FAST WAVE MODE CONVERSION IN MULTICOMPONENT NONUNIFORM PLASMAS

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The ICRF mode conversion heating scenario relevant to the start-up phase of ITER operation is studied. The 1D theory of fast wave (FW) propagation in fusion plasmas is applied to study the inverted ICRF (^{3}He)H scenario with two ion-ion hybrid resonances for the typical conditions of the tokamak JET. The role of the intrinsic impurity C^{6+} ions in the mode conversion for the considered heating scenario is discussed. It is shown that for the modest concentrations of carbon impurity (above ~ 1.5%) the corresponding evanescence layer is enough wide to reflect the FW and produce the interference pattern which, in turn, determines the mode conversion efficiency and subsequent local electron heating.
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1. INTRODUCTION

The hydrogen H plasma will be used during the initial phase of the ITER operation to minimize the activation of the tokamak. The two ITER-relevant ICRF heating scenarios using the minority ions of deuterium D and helium three ^{3}He has been studied recently on the JET tokamak both in the minority heating (MH) and mode conversion (MC) regimes [1,2]. These scenarios are inverted, i.e. the charge-to-mass ratio of the minority ions is smaller than that of the majority ions, $Z_{min}/A_{min} < Z_{maj}/A_{maj}$. In such plasmas the ion-ion hybrid (IIH) resonance layer is located on the low field side (LFS) of the minority cyclotron resonance. Therefore the FW launched by the ICRF antenna from the LFS of the tokamak approaches the IIH resonance layer before reaching the cyclotron resonance layer.

MH regime occurs for the small concentrations of the minority ions less than some critical value. In this regime the minority ions are effectively heated and the energetic tail in the minority ion distribution function is produced. The subsequent electron and background ion heating happens after the several slowing down times. With the increase of the minority concentration the transition from MH to MC regime occurs.

In the MC regime the launched FW is partially converted to the slow wave (SW) in the vicinity of the IIH resonance layer. Regardless of the nature of SW (it depends both on temperature and poloidal magnetic field effects) it is effectively absorbed by electrons due to the strong ELD mechanism which gives rise to the direct electron heating.

It was found that the MH regime is inaccessible in (D)H plasmas due to the presence of the intrinsic impurity ions with Z/A=1/2 (particularly, C^{6+} ions) [1,2]. The charge-to-mass ratio of such ions is the same as for D ions. Such impurities together with the D ions define the properties of the evanescence layer. Typically, the carbon concentration is ~ 1-3% which immediately leads to the MC heating regime.

In this paper the role of C^{6+} impurity ions which produce the second IIH resonance layer in (^{3}He)H plasma is discussed. The similar heating scenario of (H,^{3}He)D plasma with two IIH resonance layers was studied in [3]. This scenario is relevant to the high field side (HFS) antenna location.

Here the theory of FW propagation in nonuniform plasmas with two IIH resonances [4] is used to analyze the (^{3}He)H heating scenario. It is shown that the efficient mode conversion and subsequent electron heating could be achieved due to the interference effects between two reflected waves. This effect is similar to the beating effect described in [5]. But for the considered conditions the second reflected wave exists due to the reflection from the additional evanescence layer instead of reflection from the HFS R-cutoff at low plasma density.

2. THE ROLE OF C^{6+} IONS DURING THE MODE CONVERSION IN (^{3}He)H PLASMAS

The propagation of the FW in nonuniform plasma is usually described by the wave equation for the E_y component of the electric field

$$\frac{d^2 E_y}{dx^2} + Q(x) E_y = 0. \qquad (1)$$

The potential function Q(x) is proportional to the square of the perpendicular refractive index given by the dispersion relation

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

where S, L, and R are the components of the plasma dielectric tensor in the Stix notation and $n_\parallel = ck_\parallel/\omega$ is the parallel refractive index. The ion-ion hybrid resonances ($S = n_\parallel^2$) and L-cutoffs ($L = n_\parallel^2$) form the evanescence layers which are the barriers for the FW propagation. The number of the evanescence layers depends on the number of the ion species with the different charge-to-mass ratio. The equation $R = n_\parallel^2$ defines R-cutoffs which appear at the plasma edge where the plasma density is enough small.

The typical dispersion relation for the plasma which consists of H, ^{3}He and C^{6+} ions is shown in Fig. 1. The FW launched by the antenna from the LFS is partially reflected from L_1 and L_2 cutoffs.

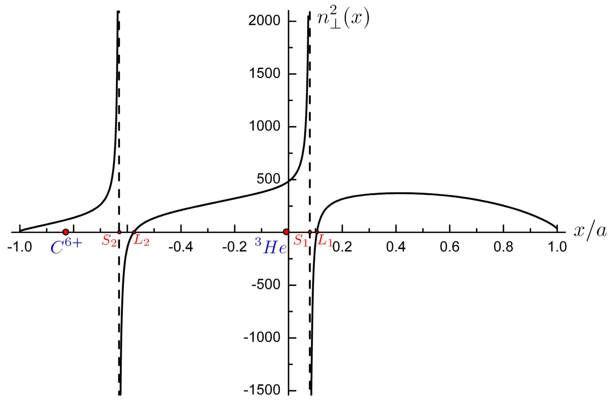

Fig.1. The real part of $n_\perp^2(x)$ *as a function of the normalized distance, x/a. The plasma consists of H, ^{3}He, C^{6+} ions with the fractions 0.83, 0.025 and 0.02, respectively*

As shown in [4] the scattering characteristics (transmission, reflection and mode conversion coefficient) depend on the value of the tunnelling parameters of each evanescence layer η_1 and η_2

$$\eta_{1,2} = \frac{2}{\pi}\int_{S_1,S_2}^{L_1,L_2} (-Q(x))^{1/2}\,dx \qquad (3)$$

and also on the phase difference between the reflected waves $\Delta\varphi$

$$\Delta\varphi = 2\Phi + \Psi_2 - \Psi_1, \qquad (4)$$

$$\Phi = \int_{L_2}^{S_1} Q(x)^{1/2}\,dx,$$

$$\Psi_{1,2} = \mathrm{Arg}\left(\frac{2\pi\, i\exp(2k_{1,2}(\ln k_{1,2}-1))}{\Gamma(k_{1,2})\Gamma(1+k_{1,2})}\right),\ k_{1,2} = -i\eta_{1,2}/2.$$

The mode conversion coefficient C is given by the formula

$$C = T_1T_2(1-T_1T_2) + 4T_1(1-T_1)(1-T_2)\sin^2(\Delta\varphi/2), \quad (5)$$

where $T_{1,2}=\exp(-\pi\eta_{1,2})$ are the transmission coefficients through the corresponding evanescence layers. The values of the tunnelling parameters depend on the positions of the IIH resonance layers in plasma and are very sensitive to the ion species mixture. With the increase of the minority concentration the corresponding IIH resonance layer moves from the fundamental cyclotron resonance layer towards LFS. The formula (5) provides the conditions to achieve the efficient mode conversion: the tunneling parameter η_1 should be close to the optimal value η_1=0.22 (T_1=0.5) and the second layer should be enough wide to reflect the FW transmitted through the first layer. The phase condition $\Delta\varphi = \pi(2n+1),\ n\in Z$ should be satisfied to provide the enhanced mode conversion.

The typical parameters of the JET experiments are used for the numerical simulations. The magnetic field $B_0 = 3.6\,T$ and the antenna frequency $f = 37.0\,MHz$ are chosen in such a way to locate ^{3}He fundamental cyclotron layer in the centre of the plasma column. The density profile is assumed to be

$$n_e(r) = n_0(0.95(1-r^{1.8})^{0.8} + 0.05)$$

with the central electron density $n_0 = 2.5\cdot 10^{13}\ cm^{-3}$.

In order to study the effect of C^{6+} ions the carbon concentration was varied in the range from 1 to 3 % for several concentrations of ^{3}He ions. The results are shown in Fig. 2 with the contour plots of the constant levels of the maximal conversion coefficient C_{opt} [4]

$$C_{opt} = T_1T_2(1-T_1T_2) + 4T_1(1-T_1)(1-T_2). \qquad (6)$$

It is clear that for the considered conditions the evanescence layer associated with the carbon ions is enough wide to reflect most of the energy transmitted through the first evanescence layer. The transmission coefficient T does not exceed 15 % for the carbon concentrations above ~1.5%. It means that the evanescence layer produced by carbon ions acts similar to R-cutoff in the theory of triplet configuration [5].

The C_{opt} is the maximal possible mode conversion coefficient provided by the interference phase condition. As shown in Fig. 2 the tunneling parameters are increased with the increase of the carbon concentration (η_2 is increased linearly) which results in the decrease of the transmission coefficient T and the formation of the non-transparent second barrier for the FW propagation. The mode conversion coefficient C_{opt} is varied in the range from 85 to 50% for the considered minority fractions.

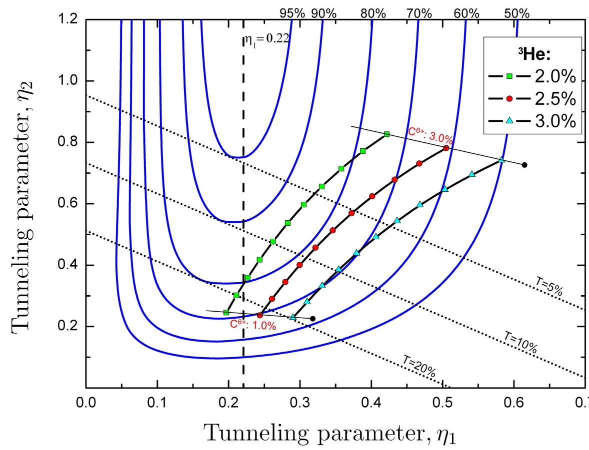

Fig.2. The dependence of the tunneling parameters η_1 and η_2 on the carbon concentration

3. DISCUSSIONS

As it was mentioned the mode conversion coefficient is determined by the phase difference between the reflected waves. The phase conditions corresponding to the parameters of Fig. 2 as a function of the carbon concentration are shown in Fig. 3. With the increase of the carbon concentration the evanescence layer moves from the carbon cyclotron resonance towards LFS. As a result the distance between L_2 and S_1 layers and respectively the phase difference $\Delta\varphi$ are decreased. The optimal phase conditions are achieved for some relations between carbon and helium concentrations. In this case the mode conversion coefficient is equal to C_{opt}: 85%, 75% and 40% (depending on the ^{3}He concentration). It means the experimental conditions should be optimized with the correction on C^{6+} presence to achieve the enhanced mode conversion efficiency.

The several numerical calculations were carried out to study the influence of the central electron density n_0 on the mode conversion process. The change in the central density results in the change of each tunneling parameter and the phase difference. With the increase of the central density both tunneling parameters are increased (roughly as the square root of the central density). It happens due to the increase of the perpendicular wavenumber while the location of the resonances and L-cutoffs is almost unchanged. The density change has the stronger influence on the phase condition. The phase difference is increased because of the decrease of the perpendicular wavelength.

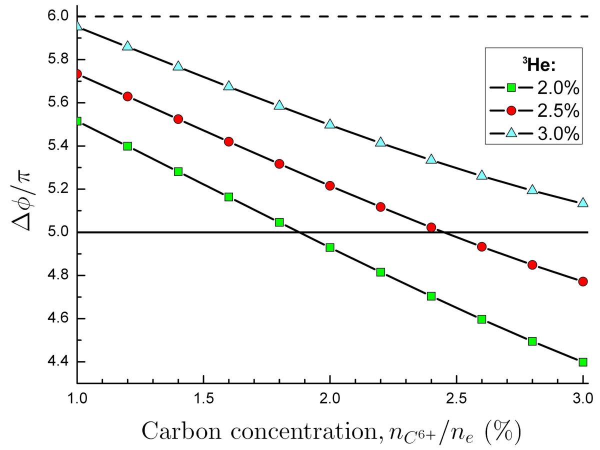

Fig.3. The phase difference Δφ as a function of the carbon concentration

The ICRF antenna launches the spectra of fast waves with different $k_{||}$ depending on the antenna phasing. The dependence of the mode conversion coefficient on $k_{||}$ is opposite to the dependence on the carbon fraction: with the increase of $k_{||}$ the width of the evanescence layers is decreased. It means that different experimental conditions should be provided for the different antenna phasings to achieve the efficient mode conversion.

CONCLUSIONS

The role of the intrinsic impurity ions with Z/A=1/2 (e.g. C^{6+}) in the fast wave mode conversion in (^{3}He)H plasmas is studied. It is shown that the second ion-ion hybrid resonance plays the important role in the mode conversion process for the typical experimental conditions. The relation between the minority ^{3}He and impurity C^{6+} ion concentrations defines the conditions of the interference between the fast waves reflected from two evanescence layers. As a result the launched fast wave power can be either almost totally converted if the reflected waves come with the opposite phases or almost totally reflected for the co-phase case. Thus the presence of the intrinsic impurity C^{6+} ions should be taken into account to describe correctly the mode conversion heating of (^{3}He)H plasmas.

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КОНВЕРСИЯ БЫСТРОЙ МАГНИТОЗВУКОВОЙ ВОЛНЫ В МНОГОКОМПОНЕНТНОЙ НЕОДНОРОДНОЙ ПЛАЗМЕ

Е.О. Казаков, И.В. Павленко, И.А. Гирка, Б. Вейссов

Изучается сценарий высокочастотного нагрева плазмы в режиме конверсии мод, имеющий отношение к начальной стадии работы токамака ITER. Одномерная модель распространения быстрых магнитозвуковых волн (БВ) в плазме была применена для изучения (^{3}He)H сценария нагрева с двумя ион-ионными гибридными резонансами для типичных условий токамака JET. Рассматривается влияние C^{6+} ионов примеси на процесс конверсии для данного сценария нагрева. Показано, что для умеренных значений концентрации углерода (больше ~1.5%) соответствующий слой непрозрачности является достаточно широким для того, чтобы отразить БВ и создать интерференционную структуру, которая, в свою очередь, определяет эффективность конверсии и последующего локального нагрева электронов.

КОНВЕРСІЯ ШВИДКОЇ МАГНІТОЗВУКОВОЇ ХВИЛІ В БАГАТОКОМПОНЕНТНІЙ НЕОДНОРІДНІЙ ПЛАЗМІ

Є.О. Казаков, І.В. Павленко, І.О. Гірка, Б. Вейссов

Досліджується сценарій високочастотного нагрівання плазми в режимі конверсії мод, який має відношення до початкової фази роботи токамака ITER. Одновимірна модель поширення швидких магнітозвукових хвиль (ШХ) в плазмі була застосована для вивчення (^{3}He)H сценарія нагрівання з двома іон-іонними гібридними резонансами для типових умов токамака JET. Розглядається вплив іонів домішки вуглецю C^{6+}на процес конверсії для даного сценарію нагрівання. Показано, що для помірних значень концентрації вуглецю (більше за ~1.5%) відповідний шар непрозорості є достатньо широким для того, щоб відбити ШХ та створити інтерференційну структуру, яка, в свою чергу, визначає ефективність конверсії та подальшого локального нагрівання електронів.