Workshop on AI for Accelerating Fusion and Plasma Science

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Fourier Neural Operator for Plasma Emulation in Simulation and Experiment

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Predicting the evolution of plasma instabilities and turbulence within a tokamak power plant is essential for achieving sustainable fusion. Efficiently forecasting the spatio-temporal evolution of plasma enables rapid iteration over design and control strategies for both current tokamak devices and future power plants. However, traditional numerical solvers for modelling plasma evolution are computationally expensive and require hours of processing on supercomputers. In this study, we demonstrate the application of an AI framework called Fourier Neural Operators (FNO) to accurately predict plasma evolution in both simulation and experimental domains.

Our research shows that FNO provides a remarkable speedup of six orders of magnitude compared to traditional solvers when predicting plasma blob dynamics simulated from fluid models in slab geometry. Despite this significant speed improvement, FNO maintains reasonable accuracy, especially across short temporal domains. A modified version of FNO is developed to allow for solving multi-variable Partial Differential Equations, capturing the interdependence among different variables within a single model.

Furthermore, FNOs exhibit the ability to predict plasma evolution using real-world experimental data obtained from cameras positioned within the MAST tokamak. The predictive power extends up to six milliseconds ahead, making it suitable for real-time plasma evolution monitoring. Additionally, we showcase FNO's proficiency in forecasting plasma shape and the general structure of the filaments observed during plasma shots under study.

FNO emerges as a promising surrogate modelling approach due to its quick training and inference times, as well as its ability to perform zero-shot super-resolution (i.e. produce higher resolution solutions without any further training), providing discretization invariance across the models. To address predictive uncertainty, we incorporate conformal prediction over the FNO output, allowing statistically guaranteed error bars across the high-dimensional space of field evolution.

In this work, we also explore the utility of PDE residuals for evaluating trained emulators, offering valuable insights into the model's performance. Moreover, we investigate the application of state-space-based neural operators for emulating the long-term evolution of fluxes associated with gyrokinetic turbulence, originally modelled using GX.

Overall, our research presents FNO as a powerful alternative for emulating plasma evolution, paving the way for enhanced efficiency in emulating fusion power plant design and control strategies.

Speaker's Affiliation

UK Atomic Energy Authority, Oxford

Member State or IGO/NGO

United Kingdom

Primary authors: GOPAKUMAR, Vignesh (UK Atomic Energy Authority); PAMELA, Stanislas (CCFE - UKAEA)

Co-authors: ZANISI, Lorenzo (CCFE); GRAY, Ander; Mr BRENNAND, Daniel (UKAEA); Mr LI, Zongyi (Caltech); Dr ANANDKUMAR, Anima (Caltech); Dr KUSNER, Matt (University College London); Dr DEISENROTH, Marc (University College London)

Presenter: GOPAKUMAR, Vignesh (UK Atomic Energy Authority)

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