

Data-Driven Tokamak Plasma Magnetic Response Modelling

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Traditional first-principle-based tokamak plasma magnetic response models, while possessing clear physical significance, often exhibit significant deviations when compared with actual experimental data, limiting our deep understanding of plasma dynamics processes. This study develops an autoregressive neural network model based on improved WaveNet architecture that directly learns plasma behavior patterns from HL-3 device experimental data, achieving high-precision reproduction of real plasma responses. The model takes experimental measurements of poloidal field coil currents and central solenoid coil currents as inputs, predicting key parameters such as plasma current, position, minor radius, elongation, and triangularity reconstructed by EFITNN[1]. Addressing the specific requirements of experimental data validation, we designed an innovative dual loss function mechanism that combines teacher forcing and autoregressive training approaches, effectively mitigating exposure bias issues and enabling the model to better handle long-term sequence autoregressive predictions. The loss function employs a weighted combination of MSE, MAE, and MTE, providing differentiated optimization gradients for prediction errors of different magnitudes, significantly improving the model's fitting capability for both regular variations and sudden events in experimental data. To simulate measurement noise and uncertainties in real experimental environments, we introduced random walk noise layers and Gaussian noise layers during model training. This design enables the neural network to adapt to various perturbations present in actual experimental data and effectively suppress cumulative errors in long-period predictions. Validation based on experimental data from HL-3 device shots #2000 #6698 demonstrates that the model can reproduce single-step experimental measurement results with 99.5% accuracy, while maintaining 97.5% accuracy in autoregressive mode. More importantly, the high consistency between model predictions and real experimental data indicates that the neural network successfully captures the intrinsic physical laws of plasma magnetic response, providing a new perspective for understanding tokamak plasma dynamic behavior. Through comparative analysis with traditional physics models, we found that data-driven methods have significant advantages in reproducing experimental observations, particularly excelling in handling nonlinear coupling effects and long-term evolution processes. This modeling approach based on real experimental data validation not only provides effective tools for current fusion device physics research but also establishes a foundation for plasma behavior prediction and analysis in future large-scale devices such as ITER.

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