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Particle-in-Cell Simulations of Wave Propagation in front of a Lower Hybrid Grill

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1. INTRODUCTION

Particle-in-cell (PIC) codes can be applied to model wave coupling, propagation and absorption. The electrostatic PIC code XPDP2 [1] has been used to analyse the edge plasma and the formation of fast electrons in front of the LH launcher [2]. PIC codes take into account the kinetic and nonlinear effects, which are in some LHCD cases important, e.g., fast electron generation in edge plasmas [3] and possible parametric instabilities. These effects are not included in linear coupling codes like SWAN [4].

Particle-in-cell (PIC) codes are based on solving the equations of motion for the charged particles and the Maxwell equations for the fields. The particles move freely in the phase space and interact with the electric and magnetic fields defined on the grid. The motion of the charged particles generates current and charge densities acting as source terms in the Maxwell equations. Consequently, the fields and the particle motion are solved self-consistently. The disadvantage is the fairly high noise level, which can be slightly reduced by increasing the number of particles.

In this work, an electromagnetic particle-in-cell code OOPIC [5] has been used to model wave launching from a 32 waveguide LH grill similar to the grill in Tore Supra and JET.

2. MODEL OF LOWER HYBRID GRILL

The 2D model of the LH grill is constructed of 32 parallel plate waveguides assuming that the poloidal dimension of the grill extends to infinity. With this assumption, all the poloidal modes are neglected since there is no y-dependence of the fields in the waveguides of our model. We neglect all the structure before the multijunction and concentrate on the waveguide array facing the plasma.

The width of the waveguides is L_{wg} = 8.5 mm and the perfectly conducting wall between them is L_{wall} = 2 mm. The length of the waveguides in the radial direction is chosen to be 2 vacuum wavelengths, i.e. L_{lg} = 16.05 cm. The waveguides are fed with a transverse electromagnetic (TEM) mode. This is justified since the TE_{01} mode used in real, rectangular waveguides reduces to the TEM mode when the toroidal mode number is 0 and the poloidal dimension of the waveguide is extended to infinity. The boundary conditions in the toroidal z-direction are assumed to be periodic for the particles and absorbing for the TEM wave. The boundary at x = 4 cm is absorbing both particles and waves.

The wave is launched at the time t =1.2 ns so that a transient perturbation resulting from the initial loading of the plasma does not affect the wave propagation in the waveguides. The frequency of the launched wave is 3.7 GHz and the phase difference between adjacent waveguides is $\pi/2$. The power level 262 MW/m^2 was chosen to be well above the high noise level. A temperature of 1 keV was assumed for both electrons and ions. The high temperature was used to keep the thermal energy density of the plasma larger than the energy density of the field to avoid possible nonlinear effects. Initially, the plasma in front of the grill was assumed to have a homogeneous density with $n_{e0}= 10^{18}$ m^{-3}. The other parameters are following: toroidal width of plasma area L_z = 39.9 cm, width of the grill L_{grill} = 33.4 cm, radial length of plasma area L_{pl} = 4.0 cm, magnetic field B_T = 2.78 T, and number of simulation particles 1 799 768.

3. WAVE COUPLING AND PROPAGATION IN THE PLASMA

The waveguides are fed by a pure TEM mode. In order for the TEM fields of the waveguides to match to the sinusoidal field in the plasma, transverse magnetic (TM) modes are generated at the grill mouth. Higher order TE modes are not generated at the grill mouth as long as the launched wave has an electric field component only in the toroidal direction [6]. Then, the wave will couple to the slow wave at the plasma edge and will remain a slow one if the condition $n_{||}^2-1 >> \omega_{pe}/\Omega_e$ is valid. This is well satisfied for the present simulation parameters.

Part of the LH power is reflected back into the waveguides at the grill mouth. The reflection coefficients of the waveguides are determined from the decrement of the time averaged Poynting fluxes. The reflection coefficient of each waveguide at the time t = 6 ns is shown in Figure 1. There is a very large reflection in waveguides number 1, 7 and 32. The smallest reflection is found in waveguides 27 and 28. Actually all the waveguides from 16 to 28 have a very small reflection. The average reflection coefficient of this grill is obtained by taking the average of the reflection coefficients of the individual waveguides. The value is approximately R_{ave} = 2.3%.

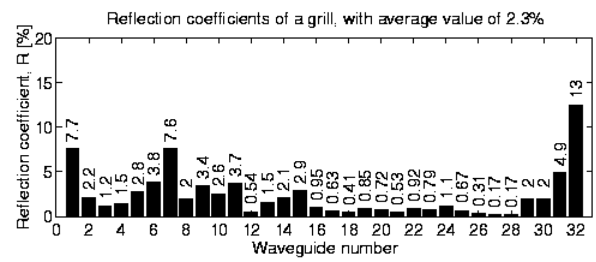

Fig.1: *Reflection coefficients at time t = 6 ns of launcher with 32 waveguides. The average value is R_{ave}=2.3%.*

Figure 2 shows the power spectrum of the wave versus the parallel refractive index at different distances from the grill mouth. The grill launches a spectrum containing the principal mode $n_{||} = -1.9$ and its odd harmonics $n_{||}$ = 5.8, −9.6 and 13.4. These modes are those of the TEM wave and can be found by an analytic calculation. The higher harmonics are much weaker than the principal mode, as was expected. Figure 2d shows the spectrum inside the waveguides

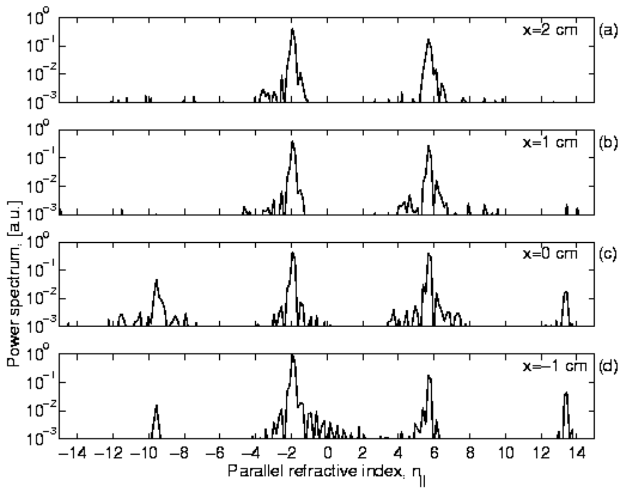

Fig. 2: *Power spectra versus the parallel refractive index integrated over three wave periods at different distances from the grill mouth: (a) – (c). (d) is the spectrum inside the waveguide at x = -1 cm.*

and 2c just at the mouth. At the mouth, there are much more side bands around the peaks than inside the waveguides. On the plasma side, in Fig. 2a and 2b, the two highest harmonics have been absorbed. The phase velocities, $c/n_{\|}$ of these two modes $n_{\|} = -9.6$ and 13.4 correspond to $-2.4v_e$ and $1.7v_e$, respectively. The phase velocity of the mode $n_{\|} = 5.8$ is $3.9v_e$.

Figure 3 shows an interferogram of the toroidal electric field in the *xz*-plane. Interferometer techniques are used to reduce noise typical for PIC codes by picking the signal oscillating at the given frequency. The interferogram has been calculated over two wave periods. The propagation cones of the lower hybrid wave bending towards the upper left corner can be seen clearly. This is due to the phase difference of $\Delta\varphi = \pi/2$ between the waveguides. The main contribution comes from the principal mode with $n_{\|} = -1.9$. However, one can also see waves at $n_{\|} = 5.8$ propagating to the opposite direction from the one of the principal mode.

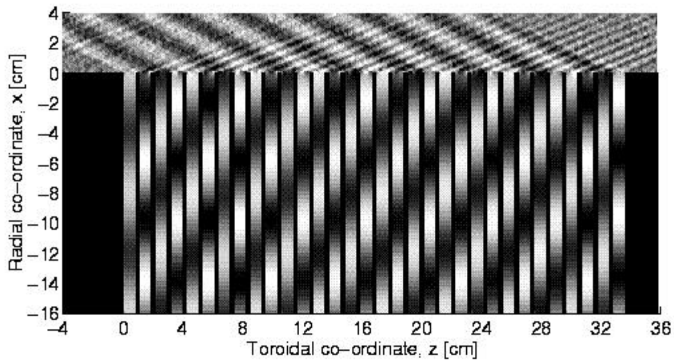

Fig. 3: *The interferogram of the toroidal electric field E_z in the xz-plane at t = 6 ns.*

The Poynting vectors at the grill mouths of typical waveguides are shown in Figure 4. The vectors have been averaged over two wave periods starting at $t = 6$ ns. Therefore, the Poynting flux reveals the overall power flow. Figure 4a shows the downstream waveguides, i.e. the 6 first waveguides. Figure 4b shows waveguides from the centre of the grill, i.e. waveguides 13 to 20 and Fig. 4c the upstream ones, waveguides 26 to 32. The main direction of the power flow is towards the upper left corner. This is the direction of the principal mode at $n_{\|} = -1.9$. The effect of the first forward propagating mode can also be seen. At the grill mouth, the power is bent around the corners of the walls. In figure 4c, on the upstream side of the grill, i.e., in front of the last waveguides, one can clearly see the power flow of the mode at $n_{\|} = 5.8$ propagating towards the upper right corner.

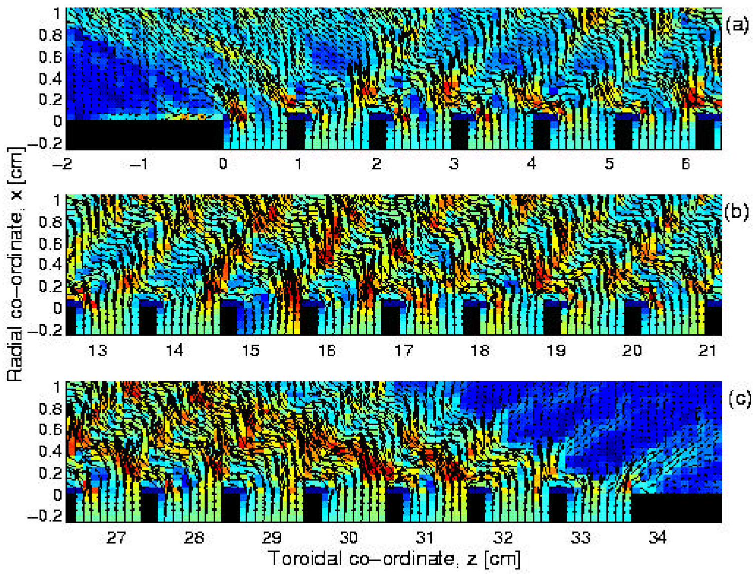

Fig 4: *The time averaged Poynting vector at t = 6 ns in the xz-plane in front of the grill mouth. The vector is averaged over two wave periods. The colour denotes the magnitude of the vector shown as arrows.*

4. SUMMARY AND DISCUSSION

A new promising tool for modelling a lower hybrid launcher has been described. An electromagnetic particle-in-cell code was used to investigate the edge plasma in front of the waveguides. The PIC code OOPIC makes it possible to have a realistic model for the LH launcher. The waveguides can be modelled with perfectly conducting walls and plasma in front of them. The PIC method takes into account also the kinetic and non-linear phenomena in front of the launcher.

In this work, a 32-waveguide launcher was considered. The intention of this study was to show that OOPIC is an appropriate tool in modelling the edge plasma in front of the LH grill. The source of a TEM wave was placed two vacuum wavelengths behind the grill mouth. The wave propagation can be followed from the source along the waveguides to the mouth where it couples to the plasma. At the grill mouth, evanescent TM modes are formed to enable the coupling of the rectangular TEM wave to the sinusoidal electric field in the plasma. Part of the incident wave is reflected from the grill mouth back into the waveguides. The code describes well the launched TEM mode and the reflected TEM and TM modes.

The reflection coefficients of the waveguides were determined from the radial Poynting flux. The reflection coefficient was obtained from the decrease in the time dependent flux. The average reflection coefficient of the grill was also determined. The value obtained for this grill was small and therefore realistic. One would expect an even smaller reflection coefficient if there would be a passive waveguide on each side of the grill. The average reflection coefficient in the Tore Supra lower hybrid launchers is below 5 % [7].

Future work will consist of improving the grill model. The passive waveguides should be taken into account as well as the modular structure of the grill. Also, a comparison between OOPIC and the SWAN code should be done as a further benchmark.

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