

Extrapolating the Performance of ICRF Heating Scenarios for JET Deuterium-Tritium Plasmas to High Coupled Powers

M.J. Mantsinen¹, M.D. Kihlman² and L.-G. Eriksson³

¹*Helsinki University of Technology, Association Euratom-Tekes, Finland*

²*Chalmers University of Technology, Euratom-VR Association, Gothenburg, Sweden*

³*Association EURATOM-CEA sur la Fusion, CEA Cadarache, St. Paul lez Durance, France*

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) ³He 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 8-9 MW 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 $|R_{\text{res}}-R_0|/a < 0.5$ ($R_0 \approx 3$ 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.

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 discharge 43015 with a record $Q = P_{\text{fus}}/P_{\text{ICRF}} \approx 0.25$ with 6 MW of deuterium minority heating ($B = 3.7$ T, $n_e = 5 \times 10^{19} \text{ m}^{-3}$; $Z_{\text{eff}} = 1.6$, $n_D/n_T = 8\%$, $T_e = 6$ keV, $T_i = 5.2$ keV) [2,5], maximum bulk ion heating of 6.2 MW and Q of 0.37 for 15 MW 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 28.5 MHz, 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. 1a). 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. 1b) and a high neutron emissivity of $(7-8) \times 10^{16}$ neutrons/m³s is obtained throughout the plasma centre inside $r/a < 0.6$. An increase in the deuterium density from $n_D = 4 \times 10^{18} \text{ m}^{-3}$ to $n_D = 6.5 \times 10^{18} \text{ m}^{-3}$ increases bulk ion heating by 1 MW at the expense of decreasing Q by 25% (Fig. 1b).

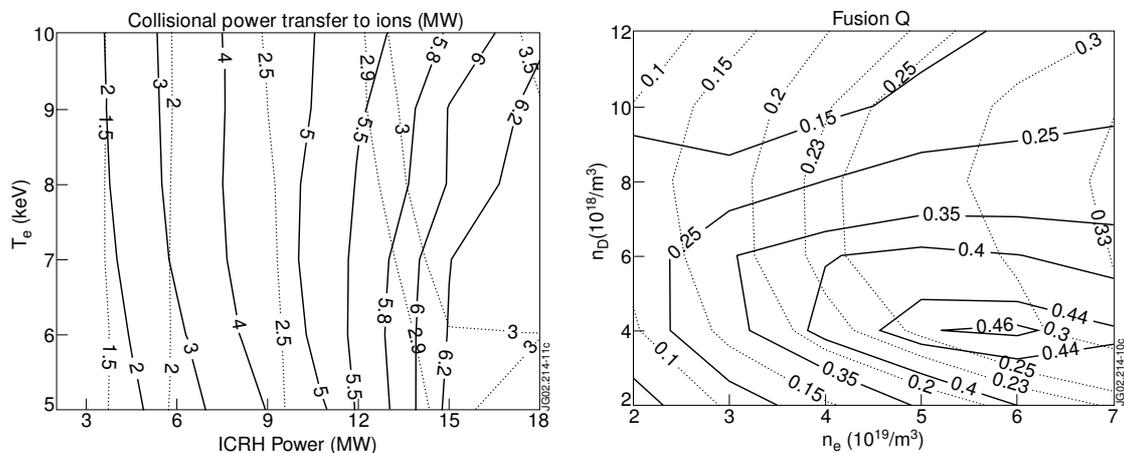


Figure 1 (a) Contour plot of ion heating as a function of ICRF power and T_e and (b) $Q = P_{fus}/P_{ICRF}$ as a function of n_D and n_e for deuterium minority heating using the optimised multiple frequency scheme (solid lines, cf. Table 1) and a single frequency scheme (dotted). Here, $T_e / T_i = 1.16$ as in DTE1 discharge 43015 [2,5]. In (b) $P_{ICRF} = 15$ MW and $T_e = 9$ keV.

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. 2a). In spite of this, the multiple frequency scheme gives somewhat better ion heating (Fig 2b) 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 ^3He in the plasma improves collisional ion heating P_{ci} significantly. The main reason for the improved P_{ci} is dominant ^3He absorption at the fundamental ^3He resonance together with the high critical energy of the ^3He ions. At $n_e = 5 \times 10^{19} \text{ m}^{-3}$ and $B =$

3.9 T, ^3He minority heating is found to give a high bulk ion heating fraction of 66% with $n_{\text{He}}/n_e = 6\%$ when 75, 10 and 15% of ICRF power (15 MW) is applied at 35.5, 37.3 and 39 MHz, respectively. As n_e is decreased, P_{ci} decreases for $P_{\text{ICRF}} \geq 10$ MW due to acceleration of ^3He ions to energies above the critical energy (Fig. 3a). The optimal power distribution among the different frequencies (and resonance locations) depends on the ^3He concentration (Fig. 3b). 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 ^3He ions at their optimal values for bulk ion heating.

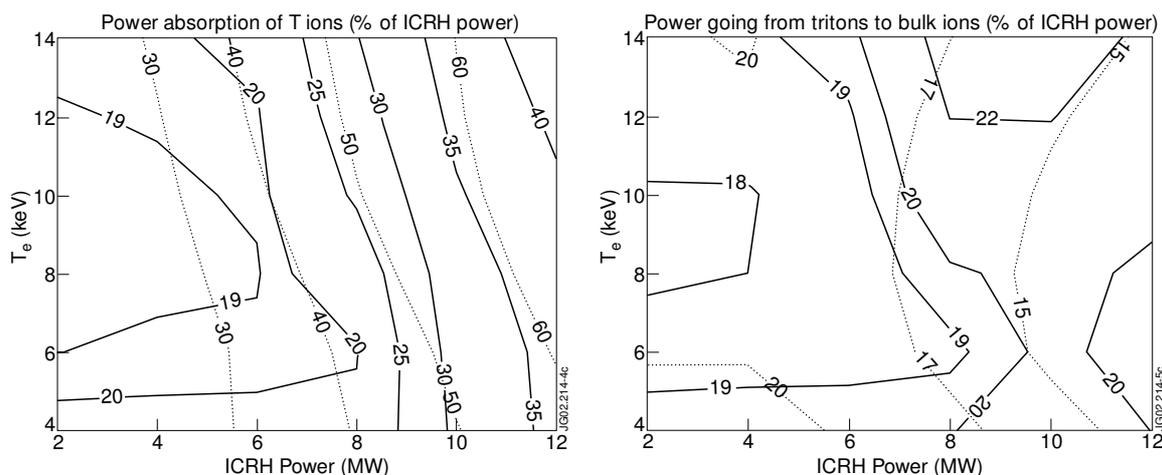


Figure 2 Contour plot of the fraction (%) of (a) ICRF power absorbed by tritons and (b) ion heating as function of P_{ICRF} and T_e for second harmonic heating of tritons using the optimised multiple frequency scheme (solid, cf. Table 1) and a single frequency scheme (dotted). Here, $n = 6.3 \times 10^{19} \text{ m}^{-3}$ and $T_e / T_i = 1.3$ as in DTE1 discharge 42753 [2,5].

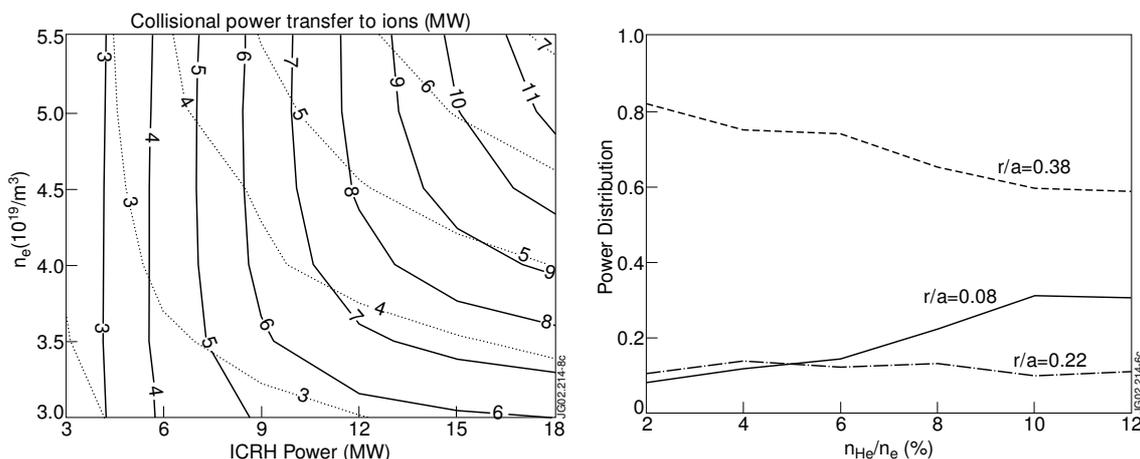


Figure 3 (a) Contour plot of collisional ion heating for ^3He minority heating with $n_{\text{He}}/n_e = 6\%$ using the optimised multiple frequency scheme (solid, cf. Table 1) and a single frequency scheme (dotted). (b) Power distribution among different ICRF resonance locations giving the strongest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

Hydrogen minority heating in DT plasma Due to their lower mass, protons have a lower critical energy compared to ^3He 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 ^3He minority heating, a lower power per particle is required. The highest ion heating fraction of about 50% is obtained with a high hydrogen concentration $n_{\text{H}}/n_{\text{e}}$ 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.

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

Scenario/ Parameter	(D)T	$\omega=2\omega_{\text{cT}}$	(^3He)DT	(H)DT
B (T)	3.7	3.8	3.9	3.5
P_{ICRF} (MW)	15	10	15	15
$(R_{\text{res}}-R_0)/a$	0.4, 0.2, 0.0	0.3, 0.0, -0.25, -0.55	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
$P_{\text{ci}}/P_{\text{ICRF}}$ (%)	34	15	66	51
nonthermal Q	0.4	-	-	-

Conclusions and discussion The performance of ICRF heating scenarios for JET D-T plasmas is studied at coupled ICRF powers in excess of 10 MW. The main results are summarised in Table 1. Deuterium minority heating with $P_{\text{ICRF}} = 15$ MW gives the highest fusion reactivity, corresponding to $Q = P_{\text{fus}}/P_{\text{ICRF}} \approx 0.45$, and a relatively high bulk ion heating fraction of $\approx 35\%$. The highest bulk ion heating fraction of $\approx 65\%$ ($P_{\text{ci}} \approx 10$ MW) is obtained with ^3He minority heating using $n_{\text{He}}/n_{\text{e}} = 6\%$, 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% ($P_{\text{ci}} = 6-7.5$ MW) when multiple ICRF frequencies are used together with a relatively high hydrogen concentration of $n_{\text{H}}/n_{\text{e}} \approx 10-12\%$. In this case, however, the ICRF power deposition has to be spread further out than in the case of deuterium or ^3He 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 ^3He 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.

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

- [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.*, Nucl. Fusion 39 (1999) 337. [6] T.H. Stix, Plasma Phys. 14 (1972) 367.