

Particle-in-cell Simulations of the Emission Mechanism for Fusion Product-Driven Ion Cyclotron Emission from Tokamak Plasmas

J W S Cook¹, S C Chapman¹ and R O Dendy^{2,1}

¹Centre for Fusion, Space and Astrophysics, Department of Physics,
Warwick University, Coventry CV4 7AL, U.K.

²Euratom/UKAEA Fusion Association, Culham Science Centre, Abingdon,
Oxfordshire OX14 3DB, U.K.

Abstract

Self-consistent particle-in-cell (PIC) simulations of fusion born protons in the outer mid-plane edge of JET and TFTR deuterium plasmas illuminate the linear and nonlinear phases of the instability responsible for ion cyclotron emission (ICE) as seen by Cottrell [1].

Suprathermal ion cyclotron emission (ICE) was the first collective radiative instability, driven by contained fusion products, that was observed on JET [1,2] and TFTR [1]. Strong emission is found at sequential cyclotron harmonic peaks of the energetic ion population, evaluated at the outer mid-plane edge. The measured intensity of ICE spectral peaks scales linearly with measured fusion reactivity, including its time evolution in the course of a discharge. It appears that the underlying emission mechanism is the magnetoacoustic cyclotron instability (MCI), identified theoretically in 1976 [3] and subsequently extended to JET [4] and TFTR [5,6] regimes. The MCI involves resonance between: the fast Alfvén wave; cyclotron harmonic waves supported by the energetic particle population and by the background thermal plasma; and a subset of the centrally born fusion products, lying just inside the trapped-passing boundary in velocity space, whose drift orbits make large radial excursions to the outer mid-plane edge. Properties of the linear growth rate of the MCI in this regime have been intensively studied analytically, and yield good agreement [2,6] with the key observational features of ICE. Remarkably, this agreement extends to where a nonlinear treatment might be thought necessary, notably the scaling of intensity with fusion reactivity and the fine structure of the spectral peaks. To explain this, and to address outstanding issues, notably observed emission at background cyclotron harmonics that are non-degenerate with energetic particle harmonics, we have developed a fully nonlinear first principles treatment of the MCI scenario for ICE. We use a PIC code that self-consistently evolves electron and multi-species ion macroparticles together with the full Maxwell equa-

tions in one spatial dimension and three velocity dimensions. Our PIC code has been benchmarked against many complex analytical formulations relevant to cyclotron harmonic wave phenomenology in general, and ICE in particular. The growth rate of the MCI as it evolves from the linear into the nonlinear regime for JET-relevant parameters is the focus of this paper.

The trajectories of background thermal electrons and deuterons (both 10keV) evolve in time alongside the minority energetic protons (3MeV) which initially have a velocity distribution given by [4–6]:

$$f_p = \frac{1}{uv_r} \delta(v_{||} - v_d) \delta(v_{\perp} - u) \tag{1}$$

where v_d is the drift velocity along the magnetic field and u is the radius of the ring in perpendicular velocity space (see figure 3(a)). Simulations are run with 1000 particles per cell and 1024 cells whose size resolves electron Debye length and gyroradii of both background species. Cyclotron frequencies are well resolved in time and periodic boundary conditions are used. The effect of changing the angle (θ) of wave propagation with respect to the applied magnetic field is studied for $\theta = 80^\circ, 84^\circ$ and 88° . As expected, there is no instability at $\theta = 90^\circ$ ($k_{||} = 0$). The initial pitch angle α of the ring distribution is fixed at 135° with respect to the magnetic field [3] for all simulations discussed in this paper. The experiments simulate a neutral plasma with an electron number density of $5 \times 10^{19} m^{-3}$, and an applied magnetic field of $3T$. The fraction of protons to deuterons, $\frac{n_p}{n_d}$, used are $10^{-1}, 10^{-2}$, and 10^{-3} . Figure shows the time evolution of the total energy in the component of the electric field in the simulation domain (along \mathbf{k}), which grows exponentially and becomes nonlinear.

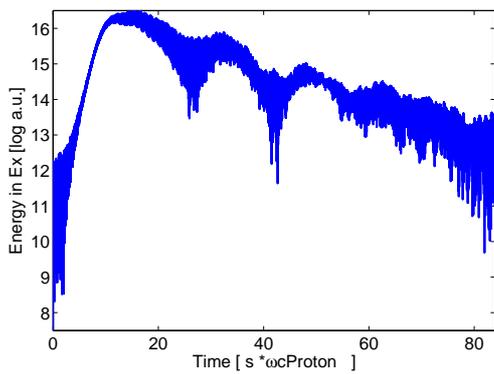


Figure 1: Natural log of the energy in the simulation domain component of the electric field as a function of time.

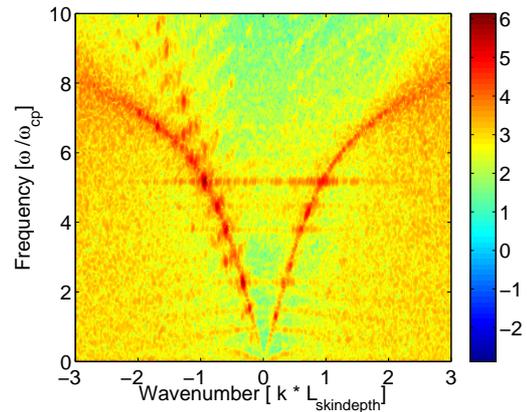


Figure 2: Dispersion relation obtained from the electrostatic field component during the linear growth phase of the instability. $\frac{n_p}{n_d} = 10^{-2}$, $\theta = 84^\circ$ and $\frac{m_p}{m_e} = 100$.

The growing wave modes appear as dark red patches on the dispersion relation (Figure) where the colour bar indicates a \log_{10} scale of power. The diagonal stripes with a positive gradient are the Doppler shifted proton cyclotron (DSPC) harmonics. Where the V-shaped Alfvén wave intersects these harmonics the power is at its greatest. These intersections are of particular interest at low $|\mathbf{k}|$ where they coincide with the deuteron cyclotron harmonics (DCH). In this case three waves (fast Alfvén, DSPC and DCH) couple and the DCH become suprathermally powerful. The self-consistent collective resonant interaction physics underlying wave growth can be seen in the perturbation to the velocity space distribution of the energetic particles in Fig. 4(a). During the linear phase the distribution deforms in a regular way suggestive of gyrophase bunching, as can be seen in Figures 3(a) and 3(b). Gyrophase bunching can also be clearly seen in Figure 4(a) which is a snapshot in time close to the end of the linear phase. Figure 4(b) is another visualisation of the dependence of $f(\theta, \alpha)$.

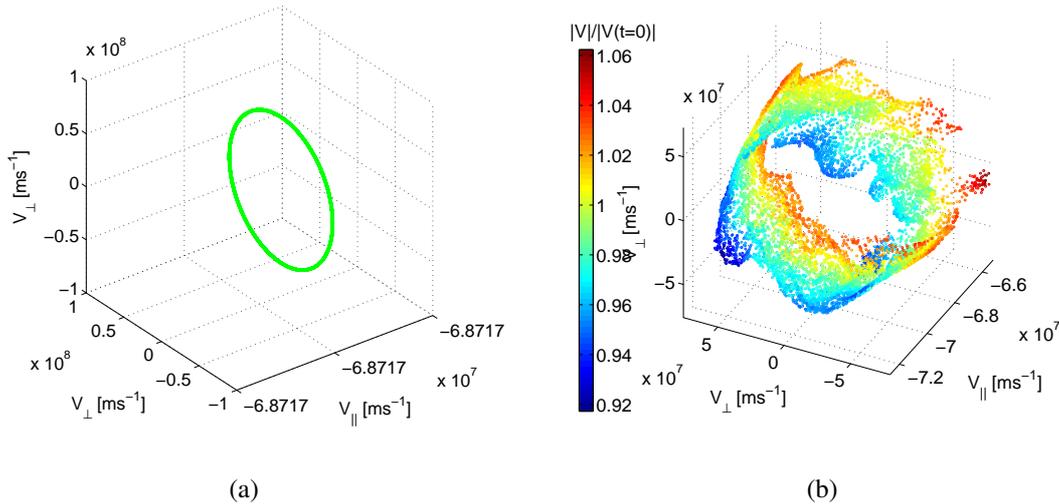


Figure 3: Velocity space distribution of the energetic protons at (a) $t=0$ and (b) during the linear phase of the fastest growing mode, showing gyrophase bunching and velocity dispersion.

Growth rates obtained for the linear phase of the fastest growing modes have been compared with equation 8 of McClements et al. [6], yielding agreement to the correct order of magnitude between the code and the earlier analytical model. The variation of growth rate with concentration of energetic particles, $\frac{n_p}{n_d}$, shows elements of wave-wave, 3-wave and wave-particle interactions as described in equation 69 in Dendy et al. [7].

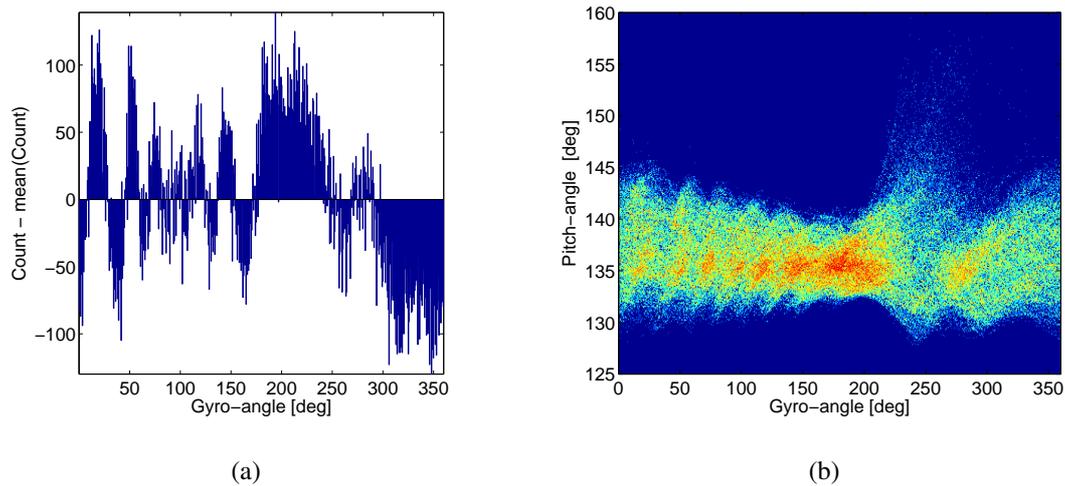


Figure 4: (a) Distribution of gyro-angles of energetic species at the end of the linear phase showing the gyro-bunching. (b) Distribution function of particles in gyro-angle and pitch-angle at the end of the linear growth phase of the fastest growing mode.

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