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LETTER TO THE EDITOR

Ion Cyclotron Emission from Charged Fusion Products

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Abstract - Ion cyclotron emission (ICE) spectra from ohmically heated D^+ JET tokamak plasmas have been measured. In the range 10-100 MHz the spectra show characteristic peaks having frequencies proportional to the magnetic field B_T and intensities correlated with the DD fusion neutron yield. We examine a model in which cyclotron emission from the charged fusion products generates the ICE spectrum.

The possibility of observing optically thick (τ>>1) ICE in large and dense thermonuclear tokamak plasmas has stimulated experiments on TFR (CLARK 1984) and on JET (COTTRELL 1985) to attempt to measure emission from thermal ions. If, however, the plasma contains an additional population of 'hot' ions with $E \gg kT_i$ (arising for example from injected ions or confined fusion products), then the ICE level is enhanced above the thermal level. In the earlier JET work, typical spectra (Fig 1) were found in which the emission patterns change frequency in proportion to the magnetic field. In this paper we have now found, in addition, that the level of ICE emission for the major spectral peaks is proportional to the measured DD reaction rate of the plasma. In the experiments on ohmic D^+ plasmas discussed here, the primary DD reactions of most importance are:

$$ {}^2_1D + {}^2_1D \begin{cases} \nearrow\ {}^3_2He\ (0.8\ MeV) + {}^1_0n\ (2.5\ MeV) \\ \searrow\ {}^3_1T\ (1.0\ MeV) + {}^1_1P\ (3.0\ MeV) \end{cases} \quad (1) $$

We have attempted, experimentally, to identify the ICE mechanism as emission from the charged products of (1), by deliberately replacing a fraction of the D^+ ions with H^+ ions thereby changing plasma reactivity and observing changes to the ICE intensity. In a sequence of discharges of almost constant overall conditions (I_p = 2.0 MA, B_T = 2.6 T, $\bar{n}_e = 1.5 \times 10^{19}\ m^{-3}$), the D^+ fraction was varied by replacing the torus filling gas with H_2. Although complete replacement was not possible (owing to desorption of D_2 from the vessel walls), the total DD reaction rate (Y_{DD}) derived from 2.5 MeV neutron flux measurements (JARVIS et al 1984) was reduced by a factor ~ 6. ICE measurements were made using the calibrated system described earlier (COTTRELL 1985) in which an ICRF antenna (JACQUINOT et al 1985)is used as detector. In the range (25-47) MHz the antenna response has been measured by transmission and reflexion measurements. No corrections have been applied at higher frequencies. The antenna was used in dipole configuration with $k_{//} = (0 \pm 5)\ m^{-1}$ and is polarised to receive the fast magnetosonic wave. Fig. 1 shows two superposed spectra from two discharges, having different values of Y_{DD}. Qualitatively, the spectra are similar to the ones measured earlier in JET in which the frequencies of the peaks A-E were found to be proportional to the magnetic field, B_T, thus indicating a cyclotronic origin. The observed proportionality (over a range of almost three orders of magnitude) between the amplitude of the ICE and the fusion reaction rate Y_{DD}(Fig. 2) indicates a connection between the ICE generation and the birth of the fusion products.

It is of interest to compare the measured ICE intensity with the expected thermal blackbody level associated with the bulk ions (temperature T_i). In the optically thick state, the power coupled to the antenna is given by $P_{BB} = I_{BB}\left[1-\rho_c^2\right] \Delta f\ \Delta\Omega\ \Delta A$ where ρ_c is the voltage reflexion coefficient at the antenna/plasma interface and Δf,$\Delta\Omega$, and ΔA are bandwidth, solid angle and antenna area respectively. The blackbody intensity $I_{BB} = \omega^2 kT_i/8\pi^3 c^2$. Assuming a parabolic form for $T_i(R)$, Fig. 1 shows the expected spectrum for $2\omega_{cD}$ blackbody emission. This result shows that the broad underlying emission could be of thermal origin, but the bright peaks A-E must be superthermal.

To calculate the source term for the fusion product emission, we have used an orbit code to model the ICE distribution from the particles. The code traces the full individual orbits (MARTIN 1985). We have modelled the D-shaped JET magnetic geometry and have included both the Shafranov shift as well as divergence free fields. At each point along the orbit, the extraordinary mode contribution (BEKEFI 1966) to each harmonic of the cyclotron frequency $n\omega_{ci}$ for the i^{th} particle of charge +Ze and perpendicular velocity $v_\perp$ is calculated,

$$P_{in} = \frac{(Ze)^2 \ \omega_{ci}^{\ 2} N}{8\pi^2 \ \varepsilon_o c} \cdot \left[\frac{n \ v_\perp N}{c}\right]^2 \quad J_n'^2 \left[\frac{n \ v_\perp N}{c}\right] , \tag{2}$$

where $N(\approx \omega_{pi}/\omega_{ci})$ is the local refractive index. For the conditions of the experiments (Fig. 1) we have launched 10,000 test particles with an isotropic birth velocity distribution and with incremental scans in launch position. The distribution was weighted according to a peaked birth profile of the form $(1-(r/a)^2)^P$ with $5 \leq P \leq 10$. The final spectra were rather insensitive to the value of P and we chose P = 7 as a reasonable value.

In order to keep computing time within tolerable limits, calculations were stopped after one full orbit. The effect of the slowing-down history of the fast ions was then introduced retrospecively by weighting the 1-orbit calculated spectra with the factors

$$W_{in} = [\ \tau_i/f_i(v_b) \ P_{in} \ (v_{\perp b})] \int_o^{v_b} f_i(v) \ P_{in}(v_\perp) \, dv \tag{3}$$

where τ_i is the slowing down time for the i^{th} fusion product, $f_i(v)$ is its velocity distribution function, v_b the birth velocity of the ion and P_{in} the ICE power as a function of harmonic number, n. The result is shown in Fig. 3a.

The effect of bulk plasma absorption at harmonics (2-4) of the cyclotron frequency $(\omega = n\omega_{cD})$ was treated by appealing to a simple plane-parallel wall reflexion model giving the resultant intensity at the antenna;

$$I_A \ \alpha \ \frac{S_{FP} \ e^{-\tau} + S_{th} \ (1-e^{-\tau})}{(1 - r^2 \ e^{-2\tau})} \tag{4}$$

where S_{FP} and S_{th} are the source terms respectively for the fusion product and blackbody thermal emission and r is an effective wall reflectivity (assumed to be independent of frequency). The single path absorption coefficient: τ was based on assuming a pure D^+ plasma; for the case of second harmonic absorption we have

$$\tau_{2\omega cD} = \frac{\pi}{2} R_o \frac{\omega_{pi}}{c} \beta_i \qquad (5)$$

where β_i is the ion beta (BRAMBILLA 1982). The result is shown in Fig. 3b. This model shows the enhancement of the emission by wall reflections as well as the partial absorption of the 3 MeV ^1_1P emission peak (n = 1). The first significant peak in the spectrum (at ≈ 27 MHz) lies close to a measured peak (A in Fig. 1) and comes from ^3_2He (n = 1) radiation. The second significant peak in Fig 3b is seen at ≈ 45 MHz and lies close to measured peak B in Fig. 1, although it is broader. The effect of the absorption in this frequency range is to not only depress the intensity of the ^1_1P (n = 1) peak but also up-shift its apparent maximum frequency. The self-absorption model (Eq 4) generally shows reasonable qualitative agreement with experiment using a fitted value r = 0.8, although at high frequencies (> 50 MHz), uncertainties in the frequency response of the antenna makes detailed comparison difficult. Detection below 20 MHz is strongly attennuated by a cut-off in an impedance matching transformer. We note that this simple absorption model includes no ion-ion hybrid effects. Close to the hybrid resonance frequency (in Fig 1 this is at around 40 MHz) we recognise that the absorption may be enhanced. In order to explain the finer details of the observed spectra it will be necessary to consider three improvements in our model. Firstly it will be important to follow the particle orbits for the whole slowing-down history. This will influence the width of the emitted spectral lines as the orbits change size. Secondly, it may be important to include a more realistic toroidal wall reflexion model; this will influence the spectra in the weak damping limit. Thirdly, in the strong damping limit, the antenna response pattern may be significant. Nevertheless, even with a simple model it has been possible to explain the gross features of the ICE spectra namely i) the existence of peaks A and B at frequencies which are proportional to the magnetic field, B_T, and ii) the correlation of intensity with fusion reaction rate and therefore density of fusion products in the discharge.

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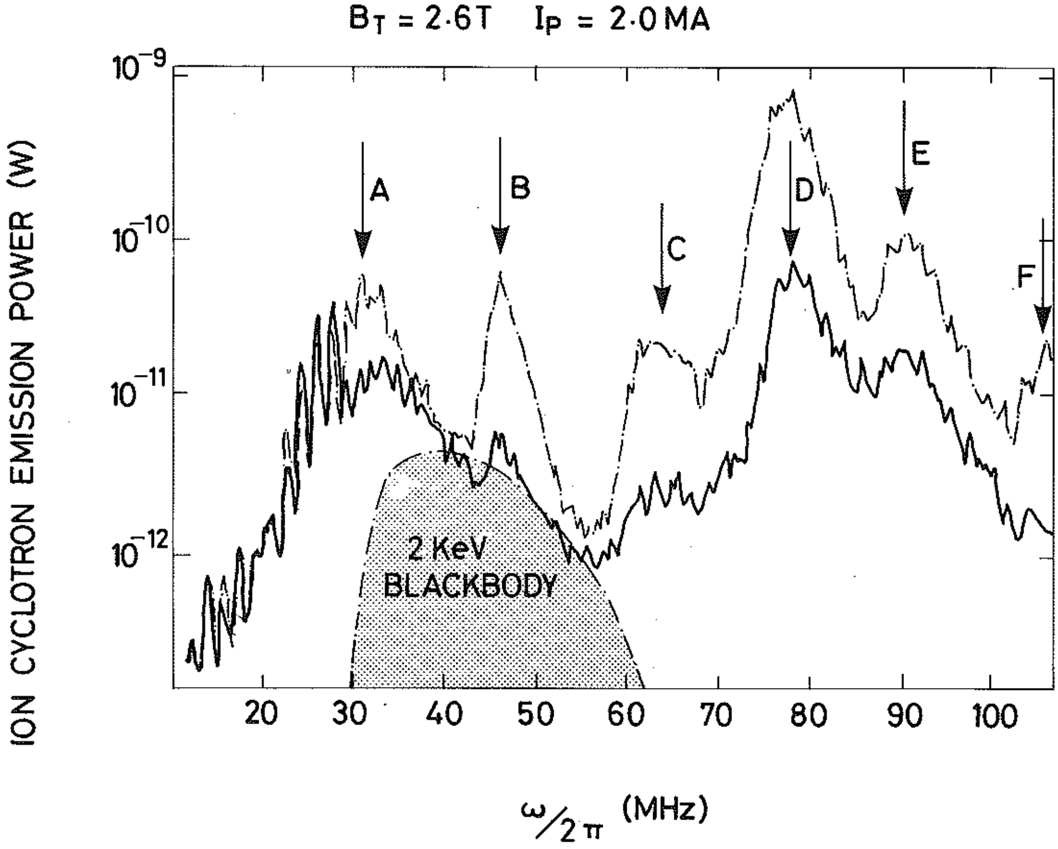

Fig. 1 Ion cyclotron emission (ICE) spectra from two JET D^+ ohmic discharges with different DD fusion reactivities. Upper (dashed) spectrum obtained with a total fusion neutron yield ~ 6 times the value corresponding to the lower (solid) spectrum. This was achieved by dilution of the D^+ with H^+ ions (upper curve: $n_H/n_D \sim 0.3$, lower curve $n_H/n_D \sim 0.8$). Other plasma parameters were almost constant. For comparison, the shaded region shows the expected thermal blackbody spectrum ($\omega = 2\omega_{cD}$) from the majority ions.

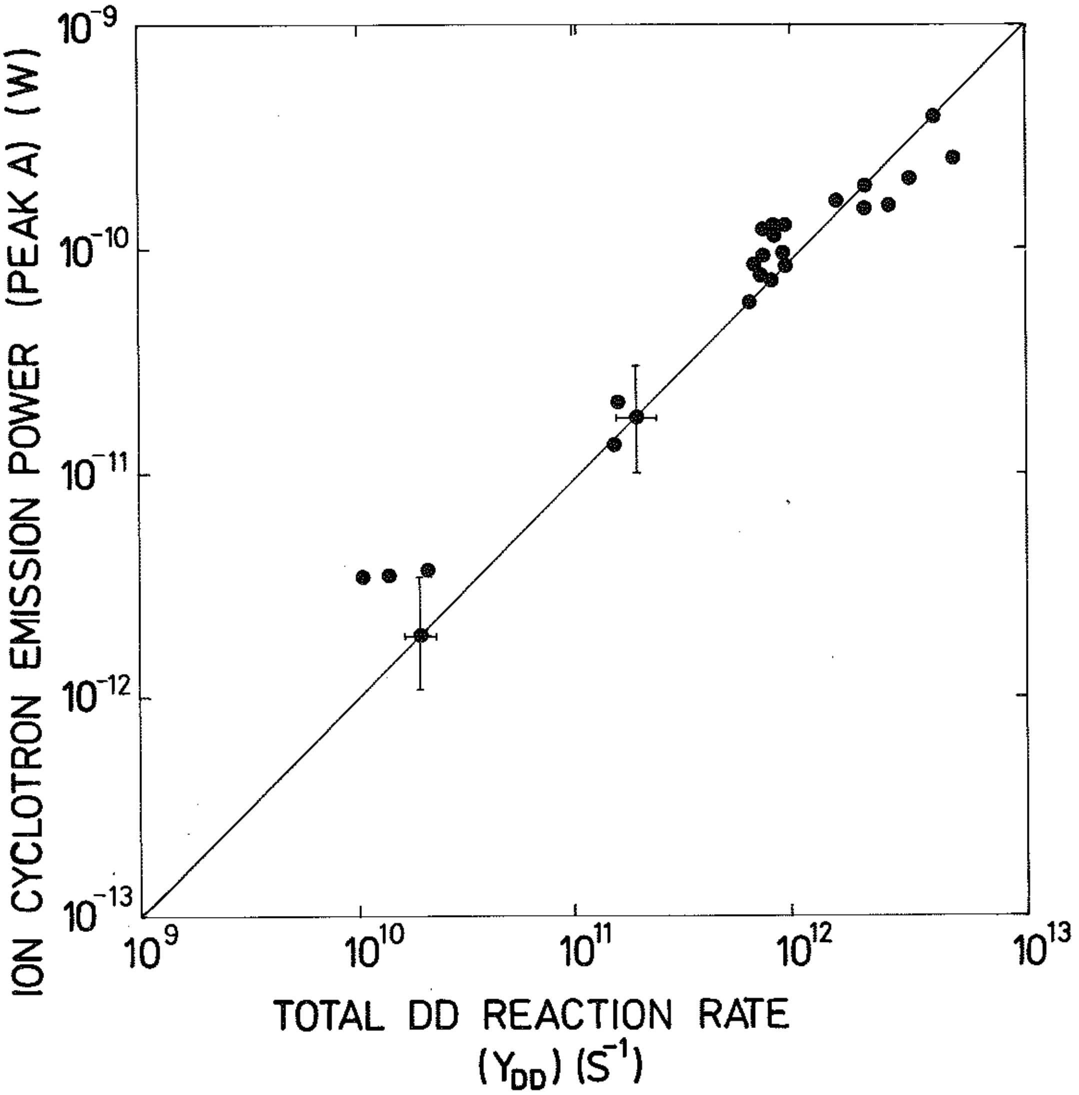

Fig. 2 Variation in measured intensity of an ICE peak (A in Fig. 1) with total DD reaction rate, Y_{DD}, determined from 2.5 MeV fusion neutron measurements.

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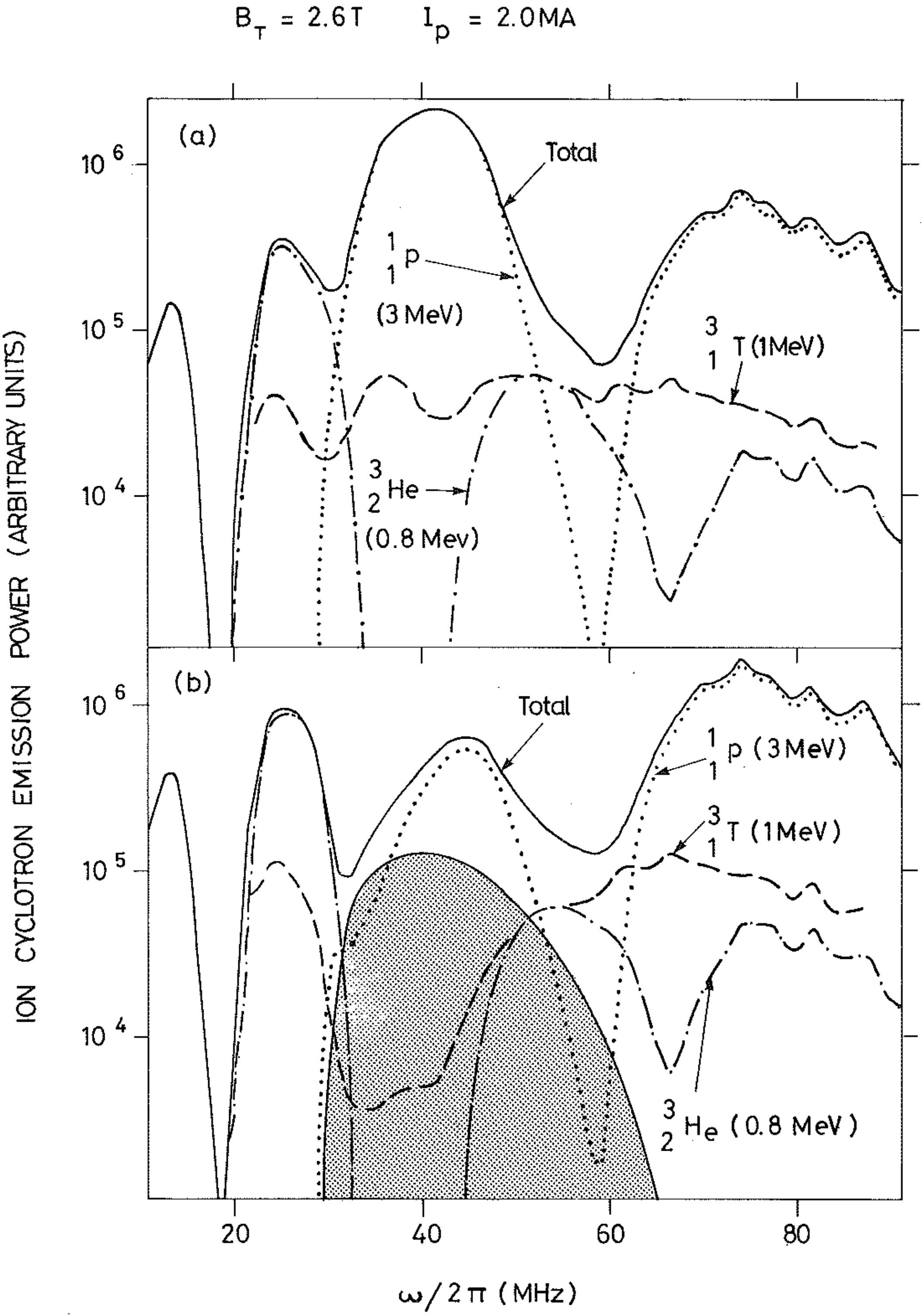

Fig. 3 (a) Calculated source emission ICE spectrum for the conditions of Fig. 1. Correction has been made for the slowing down distribution function of the fusion products. No correction has been applied for ths self-absorption of the ICE radiation at harmonics of the bulk ions ($\omega = n\omega_{cD}$) and the effect of multiple reflexions at the plasma boundary. (b) Same calculation as in (a) except that the bulk plasma absorption model has now been included together with an effective wall reflectivity $r = 0.8$. The component of thermal radiation from the bulk ions ($T_i(0) = 2\,\mathrm{keV}$) is shown by the shaded curve for the second harmonic ($\omega = 2\omega_{cD}$).