ICRH physics for relevant schemes in D-T experiments at JET

D. Gallart[1], M.J. Mantsinen [1,2], E. Planas[1], J. Manyer[1], D.M.A. Taylor[3] and JET Contributors*

*EUROfusion Consortium, JET, Culham Science Centre, Abingdon, OX14 3DB, UK**

[1] *Barcelona Supercomputing Center, Barcelona, Spain*

[2] *ICREA, Barcelona, Spain*

[3] *CCFE, Culham Science Centre, Abingdon, OX14 3DB, UK*

Abstract We report on simulations aimed at optimizing external heating using neutral beam injection (NBI) and radiofrequency waves in the ion cyclotron range of frequencies (ICRF) for high fusion yield in the JET tokamak. In this paper, we perform a DT prediction using a record baseline discharge as a reference, which is analyzed taking into account the NBI+RF synergy. We focus on two different minority ICRF schemes, ^{3}He and H, respectively. These two ICRF schemes reach high performing conditions by different means. While the ^{3}He minority is a strong scheme for bulk ion heating, H is best for ICRF fusion enhancement via 2nd D harmonic heating. Both features are beneficial for boosting the neutron yield. However, their particular advantages strongly depend on the concentration of these minority ions. The main purpose of this study is to assess the concentration range at which both minority schemes can perform optimally regarding bulk ion heating and ICRF fusion enhancement, for ^{3}He and H, respectively. Our results show that under these conditions H concentration should remain below 2.2% as to maximize 2nd D harmonic heating and ^{3}He concentration should remain above 1.2% as to maximize bulk ion heating.

Introduction The Joint European Torus (JET) is preparing for its second deuterium-tritium (D-T) campaign (DTE2) [1]. This campaign will serve as a basis for the future ITER experiments. In this work, we focus on the plasma heating schemes in D-T. There are several schemes envisaged to operate during DTE2 such as D minority [2] and different three-ion schemes [3]. However, we focus on the H and ^{3}He minority schemes which are the workhorse RF schemes for the high-performance baseline and hybrid scenarios. From the heating point of view, there are mainly two ways to boost the neutron yield: either by increasing the bulk ion temperature or by developing a fast ion tail in D or T ions. Both minority schemes provide different ways to boost the fusion yield, while ^{3}He minority has a high critical energy which leads to high bulk ion heating (see equation 1), H minority is a good scheme for channeling the power to D ions (see equation 2). The object of this work is to evaluate the concentration range of the minority ions where their main features, i.e., bulk ion heating for ^{3}He and ICRF fusion enhancement

*See the author list of J. Mailloux et al.[1]

for H are optimized. For this we use the ICRF modelling code PION [4] coupled to the beam deposition code PENCIL [5] which take into account the ICRF+NBI synergy.

Basic concepts The critical energy is the energy at which fast ions transfer energy equally to background ions and electrons:

$$E_{crit} = 14.8 A T_e \left[\sum_j \frac{n_j Z_j^2}{n_e A_j} \right]^{\frac{2}{3}}. \quad (1)$$

Where A is the atomic mass of the resonant ions, Te the electron temperature and the sum goes over thermal species, where n_i is the ion density, Z_i the atomic number and n_e the electron density. The ICRF fusion enhancement is a measure of the impact of ICRF heating on the neutron production due to fast ions. The equation is the following:

$$\mathrm{RF}(\%) = \frac{\mathrm{R_{NT}(NBI+ICRF)} - \mathrm{R_{NT}(NBI)}}{\mathrm{R_{NT}(NBI+ICRF)}}. \quad (2)$$

Where $\mathrm{R_{NT}(NBI+ICRF)}$ is the neutron rate taking into account NBI and ICRF, while $\mathrm{R_{NT}(NBI)}$ only NBI. The critical energy, E_{crit}, is larger for the ^{3}He ions as compared to H, while the ICRF enhancement is typically larger in the H scheme as explained in [6].

Scenario parameters and validation We take an existing baseline JET high-performance shot (96482) as the starting point. The original plasma composition has been replaced by that of a 50%:50% D-T plasma and has been modelled with excellent agreement against the experimental data (figure 1).

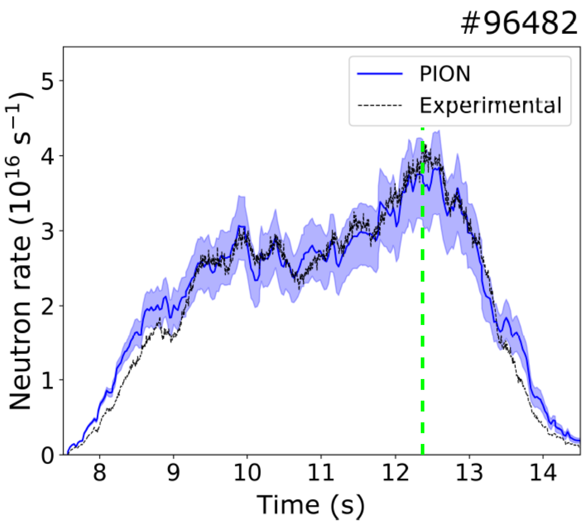

Figure 1: Experimental (black dotted) and model (blue solid) neutron rate for discharge 96482. The shaded area is the error assumed in the model due to error in the input data. The green line marks the time slice used to model the D-T prediction (t = 12.3s).

For the modelling we take the plasma parameters input from a time slice, t = 12.3s in this case, and proceed to find the steady state solution of the velocity distribution function of resonant ions. The ICRH schemes are H minority ($\omega = \omega_{cH} = 2\omega_{cD} = 3\omega_{cT}$) and ^{3}He minority ($\omega = \omega_{c^3He} = 2\omega_T$). The main modelling parameters are shown in Table 1.

Table 1: Main modelling parameters for discharge 96482.

Discharge	B_T	I_p	$n_e(0)$	$T_e(0)$	T_i/T_e	P_{ICRH}	P_{NBI}
96482	3.3T	3.5MA	$9.7\cdot10^{19}m^{-3}$	6.8keV	1.3	5MW	30MW

Results As shown in figure 2.a, ^{3}He is a strong absorber, leaving little energy to T as explained in [7], on the other hand, H minority scheme channels most of the ICRH power to 2nd D harmonic for concentrations of H below 2.2%. This power channeling to 2nd D harmonic develops a strong tail in the D velocity distribution (figure 3.b) which boosts the neutron yield (figure 3.a).

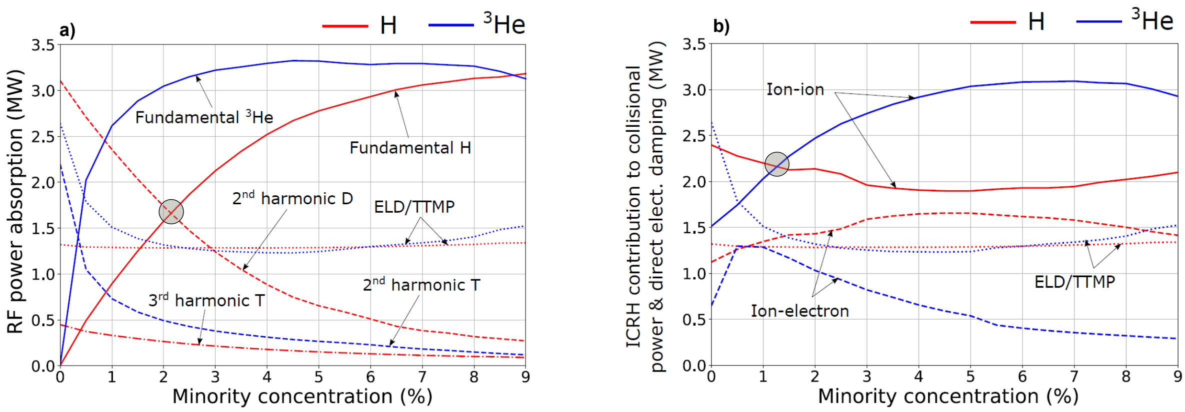

Figure 2: a) Power absorption in H and ^{3}He schemes in a D-T plasma predicted from discharge 96482. The dot marks the H concentration where H and D absortpion is equal. b) ICRH collisional power transfer from resonant ions in ^{3}He and H schemes in a D-T plasma predicted from discharge 96482. The dot marks the ^{3}He concentration where bulk ion heating is equal with the H scheme.

Figure 2.b shows the ICRH collisional power from resonant ions to background ions and electrons. Notice that ^{3}He relies solely on bulk ion heating to boost fusion yield and it cannot provide a higher bulk ion heating as compared to H below a concentration of 1.2%. The ICRF fusion enhancement that this scheme provides is not strong (figure 3.a) as ^{3}He absorbs almost all the power of the wave which avoids the formation of a strong tail in the T velocity distribution (figure 3.b). Therefore, it needs to remain above this concentration value.

Regardless of the predicted fusion power (~12MW, figure 3.a), this study has focused rather on the physics of the two tackled schemes. Notice the large separation between the NBI+ICRH and NBI simulations for H. This indicates a strong ICRF fusion enhancement while in the ^{3}He scheme there is almost no difference except for small ^{3}He concentrations where the power channeled to T is not negligible. Bear in mind that these simulations are interpretive and, therefore, the potential increase of ion temperature, T_i, in the ^{3}He scheme is not accounted for. Taking this into account, these simulations are probably showing a lower threshold of the neutron yield for the ^{3}He scheme.

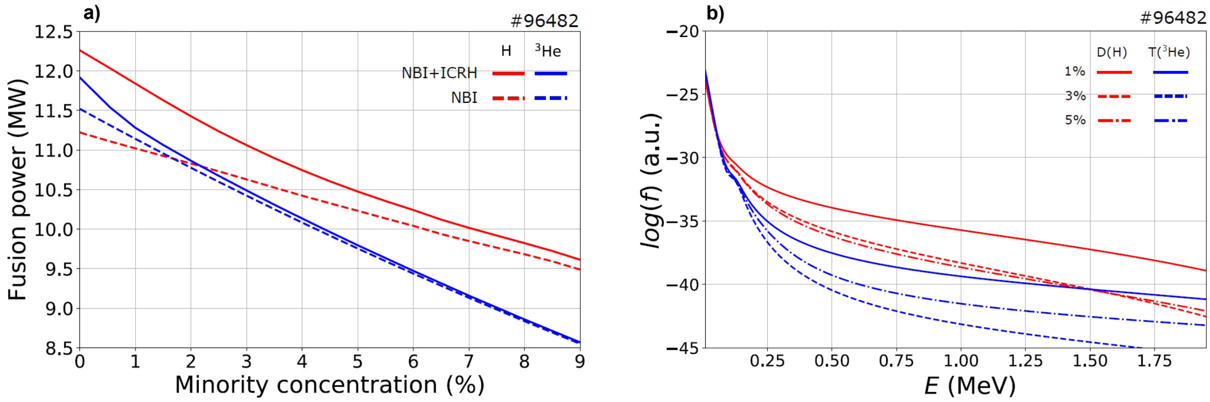

Figure 3: a) Predicted fusion power for H (red) and ^{3}He (blue) minority schemes. b) $\log(f_{res}(v))$ of resonant D (red) in H minority and T (blue) in ^{3}He minority, at different minority concentrations.

Conclusions In this work we tackled the range of minority concentration for H and ^{3}He that leverages their main features. Under the conditions explored in this scenario:

- H concentration should remain below 2.2% as to maximize 2nd D harmonic heating.
- ^{3}He concentration should remain above 1.2% as to maximize bulk ion heating.

Fusion power prediction shows strong ICRH fusion enhancement in the H scenario, as expected. The maximum obtained is roughly 12MW which is in line with other modelling efforts.

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