

FELHS code for Lower-Hybrid launcher coupling and near fields

R. Bilato, M. Brambilla

Max-Planck Intitut für Plasmaphysik – Euratom Association – Garching, Germany

Introduction

In the last few years off axis Lower Hybrid (LH) current drive in ITER has attracted new attention [1]. This interest has motivated recent efforts in numerical modelling, devoted to go beyond the WKB approach for the description of wave propagation, and to benchmark existing codes, with particular attention to the interface between ray-tracing modules and Fokker-Planck solvers [2]. Indeed, the prediction of power deposition and driven current profiles are the primary goals of numerical modelling. However, the experience gained in the last 20 years in different devices has pointed out the critical issue of understanding, and thus controlling, the interaction between the launcher and the plasma [3]. To design the launcher for ITER, it will be essential to have numerical tools able to calculate the fields inside the launcher and in the first few centimeters in front of it in the presence of the plasma. A first approach has been to interface commercial codes for the launcher analysis, such as HFSS, to simplified plasma codes like SWAN [4]. Recently a different tool TOPLHA [5], originated from TOPICA code for the ion cyclotron antennas, has been developed for LH launcher analysis. For the plasma description, TOPLHA incorporates Finite Element Lower Hybrid Solver (FELHS), which solves the full wave equation in slab geometry and in cold plasma approximation. FELHS has been originally developed for the Reversed Field Pinch [6], and it includes the evaluation of the radiated power spectrum of the traditional grill. Recently, we have added to this code an algorithm for the evaluation of the fields inside the launcher in the presence of waveguide splitting (E-junctions) and other discontinuities, based on the Mode-Matching (MM) method [7]. We discuss mainly these new developments which allow to analyze the active and passive-active mutijunction (PAM) [8], the latter of which has been proposed for ITER. Although assuming a somewhat simplified geometry (for instance, only sharp edges), FELHS can be the fast and reliable tool for realistic prediction of the performances and radiated spectrum of the launcher, mandatory step for the analysis of wave propagation and absorption in the plasma.

Code description

For the launcher the plasma is a load which can be described by an impedance, whereas the launcher determines the boundary conditions of the wave propagation inside the plasma. In this sense the analysis of the launcher and wave propagation in the plasma can be addressed separately. To analyze the launcher, at each waveguide splitting we apply the MM method [7].

On each side of the junction the field is represented as a superposition of waveguide eigenmodes (TE_{nm} and TM_{nm}); the appropriate continuity conditions for the tangential field components at the discontinuity are transformed into an algebraic system of equations for the unknown coefficients of the superposition (later called a and b for waves travelling or evanescent towards the plasma and the generator, respectively) by exploiting the orthogonality of the waveguide modes. As a first step, the reflection and transmission matrices for waves incident from the left (generator) and from the right (plasma) are evaluated at each splitting

$$\begin{cases} \underline{b}_i^+ = \underline{0} \\ \underline{a}_i^+ = \underline{\mathcal{T}}_i^- \cdot \underline{a}_i^- \\ \underline{b}_i^- = \underline{\mathcal{R}}_i^- \cdot \underline{a}_i^- \end{cases} \quad \text{and} \quad \begin{cases} \underline{a}_i^- = \underline{0} \\ \underline{a}_i^- = \underline{\mathcal{R}}_i^+ \cdot \underline{b}_i^+ \\ \underline{b}_i^- = \underline{\mathcal{T}}_i^+ \cdot \underline{b}_i^+ \end{cases} \quad (1)$$

with superscript $+$ and $-$ for the right and left side of the splitting, respectively. These matrices are evaluated taking into account the finite thickness of the wall between adjacent guides, and the presence of arbitrary filling dielectrics. When combining different discontinuities together, the presence of intermediate phase shifters is also foreseen.

When splitting occurs in more than one step, reflections and transmissions from each discontinuity must be combined. Since waves are launched from the generator and propagate towards the mouth of the launcher, we are interested in the coefficients a_i^+ and b_i^- for a given set of incident coefficients a_i^- :

$$\begin{cases} \underline{a}_i^+ = \underline{\mathcal{T}}_i^- \cdot \underline{\tilde{a}}_i^- + \underline{\mathcal{R}}_i^+ \cdot \underline{\tilde{b}}_i^+ \\ \underline{b}_i^- = \underline{\mathcal{R}}_i^- \cdot \underline{\tilde{a}}_i^- + \underline{\mathcal{T}}_i^+ \cdot \underline{\tilde{b}}_i^+ \end{cases} \quad \text{and} \quad \begin{cases} \underline{\tilde{a}}_i^- = \underline{\mathcal{L}}_i \cdot \underline{a}_i^- \\ \underline{\tilde{b}}_i^+ = \underline{\mathcal{D}}_i \cdot \underline{a}_i^- \end{cases} \quad (2)$$

where $\underline{\mathcal{L}}_i$ and $\underline{\mathcal{D}}_i$ are the matrices describing the multiple transits of the guide modes between the adjacent discontinuities i and $i+1$

$$\begin{cases} \underline{\mathcal{L}}_i = \left(\underline{\mathbb{I}} - \underline{\mathbf{T}}_{i,i-1}^a \cdot \underline{\mathcal{R}}_{i-1}^+ \cdot \underline{\mathbf{T}}_{i-1,i}^b \cdot \underline{\mathcal{R}}_i^- \right)^{-1} \\ \underline{\mathcal{D}}_i = \underline{\mathbf{T}}_{i,i+1}^b \cdot \underline{\mathcal{R}}_{i+1}^- \cdot \underline{\mathbf{T}}_{i+1,i}^a \cdot \left(\underline{\mathbb{I}} - \underline{\mathbf{T}}_{i,i+1}^b \cdot \underline{\mathcal{R}}_{i+1}^- \cdot \underline{\mathbf{T}}_{i+1,i}^a \cdot \underline{\mathcal{R}}_i^+ \right)^{-1} \cdot \underline{\mathcal{T}}_i^- \end{cases} \quad (3)$$

$\underline{\mathbf{T}}_{i,j}^{a,b}$ are the diagonal matrices of the phase shifts due to the propagation (or the evanescence below cutoff) along the guides. Finally, when all junctions are considered together, Eq. (2) must be recursively generalized

$$\begin{cases} \underline{\tilde{\mathcal{L}}}_i = \underline{\mathcal{L}}_i + \underline{\mathbf{T}}_{i-1,i}^a \cdot \underline{\mathcal{T}}_{i-1}^- \cdot \underline{\tilde{\mathcal{L}}}_{i-1} \cdot \underline{\mathcal{T}}_{i-1}^+ \cdot \underline{\mathbf{T}}_{i-1,i}^b \cdot \underline{\mathcal{R}}_i^- \cdot \left(\underline{\mathbb{I}} - \underline{\mathbf{T}}_{i-1,i}^a \cdot \underline{\mathcal{R}}_{i-1}^+ \cdot \underline{\mathbf{T}}_{i-1,i}^b \cdot \underline{\mathcal{R}}_i^- \right)^{-1} \\ \underline{\tilde{\mathcal{D}}}_i = \underline{\mathcal{D}}_i + \underline{\mathbf{T}}_{i,i+1}^b \cdot \underline{\mathcal{T}}_{i+1}^+ \cdot \underline{\tilde{\mathcal{D}}}_{i+1} \cdot \underline{\mathcal{T}}_{i+1}^- \cdot \underline{\mathbf{T}}_{i+1,i}^a \cdot \left(\underline{\mathbb{I}} - \underline{\mathbf{T}}_{i,i+1}^b \cdot \underline{\mathcal{R}}_{i+1}^- \cdot \underline{\mathbf{T}}_{i+1,i}^a \cdot \underline{\mathcal{R}}_i^+ \right)^{-1} \cdot \underline{\mathcal{T}}_i^- \end{cases} \quad (4)$$

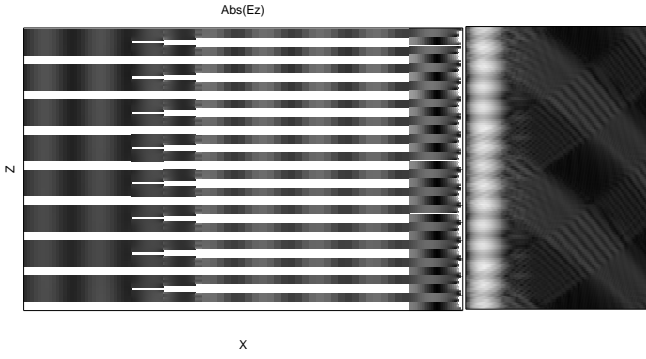


Figure 1: E_z modulus inside the waveguides and in the first 20 cms in plasma with a 180° phasing. The white regions represent the filled metallic part of the launcher.

The iteration starts from the generator with $\underline{\mathcal{R}}_0^+$ for $\underline{\mathcal{L}}_1$ and with the plasma scattering matrix $\underline{\mathcal{R}}_{N+1}^- = S_{\text{pl}}$ for $\underline{\mathcal{D}}_N$. S_{pl} is the only term depending on the plasma parameters, and couples all guides to each others. It is evaluated using the plasma response described by the plasma surface impedance, defined for each partial wave by [9]

$$\vec{E}_t(n_y, n_z) = \underline{\mathcal{L}}(n_y, n_z) \cdot \vec{B}_t(n_y, n_z) \quad \text{with :} \quad \begin{cases} \vec{E}_t = \vec{E} - (\hat{u}_x \cdot \vec{E}) \hat{u}_x = E_y \hat{u}_y + E_z \hat{u}_z \\ \vec{B}_t = -\hat{u}_x \times \vec{B} = B_z \hat{u}_y - B_y \hat{u}_z \end{cases} \quad (5)$$

Since we consider waveguides of finite height, it is necessary to take into account in the plasma both the slow (LH) and the fast wave, hence $\underline{\mathcal{L}}$ is a 2×2 matrix. The fast wave is very poorly radiated, but can influence the spectrum around $n_\perp^2 = 1$ and the efficiency of the launcher. $\underline{\mathcal{L}}$ is obtained by integrating the full wave equations in slab geometry, with outward radiation conditions at a sufficient distance from the plasma surface. Density profile and magnetic field shear can be specified arbitrarily, and a vacuum layer between the grill mouth and the plasma surface can be included. The scattering matrix at the grill mouth itself is obtained with the MM method used for the standard grill.

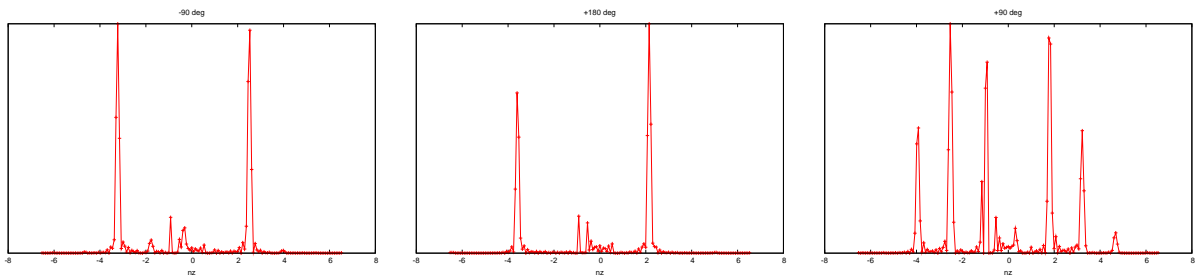


Figure 2: Radiated power of the PAM launcher [10] as function of n_z for three different phases.

Example

The present MM implementation allows to simulate a three-dimensional launcher, including tapering of the septa between guides and the possible presence of passive guides. As an example,

we have considered the PAM launcher discussed by [10], an ITER-like launcher for Tore Supra. A row with alternating active and passive guides is sketched in Fig. 1. We have considered the same parameters as in reference [10], namely a frequency of 3.7 GHz, a linear density profile with an initial value of $3.4 \times 10^{19} \text{ m}^{-3}$ and a slope of $3.4 \times 10^{20} \text{ m}^{-4}$. Inside the plasma one can recognize the pattern of the resonant cones characteristic of LH waves. The small white spots at the launcher mouth are regions of large hf field due to the excitation of evanescent

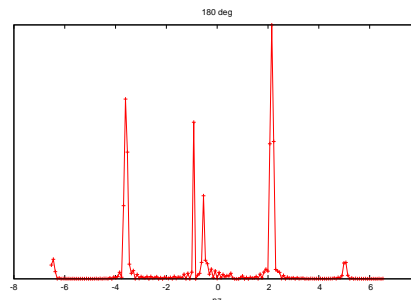


Figure 3: Radiated spectrum for passive waveguides shorter than those in Fig. 2.

modes TE_{nm} and TM_{nm} at the launcher–plasma discontinuity. In Fig. 2 the radiated power spectra for three different phasing are reported as function of $n_z \approx n_{\parallel}$.

The rationale of having the passive waveguides [8] is to reduce the fraction of power spectrum in the inaccessible range $n_z^2 \leq 1$, with the beneficial effect of improving the antenna coupling. The influence of the passive guides depends critically on the phase difference between the waves entering from the aperture and those reflected by the back wall. As expected, for a phasing of 180° , assuming the depth of the passive guides to be 1 cm shorter than optimum value appreciably increases the peaks in the unaccessible range $n_z \approx n_{\parallel} < 1$, as shown in Fig. 3. In fact, waves at $n_z < 1$ do not access the plasma core but they are radiated as guided waves trapped between the wall and the cutoff just inside the plasma. Thus, power carried by these waves must be considered lost with a decrease of the global efficiency of the launcher.

References

- [1] GORMEZANO, C., SIPS, A., LUCE, T., et al., *Nuclear Fusion* **47** (2007) S285.
- [2] BONOLI, P., Benchmarking of lower hybrid current drive codes with application to iter relevant regimes, in IAEA, editor, *Plasma Physics and Controlled Nuclear Fusion Research*, pp. IT/P1–2, Chengdu, China, 1998, IAEA.
- [3] RANTAMAKI, K. M., PATTIKANGAS, T. J. H., KARTTUNEN, S. J., et al., *Plasma Physics and Controlled Fusion* **44** (2002) 1349.
- [4] BELO, J., BIBET, P., MISSIRLIAN, M., et al., *Fusion Engineering and Design* **74** (2005) 283.
- [5] MILANESIO, D., LANCELLOTTI, V., MENEGHINI, O., et al., *Toppha: an accurate and efficient numerical tool for analysis and design of lh antennas*, volume 933, pp. 301–304, AIP, 2007.
- [6] BILATO, R. and BRAMBILLA, M., Radio frequency cd by lh waves in the reversed field experiment, volume 485, pp. 202–206, AIP, 1999.
- [7] MITTRA, R. and LEE, S. W., *Analytical techniques in the theory of guided waves (Macmillan series in electrical science)*, Macmillan, 1971.
- [8] BIBET, P., LITAUDON, X., and MOREAU, D., *Nuclear Fusion* **35** (1995) 1213.
- [9] BRAMBILLA, M. and CARDINALI, A., *Nuclear Fusion* **32** (1992) 465.
- [10] BELO, J. H. and BIBET, P., Coupling properties of tore supra’s iter-like lh pam launcher, volume 28G, pp. P–4.109, AIP, 2004.