# Ion Cyclotron Emission by Spontaneous Emission

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## 1 introduction

Ion Cyclotron Emission (ICE) in the frequency range 10-350 MHz has been measured in different tokamaks for the last 10 years. It is detected using an ICRH antenna in reception mode or a probe. It is a good candidate for a fast ion, especially fusion α-particle, diagnostic similar to the Electron Cyclotron Emission (ECE). A common feature of the experimental ICE spectra in this frequency range is the narrow regularly spaced peaks. They are at the majority ions cyclotron frequency harmonics at the plasma outer edge. This last point represents a challenge to interpretative theories. These results were confirmed during JET's 1991 Preliminary Tritium Experiment (PTE)[1].

## 2 hypothesis and method

The goal of this study is to see whether the spontaneous emission can account for ICE experimental results, or part of them. We chose a straightforward approach to plasma emission, by investigating the near equilibrium wave radiation by gyrating ions, and thus building from the majority and fast fusion ions the plasma fluctuations and emission on the fast magnetoacoustic or compressional Alfvén wave mode in the IC frequency range. The plasma is assumed infinite and homogeneous.

The calculation proceeds from the electric current created by one gyrating test particle, a Fourier analysis from $(\vec{r},t)$ space to $(\vec{k},\omega)$ space, the hot plasma dielectric tensor in a plane perpendicular to $\vec{B}$ to express the electric field radiated in the fast magnetoacoustic mode by one particle, a statistic summation over all the ions using their specific distributions (Maxwellian distribution for the bulk deuterium and slowing-down distribution for the α-particles at the plasma centre) and a numerical resolution of the dispersion relation to find the frequencies solution for each wave number in the range where the mode is coupled with the Bernstein modes, and therefore the fast ions, through a finite Larmor radius effect.

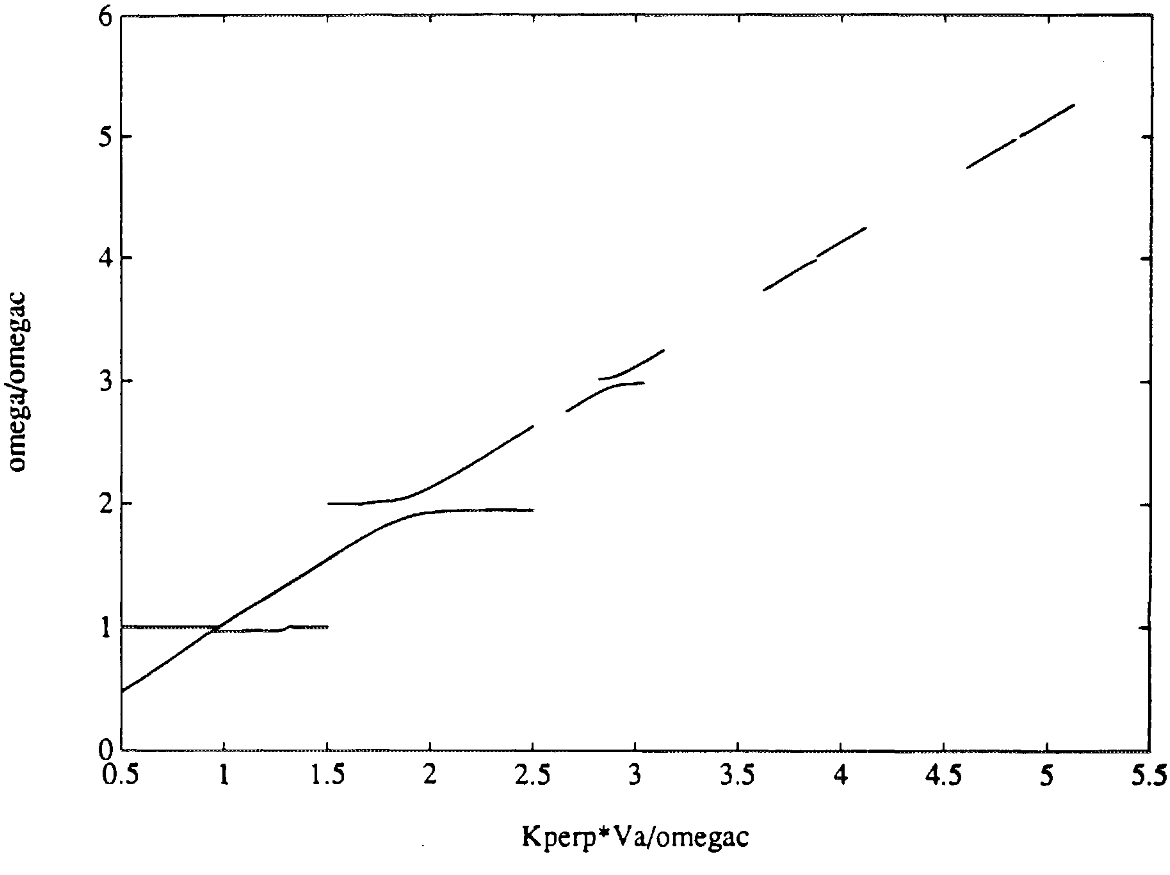
For each $k_\perp$ and $k_{//}$ we calculate the solution ω of the dispersion relation and the temporal damping rate (imaginary part of ω for $\vec{k}$ real), the wave electric and magnetic field, the plasma electromagnetic energy density for these modes, the power flux (Poynting vector) in each direction, the group velocity obtained from the dispersion relation slope and the spatial damping rate or damping length (imaginary part of $\vec{k}$ for ω real) obtained from the temporal damping rate and the group velocity. We integrate the electromagnetic energy density and the power flux for $\omega(k_\perp)$ solution of the dispersion relation.

## 3 modelling results

The numerical simulations are done with the plasma parameters at the plasma centre of JET's PTE discharge #26148[2]. In particular the relative α-particle concentration to deuterium is $1.3*10^{-3}$. The value of 1 $m^{-1}$ for $k_{//}$ is taken for illustration.

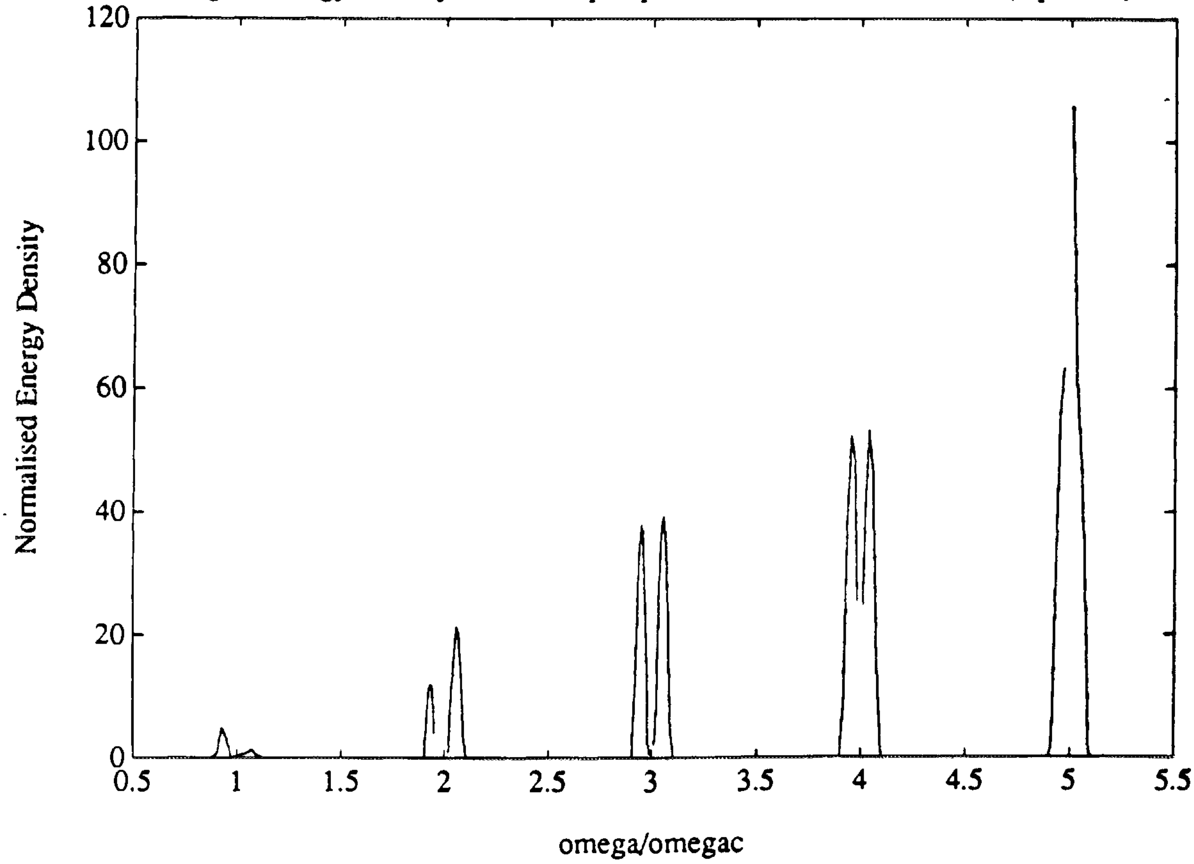
Figure 1 displays the fast magnetoacoustic mode dispersion relation for the first five ion cyclotron harmonics. Between two harmonics, the mode is well approximated by the cold plasma mode, whose phase and group velocities are equal to the Alfvén velocity. At each harmonic it separates into two different branches, one below the harmonic frequency and one above. This represents the coupling with the ion Bernstein modes.

Fig.1: Fast Magnetoacoustic Wave Dispersion Relation (Kpara=1)




The emission spectra shape is similar to the energy density spectra shape. Figure 2 shows for illustration spectra of integrated energy density (integrated in respect to $k_\perp$) versus the normalised frequency in a deuterium + alpha plasma. The energy density is normalised to $K_B$ (Boltzman constant) * $T_D$ (deuterium temperature). These computed spectra have a shape similar to the experimental emission spectra. The emission being created by the resonance between the fast ion $v_{//}$ and the wave parallel phase velocity, the splitting of the dispersion relation into two branches near each harmonic explains why the computed emission peaks are split into doublets. This double-line shape of the emission peaks is a well-known experimental feature[1].

Fig.2: Energy Density in a D + alpha plasma normalised to Kb*Td (Kpara=1)




In the presence of α-particles, the electromagnetic energy density level is much larger than $K_B * T_D$ and increases strongly with the harmonic. On the contrary in the case of a pure deuterium plasma, the electromagnetic energy density level of the dispersion relation two branches is close to the classical energy level in a thermal plasma ($K_B * T_D$) and stays constant with the harmonic. This is due to the larger α-particle Larmor radius.

The damping length or spatial decay is a very meaningful quantity. It represents physically the minimum spatial depth the plasma should have if it was to emit as a black body. In a pure deuterium plasma it is found to be very large compared to the emission layer width and to decrease with the harmonic. In a D + alpha plasma it is about 20 times smaller and decreases also with the harmonic.

Although the whole modelling is done for an infinite and homogenous plasma, we can apply some of the results to a tokamak plasma in the following simplified way. The frequency width of the power flux peaks in a D + alpha plasma for $k_{//} = 1$ and $V_{\alpha birth}$ = 3.6 MeV is $\Delta\omega \approx 0.04\omega_c$ (Fig.2), what is equivalent to a spatial width of the emission layer: $\frac{\Delta R}{R} = \frac{\Delta\omega_c}{\omega_c} = \frac{\Delta\omega}{\omega} \approx \frac{\Delta\omega}{n\omega_c} \approx \frac{0.04}{n}$, n harmonic number. As R(centre)=3m. in JET, $\Delta R \approx \frac{0.12}{n} m.$. The emission of a $\Delta R$ width layer with a damping length D, $P_{\Delta R}$, is deduced from the black body level, $P_B$, in a ratio obtained from the Kirchhoff radiation law: $P_{\Delta R} = \left(1 - e^{-\frac{2\Delta R}{D}}\right) P_B$.

A pure deuterium plasma is therefore white in the IC frequency range, whereas a D + alpha plasma is white at the first harmonic and grey from the second to the fifth. We explain consequently why the ICE of a plasma without fast particles is very difficult to detect and why the fast ion emission increases strongly with the harmonic[1]. The strong emission increase with the harmonic was also observed in a pure D plasma because of the H fusion fast ions. This explains also why the even-harmonic peaks are more intense[1] in both cases: H cyclotron frequency is twice as large as the D cyclotron frequency.

## 4 conclusion

The investigation of the fast magnetoacoustic mode spontaneous emission in fusion plasma shows significant similarities with the ICE experimental observations: the emission peaks at each ion cyclotron frequency harmonic, the large radiation temperature in the presence, even in a very small amount ($n \approx 10^{-3}$), of fast ions, the strong fast ion emission increase with the harmonic, the fine double-line splitting of each peak, the linear but not proportional increase of the peak width with the harmonic.

Further developments will include non-homogeneity effects, an estimation of the total power radiated in a tokamak and the consequence of the non-monotonic and anisotropic $\alpha$-particle distribution at the edge.

## 5 references


1 G.A. Cottrell, O. Da Costa et al., 19th EPS Conference, Innsbruck, 1992; G.A. Cottrell, O. Da Costa et al., Nuclear Fusion, vol.33, n.9, 1993.

2 JET-Team, Nuclear Fusion, vol.32, n.2, 1992.

3 D.B. Melrose: 'Plasma Astrophysics', vol.1: 'The Emission, Absorption and Transfer of Waves in Plasmas', chap. 4, Gordon & Breach, 1980, presents a similar approach to ICE but for astrophysics plasma.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