Solving Plasma Forward and Inverse Problems with Physics-Informed Neural Networks in Nuclear Fusion

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Abstract.

Forward and inverse problems play a fundamental role in many areas of plasma physics and nuclear fusion, including plasma performance prediction, instability evolution analysis, transport modelling, equilibrium reconstruction, and tomography. Typically, forward numerical models are developed under specific assumptions, and their parameters are iteratively adjusted to match experimental data. Conversely, inverse problems often rely on simplifying hypotheses or limited measurements, which can restrict their accuracy and physical consistency.

A relatively new and promising methodology to address both forward and inverse problems is based on Physics-Informed Neural Networks (PINNs). PINNs combine data and physics in a fundamentally different way, offering an alternative to conventional numerical models. Among their distinctive features are the ability to handle incomplete physical models, manage noisy or line-integrated boundary conditions, and operate as meshless solvers.

This work introduces and explores the application of PINNs to solve forward and inverse problems in plasma physics, and more specifically in nuclear fusion, with examples such as equilibrium and tomography reconstruction. It demonstrates how to implement a multi-diagnostic approach with high-fidelity physics-based modelling of diagnostics to account for non-linear effects, how to treat noisy data, and how to appropriately balance the contributions of prior physics knowledge and experimental measurements to ensure accurate and reliable results. Finally, future developments, in terms of both physics applications and methodological upgrades, are also discussed.

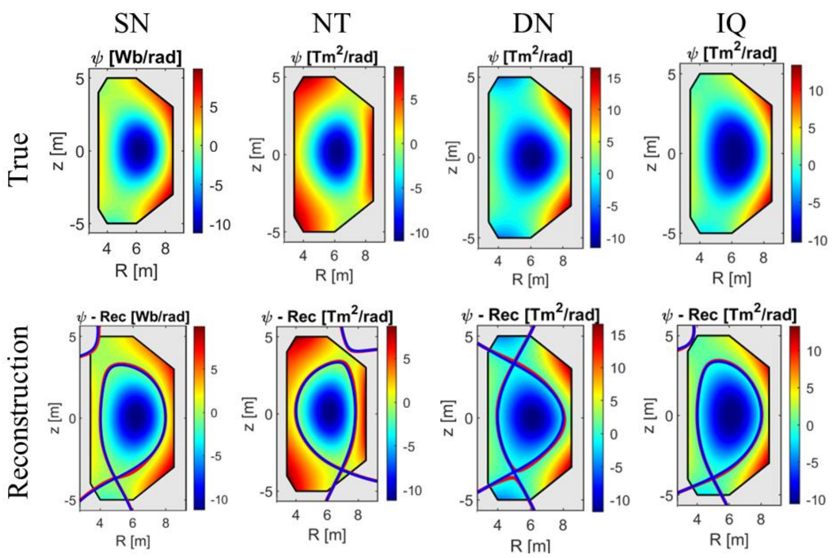

Figure 1: Target vs reconstructed equilibria in different plasma scenario using Physics-Informed Neural Networks.