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INTRODUCTION

The 2003 JET Trace Tritium Experimental (TTE) campaign [1] provided a rare opportunity to study Ion Cyclotron Resonance Frequency (ICRF) heating of Tritium (T) at low concentrations in deuterium plasmas. Accelerating the T minority at its fundamental cyclotron frequency ($\omega = \omega_{cT}$) is a physically attractive though technically challenging heating scenario, which is currently outside the ITER RF system frequency range but would be quite relevant during its operation at low to moderate tritium concentrations. It was first very briefly investigated during the JET DTE1 experimental campaign of 1997 [2, 3] with ~5% T and on TFTR [2] with up to 20% T. On JET it requires the highest equilibrium magnetic fields (B_0 = 3.9 to 4T) and the lowest available generator frequency (~23MHz), at which only modest levels of ICRF power ~1.5MW are available. This scenario received most of the emphasis during the TTE ICRF experiments, as only one successful shot was available from DTE1. In a few other discharges tritium was accelerated at its second cyclotron harmonic ($\omega = 2\omega_{cT}$ at 37MHz with B_0 = 3.7T). At higher T concentrations (50-50 D-T mix), this is the reference ITER scenario, investigated during the JET DTE1. The goal of the TTE discharges was to study the RF power deposition in the low concentration range. A detailed account of the latter experiment will be given elsewhere.

In TTE, tritium was introduced either by gas puffs of ~5mg per discharge, or in a few instances by beam injection (~0.2mg in 300ms). The T plasma concentration reached levels estimated up to ~3%.

1. MINORITY TRITIUM HEATING: (T)D AT $\omega = \omega_{CT}$

The fundamental tritium and deuterium cyclotron layers are shown on Figure 1 for the TTE experiments at 4T and 23.1 to 24.4MHz. The location of the T layer is the most central one achievable on JET. In this instance of a so-called inverted minority heating scenario ($Z_T/A_T = 1/3 < 1/2 = Z_D/A_D$), a cut-off of the fast magnetosonic wave occurs on the antenna side of the T fundamental cyclotron layer. Moreover, at large wave toroidal mode numbers nf, the ($n^2_{\|} = R_{Stix}$) cut-off surface usually located near the plasma edge becomes considerably distorted and the bulk propagation region shrinks as illustrated Figure 1. During the TTE ICRH experiments power delivery proved indeed easier and steadier with directive antenna phasings (discharges such as illustrated Figure 4), which have lower dominant toroidal mode indices ($n_\phi = \pm 13$) than standard dipole phasing (Figure 2, dominant $n_\phi = \pm 27$). With the latter, global eigenmodes (characteristic of low single-pass wave damping) were observed on the antenna coupling resistances and on the signal of a RF probe located on the top high-fieldside of the JET chamber. In this configuration the slight frequency differences (up to 1MHz) between the four ICRF antennas led to notably different time variations of their coupling. Such data provide interesting material for advanced benchmarking of ICRF full-wave codes.

Direct deposition of ICRH power on the puffed tritium by cyclotron damping strongly increases the D-T fusion reactivity. The resulting neutron yield is dominated by 14MeV suprathermal emission, which increases by some three orders of magnitude during the RF pulses, up to 2.9 10^{16}/s with gas puff as illustrated Figure 2. Analysis of Neutron Emission Spectroscopy (NES) data [6] indicates high energy T equivalent perpendicular temperatures of 113±8keV for this discharge, and between 80 and 120keV for the whole experiment. Such values correspond to T fuel energies close to the fusion reactivity maximum (~80keV), and to the critical energy Ecr~78keV at which triton collisional power transfers to bulk D and electrons are equal. Other wave absorption mechanisms compete with T cyclotron damping: (a) electron Landau damping and TTMP; (b) parasitic cyclotron damping: at $B_0 = 4T$ a large deuterium flux is measured by the neutral particle analyser located in the outboard mid-plane, providing evidence of some D absorption in the edge, which however did not significantly perturb the discharges. Curiously the D flux is absent at $B_0 = 3.9T$ (with the D resonance layer shifted ~10cm inward), and this difference is under investigation; (c) simulations also indicate the possibility of significant damping on traces of Be impurity around R»3.4m.

Detailed code modelling of the experiments is under way with the SELFO [6] and CYRANO codes. The former combines wave and Fokker-Planck solvers; the latter allows a precise description of poloidal field effects on wave propagation. Direct electron heating is found dominant up to ~1%T, whilst RF power sharing between ions and electrons becomes even around 2%. SELFO has successfully simulated the observed T tail characteristics and total neutron yield in dipole phasing. The comprehensive information provided by neutron [4] and gamma-ray [7] emissivities (including energy, time and space resolution) should allow a much stronger test of the present modelling capability of RF wave-particle interactions. Given the sensitivity of these data and of RF power partition to the T concentration profile, this is a long term effort to pursue interactively with transport studies.

With T puff, the neutron emissivity profiles exhibit a maximum located slightly on the low field side of $\omega = \omega_{cT}$ (compare Figures 1 and 3). This observation is consistent with a significant number of fast tritons populating trapped orbits with turning points near the latter. With T beam injection, beam-plasma reactions provide a large contribution to the D-T yield, and the emissivity maximum is closer to the magnetic axis. Detailed modelling is required to analyse the role of ICRH in this case.

2. ANTENNA PHASING EXPERIMENTS

Opposite directive antenna phasings were compared in otherwise well-matched discharges with T minority heating. In the example shown Figure 4, the counter-current wave launch (so-called -90° phasing) has slightly higher electron and ion temperatures, but produces ~20% less neutrons than the co-current launch ($+90^o$). This observation is consistent with inward / outward radial drifts of fast triton orbits induced by co / counter current wave launch, providing a new instance of the 'pinch orbit' effect [8] for which much evidence has already been accumulated on JET, see e.g. [9]. The tritium fraction NT/ND was very similar in the two shots and estimated ~2.5% based on the ratio of D-T to D-D neutron emissivities during diagnostic D neutral beam blips following the ICRF pulse (9<t<9.6s).

Furthermore, in the same set of discharges, neutron emission spectroscopy has also provided the first evidence of fast T toroidal rotation ~300km/s, in the same direction as the preferential wave launch [5]. With dipole antenna phasing this rotation is much smaller (~60km/s co-current) and comparable to its experimental error.

CONCLUSIONS

ICRF heating of minority tritium at its fundamental cyclotron frequency, hitherto scarcely documented, is confirmed as an attractive heating scenario at low concentration, boosting the D-T neutron yield by direct T acceleration (which would make its use quite interesting in a neutron source), and simultaneously providing good bulk electron heating. The moderate triton tail energies also provide good ion heating, but this takes place off-axis in the JET configuration. The possibility to incorporate this scenario in the ITER ICRF design - which would require extension of the operating frequency range to lower frequencies - should be revisited after further experiments at intermediate T concentrations. A full D-T campaign on JET would be an ideal opportunity for this purpose. Detailed interpretation and modelling of the TTE ICRF experiments are proceeding; these activities benefit from the neutron and gamma ray emissivity data, which should lead to interesting new code benchmarks and enhancements.

ACKNOWLEDGEMENT

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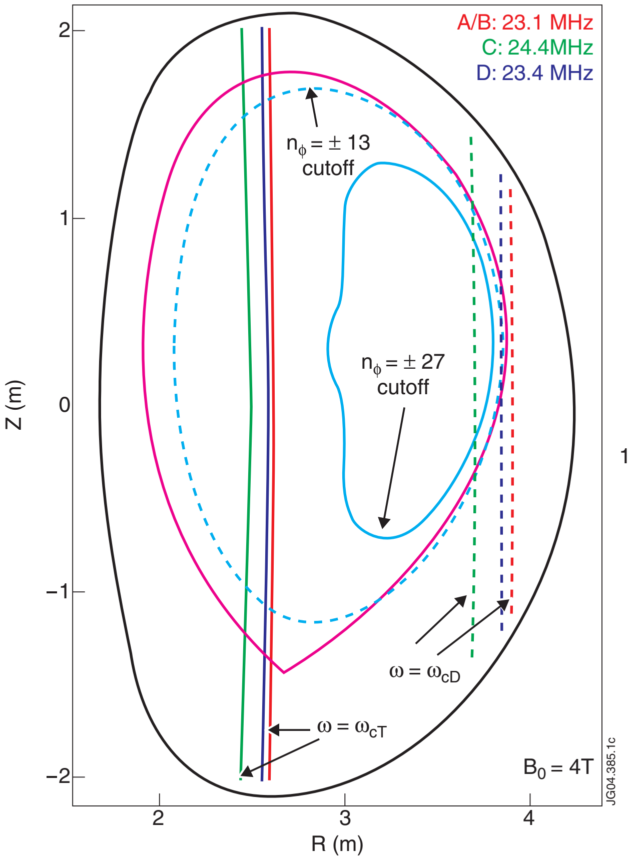


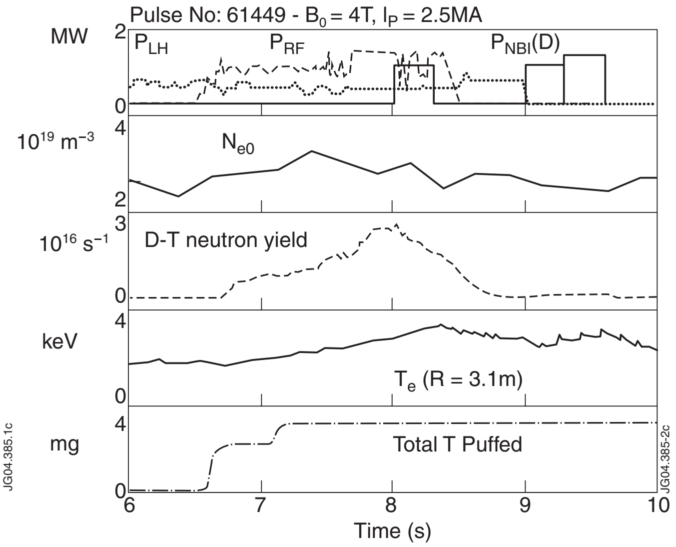


Figure 1: Cyclotron resonance layers for the (T)D scenario on JET, for each of the four ICRF antennas A, B, C, D. Fast wave cutoff surfaces are shown for the dominant wave modes launched in dipole and ±90° phasings (resp. plain and interrupted light blue lines), assuming 2.5%T.

Figure 2: Minority ICRF heating (23MHz, 4T) of tritium introduced by gas puff (total 4mg). The maximum neutron yield is 2.9 10^{16}/s for a maximum coupled power of 1.4MW. (The short D neutral beam injection pulses are for diagnostic purposes.)

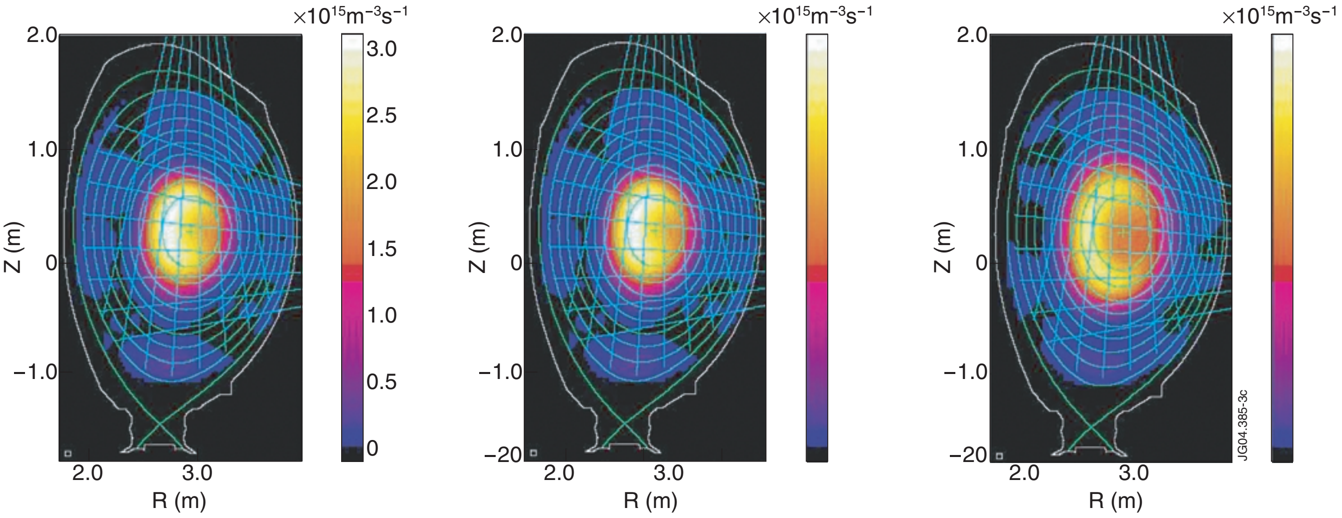
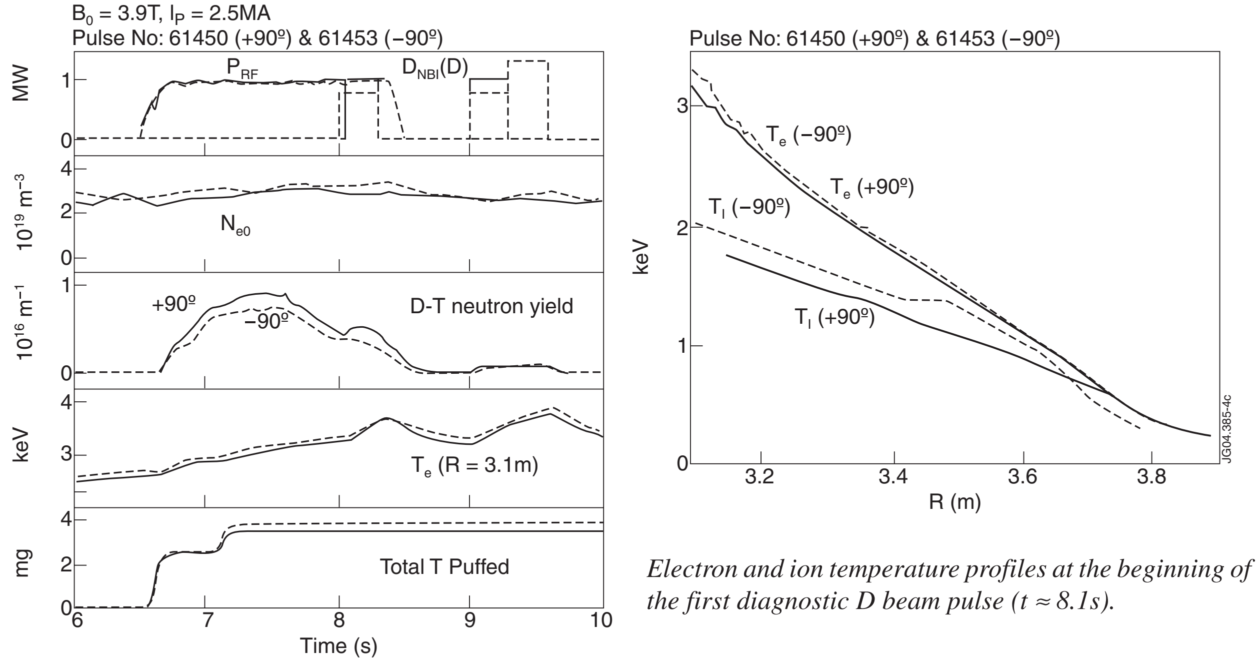


Figure 3: D-T neutron emissivity profiles for (T)D ICRF heating in dipole antenna phasing. Left and centre: T puff, B_0 = resp. 4T and 3.9T. Right: T beam injection, 3.9T. The discharges had respectively 0, 1.5 and 1.4MW of LHCD.



Electron and ion temperature profiles at the beginning of the first diagnostic D beam pulse ($t \approx 8.1s$).

Figure 4. T minority heating with co- and counter-current ICRF wave launch (resp. $+90^o$, -90^o).