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

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During ELM crashes in deuterium plasmas in the KSTAR tokamak, the emitted electromagnetic radiation 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 are explained (B Chapman *et al.*, *Nucl. Fusion* **57** 124004 (2017)) as ion cyclotron emission (ICE) driven by a subset of the 3MeV protons 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. Its sharply defined non-Maxwellian distribution in velocity space means that this energetic proton minority can undergo the magnetoacoustic cyclotron instability (MCI) in the edge plasma. The MCI drives waves on the fast Alfvén-cyclotron harmonic wave branch, which are observed as ICE. During KSTAR ELM crashes, the duration of the proton ICE features is brief, typically a few microseconds. The chirping results from rapid changes in the density of the ambient plasma in which the energetic ions are embedded. Some chirping ICE features below ~500 MHz are accompanied, after a time delay $< 1\mu s$, by a fainter detached ("ghost") chirping feature in the range 500MHz to 900MHz. This frequency range exceeds the local lower hybrid frequency, and cold plasma waves propagating quasi-perpendicular to the magnetic field are expected to be evanescent here. Nevertheless, we show that the "ghost" chirping ICE feature is a real physical phenomenon. It is generated by strong nonlinear wave-wave coupling between different spectral peaks within the primary chirping ICE feature below ~500MHz. We demonstrate this 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 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.

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