

A Cross Machine and Parametric Neural Operator Surrogate Model for MHD Simulations

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High-fidelity nonlinear MHD simulations, such as those performed with the M3D-C1 code, are essential for understanding plasma instabilities and disruption dynamics but remain prohibitively expensive for optimization tasks and large-scale parametric studies. We present a neural operator-based surrogate model that enables both cross-machine generalization and parametric extrapolation, offering a computationally efficient alternative for disruption prediction and mitigation research. The surrogate model advances the system by taking the field functions and source terms at the current time step and predicting their evolution for the next time step. To achieve device-independent generalization, field functions are mapped from physical space into a normalized computational domain via conformal mapping, enabling geometry-agnostic training across fusion devices. Parameter extrapolation is achieved using an equation-recast strategy, which treats deviations between training and target parameters as perturbation sources. This allows accurate extrapolation while strictly preserving physics constraints, significantly reducing data requirements. Training on a single plasma state is sufficient for the surrogate to generalize across diverse parameter configurations. The developed surrogate can be integrated into plasma instability control systems for rapid state prediction or integrated into the M3D-C1 solver as a preconditioner to accelerate convergence. This cross-machine and parametric surrogate model provides a reliable and interpretable pathway for advancing MHD simulations.

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