

Developing a machine learning based plasma control system for ISTTOK

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Introduction

Applying Machine Learning (ML) techniques to deal with complex systems/problems has, nowadays, become an increasingly used approach which has already demonstrated significant improvements with respect to conventional methods. Therefore, demonstrating its applicability to nuclear fusion devices, such as tokamaks, as well as, learning and gaining experience on how to develop and implement it, are of utmost importance. Next Step Fusion (NSF) [1] develops, among other things, ML algorithms for tokamak control by making use of the Reinforcement Learning (RL) technique, where a non-linear controller is trained by a trial-and-error approach in a simulation environment – digital twin. This environment is therefore of crucial importance as it will represent the plasma response during the training phase of the Agent. NSF, and the DIII-D team, have successfully implemented and tested a ML based plasma control in DIII-D tokamak [2]. To demonstrate the applicability of NSF's solutions to other machines, they are now developing and testing a new controller for ISTTOK, a significantly different tokamak with its own challenges.

ISTTOK is a large aspect ratio circular cross-section tokamak located in Portugal ($a = 8.5$ cm, $R = 46$ cm, $B_T = 0.5$ T, $I_p = 4$ kA, $n_e(0) = 5 \times 10^{18} \text{ m}^{-3}$, $T_e(0) \sim 120$ to 150 eV, $\Delta\Phi = 0.25$ Vs) and capable of operation with alternate plasma current (AC) discharges [3]. These AC discharges consist of reversing the plasma current (between positive and negative direction – one cycle) several times during a single plasma pulse. A semi-cycle (single plasma current direction) usually lasts about 25 ms, while a full-length AC discharge can go up to 1 s (40 consecutive semi-cycles), as illustrated in the upper plot of figure 1. The extension to 1 s brings ISTTOK plasma durations comparable to larger tokamaks allowing for relevant control studies and longer exposure times, e.g., for plasma-material interaction.

ISTTOK: challenges and opportunities

Unlike most conventional tokamaks, ISTTOK has a particularly thick copper shell (conducting metallic structure) surrounding the vacuum vessel and it operates closely linked

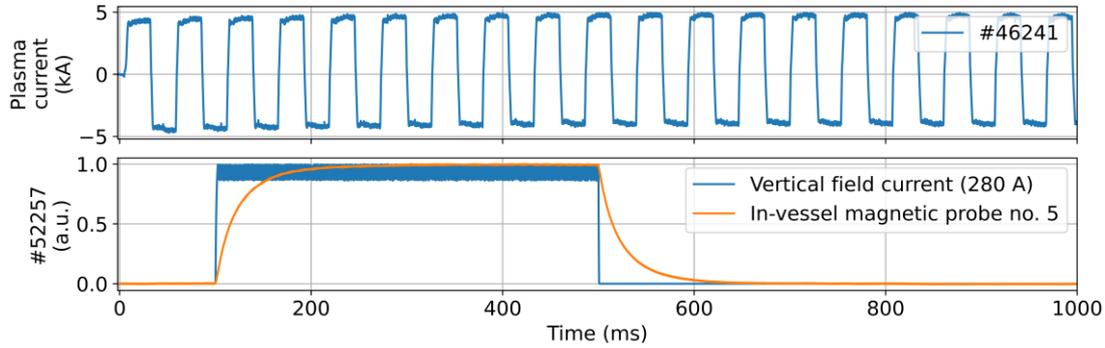


Figure 1: Upper plot is plasma current showing 37 semi-cycles; the lower plot shows the vertical field current and the signal of in-vessel magnetic pickup probe no. 5. They illustrate the response of the magnetic field in the vessel due to the external current: the equilibrium is only reached after several semi-cycles.

with an iron core transformer, making its operation challenging. In addition, ISTTOK presents several interesting fusion reactor-relevant features which makes it relevant for the creation of a digital twin. The device has an intrinsically reduced set of plasma diagnostics, most of which are affected by large eddy currents in the copper shell, complicating the reconstruction of the plasma state. It is also a significantly different tokamak (compared to DIII-D), which can be valuable for testing machine-agnostic modules/components, such as the Plasma State Monitor being developed by NSF. ISTTOK contains a copper shell that attenuates external fields and introduces delays to the actuation on the plasma, see bottom plot of figure 1. It is a type of blanket and shielding imitation of significant plasma-coil gaps in future tokamak reactors. Additionally, this unique experimental device presented numerous uncertainties related to magnetic diagnostics and machine configurations, making the creation of a digital twin particularly challenging.

Model preparation and development: digital twin

Developing an environment that precisely reproduces plasma dynamics and the device features in the ISTTOK tokamak is, in itself, a challenge due to: (i) the iron core, as the discharge progresses, the iron core's magnetization and permeability change, creating a nonlinear response, with the added possibility of reaching saturation; (ii) the uncertainties of the position and orientation of the magnetic diagnostics, as well as the large toroidal variability of the poloidal field (PF) coils' location and shape, complicates the design and validation of the model; and (iii) the thick copper shell surrounding the vessel features one toroidal electrical interruption, an equatorial cut (possibly with reduced electrical conductivity) and holes for diagnostic ports, unlike an ideal symmetrical conductor, these asymmetries will affect the eddies' current paths and corresponding magnetic fields.

The model is based on the NSFsim code, a free-boundary Grad-Shafranov and transport solver [4], which assumes toroidal symmetry – a simplification that allows simulations to run

more efficiently. The tokamak model comprises PF coils, passive conducting structures (such as the vacuum vessel), and magnetic sensors (such as probes and flux loops). As part of the model development and validation, and due to the challenges mentioned above, the elements of the model are tuned until the simulated sensor signals align with the experimental results.

The model validation process begins with plasma-free discharges (dry runs) where the different PF circuits and coils are energized independently with specific configurations and waveforms. This type of discharges allows to assess the dynamic electromagnetic response of the machine itself in respect to each one of the PF circuits, as well as the static/equilibrium state of the magnetic fields (when eddy currents no longer exist), obtained with long stationary PF current waveforms. The latter is used as the first validation test, as transient effects are not present, allowing therefore for a simpler interpretation of the results.

The static phases of the dry runs, when magnetic fields are in equilibrium, are used to validate the polarity and amplitude of the simulated field, as well as to refine the position of the magnetic pickup coils and PF coils. The latter was obtained by an optimization fitting process which minimized errors between the simulated magnetic fields and the experimental ones measured by the pickup coils. To achieve this, the constraints for the PF coils' locations and angles of the pickup coils were defined based on (i) mechanical constraints of the tokamak, (ii) estimated deviations from the nominal parameters, and (iii) manufacture uncertainties for the pickup coils. Figure 2 shows the

new optimized locations of the PF coils. The adjustment required for the pickup coils' angles was very small ($< 5^\circ$). The large correction of the PF coils' locations (especially for horizontal and vertical coils) was expected given the mechanical constraints present at that toroidal

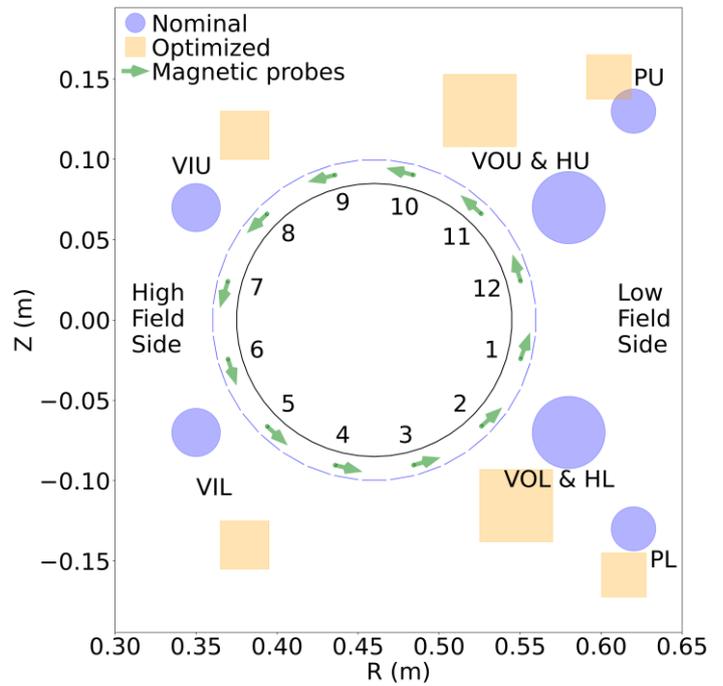


Figure 2: Vacuum vessel (blue dashed line), limiter location (black solid line) poloidal set of 12 in-vessel magnetic pickup coils and PF coils' locations. PF coil naming: P – primary, V – vertical, H – horizontal, O – outer, I – inner, U – upper and L – lower. The Vertical field consists of a quadrupole with 5 turns per coil, the Horizontal field consists of two coils with 4 turns each. The primary coils, 2×14 turns, induce the plasma current and also generate a vertical field for equilibrium. The circles correspond to the nominal locations of the PF coils while the squares to the locations resulting from the optimization process.

location, where pickup coils are also located. Figure 3 shows the results for the vertical and horizontal fields, where a reasonably good agreement was obtained.

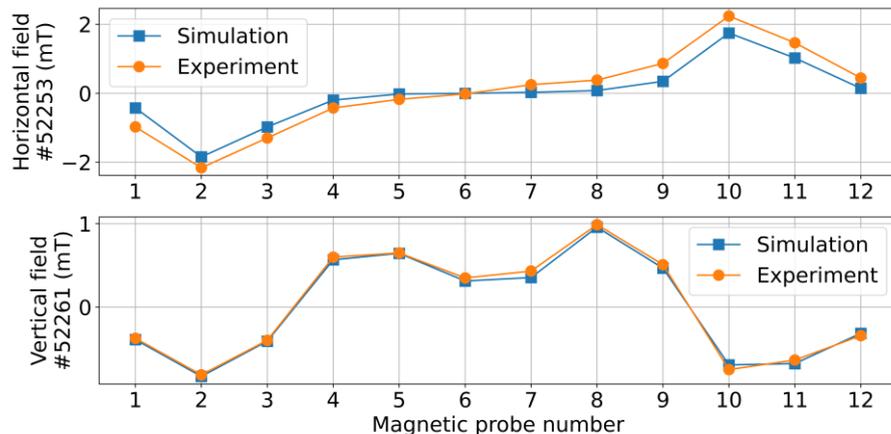


Figure 3: Comparison of the magnetic pickup coils' experimental and simulated data during dry runs.

Conclusions and future work

Modelling ISTTOK has demonstrated to be a challenging task, as anticipated. The NSF model of ISTTOK has shown satisfactory results for stationary fields when compared with experimental data from plasma-free discharges. The remaining steps towards the full development and validation of the model are (i) the optimization of the passive structures' configuration, so that the transient effects (which includes eddy currents) are well represented and (ii) the validation of the iron core simulation. After completion of the validation process, the RL controller will be trained and implemented in ISTTOK experiments.

Acknowledgment

IPFN activities were supported by FCT - Fundação para a Ciência e Tecnologia, I.P. by project reference UIDB/50010/2020 and DOI identifier 10.54499/UIDB/50010/2020 (<https://doi.org/10.54499/UIDB/50010/2020>), by project reference UIDP/50010/2020 and DOI identifier DOI 10.54499/UIDP/50010/2020 (<https://doi.org/10.54499/UIDP/50010/2020>) and by project reference LA/P/0061/202 and DOI 10.54499/LA/P/0061/2020 (<https://doi.org/10.54499/LA/P/0061/2020>). The activities in this work were additionally supported by Next Step Fusion S.a.r.l..

References

- [1] <https://nextfusion.org/>, accessed on 12th of June 2025
- [2] G. F. Subbotin et al., "Reconstruction-free magnetic control of DIII-D plasma with deep reinforcement learning", arXiv physics.plasm-ph, 2506.13267 (2025), <https://doi.org/10.48550/arXiv.2506.13267>
- [3] Ivo S. Carvalho et al., "Real-time control for long ohmic alternate current discharges", Fusion Eng. Des. 89, Issue 5, May 2014, pages 576-581, <https://doi.org/10.1016/j.fusengdes.2014.03.029>
- [4] Clark, R. et al., "Validation of NSFsim as a Grad-Shafranov equilibrium solver at DIII-D", Fusion Eng. Des. 211, 114765 (2025), <http://dx.doi.org/10.1016/j.fusengdes.2024.114765>