Reduction in the transition concentration of helium-3 ions caused by impurities in (^{3}He)–H plasmas heated with ICRH

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Introduction Ion cyclotron resonance heating (ICRH) has been used successfully for bulk ion and electron heating in present-day fusion devices and is considered to be installed in ITER. It will start its operation using predominantly hydrogen (H) or helium-4 (^{4}He) plasmas to avoid neutron generation. Maximizing the efficiency of the heating systems, including ICRH, is of particular importance for this stage of ITER in order to reach H-mode of operation.

The fundamental resonance heating of helium-3 (^{3}He) ions is one of a few ICRH schemes available for ITER hydrogen plasmas. A number of experiments were performed at JET aimed at studying (^{3}He)–H heating scenario and its optimization [1–3]. These experiments (performed with the old CFC first wall) highlighted an essential effect of carbon (C) impurities on the ICRH performance in (^{3}He)–H plasmas. First, the heating region was found to be shifted appreciably away from where it was expected for pure plasma. Second, mode conversion (MC) heating was complicated further through the appearance of the supplementary MC layer associated with C ions [3, 4]. In addition, the transition from minority ion heating (MH) to mode conversion was observed to occur at very low ^{3}He concentrations. Whereas numerical simulations predicted $X_{\mathrm{crit}}[^3\mathrm{He}] \sim 5\%$, the experimental values were almost twice as low, $\sim 2-3\%$.

Since 2011 JET is operating with the new ITER-like wall, and uses beryllium (Be) and tungsten (W) as the new plasma facing materials. These impurities will unavoidably enter the plasma and should manifest themselves in H plasmas heated with ICRH in a similar way as C ions earlier. In this paper we discuss how impurities affect the MH-MC transition in (^{3}He)–H plasmas and suggest a potential method for reducing ^{3}He level needed for ICRH operation by puffing an extra ^{4}He gas to (^{3}He)–H mixture.

Transition from MH to MC ICRH regime In a two-ion species plasmas, including majority and minority ions, the dominant absorption mechanism depends on the minority concentration, X_2. For relatively low X_2 values, most of the ICRH power is absorbed by a small fraction of resonant ions (minority heating), which then transfer their energy to bulk ions and electrons via Coulomb collisions. As the minority concentration gradually increases, a smooth transition from MH to MC heating occurs. The latter regime relies on the mode conversion of the fast wave (FW), which it undergoes at the ion-ion hybrid (IIH) resonance. The converted wave has a shorter wavelength and is commonly absorbed by electrons within a narrow radial region.

Figure 1(a) shows the single-pass absorption coefficients in (^{3}He)–H plasma computed with the 1D full-wave code TOMCAT [5]. The considered parameters correspond to the central location of ^{3}He resonance and are similar to the conditions reached at past JET experiments: $B_0 = 3.1\,\mathrm{T}$, $f = 32.2\,\mathrm{MHz}$, $n_{\mathrm{tor}} = 27$ (dipole phasing), $n_{e0} = 3.2 \times 10^{19}\,\mathrm{m}^{-3}$, $T_0 = 5.0\,\mathrm{keV}$. As follows from the figure, for the given set of parameters the transition from MH to MC occurs at $X_{\mathrm{crit}}[^3\mathrm{He}] \approx 5.9\%$. For ^{3}He concentrations lower than the critical value, most of the ICRH power is absorbed by minority ions; vice versa, at $X[^3\mathrm{He}] > X_{\mathrm{crit}}[^3\mathrm{He}]$ electron heating via MC dominates.

The transition from MH to MC heating can be qualitatively explained as follows. Minority cyclotron resonance has a finite Doppler width, $\Delta R = p_0\sqrt{2}k_{\parallel}v_{t2}/\omega$, where $k_{\parallel}$ is the FW parallel wavenumber, $\omega = 2\pi f$, $v_{t2} = (T_2/m_2)^{1/2}$ is the thermal speed of minority ions, and the numerical coefficient p_0 is of the order of unity. Let us denote δ as a distance between the IIH resonance and the minority cyclotron layer. For small X_2 the IIH layer is located within the Doppler broadened cyclotron resonance ($\delta < \Delta R$) and MH dominates. For large minority concentrations the IIH resonance is located out of the region, where the cyclotron damping by minority ions is important ($\delta > \Delta R$), and electron heating via MC becomes the main absorption mechanism. The transition from MH to MC is reached, when the mode conversion layer passes through the Doppler broadened minority cyclotron resonance.

In Refs. [6, 7] the concentration of minority ions, marking the transition, was found to be

$$X_{2,\mathrm{crit}} \approx p_0 \frac{\sqrt{2}k_{\parallel}v_{t2}}{\omega}\left[\frac{\mu^2}{|1-\mu^2|} \pm \frac{k_{\parallel}^2 v_{A1}^2}{\omega^2}\right], \tag{1}$$

where the subscripts '1' and '2' denote majority and minority ions, respectively; $\mu = \omega_{c1}/\omega_{c2}$ and v_{A1} is the Alfvén speed of the majority ions. The plus or minus sign in Eq. (1) is to be taken for the standard ($\mu < 1$) and inverted ($\mu > 1$) ICRH scenarios, respectively [7]. The numerical coefficient for (^{3}He)–H plasmas was calculated to be $p_0 \approx 2.3$. In such a way, according to Eq. (1) the transition helium-3 concentration in (^{3}He)–H mixture increases with plasma temperature, FW parallel wavenumber and plasma density, and is inversely proportional to the ICRH frequency.

Effect of impurities on the transition helium-3 concentration Eq. (1) is derived for two-ion species plasmas neglecting a presence of impurities. Accounting for the latter, $X_{\mathrm{crit}}[^3\mathrm{He}]$ is upshifted or downshifted since the location of the IIH resonance depends on the level of impurity contamination. The corresponding factor, which connects the transition concentration in plasmas with and without impurities, is approximately given by [7]

$$M_{\text{imp}} = \frac{X_{2,\text{crit}}^{(\text{imp})}}{X_{2,\text{crit}}^{(\text{pure})}} = 1 - \sum_{\text{imp}} \frac{(\mathscr{Z}_1 - \mathscr{Z}_{\text{imp}})(\mathscr{Z}_2^2 + \mathscr{Z}_1 \mathscr{Z}_{\text{imp}})}{\mathscr{Z}_1(\mathscr{Z}_2^2 - \mathscr{Z}_{\text{imp}}^2)} f_{\text{imp}} \ , \tag{2}$$

where $\mathscr{Z}_i = Z_i/A_i$ is the ratio of the charge number to the atomic mass for ion species, $f_{\text{imp}} = Z_{\text{imp}} X_{\text{imp}}$, and the sum is to be taken over all impurity species present in the plasma.

For (^{3}He)–H plasmas, Eq. (2) yields

$$M_{\text{imp}} = 1 - 8X[\text{Be}] - 14.6X[\text{C}^{6+}] - 33.6X[\text{W}^{28+}] - 62.7X[\text{W}^{46+}] - 51.4X[\text{Ni}^{26+}], \tag{3}$$

such that the presence of impurities allows lowering the ^{3}He concentration, which marks the transition from MH to MC. Good agreement between an analytical estimate for the reduction factor associated with Be impurities, Eq. (3) and numerical results was obtained. $X[\text{Be}] = 2\%$ is a typical value for JET operating with a new ITER-like wall. For such Be concentration, Eq. (3) predicts $X_{\text{crit}}[^3\text{He}]$ to be reduced in (^{3}He)–H plasmas by a factor of $M_{\text{imp}} \approx 0.84$. It means that if the transition in pure two-ion species plasma is to occur at $X[^3\text{He}] = 5.9\%$ (as for conditions of Fig. 1(a)), in the same plasmas, but including 2% of Be ions, the transition will be reached already at $X[^3\text{He}] \approx 5.0\%$.

Retuning of ICRH scenarios involving helium-3 The ^{3}He concentration required during a pulse depends on whether MH or MC regime is envisaged for ICRH. In ITER and future machines, where higher plasma temperatures are expected, the MH-MC transition is to occur at higher ^{3}He concentrations than in JET. Along with rapidly increasing market price for ^{3}He and the fact that the plasma volume in ITER is almost 10 times larger than in JET, this increases significantly the operational costs for using ^{3}He in future fusion devices. Here, we suggest a potential method to reduce ^{3}He level needed for ICRH operation. The idea is to fake the effect ^{3}He has on the wave polarization by substituting it by some quantity of extra ^{4}He gas in (^{3}He)–H mixture [7].

According to Eq. (2), a reduction factor linearly decreases with ^{4}He concentration as $M_{\text{imp}} = 1 - 4.9X[^4\text{He}]$. Figure 1(b) shows M_{imp} plotted as a function of $X[^4\text{He}]$ for various Be concentrations. Eq. (2) slightly overestimates the contribution of ^{4}He ions to M_{imp}. The calculated values suggest the corresponding coefficient for ^{4}He to be 4.4, i.e. $M_{\text{imp}} = 1 - 8X[\text{Be}] - 4.4X[^4\text{He}]$. Then, by puffing 5% of ^{4}He ions to (^{3}He)–H plasmas including 2% of Be impurities, one might expect further reduction of $X_{\text{crit}}[^3\text{He}]$ to the level $\sim 3.7\%$ ($M_{\text{imp}} \approx 0.62$). Note that the impurity contamination affects not only the transition helium-3 concentration, but it also leads to a reduction of the ^{3}He concentration, at which a single-pass ion absorption is maximized.

Adding a small fraction of ^{3}He ions ($X[^3\mathrm{He}] \sim 3.5\%$) in D–T plasma can significantly improve ion heating efficiency and fusion yield [8, 9]. To reduce ^{3}He concentration required for ICRH in D–T plasmas, Eq. (2) suggests to make use of hydrogen ions. For 50:50 D–T plasmas, Eq. (2) yields: $M_{\mathrm{imp}} = 1 + 1.1X[\mathrm{Be}] - 2.3X[\mathrm{H}]$. In such a way, puffing $X[\mathrm{H}] = 5\%$ to the plasma allows lowering $X[^3\mathrm{He}]$ by a factor of ~ 0.9. The price to be paid for this gain is a slight reduction in the density product of fuel ions, $n_{\mathrm{D}}n_{\mathrm{T}}$.

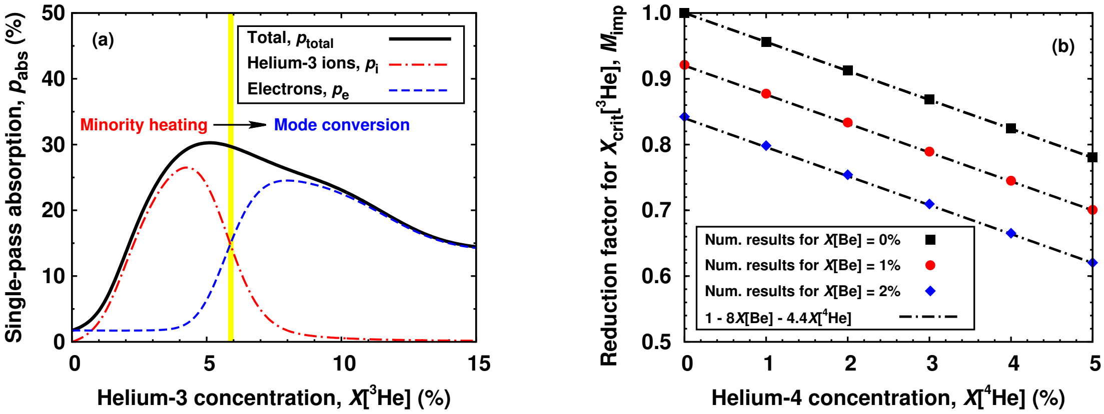

Figure 1: (a) An example of the transition from minority ion to mode conversion heating in (^{3}He)–H plasma, which for the given set of parameters occurs at $X_{\mathrm{crit}}[^3\mathrm{He}] \approx 5.9\%$. (b) Reduction factor for $X_{\mathrm{crit}}[^3\mathrm{He}]$ as a function of Be and ^{4}He impurity concentrations.

Conclusions Impurities have a significant impact on the ICRH performance in (^{3}He)–H plasmas. The ^{3}He concentration, at which the transition from minority ion to mode conversion heating occurs, is shown to be reduced if accounting for impurities. We derive the corresponding reduction factor, which scales almost linearly with the impurity concentrations. For a typical Be concentration $\sim 2\%$ at JET equipped with the new wall, a reduction of $X_{\mathrm{crit}}[^3\mathrm{He}]$ by a factor of ~ 0.84 is predicted. We propose a potential method to minimize ^{3}He concentration needed for ICRH operation in (^{3}He)–H and (^{3}He)–DT mixtures, which is based on the extra puffing of ^{4}He and H gas to the plasma, respectively.

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