UKAEA-CCFE-CP(23)26

R O Dendy, B Chapman, B C G Reman amd J W S Cook

Collective energy transfer from neutral beam-injected ions to fusion-born alpha-particles on cyclotron timescales

Collective energy transfer from neutral beam-injected ions to fusion-born alpha-particles on cyclotron timescales

R O Dendy, B Chapman, B C G Reman amd J W S Cook

This paper has been submitted to
47th EPS Plasma Physics Virtual Conference, 21-25 June 2021

Collective energy transfer from neutral beam-injected ions to fusion-born alpha-particles on cyclotron timescales

R O Dendy[1,2], B Chapman[1,2], B C G Reman[2,3], and J W S Cook[1]

[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]*Laboratoire Plasma et Conversion d'Energie, Université Toulouse 3, F-31062 Toulouse, France*

1. Introduction

We report a new collective process that can rapidly transfer kinetic energy from energetic neutral beam injected (NBI) deuterons to fusion-born alpha-particles in magnetically confined fusion (MCF) plasmas, on cyclotron timescales. Our studies show that the physics involves a new regime of the magnetoacoustic cyclotron instability (MCI)[1-5]. The MCI is well known as the instability underlying observations of ion cyclotron emission (ICE) from toroidal MCF plasmas. Particularly relevant to the present study are recent observations and interpretation of ICE from the KSTAR tokamak[6] and LHD heliotron-stellarator[7,8]. These show[6-8] that this ICE is driven by the collective relaxation, via the MCI, of NBI ion populations in the edge plasma near their injection point. The spectrum of the resulting ICE has strongly suprathermal peaks at sequential cyclotron harmonics of the energetic ions in the edge region. This ICE has been simulated [6-8] from first principles using particle-in-cell (PIC) kinetic codes, notably EPOCH[9], which solve the Maxwell-Lorentz equations for tens of millions of gyro-orbit-resolved particles together with their self-consistent electric and magnetic fields.

The foregoing experimental and simulated ICE results relate to plasmas that contain a single majority thermal ion species, which has a temperature of order 1keV. The thermal ion species is identical to the minority energetic NBI ion species: deuterons at 80keV to 100keV in KSTAR[6]; protons at 40keV[7] and deuterons at 70keV[8] in LHD. What happens if a third ion species is also present: specifically, a collisionally slowed-down population of fusion-born alpha-particles ("helium ash"), whose characteristic energy is much higher than that of the thermal ions, and is comparable to that of the NBI ions? The EPOCH simulations reported here show that, in this case, electric and magnetic fields are collectively excited by a new regime of the MCI, and mediate the energy transfer from the NBI ions to the alpha-particles. This is the dominant energy channel, in contrast to the related ICE case, where radiation field excitation on the fast Alfvén-cyclotron harmonic wave branch is dominant. This new effect is strongest for edge plasma conditions, where the velocity-space distribution of the NBI ions approximates to a ring-beam, and for characteristic helium ash temperature 0.1MeV which is comparable to the injection energy of NBI deuterons. Energy transfer is primarily between NBI ions and alpha-particles that have similar Larmor radii. NBI energy of order ten per cent can be transferred to the alpha-particles. To our knowledge, this is the first study of direct collective energy transfer from NBI ions to local alpha-particles, on cyclotron timescales.

2. PIC code simulation model parameters and outputs

We have run PIC calculations of the Maxwell-Lorentz dynamics of tens of millions of interacting particles, together with their self-consistent electric and magnetic fields, drawn from four populations. Two are thermal: electrons, and majority deuterons, with T_D = 5keV = T_e. Two are energetic minorities. First, the minority NBI deuterons with injection energies E_{NBI} = 80keV, 140keV, or 200keV, represented by an initial delta-function in perpendicular velocity. Second, the minority alpha-particles, represented by a Maxwellian with temperatures $T_{th,\alpha}$ = 0.1MeV, 0.5MeV or 1.0MeV. Simulation parameters are broadly representative of JET plasmas, with electron number density n_e = 9.8×10^{19} m^{-3} and magnetic field strength B_z = 2.7T oriented perpendicular to the 1D3V PIC code spatial domain. Each PIC simulation uses 10150 grid cells with 1000 particles per cell. In most cases, the ratio of alpha-particles to thermal deuterons $\xi_\alpha = 10^{-3}$, and the ratio of NBI deuterons to thermal deuterons $\xi_{NBI} = 10^{-3}$.

The multi-species plasma, initialised as above, relaxes, and the resulting time evolution of particle and field energy densities is shown in Fig.1 for nine representative cases. The

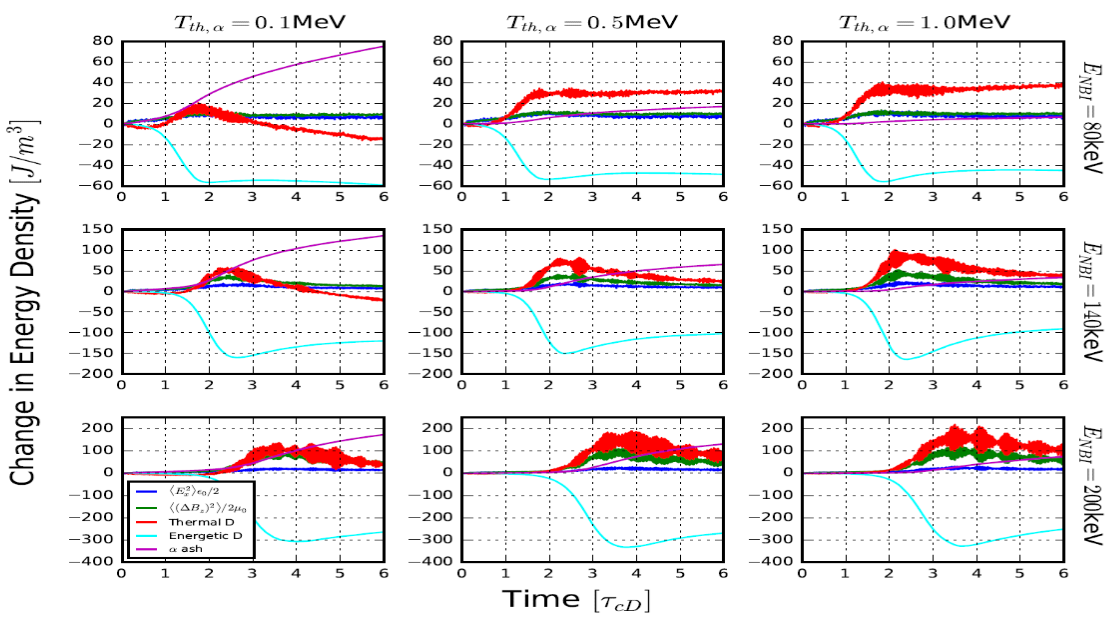

Fig.1 Time evolution of the change in energy density of particles and electric and magnetic fields in multiple PIC simulations with initial NBI deuteron energies 80keV, 140keV, and 200keV (rows), and initial helium ash temperatures 0.1MeV, 0.5MeV, and 1.0MeV (columns). Time is normalised to the deuteron gyroperiod τ_{cD}. The traces, ordered from top to bottom in the upper left panel, are: Top (magenta) the change in kinetic energy density of the minority alpha-particles; Second (red) the change in kinetic energy density of the thermal bulk plasma deuterons; Third (green) the energy density of the magnetic field perturbation B_z; Fourth (blue) the energy density of the electrostatic field E_x; Fifth (cyan) the change in kinetic energy density of the minority energetic NBI deuterons.

right-hand column of Fig.1 shows ICE-type phenomenology, dominated by energy transfer from NBI deuterons to excited fast Alfvén waves, which include the kinetic energy of thermal deuteron oscillation. The left-hand column shows the new effect: after an initial ICE-type phase, in the nonlinear regime the dominant long-term energy transfer is from both NBI and thermal deuterons to the 0.1MeV alpha-particle population. About ten per cent of the NBI deuteron kinetic energy is lost, with much of this transferred to the alpha-particles in the most dramatic cases in the left column of Fig.1.

Figure 2 shows the corresponding evolution of the alpha-particle distribution in perpendicular velocity-space. Evidently the energy transfer between NBI deuterons (initially ring-beam delta-function in perpendicular velocity) and the alpha-particles (initially Maxwellian with $T_{\mathrm{th},\alpha}$ = 0.1MeV) is strongly localised in velocity space. Energy transfer is primarily from NBI deuterons to alpha-particles that have the same perpendicular velocity, and hence the same Larmor radius, implying a strongly cyclotronic character for their interaction.

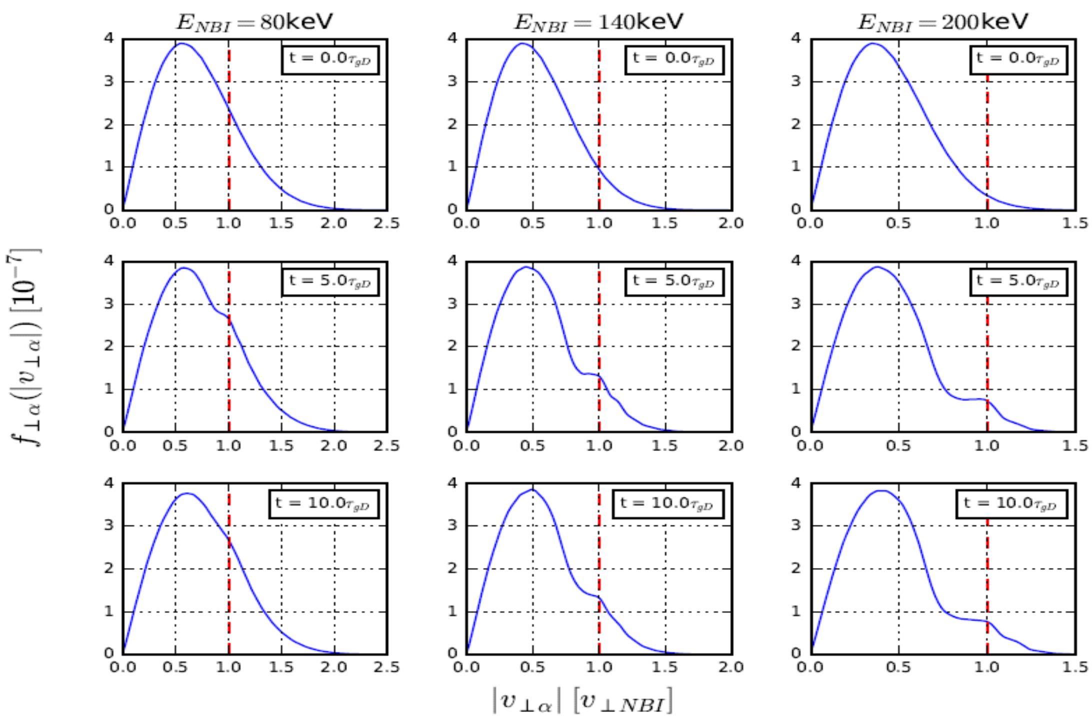

Fig.2 Snapshots of the alpha-particle distribution (blue) with respect to perpendicular velocity, obtained from our PIC simulations at times t = 0, 5τ_{cD} and 10τ_{cD}. The three columns are for the three different deuteron NBI energies, see caption to Fig.1. The perpendicular velocity of the alpha-particles is normalised to that of the NBI deuterons. The vertical dashed line (red) denotes where the Larmor radius of alpha-particles equals that of NBI deuterons.

This interaction is mediated by excited fields whose spectral energy density is shown in Fig.3, from PIC-hybrid simulations (that is, with fluidised electrons) for NBI deuterons at 140 keV in deuterium plasma. The two panels of Fig.3 are for two different concentrations (one negligible) of minority alpha-particles with $T_{\mathrm{th},\alpha}$ = 0.1MeV. Each ion species is represented with 400 particles per cell, and the simulation domain has 1024 cells. The spectra result from Fourier transforming the self-consistent fields that are excited in the simulations, summing over a time interval $10\tau_{cD}$.

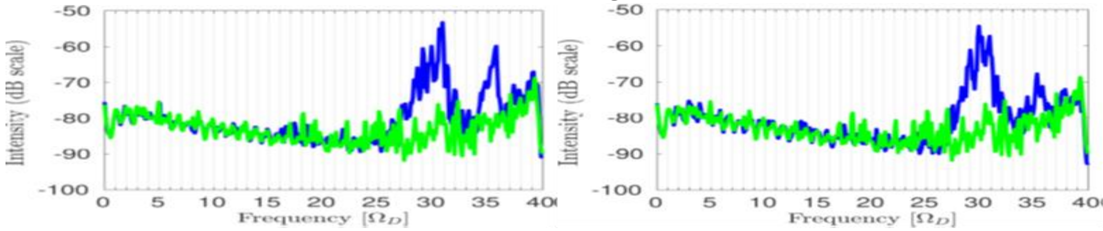

Fig.3 Frequency power spectra (blue) obtained from the spatiotemporal Fourier transform of excited fields in PIC-based simulations at $t = 10\tau_{cD}$. In both cases NBI deuteron concentration $\xi_{NBI} = 10^{-3}$. The left panel is for negligible alpha-particle concentration $\xi_\alpha = 10^{-6}$, hence a pure ICE scenario. The right panel is for $\xi_\alpha = 10^{-3}$, the scenario of Figs.1 and 2. Green traces are the fluctuation-dissipation noise baseline. Frequency is in units of the deuteron (equivalently alpha-particle) gyrofrequency.

The spectral character of the mediating field does not greatly differ between ICE-type scenarios and the new energy transfer scenario, in which the excited fields are a mediating rather than dominant feature. In both cases there is strong cyclotronic structure, with dominant spectral peaks in the range between the 25th and 40th cyclotron harmonics. The diminished field energy around the 37th cyclotron harmonic in the right panel reflects energy which has instead flowed to the alpha-particles.

3. Conclusions

We have identified a new collective cyclotronic energy transfer process that can shift energy from NBI deuterons to alpha-particles. The physics is a generalisation of the MCI that underlies observations of ICE from NBI ion populations in KSTAR and LHD. The effect is likely to be strongest in edge plasmas, where the NBI ions approximate to a ring-beam in velocity space, and for helium ash energies ~ 0.1MeV. Energy transfer occurs predominantly between NBI ions and alpha-particles that have similar Larmor radii. Experimental testing of the present theory could perhaps be carried out using minority energetic Helium ion populations generated, as in Ref.[10], using a three-ion cyclotron resonant heating scenario[11,12].

[1] R O Dendy, C N Lashmore-Davies, K G McClements & G A Cottrell *Phys. Plasmas* **1** 1918 (1994)
[2] K G McClements, R O Dendy, C N Lashmore-Davies, G A Cottrell *et al*., *Phys. Plasmas* **3** 543 (1996)
[3] J W S Cook, R O Dendy & S C Chapman, *Plasma Phys. Control. Fusion* **55** 065003 (2013)
[4] L Carbajal, R O Dendy, S C Chapman & J W S Cook, *Phys. Plasmas* **21** 012106 (2014)
[5] L Carbajal, R O Dendy, S C Chapman & J W S Cook, *Phys. Rev. Lett.* **118** 105001 (2017)
[6] B Chapman, R O Dendy, S C Chapman, K G McClements *et al*., *Nucl. Fusion* **59** 106021 (2019)
[7] B C G Reman, R O Dendy, T Akiyama, S C Chapman *et al*., *Nucl. Fusion* **59** 096013 (2019)
[8] B C G Reman, R O Dendy, T Akiyama, S C Chapman *et al*., *Nucl. Fusion* **61** 066023 (2021)
[9] T D Arber, K Bennett, C S Brady *et al*., *Plasma Phys. Control. Fusion* **57** 113001 (2015)
[10] A Kappatou, M Weiland, R Bilato, Ye O Kazakov *et al*., *Nucl. Fusion* **61** 036017 (2021)
[11] Ye O Kazakov, D van Eester, R Dumont & J Ongena, *Nucl. Fusion* **55** 032001 (2015)
[12] J M Faustin, J P Graves, W A Cooper, S Lanthaler *et al*., *Plasma Phys. Control. Fusion* **59** 084001 (2017)

This work received support from the UK EPSRC grant no. EP/T012250/1. It was carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.