9th Asia-Pacific Conference on Plasma Physics, 21-26 Sep, 2025 at Fukuoka

Adaptive model predictive control of fusion plasma based on data assimilation system ASTI

Y. Morishita[1], S. Murakami[1], N. Kenmochi[2], H. Funaba[2], M. Yokoyama[2], G. Ueno[3], and M. Osakabe[2]
[1] Department of Nuclear Engineering, Kyoto University, [2] National Institute for Fusion Science, [3] The Institute of Statistical Mathematics

e-mail (speaker): morishita@p-grp.nucleng.kyoto-u.ac.jp

Achieving reliable and flexible control of plasma behavior is essential for future fusion reactors. However, plasma dynamics are nonlinear and involve many interacting variables, while available measurements are often limited. To address this challenge, we have developed a control system called ASTI (Assimilation System for Toroidal Plasma Integrated simulation)[1]. ASTI integrates a predictive plasma model (digital twin), real-time measurement data, and actuator control into a unified framework based on data assimilation techniques. This system enables adaptive prediction and control of fusion plasmas under uncertain and partially observed conditions, allowing more robust and intelligent operation.

ASTI was implemented in the Large Helical Device (LHD) to demonstrate its feasibility and performance in real-time plasma control [2]. The digital twin is constructed using the integrated transport simulation code TASK3D, which simulates plasma transport dynamics in response to actuator inputs. Real-time Thomson scattering measurements provide electron temperature and density radial profiles every 0.3 seconds, which are assimilated into the state probability distribution using an ensemble Kalman filter and particle filter. The actuators include neutral beam injection (NBI), electron cyclotron heating (ECH), and gas puffing, all operated in a coordinated manner. Control decisions are updated every 0.3 seconds based on the prediction by the digital twin.

Figure 1 shows an overview of the control system implemented in LHD. The system operates on high-performance computing platforms, including a vector machine (up to 384 ensemble members) and the Plasma Simulator RAIJIN (up to 12,288 members using 6144 parallel processes). This enables ASTI to accurately represent the probabilistic state of the plasma and generate control actions that are robust to uncertainty. In addition to observable quantities, ASTI can estimate and control unobservable internal states and model parameters in real time.

We demonstrated ASTI's capability through control experiments involving the simultaneous control of electron temperature profile, density, and ion temperature. Two gyrotrons (~700 kW) targeted ρ = 0, while three (~1500 kW) targeted ρ = 0.4. NBI was used for ion heating. Transport model parameters, such as particle thermal diffusivities, were included in the state vector and optimized through data assimilation.

The results showed rapid convergence to the desired profiles and good agreement between predicted and measured values. Despite ion temperature not being observed in real time, ASTI successfully controlled it using the inferred model state, demonstrating control of unobserved variables. This highlights ASTI’s strength in integrating physics-based models with partial real-time observations to achieve multivariate, nonlinear control.

Future work includes applying ASTI to tokamak plasmas, including simulations with JT-60U data and planned experiments with JT-60SA. We are also developing methods to reduce computational cost, such as ensemble optimization, surrogate modeling, and reduced-order modeling, to enable more scalable and real-time capable control for future reactor-scale systems.

References

[1] Morishita *et al.*, J. Comput. Sci. **72**, 102079(2023).
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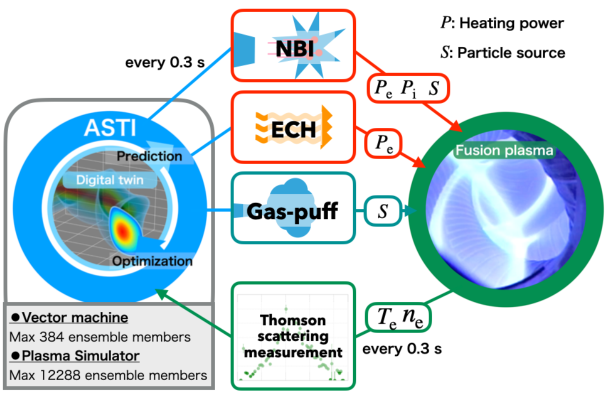

Figure 1. An overview of the control system in LHD