

EDGE2D-EIRENE: Fast 2D Surrogate Models for Plasma-Edge Simulation

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MOTIVATION

Why model the divertor? The divertor must handle the intense particle and heat exhaust from the fusion plasma while removing helium ash and impurities.

Challenge: divertor plasma simulations are computationally expensive, limiting their use in large parameter scans and integrated whole-plasma modelling.

MAST-U provides an experimental platform for investigating alternative divertor configurations, including:

- Conventional divertor
- Super-X divertor
- Long-leg divertor

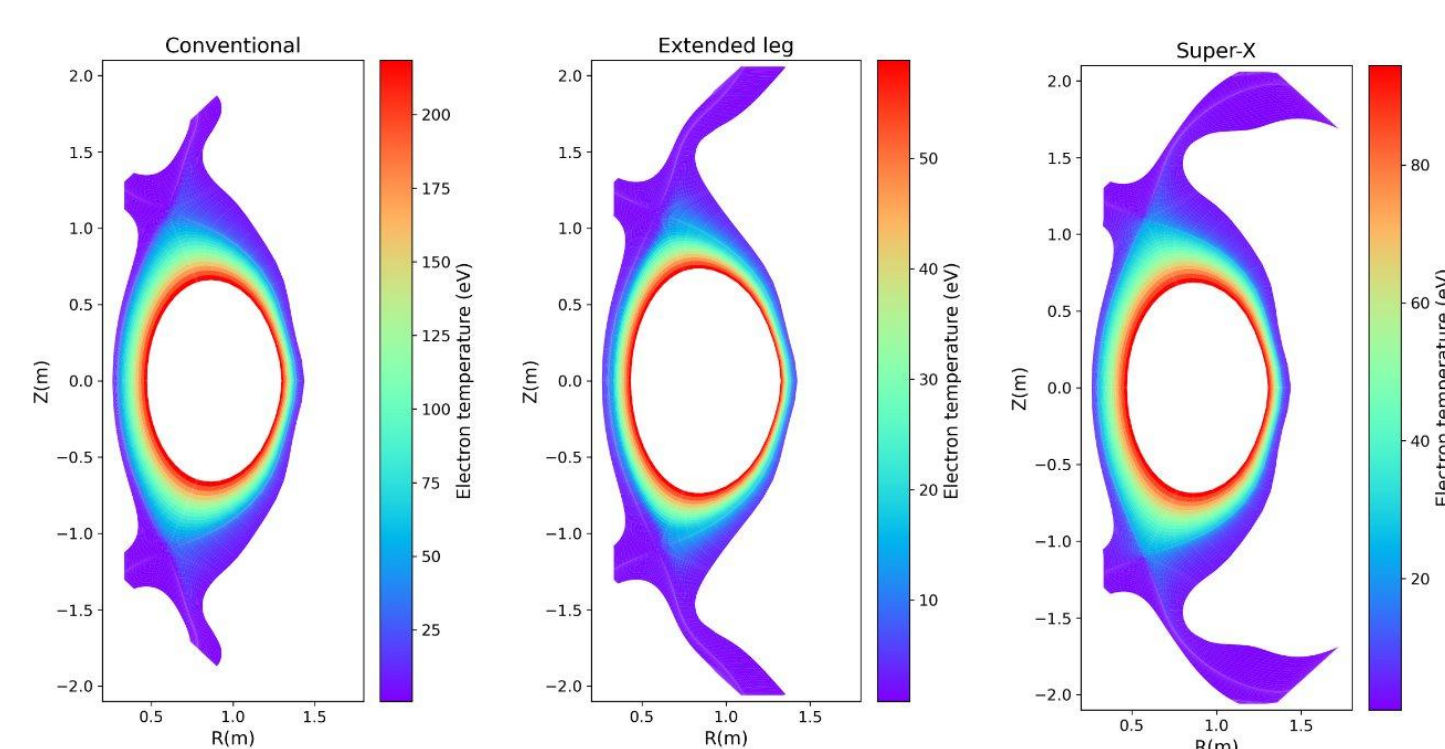
Aim: develop a fast surrogate for the computationally expensive EDGE2D-EIRENE simulations.

EDGE2D-EIRENE DATASET

- 2D plasma transport + 3D neutral kinetic model for the SOL
- Used for a variety of tasks such as simulating different divertor configurations
- 24,000 simulations -> 8,457 deuterium-puff simulations used in surrogate dataset

Inputs: power (MW), separatrix deuterium density (cm^{-3}), gas-puff location (out of 4)

Outputs: Predicts 2D plasma & neutral fields



MODEL (TRANSOLVER)

- Encode puff locations into learnt embeddings
- Target field is logged, inputs and outputs are all scaled
- Model architecture (Transolver)
 - Transformer-based methods that adapt the self-attention mechanism to point clouds.
 - Train the model to learn to segment the point cloud into different subsets of said points and apply self-attention between them

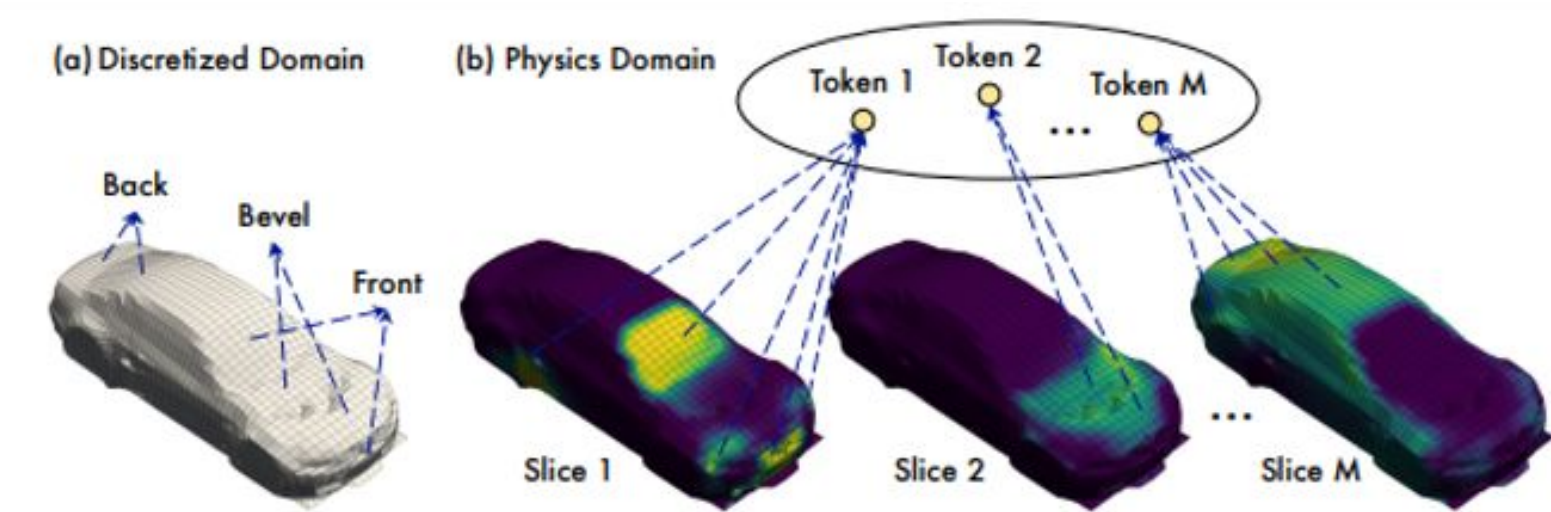


Figure 2. Learning physics-aware tokens from Transolver slices.

Different equilibria in the dataset: <https://github.com/psatinek/simshift>
Image taken from the Transolver paper: <https://arxiv.org/pdf/2402.02366>

MAIN RESULTS

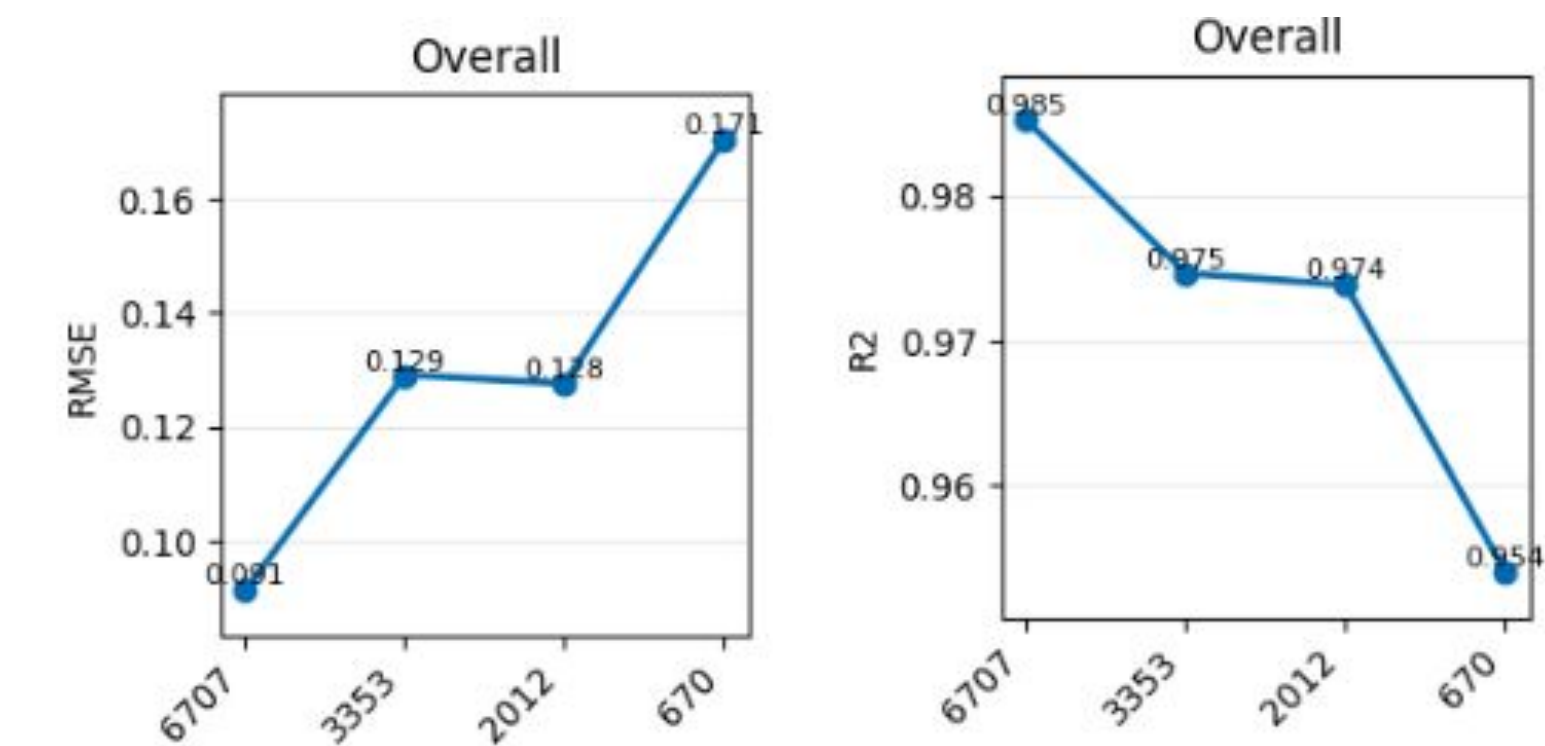
- Good performance with EDGE2D-EIRENE test simulations across the three MAST-U divertor configurations.

- Good accuracy even with reduced dataset sizes which is promising for data-scarce applications

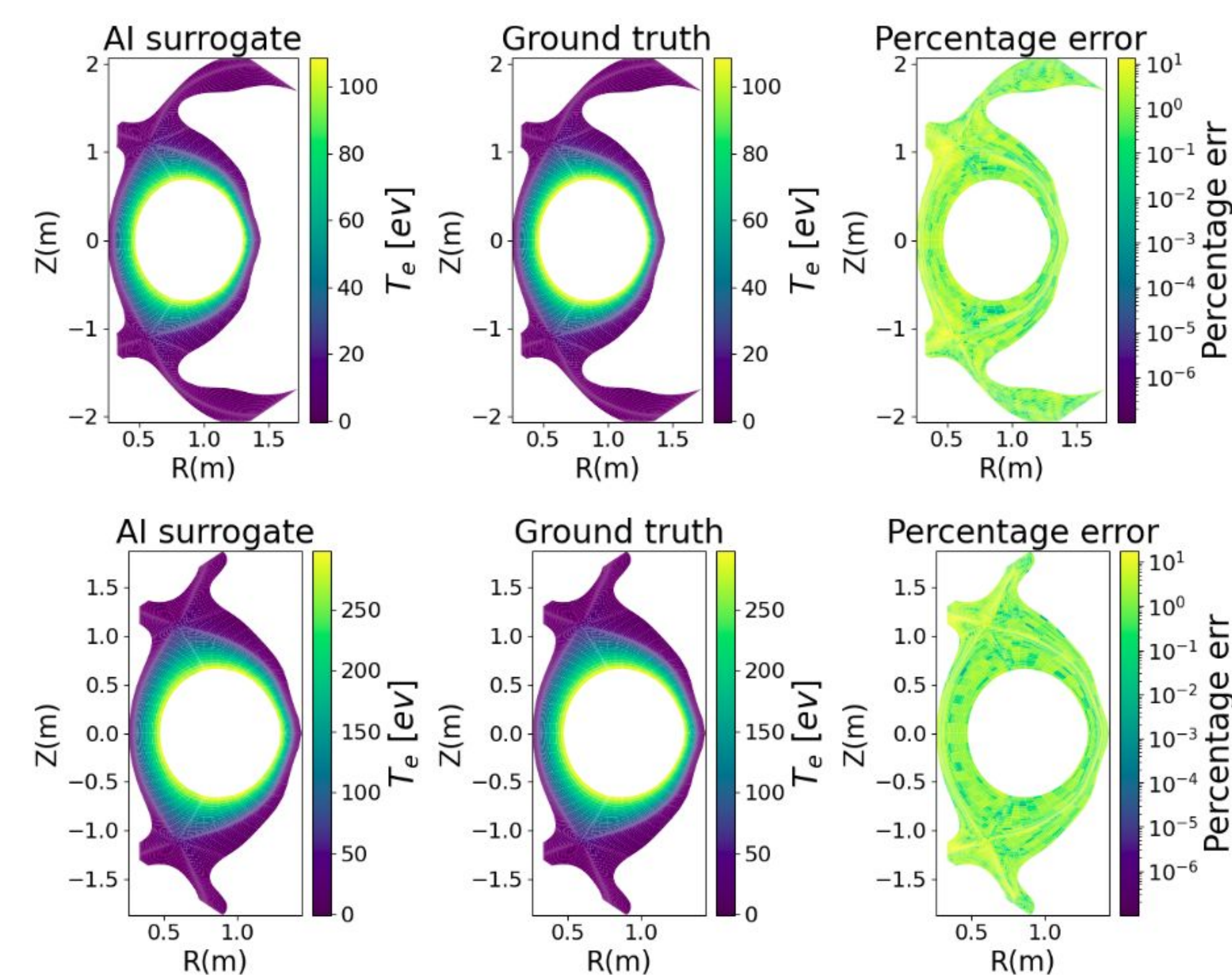
- Example predictions reproduce spatial structure well with A spike in error around the separatrix

RMSE (CD/SX/ED)	0.091 (0.166/0.123/0.076)
R2 (CD/SX/ED)	0.985 (0.955/0.977/0.988)

Error across entire point cloud and all samples in validation dataset, averaged across all variables



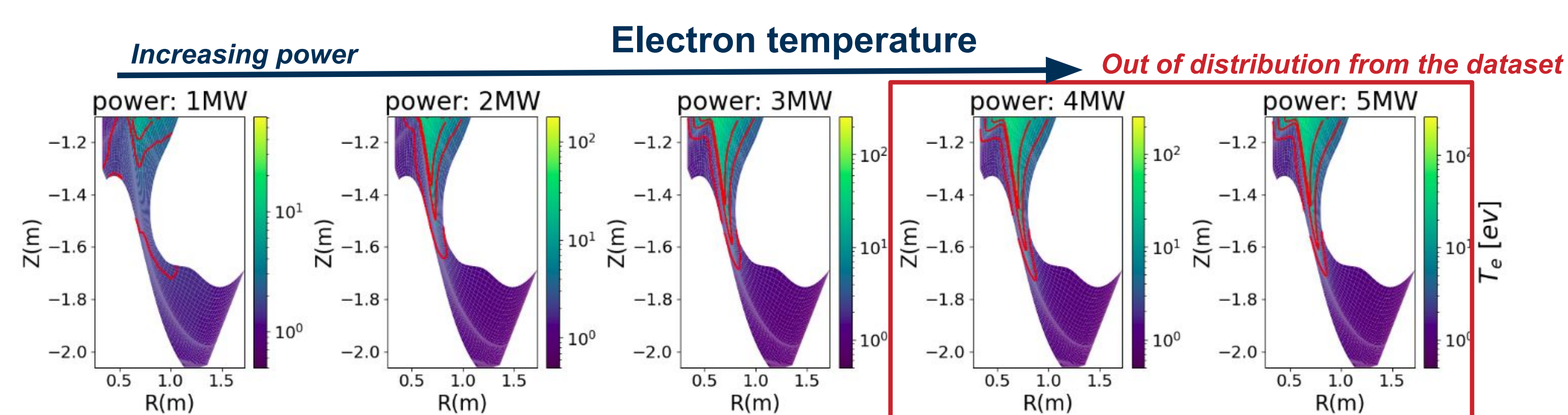
Model performance across different dataset sizes



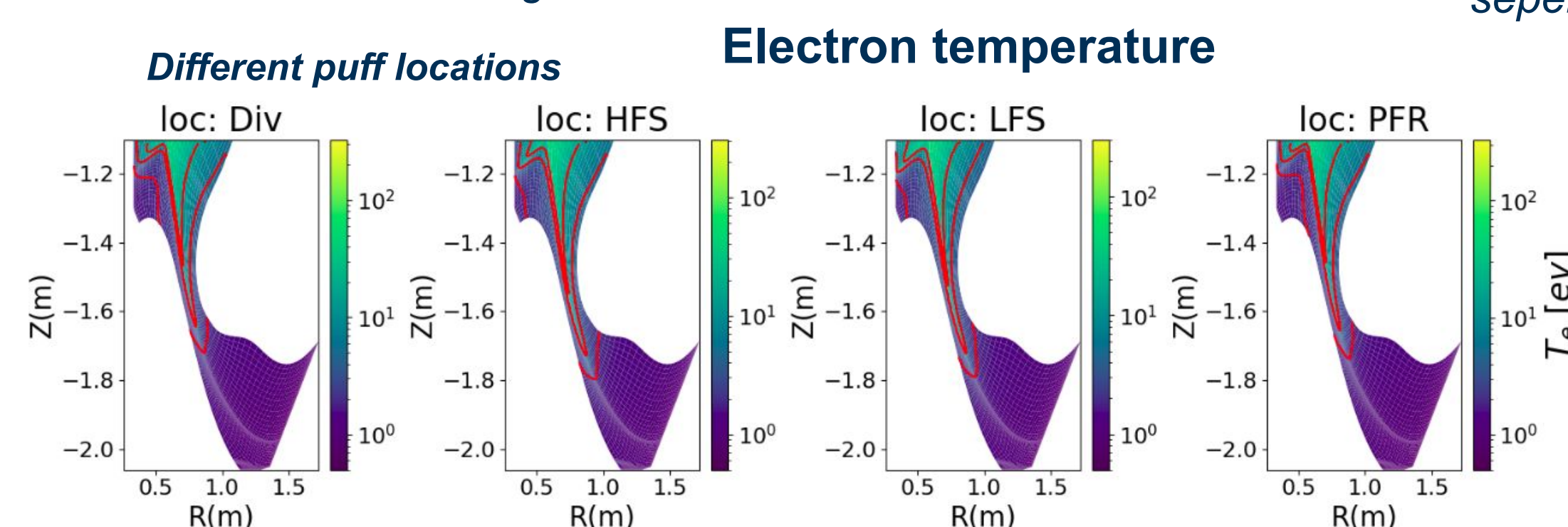
Example outputs (top: Super-X divertor, bottom: conventional divertor)

PARAMETER SCANS

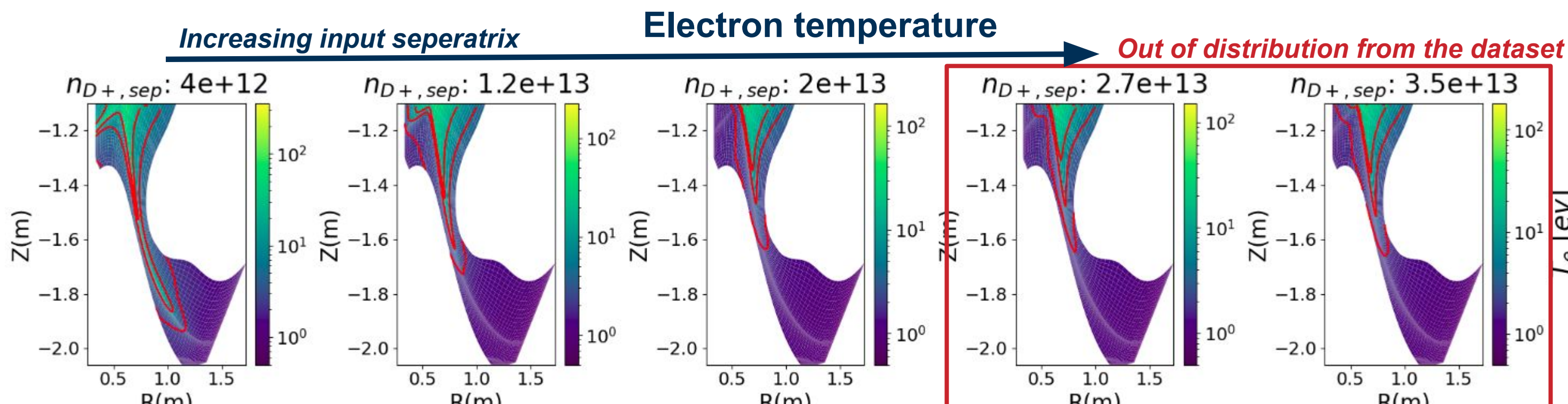
Fixing the other 2 variables and varying the 3rd to see if the surrogate has learnt physical performance.



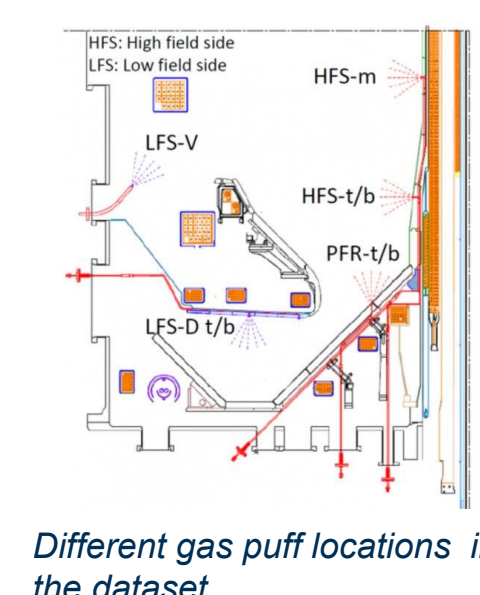
At fixed separatrix density and puff location, the surrogate reproduces changes in the plasma state as input power is varied such as detachment front moving down.



Different gas puff locations in the dataset



At fixed power and puff location, the surrogate reproduces changes in the plasma state as input separatrix density is varied such as detachment front moving up.



Different gas puff locations in the dataset

CONCLUSION

- Trained good performant models on EIRENE-EDGE2D dataset for deuterium puffs.
- Investigated dataset size scaling and some hyperparameter searches run.
- Looking at parameter scans for model
- This work enables fast, accurate prediction of divertor plasma and neutral conditions, providing a pathway towards efficient edge modelling within integrated whole-plasma simulations.

FUTURE WORK

- Integrate into JINTRAC for fast, surrogate-based integrated edge predictions
- Optimise the architecture through hyperparameter and model-size studies
- Extend into nitrogen impurity puff (potentially investigating exploiting partially converged simulations)
- Investigate physics-informed inputs such as magnetic fields and diffusion coefficients to general to arbitrary divertor geometry