Application of Neural Ordinary Differential Equations for Tokamak Plasma Dynamics Analysis

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Background

Controlled Fusion: Tokamak reactors aim to harness fusion energy by confining high-temperature plasma, which involves complex energy transfer processes.

Challenges: Modeling the energy transfer within burning plasma is challenging due to its multi-region, multi-timescale nature.

Problem Statement

Develop a model that accurately captures the intricate energy transfer and interactions between electrons and ions in different regions of a tokamak.

Methodology

Multi-Nodal Model:

Segment tokamak plasma into core, edge, and scrape-off layer (SOL) regions.

Model particle and energy balance equations, including external heating, radiation, transport, collisional energy transfer, atomic processes, and ion orbit losses.

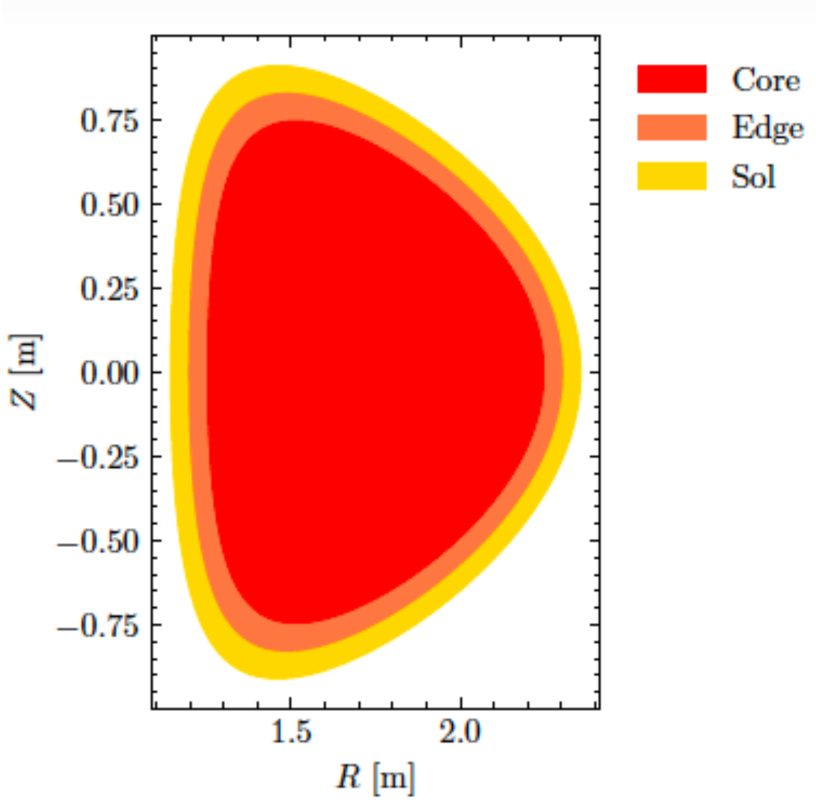
Determine internodal transport timescales for accurate energy transfer simulation.

Neural ODEs:

Use Neural ODEs to derive optimal diffusivity parameters from DIII-D experimental data.

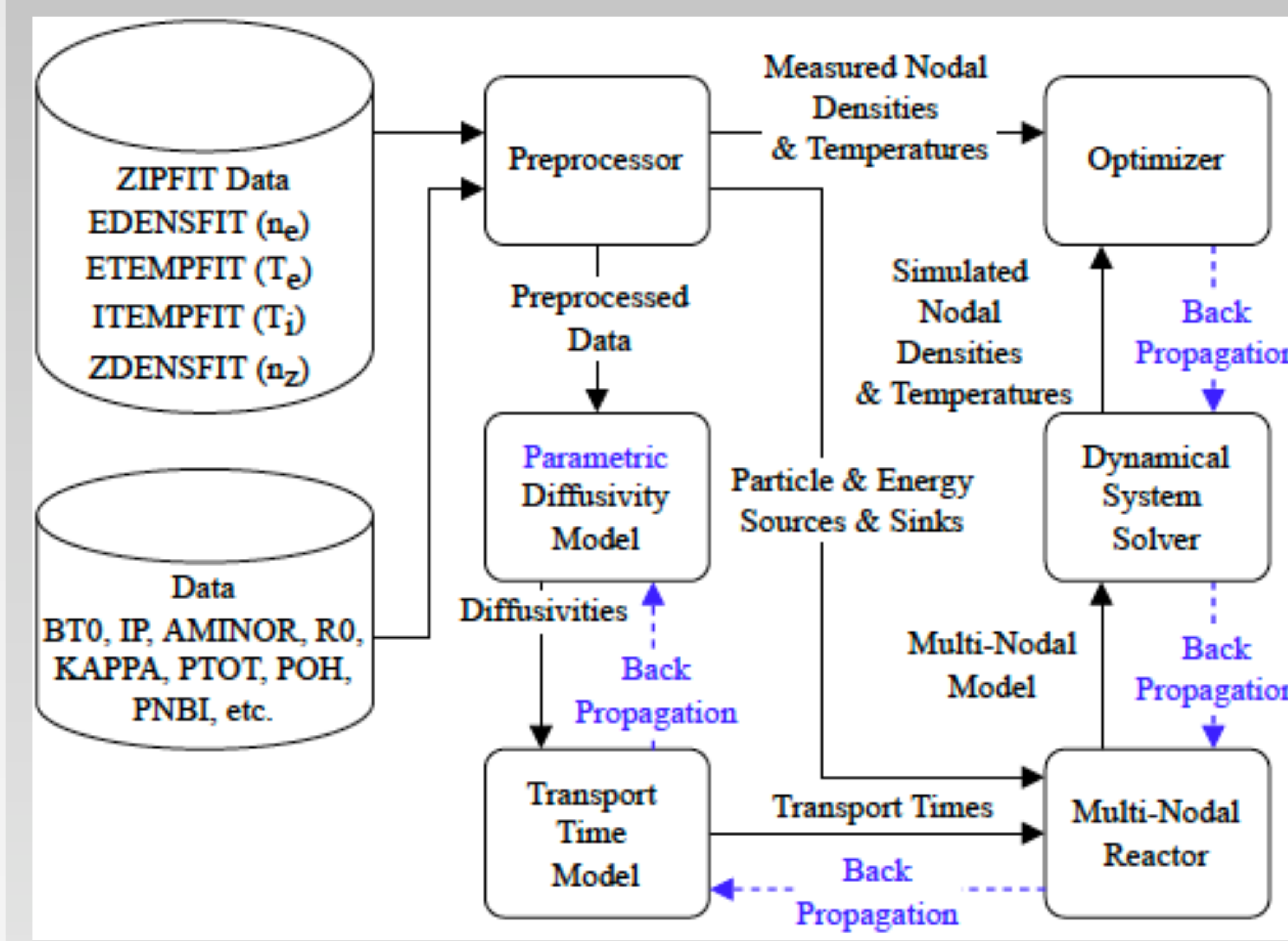
Employ backpropagation to minimize the mean squared error (MSE) between predicted and observed densities and temperatures.

Adjust diffusivity parameters dynamically for each region to accurately simulate energy interactions across timescales.



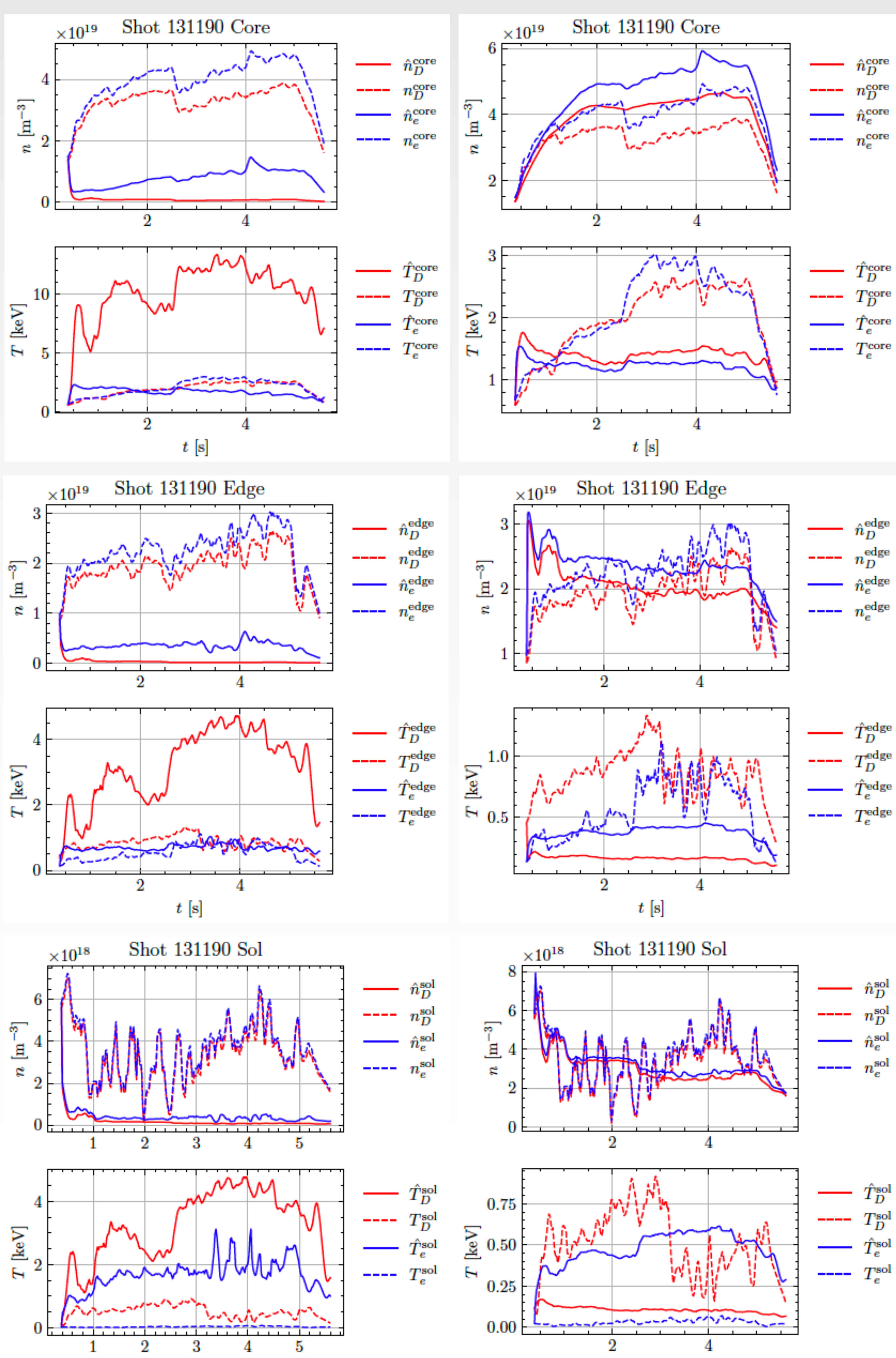
Computational Framework

The computational framework integrates experimental data preprocessing, diffusivity calculation, transport time modeling, Neural ODE-based simulation, and backpropagation optimization to refine plasma behavior predictions across various tokamak regions.



Experiment Results

Original Diffusivity Model | **Optimized Diffusivity Model**



Key Findings

Model Accuracy: The optimized model significantly reduces mean squared error (MSE) by over 98% on average compared to the baseline empirical model.

Predictive Capability: Demonstrates accurate predictive performance even on unseen testing data.

Testing Shot #	Original MSE	Optimized MSE	Decrease
131190	11.586	0.408	96.5%
140418	56.686	0.317	99.4%
140420	70.365	0.588	99.2%
140427	29.797	0.711	97.6%
140535	88.421	0.735	99.2%
Avg.	**51.371**	**0.552**	**98.9%**

Applications

The optimized model can be applied to improve the analysis and performance of tokamak operations, including future fusion experiments such as ITER.

Future work includes refining the model for more accurate edge transport predictions and handling different heating mechanisms more accurately.

References

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