraction losses are about 50%. The theoretical values of the optical depth, τ_{th} , have been obtained by using the measured values of n_e and T_e in Eq. (1). It is apparent from Table 1 that there is good agreement between theory and experiment for values

of τ in the range $0.1 < \tau \leq 2$. The standard deviations in the values of τ_{exp} are smaller than those in τ_{th} because of the statistical variations in the density and temperature measurements.

As seen from Eq. (1), for $f_{pe} \approx f_{ce} = f$, $\tau \approx n_e T_e$. Thus, the f_{ce} -ordinary mode propagation studies could be used to determine the local electron pressure, i.e., either local n_e or T_e if one of the quantities is measured separately.

Now we present our results for f_{ce} -ordinary mode emission from the PWT plasma. For our receiver system, the power P collected by the receiving antenna is $P = kT_e(r, t) \Delta f (1 - e^{-\tau})$, where $\Delta f = 400$ MHz is our receiver bandwidth. If the optical depth of the emitting cyclotron layer is much larger than one, then the emitting from the f_{ce} -layer is optically thick (i.e., $\tau(r) \gg 1$) and yields blackbody emission.

In Fig. 2 we show a comparison of the temperature profiles obtained from ordinary-mode fundamental cyclotron emission assuming the blackbody conditions (the dashed line) with the corresponding profile obtained from laser Thomson scattering (the solid line). The cyclotron emission profile, taken along the major radius in the horizontal plane, shows an outward shift of the plasma by about 2 to 3 cm while the Thomson scattering profile, taken along a vertical chord through the plasma center, does not show this shift. With this difference taken into account, good agreement is found between the two profiles, demonstrating that the emission is near the blackbody level over the range of r shown. The $T_e(R)$ profile has been measured by keeping the receiver at a fixed frequency of 70 GHz and changing the central

magnetic field $B(R_0)$. An absolute calibration of the receiver was achieved with the aid of a noise tube. For the data used in this figure, $n_e(0) \approx 4 \times 10^{13} \text{ cm}^{-3}$ and $T_e(0) \approx 1.4 \text{ keV}$. Thus, according to Eq. (1), $\tau(0) \approx 3.2$. Hence, only in the neighborhood of the plasma center is the emitting cyclotron layer optically thick since n_e and T_e are decreasing with r . This indicates that reflections from the vacuum vessel leading to multiple transits of the emitted radiation are enhancing the emission to near the blackbody level for $r > 20 \text{ cm}$. If b is the wall reflection coefficient, then the effective collected power becomes $P_{\text{eff}} \approx \kappa T_e \epsilon f (1 - e^{-\tau}) / (1 - be^{-\tau})$. Even though the measured n_e and T_e at $r = 30 \text{ cm}$ give $\tau \approx 0.42$, the measured power will be $\sim 90\%$ of the blackbody level for $b \geq 0.95$. Thus, a reflectivity of this level is indicated for the stainless steel vessel of PLT.

Taking advantage of this large reflectivity, we measure $T_e(r, t)$ profiles from ordinary cyclotron emission detection over the outer half of the plasma column by repetitively sweeping the local oscillator frequency from 60 to 90 GHz every 10 msec. In Fig. 3 a three-dimensional computer plot of the time evolution of the electron temperature profile, $T_e(r, t)$, measured for a typically ohmically heated PLT discharge is given.⁸ Such measurements significantly facilitate monitoring $T_e(r, t)$ during a single discharge and are particularly valuable in evaluating effects of auxiliary heating of plasmas.

In conclusion, we have presented the first experimental verification of the predictions of relativistic hot plasma theory (of Refs. 5 and 6) for the propagation of the ordinary

mode near the electron cyclotron frequency in a hot collisionless tokamak plasma. Our absorption and emission measurements are in good agreement with Kirchhoff's radiation law² when reflections are considered. In PLT, wall reflections play a significant role in enhancing the emission to approximately the blackbody level for $r > 20$ cm. Thus, for plasma conditions comparable to those in PLT, ECRH is quite promising to the extent that these results are applicable to high rf power levels. Single pass absorption is essentially total in the plasma core, permitting focusing of the power for heating this region while avoiding loss of power via port leakage. For the conditions studied here, heating the plasma surface requires multipass absorption with inherent leakage, and the power focusing is then influenced by the wave damping profile along the resonance layer. However, heating in the plasma surface will still peak in the horizontal midplane of the plasma and can be confined to a peripheral region. Thus, surface heating to modify the T_e profile, e.g., to stabilize MHD activity⁹ should be possible. Of course, higher density and temperature conditions can be employed to provide better localization of the heating in the surface by increasing τ .

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TABLE 1

$T_e(r)$ (eV)	$n_e(r)$ (10^{13} cm^{-3})	τ_{th}	τ_{exp}
150 ± 88	0.384 ± 0.08	0.05 ± 0.03	0
293 ± 171	0.716 ± 0.246	0.21 ± 0.16	0.09 ± 0.03
240 ± 14	0.7 ± 0.14	0.14 ± 0.04	0.11 ± 0
647 ± 35	1.09 ± 0.11	0.57 ± 0.06	0.38 ± 0.05
900 ± 115	1.32 ± 0.087	0.98 ± 0.16	0.876 ± 0.06
270 ± 57	1.30 ± 0	0.29 ± 0.06	0.3 ± 0.028
416 ± 186	0.96 ± 0.23	0.35 ± 0.18	0.33 ± 0.07
760 ± 57	2.59 ± 0.41	1.43 ± 0.13	1.49 ± 0.15
850 ± 70	2.7 ± 0.42	1.65 ± 0.30	1.89 ± 0.0

A comparison of the measured experimental values of the optical depth τ_{exp} with the corresponding theoretically calculated values τ_{th} for the propagation of f_{ce} -ordinary mode [see Eq.(1)]. The data was collected over two separate experimental runs and is partitioned in this table.

Fig. 1. Block diagram of the experimental arrangement.

Fig. 2. A comparison of the temperature profiles obtained from blackbody-ordinary mode fundamental cyclotron emission (i.e., the dashed line) with the corresponding profile obtained from laser Thomson scattering, TVTS, (i.e., the solid line).

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Fig. 3. A computer plot of the time evolution of the electron temperature profile of a typical inductively heated FET plasma discharge determined from the measurement of the ordinatized fundamental electron cyclotron emission by the fast-scanning heterodyne receiver. In order to easily visualize the contents of the three-dimensional graph, only seventeen radial positions of every other temperature profile actually determined from the emission are plotted.