Search for Ion Heating Scenarios in Burning D-T Plasmas with ICRH

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Abstract. Various ICRH scenarios relevant for the D-T phase of the JET tokamak operation are studied. It is known that an enhancement of the heating efficiency in the mode conversion regime (when the concentrations of D and T species are comparable) is possible due to the constructive interference of the reflected fast waves. Such a heating enhancement in D-T plasma is investigated first for the JET-like conditions for both dipole and $+\pi/2$ ICRH antenna phasings, and for T concentration varied from 0 to 100%. It is shown that most of the considered scenarios suffer from the parasitic absorption caused by the presence of fusion-born alpha-particles and NBI-produced fast particles. It is found that thermal ion heating becomes dominant in tritium-rich plasmas with T concentration ~80%. This scenario is compared with the alternative ^{3}He minority ICRH scenario in D:T=50:50 plasmas.

1. Introduction

Plasma heating using electromagnetic waves in the ion cyclotron range of frequencies (ICRH) is widely used in present-day fusion devices and is foreseen as one of the main heating schemes in the next-step burning plasma ITER experiment [1]. ICRH has a number of advantages among another radiofrequency (RF) methods: technological feasibility of the RF system for this frequency range (f = 20–120 MHz), no density limits for the fast Alfvén (compressional) wave (FW) to access the high-density plasma core, satisfactory coupling efficiency, existence of various efficient linear damping mechanisms that allows to change the channel of heating to ion or electron according to the chosen heating scenario [2, 3]. ICRH is also one of the most cost effective heating systems envisaged for ITER.

In contrast to fusion-born alpha-particles and MeV-range NBI-produced ions in ITER, which mostly heat electrons, ICRH is the only scheme capable of delivering direct heating of thermal ions. The use of ion heating scenarios could enhance significantly the fusion reactivity and also make a bridge to present-day large tokamaks, in which the main heating power of 100-150 keV NBI provides dominant ion heating.

It is well known that for efficient ICRH heating at the fundamental cyclotron frequency ($\omega = \Omega_i$) one needs to operate with the plasma consisting of at least two different ion species. Depending on the relative concentration of ion species, two heating regimes are usually distinguished: ion minority heating (MH) and mode conversion (MC) [4]. In the MH regime, the majority ions provide favorable polarization of the FW at the region of the fundamental resonance of the minority ions, which absorb the RF energy and transfer it to bulk plasma particles via collisions leading to either ion or electron heating, depending on the ratio between the minority tail energy, $E_{\rm tail}$, and the critical energy, $E_{\rm crit} = 14.8\, A_f T_e (\sum_i n_i/n_e\, Z_i^2/A_i)^{2/3}$ (here, A_f and A_i are the atomic masses of fast and bulk ions). The MC regime becomes dominant at enough large concentrations of minority species, and it is characterized by a partial conversion of the FW to a short wavelength wave at the region of the ion-ion hybrid resonance. The converted wave is usually efficiently absorbed by electrons within a narrow spatial region.

An enhancement of ICRH efficiency in the MC regime due to the constructive/ destructive interference effect described in [5] was experimentally validated recently in (^{3}He)-D and (^{3}He)-H JET plasmas [6, 7]. This paper aims at exploiting the interference effect for increasing the efficiency of MC and bulk ion heating in D-T plasma for the conditions of tokamak JET. Previously, ICRH scenarios relevant for ITER D-T phase were studied in [8, 9]. Since most of the considered ICRH scenarios could suffer from the parasitic absorption by fast ion populations [10, 11], one should optimize the heating scenarios for lower values of the parasitic absorption by NBI-produced fast ions and alpha-particles.

2. Heating enhancement in D-T plasma due to the constructive interference effect

For a reference D-T scenario, consider the plasma parameters which are close to those obtained in D-T experiments performed on the JET tokamak [12, 13]. The antenna frequency is kept as low as possible ($f=\omega/2\pi=23$ MHz), the central magnetic field is $B_0=3.6$ T, which places both the fundamental cyclotron layers of deuterium and tritium inside the plasma ($R_D=3.53$ m, $R_T=2.35$ m) on an equal distance from the plasma edge (Fig. 1(a)). This choice of B_0 and f allows to vary the heating channel (deuterium, tritium or electron) changing the D:T ratio. Central plasma density and temperature are assumed to be: $n_{e0}=3.0*10^{13}$ cm^{-3}, $T_{e0}=7.2$ keV, $T_{i0}=6.6$ keV. Fig. 1(a) also shows the location of the mode conversion and fast wave cutoffs layers for the tritium concentration $X[T]=n_T/n_e=70\%$ and toroidal wavenumber $n_\varphi=27$ (dominant wavenumber for the dipole phasing of A2 ICRH antenna [14]).The shaded area represents a region where the FW is a propagative mode, $k_{\perp,\mathrm{FW}}^2 > 0$.

Spatial variation of the perpendicular wavenumber for the FW propagating in the equatorial plane is shown in Fig. 2(b). The R-cutoff located at the low field side (LFS) edge, $x_{R,\,LFS}$ complicates the coupling of the RF energy from ICRH antenna to the plasma. The FW – as a carrier of the RF energy – must first tunnel through the evanescence layer in front of the antenna before it starts its propagation in the plasma. Reaching the plasma center, the FW is partially reflected from the L-cutoff, x_L. As Fig. 1(a) shows, part of the FW is transmitted through the MC layer, x_S, which is then reflected back from the R-cutoff at the high field side (HFS), $x_{R,\,HFS}$. The FW reflected from the HFS R-cutoff tunnels through the MC layer without supplementary reflection. As a result, the total reflection and, thus, absorption coefficients depend on the amplitudes and phases of these two reflected fast waves. Provided the reflected waves have equal amplitudes and the opposite phases, the reflection coefficient is diminished that, in turn, results in the MC heating enhancement. Analytical formula for the conversion coefficient (and subsequently, for electron heating provided direct electron damping of the FW and minority ion absorption are negligible) in such a structure known as a triplet configuration was derived in [5]:

$$P_e = 4T(1-T)\sin^2(\Delta\phi/2), \tag{1}$$

where $T=\mathrm{e}^{-\pi\eta}$ is the transmission coefficient through the MC layer, and $\Delta\phi$ is the phase difference between two reflected waves (determined mostly by the distance between the MC layer and the HFS R-cutoff). The tunneling factor, η, which is as a product of the FW perpendicular wavenumber (density dependent) by the width of the conversion layer, defines the accessible maximal level of the MC. It depends on most of plasma parameters, such as plasma density, minority concentration, magnetic field, etc. The tunneling factor is also particularly sensitive to the FW toroidal wavenumber. On JET, ICRH A2 antenna consists of four vertical current straps which can be phased individually ±180º with respect to a phase reference signal. Varying the phase difference between the currents in two adjacent straps, different antenna spectra can be employed. As shown in Fig. 2(a), changing the antenna phasing from the dipole ($n_\varphi=27$) to $+\pi/2$ phasing ($n_\varphi=14$), results not only in the increase of the MC layer width by a factor of 2, but it also leads to a pronounced shift of the HFS R-cutoff towards the edge extending largely the region of the FW propagation in the plasma.

ICRH absorption efficiency was evaluated with the 1D full-wave code TOMCAT [15]. This code solves a 12th order wave equation system accounting for the toroidal curvature of the tokamak, but omitting the finite poloidal magnetic field effects. The imposed boundary conditions correspond to the pure excitation of the FW from the low field side. TOMCAT gives scattering coefficients (reflection, transmission, conversion and absorption) for a double transit over the plasma. The evaluation of a douple-pass absorption coefficient allows one to estimate qualitatively the heating efficiency of the studied ICRH scenario. However, this gives only qualitative results since a number of effects are omitted in 1D geometry. More rigorous treatment of the FW propagation and mode conversion in tokamaks should be essentially based on the 2D full-wave modelling.

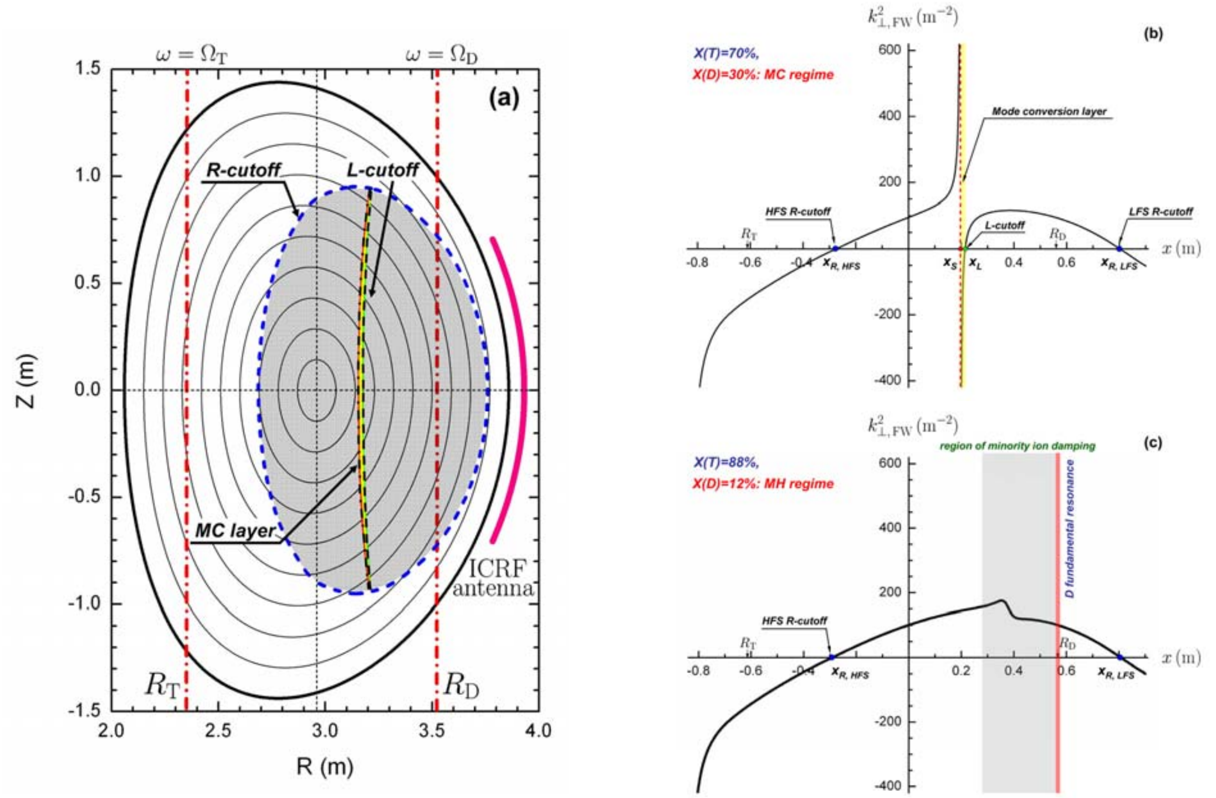

Figure 1. *(a) Locations of the fundamental cyclotron resonance layers of deuterium and tritium (R_D and R_T) with the locations of the mode conversion and fast wave cutoffs layers in the poloidal cross-section, n_φ=27, B_0=3.6 T, f=23 MHz, T:D=70:30. (b),(c) Dispersion of the FW propagating in the equatorial plane: (b) X[T]=70% (MC regime), (c) X[T]=88% (MH regime).*

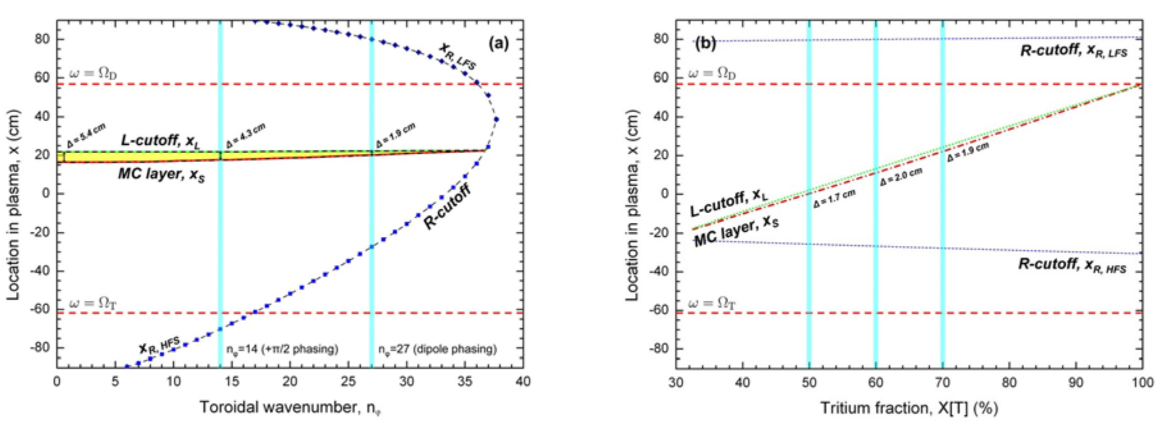

Figure 2. *(a) Locations of the FW cutoffs and mode conversion layer vs. the toroidal wavenumber. (b) Locations of the FW cutoffs and mode conversion layer vs. the tritium fraction, n_φ=27.*

Figs. 3(a) and 3(b) show the computed dependence of the absorption efficiency as a function of the tritium concentration for n_φ=27 and n_φ=14, respectively. By varying X[T], one changes the transparency of the MC layer (which defines maximal absorption) as well as the distance between the MC layer and the HFS R-cutoff, hence, modifying the interference phase conditions (Fig. 2b). As predicted by (1), the absorption coefficients vary oscillatory with the change of X[T]. For n_φ=27 there are three pronounced maxima achieved at X[T]=44%, X[T]=69% and X[T]=88%. The first two correspond to the MC regime and give rise to electron heating. The third maximum at X[D]=12% corresponds to the MH ion regime. For n_φ=14 absorption curves have more number of maxima since for this phasing the R-cutoff is located far closer to the HFS edge.

2.1. Ion heating enhancement in the MH regime

It was previously shown in [5, 16], that due to the additional reflection of the FW from the HFS R-cutoff or the supplementary MC layer significant improvement of the electron heating is possible. As shown in this paper below, the interference effect could increase not only electron heating in the MC regime, but also ion heating in the MH regime.

We apply similar logics to that described in [5, 16] to explain the ion heating enhancement in the MH regime caused the additional reflection of the FW from the HFS R-cutoff (Figs. 3(a) and (b)). First, consider the distribution of RF power in a system without R-cutoff. Then, while propagating through minority fundamental resonance layer ($\omega \approx \Omega_{\min}$), part of the FW energy is transmitted, T and part of the energy is absorbed, P_1 which is usually referred to as a single-pass absorption coefficient. However, there is also a small non-zero fraction of the reflected energy (Fig. 4(a)). Being usually very small ($R \lesssim 5\%$), this reflection plays a minor role in a single-pass transit. But for a double-pass transit, this non-zero reflection is a key condition for the ion heating enhancement.

Fig. 4(b) shows that if the HFS R-cutoff is present in the plasma, then the transmitted wave is reflected back to the plasma center. After transmitting the resonance layer $\omega \approx \Omega_{\min}$, the FW field pattern at the LFS is again (as for the MC regime) determined by the interference of two reflected wave. One should prove that in such a system (Fig. 4(b)) a double-pass ion absorption coefficient equals to:

$$\begin{gathered} P_i = P_{\min} + 4T\sqrt{R}\,\sin^2(\Delta\phi/2), \\ P_{\min} = 1 - (T + \sqrt{R})^2 = P_1 + T(1 - T - 2\sqrt{R}), \\ P_{\max} = P_{\min} + 4T\sqrt{R} = P_1 + T(1 - T + 2\sqrt{R}). \end{gathered} \tag{2}$$

If the reflection coefficient equals to $R = (1-T)^2$ (this case describes the isolated Budden MC layer), then formulas (2) reduce to the that obtained by Fuchs in [5]: $P_{\min} = 0$, $P_{\max} = 4T(1-T)$, $P = 4T(1-T)\sin^2(\Delta\phi/2)$. However, for the ion heating scenarios the reflection coefficient, R is usually only a few percent. So, for the given P_1 and T the ion absorption coefficient varies from its minimal ($P_{\min}$) to its maximal ($P_{\max}$) value depending on the exact value of the phase difference, $\Delta\phi$. As shown later, even a small reflection of the FW from $\omega \approx \Omega_{\min}$ resonant layer at the level 3-5% could lead to the increase of the ion heating efficiency by ~40-50%. This effect was numerically shown in [6, Fig. 2(a)], where a pronounced maximum at X[^{3}He]=8% gave rise to an efficient minority ion heating in (^{3}He)-D plasma.

Figs. 3(a) and 3(b) depict that it is possible to tune the plasma parameters in such a way providing efficient ICRH heating in D-T plasma (both for the MC and the MH regimes) due to the additional reflection of the FW from the HFS R-cutoff. However, this modelling excludes any fast ion populations in D-T plasma, such as NBI-produced fast ions and fusion-born alpha-particles.

n_φ=27 (dipole phasing): **n_φ=14** (+π/2 phasing):

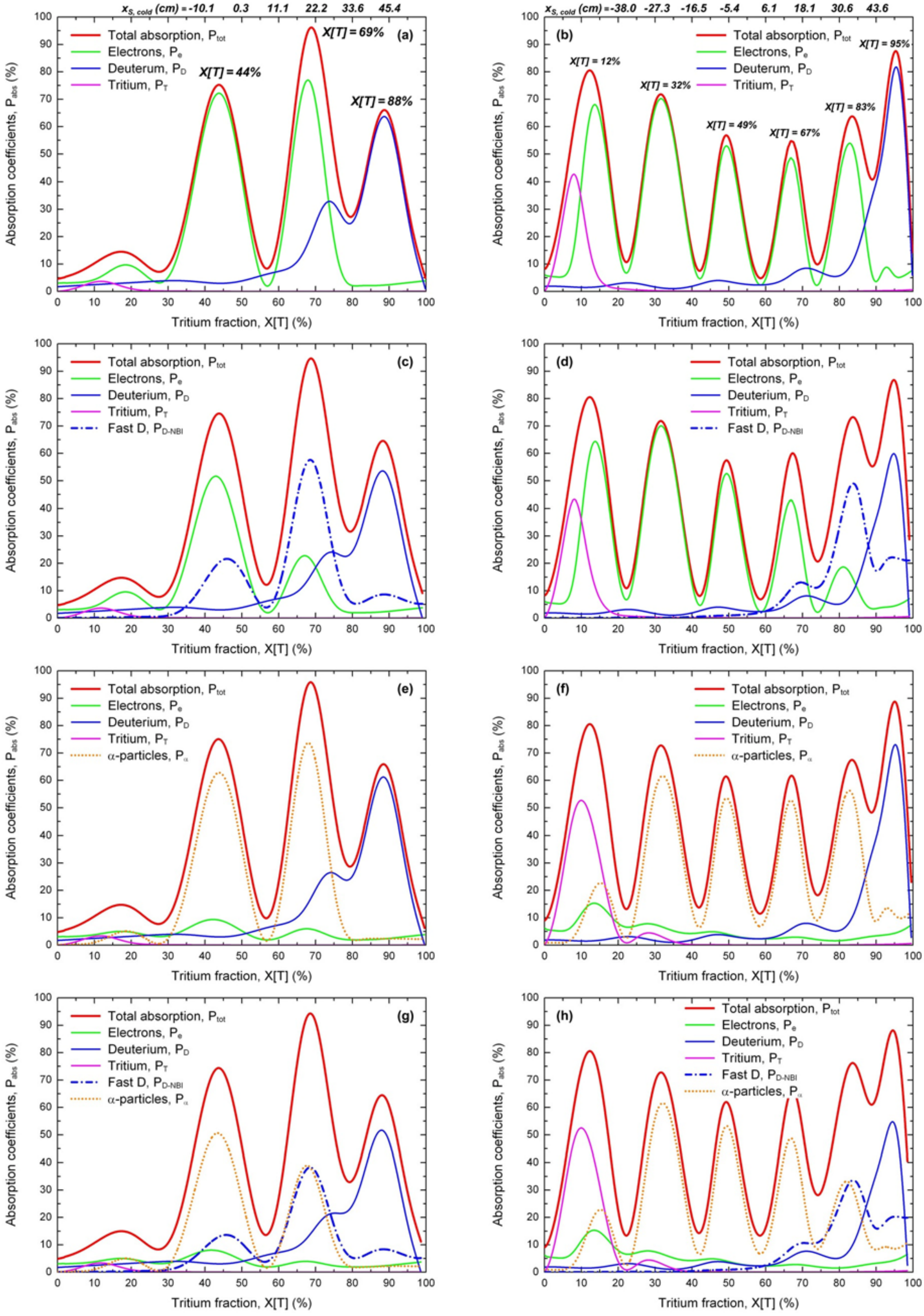

Figure 3. *Absorption coefficients vs. the tritium concentration. Left figures are calculated for n_φ=27, right figures – for n_φ=14. (a)-(b): no fast particles; (c)-(d) NBI D-beam, $X[D_{NBI}]$=1%, $T_{eff,0}$ =55 keV; (e)-(f) alpha-particles, X[α]=0.2%, $T_{eff,0}$=1.12 MeV; (g)-(h) NBI D-beam + alpha-particles.*

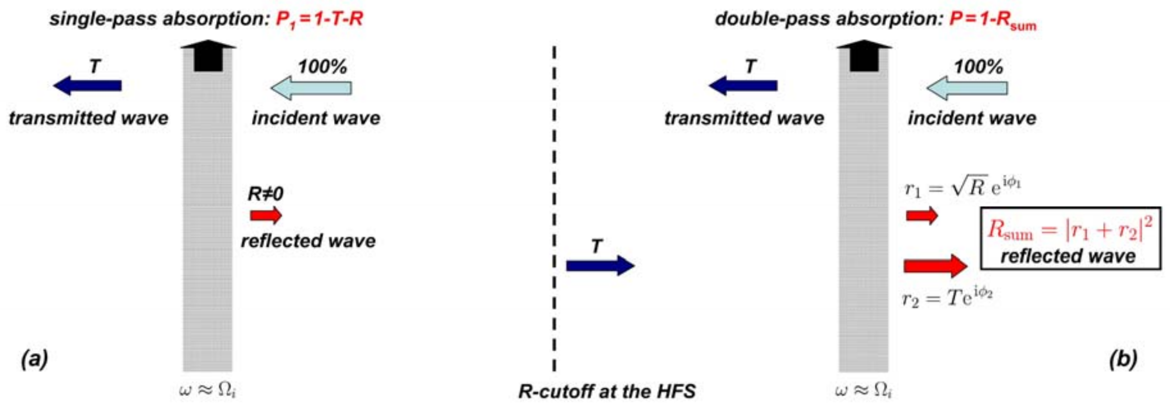

Figure 4. *The enhancement of the ion heating in the MH regime is also possible due to the additional reflection of the FW from the HFS R-cutoff. (a) Crossing the resonant layer $\omega \approx \Omega_i$, the FW is not only partially absorbed and transmitted, but there is also a finite reflection, $R \neq 0$. (b) Minority heating enhancement is caused by the interference of the reflected fast waves.*

3. Effect of fast particles on ICRH power distribution

In order to achieve fusion-relevant plasma temperatures several auxiliary heating methods will be used simultaneously [1]. NBI heating relies on the injection of the neutral particles of high energies into the plasma where they are ionized and transfer their energy to ions or electrons via collisions. NBI has been routinely used both for heating and fuelling the plasma. For instance, JET is equipped with two NBI modules which accelerate D particles to the energies 130 keV and 80 keV [6]. In this paper, a qualitative investigation of the effect of non-thermal subpopulations of ions is given for ICRH scenarios. All species (including fast ions) are assumed to be Maxwellian with a certain effective temperature [11]. This constraint condition is imposed in many ICRH full-wave solvers. More rigorous description requires coupling of ICRH solver with Fokker-Planck code in a self-consistent way [17, 18]. This, however, is far beyond the scope of the present paper.

Figs. 3(c) and 3(d) show that adding a small subpopulation of 1% of NBI-produced fast D ions with the effective temperature 55 keV [17] dramatically diminishes the efficiency of electron heating in the MC regime. Though the total absorption efficiency remains unchanged, the redistribution of the RF power is different. Most of the RF power in the MC regime is absorbed by fast ions because of the large Doppler-shift of their resonance. For thermal particles this shift is small, so these particles absorb the RF power close to their cyclotron resonance layer. In contrast, fast particles can absorb the RF energy far from the cold ion cyclotron region resulting in broad RF deposition profiles. Note that for the conditions of the MH maximum (X[D]=12%) the effect of D beam on the RF power distribution is much weaker.

The interaction of fast NBI ions with ICRH was identified earlier at different tokamaks [19-21]. D beam ion heating by ICRH was successfully implemented in recent experiments on fundamental RF heating of JET deuterium plasmas [17, 22]. The obtained results suggest that NBI-produced fast ions could be accelerated to the energies much higher than their initial birth energy. The synergy between NBI and ICRH could lead to the enhanced losses of fast particles accelerated to MeV energies which was experimentally demonstrated in (^{3}He)-D plasma [6] with the γ-ray spectroscopy [23].

The parasitic absorption of ICRH power by alpha-particles is another significant effect to be considered for ICRH in D-T plasma [10, 11]. Similar to NBI-produced fast D ions, alpha-particles with the same charge-to-mass ratio as D ions – as soon as they are born in D-T fusion reactions – should provide even more significant effect on RF power distribution. Although it is difficult to make self-consistent calculations of such an effect accounting for the dielectric tensor modification and the complicated distribution function of fast ions, good qualitative estimates could be obtained by representing alpha-particles as Maxwellian population with an effective temperature 1.12 MeV [11]. Taking into account the typical values of alpha-particle density in JET D-T discharges (see, e.g. [24]), we assume X[α]=0.2% throughout in our calculations. Figs. 3(e) and 3(f) confirm that the considered ICRH scenario suffer from the unwanted absorption by alpha-particles in a wide range of D:T concentrations. Results for D-T mix with both D beam and alpha-particles (Figs. 3(g) and 3(h)) show that they absorb comparable fractions of the RF energy. These figures show that only for T rich plasma (X[T]>80%) the effect of fast particles on the RF power distribution is quite low.

Below we evaluate two ICRH scenarios which have: i) good ion heating efficiency (due to the heating enhancement in the MH regime); ii) low impact of fast ions on the RF power absorption. The first is (D)-T scheme with dominant absorption by D minority ions [25]. The second is (^{3}He)D-T scenario [12, 13, 25] in which most of the RF energy is absorbed by ^{3}He minority ions in a balanced D-T mix.

4. (D)-T minority heating scenario: X[D]=20%

As follows from Fig. 3, efficient ion heating can be achieved in a range X[D]=5–25%, which is in agreement with experimental results [12, 13]. Consider (D)-T ICRH scenario with the following plasma parameters: T:D=4:1 mix, n_φ=27, B_0=3.6 T, f=24 MHz (somewhat higher frequency is used than that for Figs. 1-3, which allows to locate the ion heating region closer to the plasma center; increasing further the antenna frequency, e.g. f=25 MHz, the tritium resonance layer shifts towards the HFS plasma edge which is dangerous for the machine operation), T_0=8 keV.

Fig. 5(a) shows the dependence of the absorption coefficients as a function of the central plasma density. Table 1 summarizes the numerical and theoretical results for ion heating efficiency. As follows from the table and the figure, theoretical values predicted by formulas (2) are in a good agreement with the numerical results. The ion heating coefficient varies oscillatory as expected. For example, for $n_{e0}=4.0*10^{13}$ cm^{-3} the ion heating coefficient reaches ~100% whereas the single-pass absorption is ~60% only. Fig. 5(b) shows how the absorption coefficients depend on the toroidal wavenumber for this central plasma density. Again, it is an oscillatory function of this parameter, since varying n_φ one changes the location of the HFS R-cutoff.

The ICRH power deposition profiles for this scenario accounting for the presence of fast particles (X[D_{NBI}]=1%, X[α]=0.2%) are shown in Fig. 5(c). In contrast to the MC scenarios (Fig. 3) where the parasitic absorption diminishes electron absorption, for the considered scenario minority D ions are still the main channel of heating: P_{tot}=98.4%, P_e=2.8%, P_D=72.0%, $P_{D\text{-}NBI}$=16.8%, P_α=6.8%. Most of the RF power is absorbed by the thermal D ions, whereas the parasitic absorption by D beam and alpha-particles contributes in sum ~ 24%.

It is important to clarify how the ICRH distribution varies with the subsequent increase in plasma temperature. Fig. 5(d) shows the dependence of the absorption coefficients as a function of the central plasma temperature. As clearly seen from the figure, with the increase of T_0 parasitic absorption further decreases. For T_0 > 15 keV its contribution to the total absorption is less than 10%. In such a way, this scheme has better performance in pre-heated plasma with temperature T_0 > 10 keV.

Table 1. Absorption coefficients for (D)-T minority heating scenario. Theoretical results predicted by formulas (2) are in a good agreement with the numerical values.

n_{e0} (10^{13} cm^{-3})	x_R (cm)	Double-pass absorption			Single-pass absorption			Formulas (2)	
			P_t	P_D	P_1	T	R	P_{min}	P_{max}
2.3	-17.3	**Min**	**22.0%**	20.4%	24.0%	73.5%	2.5%	**20.2%**	66.7%
2.85	-29.0	**Max**	**84.2%**	81.0%	38.4%	58.1%	3.5%	41.0%	**84.5%**
3.4	-37.0	**Min**	**56.0%**	53.0%	50.1%	45.2%	4.7%	**55.3%**	94.5%
4.0	-43.4	**Max**	**99.4%**	94.5%	59.3%	34.0%	6.7%	64.1%	**99.3%**
4.6	-48.3	**Min**	**71.9%**	67.9%	66.2%	26.5%	7.3%	**71.4%**	100%

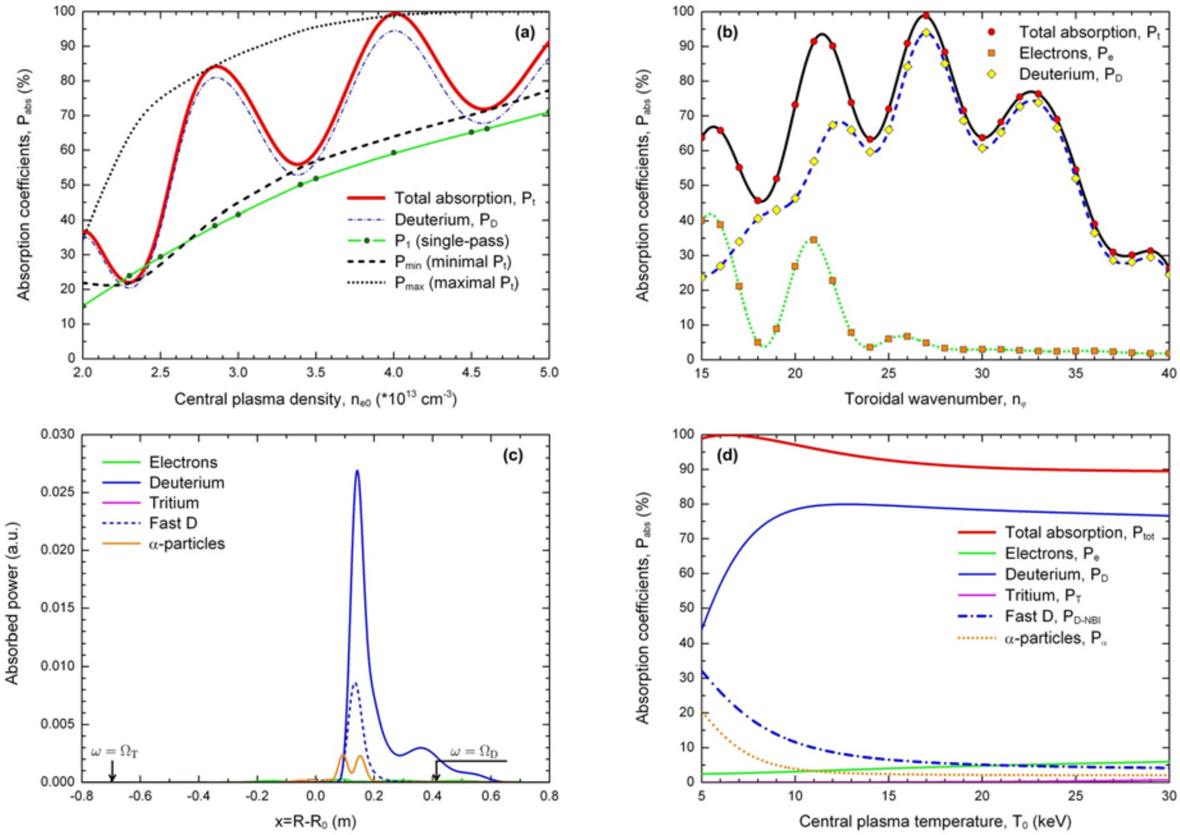

Figure 5. *(D)-T ICRH scenario, T:D=4:1, n_φ=27, f=24 MHz, B_0=3.6 T, T_0=8 keV. (a) Absorption coefficients (without fast particles) vs. the central plasma density; (b) Absorption coefficients (without fast particles) vs. the toroidal wavenumber, n_{e0}=4.0*10^{13} cm^{-3}; (c) ICRH power deposition profiles (with fast particles). (d) Absorption coefficients (with fast particles) vs. the central plasma temperature.*

5. (^{3}He)-DT minority heating scenario: X[^{3}He]=3.5%

For ITER activated phase the main operation ICRH scenario foreseen is the second harmonic tritium absorption [1]. Heating at $\omega = 2\Omega_T$ is a finite Larmor radius effect, thus plasma pre-heating with NBI is essential for this scheme. In TFTR experiments the central ion temperature was increased by ~10 keV with 5.5 MW of ICRH in addition to 23.5 MW of NBI [26, 27]. For typical conditions of JET single-pass absorption of this scheme is weaker.

It was suggested earlier that adding a small fraction of ^{3}He ions in D-T plasma can significantly improve ion heating efficiency and fusion yield [8, 9, 13]. Using ^{3}He ions as a minority instead of the commonly used H minority is beneficial due to the higher collisionality of ^{3}He ions: the value of critical energy for ^{3}He ions below which the power flows from the fast ions mainly to thermal ions is $E_{\text{crit}}(^3\text{He}) \simeq 25\,T_e$, is much higher than this one for H ions, $E_{\text{crit}}(\text{H}) \simeq 8.25\,T_e$. Thus, the fast ^{3}He tail accelerated with ICRH favors the collisional transfer of energy from ^{3}He to bulk ions rather than electrons.

Consider the following scenario: X[^{3}He]=3.5%, balanced D-T mix, f=34 MHz, B_0=3.6 T, n_φ=27, T_0=6 keV. Fig. 6(a) shows that for the given conditions minority absorption is maximal at n_{e0}=3.6*10^{13} cm^{-3}: P_t=88.7%, P_{3He}=75.5%, i.e. most of the RF energy is absorbed by minority ^{3}He ions in a narrow region close to the plasma center. Fig. 6(b) shows the constructive/destructive interference effect on the ion heating efficiency manifested scanning the toroidal wavenumber.

Though the location of ^{3}He fundamental and T second harmonic layers coincides, tritons absorb only a few percent of the RF energy (Fig. 6(c)). Fig. 6(d) shows the absorption coefficients as a function of the central plasma temperature. It is clearly seen that in this scenario fast particles provide a low impact on the RF power distribution regardless T_0. ^{3}He ion heating efficiency varies between 60% and 70% in a wide range of plasma parameters. Thus, we confirm that ICRH scenario with ^{3}He minority in a balanced D-T mix is one of the best scenarios for tokamaks [8, 9, 13].

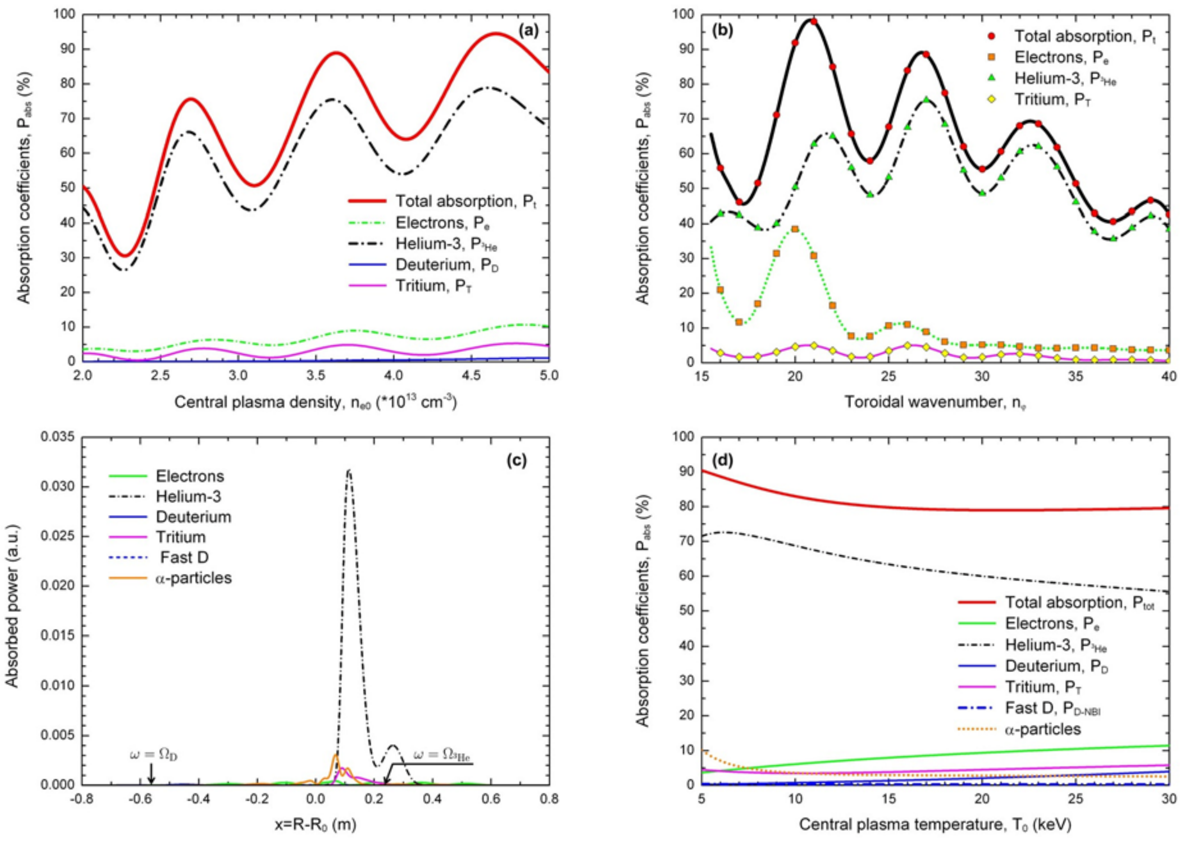

Figure 6. *(^{3}He)-DT ICRH scenario, X[^{3}He]=3.5%, T:D=1:1, n_φ=27, f=34 MHz, B_0=3.6 T, T_0=6 keV. (a) Absorption coefficients (without fast particles) vs. the central plasma density; (b) Absorption coefficients (without fast particles) vs. the toroidal wavenumber, n_{e0}=3.6*10^{13} cm^{-3}; (c) ICRH power deposition profiles (with fast particles). (d) Absorption coefficients (with fast particles) vs. the central plasma temperature.*

6. Conclusions

A possibility to enhance ICRH ion heating efficiency in D-T plasma due to the constructive/destructive interference effect has been studied. It is proved that ion heating improvement is possible due to the additional reflection of the FW from the HFS R-cutoff. ICRH limitations caused by the parasitic absorption of the RF power in the presence of the NBI-produced fast ions and fusion-born alpha-particles are identified. It is shown that efficient ICRH thermal ion heating is possible in minority deuterium, (D)-T and minority helium-3, (^{3}He)-DT plasmas.

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