Ion Cyclotron Emission from JET D-T Plasmas

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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 the Joint European Torus. 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 channeling. [S0031-9007(99)08608-1]

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Collective effects driven by fusion α particles in deuterium-tritium (D-T) plasmas have been a primary research objective of JET [1] (the Joint European Torus) and TFTR [2,3] (the Tokamak Fusion Test Reactor). The most easily excited phenomenon is spectrally structured, suprathermal ion cyclotron emission (ICE): this was observed from the outer edge regions of the earliest D-T plasmas, in JET hot ion H-modes [1], and TFTR supershots [2] (indeed, ICE driven by fusion products was observed in JET before the use of T [4], and ICE driven by beam ions has been observed in TFTR [5]). 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 and diagnostic implications of α-particle-driven ICE have been subjects of considerable theoretical interest [6–8]. The consensus is that emission of α-particle-driven ICE is due to the magnetoacoustic cyclotron instability (MCI) [9], involving fast Alfvén wave excitation at α-particle cyclotron harmonics; MCI is also successful in interpreting related phenomena observed in space [10] and astrophysical [11] plasmas. In tokamaks MCI is driven by centrally born, marginally trapped fusion products undergoing radial drift excursions to the outer edge plasma. Since the radial excursion increases as the cube root of energy [12], the velocity distribution of fusion products in the ICE source region has a local maximum at finite speed and pitch angle, which can drive the MCI.

ICE data from JET D-T 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]. Prior to 1997, energetic particle-driven ICE was observed only in JET plasmas heated Ohmically and by neutral beam injection (NBI) [1,4]. ICE spectra from ICRH discharges contained peaks at harmonics and half harmonics of the ICRH frequency, but no emission which could be attributed to energetic particles [13]. The ICE diagnostic was not available in the highest performance 1997 D-T discharges, but clear evidence was obtained of energetic particle-driven ICE during ICRH. Figure 1 shows neutron flux S_n in optimized shear pulse 42697, with combined ICRH (6 MW) and NBI (8–20 MW). The spectra in Fig. 2 were obtained by sweeping through the range 0–100 MHz over 0.6 s intervals. The 25 and 95 MHz peaks are calibration markers. In the first spectrum the 50 MHz peak is due mainly to the ICRH source, but part of this peak is also a marker. Dashed bars indicate harmonics of the 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, 60, 80, 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 [13]. ICE spectra obtained previously in JET [1,4] and TFTR [2,3,5] show emission at cyclotron harmonics of fusion products and beam ions in the outer midplane edge. Combined T and D beam injection was used in pulse 42697, the beam T fraction being 30%, so one would expect the intensity of T beam ICE to be comparable to that of $\nu_{D/\alpha}$ harmonics if the latter were produced by beam D. In fact, there is little or no evidence of emission at T harmonics other than those coinciding with D harmonics. Thus, 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 analyzer reached 60 MHz). We note finally in both spectra a narrow line between ν_T and $\nu_{D/\alpha}$.

Figure 3 shows spectra from a sequence of H-mode pulses (41572–41574) in which pure T NBI was the only source of auxiliary heating: similar data were obtained during pulses 41571 and 41576. The 25, 50, and 95 MHz peaks are again calibration markers. In every case the strongest emission occurs at $\nu \simeq \nu_{D/\alpha}$. For pulses 41571–41576 we can determine a relation between ICE

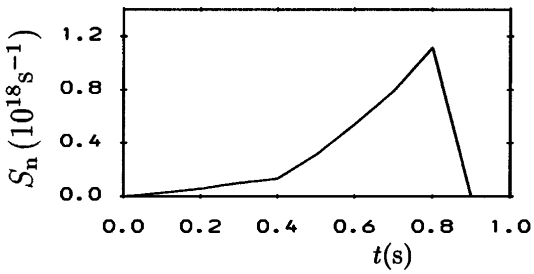

FIG. 1. Time profile of neutron flux in pulse 42697.

intensity P_{ICE} at $\nu \simeq \nu_{\mathrm{D}/\alpha}$ and S_n at the time of the ICE measurement. Setting $P_{\mathrm{ICE}} \propto S_n^{\delta}$ we obtain $\delta = 1.3 \pm 0.4$, which is consistent with a linear relation observed previously [1] and suggests α-particle drive. Apart from weak emission close to $4\nu_{\mathrm{T}}$, there is no evidence of wave excitation by beam tritons. In pulse 41574 [Fig. 3(c)], as in pulse 42697, a narrow line appears between ν_{T} and $\nu_{\mathrm{D}/\alpha}$.

The model proposed in [1,6,7] requires centrally born trapped α particles to undergo radial excursions to the outboard plasma edge. In the uniform safety factor approximation, the maximum radial excursion Δ_α is [12]

$$\frac{\Delta_\alpha}{a} \simeq 8.8\left(\frac{a}{R_0}\right)^{1/3}\left(\frac{m_\alpha v_\perp}{Z_\alpha e \mu_0 I_p}\right)^{2/3}, \qquad (1)$$

where R_0 and a are major and minor radii; m_α and $Z_\alpha e$ are the α-particle mass and charge; $v_\perp$ is perpendicular speed in the plasma center; μ_0 is free space permeability; and I_p is plasma current. Setting $R_0 = 3$ m and $a = 1$ m for JET, particles with speed v reach the plasma edge ($\Delta_\alpha \geq a$) if

$$v/v_\alpha \geq 0.3 I_p(\mathrm{MA})\mathrm{cosec}\psi\,, \qquad (2)$$

where $v_\alpha \simeq 1.3 \times 10^7$ ms^{-1} is the mean birth speed and ψ is the pitch angle. The pitch angle of the trapped/counter-passing boundary ψ_{tp} (where the largest radial excursions occur) can be estimated from Eq. (7) in [12]: in JET, a typical value is $\psi_{\mathrm{tp}} \simeq 112°$. Although JET D-T plasmas had currents of up to 4.0 MA, in pulse 42697 $I_p \simeq 2.4$–2.8 MA and in pulses 41571–41576 $I_p \simeq 2.5$–2.6 MA. Substituting these values in Eq. (2), and setting $\psi = 112°$, we find that α particles with $v/v_\alpha \geq 0.78$–0.9 could traverse the outer plasma edge in these pulses. In the 1991 preliminary tritium experiment (PTE) I_p was 3.1 MA [1]: with $\psi = 112°$, this yields $0.3I_p(\mathrm{MA})\mathrm{cosec}\psi \simeq 1.0$. Thus, only the most energetic α particles, having $\psi \simeq \psi_{\mathrm{tp}}$, could reach the ICE source region in the PTE. Although only a small fraction of α particles occupied this region of velocity space, the fact that the local α particle velocity distribution in the outer plasma edge $f_\alpha(\mathbf{v})$ was strongly peaked at $v_\perp > c_A$, the local Alfvén speed, meant that the MCI was strongly driven under PTE conditions [1,6]. Newly born α particles in the discharges considered here were also

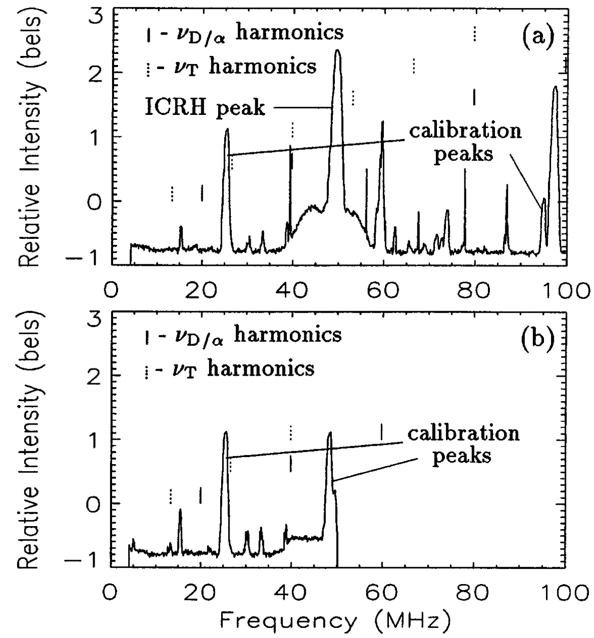

FIG. 2. ICE spectra at (a) $t = 0$–0.6 s and (b) $t = 0.6$–1.2 s in pulse 42697, with combined ICRH and NBI.

super-Alfvénic. However, the fact that I_p was lower than in the PTE suggests that $f_\alpha(\mathbf{v})$ in the plasma edge was less strongly peaked, and consequently that the MCI was less strongly driven, despite higher S_n in some cases.

The α particles in the plasma core initially have f_α strongly peaked at the mean birth energy [14]. If they interact with the plasma solely through Coulomb collisions, and prompt losses are negligible, f_α evolves to a slowing-down distribution of the form $1/(v^3 + v_c^3)$, where v_c is the critical speed [15]—this is referred to as classical confinement. The evolution of f_α can be approximated analytically [14] if one neglects finite orbit width effects, velocity-space anisotropy, and time variations in the slowing-down time τ_s. Denoting the rate of α-particle production by $S_\alpha(v, r, t)$, where r is minor radial distance, one obtains

$$f_\alpha(v, r, t) = e^{3t/\tau_s}\int_0^t e^{-3\eta/\tau_s} S_\alpha(v', r, \eta)\, d\eta\,, \qquad (3)$$

where $v' = [(v^3 + v_c^3)e^{3(t-\eta)/\tau_s} - v_c^3]^{1/3}$. We assume that S_α can be factored into functions ψ of speed and H of time: $\psi(v) \sim \exp[-(v^2 - v_\alpha^2)^2/\delta v^4]$ is an appropriate form [16], with $\delta v = [8v_\alpha^2 T_i/(m_n + m_\alpha)]^{1/4}$, m_n being neutron mass and T_i an effective ion temperature. The choice of $H(t)$ is determined by $S_n(t)$ [7].

Figure 4 shows computations of f_α in the plasma core ($r = 0$), for parameters corresponding to pulses (a) 42697 and (b) 41573 (representative of pulses 41571–41576). High power ICRH and NBI in pulse 42697 produced a peak electron temperature T_e, time averaged over the scanning time of the first spectrum in Fig. 2, of 10.4 keV; the time-averaged peak T_e in pulse 41573 was less than

4 keV. The electron densities n_e in the two discharges were similar, and so $\tau_s \propto T_e^{3/2}/n_e$ was longer in pulse 42697 (1.8 s) than in pulse 41573 (0.3 s). Another key difference is that S_n peaked sooner in the NBI-only discharges than in pulse 42697: in (a) $H(t)$ was taken to vary as t^2 and in (b) $H(t) \propto t^{1/2}$. The broken curves in Fig. 4 represent f_α when the spectrum analyzer reached $\nu \simeq \nu_{D/\alpha}$ in the first frequency sweep ($t = t_1$); the solid curves show f_α when the spectrum analyzer reached $\nu \simeq 5\nu_{D/\alpha}$ ($t = t_2$). At $t = t_2$ f_α is insensitive to T_i, being determined essentially by τ_s and $S_n(t)$.

To assess the implications of Fig. 4 we consider the stability of a model f_α used in previous ICE studies [7],

$$f_\alpha \sim \exp\left[-\frac{(v_\perp - v_{\perp 0})^2}{\delta v_\perp^2}\right]\exp\left[-\frac{(v_\parallel - v_{\parallel 0})^2}{\delta v_\parallel^2}\right]. \quad (4)$$

The values of $v_{\perp 0}$, $v_{\parallel 0}$, $\delta v_\perp$, and $\delta v_\parallel$ are determined by the speed at which f_α peaks in the plasma core; the velocity-space width of the core f_α; the value of $\psi_{\rm tp}$; the plasma current profile; and the radial α-particle birth profile. It is difficult to take all these effects into account (partly because of experimental uncertainties), but the velocity dependence of Δ_α indicates that α particles in the edge have a more strongly peaked distribution than those in the core. The method used to calculate the MCI growth rate γ is described in [6]. In Fig. 5 γ is plotted for $\delta v_\perp = \delta v_\parallel$, $v_{\perp 0} = 4v_{\parallel 0} = 1.2c_A$, $\delta v_\perp/v_{\perp 0} = 0.04-0.08$, α-particle concentration $n_\alpha/n_i = 10^{-3}$, and harmonic number $\ell = 1, 5$. The frequency ω and γ are normalized to $\Omega_\alpha = 2\pi\nu_{D/\alpha}$. The chosen wave vector components $k_\parallel$, $k_\perp$ give maxima in γ. For $\ell = 5$ the instability drive is very sensitive to the velocity-space width of f_α, the maximum γ falling by 93% when $\delta v_\perp$ is doubled. For $\ell = 1$ the drive is much less sensitive to $\delta v_\perp$. The theoretical basis for such frequency-dependent stabilization was given in [9]. The sensitivity of γ to $\delta v_\perp/v_{\perp 0}$ at high ℓ (lower frame of Fig. 5), combined with the sensitivity of the core f_α to τ_s (Fig. 4), suggests that $P_{\rm ICE}$ falls off more rapidly with ℓ in Fig. 3 than in Fig. 2 for the following reason: α particles in the plasma core slowed down to a greater extent in the NBI-only pulses 41572–41574 (Fig. 3; $\tau_s \simeq 0.3$ s) than in the ICRH pulse 42697 (Fig. 2; $\tau_s \simeq 1.8$ s), and the instability drive at high ℓ was consequently much lower in the NBI-only cases.

The peaks between $\nu_{\rm T}$ and $\nu_{D/\alpha}$ in Figs. 2 and 3(c) have frequencies and bandwidths consistent with ion hybrid waves [17]. In a D-T plasma the ion hybrid frequency is given by [17] $\Omega_{ii}^2 = (\Omega_{\rm D}^2\omega_{p\rm T}^2 + \Omega_{\rm T}^2\omega_{p\rm D}^2)/(\omega_{p\rm T}^2 + \omega_{p\rm D}^2)$, where $\Omega_{\rm D,T}$, $\omega_{p\rm D,T}$ denote cyclotron and plasma frequencies of D and T. If the ion hybrid wave interpretation is correct, and the T concentration $\eta_{\rm T}$ is known,

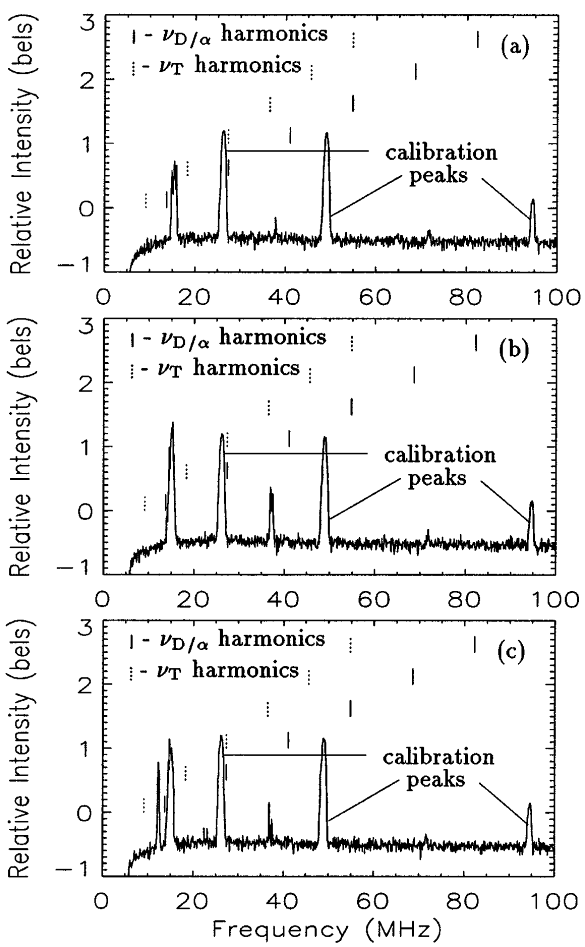

FIG. 3. Spectra in pure NBI pulses (a) 41572 ($P_{\rm fus} =$ 0.21 MW), (b) 41573 (0.64 MW), and (c) 41574 (0.56 MW).

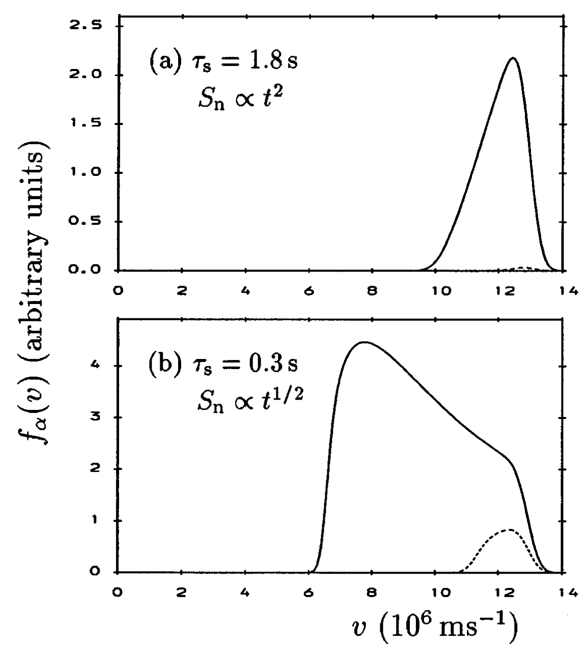

FIG. 4. Computed f_α in the plasma core. The parameters are those of pulses (a) 42697 and (b) 41573. The broken (solid) curves represent f_α when the spectrum analyzer reached $\nu \simeq \nu_{D/\alpha}$ ($5\nu_{D/\alpha}$) in the first frequency sweep.

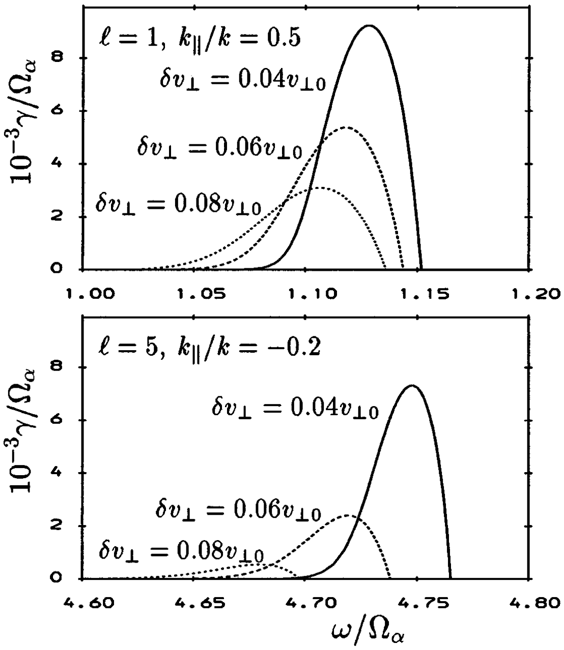

FIG. 5. Computed MCI growth rate versus ω for $\delta v_\perp = \delta v_\parallel$, $v_{\perp 0} = 4 v_{\parallel 0} = 1.2 c_A$, and $n_\alpha/n_i = 10^{-3}$.

we can locate the source of the emission by equating the observed frequencies to Ω_{ii}. Spectroscopic and neutral particle measurements in pulse 42697 give $\eta_T \sim 20\%$ in the plasma edge; in pulse 41574 η_T was $\leq 2\%-3\%$ at the edge, but $\sim 10\%-20\%$ inside the plasma. On the basis of the ion hybrid wave interpretation, these figures imply that the 15 MHz line in Fig. 2 was produced close to the plasma edge, at major radius $R \sim R_0 + 0.9a$, and that the 12 MHz line in Fig. 3(c) originated from deeper inside the plasma, at $R \sim R_0 + 0.3a$. The intensity of the emission in Fig. 2 rose by a factor $\simeq 2$ between the first and second frequency sweeps, while the NBI power rose by a similar factor (from 8 to 20 MW), and the line first appeared when S_n was very low. Thus, it was almost certainly driven by beam ions rather than α particles (unlike the MCI, the hybrid wave can be strongly driven by sub-Alfvénic fast ions [17]). Direct excitation of the hybrid wave by fast particles, predicted [17] but not previously observed in tokamaks, could be used to heat electrons and ions; this is one of several possible schemes for channeling α-particle energy into thermal plasma before the α particles have slowed down collisionally [18]. In Figs. 2 and 3(c) the received power in the lines tentatively identified as ion hybrid emission is many orders of magnitude lower than required for viable α channeling. However, the ion hybrid instability occurs at shorter wavelengths than the MCI, and is thus predominantly electrostatic, whereas the ICRH antenna can detect only electromagnetic signals: the total power may be much greater than that of the electromagnetic component which is detected.

The D-T campaign on JET has made possible the detection, for the first time, of α-particle-driven ICE in ICRH discharges. The use of ICE as an α-particle diagnostic has thus been extended to new operating regimes. 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 channeling. The importance of ICE as an α-particle diagnostic is underlined by the fact that it remains the only clear manifestation of spontaneous collective instability driven by α particles in JET—the α-particle pressure gradient in the D-T experiments was too small to excite toroidal Alfvén eigenmodes (TAEs) [19]. A model based on classical α-particle confinement is broadly consistent with ICE data: this strengthens confidence in extrapolations of α-particle behavior to future experiments.

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