Recent advances in self-consistent RF sheath modeling and related physical properties: Application to Tore Supra IC antennae

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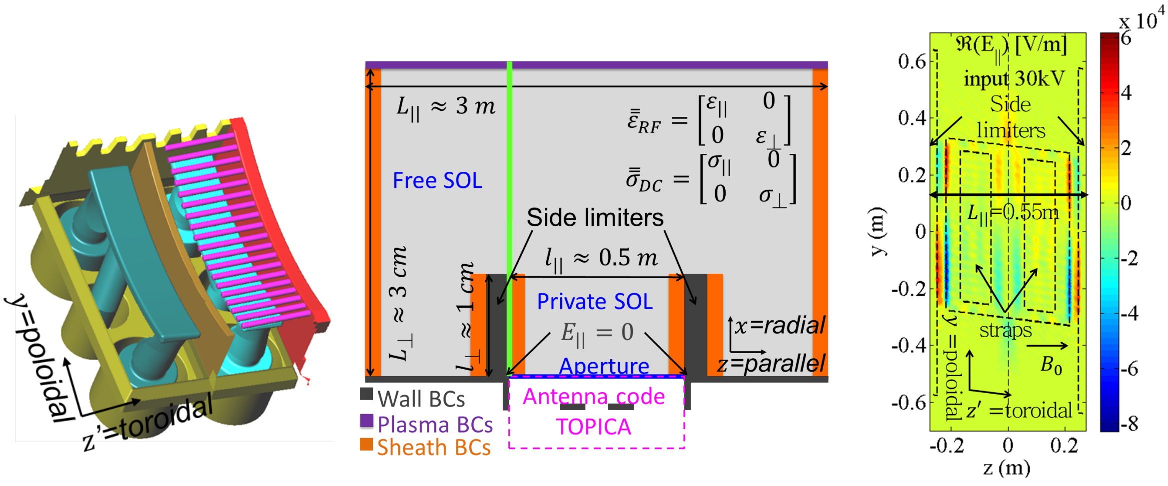
Introduction

Non-linear wave-plasma interactions in the plasma edge often set operational limits for Radio-Frequency (RF) heating systems (via e.g. impurity production, hot spots,...) [1]. Some peripheral Ion Cyclotron (IC) wave energy loss [2] is attributed to a Direct Current (DC) biasing of the edge plasma by RF-sheath rectification [3]. IC waves are excited by phased arrays of straps covered with a Faraday Screen (FS) (see e.g. Fig. 1(a)). Side limiters protect this antenna from the main plasma fluxes by producing a private Scrape-Off Layer (SOL) with reduced density. Recently, a new FS was tested on Tore Supra. Its electrical design tried to mitigate RF sheaths by minimizing the integrated parallel RF electric field $\int E_{\parallel} dl$ on the "long field lines" in the free SOL [4]. Heat fluxes were quantified experimentally on the new FS and surrounding side limiters [5]. RF sheaths appeared more intense as compared to the "classical" FSs [1], questioning the validity of the $\int E_{\parallel} dl$ approach. With both FS, sheath effects on side limiters exhibit a poloidal structure with local maxima near the top and bottom of the antenna box [5].

This paper shows a first step towards understanding the underlying mechanisms driving these wave/plasma interactions, by modeling self-consistently the interplay between the Slow magnetosonic Wave (SW) penetration and the resulting positive DC biasing of the SOL plasma. The paper first outlines the method used, and then compares the first simulations of RF sheaths along the side limiters with experimental observations. Some prospects are finally given on more Physics to add and a simulation strategy to identify a faulty element of design.

Brief outline of the SSWICH model

Fig. 2 illustrates the three-field fluid approach followed for the modelling, called SSWICH (Self-consistent Sheaths and Waves for IC Heating). Its underlying concepts rely on earlier works on RF plasma discharges [6], [7], and their application on tokamaks [8], [9], [10], [11]. A complete description can be found in [12]. The simulation domain, sketched on Fig. 1(b), is a set of bounded magnetic field lines in the SOL in the vicinity of an IC antenna. The domain contains protruding material objects able to intercept magnetic field lines, e.g. antenna side limiters, developing sheaths. Inside this domain, three fields are solved for: the RF parallel field $E_{\parallel}$, oscillating sheath voltages V_{RF} (both varying as $exp(-i\omega_0 t)$ at the RF pulsation ω_0) and the DC plasma potential V_{DC}. Within this framework the coupled system of equations reads:



(a) (b) (c)

Figure 1: (a) 3D antenna geometry with new FS in TOPICA. (b) 2D cut through the 3D computational domain and dimensions. (c) Parallel/poloidal map of $(Re(E_{||}))$ with new FS from TOPICA as input to SSWICH. In tilted coordinates, the antenna appears like a parallelogram.

$$\varepsilon_{||}\Delta_{||}E_{||} + \varepsilon_\perp\Delta_\perp E_{||} + \varepsilon_{||}\varepsilon_\perp (\omega_0/c)^2 E_{||} = 0 \text{ [Slow Wave propagation]}, \tag{1a}$$

$$\varepsilon_\perp\Delta_\perp V_{RF} = \pm\varepsilon_{||}\partial_{||}E_{||} \text{ [RF voltage excitation from RF fields]}, \tag{1b}$$

$$\sigma_{||DC}\Delta_{||}V_{DC} + \sigma_{\perp DC}\Delta_\perp V_{DC} = 0 \text{ [DC charge conservation w/o sources]}. \tag{1c}$$

In these equations $\varepsilon_{||}$ and $\varepsilon_\perp$ are the diagonal elements of the plasma dielectric tensor at the RF pulsation ω_0, $\sigma_{||DC}$ is the Spitzer parallel DC conductivity, $\sigma_{\perp DC}$ a small effective DC perpendicular conductivity. The modules for the 3 physical quantities are coupled together by sheath boundary conditions (SBC) applied on all lateral boundaries located in orange in Fig. 1(b):

$$E_{||} = \varepsilon_{sh}V_{RF}/\varepsilon_{||}\delta \text{ with } \delta = \lambda_e (V_{DC}/T_e)^{3/4} \text{ [sheath capacitance]}, \tag{2a}$$

$$V_{RF} = 0 \text{ at both radial ends of lateral boundaries}, \tag{2b}$$

$$i^+\left[1 - \exp\left(\frac{V_b - V_{DC}}{T_e}\right)\right] = \bar{\bar{\sigma}}_{DC}\cdot\nabla_n V_{DC},\ V_b = V_f + \ln\left[I_0\left(|V_{RF}/T_e|\right)\right] \text{ [rectification]}. \tag{2c}$$

Here δ is the sheath width, $\varepsilon_{sh} \approx 1$ is the dielectric constant of the sheath [6], [7], i^+ is the ion saturation current, V_f is the plasma potential in absence of RF waves, $T_e = 10$ eV is the electron temperature, I_0 is the modified Bessel function of order 0, λ_e the electron Debye length and $\mathbf{n}$ the normal to the surface. Classical metallic BC, written $E_{||} = 0$, $V_{RF} = 0$, $\mathbf{j_{DC}}\cdot\mathbf{n} = 0$, are imposed at the outer vessel boundary, whereas $E_{||} = 0$, $V_{RF} = 0$, $V_{DC} = V_f$ are enforced on the main plasma side of the simulation domain. The whole system is excited by imposing a 2D (toroidal/poloidal) map of $E_{||}$, shown in Fig. 1(c), at an "antenna aperture" in the outer boundary of the $E_{||}$ module. This input map is computed with the antenna code TOPICA [13] in the absence of sheaths with the geometry shown in Fig. 1(a). The near field amplitudes are scaled by the RF voltages V_{strap} on the straps. In order to comply with the magnetic field $\mathbf{B_0} \perp$ wall in the SBCs, the input RF field map was expressed in a tilted coordinate system where y and z are respectively poloidal and parallel directions (Fig. 1(c)). It was also necessary to slightly modify the field map to satisfy the condition $E_{||} = 0$ at the toroidal extremities as shown in Fig. 1(b).

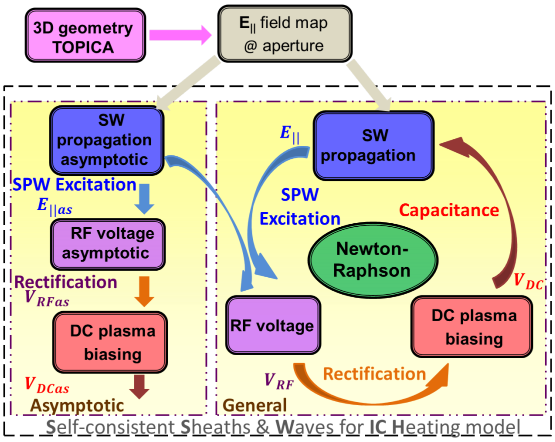


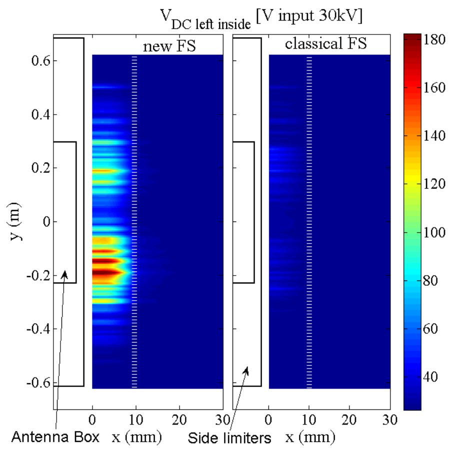
Figure 2: Sketch of the SSWICH code.

The physical model is implemented numerically using the COMSOL Finite Element solver and a Newton-Raphson iterative algorithm. To ease convergence of the iterations, a first guess of the final solution is needed and is provided by an asymptotic version of SSWICH [12]. The asymptotic model assumes very large sheath widths, so that the BCs for $E_{||}$ get simplified as δ vanishes from Eq. (2a). The SW module can thus be solved explicitly without prior knowledge of the DC plasma potentials. Due to limited computational resources, a multi-2D approach was applied, whereby several radial/toroidal planes at different poloidal positions are solved independently.

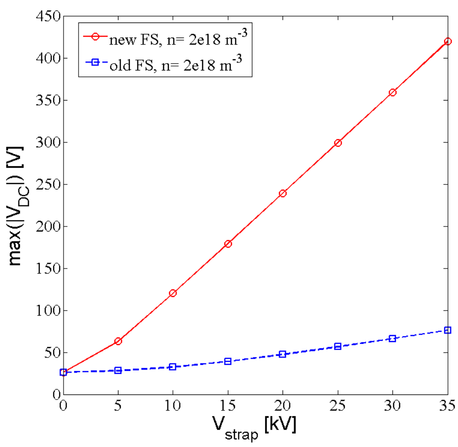
First simulation results for the comparison of two Tore Supra FSs

The SSWICH code was run to estimate DC potentials near Tore Supra antenna side limiters, using input RF field maps produced with the classical and new FS. The two field maps look similar in their overall spatial structure but with amplitudes several times higher for the new FS.

For $V_{strap} = 30$ kV, Fig. 3(a) shows for both FSs the map of V_{DC} in the poloidal/radial plane on the inner side of the left side limiter (location marked in green in Fig. 1(b)). Simulations produce a two-hump poloidal structure for V_{DC}, with maxima near the FS corners and minimum near the equatorial plane, as observed experimentally on both infrared camera and Langmuir probes. The ratio of V_{DC} amplitudes between the two FS is also compatible with probe measurements. But probes are connected to the external face of the limiter. So far enhancing the DC potentials in the free SOL has revealed difficult. Linking the DC potential and the parallel heat flux densities



(a)



(b)

Figure 3: (a) Map of the DC potential V_{DC} in the poloidal/radial plane at the location indicated in green in Fig. 1(b) for both the classical and new Faraday screens. The white dashed line locates the leading edge of the side limiters. $x = 0$ at FS. (b) $\max(V_{DC})$ versus V_{strap} for both FSs performed with the asymptotic version of SSWICH.

using classical sheath formulas [15], typical heat loads in the range 2 MW/m^2 are found for the classical FS and 4 MW/m^2 for the new one, compatible with experimental estimates from [5]. The detailed amplitudes are found to be sensitive to loosely constrained simulation parameters (e.g. density in private SOL, $l_{\parallel}, l_{\perp}, \sigma_{\perp DC}$...). The input RF field map is also not provided on the FS but a few mm in front of it, lowering the amplitude due to the SW evanescence.

A scan in V_{strap} was performed using the asymptotic version of SSWICH with a constant density in the private region. Fig. 3(b) shows that without RF power, no DC biasing arises and $V_{DC} = V_f = 27V$. The maximum of V_{DC} over the 2D plane scales linearly with the strap voltage beyond a threshold different for the two FSs. For $V_{strap} = 30$ kV, V_{DC} computed with the new FS (≈ 400 V) is several times higher than the classical one (≈ 80 V), as seen with the probes.

Conclusions & Perspectives

The SSWICH code has already allowed improvements in RF sheath modeling by getting closer to the first principles. The procedure has been applied for the first time to compare two Tore Supra Faraday Screens showing the compatibility and complementarity between TOPICA and SSWICH. However more work is needed to ensure a better consistency of BCs between the two codes and to improve the space resolution of the input field maps. Experimental observations showed that the new FS enhances RF sheaths instead of reducing them. Simulation is able to reproduce this trend qualitatively, as well as the overall poloidal structure of sheaths on side limiters. The code is not able yet to produce significant DC potentials in the free SOL. Despite high sensitivity to input parameters, the simulated heat fluxes are in the correct range.

The next step in investigating the new FS will be to modify individually some elements of its design in order to find which is responsible for sheath enhancement. Upgrading the SSWICH model is also in prospect, in collaboration with RMA Brussels [11] and IJL Nancy, by including a more rigorous model for the transverse transport of the DC current [16] and sheaths BCs valid for any angle with respect to the magnetic field. The Fast Wave will have to be added to obtain a full wave code with both polarizations requiring a multi-mode perfectly matched layer.

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References

[1] L. Colas et al., Fusion Science and Technology **56** 3, pp1173-1204 (2009)

[2] J.-M. Noterdaeme, G. Van Oost, PPCF **35**, 1481 (1993)

[3] F.W. Perkins, Nucl. Fusion **29** 4, p.583 (1989)

[4] A. Mendes et al., Nucl. Fusion **50**, 025021 (2010)

[5] Y. Corre et al., submitted to Nuclear Fusion (2012)

[6] V. Godyak, N. Sternberg, Phys. Rev. A **42**, p.2299 (1990)

[7] M.A. Libermann, IEEE trans on plasma science **PS-16**, p.638 (1988)

[8] D.A. D'Ippolito, J.R. Myra, Physics of Plasmas **13**, 102508 (2006)

[9] B. Van Compernolle et al., proc. 35th EPS ECA vol.**32D** P-2.105 (2008)

[10] H. Kohno et al., PoP **19** 012508 (2012)

[11] K. Crombé et al., This conference P-4.045 (2012)

[12] L. Colas et al., submitted to PoP (2012)

[13] V. Lancellotti et al, Nucl. Fusion **46** S476 (2006)

[14] J.R. Myra, D.A. D'Ippolito, PPCF **52**, 015003 (2010)

[15] P.C. Stangeby, "The Plasma Boundary of Magnetic Fusion Devices" (IOP Publishing Ltd, 2000)

[16] V.A. Rozhansky, Reviews of Plasma Physics **24**, ed. Springer 1-52 (2008)