ENHANCED MODE CONVERSION IN FUSION DISCHARGES WITH LARGE CONCENTRATION OF MINORITY IONS

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The efficiency of Fast Wave (FW) mode conversion to Ion Bernstein Wave (IBW) is studied for two-component ion species plasmas with high minority concentration. The analysis of the mode conversion efficiency is carried out, as an example, for D(H) plasmas of tokamak JET. The 1D wave code consideration is based on the developments of the Budden [1] and triplet [2] approximations taking into consideration the treatment by [3]. It is shown how to choose the antenna phasing to reach the most effective mode conversion for a given plasma density profile. At the same time, there is no important dependence of the efficiency on the minority concentration, when it exceeds some value (about 10 % for D(H) plasmas of tokamak JET). The reaching of the effective mode conversion is easier in the layer at High Field Side (HFS). The obtained results are important to study a local electron heating in the discharges with a minority concentration which is higher than that in the usual mode conversion regimes.

1. Introduction

Traditionally, the FW propagation in two-component ion species fusion plasmas is separated on the minority heating regime and the mode conversion regime [4]. When FW power fraction absorbed by the minority ions on the harmonic of the cyclotron resonance is larger than the wave power fraction converted to the IBW, the regime is called “minority heating”. Opposite case corresponds to the “mode conversion” regime. From the technological point of view, the ICRH antenna can launch FW into plasma from High Field Side (HFS) or Low Field Side (LFS) of the magnetic field. The first case is preferable for the ICRH antenna operating with two-component plasmas because all wave power will be absorbed effectively in plasma. As a result, there is not a power reflection from the plasma back to the antenna. But, in the case of LFS launching, the fraction of reflected power depends on the width of the evanescence layer and the wave number of FW. When the width is increased, the reflected fraction is also increased, and the converted fraction leads to zero.

The FW power converted to the IBW is absorbed effectively by electrons. The width of an absorption layer is equal to few IBW wavelengths. Therefore, the power deposition profile is enough narrow to study the transport with a well-determined heat source [5]. Also the local plasma heating is preferable, for example, for the impurity profile control in the discharges with the impurity seeding [6]. Thus, the optimal experimental conditions should be determined to get the fraction of the mode converted power as much as possible. The case of a low minority concentration which corresponds to the minority heating regime is out of the consideration. The regimes, when the wave power transmitted through the cutoff-resonance pair (the ion-ion hybrid layer at HFS and the L-cutoff layer at LFS) is of the same order as the wave power reflected from the pair, will be under consideration. Since the fraction of the mode converted power depends strongly on the width of the evanescence layer, the minority hydrogen (H) concentration in deuterium (D) plasmas of tokamak Joint European Torus (JET) will be tested for the optimal mode conversion. But the results of the consideration can be easily generalized for smaller tokamaks and other cases of the plasma composition. Since the main attention will be paid to the mode conversion in the discharges with large minority concentration, the thermal effects of FW damping on electrons and ions will not be taken into consideration. They can be included later on, when the optimal conditions for the mode conversion will be determined.

Historically, the analytical solution of the FW wave equation for two-component plasmas is related to the Budden problem of the mode conversion in a uniform density plasma [1]. According to the theory, the mode conversion coefficient (the mode converted fraction) cannot exceed 0.25 for a particular value of the FW parallel wave vector component $k_{||}$. The more realistic analytical consideration of FW mode conversion in nonuniform plasmas which will be called here as the

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triplet approximation takes into consideration the R-cutoff layer at HFS which reflects FW back to the antenna [2,7–10]. In the triplet approximation, the mode conversion coefficient can reach 1.00 for some particular value of $k_{||}$. The effect is provided by the interference of the FW reflected from the R-cutoff at HFS and the FW reflected from the cutoff-resonance pair. The phase difference between two reflected waves defines the FW conversion and reflection coefficients for given $k_{||}$. In this way, the mode conversion coefficient can reach some optimal value (up to 100%) or drop to 0.

The FW mode conversion in D(H) plasma with large H concentration was studied at Alcator C-Mod [11]. The effective FW mode conversion to IBW and Ion Cyclotron Wave (ICW) has been reported for the H concentrations in the interval of 0.15-0.25. The fraction of the RF power going on the electron heating due to the mode conversion has been obtained experimentally and numerically. The comparison has been carried out between the powers of electron heating through the mode conversions to IBW and to ICW. The paper paid the main attention to the mode conversion to the ICW, and the conditions of the mode conversion to the IBW were not analyzed.

The consistent picture of the mode conversion at the ion-ion hybrid resonance in the bounded plasmas based on the model of a triplet resonator has been discussed in [3]. The examples of the picture have been presented for the discharge conditions of Tore Supra with a large concentration of hydrogen in helium plasmas ($n_{\rm H}/n_{\rm He} = 0.4$). The analysis has been carried out for any value of tunnelling factor η irrespective of the $k_\|$ value. It hides the information about the antenna spectrum which could be optimal for the enhanced mode conversion. The radial position of the cutoff-resonance pair was defined by the antenna frequency, but the effect of the distance between the pair and R-cutoff position on the mode conversion was not studied. It is clear that the mode conversion process depends strongly on the plasma density profiles, but how do the concentrations of the plasma ions affect the mode conversion efficiency?

The practical recommendations to optimize the mode conversion experiments for expected plasma density profiles have to be developed. For this goal, the largest operating tokamak JET will be tested for the optimal experimental conditions of the mode conversion in D(H) plasmas. The D(H) plasma composition is convenient to outline the features of the mode conversion, because it allows one to change the width of the evanescence layer and its radial position in wide ranges. The analysis of the mode conversion with another plasma compositions for another tokamaks can be carried out in a similar way. The mode conversion coefficient averaged over typical JET antenna spectra (the mode conversion efficiency) will be obtained to compare the mode conversion with the different antenna phasing.

2. Wave Equation

2.1. Dispersion relation

The problem of wave propagation through a plasma column with nonuniform density is considered in the one-dimensional geometry. The fourth-order dispersion relation for the wave propagation in plasma

$$Sn_\perp^4 - (RL + PS - n_{||}^2(P+S))n_\perp^2 + P(R - n_{||}^2)(L - n_{||}^2) = 0, \quad (1)$$

where S, P, R, and L are the components of the cold plasma dieletric tensor in the Stix notation [12], $n_\perp$ and $n_{||}$ are perpendicular and parallel refractive numbers, respectively, can be reduced to the second-order one [4] which describes the FW in the cold plasma approximation:

$$n_{\perp,\rm FW}^2 = \frac{(R - n_\|^2)(L - n_\|^2)}{S - n_\|^2}. \quad (2)$$

In the vicinity of the ion-ion hybrid resonance (given by $S = n_{||}^2$), the FW is converted to IBW which cannot be described in the cold plasma approximation, but its dispersion relation can be written taking into consideration the thermal contribution σ [4]:

$$n_{\perp,\rm IBW}^2 = \frac{S - n_\|^2}{\sigma}, \quad (3)$$

$$\sigma = \frac{1}{4}\sum_\alpha \frac{\omega_{p\alpha}^2}{\Omega_{c\alpha}^2}\frac{v_{th\alpha}^2}{c^2}\Bigg\{\Big[\zeta_{0\alpha}Z(\zeta_{+1\alpha}) + \zeta_{0\alpha}Z(\zeta_{-1\alpha})\Big] - \Big[\zeta_{0\alpha}Z(\zeta_{+2\alpha}) + \zeta_{0\alpha}Z(\zeta_{-2\alpha})\Big]\Bigg\}. \quad (4)$$

IBW is a short-wavelength electrostatic wave which is damped effectively at electrons. If the FW is converted effectively to IBW, the power will be deposited at the distance in some IBW wavelengths on the high field side from the ion-ion hybrid resonance layer. Generally speaking, the FW can be converted also to a slow shear Alfvén wave (SAW) [13] or the ion cyclotron wave (ICW) [14]. But, in the present study, the plasma density is enough high to make the mode conversion to SW negligible. At the same time, the mode conversion to ICW is possible only when there is a poloidal component

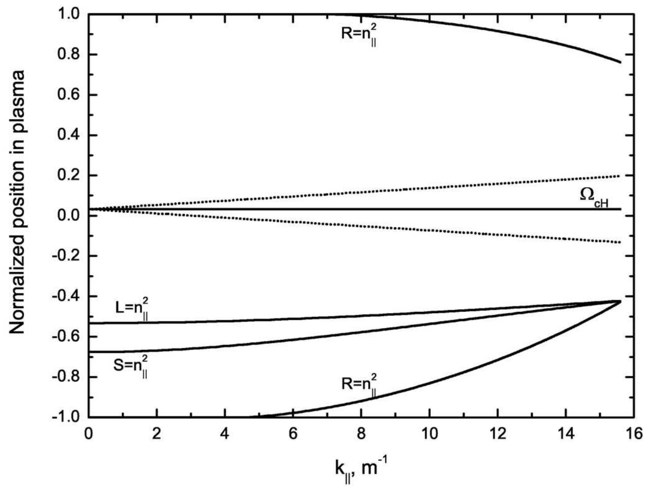

Fig. 1. Radial positions of the R-cutoff at HFS ($R_{\rm HFS}$) and LFS ($R_{\rm LFS}$), the L-cutoff, the ion-ion hybrid resonance (S), and the hydrogen fundamental cyclotron resonance $\Omega_{c\rm H}$ as functions of the parallel wave vector $k_{||}$. The major radius R_0 is 2.96 m, the plasma radius a is 0.9 m, the electron density profile was chosen as $n_e(r) = 3.0 \times 10^{13}(0.9(1 - r^{1.8})^{0.8} + 0.1)$, the central toroidal magnetic field value is 2.5 T, the antenna frequency is 38.0 MHz, and the hydrogen concentration is $n_{\rm H}/n_e = 0.34$. The borders of the range where the thermal effects cannot be neglected (the minority heating regime) are shown by the dotted lines

of the confinement magnetic field which is out of our consideration. The FW is launched at the Low Field Side (LFS) (positive direction of the x coordinate axis) and propagates to the High Field Side (HFS) (negative direction of the x coordinate axis) reflecting from and transmitting through the cutoff-resonance pair. The confinement magnetic field is nonuniform and its space dependence will be taken in following form:

$$B(x) = B_0 \frac{R_0}{R_0 + x}, \tag{5}$$

where B_0 is the magnetic field value at the magnetic axis and R_0 is the large radius of the torus. The plasma density is nonuniform along the x coordinate, and its radial dependence will be chosen from the typical discharges with D(H) compositions. At low edge densities, there are two R-cutoff layers ($R - n_{||}^2 = 0$) which are the barriers for the wave propagation. Due to the magnetic field nonuniformity, the R-cutoff at LFS appears at a lower density than that at HFS. The wave propagation barrier is more penetrable at LFS. The processes of FW absorption at plasma species due to the heat effects are not taken into consideration, because the main goal of the study is to optimize the experimental conditions for the most effective mode conversion. The range of $k_{||}$, where the heat effects cannot be neglected, will be estimated in Fig. 1.

2.2. Budden approximation

The wave equation for the FW propagation through a plasma column can be written in the Budden approximation [1] as

$$\frac{d^2 E_y}{dx^2} + Q(x) E_y = 0, \tag{6}$$

where a potential function $Q(x)$ is expressed in the Budden notation as $Q(x) = \kappa_A^2 \left(1 - \frac{\Delta}{x}\right)$ or can be presented for the FW propagation problem through the dispersion relation $Q(x) = \frac{\omega^2}{c^2} n_{\perp,\rm FW}^2(x)$. Here, κ_A is the FW wave vector at $x = \infty$, and Δ is the evanescence layer width. Originally, the plasma density is uniform in the Budden problem [1]. Therefore, $n_{\perp,\rm FW}$ is a constant far away from the ion-ion hybrid resonance layer. The most simplified model of the dispersion function is constructed by interpolating the numerical points of the dispersion relation closed to the ion-ion hybrid resonance to the constant values of the square of the perpendicular refractive index at $x = -\infty$ and $x = \infty$. The evanescence layer of the FW propagation is restricted by the ion-ion hybrid layer at HFS and the L-cutoff layer at LFS which create together a cutoff-resonance pair. The solution of the Budden equation gives the dependence of the transmission T, reflection R, and mode conversion C coefficients on $k_{||}$ of the launched FW [1, 2, 9, 10]:

$$T(\eta) = e^{-\pi\eta}, \tag{7}$$

$$R(\eta) = (1 - T)^2, \tag{8}$$

$$C(\eta) = 1 - R - T = T(1 - T). \tag{9}$$

Here, $\eta = \kappa_A \Delta$ which will be called here "tunneling parameter". The dependence on $k_{||}$ is presented implicitly in κ_A and Δ. The reader should be careful with the symbol R which means above the wave reflection coefficient, but not the plasma dielectric tensor component by Stix. Historically, they are used simultaneously to describe the considered problems. Therefore, we did not changed the notation. According to the Budden approximation, the conversion coefficient C does not exceed 25 % and has a maximum for $\eta = \frac{\ln 2}{\pi} \approx 0.2206$. Thus, the coefficient of the FW mode conversion cannot exceed 25% even for enough narrow evanescence layers, when the minority ion concentration is small. For the large minority concentration domain which is more interesting for the local electron heating and the ICRH effect on the impurities, the expected mode conversion is much more poor, and only few percents of the wave power are predicted to be converted to IBW.

2.3. Model of triplet configuration

A more realistic model of the potential function in the wave equation (6) is a triplet configuration [2, 7–10]. It takes into consideration the R-cutoff layer of FW propagation at HFS of a plasma column. In the uniform plasma approximation, the R-cutoff layer can exist at HFS, but it does not appear at LFS. The FW launched from LFS is partially reflected from and partially transmitted through the cutoff-resonance pair. Transmitted FW is completely reflected from the R-cutoff at HFS and transmitted back through the cutoff-resonance pair. Due to the interference of two reflected waves, the FW mode conversion coefficient can be increased essentially and reach 100 % [2,9,10]. The model has been applied also to a nonuniform plasma column, but it does not take into consideration the appearance of an R-cutoff layer at LFS.

The R-cutoffs of the FW propagation appear at the plasma edges, where the plasma density is low, but the R-cutoff at HFS exists at a higher density (deeper into the plasma column) than the R-cutoff at LFS due to the magnetic field nonuniformity. With increase in $k_\parallel$, the R-cutoffs are shifted to the plasma column center, where the plasma density is higher. At the same time, the width of the evanescence layer between the ion-ion hybrid resonance and the L-cutoff is decreased with increase in $k_\parallel$. Therefore, a general conclusion of the triplet-model-based consideration is that the enhanced mode conversion in the two-ion plasmas can be obtained for the FW with large $k_\parallel$.

The potential function of the wave equation (6) in the triplet configuration is modeled, as a rule, by the dependence [2]

$$Q(x) = \begin{cases} \gamma_1 - \dfrac{\beta}{x}, & \text{if} \quad x > 0, \\ \alpha x + \gamma_2 - \dfrac{\beta}{x}, & \text{if} \quad x < 0, \end{cases} \tag{10}$$

where the point $x = 0$ corresponds to the position of the ion-ion hybrid resonance. Then the FW mode conversion coefficient (9) in the framework of the triplet model can be expressed as

$$C = 2T(1 - T)(1 + \sin(2\Phi - \Psi)), \tag{11}$$

where $\Phi = \int_{x_R}^{0} Q^{1/2}(x)dx$ is the phase of the FW reflected from R-cutoff layer at HFS and $\Psi = arg(T_L)$ is the phase of the FW reflected from the L-cutoff layer. Here, $T_L = \dfrac{2\pi i e^{2\kappa(ln\kappa-1)}}{\Gamma(\kappa)\Gamma(\kappa+1)}$ and $\kappa = -\dfrac{i\eta}{2}$. To be more precise, the FW conversion coefficient has an oscillatory dependence on $k_\parallel$, and the envelope curve of these oscillations coincides with the dependence (11) multiplied by 4. This envelope curve will be called here as a Budden envelope. So the total coefficient of the wave power conversion has to be integrated value over the ICRH antenna spectrum.

In such a way, the triplet approximation of the FW propagation in nonuniform plasmas is more realistic than the Budden one. Moreover, it predicts a possibility of 100 % FW mode conversion in contradiction to the maximum of 25% in the framework of the Budden's problem. Generally speaking, it can be reached only when one of the maxima of the oscillatory dependence (11) coincides with the maximum of Budden's curve (9). But it can be always provided by changing the distance between the radial positions of the R-cutoff and the cutoff-resonance pair. The goal is to identify the experimental conditions when the FW mode conversion will be most effective and to clarify how robust are these conditions in relation to changes of the plasma parameters.

3. Mode Conversion Efficiency

The mode conversion process depends strongly on the plasma density. As an example, the radial profile of the plasma density from the typical JET discharges with impurity seeding $n_e(r) = n_0 \times 10^{13}(0.9(1-r^{1.8})^{0.8}+0.1)$ will be taken for the numerical calculations; here, the parameter n_0 defines the center electron density in cm^{-3}. The dependence of the mode conversion efficiency on the plasma density can be studied by changing the n_0 parameter.

The mode conversion coefficient C is calculated numerically as a solution of the wave equation (6), when the radial dependence of the potential function $Q(x)$ is defined from the experimental conditions in the local approximation. The two R-cutoffs of FW propagation play a fundamental role in the problem (Fig. 1). The R-cutoff at HFS works as a reflector for the FW propagating from LFS. Just due to the FW reflection and the interference between an antenna and

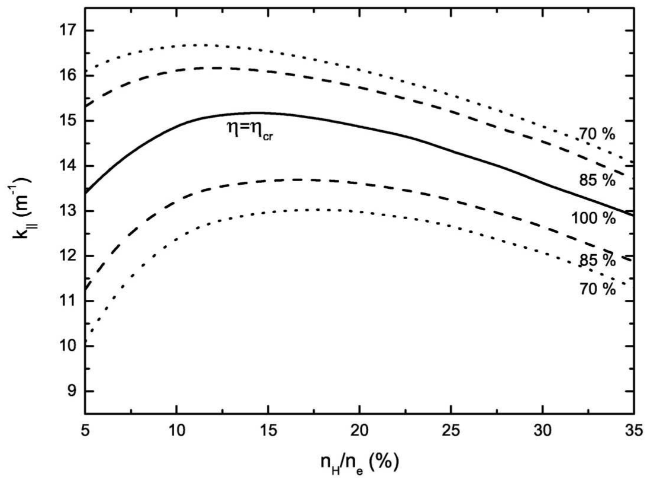

Fig. 2. Contour lines of the tunneling parameter η as a function of the hydrogen concentration and $k_{\|}$. The parameters are the same as in Fig. 1

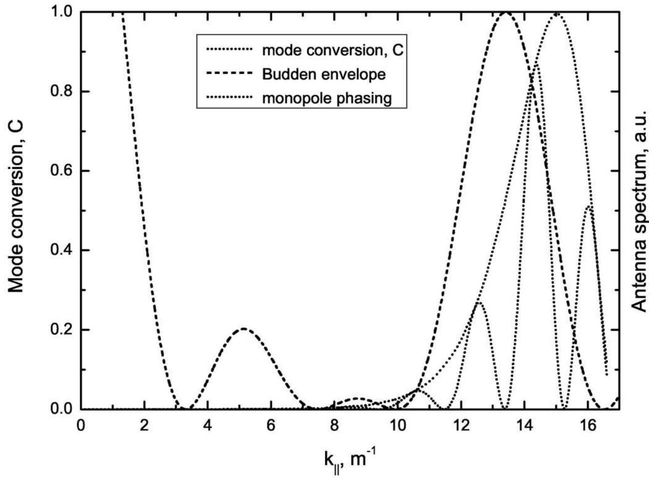

Fig. 3. Mode conversion coefficient C (solid line), Budden envelope (dashed line), and the antenna spectrum (dotted line) as functions of the parallel wave vector $k_{\|}$. The cutoff-resonance pair is at the center of the plasma column. The magnetic field value is 3.0 T. Other parameters are the same as in Fig. 1

the ion-ion hybrid resonance layer, the mode conversion coefficient can reach theoretically a unity for FW with some value of $k_{\|}$. But the R-cutoff at LFS reflects the power launched by an antenna. Therefore, a deeper position of the R-cutoff at LFS causes a weaker FW coupling from an antenna. The ideal condition of the consideration could be to have the R-cutoff at HFS into plasma but the R-cutoff at LFS outside plasma. That is possible, but the evanescence layer width under these conditions is enough large, and the FW transmission coefficient goes to zero. If the presence of the R-cutoff at LFS into plasma cannot be avoided, the distance from it to the plasma edge should be minimized. It is reached when the evanescence layer is close to the edge at HFS (see Fig. 1). Thus, the FW launching with the large $k_{\|}$ values faces less problems under conditions of the mode conversion at HFS.

The mode conversion problem is solved in the cold plasma approximation for D(H) plasmas with a large H concentration. The thermal effects become more important for the FW propagation with large $k_{\|}$ values. The borders of the range where the thermal effects cannot be neglected (the minority heating regime) are shown in Fig. 1 by the dashed lines.

According to both the Budden and triplet approximations, the most effective mode conversion can be reached for $\eta \simeq 0.22$. The precise maximum of C(η) depends on the relation between the phases Φ and Ψ in (11). The contour lines of the tunneling parameter η as a function of the hydrogen concentration and $k_{\|}$ are presented in Fig. 2. The value of $k_{\|}$ which is optimal for the mode conversion depends weakly on the hydrogen concentration when the last one exceeds 10 %. Figure 2, for example, allows us to conclude that the mode conversion will be efficient for the wave spectrum with the $k_{\|}$ peak in the range 12 $\mathrm{m}^{-1} < k_{\|} < 14$ m^{-1}, and it is almost independent of the hydrogen concentration. By concluding, we note that, for a given plasma density profile, the ICRH antenna phasing can be chosen with the essential peak in the calculated $k_{\|}$ range. For the reference density profile, it can be the $\{0,0,0,0\}$ antenna phasing having two peaks at $k_{\|} = \pm 13.4$ m^{-1}.

When the most suitable antenna phasing (for the expected plasma density) is chosen, the attention has to be paid to provide an appropriate relation between the phases Φ and Ψ for the optimal interference. There are two limit cases for the relation between the phases Φ and Ψ. They are illustrated in Figs. 3 and 4, where the antenna spectrum, Budden envelope, and the mode conversion coefficient are shown in the same plot. The first case is realized when the distance from the cutoff-resonance pair to the R-cutoff at HFS is enough large (Fig. 3). Then the period of oscillations of the mode conversion coefficient in (11) is smaller than the antenna peak width. If the minimum of the oscillatory dependence of (11) coincides with the maximum of the antenna spectrum, the general contribution to the mode conversion coefficient after integrating over the antenna spectrum will be poor. The second case takes place when the mode conversion layer is closed to the R-cutoff at HFS. Then the peak of oscillations of the mode

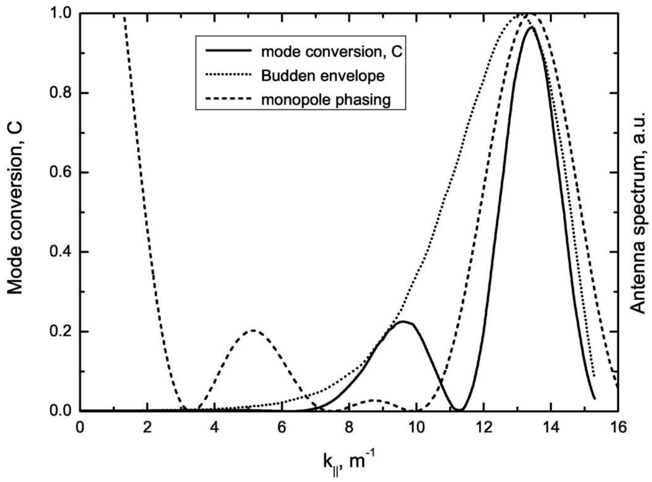

Fig. 4. Mode conversion coefficient C (solid line), Budden envelope (dashed line), and the antenna spectrum (dotted line) as functions of the parallel wave vector $k_{\|}$. The cutoff-resonance pair is at HFS. Other parameters are the same as in Fig. 1

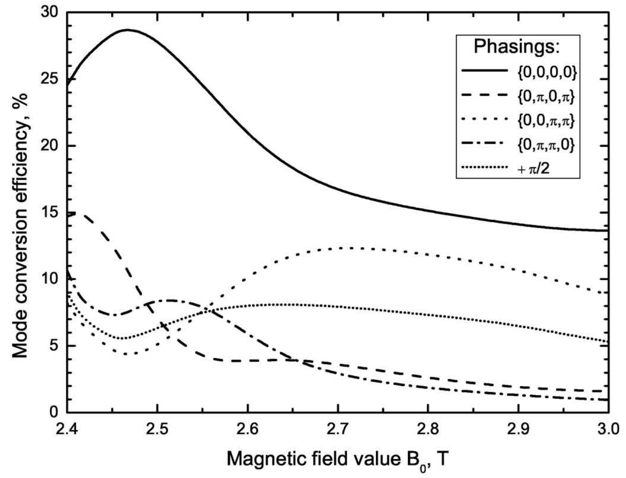

Fig. 5. Dependence of the mode conversion efficiency on the magnetic field strength for different antenna phasings. Other parameters are the same as in Fig. 1

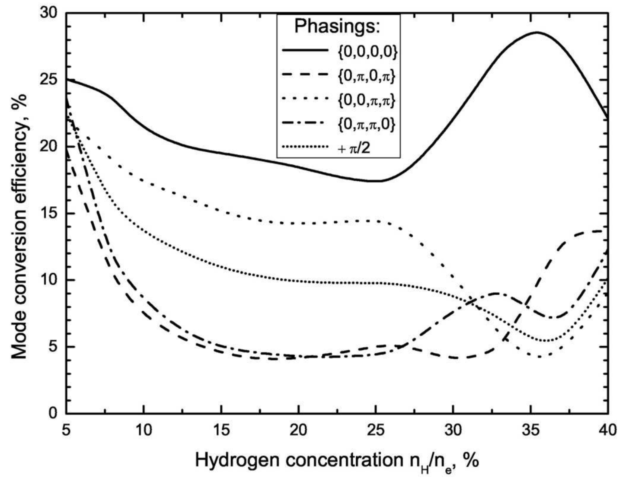

Fig. 6. Dependence of the mode conversion efficiency on the H concentration for different antenna phasings. Other parameters are the same as in Fig. 1

conversion coefficient coincides approximately with the peak of the antenna spectrum, and its half period coincides with the antenna spectrum width (Fig. 4). As a result, the mode conversion coefficient integrated over the antenna spectrum is larger in the second case, when the waves with $k_{\|}$ from the range $12\ \mathrm{m}^{-1} < k_{\|} < 15\ \mathrm{m}^{-1}$ are converted effectively to the IBW.

Now when the antenna phasing has been chosen, and the optimal conditions for the wave interference have been defined, the mode conversion efficiency will be calculated numerically by integrating over the typical JET antenna spectra. The integrated mode conversion coefficient as a function of the magnetic field strength is presented in Fig. 5. Smaller magnetic field values correspond to the position of the ion-ion hybrid resonance layer at HFS. The figure proves the choosing of the $\{0, 0, 0, 0\}$ antenna spectrum as an optimal for the mode conversion for a given plasma density profile. Moreover, the conditions for the mode conversion is really better at HFS: the mode conversion coefficient drops from 28% at HFS to 13% at LFS. Other antenna phasing gives much smaller mode conversion efficiency. This agrees completely with the analysis of the $\eta \simeq 0.22$ dependence.

The dependence of the mode conversion efficiency on the hydrogen concentration when the ion-ion hybrid resonance layer is placed at HFS is shown in Fig. 6. For the $\{0, 0, 0, 0\}$ antenna phasing, the mode conversion efficiency is changed in the range $18 \div 28\%$. This means that at least a quarter of the launched power will be converted to short waves almost independently on the hydrogen concentration if the last one is changed in the range $10 \div 35\%$.

4. Evanescence Layer in Front of the Antenna

The R-cutoff at HFS reflects the FW propagating in the plasma column, but a presence of the R-cutoff at LFS affects the FW launching to the plasmas. The effect of the evanescence layer at LFS in front of the ICRH antenna can be estimated according to [15]. The power P_{trans} transferred from the ICRH antenna into plasma can be expressed through a constant P_0 which is proportional to the square of the current value in the antenna:

$$P_{\text{trans}} \simeq P_0 e^{-\tau \kappa_\parallel L_c}, \qquad (12)$$

where L_c is the distance from the antenna to the R-cutoff at LFS, and τ is a constant obtained by integrating over the vacuum and plasma ranges between the antenna and the R-cutoff. Though the ICRH antenna coupling needs a more detailed consideration in a two-dimensional geometry, the proposed mechanisms of the FW transmission, reflection, and conversion always work when the wave has been already launched into plasma.

5. Conclusions and Discussions

The FW mode conversion can be efficient for the scenarios with large minority ion concentration. It is actual for the local electron heating to study the transport processes and to generate the outward pinch for impurities. The mode conversion efficiency is not sensitive to the H concentration in D plasmas when the concentration exceeds 10%. It is very sensitive to the plasma density, but, for the moderate ones, it is always possible to select the conditions of the experiment (the antenna phasing and the position of the ion-ion hybrid resonance by choosing a relation between the operating frequency and the magnetic field strength) when the mode conversion efficiency will be of the order of 30%.

The role of the high field side R-cutoff is taken into consideration according to the theory of the triplet configuration. The ion-ion hybrid resonance layer at HFS is more preferable for both the mode conversion and the wave launching with large $k_\parallel$. The main attention has been paid to the particular conditions of the JET D(H) experiments, but it is clear that all results obtained and discussed here can be corrected for the plasma composition with impurity ions. The presented consideration allows one to estimate the fraction of the converted wave power. It is important to get a general power balance in the ICRH experiments with the selective impurity heating [16].

The work does not consider the processes of wave absorption just to outline the fraction of the power converted to short IBW waves. Including the thermal effects will allow one to calculate the fraction of the absorbed FW wave power. The power analysis of the FW conversion and the mechanisms of FW damping (the direct FW damping on electrons and the damping on cyclotron harmonics) gives a possibility to optimize the experimental conditions of the discharges with a large H concentration which are traditionally dangerous for the ICRH antenna operation.

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ПОКРАЩЕНА КОНВЕРСІЯ МОД У РОЗРЯДАХ ЯДЕРНОГО СИНТЕЗУ З ВЕЛИКОЮ КОНЦЕНТРАЦІЄЮ ІОНІВ МАЛОЇ ДОБАВКИ

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Р е з ю м е

Ефективність конверсії швидкої магнітозвукової хвилі в іонну бернштейнівську хвилю вивчається для двокомпонентної плазми з великою концентрацією іонів малої добавки. Як приклад проведено аналіз ефективності конверсії для D(H) плазми токамака JET. Числове вивчення на основі одновимірного хвильового коду базується на розвитку моделей Баддена [1] та триплет [2] з урахуванням трактовки [3]. Показано, як вибрати фазування антени, щоб досягти найбільш ефективної конверсії для заданого профілю густини плазми. Разом з тим не існує суттєвої залежності ефективності від концентрації іонів малої добавки, коли остання перевищує певну величину (близько 10% для D(H) плазми токамака JET). Досягти ефективної конверсії простіше у прошарку з боку сильного магнітного поля.