Modelling of three-ion ICRF schemes with PION

M.J. Mantsinen[1,2], Ye. O. Kazakov[3], V. Bobkov[4], T. Craciunescu[5],
D. Gallart[1], L. Giacomelli[6], A. Kappatou[4], M. Nocente[7,8], M. Weiland[4],
JET Contributors*, the EUROfusion MST1 Team** and the ASDEX Upgrade Team

[1] Barcelona Supercomputing Center, Barcelona, Spain
[2] ICREA, Barcelona, Spain
[3] Laboratory for Plasma Physics, LPP-ERM/KMS, Brussels, Belgium
[4] Max-Planck-Institut fur Plasmaphysik, Garching, Germany
[5] National Institute for Laser, Plasma and Radiation Physics, Magurele-Bucharest, Romania
[6] Istituto di Fisica del Plasma "P. Caldirola" (IFP-CNR), 20125 Milan, Italy
[7] Dipartimento di Fisica "G. Occhialini", Università di Milano-Bicocca, Milan, Italy
[8] Institute for Plasma Science and Technology, National Research Council, Milan, Italy
**See the author list of E. Joffrin et al., accepted for publication in Nucl. Fusion Special issue 2019, https://doi.org/10.1088/1741-4326/ab2276.*
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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-(^{3}He)-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}.

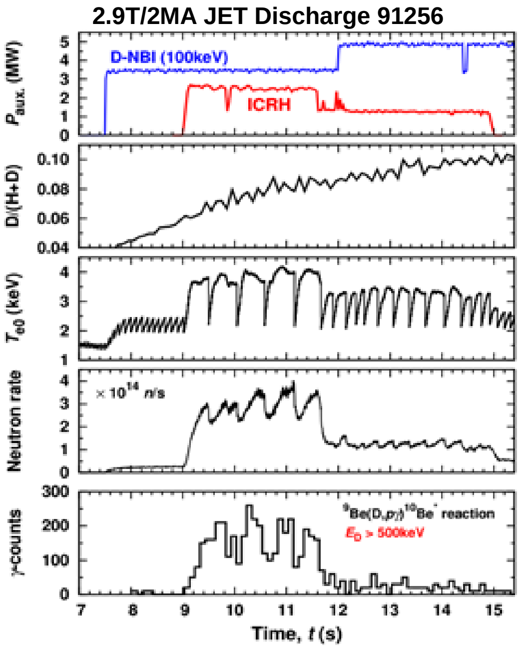

Figure 1 Main plasma parameters for JET discharge 91256 with D-(D_{NBI})-H ICRF scheme.

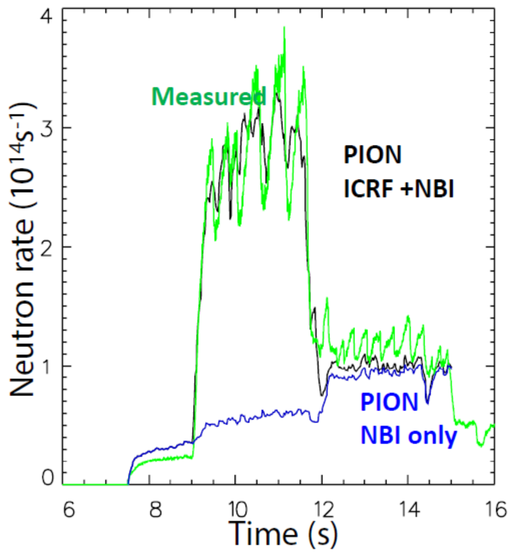

Figure 2 Neutron rate as given by PION together with the measured neutron rate for JET discharge 91256. The neutron rate as calculated by PION without including ICRF in the simulation is also shown.

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.

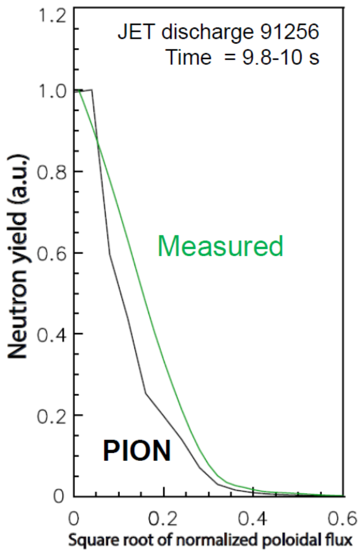

Figure 3 The measured radial profile of the neutron yield together with that calculated by PION.

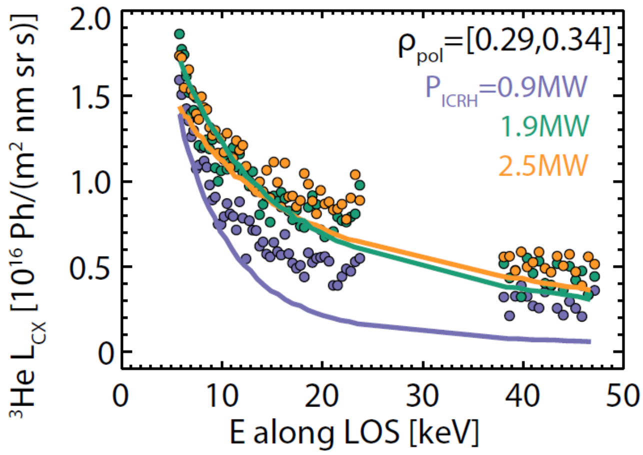

Figure 4 Measured (circles) CX intensity, together with the predicted CX intensity (lines) obtained using the method outlined in [6] and PION distribution functions calculated assuming $n(^3He)/n_e$=0.6% for three ICRF power levels in AUG discharge 34704, plotted as a function of the ^{3}He ion energy projected along the CX line-of-sight at $\rho_{pol}\approx 0.3$.

PION modelling of D-(^{3}He)-H scheme in AUG We have analysed two AUG discharges with D-(^{3}He)-H scheme [2] using the PION code. The first discharge was carried out at 2.8T and 0.8MA with $n_H/(n_H+n_D)$ of 70-80% and $n(^3He)/n_e$ of 0.5-1%. The ICRF frequency was 30MHz which placed the ^{3}He minority resonance off-axis at a normalized minor radius of r/a ≈ 0.3 on the high field side in the region of enhanced $|E_+|^2$ 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}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 $n(^3He)/n_e$ = 0.6% plotted as a function of the ^{3}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 $n(^3He)/n_e$; our results suggest that $n(^3He)/n_e$ 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-(^{3}He)-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}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 concomintant 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.

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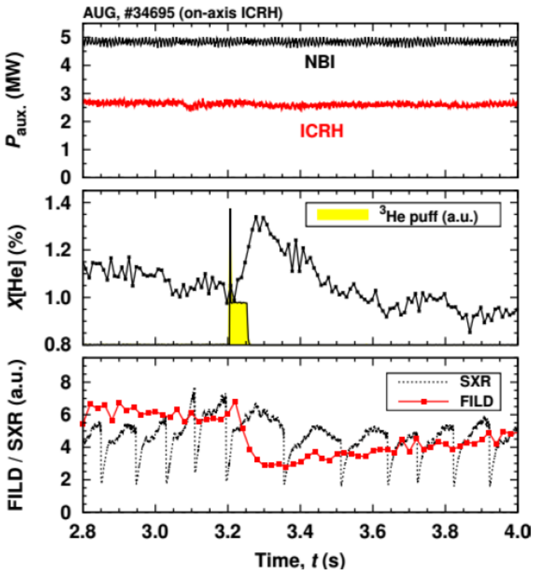

Figure 5 Main parameters of AUG discharge 34695 heated with D-(^{3}He)-H scheme.

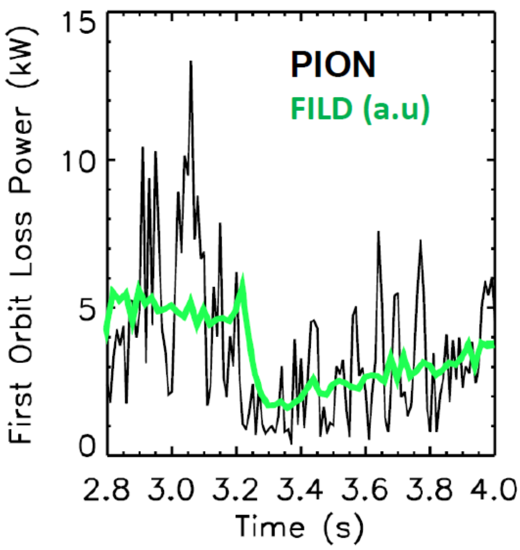

Figure 6 First orbit loss power due to fast ^{3}He ions as given by PION for AUG discharge 34695. Measured fast ion losses (in a.u.) are also shown.

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