Modelling of three-ion ICRF schemes with PION

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Introduction
ICRF heating is one of the three auxiliary heating methods planned for ITER. First ITER plasmas with ICRF heating are foreseen for its non-active phase of operation. A detailed assessment of ICRF schemes available in this phase was recently carried out [1]. As a result, the ICRF schemes considered for ITER include the so-called three-ion ICRF heating schemes in addition to the standard minority and majority ion heating schemes. Over the past few years, such three-ion ICRF schemes have been a focus of intensive research from the theoretical, numerical and experimental point of view [2]. In the present work, we analyse discharges carried out with D-(D_{NBI})-H and D-(^3He)-H three-ion ICRF schemes on JET and ASDEX Upgrade tokamaks using the ICRF modelling code PION [3].

PION code
PION computes the time-evolution of ICRF power absorption and the distribution functions of the resonant ions in a self-consistent way [3]. It has been extensively compared against experimental data for a large variety of minority and majority ion heating schemes on JET, AUG, DIII-D and Tore Supra. It is based on simplified models, which makes it relatively fast. Thanks to its speed, it forms a part of the automated data processing chain at JET, and it is being installed in the ITER Integrated Modelling and Analysis Suite (IMAS) for the use in integrated predictive modelling of ITER plasmas. First results from PION modelling of ICRF heating in the non-activated phase of ITER are reported in [4].

PION modelling of D-(D_{NBI})-H scheme in JET
We have analysed 2.9T/2MA hydrogen-rich L-mode discharge 91256 carried out in JET with D-(D_{NBI})-H ICRF scheme [2] with PION. In this discharge, up to 2.5 MW of ICRF power was applied using dipole phasing at a frequency of 25 MHz, aligning the Doppler shifted fundamental resonance of D NBI
particles with a maximum injection energy of 100 keV in the region of the enhanced wave field $|E|^2$ in the vicinity of the ion-ion hybrid layer of D and H ions. The main plasma parameters are shown in Fig. 1. The discharge has three different phases of applied ICRF to D NBI power: NBI-only phase and two phases with a varied $P_{ICRF}/P_{NBI}$ ratio, one with $P_{ICRF}/P_{NBI} = 0.7$ and the other with $P_{ICRF}/P_{NBI} = 0.3$. As can be seen in Fig.1, the central electron temperature, sawtooth-free period, neutron rate and gamma ray emission are greatly enhanced when ICRF power was applied. Moreover, their enhancements depend on $P_{ICRF}/P_{NBI}$.

According to PION, using measured data as input, damping of ICRF power by D is about 2 MW with $P_{ICRF}/P_{NBI}$ of 0.7 and it drops to 0.2-0.4 MW with $P_{ICRF}/P_{NBI}$ of 0.3. The rest of the ICRF power is absorbed by electrons. As a result of the absorption of wave power by resonant D ions, PION predicts that a high-energy tail forms in the distribution of resonant D ions, which is confirmed by multiple diagnostics measuring deuterons up to 1.5 MeV [2]. The effective D ion tail temperature $T_{eff,D}$ as given by PION is up to about 150 keV at $t = 11$ s, which is in good agreement with $T_{eff,D}$ of 180 and 140 keV as measured with high-energy neutral particle analyser and as calculated by TRANSP code [5], respectively. The magnitude and the time evolution of the total neutron rate together with its radial profile as given by PION agree with those measured as shown in Figs 2 and 3, respectively. Sensitivity analysis of our results with respect to the input data will be presented elsewhere.
Figure 3 The measured radial profile of the neutron yield together with that calculated by PION.

**PION modelling of D-(³He)-H scheme in AUG** We have analysed two AUG discharges with D-(³He)-H scheme [2] using the PION code. The first discharge was carried out at 2.8T and 0.8MA with \( n_{\text{H}}/(n_{\text{H}}+n_{\text{D}}) \) of 70-80\% and \( n(\text{³He})/n_e \) of 0.5-1\%. The ICRF frequency was 30MHz which placed the \(^3\text{He}\) minority resonance off-axis at a normalized minor radius of \( r/a \approx 0.3 \) on the high field side in the region of enhanced \(|E_i|^2\) at the ion-ion hybrid resonance layer of D and H ions. According to PION, about 85\% of the ICRF power was absorbed by \(^3\text{He}\) ions, and the rest is damped by electrons. Figure 4 shows the measured CX intensity in comparison with the predicted one, obtained using PION distribution functions assuming \( n(\text{³He})/n_e = 0.6\% \) plotted as a function of the \(^3\text{He}\) ion energy along the CX line-of-sight, at three ICRF power levels at the normalized minor radius of the ICRF resonance. For more details on CX measurements and forward-modelling, see [6]. The forward-modelled CX intensities depend strongly on the assumed \( n(\text{³He})/n_e \); our results suggest that \( n(\text{³He})/n_e \) was in the range of 0.4-0.6\% at the ICRF resonance location. At more central radial locations, the experimental CX intensities are somewhat stronger (not shown in Fig. 4), which is likely due to the simplifications in the way PION takes into account the finite-orbit-width effects. Wave-induced radial transport of resonant fast ions [7], which is not included in PION, may also play a role.

The other AUG discharge with the D-(³He)-H scheme that we have analysed with PION is discharge 34695 carried out at 3T and 0.8 MA using the ICRF frequency of 30 MHz and dipole phasing. In this discharge the \(^3\text{He}\) minority resonance coincided with the region of
strong wave field in the vicinity of the ion-ion hybrid resonance layer located on-axis. A 50-ms long pulse of $^3$He gas puffing was applied, which resulted in a sudden increase in the $^3$He concentration, with a concomitant increase of the sawtooth-free period and a decrease of the measured fast ion losses as shown in Fig. 5. According to PION, the increase in the $^3$He concentration improved the confinement of ICRF-accelerated $^3$He ions due to a decrease in the power per resonant $^3$He ion and, thereby, in their energy. The time-behaviour of the measured fast ion losses follows that of the first orbit losses given by PION (c.f. Fig. 6).

Conclusions Despite its relatively simple physics model [3], PION reproduces the main features observed in the experiments using three-ion ICRF schemes on JET and AUG. They include strong ion cyclotron damping by third ion species despite their low concentration, strong ICRF acceleration of resonant ions into the MeV range, and the dependence of confined and lost resonant ions distribution functions on experimental parameters. The results increase our confidence in using PION for predictive simulations of future experiments using such schemes as those planned in the JET D-T campaign and ITER.

Acknowledgements This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 and 2019-2020 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.