Pellet Fueling: AI-Enhanced Surrogate Modeling and Integrated Modelling

A. Panera Alvarez[1], E. Geulin[2], F. Koechl[3], P. Lang[4], S. Wiesen[1], C. Bourdelle[2], the WEST Team[5] and the AUG Team[6].

[1] DIFFER- Dutch Institute for Fundamental Energy Research, [2] CEA, IRFM, [3] ITER Organization, [4] Max-Planck-Institut für Plasmaphysik, [5] See author list http://west.cea.fr/WESTteam and [6] See author list of H. Zohm et al, 2024 Nucl. Fusion https://iopscience.iop.org/article/10.1088/1741-4326/ad249d

e-mail (speaker): a.paneraalvarez@differ.nl

Effective core fuelling remains one of the fundamental challenges in magnetically confined fusion plasmas, particularly in reactor-relevant regimes such as those expected in ITER. Among the available strategies, pellet injection has demonstrated the greatest potential for delivering fuel deep into the plasma core [1], where gas puffing is insufficient for effective fueling of reactor-scale plasmas. Nevertheless, the simulation of pellet ablation and deposition is computationally intensive and not particularly well suited for applications requiring fast outputs, such as scenario optimization, real-time control, or digital twin implementations.

In this work, we present HPI2-NN, a machine learning-based surrogate model trained on outputs from the high-fidelity HPI2 pellet code [2,3], which simulates hydrogenic pellet injection in magnetized plasmas. The surrogate is constructed using a comprehensive database of HPI2 simulations spanning WEST, AUG, and ITER conditions, and is capable of reproducing density deposition and thermal profiles, with an average error below 10%, while achieving a speedup of more than four orders of magnitude (from 15 minutes to ~20 ms per evaluation).

A salient aspect of this development is the preprocessing of plasma profile data—electron temperature and density—using Principal Component Analysis (PCA). This allows for dimensionality reduction and efficient encoding of input profiles in a form that the neural network can interpret, while preserving the relevant physics. This feature makes HPI2-NN compatible with both synthetic and experimental data sources and facilitates its use in existing modeling workflows.

The surrogate model is natively integrated within the High Fidelity Pulse Simulator (HFPS) integrated modeling suite, enabling full-discharge simulations that include self-consistent transport, sources, and pellet fuelling physics. Within this framework, HPI2-NN can be invoked as a drop-in substitute (in terms of real time control, and scenario optimization) for the original HPI2 code, allowing for efficient scenario studies without compromising predictive quality. While some validation against experimental WEST discharges is presented, the focus lies on demonstrating the operational readiness of this tool within large-scale integrated modeling and tokamak control.

This talk will also provide a concise yet thorough overview of the physics and operational role of pellet fuelling. We will discuss the technical and computational considerations behind the development of HPI2-NN, its integration into HFPS, and the broader implications for data-driven acceleration of physics-based workflows in fusion science.

References
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