MODELING OF EB WAVE LAUNCH IN SPHERICAL TOKAMAK GLOBUS-M

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The interaction of waves with magnetically confined plasmas in the electron cyclotron (EC) frequency range has been studied for 40 years. This frequency range is used for various purposes: plasma heating, current profile control and diagnostics. Basically there are three types of the waves in this range: two differently polarized electromagnetic waves (*O* and *X* modes) and a slow electrostatic wave (Bernstein *B* mode). The excitation and propagation of those waves in magnetically confined plasmas is determined to a large extent by a dimensionless parameter $\omega_{pe}^2/\omega_{ce}^2$ — the ratio of the plasma frequency to the electron cyclotron frequency in the plasma center. In particular, this parameter determines the location of the cutoffs for the electromagnetic waves.

Extensive studies (both theoretical and experimental) have been carried out for conventional tokamaks where $\omega_{pe}^2/\omega_{ce}^2 \sim 1$. But recently a lot of interest has been paid to the use of EC frequency range in spherical tokamaks, where the magnetic field is relatively low and $\omega_{pe}^2/\omega_{ce}^2 >> 1$. In this case both *O* and *X* modes are propagating in a very narrow peripheral layer as the cutoff and upper hybrid resonance (UHR) surfaces are very close to the plasma boundary with a typical length scale in the radial direction much less than the vacuum wave length. Due to that fact the *X* mode launched from the low magnetic field side can be effectively transformed to the *B* mode in the UHR region (so-called *X-B* process), and the *O* mode can be effectively coupled with the *X* mode near the cutoff with further transformation of the latter to the *B* mode (*O-X-B* process). The heating scenario based on the peripheral transformation of the launched electromagnetic waves to a Bernstein wave propagating into the dense plasma and absorbed there was proposed first for the NSTX device [1, 2].

Below we present the results of modeling of Bernstein wave excitation in the spherical tokamak GLOBUS-M [3] constructed recently in the Ioffe Physico-Technical Institute (R_0 = 36 cm, a_0 = 24 cm, B_{0vac} = 0.4 T, I_p = 300 kA, $n_{e0} \le 5\cdot10^{13}$ cm^{-3}, T_{e0} = 500 eV, T_{eb} = 20 eV). For this device the parameter $\omega_{pe}^2/\omega_{ce}^2 \approx 15$. We assumed a flat density profile inside the separatrix: $n_e = (n_{e0} - n_{eb})\cdot(1 - (r/a_0)^6) + n_{eb}$, which is typical for spherical tokamaks. An exponential decay of the density was assumed in the scrape-off layer (SOL). The frequency f_0 = 14 GHz corresponded to the position of the EC resonance near the magnetic axis which should have guaranteed the damping of the Bernstein waves in the central parts of the plasma.

In order to estimate the efficiency of transformation to the Bernstein wave we studied the incidence of a plane monochrome wave from the vacuum half-space on a flat peripheral plasma layer which included all cutoffs and UHR. This task divided into two stages. At the first stage we found the relation between the tangential components of the wave electric and magnetic fields at the plasma boundary — the surface impedance matrix. It was found as a solution of a plasma wave equation in a plane 1D geometry [4]. We used a Cartesian reference system with plasma parameters varying only along the *x* axis perpendicular to the plasma surface, and the *z* axis was directed along the plasma magnetic field (parallel to the plasma surface). The wave equation was solved in a warm plasma approximation taking into account second order terms in the Larmor radius expansion. At the inner side of the plasma layer a free irradiation condition was imposed.

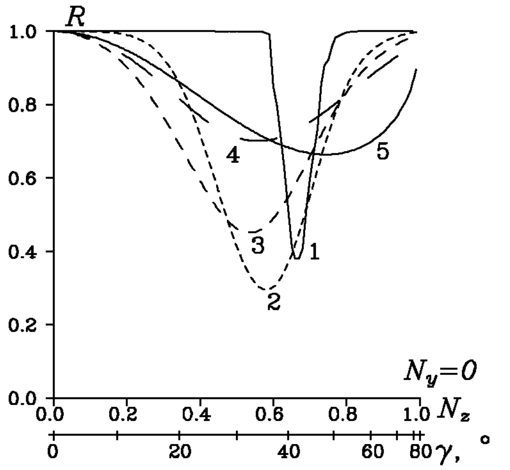

Fig.1. Reflection coefficient versus angle of incidence (O mode) for different density gradients (see text).

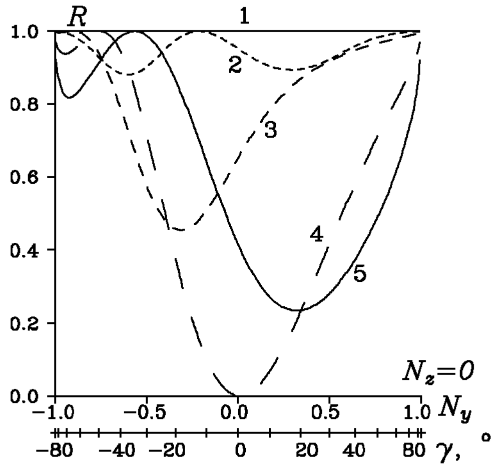

Fig.2. Reflection coefficient versus angle of incidence (X mode) for different density gradients (see text).

At the second stage we considered the incidence of a plane vacuum wave on the plasma surface where the plasma surface impedance matrix was used as a boundary condition. We investigated the incidence of differently polarized waves at all possible angles and estimated the reflection coefficient R as the ratio of the power reflected from the plasma to the incident power. We shall conventionally refer to the incident vacuum wave with electric field parallel to the constant magnetic field as an O mode and to the perpendicularly polarized wave as an X mode. (Strictly speaking, at both polarization a mixture of O and X mode will propagate in plasma at a finite angle of incidence, so that both *X-B* and *O-X-B* process are taking place. But on the other hand, as the typical length scale is much less than the electromagnetic wave-length, the distinction between the O and X modes assumed in the WKB approximation is rather questionable).

It was found out that there are some optimal angles of incidence (with minimal R) depending on the wave polarization and on the plasma parameters. In Fig. 1 the plots of R versus the parallel refractive index N_z (at $N_y = 0$) are presented for the incident O mode. Here we assumed a linear density profile at the periphery with the boundary density $n_{eb} = 10^{11}$ cm^{-3} and five different values of the plasma density gradient: *1* — $2{\cdot}10^{11}$ cm^{-4}, *2* — $1.2{\cdot}10^{12}$ cm^{-4}, *3* — $2{\cdot}10^{12}$ cm^{-4}, *4* — $3.2{\cdot}10^{12}$ cm^{-4}, *5* — 10^{13} cm^{-4}. Corresponding values of the angle of incidence γ are plotted at the auxiliary x axis below the figure.

J.Preinhaelter was the first to investigate the optimal angles of incidence in tokamak applications [5], but actually this fact was discovered much earlier during ionosphere studies as the “trebling of the reflected signal” [6]. These previous studies were carried out in the frame of WKB approximation, but here the density gradients are too large and only the case corresponding to curve *1* could be roughly described by geometrical optics.

In Fig. 2 the plots of the reflection coefficient versus the refractive index N_y (at $N_z = 0$) are presented for the incident X mode for $n_{eb} = 10^{11}$ cm^{-3} and the following plasma density gradients: *1* — $4{\cdot}10^{11}$ cm^{-4}, *2* — $2{\cdot}10^{12}$ cm^{-4}, *3* — $3.2{\cdot}10^{12}$ cm^{-4}, *4* — $6{\cdot}10^{12}$ cm^{-4}, *5* — $1.6{\cdot}10^{13}$ cm^{-4}. An important feature of this dependence is its asymmetry relative to the sign of N_y which once again proves the fact that here we are far outside the scope of WKB theory.

In Figs. 3 and 4 the 2D plots showing the dependence of the reflection coefficient on both N_y and N_z (solid curves) are presented for the incident O and X modes, respectively. Here

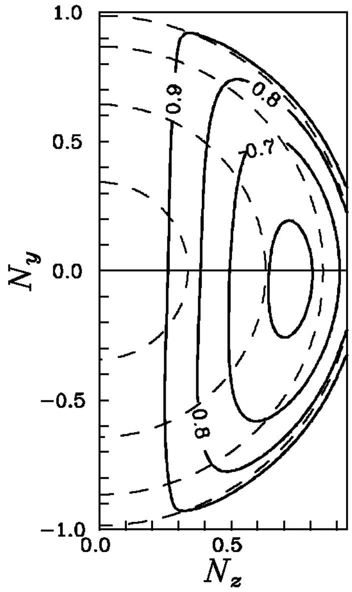

Fig.3. 2D representation of the reflection coefficient for O mode (standard case).

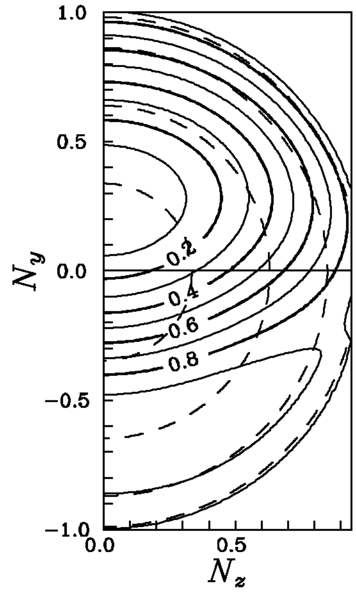

Fig.4. 2D representation of the reflection coefficient for X mode (standard case).

we assumed a more realistic plasma density profile described above: $(1 - (r/a_0)^6)$ dependence in the bulk plasma with $n_{e0} = 5{\cdot}10^{13}$ cm^{-3} and $n_{eb} = 2{\cdot}10^{12}$ cm^{-3} at the separatrix and 1 cm wide scrape-off layer with a 0.2 cm length of the density exponential decay (we refer to it as a standard case). The dashed semi-circles correspond to the angles of incidence 20°, 40°, 60° and 80°. One can see relatively broad optimal regions where the reflection coefficient is minimal. We also discovered that the general pattern does not change essentially at the variation of the plasma parameters.

We have also carried out the modeling of the characteristics of waveguide antennae exciting the RF waves of different polarizations. This analysis seems to be very important for practice — both for the antenna design and for plasma heating experiment set-up. We used the previously computed plasma surface impedance matrix (which incorporates all information about the wave processes inside the plasma) as a boundary condition for the CRILL3D code [7] computing the coupling efficiency and the excited wave spectrum for a waveguide antenna. Two antenna designs was considered: (1) — antenna consisting of two adjacent waveguides radiating in phase, imitating a small horn antenna and exciting a broad wave spectrum; (2) — multi-waveguide grill consisting of 4 vertical stacks of waveguides with 12 waveguides in each stack, exciting a narrow spectrum in the region of the minimum reflection coefficient. In both cases the inner dimensions of an individual waveguide was 1.8×0.8 cm^2, so that the total antenna cross-sections were ~2×2 cm^2 and ~8×12 cm^2, respectively. The first antenna could be turned around its axis and so excited waves with different polarization. In Fig. 5 we show the dependence of the total reflection coefficient of the antenna on the angle of antenna rotation α (0° corresponds to the X mode excitation, 90° — to the O mode excitation) for the following plasma parameters: *1* — $n_{e0} = 5{\cdot}10^{12}$ cm^{-3}, $n_{eb} = 5{\cdot}10^{11}$ cm^{-3}, SOL = 0.3 cm; *2* — $n_{e0} = 10^{13}$ cm^{-3}, $n_{eb} = 10^{12}$ cm^{-3}, SOL = 1 cm; *3* — $n_{e0} = 5{\cdot}10^{13}$ cm^{-3}, $n_{eb} = 2{\cdot}10^{12}$ cm^{-3}, SOL = 1 cm (standard case). The SOL density decay length was 0.2 cm in all three cases. One can see that at $\alpha = 90°$ (O mode excitation) the reflection coefficient never exceeds 20%. At high densities the low reflection coefficient is observed for all angles of rotation.

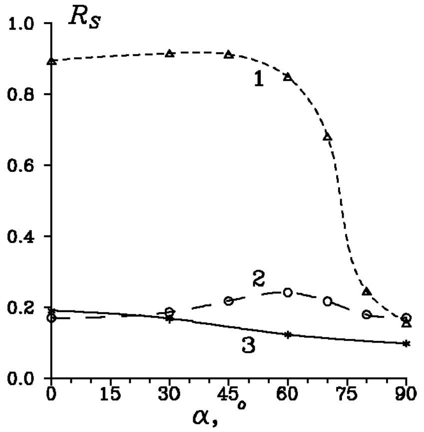

Fig.5. Reflection coefficient of 2 waveguide antenna versus angle of rotation α for different central densities (see text).

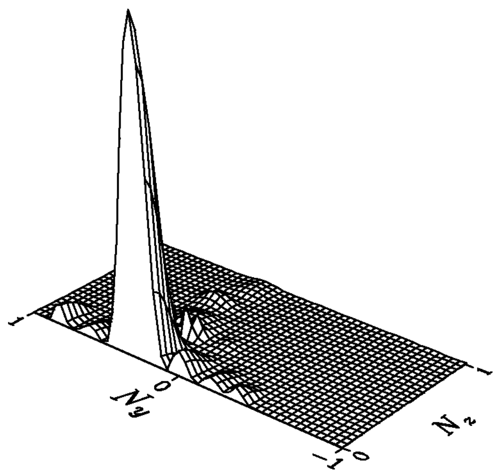

Fig.6. 2D spectrum excited by 4×12 waveguide antenna at α = 0°.

The situation is different in the case of the second type antenna exciting a narrow wave spectrum. The wave spectrum excited by a 4×12 grill is shown in Fig. 6 (the plasma parameters correspond to the standard case). The antenna orientation corresponds to the *X* mode excitation. The phase shift between the adjacent waveguides in the same stack is 45°. The grill excites a nearly monochromatic spectrum corresponding to the transparency window in Fig. 4. The total reflection coefficient is below 4% (while for the first antenna type it was 10–12%). The efficiency of the Bernstein wave excitation is very high. (It should be noted that in practice one can use a 2×8 grill (or even simpler) or a properly oriented horn antenna tilted by a corresponding angle.)

We have also carried out the analysis of the spatial structure of the electromagnetic field inside the plasma excited by the antenna. For the first-type antenna exciting a wide spectrum of the waves we observed a substantial broadening of the fields in the direction parallel to the plasma surface so that the efficiency of the transformation to the *B* mode seems to be quite low (numerous reflections from the metal wall surrounding the antenna). On the contrary, this broadening was very small for a 4×12 antenna exciting a narrow wave spectrum (the perpendicular dimensions of the field pattern was mainly determined by the antenna cross-section) which indicates at the high efficiency of a single-pass transformation to the *B* mode.

Thus according to the estimates presented here one can expect an effective launch of RF power to spherical tokamak plasmas in the EC frequency range. The problem of propagation and absorption of the Bernstein wave requires further investigation with the use of ray tracing technique.

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