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Recent Analysis of the ITER Ion Cyclotron Antenna With the TOPICA Code

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Abstract. Plasma heating in the Ion Cyclotron Range of Frequencies (ICRF) is adopted in most of the existing nuclear fusion experiments and is also one of the three auxiliary heating systems of ITER. Two identical ICRF antennas will be installed in ITER with the aim of delivering 10MW per antenna to the plasma for the baseline design configuration (upgradable to 20 MW/antenna). In order to optimize the feeding circuit and to evaluate and predict the overall performances of an ICRF launcher it is fundamental to perform radio-frequency simulations of the antenna detailed geometry loaded with a realistic plasma, and to extract the antenna input parameters, the electric current on conductors and the radiated field. In this work, we analyze the current ITER ICRF launcher, for the first time including the surrounding cavity between the port plug and the port extension, and a portion of the blanket tiles in the TOPICA code; the geometrical description of the antenna has reached an unprecedented level of accuracy. The ITER ICRF antennas have been the object of a comprehensive analysis, varying the working frequency, the plasma conditions and the poloidal and toroidal phasings between the feeding transmission lines. The performances of the antennas have been documented in terms of input parameters, power coupled to plasma and electric fields, for a reference set of ITER plasma equilibria and assuming a maximum voltage on the system.

INTRODUCTION

Ion Cyclotron Resonance Heating (ICRF) is one of the auxiliary heating systems in ITER [1]. The capability to predict with accuracy the IC antenna behavior in terms of input parameters, electric currents, power coupled to plasma and radiated fields is vital to assist its design.

This paper provides a complete picture of the antenna performances at different frequencies and loading conditions relevant to ITER, with the help of TOPICA code.

The paper first includes a short description of the TOPICA code, of the simulated geometries and of the set of assumed reference plasma profiles respectively. Then it reports the analysis of the latest optimized geometry with the antenna plug/port cavity in place (it is the cavity that is formed by the antenna and the port where it is installed). It is important to stress here that this paper fully documents only one geometry of the TOPICA related actions for the analysis of the ITER IC launcher. However, being this a wider cooperative design task, this paper has to be considered in synergy with the other published material on the same topic. In particular, interested readers can refer to [2], [3], [4] and [5] for the COMSOL and Petra-M modelling of the ITER ICRF antennas and the excellent agreement with the TOPICA results. Also, references [6] and [7] analyse the fields extracted from the TOPICA simulations (near fields in front of the antenna, and fields inside the antenna plug/port cavity respectively).

ADOPTED TOOLS AND SETUP

The TOPICA code

All the results reported here have been computed using the TOPICA code, which will be roughly described in the following lines. We refer the interested reader to [8] and [9] for a more comprehensive description of the code.

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TOPICA is a tool realized for the 3D/1D simulation of ICRF antennas; it simulates IC antennas with their realistic 3D geometry and with an accurate 1D plasma model. The code self-consistently evaluates the electric current distribution on conductors by means of an integral-equation formulation. The full antenna environment is split into a vacuum region and a plasma region, which are coupled via the electromagnetic current distribution on their interface, often referred to as *aperture*. A plasma surface impedance accounts for the plasma loading itself, which is currently generated by a modified version of FELICE code [10]. The TOPICA code is also fully parallelized and it currently runs on the MARCONI cluster at CINECA (www.hcp.cineca.it), characterized by 3188 computing nodes, featuring Intel Xeon Skylake (SKL) processors and capable of a total peak performance of about 20 PFlop/s. The usage of such a powerful cluster determines a substantial reduction of computation time and the removal of any limitation in terms of the geometrical complexity of the simulated arrays.

List of geometries

All simulated models consist of an array of 24 straps enclosed within a cavity, as required by the TOPICA formulation (please refer to [8] for further details), including a section of the input transmission lines. A Faraday Screen (FS), if available, a portion of the blanket shielding modules (BSM), the four port junction (4PJ) and the grounding connections are also included in some models to guarantee the maximum level of geometrical accuracy.

While addressing the reader to [11] and to [12] for a detailed description of the simulated geometries, we would like to list here the main steps to provide a broader view of the design activity. TOPICA analysis started with the Preliminary Design Review (PDR) antenna from 2010 (labeled here as "CY8a"), i.e. with the outcome of the first design phase ([13], [14]). "CY8a" was a top-bottom asymmetric launcher with a curved antenna-plasma interface (i.e. *aperture*) and a simplified FS. The following model, namely "CY8b", was used as a reference for the recent analysis instead; "CY8b" has a simplified curved antenna-plasma interface with top/bottom and left/right symmetry.

The next group of geometries was characterized by a top-bottom symmetry and by a reduced distance between the straps in the toroidal direction, as dictated by the mechanical review of the 2012 PDR antenna. A first model, namely "CY9" was used to verify the impact of the FS, by testing it with a simplified version, with a more realistic design and without FS at all. For this model, the same simplified aperture of "CY8b" was considered. Eventually, "CY10" can be considered as the final geometry and it has been extensively tested and reported in [11]; for this geometry, a more realistic aperture based on recent equilibrium studies was adopted. The next model, "CY11", included the presence of the 4 port junction (4PJ) and it is detailed in [12] instead.

The last antenna, namely "CY12", is the antenna model used in this paper and it includes the antenna plug/port cavity, as depicted in Figure 1. Figure 2 reports on the left the position of the surfaces where the electric field was computed within the vacuum volume of the TOPICA model, while a front view of the meshed launcher is depicted on the right. This analysis is extremely important to determine if the presence of the cavity has an impact on the antenna input parameters and on the electric field distribution. This paper describes the performances of this antenna with a large number of plasma profiles for five frequency points; please refer to the correspondent section for an accurate description of the adopted loadings.

Table I summarizes some relevant features of the most important geometries listed before; geometry "CY12" is added to what was already documented in [12].

List of plasma profiles

As a preamble, it is important to mention here how TOPICA handles a plasma profile. Firstly, the portion of the profile that lies beyond the aperture (i.e. within the previously mentioned vacuum region of the TOPICA formulation) has to be removed. Afterwards, since the FELICE code does not correctly process the S=0 resonance (lower hybrid resonance), an "equivalent" layer of vacuum with the same thickness has to take place of the part of the profile where the resonance is located. On average, this happens for 75% of the adopted plasma profiles, but the amount of equivalent vacuum is usually of the order of a few centimeters. This can be considered the most conservative approach in terms of power coupled to plasma, as better documented in [12]. Once the above-mentioned actions are performed, a profile can also be radially shifted to investigate the effect on the antenna input parameters and on the power coupled to plasma, as described in [12].

While addressing again the interested reader to [12] for a detailed description of the loaded plasma profiles, we briefly introduce them here.

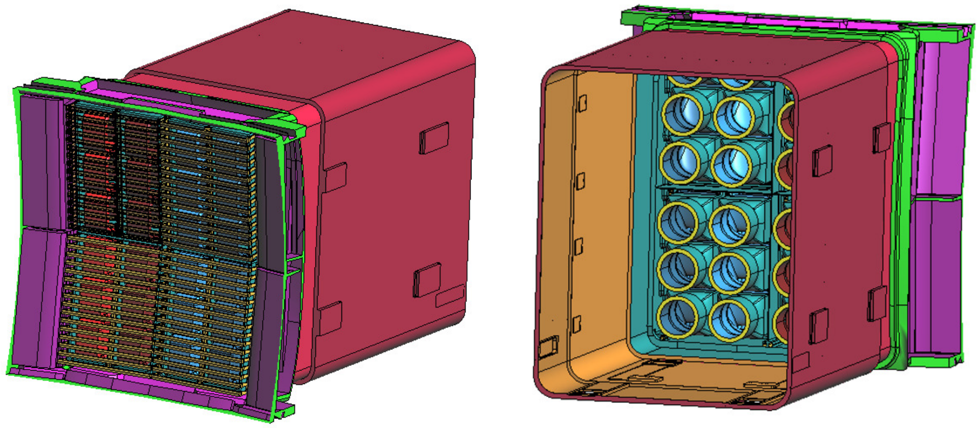

FIGURE 1. Front and back view of the "CY12" launcher.

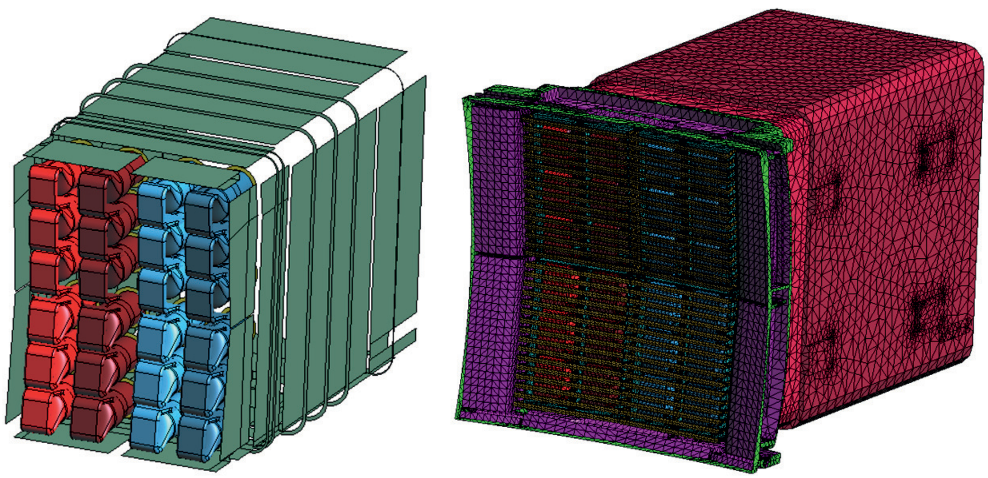

FIGURE 2. Position of the surfaces along the cavity where the electric field was computed for the "CY12" launcher (left) and front view of the meshed geometry (right).

ITER Organization originally released two reference D-T plasma profiles in 2010, representing the extremes expected for ITER plasmas given the uncertainties on edge physics. The low density profile was also shifted by 2cm, 4cm and 5cm towards the antenna, while a 4cm shift away from it was considered for the high density case. The low density scenario was also rigidly shifted 150cm far from the antenna mouth, to reproduce the effect of vacuum loading. More recently, in 2020, ITER Organization provided several additional plasma profiles [15], obtained with the latest self-consistent core-edge modelling. Once more, radial shifts were implemented in some cases. In addition, a few cases were added to verify the effect of local gas puffing on the antenna performances.

ANALYSIS OF THE "CY12" GEOMETRY WITH THE ANTENNA PLUG / PORT CAVITY

As an example of the analysis performed with "CY12" geometry, the power coupled to the plasma is shown in Figure 3 at 55MHz and 47.5MHz; the near electric fields (E-fields at 2-3mm in front of the antenna) are depicted in Figures 4 and **??** at 47.5MHz and 40MHz respectively. Figure 3 shows that the presence of the cavity does not influence at all the power coupled to plasma outside the resonance frequency (around 47.5MHz, see also [7]) and for the typical H&CD phasings ($0\pi0\pi$, $0\pi\pi0$, tapered $0\pi0\pi$, +CD, etc.). The only exception is monopole phasing (which is not

Geometry label	**CY8a**	**CY8b**	**CY9(a/b/c)**	**CY10**	**CY11**	**CY12**
Motivation	2010 PDR	Reference	Impact of mesh, FS, strap inter spaces modification and the strap short circuit	Final model and impact of stretching procedure	Impact of 4PJ	Impact of grounding
Strap-plasma distance	40÷94 mm	78÷98 mm	78÷98 mm	65÷110 mm	as CY10	as CY10
FS description	2010 PDR	Simplified	Different versions (no FS, very detailed FS, simplified FS)	Simplified	as CY10	as CY10
Left-right Symmetry	Yes	Yes	Yes	Yes	Yes	Yes
Top-bottom symmetry	top:6.76° bottom:4.78°	Yes (6.76°)	as CY8b	as CY8b	as CY8b	as CY8b
Total unknowns	172k	181k	145k÷267k	263k	277k	291k
Mesh max size on conductors	8.5 cm	8 cm	5 cm	8 cm	as CY10	as CY10
Mesh max size on aperture	9.2 cm	7.4 cm	7.4÷9.8 cm	8.0 cm	as CY10	as CY10
Mesh min size on aperture	6.0 cm	5.1 cm	5.1÷6.8 cm	5.6 cm	as CY10	as CY10

TABLE I. Most relevant simulated geometries

going to be adopted), for which the relative error is remarkable at all frequencies and above 20% in some cases. Figure 4 documents the effect of the antenna plug/port cavity on the near fields computed close to its resonance, going from an average value (in magnitude) of about 12 kV/m to 21 kV/m. Figure 5 shows that at 40MHz the presence of the antenna plug/port cavity has negligible influence on the local fields instead.

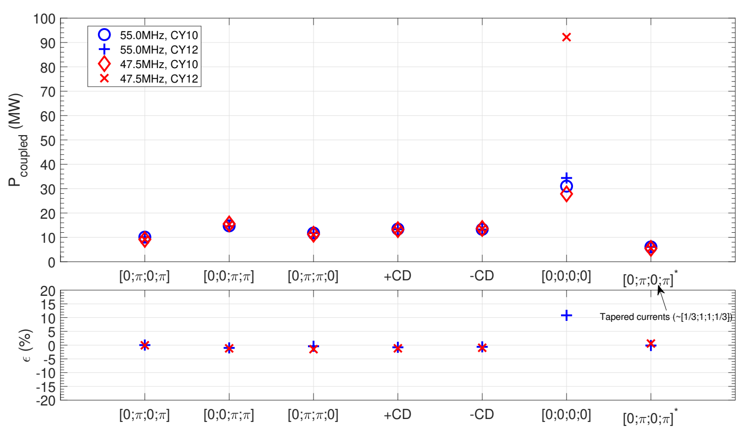

FIGURE 3. Coupled power for the low density 2010 baseline scenario as a function of frequency (47.5MHz and 55MHz are shown) for the "CY10" and the "CY12" geometries (top) and relative error (bottom). A peak voltage of 45kV is assumed in the circuit, with several toroidal phasings and a constant 0/-90 poloidal one. The relative error is computed as $(P_{CY12} - P_{CY10})/P_{CY10}$ for each case.

CONCLUSION

This paper details one of the geometries simulated with TOPICA within the frame of the ITER IC antenna design. To be more specific, "CY12" launcher is the same as the reference ITER IC antenna ("CY10"), with the addition of the antenna plug/port cavity. The comparison of the antenna input parameters and of the electric fields along the cavity with the reference model showed that the presence of the antenna plug/port cavity can have a substantial impact

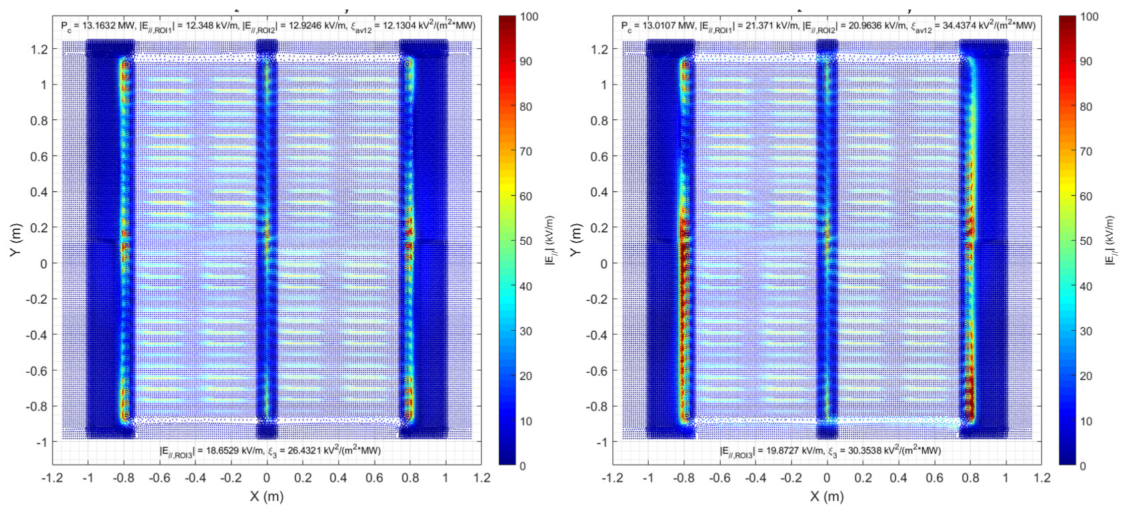

FIGURE 4. Electric field distribution in front of the antenna for the reference "CY10" geometry (left) and for the "CY12" launcher with grounding (right). The 2010 low density baseline scenario is loaded for both geometries at 47.5MHz. A peak voltage of 45kV is assumed in the circuit, with 0/90/180/270 toroidal phasing and 0/-90 poloidal one. The average field magnitude is also reported for the left (ROI1) and right limiter (ROI2), as seen from the plasma side.

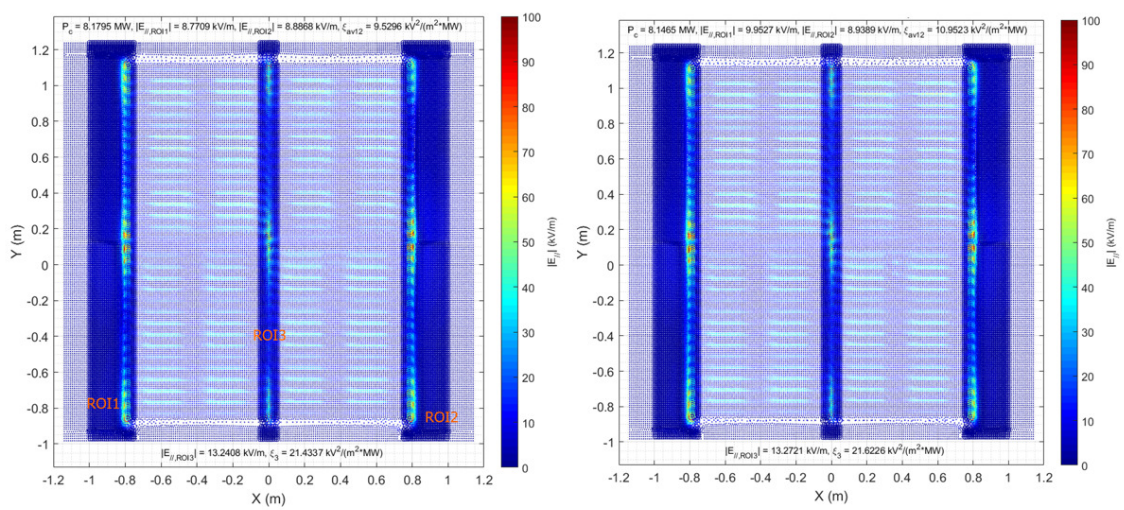

FIGURE 5. Electric field distribution in front of the antenna for the reference "CY10" geometry (left) and for the "CY12" launcher with grounding (right). The 2010 low density baseline scenario is loaded for both geometries at 40MHz. A peak voltage of 45kV is assumed in the circuit, with 0/90/180/270 toroidal phasing and 0/-90 poloidal one. The average field magnitude is also reported for the left (ROI1) and right limiter (ROI2), as seen from the plasma side.

(above all on near fields) around the cavity resonance frequency, while it can be neglected elsewhere, in particular for heating and current-drive.

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