The consequences of tritium mix for simulated ion cyclotron emission spectra from deuterium-tritium plasmas

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What is Ion Cyclotron Emission (ICE)?

- Strongly suprathermal emission and highly spectrally structured ICRF signal spontaneously emitted from most large MCF plasmas
- Driven by energetic ion populations: fusion-born in deuterium and deuterium-tritium (DT) plasmas, also NBI and occasionally ICRH
- Spectral peaks at local cyclotron harmonics of energetic ion population
- Driven by the magnetoacoustic cyclotron instability (MCI)
  - Brought on by strong positive gradients in energetic minority particle's velocity-space distribution
  - Originally detected in JET using ICRH antennae used to launch fast Alfvén wave

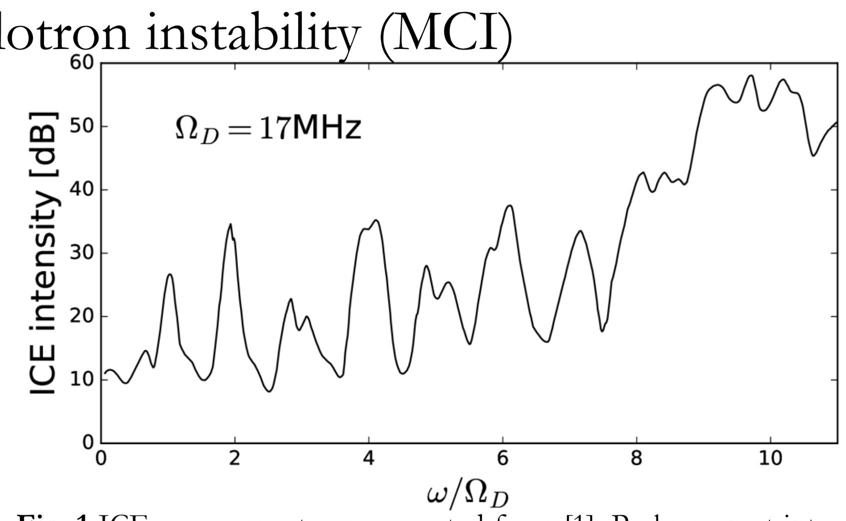


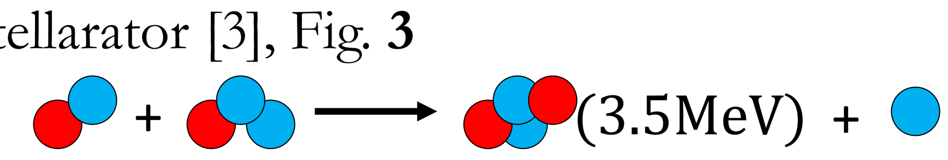
Fig. 1 ICE power spectrum, recreated from [1]. Peaks seen at integer deuteron ion harmonics, for a cyclotron frequency of 17MHz.

Why do we measure ICE?

- By understanding ICE physics, we can use ICE measurements to infer features of the energetic ion distribution
- Passive and non-intrusive
- Scaled linearly with fusion reactivity in JET
- Observed at various poloidal angles around tokamak
- ICE frequency ranges are typical of antennae already used in tokamaks

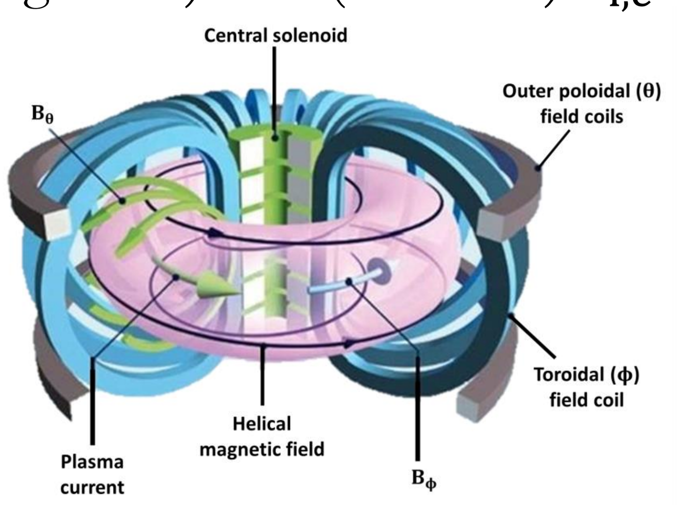
Experimental setup

- ICE is observed from most large MCF plasmas, including JET tokamak [2], Fig.**2** , and LHD heliotron-stellarator [3], Fig. **3**
- DT fusion reaction considered:



- Thermal bulk (background) ions (electrons) $T_{i,e}$~keV

Fig. 2 The general tokamak layout, adapted from [4], with the poloidal (**θ**) and toroidal (**ϕ**) magnetic fields as labelled. Poloidal field generated from applied plasma current, producing an overall helical magnetic field, spiralling around the plasma.



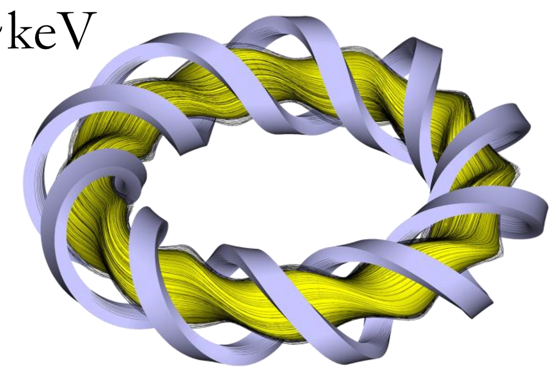


Fig. 3 The layout of the LHD stellarator with the magnetic coils (blue) controlling the plasma (yellow). Overall magnetic field is helical around the plasma.

Simulation setup & Tritium ion concentration

- 1D3V PIC code EPOCH [5] self consistently evolves Maxwell-Lorentz system of equations
- 3.5MeV α-particle distributed as ring-beam, eq. **(1)**, where ⊥ & ∥ are w.r.t magnetic field B_z component

$$f_\alpha(v_\parallel, v_\perp) \propto \exp\left(-\frac{(v_\parallel - v_0)^2}{v_r^2}\right)\exp\left(-\frac{(v_\perp - u_0)^2}{u_r^2}\right) \qquad (1)$$

- Particle volumes held equal according to the numerical weighting, eq. **(2)**, to remove linear heating across all species, indexed σ,

$$\frac{n_\sigma}{N_{s\sigma}} = const \qquad (2)$$

- General parameters of the JET 26148 plasma: $n_e = 10^{19}m^{-3}$; $B_0 = 2.1T$; $B\angle k = 89°$; $T_{i,e} = 1keV$; $n_\alpha/n_e = 2\times10^{-3}$

[1] Cottrell G A *et al.* 1993 *Nucl. Fusion* **33** 1365–87
[2] McClements K G *et al.* 1999 *Phys. Rev. Lett.* **82** 2099–102
[3] Reman B C G *et al.* 2019 *Nucl. Fusion* **59** 096013
[4] D. O. E. https://www.energy.gov/science/doe-explainstokamaks
[5] Arber T D *et al.* 2015 *Plasma Physics and Controlled Fusion* **57** 113001
[6] Naylor T and Jeffries R D 2006 *MNRAS* **373**
[7] Dendy R O *et al.* 2023 *Phys. Rev. Lett.* **130** 105102

Power spectra & Frequency offsets

Using the spatiotemporal Fourier transform of the oscillatory field component, ΔB_z, we integrate over a range of wavenumbers, k, to return the power spectra as a function of frequency, Fig. **4**. There are noticeable ICE peaks in all primary traces and a noticeable shifting of the dominant region ($16<\omega/\Omega_D<21$) as triton concentration increases.

Using various correlation methods including the cross-correlation, phase-correlation and shared area we defined this frequency shift by a linear relation w.r.t tritium concentration:

$$\boxed{\omega_{off}/\Omega_D = (-4.74 \pm 0.34)\,\xi_T + (-0.01 \pm 0.16)} \qquad (3)$$

Frequency shifts are described as the preferential driving of lower energy waves for heavier, more inertial, plasmas. Best fitting simulated spectra to those in Fig. **1** is that of the 11% case, according to a τ^2 fitting method [6].

Fig. 4 Power spectra of varying triton concentrations as per legend.

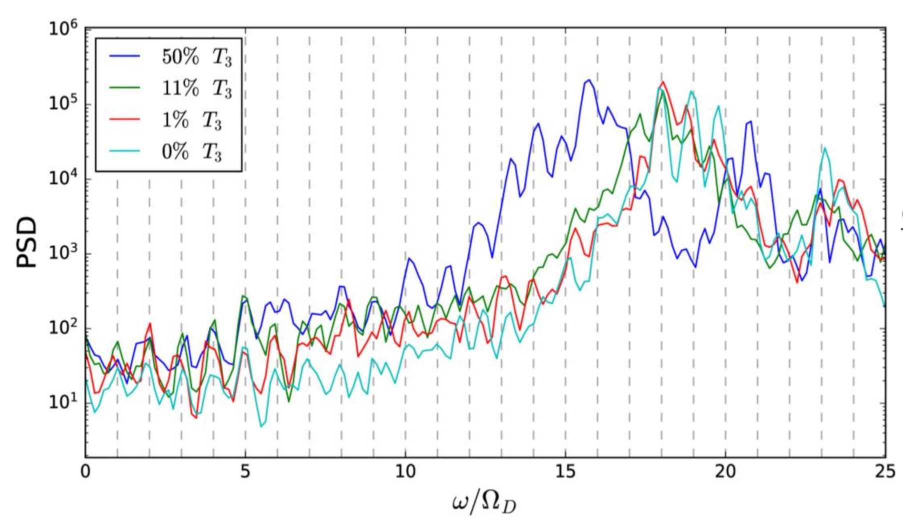
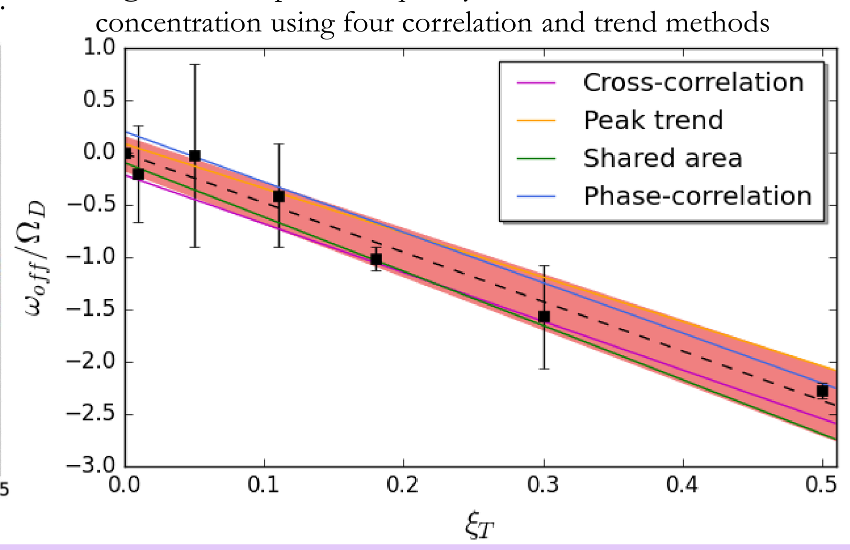


Fig. 5 Power spectra frequency offset as a function of tritium concentration using four correlation and trend methods



Energy densities & Three-ion species gyro-resonance

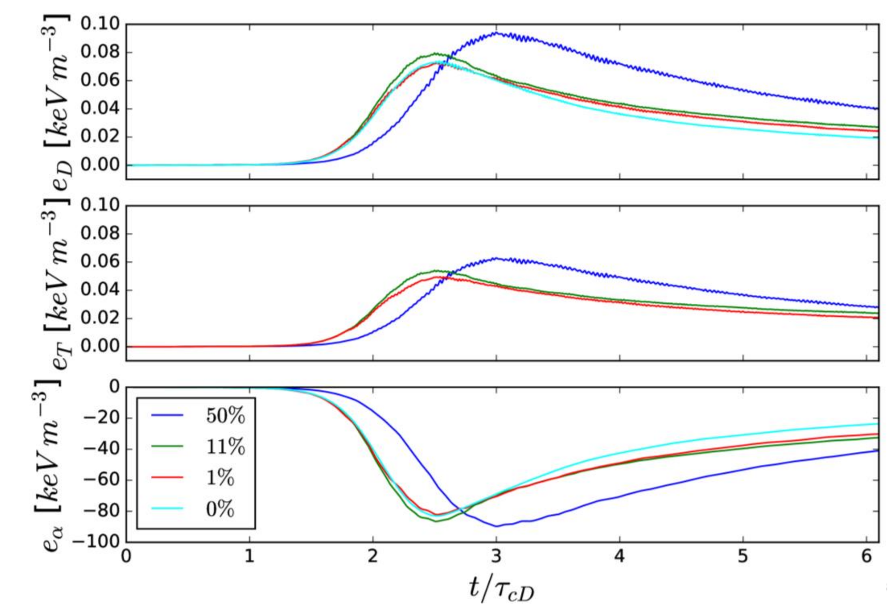
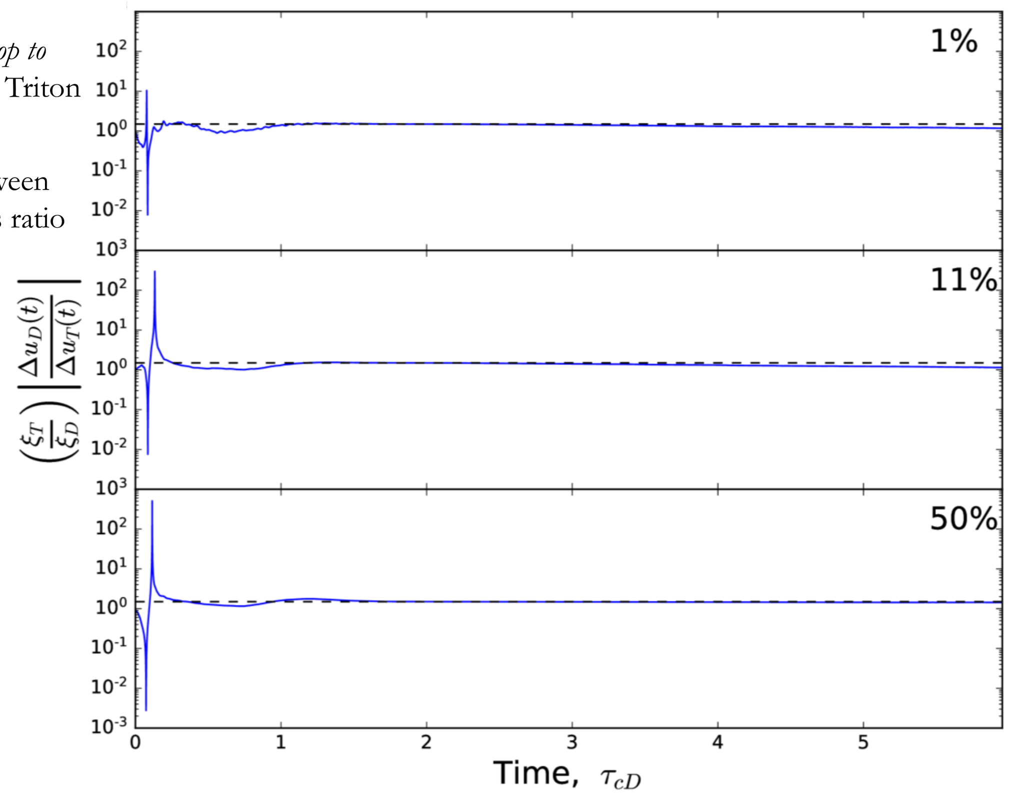


Fig. 6 (above) Change in energy densities per ionic species (*top to bottom*) of deuterons, tritons and alpha-particles through time. Triton concentration as labelled.

Fig. 7 (right) Change in energy density per-particle ratio between the deuterons and tritons, through time, with the inverse mass ratio plotted as a dashed grey line.

<ins>Higher ξ_T leads to:</ins>

- Lessening of MCI growth rate and increased de-energisation time
- Overall increased energisation of bulk ions
- Peak Δu ratio in accordance to mass ratio (gyro-resonance)



By assuming both DT species reach gyro-resonance through Larmor radii matching [7], one derives the ratio between their change in energy densities per-particle as the inverse of their mass ratios, Fig. **7**.

Conclusions

- <ins>First principles simulations of ICE spectra with tritium concentrations in the range 0% to 50% show best agreement with JET 26148 ICE when concentration = 11%, which coincides with the actual experimental value</ins>
- Preferential driving of shorter and slower plasma waves
- An increase in the magnitude of energy transfer from the alpha-particles to the DT bulk through slower growing MCI
- Frequency offset following a linear relation w.r.t ξ_T, eq. **(3)**
- Gyro-resonance between DT species, Fig. **(7)**