Scaling of the measured intensity of ion cyclotron emission with the concentration of energetic ions in large tokamak plasmas

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1. Introduction

Ion cyclotron emission (ICE) is highly suprathermal and its frequency spectrum displays narrow peaks at sequential cyclotron harmonics of energetic ions, at values which imply an emitting region localised to the outer mid-plane edge of the plasma. ICE was the first collective radiative instability driven by confined fusion-born ions that was observed from deuterium-tritium (D-T) plasmas in JET[1-3] and TFTR[4]. It is used as an energetic ion diagnostic on the largest contemporary tokamaks including DIII-D[5], ASDEX-Upgrade[6,7] and JT-60U[8,9], and in the large stellarator-heliotron LHD[10]. The most likely emission mechanism is the magnetoacoustic cyclotron instability (MCI)[11-18], whose role in relation to ICE observations was recently reviewed in Ref.[19]. The use of ICE as a diagnostic for confined energetic ion populations in ITER is under active consideration[20], and also for future D-T plasmas in JET. Diagnostic exploitation of ICE would be greatly assisted by theoretical understanding of the experimentally observed linear scaling, at low cyclotron harmonics, of its measured intensity with the number density concentration, n_α/n_i, of fusion-born energetic ions n_α relative to the background thermal ions n_i. Here we provide a preliminary report of studies[21] which address this key observational aspect of ICE using a 1D3V hybrid code which simulates the self-consistent full orbit kinetics of energetic and thermal ions in the presence of a massless neutralising fluid of electrons. Importantly, these simulations are carried out in the fully nonlinear regime of the MCI, which has recently been shown[4] to generate, uniquely, the full observed ICE spectrum from the fundamental cyclotron frequency of the energetic ions upwards. We find that the experimentally observed linear scaling of ICE intensity with n_α/n_i at low harmonics is recovered by these simulations, and we relate this welcome outcome to the analytical theory of the MCI. These new results provide further support for, and understanding of, the MCI as the emission mechanism for ICE. This enhances the prospects for the successful exploitation of ICE as a diagnostic[20] for confined fusion products in future D-T plasmas in JET and ITER.

2. Hybrid simulation model results

The hybrid model resolves ion kinetics including gyromotion, and hence resolves the gyrophase-dependent physics of ion cyclotron harmonic resonance which is central to the MCI. The position of each ion evolves continuously in physical space and in velocity space under the self-consistent local Lorentz force. The magnetic field is updated using

Faraday's law, and the electric field using the momentum equation for the electron fluid in the limit of zero electron inertia[18,22]. This enables the study of fast instabilities such as the MCI that evolve on ion gyro timescales, and are rapid compared to gyro-averaged or fluid phenomena. In this preliminary account of the simulations to be reported more fully in Ref.[21], in addition to the majority thermal plasma there is an energetic minority alpha-particle population, whose concentration ξ_α relative to the thermal ions is in the range $n_\alpha/n_i = \xi_\alpha = 10^{-4}$ to 10^{-3}, which forms a ring-beam distribution in velocity space with characteristic energy 3.5MeV. Plasma parameters are similar to those at the outer mid-plane edge of D-T plasmas in JET: background magnetic field strength B_0 = 2.1T, total number density $10^{19}m^{-3}$, electron temperature 1keV. The periodic 1D3V simulation domain comprises 8192 grid cells, each of order the deuteron Larmor radius so that ion gyromotion is fully resolved computationally, with 200 particles of each ion species per cell. Total energy is conserved within 3% of its initial value, and this change is smaller than any change in the energy of the ions and electromagnetic fields during the instability. Spectra obtained from our simulations in the fully nonlinear regime, for two different values of ξ_α, are shown in Fig.1.

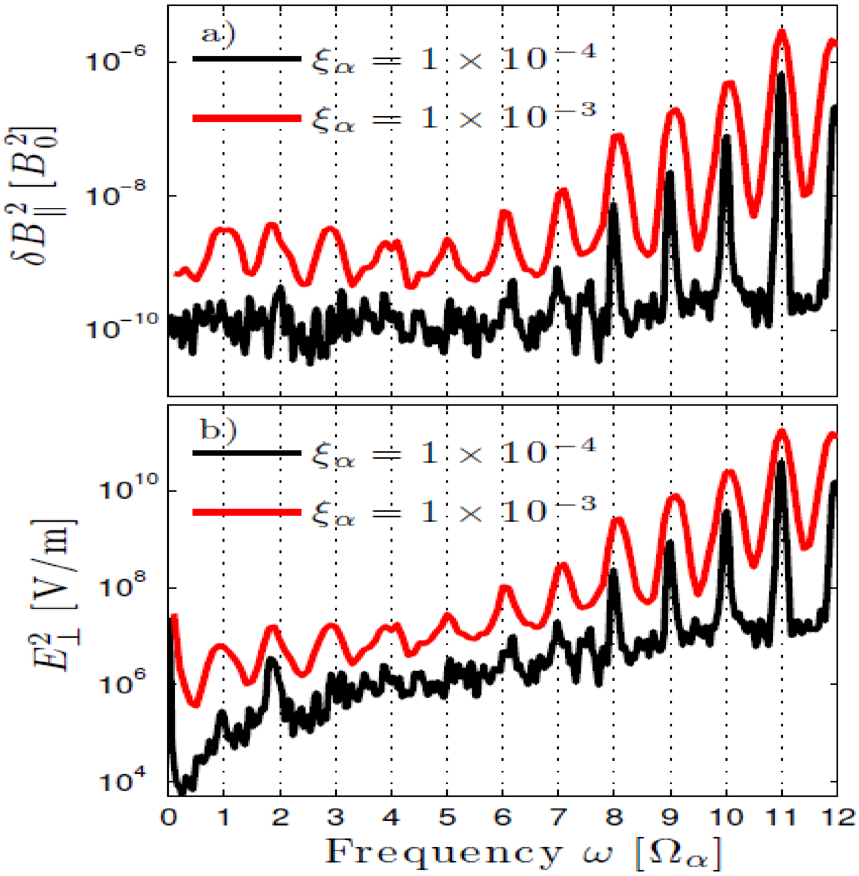

Fig.1 Log-normal frequency domain plot of the intensity of fields excited in hybrid simulations of deuterium plasmas containing an energetic minority alpha-particle population, undergoing the magnetoacoustic cyclotron instability: a) power density of the perturbed magnetic field for alpha-particle concentrations ξ_α = 10^{-3} (top red trace) and $\xi_\alpha = 10^{-4}$ (bottom black trace); b) power density of the transverse component of the electric field from the same simulations as panel a).

The simulation results are less intensive in their use of computational resources than those of the low-noise simulations to be reported in Ref.[21], but nevertheless enable us to investigate satisfactorily the scaling of the intensity of MCI-excited field energy with energetic ion concentration, in the fully nonlinear regime of the MCI. The objective is to obtain, from our simulation results at different alpha-particle concentrations, values for the conjectured scaling exponent η in the expression

$$(\delta B_{\|}/B_0)^2 \sim (\xi_\alpha)^\eta,$$

for comparison with the experimentally measured value of η for ICE in JET and TFTR,

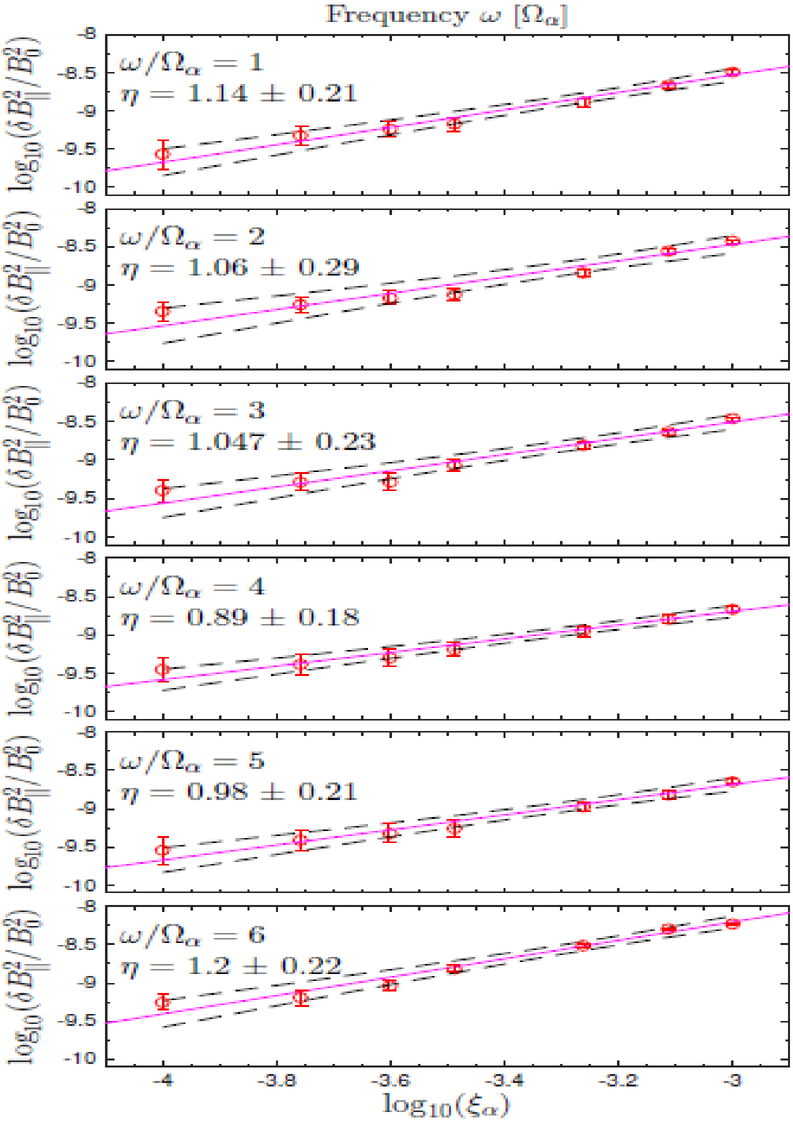

Fig.2 Scaling of the normalized magnetic field energy with alpha-particle concentration ξ_α in the hybrid simulations. The six panels display weighted least-squares linear fits for the base ten logarithmic plots of the normalized magnetic field energy $(\delta B_{\|}/B_0)^2$ versus ξ_α for the first six alpha-particle cyclotron harmonics $\omega = n\Omega_\alpha$. The black dashed lines in each of these panels represent the confidence interval of the weighted linear fit value of η, which is unity to within error bars at all six harmonics.

which is η ≈ 1 as noted above[1,4]. Figure 2 shows that, to within error bars, our simulations indeed yield η = 1 for the six lowest cyclotron harmonics, and there are strong indications that this is the case also for higher harmonics.

3. Conclusions

The scaling of the MCI-excited magnetic field energy density with alpha-particle concentration in the fully nonlinear regime of these preliminary hybrid simulations is found to be linear. This conclusion includes the modes at low cyclotron harmonics, which are not predicted to be linearly unstable according to the analytical theory of the MCI. These simulation results are in good agreement with observations of ICE intensity in JET and TFTR. They further strengthen the capability to exploit ICE, through understanding of the emission mechanism, as a diagnostic for fusion-born alpha-particles in future D-T plasmas in JET and ITER. The relation between the simulation-derived scaling of η, examined here, and the scaling properties of the linear analytical growth rate of the MCI[14,15,4], will be discussed further in Ref.[21].

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