Progress and verification of DTT ICRF antenna simulation using COMSOL

Original
Progress and verification of DTT ICRF antenna simulation using COMSOL / Torrisi, G.; Mascali, D.; Mauro, G. S.; Pidatella, A.; Ceccuzzi, S.; Baiocchi, B.; Cardinali, A.; Milanesio, D.; Mirizzi, F.; Ponti, C.; Ravera, G. L.; Tuccillo, A.; Vecchi, G.. - In: AIP CONFERENCE PROCEEDINGS. - ISSN 0094-243X. - ELETTRONICO. - 2984:(2023). (Intervento presentato al convegno 24th Topical Conference on Radio-Frequency Power in Plasmas tenutosi a Annapolis, USA nel 26–28 September 2022) [10.1063/5.0162609].

Publisher:
AIP Publishing

Published
DOI:10.1063/5.0162609

.

Development/Extension of a COMSOL Full-wave Anisotropic Model for the ICRH Heating

G. Torrisi,[1, a)] D. Mascali,[1, b)] G. S. Mauro,[1, c)] A. Pidatella,[1, d)] S. Ceccuzzi,[2, 3, e)] B. Baiocchi,[4, f)] A. Cardinali,[3, g)] D. Milanesio,[5, h)] F. Mirizzi,[6, i)] C. Ponti,[7, j)] G. L. Ravera,[3, k)] A. Tuccillo,[2, 3, l)] and G. Vecchi[5, m)]

[1)] *INFN-LNS, Via Santa Sofia 62, 95123, Catania, Italy.*
[2)] *DTT S.C. a r.l., Via Enrico Fermi 45, 00044, Frascati, Italy.*
[3)] *ENEA, Via Enrico Fermi 45, 00044, Frascati, Italy*
[4)] *CNR-ISTP, Via Roberto Cozzi 53, 20125, Milano, Italy*
[5)] *Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129, Torino, Italy*
[6)] *CREATE, Via Claudio 21, 80125, Napoli, Italy*
[7)] *Università degli Studi Roma Tre, Via Vito Volterra 62, 00146, Roma, Italy.*

[a)] *Corresponding author: giuseppe.torrisi@lns.infn.it*
[b)] *Electronic mail: davidmascali@lns.infn.it*
[c)] *Electronic mail: mauro@lns.infn.it*
[d)] *Electronic mail: pidatella@lns.infn.it*
[e)] *Electronic mail: silvio.ceccuzzi@enea.it*
[f)] *Electronic mail: Benedetta.baiocchi@istp.cnr.it*
[g)] *Electronic mail: alessandro.cardinali@enea.it*
[h)] *Electronic mail: daniele.milanesio@polito.it*
[i)] *Electronic mail: francesco.mirizzi@outlook.it*
[j)] *Electronic mail: cristina.ponti@uniroma3.it*
[k)] *Electronic mail: gianluca.ravera@enea.it*
[l)] *Electronic mail: angelo.tuccillo@dtt-project.it*
[m)] *Electronic mail: giuseppe.vecchi@polito.it*

Abstract. In this paper we present the extension of a full-wave FEM model (COMSOL®+MATLAB®) - initially developed to compute the electromagnetic field in presence of the anisotropic inhomogeneous plasma of the Electron Cyclotron Resonance Ion Sources (ECRISs) – to the Ion Cyclotron Range of Frequency (ICRF). The model - based on the full non-uniform dielectric tensor in "cold plasma" approximation - has been employed to study antenna geometries of increasing complexity. Various antenna types have been analyzed, starting from single flat strap up to the three straps of the antenna currently in the design phase for the Divertor Tokamak Test facility (DTT). The results have been compared, cross-checked and validated with a simpler COMSOL-based tool and with the TOPICA code.

INTRODUCTION

This paper presents the extension of a 3D full wave COMSOL Multiphysics-based code - already developed for the simulation of microwaves-plasma interaction in electron cyclotron resonance ion sources (ECRISs) [1] - to the ion cyclotron resonance frequency (ICRF) range for the simulation of IC antennas in the Divertor Test Tokamak (DTT) scenario [2]. The design of ICRF antennas and their coupling with magnetized plasma is of crucial importance because IC heating is one of the three auxiliary heating tools used almost in all tokamak machines. In literature several codes can be found to model the wave behaviour in the ICRH range, such as TOPICA (TOrino Polytechnic Ion Cyclotron Antenna [3]) and ICANT [4] based on the plasma surface impedance, CST MWS codes [5] where the plasma load is modeled as equivalent dielectric isotropic medium having an high dielectric constant. In order to deal with the complex 3D ICRF antenna geometry, 3D electromagnetic codes based on Finite Element Method (FEM) commercial software can be used [6]. In our model [1], Maxwell'equations are solved by using COMSOL Multiphysics FEM direct solver whose input parameters are provided by a dedicated software running in MATLAB explioting the COMSOL LiveLink®with MATLAB itself. The 3D space-varying full non-uniform dielectric tensor in cold-plasma approximation is computed in Matlab (see Fig. 1) to load the anisotropic non-homogeneous plasma.

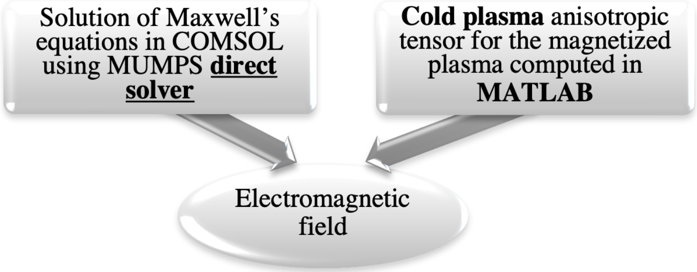

FIGURE 1. Full-wave model scheme

The extension of the code to the ICRH regime has been achieved by including the ion species to the "cold" plasma dielectric tensor. Moreover, in order to finite the otherwise semi-infinite space domain in front of the IC antennas, Perfectly Matched Layer (PML) boundary conditions have been implemented around the edges of the cold magnetized plasma. The model has been firstly applied on a simple single strap geometry and then on a preliminary version of the ICH DTT antenna, currently under design [7, 8, 9, 10]. In both cases results have been cross-checked and compared for validation with TOPICA code and with a simpler COMSOL-based tool - hereinafter indicated with SC - which is described in [11].

MODEL EXTENSION FOR ICRH HEATING

The "cold plasma" dielectric tensor $\bar{\bar{\varepsilon}}$ [1], formerly developed for electrons in ECR Ion Sources plasmas, has been extended to ions and to a tokamak magnetic field scenario. The Artificial Stretching Tensor $\bar{\bar{\varepsilon}}_{PML}$ [12] has been included by using the polynomial stretching functions which represent a common choice for the PML stretching functions: $S_r(r) = 1 + (S'_r + S''_r)(r/L_{PML_r})^{p_r}$, where L_{PML_r}, p_r , S'_r and S''_r are respectively the the PML depth, the order of the stretching function, the real stretch and the imaginary stretch. In our compution we fix $S''_r = 1$, $S''_r = -1$ and $p_x = 3$. These functions provide a PML (or non-reflecting boundary condition) for the DTT plasma edge in front of the ICH antennas, which can be added at the boundaries of the open-domain problem (see Figure 2 a)) contrarily to the closed domain delimited by the lossy cavity walls of the ECRIS plasma chamber [1]. From the general dielectric tensor $\bar{\bar{\varepsilon}}$, one obtains the perfectly matched tensor $\bar{\bar{\varepsilon}}_{PML}$:

$$\bar{\bar{\varepsilon}}_{PML} = \Lambda \cdot \bar{\bar{\varepsilon}} \cdot \bar{\bar{S}}^{-1} = \begin{bmatrix} \varepsilon_{xx} \frac{S_y(y)S_z(z)}{S_x(x)} & \varepsilon_{xy} S_z(z) & \varepsilon_{xz} S_y(y) \\ \varepsilon_{yx} S_z(z) & \varepsilon_{yy} \frac{S_z(z)S_x(x)}{S_y(y)} & \varepsilon_{yx} S_x(x) \\ \varepsilon_{zx} S_y(y) & \varepsilon_{zy} S_x(x) & \varepsilon_{zz} \frac{S_x(x)S_y(y)}{S_z(z)} \end{bmatrix} \tag{1}$$

where $\Lambda = det(\bar{\bar{S}})\bar{\bar{S}}^{-1}$ and $det(\bar{\bar{S}}) = S_x S_y S_z$. The same stretching has been applied to the magnetic permeability tensor $\bar{\bar{\mu}}_{PML}$. Due to the challenging problem, geometries of increasing complexities have been considered. Both the "Import 3D from .stp" file to COMSOL and a step-by-step geometry build - in order to have fully parameterized antenna geometry (in terms of strap distance, strap width, Box width, etc.) - have been tested (see Figure 2). The vacuum and plasma volumes near the antenna are meshed with tetrahedral elements.

Simple single strap geometry

As a first validation of the COMSOL model, a simple scenario has been chosen and results have been compared with a simple COMSOL-based tool. The geometry, plasma density and toroidal magnetic field profiles are depicted in

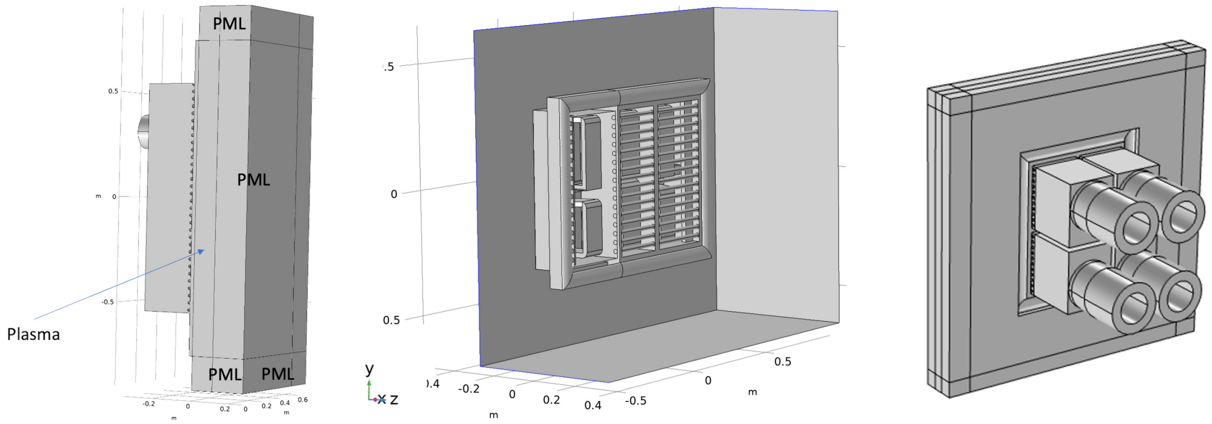

FIGURE 2. Examples of a COMSOL geometries

Figure 3 a), b) and c) respectively. The frequency has been fixed to 30 MHz, R_0 = 1.65 m, B_0 = 2 T.

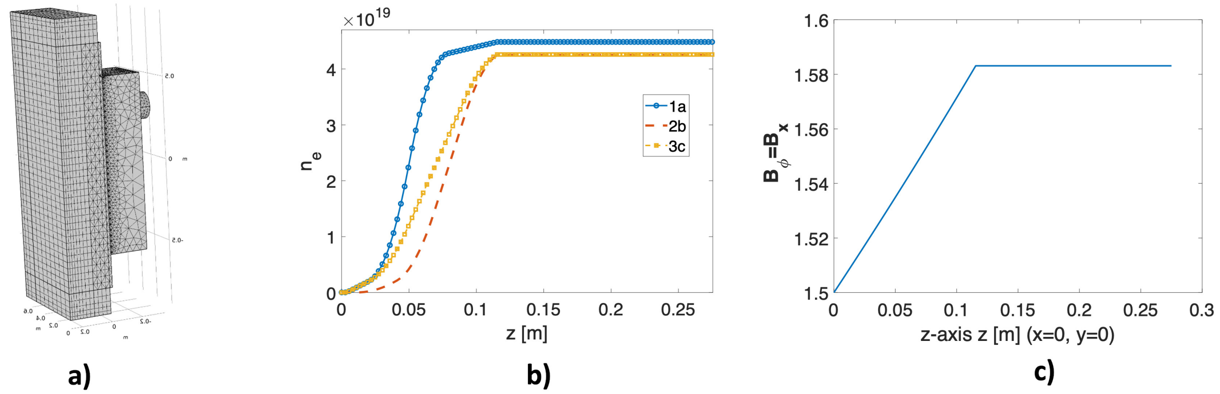

FIGURE 3. Geometry (a), density profiles (b) and toroidal magnetic field profile (c)

Both the Electric field, power loss and S-parameters - computed at different input density profiles and frequencies – have been retrieved and compared. Results shown in Figure 4, Figure 5 and in Table I are in very good agreement.

TABLE I. Comparison of $|S_{11}|$ and $\angle S_{11}$ results of the COMSOL model vs the SC model [11] for three different density profiles.

density profile[a]	$\lvert S_{11}\rvert$ **COMSOL**	$\lvert S_{11}\rvert$**SC**	$\angle S_{11}$ **COMSOL**	$\angle S_{11}$**SC**
n_e1a)	0.90378	0.9037	-19.36°	-19.416°
n_e2b)	0.9397	0.9387	-23.768°	-23.849°
n_e3c)	0.9563	0.9557	-25.515°	-26.016°

[a] see Fig. 3(b)

Three-strap geometry

A direct comparison of the COMSOL full-wave code, including a fully 3D anisotropic plasma tensor, has been carried out as a benchmark with COMSOL SC and TOPICA models, considering the antenna reported in Figure 6 for the

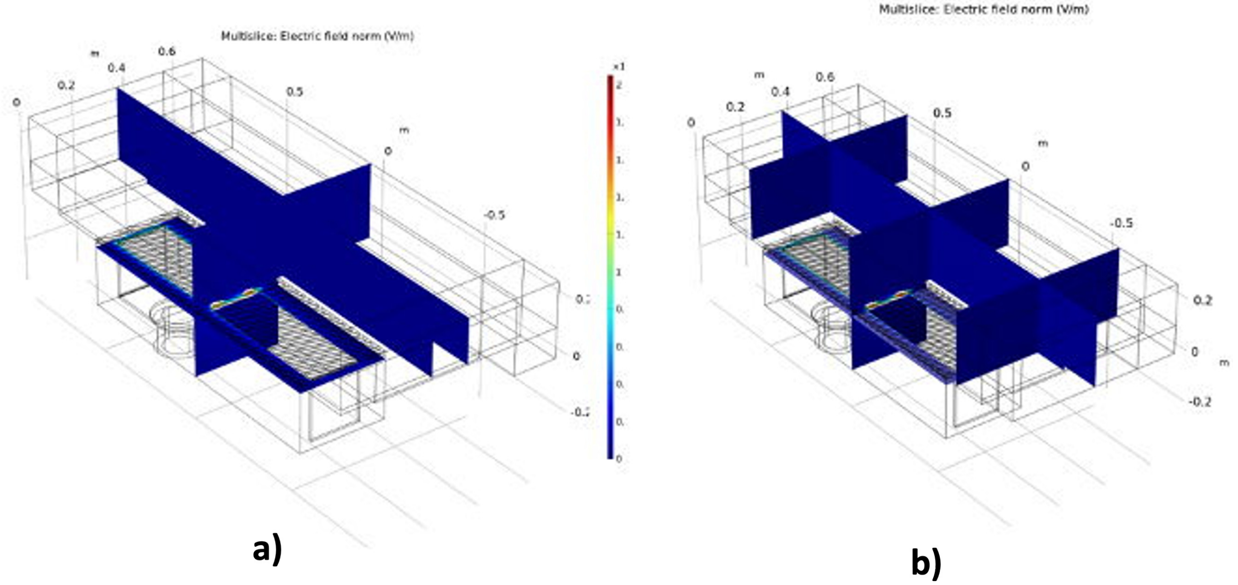

FIGURE 4. Electric field results comparison: a) COMSOL code; b) SC code

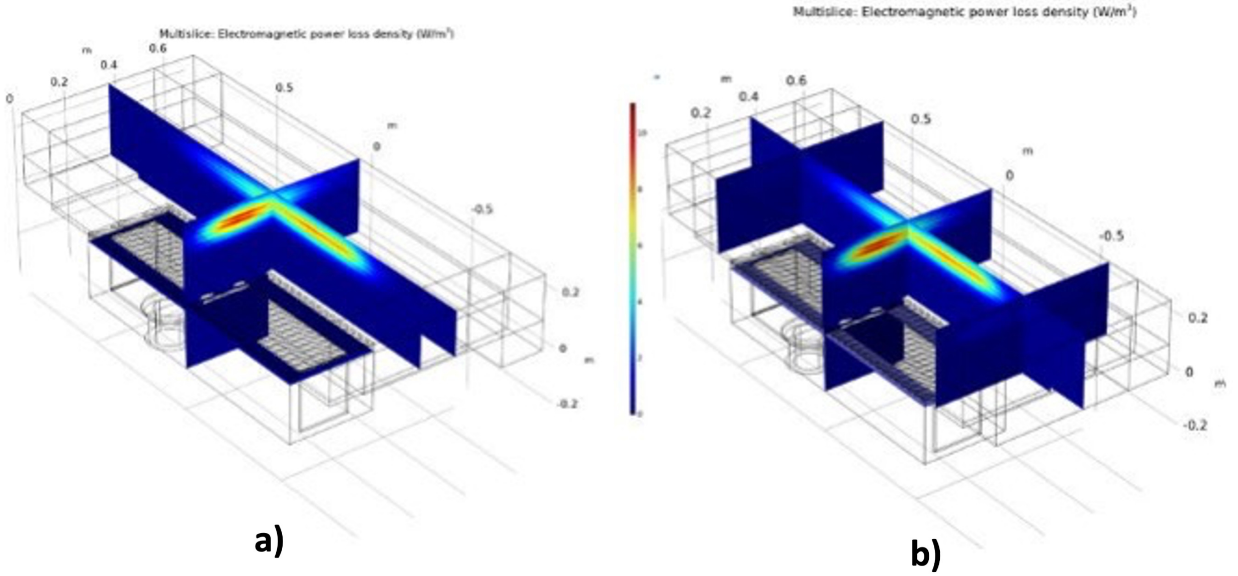

FIGURE 5. Power loss results comparison: a) COMSOL code; b) SC code

following parameters: R_0 = 2.14 m, B_0 = 6.0 T at two different magnetic field tilt angles with respect to the antenna horizontal axis, $\alpha = 0°$ and $\alpha = -17.8°$. In Figure 7, we report the comparison of the coupled power. It can be observed a very good agreement among the different codes. At $\alpha = -17.8°$, slightly larger differences to be further investigated have been observed

CONCLUSION

A 3D full wave COMSOL Multiphysics-based code - already developed for ECRISs - has been developed for for the simulation of IC antennas in the Divertor Test Tokamak (DTT) scenario. ICH antennas in front of different plasma

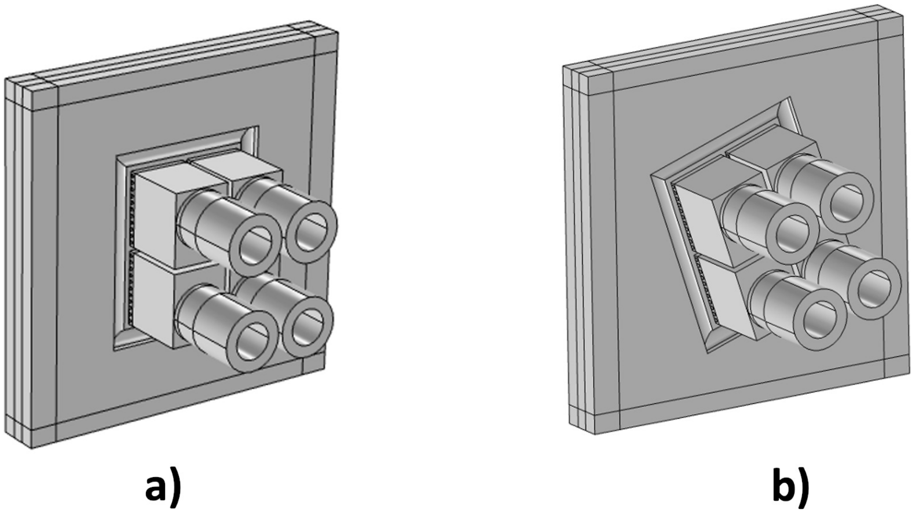

FIGURE 6. DTT-like Antenna for INFN code benchmarking for magnetic field tilt angles $\alpha = 0°$, (a) and $\alpha = -17.8°$ (b)

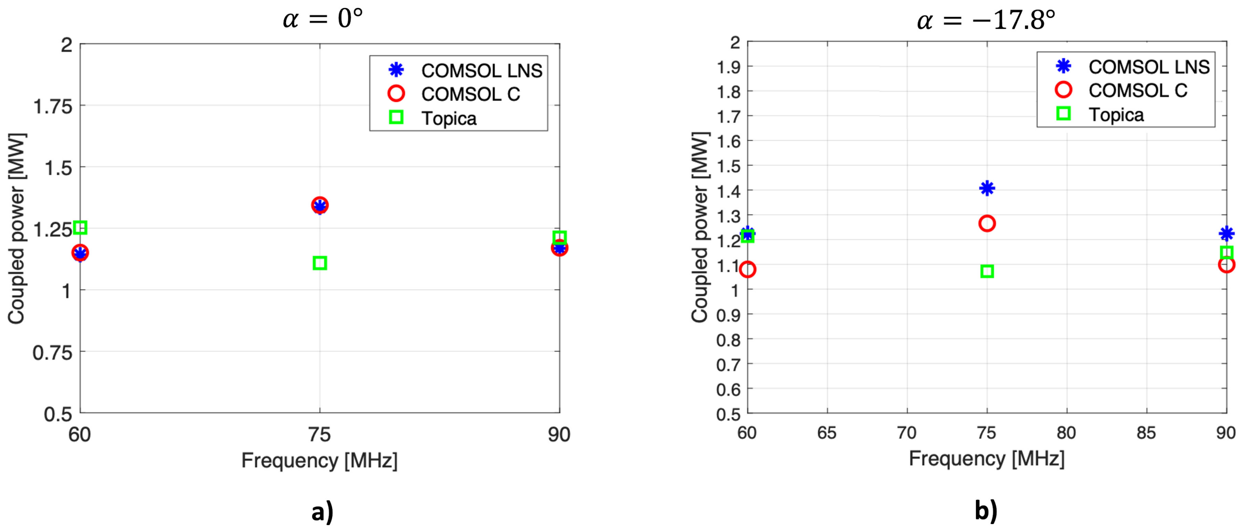

FIGURE 7. $P_c = V^2_{standoff}/(2Z_0 VSWR)$: $\alpha = 0°$ (a), $\alpha = -17.8°$, (b)

profiles modeled as a using a simple cold plasma description - and at different frequencies have been simulated and compared with TOPICA and simpler version [11]. A very good agreement has been found for the predictions of the coupled Power. Computational cost in terms of RAM and CPU requirement.

REFERENCES

1. G. Torrisi, D. Mascali, G. Sorbello, L. Neri, L. Celona, G. Castro, T. Isernia, and S. Gammino, Journal of Electromagnetic Waves and Applications **28**, 1085 (2014), https://doi.org/10.1080/09205071.2014.905245.
2. R. Martone, R. Albanese, F. Crisanti, P. Martin, and A. Pizzuto, *Divertor Tokamak Test Facility: Interim Design Report* (Green book, 2019).
3. V. Lancellotti, D. Milanesio, R. Maggiora, G. Vecchi, and V. Kyrytsya, Nuclear Fusion **46**, S476 (2006).
4. L. Colas, S. Heuraux, S. Brémond, and G. Bosia, Nuclear Fusion **45**, 767 (2005).
5. P. Lamalle, A. Messiaen, P. Dumortier, and F. Louche, Nuclear Fusion **46**, 432 (2006).
6. M. Usoltceva, R. Ochoukov, W. Tierens, A. Kostic, K. Crombé, S. Heuraux, and J.-M. Noterdaeme, Plasma Physics and Controlled Fusion **61**, 115011 (2019).

7. S. Ceccuzzi *et al.*, this conference (2022).
8. F. Mirizzi *et al.*, submitted to SOFT 2022 (2022).
9. G. S. Mauro *et al.*, submitted to SOFT 2022 (2022).
10. D. Milanesio *et al.*, submitted to SOFT 2022 (2022).
11. S. Ceccuzzi, A. Cardinali, G. L. Ravera, and A. A. Tuccillo, AIP Conference Proceedings **2254**, 050004 (2020), https://aip.scitation.org/doi/pdf/10.1063/5.0014864.
12. J. Jacquot, L. Colas, F. Clairet, M. Goniche, S. Heuraux, J. Hillairet, G. Lombard, and D. Milanesio, Plasma Physics and Controlled Fusion **55**, 115004 (2013).