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2D Numerical Modeling of O–X Conversion in Spherical Tokamaks

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An O–X–B mode conversion scheme [1] is paid much attention nowadays as it is the most promising candidate to provide auxiliary microwave electron heating and current drive in spherical tokamaks. Its efficiency is determined mainly by O–X conversion process near the O cut-off. An accurate account of 2D plasma inhomogeneity and of the realistic magnetic field geometry in spherical tokamaks are required for correct estimation of the conversion efficiency. The analytical results obtained recently [2,3] are sometimes contradictory, need confirmation and have a limited validity domain.

Having this in mind we present here results of 2D full-wave simulation of O–X conversion process based on the numerical solution of plasma wave equation in 2D inhomogeneous tokamak plasma [4] — the code based on M.Brambilla ideas [5]. A flux-bound reference system (ρ, θ, φ) — flux, poloidal and toroidal coordinates — was used with functions $\Delta(\rho)$ (Shafranov shift), $\lambda(\rho)$ (ellipticity) and $\gamma(\rho)$ (triangularity) describing non-circular shape of the flux surfaces. The electric field was sought as a solution of the wave equation:

$$\nabla \times \nabla \times \vec{E} = \frac{\omega^2}{c^2} \vec{\varepsilon} \vec{E} \,, \tag{1}$$

where ε is the local dielectric tensor. Electric field was represented as a sum over toroidal and poloidal modes. Poloidal modes (m) are coupled due to the poloidal inhomogeneity, but toroidal modes (n) are not coupled so the solution was sought separately for each toroidal mode:

$$\vec{E}(\rho,\vartheta,\varphi) = e^{in\varphi} \sum_m e^{im\vartheta} \vec{E}(\rho) \tag{2}$$

Cyclotron damping was taken into account by introducing the plasma dispersion function Z for electrons in the appropriate tensor components. Collisional damping was also taken into account. Tangential electric fields at the surface were imposed as a boundary condition and regularity conditions were imposed on the magnetic axis. The wave equation (1) was solved by FEM (Galerkin) technique similar to the one proposed by M.Brambilla [5].

In order to underline the 2D features of O–X conversion phenomenon a special plasma model was assumed — a hypothetical tokamak (R_0 = 12 cm, a_0 = 8 cm, k = 1.6, γ = 0.18, n_{e0} = 6×10^{13} cm^{-3}, I_p = 20 kA, B_0 = 10.7 kGs) with a peaked density profile and a very low density at the outer half of the minor radius, so both the cut-offs and UHR were shifted far from the wall. The frequency f_0 = 30 GHz. Some part of RF power (corresponding to O–mode) is reflected from the conversion region back to the periphery. To avoid numerous reflections a strong artificial damping region was placed along the wall.

We carried out the computations for a single toroidal mode n = 60 corresponding to the toroidal angle closest to the optimum (maximum conversion efficiency). The Gaussian transverse profile of the RF beam electric field (with the beam width 3cm by e-fold level) was assumed. The beam was launched from different positions in respect to the equatorial plane and at various elevation angles (see Fig. 1), which was modeled by choosing an appropriate poloidal spectrum of the boundary electric field. O and X cut-offs are marked by blue curves, ECR and UHR by green and purple curves, respectively. An example of 2D image map of the electric field (absolute value) in poloidal cross-section is shown in Fig. 2 (launch from position 4). Initially the beam has O–mode polarization, it propagates inside and is reflected from the cut-off, where part of the power is conversed to X–mode and absorbed at UHR (by collisions), and what is left in O–mode propagates back to the wall and is absorbed in the damping layer.

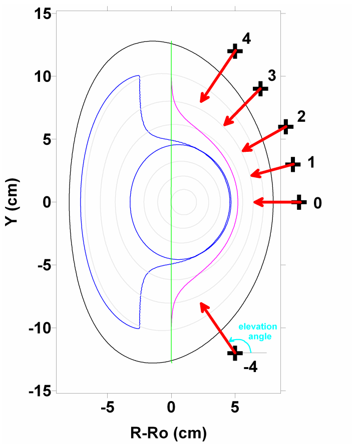

Fig. 1. RF power launching scheme.

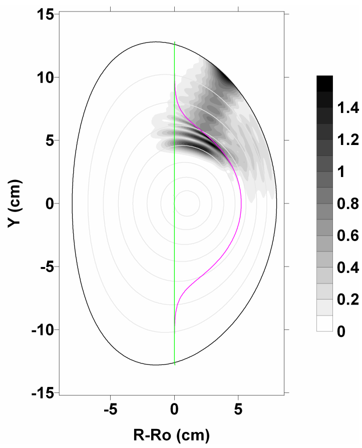

Fig. 2. 2D map of |E| (poloidal cross-section).

An important 2D effect is the dependence of the conversion efficiency on the direction of the toroidal magnetic field which was first discovered (analytically) in [2] and is discussed in details in [6]. In this work the conversion efficiency was defined as the ratio of RF power absorbed at the UHR surface over the power incident at the conversion region from the periphery. It is justified by the fact that the power absorbed at the UHR (by collisions) in the cold plasma model is exactly equal to the one that is transformed to the Bernstein wave in a hot model. In Fig. 3 RF power absorption near UHR is shown for two opposite directions of the toroidal magnetic

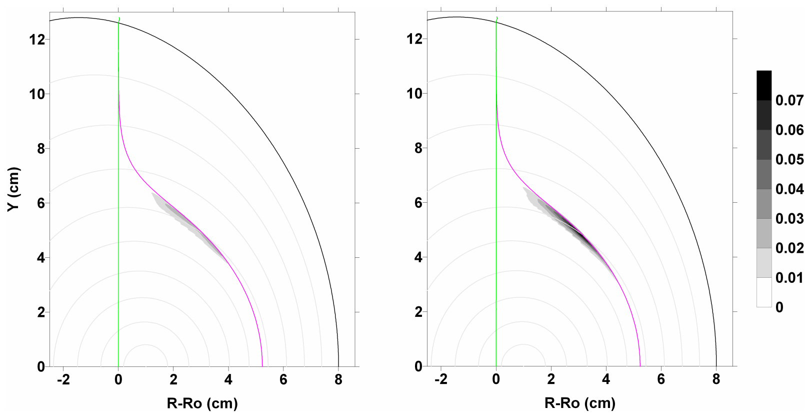

Fig. 3. Power deposition at UHR: left – $B_\varphi > 0$, right – $B_\varphi < 0$

field B_φ and one can clearly see that the absorbed power (and hence, conversion efficiency) is much higher in the case $B_\varphi < 0$.

A more detailed dependence of the O–X conversion efficiency on the beam starting position and elevation angle is shown in Fig. 4. For each starting position (R, Y) there is an optimum elevation angle, also the conversion efficiency is different for opposite magnetic field directions. While there is nearly no difference for the equatorial plane launch (Y = 0 cm), it is very pronounced for the starting positions far from this plane (Y = 9 cm, 12 cm). It should be noted that swapping B_φ direction has the same effect as flipping the launching position from above to below equatorial plane, or vice versa (i.e. Y => –Y).

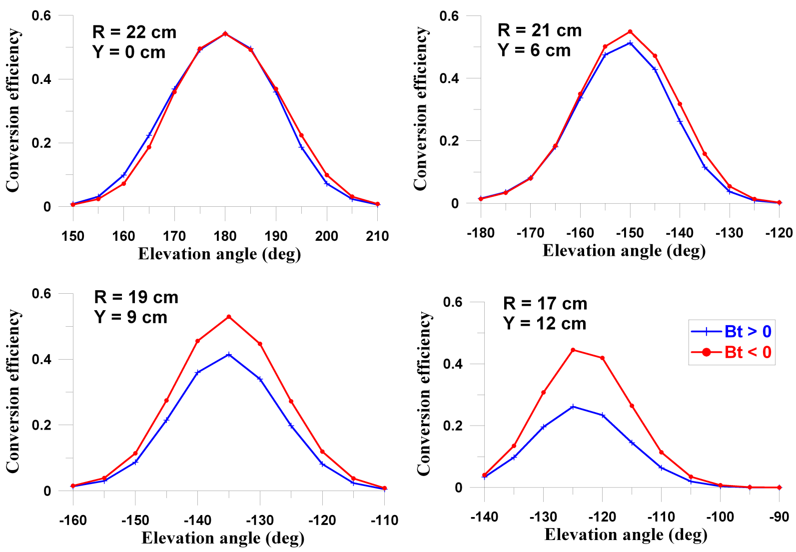

Fig. 4. O–X conversion efficiency versus elevation angle

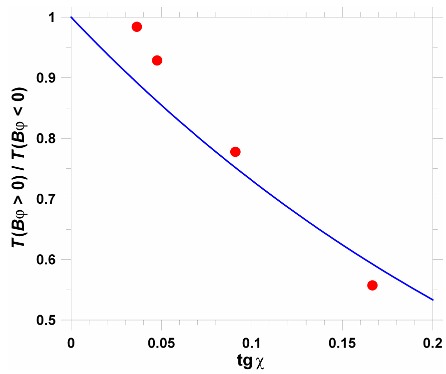

Fig. 5.

The ratio of conversion efficiencies T for opposite B_φ directions versus the angle χ between X and O cut-offs is shown in Fig. 5 where we compare numerical simulation results (red dots) with theoretical predictions [6] (blue line) which appear to fit fairly close

Our modeling did not confirm the result of numerical simulation reported in [7] that the UHR plays an important role in RF power deposition when O-mode is launched at the fundamental harmonic and no conditions for effective O–X conversion are provided. This is illustrated by Figs. 6 and 7, corresponding to the O–mode launch from the LFS and HFS in FT-2 tokamak (R_0 = 55 cm, a_0 = 8 cm, n_{e0} = 3×10^{13} cm^{-3},

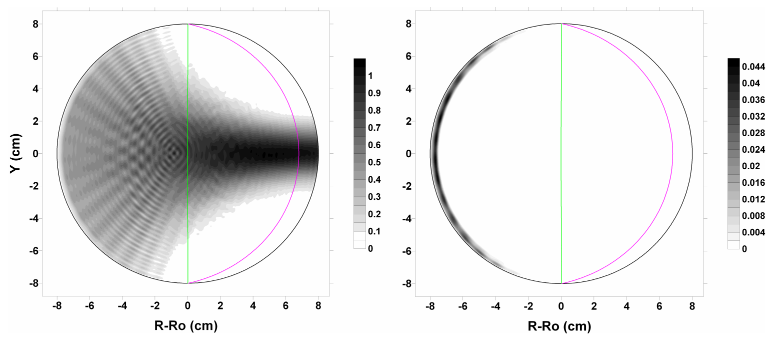

Fig. 6. |E| (left) and power absorption (right). LFS launch.

B_0 = 21.4 kGs, f_0 = 60 GHz, N_φ = 0.5). In both pictures |E| is presented on the left and RF energy absorption on the right. In both cases no traces of O–mode absorption near UHR was detected. All RF power was absorbed in the damping layer at the wall opposite the launching position that was introduced in order to avoid multiple reflections from the wall which would complicate the picture.

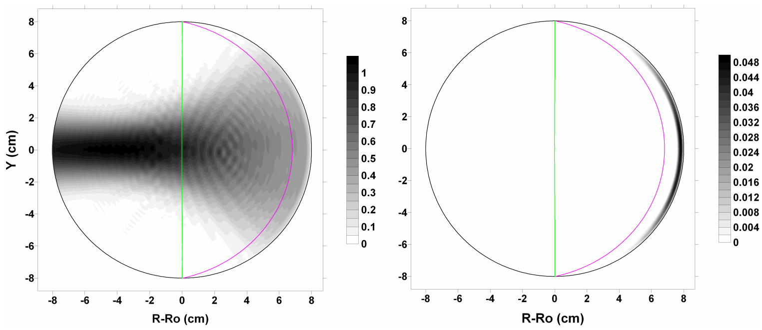

Fig. 7. |E| (left) and power absorption (right). HFS launch.

Vertical profiles of |E| at various R for HFS launch are shown in Fig. 8, where the numerical results (blue curves) are compared with beam-tracing modeling [8] (black curves).

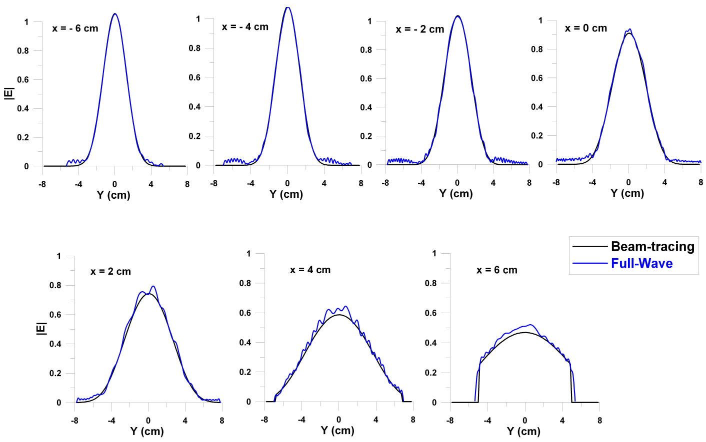

Fig. 8. Vertical profiles of |E| at various $x = R–R_0$.

So, both numerical modeling and analytical theory [6] provide a good tool for optimizing O–X–B conversion scheme to be used for effective microwave heating in spherical tokamaks where 2D effects might be important, in particular, the conversion efficiency appear to be different for the opposite directions of toroidal magnetic field (or for the antenna positions above or below the equatorial plane).

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