Tritium mix in simulations of D-T plasmas; on the investigation of ion cyclotron emission spectra



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JROfusion





- Motivation
- Ion cyclotron emission (ICE)
- Magnetoacoustic cyclotron instability (MCI)
- Simulating the fusion plasma (PIC code)
- **Results;** power spectra, energy, Fourier transforms...
- Summary & Future work

Motivation



$D + T \rightarrow \alpha(3.5 \text{MeV}) + n$ ** CroeMai PHYSICAL REVIEW LETTERS PHYSICS OF PLASMAS 21, 012106 (2014) Plasma Physics and Controlled Fusion Linear and nonlinear physics of the magnetoacoustic cyclotron instability of fusion-born ions in relation to ion cyclotron emission ulated Emission of Fast Alfvén Waves within Magnetically Confined Fusion Plasma J.W.S. Cook,12,8 R.O. Dendy,31 and S.C. Chapman¹ L. Carbajal, ^{1,4)} R. O. Dendy,^{2,1} S. C. Chapman, ^{1,3,4} and J. W. S. Cook¹ ¹Craws for Faulus, Source and Astrophysics, Department of Physics, The University of Warwick, J. W. S. COM, C. W. D. DRADY, "and S. C. Chapman," anion, Space and Attrophysics, Department of Physics, Warrisk University, Coverstry CV4 7AL, U First Light Fasion Lid, Unit 10, Oxford Industrial Park, Tarnaso DXS 10U, United Kingdom ¹CCFE, Callian Science Contre, Abingdon, Oxfordshire 0X14 3DB, United Kingdom (Received 24 May 2016; revised manascript received 31 Oxtober 2016; published 4 May 2017) Comparing theory and simulation of ion Country CV4 7AL United Kineds ¹Centre for Fusion, space and Astrophysics, Department of Physics, i.m. Conversivy of Landson, Corentry CV4 7AL, United Kingdom ²EUDATOBOCCFF Patient Association, Calham Science Centre, Abingdon OX14 3DB, Oxfordshire cyclotron emission from energetic ion iied Kingdom pariment of Mathematics and Statiatics, University of Tromap, N-9037, Tromap, Norway as Planck Institute for the Physics of Complex Systems, D-01187, Dresden, Germany A fast Alfvén wave with a finite amplitude is shown to grow by a stimulated emission process that w populations with spherical shell and ringropose for exploitation in toroidal magnetically confined fusion plasmas. Stimulated emission occur (Received 18 November 2013: accented 21 December 2013: rublished online 17 January 2014 which the wave popagates inward through the outer midplane plasma, where a population inversion of the energy distribution of fusion-born ions is observed to arise naturally. Fully nonlinear first-principles simulations, which effectionsitestity revolves particles and fields under the Maxwell-Lorentz system, demonstrate this novel "a-particle channeling" scenario for the first time. beam distributions in velocity-space e magnetoscoutic cycletron instability (MCI) probably underlies observations of on cycletron ission (ICE) from energetic ion populationi in tokamak plasmas, including fusion-ben ha particles in JET and TPTR [Dendy *et al.*, Nucl. Fusion 35, 1733 (1995)]. ICE is a patential genesific for Isot alpha-particles in ITER; furthermore, the MCI is representative of a class of B Chapman^{1,2}^o, R O Dendy^{1,2}, S C Chapman²^o, L A Holland^{2,3} S W A Irvine² and B C G Reman^{2,4} DOE 10.1103/PhysRevLett.118.18500 lective instabilities, which may result in the partial channelling of the free energy of energet where is sublicity, which may read in the partial channeling of the investory of energies of the state of the whething evidence for the normal exception of the second of elevisors. These simulations for mail interview of elevisors of the second of the ¹ CCFE, Calham Science Centre, Abingdon, OX14 3DB, United Kingdom ² Centre for Fasion, Space and Astrophysics, University of Warwick, Coventry, CV4 7AL, United e, Department of Physics, University of York, YO10 SDQ, United Kingdom rse, Laboratoire Plasma et Conversion d'Energie, 118 route de Narbonne, F-3100 * PHYSICAL REVIEW LETTERS week ending 10 MARCH 2017 **** CEEN ACCER 1 A Public Conditional Atomic Energy Agency ccl. Funior (2011) 000007 riboti RIP Processory: Phones Proc. Control. Proceeds 55 (2012) 955007-05401 Plana Physics and Cormoled Fasiar Quantifying Fusion Born Ion Populations in Magnetically Confined Plasmas using Ion Cyclotron Emission 019, sevised 5 February 2020 n 26 February 2020 ۲ Nonlinear wave interactions generate Particle-in-cell simulations of the L. Carbajd.¹²⁷ R. O. Dendy,²³ S. C. Chapman,² and J. W. S. Cock²⁴ (and Marke Anisotic Librarian, 17 dr In: 306, 608, Reije, Tennice 373) 4460, 1231. ¹Centre for Foint, General Laboration, 17 dr Densen, Optical Dense, 19 de Dense, Optical Dense, 19 de Dense, The second seco Doublet splitting of fusion alpha particle high-harmonic cyclotron emission from recently been made of ion cyclotron emission (UCI) that originates from the OHE-10 Theore at 2018 Rev. Sci. housens, 409 (1010); Theore at 2019 Neu-Distance at 2019 Rev. Sci. housens, 409 (1010); Theore at 2019 Neu-Anneone 400 (1010); Anneole at 2019 Neu-anneone 400 (1010); Anneole at 2019 Neu-Ress, in contextu the bindress our algoritht chalconism of the ICI source to edge in tokama and addituries planma. Creb ICI is tomposily remoint, and could by the applied out and answers of theory means and theory for the edge in tokama and addituries planma. Creb ICI is tomposily remoint, and could by the applied out and answers of tokamis means in the source of the sourc magnetoacoustic cyclotron instability driven ion cyclotron emission fusion-born protons during a KSTAR of fusion-born alpha-particles in ELM crash JWS Cook Ion cyclotron emission (ICE) offers a unique promise as a diagnostic of the fusion born alpha-particl tokamak plasmas ion in marnetically confined plasmas. Pioneerine observations from JET and TFTR found that IC UKAEA-CCHE, Calhan Science Center, OK14 3DB Abingdon, United Kingdo neasity Processales approximately linearly with the measured neutron flux from fusion reactions, and with attenty τ_{eff} and composition of the start of the st B. Chapman¹⁽⁶⁾, R.O. Dendy^{1,2}, S.C. Chapman¹⁽⁶⁾, K.G. McClements²⁽⁶⁾, G.S. Yun¹⁽⁶⁾, S.G. Thatipamula¹ and M.H. Kim³ and/o by the lique control of the second of E mail: james.cook@akaca.ak J W S Cook¹, R O Dendy^{1,2} and S C Chapman^{1,3} For Fusion Space and Autophysics, Department of Physics, Warwick Univer y CV8 7AL, UK Received 25 May 2022, ervised 28 July 20 Accepted for publication 22 August 2022 Published 30 September 2022 ¹ Centre for Fusion, Space and Astrophysics, University of Warwick, Coventry, CV47AL, otron instability (MCI), which is the excitation process Association, Culham Science Contre, Abiophon, United Kingdom of Great Britain and Northern Ireland ² CCHF, Culham Science Centre, Abingdon, OX14 3DB, United Kingdom of Great Britain and Northe der core plasma conditions, direct numerical simulations of ICE generation i nibution of fusion-born ions in velocity-space. These energetic minority io offectively in particle-in-cell (PIC) computations which follow their self-Inclund ³ Pohang University of Science and Technology, Pohang, Gycongbul: 37673, Korea, Republic of n and Statistics, University of Tronsa, N 4017 Tronsa, Norwer, <text><text><text> -000 4 December 2012, in final form 20 March 2013 solved dynamics, together with that of the majority thermal ions and Ion cyclotron emission (RCE) originating from confined populations of fast ions is fusion plasmar is an important new invasive, panvice diagnostic for current and ne devices. The ability to model RCE signals accurately is an essential step towards is E-mail: B.Chapman@warwick.ac.uk Received 30 January 2018, revised 21 June 2018 Accornied for publication 27 June 2018 devices, the articly is mode it.) regime accuracy is an essential only because inter-characteristics of conflicted mergelic alpha particles or fast neutral beam ison and back planta. In this paper, the linear growth rates of the magnetisacontic cyclumon instability is the leading explanation for RE's, are calculated in high resolutions (2D (k_1 , k_2) space parameters recomposining to 2D (R). Thus No. 37.168. These calculations further highligh Accepted for publication Published 12 July 2018 ns relaxing under the MCI. We find that the MCI is excited in a nion (RT) is the only collective radiative instability, driven by co-Constructions reacting mode the Preck, we take the Preck to constant in an interar growth phase of the shell simulation typically takes almost twice as long than in the ring-beam simulations. It is shown that for both types of velocity car wave wave interactions play a wild role in the excitation of the ICE spectral olsen harmonics which are typically detected in experiments. We conclude that en alpha particles, observed from Assterium-tetitism (DT) plasmas in both JET and ing first principles particle-in-cell simulations of the magnetoacoustic ejectorum (MCT), we elocidate some of the fully kinetic realistar processes that may under origin of doublet splitting of the cre he radio frequency detection system on the KSTAR tokamak has exceptionally high spectral teractions with 1D3V particle-in-cell stud visual Society under the terms of fusion 4.0 International license. The name respects processing points and the second uplitudes. The inclusion of signals of KE from a well-reso in also account for these effects. various of RT: from fusion products in these large statements without processes that iting under scalely self-finiting on score fast timescales, which may help explain the observed ition between linear theory and elseweed RE: intensities. The simulations elaborate the of the exteriol elsectric and magnetic fluctuations, from first principles, confirming the a Automation 4.0 International ficenzie, ithis work must maintain attribution to sublished article's title, journal citation, Th s for ICE interpretation, ring-beam distributions may provide an accepta geometry, namely, the compressional Alf Keywords: ion exclution emission, magnetoacoustic exclution instability, BT, doublet splitting include those of Refs. 15 and 16. In the anal formulation of the linear MCI theory of R potential a-channeling applications of a which exhibits charge on sub-microscond timescales. Its spectral peaks correspond to harmonical of the prodo systems frame(set j_{int} all to easier induktor edge, where l = 20. 36 This frequency range exceeds estimates of the local lower hybrid frequency j_{int} in the KSTMM determing takens. The sen feature is time-induktor with respect to a brighter lower-frequency charging (EZ i features in the range 200 MHz (6 j_{c0}) = 500 MHz (2 j_{c0}), which is probably drive (Langman *et al* 2017 Mez, Fasian ST 2000 by ST AMV biolise-horn protous machinghing (Some lowers may arrest in colour only in the colour issued) t nie of fast Allvénic and regress microanno, must terr proceptic, contribuing (8)/185001(5) Published by the American 21,012106-1 $\begin{array}{l} \mbox{Standardism} \\ \mbox{Constraints} (GT) has been reported in monoid in product a monoid in the standard standard of the standard stand$ Some figures may appear in colour only in the online issueds Chaptene et al 2017 Next Failure T 12000 FL, "Sector and compare weak in protony flow the definition of additional to the magnetization of constraints of the sector of th Landactine Man supplied by frame how and play particles outfings with model of the finance of the planet of the pla $\label{eq:product and the second se$ Keywords: ion cyclotron emission, magnetoacoustic cyclotron instability, FLM, tokamak, bispectral analysis, KSTAR, particle-in-cell simulation (Some figures may appear in colour only in the online journal) metrugs excitation of chems and paragents coefficients: the statistical galaxies are present [15, 17]. The statistical galaxies are present [15] and parameters [15] ions as the analytical treatments in that the plasma is initiall content from this work may be used under the le Control Control Control from this work may be used under the terms of the Creative Commons Attribution 3.0 bence. Any further distribution of this work must maintain attribution to the author(s) and the tille Original Contract from this work may be used under the terms of the Contract Commune. Any Index Antibiation of this work user maintain attribution to the antibiation of the riths of the work, justical chairing and (OK). tant because, in future experiments with burning plasma, in the neutron source rate (cf. Fig. 3 of Ref. [6]). In eigenenodes, which as with RE, are also fast Alfvén modes GEURATOM 2018 Printed in the UK 1 0 2011 KP Publishing Lid Printed in the UK & the UK © 2017 American Physical Society the statement of the later 0031-9007/17/118(10)/105001(5) 105001-1 © 2022 Crown copyright. 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- ** Chapman B et al. Plasma Phys. Control. Fusion 62 055003, 2020
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Ion cyclotron emission (ICE)



- Driven by the MCI, driven by strong gradients in energetic minority (alphaparticles) velocity-space distribution
- Measurement is passive, non-intrusive and multi-angled

$$\Omega_{\sigma} \equiv \omega_{c\sigma} = \frac{q_{\sigma}B}{m_{\sigma}}$$
$$n\Omega_{\alpha} \forall n \in \mathbb{Z}^{+}$$



 v_0

Ion cyclotron emission (ICE)



Scales with:

- Minority concentration (ξ_{α})
- Fusion reactivity
- $v_{0\perp}/v_A$ ratio
- Pitch-angle (ϕ)
- Fuel ratio $(\xi_2/\xi_1$; this work)
- Magnetic field angle (θ)



FIG. 5. Correlation between ICE intensity P_{ICE} and total neutron emission rate R_{NT} for Ohmic and NBI heated JET discharges, over six decades of signal intensity. The best fitting relation is $P_{ICE} \propto R_{NT}^{0.9\pm0.1}$.

Ion cyclotron emission (ICE)



Location of ICE location in tokamak inferred from spacing between peaks

$$B(r) = \frac{\Omega m}{Ze}$$

$$B_{\theta}^{(0)}(r) = \frac{\mu_0 I_P}{2\pi r} \left(1 - \left[1 - \left(\frac{r}{a} \right)^2 \right]^{\gamma} \Theta(a - r) \right)^*$$



ICE spectra observed from JET plasma 26148 **, spacing of 17MHz between peaks.

* Caldas I L et al. Chaos Solitons and Fractals **7** 991–1010, Jul. 1996 * * G. A. Cottrell et al., Nuclear Fusion, vol. 33, pp. 1365–1387, Sept. 1993

Magnetoacoustic Cyclotron Instability (MCI)





Brought on by "a small quantity of thermonuclear reaction products in a plasma" which are "sufficient to excite magnetoacoustic cyclotron waves" * "resonation excitation of perpendicular fast Alfvén waves with ion Bernstein waves" which was "driven by the energetic products of fusion reactions" **

MCI is characterised by the cyclotron resonance between the FAW (in the bulk) and an energetic minority ion (alphas)

Magnetoacoustic Cyclotron Instability (MCI)





Simulations (PIC)



Use of the particle-in-cell (PIC) code EPOCH *



Simulations (PIC)



- Inclusion of tertiary ion (tritium)
- Number density weighting (NDW) conserved

$$\mathbf{NDW} = \frac{n_{\sigma}}{N_{\sigma}}$$

- Introduced ξ_T (%) and fuel ratio (ξ_T/ξ_D)
- Deuteron (0%), trace tritium (1%) JET 26148 (11%) and ITER (≥50%)
- Supplementary simulations

Simulations (PIC)



2d representation



Results : Energy





Results : Fourier transforms





Results : Power spectra



Results : Frequency offset





 $\omega_{off}(\xi_T)/\Omega_D = (-4.74 \pm 0.34)\xi_T + (-0.01 \pm 0.16)$

Results : Bicoherence





Results : Growth rates





Results : Tau-squared





 τ^2 is minimised for best fitting data to model

Normalised to number of peaks to find τ^2 contribution minimisation

I 1% simulation best represents the JET 26148 data

$\xi_T [\%]$	τ^2/N_{peaks}
0	30.0
1	28.7
5	29.8
11	27.9
18	28.7
30	29.9
50	30.0





- Bulk ions energise slower with increasing ξ_T
- Ratio of D-T energisation equivalent to their mass ratios, Larmor radii matching/gyro-resonance
- Power spectra shifted quantified by negative linear correlation w.r.t ξ_T
- JET plasma 26148 is best represented by the 11% simulation
- Simulation of three ions is a necessity for $\xi_T > 1\%$, especially for ITER





Thank you for listening