DIVCONTROLNN: A GAME-CHANGER FOR REAL-TIME DIVERTOR PLASMA DETACHMENT CONTROL IN MAGNETIC FUSION DEVICES

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The development and successful testing of a machine learning-based surrogate model, **DivControlNN**, marks a significant milestone in advancing detachment control strategies for future fusion reactors. Trained on over 70,000 2D UEDGE simulations of KSTAR, DivControlNN provides quasi-real-time (e.g., within 0.2 ms) predictions of divertor plasma conditions, achieving a computational speed-up of over 10^8 compared to traditional simulations while maintaining a relative error of less than 20%. In the 2024 KSTAR experimental campaign, a prototype model-based detachment control system utilizing DivControlNN demonstrated successful detachment control on its first attempt, despite operating without fine-tuning for the newly upgraded tungsten divertor configuration. These results highlight the transformative potential of DivControlNN in overcoming diagnostic challenges in future fusion reactors by providing fast, robust, and reliable predictions for advanced integrated control systems.

Given the excessive heat exhaust expected in the future fusion reactors, achieving a radiative boundary plasma and a partial or fully detached divertor is essential. Consequently, precise control of boundary plasma conditions, particularly the level of divertor detachment, is crucial and remains an active area of research. Currently, in addition to empirical experience, real-time feedback detachment controls have been developed and tested in various experiments, such as DIII-D/EAST [1], KSTAR [2], and TCV [3]. However, these control systems rely on in-situ diagnostic measurements, such as ion saturation current on the divertor plates from Langmuir probes [2] or C-III emission images from the MANTIS diagnostic [3]. Unfortunately, these diagnostic tools may not be feasible in future reactor-grade machines due to spatial constraints and/or the challenging radiative environment. Therefore, a more sophisticated controller, such as a model-based controller that does not solely rely on in-situ diagnostics but incorporates an embedded physics model, would be extremely beneficial. Historically, due to the inherent complexity and nonlinearity of boundary and divertor physics, even low-fidelity transport models are too time-consuming for many applications, such as discharge scenario development and real-time control. However, emerging machine learning techniques offer an alternative solution by constructing fast, yet accurate surrogate models tailored to specific applications via a data-driven approach.

A proof-of-principle study was first conducted to explore this novel approach using simplified 1D UEDGE simulations [4], which successfully demonstrated that complex divertor plasma states can be efficiently

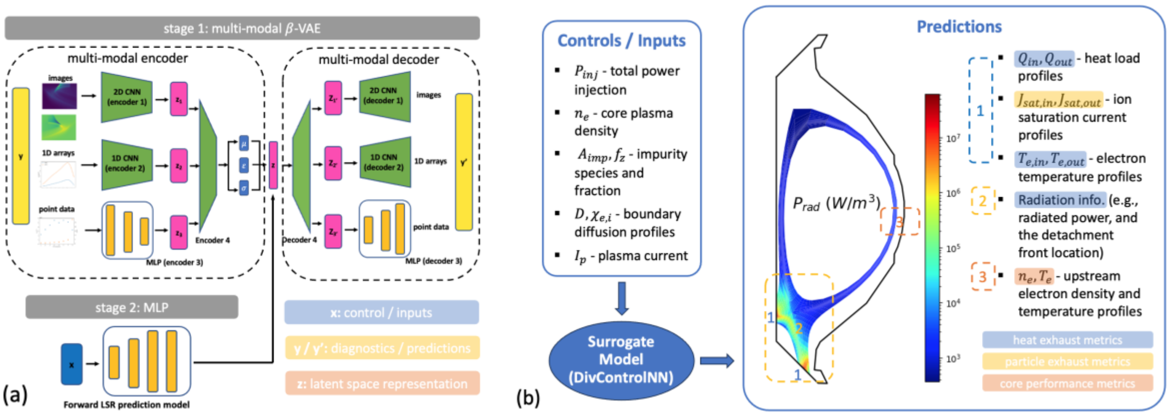

FIGURE 1: (a) Illustration two-stage surrogate model training process, and (b) DivContrlNN inputs and outputs for KSTAR. Note that the model inputs are either real-time discharge control parameters (i.e., P_{inj}, I_p), diagnostic (i.e., $n_{e,core}$), or estimates (i.e., diffusivity and impurity fraction). The model can predict plasma conditions at multiple locations (e.g., 1 target plates, 2 divertor region, and 3 outboard mid-plane) which can be utilized for heat, particle exhaust and fusion performance control.

represented in a reduced, low-dimensional latent space, enabling the development of fast and robust surrogate models for 2D/3D systems. To construct such a surrogate model, a two-stage training process is employed as illustrated in Figure 1 (a): first, to identify an appropriate latent space representation (LSR) of plasma states by compressing the desired synthetic diagnostics through a multi-modal beta-variational autoencoder (β-VAE); and second, to project a set of discharge and control parameters to their corresponding LSR using a multi-layer perceptron (MLP). By combining the trained MLP with the decoder network from the autoencoder, this new data-driven surrogate model can thus predict a consistent set of plasma conditions based on a limited number of discharge and control parameters.

Figure 1 (b) shows the inputs and outputs of the surrogate model, DivControlNN, which is designed for real-time detachment control purposes. The latest surrogate model has been trained and tested on approximately 70,000 2D UEDGE KSTAR simulations, covering a wide parameter range in the KSTAR operation space (e.g., $P_{inj} \in [1,8]MW, n_{e,core} \in [1.5,7] \times 10^{19} m^{-3}, f_Z \in [0,0.04], f_D \in [0.6, 2.0], I_p \in [500, 800]kA$). Based on real-time discharge control and diagnostic signals, this model is designed to self-consistently predict key boundary plasma conditions at multiple locations, including (1) electron temperature, ion saturation current and heat load profiles at both inner and outer divertor plates, (2) radiation information (e.g., overall and divertor radiation fraction, peak radiation power, detachment front location), and (3) outboard midplane electron density and temperature profiles. By leveraging the highly effective latent space mapping [5], our ***surrogate model attains predictions in just 0.2 milliseconds***, a speed-up of over 10^8 times ***compared to the hours required for traditional simulations (if they converge)***, while maintaining ***less than 20% relative error*** which is sufficient for detachment control. More importantly, it can successfully predict detachment onset (i.e., when the controller is most needed) and well capture divertor plasma dynamics under external actuation (e.g., upstream plasma density, injection power, etc.).

With the surrogate model's exceptional performance, a prototype of the model-based detachment control was employed and tested during the recent 2024 KSTAR Campaign in December 2024. Despite being a prototype controller built on a surrogate model that has not yet been fine-tuned (i.e., this surrogate model was not trained on the latest tungsten divertor configuration, and the controller is not pre-calibrated due to the tight experimental time constraints), its performance exceeded expectations. As shown in Figure 2, successful detachment control was achieved effectively on its first attempt [6].

This surrogate model and consequently promising experiment result are revolutionary, as they not only alleviate the concern of losing crucial divertor plasma measurements due to limited available diagnostics in reactor-grade tokamaks but also deliver complete and consistent boundary plasma information for more advanced multi-objective integrated controllers with potential applications in future fusion power plants.

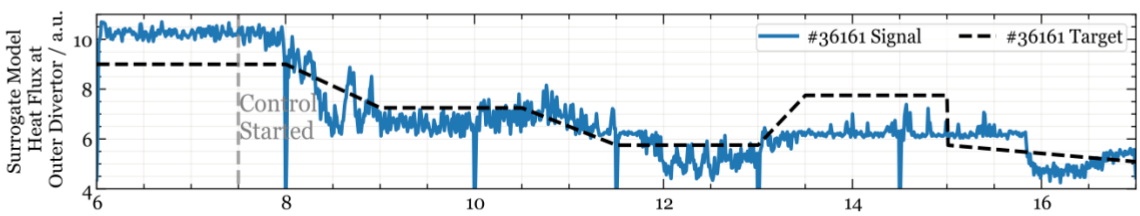

FIGURE 2: Demonstration of successful detachment control using the surrogate model, DivControlNN, on KSTAR shot #36161. The black dashed line represents a prescribed control target sequence, while the blue line indicates the real-time surrogate model prediction which is used for real-time feedback control. At 13-15s, the controller is unable to increase the heat flux all the way back to target value, likely due to the range constraints imposed by the actuator.

ACKNOWLEDGEMENTS

This work was performed for USDOE by LLNL under DE-AC52-07NA27344. LLNL-ABS-2002000

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