EUROFUSION CP(15)03/10

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(27th April 2015 – 29th April 2015)
Lake Arrowhead, California, USA

This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014-2018 under grant agreement No 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

Fast Ion Generation and Bulk Plasma Heating with Three-Ion ICRF Scenarios

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Abstract. Launching electromagnetic waves in the ion cyclotron range of frequencies (ICRF) is an efficient method of plasma heating, actively employed in most of fusion machines. ICRF has a number of important supplementary applications, including the generation of high-energy ions. In this paper, we discuss a new set of three-ion ICRF scenarios and the prospect of their use as a dedicated tool for fast ion generation in tokamaks and stellarators. A distinct feature of these scenarios is a strong absorption efficiency possible at very low concentrations of resonant minority ions ($\sim$ 1% or even below). Such concentration levels are typical for impurities contaminating fusion plasmas. An alternative ICRF scenario for maximizing the efficiency of bulk D-T ion heating is suggested for JET and ITER tokamaks, which is based on three-ion ICRF heating of intrinsic Beryllium impurities.

Keywords: ICRH, fast ion generation, impurities, minority heating, mode conversion
PACS: 52.55.Fa, 52.25.Os, 52.25.Vy

INTRODUCTION

Plasma heating with waves in the ion cyclotron range of frequencies (ICRF) is widely used in most of the present-day fusion devices. It will also be installed in ITER [1] and is considered as an auxiliary heating system for a demonstration tokamak-reactor DEMO [2]. Beyond plasma heating itself, ICRF system has a number of other important applications beneficial for improving plasma operation [3]. This includes impurity and transport control, current drive, wall conditioning, etc. Generation of high-energy ions is another promising application of ICRF in tokamaks and stellarators. This is typically needed for fusion product studies, when RF heating is applied to accelerate a small group of resonant ions to very high energies. Such particles mimic fusion-born alphas, and this allows to fill in the knowledge on fast ion dynamics in fusion plasmas. RF-generated fast ions can also be used for checking and optimizing the quality of plasma confinement in a fusion device. In fact, this is the main function of the ICRF system in the Wendelstein 7-X (W7-X) project [4]. W7-X is an optimized modular stellarator under construction in Greifswald, Germany [5], and the first plasma is expected already in 2015. One of the main scientific objectives of this device is to prove a good confinement of energetic particles in such a complicated 3D magnetic geometry. If proven, this will allow to extrapolate W7-X results towards a stellarator fusion reactor. Particles with energies of the order of $\sim$50–100 keV need to be generated as a proof-of-principle for W7-X. Such ions will have a similar normalized Larmor radius ρ_L/a (a is the minor radius of the machine) as the fusion-born alpha particles in a HELIAS reactor [6]. In present-day fusion experiments, resonant ion concentrations of a few percent are used for ICRF minority heating and this results in acceleration of fast ions to the energies of the order of a few hundred keV. However, the tail energy of minority ions heated at the fundamental $(N = 1)$ cyclotron resonance scales inversely with the square of the plasma density [7]. In W7-X, good fast-ion confinement is predicted if the plasma beta is rather high $\beta > 4\%$, and the stellarator is envisaged to operate at very large plasma densities, $n_{e0} \simeq 2 \times 10^{20}$ m^{-3}. As a result, the tail energies generated by the standard minority heating will be dramatically smaller than those reached in the present-day machines. The same argument stands for the next-step tokamaks ITER and DEMO, which are designed to have much larger plasma volume (resulting in lower RF power densities) and to operate at the nominal central plasma densities of the order $n_{e0} \simeq 1 \times 10^{20}$ m^{-3}. Applying second or third harmonic ICRF heating is a possible solution for the generation of MeV-range particles [8]. This method, however, essentially relies on the simultaneous use of neutral beam injection (NBI) heating together with ICRF.

If extrapolating ICRF towards future fusion machines, one has to outline that it is the only auxiliary heating system capable of providing a significant fraction of bulk ion heating. As discussed in [9, 10], preferential bulk ion heating during the ramp-up phase has a number of advantages over electron heating. This includes an improved control over

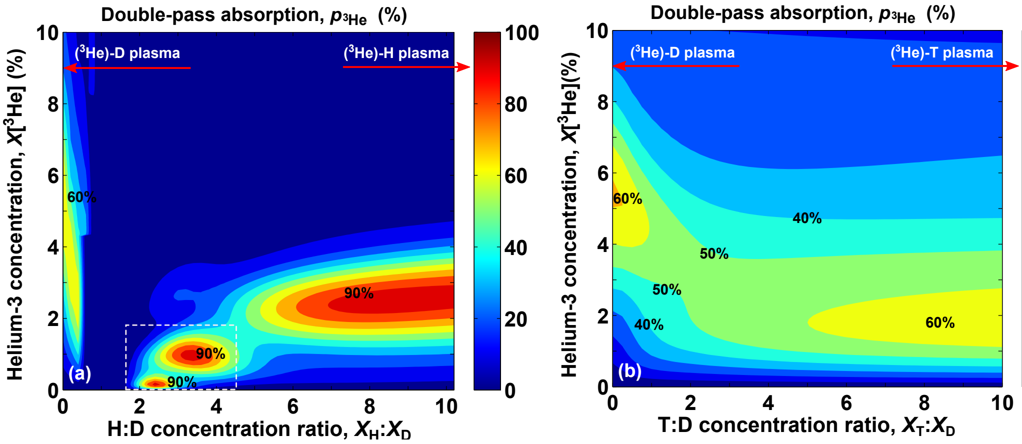

FIGURE 1. Double-pass absorption efficiency by ^{3}He minority ions in: (a) (^{3}He)-D-H and (b) (^{3}He)-DT plasmas as a function of ^{3}He concentration and H:D and T:D density ratio (JET-like plasma, $f = 32.5$ MHz, $B_0 = 3.2$ T, $n_{\text{tor}} = 27$, $T_0 = 4$ keV, $n_{e0} = 4 \times 10^{19}$ m^{-3}).

the path to the burn phase and keeping away from the region, where the interaction between thermal ions and thermal electrons is weak. Reaching the operational point with higher Q can be done faster and using less auxiliary heating power than for an electron heating scenario [10].

In this paper, we discuss shortly two applications of three-ion ICRF scenarios introduced recently in [11]: i) fast ion generation and ii) bulk ion (T_i) heating. These scenarios are very similar to the standard two-ion minority heating as both rely on $N = 1$ ion absorption mechanism, and thus NBI pre-heating is not such essential as for the harmonic ICRF scenarios. A distinct feature of the three-ion scenarios is a high efficiency of RF power absorption at extremely low concentrations of resonant ions ($\sim$ 1% and even below). This is possible because of the improved wave polarization in the absorption region.

Figure 1(a) illustrates the potential of the proposed three-ion scenarios. It shows the double-pass absorption (DPA) by ^{3}He ions in D-H plasma (a fraction of the incoming RF power absorbed by ^{3}He ions as the wave propagates from the low-field side edge to the high-field side edge and back) as a function of the H:D concentration ratio and ^{3}He concentration. The results are computed with the 1D full-wave code TOMCAT [12]. Here, typical JET-like plasma conditions have been used in simulations: f=32.5 MHz, B_0 = 3.2 T, n_{tor} = 27 (dipole phasing), T_0 = 4 keV, $n_{e0} = 4 \times 10^{19}$ m^{-3}. As follows from the figure, minority ion absorption in (^{3}He)-D plasma maximizes at $X[^3\text{He}] = n_{^3\text{He}}/n_e \approx 5-6\%$. For the H majority plasmas, maximum absorption occurs at lower ^{3}He concentrations $X[^3\text{He}] \approx 2-3\%$. This is consistent with the fact that (^{3}He)-H heating is an inverted ICRF scenario and the transition from minority heating to mode conversion (MC) occurs at lower ^{3}He concentrations [13, 14, 15]. Three-ion ICRF heating corresponds to the conditions highlighted in Fig. 1(a). One region with very efficient ^{3}He absorption is reached at $X[^3\text{He}] \approx 1\%$ and $X[\text{H}] \approx 75\%$ (H:D≈3.3). The second region of efficient $p_{^3\text{He}}$ occurs at $X[\text{H}] \approx 70\%$ (H:D≈2.3), and even smaller $X[^3\text{He}] \approx 0.1\%$ is sufficient for almost total wave damping. For the latter heating regime, the concentration of ions, which absorb the RF power, is lower by an order of magnitude than for the standard minority heating scenarios. Hence, this potentially allows to accelerate resonant ions to much higher energies (MeV-range) in present-day devices or to compensate $\propto 1/n_e^2$ reduction of the minority tail energy in future machines. The former heating regime with $X[^3\text{He}] \sim 1\%$ can be used for bulk plasma heating, with the advantage of reduced ^{3}He consumption.

Figure 1(b) depicts the double-pass absorption by ^{3}He ions in (^{3}He)-DT plasmas (the only difference with Fig. 1(a) is that hydrogen fuel ions have been replaced with tritium ions). ^{3}He minority heating with $X[^3\text{He}] \approx 2-4\%$ is presently considered as the main ICRF option for the ramp-up phase in ITER D-T plasmas [1]. It is clear that in contrast to the (^{3}He)-D-H scenario, there is no region of the enhanced ^{3}He absorption at low $X[^3\text{He}] \lesssim 1\%$ in the intermediate D:T range. Then, one can conclude that a presence of three ion species is a necessary, but not a sufficient condition for the improved ion absorption at low X_{mino}. The next section of the paper shortly discusses the physics behind three-ion ICRF scenarios.

TWO-ION VS. THREE-ION MINORITY HEATING

ICRF heating relies on launching the fast magnetosonic wave (FW) into the plasma by external antennas, typically located at the low-field side (LFS) edge of the plasma. FW propagation across the plasma is fairly well described by the well-known dispersion relation [16, 17]

$$n_{\perp,\mathrm{FW}}^2 \simeq \frac{(\varepsilon_\mathrm{L} - n_\parallel^2)(\varepsilon_\mathrm{R} - n_\parallel^2)}{\varepsilon_\mathrm{S} - n_\parallel^2}, \tag{1}$$

where $n_{\perp,\parallel} = ck_{\perp,\parallel}/\omega$ is the perpendicular/parallel FW refractive index (with respect to the confining magnetic field), and the tensor components ε_S, ε_L and ε_R are those given by Stix [16]. ICRF power can be absorbed both by ions and electrons, depending on the chosen conditions for plasma heating. FW is absorbed by ions, when the wave crosses the ion cyclotron (IC) resonance ($\omega = \omega_{ci}$) and harmonic ($\omega = N\omega_{ci}$, $N \geq 2$) layers. Electron absorption is possible via a combination of electron Landau damping and transit time magnetic pumping, which have higher efficiency at higher plasma beta. Electron heating can also occur via mode conversion of the incoming FW to the shorter wavelength modes, which takes place at the ion-ion hybrid (IIH) resonance(s) in multi-ion plasmas.

FW is an elliptically polarized mode and its electric field can be decomposed as a sum of two components: the left-hand polarized component E_+, which rotates in the sense of ions in the magnetic field, and the right-hand polarized component E_- that is aligned with electron rotation. In his seminal paper [7], Stix showed that the absorbed RF power by thermal ions is almost merely due to the left-hand polarized component E_+. It is important to highlight here that it is the plasma, rather than the ICRF system, which defines the wave polarization and imposes the ratio between E_+ and E_- electric field components [18]

$$\left|\frac{E_+}{E_-}\right| \simeq \left|\frac{\varepsilon_\mathrm{R} - n_\parallel^2}{\varepsilon_\mathrm{L} - n_\parallel^2}\right|. \tag{2}$$

Though the characteristic $n_\parallel$, which appears in Eqs. (1) and (2), can be varied by changing the ICRF antenna phasing and operational frequency, the main contribution to Eq. (2) generally comes from the tensor elements.

One option for ion absorption in fusion plasmas is applying IC harmonic heating $N \geq 2$, for which $|E_+/E_-| \simeq (N-1)/(N+1)$. This damping mechanism is, however, a finite Larmor radius effect and hence is not appropriate for the beginning of the heating phase (low densities and low temperatures). More frequently another option for providing $E_+ \neq 0$ is adopted. For example, if one adds a few percent of hydrogen ions to the deuterium plasma, a very efficient absorption of RF power near the IC resonance of minority ions $\omega = \omega_\mathrm{cH}$ occurs. Two-ion minority heating is a well-established method, which has been routinely used for plasma heating. This scenario typically shows the best performance if operating with the minority concentrations $X_\mathrm{mino} \simeq 3-10\%$. However, the ratio of the left- to the right-hand polarization for such heating scenarios is limited [18]

$$\left|\frac{E_+}{E_-}\right|_{\omega=\omega_{c2}} \approx \left|\frac{\mathcal{Z}_2 - \mathcal{Z}_1}{\mathcal{Z}_2 + \mathcal{Z}_1}\right| < 1. \tag{3}$$

Here, we have introduced the notation $\mathcal{Z}_i = (Z/A)_i$, which stands for the ratio of the charge state to the atomic mass for various ion species. By way of example, for (H)-D minority heating $|E_+/E_-|_{\omega=\omega_\mathrm{cH}} \approx 1/3$, and this is well enough to obtain an efficient single-pass wave absorption at $X_\mathrm{H} \simeq 5\%$ (a typical H concentration used in the experiments). Yet, two-ion ICRF minority heating at much lower X_mino is usually characterized by poor wave absorption and for this reason is not often used in practice.

Now, we discuss briefly basic principles of the three-ion ICRF heating, taking (^{3}He)-D-H plasma illustrated in Fig. 1(a) as an example. Let first consider a two-ion deuterium-hydrogen plasma, without any ^{3}He present. When hydrogen concentration is small, the power absorption region is located close to $\omega = \omega_\mathrm{cH}$ resonance. As X_H is increased, the absorption region moves towards the IC resonance of D ions (see Fig. 2(a)). In the opposite limit, when deuterium concentration is small, the absorption should occur near $\omega = \omega_\mathrm{cD}$. However, (D)-H minority heating was not observed in JET with the carbon wall since the background level of carbon impurities (having the same $Z/A = 1/2$ as D ions) was too high [14]. In the intermediate range of H and D concentrations (see [15] for the discussion of the transition from minority ion to mode conversion heating), a mode conversion (MC) layer exists in the plasma bounded by the L-cutoff ($\varepsilon_\mathrm{L} = n_\parallel^2$) and the IIH resonance ($\varepsilon_1 = n_\parallel^2$). Within this region $n_{\perp,\mathrm{FW}}^2 < 0$ and FW is evanescent: its power is transmitted through the MC layer via tunneling. At the IIH resonance, FW is linearly polarized (this fact can be used for indirect estimation of the plasma composition in magnetospheric plasmas [19]). Fast wave

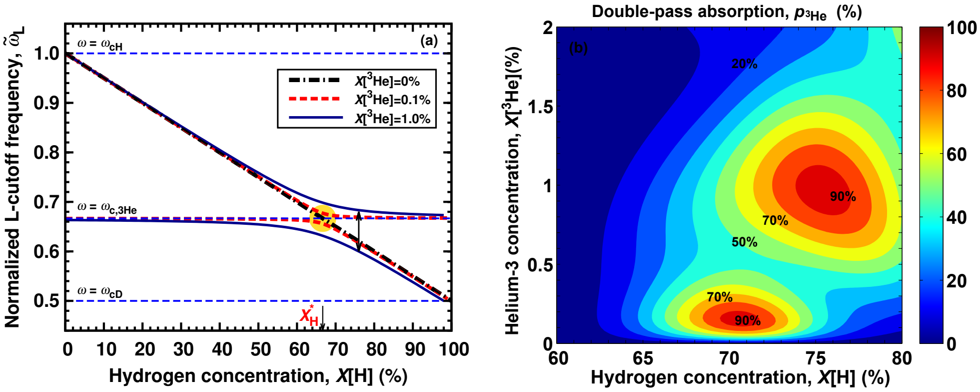

FIGURE 2. (a) Normalized L-cutoff frequency $\tilde{\omega}_L = \omega_L/\omega_{cH}$ (cold-plasma roots) as a function of hydrogen and ^{3}He concentrations in a (^{3}He)-D-H plasma. (b) Zoom of the $p_{^3He}$ absorption diagram shown in Fig. 1(a) and plotted as a function of $X[H]$ and $X[^3He]$.

becomes almost purely left-hand polarized at the L-cutoff, as E_- component vanishes according to Eq. (2). However, if a plasma includes only two ion species (D and H in the considered example), none of them is able to profit from the E_+ enhancement since the MC layer is located too far from the IC resonances. Setting low the concentration of one of ion species, brings the absorption region close to the $\omega = \omega_{ci}$ resonance, but a back transition to two-ion minority heating occurs.

An improved ion absorption at low X_{mino} becomes possible if the third ion species is present in the plasma and the L-cutoff in a two-ion plasma is located close to the IC resonance of the third species. Since ω_L is bounded between ω_{c1} and ω_{c2}, one of the required conditions for the three-ion ICRF heating is

$$\min\{\mathcal{Z}_1, \mathcal{Z}_2\} < \mathcal{Z}_3 < \max\{\mathcal{Z}_1, \mathcal{Z}_2\}. \tag{4}$$

(^{3}He)-DT heating scenario does not satisfy Eq. (4), and this explains a dramatic difference between the two scenarios depicted in Fig. 1. For D-H plasmas, the third ion species should have Z/A ratio between 1/2 and 1 that justifies the choice of ^{3}He ions with $\mathcal{Z}_3 = 2/3$ as a resonant absorber. For the given $\mathcal{Z}_i$ values of three ion species present in the plasma, one needs also to set a proper density ratio between the two main species. It is clear that the here discussed effect is maximized in the vicinity of the resonant intersection of two curves ω_L and ω_{c3}, as highlighted in Fig. 2(a). The optimal concentrations of two main ion species can be estimated as follows [11]

$$X_1^* = \frac{1}{Z_1}\left[\frac{\mathcal{Z}_1 - \mathcal{Z}_3}{\mathcal{Z}_1 - \mathcal{Z}_2}\right], \quad X_2^* = \frac{1}{Z_2}\left[\frac{\mathcal{Z}_3 - \mathcal{Z}_2}{\mathcal{Z}_1 - \mathcal{Z}_2}\right]. \tag{5}$$

In D-H plasmas, the L-cutoff intersects the IC resonance layer of ^{3}He ions at $X_H^* \approx 67\%$. Figure 2(a) also illustrates solutions of the equation for the L-cutoff frequency in a cold-plasma approximation computed for two different ^{3}He concentrations. One can notice a strikingly different behaviour of ω_L for $X[^3\text{He}] = 0$ and $X[^3\text{He}] \neq 0$: for the latter case, the curve for ω_L is split into two near $X_H \approx X_H^*$.

Figure 2(b) is a zoom of the $p_{^3He}$ absorption diagram shown in Fig. 1(a) and is plotted as a function of H and ^{3}He concentrations. The approximation given by Eq. (5) is in good agreement with numerical results: TOMCAT predicts the enhanced ^{3}He absorption $p_{^3He} > 90\%$ at $X_{^3He} \approx 0.1\% - 0.2\%$ and $X_H \approx 70\% - 71\%$. For $X_{^3He} = 0.15\%$, the double-pass absorption remains strong $p_{^3He} > 50\%$ for relatively wide range of hydrogen concentrations, viz. $X_H \approx 66\% - 75\%$. The second region with efficient ^{3}He absorption is reached at $X_{^3He} \approx 1\%$ and $X_H \approx 76\%$. By exploring Fig. 2(a), it is clear why for this heating regime the hydrogen concentration should be somewhat higher than X_H^*: for $X < X_H^*$, the MC layer and L-cutoff start to move quickly out of the ion heating region $\omega \approx \omega_{c,^3He}$ towards the LFS edge.

The radial dependence of the FW perpendicular wavenumber for the two computed cases of optimal ^{3}He heating is plotted in Figs. 3(a) and (b). In both cases the RF power is absorbed by ^{3}He minority ions close to their fundamental resonance. The heating maximum is located at the place, where a sharp change of $\text{Re}[k_{\perp,\text{FW}}^2]$ and a maximum of $\text{Im}[k_{\perp,\text{FW}}^2]$ occur. This almost coincides with the cold-plasma IIH resonance; however, in a hot plasma, the well-separated MC layer is not formed yet for such low minority concentrations. At the IIH resonance, FW is polarized

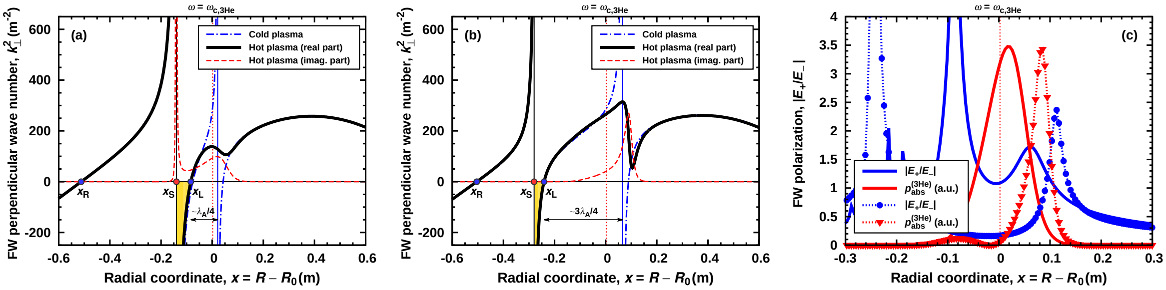

FIGURE 3. Radial dependence of $k^2_{\perp,\mathrm{FW}}$ for two optimal ^{3}He absorption cases depicted in Fig. 2(b): (a) $X[^3\mathrm{He}] = 0.15\%$ and $X[\mathrm{H}] = 71\%$; (b) $X[^3\mathrm{He}] = 1\%$ and $X[\mathrm{H}] = 76\%$. (c) Radial dependence of $|E_+/E_-|$ and 1D ^{3}He power deposition profiles for cases with $X[^3\mathrm{He}] = 0.15\%$ (solid lines) and $X[^3\mathrm{He}] = 1\%$ (dotted lines with symbols).

linearly $E_+/E_- \simeq 1$, which implies $E_y \to 0$ (the poloidal RF electric field). Consequently, the local spatial damping decrement, which is proportional to $|E_+/E_y|^2$ [17], can be enhanced. Polarization $|E_+/E_-|$ varies strongly radially in the vicinity of the IC resonance of ^{3}He ions (Fig. 3(c)). For conditions of Fig. 3(a), $|E_+/E_-|$ has a local minimum ≈ 1.1 that is much higher than the characteristic value for the two-ion minority heating (Eq. (3)). In case of heating regime shown in Fig. 3(b), $|E_+/E_-|$ is maximized at the L-cutoff points and has a minimum near ^{3}He resonance $|E_+/E_-| \approx 0.16$.

A more detailed dispersion analysis reveals an importance of the constructive/destructive interference on the absorption efficiency $p_{^3\mathrm{He}}$. The FW excited from the LFS edge is reflected the first time in a region close to ^{3}He IC resonance, where $\mathrm{Im}[k^2_{\perp,\mathrm{FW}}]$ is maximized and a variation of $\mathrm{Re}[k^2_{\perp,\mathrm{FW}}]$ occurs. The wave transmitted through this region is reflected then from the L-cutoff located to the higher magnetic field side of $\omega = \omega_{c,^3\mathrm{He}}$ resonance (denoted as x_L). The wave reflected at x_L propagates back towards ^{3}He resonance and is reflected back again (though Budden theory predicts zero wave reflection for the high-field side (HFS) wave incidence, a non-zero wave reflection occurs due to the finite $\mathrm{Im}[k^2_{\perp,\mathrm{FW}}]$). The resulting reflected wave at the LFS edge depends on the amplitudes and phases of such elementary reflected waves. Not surprisingly, we find that ^{3}He absorption maximizes, when approximately an odd number of the quarter of the average FW wavelength (for the considered conditions, $\lambda_\mathrm{A} \approx 40$ cm) fits within the two reflecting points. For the three-ion heating with $X[^3\mathrm{He}] \approx 0.15\%$, the separation distance is about $\lambda_\mathrm{A}/4$, whereas for the heating regime with higher $X[^3\mathrm{He}] \approx 1\%$, this distance is $\approx 3\lambda_\mathrm{A}/4$. For the heating regime with lower $X[^3\mathrm{He}]$, the radial width of the MC layer is larger and hence less power undergoes parasitic mode conversion at the IIH resonance and reaches the HFS R-cutoff x_R.

There is another argument in support of the three-ion ICRF scenarios. The spectrum of the FW parallel wavenumbers $k_\parallel$ excited by the ICRF antenna, affects not only RF absorption, but also determines the RF coupling efficiency. Before FW starts its propagation in the plasma, it needs first to tunnel through the evanescence layer in front of the antenna ($n^2_{\perp,\mathrm{FW}} < 0$ between the antenna strap and the low-density R-cutoff, defined by $\varepsilon_\mathrm{R} = n^2_\parallel$). Because of the large evanescence gap, solving the coupling problem (see [20]) is the main challenge for the ICRF system in the next-step fusion machines. For the traditional two-ion ICRF minority heating there is a well-known tradeoff between efficient coupling, which requires low $k_\parallel$, and efficient absorption that increases for higher $k_\parallel$. The reduction of RF coupling at higher $k_\parallel$ is due to the fact that the tunneling efficiency exponentially decreases with the product $|k_\parallel|d$, where d is the width of the evanescence layer in front of the ICRF antenna. An active studies are ongoing to improve ICRF coupling in H-mode plasmas. For example, puffing an extra gas in front of the antenna to increase the local plasma density and thus decrease d has been extensively explored [21, 22].

A substantial decrease of p_abs for lower $k_\parallel$ is clearly seen in Fig. 4(a) for (H)-D heating scenario with $X[\mathrm{H}] \approx 5\%$. The same trend is observed for the three-ion ICRF heating with higher $X[^3\mathrm{He}] \approx 1\%$ and $X[\mathrm{H}] \approx 76\%$. However, for the three-ion regime with very small $X[^3\mathrm{He}] \approx 0.1\%$, RF absorption efficiency remains very strong $p_{^3\mathrm{He}} > 70\%$ for all practically relevant $k_\parallel$. Therefore, for this heating scenario, operation with ICRF phasings with lower-$k_\parallel$ spectra (e.g., $[0;\pi;\pi;0]$, $[0;0;\pi;\pi]$ or current drive $\pm\pi/2$) might be beneficial in view of increasing the coupling efficiency and avoiding low absorption regimes. From the point of improving antenna-plasma coupling, reducing d or reducing the dominant $|k_\parallel|$ for operation is equally good.

The considered three-ion absorption scenarios implicitly assume that the FW mode conversion efficiency is small. If that is not justified, a significant fraction of the FW power can tunnel through the MC layer and be converted to the

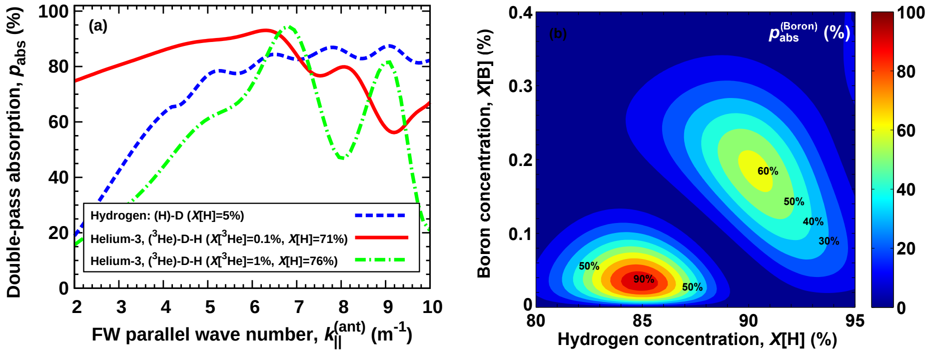

FIGURE 4. (a) Double-pass absorption efficiency as a function of the FW parallel wavenumber for (H)-D and (^{3}He)-D-H ICRF scenarios. (b) (B)-T-H three-ion ICRF scenario: an efficient RF absorption by boron ions is possible in T:H≈15%:85% plasmas.

ion Bernstein or ion cyclotron waves. This will result in a loss of the efficiency of minority ion heating near $\omega \approx \omega_{c3}$. Since the tunneling factor η, which determines the fraction of power transmitted through the MC layer $\mathcal{T} = e^{-\pi\eta}$, increases with plasma density and R_0, parasitic MC effects will be less important for larger machines operating at higher n_e.

FAST ION GENERATION

Because of high absorption efficiency at very low minority concentrations, the three-ion ICRF scenarios have a potential to be more effective for fast ion generation than the standard minority heating. According to Stix, the tail energies of minority ions heated at $N = 1$ resonance are given by [7]

$$E_{\text{mino}} \simeq k_0 T_e \xi_{\text{mino}}^{(\text{Stix})}, \quad \xi_{\text{mino}}^{(\text{Stix})} = \frac{m_{\text{mino}} v_{te} \langle P_{\text{RF}} \rangle}{4\sqrt{2\pi} X_{\text{mino}} n_e^2 Z_{\text{mino}}^2 e^4 \ln\Lambda}. \tag{6}$$

Here, n_e is the local plasma density, $\langle P_{\text{RF}} \rangle$ stands for the local RF power density absorbed by minority ions, $v_{te} = (T_e/m_e)^{1/2}$ is the thermal velocity of electrons; X_{mino}, Z_{mino} and m_{mino} is the concentration, the charge state and the mass of the resonant ions, respectively. As discussed above, future fusion devices will operate at higher plasma densities and will be larger in linear size (lower power densities). Hence, $\xi_{\text{mino}}^{(\text{Stix})}$ will be smaller than for the present-day experiments (for comparable RF power coupled) and minority tails will be less energetic. Accordingly, RF-heated minority ions will transfer a larger fraction of power to bulk ions via collisions. However, if fast ions are needed in a plasma for any reason, their generation in a higher density plasmas becomes more complicated. Basically one should either couple more RF power to the plasma or develop RF scenarios with lower X_{mino}.

For the (^{3}He)-D-H scenario, Eq. (6) yields $\xi_{^3\text{He}} \approx 0.18\, T_{e,\text{keV}}^{1/2} P_{\text{RF}}/(n_{e,20}^2 X[^3\text{He}])$, where $n_{e,20}$ is the plasma density expressed in the units 10^{20} m^{-3} and the absorbed power density is in MW/m^3. For the conditions of Fig. 1, the evaluated power densities are of the order of $P_{\text{RF}} \approx 1.5$ MW/m^3 per 1 MW of ICRF power injected to the plasma (if ^{3}He temperature is kept at the thermal level). The deposited power density reduces if accounting for the development of the high-energy ^{3}He tail. For $T_{\text{eff}}[^3\text{He}] = 1$ MeV, we have evaluated central power densities $P_{\text{RF}} \approx 0.5$ MW/m^3/MW$_{\text{inj.}}$ For JET-like plasmas with $X[^3\text{He}] = 0.2\%$, the (^{3}He)-D-H heating yields the acceleration factor $\xi_{^3\text{He}} \simeq 200 P_{\text{RF}}(\text{MW})$. With a very modest amount of ICRF power coupled to the plasma, one can expect generation of MeV-range ions. For the baseline parameters of W7-X ($T_0 = 3$ keV, $n_{e0} = 2\times 10^{20}$ m^{-3}), Eq. (6) yields $\xi_{\text{mino}} \approx 0.1 A_{\text{mino}} \langle P_{\text{RF}} \rangle / (Z_{\text{mino}}^2 X_{\text{mino}})$. For W7-X, $\xi_{\text{mino}} \gtrsim 20-30$ is to be achieved ($E_{\text{mino}} \simeq 50-100$ keV). Then,

$$P_{\text{ICRF}}(\text{MW}) \gtrsim 2.5 X_{\text{mino}}(\%) (Z_{\text{mino}}^2/A_{\text{mino}}) \Delta V(\text{m}^3), \tag{7}$$

gives an estimate of the required coupled ICRF power. Here, ΔV is a volume where the RF power is deposited. The volume of W7-X plasma is 30 m^3 and $\Delta V \simeq 5$ m^3 is assumed for the illustration purpose. If applying H minority heating with $X[\text{H}] = 1\%$, $P_{\text{ICRF}} > 10$ MW is needed in order to generate fast hydrogen ions of the required energies at the given high plasma density. In W7-X, the planned coupled ICRF power is 1–2 MW only. Clearly, lowering the operational plasma density by a factor 2–3 is a possible way out, at the expense of decreasing β. Another solution is a further reduction of the concentration of minority ions $X_{\rm mino}$ ($\sim$ by an order of magnitude). Our computations show that for the W7-X conditions $p_{^3\rm He} > 80\%$ is reached for such low $X[^3\rm He]$ as 0.02% [11], and therefore the task envisaged for the ICRF system in W7-X seems to be plausible if a potential of the three-ion ICRF scenarios is confirmed experimentally. These estimates do not account for the actual 3D geometry of the W7-X and do not include a self-consistent treatment of the evolution of the distribution function and absorption efficiency. The main message behind the arguments given in this paragraph is to show that one needs to utilize minority concentrations much less than 1% for fast ion generation in W7-X operating at the full plasma density. Finally, a very similar ICRF scenario is relevant for the non-activated phase of ITER or any other fusion machine: if neutron generation is forbidden, deuterium ions can be replaced with an equivalent content of ^{4}He ions, which have the same $Z/A = 1/2$.

It goes without saying that before the potential of the three-ion ICRF scenarios is verified experimentally, any discussion of their applications is rather speculative. However, as noted in [11], we believe that there is already an experimental evidence of the strength of the three-ion ICRF heating. In [23], it was reported that in the initial D-T experiments in the TFTR tokamak, most of the RF power was absorbed by residual ^{7}Li impurities. This impurity satisfies Eq. (4), and the D:T ratio required for the efficient three-ion absorption is very close to the optimal D:T=1:1, most often used experimentally. According to the results reported in [23], most of the RF power was absorbed directly by ^{7}Li impurities ($X[^7\rm Li] \simeq 0.5\%$) and only about 20% of the RF power was channeled to electrons.

Another possible three-ion ICRF scenario is the acceleration of boron ions ($\mathcal{Z}_3 = 5/11$) in a tritium-hydrogen plasma mixture. This could be relevant for the aneutronic fusion studies: $p + {}^{11}\rm B \longrightarrow 3\alpha + 8.7$ MeV. The cross-section of this fusion reaction peaks at the center-of-mass energy $E_{\rm CM} \approx 590$ keV [24]. Typically, a boron target is bombarded with a high-energy proton beam. Using the three-ion (B)-T-H scheme, boron ions can be accelerated to MeV energies ($E_{\rm B} \simeq 7$ MeV comes from the transformation of $E_{\rm CM}$ to the laboratory frame) in a way discussed above and will collide with the relatively cold background protons. Figure 4(b) illustrates that a very efficient RF power absorption occurs at $X[\rm B] \approx 0.05\%$ in T:H=15%:85% plasmas. For the computations, we have used similar parameters as for Fig. 1, except of $B_0 = 3.6$ T, $f = 25$ MHz and $n_{\rm tor} = 14$. Though the discussion of the economic relevance of the proposed method is out of scope of the paper, we wish to highlight an application of the three-ion heating scenarios as a tool for ion acceleration. Note that (B)-T-H scenario can not be checked in JET with the new ITER-like wall (ILW) installed: the background concentration of beryllium impurities, which have a similar Z/A ratio as B ions, is already too high.

BULK ION HEATING

Since August 2011, JET is operating with the new ITER-like wall, and uses beryllium (Be) and tungsten as the new plasma facing materials. Since $\mathcal{Z}_{\rm T} < \mathcal{Z}_{\rm Be} < \mathcal{Z}_{\rm D}$, we suggest (Be)-D-T scenario as a heating scheme for the activated operation phase of JET and ITER. Accurate measurements of the concentration of Be impurities in the plasma center are not readily available. The background level of Be impurities in JET-ILW has been estimated to be $1-3\%$. For the central Be heating, the RF frequency should satisfy $f(\rm MHz) \approx 6.8\, B_0(T)$. For JET operating at $B_0 = 3.6$ T, the lowest frequency available for A2 ICRF antennas $f = 25$ MHz has to be adopted.

This scheme is particularly relevant for the ramp-up phase of a plasma pulse. Currently, $X[^3\rm He] = 2\% - 4\%$ minority heating is considered as a main option for D-T plasmas. Beryllium impurity heating has two advantages over ^{3}He minority heating. Firstly, adding $X[^3\rm He]$ results in a plasma dilution. This effect is not negligible: e.g., for $X[^3\rm He] = 4\%$, the fusion reactivity decreases by 15% because of lower $n_{\rm D}n_{\rm T}$. The second advantage of Be heating is a higher fraction of bulk ion heating than for (^{3}He)-DT scenario. Be impurities are three times heavier than ^{3}He ions and the critical energy $E_{\rm crit}$ (fast-ion energy at which it transfers an equal power to bulk ions and to electrons) is higher by the same factor. Figure 5 shows the DPA coefficients by Be impurities (direct RF absorption) in D-T JET-like plasma for three different toroidal wavenumbers. For the given parameters, $p_{\rm Be} \simeq 70\%$ can be reached. The rest of the power is absorbed by D ions ($p_{\rm D} \sim 20\%$) and electrons ($p_e \sim 10\%$). As T_i increases, the fraction of fusion-born alpha-particles starts to increase. Parasitic RF power absorption by high-energy alphas might be a potential showstopper for this scenario during the burn phase of a pulse. Note that for the JET pulse 42769, $X_{\rm Be} \approx 1.5\%$ was reported and Be impurities were estimated to absorb about 40% of the RF power [18]. Such a non-negligible Be heating was observed even though the IC resonance of Be impurities was located off-axis and although the used D:T ratio ($X_{\rm D} = 18\%$) was quite different to the optimal values we have computed.

(Be)-D-T heating scenario is also relevant for ITER. For the full-field ITER regime ($B_0 = 5.3$ T), the impurity absorption region is located HFS off-axis ($r/a \simeq 0.35$) if operating at $f = 40$ MHz. ITER RF generators are foreseen to deliver RF power in the range $f = 35-65$ MHz [25]. A more central heating can be obtained if the ITER frequency range can be extended to include the operational frequency $f \approx 37-38$ MHz. For ITER, we have estimated that about 80% of the RF power is transferred collisionally to fuel D and T ions for Be heating scenario. Finally, the proposed

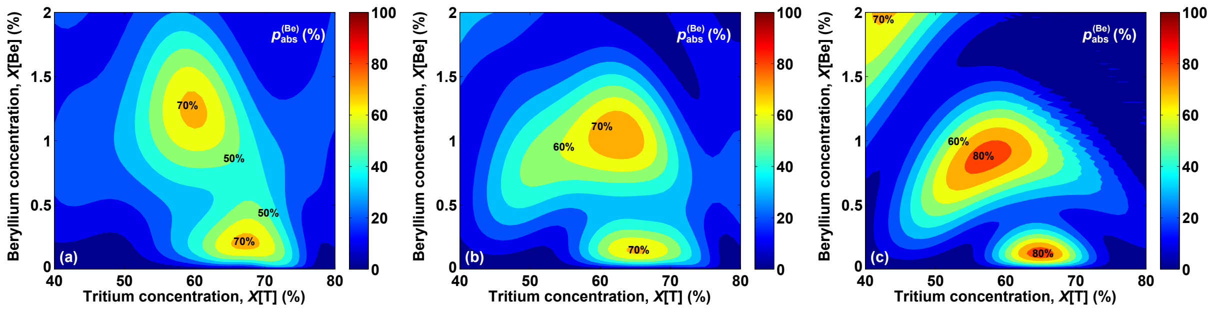

FIGURE 5. Double-pass absorption by Be impurities in D-T plasma: (a) $n_{\rm tor} = 27$; (b) $n_{\rm tor} = 21$ and (c) $n_{\rm tor} = 14$. (JET-like plasma, f=25 MHz, B_0 = 3.6 T, T_0 = 4 keV, $n_{e0} = 7 \times 10^{19}$ m^{-3}).

$N = 1$ impurity heating in D-T plasmas is equally relevant for DEMO and future fusion reactors. If for any reason Be can not be used as a wall material, this can be equally replaced with the other impurities with a similar charge-to-mass ratio, viz. ^{7}Li, ^{22}Ne, ^{40}Ar.

CONCLUSIONS

Plasma heating with ICRF waves is an efficient method of plasma heating in present-day tokamaks and stellarators. A new set of three-ion heating scenarios discussed in the paper have a potential to extend applications of ICRF system in fusion research. The scenarios in question have a strong RF power absorption possible if operating with very low concentrations of resonant ions, $\sim$ 1% and even below. Because of this feature, three-ion ICRF heating can push minority ions to much higher energies than for the standard minority heating. Acceleration of ^{3}He ions in D:H $\approx$ 1:2 (or alternatively ^{4}He:H) plasmas is proposed as a dedicated tool for fast ion generation in JET and future higher density devices like W7-X and ITER. Heavy intrinsic impurities with $1/3 < Z/A < 1/2$ can be an efficient absorber of the ICRF power in D-T plasmas. Fundamental ICRF heating of beryllium impurities is suggested for increasing the temperature of bulk ions during the ramp-up phase of plasma pulses in JET and ITER.

Acknowledgements. This work has been carried out within the framework of the EUROfusion Consortium and has received funding from the Euratom research and training programme 2014–2018 under grant agreement No. 633053. The views and opinions expressed herein do not necessarily reflect those of the European Commission.

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