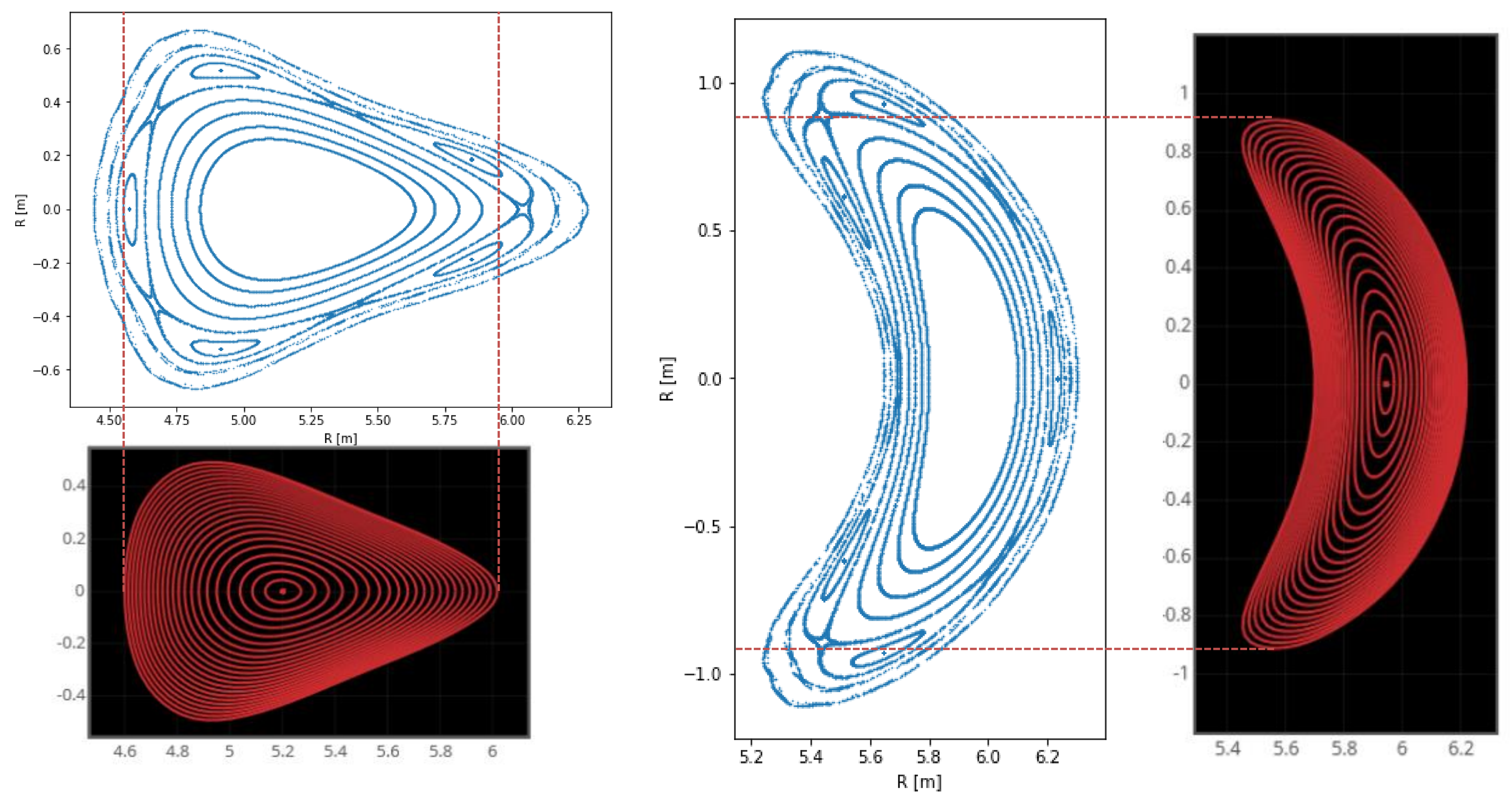
Flux surface mapping in non-nested topologies and its acceleration with deep neural networks on Wendelstein 7-X

A. Knieps[1], M. Brenzke[1], D. Böckenhoff[2], P. Drews[1], M. Endler[2], Y. Gao[2], J. Geiger[2], Y. Liang[1], Y. Suzuki[3], S. Wiesen[1], and the W7-X team

[1] Forschungszentrum Jülich GmbH, 52425 Jülich, Germany
[2] Max-Planck-Institut für Plasmaphysik, 17491 Greifswald, Germany
[3] Hiroshima University, 739-8527 Higashi-Hiroshima, Japan

Contact: a.knieps@fz-juelich.de

Motivation



Poincaré plots of the W7-X magnetic standard configuration and the approximated magnetic surfaces in VMEC

Plasma diagnostics in fusion research devices often observe distinct locations in the target plasma. To gain a consistent picture and separate geometric effects from 3D transport phenomena, these observations are commonly mapped into a radial coordinate, often using surfaces reconstructed by VMEC.

Such an approach, however, can not map out magnetic islands and other non-nested magnetic topologies, which severely hampers its extension onto the plasma edge. To analyze the edge-core relationship and define approximate profiles in the plasma edge, we would like to construct a general approach to magnetic surface mapping, which does not require these surfaces to form simple nested topologies.

Mapping approach

Distance metric

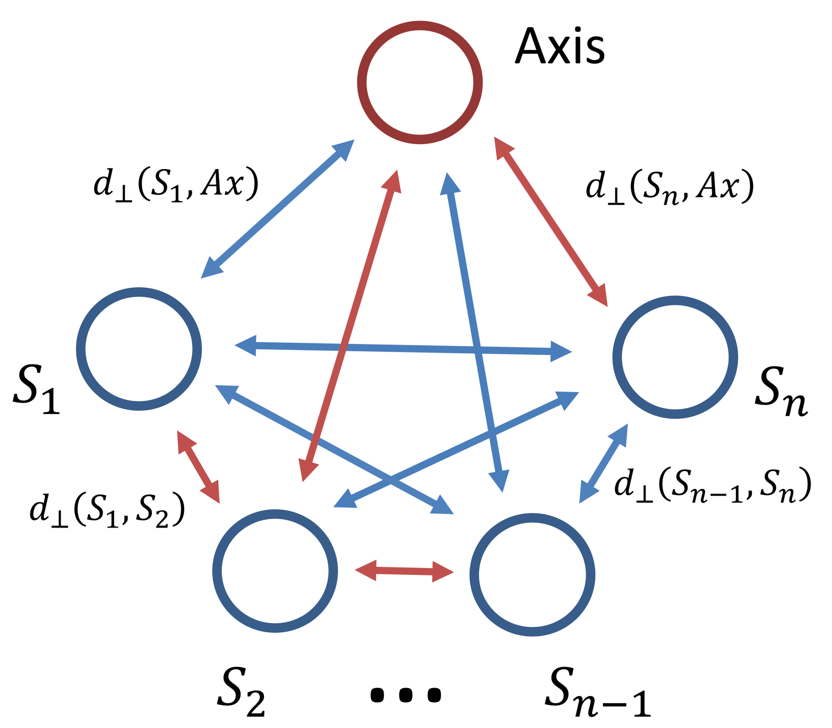
For each path $\gamma: [0,1] \to \mathbb{R}^3$ define **perpendicular path length** as

$$l_\perp(\gamma) = \int_0^1 \left|B\big(\gamma(\tau)\big) \times \dot{\gamma}(\tau)\right| d\tau$$

For two magnetic surfaces $S_1, S_2 \subset \mathbb{R}^3$ we define their **perpendicular distance** as

$$d_\perp(S_1, S_2) = \min_{\substack{\gamma:[0,1]\to\mathbb{R}^3 \\ \gamma(0)\in S_1, \gamma(1)\in S_2}} l_\perp(\gamma)$$

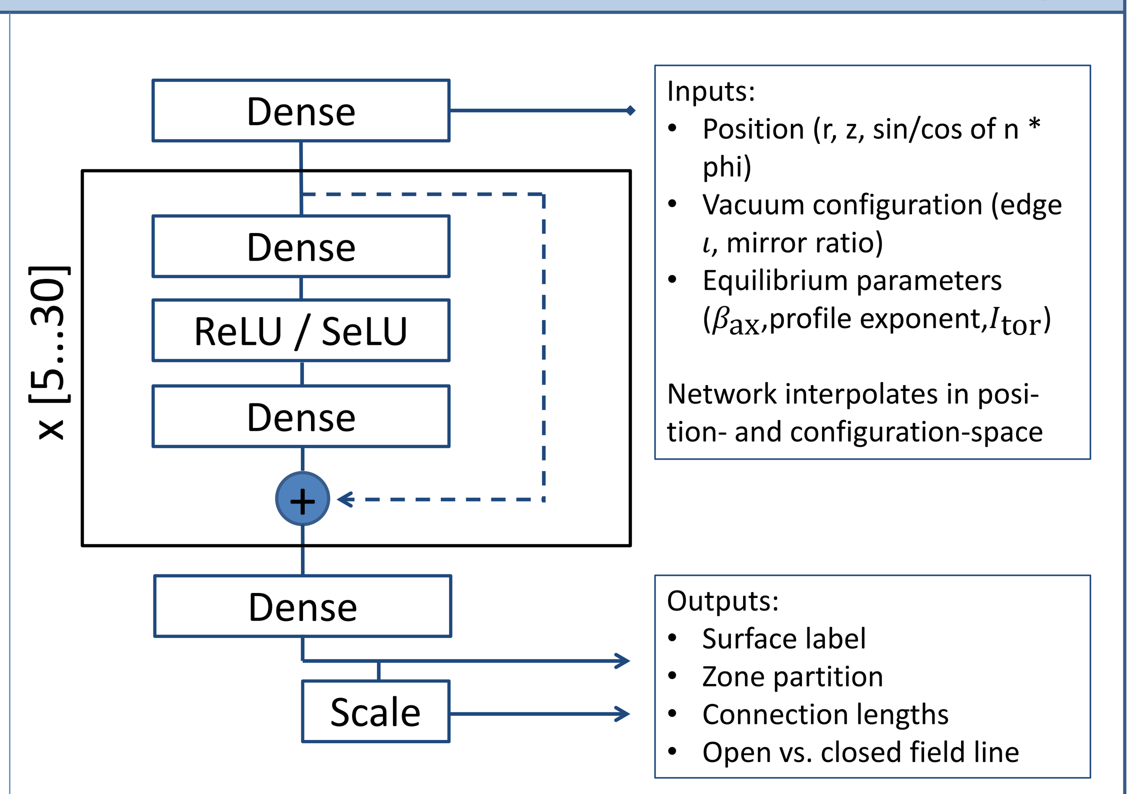
Approximation



1. Sample magnetic surfaces via magnetic field line tracing-based Poincaré maps.
2. Approximate perpendicular distance between magnetic surfaces (and to axis) through minimal pairwise distance between sample points. Limit comparison to point pairs in same toroidal plane
3. Identify **shortest paths** from axis to magnetic surfaces with Dijkstra's algorithm to obtain perpendicular radius.

Acceleration with deep learning

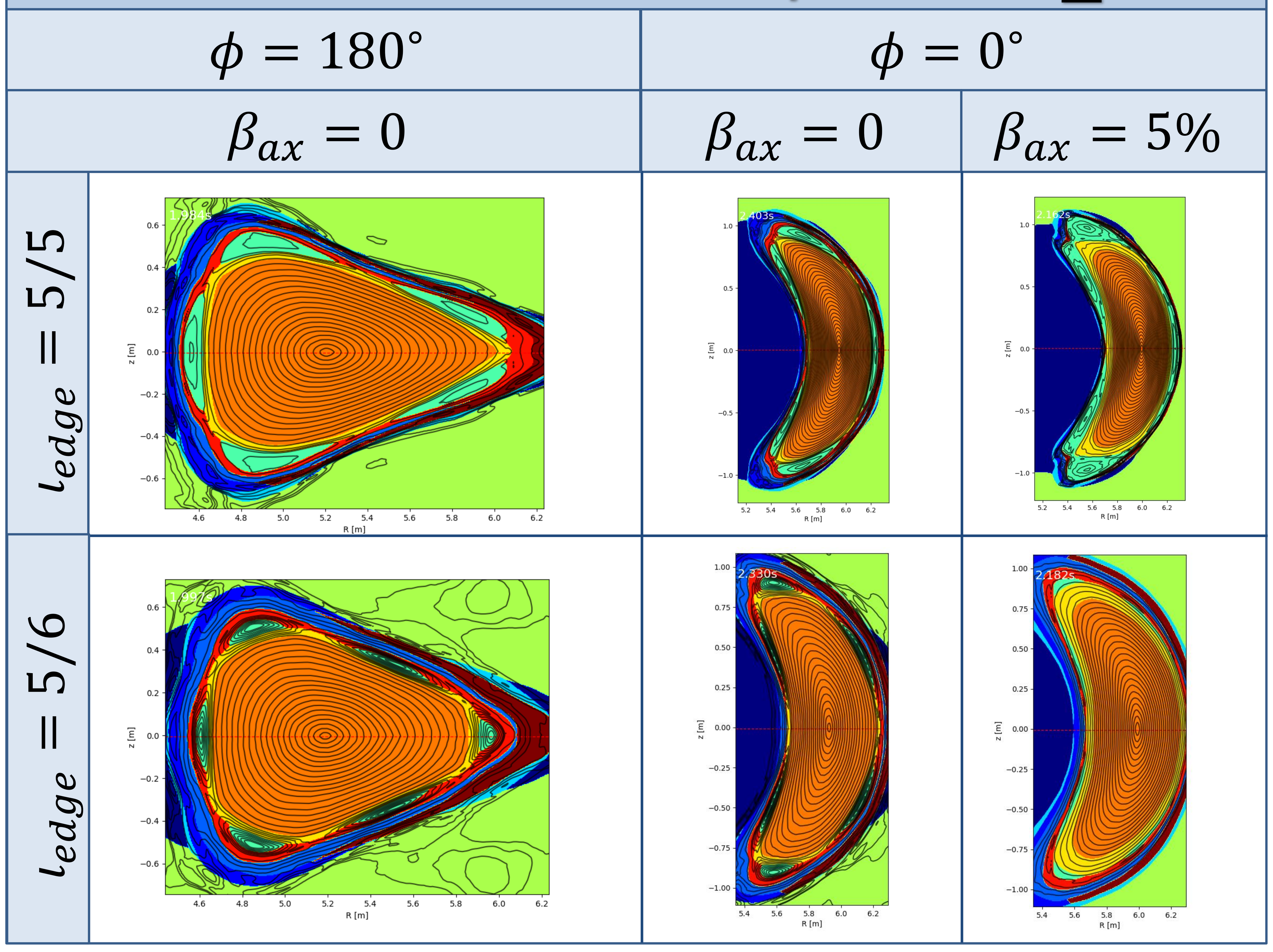
- Accelerator / interpolator based on deep neural network (residual or self-normalizing)
- Trained using population-based training and ADAM optimizer
- Hyperparameters (network bandwidth, depth, learning rate) selected through Tree Parzen Estimator
- Can reach 10^5 evaluations on GPU



Built in TensorFlow

Trained with Optuna

Contours of computed $r_\perp$



Conclusion & Outlook

- It is possible to define magnetic surface labels which are compatible with non-nested topologies (islands, divertor fields, partially stochastic regions)
- The computation of these labels can be made real-time feasible through approximation by neural networks. For training, only sample points of the magnetic surfaces are required.
- ➢ Future plans: Improve training stability
- ➢ Package training facility to ease application outside W7-X

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