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Effective fast wave mode conversion in deuterium plasmas with large hydrogen concentration

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Introduction. Radiative improved modes are considered as the discharges which will allow to develop the operation scenario for tokamak working in a quasi steady state regime [1]. But a noble gas puffing produces both a radiation mantle at the plasma edge and an impurity accumulation in the center. One of the ways to avoid this problem is the extraction of the heavy impurities from the center by applying some external action, for example, by a selective ICRH heating of the impurities [2]. This work considers a possibility of the effective Fast Wave (FW) mode conversion to heat selectively the puffing impurities in JET impurity seeding discharges using facilities of the ICRH antenna. A peculiarity of the consideration is a large fraction of the minority ions.

Mode conversion models. The approximate reduced second-order dispersion relation for the FW propagating in non-uniform plasma is given by:

$$n_\perp^2 = \frac{(L - n_\parallel^2)(R - n_\parallel^2)}{S - n_\parallel^2}, \tag{1}$$

where S, L and R are the components of the cold plasma dielectric tensor in the Stix notation. In the vicinity of the ion-ion hybrid resonance the FW is partially converted to the Ion Bernstein Wave (IBW). The IBW is strongly damped on electrons at the distance of some IBW wavelengths on the high field side from the ion- ion hybrid resonance layer. The FW is launched at the Low Field Side (LFS) (positive x direction) and it propagates to the High Field Side (HFS) (negative x direction) reflecting from and transmitting through the ion-ion hybrid resonance layer.

The FW wave equation can be written in the Budden approximation:

$$\frac{d^2E_y}{dx^2} + k_A^2(1 - \Delta/x)E_y = 0, \tag{2}$$

where k_A is the FW wave vector at $x = \infty$ and Δ is the evanescent layer thickness. The solution of the Budden equation gives the dependence of mode conversion C coefficients: C=T (1–T). Here $T = e^{-\pi\eta}$, where $\eta = k_A \Delta$ is called the tunneling factor. According to the Budden approximation the conversion coefficient C has the maximum value 25% for $\eta_{cr} = 0.22$.

More realistic triplet configuration model takes into consideration the existence of the R-cutoff at the HFS of the plasma [3]. The FW launched from the LFS is transmitted through the ion-ion hybrid resonance layer and is reflected from the R-cutoff at the HFS. Due to the interference of the waves reflected from the L- and R-cutoff the efficiency of the FW mode conversion can be increased essentially. The FW conversion coefficient in the triplet configuration has the oscillatory dependence on the $k_{||}$ value and can reach 100% [3]:

$$C = 2T(1-T)(1+\sin(2\Phi - \Psi)) \tag{3}$$

where Φ is the phase of the FW reflected from the R-cutoff at the HFS and Ψ is the phase of the FW reflected from the L-cutoff. The mode conversion efficiency is the integrated value over the ICRH antenna spectrum. The FW mode conversion in D(H) plasma with large H concentration was studied at Alcator C-Mod [4] and Tore Supra [5].

Mode conversion efficiency. The mode conversion process depends strongly on the plasma density. For the numerical simulations the plasma density profile typical for the Ar impurity seeding discharges at JET $n_e(r) = n_0 \cdot 10^{13} \cdot ((1 - r^{1.8})^{0.8} + 0.1)$ is used, where n_0 is the "central" electron density. Here the wave spectra of the JET antenna will be used to get the integrated mode conversion efficiency in D(H) plasmas with large H concentration. Particular cases of interest are the H concentrations n_H/n_e=32%, n_H/n_e=23% and n_H/n_e=14% which correspond to the coincidence of the ion-ion hybrid resonance layer with the second cyclotron harmonic resonance layer of Ar^{+16}, Ar^{+17} and Ar^{+18} respectively. Numerical research shows (Fig. 1) that the tunneling factor η depends weekly on the parallel wave vector $k_{||}$ when the H concentration is in the range [0.1;0.4]. Therefore the H concentration 0.32 will be tested here.

Figure 2 presents the dependence of the tunneling factor η on the position of the ion-ion hybrid resonance layer for n_0=2.4 and different values of $k_{||}$. The position of the ion-ion hybrid resonance layer is varied by the magnetic field changing. Triplet model predicts the effective mode conversion for tunneling factor values in the range [0.05;0.61] (these values are indicated by the dashed horizontal lines). Analysis of the figure allows to make a conclusion that mode conversion can be effective for the antenna spectra which have the peaks in the range 11÷15 m^{-1}. For the JET antenna just monopole (0,0,0,0) phasing has the peak at $k_{||}$=13.4 m^{-1}. So a good mode conversion is expected for this phasing.

Scan results of the mode conversion efficiency integrated over the JET antenna spectra on the magnetic field value (the radial position of the ion-ion hybrid layer depends on the $k_{||}$ value) are presented in Figure 3. Indeed the fraction of the mode converted power is the largest for the monopole phasing and is decreased from 0.33 at the HFS to 0.075 at the LFS (with the magnetic field increasing). A reason of such dependence is the following. The mode conversion coefficient depends on the phase $2\Phi-\Psi$ value (3). For mode conversion at the HFS the distance between the R-cutoff and the ion-ion hybrid resonance is small. Therefore the oscillation period of the mode conversion coefficient becomes approximately equal to the width of the antenna spectrum peak (Fig. 4). It is clear that the integration over the antenna spectrum gives the maximal contribution from the peak at $k_{||}$ = 13.4 m^{-1}. But for the mode conversion at the LFS the distance between the R-cutoff and the ion-ion hybrid resonance is large. Therefore the period of the coefficient oscillation is much smaller than antenna spectrum width. The integration over the antenna spectrum gives only 15 % of the efficiency.

Scan results of the integrated mode conversion efficiency on the H concentration for the magnetic field 2.5 T are presented in Figure 5. In this case the ion-ion hybrid resonance layer is located at the HFS and the mode conversion efficiency for the monopole phasing is changed from 22.5 % to 32.5 %. Figure 6 demonstrates the solution of the wave equation for E_y component of the wave electric field for $k_{||}$=13.4 m^{-1}. The small oscillation amplitude at the LFS from the ion-ion hybrid resonance represents the small reflection and almost the total conversion of the FW with the considered $k_{||}$.

Another important remark for the mode conversion at the HFS is related to the wave launching with large $k_{||}$. The effective mode conversion at the HFS is reached for smaller magnetic field values compared with the mode conversion at the LFS. It means the R-cutoff for the LFS mode conversion appears at lower densities and as a result the evanescence layer in front of the antenna is smaller. Therefore the mode conversion at the HFS is preferable for launching the waves with large $k_{||}$ in plasmas.

Discussions and conclusions. The FW mode conversion can be effective for the scenario with the large minority ion concentration. The mode conversion efficiency is not sensitive to the H concentration in D plasmas when the H concentration exceeds 10% (just such large minority concentrations are interesting for the selective ICRH impurity heating). It is very sensitive to the plasma density but for the moderate densities it is always possible to select the conditions of the experiment (antenna phasing and the position of the ion-ion hybrid resonance by choosing the operating antenna frequency or the magnetic field value) 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 location of the ion-ion hybrid resonance at the HFS is more preferable for the effective mode conversion and for the waves launched with large $k_{||}$. The effective mode conversion provides the conditions to use the increased left-hand polarized component of the electric field E_+ to heat effectively the impurities at the second harmonic of the cyclotron resonance. The effective IBW damping at the electrons allows to avoid the wave power reflection back to the antenna.

The main attention has been paid to the particular conditions of the JET D(H) experiments with ICRH heating in the impurity seeding modes. Including the finite plasma temperature effects will allow to estimate the fraction of the absorbed wave power. As a result the wave coupling will be predicted and the impurity heating will be calculated for the considered ICRH scenarios.

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References

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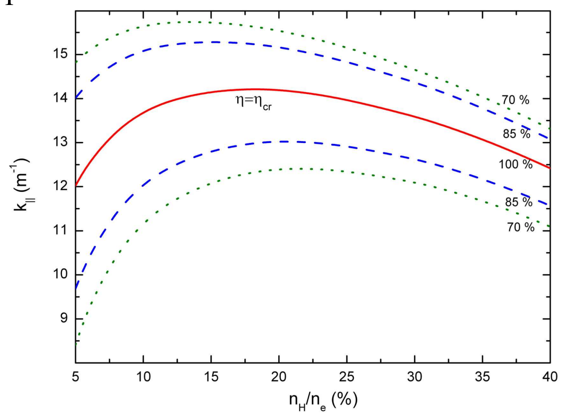

Fig.1. Contours of the tunneling factor as a function of the H concentration and $k_{||}$.

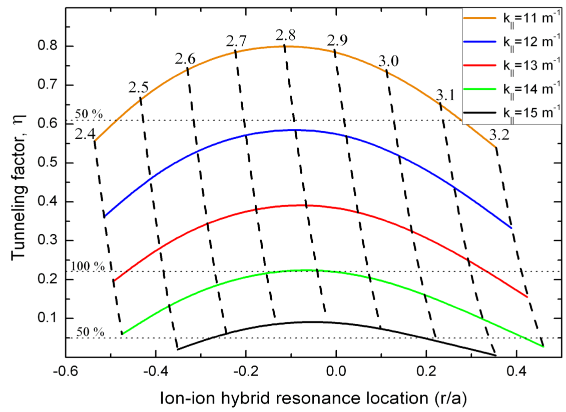

Fig.2. The tunneling factor dependence on the position of the ion-ion hybrid resonance layer.

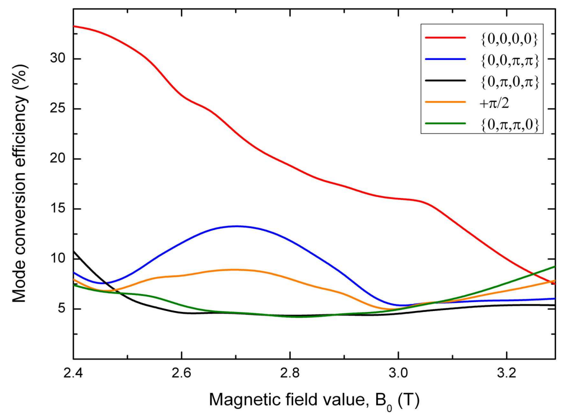

Fig.3. The dependence of mode conversion efficiency on the magnetic field value.

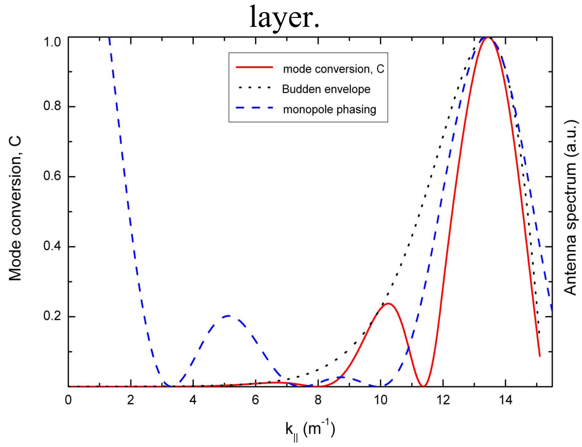

Fig.4. Mode conversion coefficient, Budden envelope and antenna spectrum.

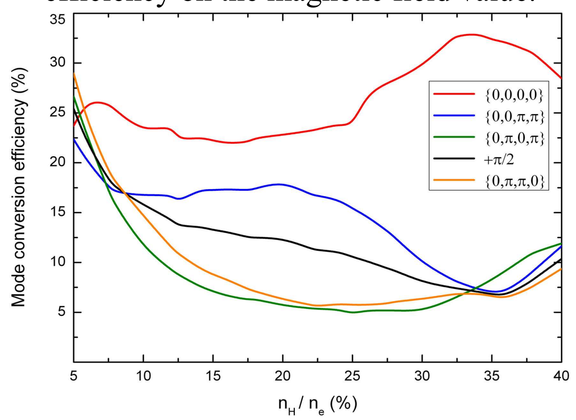

Fig.5. The dependence of mode conversion efficiency on the H concentration.

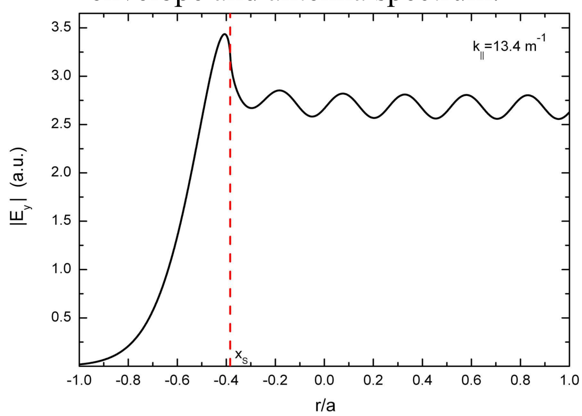

Fig.6. $|E_y|$ radial dependence, f=37.4 MHz, B_0=2.5 T.