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

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Measurements of ion cyclotron emission (ICE) from magnetically confined fusion (MCF) plasmas are helpful for understanding the physics of minority energetic ion populations therein. ICE is observed from both tokamak and stellarator plasmas, and is characterised by strongly suprathermal spectral peaks at frequencies corresponding to local cyclotron harmonics of energetic ion populations [1]. The location of emitting ions in physical space is inferred from the local magnetic field strength from the cyclotron frequency spacing, and their velocity space distribution must incorporate a region of strong positive gradient to drive collective radiative instability [2,3]. This has been found to be the magnetoacoustic cyclotron instability (MCI) [1–5] in most cases. The MCI involves the resonant collective excitation of electromagnetic waves at or near the intersection of cyclotron harmonic modes with the fast Alfvén wave in frequency-wavenumber space. ICE has been observed from plasmas in most large magnetically confined fusion (MCF) facilities [4–12], where it can be used for diagnosing the velocity-space distributions of energetic ion populations. It has substantial further potential for deuterium-tritium (DT) plasmas in ITER. Here we therefore focus on analysis of the dependence of simulated ICE spectra on tritium mix in DT plasmas.

Our kinetic simulations were performed using the particle-in-cell (PIC) code EPOCH [13]. This self-consistently solves the full Maxwell-Lorentz system of equations, updating the positions of tens of millions of particles positions self-consistently with the time-evolving electric and magnetic fields, across a discretized grid. Importantly for cyclotron resonant phenomena such as ICE, the code resolves full orbit gyromotion. EPOCH simulations are known to reproduce key features of observed ICE spectra, arising from the underlying MCI phenomenology, which is here an emergent property of the first principles physics [14,15]. In the present paper we revisit the ICE spectrum driven by fusion-born alpha-particles in the outer midplane edge regions of JET plasma 26148 [1,4], which contained an 11% tritium admixture to deuterium. This ICE spectrum has been used to benchmark first principles computational simulations of the MCI [14] in combination with analytical theory, revealing details of the relative contribution of linear and nonlinear MCI phases in building the observed ICE spectrum [5,16]. Computational expense has constrained previous simulations [14–17] to omit the minority thermal triton population, while retaining the majority thermal deuterons, thermal electrons, and fusion-born alpha-particles. Here, for the first time, we include thermal triton populations, spanning the range 1% to 50%, and examine the consequences for simulated ICE spectra relevant to JET plasma 26148.

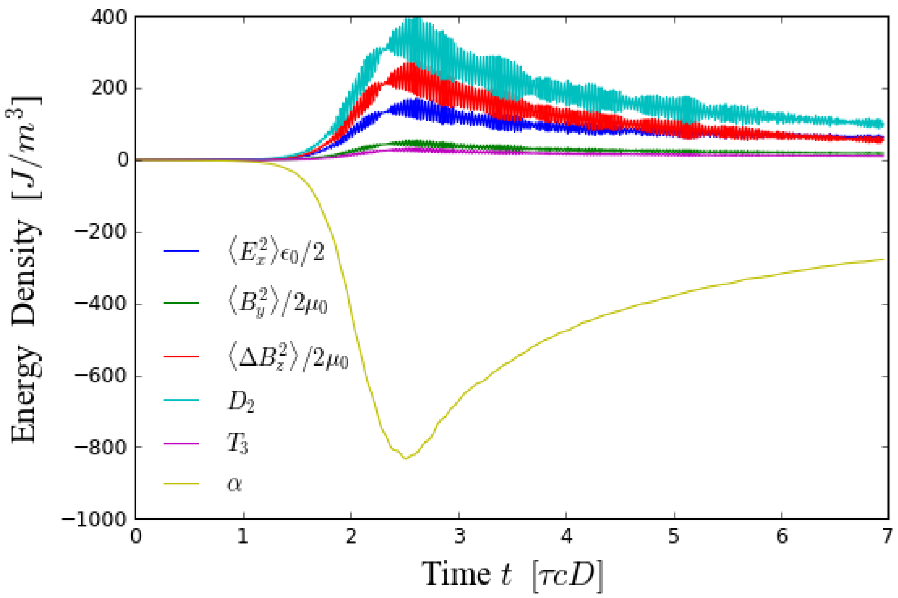


**Fig. 1** Time evolution of the change in energy density of the particles and fields for a DT thermal plasma with 11% tritium, containing a minority 3.5MeV energetic alpha-particle population initialised as a ring-beam in velocity space. Time is normalised to the deuteron cyclotron period $\tau_{cD}$.

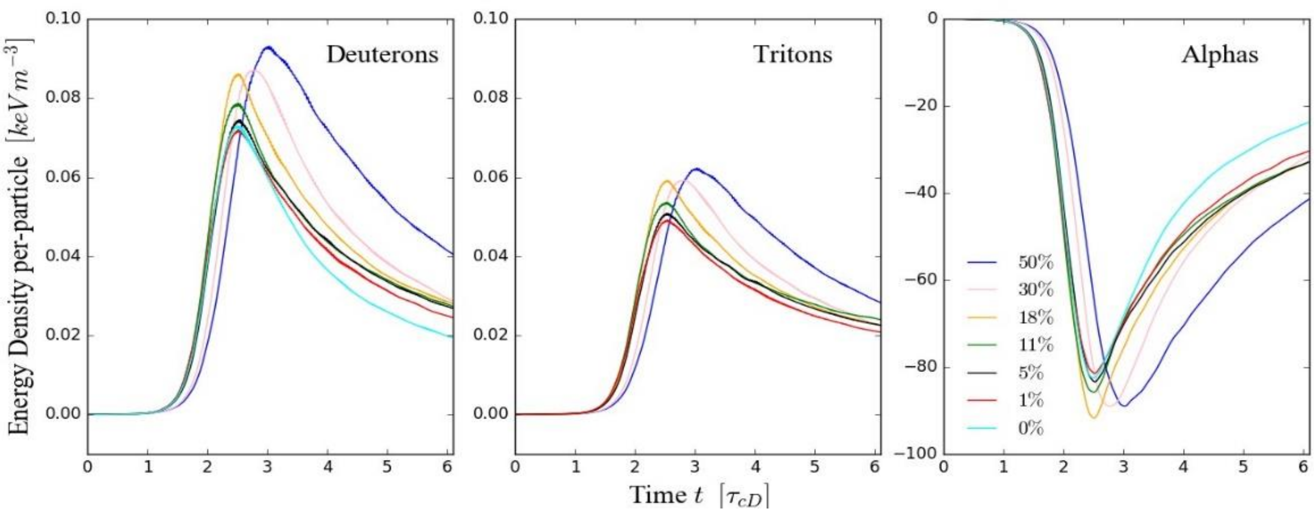


**Fig. 2** Time evolution of the change in kinetic energy density per ion, for different thermal tritium concentrations (legend in right panel), for the three species: deuterons (left panel); tritons (centre); and energetic alpha-particles (right).

Figure 1 plots the time evolution of the particle and field energy densities obtained from a 1D3V EPOCH PIC simulation of a thermal DT plasma with a minority 3.5MeV energetic alpha-particle population. The latter is distributed initially as ring-beam in velocity space, for reasons described in Ref. [1]. As in JET plasma 26148, the tritium concentration is 11%. The relaxation of the alpha-particle population results in excitation of predominantly electromagnetic waves, as seen from the growth of the $B_z$ field component, on the fast Alfven-ion cyclotron harmonic branch. These waves involve coherent oscillation of the deuterons and tritons, which acquire kinetic energy. The fully gyro-resolved neutralising electron population, which can support electrostatic oscillations, has number density $n_0 = 10^{19}m^{-3}$, and temperature 1keV, equal to that of the deuterons. The spatial orientation of the simulation domain ($x$) is quasi-perpendicular (89°) to the direction of the 2.1T background magnetic field ($z$), as the MCI is known to grow most strongly for quasi-perpendicular propagation [1,3,5,15]. Whereas the field and deuteron and electron traces in Fig. 1 are characteristic of previous simulations of the MCI, with initial linear growth for times $< 2\tau_{cD}$, and subsequent nonlinear saturation, the tritium trace in Fig. 1 is novel.

We performed 1D3V EPOCH PIC computations as outlined above for a range of tritium concentrations. The seven cases span zero-percent tritium (for benchmarking purposes), 1% (trace), 5%, 11% (JET 26148 as in Fig. 1), 18%, 30% and 50% (high power DT). In the present paper we address two aspects of the simulated ICE physics: the nature of the kinetic energy flow between the three ion species present, together with its partitioning between deuterons and tritons (Fig. 2); and the change in character of the simulated ICE spectrum as the tritium concentration is varied (Fig. 3).

It is evident from Fig. 2 that the overall character of the MCI is invariant with respect to tritium concentration. As the tritium concentration rises, the magnitude of the energy transfer from the alpha-particles to the deuterons and tritons increases, and the MCI takes longer to evolve. Comparisons of the per particle peak energy transfer between deuterons and tritons yield a striking result: in that it is invariant, and in the ratio of the isotope mass ratio, for all tritium concentrations considered. This may arise from a Larmor radius matching criterion at cyclotron resonance, akin to that found empirically in Ref. [18].

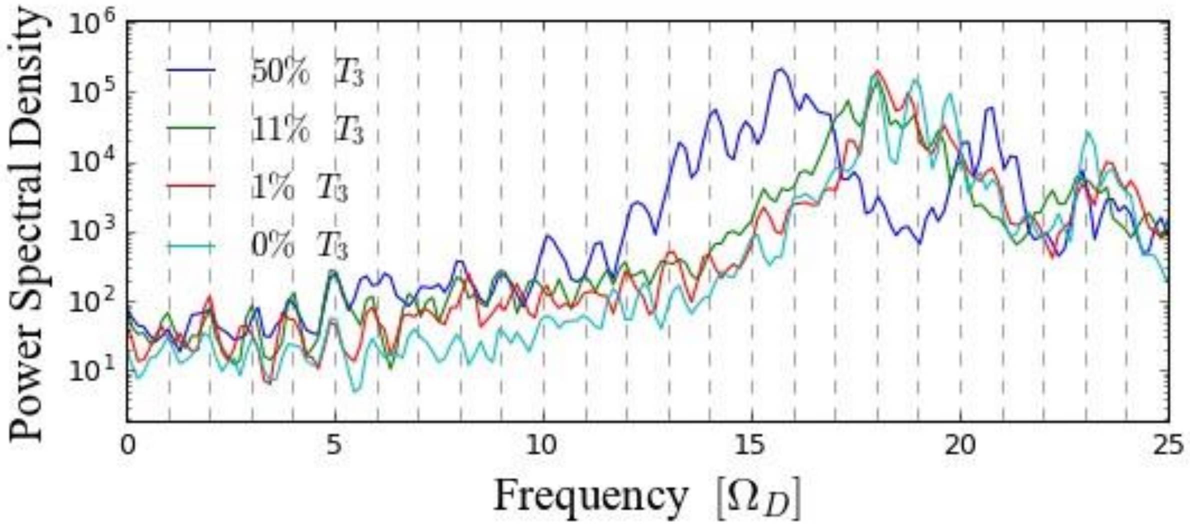


**Fig. 3** Simulated ICE power spectra densities obtained from EPOCH PIC computations of the relaxation of an identical alpha-particle population in JET 26148 DT plasma with four different tritium concentrations (see legend).

The simulated ICE spectra in Fig. 3 are power spectral densities (PSD) calculated by integrating the square of the spatiotemporal Fourier transform of the excited $B_z(x,t)$ field component over a $k > 0$ region encompassing the fast Alfvén wave. Their overall intensity is suprathermal, as it is at least two orders of magnitude above the thermal plasma level. Narrow spectral peaks arise at, or close to, sequential integer harmonics of the deuteron cyclotron frequency $11\Omega_D$. The simulated ICE spectrum for 11% tritium concentration is in particularly good agreement with the observed JET 26148 ICE spectrum. Doublet splitting [15] of some spectral peaks is found; this also matches the data well, especially at the $6^{th}$ deuteron harmonic, which is a joint harmonic of the deuteron and triton species. At the highest tritium concentration, the underlying shape of the simulated ICE spectrum can in Fig. 3 be seen to differ significantly from those at lower concentrations.

The power spectra in Fig. 3 show a frequency shift of spectral peak location, with respect to exact integer deuteron cyclotron harmonics, which increases with tritium concentration. Utilising various cross-correlation methods, we find this frequency shift $\omega_{off}$ scales linearly with tritium concentration $\xi_T$ under the best fit relation, $\omega_{off}(\xi_T)/\Omega_D = (-4.74 \pm 0.34)\,\xi_T + (-0.01 \pm 0.16)$. Thus, in a JET-like DT plasma, a ~20% increase in triton concentration would cause a downshift in spectral frequencies by approximately one deuteron cyclotron frequency. The fall in Alfvén wave speed with increased triton concentration, and hence density, in otherwise identical plasmas, may contribute to preferential excitation of waves with lower phase velocity.

For the first time, we have included a fully gyro-resolved triton population in first principles kinetic PIC simulations of ICE driven by collective relaxation of alpha-particles in a DT plasma. The simulations here are for plasma and magnetic field parameters close to those of the ICE-emitting region of JET DT plasma 26148 and have tritium concentrations spanning the range from 0% to 50%. Of these, the simulated ICE spectrum with 11% tritium concentration best agrees with the actual ICE spectrum of JET plasma 26148, which indeed had 11% tritium concentration. We find that the tritons participate in the MCI physics underlying ICE, and that the spectral features of the simulated ICE vary noticeably, and systematically, with tritium concentration. Quantitative understanding of this phenomenology will be important for exploitation of ICE as a diagnostic of energetic ion populations in future ITER DT plasmas with high tritium concentrations ~50%. This applies *a fortiori* to projected aneutronic fusion plasma scenarios in other experiments where, in the absence of neutrons, ICE may play a unique role as a reactivity diagnostic.

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