Application of three-ion species ICRH scenarios for ITER operations

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1. Introduction

Auxiliary plasma heating is essential for future fusion reactors in order to reach ion temperatures in excess of 100 million degrees necessary for the D-T fusion. The application of heating and current drive systems, including ion cyclotron resonance heating (ICRH), has been recently reassessed for the revised ITER schedule [1].

Recent theoretical and experimental developments of novel ICRH absorption schemes, hereafter referred to as ‘three-ion species scenarios’ [2, 3], have opened new promising routes for plasma heating in contemporary and future fusion devices. In its simplest form, this novel scenario requires a plasma including at least three ion species with a different $(Z/A)_i$. In what follows, we use indices ‘1’ and ‘2’ for the main ions with the largest and lowest $(Z/A)_i$, respectively, and index ‘3’ for the absorbing minority. The (Z/A) value for the resonant ‘third’ species should be ‘sandwiched’ between that of the two main ions, $(Z/A)_2 < (Z/A)_3 < (Z/A)_1$. As shown in [2], depositing nearly all RF power to a very small number of minority ions (of the order ~0.1%) is maximized in plasmas with main ion concentrations given by

$$X_1^* = \frac{1}{Z_1}\frac{(Z/A)_1 - (Z/A)_3}{(Z/A)_1 - (Z/A)_2}, \quad X_2^* = \frac{1}{Z_2}\frac{(Z/A)_3 - (Z/A)_2}{(Z/A)_1 - (Z/A)_2}, \tag{1}$$

where $X_i = n_i/n_e$. Plasma heating at higher concentrations of minority ions (of the order ~1%) is equally possible; for such regimes concentrations of the main ion species $X_2 \leq X_2^*$ ($X_1 \geq X_1^*$) are more optimal.

The novel technique is relevant for heating various multi-ion plasmas containing not only H or He isotopes like e.g. D-T, H-D, H-T, H-^{4}He or D-^{3}He mixtures, but also allows making use of intrinsic and extrinsic impurities e.g. ^{9}Be, ^{22}Ne, Ar, etc. to optimize ICRH power deposition in fusion plasmas. Intrinsic impurities were earlier shown to have an impact on RF power absorption for the inverted ICRH scenarios in hydrogen plasma [4, 5]. Recent developments suggest methods on how to exploit impurity ions and controlling the plasma mixture in order to expand the range of available heating options and applications of ICRH. In this contribution, we give an overview of various three-ion species ICRH scenarios that hold promise for ITER operations and also shortly highlight their possible applications beyond heating.

2. Heating H-^{9}Be non-active plasmas with ^{4}He minority ions

In JET-ILW and ITER, the plasma facing components (PFC) consist of beryllium in the main chamber and tungsten in the divertor. Thus, ITER plasmas will unavoidably contain a small amount of ^{9}Be impurities. An important observation in view of ICRH operations in ITER is that fully ionized intrinsic ^{9}Be ions have a $Z/A = 4/9$, which is different from that for H and He isotopes. Because $(Z/A)_{9\mathrm{Be}} < 1/2 < (Z/A)_\mathrm{H}$, minority heating of ion species with $Z/A = 1/2$, in particular ^{4}He and D ions, can be potentially made effective in hydrogen majority plasmas in ITER ($B_0 = 5.3$T, $f = 40$MHz). We note that because of the unavoidable presence of ^{9}Be impurities in ITER and JET-ILW plasmas, neither pure (^{4}He)-H, nor (D)-H minority scenario

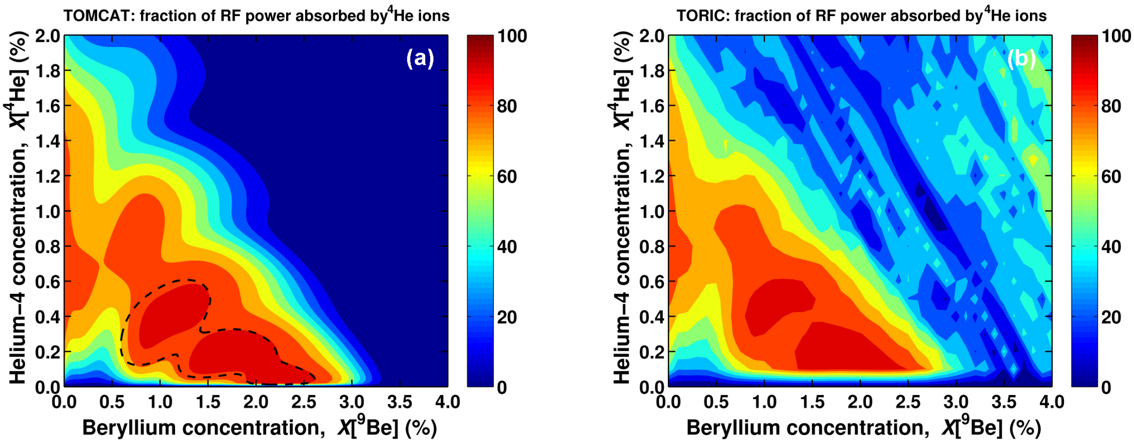

Figure 1: Fraction of ICRH power absorbed by ^{4}He minority ions for the ^{9}Be-(^{4}He)-H three-ion species scenario (B_0 = 5.3T, f = 40MHz, n_{tor} = 27, $n_{e0} = 6\times10^{19}$ m^{-3}, T_0 = 10 keV) as a function of ^{9}Be and ^{4}He concentrations: (a) TOMCAT modeling (the dashed line marks the region where the double-pass absorption by ^{4}He minority ions is larger than 50%); (b) TORIC modeling.

can be realized in these machines. Accordingly, an optimal concentration of ^{4}He or D minority ions for optimizing ICRH deposition strongly depends on the core X[^{9}Be]. For typical core ^{9}Be levels in JET-ILW L-mode plasmas X[^{9}Be] ≈ 0.5%, D minority concentrations of ~2% were found to be optimal for plasma heating [6]. We also note that minority heating of D and ^{4}He ions is not accessible in machines with carbon PFCs since a small amount of ^{12}C impurities (having the same Z/A = 1/2 as the resonant minority ions) directly leads into the mode conversion regime [7].

For ITER, minority heating of ^{4}He ions is a promising technique for heating H majority plasmas, naturally contaminated with ^{9}Be impurities. This is an ICRH scenario for full field H majority plasmas and therefore L-mode regime is expected (H-mode access in hydrogen at full field is predicted to require more than 100 MW of heating power [8]). Figure 1 shows the fraction of ICRH power absorbed by the ^{4}He minority as a function of the ^{9}Be and ^{4}He concentrations, computed by the 1-D TOMCAT [9] and 2-D TORIC [10] codes. It is clear that the optimal ^{4}He concentration leading to strong absorption of RF waves depends crucially on the core X[^{9}Be]. At low X[^{9}Be] ≤ 0.5%, wave absorption is maximized at X[^{4}He] ≈ 1%. In agreement with Eq. (1), efficient heating at much lower ^{4}He concentrations down to 0.1–0.2% should be possible for core X[^{9}Be] ≈ 1.5–2.5%. We also note that if X[^{9}Be] in ITER is larger than 3%, minority heating of ^{4}He ions becomes a poor heating scenario with very low single-pass absorption. A moderate to good absorption by ^{4}He minority ions shown in the upper right corner of Fig. 1(b) is misleading. Under these conditions, the numerical model in TORIC (or any other full-wave code assuming all RF power to be eventually absorbed in the plasma and excluding edge mechanisms for power absorption) is limited for evaluating the scenario performance. For scenarios with very low single-pass wave damping, non-linear edge mechanisms of RF power absorption become dominant and for this reason these scenarios do not provide efficient main plasma heating.

Although X[^{9}Be] in ITER might vary for different divertor configurations, injection of gases with (Z/A) values close to that of ^{9}Be offers a possibility to control and tune the three-ion species ^{9}Be-(^{4}He)-H ICRH scenario. Of particular relevance are argon (Z = 18, A = 40) and ^{22}Ne (Z = 10, A = 22) ions since Ar and Ne are currently also foreseen for impurity seeding in ITER [11]. We define the effective concentration of ^{9}Be-like species as follows

$$X[{}^9\mathrm{Be}]_\Sigma \approx X[{}^9\mathrm{Be}] + (18/4)X[\mathrm{Ar}] + (10/4)X[{}^{22}\mathrm{Ne}]. \qquad (2)$$

The numerical coefficients, which appear in Eq. (2), reflect the fact that Ar and ^{22}Ne ions have a higher charge than ^{9}Be ($Z = 4$) (note that $\omega_{pi}^2 \propto X_i Z_i \times (Z_i / A_i)$). For example, if for a given plasma condition and divertor configuration $X[^{9}\mathrm{Be}] \approx 0.5\%$, injecting ~0.1–0.2% of Ar impurities would then lead to $X[^{9}\mathrm{Be}]_{\Sigma} \approx 1-1.4\%$, thus sufficient to maximize RF absorption on ^{4}He ions at concentrations $X[^{4}\mathrm{He}] \approx 0.5\%$ and below (see Fig. 1).

In order to understand the sensitivity of the RF absorption to the core ^{9}Be concentration, we note that for ITER conditions the radial distance between the ion cyclotron resonance layers of the resonant ^{4}He and non-resonant ^{9}Be species is as large as 70 cm. Furthermore, for every per cent increase in the core ^{9}Be concentration, the ion-ion hybrid (IIH) pair in H-^{9}Be plasmas shifts by about 30cm to the low magnetic field side. Thus, the IIH layer is located in very close proximity to the cyclotron resonance of ^{4}He ions at $X[^{9}\mathrm{Be}] \sim 2\%$, allowing a very efficient absorption of ICRH power by a very low number of ^{4}He ions.

3. Heating H-^{4}He non-active plasmas with ^{3}He minority ions

Depositing ICRH power to a small amount of ^{3}He ions ($Z/A = 2/3$) is another option for heating hydrogen majority plasmas in ITER [12]. We note that for this scenario RF frequencies of ~53MHz are optimal to achieve core absorption, and more coupled ICRH power is expected at this frequency than for ^{4}He ICRH at 40MHz [13]. The single-pass absorption for the (^{3}He)-H scenario is computed to maximize at $X[^{3}\mathrm{He}] \approx 2–3\%$, and the presence of a small amount of ^{9}Be impurities plays a minor role in this scenario.

By selecting a target plasma consisting of H and ^{4}He as main ions, the optimal concentration of the resonant ^{3}He minority ions can be significantly reduced. As follows from Fig. 2, ^{3}He concentrations below 0.5% can be applied to achieve efficient heating of H-^{4}He plasmas with $5\% \le X[^{4}\mathrm{He}] \le 16\%$ (cf. also Eq. (1)). Computations show that in ITER these energetic ^{3}He ions are well confined and should provide efficient bulk plasma heating as a result of their collisional slowing down.

A possible additional advantage of the ^{4}He-(^{3}He)-H scenario for ITER is linked to recent JET-ILW observations of the reduced L-H transition power threshold with ^{4}He fueling into H plasmas. As reported in Refs. [14, 15], a ~25% reduction in $P_{\mathrm{L\text{-}H}}$ was observed with injecting about 10% of ^{4}He into a hydrogen plasma.

Since ITER lacks an efficient ICRH absorption scenario at half-field H plasmas, an optional scheme that is promising for H-mode access studies in H majority plasmas at $B_0 = 3.0–3.3$T has been recently proposed [12]. It relies on the off-axis deposition of ICRH power using the ^{4}He-(^{3}He)-H scenario at 40MHz. We note that off-axis ^{3}He ICRH heating in equivalent H-D plasmas was already successfully tested on JET and, more recently, on AUG [16]. Further experimental investigations are foreseen on JET-ILW to develop this ITER-relevant scenario in H-^{4}He plasmas.

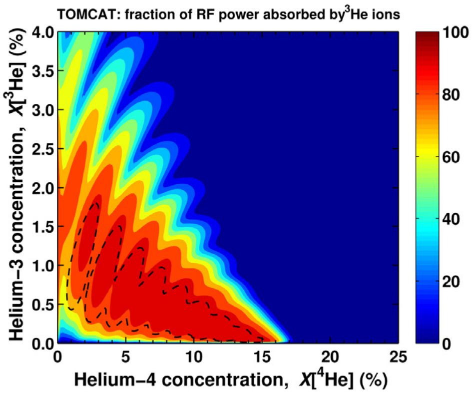

Figure 2: Fraction of ICRH power absorbed by ^{3}He minority ions for the ^{4}He-(^{3}He)-H three-ion species scenario ($B_0 = 5.3$T, $f = 53$MHz, $n_{\mathrm{tor}} = 27$), computed with the TOMCAT code. The dashed lines mark the regions where the double-pass absorption by ^{3}He minority ions is larger than 50%.

4. Bulk ion heating in D-T plasmas with ^{9}Be as absorbing species

Since $(Z/A)_{\mathrm{T}} < (Z/A)_{\mathrm{9Be}} < (Z/A)_{\mathrm{D}}$, intrinsic ^{9}Be impurities can efficiently absorb ICRH power in D-T full-field plasmas ($f = 40$MHz), see [17]. Note that three-ion species scenarios do not necessarily have to rely on using extremely low minority concentrations. For example, the optimal ^{9}Be concentration to maximize RF absorption in D-T = 50%:50% plasmas is in the range $X[^9\mathrm{Be}] \approx 0.5$–1% [17]. Channelling RF power to ^{9}Be impurities can reduce the need for using expensive ^{3}He gas during the ramp-up heating phase in ITER D-T pulses. In addition, ^{9}Be impurities will even more effectively deposit absorbed RF power to bulk D and T ions during the collisional slowing down (due to their higher atomic mass) than the commonly used scenario with ^{3}He as a minority, a feature particularly attractive for a fusion reactor. ICRH heating of ^{9}Be in D-T plasmas at 40MHz in ITER shows a maximum in the RF power deposition at $r/a \approx 0.3$, which is still well inside the $q = 1$ surface. Central bulk ion heating with ^{9}Be impurities would require ICRH operation at 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.

We note that the high RF heating efficiency of a three-ion scenario in D-T plasmas was seen in past TFTR experiments, in which Li wall conditioning was used and a small amount of ^{7}Li impurities ($Z/A = 3/7$, $X[^7\mathrm{Li}] \approx 0.5\%$) absorbed most of the launched RF power [18] via a T-(^{7}Li)-D scenario.

5. Using NBI ions as resonant species for ICRH heating of mixture plasmas

Finally, an extension of the three-ion species technique consists in using fast injected NBI as an equivalent ‘third’ ion species. This was shown in recent JET-ILW experiments, where D-NBI ions with injection energies of ~100 keV heated effectively H-D ≈ 85%-15% plasmas [19]. The large Doppler shift of those fast ions replaces the role of the different $(Z/A)_3$ to displace the resonance position in between the cyclotron resonances of two main ion species. Those ions in the beam distribution that have a Doppler-shifted cyclotron resonance close to the ion-ion hybrid layer in a mixed plasma will then efficiently absorb the 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 with a ^{4}He-($\mathrm{H_{NBI}}$)-H heating scenario by applying H-NBI ions to absorb ICRH power in ^{4}He-H plasmas. As discussed in [20], H-NBI heating increases the fraction of ICRH power directly absorbed by hydrogen, and substantially broadens the profile of ICRH power absorbed by hydrogen. In a similar way, D-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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References

[1] M. Schneider et al., *Proc. 44th EPS Conf. on Plasma Physics*, ECA **41F**, P5.153 (2017)
[2] Ye.O. Kazakov et al., *Nucl. Fusion* **55**, 032001 (2015)
[3] Ye.O. Kazakov et al., *Nature Physics* **13**, 973-978 (2017)
[4] M.-L. Mayoral et al., *Nucl. Fusion* **46**, S550-S563 (2006)
[5] D. Van Eester et al., *Plasma Phys. Control. Fusion* **54**, 074009 (2012)
[6] D. Van Eester et al., *EPJ Web Conf.* **157**, 03061 (2017)
[7] P.U. Lamalle et al., *Nucl. Fusion* **46**, 391-400 (2006)
[8] Y.R. Martin et al., *J. Phys.: Conf. Ser.* **123**, 012033 (2008)
[9] D. Van Eester and R. Koch, *Plasma Phys. Control. Fusion* **40**, 1949-1975 (1998)
[10] R. Bilato et al., *Nucl. Fusion* **51**, 103034 (2011)
[11] X. Bonnin et al., *Nuclear Materials and Energy* **12**, 1100-1105 (2017)
[12] M. Schneider et al., *EPJ Web Conf.* **157**, 03046 (2017)
[13] A. Messiaen et al., *Nucl. Fusion* **50**, 025026 (2010)
[14] X. Litaudon et al., *Nucl. Fusion* **57**, 102001 (2017)
[15] J. Hillesheim et al., *27th IAEA Fusion Energy Conference,* EX/4-1 (2018)
[16] A. Kappatou et al., *Proc. 45th EPS Conf. on Plasma Physics*, O2.105 (2018)
[17] Ye.O. Kazakov et al., *Phys. Plasmas* **22**, 082511 (2015)
[18] J.R. Wilson et al., *Phys. Plasmas* **5**, 1721-1726 (1998)
[19] J. Ongena et al., *EPJ Web Conf.* **157**, 02006 (2017)
[20] R. Bilato et al., *Proc. 45th EPS Conf. on Plasma Physics*, P1.1070 (2018)