Ion cyclotron emission (ICE) during ELM crashes in KSTAR tokamak plasmas resolves local density changes on very fast timescales

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1. Introduction

During edge localised mode (ELM) crashes in KSTAR deuterium plasmas, bursts of spectrally structured ion cyclotron emission (ICE) are detected. Usually the ICE spectrum chirps downwards during an ELM crash, on sub-microsecond timescales; see [1]. For KSTAR ICE where the separation of spectral peak frequencies is close to the proton cyclotron frequency Ω_{cp} at the outer plasma edge, our calculations suggest that the driving population of energetic ions is a subset of the 3MeV fusion protons, born centrally on deeply passing orbits; see Fig.2 of [2]. Here we report first principles modelling [2] of this scenario using a 1D3V version of the EPOCH particle-in-cell (PIC) code [3]. This evolves the full orbit dynamics of large numbers of energetic ions, thermal ions, and electrons self-consistently with the electromagnetic fields. The Fourier transform of the excited fields in the nonlinear saturated regime of the simulations is the theoretical counterpart to the measured ICE spectra. We carry out multiple simulation runs for different, adjacent, values of the plasma density under KSTAR edge conditions. From these we infer the theoretical dependence of ICE spectral structure on the local density. By matching this density dependence to the observed time-dependence of chirping ICE in KSTAR, we obtain sub-microsecond time resolution of the evolving local density during the ELM crash; see Fig. 5 of [2]. There are also rare upward chirps, which our modelling suggests may be due to locally rising edge density probably associated with ELM filaments. ICE comprises suprathermal radiation in the ion cyclotron range of frequencies, whose spectrum peaks at successive local cyclotron harmonics of the emitting ion population. ICE has previously been observed in all large toroidal magnetically confined fusion (MCF) plasmas [4]. ICE is caused by a collective instability, which in its linear phase corresponds to the magnetoacoustic cyclotron instability (MCI) [5, 6, 7, 8, 9], which can occur because of an edge localised population inversion in velocity space that is caused by the large drift excursions of energetic ions.

2. Examples of chirping ICE observations in KSTAR

Figure 1 shows downward chirping ICE bursts for KSTAR plasmas 11462 and 11513. Both have plasma current $I_p \simeq 600$kA, with toroidal magnetic field at the magnetic axis $B_0 \simeq 1.7$T and $B_0 \simeq 1.99$T respectively. The far right panel shows upward ICE chirping for KSTAR plasma 11474, which has $B_0 \simeq 2.27$T; see Fig. 6 of [2]. The detection system for the fast RF spectrum is located close to the outer mid-plane of KSTAR [1], which has minor radius $a = 0.45$m. The frequency spacing between successive spectral features is ~ 21.5MHz for plasma 11462 and $\sim$ 25MHz for plasma 11513. If this is the local proton cyclotron frequency, the inferred magnetic fields are $B \approx 1.41$T and $B \approx 1.64$T respectively which are correct for the outer midplane edge. This suggests that the observed ICE frequency chirping is due to rapid time evolution of the character of the MCI underlying the ICE locally driven by fusion born protons.

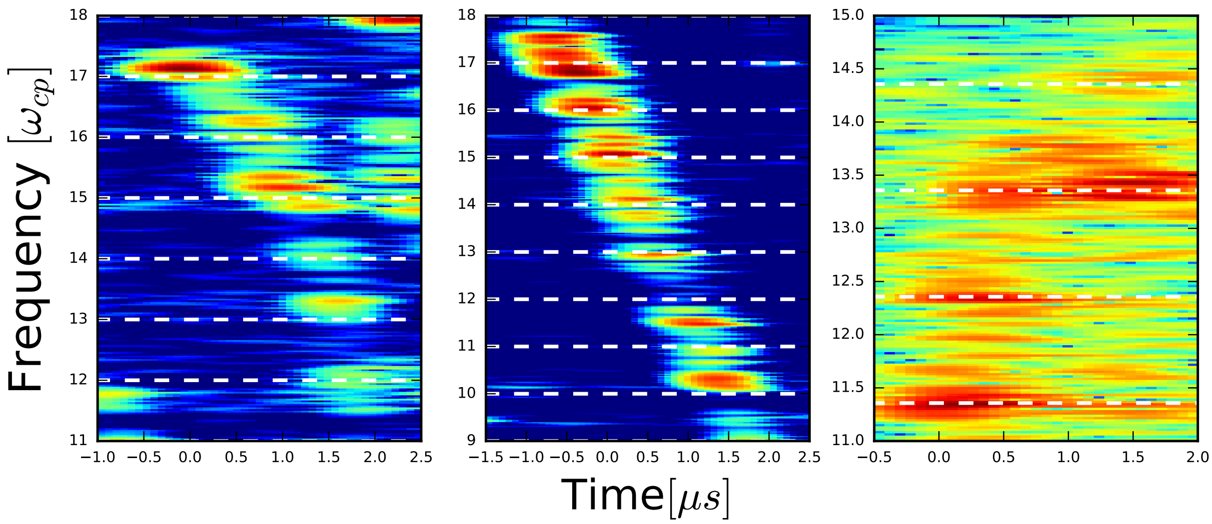

Figure 1: *Time evolution of ICE spectra during an ELM crash in KSTAR plasmas 11462 (left), 11513 (centre), and 11474 (right). Time is measured relative to the moment chirping bursts are observed during the ELM crash ($\sim 100\mu s$ after the start of the crash). The horizontal dashed lines in the spectrogram indicate proton cyclotron harmonics.*

3. First principles simulation results

Here we focus on the effect of the lower hybrid frequency ω_{LH} on the ICE spectra that arise in our simulations. Multiple simulations at different densities for a range of magnetic field strengths have been carried out using the EPOCH PIC code [3]. The range of densities in the simulations is determined by Thomson scattering measurements in the edge pedestal [1]: $n_e = 0.2 \times 10^{19}\,\mathrm{m}^{-3}$ to $n_e = 2.4 \times 10^{19}\,\mathrm{m}^{-3}$.

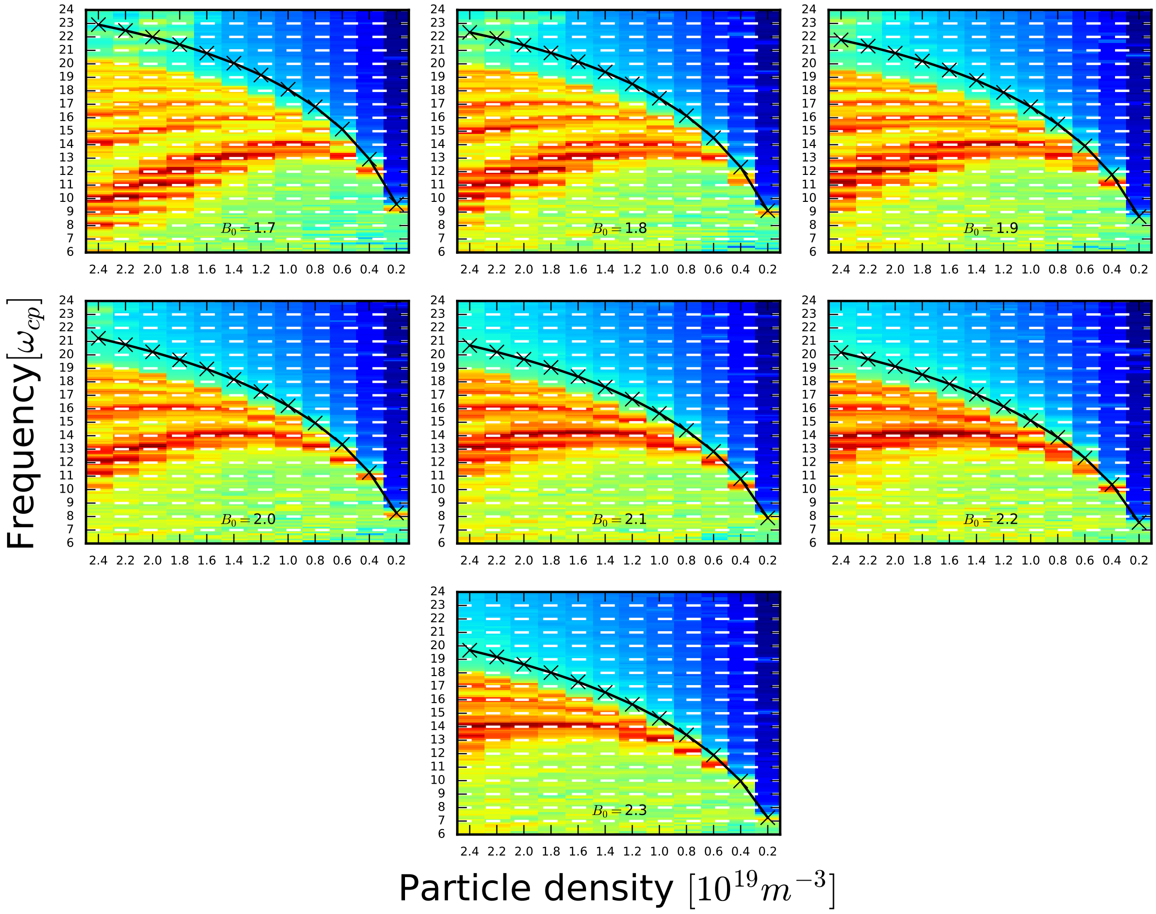

Figure 2: *Spectral power as a function of plasma density for a range of magnetic field strengths corresponding to the nonlinear saturated phase of the MCI. Shading indicates the* $\log_{10}$ *of the spectral power in the* B_z *field component of each simulation. Each panel represents a series of simulations each at different density at constant background magnetic field strength ranging from* $B = 1.7$T *(top left) to* $B = 2.3$T *(bottom). The black line joins points at* ω_{LH} *for each density; this defines the boundary of evanescence in the cold plasma limit.*

The amplitude spectrum of the B_z field component of each simulation is determined in Fourier transformed frequency-wavenumber space, and the signal power $\propto B_z^2$ as a function of frequency is calculated by integrating over the $k > 0$ region of the Fourier transform. From this we build an image of how the power at each frequency varies as a function of density for a given magnetic field. This is shown in Fig. 2, in each panel the ICE intensity is plotted using a colour scale and density decreases from left to right. The white lines indicate successive proton cyclotron harmonics and the black lines plot the lower hybrid frequency ω_{LH} in units of the proton cyclotron frequency. Figure 2 shows how the allowed range of excited frequencies decreases as density decreases, in line with the density scaling of ω_{LH}. For $n \leq 1 \times 10^{19}\,\mathrm{m}^{-3}$, the spectrum is dominated by a single cyclotron harmonic, with the harmonic number falling monotonically as the density drops. For values of $n_e > 1.0 \times 10^{19}\,\text{m}^{-3}$, the number of excited frequencies decreases as the magnetic field increases, and for a given density, the difference between the harmonic numbers of the highest and lowest excited spectral peaks reduces as the value of the magnetic field increases. For frequencies approaching ω_{LH}, the variation of ICE intensity with density resembles the experimentally-observed variation of intensity with time, see Figs. 3, 4, and 5 of [2]. Figure 2 highlights that the trend in ICE spectral power, as a function of frequency and electron number density, is the same for all values of magnetic field.

4. Conclusions

We have shown [2] that harmonic ICE with spacing equal to Ω_{cp} at the outer midplane in KSTAR deuterium plasmas is driven by a small subset of the fusion-born proton population originating in the core of the plasma. The drift orbits of these protons have large radial excursions to the outer midplane edge. We have compared the nonlinearly saturated field spectra obtained from multiple PIC simulations of MCI physics at different plasma densities to the experimentally observed time evolving ICE spectra. By comparing different simulation spectra with the bursts of chirping ICE observed during KSTAR ELM crashes, we infer that the chirping is caused by large local density changes on micro-second time scales [2].

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