29th EPS Conference on Plasma Phys. and Contr. Fusion Montreux, 17-21 June 2002 ECA Vol. **26B**, P-4.106 (2002)

Particle-in-Cell Simulations for Lower Hybrid Coupling near Cut-off Density

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1 Introduction

For the use of lower hybrid waves in the future tokamaks, the wave coupling to plasma is the most important issue. Usually, the coupling is modelled with the aid of linear wave equations [1]. Recently, the particle-in-cell (PIC) method has been proposed and applied to this kind of simulations [2]. The advantage of the PIC method is that it takes into account also the non-linear and kinetic effects. In some cases these effects may be important.

The electromagnetic PIC simulations are now well enough developed to enable simulations of the coupling problem. In this work, the coupling of lower hybrid power is studied with the 2d3v particle-in-cell code XOOPIC [3], which is fully electromagnetic. The grill is modelled with parallel-plate waveguides having perfectly conducting walls.

With this new tool it is possible to study the coupling also at very low densities. The usual approximations fail at densities close to or below the cut-off density. The PIC method can however, be used to study the coupling at these densities below which the wave cannot propagate. The PIC method also enables coupling calculations with steep gradients. In this work, we have studied the coupling around the cut-off density at various densities and density gradients.

2 Simulation Model of a Lower Hybrid Grill

The 2d model of the LH grill is constructed of parallel plate waveguides having perfectly conducting walls. Due to the slab geometry of the code the y-dependence is neglected and the poloidal dimension of the grill is assumed infinitely high. The magnetic field is along the z-axis, which is therefore called the toroidal one. Consequently, the other simulated direction, the x-direction, is called the radial one.

In this preliminary work, only 4 waveguides are used in order to speed up the simulations. The width of the waveguides is $L_{\rm wg} = 9$ mm and the wall between them is $L_{\rm wall} = 2$ mm. These parameters correspond to those of the JET LH launcher. The source feeding the waveguides is placed one vacuum wavelength behind the grill mouth, i.e. at $L_{\rm g} = -8.1$ cm. The waveguides are fed with a pure transverse electromagnetic (TEM) mode. This is justified since the TE_{01} mode used in real, rectangular waveguides

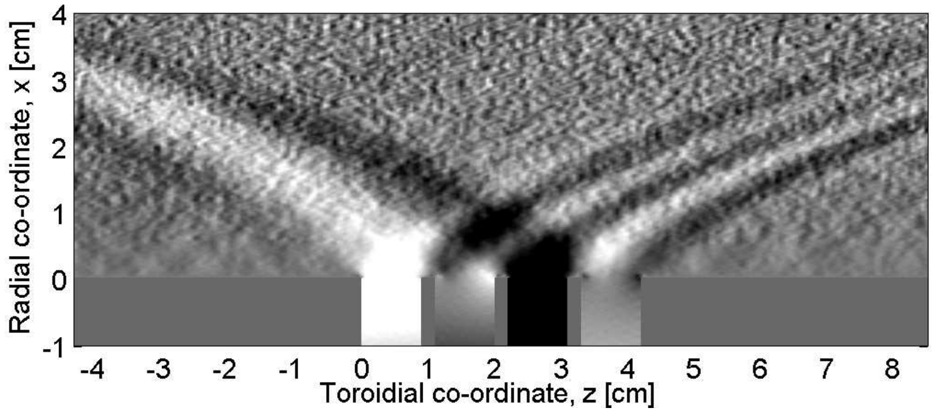

FIG. 1. Interferogram of the toroidal electric field showing the geometry of this work. The edge density is $n_{\mathrm{e}} = 1 \times 10^{17}$ m^{-3} *and the density scale length is* $L_n = 2$ *mm.*

reduces to the TEM mode when the toroidal mode number is 0 and the poloidal dimension of the waveguide is extended to infinity.

The geometry used in this work is shown in Fig. 1. The figure shows an interferogram of the toroidal electric field. Interferograms are used to reduce noise inherently present in PIC simulations.

The boundaries on the plasma side are transparent for the wave with matching impedance and semitransparent for others. The impedance is obtained for the TM wave as $Z_{\mathrm{TM}} = nZ_{\mathrm{TEM}}$, where n is the refraction index perpendicular to the wall. On the two walls in the toroidal direction $n = n_{||}$ and on the top wall $n = n_{\perp}$ were used. All the walls were absorbing particles. In order to compensate for the loss of particles to the walls, inwards particle fluxes were used in the toroidal z-directions. The inward currents were estimated from a thermal flux.

A fairly high edge temperature of $T_{\mathrm{e}} = 1$ keV was used in order to avoid numerical heating due to a so-called non-physical cold beam instability [4]. The edge density in front of the grill mouth was varied from $n_{e0} = 1 \times 10^{17}$ m^{-3} to 3×10^{18} m^{-3}. The density scale length $L_n = n/n'$ was varied from $L_n = 1$ mm to 2 cm. A density scan was also made with a homogeneous density. The magnetic field was $B_{\mathrm{T}} = 2$ T. The grill frequency was 3.7 GHz and the phase difference between adjacent waveguides was $\Delta\varphi = \pi/2$.

3 Wave Coupling and Propagation

In order to study the density dependence of the coupling, a set of simulations with a homogeneous density from $n_{\mathrm{e}} = 1 \times 10^{17}$ m^{-3} to $n_{\mathrm{e}} = 30 \times 10^{17}$ m^{-3} was made. This study showed that the reflection at the grill mouth clearly depends on the density. The lowest densities of this study were below the cut-off density at $n_{\mathrm{cut-off}} = 1.7 \times 10^{17}$ m^{-3}.

The coupling was studied from the reflection coefficient. The reflection coefficient can be obtained from the decrease in the time averaged Poynting flux measured in each waveguide [2].

The PIC simulations reproduce very well the qualitative dependence of the reflection on the density. A quantitative comparison is not very interesting in this case since the number of waveguides is much smaller than in the real grill of e.g. JET. The size of the grill affects the wave spectrum and consequently the coupling. However, compared to linear coupling codes the PIC simulations give a quite similar dependence.

Figure 2 shows the results of the PIC simulations as a function of the edge density. The reflection increases strongly when the density approaches the cut-off density. The reflection also increases at larger densities. There is a clear optimum density for the coupling seen in Fig. 2. The PIC simulation for the frequency of 3.7 GHz predict that the reflection is smallest at densities close to $n_\mathrm{e} = 7 \times 10^{17}$ m^{-3}. The optimal electron density for good coupling is about $n_\mathrm{e,opt} = n_{||0}^2 n_\mathrm{cut-off}$, where $n_{||0}$ is the parallel refractive index of the principal mode [5]. For JET parameters we have $n_{||0} = 1.84$ and consequently $n_\mathrm{e,opt} \approx 5.8 \times 10^{17}$ m^{-3}. This value is slightly lower than the optimum density predicted by the PIC simulations. However, a density closer to this one was not used.

A previous study with PIC simulations with a density around $n_\mathrm{e} = 10^{18}$ m^{-3} showed that the coupling does not depend strongly on the density gradient [2]. This is the case close to the optimum density and for density scale lengths larger than about $L_n = 1$ cm. However, in real experiments the density just in front of the grill may be lower than the above value. This is especially the case in ELMy H-mode plasmas where the density can drop below the cut-off density and has a very steep gradient. At these low densities the wave becomes evanescent. At densities close to or lower than the cut-off density, the steep gradient is expected to play a larger role.

In order to study the effect of the density gradient on the coupling, three other sets of simulations were made with edge densities around the cut-off density. The edge densities were $n_\mathrm{e} = 1 \times 10^{17}$ m^{-3}, $n_\mathrm{e} = 1.6 \times 10^{17}$ m^{-3} and $n_\mathrm{e} = 2 \times 10^{17}$ m^{-3}, where only the last one is slightly above the cut-off density. The density scale lengths were chosen from $L_n = 0.1$ cm to $L_n = 3$ cm.

Figure 3 shows the simulations results. The reflection coefficient depends clearly on the density as the coefficient decreases with increasing density. Again, the large density scale length does not have a very strong effect on the coupling. However, the steep gradients, resulting in short scale lengths, remarkably increase the coupling. The effect is especially strong at the edge density clearly below the cut-off density.

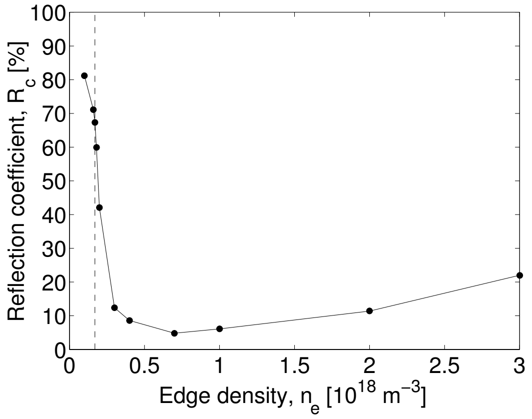

FIG. 2. Reflection coefficient versus edge density with homogeneous density profiles. The bullets denote the simulations points and the dashed line is the cut-off density.

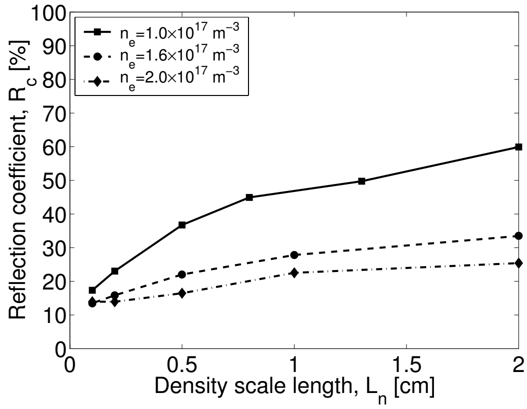

FIG. 3. Reflection coefficient versus density scale length for three different edge densities shown in the legend. The bullets denote the simulations points.

4 Summary and Discussion

A new tool for coupling studies in lower hybrid current drive has been introduced. An electromagnetic PIC code was used to study the coupling at densities close to the cut-off density. The PIC simulations offer a tool to study the coupling in regions where the usual approximations fail, like the density region below the cut-off density.

The results of the PIC simulations agree quite well with the linear coupling codes. In the study with homogeneous densities, the reflection coefficients obtained from the PIC simulations behave qualitatively in an expected way [6] increasing strongly when approaching the cut-off density. The obtained optimum density was of the same order as the analytically predicted one. Away from the cut-off density and at modest density gradients the PIC results agree with the results from the linear models

The coupling was also studied as a function of the density gradient. The study showed that long density scale lengths, $L_n \geq 1$ cm only have a weak effect on the coupling. However, at edge densities around and below the cut-off density, a steep gradient remarkably improves the coupling.

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