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Modelling of combined ICRF and NBI heating in JET hybrid plasmas

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Abstract. During the 2015-2016 JET campaigns many efforts have been devoted to the exploration of high performance plasma scenarios envisaged for ITER operation. In this paper we model the combined ICRF+NBI heating in selected key hybrid discharges using PION. The antenna frequency was tuned to match the cyclotron frequency of minority hydrogen (H) at the center of the tokamak coinciding with the second harmonic cyclotron resonance of deuterium. The modelling takes into account the synergy between ICRF and NBI heating through the second harmonic cyclotron resonance of deuterium beam ions which allows us to assess its impact on the neutron rate R_{NT}. We evaluate the influence of H concentration which was varied in different discharges in order to test their role in the heating performance. According to our modelling, the ICRF enhancement of R_{NT} increases by decreasing the H concentration which increases the ICRF power absorbed by deuterons. We find that in the recent hybrid discharges this ICRF enhancement was in the range of 10-25%. Finally, we extrapolate the results to D-T and find that the best performing hybrid discharges correspond to an equivalent fusion power of ~7.0 MW in D-T.

1 Introduction

During the 2015-2016 JET campaigns many efforts have been devoted to the exploration of high performance plasma scenarios envisaged for ITER operation [1]. The inductive (baseline) scenario and the hybrid scenario have shown major improvements during these campaigns surpassing the previous ITER-like-wall fusion record of 2.3x1016 n/s, thus showing good progress towards demonstrating the fusion rate needed for DT (milestone for DT-ready plasma is 5×10^{16} n/s). The hybrid scenario reached with 33 MW of combined ICRF and NBI power a record neutron rate R_{NT} of 2.9×10^{16} n/s. Experimental results related to optimizing the use of ICRF waves in the hybrid scenario including the discharge time-behaviour are given in [2,3].

We report on simulations aimed at modelling of combined NBI and ICRF heating for high fusion yield in these recent hybrid discharges. We evaluate the performance of H minority heating in the presence of D beam ions using the ICRF modelling code PION [4] coupled to the beam deposition code PENCIL [5]. Our modelling takes into account the synergy between ICRF and NBI heating through the second harmonic cyclotron resonance of deuterium beam ions, which allows us to assess its impact on the fusion performance. We model a number of key discharges with H minority that were designed in order to evaluate key ICRF aspects as the

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avoidance of impurity accumulation with ICRF waves and its dependence on the ICRF resonance position, the ICRF fusion performance enhancement and the impact of H concentration on the ICRF damping mechanisms, i.e, the fundamental H resonance, the 2nd D hearmonic resonance and the direct electron damping. Finally, we model and extrapolate a record discharge to a 50:50 DT fuel mixture.

2 Resonance position scan for ICRF impurity control

Dedicated discharges were carried out to assess the dependence of ICRF impurity control on the ICRF resonance position in hybrid plasmas. In these five discharges up to 5 MW of ICRF power at a frequency of 42 MHz and up to 25 MW of NBI power were used. The magnetic field B_T was modified for each discharge and, therefore, the ICRF resonance was located at different major radii ranging from the high-field-side to the low-field-side. The main plasma parameters were the same for each discharge; see Ref. 2 for more details on the experimental setup and results.

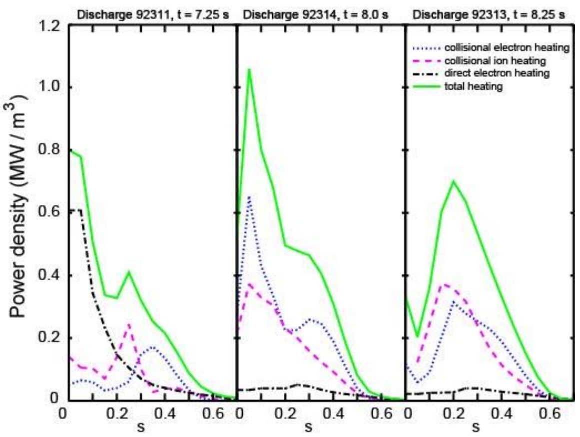

Fig 1. The radial profiles of the collisional ion heating, collisional electron heating and direct electron heating due to ICRF waves as given by PION for discharges 92311, 92314 and 92313 with a HFS, central and LFS ICRF resonance, respectively. Here, s is the square-root of the normalised poloidal flux and the profiles are shown after 1.75 s from the start of the main heating.

Figure 1 shows the radial profiles of the collisional ion heating, collisional electron heating and direct electron heating due to ICRF waves as given by PION for discharges 92311, 92314 and 92313 with a HFS, central and LFS ICRF resonance, respectively. The profiles are shown after 1.75 s from the start of the main heating.The maximum bulk ion heating is located at s ≈ 0.25 for the discharges with an off-axis resonance, where s is the square-root of the normalised poloidal flux. According to PION, direct electron damping becomes dominant in the plasma core for HFS heating (92311) while is almost negligible for LFS heating (92313) and central heating (92314). Nevertheless, this discharge as the other discharge with an off-axis resonance $|R_{res} - R_0| > 15$cm suffered impurity accumulation unlike the discharge with a central resonance, giving rise to overall better central heating [2].

3 Hydrogen concentration scan

A set of discharges were carried out to assess the impact of the H concentration on the ICRF heating and fusion performance. These discharges were prepared in the same way except for the different H concentration, see Table 1 [3]. Here, we quote the H concentration $n_H/(n_H+n_D)$ as deduced from the ratio of the D_α and H_α light collected along lines of sight through the plasma. Penning gauge spectroscopy in the divertor gave somewhat higher $n_H/(n_H+n_D)$ of 3-4%. According to our modelling, however, the experimental results are more consistent with the values deduced from the D_α and H_α light. Note that only a few percent of hydrogen is used and there is only a small difference between the hydrogen concentration between the discharges but it is large enough to have an impact in the way plasma damps the ICRF wave energy and consequently, the plasma performance.

Table 1. The H concentration for discharges in the H concentration scan.

	92321	92322	92323
$n_H/(n_H+n_D)$ (%)	~2.0	~1.5	~3.0

As in the previous case, ICRF power was applied with a central $\omega = \omega_{cH} = 2\omega_{cD}$ resonance. Figure 2 shows the impact of H concentration on the power partition between the H and D ions at t = 11.5 s during the main heating phase. In first order, the ratio of H to D damping scales roughly as $n_H/(n_H+n_D)$, as expected. Typically, for this ICRF scenario, the hydrogen minority is the main absorber at low plasma densities and temperatures that take place during the ramp up. Once the deuterium beams are injected and the plasma gets hotter, damping by resonant D ions becomes the main damping mechanism in the plasma core. As the H concentration decreased from ~3% to ~1.5%, D damping increased from 35 % to 50% and H damping decreased from 55% to 40%, while direct electron damping stayed roughly the same, i.e. 10%, of the total ICRF power.

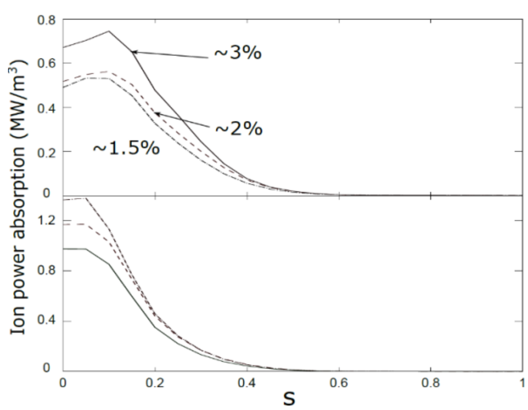

Fig 2. ICRF ion power absorption profile for fundamental H (top) and 2nd D harmonic resonance (bottom) at t = 11.5 s.

The second harmonic D damping has an advantageous effect on the fusion yield. This is due to the fact that an energetic tail develops in the D distribution function, which enhances the fusion yield. Figure 3 shows the simulated neutron rates for the three discharges which are consistent with the measured neutron rates [2]. The difference between the discharge with the lowest H concentration and the discharge with the highest concentration is about 10-25% which is in good agreement with the experimental results.

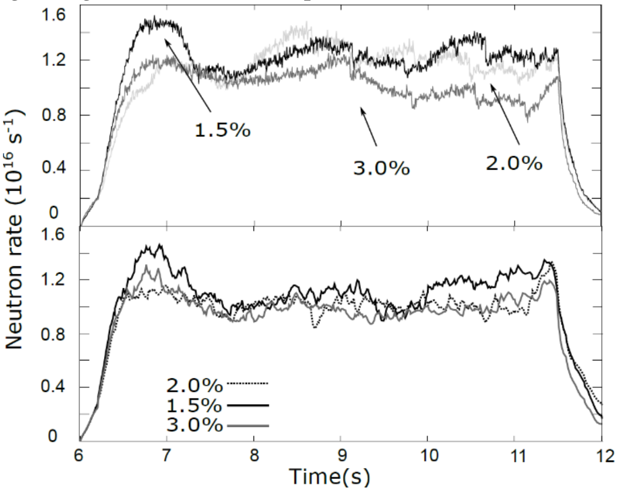

Fig 3. Comparison of experimental neutron emission rate (top) and modelled neutron emission rate (bottom) of the H scan discharges.

4 High-performance hybrid discharge

One of the main goals of the recent experiments with hybrid plasmas was to improve the fusion performance with respect to the previous neutron rate record of 2.3x10^{16} n/s. Here, we analyse one of the best discharges, i.e. 2.8 T/2.2 MA discharge 92398. In this discharge the ICRF antenna frequency was 42.5 MHz and 5 MW of ICRF power was applied tuned to a central fundamental H and second D harmonic resonance. Together with deuterium NBI power of 26 MW, the total external heating power was 31 MW. For more details on the experimental scenario see Ref. [2].

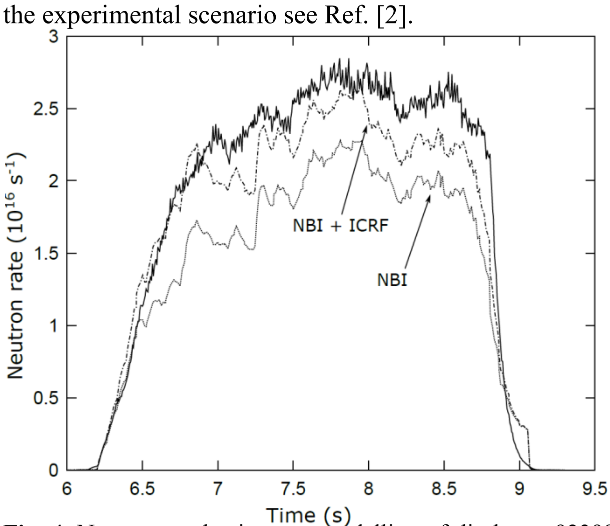

Fig. 4. Neutron production rate modelling of discharge 92398 with ICRF and without ICRF.

The experimental and modelled neutron rates are shown in Fig. 4. In these simulations, we have used a Ti/Te ratio deduced from the X-ray crystal spectroscopy data. This data suggests that the Ti/Te ratio is around 1.25-1.6. Here, we apply the H concentration (~2.0%) $n_H/(n_H+n_D)$ as deduced from the ratio of the D_α and H_α light collected along lines of sight through the plasma. Figure 4 shows good agreement between the modelled and the experimental neutron yield. However, there are uncertainties in the prediction of the neutron yield due to uncertainties in some of the measured quantities such as the impurity content, with impact on dilution and uncertainties in the Ti measurement. Figure 4 also shows the modelled neutron rate evaluated with no ICRF heating while keeping all the other parameters exactly the same. The difference between the modelled neutron rates with and without ICRF power allows us to estimate the ICRF enhancement of the neutron rate (Fig.5).

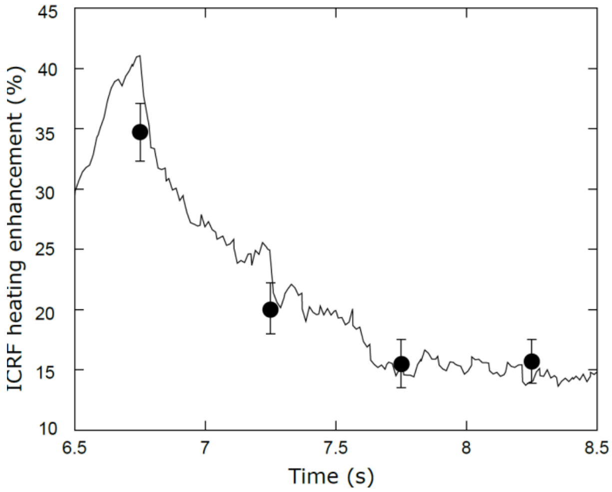

Fig. 5. ICRF enhancement of neutron yield for discharge 92398. Comparison of PION (solid line) and experimental results based on TOFOR (black dots) measurements.

As we can see, this enhancement is of the order of 30-15% and decreases in time. The reason of this decrease in time is due to the increasing temperature and density. The neutron emission from NBI increases with these parameters reducing the impact of ICRF in the neutron yield. These results are in good agreement with the ICRF enhancement estimated from a spectroscopic analysis of data collected with the neutron time-of-flight spectrometer TOFOR.

Figure 6 shows ICRF power partitioning between the three ICRF wave power absorption mechanisms. The same ICRF physics prevail in this discharge as in the H concentration scan explained above. Fundamental H damping dominates during the ramp up and the 2nd D harmonic damping during the main heating phase.

The simulated collisional ion and electron heating as well as direct electon damping are shown in Fig. 7. As we can see, collisional ion heating is dominant through the discharge after the transient ramp-up phase where collisional electron heating dominates.

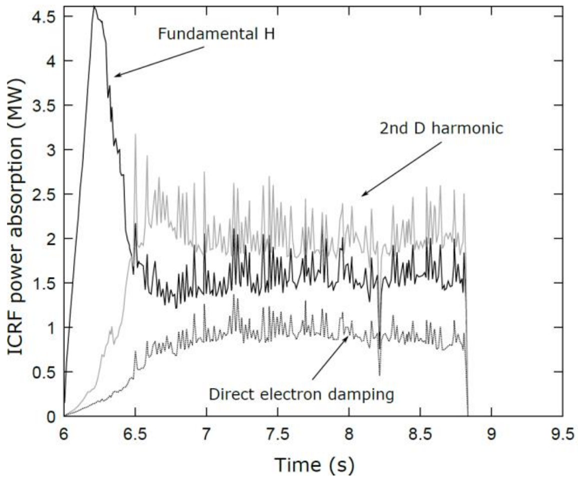

Fig. 6. ICRF power absorption mechanisms, fundamental H, 2nd D harmonic and direct electron damping for discharge 92398.

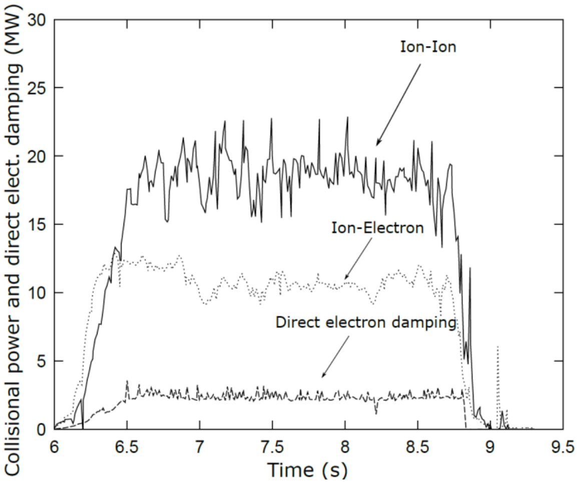

Fig. 7. Direct electron damping and collisional power transferred to ions and electrons from ion-ion collisions and io-electron collisions, respectively.

4.1 Predictions for D-T

For the prediction of the high-performance hybrid discharge 92398 to D-T, we have kept all the plasma parameters identical to those in the experiment. The only modification consisted of replacing half of the deuterium ions in the main plasma and in NBI by tritium, hence modelling a 50%:50% DT plasma.

In this scenario, the third T harmonic resonance is present in addition to the ICRF damping mechanisms discussed previously. The dominant mechanism is the second D harmonic once the beams are injected. However, as opposed to the D-D fusion reaction, the D-T reaction has an optimal energy at ~120 keV where its cross section peaks. Beyond this energy the cross section value drops drastically, and, therefore, if ICRF heating induces a high energy tail in the distribution function of the resonant particles it could eventually decrease the neutron production rate. In this analysis we took into account the same plasma density and ICRF power output as in the experiment and, thus, we have not assessed how the ICRF performance could be optimised, for more details see [6].

The resulting ICRF enhancement of the neutron rate is about ~5% in D-T and thus lower than that in the D-D. This is because the D beams have an energy around 100 keV which is close to the optimal energy for D-T fusion reactions to occur. Therefore, almost all fusion reactions are produced through NBI. According to our prediction, the equivalent D-T fusion power is about 7 MW.

5 Conclusions and further steps

The development of the hybrid plasma scenario has progressed significantly in the recent JET campaign. A higher neutron emission rate and extended duration has been achieved with regards to the previous ILW neutron record.

A number of key topics have been modelled and analysed in this paper, such as the impurity control using ICRF waves, the impact of H minority concentration on the ICRF performance and the ICRF properties and neutron yield enhancement of a high performance hybrid discharge in addition to its D-T prediction. The final conclusions are that heating with ICRF waves centrally has shown to be beneficial in order to avoid impurity accumulation while heating further away from the centre can cause impurity accumulation in some cases. Low H minority concentration tends to make 2nd D resonance more dominant with an advantageous effect in the fusion yield. Finally, the ICRF enhancement in the neutron yield of the high performance discharge has demonstrated to be relevant while in the D-T prediction its importance is diminished.

From the experimental point of view, using ^{3}He minority scheme instead of H minority may be beneficial, as modelling predicts improved bulk ion heating and improved fusion performance with ^{3}He minority heating as compared to H minority heating [1,6].

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