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Observations and Interpretation of Energetic Particle–Driven Ion Cyclotron Emission from JET DT Plasmas

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ABSTRACT

Ion cyclotron emission (ICE) excited by collective instability of fusion α-particles has been observed during deuterium-tritium experiments with radio-frequency heating and neutral beam injection (NBI) in JET. A model based on classical α-particle confinement is broadly consistent with this data. ICE spectra from discharges with high power NBI also show evidence of ion hybrid wave excitation by beam ions, relevant to α-channelling.

1. INTRODUCTION

Collective effects driven by fusion α-particles in deuterium-tritium (DT) plasmas have been a primary research objective of JET [1] and TFTR [2]. The most easily-excited such phenomenon is spectrally-structured, suprathermal ion cyclotron emission (ICE). Because of the crucial role played by confined α-particles in sustaining a thermonuclear plasma, and the difficulty of detecting such particles by other means, the mechanism of α-particle-driven ICE has been of considerable theoretical interest [3-5]. The consensus is that emission of α-particle-driven ICE is due to the magnetoacoustic cyclotron instability (MCI) [6], involving fast Alfvén wave excitation at α-particle cyclotron harmonics by centrally-born, marginally-trapped fusion products undergoing radial drift excursions to the outer edge plasma. The velocity distribution of fusion products traversing that region peaks at finite speed and pitch angle, thereby driving the MCI.

2. OBSERVATIONS

ICE data from JET DT plasmas were obtained with a fast wave antenna at the outer plasma edge, used primarily as a source of ion cyclotron resonance heating (ICRH) but also as a receiver [1]. Recently, an inboard probe has been used to detect ICE from deuterium (D) JET plasmas with heated minority hydrogen [7]. The spectra in Fig.1 were obtained using the outboard detector by sweeping through the range 0-100 MHz over 0.6 s intervals in optimized shear DT pulse 42697, with combined ICRH (6 MW) and NBI (8-20 MW). Dashed bars indicate harmonics of the tritium (T) cyclotron frequency in the outer midplane ν_T; solid bars indicate harmonics of the D/α-particle cyclotron frequency $\nu_{D/\alpha}$. In the first spectrum there are four high intensity peaks whose frequencies ν lie close to the second, third, fourth and fifth harmonics (40 MHz, 60 MHz, 80 MHz and 100 MHz) of $\nu_{D/\alpha} \simeq 20$ MHz. The signal at $\nu \simeq 100$ MHz may incorporate second harmonic emission from the ICRH source [7]. ICE

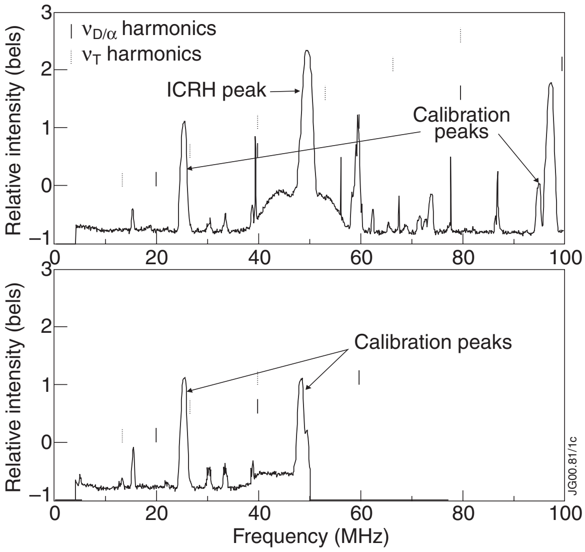

Fig.1: ICE spectra at t = *0-0.6 s (upper plot) and* t = *0.6-1.2 s (lower plot) in pulse 42697.*

spectra observed previously in DT plasmas show emission at cyclotron harmonics of beam ions as well as fusion products in the outer midplane edge [2,8]. The beam T fraction in pulse 42697 was 30 %. However, there is no strong emission at T harmonics other than those coinciding with D harmonics, and so there are strong indications that the spectrum incorporates fusion product-driven ICE. In the second spectrum there is no emission at $\nu_{D/\alpha}$, but there is a weak peak at $\nu \simeq 2\nu_{D/\alpha} \simeq 40$ MHz (the plasma had disrupted by the time the spectrum analyser reached 60 MHz). In both spectra there is a narrow line between ν_T and $\nu_{D/\alpha}$.

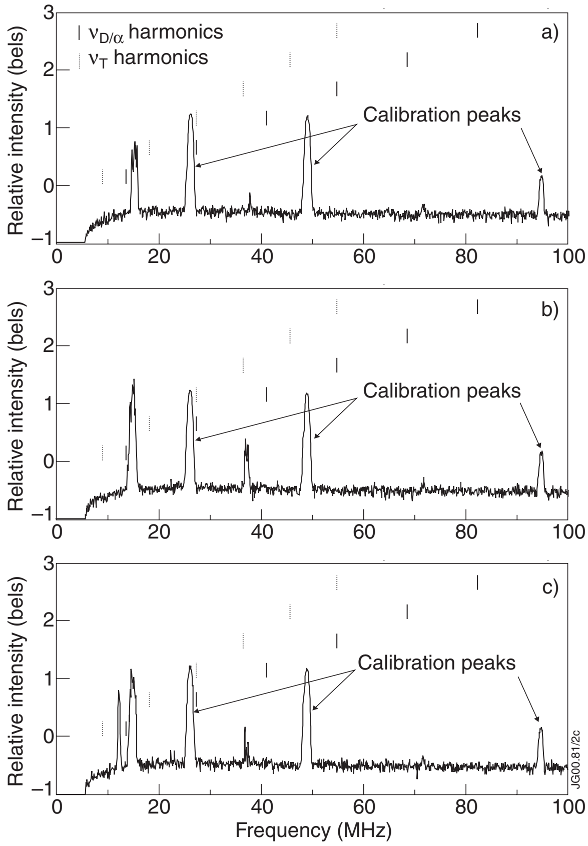

Fig.2: Spectra in pure NBI pulses (a) 41572 (P_{fus} = 0.21 MW), (b) 41573 (0.64 MW), (c) 41574 (0.56 MW).

Figure 2 shows spectra from a sequence of H-mode DT pulses (41572-41574) in which pure T NBI was the only source of auxiliary heating: similar data were obtained during pulses 41571 and 41576. In every case the strongest emission occurs at $\nu \simeq \nu_{D/\alpha}$. For pulses 41571-41576 we can determine a relation between ICE intensity P_{ICE} at $\nu \simeq \nu_{D/\alpha}$ and neutron flux S_n. Setting $P_{ICE} \propto S_n^{\delta}$ we obtain $\delta = 1.3 \pm 0.4$, consistent with a linear relation observed previously [1] and suggesting α-particle drive. In pulse 41574 a narrow line again appears between ν_T and $\nu_{D/\alpha}$.

3. MODELLING AND INTERPRETATION

The maximum radial excursion Δ_α of a centrally-born trapped α-particle is [9] $\Delta_\alpha \simeq 8.8a\,(a/R_0)^{1/3}\,[m_\alpha v_\perp/(Z_\alpha e \mu_0 I_p)]^{2/3}$, where: R_0, a are major and minor radii; m_α, $Z_\alpha e$ are α-particle mass and charge; $v_\perp$ is perpendicular speed in the plasma centre; μ_0 is free space permeability; and I_p is plasma current. Setting $R_0 = 3$ m and $a = 1$ m for JET, we find that particles with speed v reach the plasma edge ($\Delta_\alpha \geq a$) if $v/v_\alpha \geq 0.3 I_p$ (MA) cosec ϕ, where $v_\alpha \simeq 1.3 \times 10^7$ ms^{-1} is the mean birth speed and ϕ is pitch angle. In JET, a typical value of ϕ at the trapped/counter-passing boundary is 112° [5]. In pulse 42697 $I_p \simeq$ 2.4-2.8 MA and in pulses 41571-41576 $I_p \simeq$ 2.5-2.6 MA. These figures indicate that centrally-born α-particles with $v/v_\alpha \geq$ 0.78-0.9 could traverse the outer plasma edge. In order to determine the shape of the edge α-particle distribution $f_{\alpha,\mathrm{edge}}$, one can approximate analytically the collisional evolution of the distribution in the core f_α [5], and use a constants-of-motion approach [10] to relate f_α to $f_{\alpha,\mathrm{edge}}$. Using EFIT reconstructions of JET equilibria, we have evaluated the range of pitch angles [ϕ_1, ϕ_2] of α-particles whose guiding centres passed within one Larmor radius of a specified point in the outboard midplane, with major radius $R = R_{\mathrm{out}}$. One can then write

$$f_{\alpha,\mathrm{edge}}(v,t) \propto \int_{R_0}^{R_{\mathrm{out}}} dR \int_{\phi_1}^{\phi_2} \sin\phi d\phi f_{\alpha}(v,R,Z=0,t) \tag{1}$$

where Z is distance above the midplane. Figure 3 shows computations of $f_{\alpha,\mathrm{edge}}$ in pulses (a) 42697 and (b) 41573, for times $t = t_1$, when the spectrum analyzer was detecting emission at $v = v_{D/\alpha}$, and $t = t_2$, when emission at 5 $v_{D/\alpha}$ was being detected.

The slowing-down time in the core $\tau_s(0) \propto T_e^{3/2}/n_e$ was longer, and $S_n(t)$ rose more gradually, in pulse 42697 than in pulse 41573. The result is that whereas $f_{\alpha,\mathrm{edge}}$ in pulse 42697 was negligible at t_1, and strongly-peaked at t_2, in pulse 41573 the distribution was strongly-peaked at t_1, but much broader at t_2. In both cases $f_{\alpha,\mathrm{edge}}$ has a narrow radial length scale, of order 0.05 m. To assess the implications of Fig.3 we consider the stability of a model α-particle distribution

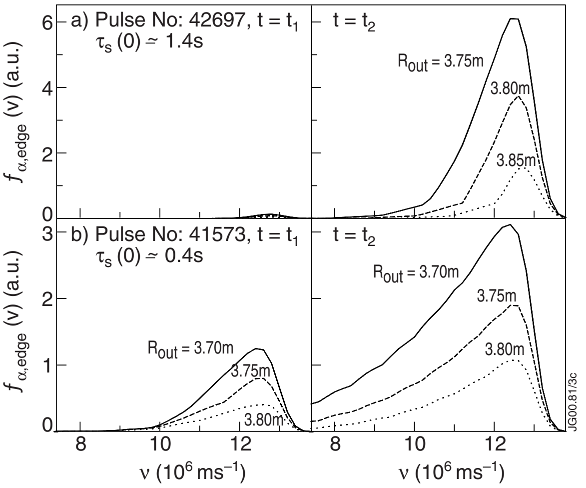

Fig.3: $f_{\alpha,edge}$ (v,t) *at various major radii* R_{out} *in pulses (a) 42697 and (b) 41573.*

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

The method used to calculate the MCI growth rate γ is described in [3]. In Fig.4 γ is plotted for $\delta v_{\perp} = \delta v_{\parallel}$, $v_{\perp 0} = 4v_{\parallel 0} = 1.2c_A$, $\delta v_{\perp}/v_{\perp 0} = 0.04\text{-}0.08$, and α-particle concentration $n_{\alpha}/n_i = 10^{-3}$. Frequency ω and γ are normalized to $\Omega_{\alpha} = 2\pi v_{D/\alpha}$. The wavevector components $k_{\parallel}$, $k_{\perp}$ give maxima in γ. For $l = 5$ instability drive is sensitive to the velocity—space width of f_{α}, the maximum γ falling by 93% when $\delta v_{\perp}$ is doubled. For $l = 1$ the drive is much less sensitive to $\delta v_{\perp}$. This dependence of γ on $\delta v_{\perp}/v_{\perp 0}$ and l, combined with the sensitivity of $f_{\alpha,\mathrm{edge}}$ to τ_s, suggests that P_{ICE} falls off more rapidly with l in Fig.2 than in Fig.1 for the following reason: α-particles traversing the edge slowed-down to a greater extent in pulses 41572-41574 than in pulse 42697, and the instability drive at high l was consequently much lower in the former.

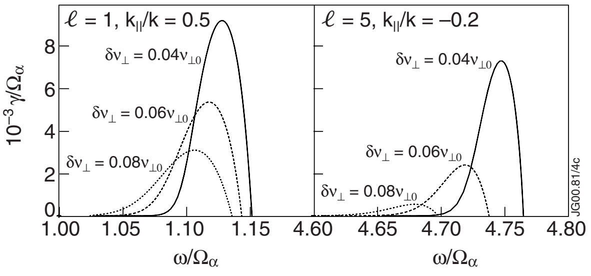

Fig.4: Computed growth rate versus ω *for* $\delta v_{\perp} = \delta v_{\parallel}$, $v_{\perp 0} = 4v_{\parallel 0} = 1.2c_A$, $n_{\alpha}/n_i = 10^{-3}$.

The peaks between v_T and $v_{D/\alpha}$ in Figs.1 and 2(c) may be due to ion hybrid waves. If this interpretation is correct, the 15 MHz line in Fig.1 was produced close to the plasma edge, while the 12 MHz line in Fig.2(c) originated from deeper inside the plasma [5]. In the case of Fig.1, the emission intensity and NBI power both doubled between the first and second frequency sweeps, and the line first appeared when S_n was very low. Thus, it was almost certainly driven by beam ions rather than α-particles.

4. SUMMARY

The DT campaign on JET has made possible the first detection of α-particle-driven ICE during ICRH. Spectra from ICRH discharges show strong emission at sequential α-particle cyclotron harmonics; spectra from discharges with high power NBI contain evidence of ion hybrid wave excitation by fast particles, which may be significant for α-channelling [11]. The importance of ICE as an α-particle diagnostic is underlined by the fact that it remains the only unambiguous manifestation of spontaneous collective instability driven by α-particles in JET – the α-particle pressure gradient in the DT experiments may have been too small to excite toroidal Alfvén eigenmodes [12]. A model based on classical α-particle confinement is broadly consistent with ICE data: this strengthens confidence in extrapolations of α-particle behaviour to future experiments.

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REFERENCES

[1] G.A. Cottrell et al., Nucl. Fusion **33**, 1365 (1993)

[2] S. Cauffman et al., Nucl. Fusion **35**, 1597 (1995)

[3] R.O. Dendy et al., Phys. Plasmas **1**, 1918 (1994)

[4] T. Fülöp and M. Lisak, Nucl. Fusion **38**, 761 (1998)

[5] K.G. McClements et al., Phys. Rev. Lett. **82**, 2099 (1999)

[6] V.S. Belikov and Ya.I. Kolesnichenko, Sov. Phys. Tech. Phys. **20**, 1146 (1976)

[7] G.A. Cottrell, Phys Rev Lett. **84**, 2397 (2000)

[8] R.O. Dendy et al., Phys. Plasmas **1**, 3407 (1994)}

[9] T.E. Stringer, Plasma Phys. **16**, 651 (1974)

[10] K.G. McClements and R.O. Dendy, Fifth IAEA Technical Committee Meeting on Alpha Particles in Fusion Research, Contributed Papers, p105 (1997)

[11] N.J. Fisch and J.-M. Rax, Phys. Rev. Lett. **69**, 612 (1992)

[12] S.E. Sharapov et al., Nucl. Fusion **39**, 373 (1999)