Measurements of Electron Cyclotron Emission from High-Density Tokamak Plasmas in TFR

A. E. Costley
Division of Electrical Science, National Physical Laboratory, Teddington, Middlesex, TW11 0LW, England

and

TFR Group*
Association Euratom–Commissariat à l'Energie Atomique, 92260 Fontenay-aux-Roses, France
(Received 19 July 1976)

We present measurements of the electron cyclotron emission from high-density ($n_{e0} > 3 \times 10^{19}$ m^{-3}) low-runaway plasmas produced in the TFR tokamak device. The emission is, as predicted, self-absorbed, but contrary to expections is the same both along a major radius and along a vertical chord, is the same in both the extraordinary and ordinary modes, and peaks at the plasma frequency and, in addition, at n times the electron cyclotron frequency (for $n=1,2,3,4$). We compare the measurements with the predictions of theory.

Extensive theoretical work has established that the power loss due to electron cyclotron emission in a thermonuclear fusion reactor will depend on the degree of self-absorption of the radiation and on the effectiveness of the vacuum chamber as a radiation reflector.[1-3] It has also predicted that a measurement of the electron cyclotron emission from present-day toroidal plasmas should be an informative diagnostic technique.[4] Measurements have shown that the level and frequency dependence of the emission from tokamak plasmas are sensitively dependent on the runaway level and that the spectrally integrated emission is usually not polarized probably because of reflections of the radiation inside the vacuum chamber.[5-8]

The prediction for self-absorption of the radiation has not been tested, however, mainly because the investigated plasmas have not been sufficiently dense and hot. More generally, a clear comparison of experiment and theory has not been possible mainly because the investigated plasmas have not been adequately diagnosed and because the uncertainties on the measured levels of emission are large—typically an order of magnitude.

In this Letter we present measurements of the electron cyclotron emission from three high-density low-runaway[9] plasmas produced in the TFR tokamak device[10] (Table I). The densities and temperatures are such that substantial self-absorption of the radiation should occur, and the plasma diagnosis and measurement uncertainties are such that a clearer comparison of experiment and theory is now possible.

Emission measurements.—The plasma is observed through wedge-shaped windows of crystal quartz (z cut) both along a major radius and along a vertical chord. The chord is 100 mm off the plasma center in the direction of increasing major radius. In each case the plasma radiation is directed with overmoded light pipes (diameter $\sim 10\lambda_{max}$) into a two-beam polarization-type interferometer,[11] and the output of the latter is detected with a Putley indium antimonide detector. The path difference (x) within each interferometer is scanned rapidly—typically in 10 ms and over the range -1 mm $< x <$ 14 mm—by electromechanical oscillation of one of the interferometer mirrors, and the detected interference patterns are displayed on an oscilloscope and recorded on polaroid film. Subsequent enlargement, measurement, and Fourier transformation of the interference patterns, and calibration of the apparatus yield the emission spectra.

In the calibration the time dependence of the path difference is measured with an HCN laser

TABLE I. Values of the principal parameters of the investigated plasmas A, B, and C. n_{e0} is the central electron density, T_{e0} the central electron temperature, B_0 the central toroidal flux density, I_p the plasma current, and V_L the loop voltage.

	n_{e0} (m^{-3})	T_{e0} (keV)	B_0 (T)	I_p (kA)	V_L (V)
A	5×10^{19}	1.3	2.6	140	2.7
B	5×10^{19}	1.8	3.9	150	1.8
C	7×10^{19}	2.0	5.0	300	2.4

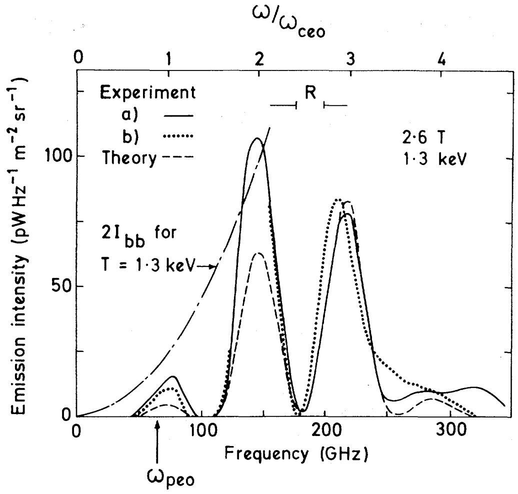

FIG. 1. Emission spectra for plasma conditions A. Experiment: curve a, radial direction; curve b, vertical direction. Observation time $t_0 \sim 160$ ms after initiation of discharge. $R = 22$ GHz. Note curve b is normalized to curve a at $\omega = 2\,\omega_{ce0}$. Theory: predictions for radial emission by assuming that reflections maintain the radiation path but including polarization scrambling ($p = 0.15$). $I_{bb} = \omega^2 kT/8\pi^3 c^2$ is single-mode blackbody intensity for measured T_{e0}. $I(2\omega_{ce0}) \neq 2I_{bb}(2\omega_{ce0})$ because predicted polarization scrambling is not total and because of (convolved) instrumental broadening. Main descrepancy between experiment and theory is on relative heights of emission lines.

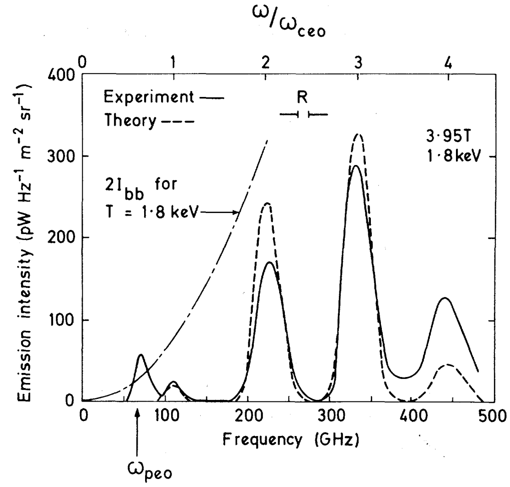

FIG. 2. Emission spectra for plasma conditions B. Experiment: radial direction, $t_0 \sim 150$ ms, $R = 13$ GHz. Theory: predictions for radial emission. See caption to Fig. 1.

and the frequency dependence of the response of each interferometer-detector system is measured with a 2-mm-wavelength microwave source of known power.

The uncertainties in the measurement method are such that the relative shape and frequency positions of the spectral features are reliable to about ±10%, that the absolute level of the emission in the radial direction is reliable to about ±40%, and that the level of the emission in the vertical direction is reliable only to about a factor of 4. This latter uncertainty arises mainly because in this direction the influence of the torus side arm is considerable and the associated antenna pattern is complicated. The resolution (R) in the spectrum is 22 GHz for a time resolution of 10 ms, or 13 GHz for a time resolution of 15 ms ($R = cx_{\max}^{-1}$).

The emission spectra measured in the radial direction under plasma conditions A and B are shown in Fig. 1 (curve a) and Fig. 2, respectively. As expected, emission peaks occur at $n\omega_{ce0}$ where $n = 1, 2, 3, \ldots$, and where ω_{ce0} is the electron cyclotron frequency corresponding to the magnetic field B_0 at the center of the plasma. We note that the total plasma emissions are such that $I(\omega_{ce0}) < I(2\omega_{ce0})$ as shown in Fig. 1 and such that $I(\omega_{ce0}) < I(2\omega_{ce0}) < I(3\omega_{ce0})$ as shown in Fig. 2, even though the corresponding emissions per unit volume are expected to be such that $j(\omega_{ce0}) > j(2\omega_{ce0}) > j(3\omega_{ce0})$. Self-absorption of the radiation would have this effect and this phenomenon is most probably occurring here as expected (Table II).

Under plasma conditions B and C, an additional peak occurs at $\omega \sim \omega_{pe0}$, where ω_{pe0} is the electron plasma frequency corresponding to the measured value of n_{e0}. Spectra obtained at different times in the discharge duration show that the amplitude of this peak is initially above the blackbody level for the measured electron temperature and that it decays with a time constant ~100 ms. The amplitude of this peak suggests that the level of fluctuating fields in the plasma is above

TABLE II. Calculated optical depths (τ) for extraordinary-mode radiation [from Eq. (2), Ref. 5]. Substantial self-absorption should occur when $\tau \gg 1-(r-f) \sim 0.06$.

n	1	2	3	4
A	2100	10.3	0.14	0.003
B	1256	8.8	0.16	0.005
C	1300	10.2	0.20	0.007

the thermal expectation.[12] The origin of this enhancement is at present unknown but it is likely that it is associated with a residual runaway component.

The emission spectrum measured in the vertical direction under plasma conditions A is shown in Fig. 1 (curve b). Within the experimental uncertainties the level of the emission in this direction is the same as that in the radial direction and so, for comparison, the level of the spectrum is normalized to that in the radial direction at $\omega = 2\omega_{ce0}$. We note that the frequency dependence of the emission in the two observation directions is almost the same.

Polarization measurements.—The light pipes in the radial direction are removed and an optical system which excludes reflections in the torus side arm is constructed. A wire grid polarizer in the interferometer is rotated through 90° between nominally identical tokamak shots so that the extraordinary- and ordinary-mode emissions are measured sequentially. Four shots are observed under plasma conditions C in each case.

Figure 3 shows the average spectra obtained. We note (i) that within the discharge reproducibility—shown by the scatter bars for one standard error of the mean—the spectra are identical even though the emission per unit volume is expected to be dominantly into the extraordinary mode, and (ii) that there is emission in the extraordinary mode at $\omega = \omega_{ce0}$ even though for this

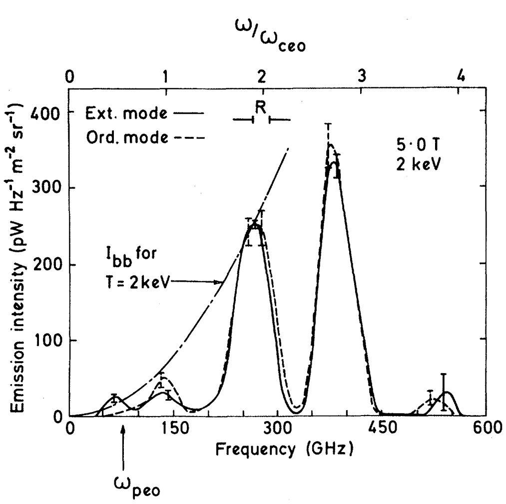

FIG. 3. Average experimental extraordinary- and ordinary-mode emission spectra for plasma conditions C. Observation direction is radial. Bars represent one standard error of the mean. $t_0 \sim 400$ ms, $R = 22$ GHz. Predicted $I_o/I_e = 0.71$.

emission an absorbing layer (upper hybrid resonance) occurs in the line of sight. As before, the most probable explanation for the first observation is that reflections of the radiation inside the torus are scrambling the polarization.

The convolution of the Fourier-transform instrument function[13] with the predictions of a theory of radial tokamak cyclotron emission[5] are shown in Figs. 1 and 2 for comparison with experiment. In this modified theory the effect of reflections which do not change the path of the radiation is included as is, also, absorption of the extraordinary-mode fundamental in the upper hybrid region.[14] Further, polarization scrambling on reflection is included by introducing a transfer fraction p between the extraordinary modes. When the predictions are made the measured values of B_0, $n_e(s)$, and $T_e(s)$ are used, p is taken somewhat arbitrarily as 0.15, and the presence of ports is taken into account by reducing the conductivity value for the reflectivity of the wall material (r) by an appropriate factor, f, which is the ratio of surface area of the ports to that of the torus; for TFR, $f = 0.05$. Not shown in the figures is the predicted ratio of the ordinary- to extraordinary-mode emissions, $I_o/I_e = 0.71$.

The agreement between experiment and prediction is evidently good but some discrepancies remain. In particular, the relative heights of the harmonics are not exactly the same and the measured value of $I_o/I_e \sim 1$ is larger than that calculated. The first discrepancy could be due to the fact that reflections of the radiation inside the torus change the path of the radiation (see below), or to emission from a relatively low-density hot-electron component.[5] The second could be due to an oversimplification of the phenomenon of polarization scrambling on reflection[15] or, perhaps, to polarization scrambling by turbulence in the plasma.

Since the variation of the magnetic field in the vertical direction is relatively small, the emission in this direction should consist of relatively narrow lines at $n\omega_{ce}(s)$, where $\omega_{ce}(s)$ is the electron cyclotron frequency corresponding to the value of the toroidal field appropriate to the position of the observation port. The widths of the measured lines should be $\sim R$ because of instrumental broadening.[16] The relative heights of the lines should depend on the electron-density and electron-temperature profiles in the line of sight; and for plasma conditions A, calculations based on the mildly relativistic expressions given in Ref. 11 give $I_2/I_3 \sim 0.6$ and $I_2/I_4 \sim 20$.[17] Experimentally, however, with an observation port at $s = 100$ mm $[\omega_{ce}(100) \sim 0.9\omega_{ce}(0)]$ we measure lines at $n\omega_{ce}(0)$ with widths and relative heights the same as those measured in the radial direction. These findings suggest strongly that reflections of the radiation inside the torus change the path of the radiation and thereby, in effect, destroy the anisotropy of the emission.

In a reactor, polarization scrambling and "anisotropy destruction" would represent a reduction in the effectiveness of the vacuum chamber as a radiation reflector and there would be a corresponding increase in the power loss due to cyclotron emission. Detailed calculations on specific geometries are required to determine typical magnitudes of the enhancement.

We wish to acknowledge useful discussions with Dr. R. J. Bickerton, Dr. A. Dellis, and Dr. J. W. M. Paul, and to thank Mr. R. J. Hastie for carrying out the predictions of the vertical emission, and the Culham Laboratory, U. K. Atomic Energy Authority, for supporting part of this work.

*Members of the TFR Group are C. Breton, J. Breton, Ph. Brossier, J. P. Bussac, R. Cano, R. Chatelier, M. Cotsaftis, J. P. Crenn, R. Dei Cas, C. De Michelis, P. Ginot, J. P. Girard, R. Gravier, F. Hennion, F. Koechlin, D. Launois, P. Lecoustey, J. Lelegard, E. Maschke, M. Mattioli, C. Mercier, P. Moriette, R. Papoular, P. Platz, P. Plinate, C. Renaud, A. Samain, A. Schram, Z. Sledziewski, P. Smeulders, J. L. Soule, J. Tachon, A. Torossian, J. Touche, D. Veron, F. Werkoff, and B. Zanfagna.

[1]B. A. Trubnikov and A. E. Bazhanova, in *Plasma Physics and the Problems of Controlled Thermonuclear Reactions*, edited by M. A. Leontovich and J. Turkevich (Pergamon, New York, 1959), Vol. 3, p. 141.

[2]W. E. Drummond and M. N. Rosenbluth, Phys. Fluids 6, 276 (1963).

[3]M. N. Rosenbluth, Nucl. Fusion 10, 340 (1970).

[4]F. Engelmann and M. Curatolo, Nucl. Fusion 13, 497 (1973).

[5]A. E. Costley, R. J. Hastie, J. W. M. Paul, and J. Chamberlain, Phys. Rev. Lett. 33, 758 (1974).

[6]V. S. Vlasenkov, M. M. Larionov, and V. V. Rojdest-Vienskii, Zh. Tekh. Fiz. 45, 2521 (1975) [Sov. Phys. Tech. Phys. 20, 1571 (1975)].

[7]TFR Group and NPL Submillimetre-Wave Group, in *Proceedings of the Seventh European Conference on Controlled Fusion and Plasma Physics, Lausanne, Switzerland, 1975* (European Physics Society, Geneva, 1975), Papers 14a and 14b.

[8]D. A. Boyd, F. J. Stauffer, and A. W. Trivelpiece, Phys. Rev. Lett. 37, 98 (1976).

[9]As indicated by standard x-ray diagnostics.

[10]TFR Group, in *Proceedings of the Fifth International Conference on Plasma Physics and Controlled Nuclear Fusion Research, Tokyo, Japan, 1974* (International Atomic Energy Agency, Vienna, Austria, 1975), Vol. 1, p. 135.

[11]D. H. Martin and E. Puplett, Infrared Phys. 10, 105 (1970).

[12]G. Bekefi, *Radiation Processes in a Plasma* (Wiley, New York, 1966), Chaps. 5 and 6.

[13]W. J. Burroughs and J. E. Harries, Infrared Phys. 11, 99 (1971).

[14]Note that the theory is applied at the fundamental even though at this frequency one of the basic assumptions $(\omega_{pe}^2/\omega^2)\ c/v_{\mathrm{th},e} \ll 1$ is not valid.

[15]In particular, the transfer fraction may not be the same for each reflection.

[16]The antenna pattern will also contribute to the widths of the lines but in the present case this contribution is $\sim 4.5n$ GHz, i.e., $< R$.

[17]With the assumption of path-maintaining reflections with polarization scrambling ($p = 0.15$).

Nonlinear Evolution of Electrostatic Wave Packet in a Plasma

N. Sato, K. Saeki, and R. Hatakeyama
Department of Electronic Engineering, Tohoku University, Sendai, Japan
(Received 4 March 1977)

Measurements are made on spatial evolutions of a large-amplitude wave packet of electron plasma wave in a collisionless plasma. There appears a new wave emitted in front of the wave packet, which results in a spreading of the wave packet along the propagation direction.

Nonlinear evolution of dispersive waves are of current interest in plasma physics.[1] Particles trapped in the wave potential are important for understanding nonlinear electrostatic waves in a collisionless plasma.[2] In the presence of the finite wave damping, however, it is also necessary to take account of detrapped particles which emerge out of a locally defined trapping region, as predicted by Bussac *et al.*[3] on the sideband instability. Recent experiments on continuously launched sinusoidal waves have well demonstrated that the detrapped particles generate a "bump