OLGA – efficient full wave code for the coupling of LH grills

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Lower hybrid (LH) waves are very important for heating and current drive in tokamaks. Phased arrays of rectangular waveguides, generally called grills, are typically used as launchers. We have developed a full wave code OLGA [1] which solves, in the 3D geometry of the grill structure, the problem of efficient coupling, namely, the power density spectrum of the emitted waves, the power reflection coefficient, the power lost by the waves launched in the inaccessible region and the directivity of the waves transmitted to the accessible region. An efficient adaptive full wave solver is used to determine the wave propagation in 1D plasma slab geometry. We adopted an iterative evaluation of the integrands in the inaccessible region to handle to the present overlooked near to singular behavior of the integrands and the spectral power density caused by eigenmodes.

We have implemented the scattering matrix formalism for determining the coupling of multirow multijunction active passive structures (like the LH1 ("C3") and LH2 ("C4") launchers on TORE SUPRA/WEST) to the plasma [2]. The extended code is still computationally fast by the use of 2D splining of the plasma surface admittance in the accessibility region of the $k-$space, by the use of high order Gaussian quadrature rules for the integration of the coupling elements and by the application of the symmetry rules of the coupling elements for the multiperiodic structures. We successfully benchmark the coupling of the LH1 and LH2 launchers as determined OLGA with the ALOHA-1D, ALOHA-2D [3] and TOPLHA [4] results for a TORE SUPRA discharge.

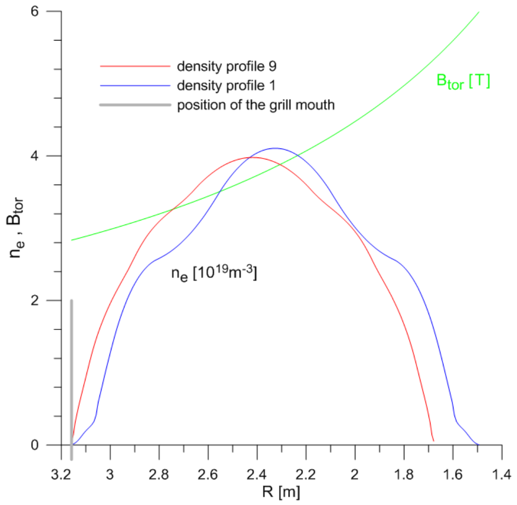

Fig. 1a. Profiles of the density and the toroidal magnetic field in TORE SUPRA, # 43016. The red line corresponds to the profile #9 from the beginning of discharge and the blue line to the profile #1 from the end of discharge when the plasma column retreats from the grill mouth. Grill mouth is situated at $R = 3.158$ m.

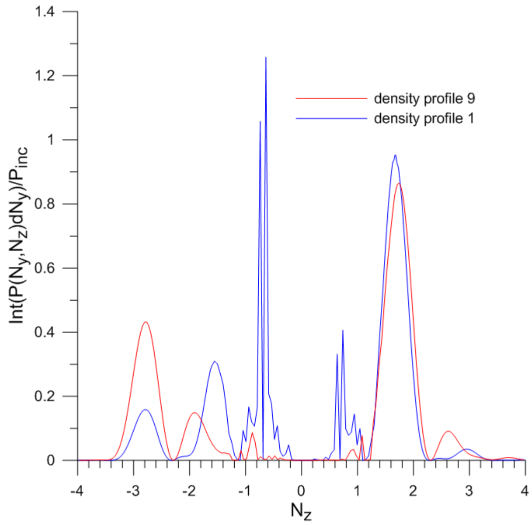

Fig. 1b. Spectral power density integrated over the poloidal component of the refraction index N_y as a function of the toroidal component N_z. Reduced C4 launcher operating on 3.7 GHz, with phasing 180^o.

Coupled slow to fast waves influence not only efficiency of coupled power to heat and generate current in the central part of plasma but they also lead to the emergency of the plasma slab eigenmodes. Due to their resonant character, they accumulate substantial part of the coupled power namely when the plasma density in front of grill is low and the coupling is bad. The corresponding electric field of partial waves of the Fourier spectrum for the strongest eigenmodes can reach megavolts even for relatively large collision frequency as $\nu / \omega = 0.001$. In paper [1] we found that the interference smoothes the final electric field in cases when the coupling of grill was excellent and the plasma slab eigenmodes were unimportant. We calculate the 3D electric field in front of grill and estimate effects of the plasma slab eigenmodes in cases of the bad and good coupling of C3 and C4 launchers to the TORE SUPRA plasma. We test their coupling on two profiles used in paper [2], Table. 1., namely the density profile #1 with low density in front of grill ($n_{mouth} = 3.8\times10^{16}$ m^{-4}) and the profile #9 with the optimum density $n_{mouth} = 5.3\times10^{17}$ m^{-4} (Fig. 1a).

In this paper we focus on investigation of a reduced structure corresponding to the upper row of the central part of the C4 launcher consisting from two C4 modules and three passive waveguides (result for C3 will be presented only on the conference poster). The coordinate system is chosen that the origin is placed to center of the launcher, z - axis parallel to B_{tor} , y - axis in the poloidal direction and x-axis is directed radially into the plasma.

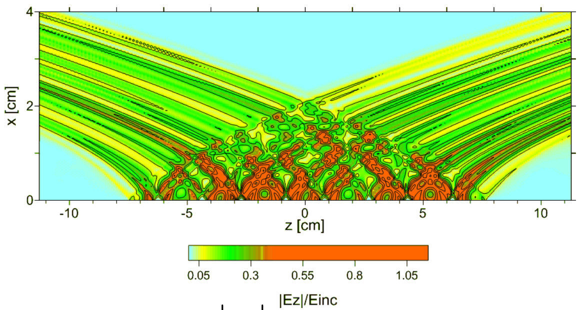

Fig. 2a. 2D profile of $|E_z|$ in front of the reduced C4 launcher with phasing 180^o. Cut is situated at the half height of the central row of waveguides ($y = 0$). The density profile #9 (supercritical density in front of grill).

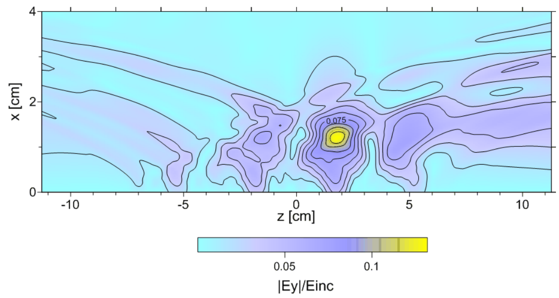

Fig. 2b. 2D profile of $|E_y|$ in front of the reduced C4 launcher. In this case the fast waves are not excited and the poloidal component of the electric field is weak. The density profile #9.

If the density in front of grill is sufficiently high as in the case plasma with the density profile #9 ($n_{surf} = 3.13\times n_{crit}$, where $n_{cri} = 1.697\times10^{17}$ m^{-3} for $f = 3.7$ GHz) the coupling of the reduced C4 launcher is acceptable with the power reflection coefficient (PRC) 2.6%, and 76% of the incident power is transmitted as traveling (slow) waves. The relatively large portion of the power converted to plasma slab eigenmodes, 22% can be explained by the rather broad peaks of this short structure (Fig. 1b, red curve) and the accessibility limit $N_z = 1.66$. The full C4 launcher produces only 10% slow to fast coupled waves (eigenmodes) at the same conditions. The electric field in front of grill is dominated by the excited slow waves with the electric field directed along the toroidal magnetic field. The power is transmitted into the plasma and the maximum amplitude is comparable to the amplitude of the incident field in the powering waveguides (Fig. 2a). The poloidal component is small because no vacuum waves are excited (Fig. 2b).

The passive-active launcher C4 has good coupling even in the case that the plasma column retreats from the grill mouth (the profile #1). The power reflection coefficient in this case is 3.95 % but 54 % of the incident power is converted into plasma slab eigenmodes, partly to the coupled slow to fast waves and partly (18.5 %) to the vacuum waves (the fast waves, see peaks at $|N_z| < 1$ in Fig. 1b.).

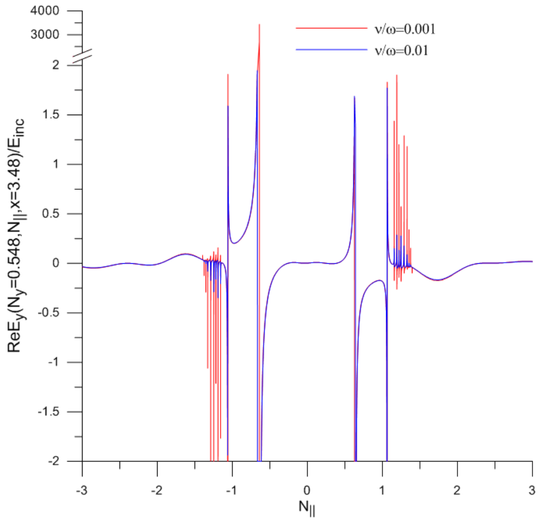

Fig. 3a. Fourier coefficients of the poloidal component of the electric field (E_y) at the radial distance $x = 3.48$ cm. Here the main eigenmode, situated at $N_y = 0.548$, $N_z = -0.64$, reaches the maximum of the electric field ($\sim 4000 E_{inc}$ when $\nu / \omega = 0.001$). Reduced C4 launcher with phasing 180^o and plasma profile 1.

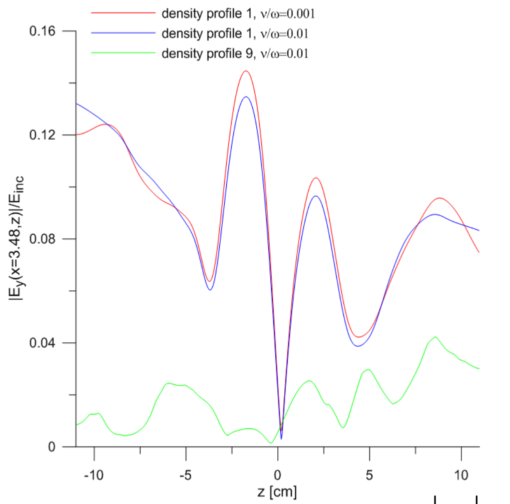

Fig. 3b. Profile of the poloidal electric field $|E_y|$ at the radial distance $x = 3.48$ cm and at the half of height of the central row waveguides ($y = 0$). Reduced C4 launcher with phasing 180^o and plasma profile 1.

To determine the electric field in front of grill in plasma we must first solve coupling problem to find out, for each N_y, N_z, the amplitudes of partial waves (the tangential components of the electric field) on the plasma boundary. Then we must solve full wave problem once more with these amplitudes and collect Fourier coefficients of the electric field on some mesh of radial positions. Finally, we must carry out the inverse Fourier transform for all components of the electric field on the considered radial positions.

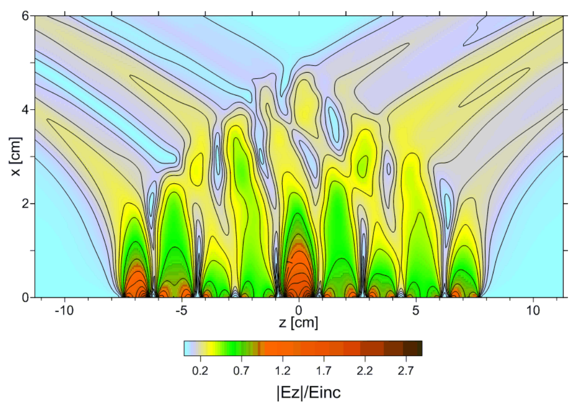

Fig. 4a. 2D profile of the $|E_z|$ in front of the reduced C4 launcher with phasing 180^o between modules. Cut is situated at the half height of the central row of waveguides ($y = 0$). The density profile #1 (subcritical density in front of grill).

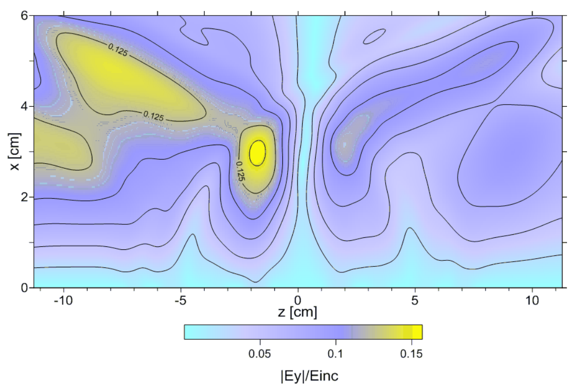

Fig. 4b. 2D profile of the $|E_y|$ in front o the reduced C4 launcher. The field belongs to the excited fast wave eigenmodes. The waves propagate parallel to the wall of the vessel. The density profile #1.

The intensity of the electric field of the plasma slab eigenmodes strongly increases with decreasing collision frequency (due to resonant character of eigenmodes, it will be infinite in the absence of damping). In Fig. 3a we compare profile of the Fourier coefficients of the poloidal component of the electric field E_y on N_z for two model collision frequencies. We see strong increase of the amplitude of $\mathrm{Re}(E_y(N_y, N_z, x = 3.48))$ with decreasing collisions. This effect is related only to eigenmodes (peaks in Fig. 3a), the rest of this function is unchanged. The profile of the electric field in the toroidal direction is not influenced by the magnitude of the collision frequency (Fig. 2b) – the interference between the partial waves works properly.

If Figs. 4a,b we depict the electric field in front of the reduced C4 launcher coupled to the plasma with subcritical surface density. The toroidal component of the electric field is dominant (Fig. 4a) but the power is now partly accumulated in front of grill to the double radial distance than in the preceding case (see Fig. 2a) and only weakly transmitted into the plasma. The maximal amplitude of $|E_y|$ reaches three times the amplitude of the incident field. The poloidal component fills the space in front of grill. It is formed mainly from fast waves forming eigenmodes between plasma surface and density cutoff radial layer.

References

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