Sensitivity Analysis of Transport and Radiation in NeuralPlasmaODE for ITER Burning Plasmas

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Introduction

- **ITER** requires accurate prediction of **burning plasma behavior**, where **heating**, **transport**, **radiation**, and **impurities** interact in complex nonlinear ways.
- Traditional **empirical models** lack flexibility; **NeuralPlasmaODE** provides a **physics-informed**, **data-driven** neural ODE framework for **core-edge plasma dynamics**.
- This study applies **sensitivity analysis** to identify which **parameters** (transport, ECR, impurities, ion orbit loss) most strongly affect **ITER's inductive scenario**.

Model Overview

- **Plasma** is partitioned into **core and edge regions**, each governed by **particle and energy balance equations** solved with **neural ODEs**:

$$\frac{dn_\sigma^{\text{node}}}{dt} = S_{\sigma,\text{ext}}^{\text{node}} + S_{\sigma,\text{fus}}^{\text{node}} + S_{\sigma,\text{tran}}^{\text{node}} + S_{\sigma,\text{IOL}}^{\text{node}}$$

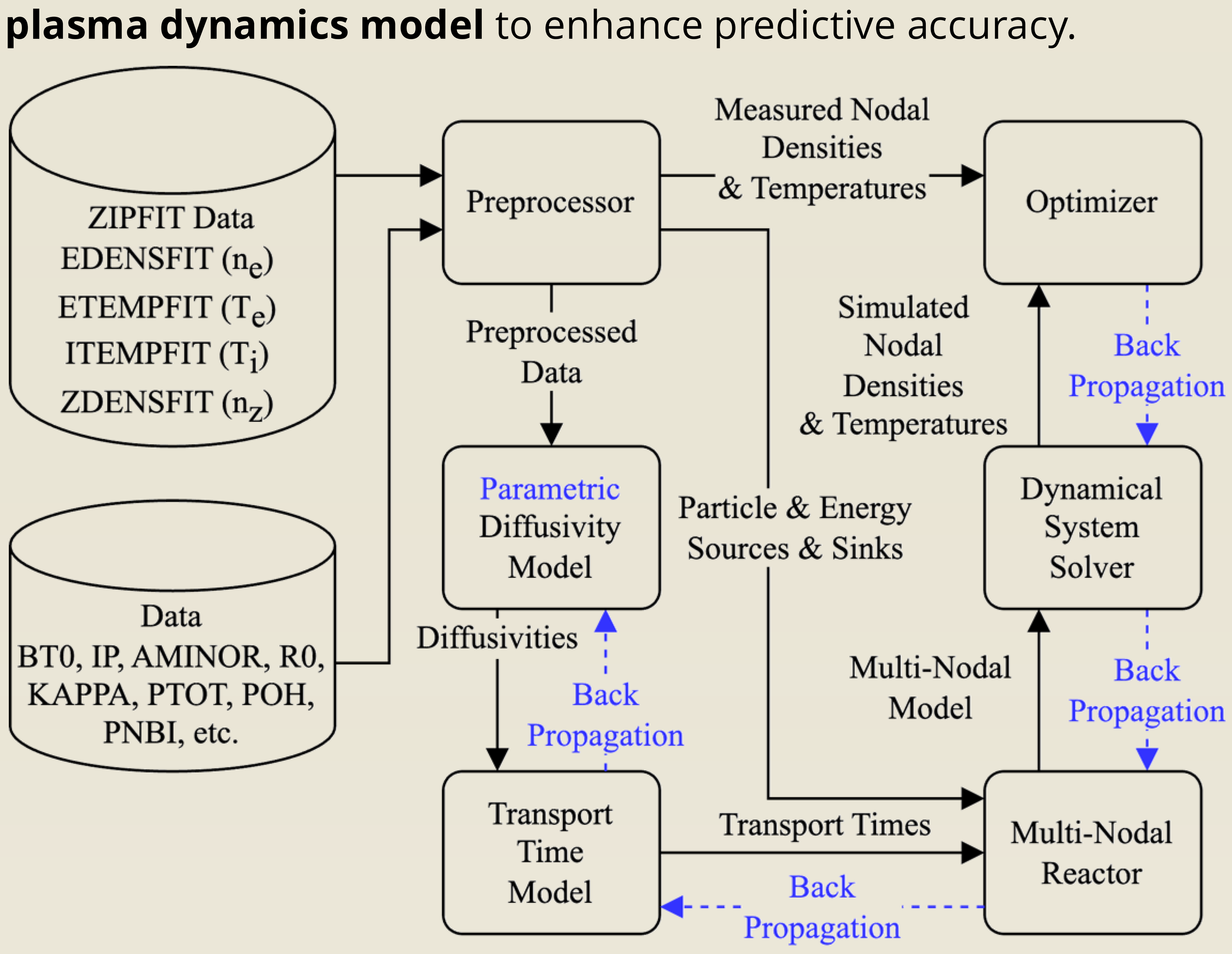
$$\frac{dU_\sigma^{\text{node}}}{dt} = P_{\sigma,\text{aux}}^{\text{node}} + P_{\sigma,\text{fus}}^{\text{node}} + Q_\sigma^{\text{node}} + P_{\sigma,\text{tran}}^{\text{node}} + P_{\sigma,\text{IOL}}^{\text{node}}$$

$$\frac{dU_e^{\text{node}}}{dt} = P_\Omega^{\text{node}} + P_{e,\text{aux}}^{\text{node}} + P_{e,\text{fus}}^{\text{node}} - P_{\text{rad}}^{\text{node}} + Q_e^{\text{node}} + P_{\sigma,\text{tran}}^{\text{node}}$$

- The model provides a **transparent** yet **data-informed** framework that balances **physics fidelity** with **flexibility**.

Computational Framework

- **NeuralPlasmaODE** combines **Neural ODEs** with the **burning plasma dynamics model** to enhance predictive accuracy.



Sensitivity Analysis

- We apply **normalized sensitivity analysis** to measure the effect of small parameter changes on plasma responses:

$$S(y|p) = \frac{p}{y}\frac{\partial y}{\partial p}$$

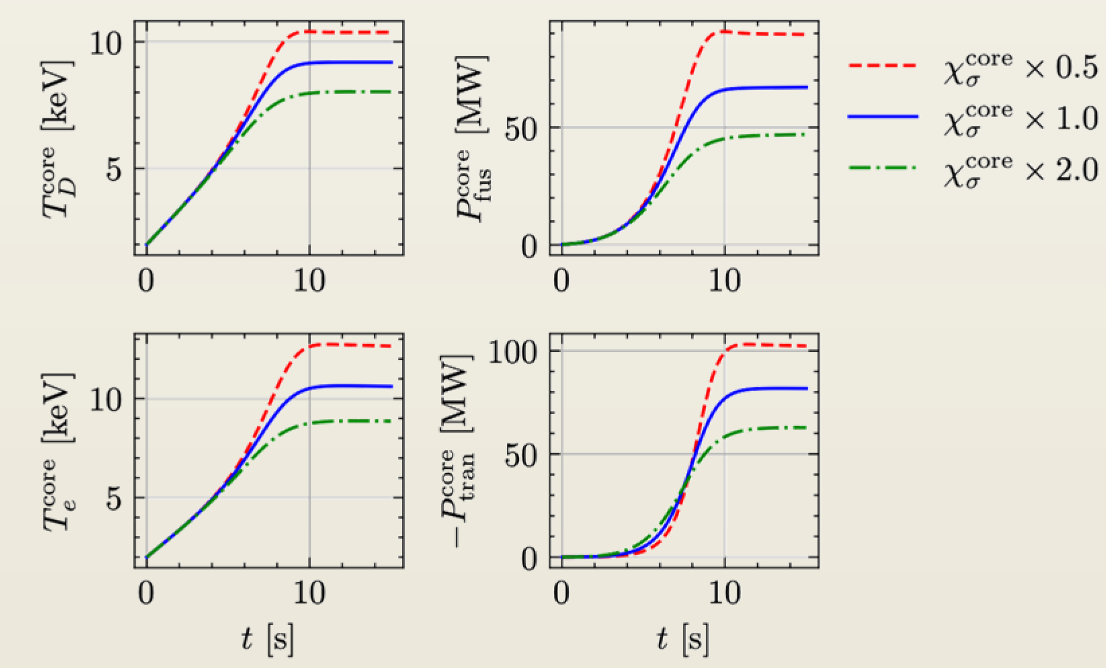
- Both **steady-state shifts** and **dynamic time evolution** were examined to capture **stability** and **transient effects**.

Conclusion

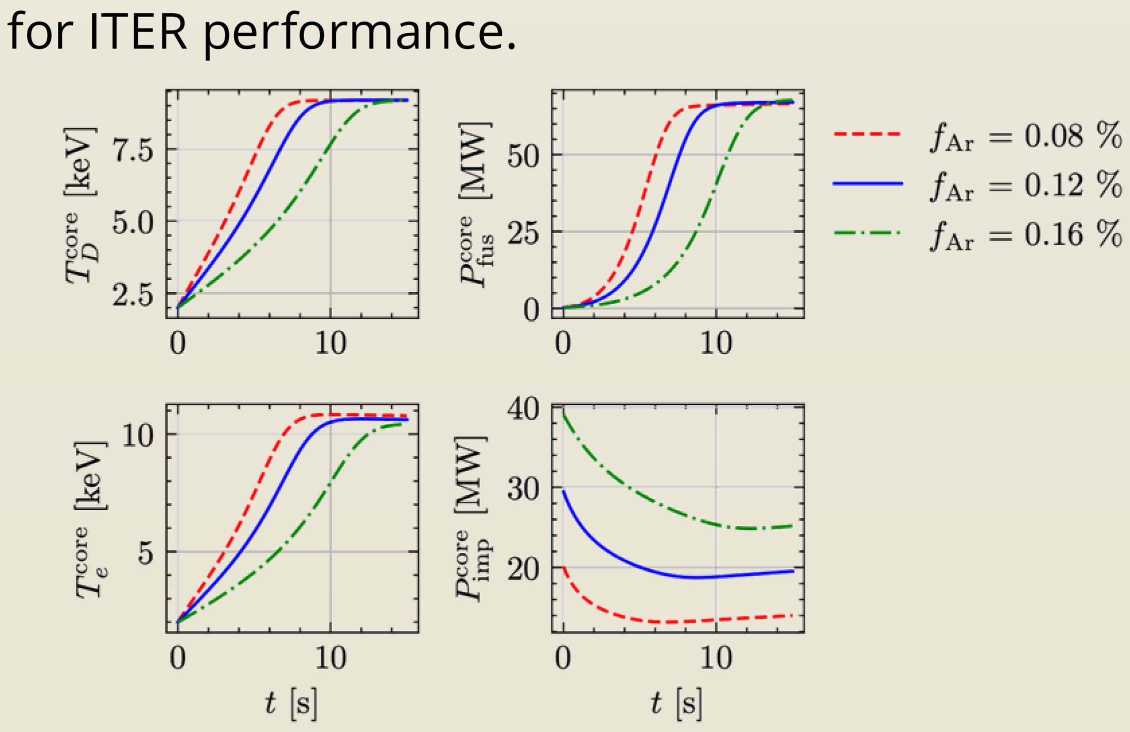
- **Transport physics** (magnetic field, safety factor, temperature gradients) are the dominant control parameters for ITER performance.
- **Impurity fractions**, especially argon, strongly impact confinement through enhanced radiative losses.
- **NeuralPlasmaODE** with **sensitivity analysis** offers a predictive, interpretable tool for optimizing and controlling burning plasma scenarios.

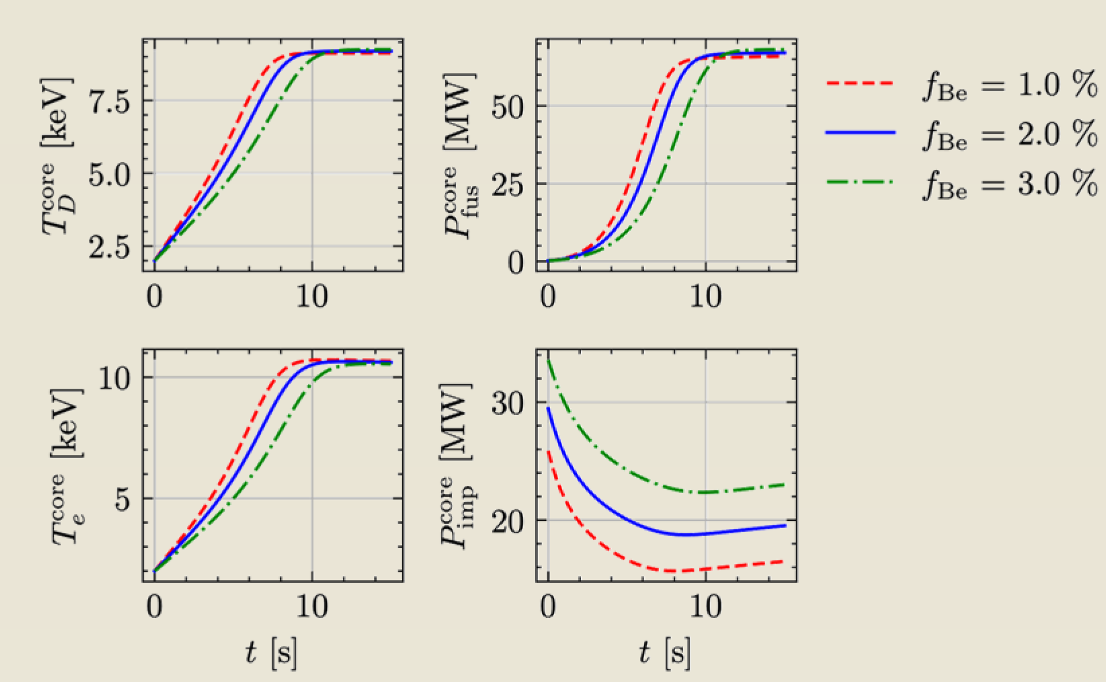
Key Results

- **Transport diffusivities** are the strongest drivers of plasma behavior. Magnetic field, safety factor, and temperature scaling exert dominant control, with temperature-dependent transport providing a stabilizing self-regulation against runaway heating.

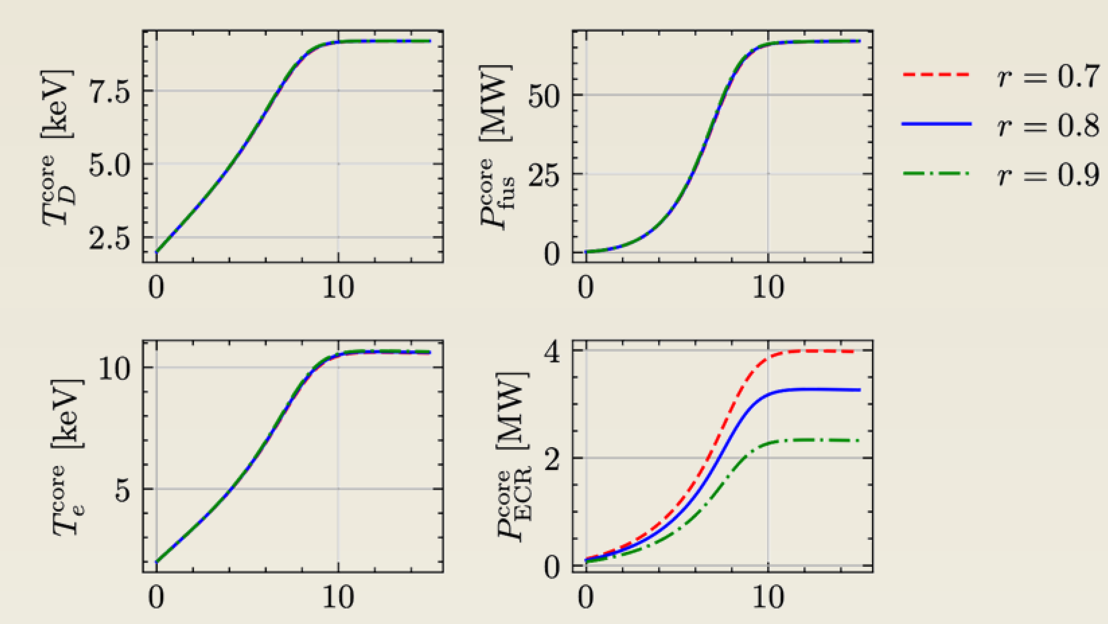


- **Impurity effects** are significant: argon impurities sharply reduce electron temperature via radiative losses, while beryllium has a weaker but still noticeable impact. Impurity management is thus critical for ITER performance.





- **ECR parameters** (particularly wall reflectivity) influence electron energy balance but have modest overall effect compared to transport and impurities, though uncertainties in wall conditions remain important.



- **Ion orbit loss** plays a negligible role in ITER's inductive scenario, confirming that transport and impurities are the key levers for confinement optimization.

References

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