ICRF MODE CONVERSION EFFICIENCY IN A TWO-ION COMPONENT PLASMA OF A TOKAMAK

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Mode conversion of fast magnetosonic wave (FMSW) into a short-wavelength wave is studied in the presence of ion cyclotron absorption and direct electron damping in a tokamak plasma. In plasmas with two (a majority and a light minority) ion species, FMSW launched from the low-field side ICRF antenna can convert to a slow mode which runs towards the minority cyclotron resonance point, if the component of confining filed along the big radius of torus is sufficiently large. The efficiency of conversion has been studied with the help of one-dimensional code which computes full-wave solution of Maxwell equations with cold plasma conductivity. The dependencies of conversion efficiency on plasma density and minority concentration have been established.

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1. INTRODUCTION

A most successful way of delivering radio frequency power in the ion-cyclotron range of frequencies (ICRF) into a tokamak plasma is through fast magnetosonic waves (FMSW) exited from the low magnetic field side (LFS) of a tokamak. The coupling, propagation and damping of FMSW's have been extensively studied theoretically earlier [1, 2]. In plasma consisting of at least two ion species, the ion-ion hybrid resonance is present if the frequency of the wave is in between the cyclotron frequencies of the two ion species. In the vicinity of this resonance, the FMSW can couple to the slow mode (SM). Such regimes are known as mode conversion regimes. These regimes are expected to be favorable for current drive in the ion cyclotron frequency range (ICCD). Therefore, it is important to determine the dependence of mode conversion efficiency on plasma parameters.

2. FORMULATION OF THE PROBLEM

In the following, mode conversion is studied in the deuterium plasma of the medium size tokamak (big radius $R_0 = 2\,m$) with hydrogen or ^{3}He minority. Here we consider one-dimensional problem where a plasma slab inhomogeneous along X axis is bounded by ideally reflecting walls at $x = x_{in} = -0.6\,m$ and $x = x_{out} = 0.6\,m$ respectively. Magnetic field has a form $\breve{B} = \breve{e}_x B_x + \breve{e}_z B_z$ where $B_z = B_z(x) = B_{z0}(1 + x/R_0)^{-1}$ is a toroidal field with $B_{z0} = 2T$, $B_x = B_{z0}\tan(\gamma)$ is a poloidal field and $\gamma = 0.1$. Profiles of ion densities are of the form

$$n_\alpha(x) = \begin{cases} n_{\alpha 0}\left(1 - x^2/r_{ef}^2\right), & |x| < r_p; \\ n_{\alpha 1}\exp\left(\left(r_p - |x|\right)/\Delta\right) + n_{\alpha b}, & |x| \ge r_p. \end{cases}$$

Here $n_{\alpha 0}$ and $n_{\alpha b}$ are α species central and boundary densities. Matching parameters r_{ef} and $n_{\alpha 1}$ are chosen from continuity condition of density and its first derivative at $x = r_p$. Parameter values are $r_p = 0.5\,m$, $\Delta = 0.01\,m$, $\sum_\alpha n_{\alpha b} = 10^{16}\ m^{-3}$. Other parameters have been varied in the study.

The efficiency of conversion has been studied with the help of one-dimensional code which computes full-wave solution of Maxwell equations with cold plasma conductivity. The following harmonic dependence of electromagnetic field on *y*, *z* variables and time is assumed $E, B \propto \exp\left(ik_y y + ik_z z - i\omega t\right)$ with various k_z and $k_y = 5\,m^{-1}$. Wave frequency ω equals to the minority cyclotron frequency in the slab centre $x = x_{res} = 0$. Waves were excited by the antenna current located at $x = 0.55\,m$.

Note that for large enough poloidal field both, fast and slow modes have a negligible small value of parallel electric field. Thus, in WKB approximation the dispersion can be described by forth order equation for x-component of the refraction index $N = kc/\omega$,

$$N_\perp^2\left(\varepsilon_1 - N_\parallel^2\right) - (\varepsilon_1 - N_\parallel^2)^2 + \varepsilon_2^2 = 0\,.$$

Here the notation is $N_\perp^2 = \left(N_x B_z - N_z B_x\right)^2 / B^2 + N_y^2$, $N_\parallel = \left(N_x B_x + N_z B_z\right)/B$. In the plasma with two ion species and large enough poloidal magnetic field FW launched from the low field side antenna penetrates through the opacity region, reflects from the high field side cut-off and partly converts to a slow mode traveling to the minority ion cyclotron resonance point where it is fully absorbed (Fig. 1).

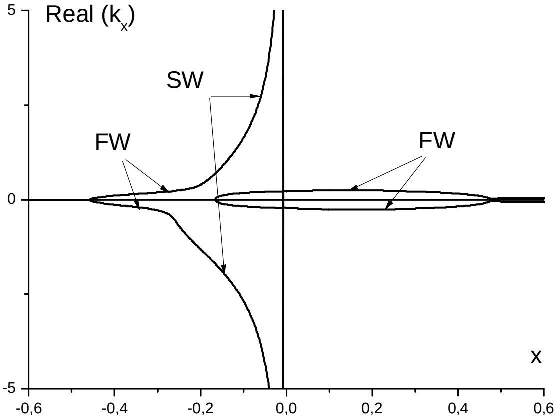

Fig. 1. Wave dispersion

Singular behavior of slow mode wave vector at minority cyclotron resonance point corresponds to magnetic beach scenario. The higher fraction of FW energy is transformed into SW the more efficient is mode conversion current drive.

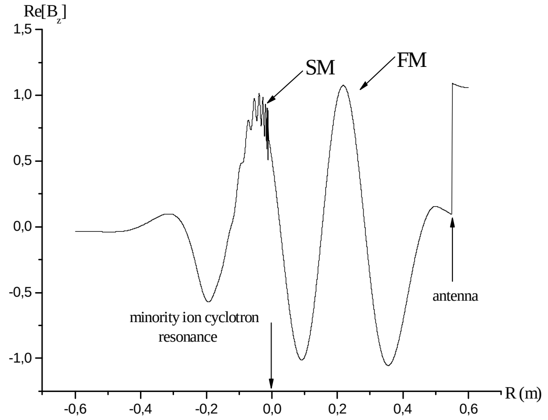

Fig. 2. The real part of z-component of magnetic field of fast and slow modes

This fraction is characterized by the ratio of electrostatic energy of parallel electric field to the energy contained in z component of the wave magnetic field,

$$\eta_C = \int_{x_{in}}^{x_{res}} \left|E_{\parallel}\right|^2 dx \Bigg/ \int_{x_{res}}^{x_{out}} \left|B_z\right|^2 dx .$$

3. MODELLING RESULTS

Behavior of electromagnetic field corresponding to dispersion in Fig. 1 is shown in Fig. 2. Dependencies of conversion efficiency η_C on plasma density and minority concentration are shown for a single wave mode and hydrogen minority in Fig. 3, for a single wave mode and ^{3}He minority in Fig. 4 and for the whole antenna spectrum and hydrogen minority in Fig. 5. In all cases η_C demonstrate an oscillatory behavior with highest maximum in the range of high minority concentrations (30 – 35 % for hydrogen and 20…30% for ^{3}He minority). This optimum is weakly dependent on plasma density.

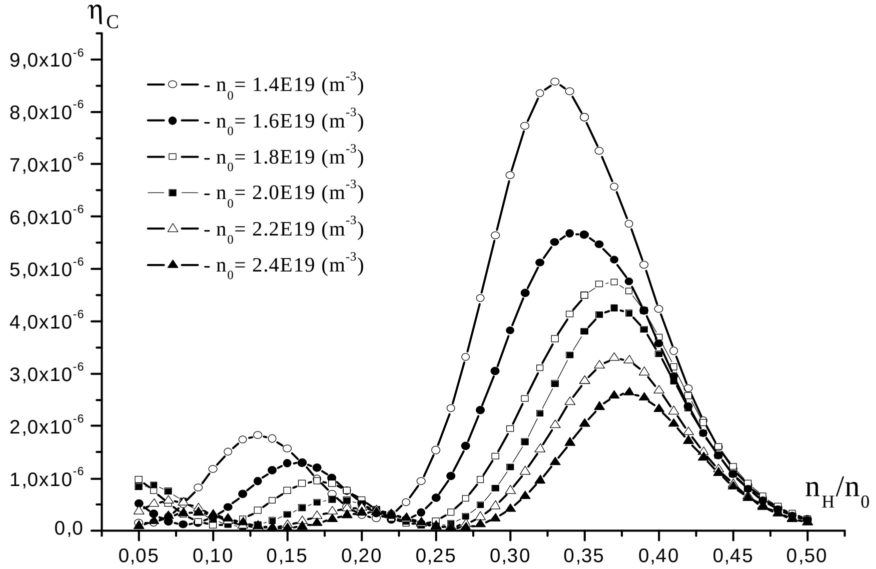

Fig. 3. Mode conversion efficiency depends on minority concentration of H for a single wave mode; $H + D$

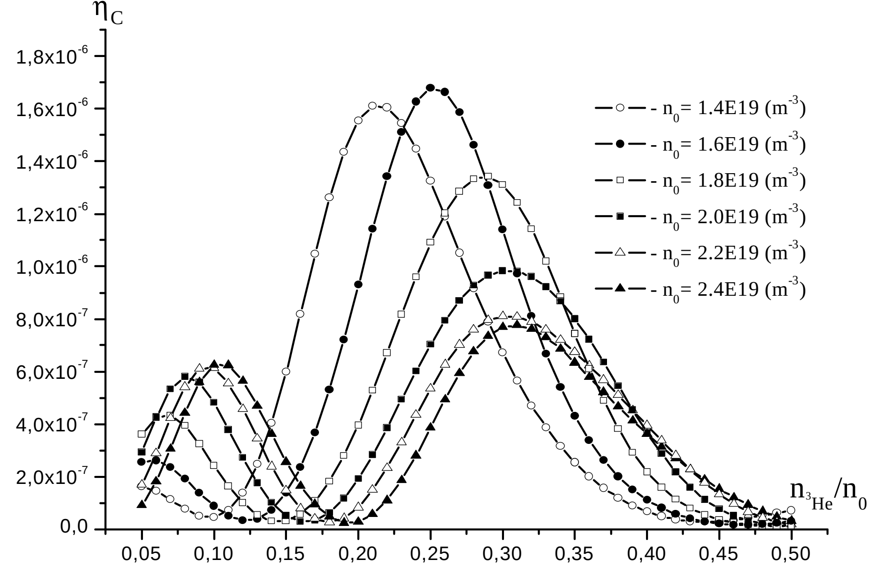

Fig. 4. Mode conversion efficiency depends on minority concentration of ^3He for a single wave mode; $^3He + D$

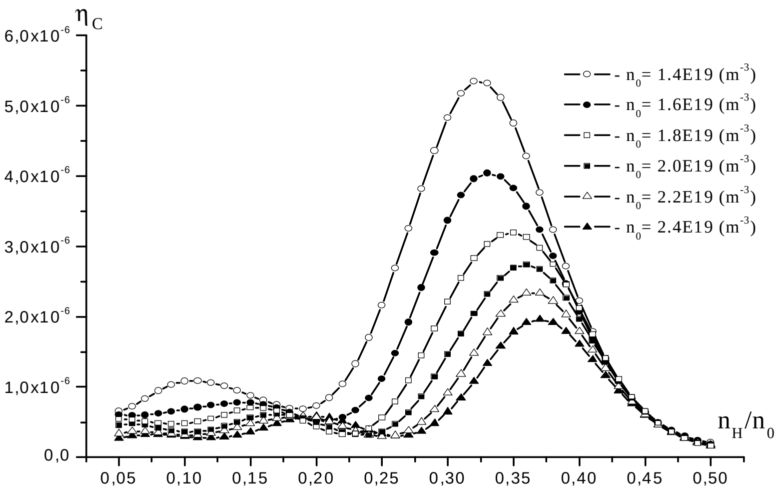

Fig. 5. Mode conversion efficiency depends on minority concentration of H for the whole antenna spectrum; $H + D$

4. DISCUSSION

Oscillatory dependence of conversion efficiency agrees qualitatively with analytical predictions of Refs.[3, 4]. The sinusoidal variation of conversion efficiency depends on the FW phase shift between the conversion point x_c $\left(\varepsilon_1(x_c)=N_z^2\right)$ and high field side cut-off point x_{cut},

$$\Phi = 2\int_{x_{cut}}^{x_c} k_x(x)dx\,.$$

Change of conversion efficiency from maximum to minimum corresponds to the change Φ by π.

Besides the minority concentration, parameters which can essentially influence conversion efficiency are cyclotron resonance position and toroidal wave number k_z.

Due to k_z dependence, if the full antenna spectrum is taken into account, the ratio between maximum and minimum efficiency values decreases.

Despite rather large opacity barrier width the optimum minority concentration is rather high for medium size tokamak such as TEXTOR. The present results allow to determine optimal conditions for mode conversion experiments on TEXTOR tokamak.

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ЭФФЕКТИВНОСТЬ КОНВЕРСИИ МОД В ДВУХКОМПОНЕНТНОЙ ПЛАЗМЕ ТОКАМАКА В ДИАПАЗОНЕ ИОННЫХ ЦИКЛОТРОННЫХ ЧАСТОТ

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Исследована конверсия быстрой магнитозвуковой волны (БМЗВ) в медленную волну (МВ) в плазме токамака с учетом ионного циклотронного поглощения МВ и затухания МВ на электронах. В двухкомпонентной плазме БМЗВ, излучаемая со стороны слабого магнитного поля, может трансформироваться в МВ, которая распространяется в направлении циклотронного резонанса ионов малой добавки, если проекция полоидального магнитного поля на направление большого радиуса тора достаточно велика. Эффективность конверсии изучалась с помощью одномерного кода, который решал систему уравнений Максвелла в приближении холодной плазмы. Получена зависимость эффективности конверсии от концентрации малой добавки и плотности плазмы.

ЕФЕКТИВНІСТЬ КОНВЕРСІЇ МОД В ДВОКОМПОНЕНТНІЙ ПЛАЗМІ ТОКАМАКА У ДІАПАЗОНІ ІОННИХ ЦИКЛОТРОННИХ ЧАСТОТ

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Досліджено конверсію швидкої магнітозвукової хвилі (ШМЗХ) в повільну хвилю (ПХ) в плазмі токамаку з урахуванням іонного циклотронного поглинання ПХ та поглинання ПХ на електронах. В двокомпонентній плазмі ШМЗХ, що випромінюється з боку слабкого магнітного поля, може трансформуватися у ПХ, яка поширюється в напрямку циклотронного резонансу іонів малої добавки, якщо проекція полоїдального магнітного поля в напрямку великого радіусу тора достатньо велика. Ефективність конверсії вивчалась за допомогою одновимірного коду, який розв'язував систему рівнянь Максвелла в наближенні холодної плазми. Отримано залежність ефективності конверсії від концентрації малої добавки та густини плазми.