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Interpretation of Minority Ion Cyclotron Emission during ICRF Heating in JET

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1. Introduction

Ion cyclotron emission (ICE) has been detected recently using an inboard probe in JET during ion cyclotron range of frequency (ICRF) heating of minority protons [1]. Previously, ICE has provided an important diagnostic of charged fusion products, including α-particles, in both JET [2] and TFTR [3]. The new JET data provides an opportunity to extend our understanding of the ICE phenomenon, and hence to exploit fully its potential as a fast particle diagnostic, without the need to use tritium. In this paper we show that minority ion cyclotron emission (MICE) can be interpreted in terms of the magnetoacoustic cyclotron instability (MCI), invoked previously to explain fusion product-driven ICE [2-3].

2. Observations

In common with ICE produced by charged fusion products, MICE spectra display narrowband emission lines, at frequencies ω centred on low integer multiples of an energetic ion cyclotron frequency at the outer midplane edge: in the case of MICE, the energetic ions are minority protons, with edge cyclotron frequency ω_{cH}. A significant difference between MICE and fusion product-driven ICE is that the former is dominated by emission at the fundamental $\omega = \omega_{cH}$ (see Fig. 1), whereas fusion product-driven ICE generally includes several harmonics of ω_{cH}. Another difference is that there is a time delay of typically 400 ms between the start of full power ICRF heating and the first appearance of the emission: in the case of fusion product-driven ICE, no such delay was observed. This may be linked to the fact that the minority ion tail temperature rises towards its maximum value on a timescale of the order of the slowing-down time, whereas fusion products are born in the plasma at their maximum energy [1].

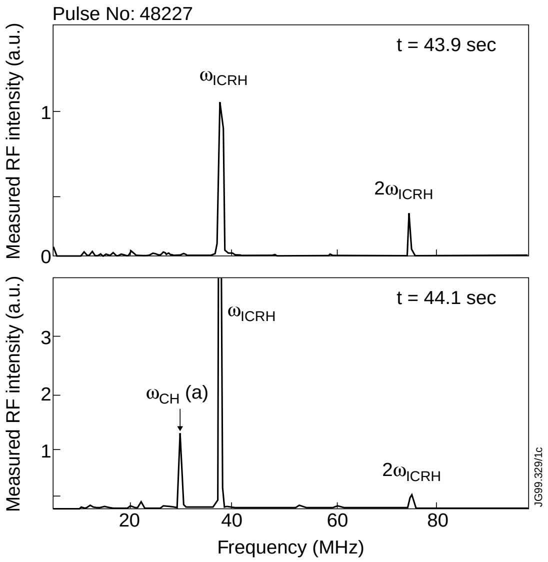

Fig. 1. *Radio-frequency spectra during pulse with single frequency ICRF heating, 240ms (upper plot) and 440ms (lower plot) after ICRH flat-top was reached.*

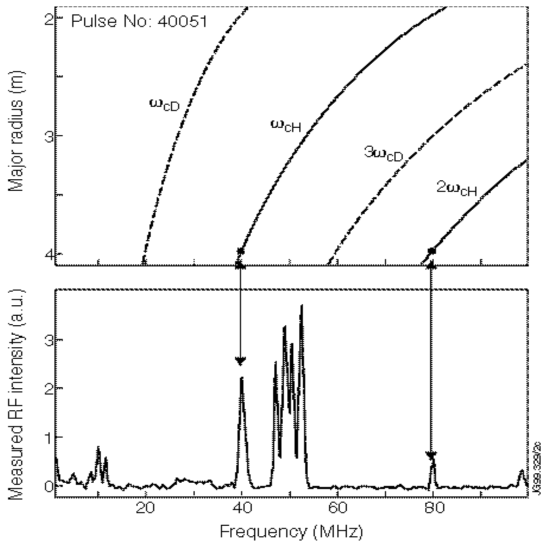

Fig. 2. *Upper plot: major radii of H and D cyclotron resonances in JET pulse with 4-frequency ICRF heating. Lower plot: radio-frequency spectra during this pulse.*

3. Interpretation

All previous observations of ICE in JET were obtained using an ICRF antenna on the outboard side of the plasma [2], while the TFTR observations were obtained using edge-mounted probes located approximately in the vertical plane of the magnetic axis [3]. The TFTR data, and now the inboard MICE data from JET, indicate that the eigenfunctions of the excited modes extend over a wide range of poloidal angles. The fact that in all cases the measured frequencies are characteristic of the outer midplane edge is likely to be due to peaking of the fast particle drive in that region: both fusion product-driven ICE [2] and MICE [1] are believed to be driven by fast particles undergoing large drift orbit excursions from the plasma core to the edge. Strong damping in the core would not prevent radially-extended eigenmodes from being detected, if the drive in the edge were strong enough.

If the ICRF resonance surface passes close to the magnetic axis a minority ion accelerated at that surface with pitch angle 90° has parallel velocity at the outer midplane edge $v_z \approx v/2$, where the speed v must be of the order of the AlfvØn speed c_A for the MCI to be strongly excited [3]. If the emission has parallel wavenumber k_z, the frequency in the laboratory frame is Doppler-shifted by $\delta\omega = k_z v_z$ from the frame in which $v_z = 0$: in the latter frame, the emission frequency is close to $\ell\omega_{cH}$ where ℓ is an integer [4]. MICE spectra such as those shown in Figs. 1 and 2 indicate that the strongest emission occurs at a frequency very close to ω_{cH}, which implies that k_z is less than 4% of the total wavenumber k. In a strictly uniform plasma the MCI drive at $\omega = \omega_{cH}$ is very weak when k_z is this small, and tends to zero for strictly perpendicular propagation [4]. The drive is predicted to be much stronger, however, when toroidal precession is taken into account [5]: since the precession frequency ω_{dH} is velocity-dependent, a wave-particle resonance is possible even for $k_z = 0$. In view of the observational constraint on this parameter, we consider only the case of perpendicular propagation. Neglecting bulk plasma thermal effects, and assuming that $\omega^2 >> \omega_{cD}^2$, where ω_{cD} is the bulk ion (deuteron) cyclotron frequency, one finds that the growth rate of fast magnetoacoustic waves propagating in the *x* direction is [5]

$$\gamma = -\frac{\omega_0^3}{2\omega_{pD}^2}\mathrm{Im}(\varepsilon_{xx}^h) \ , \tag{1}$$

where ω_{pD} is the deuteron plasma frequency, $\omega_0 = kc_A$, ε_{xx}^h is the contribution of ICRF ions to the (*x,x*) component of the dielectric tensor, and Im denotes the imaginary part. The quantity ε_{xx}^h depends on the ICRF-heated ion distribution f_h, which we model by

$$f_h = \frac{(E_* - \mu_* B)^{1/2}}{(2\pi)^{1/2} B\delta E}\delta(\mu - \mu_*)\exp\left[-\frac{(E - E_*)^2}{\delta E^2}\right]. \tag{2}$$

Here, E and μ are energy and magnetic moment per unit mass, B is magnetic field, δ is the delta function, and E_*, μ_*, δE are constants. If the ICRF resonance surface passes through the magnetic axis, where $B = B_0$, it is appropriate to set $\mu_* = E_*/B_0$. Using E and μ as the velocity-space variables, ε_{xx}^h is given by [5]

$$\varepsilon_{xx}^h = \sqrt{2}\pi\sum_{\ell=-\infty}^{\infty}\frac{\omega_{pH}^2}{\omega^2}\iint_D \frac{d\mu dE}{(E-\mu B)^{1/2}}\frac{2\mu B\Pi f_h}{\omega - \ell\omega_{cH} - \omega_{dH}}\frac{\ell^2 J_\ell^2(\xi)}{\xi^2}, \tag{3}$$

where ω_{pH} is the ICRF ion plasma frequency, $\xi = k(2\mu B)^{1/2}/\omega_{cH}$, $\omega_{dH} = -m(2E-\mu B)/\omega_{cH}aR$ (a is minor radius, R is major radius and m is poloidal mode number), the integration domain D is defined by $E \geq \mu B$, J_ℓ is the Bessel function of order ℓ, and Π is the operator

$$\Pi = \omega\frac{\partial}{\partial E} + \frac{(\omega - \omega_{dH})}{B}\frac{\partial}{\partial \mu}. \tag{4}$$

The imaginary part of the integral in Eq. (3) can be evaluated analytically for $\omega \approx \ell\omega_{cH}$ using the change of variable ° = E-μB/2. Substituting the result into Eq. (1) we obtain

$$\frac{\gamma}{\omega_{cH}} = -\frac{\ell^4\pi^{3/2}}{4m}\left(\frac{\omega_{pH}}{\omega_{pD}}\right)^2\left(\frac{E_* - \mu_* B}{E_0 - \mu_* B}\right)^{1/2}\frac{\omega_{cH}^2 aR}{\delta E}\exp\left(-\frac{(E_0 - E_*)^2}{\delta E^2}\right)$$
$$\times\left[\frac{2(E_* - E_0)}{\delta E^2}\frac{J_\ell^2}{\xi_*^2}\mu_* + \frac{\omega_{cH}^2}{2k^2B^2}\left(2J_\ell J_\ell^{'}\frac{\xi_*}{\mu_*} + \frac{J_\ell^2 B}{2(E_0 - \mu_* B)}\right)\right], \qquad (5)$$

where $E_0 = \mu_* B/2 - aR\omega_{cH}(\omega - \ell\,\omega_{cH})/(2m)$ is the ICRF ion energy at which there is a precessional drift resonance and $\xi_* = k(2\mu_* B)^{1/2}/\omega_{cH}$ is the argument of J_ℓ and $J_\ell^{'}$. Eq. (5) is valid if $E_0 > \mu_* B$, which requires that $m < 0$ if $\omega > \ell\,\omega_{cH}$: the equation indicates that instability can occur in this case. Evaluating the right hand side of Eq. (5) for $E_* = 3$ MeV, minority ion concentration $n_H/n_D = 10^{-4}$ [1], $\ell = 1$ and low negative values of m yields growth rates γ/ω_{cH} of typically 1%: ICRH ions can thus provide strong instability drive.

4. Discussion and Conclusions

Equation (5) indicates that the scaling of growth rate with ℓ depends on the ratio of ICRH ion perpendicular speed to c_A: if this is less than unity, γ can be a decreasing function of ℓ. The fact that MICE occurs mainly at $\ell=1$ could thus be due to ICRF ions in the outer edge plasma being predominately sub-AlfvØnic. Since the MICE data were obtained using an inboard probe, an alternative possible explanation is that the poloidal extent of the MICE eigenmode is frequency-dependent. Further studies will be required to determine the most probable cause of the observed fall-off in MICE intensity with increasing ℓ. In any event, the present study indicates that an emission mechanism based on the magnetoacoustic cyclotron instability is fully consistent with the MICE data.

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