Fully nonlinear kinetic simulations of fusion product-driven ion cyclotron emission from tokamak plasmas

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1. Introduction

Ion cyclotron emission (ICE) was the first collective radiative instability, driven by confined fusion-born ions, that was observed[1-6] from the JET and TFTR tokamaks. It was the only collective instability driven by fusion alpha-particles that was detected from deuterium-tritium experiments in both JET and TFTR[3-6]. ICE from energetic ion populations has recently been detected on the large tokamaks JT-60U[7] and ASDEX-U[8], and its diagnostic potential for confined fusion products in ITER is under consideration[8]. Suprathermal emission, strongly peaked at the frequencies of sequential ion cyclotron harmonics as evaluated at the outer mid-plane edge, was detected using heating antennas in receiver mode on JET and using probes in TFTR. The measured intensity of ICE spectral peaks scaled linearly with measured fusion reactivity[1-5] and correlated with sawtooth activity[2]. The underlying emission mechanism appears to be the magnetoacoustic cyclotron instability[9] (MCI), whose analytical theory was extended to JET and TFTR regimes[3-5,10-13]. 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 centrally born fusion products, lying on the trapped side of the trapped-passing boundary in velocity space, whose drift orbits make large radial excursions to the outer mid-plane edge. Analytical studies show that the characteristics of the MCI in this regime yield good agreement[3-5,10,11] with key observational features of ICE. In particular, the properties of the observed spectra correlate remarkably well with those of the linear MCI growth rate. Perhaps surprisingly, this agreement extends into areas where a nonlinear treatment might be thought essential, notably the scaling of measured ICE intensity with fusion reactivity, which is an important aspect of the diagnostic potential of ICE. To help explain this, we have carried out direct numerical simulations using a particle-in-cell (PIC) code which has been extensively exercised on related plasma physics questions, for example in modelling alpha-channelling scenarios[14,15]. Importantly, our PIC approach captures the physics of cyclotron resonant coupling between ions and fields at the single-particle level; for example, gyrobunching[16]. The code self-consistently evolves electron and multi-species ions, together with the electromagnetic field in one spatial and three velocity space co-ordinates, enabling a fully nonlinear treatment of the MCI scenario for ICE previously studied analytically in the linear regime. The results from extending MCI theory from the linear into the nonlinear regime for JET-relevant edge plasma parameter sets form the focus of this paper, and shed light on the issues outlined above.

2. Simulation results

Figure 1 shows the frequency spectral characteristics of the waves excited in a PIC simulation of an ICE scenario motivated by the earliest observations in JET[1,2], which were driven by fusion-born protons in a deuterium plasmas. As discussed in the literature, the instability rests on perpendicular free energy associated with a population inversion due to large drift orbit excursions, and for this reason the energetic ions are initially distributed as a ring in perpendicular velocity space in this simulation. Here the ratio of the number density of 3MeV ring protons to that of 100eV thermal deuterons is 10^{-2}. Electron density is $10^{19}m^{-3}$ and temperature is 100eV. A 3T magnetic field is oriented in the *z*-direction. There are strong sequential cyclotron harmonic peaks in Fig.1: compare, for example, the observed spectrum of ICE from JET deuterium-tritium plasma 26148, Fig.2 of Ref.[3].

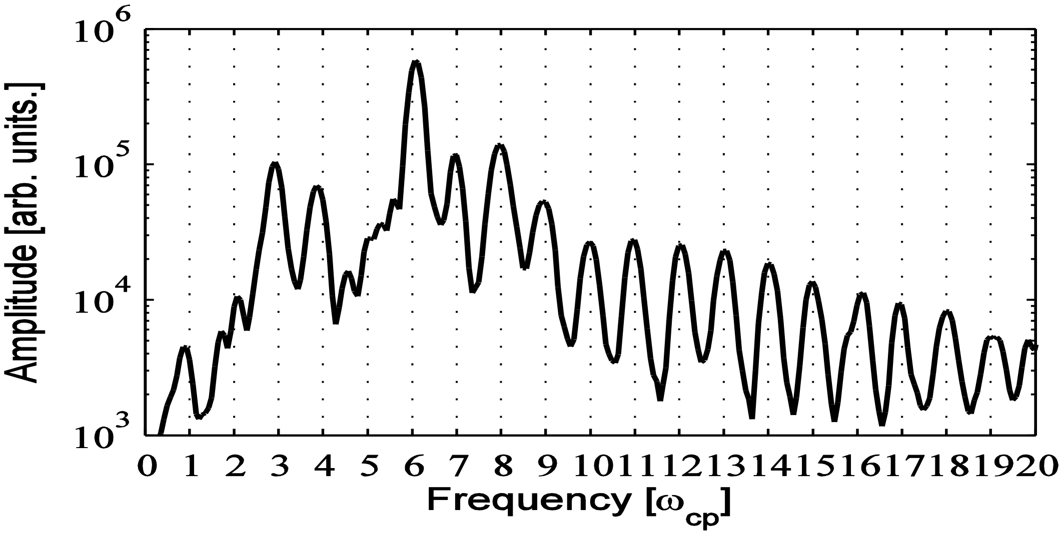

Figure.1 Frequency spectrum of fluctuations in the *y*-component of electric field obtained from a PIC simulation. Logarithmic plot of amplitude; frequency plotted in units of the proton cyclotron frequency.

Figure 2 shows the Fourier transform in frequency-wavenumber space (ω,k) of a component of the excited electric field; the frequency spectrum plotted in Fig.1 corresponds to the integral over k of this plot, where k denotes wavenumber along the spatial domain x of the 1D3V simulation. The perpendicular fast Alfvén wave with multiple intersections with cyclotron harmonic waves is visible. The time-evolving traces of energy density in B_z and E_x, shown in Fig.3, demonstrate that the excited field oscillation combines fast Alfvénic (magnetosonic B_z) and electrostatic Bernstein (E_x) characteristics, at the most elementary level of description, thus confirming a key assumption of the analytical theory of the MCI. The linear phase of the instability is well defined but brief, lasting approximately five proton cyclotron periods in Fig.3. The time trace of energy density of the deuteron population in Fig.3 reflects the fact that the excited waves involve oscillation of the majority background thermal ions. The associated kinetic energy, together with the electric and magnetic field energy, is drawn from the energetic protons, initially at 3MeV. Figure 3 shows that the energy density of this driving population (whose high initial energy density is required by computational constraints) declines by about fifteen per cent on a timescale of half-a-dozen proton cyclotron periods.

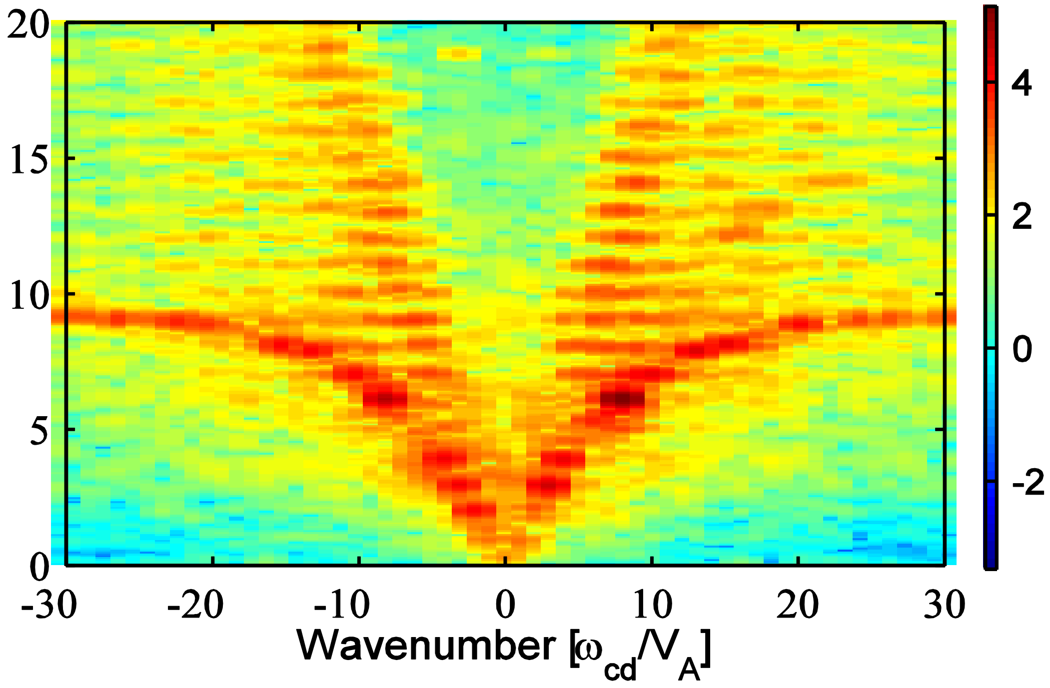

Figure 2. Fourier transform of energy density in the *y*-component of electric field. Frequency (vertical axis) is in units of proton cyclotron frequency; wavenumber (horizontal axis) in units of deuteron cyclotron frequency divided by Alfvén velocity.

By the end of the simulation, the instability has ceased to grow. This reflects the overall energy loss by the energetic ion population, together with its structural evolution in velocity space, which have the effect of terminating the instability drive on this fast timescale.

3. Conclusions

We conclude that first principles study of this energetic minority ion instability by means of PIC simulations yields significant new insights into the plasma physics processes that underlie observations[1-8] of ICE from large tokamaks. These include the nature of the excited electric and magnetic fluctuations, for which a combination of fast Alvénic and electrostatic components is assumed *ab initio* in analytical treatments, and crucially the correlation between linear analytical MCI growth rate and observed ICE intensity. It appears that this imprinting may arise because the timescale of the instability, see Fig.3, is so rapid that the driving population becomes disrupted by the instability faster than it can be replenished; once replenished, the instability repeats. In this picture, the ICE spectrum is continually imprinted with the linear properties of the underlying instability.

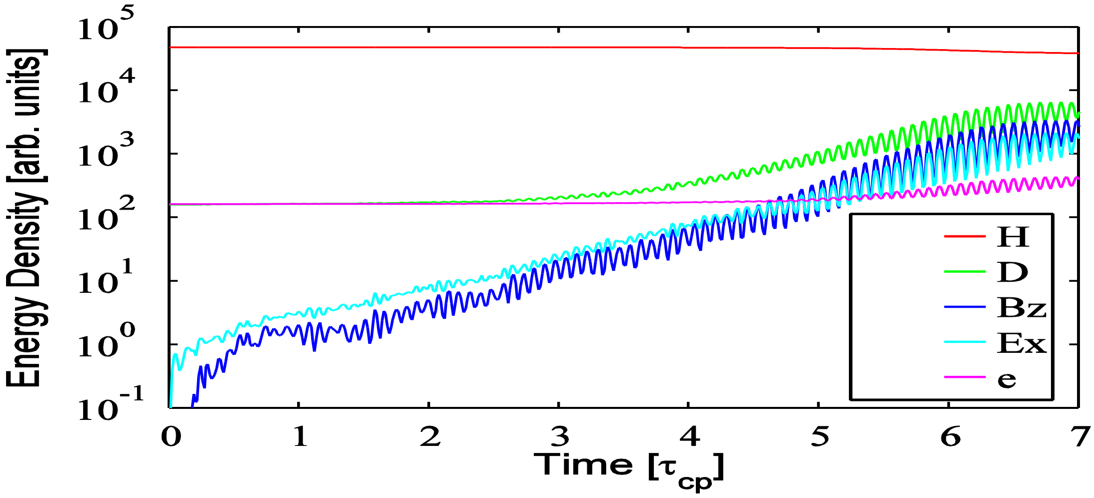

Figure 3. Time evolution of the energy density in the particle populations (protons, deuteron, electrons) and in selected electric and magnetic field components, as the instability proceeds. The unit of time is one proton gyroperiod. This logarithmic plot captures the entire linear phase of the instability.

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