Towards machine learning assisted TORIC-PetraM ICRF core-edge coupling

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The design of radiofrequency (RF) actuators for magnetic fusion confinement in the ion cyclotron range of frequencies (ICRF) requires high-fidelity models of the RF-power coupling in realistic reactor relevant geometries. The Hybrid Integration of scrap-off-layer (SOL) plasmas to TORIC [1] (HIS-TORIC) introduced by S. Shiraiwa et al. [2] provides a framework to achieve core-edge coupled solutions of the ICRF wave propagation and plasma heating in tokamak plasmas. The HIS-TORIC workflow employed is that adapted to the finite element method (FEM) platform PetraM [3]. The plasma core is modeled by TORIC, a spectral-FEM ICRF solver of the wave propagation and absorption in arbitrary axisymmetric geometries able to model compressional and shear Alfven waves and ion Bernstein waves (IBWs) excited by linear mode conversion. HIS-TORIC uses a cold-plasma approximation implemented in the PetraM FEM model to model SOL-edge plasmas, allowing to deal with complex antenna and wall geometries as well as multiple types of boundary conditions, including the RF-sheath. Therefore, HIS-TORIC solves Maxwell's inhomogeneous wave equation in frequency domain

$$\nabla \times \mu^{-1} (\nabla \times \mathrm{E}) - \omega^2 \epsilon E = i\omega J_{ant},$$

where $\omega, \mu, \epsilon,$ and J_{ant} are the wave angular frequency, the complex plasma dielectric permittivity, the magnetic permeability, the antenna external current, respectively, in two domains: 1) Ω_1: hot plasma core 2) Ω_2: cold plasma edge. Special care is dedicated in the method to the boundary $\delta\Omega$, where the matching is carried out. An essential Dirichlet boundary condition allows to excite multiple poloidal modes m, up to the maximum poloidal resolution m_{max}. These are also excited in the cold plasma FEM simulation in PetraM, providing solutions of the propagation of these modes in the SOL-plasma region. Another simulation runs the antenna excitation pattern imposed as a tangential field excitation in the boundary of the antenna. The workflow assembles the admittance matrices from both domains and obtains the mode reconstruction. By direct application of the superposition principle, it is possible to reconstruct the electric field of the coupled solution. As a result, an ICRF core-edge coupled simulation can be obtained.

In this case we revisit this workflow and apply it to the WEST tokamak [4]. The scenario investigated is that of shot 56898 with plasma current 483kA, magnetic field on axes $B_0 = 3.6T$, for the peak in the toroidal spectrum of the WEST ICRF antenna (i.e. $N_\varphi = 30$). The plasma properties are assumed to follow the law:

$$\mathrm{T}_e = \mathrm{T}_{e1} + (\mathrm{T}_{e0} - \mathrm{T}_{e1})(1 - \rho^\alpha)^\beta$$

where subscript e refers to electrons, 0/1 to core/edge, ρ is the radial coordinate, and α/β are the inner and outer exponents, respectively. For the simulations analyzed here: T_{e1}=100 eV, $\mathrm{n}_{e0} = 7 \times 10^{19} m^{-3}$, $\mathrm{n}_{e1} = 0.2\,\mathrm{n}_{e0}$, $\alpha = 2$, $\beta_n = 0.5$, $\beta_T = 1$ and $X_H = 0.05$. We analyze and compare the coupled ICRF solutions of HIS-TORIC for two levels of damping: A) $T_{e0} = 1$ keV and B) $T_{e0} = 3$ keV.

We carry out the parametric scan over the poloidal mode number m on TORIC simulations A) and B). The results of the electric fields and power deposition profiles are shown in Figure 1 and 2 for cases A and B, respectively. The poloidal scan shows that the most significant impact of the poloidal mode number is on the power deposition of hydrogen at the fundamental (PIF1), whose peak moves radially depending on m. The wave electric field shows a clear mode conversion from the fast wave (FW) to the IBW. It appears that the fraction of deuterium power is also correlated to this variable, as well as that of the electron species. The wavefield solutions are evanescent for high $|\, m \,|$ with E_η excitation as well as for all modes in the case of E_ζ excitation. The major impact of core electron temperature is observed in the smoothness of the power deposition profiles, which increases the higher the core electron temperature. Another effect observed is the more evident contribution to absorption from deuterium and electron species.

In the case of PetraM solutions, the poloidal parametric scan shows that the solution is independent of the core plasma properties and after coupling admittances from core and edge, we can reconstruct the mode solutions in the boundary.