Influence of Impurities on the Transition from Minority to Mode Conversion Heating in (^{3}He)–H Plasmas

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Abstract. Ion cyclotron resonance heating (ICRH) is one of the main auxiliary heating systems used in present-day tokamaks and is planned to be installed in ITER. In the initial full-field phase of ITER operating with hydrogen majority plasmas, fundamental resonance heating of helium-3 ions is one of a few ICRH schemes available. Past JET experiments with the carbon wall revealed a significant impact of impurities on the ICRH performance in (^{3}He)–H plasmas. A significant reduction of the helium-3 concentration, at which the transition from minority ion to mode conversion heating occurs, was found to be due to a high plasma contamination with carbon ions. In this paper we discuss the effect of Be and another impurity species present at JET after the installation of a new ITER-like wall on the transition helium-3 concentration in (^{3}He)–H plasmas. We suggest a potential method for controlling helium-3 level needed for a specific ICRH regime by puffing an extra helium-4 gas to the plasma.

Keywords: ICRH, tokamak, minority heating, mode conversion, impurities.
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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. It is one of the three auxiliary heating systems considered to be installed in ITER. The current design of the ICRH system for ITER foresees coupling of 20 MW of radio frequency (RF) power to the plasma within the frequency range $f = [40–55]$ MHz. During the initial stage of ITER predominantly hydrogen (H) or helium-4 (^{4}He) plasmas will be used to avoid neutron generation and minimize the activation of the tokamak components. The existing scalings suggest the power threshold to reach a high confinement mode (H-mode) of operation to be higher by a factor of two for hydrogen plasmas than for deuterium. Therefore, the access to the H-mode is not assured for hydrogen plasmas in ITER with the heating powers that will be available. Thus, it is particularly important to optimize the efficiency of RF heating for the scenarios relevant for this experimental stage of ITER.

Figure 1(a) shows the locations of the ion cyclotron (IC) resonance layers for ITER operating at the nominal magnetic field $B_0 = 5.3$ T as a function of the ICRH frequency. For the accessible frequency range, heating of the helium-3 ions at the fundamental cyclotron frequency ($f \approx 53$ MHz) is one of a few ICRH schemes available for hydrogen plasmas. A number of experiments were performed at JET aimed at studying (^{3}He)–H heating scheme and its optimization [1–3]. In (^{3}He)–H JET experiments reported in Refs. [1, 2], plasma heating was studied at very low ^{3}He concentrations. Mode conversion (MC) was found to be reached at helium-3 concentrations $X[^3\mathrm{He}] = n_{3\mathrm{He}}/n_e = 2–3\%$, which were substantially smaller than the values observed in (^{3}He)–D plasmas ($X[^3\mathrm{He}] \approx 10–15\%$). Such a difference is explained by the fact that (^{3}He)–H plasma is one of the so-called 'inverted' ICRH scenarios. It means that the charge-to-mass ratio for minority species (helium-3) is less than that for majority species (hydrogen), $(Z/A)_{\mathrm{mino}} < (Z/A)_{\mathrm{majo}}$. For inverted heating scenarios the MC layer is located between the ICRH antenna at the outer side of the torus and the minority cyclotron resonance, and thus the fast wave (FW) encounters first the MC layer and only then the minority cyclotron layer. In standard scenarios, the opposite is the case.

Past JET experiments highlighted an essential effect of carbon (C) impurities on the ICRH performance in (^{3}He)–H plasmas. The presence of carbon in JET plasmas up to 2011 was a direct consequence of the inner vessel consisting of carbon tiles. Three important issues due to plasma dilution with the carbon impurities were outlined. First, the heating region was found to be shifted appreciably away from where it was expected for pure plasma. Second, MC heating was complicated further through the appearance of the supplementary MC layer associated with carbon ions [3, 4]. In addition, a significant reduction of the transition helium-3 concentration, $X_{\rm crit}$ [^{3}He], which corresponds to a change of ICRH heating regimes, was observed. Full-wave ICRH simulations have shown that for the plasma without the carbon the transition from minority ion to mode conversion heating should occur at $X_{\rm crit}$ [^{3}He] ≈ 5%, while the experimentally observed levels at JET were lower.

Since August 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 hydrogen plasmas heated with ICRH in a similar way as carbon ions earlier. In this paper we find a reasonable estimate for $X_{\rm crit}$ [^{3}He] in (^{3}He)–H plasmas and discuss the effect of typical impurities at JET on that.

TRANSITION FROM MINORITY ION TO MODE CONVERSION HEATING IN (^{3}He)–H PLASMAS

In two-ion species plasmas, including minority and majority ions, one usually distinguishes minority ion and mode conversion heating regimes. Minority ion heating (MH) occurs at relatively low minority concentrations less than some value, which depends on plasma and ICRH parameters [5]. In this regime the majority ions assure favourable polarization of the FW launched by the ICRH antenna at the region of the fundamental cyclotron resonance of minority ions. Resonant minority ions absorb the RF energy and transfer it to bulk plasma ions and electrons via Coulomb collisions. With the gradual increase in the minority concentration the MH efficiency reduces and at large enough minority concentrations plasma heating via MC becomes dominant. This regime is characterized by a partial conversion of the FW to the short wavelength modes, ion Bernstein wave (IBW) or ion cyclotron wave (ICW), at the MC layer. The converted wave is commonly strongly absorbed by electrons within a narrow spatial region on much shorter time scale than the characteristic time for indirect bulk plasma heating via MH. Figure 1(b) shows an example of such a transition in (^{3}He)–H plasma. Single-pass absorption coefficients by minority ions and electrons are calculated using a 1D full-wave code TOMCAT [6] (which omits poloidal field effects) and are plotted as a function of helium-3 concentration. The parameters used in the modeling are the following: $B_0 = 3.1$ T, $f = 32.2$ MHz, $n_{\rm tor} = 27$, $n_{\rm e0} = 3.2 \times 10^{19}$ m^{-3}, $T_0 = 5.0$ keV. From Fig. 1(b) it follows that for X[^{3}He] < 5.9% absorption by helium-3 ions exceeds that by electrons, and vice versa at higher helium-3 concentrations electron absorption via MC dominates. The helium-3 concentration, at which electron absorption balances the absorption by minority ions, is referred to as a transition minority concentration and is a subject of this paper.

Qualitatively the transition from MH to MC heating can be explained as follows. Minority cyclotron resonance has a finite Doppler width, $\Delta R = p_0 \sqrt{2} k_\parallel {\rm v}_{t2} R / \omega$, where $k_\parallel$ is the FW parallel wavenumber, $\omega = 2\pi f$, ${\rm v}_{t2} = (k_{\rm B}\, T_2/m_2)^{1/2}$ is the thermal speed of minority ions with $k_{\rm B}$ the Boltzmann constant, and the numerical coefficient p_0 is of the order of unity. Let us denote δ as a distance between the cold plasma ion-ion hybrid (IIH) resonance and the minority IC layer. For small minority concentrations the IIH layer is located within the Doppler broadened IC resonance ($\delta < \Delta R$) and minority heating dominates. For large minority concentrations the IIH resonance is located out of the region, where the cyclotron damping by minority ions is important, such that $\delta > \Delta$R, and electron heating via MC will become the main absorption mechanism. The transition from MH to MC is reached when $\delta = \Delta R$, i.e. when the mode conversion layer passes through the Doppler broadened IC resonance.

In Refs. [5, 7] the transition concentration of minority ions was found to be

$$X_{2,\rm crit} \approx p_0 \frac{\sqrt{2} k_\parallel {\rm v}_{t2}}{\omega} \frac{2A_1}{A_2 Z_1} \left[\frac{\mu^2}{|1-\mu^2|} \pm \frac{k_\parallel^2 {\rm v}_{\rm A1}^2}{\omega^2} \right], \tag{1}$$

where the subscripts '1' and '2' denote majority and minority ions, respectively; $\mu = Z_1 A_2/(A_1 Z_2)$ and ${\rm v}_{\rm A1}$ is the Alfvén speed of the majority ions. The plus or minus sign for the second term within brackets in Eq. (1) is to be taken for the standard and inverted ICRH scenarios, respectively. The numerical coefficient for (^{3}He)-H plasma was shown 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.

Eq. (1) is derived for two-ion species plasmas neglecting a presence of impurities. Accounting for the latter, the transition level 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, was shown to be [7]

$$M_{\rm imp} = \frac{X_{2,\rm crit}^{\rm (imp)}}{X_{2,\rm crit}} \approx 1 - \sum_{imp} \frac{(z_1 - z_{\rm imp})(z_2^2 + z_1 z_{\rm imp})}{z_1 (z_2^2 - z_{\rm imp}^2)} (Z_{\rm imp} X_{\rm imp}), \tag{2}$$

where the sum is to be taken over all impurity species present in plasmas and $z_j = Z_j / A_j$. For (^{3}He)-H plasmas, Eq. (2) yields

$$M_{\rm imp} \approx 1 - 8X[\rm Be] - 14.6X[C^{6+}] - 33.6X[W^{28+}] - 62.7X[W^{46+}] - 51.4X[Ni^{26+}] - ..., \qquad (3)$$

such that the presence of impurities allows lowering the ^{3}He concentration, which marks the transition. Figure 2(a) shows good agreement for the reduction factor associated with Be impurities between an estimate based on Eq. (3) and numerical results. For X[Be] = 2.0%, which is a typical value for JET operating with a new ITER-like wall, one could expect the transition helium-3 concentration in (^{3}He)-H plasmas to be reduced by a factor of $M_{\rm imp} \sim 0.84$. It means that if the transition in pure two-ion species plasma is to occur at $X[^3\rm He] = 5.9\%$ (as for conditions of Fig. 1(b)), in the same plasmas, but including Be ions, the transition will be reached already at $X[^3\rm He] \approx 5.0\%$.

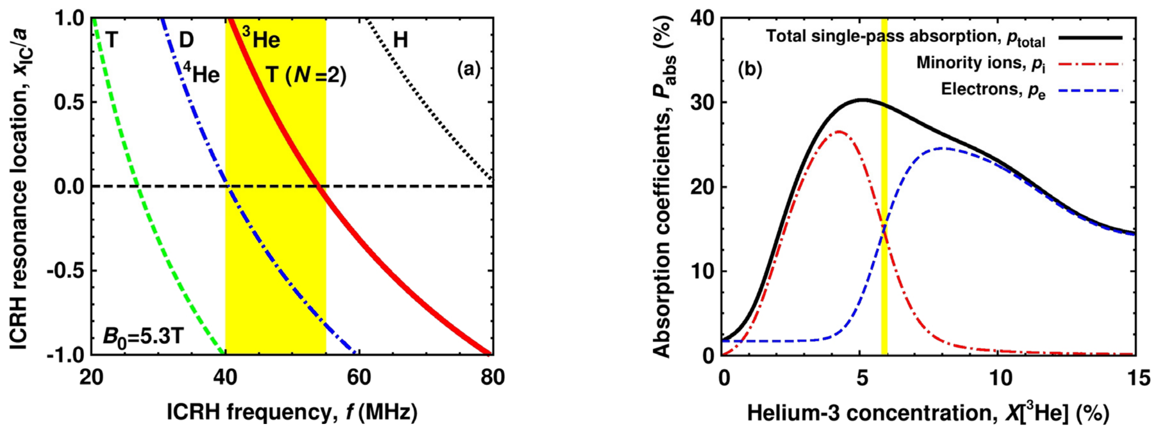

FIGURE 1. (a) Locations of the ion cyclotron resonance layers for ITER operating at the nominal magnetic field (B_0 =5.3 T). (b) Single-pass absorption coefficients vs. helium-3 concentration calculated with the TOMCAT code for (^{3}He)–H plasma.

EXTRA GAS PUFFING AS A TOOL TO CONTROL MINORITY ION LEVEL NEEDED FOR ICRH OPERATION

Depending on the specific goals envisaged for the ICRH system one might need to set the experimental conditions to reach either MH ($X[^3\rm He] < X_{\rm crit}[^3\rm He]$) or MC heating ($X[^3\rm He] > X_{\rm crit}[^3\rm He]$): operating in the MH regime is preferred to increase the fraction of thermal ion heating in (^{3}He)–H plasmas, whereas MC could be potentially used for driving the current or local plasma control. In future machines like ITER, where higher plasma temperatures are expected for the tokamak operation, the transition to MC in (^{3}He)–H plasmas is to occur at higher ^{3}He concentrations than in JET. Due to increased ^{3}He demand and industrial consumption, the typical market price for ^{3}He has risen from \$100–\$200 per liter to \$2,000 per liter in recent years [8]. Along with 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. Therefore, the development of the methods to decrease and possibly control the minority concentrations needed for efficient ICRH performance is of high importance. Here, we suggest a method to retune ICRH scenarios involving helium-3 ions to minimize ^{3}He concentrations needed for MH and MC heating. The basic idea is to fake the effect ^{3}He has on the polarization by substituting it by some quantity of extra ^{4}He gas in (^{3}He)–H mixture [8].

According to Eq. (2), $M_{\rm imp}$ linearly decreases with helium-4 concentration as $M_{\rm imp} = 1 - 4.9\,X[^4\rm He]$. Figure 2(b) shows a reduction factor as a function of central plasma temperature for various ^{4}He concentrations. As follows from the figure, Eq. (2) slightly overestimates the contribution of ^{4}He ions to $M_{\rm imp}$; the numerical coefficient for ^{4}He ions is found to be 4.4 instead of 4.9. Therefore, we can conclude

$$M_{\rm imp} \approx 1 - 8X[\rm Be] - 4.4X[^4He]. \qquad (4)$$

By puffing $X[^4\rm He] = 5\%$ to (^{3}He)–H plasmas including 2% of Be impurities, one might expect further reduction of the ^{3}He transition concentration to the level ~ 3.7% ($M_{\rm imp} \approx 0.62$). Note that the impurity presence 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. Thus, puffing of an extra ^{4}He gas to (^{3}He)-H plasma could potentially serve as a method to minimize ^{3}He level needed for ICRH operation both in the MH and MC regime, and it seems to be worth exploring this option in detail in separate studies to confirm or disconfirm its potential.

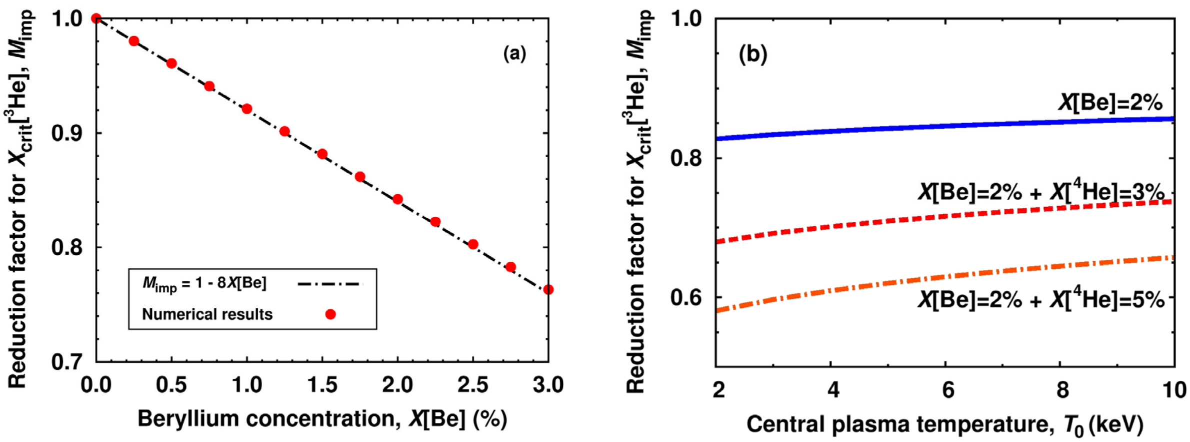

Figure 2. Reduction factor for the transition helium-3 concentration in (^{3}He)-H plasmas as a function of X[Be], (a) and central plasma temperature for various ^{4}He concentrations, (b).

CONCLUSIONS

ITER will start its operation using the hydrogen majority plasmas to minimize the activation of the tokamak components. ICRH is one of the heating systems to be used in ITER, and a number of ICRH experiments were carried out at JET to develop and optimize heating scenarios relevant for hydrogen plasmas. One of the promising ICRH schemes relies on the use of the resonant minority ^{3}He ions to absorb the RF energy. The concentration of minority ^{3}He ions, at which the transition from MH to MC occurs, was reported to be lower than that predicted by numerical simulations if the effect of impurities was neglected. In this paper we discuss how the transition concentration of ^{3}He ions depends on the plasma and ICRH parameters. We show that X_{crit} [^{3}He] is related to the Doppler broadening of the minority IC layer, and thus is inversely proportional to the antenna frequency and increases with the plasma temperature, FW parallel wavenumber and central plasma density.

Accounting for multiple impurity species always present in the plasma, we show that X_{crit} [^{3}He] decreases and scales almost linearly with the impurity concentrations. An analytical estimate for the relative change in X_{crit} [^{3}He] due to impurities is derived, and is shown to be in good agreement with the numerical results. We demonstrate that Be is to be the main impurity species affecting X_{crit}[^{3}He] in (^{3}He)–H plasmas for JET equipped with the new ITER-like wall. A reduction of X_{crit}[^{3}He] by a factor of ~ 0.8 is predicted if considering typical Be and other impurity concentrations at JET. A possible method to reduce and control the ^{3}He level, at which the transition from MH to MC is to occur, is suggested: the method relies on the additional puffing of ^{4}He ions to (^{3}He)–H mixture. We show that for X[^{4}He] = 5% the reduction of the transition concentration of helium-3 ions by a factor of ~ 0.6 can be expected.

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