Superthermal Radiation from Fusion Products in JET

G. A. Cottrell
JET Joint Undertaking, Abingdon, Oxfordshire OX14 3EA, England

and

R. O. Dendy
Culham Laboratory (Euratom–United Kingdom Atomic Energy Authority Fusion Association), Abingdon, Oxfordshire OX14 3DB, England
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Observations of superthermal ion-cyclotron emission from JET Ohmic- and neutral-beam–heated discharges are presented. Previously unobserved narrow-band spectral features correspond in both cases to multiple harmonics and half-harmonics of the proton gyrofrequency at the outer edge of the plasma. In this region, fusion products with large radial excursions and injected fast ions produce anisotropic velocity distributions with positive perpendicular gradient. It is discussed how these may relax by maser action, giving rise to the observed localized radiation.

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Measurements of superthermal ion-cyclotron emission (ICE) from tokamak plasmas can yield information about the fast-ion population. Early observations in TFR[1] and JET[2] deuterium Ohmic discharges revealed radiation intensities that exceeded the blackbody level by several orders of magnitude. Further observations on JET[3] demonstrated a linear correlation between the measured ICE intensity and the measured DD fusion reaction rate, based on 2.5-MeV neutron fluxes. This indicated that the charged fusion products of the primary DD reaction,

$$ {}^2_1\mathrm{D} + {}^2_1\mathrm{D} \begin{array}{l} \nearrow {}^3_2\mathrm{He}(0.82\ \mathrm{MeV}) + {}^1_0n(2.5\ \mathrm{MeV}) \\ \searrow {}^3_1\mathrm{T}(1.0\ \mathrm{MeV}) + {}^1_1\mathrm{H}(3.0\ \mathrm{MeV}), \end{array} \qquad (1)$$

and the secondary branches,

$$ \begin{array}{l} {}^3_2\mathrm{He} + {}^2_1\mathrm{D} \rightarrow {}^1_1\mathrm{H}(14.7\ \mathrm{MeV}) + {}^4_2\mathrm{He}(3.7\ \mathrm{MeV}), \\ {}^3_1\mathrm{T} + {}^2_1\mathrm{D} \rightarrow {}^4_2\mathrm{He}(3.6\ \mathrm{MeV}) + {}^1_0n(14.7\ \mathrm{MeV}), \end{array} \qquad (2)$$

provide the free energy to generate the ICE. An earlier treatment[3] of the emission mechanism was based on single-particle ion-cyclotron radiation, integrated over a stochastic ensemble of calculated orbits in the tokamak field. Here we report new measurements on JET which suggest an interpretation of the emission mechanism in terms of collective instability. The instability arises from the anisotropic velocity distribution created either by hydrogen neutral-beam injection (NBI) or by large radial orbit excursions of the centrally born fusion products.

The ICE was measured during experiments on JET (major radius $R_0 = 2.96$ m, minor radius $a = 1.25$ m, elongation ratio $b/a \leq 1.6$, plasma current $I_p \leq 5$ MA, toroidal field $B_T \leq 3.4$ T) both with Ohmic heating and with H^0 neutral-beam injection at 58° (at $R = R_0$) to the field in the direction parallel to the plasma current. An ion-cyclotron radio-frequency antenna[4] on the low-field side of the torus was used to receive rf emission from the plasma in the range 10–100 MHz. Swept-frequency spectrum analyzers were used, with the antenna phased as a toroidal dipole. Figure 1 shows ICE spectra measured before and during 55-keV $H^0 \rightarrow D^+$ NBI into a single discharge. Hydrogen injection gives rise to emission lines that are both intense ($\leq 10^4$ above the background) and narrow ($\Delta\omega/\omega \simeq 0.05$). To our knowledge, these emission lines have not been reported previously. The center frequencies of the lines are equally spaced and (by comparison with similar discharges having lower fields) the spacing is proportional to B_T. The NBI-induced emission-line frequencies coincide with

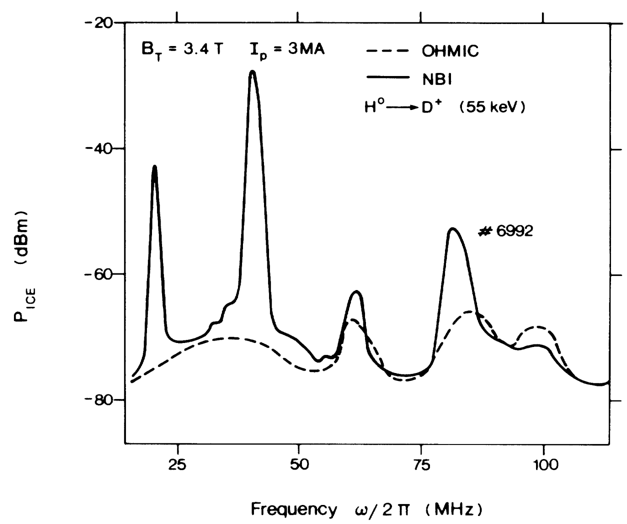

FIG. 1. ICE spectrum measured before and during 4-MW H^0 neutral-beam coinjection into a D^+ limiter plasma.

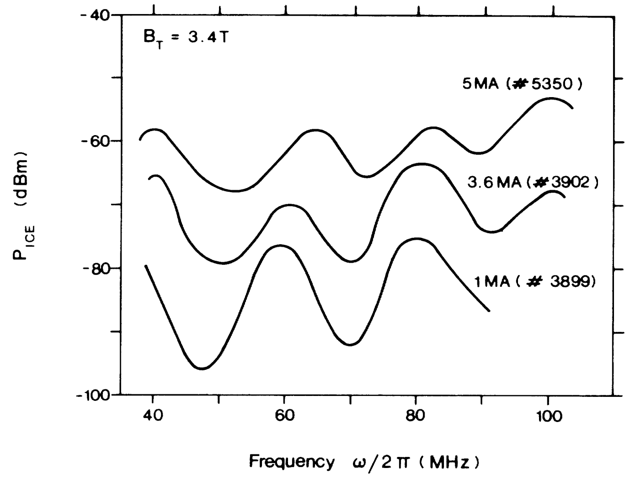

FIG. 2. ICE spectrum from three Ohmically heated deuterium limiter discharges with constant toroidal field but with different plasma currents.

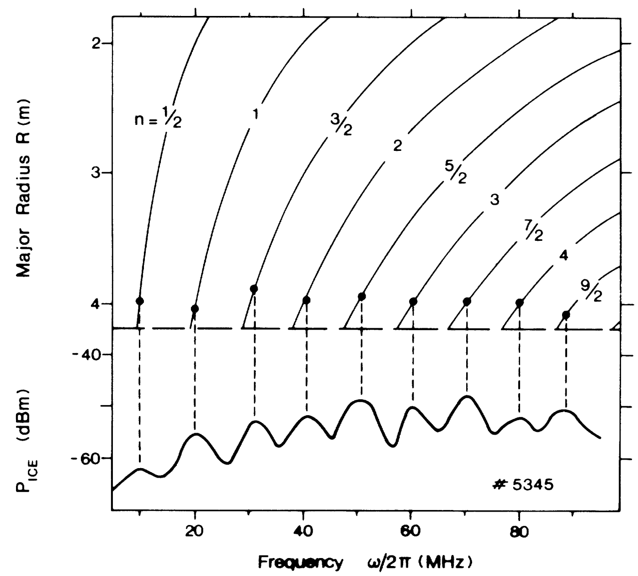

FIG. 3. ICE spectrum (lower) from a 3-MA ($B_T = 1.7$ T) Ohmically heated deuterium limiter discharge compared with (upper) the calculated radial locations of the harmonic and half-harmonic proton gyrofrequencies $\omega(R) = n\omega_{c\mathrm{H}}(R)$.

weaker and broader ($\Delta\omega/\omega \simeq 0.1$) ICE peaks (30–85 MHz) observed during the Ohmic phase of the discharge. The behavior of the ICE spectrum in three Ohmic deuterium discharges of constant toroidal field $B_T = 3.4$ T but with plasma currents of $I_p = 1$, 3.6, and 5 MA is illustrated in Fig. 2. In Ohmic discharges, the intensity of the ICE peaks increases by a factor ≈ 100 in proportion to the increase in the measured total DD reaction rate from $10^{12}\ \mathrm{s}^{-1}$ at 1 MA to $10^{14}\ \mathrm{s}^{-1}$ at 5 MA. In the 5-MA case, there is a 7% upshift in the frequencies of the peaks relative to the 1-MA case, corresponding to the paramagnetic and poloidal corrections to the total field. At high current, the peak/trough ratio becomes smaller. As in the NBI case, the center frequencies of the Ohmic ICE peaks are equally spaced with spacing[2] proportional to B_T. In both NBI and Ohmic cases, the measured ICE peaks are *narrow*: $\Delta\omega/\omega \simeq 0.1 \ll a/R = 0.4$. This implies a localized origin for the detected waves. To locate the emission region, we show in Fig. 3 an ICE spectrum from a D^+ Ohmic discharge, as well as the radial location of harmonics and half-harmonics of the proton gyrofrequency $\omega_{c\mathrm{H}}$ calculated with use of the $1/R$ toroidal field variation. Peaks up to harmonic number $n = \frac{9}{2}$ are visible. We note that these peaks also correspond to the integer cyclotron harmonics $n\omega_{c\mathrm{D}}$ of the background deuterium plasma. Figure 3 shows that a unique match between the observed peaks and the local harmonic and half-harmonic proton gyrofrequencies exists at only one radius, $R \approx 4.0 \pm 0.1$ m. We must therefore conclude that it is the superthermal proton population which is responsible for generation of the ICE at $R \simeq 4.0$ m, in the near-field region of the antenna ($R_{\mathrm{ant}} \simeq 4.17$ m). Attempts to match the peaks to the resonance lines in any other way lead to unnatural models in which the different harmonics and half-harmonics are generated in different regions of the plasma.

The interpretation of the superthermal emission raises a number of questions: the identity of the wave mode detected, the nature of the excitation mechanism, and the relation of these to the spatial and velocity distributions of the fusion product and NBI ion populations. We note first that the large radial excursion of the banana orbits[5,6] of trapped fusion products originating in the center of the plasma (particularly the 3- and 14.7-MeV protons) will create an excess of particles with large $v_\perp$ on the low-field side. Similarly, Fokker-Planck calculations in toroidal geometry[7] have shown that for steady-state, near-perpendicular NBI, the energetic-ion distribution includes regions where $\partial f/\partial v_\perp > 0$, particularly in the cool, less dense outer parts of the plasma, where pitch-angle scattering is less dominant than in the center.

The pickup antenna, although polarized to emit or receive the fast Alfvén wave, may also couple to electrostatic wave modes. Calculations[8] for typical JET plasma-antenna interfaces show that the electrostatic component can contribute up to 20% of the total loading impedance. For the ion Bernstein wave (IBW), the local Harris[9] dispersion relation is

$$\epsilon = 0 = 1 + \sum_s \frac{\omega_{ps}^2}{k^2} \sum_{n=-\infty}^{\infty} \int_{-\infty}^{\infty} dv_\parallel \int_0^\infty 2\pi v_\perp dv_\perp \frac{J_n^2(k_\perp v_\perp/\omega_{cs})}{\omega - k_\parallel v_\parallel - n\omega_{cs}} \left[k_\parallel \frac{\partial f_s}{\partial v_\parallel} + \frac{n\omega_{cs}}{c} \frac{\partial f_s}{\partial v_\perp} \right], \quad (3)$$

where ω_{ps} and ω_{cs} are the species plasma and cyclotron frequencies, $k_\perp$ and $k_\parallel$ are the components of the wave vector perpendicular and parallel to the magnetic field, J_n is the nth-order Bessel function, and $f_s(\mathbf{v})$ is the velocity distribution function of the species. Following Refs. 5 to 7, we expect part of the proton distribution function to exhibit population inversion such that $\partial f_p/\partial v_\perp > 0$. This inversion enables the proton distribution to relax by maser action, of which two classes may apply.

First, Eq. (3) may have complex roots, with the imaginary part giving wave growth. Given a sufficiently large $\partial f/\partial v_\perp > 0$, the growth of Bernstein waves is predicted for ring, shell,[10] and beam-plasma[11] systems. Observations[12] of half-harmonic electron-cyclotron waves in magnetospheric turbulence have been interpreted[13] in terms of loss cones. However, this mechanism requires the number density of electrons in the hot loss cone to exceed that in the cold background. Similarly, our numerical investigations of the beam-plasma system of Ref. 11 indicate that, to obtain growth, the number density of the inverted population must be a significant fraction of the background density, whereas the fusion-product number density in JET is at present $< 10^{-4}$ of the background density.

The second class of maser action was considered by Bers and Gruber,[14] which showed the existence of negative-energy waves at cyclotron harmonics in a beam-plasma system. The negative-energy waves can grow, even at low beam densities, provided there is coupling to the background plasma through wave resonance or dissipation. This mechanism can operate in mirror plasmas[15,16] where the loss cone provides the inverted population. To show the role of negative energy in two-ion-species plasmas, consider the proton distribution function

$$f_p(\mathbf{v}) = u\left(\frac{v_\perp}{v_m}\right)\frac{\exp[-(v_\perp^2+v_\parallel^2)/v_m^2]}{\pi^{3/2}v_m^3}. \qquad (4)$$

In mirror theory, Eq. (4) has been used[17] with $u(x) \sim x^p$, giving $\partial f_p/\partial v_\perp > 0$ for $0 < v_\perp < (p/2)^{1/2}v_m$. The dielectric response function is obtained by the substitution of Eq. (4) into Eq. (3) and the normal modes propagating perpendicular to the field ($k_\parallel = 0$) are given by

$$\epsilon = 0 = 1 - \frac{2\omega_{pD}^2}{k^2 v_D^2}\sum_{m=1}^{\infty}\exp(-z_D)I_m(z_D)\frac{2m^2(\omega_{cH}/2)^2}{\omega^2 - m^2(\omega_{cH}/2)^2} - \frac{2\omega_{pH}^2}{k^2 v_m^2}\sum_{n=1}^{\infty}(G_{0n}-G_{1n})\frac{2n^2(\omega_{cH}/2)^2}{(\omega^2 - n^2\omega_{cH}^2)}, \qquad (5)$$

where $z_D = k_\perp^2 v_D^2/2\omega_{cD}^2$, v_D is the thermal velocity of the background D Maxwellian plasma, I_m denotes the modified Bessel function of order m, and we have used the fact that $\omega_{cD} = \omega_{cH}/2$; also,

$$G_{0n}(u;k_\perp) = \int_0^\infty J_n^2(k_\perp v_m x/\omega_{cH})\exp(-x^2)2xu(x)\,dx, \qquad (6)$$

$$G_{1n}(u;k_\perp) = \int_0^\infty J_n^2(k_\perp v_m x/\omega_{cH})\exp(-x^2)(du/dx)\,dx. \qquad (7)$$

When $u(x)$ has a positive slope, G_{1n} can exceed G_{0n} for some range in $k_\perp$, so that a negative-energy contribution arises from the protons. Wave energy is proportional to $[\omega\,\partial\epsilon/\partial\omega]_{\epsilon=0}$ and, by Eq. (5), the proton contribution is

$$\left[\omega\frac{\partial\epsilon}{\partial\omega}\right]_H = \frac{4\omega_{pH}^2}{k^2 v_m^2}\sum_{n=1}^{\infty}(G_{0n}-G_{1n})\frac{2n^2\omega_{cH}^2\omega^2}{(\omega^2-n^2\omega_{cH}^2)^2}. \qquad (8)$$

This is negative when $(G_{0n}-G_{1n}) < 0$. Depending on the values of G_{0n} and G_{1n}, this negative-energy contribution may be sufficient to allow growth of resonant positive-energy IBW's supported by the deuterium background, described by the first summation in Eq. (5).

Two additional factors should be considered in a full treatment of the emission mechanism. First, as a result of nonlinear effects on ion orbits, IBW's can be absorbed at half-harmonic frequencies.[18,19] A recent numerical study[20] shows how this mechanism can operate in the IBW heating of two-species plasma. Furthermore, half-harmonic cyclotron damping has only been observed in conjunction with IBW heating; this suggests that an inverse mechanism associated with nonlinear Landau damping of the IBW may play a role. Second, when $k_\parallel$ is nonzero, a second electrostatic-wave branch exists in each cyclotron harmonic band, which may contribute to wave coupling and instability.[10] It is also possible that the signal detected is the fast Alfvén wave[21,22] although, unlike the IBW, this wave is not limited to propagation in cyclotron harmonic bands. Experimentally, it should in the future be possible to identify the wave mode by measurement of the $k_\parallel$ emission spectrum with two phased antennas. Coherent signals with finite $k_\parallel$ would indicate global fast Alfvén waves. One aspect of the observations may be compatible with the detection of waves with finite $k_\parallel$. As noted above, the ratio of the widths of the ICE peaks for the NBI and fusion-product cases is a few times 0.1, compared with the ratio $[(55\text{ keV})/(3\text{ MeV})]^{1/2} \simeq 0.1$ of initial velocities of the respective superthermal populations, so that the widths may be interpreted in terms of Doppler broadening, given finite $k_\parallel$.

We have reported new observations of localized, narrow-band, nonthermal ion-cyclotron emission from Ohmic- and H^0 neutral-beam-heated discharges in JET. These suggest strongly an interpretation in terms of superthermal radiation at the harmonics and half-harmonics of the proton gyrofrequency, at major radius

$R \simeq 4.0 \pm 0.1$ m, in the near-field region of the pickup antenna. In the outer parts of the plasma, both NBI and fusion-product distribution functions are expected to include regions where $\partial f/\partial v_{\perp} > 0$. Such distributions, resembling loss cones, will undergo collective relaxation through maser action, generating electrostatic ion-cyclotron radio-frequency waves with $k_{\parallel} \simeq 0$.

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