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ABSTRACT.

Experiments have been carried out on the JET tokamak to investigate differences between multiple and single frequency ICRH operation with ICRH power in the range of 3 to 8MW using H and ^{3}He minority heating. High-energy neutral particle analysis and gamma-ray emission tomography are used to measure fast ions, including their radial localisation. For 3MW of ^{3}He minority heating, the fast ^{3}He ion profile is broader according to the gamma emission data and the fast ion tail temperature T_{tail} and energy content W_{fast} are lower with polychromatic ICRH than monochromatic ICRH. Polychromatic ICRH has the advantage of producing smaller-amplitude and shorter-period sawteeth, consistent with a lower fast ion pressure inside q = 1, and higher T_i/T_e ratios (i.e. similar T_i at lower T_e). At high powers with resonances in the centre and/or on the low field side, the data indicates a larger fraction of trapped ions and a lower T_{tail} for polychromatic ICRH. Experimental results are compared with theoretical predictions.

1. INTRODUCTION

The frequency of waves launched by the four JET A2 ICRH antennas can be chosen independently. Hydrogen minority heating with multiple frequencies was used routinely in high-performance NBI-dominated plasmas before and during the 1997 deuterium-tritium campaign [1]. Using up to four frequencies, resonances were spread over a 30-40 cm wide region in the plasma centre to decrease the power density in order to improve bulk ion heating and plasma stability. However, one-to-one comparisons of monochromatic and polychromatic ICRH with identical coupled powers, including information on the fast ion radial localisation, were not obtained. Such comparisons are important in order to improve the understanding of ICRH physics and to benchmark numerical modelling codes against experiments. Recent simulations [2] suggest certain benefits for polychromatic ICRH at high powers available in the JET enhancement project, which require experimental verification.

2. OVERVIEW OF THE EXPERIMENTS

This paper reports recent experiments with ^{3}He and H minority heating on JET (R_0 3m, $a \approx 1$m) to investigate in detail the differences between multiple and single ICRH frequency operation. The experiments were carried out in a single-null divertor configuration at a magnetic field of 3.3–3.7 T and a plasma current of 1.8–2MA. High-energy neutral particle analysis [3] and gamma-ray emission tomography [4] were used to obtain information on the fast ions, including their radial localisation. The available gamma ray reactions and the average energies of ^{3}He ions and protons required for these reactions to take place [4], together with the available powers for each ICRH frequency, were the determining factors when the choice between H and ^{3}He minority heating was made.

Frequencies f_{ICRH} in the range of 33-37.5MHz were used for ^{3}He minority heating, with total coupled power in the range of 3-4.5MW (Fig.1). Higher powers, in the range of 7-8MW, were obtained with H minority heating using f_{ICRH} in the range of 46.5-51.5MHz. For monochromatic ICRH, the resonance was located in the plasma centre and the spread in f_{ICRH} around the nominal

f_{ICRH} delivered by the four antennas resulted in a natural spread ΔR_{res} of 5-10cm in the major radius of the minority ion cyclotron resonance R_{res}. For polychromatic operation, the resonances with ΔR_{res} = 30- 35cm were located in the plasma centre and on the low or high field side. The dipole ($0\pi0\pi$) phasing of the antennas was used, the ^{3}He concentration n(^{3}He)/n_e was about 1%, and the H concentration nH/n_e was in the range of 3-7 %.

3. EXPERIMENTAL RESULTS

Figure 2 summarises the experimental results in terms of the plasma diamagnetic energy W_{DIA}, fast ion energy $W_{fast} = 2(W_{DIA} - W_{th})/3$ and volume-averaged electron temperature $<T_e>$ as a function of ICRH power (W_{th} is the thermal plasma energy content deduced from measured plasma densities and temperatures). As we can see, W_{DIA}, W_{fast} and $<T_e>$ are somewhat smaller with polychromatic ICRH for P_{ICRH} = 3– 4.5MW. Here, the difference in W_{fast} is responsible for about 50% of the difference in W_{DIA}, and is consistent with smaller-amplitude and shorter-period sawteeth produced with polychromatic ICRH (cf. Fig. 3(a)) suggesting a lower fast ion energy in the plasma centre inside q = 1. For discharges with higher-power H minority heating, not only W_{fast} but also $<T_e>$ and W_{DIA} are identical within the error bars for monochromatic and polychromatic ICRH with similar P_{ICRH}. Simulations with PION [5] and SELFO [6] codes suggest that this change in the overall behaviour is due to the fact that as P_{ICRH} increases, the fast ion orbit width increases and becomes comparable to or larger than the spread in the ICRH resonances. Throughout the scan in P_{ICRH}, ion temperatures and ion temperature profiles were similar with polychromatic and monochromatic ICRH (cf. Fig. 3(b)). Unfortunately, there was no time to optimise bulk ion heating in these discharges. Nevertheless, the observed higher T_i/T_e ratios and shorter-period sawteeth make polychromatic ICRH promising for further applications.

Important information on the fast ion orbits and radial localisation was obtained with gamma emission tomography. Figure 4 shows gamma emission profiles for three discharges with ^{3}He minority heating. When P_{ICRH} is increased from 3 to 4.5MW using polychromatic ICRH (discharges 57252 and 57300), the gamma emissivity increases and the shape of the gamma emission changes, suggesting a larger fraction of trapped ions located on the low field side at high P_{ICRH}. This change is consistent with the expected increase in the average energy of the fast ions above the energy E 34 T_e (keV) 150-200keV at which pitch-angle scattering becomes weak [7], with a concomitant increase in the fraction of trapped ions. With monochromatic ICRH (Pulse No: 57301), the maximum gamma emission is located on the low-field side of the resonance, but closer to it than in Pulse No: 57300 with polychromatic ICRH, and the intensity of the emission increases with P_{ICRH}. This suggests a larger fraction of fast non-standard (co-passing and potato) orbits on the low-field of the resonance with monochromatic ICRH. PION and SELFO code modelling of the discharges show similar trends as the measurements (cf. Fig.5).

Gamma-ray data for discharges with high- power H minority heating show similar trends as for Pulse No: 57300 and 57301 with lower-power ^{3}He minority heating, but the peak gamma emissivity is located further to the low-field side and the profile of the gamma emission is broader, consistent with larger fast ions orbits. Measurements with high-energy NPA during H minority heating indicate about a 25% higher Ttail for fast protons with monochromatic ICRH than with polychromatic ICRH. To conclude, experimental results show trends expected from theory. Detailed comparisons with simulations are underway and will be reported elsewhere.

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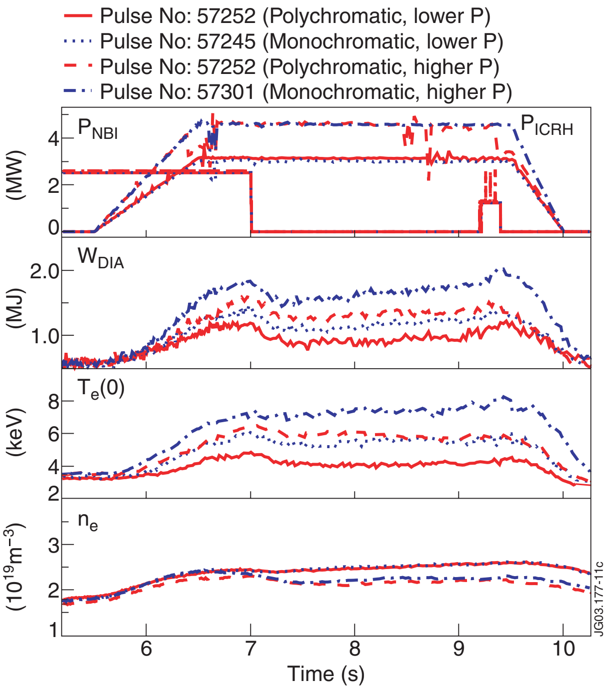

Figure 1: Overview of main plasma parameters for discharges with polychromatic and monochromatic ^{3}He minority heating.

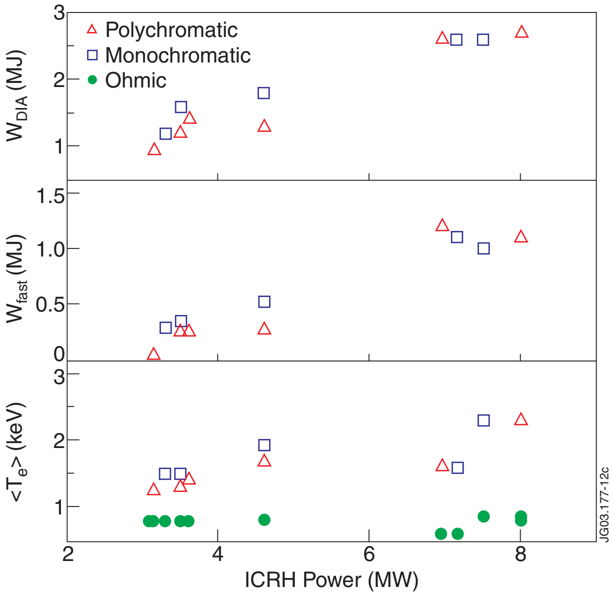

Figure 2: Plasma diamagnetic energy, fast ion energy and volume-averaged electron temperature as a function of ICRH power.

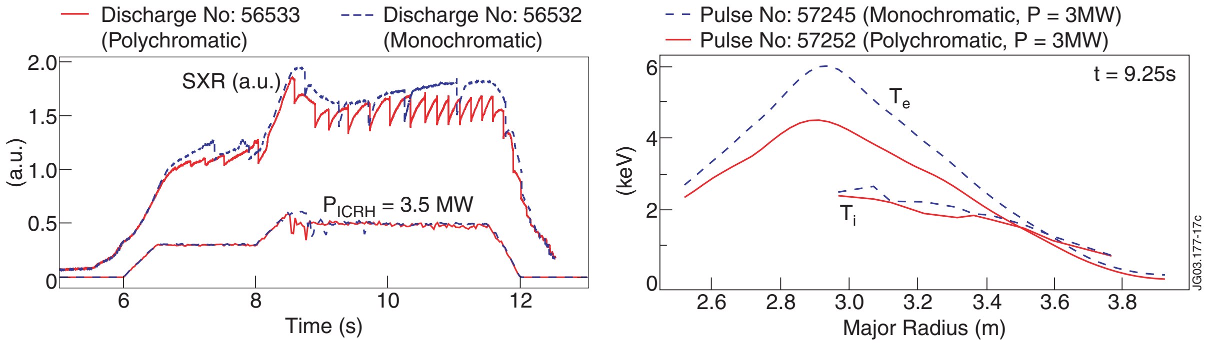

Figure 3: (a) Soft X-ray emission and ICRH power and (b) electron and ion temperature profiles for two discharges with monochromatic and polychromatic ^{3}He minority heating.

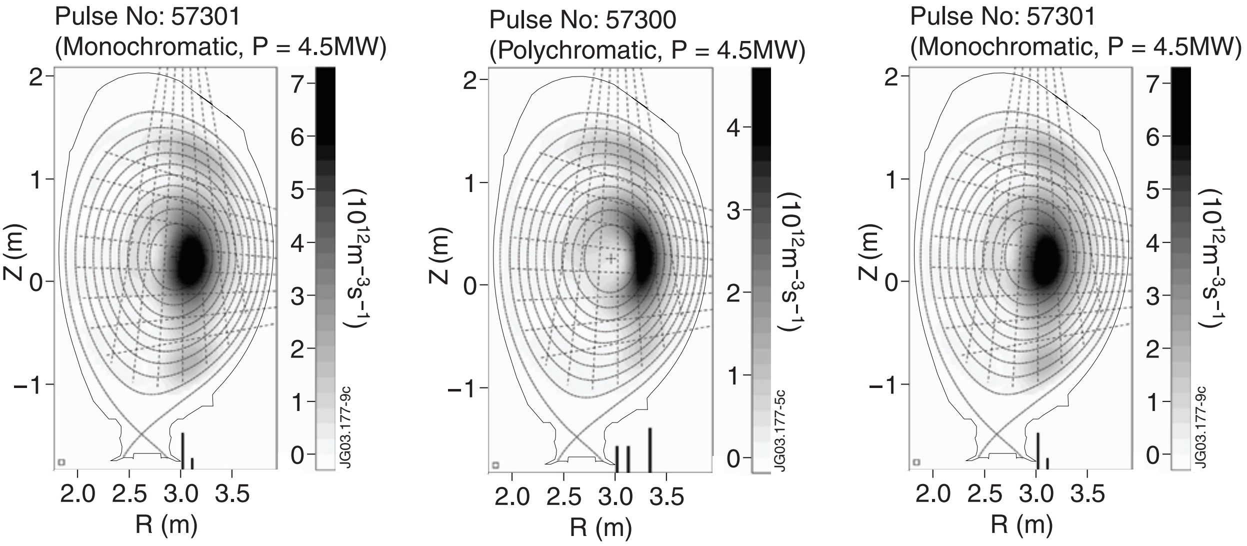

Figure 4: Gamma emissivity in the poloidal plane for three discharges with ^{3}He minority heating. Gamma emission is dominantly from reactions between fast ^{3}He and ^{9}Be which take place when E(^{3}He) > 0.9MeV. The vertical bars indicate the relative fraction of total P_{ICRH} applied at a given R_{res}.

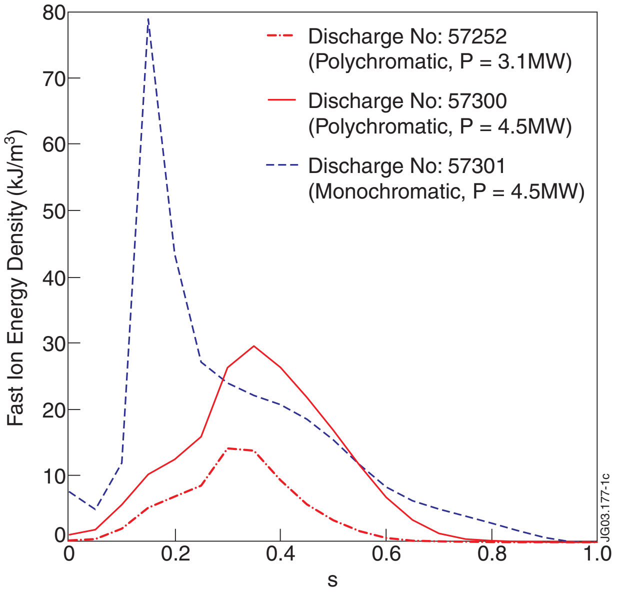

Figure 5: Fast ion energy density as given by PION for discharges in Fig.4. Here, $s\sqrt{} = \psi_p/\psi_{pa}$, where ψ_{pa} is the poloidal flux at the edge.