Aneutronic fusion born ion cyclotron emission from particle-in-cell simulations of D-^{3}He plasmas

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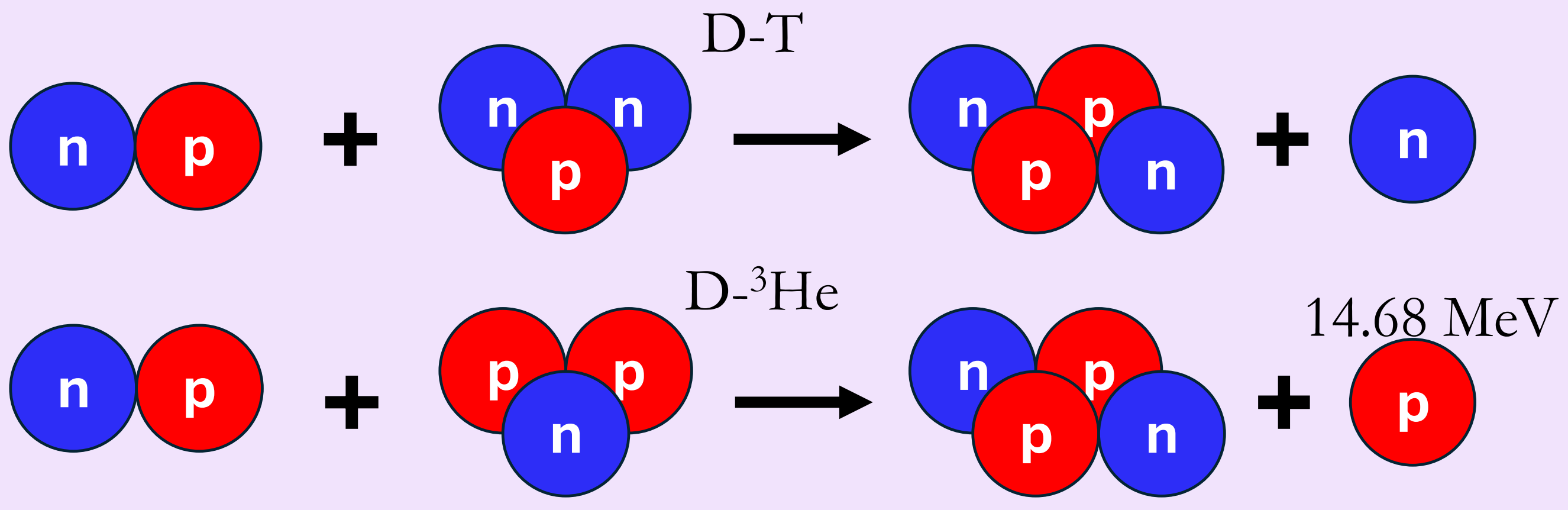
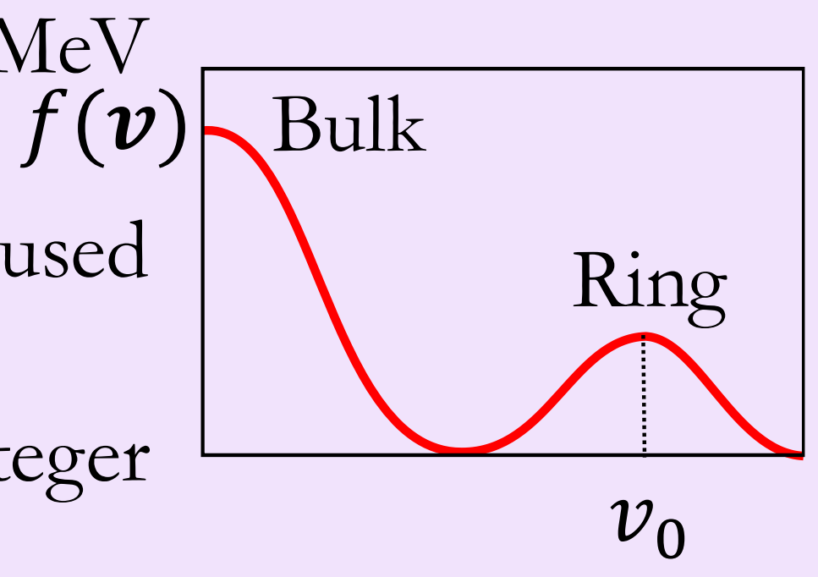
Motivation



Reactions that produce neutrons can damage tokamak reactors. The future of fusion reactions for long-term gain are therefore aneutronic. Aneutronic reactivity cannot be measured by typical means (neutron count). For this reason, we utilise a new diagnostic which scales with fusion reactivity. One such diagnostic is ion cyclotron emission (ICE).

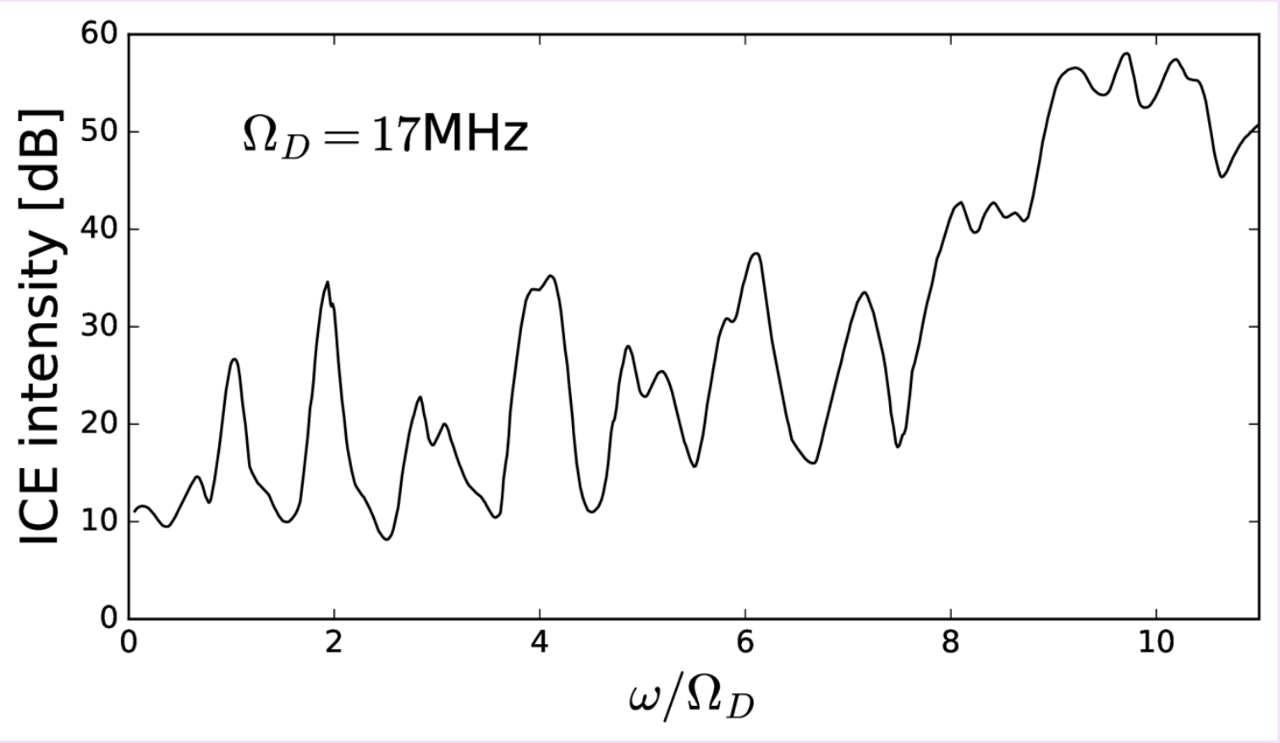
Introduction

- Magnetoacoustic cyclotron instability (MCI) is brought on by large positive gradients in velocity-space distribution $\partial f(\mathbf{v})/\partial \mathbf{v} > 0$ of minority energetic species (such as 3.5 MeV alpha-particles)
- Originally detected in JET using ICRH antennae which were used to launch fast Alfvén waves (FAW) [1]
- Minority energetic particle resonance with the FAW at integer cyclotron harmonics $n\Omega_\alpha$ form ion cyclotron emission (ICE)



Ion Cyclotron Emission (ICE)

- A suprathermal, evenly spaced, highly spectrally structured ICRF emission, spontaneously emitted in most large MCF plasmas, e.g. LHD [2]
- Passive and non-intrusive diagnostic observed at various poloidal angles
- Intensity in JET scaled linearly with fusion reactivity in JET and TFTR



ICE power spectra, adapted from [1]

Method

- We use the particle-in-cell (PIC) code EPOCH [3] which fully resolves Maxwell-Lorentz system of equations for tens of millions of computational ions
- 1D3V regime follows analytical slab geometry of the MCI, whilst resolving all three force vectors
- Particle weightings need to be held equal for multiple ion component simulations $\frac{n_\sigma}{N_\sigma} = const.$ [4]
- 14.68 MeV protons are distributed as a drifting ring-beam [5]

$$f_\alpha(v_\parallel, v_\perp) \propto \exp\left(-\frac{(v_\parallel - v_{\parallel 0})^2}{v_{th\parallel}^2}\right) \exp\left(-\frac{(v_\perp - v_{\perp 0})^2}{v_{th\perp}^2}\right)$$

- Protons are simulated alongside a bulk plasma of deuterons and helium-3 ions with varying concentrations $\xi_{He3} = n_{He3}/n_e$, see Tab. 1 for parameters
- Other parameters include: $L = 1.5m,\ \Delta x = 0.95\lambda_{De},\ T_{D,He3} = 2keV, n_e = 5 \times 10^{19} m^{-3}$ and $B_0 = 3.7$ T, following Ref. [6], motivated by JET like initial parameters and birth conditions of the energetic proton species
- Pitch angle (final row of Tab. 1) is changed since a constant $v_{\perp 0}/v_A$ is used

ξ_{He3}	**0.05**	**0.1**	**0.15**	**0.22**	**0.25**	**0.34**	**0.38**	**0.45**
ξ_D	0.899	0.799	0.699	0.559	0.499	0.319	0.239	0.099
$v_A/c\ [10^{-3}]$	27.3	27.6	28.0	28.6	28.8	29.6	30.0	30.6
$v_{\parallel 0}/v_A$	6.42	6.34	6.25	6.13	6.08	5.91	5.84	5.71
$\arctan(v_{\perp 0}/v_{\parallel 0})$	7.98°	8.08°	8.19°	8.35°	8.43°	8.66°	8.76°	8.96°

Table 1. Simulation parameters including helium-3 concentration (ξ_{He3}), deuterium concentration (ξ_D) from quasi-neutrality, Alfvén velocity (v_A), parallel birth velocity ($v_{\parallel 0}$) and pitch-angle.

Results

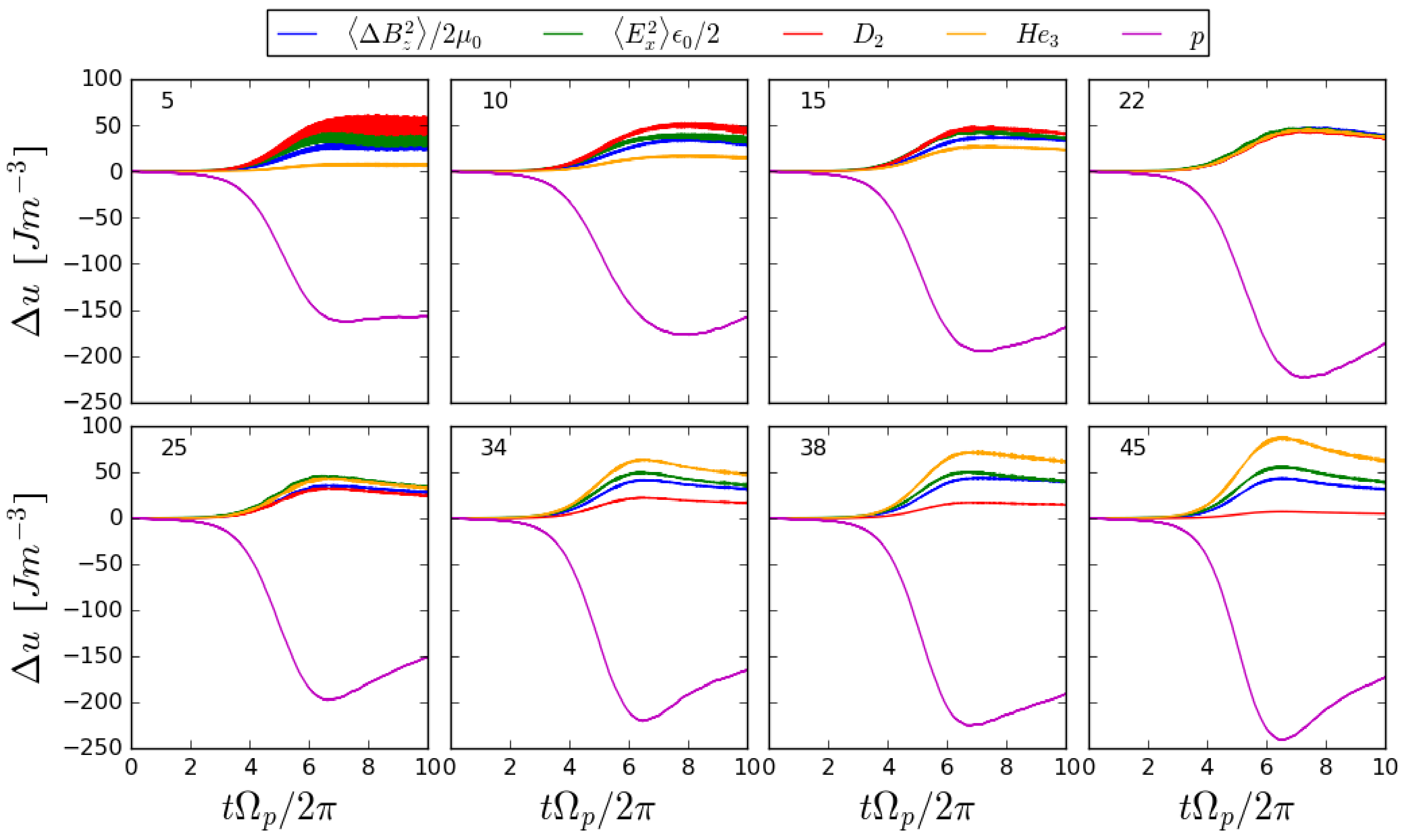


Fig. 2 Time evolution, normalised to the proton cyclotron period, of the change in energy densities of the particles and excited fields for helium-3 concentrations between five percent and 45%.

- Predominantly electrostatic ICE rather than electromagnetic (Fig. 2)
- ^{3}He concentration dependence on energy transfer (Fig. 2)
- Gyro-resonant theory [4] seen here

$$\frac{\Delta u_D}{\Delta u_{He3}} = \left(\frac{n_D m_{He3}}{n_{He3} m_D}\right) \left(\frac{q_D}{q_{He3}}\right)^2 \left(\frac{\Delta r_D^2}{\Delta r_{He3}^2}\right)$$

- Change in enclosed magnetic flux of ions is equal; $\Delta r_D^2 = \Delta r_{He3}^2$

- Large proton energies (14.68MeV) lead to large parallel velocity components with respect to magnetic field
- Parallel velocities lead to Doppler shifting in wavenumber space (Fig. 1, left)
- Doppler shift of ICE can be defined by parallel components in frame of reference of particle $\omega' = n\Omega_\text{p} - kv_0\cos\theta\cos\phi$
- Can measure power spectra in lab frame (ω) or in particle's rest frame (ω') (Fig. 1, right)

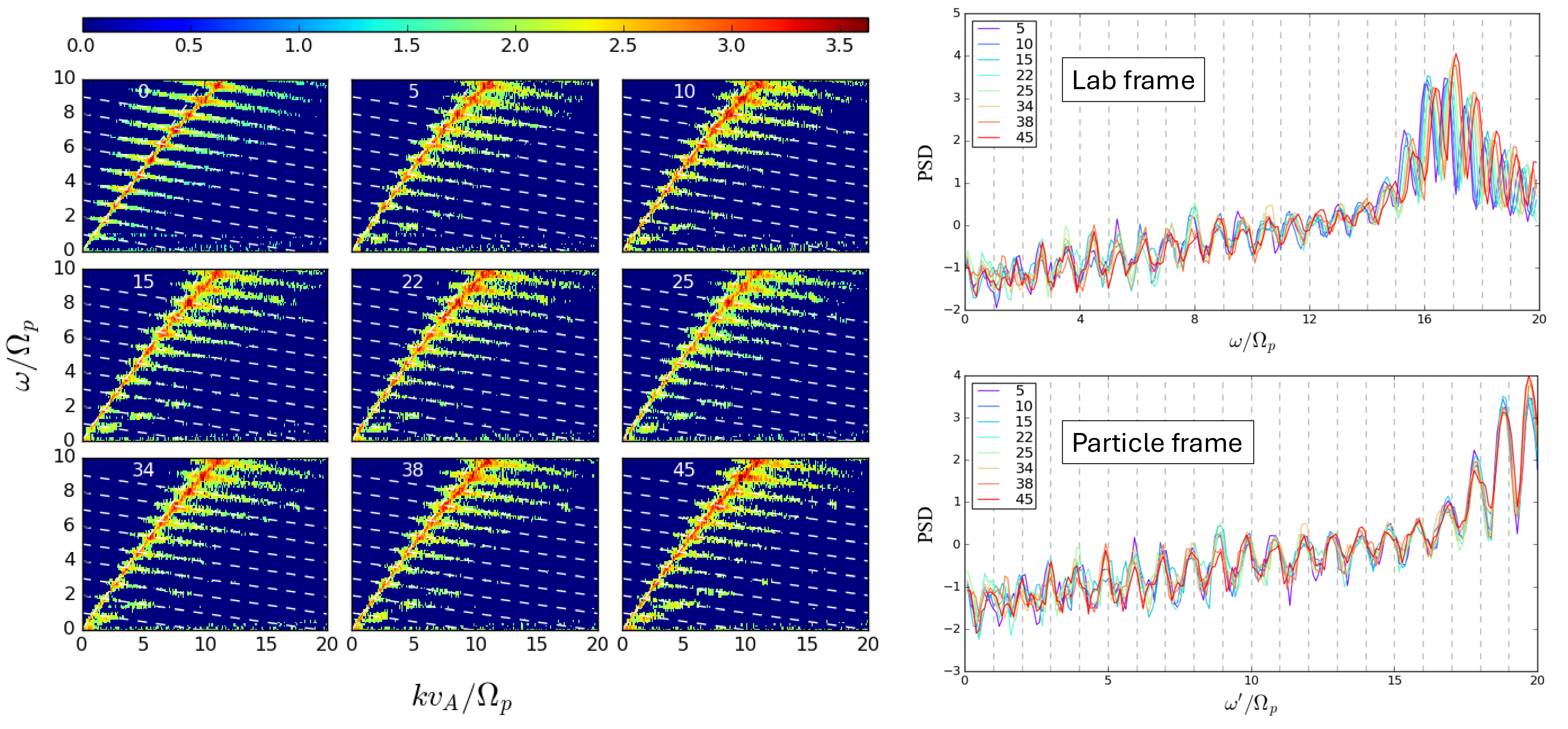


Fig. 1 (left) threshed spatiotemporal Fourier transforms of the simulation output from zero percent to 45%. Theoretical Doppler shift lines plotted as diagonal dashed white lines. (Right) power spectral densities of the left-hand data in the lab frame and in the particle's Doppler shifted frame which introduces a wavenumber dependence in frequency space.

Summary

- Doppler shifting from large proton energies, theory reveals dependency on pitch angle ϕ, magnetic field angle θ and energy of species ($u_p^2 \propto \text{E}_p$)
- Can measure power spectra in two different "frames"
- ICE in this scenario is predominantly ES rather than EM
- Partitioning of energy between bulk species is determined by their initial concentration, mass and charge
- MCI is still developed in aneutronic plasmas, and ICE is clearly visible in non-lab frame power spectra

Future work

Our simulations of the aneutronic plasma D-^{3}He for multiple ^{3}He concentrations reveal there is a need for further study of highly energetic products in aneutronic fusion plasmas. They have all been successful in producing the MCI and driving never before seen Doppler shifted ICE. Future simulations would benefit from considering the p-^{11}B reaction.

References

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