On the role of deeply sub-Alfvénic energetic ions in generating ion cyclotron emission from fusion and laboratory plasmas

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Ion cyclotron emission (ICE) is widely observed from toroidal magnetically confined fusion (MCF) plasmas in both tokamaks and stellarators, and from cylindrical plasmas in the LAPD facility. ICE is generated by the collective relaxation of non-Maxwellian energetic ion populations, notably by fusion-born protons in deuterium plasmas and alpha-particles in deuterium-tritium plasmas, and by neutral beam injected (NBI) ions. ICE is excited under conditions where the deviation of the energetic ions from a Maxwellian velocity-space distribution is both substantial and spatially localised. This results in the characteristically well-defined spectral structure of ICE, with narrow-band peaks at local cyclotron harmonics. The ICE spectrum depends both on local plasma conditions and on the velocity-space distribution, where a key parameter is the ratio of the perpendicular and parallel components of energetic ion velocity to the Alfvén speed. The magnetoacoustic cyclotron instability (MCI)[1] drives ICE, and diagnostic exploitation of ICE is assisted by simulations of the fully nonlinear MCI from first principles. Here we report such simulations for conditions relevant to deeply sub-Alfvénic NBI ions in LAPD. These simulations, which use the particle-in-cell (PIC) kinetic code EPOCH[2] to self-consistently solve the Lorentz force equation and Maxwell's equations for tens of millions of gyro-motion-resolved ions, together with electrons, are computationally expensive. The sub-Alfvénic MCI also gave rise to ICE from NBI ions in DT plasmas in the TFTR tokamak[3], investigated analytically in Ref.[4]. Our new simulations address the electrostatic versus electromagnetic character of ICE in this regime; the effect of a substantial parallel component of energetic ion velocity, which has recently enabled the identification of ICE from fusion-born proton populations in pure deuterium plasmas in the LHD heliotron-stellarator[5]; and the likely observational consequences of these effects in ICE spectra observed from NBI ions in LAPD[6]. While $v_\perp/v_A \geq 1$ (super-Alfvénic) leads to strong ICE, based on both empirical evidence and the analytical theory of the MCI, here we explore $v_\perp/v_A < 1$ sub-Alfvénic ICE in a predominantly electrostatic regime relevant to the LAPD observations. In general, ICE is primarily observed as electromagnetic phenomenon, with electrostatic observations also from *e.g.* TFTR D-T plasmas[3,4] and potentially W7-X[7]. Electrostatic aspects of the MCI are also of interest because of potential interplay with the lower hybrid drift instability at high cyclotron harmonics.

We use the 1D3V EPOCH[3] PIC code to simulate the LAPD NBI-driven ICE senario. The electrons and majority He+ ions form the thermal background. The minority fast NBI protons are initialised as a drifting ring-beam distribution in velocity space. We simulate three cases with different beam energies: 15 keV ($v_\perp/v_A$=0.32), 80 keV ($v_\perp/v_A$=0.74) and 150 keV ($v_\perp/v_A$=1.013). An external magnetic field similar to that in LAPD is applied, with the ring beam oriented 53° with respect to it, reflecting the NBI injection angle. The orientation of the simulation domain is 89.5° to the magnetic field, to capture the strongly quasi-perpendicular MCI. The system is then allowed to relax, and Fig. 1 shows the spatiotemporal FFT of the spontaneously excited electric field in the 15 keV beam energy case. Its primary features are the fast Alfvén wave (FAW) and waves on the the ion cyclotron harmonic-ion Bernstein branch, which are clearly resolved at near-degeneracy. The flattening of the FAW dispersion relation at higher frequencies is also evident. Cyclotron harmonic can be seen well beyond the flattening of the FAW.

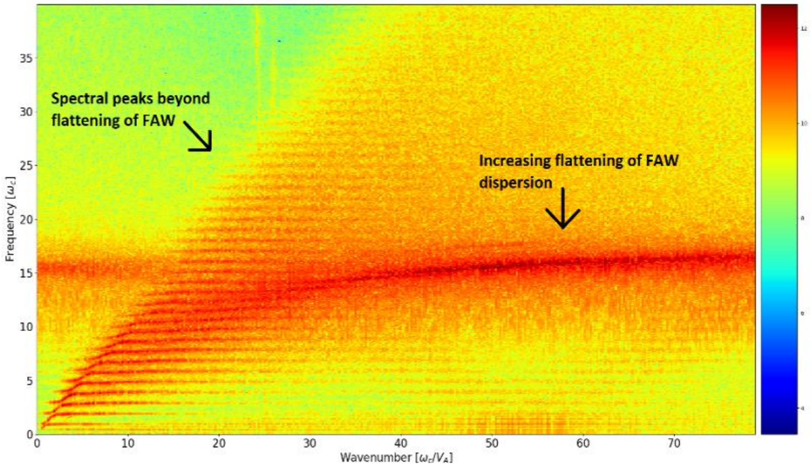

Fig. 1 Spatiotemporal FFT of x-component of the excited electric field (E_x) showing the distribution of energy across frequency-wavenumber space. Frequencies are normalised to the ion cyclotron frequency, and wavenumbers to the ratio of ion cyclotron frequency to Alfvén velocity. Shading indicates the $\log_{10}$ of the spectral density.

The corresponding power spectrum with respect to frequency is obtained by summing, over all k, the power at each frequency in Fig.1. This is shown in Fig.2(right). Figure 2(left), from Ref.[6], shows a typical observed ICE power spectrum of E_x from LAPD with 15 keV beam ions. Although the parameters of the plasma are slightly different, the observed and simulated ICE spectra in Fig.2 share the same overall shape and structure: broad spectra with distinct peaks close to harmonics of the beam gyrofrequency. In both observational and simulated cases, the spectral peaks extend well beyond the flat region of the FAW; and the spectral peak frequencies coincide with the cyclotron harmonics above the flat region, and are slightly downshifted below it. Figure 3 shows the time evolution of the particle and field beam energy for three cases: 15 keV ($v_\perp/v_A$=0.32), 80 keV ($v_\perp/v_A$=0.74) and 150 keV ($v_\perp/v_A$=1.013). It can be seen that in the 15keV case, more energy is transferred by the MCI from the NBI ions into the electrostatic field component, whereas in the other two cases, field excitation is predominantly electromagnetic. The duration of MCI also increases with energy.

Fig. 2 Left: Typical observed power spectrum of E_x (reproduced from Ref.[6]) for a 15 keV beam obtained from an LAPD plasma. **Right:** Log$_{10}$ plot of simulated spectral intensity of ICE obtained from the E_x data shown in Fig.1 for an EPOCH simulation with a 15 keV beam. The vertical lines in both the experimental and simulation power spectra correspond to integer multiples of the beam ion (proton) gyrofrequency.

Fig. 3 Time evolution of the change in energy densities of particles, electric and magnetic fields from the simulations for three different beam energies. Most of the NBI proton energy (cyan) is transferred to the electrostatic field component ((blue) than to the electromagnetic component (green) in the 15 keV beam case (top). The reverse applies to the 80 keV (centre) and 150 keV (bottom) cases.