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Fast wave mode conversion in a 30% H - 70% D plasma

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Abstract

The possibility to use ion cyclotron waves to modify in a selective way the transport of impurities in a hot plasma is analyzed. Calculations are presented for a heating scenario, using JET tokamak impurity seeding discharge parameters, for the case when the mode conversion layer of the Fast Wave (FW) in presence of the ion-ion hybrid resonance in the D(H) plasma coincides with the second harmonic cyclotron resonance of one of the ionized states of seeded Ar. The scenario is analyzed from a theoretical and a numerical point of view. Conditions on the ICRH antenna spectrum are deduced.

1 Introduction

Radiative improved (RI) mode discharges in tokamaks have many beneficial features for thermonuclear fusion. The highly radiating corona that is formed at the plasma edge leads simultaneously to a high plasma density close to the Greenwald limit, a reduced power flux on the walls and the divertor, as well as an acceptable central effective charge Z_{eff} with high confinement properties [1]-[3]. The RI mode is also expected to be sustainable in a quasi steady state regime in fusion reactors. Impurity seeding of noble gas in the tokamak JET in the ELMy H-mode has been performed, indeed producing a radiation mantle at the plasma edge. The method however has a caveat: the possibility of an impurity accumulation at the plasma center. An active control of the impurity density, balancing the high radiation level at the plasma edge and the low effective charge Z_{eff} in the plasma center, is therefore needed. Such control may be achieved in a "natural" way by means of a sawtoothing activity [4] but a method acting selectively on the seeded impurity is preferred since it would leave more flexibility to perform MHD instability control or even ash removal. Methods for protecting the plasma core from impurity penetration also comprise stochastization of the magnetic topology or the pumping-out of the heavy impurities using, for example, selective ion cyclotron resonance heating (ICRH) of the impurity.

Experimental observations of impurity pump-out using ion cyclotron waves have been reported for the tokamak TFR [5]. In the experiment, the density of one of the main plasma species was slowly varied until an efficient Ar impurity ICRH heating is obtained.

The outward impurity transport is explained by the local increase of the left-hand (LH) circularly polarized wave component near the ion-ion hybrid resonance due to the mode conversion process combined with a strong energy absorption (proportional to the square of the absolute value of the LH component of the wave intensity) at the cyclotron impurity frequency. As a result, a powerful impurity ICRH heating is observed, leading to an observable change in the impurity radial flux.

Since the scenario for impurity heating depends on the fast wave (FW) mode conversion to the slow electrostatic mode, it is desirable, to get the best wave propagation properties, to use an ICRH antenna located on the high field side of the tokamak (as in TFR). This choice allows for a full FW mode conversion. However, present days tokamaks have ICRH antennas located on the low field side for which, as the wave equation analysis shows, the FW mode conversion efficiency is either low or is oscillatory. The latter behavior being due to the reflection from the high field side cutoff at low plasma density of the FW transmitted through the wave conversion layer.

The possibility of an effective FW mode conversion as a heating source for seeded impurities in JET needs to be considered from a new perspective. We show that an efficient impurity heating at the second cyclotron harmonic is possible in a plasma containing a large fraction of minority ions (H), of the order of 32 % of the electron concentration, in a deuterium (D) plasma. The wide evanescent layer which then appears is however responsible for a strong FW power reflection from the L-cutoff layer back to the ICRH antenna.

In section II, we recall some observations on impurity heating performed at JET as well as the experimental set-up. Section III introduces the dispersion relation and different approximations useful in the case of a high H concentration in a D plasma while section IV defines the so called "Triplet configuration". Section V is devoted to an analysis of the mode conversion efficiency including a search for the best experimental conditions for JET discharges. Conclusions and final comments are given in section VI.

2 Experimental conditions of impurity seeding JET experiments

The density profiles used in the analysis are taken from data provided by the $D(H)$ discharges #63148-63157 in JET. The plasma in these experiments is made of Ar (a typical noble gas used to perform RI mode experiments at JET [6]-[8]) seeded in a minority concentration of hydrogen (of about 32% of the electron density) in deuterium. A variation of the minority concentration is required to get the right ratio H/D at which the mode conversion layer superposes to the second harmonic of the Ar^{+16} cyclotron resonance. A too large minority concentration leads to a wider evanescence layer and therefore to a stronger reflection of the small $k_{\|}$ FW waves back to the antenna. Therefore, care must be taken to avoid this regime which could endanger the ICRH antenna. The best experimental conditions are obtained numerically by studying a wide range of H concentration and $k_{\|}$ values which, as will be shown, include a regime where the FW mode conversion is very effective. This regime is a precondition for a useful Ar^{+16} heating.

The JET discharges have been simulated using the impurity transport code RITM [8]. Although the density profile is changed from one discharge to the other it is well represented by the function $n_e(\widetilde{r}) \sim 3.0 \cdot 10^{13}\,(1-\widetilde{r}^{1.8})^{0.8} + 2.8 \cdot 10^{12}$ expressed in cm^{-3}, where

$\widetilde{r}$ is a normalized plasma radius. This electron density profile for various on-axis densities is used in the numerical study. The ion densities are also obtained numerically from the transport code, assuming quasineutrality. The dependence of the mode conversion efficiency on the density profile will reported elsewhere.

The parameters in the analysis are adapted to the JET experimental conditions assuming Ar^{+16} heating since this species is distributed from 0.2 to 0.95 normalized plasma radius at the expected ion temperature with a maximum density at approximately $\widetilde{r} = 0.8$. Also to be noted is the Ar^{+16} contribution to the quasineutrality (especially at the plasma edge) together with the contribution from the carbon impurity which play a fundamental role in the FW dispersion relation.

3 The dispersion relation

The fast wave mode conversion leads to an intense left hand polarized electric field component near the ion-ion hybrid resonance. This component is the most important one in the understanding of the physics of impurity heating [9]. A one dimensional analysis of the problem is performed and provides the main features of the FW propagation through a nonuniform plasma column.

The FW propagation is analyzed starting from the fourth order dispersion relation

$$S\, n_\perp^4 - (R\, L + P\, S - n_\parallel^2\, (P + S))\, n_\perp^2 + P\, (R - n_\parallel^2)\, (L - n_\parallel^2) = 0, \tag{1}$$

where S, P, R and L are the components of the cold plasma dielectric tensor in the Stix notation [9] and $n_\perp$ and $n_\parallel$ are the perpendicular and the parallel refractive numbers respectively. This equation reduces in the cold plasma approximation to a second order equation

$$n_{\perp,FW}^2 = \frac{(R - n_\parallel^2)\, (L - n_\parallel^2)}{S - n_\parallel^2}. \tag{2}$$

However, it is well known that the region nearby the ion-ion hybrid resonance, where the FW is converted into an Ion-Bernstein wave (IBW), cannot be described in the cold plasma approximation only. In this region the dispersion relation of IBW reads:

$$n_{\perp,IBW}^2 = \frac{S - n_\parallel^2}{\sigma}. \tag{3}$$

where σ accounts for the thermal contribution. The IBW is a short wavelength electrostatic wave that is mostly damped on the electrons. When the FW is converted into an IBW, the power is deposited at a distance of some IBW wavelengths on the high field side of the ion-ion hybrid resonance layer. Generally speaking the FW can also be converted into a slow shear Alfvén wave (SAW) [10] or into an ion cyclotron wave (ICW) [11]. In the case of a high density plasma, considered here, the mode conversion to SW is negligible. The mode conversion to the ICW is also negligible in the case of a weak poloidal magnetic field. In these conditions, the FW launched from the Low Field Side (LFS) (positive x coordinate) propagates towards the High Field Side (HFS) (corresponding to the direction of negative x coordinate) until it is reflected and transmitted at the ion-ion hybrid resonance layer.

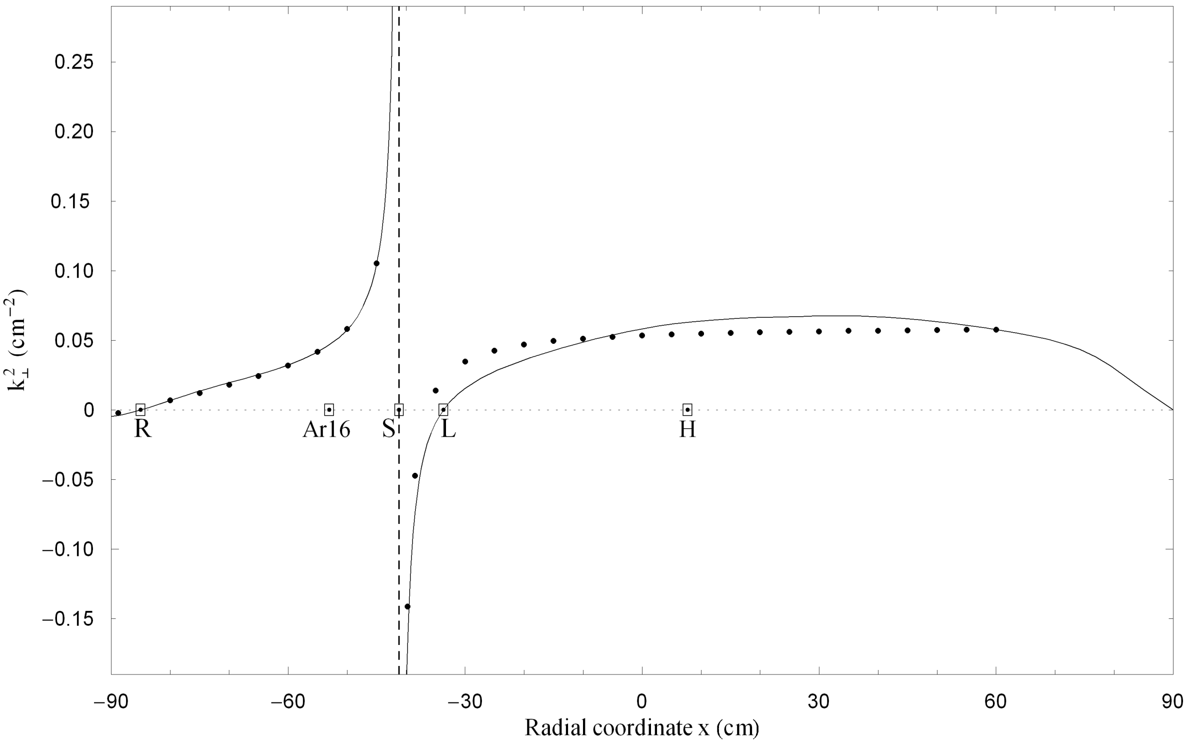

Figure 1: $k_\perp^2$ obtained from the local cold plasma dispersion relation as a function of the distance along the equatorial plane for JET-type parameters (solid line). The dots correspond to the FW dispersion in the triplet configuration Eq.(5). The parameters are: major radius $R_0 = 2.96\,\mathrm{m}$, plasma radius $a = 0.9\,\mathrm{m}$, electron density as in the text, central toroidal magnetic field $B_0 = 2.5\,\mathrm{T}$, ICRH antenna frequency is $37.4\,\mathrm{MHz}$, $k_\parallel$ is $7\,\mathrm{m}^{-1}$. Hydrogen concentration in deuterium plasma is 30 % of the electron density. The R-cutoff, ion-ion hybrid resonance layer and L-cutoff are denoted R, S and L, respectively. Hydrogen fundamental and argon+16 second cyclotron resonance layers are labeled H and Ar16, respectively.

The plasma density, which is nonuniform along the x-coordinate is, for the purpose of wave propagation analysis, extrapolated to an infinite domain $x = -\infty$ and $x = \infty$. The FW absorption by the different plasma species is not discussed here in order to focus on the main goal of the study which is to find the optimal experimental conditions for the mode conversion.

The FW wave equation, written in Budden approximation, reads

$$\frac{d^2 E_y}{dx^2} + Q(x)\, E_y = 0, \tag{4}$$

This equation depends on a potential function $Q(x) = \kappa_A^2\,(1-\Delta/x)$ which is here expressed in Budden notation. For the FW propagation problem, this potential can also be derived from the dispersion relation $Q(x) = (\omega^2/c^2)\, n_{\perp,FW}^2(x)$. Here, κ_A is the FW wavevector at $x = \infty$ and $\Delta = -2^{-1}\,(R-L)/(R-L)'$ is the evanescent layer thickness. The prime denotes a derivative along the x-coordinate [12]. Originally the plasma density in the Budden problem is uniform [13]. Thus, $n_{\perp,FW}$ is assumed to be constant far away from the ion-ion hybrid resonance layer.

A simplified model for the dispersion function is obtained by interpolating the numerical solution of the dispersion relation evaluated near the ion-ion hybrid resonance to the constant value at $x = -\infty$ and $x = \infty$ *i.e.* to the square of the perpendicular refractive index. The evanescence layer of the FW propagation is bordered by the ion-ion hybrid layer on the HFS and by the L-cutoff layer at the LFS [13] (see Fig.1). The solution of Budden Eq.(4) is then expressed in terms of the transmission coefficient T, the reflection coefficient R and mode conversion coefficient C which depend on the FW wavevector $k_{\|}$ [13]:

$$\left\{ \begin{array}{l} T(\eta) = e^{-\pi\,\eta}, \\ R(\eta) = (1-T)^2, \\ C(\eta) = 1 - R - T = T\,(1-T). \end{array} \right. \tag{5}$$

where $\eta = \kappa_A\,\Delta$. The reader should carefully note that the symbol R is used indistinctly for the plasma dielectrical tensor component derived by Stix and the wave reflection coefficient. In keeping this notation, we follow the historical evolution of the description of similar propagation problems. According to Budden approximation, the conversion coefficient C, always less than 25 %, reaches a maximum when $\eta = \pi^{-1}\,ln2 \approx 0.2206$. This is true even for the narrow evanescent layer when the minority ion concentration is small. For large minority concentration, which will prove to be a regime of interest for ICRH impurity heating, the mode conversion coefficient is even much less than 25 % and only few percent of the wave power is converted to IBW.

4 Model of triplet configuration

A model, more realistic than Budden potential function for the FW propagation is the triplet configuration [14]-[17]. It takes into consideration the plasma nonuniformity when the FW transmitted through the ion-ion hybrid resonance layer is reflected back from the R-cutoff layer. The R-cutoff on the HFS acts on the waves launched with a large $k_{\|}$. Also, the minimal $k_{\|}$ leading to the triplet configuration increases with the plasma density. The potential function in Budden wave equation for the triplet configuration is usually given by the expression:

$$Q(x) = \left\{ \begin{array}{lll} \gamma_1 - \beta/x & for & x > 0, \\ \alpha x + \gamma_2 - \beta/x & for & x < 0, \end{array} \right.$$

where $x = 0$ corresponds to the position of the ion-ion hybrid resonance. The solutions of Budden equation for the triplet configuration (solid line) and the calculated FW dispersion relation (the dots) are compared in Fig.1. The agreement is obtained for the following triplet configuration parameters: $\alpha = 867.3\,\mathrm{m}^{-3}$, $\beta = 28.89\,\mathrm{m}^{-1}$, $\gamma_1 = 591.2\,\mathrm{m}^{-2}$, $\gamma_2 = 329.5\,\mathrm{m}^{-2}$. The FW conversion coefficient for the triplet configuration can reach 100% due to an interference of the FW's reflected from ion-ion hybrid resonance layer and the ones reflected from the R-cutoff layer on the HFS. The FW mode conversion coefficient is expressed as in Ref.[14]:

$$C = 2\,T\,(1-T)\,(1 + \sin(2\,\Phi - \Psi)), \tag{6}$$

where $\Phi = \displaystyle\int_{x_R}^{0} Q^{1/2}(x)\,dx$ is the phase of the FW reflected from the R-cutoff layer on the HFS while $\Psi = arg(T_L)$ is the phase of the FW reflected from the L-cutoff layer.

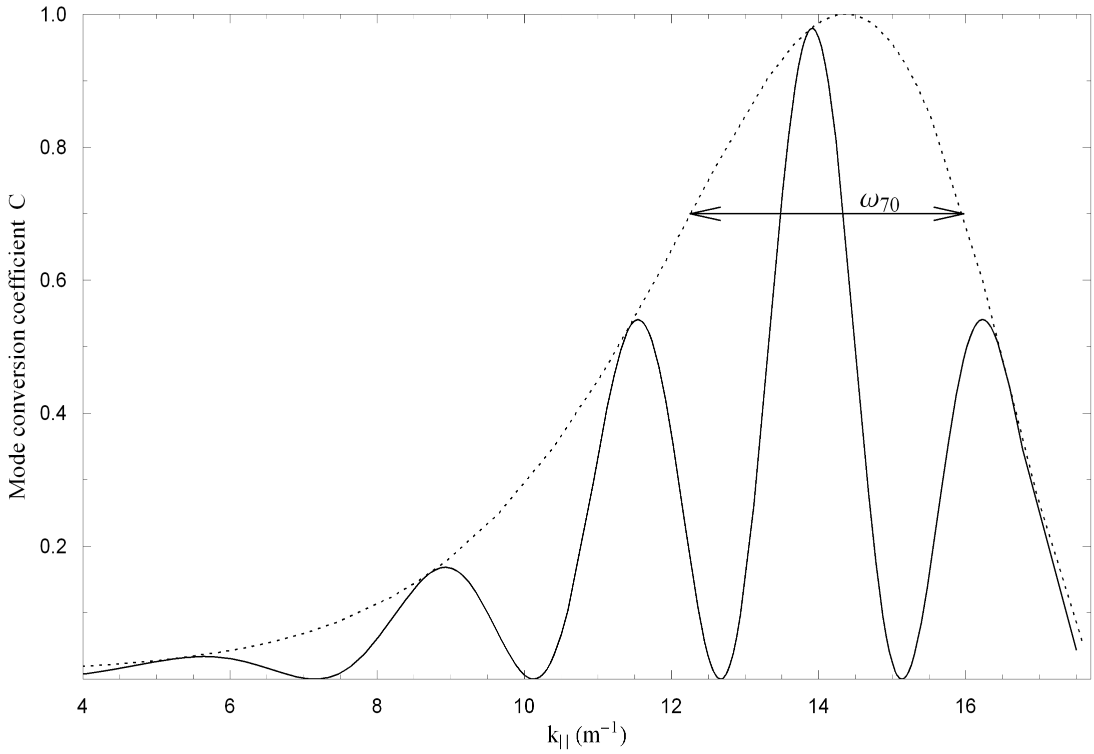

Figure 2: The mode conversion coefficient C as a function of the parallel wave vector $k_\|$ (solid line) and the envelope curve according to Budden relation (6) (dashed line). The width of Budden curve when the mode conversion coefficient is equal 0.7 is denoted by w_{70}. The hydrogen concentration is $n_H/n_e = 0.2$. Other parameters are the same as for Fig.1.

Here $T_L = 2\pi i e^{2\kappa(ln\kappa-1)}/\Gamma(\kappa)\Gamma(\kappa+1)$, $\kappa = -i\eta/2$ and $\eta = \beta/\sqrt{\gamma_1}$. To be more precise, the FW conversion coefficient has an oscillatory dependence on $k_\|$ (see Fig.2). The total FW conversion coefficient is then defined as an integral over the ICRH antenna wavevector spectrum. According to relation (6), Budden curve of the conversion coefficient, when multiplied by 4, gives the envelope of the oscillatory behavior of the triplet configuration (represented by the dotted line). The parameter w_{70} is the width of Budden curve multiplied by 4 at 70% (see Fig.2). This parameter is in the range 3.5 to $4.5\,\mathrm{m}^{-1}$ and can, without great error, be considered constant (approximated by $4\,\mathrm{m}^{-1}$) for the H concentration in the range 15 to 40%.

For small H concentration, the period of the oscillations is smaller than that of w_{70} (see Fig.2) but is of the same order when the H concentration is about 30%. As a result, for the H concentration that are considered and for a typical antenna spectrum width, the conversion coefficient integrated over the antenna spectrum will be around 50%. For larger H concentration and narrower antenna spectrum, the conversion coefficient approaches 100% or drop to 0 depending on whether the maximum of the antenna spectrum coincides with the value of $k_\|$ corresponding to the maximal or to the minimal value of the conversion coefficient respectively.

Thus, the triplet configuration of the FW propagation in a nonuniform plasmas is more realistic than Budden potential function in Eq.(4). Moreover it predicts a possibility of up to 100% FW mode conversion in contradistinction with the maximum 25% obtained in the framework of the Budden problem. Since our goal is to identify experimental conditions for an effective FW mode conversion it is now necessary to analyze the robustness of this conclusion for different sets of plasma parameters.

5 Mode conversion efficiency

A typical dispersion curve for the JET tokamak discharges is shown in Fig.1 when the hydrogen concentration is $n_H/n_e = 0.3$. However, our numerical analysis includes concentrations up to 40%. The FW dispersion is then well approximated by the triplet configuration defined by Eq.(5). Indeed, the agreement between the analytical (solid line) and calculated (dots) dispersions is then quite good (see Fig.1) except in a narrow region close to the LFS edge of the plasma column where the plasma density is low. The R-cutoff on the HFS is inside plasma and R-cutoff on the LFS is outside the plasma. The width of the evanescent layer (*i.e.* the distance between the L-cutoff and the ion-ion hybrid resonance) is approximatively 7.5 cm. The radial position of the second harmonic cyclotron resonances of Ar is also shown for reference. In order to show the large distance between the hydrogen cyclotron layer and the ion-ion hybrid resonance layer (the heating regime is far from the minority heating at low concentration) the antenna frequency used in the present calculation had to different from that of the JET experiment (the hydrogen cyclotron resonance in the experiments was outside the plasma column). The R-cutoff on the HFS obviously modifies the FW propagation. Also to be noted is the presence of R-cutoff on the LFS which could be a problem in the case of a high power FW emission by the antenna. A detailed study of the field dynamics near the antenna requires a two dimensional analysis, not reported here.

The positions of the high and low field side R-cutoff as functions of $k_\parallel$ are shown in Fig.3. The dependence indicates that the triplet configuration is valid for FW with $k_\parallel$ larger than $5\,\mathrm{m}^{-1}$. The critical value of the parallel wave number when the curves L and S are crossed is also given (approximately to $18\,\mathrm{m}^{-1}$ for the scenario shown in the figures). For larger values of $k_\parallel$ the FW does not propagate. The dependence on $k_\parallel$ is sensitive to the plasma density profile and to the radial position of the hydrogen cyclotron layer but the main conclusion drawn for the reference discharges is that the triplet configuration applies for the wide range of the FW spectrum, ranging from 5 to $16\,\mathrm{m}^{-1}$.

The level lines of Budden curve, representing the envelop of the oscillations of the mode conversion coefficient (6), are obtained in terms of the hydrogen concentration and the parallel wavevector (Fig.4). The locus of the maximum of the curves weakly depends on the hydrogen concentration when it exceeds 5%. This means that an effective mode conversion always happens when the antenna spectrum is sufficiently narrow with a maximum near $k_\parallel = 14\,\mathrm{m}^{-1}$. Generally speaking, such profile can only be obtained when one of the maximum of the oscillatory dependence (6) coincides with the maximum of a Budden curve (see Fig.2). This situation can always be created by changing the radial positions of the R- and L- cutoff and consequently changing the phases in Eq.(6). As a result the antenna spectrum can be always given as part of the definition of a reference discharge. A wide variation of the minority concentration (the hydrogen in the present case) would then be sufficient for finding the effective mode conversion regime.

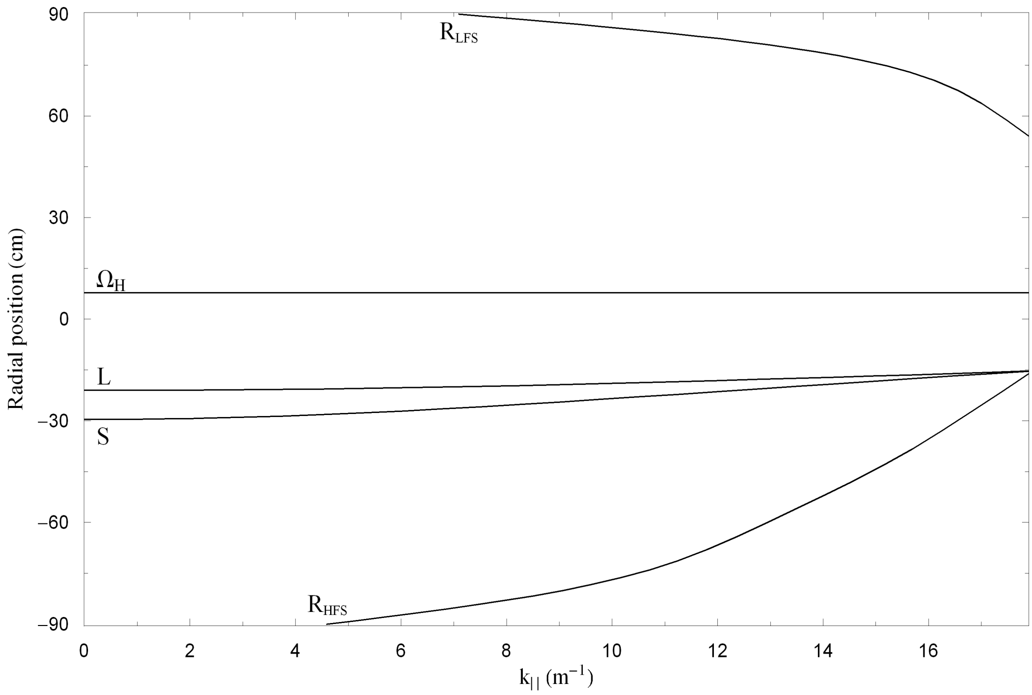

Figure 3: The radial position of the R-cutoff at HFS (R_{HFS}) and LFS (R_{LFS}), the L-cutoff, the ion-ion hybrid resonance (S), the hydrogen fundamental cyclotron resonance Ω_H as functions of the parallel wave vector $k_{\|}$. The hydrogen concentration is $n_H/n_e = 0.2$. Other parameters are the same as for Fig.1.

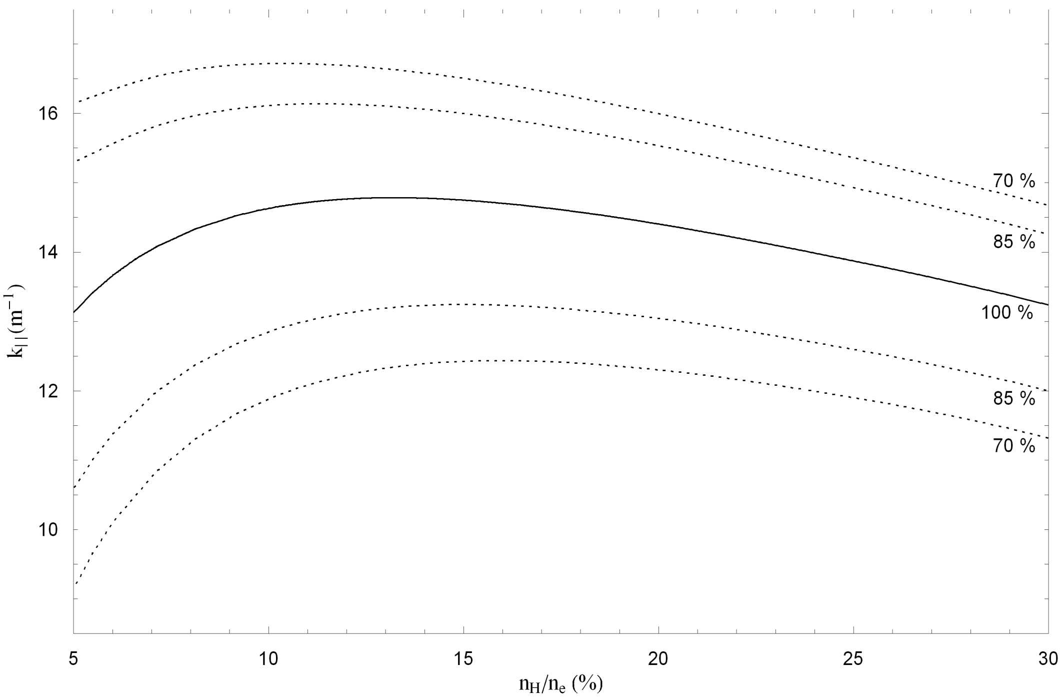

Figure 4: The level lines of Budden curve which envelop the oscillations of the mode conversion coefficient (see Fig.2) as functions of the hydrogen concentration and the parallel wave vector $k_{\|}$. The parameters are the same as for Fig.1.

6 Conclusions and discussions

It has been shown that the FW mode conversion can be effective in the case of a large minority ion concentration required to control the impurity concentration in seeded discharges. However, to achieve this goal, the ICRH antenna has to operate with a significant contribution in its wavevector spectrum in the range ± 12 to $\pm 16\,\mathrm{m}^{-1}$ (like in the case of the (0,0,0,0) phasing at JET). The mode conversion then provides an intense left hand polarized component of the electric field, which is preferred for the impurity heating at the second harmonic of the cyclotron resonance. An effective IBW damping on the electrons should help to avoid large wave power reflection back to the antenna.

The mode conversion efficiency is not sensitive to the minority H concentration when the concentration exceeds 10% (such large minority concentrations is of interest for ICRH impurity heating) but is however quite sensitive to the antenna spectrum. When the antenna spectrum shows a peak width of about $4\,\mathrm{m}^{-1}$, it is always possible to adapt the experimental conditions (for example, by changing slightly the external magnetic field) to get an efficiency of the order of 80%. Such efficiency is obtained when one of the maximum of the oscillatory mode conversion efficiency calculated in the triplet configuration coincides with the maximum of the mode conversion calculated in Budden approximation (see Fig.2).

The role of the high field side R-cutoff is quite clear in the present problem. Its position depends mainly on the density profile and, therefore, can not be controlled externally. All waves with $k_\parallel$ larger than $5\,\mathrm{m}^{-1}$ will reach this cutoff leading to the triplet configuration. Considering the problem from a different perspective, the R-cutoff on the low field side could be a problem for high power FW emission by the antenna. But, according to some estimations, this R-cutoff acts mainly on waves with $k_\parallel > 7\,\mathrm{m}^{-1}$. It is nevertheless expected that this cutoff will not cause any problem at least for moderate $k_\parallel$. At this point, we recall that our analysis is one-dimensional but should at least be two-dimensional to resolve with sufficient details the electromagnetic pattern in the vicinity of the ICRH antenna.

It is clear that all the results obtained and discussed here are very sensitive to the density profile and to the plasma species. We have paid much attention to the particular case of the JET experiments on ICRH heating of seeded Ar. Additional numerical estimates show that a decrease in the plasma density permits to lower the $k_\parallel$ required for an effective mode conversion. This preliminary conclusion is a positive result because at lower plasma density (at about $2 \cdot 10^{13}\,\mathrm{cm}^{-3}$ in the center) it appears that the FW is effectively converted when the JET antenna spectrum is such that $k_\parallel < 10\,\mathrm{m}^{-1}$.

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