EUROPEAN FUSION DEVELOPMENT AGREEMENT

EFDA–JET–CP(01)02-32

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ICRF Mode Conversion Experiments on JET

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**See appendix of the paper by J.Pamela "Overview of recent JET results", Proceedings of the IAEA conference on Fusion Energy, Sorrento 2000*

Preprint of Paper to be submitted for publication in Proceedings of the
EPS Conference,
(Madeira, Portugal 18-22 June 2001)

1. INTRODUCTION

Mode conversion (MC) heating and current drive using waves in the ion cyclotron range of frequencies (ICRF) have several attractive reactor-relevant applications. These include on-axis and off-axis electron heating and current drive [1,2], MHD activity control [2], sheared poloidal flow drive and synergism with lower hybrid waves for enhanced current drive [3,4]. They have motivated recent experiments on JET to study MC using the ^{3}He minority ICRF heating scenario in D and ^{4}He plasmas. In these experiments, the ^{3}He concentration was increased systematically to investigate the transition from the ^{3}He minority heating regime to the MC regime.

In the minority heating regime, launched fast waves are mainly absorbed by ^{3}He minority ions at $\omega \approx \omega(^3\text{He})$ and a high-energy tail of the resonating ^{3}He ions is formed. The heating of the background electrons and ions takes place on the time-scale of ion-electron and ion-ion collisions, respectively. In the MC regime, fast waves are mode-converted to short-wavelength waves. These waves damp strongly on electrons, giving rise to electron heating on the significantly shorter time scale of electron-electron collisions. For a given frequency and magnetic field, the location of the MC layer and direct electron power deposition can be varied by changing the ^{3}He concentration. This is in contrast to direct electron damping of the launched fast wave, which is central due to its dependence on the electron temperature and density.

2. EXPERIMENTAL SET-UP

The scenario used in these experiments is shown in Fig. 1. The ICRF power was square-wave modulated with a frequency of 10-20Hz and an amplitude of 50% to measure the direct electron power deposition using Fourier and break-in-slope analysis of fast spatially-resolved ECE electron temperature (T_e) data. The electron temperature was measured on the low field side about 15cm below the midplane.

Up to 6 MW of ICRF power was applied at a frequency of 34 or 37MHz and the magnetic field was in the range of 3.45-3.7T. The ^{3}He puff, applied before the ICRF heating phase, was systematically increased from discharge to discharge. Diagnostic low-power deuterium beams were added in deuterium plasmas to monitor the following decay of the ^{3}He concentration (cf. Fig. 1) using charge exchange spectroscopy.

3. DEMONSTRATION OF MC

With increasing ^{3}He puff, the T_e response to the ICRF power modulation was observed to change as shown in Fig. 2. Here, the T_e evolution for a flux surface intersecting the MC layer is displayed for two discharges with different levels of ^{3}He puff. At low ^{3}He puff, a delay in the response is observed, consistent with a contribution from indirect electron heating by ^{3}He minority ions. At higher ^{3}He puff, the electron temperature response is significantly prompter, consistent with dominant direct electron heating due to MC. These results are supported by gamma ray emission due to fast ^{3}He ions measured in the same series of discharges. Figure 3 shows the gamma ray spectra integrated over the ICRF heating phase for four discharges with different levels of ^{3}He puff. The peaks in the measured spectra are due to fast ^{3}He ions reacting with ^{9}Be and ^{12}C impurity ions. The measured spectra indicate that as ^{3}He puff is increased, the ^{3}He tail disappears. As ^{3}He puff is systematically increased from discharge to discharge, a transition from central to off-axis, more-peaked direct electron power deposition was observed, as shown in Fig. 4. These results are consistent with an increase in the mode converted power fraction and the movement of the MC layer to the high field side further away from the ^{3}He resonance, as the ^{3}He concentration was increased. In these discharges, an ICRF frequency of 37MHz was used to position the ^{3}He resonance layer on the high field side at 2.8m. By integrating the measured direct electron power deposition profiles shown in Fig. 4 over the plasma volume, the direct electron power deposition is found to increase from 15 to 70% of the launched ICRF power. It is worth noting that these values give only lower estimates for direct electron damping due to, for example, the finite spatial coverage of electron temperature measurements. These results clearly demonstrate that very efficient ICRF mode conversion can be obtained on JET.

The shapes of the measured electron temperature profiles responded to the changes in the direct electron deposition locations, as illustrated in Fig. 5. With central MC (B = 3.7T, f_{ICRF} = 34MHz), more peaked electron temperature profiles were obtained than with off-axis MC (3.45T, 34MHz). Using non-modulated ICRH with central MC and continuous ^{3}He puffing during ICRH to keep the ^{3}He concentration and the direct electron power deposition constant in time [5], an efficient electron heating regime was established: central electron temperatures in excess of 8keV for $n_e(0) \approx 3\times10^{19}\text{m}^{-3}$ were obtained with 5MW of ICRF power alone (cf. Fig. 6). The energy confinement time, $\tau_E \approx 0.28$s, corresponds to an ELMy H mode quality factor, ITERH97-P [6], of 0.7, indicating good-quality L-mode confinement.

MODELLING OF MC

Preliminary calculations, based on coupling of the full-wave ALCYON code with the ray-tracing RAYS code [7], indicate comparable direct electron power deposition profiles to those measured in these experiments [5]. The phase velocity of the waves in the MC layer is found to be close to the electron thermal velocity, resulting in strong electron damping close to the MC layer, consistent with the measured peaked electron heating profiles.

CONCLUSIONS.

Results from recent ICRF mode conversion experiments with $\omega \approx \omega(^3\text{He})$ in JET D and ^{4}He plasmas have demonstrated the feasibility of ICRF mode conversion on JET. Efficient direct electron damping of the mode converted waves has been obtained. The parametric dependence of the location of the maximum direct electron power deposition has been found to be consistent with theoretical expectations for MC. These results form a good starting point for further exploration and applications of ICRF mode conversion on JET.

ACKNOWLEDGEMENTS
This work has been performed under the European Fusion Development Agreement.

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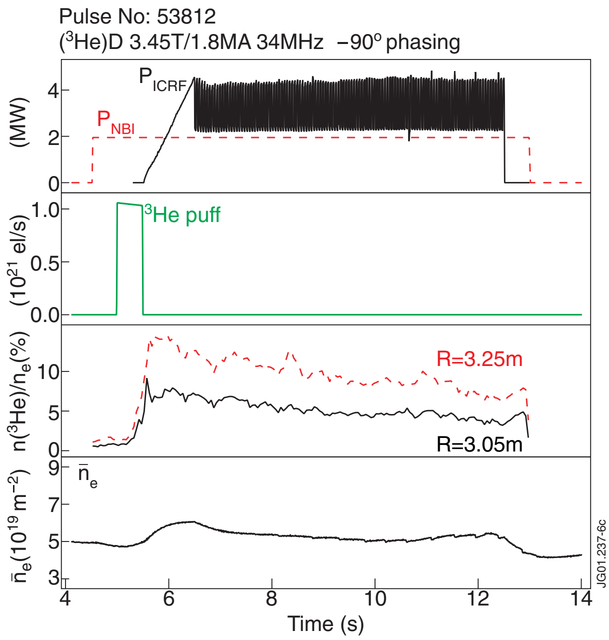

Figure 1: Key parameters of the experiment.

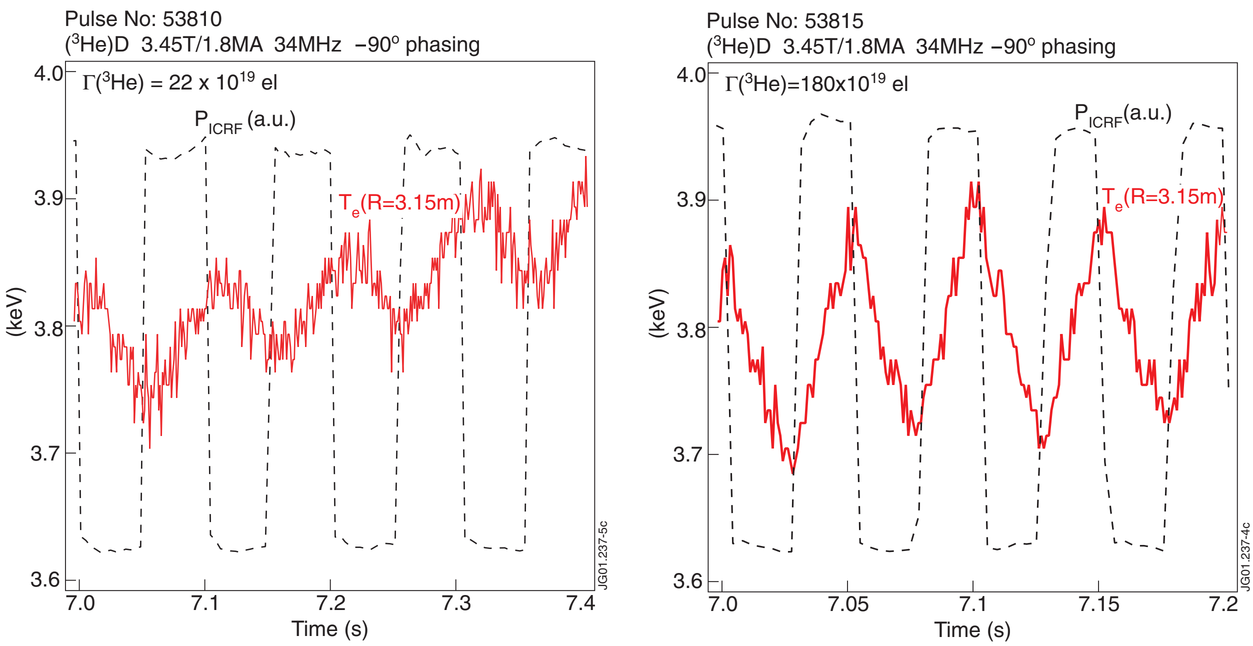

Figure 2: Electron temperature response to modulated ICRH in two discharges with different levels of ^{3}He puff. As the ^{3}He concentration increases, the MC layer moves towards the high field side further away from the ^{3}He minority resonance located at $R \approx 3.1$m.

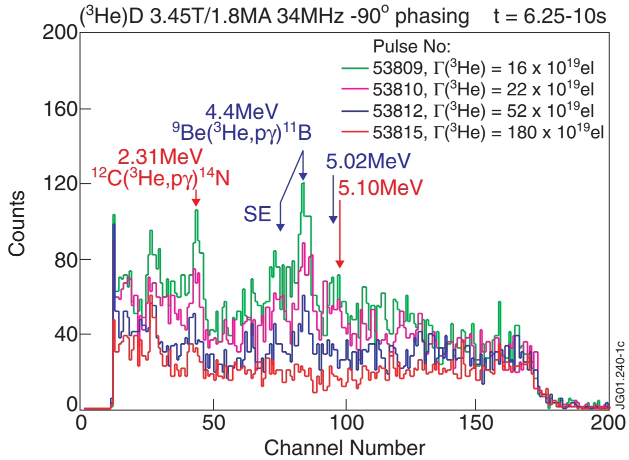

Figure 3: Gamma ray spectra measured in four discharges at different levels of ^{3}He puff.

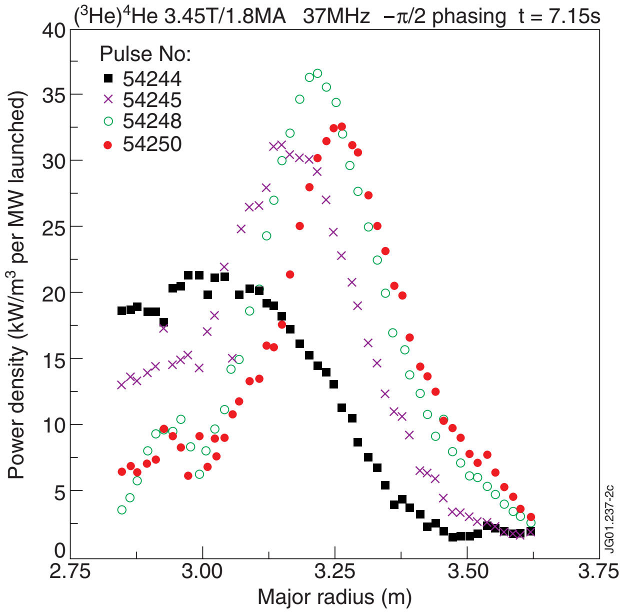

Figure 4: Direct electron heating profiles from break-in-slope analysis of T_e data. The horizontal axis is the major radius at about 15cm below the midplane.

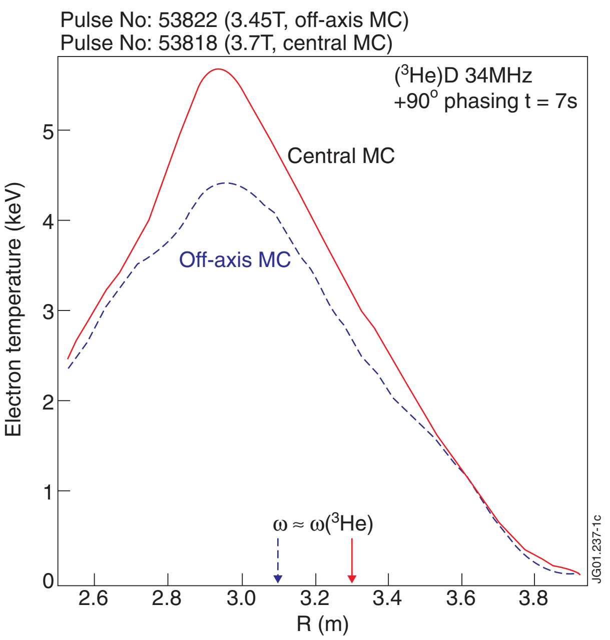

Figure 5: *Measured electron temperature profiles for central MC and for off-axis MC on the high field side. The corresponding ^{3}He resonances are also shown.*

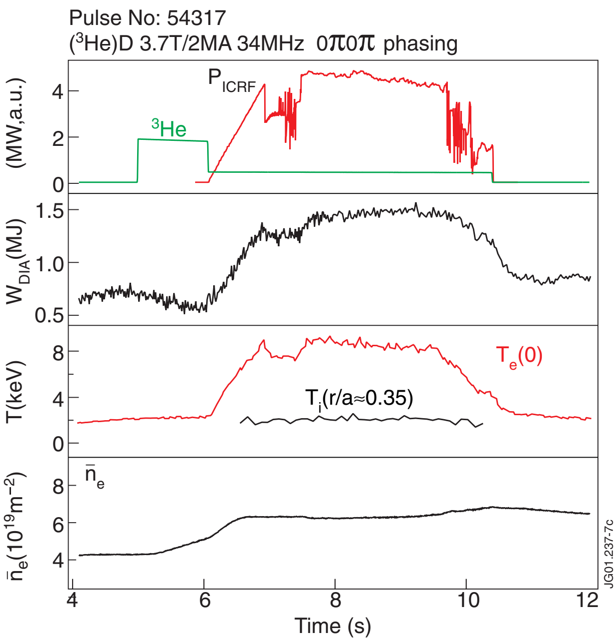

Figure 6: Overview of a discharge with central MC and continuous ^{3}He puff during non-modulated ICRH.