Self-consistent modelling of radio frequency sheath in 3D with realistic ICRF antennas

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1. INTRODUCTION

Sheath rectification has been long accused to cause strong impurity sputtering and excessive heat loads on ICRF antenna surfaces and other plasma facing components. This effect has raised many concerns for ITER since it proposes to change the first wall material to tungsten. Therefore, it is critical important to assess the impurity sputtering for ITER under the tungsten first wall. The general strategy of modelling the RF sheath rectification includes three processes, solving the RF field (E_{RF}) module, the RF oscillating sheath voltage (V_{RF}) module and the DC plasma biasing(V_{DC}) module[1-2]. This strategy was first applied in the Self-consistent Sheaths & Waves for Ion Cyclotron Heating (SSWICH) code. It is in 2D and the first version only includes the slow wave[1]. The fast wave was added in a later version[2]. When the fast wave is taken into consideration, it is found that the double-hump poloidal distribution of V_{DC} observed in varies machines[3-7] cannot be well reproduced. In addition, the V_{DC} poloidal structure suffers strong poloidal modulations, which is not obvious in the experimental observations[1,7], probably because of the adopted poloidal wavenumber k_z=0 in the 2D simulation. Besides, like any other 2D codes, simulation relies on external 3D antenna codes (generally without sheaths) to provide the RF field maps at the antenna aperture, which is not self-consistent by itself. These motivate the development of a new 3D RF sheath modelling code.

2. DESCRIPTION OF THE 3D RF SHEATH MODELLING CODE

Similar to the 2D SSWICH code, the new 3D code is based on the COMSOL finite element solver. The magnetic field is tilted in the poloidal-toroidal plane with an angle θ. In the boundary conditions, the same angle or its complementary angle is used as the incidence angle. This is correct because the sheath boundaries are either parallel or perpendicular to the toroidal direction. The code firstly computes the vectorial RF fields by solving the wave equation in the whole 3D domain. The RF waves can either be excited by the build-in antenna or by importing an external field map at the antenna aperture. The RF sheath capacitance[8] provides the constraints for two tangential E fields as sheath boundary conditions. The RF simulation domain also covers the main plasma, which is surrounded by a non-reflecting boundary condition through implementing Perfectly Matched Layers (PML)[9], in order to simulate the fast wave propagation and radiation, as shown in Figure 1. The second step is to solve the V_{RF}. It is only computed at 2D sheath boundaries. It uses Ohm's law to estimate V_{RF} from the RF field computed in the first step. The third step is to evaluate the V_{DC}. This quantity is only solved in the SOL region, making use of the conservation of the DC current as the governing equation, sheath rectification (where V_{RF} computed in the second step acts as an extra biasing) as the sheath boundary condition. At the separatrix, V_{DC} is equal to the floating potential. The loop is closed by applying the Child-Langmuir law to update the sheath width. To ease the numerical convergence, an asymptotic model based on the quasi-conducting regime is also created, where all the boundaries are set as Perfect Electric Conductors (PEC).

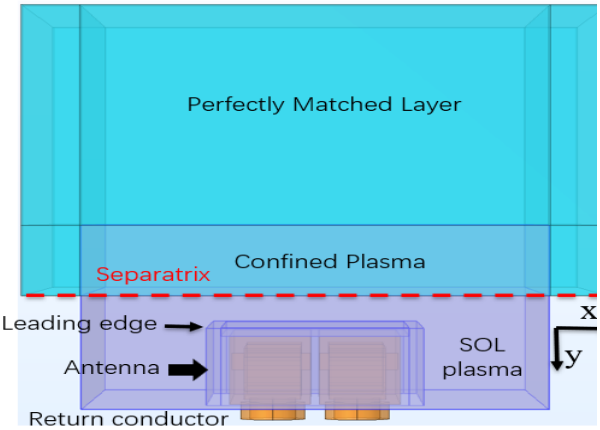

Figure 1. Geometry of the 3D RF sheath modelling code. From bottom to top, the antenna & SOL region, the confined plasma region and the PML.

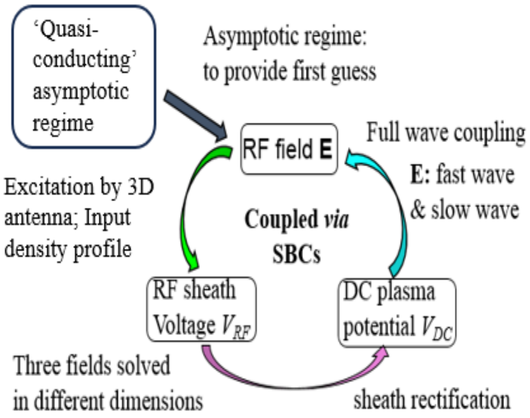

Figure 2. Workflow of the 3D RF sheath modelling code

Simulations use a realistic density profile from HL-3 tokamak [10]. The density at the antenna aperture is about $1.5 \times 10^{17}\mathrm{m}^{-3}$ and a constant extrapolation is used in the simulation beyond the aperture so as to avoid the presence of the lower hybrid layer. The mesh size is 3mm in private SOL, 3cm in free SOL and 2cm in vacuum. Further refinement to less than 1cm is conducted in the Faraday Screen (FS) bars. Simulations were done in a cluster with 80 CPUs and has a maximum RAM of 1024Gb. Taking the advantage of COMSOL cluster computing, running 5 modules once costs about 30mins. For the fully coupled model, a convergence can be reached after running a little bit more than 20 iterations with a relative tolerance of 0.01, which takes about 8 hours. Fortunately, the results from running 5 modules once are already very close to the final converged solution from the fully coupled model.