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

R. O. Dendy[1,2], B. C. G. Reman[2], T. Akiyama[3], S. C. Chapman[2], J. W. S. Cook[2],
H. Igami[3], S. Inagaki[4], K. Saito[3], G. S. Yun[5]
[1] *CCFE, Culham Science Centre, Abingdon, Oxfordshire OX14 3DB, UK*
[2] *Centre for Fusion, Space and Astrophysics, Department of Physics, Warwick University, Coventry CV4 7AL, UK*
[3] *National Institute for Fusion Science, Toki, Gifu 509-5292, Japan*
[4] *Research Institute for Applied Mechanics, Kyushu University, Kasuga 816-8580, Japan*
[5] *Department of Physics, Pohang University of Science and Technology, Pohang 37673, Korea*

1. Introduction

Ion cyclotron emission (ICE) [1, 2] is detected from all large toroidal magnetic confinement fusion plasmas and is proposed as a diagnostic for confined energetic ions in ITER, see [3–5]. Its power spectrum comprises narrow, strongly suprathermal, peaks at frequencies corresponding to sequential cyclotron harmonics of ions located in the outer regions of the plasma. ICE is driven by collective instability of energetic ion populations that have a spatially localised inversion in velocity space; the magnetoacoustic cyclotron instability (MCI) [5–10] is the most likely emission mechanism. Here we analyse ICE spectra generated by neutral beam injected (NBI) energetic ions in the outer regions of plasmas in the Large Helical Device (LHD) heliotron-stellarator [11, 12]. These spectra were measured using the ICRF heating antenna as a receiver with sampling rate 5 GHz. Importantly, these spectra span plasma regimes where the ratio of the velocity of the energetic ions V_{NBI} to the local Alfvén speed V_A is smaller or larger than unity: in particular, we examine LHD plasmas 79126 and 79003 where $V_{NBI}/V_A = 0.872$ and 1.125, respectively, in the ICE-emitting region. We calculate the full gyro-orbit kinetics of energetic and thermal ions, the electric and magnetic fields, and a massless neutralising electron fluid, using a fully nonlinear 1D3V PIC-hybrid particle-in-cell code [10]. The kinetic ions, fluid electrons, and fields are coupled self-consistently through the Lorentz force and Maxwell's equations. We follow these simulations through the linear phase of an instability that we identify as the MCI, and then deeply into its nonlinear saturated phase. The Fourier transforms of the excited fields yield frequency spectra that match the observed ICE spectra from these LHD plasmas. These simulation results for heliotron-stellarator plasmas complement and confirm earlier interpretation of ICE driven by sub-Alfvénic NBI ions in TFTR tokamak plasmas [7, 13].

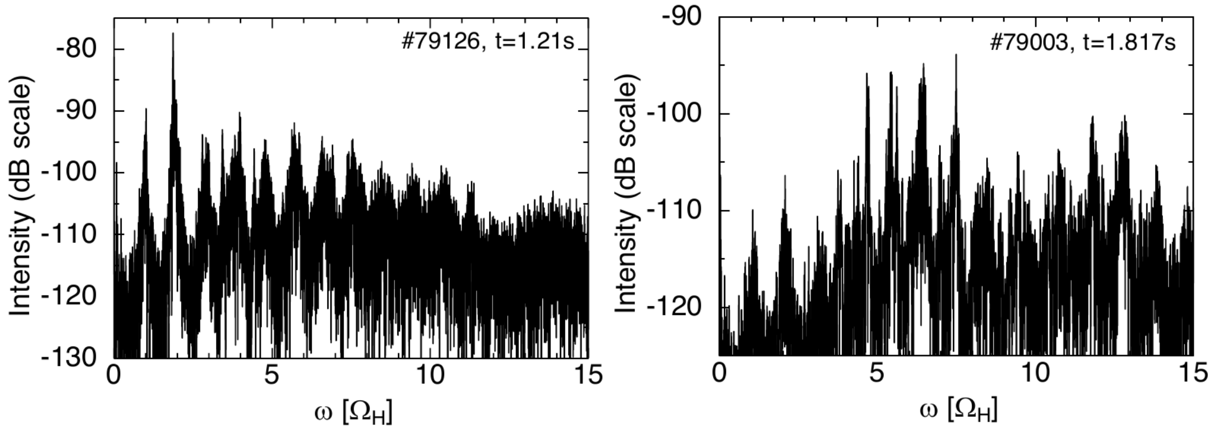

Fig. 1: Measured B field power spectrum from: (Left) LHD plasma 79126 during sub-Alfvénic perpendicular 40 keV proton NBI; (Right) LHD plasma 79003 during super-Alfvénic perpendicular 36.5 keV proton NBI. This ICE is localised at $R_{ax} = 4.62$ and 4.65m corresponding to proton cyclotron frequency $\Omega_H = 6.75$MHz and $\Omega_H = 3.67$MHz, respectively. The local temperatures $T_e \approx 150$eV and $T_e \approx 100$eV, and densities $n_e \approx 10^{19}\text{m}^{-3}$ and $n_e \approx 0.5\text{x}10^{19}\text{m}^{-3}$. In these emitting regions $V_{NBI}/V_A = 0.870$ and $V_{NBI}/V_A = 1.125$, respectively.

2. Simulations

The NBI protons are sub (super)-Alfvénic in the emitting region of LHD hydrogen plasmas 79126 (79003), whose measured ICE spectra are shown in Fig.1. In our simulations, the 40 (36.5) keV NBI proton population is taken to have particle concentration $\xi = 5\text{x}10^{-4}$ ($7.5\text{x}10^{-4}$) relative to the thermal ions. It is represented by an initial ring-beam distribution in velocity space, $f_{beam}\left(v_{\parallel}, v_{\perp}\right) = \delta(v_{\parallel})\delta\left(v_{\perp} - u\right)$ where u is the perpendicular injection velocity of the NBI protons, which are uniformly randomly distributed in gyro-angle [7].

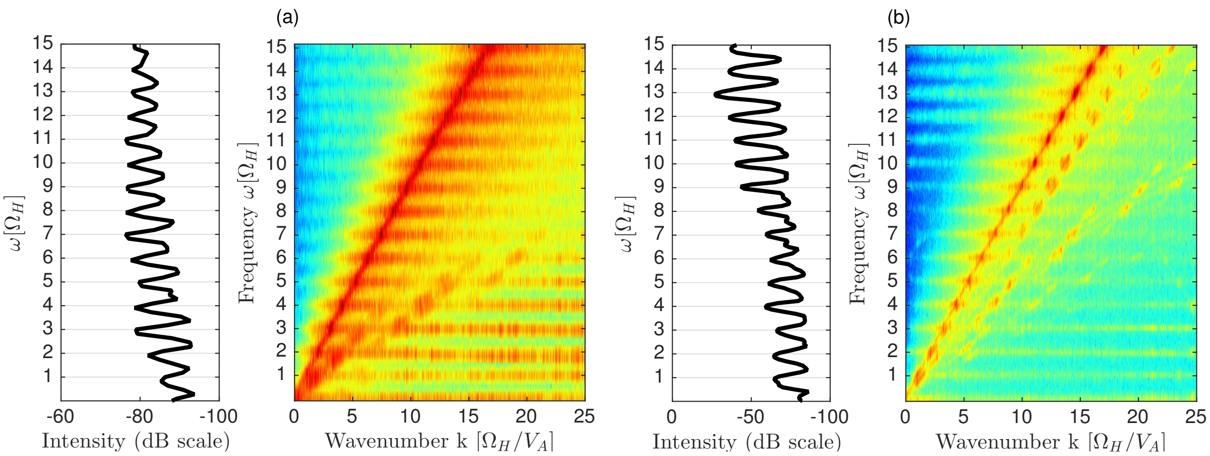

Fig. 2: Simulation outputs: Panel (a): (Left) spectral intensity and (Right) spatiotemporal Fourier transform of the z component of the oscillating part of the magnetic field for simulated LHD plasma 79126 with $u/V_A = 0.870$. Panel (b): corresponding plots for simulated LHD plasma 79003 with $u/V_A = 1.125$.

To approximately represent LHD edge plasma conditions, the thermal electrons and ions both have a temperature of 0.15 (0.10) keV, the electron density is 10^{19}m^{-3} ($5\text{x}10^{18}\text{m}^{-3}$), and the background magnetic field has strength $B_0 = 0.46$ (0.24)T. The local Alfvén speed V_A is 2.77

(2.35)x10^6ms^{-1}, hence the NBI protons are sub (super)-Alfvénic with $u/V_A \approx 0.870$ (1.125). 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 22080 (10520) computational cells and 500 macroparticles per cell. The cell size is 0.61 (1.06) times the thermal ion Larmor radius $r_L = 0.0031$ (0.0025)m; for neutral beam ions $r_{L,NBI} = 0.063$ (0.115)m. Figure 2 shows simulation outputs for the fields that are spontaneously generated by relaxation of the NBI populations. The left panel plots the power spectrum of the z component of the oscillating part of the magnetic field on a dB scale. This is obtained by summing output between $k = 0$ and $k = 25$ (in units Ω_H/V_A), and averaged between $t = \tau_H$ and $t = 6.5\tau_H$ ($12\tau_H$), where τ_H is the proton gyroperiod. It is evident that the saturated instability generates intense narrow spectral peaks at the sequential cyclotron harmonics of the 40 (36.5) keV NBI protons, as observed in LHD, see Fig.1. Figure 3 provides further confirmation that the MCI underlies these kinetic simulations, and the physics of ICE. We plot the dependence of the growth rate γ of the fields, calculated at early times in multiple simulations, on NBI ion concentration ξ in each simulation. It is evident from Fig.3 that in general $\gamma \sim \xi^{1/2}$ in our simulations. This dependence is the same as for growth rates from linear analysis [6–8] of the MCI, and from previous simulations e.g. Fig.3 of [5].

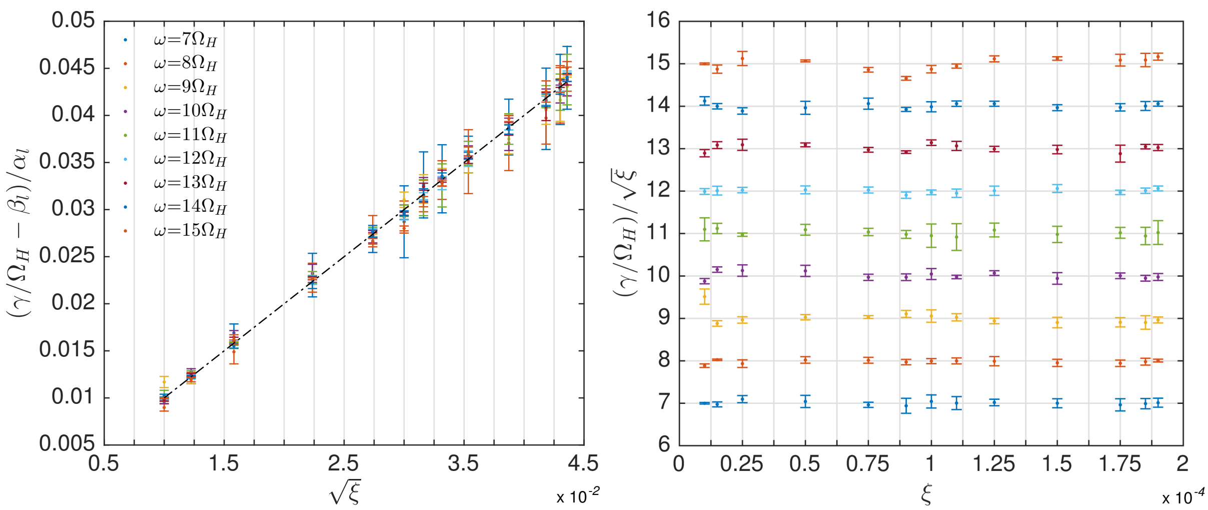

Fig. 3: Scaling of early time growth rate γ inferred from kinetic simulations of LHD plasma 79003 versus NBI ion concentration ξ in each simulation. We have obtained separate best fit scalings from each cyclotron harmonic ℓ, of the form $\gamma/\Omega_H = \beta_l + \alpha_l \xi^{1/2}$. Left: γ versus $\xi^{1/2}$ for multiple ℓ. Right: translated compensated plot of $(\gamma/\Omega_H)/\xi^{1/2}$ versus ξ for each ℓ, from $\ell = 15$ (top) to $\ell = 7$ (bottom).

3. Conclusions

The measured ion cyclotron emission (ICE) spectra (Fig.1) from LHD hydrogen plasmas with both sub-Alfvénic and super-Alfvénic perpendicular proton NBI have 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 PIC-hybrid code captures the self-consistent Maxwell-Lorentz dynamics of the plasma and fields. It is clear from the Fourier transformed code outputs that the dominant physical process driving this ICE is the magnetoacoustic cyclotron instability (MCI). The results presented here suggest there is a unified basic emission mechanism, corresponding to the nonlinear MCI, responsible for the main features of ICE in both tokamak and LHD plasmas. The spontaneously excited electric and magnetic fields in our simulations, which are carried out in local slab geometry, correspond to the fast Alfvén wave. This work helps establish a baseline for future energetic particle experiments in LHD, where magnetic geometry and toroidal eigenfunctions [14] may play a larger role. ICE links beam ion physics in LHD to fusion-born ion physics in tokamaks, and has significant diagnostic potential.

Work supported in part by the RCUK Energy Programme [grant number EP/P012450/1], NIFS budget ULHH029, NRF Korea grant no. 2014M1A7A1A03029881 and Euratom. The views and opinions expressed herein do not necessarily reflect those of the European Commission. ROD acknowledges the hospitality of Kyushu University.

References

[1] G A Cottrell and R O Dendy, Phys. Rev. Lett. **60** 33 (1988)
[2] G A Cottrell, V P Bhatnagar *et al.*, Nucl. Fusion **33** 1365 (1993)
[3] R O Dendy and K G McClements, Plasma Phys. Control. Fusion **57** 044002 (2015)
[4] K G McClements, R D'Inca, R O Dendy, L Carbajal *et al.*, Nucl. Fusion **55** 043013 (2015)
[5] L Carbajal, R O Dendy, S C Chapman, JWS Cook, Phys. Rev. Lett. **118** 105001 (2017)
[6] R O Dendy, K G McClements *et al.*, Phys. Plasmas **1** 1918 (1994)
[7] R O Dendy, K G McClements, C N Lashmore-Davies, R Majeski *et al.*, Phys. Plasmas **1** 3407 (1994)
[8] K G McClements, R O Dendy *et al.*, Phys. Plasmas **3** 543 (1996)
[9] J W S Cook, R O Dendy *et al.*, Plasma Phys. Control. Fusion **55** 065003 (2013)
[10] L Carbajal, R O Dendy, S C Chapman and J W S Cook, Phys. Plasmas **21** 012106 (2014)
[11] K Saito, H Kasahara *et al.*, Fusion Eng. Des. **84** 1676 (2008)
[12] K Saito, R Kumazawa *et al.*, Plasma Sci. Technol. **15** 209 (2013)
[13] S Cauffman, R Majeski *et al.*, Nucl. Fusion **35** 1597 (1995)
[14] N N Gorelenkov and C Z Cheng, Phys. Plasmas **2** 1961 (1995)