MASTER
ELECTRON CYCLOTRON EMISSION
FROM THE PLT TOKAMAK

BY

J. HOSEA, V. ARUNASALAM,

AND

R. CANO

PLASMA PHYSICS
LABORATORY

DISTRIBUTION OF THIS DOCUMENT IS UNLIMITED

PRINCETON UNIVERSITY
PRINCETON, NEW JERSEY

This work was supported by U. S. Energy Research and Development Administration Contract EY-76-C-02-3073. Reproduction, translation, publication, use and disposal, in whole or in part, by or for the United States Government is permitted.

DISCLAIMER

This report was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor any agency Thereof, nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or any agency thereof. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or any agency thereof.

DISCLAIMER

Portions of this document may be illegible in electronic image products. Images are produced from the best available original document.

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

Printed in the United States of America.

Available from
National Technical Information Service
U. S. Department of Commerce
5285 Port Royal Road
Springfield, Virginia 22151
Price: Printed Copy \$ * ; Microfiche \$3.00

<u>*Pages</u>	<u>NTIS Selling Price</u>
1-50	\$ 4.00
51-150	5.45
151-325	7.60
326-500	10.60
501-1000	13.60

Electron Cyclotron Emission from the PLT Tokamak

J. Hosea, V. Arunasalam, and R. Cano

Plasma Physics Laboratory, Princeton University,
Princeton, New Jersey 08540

PPPL-1362

July 1977

NOTICE

This report was prepared as an account of work sponsored by the United States Government. Neither the United States nor the United States Energy Research and Development Administration, nor any of their employees, nor any of their contractors, subcontractors, or their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness or usefulness of any information, apparatus, product or process disclosed, or represents that its use would not infringe privately owned rights.

See

Electron Cyclotron Emission from the PLT Tokamak^{*}

J. Hosea, V. Arunasalam, and R. Cano[†]

Plasma Physics Laboratory, Princeton University,
Princeton, New Jersey 08540

ABSTRACT

Experimental measurements of electron cyclotron emission from the PLT tokamak plasma reveal that black-body emission occurs at the fundamental frequency. Such emission, not possible by direct thermal excitation of electromagnetic waves, is herein attributed to thermal excitation of electrostatic (Bernstein) waves which then mode convert into electromagnetic waves. The local feature of the electrostatic wave generation permits spatially and time resolved measurements of electron temperature as for the second harmonic emission.

In fusion research there is considerable interest in understanding the emission near the electron cyclotron frequency f_{ce} and its harmonics. Such emission could constitute a significant power loss in a reactor,¹ can prescribe the proper conditions for efficient application of electron cyclotron resonance (ECRH) heating through the reverse process (Kirchhoff's radiation law²), and of more immediate interest, can provide an independent measurement of the properties of the emitting electrons^{2,3} (e.g., electron temperature T_e and/or presence of runaways). In tokamak regimes for which the runaway population is small, the emission near the second and higher harmonics can be well understood⁴ in terms of either the conventional hot plasma theory⁵ or the single particle emission theory.² However, emission near the fundamental frequency⁴ ($f \approx f_{ce}$) is found to be much larger than predicted by the hot plasma theory for direct electromagnetic wave emission. Such emission should be negligible compared to the black-body value of κT_e per mode⁶ since in the vicinity of the cyclotron frequency the electromagnetic wave is almost circularly polarized with its sense of rotation opposite to that of the gyrating electrons.

In this paper, we first present experimental evidence which demonstrates that in PLT discharges with a sufficiently low runaway population, the emission near f_{ce} , when viewed from the inside of the torus, is indeed a black-body emission from the cyclotron layer [$f \approx f_{ce}(R)$ where R is the major radius of the emitting layer]. We then show that this emission can be attributed to thermal excitation of electrostatic Bernstein waves which mode convert into

electromagnetic waves rather than direct thermal excitation of electromagnetic waves. Hence, detection of black-body emission at f_{ce} , as well as at $2f_{ce}$ ^{7,8}, gives a local time-resolved measurement of $T_e(R,t)$ as will be illustrated.

In this study, we compare the detected emission at $f \approx f_{ce}$ with that at $f \approx 2f_{ce}$ which has previously been shown to be black-body under the conditions set by the conventional hot plasma theory.^{7,8} Receiving antennas (horn or a horn-lense combination as to be noted) are located in the equatorial plane along the major radius and are oriented to receive extraordinary waves. Conventional superheterodyne detectors are used since these permit the optimum spatial resolution along R of the various detection schemes. For these systems, the output signals are proportional to the emitted power. That is, $P = \kappa T_e(R) \Delta f (1 - e^{-\tau})$, where τ is the optical depth of the emitting layer² ($\tau \geq 2$ for black-body emission), and Δf is the receiver bandwidth.

In Fig. 1(a), we present f_{ce} and $2f_{ce}$ emission profiles versus position along the major radius for the discharge conditions noted. ($R = R_0 + r$ where $R_0 = 132$ cm is the nominal major radius at the center of the plasma.) These data were obtained by setting the receiver frequencies at 70 GHz (f_{ce}) and 140 GHz ($2f_{ce}$) and placing the emitting layer at the desired R or r by choosing the appropriate magnetic field level $B_\phi(R_0)$. The spatial resolution for each receiver is set by their bandwidth $\Delta f \approx 400$ MHz which gives layer thicknesses of $\Delta R \approx 0.8$ cm (f_{ce}) and 0.4 cm ($2f_{ce}$), and by the lobe widths $\Delta\theta \approx \pm 6.5^\circ$ (f_{ce}) and $\pm 4^\circ$ ($2f_{ce}$) of simple horn antennas located at $r = -50$ cm [spot diameters are $d \approx 11$ cm (f_{ce}) and 7 cm ($2f_{ce}$) at R_0]. For comparison, the average temperature profile obtained from Thomson

scattering along a vertical line through the plasma is also shown in Fig. 1(a).

As found previously,^{7,8} the $2f_{ce}$ emission profile is in good agreement with the Thomson scattering profile as expected for black-body emission (the hot plasma theory⁹ gives $\tau \sim 10$ at $r = 5$ cm decreasing to $\tau \sim 1$ at $r = 30$ cm). The $2f_{ce}$ profile falls somewhat below the Thomson scattering profile at larger r partly due to an observed overall reduction in T_e as B_ϕ was decreased, and partly because the detection spot size weights the emission toward larger r (i.e., lower T_e).

Clearly, the f_{ce} emission profile is in good accord with the $2f_{ce}$ emission profile. Again, the difference between these profiles at larger r can be attributed to the different spot sizes of the detectors. Furthermore, the time evolution of the emission at f_{ce} is identical to that at $2f_{ce}$ as illustrated in Fig. 1(b), and indeed, within the experimental accuracy of our receiver calibrations $P_{2f_{ce}}/P_{f_{ce}} \approx 1$ as expected for the approximately one-dimensional character of our antennas. This one to one space-time correspondence between the f_{ce} and $2f_{ce}$ emission demonstrates that the f_{ce} emission is both black-body and generated at the $f = f_{ce}(R)$ layer.

This result is in sharp contrast to the spectral measurements of Costley et al.,^{4,10} for which the $P_{2f_{ce}}/P_{f_{ce}}$ ratio varied between ~ 2 and ~ 8 , instead of remaining at a fixed value of $\sim 2(2f_{ce}/f_{ce})^2 = 8$. We believe that this discrepancy between our results and theirs is due first to the fact that our antennas are approximately one dimensional and select only the extraordinary polarization, and secondly, to the fact that we detect the f_{ce} emission from the accessible side of the plasma.

The black-body emission near f_{ce} can be explained with the following theoretical model. By thermal excitation, electrostatic Bernstein waves build up to their black-body value of κT_e per mode near the cyclotron layer in accordance with the equipartition theorem.² These waves propagate towards the upper hybrid layer (lower B_ϕ) and undergo complete mode conversion into extraordinary electromagnetic waves near the upper hybrid layer. Finally, the electromagnetic waves then propagate in the direction of increasing B_ϕ , cross the cyclotron layer with negligible attenuation, and reach the antenna at the inside of the torus. In the literature, it has been shown analytically^{6,11} and by numerical solution of the wave equations¹² that, when the Bernstein wave is completely absorbed in the vicinity of the cyclotron layer, an extraordinary electromagnetic wave with $f \sim f_{ce}$, incident on the plasma from the accessible side, undergoes complete mode conversion into the Bernstein wave. Hence, the reverse process (our model) is clearly viable provided that the region near the cyclotron layer is optically thick (i.e., black) for Bernstein waves.

From the electrostatic dispersion relation for a collisionless hot plasma [Eqs. (7.13 - 7.17) and (7.21) of Bekefi² [see also Eq. (9.103) of Stix⁵]] and taking account of the effects of the relativistic mass increase,¹³ one can show that for large $\alpha_n = (2\pi/k_n v_T)(f + nf_{ce})$ and $\lambda = k_{\perp}^2 v_T^2 / 8\pi^2 f_{ce}^2$, the real $k_{\perp R}$ and imaginary $k_{\perp I}$ components of the Bernstein wave propagation constant with $f \approx f_{ce}$ may be written

$$k_{\perp R} \approx (4/\pi^{1/2})^{1/3} (2\pi f_{ce}/v_T) \{f_{pe}^2/[f^2 - (f_{ce} - \Delta f_{ce})^2]\}^{1/3}, \quad (1)$$

and

$$k_{\perp I} \approx (16\pi^{9/2} f_{pe}^2 f_{ce}^2 / k_{\perp R} v_T^3) A. \quad (2)$$

Here $\perp$ and $\parallel$ refer to directions perpendicular and parallel, respectively, to the magnetic field, $v_T^2 = 2kT_e/m$, $\Delta f_{ce} \approx f_{ce} v_T^2/c^2$ is the average relativistic decrease in the cyclotron frequency, and the line shape function A is given by¹⁴

$$A \approx (2\pi^{1/2}/k_{\parallel} v_T) \exp [-4\pi^2 (f - f_{ce})^2 / k_{\parallel}^2 v_T^2] \\ \text{for } k_{\parallel} v_T > 2\pi\Delta f_{ce}, \quad (3)$$

or

$$A \approx (4c^3 f_{pe} / \pi^{1/2} v_T^3 f_{ce}^2) (1 - f^2/f_{ce}^2)^{1/2} \exp \\ [- (1 - f^2/f_{ce}^2) c^2 / v_T^2] \text{ for } k_{\parallel} v_T < 2\pi\Delta f_{ce}. \quad (4)$$

The value of $k_{\parallel}$ below which damping due to relativistic broadening [Eq. (4)] outweighs that due to the usual cyclotron damping [Eq. (3)] is $k_{\parallel}/k_O \approx v_T/c$ (e.g., ~ 0.06 for $T_e = 1$ keV) where $k_O = 2\pi f_{ce}/c$.

It may be noted from Eq. (4) that the relativistic line broadening is highly assymetric and occurs only for $f \lesssim f_{ce}$. It is apparent from Eqs. (1) to (4) that the heavily damped Bernstein waves propagating along R have their frequencies in the range $(f_{ce} - \Delta f_{ce}) \approx f_{ce} (1 - v_T^2/c^2) \lesssim f \lesssim f_{ce}$.

The optical depth for Bernstein waves in a tokamak plasma ($B \propto 1/R$) is then

$$\tau = \int_0^{\ell} 2k_{\perp I} d\ell \approx a\pi^{1/2} (2\pi)^{7/3} (Rf_{ce}/c) (f_{pe}^2 v_T / f_{ce}^2 c)^{1/3}, \quad (5)$$

where $a \approx 1$ in the small $k_{\parallel}$ case of Eq. (3), and $a \approx (8/\pi\epsilon)^{1/2}$ for the relativistic line broadening case of Eq. (4). Here ϵ is the Napierian base. This optical depth is a weak function of density and temperature, and for the data of Fig. 1, Eq. (5) gives $5 \times 10^3 \lesssim \tau \lesssim 10^4$. Thus, the condition for black-body Bernstein-wave emission near the cyclotron layer is well satisfied and leads us to conclude that indeed the model we have described governs the fundamental emission.

The localization of the Bernstein wave generation permits local temperature measurement at $f_{ce}(R)$ with a spatial resolution (ΔR) similar to that obtained at $2f_{ce}(R)$. Black-body conditions are less restrictive at f_{ce} and the reduction in the receiver frequency facilitates frequency sweeping to obtain $T_e(r)$ repetitively during a single discharge. However, for accessibility the detecting antenna of f_{ce} emission must be placed at the inside of the torus whereas inside and outside locations are equivalent for the $2f_{ce}$ emission.

Cyclotron emission detection at both f_{ce} and $2f_{ce}$ is a powerful method for not only measuring the temperature profile, but also for making time-resolved studies of local perturbations in the electron temperature due to instabilities and/or electron heating. In Fig. 2, we present examples of temperature fluctuations due to MHD activity in PLT measured at f_{ce} and $2f_{ce}$. The $m = 0$ sawteeth relaxations presumably precipitated by $m = 1$ MHD oscillations inside the $q(r) = rB_{\phi}/R_0 B_{\theta}(r) = 1$ rational magnetic surface¹⁵ are shown in Fig. 2(a) (with an amplitude consistent with soft X-ray measurements⁸), and $m = 2$ oscillations in the vicinity of the $q = 2$ layer are shown in Fig. 2(b).

For the $2f_{ce}$ data of Fig. 2(b), a horn-lense antenna at the outside of the plasma was used, ($r = +50$ cm), and hence, the f_{ce} and $2f_{ce}$ oscillations are in phase as expected for $m = 2$, since the horns are $\phi = 180^\circ$ apart around the torus (toroidal mode number $n = 1$). The structure imposed by the $m = 2$ magnetic island on the temperature oscillations at the given minor circumference is clearly evident on the $2f_{ce}$ emission (viewed over a ~ 3 cm spot size) and is discernable on the f_{ce} emission (the f_{ce} spot size of ~ 16.5 cm here can be considerably reduced with the addition of a lense). The amplitudes and waveforms of the $m = 2$ oscillations of the f_{ce} and $2f_{ce}$ emissions tracked very closely throughout a discharge and with changes in magnetic field, even though they were very sensitive to the selected position relative to the $q = 2$ layer. Thus, this comparison affords additional proof that the f_{ce} emission is a black-body emission and comes from the cyclotron layer as opposed to the upper hybrid layer.

In conclusion we wish to emphasize that our results show that the f_{ce} emission is a black-body emission and the emission measurements at f_{ce} and $2f_{ce}$ indeed provide a powerful diagnostic tool in tokamak fusion research. We have demonstrated that by this method one can measure not only the temperature profiles but also the local MHD temperature fluctuations. We believe that our experimental and theoretical demonstration of the black-body nature of the cyclotron layer lends significant support to the use of ECRH auxiliary heating in tokamaks.

The authors would like to acknowledge the valuable assistance received from the members of the PLT group. Special thanks are due the Thomson Scattering group which provided temperature profiles for comparison.

REFERENCES

*Work supported by U.S. Energy Research and Development Administration, Contract EY-76-C-02-3073.

†Permanent address: Centre d'Etudes Nucleaires, Fontenay-aux-Roses, France.

- ¹M. N. Rosenbluth, Nucl. Fusion 10, 340 (1970).
- ²G. Bekefi, Radiation Processes in a Plasma, (Wiley, New York, 1966).
- ³F. Engelmann and M. Curatoto, Nucl. Fusion 13, 497 (1973).
- ⁴A. E. Costley, R. J. Hastie, J. W. M. Paul, and J. Chamberlain, Phys. Rev. Lett. 33, 758 (1974); TFR Group and NPL Submillimeter Wave Group (A. E. Costley), Proceedings of the European Conference on Controlled Fusion and Plasma Physics (CRPP, Lausanne, 1975) paper 14a.
- ⁵T. H. Stix, The Theory of Plasma Waves (McGraw-Hill, New York).
- ⁶I. Fidone and G. Granata, Phys. Fluids 10, 1885 (1973).
- ⁷TFR Group (R. Cano), Proceedings of the European Conference on Controlled Fusion and Plasma Physics (CRPP, Lausanne, 1975) paper 14b.
- ⁸J. Hosea and V. Arunasalam, Bull. Am. Phys. Soc. 21, 1159 (1976).
- ⁹V. Arunasalam, E. B. Meservey, M. N. Gurnee, and R. C. Davidson, Phys. Fluids 11, 1076 (1968).
- ¹⁰A. E. Costley, and TFR Group, Phys. Rev. Lett. 38, 1477 (1977).
- ¹¹T. H. Stix, Phys. Rev. Lett. 15, 878 (1975).
- ¹²J. J. Schuss and J. C. Hosea, Phys. Fluids 18, 727 (1975).
- ¹³Yu. N. Dnestrovskii, D. P. Kostomarov, and N. V. Skrydlov, Zh. Tekh. Fiz. 33, 922 (1963) [Sov. Phys. - Tech. Phys. 8, 691 (1964)].
- ¹⁴There are no transit-time broadening effects for collective normal modes of systems (such as Bernstein modes) or for thermodynamic black-body emission.
- ¹⁵S. von Goeler, W. Stodiek, and N. Sauthoff, Phys. Rev. Lett. 33, 1201 (1974).

773496
 Fig. 1(a). Cyclotron emission profiles at $t = 100$ msec for f_{ce} (●) and $2f_{ce}$ (○) emission. The average Thomson scattering profile (—) is shown for comparison [$T_e(0) \approx 1$ keV, $n_e = 3 \times 10^{13} \text{ cm}^{-3} (1 - r^2/40^2)$]. (b) Emission versus time at $r = 5$ cm.

773497
Fig. 2. Local MHD temperature fluctuations in PLT discharges.