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CYCLOTRON RADIATION FROM TOKAMAK PLASMAS

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An experiment is described in which the radiation from a Tokamak plasma in the region of the electron cyclotron frequency is measured. The results are compared with the prediction of the theory of the thermal cyclotron radiation.

1. Introduction

It has been well known that the main energy loss from a plasma at the thermonuclear temperature is by radiation, and the Lawson criterion [1] has been established by the balance of the thermonuclear energy gain against the bremsstrahlung radiation loss to give the condition beyond which the net positive energy gain can be obtained. For magnetically confined plasmas, there is another form of radiation loss besides bremsstrahlung, namely the cyclotron radiation loss, and if the latter can freely escape from the plasma, it amounts to a much bigger value than both the bremsstrahlung and the thermonuclear energy output [2], and it becomes impossible to achieve a breakeven condition. Whereas the bremsstrahlung energy is mainly in the wavelength shorter than the visible region, and cannot be absorbed in the expected thermonuclear plasma ($n_e \sim 10^{20}$ m^{-3}), the cyclotron radiation is in the far infrared region (the fundamental wavelength is 1 *mm* for $B=10$ *Tesla*), and can be reabsorbed by the plasma if it is reflected back to the plasma at the wall. Thus, the amount of the cyclotron radiation energy that can be trapped in the plasma has an important bearing on the realization of the thermonuclear fusion reactor, and ultimately decides the economic size of the reactor.

From these viewpoints, the cyclotron radiation loss was extensively studied at the beginning of the thermonuclear fusion research, but until recently the main cause of the energy loss was due to the particle diffusion across the confining magnetic field, and the obtained plasmas were neither hot nor dense enough and the magnetic field not strong enough for the cyclotron radiation to be one of the significant energy loss mechanisms.

During the last few years, however, Tokamak [3] has produced the plasma with high temperature and density, and long confinement time, and the scientific feasibility experiment of a fusion reactor is projected based on the Tokamak concept. And here once again the problem of the radiation loss

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has become important, namely that of the enhanced bremsstrahlung loss by high Z impurity ions[4] as well as the aforementioned efficiency of the reflector wall for the trapping of the cyclotron radiation.

This work has been started to study the latter problem of the likely importance of the cyclotron radiation in a thermonuclear fusion reactor. In addition, there is a possibility of using the cyclotron radiation as a plasma diagnostic tool[5]. In this paper, first the theory of the thermal cyclotron radiation is presented for the condition pertinent to the experimental setup, and secondly some preliminary experimental results are presented and compared with the theory. Finally, the discussions and the direction of the further refinements of the theory and experiment are given.

2. Theory

2.1. Slab approximation and transport equation

The experimental setup is shown in Fig. 1. As the ray coming out of the plasma to the detector is near normal to the magnetic field (the solid angle subtending from the plasma to the detector is about 3×10^{-4}), slab approximation, Fig. 2, is used. Furthermore, the following assumptions are made, implications of which on the results will be discussed in 4;

(i) low temperature limit $v/c \ll 1$ (field inhomogeneity provides all the broadening of the spectrum),

(ii) constant electron density n_e and temperature T_e across the slab,

(iii) field variation across the slab is expressed by[2]

$$\vec{B} \simeq B_0\left(1-\frac{x}{R_0}\right)\hat{i}_\varphi \tag{1}$$

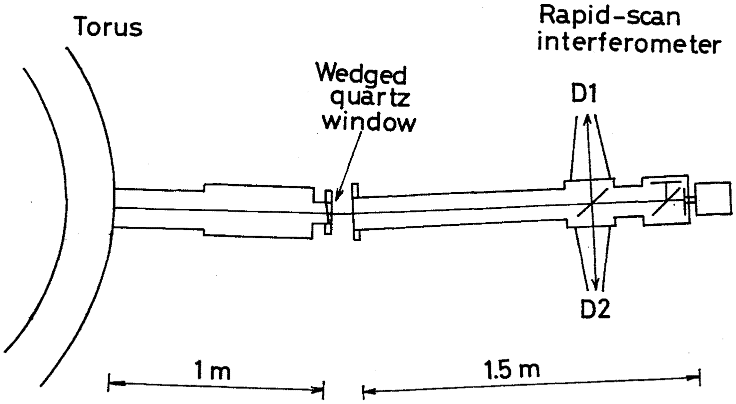

Fig. 1 Arrangement of the equipments.

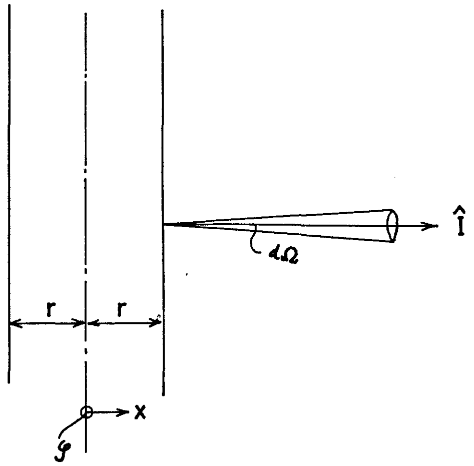

Fig. 2 Slab approximation. Radiation is at a right angle to the plasma surface and to the magnetic field.

where R_0 is the major radius of a torus and i_φ is the unit vector in φ-direction, and

(iv) reflection from the wall is neglected.

The radiative transport equation[6] for the propagation perpendicular to the slab is

$$\frac{dI}{dx}=R-\alpha I \tag{2}$$

where I is the radiation flux, and R and α are the emission and the absorption coefficients, respectively. Using the Kirchhoff's law in Eq. (2) yields after integration

$$\hat{I}=I_B\left\{1-\exp\left(-\int_{-r}^{r}\frac{R}{I_B}dx\right)\right\} \tag{3}$$

where I_B is the black-body intensity and the boundary condition $I|_{x=-r}=0$ is used (assumption (iv)).

The cyclotron emission coefficient in the n-th harmonic for the present condition is given by*

$$R_n=\frac{n_e e^2\omega^2}{8\pi^2\varepsilon_0 c}\left(\frac{\kappa T_e}{2m_e c^2}\right)^n \frac{n^{2n-2}n!}{[(n-1)!]^2}\delta(\omega-n\omega_b) \tag{4}$$

(in $watts/m^3\cdot sr\cdot(sec)^{-1}$) where ω_b is the cyclotron frequency and other notations have the obvious meanings in MKS unit. The radiation is linearly

* Using the approximation $v/c\ll 1$ in Eq. (6.14) of Ref. 6, we get this expression after integrating the resulting equation with respect to the Maxwell distribution at the electron temperature T_e.

polarized whose electric field is perpendicular to the magnetic field.

The black-body intensity is given by (Rayleigh-Jeans formula)

$$I_B = \xi T \omega^2 \tag{5}$$

where $\xi = \kappa / 8\pi^3 c^2$.

Using Eq. (1) in $\omega_b = eB/m_e$ gives

$$dx = -\frac{R_0}{\omega_0} d\omega_b \tag{6}$$

where $\omega_0 = eB_0/m_e$.

Substituting Eqs. (4), (5), and (6) into the exponential factor of Eq. (3) yields

$$-\int_{-r}^{r} \frac{R}{I_B} dx = -\sum_{n=1}^{\infty} \frac{n_e e^2}{8\pi^2 \varepsilon_0 c \xi T} \left(\frac{\kappa T_e}{2m_e c^2}\right)^n \frac{n^{2n-2} n!}{[(n-1)!]^2} \frac{R_0}{n\omega_0} \int_{\omega_0\left(1-\frac{r}{R_0}\right)}^{\omega_0\left(1+\frac{r}{R_0}\right)} \delta\left(\omega_b - \frac{\omega}{n}\right) d\omega_b \tag{7}$$

Because the overlapping of the harmonics does not occur for the case of interest as shown in the next section, the spectrum can be calculated for each harmonic separately. Note that the broadening of the spectrum is, because of the assumption (i), completely due to the field inhomogeneity, and the n-th harmonic has the spectral width n times that of the fundamental mode.

2.2. Spectra and power

Spectra are calculated for various parameters of a plasma, and an example is shown in Fig. 3, which is for $n_e = 2 \times 10^{19}\ m^{-3}$, $T_e = 5 \times 10^6\ °K$, $B_0 = 2$ *Tesla*, $R_0 = 0.9\ m$, and $r = 0.09\ m$. In this example, the fundamental mode is trapped in the black-body intensity but harmonics are not.

Integrating Eq. (3) over frequency ω, we get the radiated power, which is shown in Fig. 4 for various parameters of a plasma with the same geometrical conditions as in Fig. 3. In this calculation, a rectangular approximation (flat-topped spectrum) as shown in Fig. 3 is used for harmonics, and the errors incurred by this are negligible.

3. Experiment

The plasma on which the experiment was performed was the hydrogen plasma produced by the CLEO Tokamak at the Culham Laboratory (UKAEA)[7]. It had an electron density and temperature, on the axis of the torus 50 *ms* after the initiation ($t=0$) of the discharge, $2 \times 10^{19}\ m^{-3}$ and $2 \times 10^6\ °K$ respec-

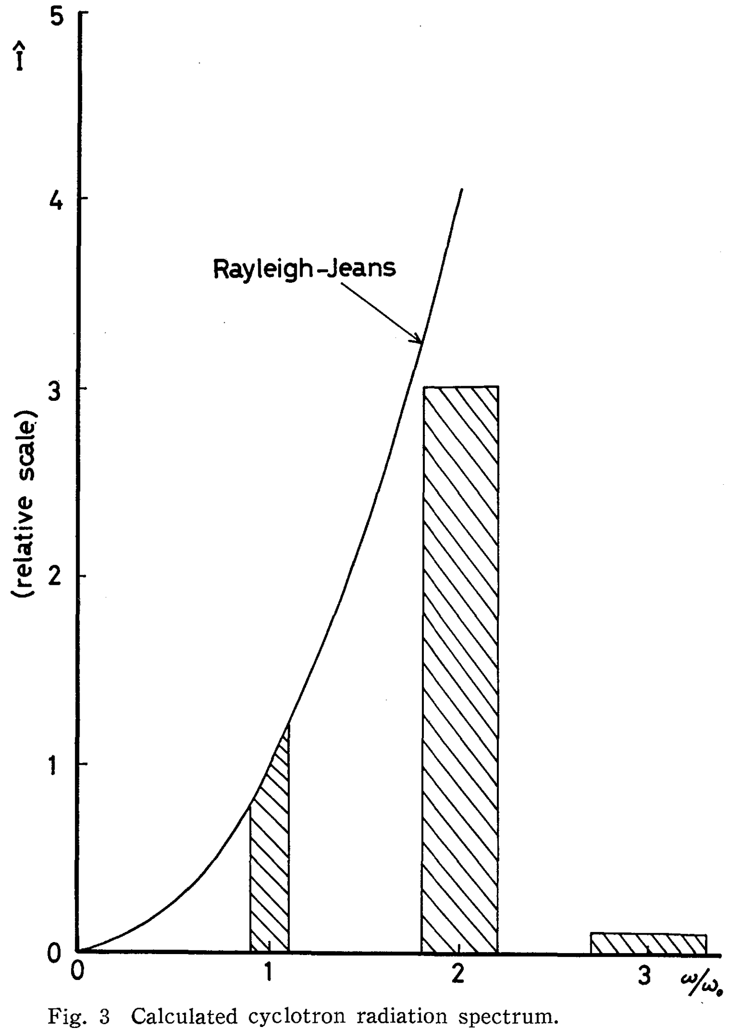

Fig. 3 Calculated cyclotron radiation spectrum.
$n_e=2\times10^{19}\,m^{-3}$, $T_e=5\times10^6\,°K$, $R_0=0.9\,m$, $r=0.09\,m$,
$B_0=2$ *Tesla* ($\omega_0=3.5\times10^{11}\,rad/sec$).

tively. It was confined for times up to 180 *ms* by a toroidal magnetic field of magnitude 2 *Tesla* (on axis).

The radiation measurements were made by a Fourier transform technique. Radiation from the plasma was directed into a two-beam interferometer (Fig. 1), the path-difference within which was rapidly (and repeatedly) scanned and the resulting interference patterns were detected and recorded. Subsequent Fourier transformation of the interference patterns and calibration of the apparatus yielded the radiation spectra.

The two-beam interferometer was of a polarization type [8] and the rapid-

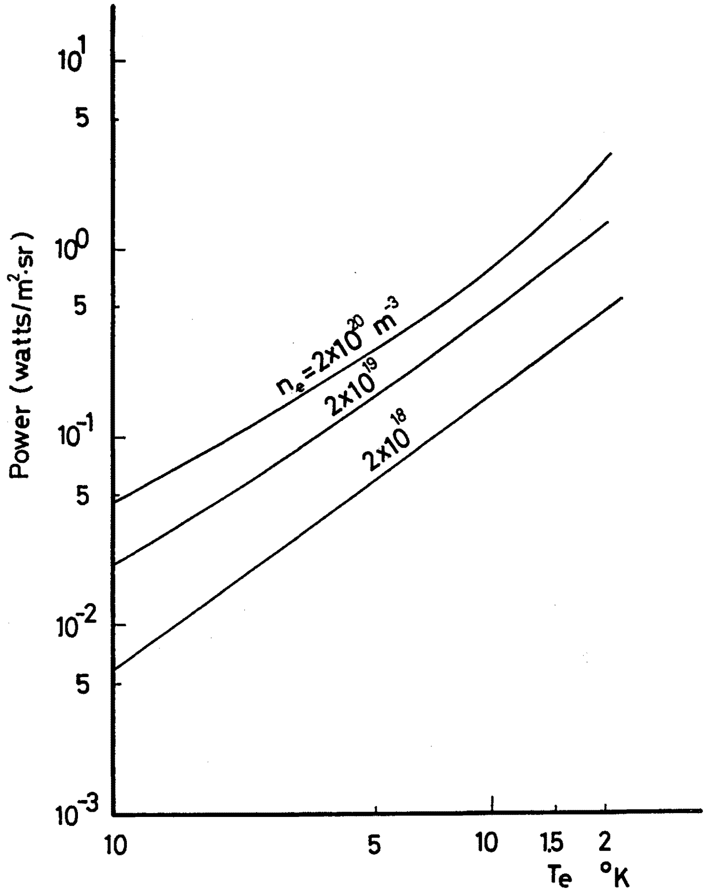

Fig. 4 Calculated cyclotron radiation power.
$R_0=0.9\,m$, $r=0.09\,m$, $B_0=2\,Tesla$.

scan was produced by oscillating one of the interferometer mirrors over a maximum displacement of 5 *mm* at 50 *Hz*. Two Putley indium antimonide detectors were used; one (D1) to monitor the level of the spectrally integrated radiation, the other (D2) to record the interferometer output. Calibration of the mirror motion was effected with an HCN laser ($\lambda=337$ *mm*) and the overall responce of the interferometer/detector arrangement was determined with a d.c. mercury arc lamp. The latter was assumed to radiate as a black-body at 300 °*K*[9].

A radiation spectrum recorded during the time interval 42 *ms* $<t<$52 *ms* on a typical Tokamak shot is shown in Fig. 5 along with the calculated results of the previous section for the given condition. The uncertainties in the method are such that the shape and frequency position of the features in the spectra are reliable to about 10 % and the absolute level to about ±

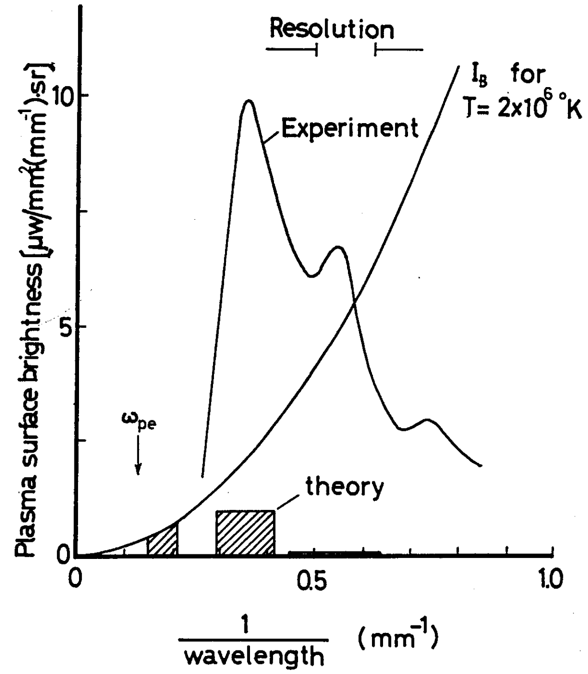

Fig. 5 Typical observed spectrum compared with a theory.

a factor of three. This latter uncertainty is a consequence of the difficulties of power calibration in this frequency region.

Experiments on the state of polarization of the radiation were carried out with free standing wire grid polarizers mounted adjacent to the quartz window and with the polarization interferometer. The radiation was found to be unpolarized at all times in the discharge history and at all frequencies in the region examined.

By comparing the output of the monitor detector with traces from x-ray monitors, a correlation between the level of the radiation and the presence of runaway electrons within the plasma was established.

On some shots, and particularly at early times in the discharge history ($t \sim 20$ *ms*), radiation spectra of the type shown in Fig. 6 were obtained. The shape of the radiation spectrum usually changed to the shape shown in Fig. 5 as t increased.

4. Discussion

We will check here the validity of the assumptions made at the beginning of the calculation (2. (i), (ii), and (iv)). First, the low temperature approximation is valid for the present purpose as $v_e = \sqrt{\kappa T_e/m_e} = 1.3 \times 10^7$ *m/sec* at $T_e = 1$ *kev* and most electrons satisfy the condition $v/c \ll 1$. Secondly,

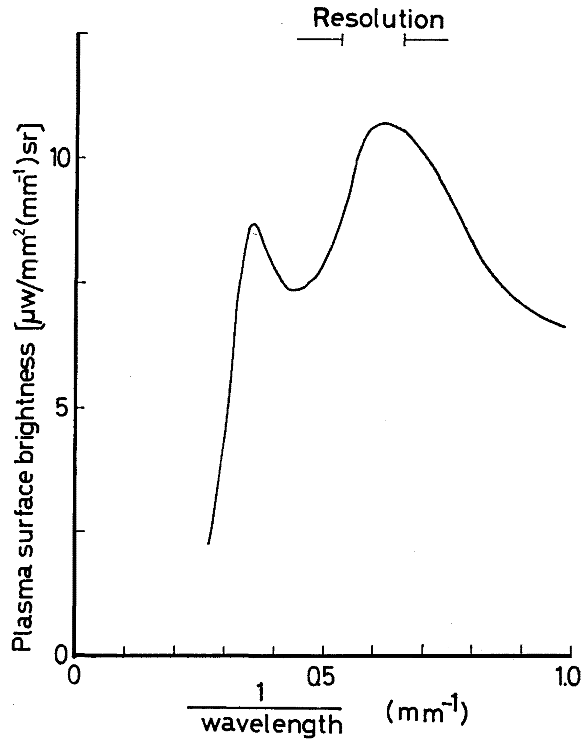

Fig. 6 Spectrum at an early time of a Tokamak discharge.

as the spectrum and radiated power are only weakly dependent on the electron density, and the measured electron temperature distribution across a torus minor diameter in a Tokamak [10] is quite well approximated by a rectangular one, constant n_e and T_e across the slab is a good approximation. And thirdly, the assumption of the negligible reflection from the wall is of some doubt, and multireflection of the radiation within the torus may account for the unexpected observations that the radiation was unpolarized and the appreciably higher radiation intensity than the calculated. Radiation from highly energetic runaway electrons may account for the relatively broad early time spectra.

Recently, some explanations have been given on these points [11], but the experiments are only preliminary, and more extensive measurements are needed before conclusive arguments can be given.

Preparations are now being made to measure the cyclotron radiation from SPAC-II [12] which has a controllable amount of runaway electrons, and from JIPP-T II of the Institute of Plasma Physics, Nagoya University which should give more reproducible plasmas with higher temperature and magnetic field than the CLEO Tokamak.

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