Detachment control in W divertor KSTAR with real-time 2D boundary surrogate model

A. Gupta[1], B. Zhu[2], D. Eldon[3], X. Xu[2], M. Zhao[2]

[1]Oak Ridge Associated Universities, [2]Lawrence Livermore National Lab, [3]General Atomics

A major milestone in working towards the goal of a reduced set of diagnostics in future burning plasma reactors has been achieved. A surrogate model, named DivControlNN, trained on 70,000 UEDGE 2D simulations of KSTAR with a mean absolute error of less than 20%, has demonstrated effective real-time performance, processing sparse data from a limited set of diagnostics to produce critical plasma parameters that would otherwise be inaccessible. Additionally, we have demonstrated that we could use the heat flux at the divertor target calculated by this model in real-time to control divertor detachment using impurity gas puffing (Fig 1.). This work provides important data to train and validate DivControlNN further to improve its fidelity, as well as, employ transfer learning to use it across other similar-sized devices such as DIII-D. After cross-validation and further improvements, the estimated plasma parameters would be useful in improving physics understanding and control possibilities without the need for additional diagnostics.

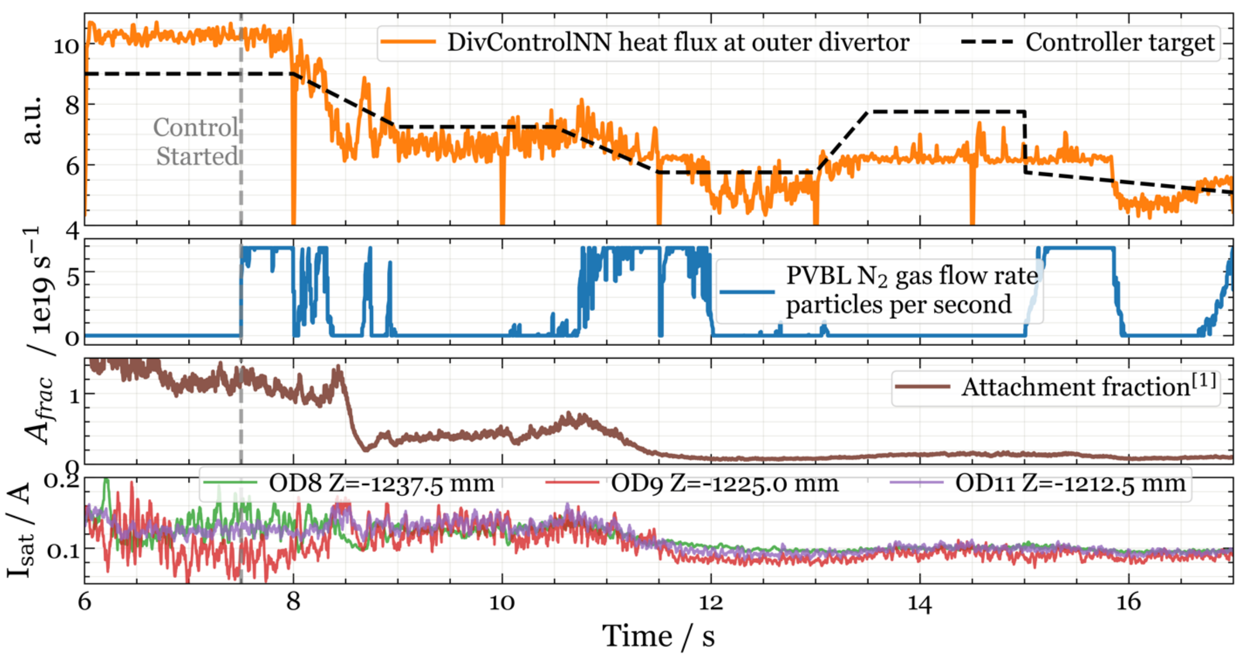

Figure 1. Successful detachment control experiment at KSTAR (shot # 36161) using heat flux at outer divertor estimated by a neural network surrogate model of UEDGE 2D.

Burning plasma reactors such as ITER would operate with a minimal set of sensors because of high heat flux, radiation, neutron fluence, and limited port space to maximize the tritium breeding blanket. Surrogate models trained on simulation data would be a useful replacement for existing sensors on which our current control systems depend. In particular, such reactors must handle the heat exhaust from the core into the scrape-off layer (SOL) region where it impinges on divertor targets. If not mitigated properly, this heat flux can damage the divertor directly or cause sputtering of high-Z impurities that would contaminate the core and could result in sudden loss of plasma confinement damaging the machine.

The heat flux can be controlled by puffing gas impurities that ionize, recombine, and charge exchange in the SOL plasma and dissipate away the heat before it reaches the divertor. A widely known way of describing this control problem is to measure the degree of detachment of SOL plasma from the divertor surface. In the past, ion saturation current from embedded Langmuir probes in divertor have been used to estimate attachment fraction[1] and control detachment level. In this work, we show that DivControlNN can estimate heat flux reliably and can be used for detachment control with real-time feedback to puff impurity gases in the vessel.

DivControlNN is the first of its kind ever implemented for performing heat flux control in real-time. It is trained on a dataset of 2D UEDGE simulations with full cross-field drifts which has been validated against experimental data of KSTAR from its carbon divertor campaign and assumes carbon as the only impurity. For inference, we provided inputs for plasma current, core electron density, and input power to the device from available real-time diagnostics. Other inputs were: a scaling factor for the diffusion profile of the plasma species which was fixed to 1.0 for lack of any other real-time estimate and the impurity concentration in the plasma which was provided by an ad-hoc estimation model that used injected gas amounts and estimated decay rates.

Despite some inputs being estimated and DivControlNN being trained exclusively on data from the previous carbon divertor campaign for carbon impurities, we still observed a strong correlation between DivControlNN output of heat flux at the outer divertor, and the attachment fraction[1]. Fig.1 shows the control attempt using DivControlNN heat flux estimate for controlling the detachment level by puffing in nitrogen. We see a fast control action maintaining the set target value well up to 13s. The attachment fraction curve validates that the divertor got detached and the signs of detachment can also be seen in raw ion saturation current from Langmuir probes in the vicinity of the strike point on the outer divertor (OD8, OD9, and OD11).

In this prototype test, we have already identified several key possibilities for improvement which makes this test successful for its purpose. The fact, that the heat flux did not rise back up between 13s to 15s even when the target was lifted gives important clues on the vulnerability of this control scheme and its limitations. We are in the process of creating a new 2D UEDGE database of KSTAR with a tungsten divertor and considering multiple charged states of additional impurities such as nitrogen, neon, and argon. New models would be trained on the expanded database and acquired experimental data from this campaign, with the input of injected gas flow instead of impurity fraction to simplify the use case of these models.

DivControlNN provides calculations for electron density and temperature at the outer mid-plane as a 1D profile along radial direction; electron temperature, ion saturation current density, and heat flux at the divertor targets as a 1D profile along the target surface; and peak radiation power density and its location, as well as, radiation power fraction coming from divertor and total radiation as a fraction of input power. These many outputs, while yet to be calibrated and tuned, provide useful trend information for understanding the behavior of plasma. In the future, such validated surrogate models can dramatically reduce reliance on traditional diagnostics and post-processing of data and would provide these plasma parameters in real-time for control purposes and quick decision making in the control room.

This material is based upon work supported by the U.S. Department of Energy, Office of Science, Office of Fusion Energy Sciences under Award DE-SC0023400.

[1] D Eldon et al 2022 Plasma Physics and Controlled Fusion 64 075002.