Nonlinear wave interactions explain high-harmonic cyclotron emission from fusion-born protons during a KSTAR ELM crash

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1. Introduction

During ELM crashes in deuterium plasmas in the KSTAR tokamak, the detected electromagnetic radiation[1] includes features with sharp spectral structure in the frequency range up to ~900MHz. Cases where the spectral peaks below ~500MHz correspond to proton cyclotron harmonics at the outer midplane edge have been successfully explained[2] as ion cyclotron emission (ICE), driven by a collective instability of a subset of the 3MeV protons that are born in deuteron-deuteron fusion reactions in KSTAR plasmas. This subset is confined because it lies on deeply passing drift orbits which carry the protons from the core to the outer plasma edge and back. At the outer midplane edge, this energetic proton minority has a sharply defined non-Maxwellian distribution in velocity space. In consequence, it can undergo the magnetoacoustic cyclotron instability (MCI). The MCI[3,4] drives waves on the fast Alfvén-cyclotron harmonic wave branch, which are observed as ICE on arrival at the detection antenna. During KSTAR ELM crashes, the duration of the proton ICE features is brief, typically a few microseconds. The ICE features exhibit frequency chirping, which is due[2] to rapid localised changes in the density of the ambient plasma in which the energetic ions are embedded. Hence ICE chirping provides a high time resolution sequence of measurements[2] of this local density.

Some chirping proton ICE features on KSTAR below ~500 MHz are accompanied, after a time delay < 1μs, by a fainter detached ("ghost") chirping feature in the range 500MHz to 900MHz. This frequency range exceeds estimates[5,6] of the local lower hybrid frequency, and cold plasma waves propagating quasi-perpendicular to the magnetic field are expected to be evanescent here. We show[5] that the "ghost" chirping ICE feature is a real physical phenomenon, generated by strong nonlinear wave coupling between different spectral peaks within the primary chirping ICE feature below ~500MHz. We demonstrate this[5] by bicoherence analysis of: first, KSTAR data files for ICE field magnitudes; and, second, the fields generated from direct numerical solution, using a particle-in-cell (PIC) code, of the self-consistent Maxwell-Lorentz system of equations for fully kinetic electrons and thermal deuterons, together with a minority ring-beam distribution representing the fusion-born 3MeV protons.

2. Observation of “ghost” ICE chirping feature in KSTAR

Figure 1 displays[5] the time evolution of ICE amplitude during an ELM crash in KSTAR plasma 11513. Time zero refers to the centre of a 200μs segment of radio-frequency data. The horizontal dashed lines in the spectrogram are at sequential harmonics of the proton cyclotron frequency f_{cp} at the low-field side outer midplane plasma edge. In addition to the main spectrally structured chirping feature below 500MHz which equates to $20f_{cp}$, addressed in [2], there is a second, faint (“ghost”), feature at frequencies above the lower hybrid frequency f_{LH} at 529MHz which equates to $21f_{cp}$. This additional, higher-frequency, chirping ICE feature is delayed in time by approximately 1μs with respect to the main chirping ICE feature.

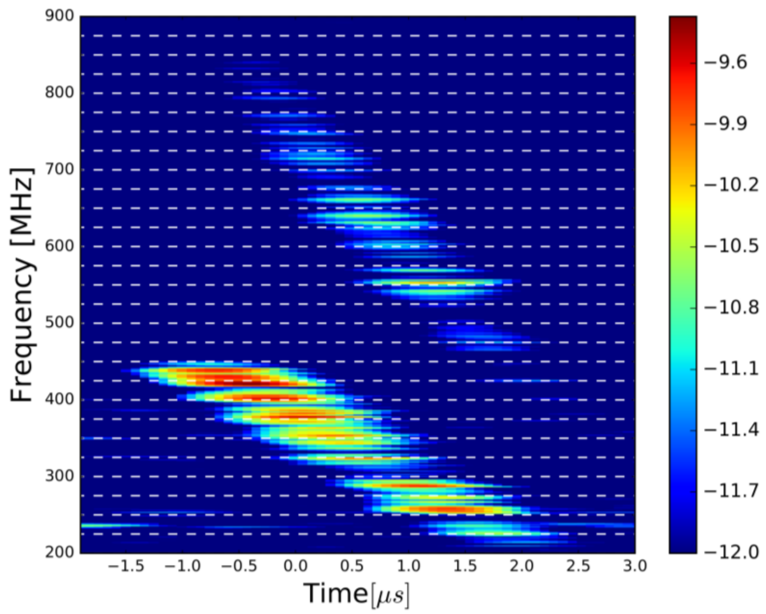


Fig.1 Two chirping ICE features measured during an ELM crash in KSTAR plasma 11513. The slightly later, fainter, higher-frequency (“ghost”) feature is addressed here[5]. The brighter, lower-frequency feature was analysed in [2]. For a higher-resolution counterpart to this Figure, see [5].

3. Particle-in-cell code simulations of the KSTAR ICE from first principles

The EPOCH PIC code[7] directly solves and evolves the self-consistent Maxwell-Lorentz system of equations for tens of millions of fully kinetic electrons and ions. The code retains full gyro-orbit dynamics for each particle, hence can capture wave-particle cyclotron resonance at the fundamental and its harmonics. To simulate the KSTAR ICE scenario, we have used EPOCH to study[5] the collective relaxation of a minority ring-beam population of confined fusion-born 3MeV protons embedded in a majority plasma comprising thermal deuterons and electrons. The ring-beam protons are deeply passing, as discussed in [2], and the perpendicular component of their energy is 150 keV, implying mildly super-Alfvénic perpendicular speed in the KSTAR edge plasma where the ICE originates.

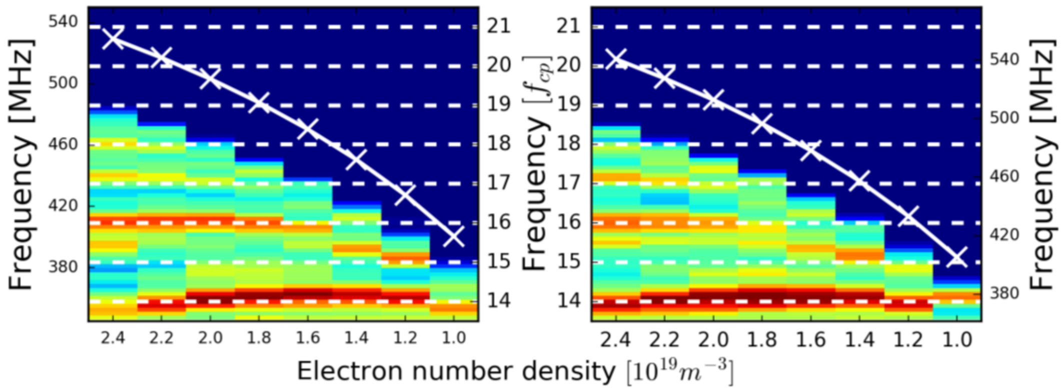


Fig.2 PIC simulation results: dependence of spectral power on plasma density across a declining sequence of neighbouring values of density, evaluated from the Fourier transform of the B_z field component that arises in the simulations during the saturated phase of the MCI. Colour scale is logarithmic. These plots imply that ICE chirping over time reflects the decline in the local plasma density over time, resolved on sub-microsecond timescales. See also Fig.2 of [5].

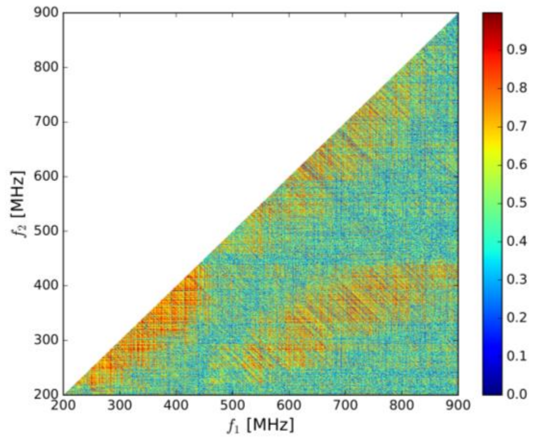
Collective relaxation of the proton population, interacting also with the majority deuterons, is found to reflect the key features of the MCI, and the frequency structure of the excited fields is strongly and narrowly peaked at sequential proton cyclotron harmonics. In short, the relaxation gives rise to ICE. The distribution of energy across the different proton cyclotron harmonics is found to depend strongly on the density; see, for example, Fig.2. By running multiple simulations in a declining sequence of slightly different densities, we are able to replicate[2,5] the chirping features displayed in Fig.1. This implies a mapping between time in Fig.1 and density in the simulations. This mapping is exploited in Figs. 5 and 7 of [2] and Fig. 5 of [5], which plot local density versus time, on sub-microsecond timescales.

3. Bicoherence analysis

Using bicoherence analysis techniques[8,9], we have tested[5] the hypothesis that the "ghost" ICE feature is driven, in a region where perpendicular-propagating waves are expected [5,6] to be evanescent, by nonlinear wave coupling between spectral peaks in the lower-frequency ICE feature. Bicoherence analysis enables the identification of regions of (k_1, k_2) space where nonlinear coupling to a wave at $k_3 = k_1 + k_2$ is strongest. We have applied[5] bicoherence techniques to both the experimental radio-frequency ICE dataset from KSTAR, and the output files from our PIC simulations of the KSTAR ICE scenario[2] using EPOCH. Figure 3 shows an example of each, from which it appears that this hypothesis is correct.

4. Conclusions

The "ghost" ICE feature detected above f_{LH} in KSTAR, shown in Fig.1, is a real plasma physics phenomenon[5]. Driven by the collective relaxation of fusion-born protons in the KSTAR deuterium plasma, "ghost" ICE arises also due to a combination of collective linear and nonlinear wave physics which is so far detected only by the KSTAR RF diagnostics, which have exceptionally high time resolution. The entire plasma physics phenomenology underpinning the “ghost” unfolds on sub-microsecond timescales during an ELM crash.



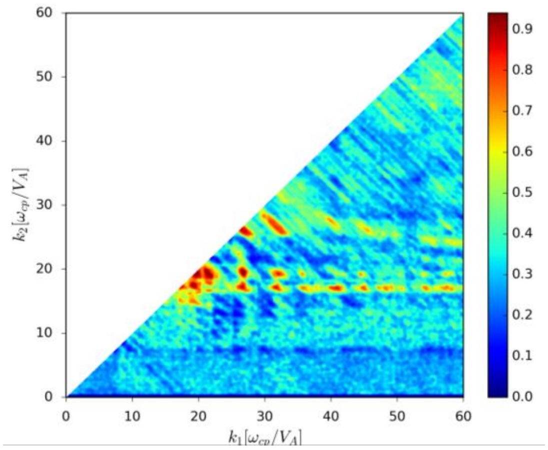


Fig.3 Bicoherence plots for (Left) the KSTAR ICE dataset and (Right) field amplitude output from a PIC simulation of the KSTAR ICE scenario in the saturated regime of the MCI. These plots display strong nonlinear coupling between spectral peaks within the lower-frequency chirping feature and higher-frequency peaks within the “ghost” feature. See also Figs.3 and 4 of [5].

The present study reinforces the case[10] for adopting ICE as a diagnostic for energetic ion populations in contemporary MCF plasmas. ICE observations have recently been reported from JET[11], ASDEX-Upgrade[12], JT-60U[13], DIII-D[14], and LHD[15].

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