EUROPEAN FUSION DEVELOPMENT AGREEMENT

EFDA–JET–CP(02)02/23

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**See annex of J. Pamela et al, "Overview of Recent JET Results and Future Perspectives", Fusion Energy 2000 (Proc. 18th Int. Conf. Sorrento, 2000), IAEA, Vienna (2001).*

Preprint of Paper to be submitted for publication in
Proceedings of the 29th EPS Conference, (Montreux, Switzerland 17-21 June 2002)

INTRODUCTION

The installation of the new ITER-like ICRF launcher [1] in JET is expected to increase the total coupled ICRF power by about a factor of two. The effects of the increased power on the performance of ICRF heating scenarios used in JET deuterium-tritium (DT) plasmas are investigated and optimised using numerical computer modelling. The optimisation includes tailoring the profile and energy of ICRF-accelerated ions using multiple frequencies to maximise bulk ion heating and/or fusion reactivity. Four main ICRF heating schemes are considered:

(a) deuterium minority heating in tritium-dominated plasmas,
(b) second-harmonic heating of tritium in DT plasmas,
(c) ^{3}He minority heating in DT plasmas, and
(d) hydrogen minority heating in DT plasmas.

The ICRF heating experiments carried out during the 1997 JET DTE1 campaign, with up to 8-9MW of ICRF power applied using single frequency operation [2], serve as the starting point for this work. The simulations have been carried out with the ICRF code PION [3,4] that has been used extensively to analyse ICRF heating in JET experiments, including those in 1997 [5]. To find regimes with maximum ion heating and/or fusion yield, a random search method was used. All parameters of interest were randomly disturbed and used for a new PION simulation. If the new parameters resulted in better performance than the old parameters, the new parameters were used for another iteration. Dipole phasing was assumed and the frequencies were chosen from the available frequencies of the current RF-generators at JET so that $|R_{res}-R_0|/a < 0.5$ ($R_0 \approx 3$m and $a \approx 1$m). In general, multiple frequency schemes were found to give improved (by up to 100%) ion heating and fusion reactivity as compared with a single resonance in the plasma centre.

1. DEUTERIUM MINORITY HEATING IN TRITIUM-RICH PLASMAS

By keeping the ion species mixture, ion and electron temperatures $T_{i,e}$ and the magnetic field B the same as in JET Pulse No: 43015 with a record $Q = P_{fus}/P_{ICRF} \approx 0.25$ with 6MW of deuterium minority heating ($B = 3.7$ T, $n_e = 5\times10^{19}m^{-3}$; $Z_{eff} = 1.6$, $n_D/n_T = 8\%$, $T_e = 6$ keV, $T_i = 5.2$keV) [2,5], maximum bulk ion heating of 6.2MW and Q of 0.37 for 15MW of ICRF power was found when 76, 17 and 7% of the total power were distributed at ICRF frequencies of 24.5, 26.5 and 28.5MHz, respectively. For a single ICRF frequency with a resonance in the centre, the higher ICRF power density gives rise to a higher average energy of fast deuterons and thereby a slower increase of ion heating with P_{ICRF} as compared to multiple frequency case (Fig.1(a)). The conservative assumption that the T_i/T_e ratio stays roughly the same and $T_e \propto \sqrt{P_e}$ as the input power is increased, gives $T_e = 9$keV and $T_i = 7.8$keV in the case of multiple frequencies. In these conditions $Q = 0.46$ (Fig. 1(b)) and a high neutron emissivity of (7-8) x 10^{16} neutrons/m^{3}s is obtained throughout the plasma centre inside $r/a < 0.6$. An increase in the deuterium density from $n_D = 4\times10^{18}m^{-3}$ to $n_D = 6.5\times10^{18}m^{-3}$ increases bulk ion heating by 1MW at the expense of decreasing Q (Fig.1(b)).

II. SECOND-HARMONIC HEATING OF TRITIUM ($\omega = 2\ \omega_{cT}$) AND 3HE MINORITY HEATING IN DT PLASMA

Owing to competing direct electron damping and second-harmonic acceleration of resonating tritons to energies in excess of the critical energy [6] for equal ion and electron power partitioning, only modest ion heating can be obtained with $\omega = 2\omega_{cT}$ on JET. The use of multiple frequencies reduces the power absorbed by tritons as compared with the single frequency case (Fig. 2(a)). In spite of this, the multiple frequency scheme gives somewhat better ion heating (Fig 2(b)) as the fast tritons have energies closer to the critical energy, which is advantageous for collisional power transfer to ions. The highest ion heating fractions with $\omega = 2\omega_{cT}$ found in this study are about 20-25% of P_{ICRF}. Adding some ^{3}He in the plasma improves collisional ion heating P_{ci} significantly. The main reason for the improved P_{ci} is dominant ^{3}He absorption at the fundamental ^{3}He resonance together with the high critical energy of the ^{3}He ions. At $n_e = 5\times10^{19}\ m^{-3}$ and B = 3.9 T, ^{3}He minority heating is found to give a high bulk ion heating fraction of 66% with $n_{He}/n_e = 6\%$ when 75, 10 and 15% of ICRF power (15 MW) is applied at 35.5, 37.3 and 39MHz, respectively. As n_e is decreased, P_{ci} decreases for $P_{ICRF} \geq 10$ MW due to acceleration of ^{3}He ions to energies above the critical energy (Fig. 3(a)). The optimal power distribution among the different frequencies (and resonance locations) depends on the ^{3}He concentration (Fig. 3(b)). As n_{He}/n_e decreases, more power needs to be deposited further out from the plasma centre in order to keep power per particle and the average energy of fast ^{3}He ions at their optimal values for bulk ion heating.

III. HYDROGEN MINORITY HEATING IN DT PLASMA

Due to their lower mass, protons have a lower critical energy compared to ^{3}He and D ions and thus for a given fast ion energy less efficient collisional transfer to bulk ions. Thus, in order to obtain similar ion heating as with deuterium or ^{3}He minority heating, a lower power per particle is required. The highest ion heating fraction of about 50% is obtained with a high hydrogen concentration n_H/n_e of 10-12% and wide spreading of the resonance positions (Table 1). In this case, multiple frequency operation improves bulk ion heating by up to 100% as compared with a single resonance in the plasma centre.

CONCLUSIONS AND DISCUSSION

The performance of ICRF heating scenarios for JET D-T plasmas is studied at coupled ICRF powers in excess of 10MW. The main results are summarised in Table 1. Deuterium minority heating with P_{ICRF} = 15MW gives the highest fusion reactivity, corresponding to $Q = P_{fus} / P_{ICRF} \approx 0.45$, and a relatively high bulk ion heating fraction of ≈35 %. The highest bulk ion heating fraction of ≈ 65 % ($P_{ci} \approx$ 10MW) is obtained with ^{3}He minority heating using $n_{He}/ n_e = 6\%$, whereas second harmonic heating of tritium gives a high bulk electron heating fraction (up to 80 - 90%). Hydrogen minority heating can give a relatively high bulk ion heating fraction of 40 - 50% (P_{ci} = 6-7.5MW) when multiple ICRF frequencies are used together with a relatively high hydrogen concentration of n_H/n_e

≈ 10 - 12%. In this case, however, the ICRF power deposition has to be spread further out than in the case of deuterium or ^{3}He minority heating. For high-power ICRF operation,further benefits could be obtained with combined scenarios. For example, an interesting option could be to combine deuterium minority heating for high nonthermal fusion reactivity and ^{3}He minority heating for strong bulk ion heating. Dedicated experiments are planned on JET to investigate the benefits of the multiple frequency ICRF operation and to assess in detail the predictive capability of ICRF modelling codes in such cases.

ACKNOWLEDGEMENTS

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

REFERENCES

[1]. F. Durodié, et al., Radio Frequency Power in Plasmas (14th Topical Conf., Oxnard, 2001) (AIP, 2001) 122.

[2]. D.F.H. Start, et al., Nuclear Fusion **39** (1999) 321; D.F.H. Start, et al., Phys. Rev. Lett. **80** (1998) 4681.

[3]. L.-G. Eriksson, T. Hellsten and U. Willén, Nucl. Fusion **33** (1993) 1037.

[4]. L.-G. Eriksson and T. Hellsten, Phys. Scripta **55** (1995) 70.

[5]. L.-G. Eriksson, et al., Nuclear Fusion **39** (1999) 337.

[6]. T.H. Stix, Plasma Phys. **14** (1972) 367.

Scenario / Parameter	(D) T	$w = 2\omega_{cT}$	(^{3}He) DT	(H) DT
B (T)	3.7	3.8	3.9	3.5
P_{ICRF} (MW)	15	10	15	15
$(R_{res}-R_0)$ / a	0.4, 0.2, 0	0.3, 0.0, −0.25, −0.55 [redacted]	0.4, 0.2, 0.10	0.5, 0.4, 0.05
ICRF power distribution (%)	76, 17, 7	52, 31, 8, 9	75, 10, 15	41, 47, 12
P_{ci} / P_{ICRF} (%)	34	15	66	51
nonthermal Q	0.4	-	-	-

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Table 1: Summary of the main results for the four ICRF scenarios with the optimised multiple frequency schemes giving strongest ion heating.

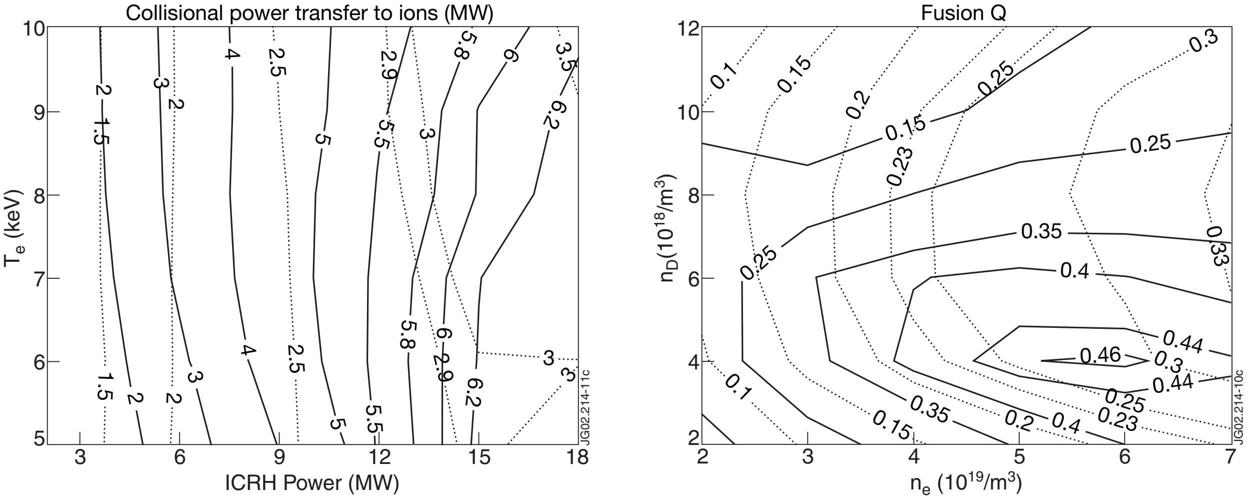

Figure 1 (a) Contour plot of ion heating as a function of ICRF power and T_e and (b) $Q = P_{fus} / P_{ICRF}$ as a function of n_D and n_e for deuterium minority heating using the optimised multiple frequency scheme (solid lines, cf. Table 1) and a single frequency scheme (dotted). Here, $T_e / T_i = 1.16$ as in DTE1 Pulse No: 43015 [2,5]. In (b) P_{ICRF} = 15MW and T_e = 9 keV.

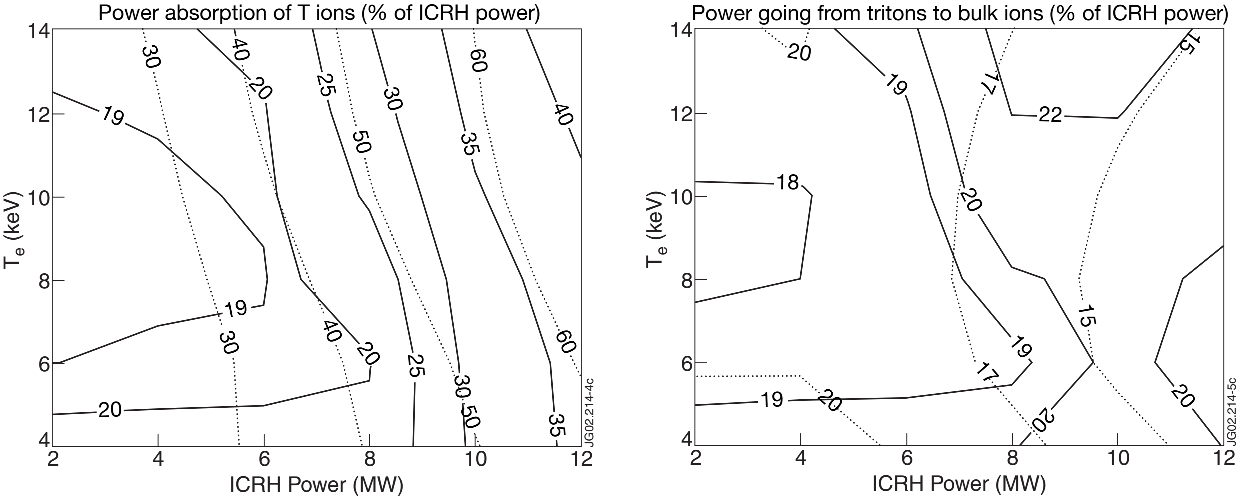

Figure 2: Contour plot of the fraction (%) of (a) ICRF power absorbed by tritons and (b) ion heating as function of P_{ICRF} and T_e for second harmonic heating of tritons using the optimised multiple frequency scheme (solid, cf. Table 1) and a single frequency scheme (dotted). Here, $n = 6.3 \times 10^{19}\ m^{-3}$ and $T_e / T_i = 1.3$ as in DTE1 Pulse No: 42753 [2,5].

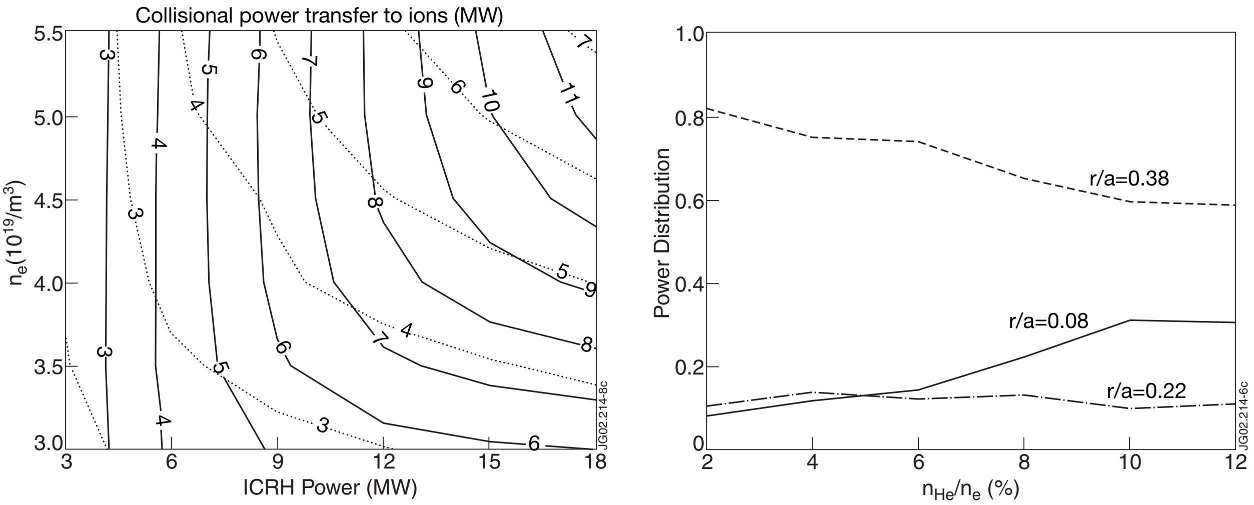

Figure 3: (a) Contour plot of collisional ion heating for ^{3}He minority heating with $n_{He}/_{ne}$ = 6% using the optimised multiple frequency scheme (solid, cf. Table 1) and a single frequency scheme (dotted). (b) Power distribution among different ICRF resonance locations giving the strongest ion heating as a function of the ^{3}He concentration.