# Modelling ion cyclotron emission from beam-injected ions in magnetic confinement fusion plasmas

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## Introduction

Suprathermal ion cyclotron emission (ICE) [1, 2] is detected from all large toroidal magnetic confinement fusion (MCF) plasmas [3–8], both tokamak and stellarator; for recent reviews, see [9, 10]. The frequency spectrum of ICE has narrow peaks at sequential cyclotron harmonics of the energetic ions at the outer mid-plane edge of the plasma. ICE was the first collective radiative instability driven by confined fusion-born ions observed in deuterium-tritium (D-T) plasmas in JET and TFTR [11–14], and the magnetoacoustic cyclotron instability (MCI) [15–19] is the most likely emission mechanism. ICE is proposed as a diagnostic for confined energetic ions in ITER [20]. Second generation ICE measurements are obtained from the LHD stellarator [4, 7] and from the conventional aspect ratio KSTAR tokamak [8], and are imminent for the QUEST spherical tokamak. These measurements are taken at sampling rates far higher than for first generation ICE, and in combination with other advanced diagnostics, notably for MHD. This enables fresh insights into the physics of confined energetic ions in MCF plasmas, and also into the interaction between these ions and MHD activity. Exploitation of second generation ICE measurements requires a corresponding advanced modelling capability for the emission mechanism, the MCI. Here we report simulations for plasma conditions relevant to ICE measurements [4] associated with neutral beam injection (NBI) of 40 keV protons in the LHD stellarator. Figure 1 shows a measured ICE power spectrum from LHD, with strong peaks at successive harmonics of the proton cyclotron frequency $\Omega_H$.

## Simulation model

We use a 1D3V hybrid code [19] which simulates the self-consistent full gyro-orbit kinetics of energetic and thermal ions, all three vector components of the electric and magnetic

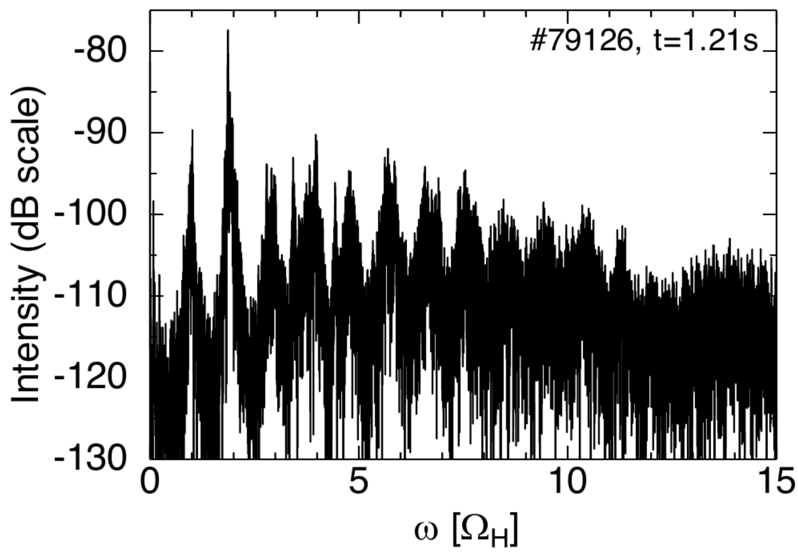


Figure 1: B field power spectrum for perpendicular 40 keV proton NBI from LHD plasma 79126. The radiation is located at $R_{ax} = 4.62$m with $\Omega_H = 6.75$MHz, the temperature $T_e \approx 150$eV and the density $n_e \approx 10^{19}\text{m}^{-3}$.

fields, and a massless neutralising electron fluid. These are coupled self-consistently through the Lorentz force and Maxwell's equations in the Darwin approximation [19–21], and the code is fully nonlinear. The NBI protons are sub-Alfvénic in the emitting region of the LHD plasmas, so that our nonlinear simulations correspond to the sub-Alfvénic regime of the MCI, previously explored analytically in the linear regime [12–16]. For the first time, we are able to follow the sub-Alfvénic MCI into the nonlinear saturated regime relevant to measured LHD ICE spectra, such as that shown in Fig. 1. The 40 keV NBI energetic minority proton population is taken to have density concentration $\xi = 0.0005$ relative to the thermal ions. This population is represented by a ring-beam distribution in velocity space, $f_{beam}\left(v_{\|}, v_{\perp}\right) = \delta(v_{\|})\delta\left(v_{\perp} - u\right)$ where $u$ is the perpendicular injection velocity of the 40 keV NBI protons, which are uniformly randomly distributed in gyro-angle [16]. To approximately represent LHD edge plasma conditions, the thermal electrons and ions both have a temperature of 0.15keV, the electron density is $10^{19}\text{m}^{-3}$, and the background magnetic field $\mathbf{B}_0$ has strength $B_0 = 0.46$T. The local Alfvén speed $V_A$ is $3.17\ 10^6\text{m}s^{-1}$, hence the injected protons are sub-Alfvénic with $u/V_A \approx 0.89$. Denoting the spatial component of the 1D3V simulation domain by $\hat{\mathbf{x}}$, the wavevector $\mathbf{k} = k\hat{\mathbf{x}}$; in our simulation, the angle between $\mathbf{B}_0$ and $\mathbf{k}$ is 89.5°. There are 2760 computational cells and 500 macroparticles per cell. The cell size is 0.43 $r_{L,bulk}$, where the bulk ion Larmor radius $r_{L,bulk} = 0.0044$m and $r_{L,ringbeam} = 0.0628$m. The domain length is $1186 r_{L,bulk} = 83 r_{L,beam}$.

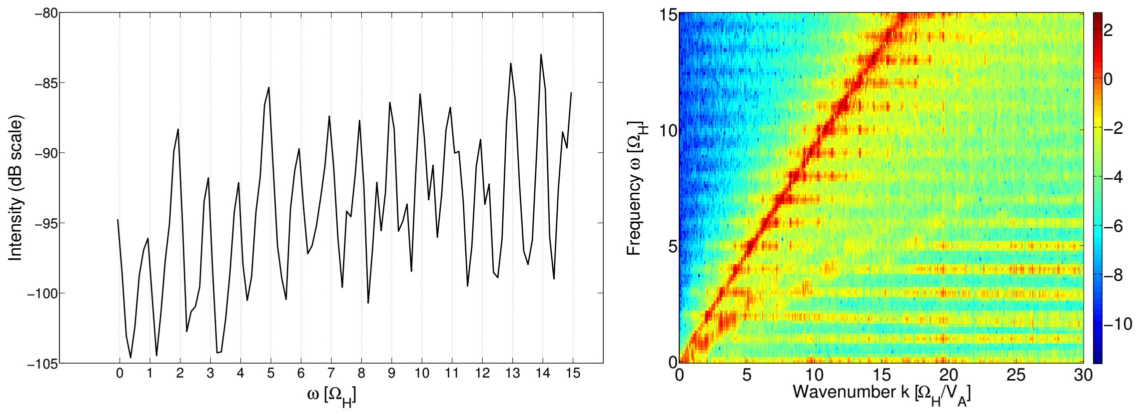


Figure 2: Left, power spectrum of $B_z/B_0$ averaged between $\tau_H = 0$ and $\tau_H = 7$, on a dB scale, $\Omega_H$ is the proton cyclotron frequency. Right, spatiotemporal Fourier transform of the oscillating part of $B_z/B_0$, on a log10 scale.

## Simulation results

Figure 2 shows representative outputs from our simulation. The left panel plots the power spectrum of the z component of the oscillating part of the magnetic field, normalized to $B_0$, on a dB scale. This plot was obtained by summing simulation output between $k = 0$ and $k = 30$ (in units $\Omega_H/V_A$), and taken between $\tau_H = 0$ and $\tau_H = 7$, where $\tau_H$ is the proton gyroperiod. It is evident that the saturated MCI generates intense narrow spectral peaks at the sequential cyclotron harmonics of the injected protons. The right plot shows the corresponding spatiotemporal Fourier transform of the z component of the oscillating part of the magnetic field, on a log10 scale. This shows how the 40keV energetic protons excite the electromagnetic fields at successive proton cyclotron harmonics. The range of $(\omega, k)$ values at which excitation occurs is strongly localised in the region for which $\omega/k \approx u$.

## Conclusion

The measured ion cyclotron emission (ICE) spectrum (Fig. 1.) from an LHD plasma with 40 keV perpendicular proton NBI has been successfully simulated (Fig. 2.) using a first principles approach. Direct numerical simulation of kinetic ions (bulk protons and minority energetic NBI protons) and fluid electrons using a 1D3V hybrid code captures the self-consistent Maxwell-Lorentz dynamics of the plasma and fields. It is evident from the Fourier transformed code outputs that the dominant physical process is the magnetoacoustic cyclotron instability (MCI) in its sub-Alfvenic regime. This was observed previously for NBI plasmas in TFTR [15] and its linear analytical properties are understood [16, 17]. Here, for the first time, we have investigated the fully nonlinear sub-Alfvénic MCI in order to match saturated field amplitudes in the simulation to the measured LHD ICE spectrum.

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