Data-driven models for fusion plasma exhaust: AI methods gaining maturity

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Self-consistent physics model frameworks for plasma exhaust allowing reliable fusion reactor predictions suffer from an increased complexity in the underlying physics models and uncertainties in large databases for atomic and surface physics underneath [1]. For optimizing divertor performance in future tokamaks, and also in view of proving compatibility of good confinement with the core plasma by employing integrated edge-core models, reliable and validated numerical models and simulation tools are required for an extrapolation from existing fusion experiments towards reactor scale [2]. For rapid design studies of future fusion power plants (FPP) or intermediate demonstration devices (DEMO), systems codes or plasma flight simulators require fast / computationally feasible models for the core (including the pedestal), exhaust and plasma-wall interactions as function of machine parameters (size, geometry, current, field) to constrain the operational window of specific quantities of interest like the level of divertor detachment or impurity concentrations at the separatrix. Pulse design tools are required to develop safe operational trajectories in any large-scale reactor like ITER, and integrated fast surrogate models could be employed also for plasma design and plasma state control.

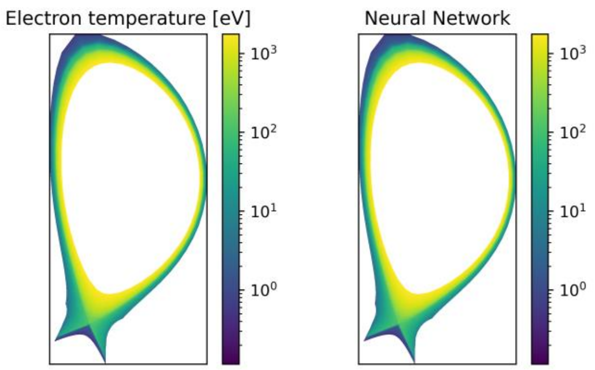

Figure 1 Direct comparison of SOLPS-NN generated ITER plasma temperature. The neural network has been transfer learned using the SOLPS-ITER database for ITER [3].

A review is given on highlights over the past 5 years of developing ML/AI deep-learning method based fast predictors for the application of fusion exhaust. Various groups have developed fast surrogate models that have demonstrated measurable accuracy and significant speed-up compared to the original "ground-truth" models. The individual research objectives have overarching aspects: a) developments of surrogate model predictors for power & particle exhaust in fusion power plants for the scrape-off layer (SOL) and divertor transport; b) surrogate models for time-dependent phenomena in the plasma-edge; and c) enhancements of pedestal models & databases through interpolators and generators (that may include uncertainty quantification). Exemplary results for a) to c) are given, demonstrating the deployed ML/ANN methods spanning from trained models for the plasma edge (c.f. fig. 1), improved regressions for the pedestal, and towards fully predictive (generative) capabilities for dynamic SOL/edge profiles identifying the detachment front (c.f. fig. 2), performing even faster than real time with sufficient accuracy.

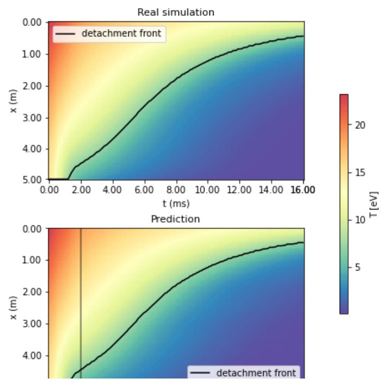

Figure 2 Accurate predictive DIV1D-NN reproduction of a detachment front in a density ramp for unseen parameters [4].

References

[1] S. Wiesen et al., Nucl. Mater. Energy, 12 (2017) 3
[2] M. Wischmeier et al., J. Nucl. Mater, 463 (2015) 22
[4] S. Dasbach, SOLPS-NN, PhD thesis 2024
[3] Y. Poels et al, Nucl. Fusion, 63 (2023) 126012