Progress with 3-ion ICRF schemes on ASDEX Upgrade and JET in support of ITER operations

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Reaching ELMy H-mode and developing ELM control techniques are one of the main priorities for the non-active ITER phase [1]. In JET-ILW, introduction of a small amount of ^{4}He ions (~ 10%) in hydrogen plasmas led to a significant reduction of the H-mode power threshold [2]. This motivated the ITER team to consider using H-^{4}He plasmas to widen the H-mode operational space in predominantly hydrogen plasmas [3]. Equally important, this mix also allows to apply the 3-ion ICRF scheme [4] with off-axis heating of ^{3}He minority ions (< 1%), as proposed in [5], capable of additionally delivering up to 20 MW of heating power in H + 10% ^{4}He plasmas in ITER. The ITER-relevant heating scenario using NBI, ECRF and off-axis ^{3}He ICRF was successfully demonstrated on ASDEX Upgrade (AUG) for the first time. A ramp of ICRF power using the 3-ion scheme was applied to trigger L-H transitions in H-^{4}He plasmas (2.5T/0.8MA). A mix of different heating systems was used to enter H-mode on AUG, including NBI+ECRH+ICRF (as in ITER), ECRH+ICRF and ICRF-only. Similar to earlier observations in H-^{4}He plasmas with H-NBI and ECRH heating on AUG [6], L-H transitions were reached at $P_{LH} \approx$ 2-3MW ($n_{e0} \approx 4\times10^{19}$ m^{-3}). Another important result of our studies on AUG is the demonstration that the 3-ion ICRF scheme with off-axis ^{3}He heating is compatible with avoiding tungsten accumulation.

In JET, the 3-ion ICRF schemes tuned to generate MeV-range fast ions in the plasma core mimic the heating conditions expected in D-T plasmas in ITER. Recently, the 3-ion scheme was applied to accelerate fast NBI ions to higher energies with ICRF in mixed D-^{3}He plasmas, generating a population of fusion-born alpha particles ($E_\alpha \approx 3.6$ MeV). The reaction rate was sufficiently high (~10^{16} s^{-1}) to validate updated JET diagnostics for alpha measurements prior to DTE2. At the same time, these plasmas provide a test bed to elucidate the role of fast ions on microturbulence and clarify the possible impact of alpha particles in future ITER plasmas. The observation at JET that $T_i \approx T_e$ in plasmas with dominant fast-ion electron heating is very promising for ITER, and is in line with recent studies showing that alphas can significantly stabilize ITG turbulence and reduce heat transport in ITER [7].

The results of AUG and JET studies illustrate beautifully the synergy between experiments and modeling in this field of plasma physics [8, 9]. In particular, PION simulations highlighted that the ratio P_{ICRF} / P_{NBI} is a key parameter to control and tailor the fast-ion distribution generated by the 3-ion ICRF + NBI scheme [8]. In this way, this technique offers a path to accelerate fast D or T NBI ions to energies of ~100-200 keV in JET, allowing to optimize the D-T fusion rate and achieve high neutron rates at moderate input heating power. The reported progress increases our confidence in extrapolating the use of these novel ICRF schemes on existing fusion facilities and in ITER.

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