

# RECENT OBSERVATIONS AND INTERPRETATION OF ION CYCLOTRON EMISSION IN JET

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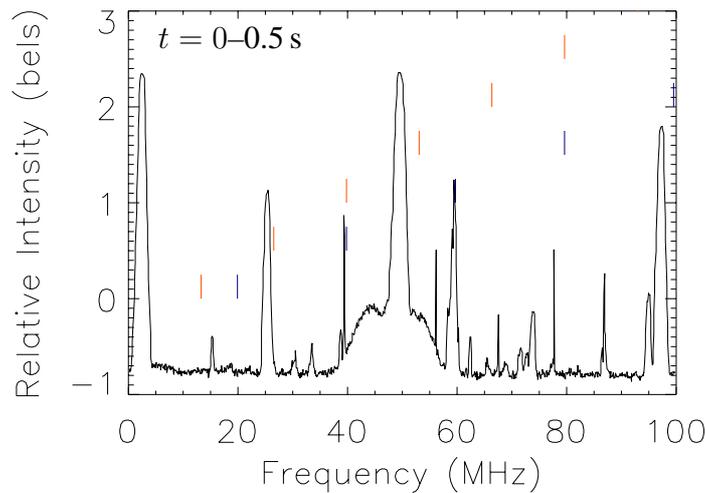
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## 1. Introduction

Spectrally-structured wave excitation at frequencies close to cyclotron harmonics of an energetic ion species is a generic feature of space and fusion plasmas. Examples of plasmas in which such emission has been observed include the Earth's magnetosphere [1] and the outer edge regions of large tokamaks [2]. Such waves, referred to in the fusion literature as ion cyclotron emission (ICE), provide useful information on the behaviour of fusion products (particularly  $\alpha$ -particles) in JET. The study of ICE in JET should facilitate predictions of  $\alpha$ -particle behaviour in Next Step devices such as the International Thermonuclear Experimental Reactor (ITER). As expected, JET discharges in the recent deuterium-tritium campaign (DTE1) have produced detectable levels of ICE. Prior to DTE1, ICE had been observed in JET in plasmas heated ohmically and by neutral particle beams (NBI) [3], in pure deuterium (D) plasmas [3], and in deuterium-tritium (D-T) plasmas [4]. In pure D ohmic plasmas the only energetic ions (hence the only source of ICE) are fusion products (protons,  $^3\text{He}$  and T). In JET, the introduction in 1991 of a low concentration of T ( $\leq 10\%$ ) produced ICE intensities ten times higher than those observed in D plasmas [4]: this was attributed to the higher D-T reaction cross-section.

## 2. ICE Measurements in DTE1

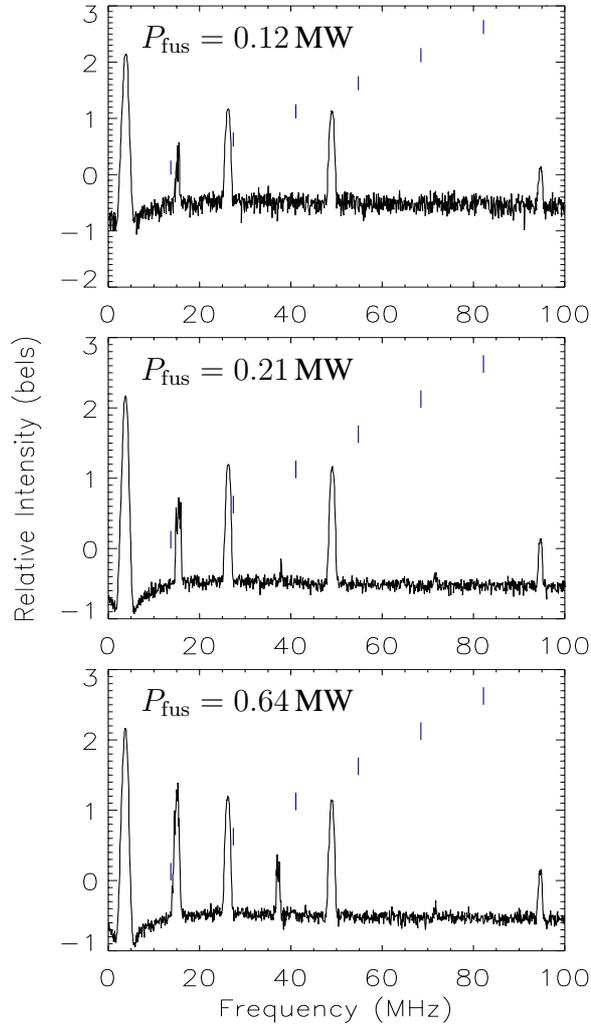
The ICE detector on JET is a fast magnetoacoustic wave antenna at the outer plasma edge, which, uniquely, can be used simultaneously as a source of ion cyclotron resonance heating (ICRH) and as a probe. A detector at the inner plasma edge has also been used. ICE has now been observed in several ICRH discharges in the DTE1 campaign.



**Figure 1.** ICE spectrum in a JET D-T discharge with NBI and ICRH (Pulse Number 42697). Orange markers indicate T cyclotron harmonics  $\ell\nu_T$  in the outer midplane ( $\ell = 1, 2, 3, \dots$ ); purple markers indicate D/ $\alpha$ -particle cyclotron harmonics  $m\nu_{D/\alpha}$  in the outer midplane ( $m = 1, 2, 3, \dots$ ).

In Fig. 1,  $t$  is measured from the start of NBI and ICRH: it takes 0.5 s to scan the frequency range 0–100 MHz. The 2 MHz peak is an artefact of the scanning process, and the 25 MHz and 95 MHz peaks are calibration markers. The 50 MHz peak is due mainly to the ICRH source, but part of this peak is also a calibration marker. Peaks with intensity 1.3–2.6 bels above the noise occur at D/ $\alpha$ -particle harmonics  $\nu \simeq m\nu_{D/\alpha}$ ,  $m = 2, 3, 4, 5$ . No comparable peaks occur at T harmonics ( $\nu \simeq \ell\nu_T$ ) which are not degenerate with deuteron harmonics ( $\nu = m\nu_{D/\alpha}$ ), despite the presence of T beams. We infer from this that the peaks at  $\nu \simeq m\nu_{D/\alpha}$  are produced by  $\alpha$ -particles rather than beam deuterons. A narrow line occurs at  $\nu = 15$  MHz, between  $\nu_T$  and  $\nu_{D/\alpha}$ ; this line also appears, with higher intensity, in a later frequency sweep. During this later period there is still a weak emission line at  $\nu = 2\nu_\alpha$ , but the higher  $\alpha$ -particle harmonics have disappeared.

In a sequence of five discharges with beam heating but no ICRH, there is emission at  $\nu \simeq \ell\nu_{D/\alpha}$ ,  $\ell \leq 3$ . Spectra from three of the discharges are shown in Fig. 2. The absence of T harmonics again implies that the emission is driven by  $\alpha$ -particles rather than beam deuterons. At the highest beam power a narrow line again appears at  $\nu_T < \nu < \nu_{D/\alpha}$ .



**Figure 2.** Spectra in JET discharges 41571–41573. The markers indicate  $\nu = m\nu_{D/\alpha}$  ( $m = 1, 2, 3, \dots$ ).

Plotting ICE intensity at the  $\alpha$ -particle cyclotron frequency versus fusion power  $P_{\text{fus}}$  in this sequence of discharges we obtain

$$I_{\text{ICE}} \propto P_{\text{fus}}^\delta, \quad \delta = 1.3 \pm 0.4. \quad (1)$$

This is consistent with a linear scaling found previously in JET [4].

### 3. Interpretation

In the model of Dendy, Cottrell and co-workers [2, 4–5] trapped  $\alpha$ -particles, born in the plasma centre with pitch angles close to the trapped–passing boundary, undergo large radial excursions to the outboard edge. The maximum radial excursion scales as the 2/3 power of the poloidal Larmor radius, and hence (for a given plasma current) as the 1/3 power of the particle energy. The  $\alpha$ -particles initially have a distribution  $f_\alpha$  which is strongly–peaked at the mean birth energy [6]: if they interact with the plasma solely through Coulomb collisions,  $f_\alpha$  evolves to a slowing–down distribution  $f_\alpha \sim 1/(E^{3/2} + E_c^{3/2})$  (where  $E_c$  is the critical energy), peaked in the plasma centre. This is referred to as classical confinement. We model the  $\alpha$ -particle distribution in the plasma edge using

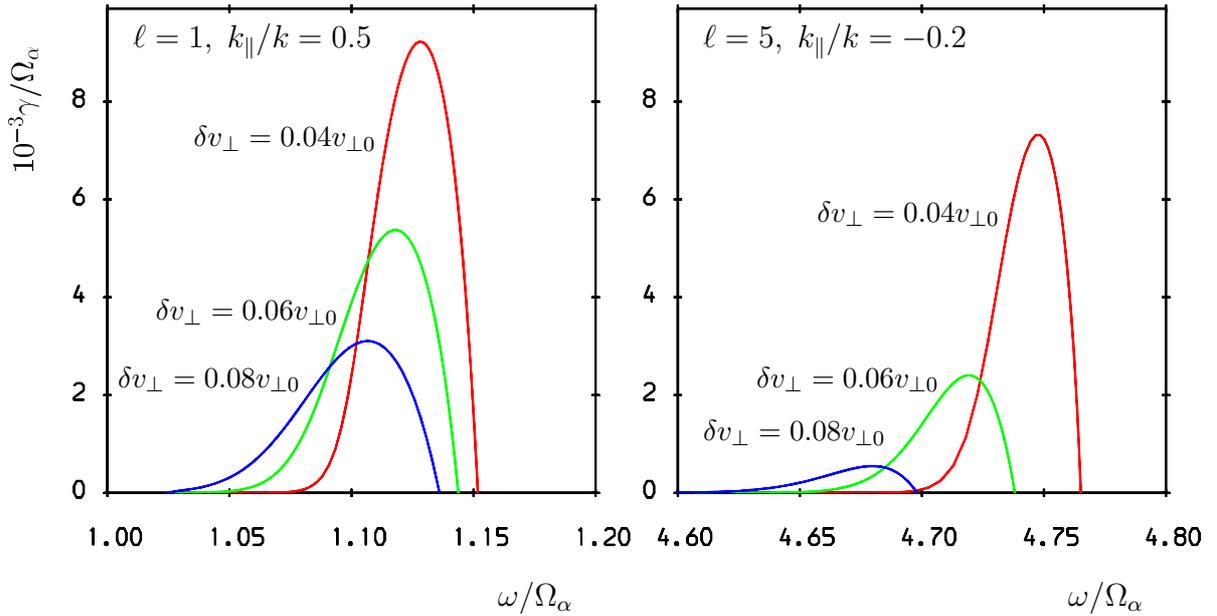
$$f_\alpha \sim \exp \left[ -\frac{(v_\perp - v_{\perp 0})^2}{\delta v_\perp^2} \right] \exp \left[ -\frac{(v_\parallel - v_{\parallel 0})^2}{\delta v_\parallel^2} \right]. \quad (2)$$

The choice of  $\delta v_\perp$ ,  $\delta v_\parallel$ ,  $v_{\perp 0}$  and  $v_{\parallel 0}$  depends on the extent to which the core  $\alpha$ -particles have slowed down, and on the  $\alpha$ -particle radial profile  $n_\alpha(r)$ : if the time elapsed since the beginning of the discharge is much less than one slowing–down time ( $\sim 1$ s) and  $n_\alpha(r)$  is strongly–peaked in the plasma centre, only  $\alpha$ -particles with a narrow range of energies and pitch angles reach the plasma edge.

The  $f_\alpha$  given by Eq. (2) is used to compute the  $\alpha$ -particle contribution to the dielectric tensor  $\varepsilon_{ij}$ : if  $\mathbf{B} = (0, 0, B)$ ,  $\mathbf{k} = (k_\perp, 0, k_\parallel)$  and  $E_\parallel = 0$  the dispersion relation is

$$\left( \varepsilon_{xx} - \frac{k_\parallel^2 c^2}{\omega^2} \right) \left( \varepsilon_{yy} - \frac{k_\perp^2 c^2}{\omega^2} \right) + \varepsilon_{xy}^2 = 0. \quad (3)$$

We have solved Eq. (3) for waves on the fast magnetoacoustic branch, using the following parameters (appropriate for the JET edge plasma):  $\delta v_\perp = \delta v_\parallel$ ,  $v_{\perp 0} = 4v_{\parallel 0} = 1.2c_A$  ( $c_A$  is the local Alfvén speed) and  $n_\alpha/n_i = 10^{-3}$ .



**Figure 3.** Computed growth rates of fast magnetoacoustic waves at  $\nu \simeq \nu_\alpha$  (left hand frame) and  $\nu \simeq 5\nu_\alpha$  (right hand frame) for various values of the perpendicular velocity width  $\delta v_\perp$ .

Wave excitation is due to the magnetoacoustic cyclotron instability (MCI), which is strongly-driven if  $\alpha$ -particles in the plasma edge are super-Alfvénic (speed  $v > c_A$ ) with a narrow range of energies and pitch angles. The growth rate is proportional to the  $\alpha$ -particle concentration  $n_\alpha/n_i$  [5]. As  $\delta v_{\parallel}$  and  $\delta v_{\perp}$  increase, the higher harmonics are stabilized first: at sufficiently large  $\delta v_{\parallel}$  and  $\delta v_{\perp}$  the growth rate falls off monotonically with  $\ell$ . Using measurements of neutron flux, ion temperature, electron temperature and electron density it is possible to compute analytically the collisional evolution of  $f_\alpha$  [2,6]: such calculations indicate that the core  $\alpha$ -particle distributions corresponding to Fig. 2 are all significantly broader, and peak at a lower speed, than that corresponding to the spectrum in Fig. 1. These results, together with the fact that  $\gamma$  is extremely sensitive to  $\ell$  and  $\delta v_{\perp}$  (Fig. 3), suggest that ICE intensity falls off more rapidly with harmonic number in Fig. 2 than in Fig. 1 because, in the former case,  $\alpha$ -particles in the plasma core have slowed-down collisionally to a greater extent.

The peak at  $\nu_T < \nu < \nu_{D/\alpha}$  appears to be an ion hybrid wave, the frequency of which in a 50:50 D-T plasma is  $\nu_{ii} = \sqrt{\nu_T \nu_D}$ . Lashmore-Davies and Russell [7] showed that the hybrid wave can be excited by fast ions. The intensity of the emission at  $\nu \simeq \nu_{ii}$  is proportional to beam power, and the line first appears when the neutron flux is very low. Thus, it is probably driven by beam ions rather than  $\alpha$ -particles. Mode conversion of the fast wave to the ion hybrid wave has been used to heat electrons in TFTR [8]. Direct excitation of the hybrid wave by fast particles could also be used to heat electrons and ions: this is one of several possible  $\alpha$ -channelling schemes [9].

#### 4. Summary

The DTE1 campaign on JET has extended the database of ion cyclotron emission (ICE). The detection of ICE in discharges with ICRH confirms that it can be used as a sensitive diagnostic of charged fusion products across a wide range of conditions. ICE is the only clear manifestation of a spontaneous collective instability driven by  $\alpha$ -particles in JET. It poses no threat to plasma performance: the total power is less than about 1 mW in discharges with several MW of fusion power. Spectra from discharges with high power beam heating contain evidence of ion hybrid wave excitation by fast particles (beam ions). A model based on classical  $\alpha$ -particle confinement is consistent with observations of high intensity cyclotronic emission. This strengthens confidence in extrapolations, based on this premise, of  $\alpha$ -particle behaviour in ITER.

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