

# Recent key contributions of ICRF heating in support of plasma scenario development and fast ion studies on JET and ASDEX Upgrade

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Ion Cyclotron Resonance Frequency (ICRF) heating plays an important role in many present day experiments and it is one of the auxiliary heating methods that will be used in ITER. In this contribution, we will review the recent key ICRF results from the JET and ASDEX Upgrade (AUG) tokamaks in preparation of ITER.

In the recent JET campaigns, the focus has been in the preparation of integrated scenarios for high fusion performance with long duration ( $P_{fus}=15\text{MW}$  for 5s) (1) and alpha physics (2) in the forthcoming campaign with deuterium-tritium (D-T) fuel mixture. Following the successful earlier characterization and optimization of hydrogen minority heating for the use in JET scenario plasmas (3), the new developments include the integration of He-3 minority heating in high-performance D plasmas for improved bulk ion heating compatible with the control of central high-Z impurity accumulation in the presence of the ITER-like metallic wall. With He-3 minority heating, the best plasma performance in terms of the neutron rate and plasma energy content was obtained at a low He-3 concentration of ~2%. The resulting modest He-3 consumption is advantageous in light of lower operational cost when using He-3 minority heating in ITER. It is also well in line with earlier computational multi-code work (4) for ITER where good absorption performance with a He-3 concentration of ~3% was found. In the coming JET campaigns, which will include a campaign with tritium and D-T plasmas, these experiments will be extended to the studies of He-3 minority heating and second harmonic heating of tritium, which are the two main ICRF heating schemes planned for ITER full-field operation in 50%-50% D-T plasmas. Further ICRF options for JET D-T campaign are discussed following a recent review (5).

On AUG, novel applications of ICRF waves for plasma heating have become possible through the improved operating space of ICRF system and, in particular, its extended frequency range (6). It has allowed the application of second harmonic heating of hydrogen on AUG for improved core electron heating in the ITER-baseline-like plasmas with pure wave heating (i.e. without NBI-induced torque to simulate ITER burning plasma conditions) (7). The extended frequency range has also been instrumental for the experiments using third harmonic ICRF heating of NBI-injected deuterons for fast ion studies and for further development of fast ion and neutron diagnostics. Figure 1 shows a typical discharge with a more than two-fold increase of the D-D fusion rate due to ICRF-accelerated deuterons achieved with this scheme in AUG. As a continuation of the very successful earlier experiments with this scheme on JET (8), this ICRF development on AUG has provided for the first time a means for simultaneous controlled variations and measurements of both the confined and the non-confined parts of ICRF-driven fast deuterium distribution. Furthermore, analysis and modeling of JET and AUG experiments in D, H-D, H-He-4 and D-He-4 plasmas heated with He-3 minority heating and the so-called three-ion ICRF schemes (9) have provided improved insights on core ICRF physics as well as nonlinear electromagnetic stabilization of ion temperature gradient (ITG) modes by fast ions (10,11).

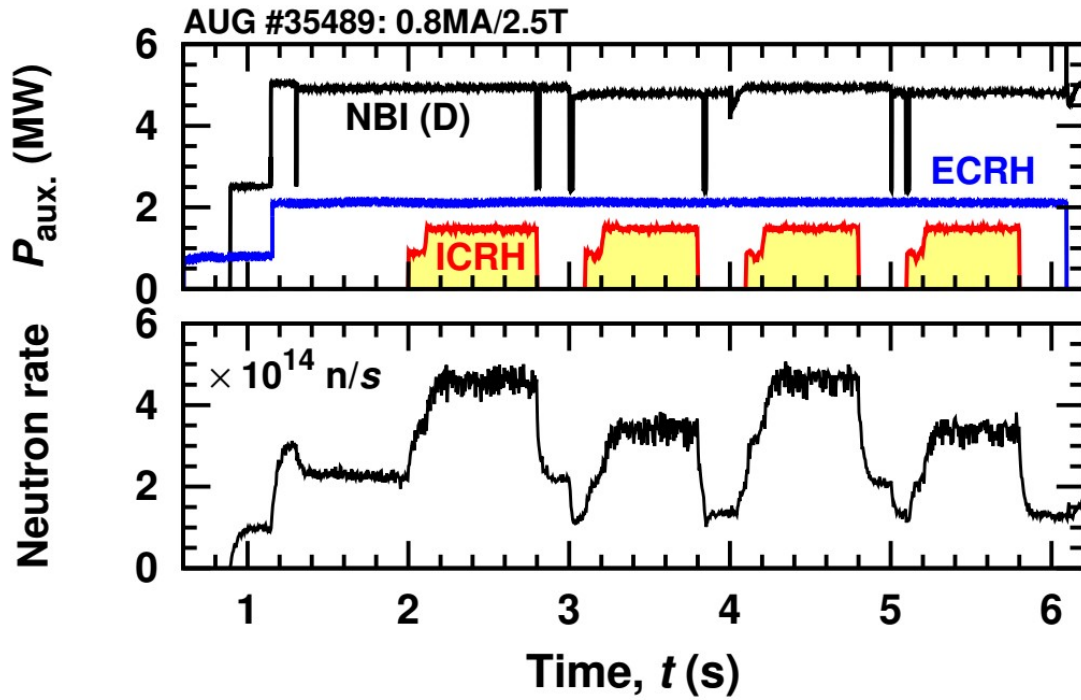


Figure 1: Time evolution of the neutron rate in 2.5T/800kA AUG discharge 35489 with pulses of ICRF power (red) tuned to central third harmonic resonance of D-NBI ions. ECRF power (blue) and NBI power (black) are virtually constant while NBI injectors with different injection energies (93keV and 60keV) are used.

The rich variety of new ICRF scenarios in various plasma scenarios (H-mode and improved confinement regimes) in the two devices of different sizes has formed a challenging test bed for the validation of numerous modelling tools. We will discuss some representative examples from the comparisons of experimental results with the ICRF modelling code PION (12). PION computes the ICRF power absorption and the distribution functions of the resonant ions in a self-consistent way. Thanks to its speed, it forms a part of the automated data processing chain at JET, and has recently been installed in the ITER Integrated Modelling and Analysis Suite (IMAS) for integrated predictive modelling of ITER.

Despite its relatively simple physics model, we find that PION reproduces successfully many features observed in the recent ICRF experiments on JET and AUG. For example, in the case of modelling the novel three-ion-schemes, it reproduces the strong ion cyclotron damping by third ion species despite its 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 (13). Our results increase our confidence in the applications of PION such as those reported in (14, 15) for predictive simulations of future experiments planned in the JET D-T campaign and ITER.

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