Application of three-ion species ICRH scenarios for ITER operation

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The application of heating and current drive scenarios, including ion cyclotron resonance heating (ICRH), has been recently reassessed for each of the four operational stages in the revised ITER schedule [1]. Recently, it has been shown that a small amount of minority particles injected into a two-ion plasma mixture can very efficiently absorb (nearly all) of the deposited RF power [2]. The application of these so-called three-ion species ICRH scenarios can be further extended to using impurity ions as part of the plasma mix or as resonant ions, as well as using beam ions as resonant species [3]. In this contribution, we give an overview of various three-ion ICRH scenarios that hold promise for ITER operations and also highlight their possible applications beyond heating.

1) Heating full-field H plasmas, including impurities with $(Z/A)_{imp} < 1/2$ such as ^{9}Be, ^{40}Ar and ^{22}Ne, with ^{4}He as absorbing species ($f \approx 40$ MHz) in the non-active phase. Since $(Z/A)_{\mathrm{imp}} < (Z/A)_{\mathrm{4He}} < (Z/A)_{\mathrm{H}}$, the optimal ^{4}He concentration for plasma heating depends strongly on the amount of intrinsic ^{9}Be impurities. In H-^{9}Be plasmas, wave absorption by the ^{4}He ions at very small concentrations is maximized at $n_{9Be}/n_e \approx 2\%$. Additional injection of Ar or ^{22}Ne impurities with a similar $(Z/A)_{\mathrm{imp}}$ as for ^{9}Be has been proposed for further optimizing wave polarization and depositing ICRH power to ^{4}He minority ions [4].

2) Heating H-^{4}He plasmas with ^{3}He as absorbing species in the non-active phase. This scenario relies on adding ~5–15% of ^{4}He ions into H plasma, and a tiny amount of ^{3}He ions (< 1%) to absorb RF power. For full-field ITER operation, central ^{3}He heating is achieved at $f \approx 54$ MHz. The advantages of this scheme in ITER include: i) more ICRH power is available at this frequency than at $f \approx 40$ MHz [5]; ii) reduction of the L-H power threshold by ~20% in H-^{4}He mixtures (w.r.t. H plasma) was reported in JET-ILW [6]. The lack of an efficient IC scenario at half-field ITER hydrogen plasmas also led to the proposal to apply off-axis ^{3}He heating in H-^{4}He plasmas at 3T and 3.3T [4]. Note that off-axis ^{3}He heating in equivalent H-D plasmas has been recently successfully shown in AUG experiments [7].

3) Bulk ion heating in D-T plasmas with ^{9}Be as absorbing species. The T-(^{9}Be)-D heating scheme can be exploited to enhance off-axis RF power absorption by ^{9}Be impurities in full-field D-T plasmas in ITER at $f \approx 40$ MHz. Due to their higher mass, ^{9}Be ions will effectively deposit absorbed RF power to bulk D and T ions via Coulomb collisions, a feature particularly attractive for a fusion reactor. This ICRH scenario is applicable for D:T=50:50 plasmas without the need to inject extra ions into the plasma (an intrinsic concentration $n_{9\mathrm{Be}}/n_{\mathrm{e}} < 1\%$ would be sufficient). Central plasma heating with ^{9}Be impurities requires somewhat lower RF frequencies, $f \approx 38$ MHz. Whether the ITER ICRH system can operate at this frequency without too strong power degradation still needs to be assessed.

4) Using NBI ions as resonant species for ICRH heating of mixture plasmas. Efficient ICRH heating of H-D plasmas with the fast injected deuterium NBI ions as resonant ‘third’ species was recently demonstrated on JET [3]. Those ions in the beam distribution that have a Doppler-shifted cyclotron resonance close to the ion-ion hybrid layer resonate with the excited fast wave and absorb RF power. The ITER NBI heating system foresees injection of H and D neutrals at energies 0.87 MeV and 1 MeV, respectively. This allows to exploit NBI+ICRH synergies using the ^{4}He-($\mathrm{H_{NBI}}$)-H heating scenario in ^{4}He-H plasmas [8]. In a similar way, deuterium NBI absorption can be further enhanced using the T-($\mathrm{D_{NBI}}$)-D scenario to contribute to efficient heating of D-T plasmas in ITER.

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