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Development of data assimilation system ASTI toward digital twin control of fusion plasma

Y. Morishita[1], S. Murakami[1], N. Kenmochi[2], H. Funaba[2], R. Ichikawa[1], M. Yokoyama[2], G. Ueno[3], M. Osakabe[2]

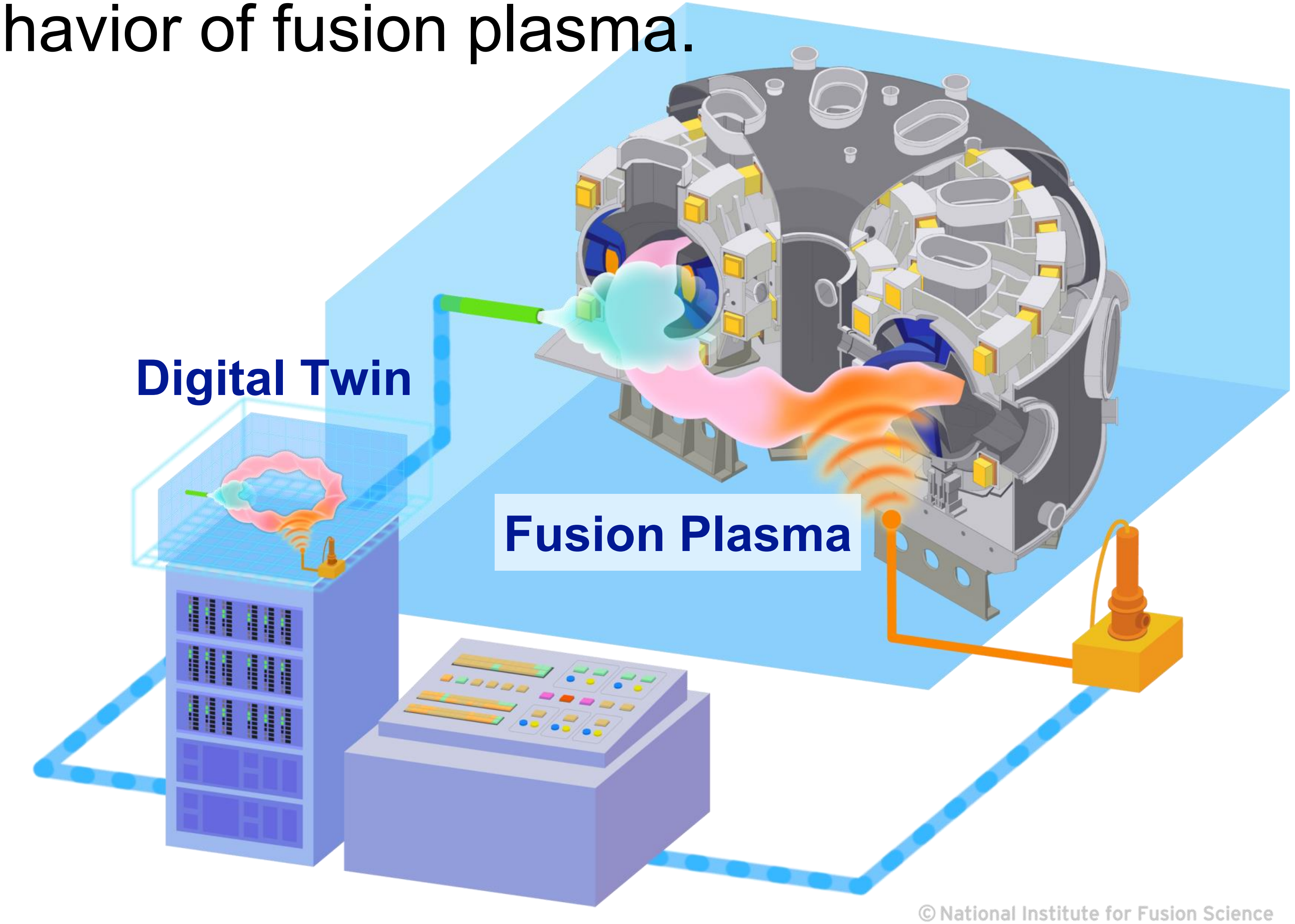
[1]Kyoto University
[2]National Institute for Fusion Science
[3]The Institute of Statistical Mathematics

Digital Twin Control

- The operation of future fusion reactors requires a system that predicts and controls fusion plasma behavior under conditions of limited observation.
- To realize such a predictive control system, a digital twin is required that can reproduce and predict the complex behavior of fusion plasma.

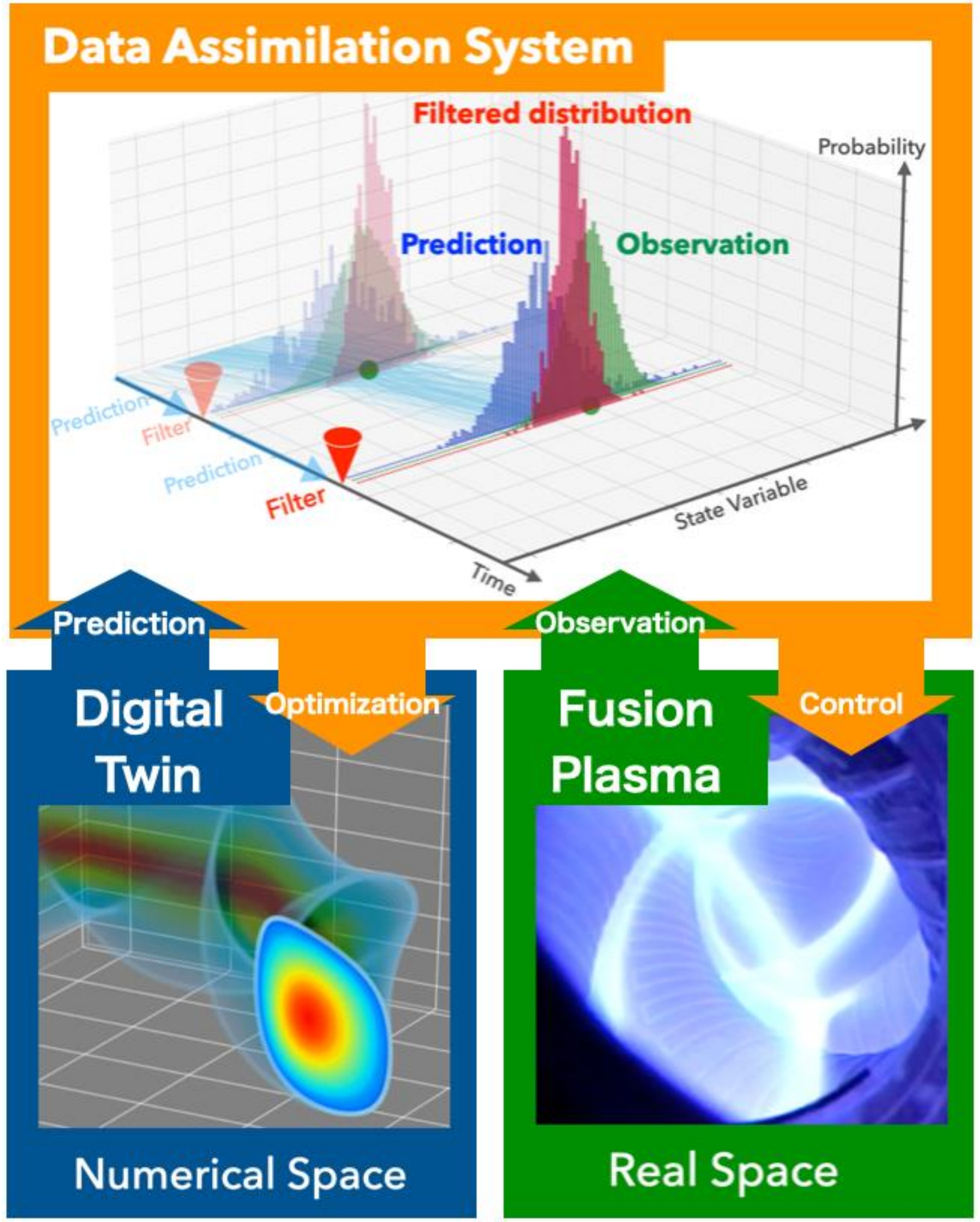
Digital twin control can achieve advanced control considering many variables under limited measurements.

However, it is difficult to get fast and accurate digital twins….



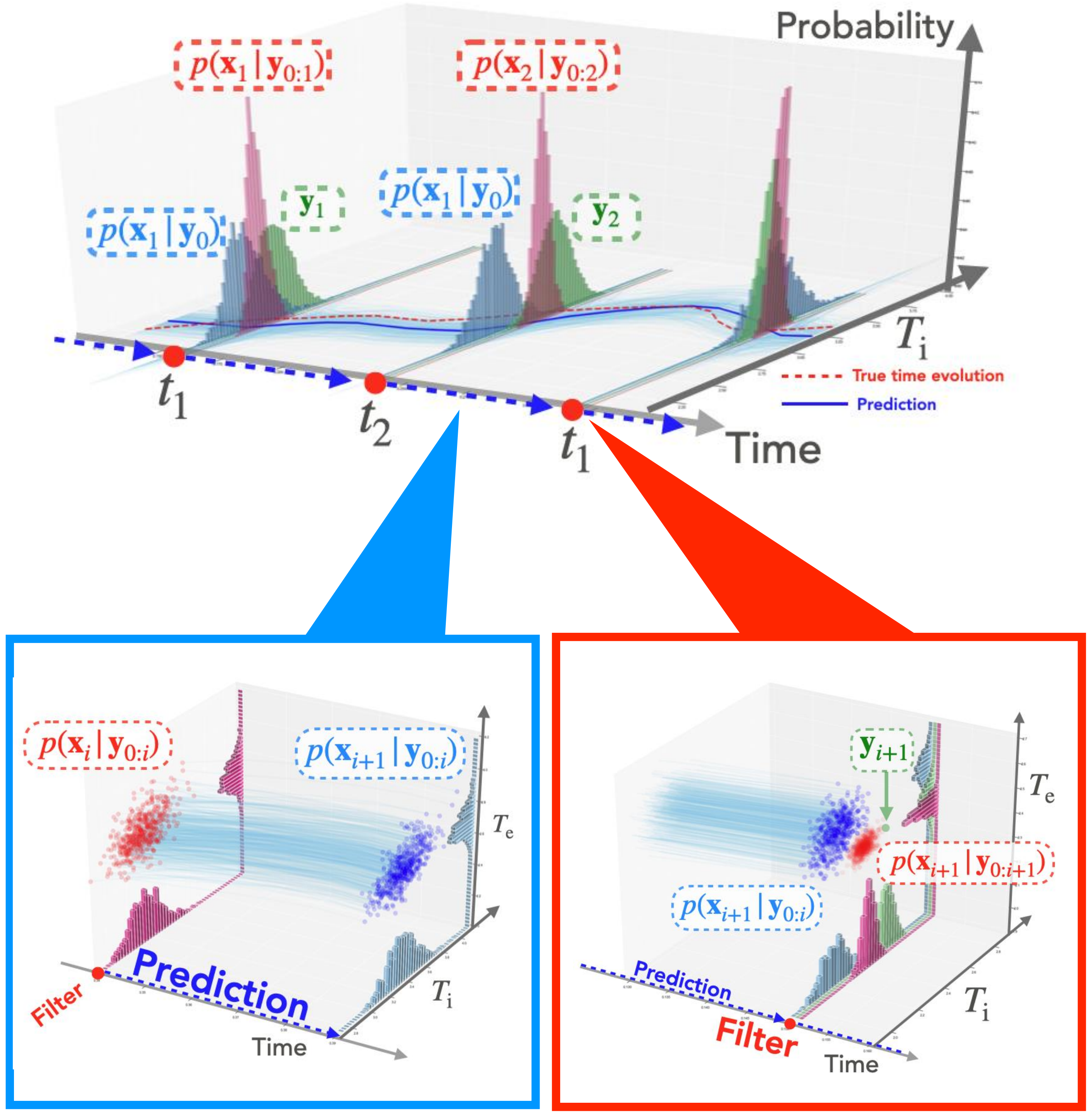
ASTI (Assimilation System for Toroidal plasma Integrated simulation)

- We are developing a data assimilation system, **ASTI**, to realize a numerical system that can accurately predict and control the behavior of fusion plasmas.
- **Data assimilation** is a statistical estimation method. It optimizes the state vector to enhance the prediction capability and reproducibility of the employed model based on the observation data.

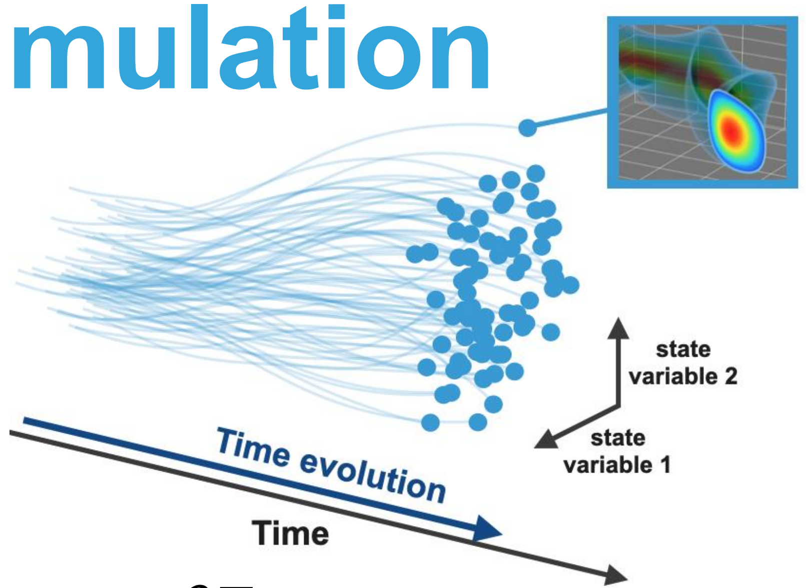


Data Assimilation Based on Ensemble Approximation

- The system state, including model parameters, is represented as a probability distribution of the state vector (state distribution).
- The state distribution is approximated by an ensemble (a bunch of simulations).
- The procedure of data assimilation (**Sequential Bayesian Filter**) consists of **prediction** and **filtering** steps.
- The filter calculates the imposition of observed information on the state distribution. It optimizes the state vector to enhance the simulation model's predictive and analytical capabilities.



Digital Twin with Uncertainties - Integrated Simulation

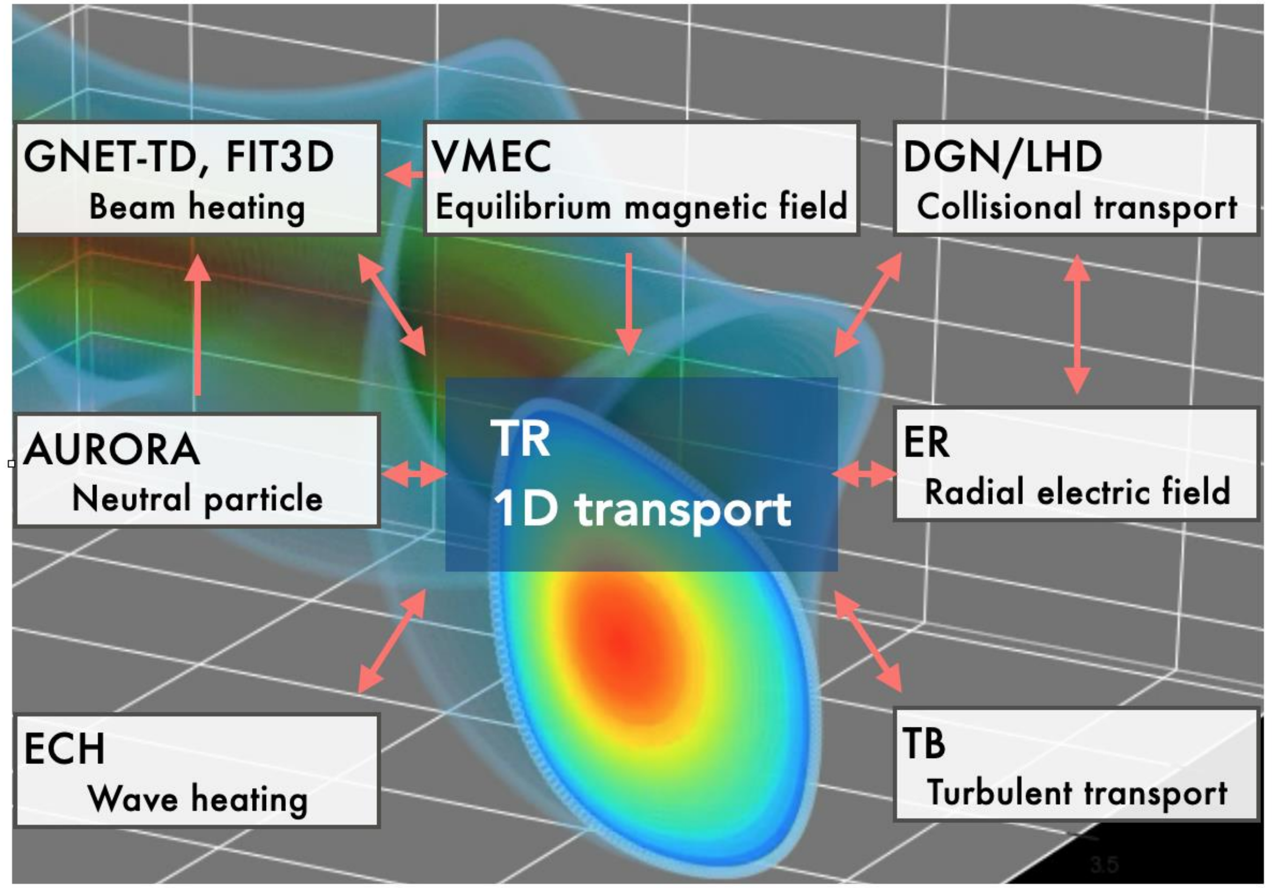


Particle transport

$$\frac{\partial}{\partial t}(n_s V') = -\frac{\partial}{\partial \rho}\left[V'\langle|\rho|\rangle n_s V_s - V'\langle|\rho|^2\rangle D_s \frac{\partial n_s}{\partial \rho}\right] + S_s V'$$

Heat transport

$$\frac{\partial}{\partial t}\left(\frac{3}{2} n_s T_s V'^{5/3}\right) = -V'^{2/3}\frac{\partial}{\partial \rho}[V'\langle|\rho|\rangle n_s T_s\left(V_{K_s} + \frac{3}{2}V_s\right) - V'\langle|\rho|^2\rangle \frac{3}{2} D_s T_s \frac{\partial n_s}{\partial \rho} - V'\langle|\rho|^2\rangle n_s \chi_s \frac{\partial T_s}{\partial \rho}] + P_s V'^{5/3}$$



Variables in the state vector <Example>

- **Thermal turbulent diffusivity**

$$\chi_s^{\mathrm{TB}*} = c_s \chi_s^{\mathrm{TB}} \qquad \chi_e^{\mathrm{TB}} = C_e \frac{T_e}{eB}\frac{\rho_i}{a}$$

- **Particle turbulent diffusivity**

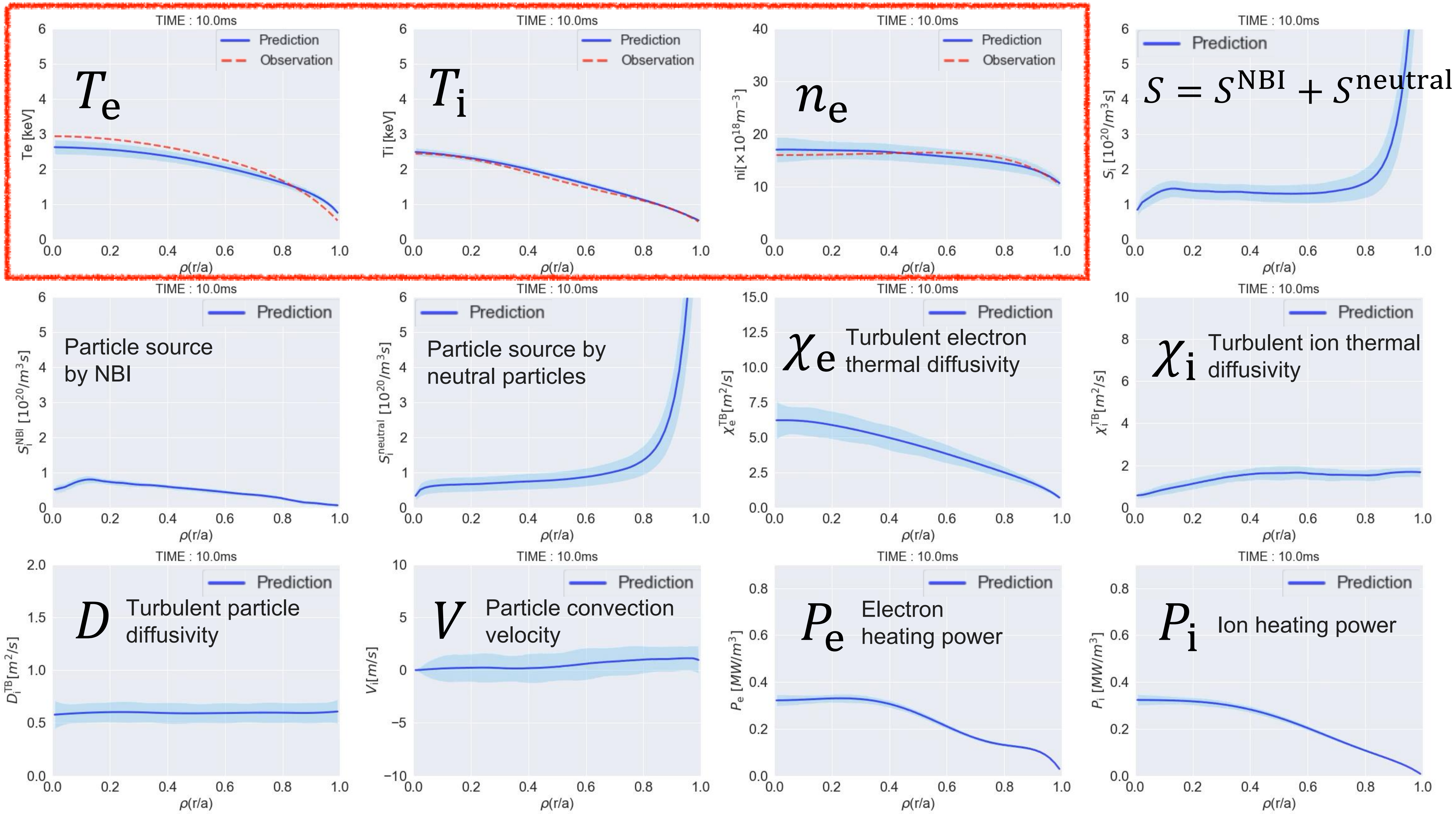
$$D^{\mathrm{TB}*} = d\, D^{\mathrm{TB}} \qquad \chi_i^{\mathrm{TB}} = C_i \frac{T_i}{eB}\frac{\rho_i}{a}\left(\frac{a\nabla T_i}{T_i}\right)$$

- **Convection velocity**

$$V^* = V + v \qquad D^{\mathrm{TB}} = \text{constant}$$

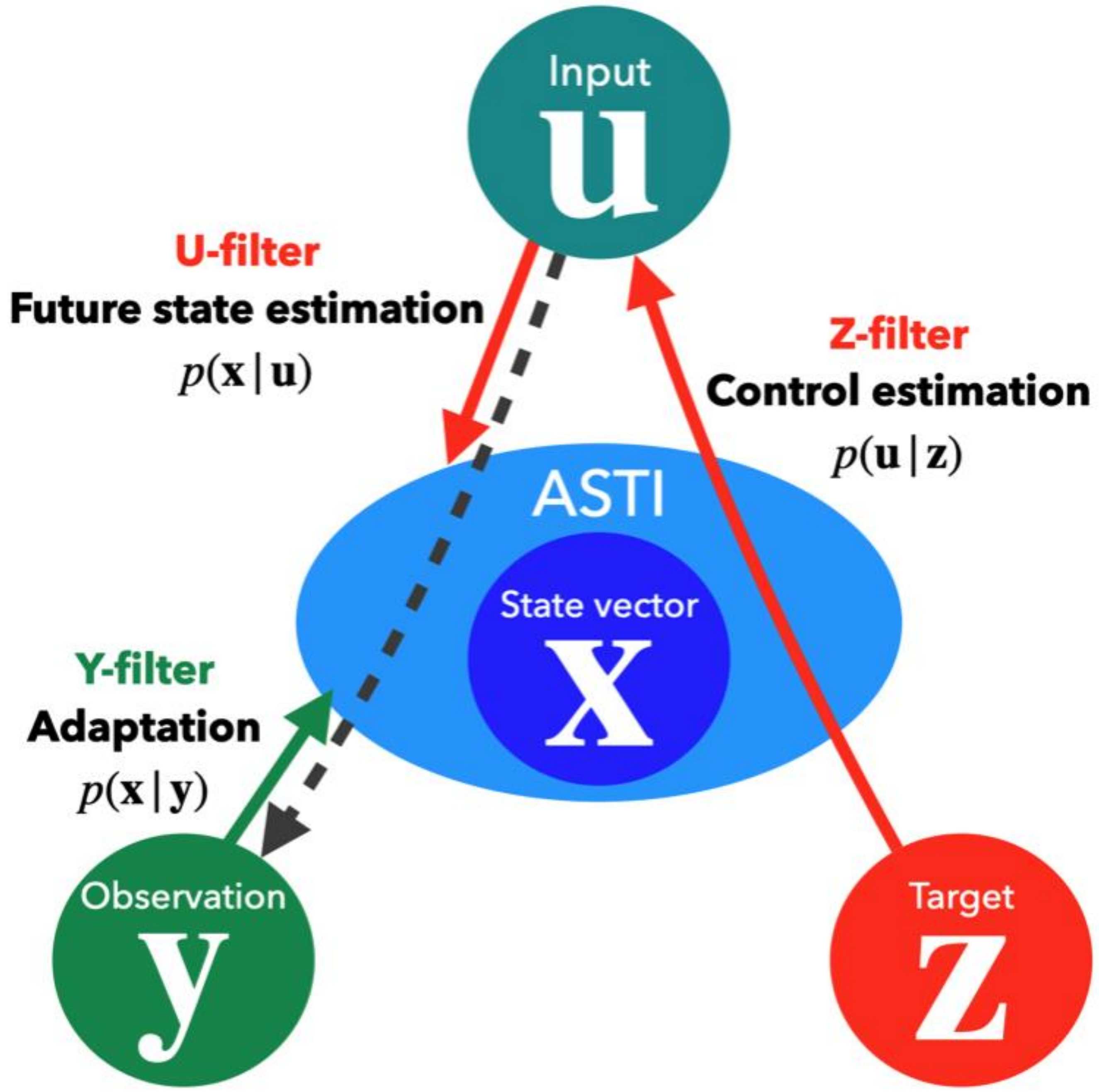
Assimilation computation

- Ensemble member : 500
- Data assimilation cycle: 40 ms
- Observation data : T_e, T_i, and n_e of LHD plasma



DACS (Data Assimilation and Control System)

The DACS framework is an extended data assimilation framework comprising 4 steps.



Normal DA

Prediction

Predict the state distribution Δt_z ahead.

$$p(\mathbf{x}_i \mid \mathbf{y}_{0:i-1}, \mathbf{u}^*_{0:i}) \rightarrow p(\mathbf{x}_{i+1} \mid \mathbf{y}_{0:i-1}, \mathbf{u}^*_{0:i})$$

y-filter **Adaptation**

Assimilate the observation $\mathbf{y}_i$ to the latest u-filtered distribution.

$$p(\mathbf{x}_{i+1} \mid \mathbf{y}_{0:i-1}, \mathbf{u}^*_{0:i}) \rightarrow p(\mathbf{x}_{i+1} \mid \mathbf{y}_{0:i}, \mathbf{u}^*_{0:i})$$

+

Control

z-filter **Control estimation**

Estimate the optimal control input $\mathbf{u}^*_{(i,j)}$ for $\mathbf{z}_{(i,j+1)}$.

$$p(\mathbf{x}_{i+1} \mid \mathbf{y}_{0:i}, \mathbf{u}^*_{0:i}) \rightarrow p(\mathbf{u}_{i+1} \mid \mathbf{y}_{0:i}, \mathbf{u}^*_{0:i}, \mathbf{z}_{i+1})$$

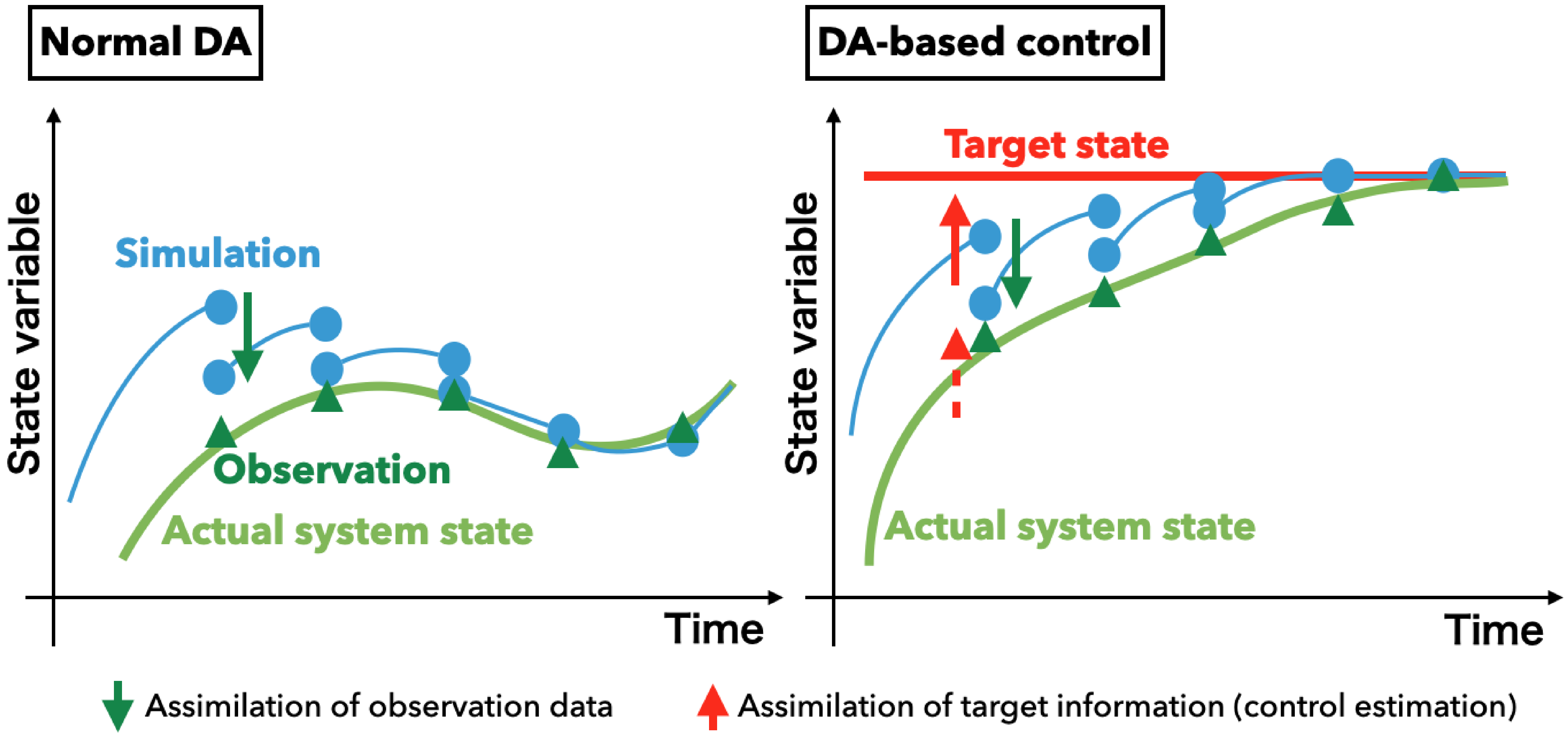
u-filter

Estimate the predicted distribution controlled by $\mathbf{u}^*_i$.

[Morishita+, J. Comput. Sci., 2023]

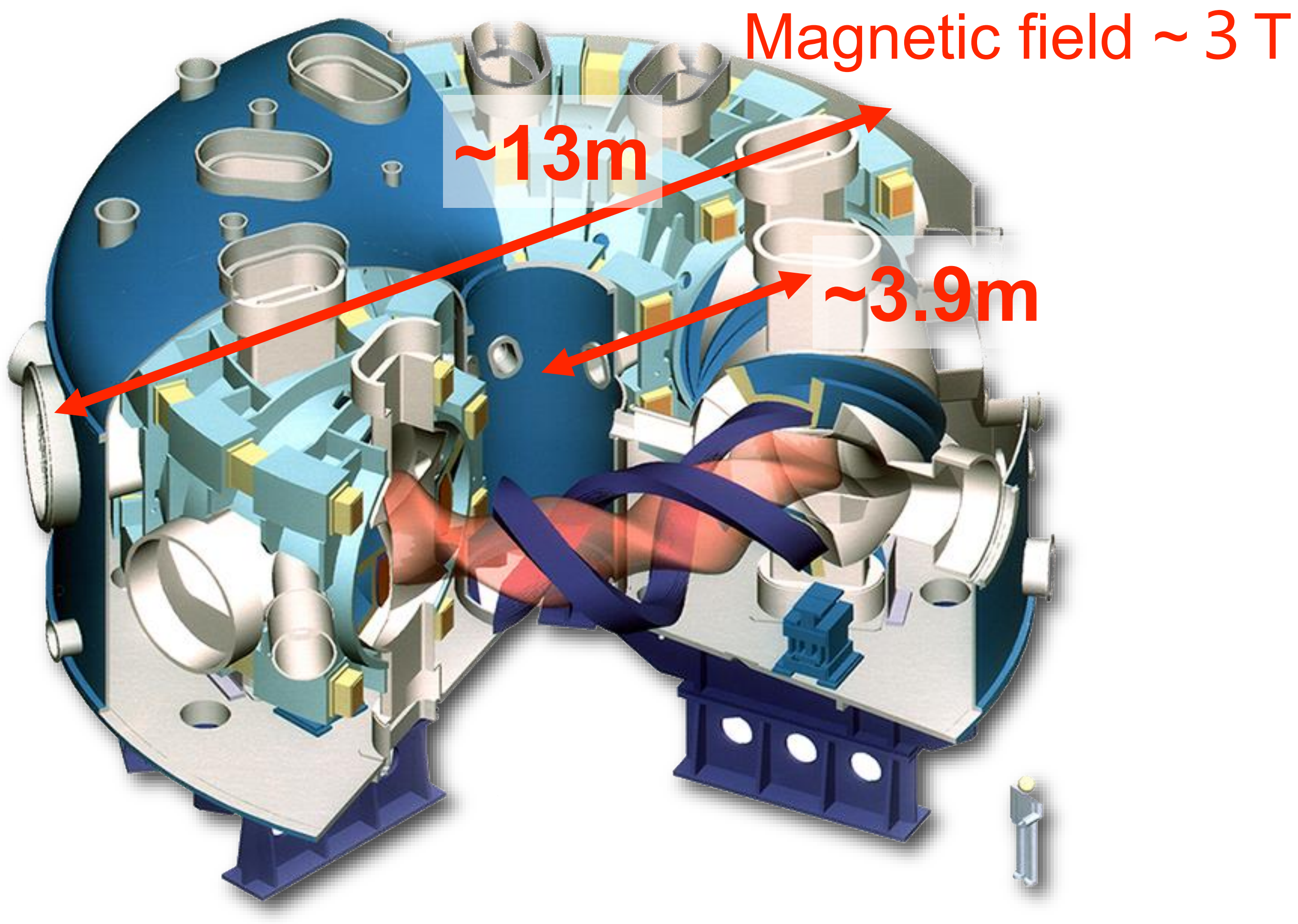
Data Assimilation-Based Control

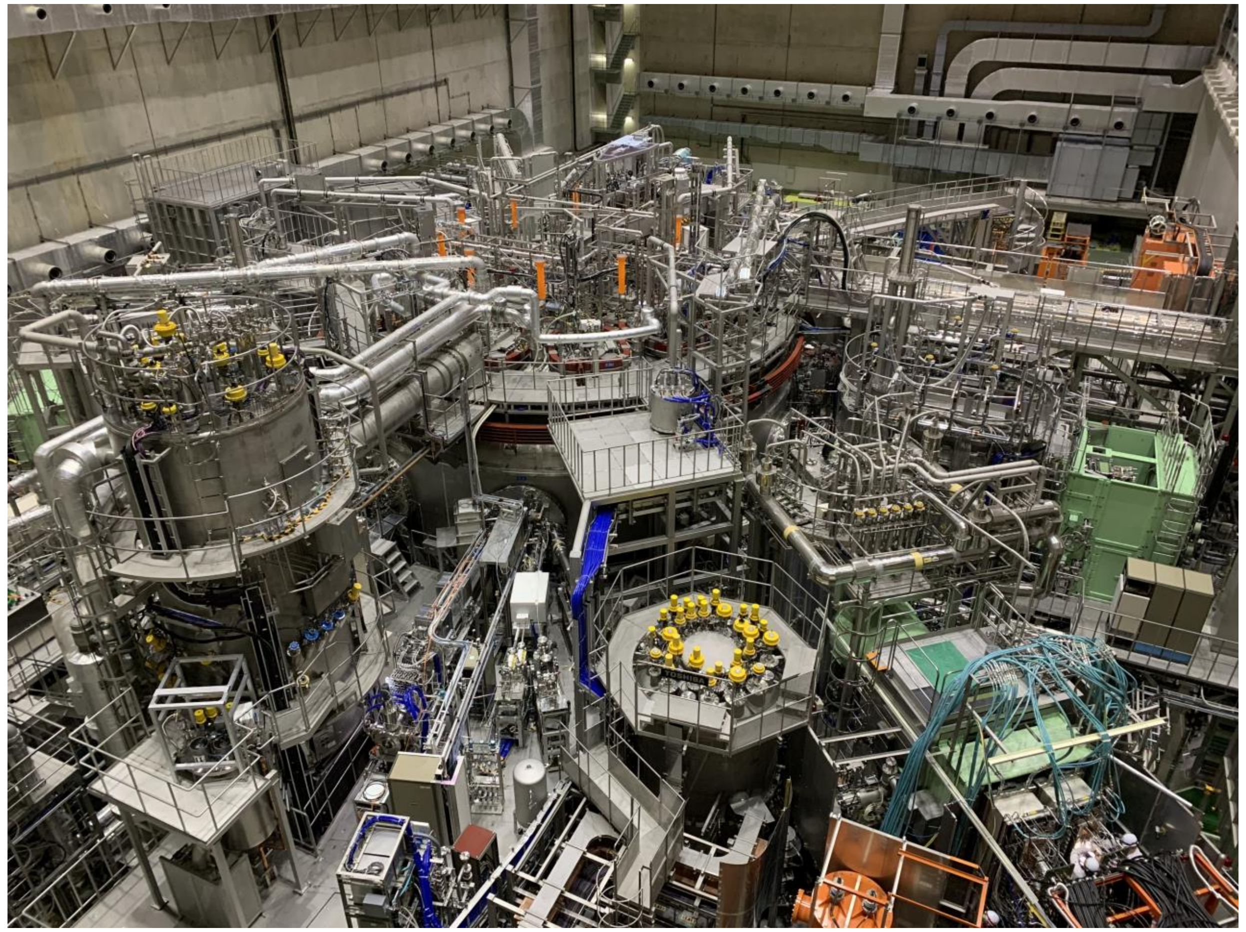
- We have developed a framework for adaptive predictive control that integrates system model updates and optimal control-input estimation.
- The DA-based control system predicts the state distribution while estimating control inputs and assimilates observations to estimate the system state, including model parameters.

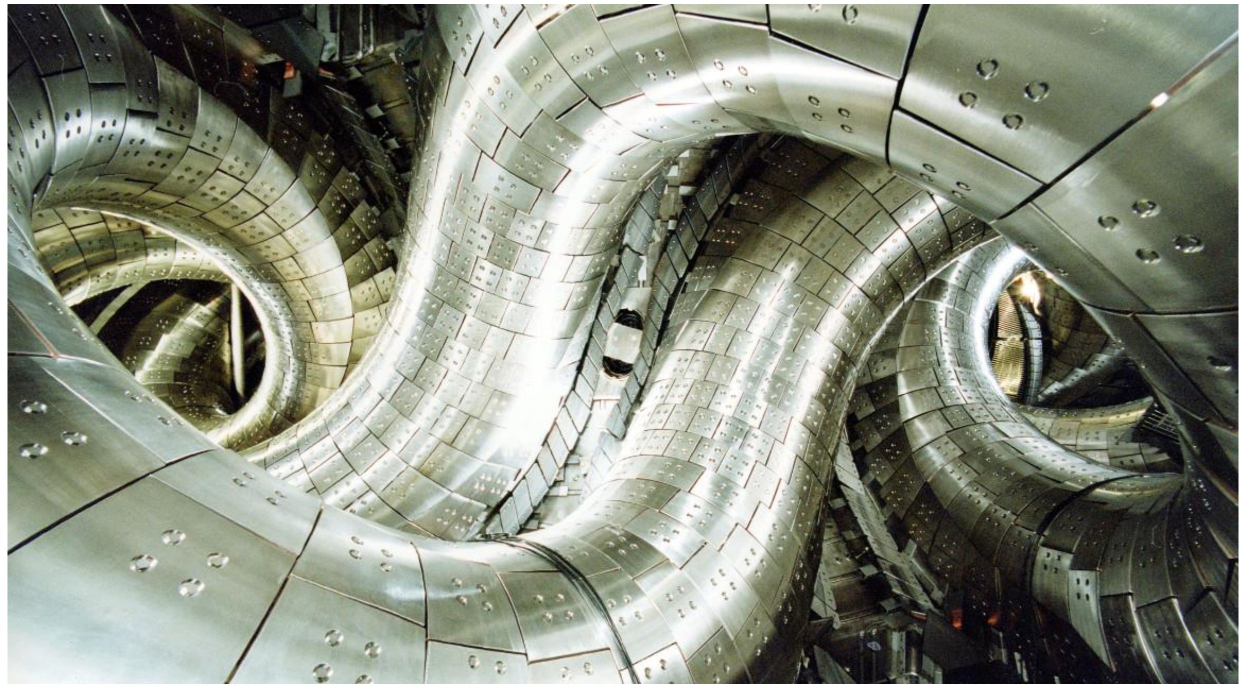


Large Helical Device (LHD)

LHD is one of the world's largest superconducting experimental devices for fusion plasma. It has a wealth of heating, fueling, and measuring equipment to conduct research on generating, maintaining, and controlling high-temperature plasma.

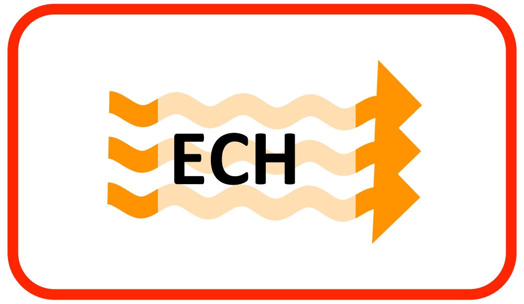






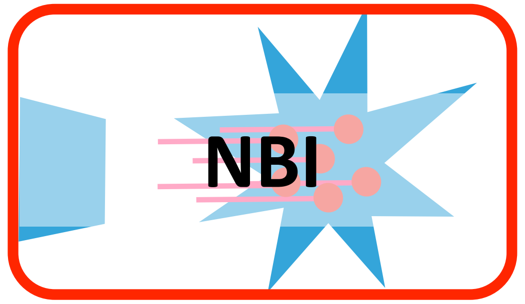
From https://www-lhd.nifs.ac.jp/pub/LHD_Project.html

Actuator in the demonstration experiments



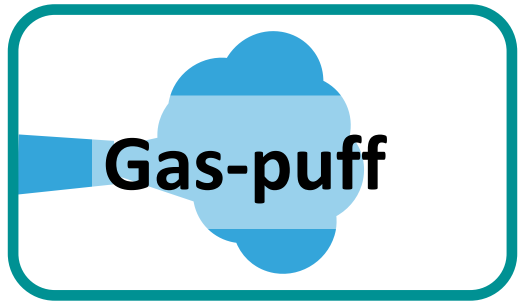
Electron Cyclotron Heating

- The ECH with two separate heating positions is used to control the radial profile of electron temperature.
- The two gyrotrons (total ~700 kW) are used for the heating at ρ=0, and the three gyrotrons (total ~1500 kW) are used for the heating at ρ=0.4.



Neutral Beam Injection Heating

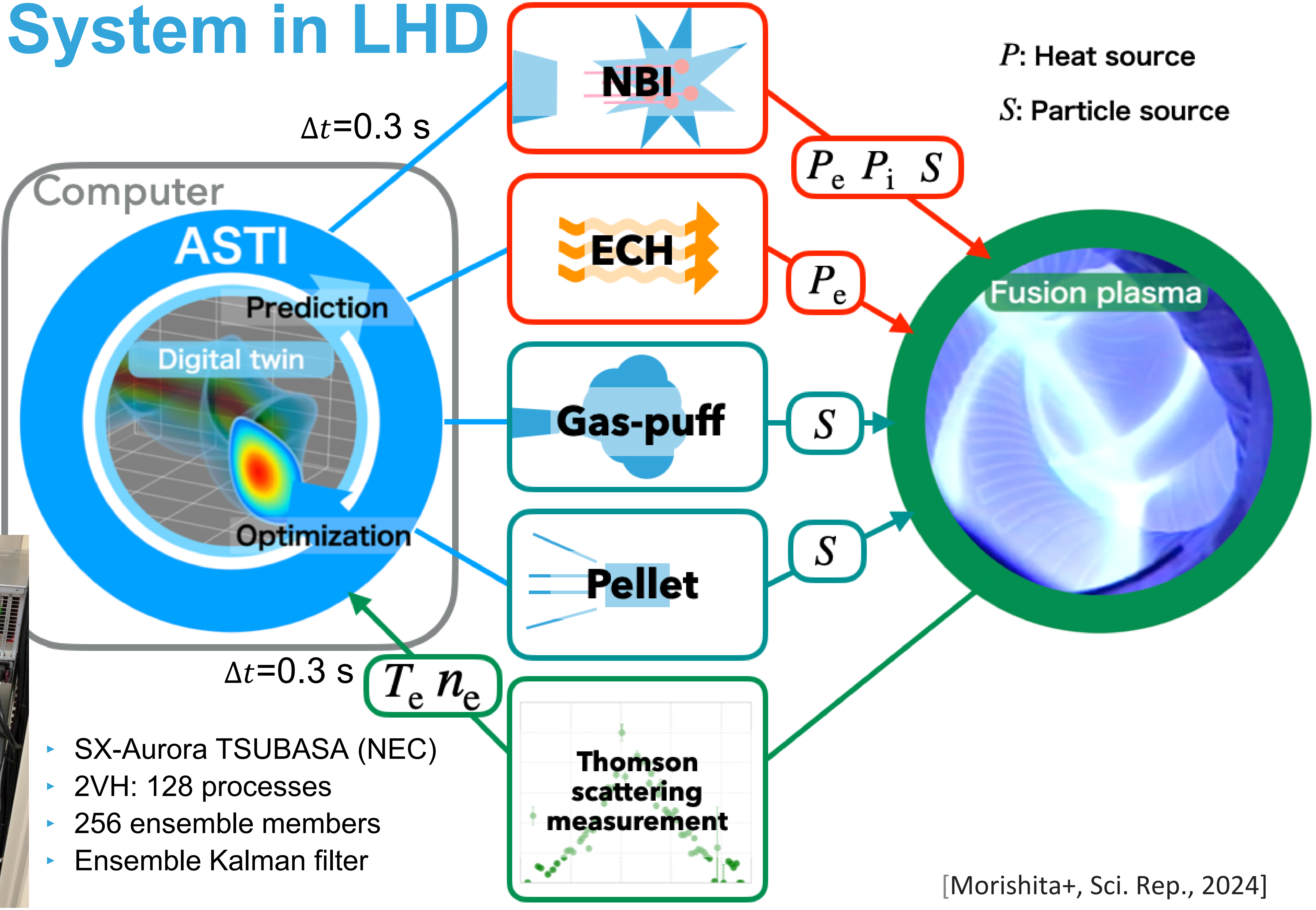
- The neutral beams are used primarily to control the ion temperature.
- Tangential: 3 beams, 180 keV beam particle
- Perpendicular: 4 beams, 40 keV beam particle

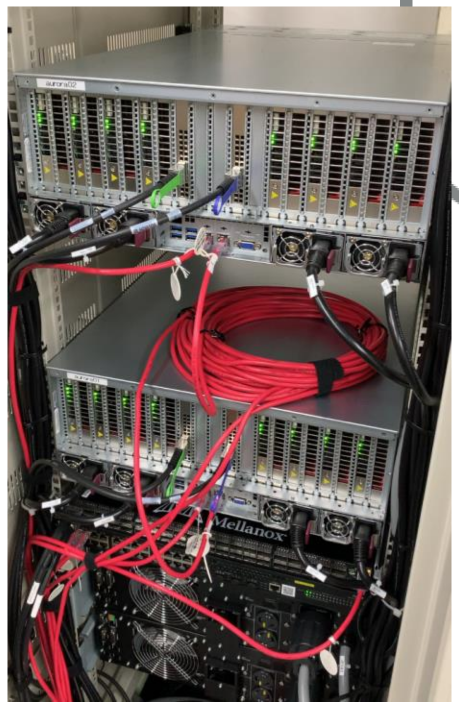


Gas puffing

- ASTI adjusts the frequency of pulsed gas-puff to control the density.

Control System in LHD





- SX-Aurora TSUBASA (NEC)
- 2VH: 128 processes
- 256 ensemble members
- Ensemble Kalman filter

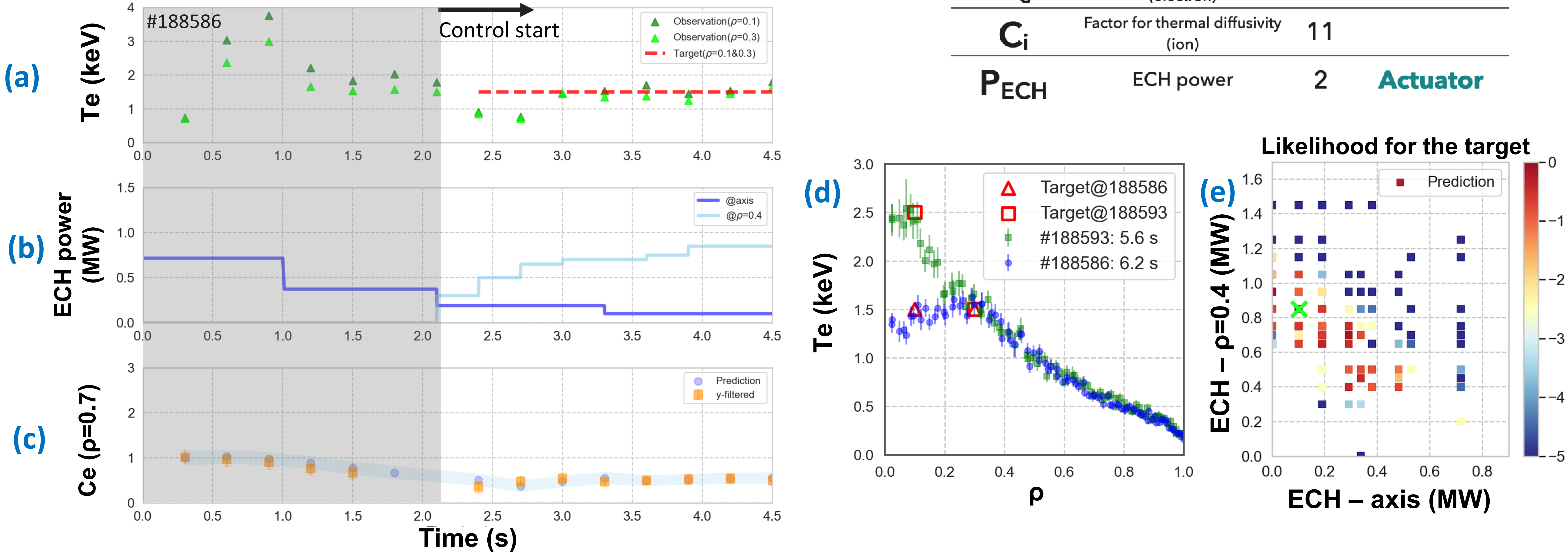
[Morishita+, Sci. Rep., 2024]

Real-Time T_e Profile Control

ASTI has successfully produced the target T_e profiles.

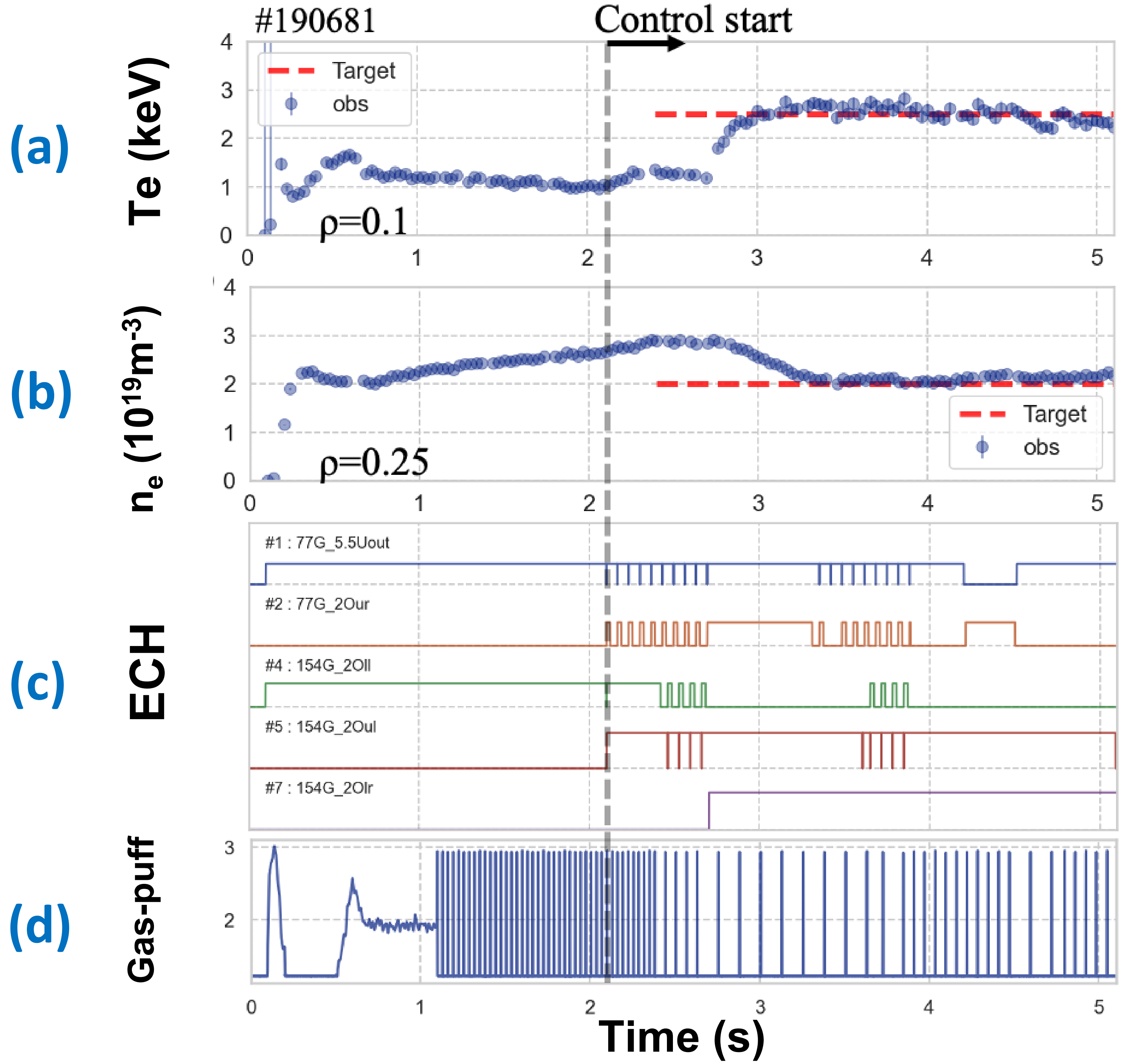
- Flat (#188586) : 1.5 keV(ρ=0.1) & 1.5 keV (ρ=0.3)
- Peaked (#188593): 2.5 keV(ρ=0.1) & 1.5 keV (ρ=0.3)

State variable		Dim	
T_e	Electron temperature	11	Obs, Target
T_i	Ion temperature	11	
n_e	electron density	11	Obs
C_e	Factor for thermal diffusivity (electron)	11	
C_i	Factor for thermal diffusivity (ion)	11	
P_{ECH}	ECH power	2	Actuator

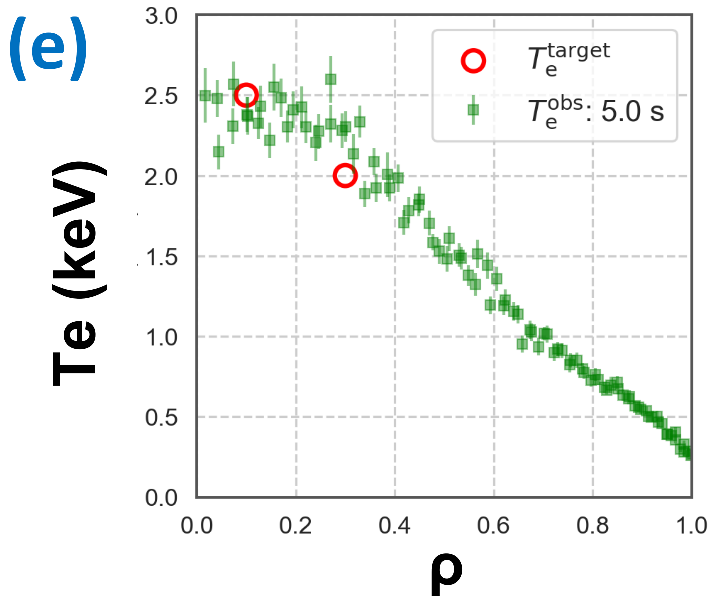


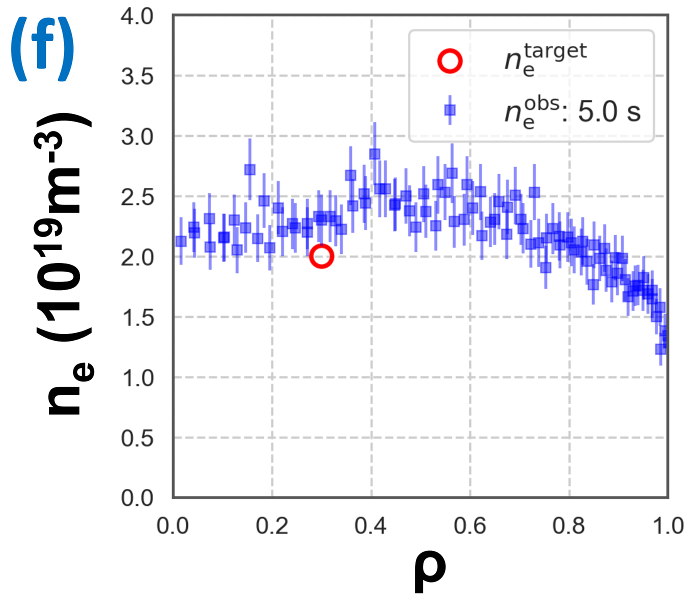
T_e profile and n_e Control

We have confirmed that the control system works appropriately and successfully produced the target T_e and n_e.

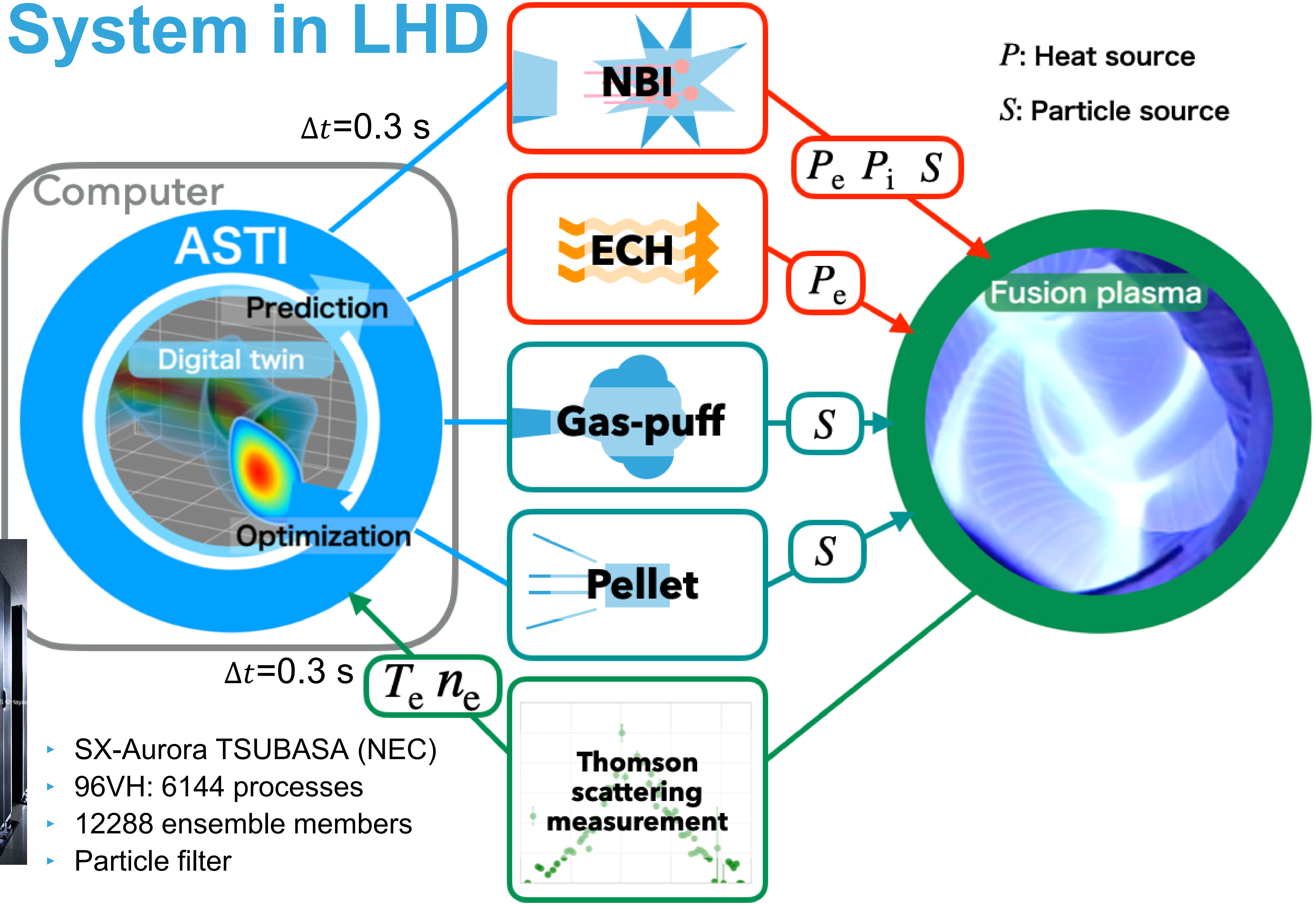


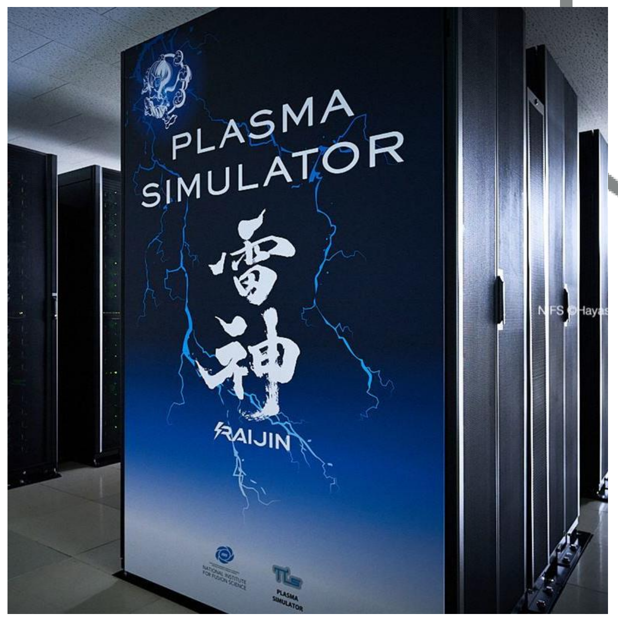
State variable		Dim	
T_e	Electron temperature	11	**Obs**, **Target**
T_i	Ion temperature	11	
n_e	electron density	11	**Obs**, **Target**
C_e	Factor for thermal diffusivity (electron)	11	
C_i	Factor for thermal diffusivity (ion)	11	
D	Factor for particle diffusivity	11	
V	Particle convection velocity	10	
g	Parameter in gas-puff model	1	
P_{ECH}	ECH power	2	**Actuator**
f_{GP}	Pulsed gas-puff frequency	1	**Actuator**





Control System in LHD



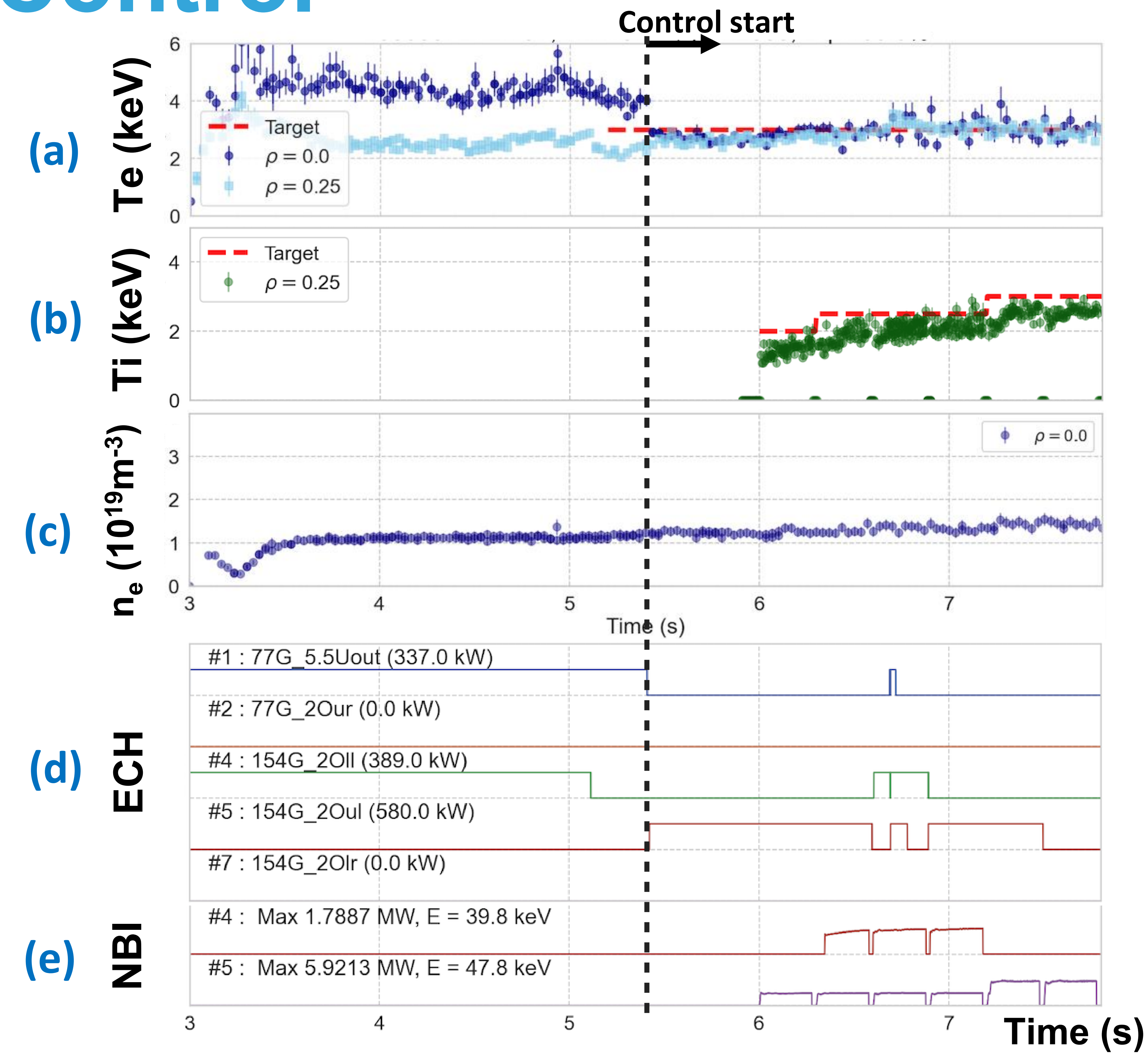


- SX-Aurora TSUBASA (NEC)
- 96VH: 6144 processes
- 12288 ensemble members
- Particle filter

Real-Time T_e and T_i Control

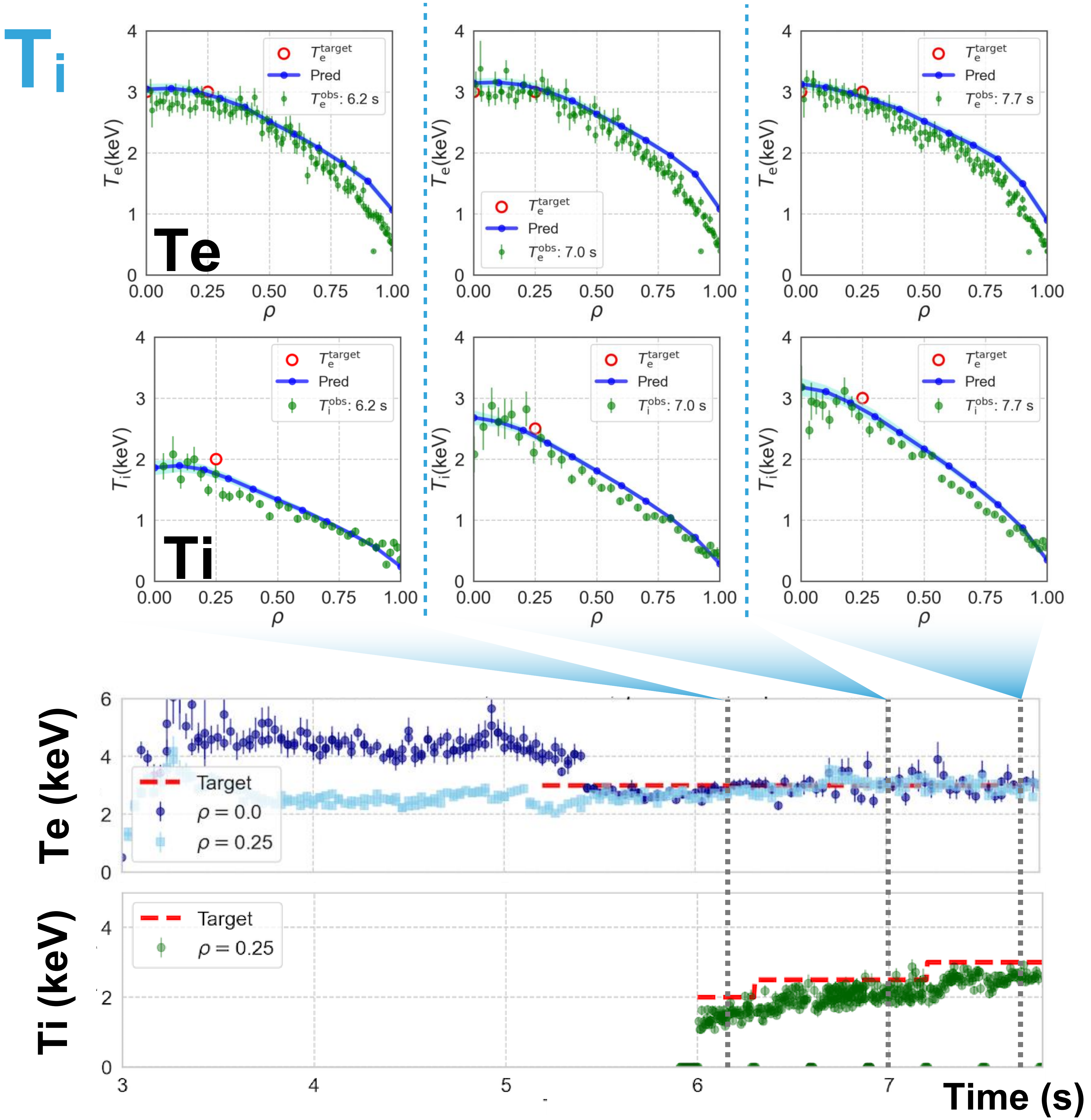
- We have successfully produced the target T_e and T_i using the ECH and NBI heating.
- ASTI provides good Ti control (error of about 0.1-0.3keV) **without real-time observation of Ti.**

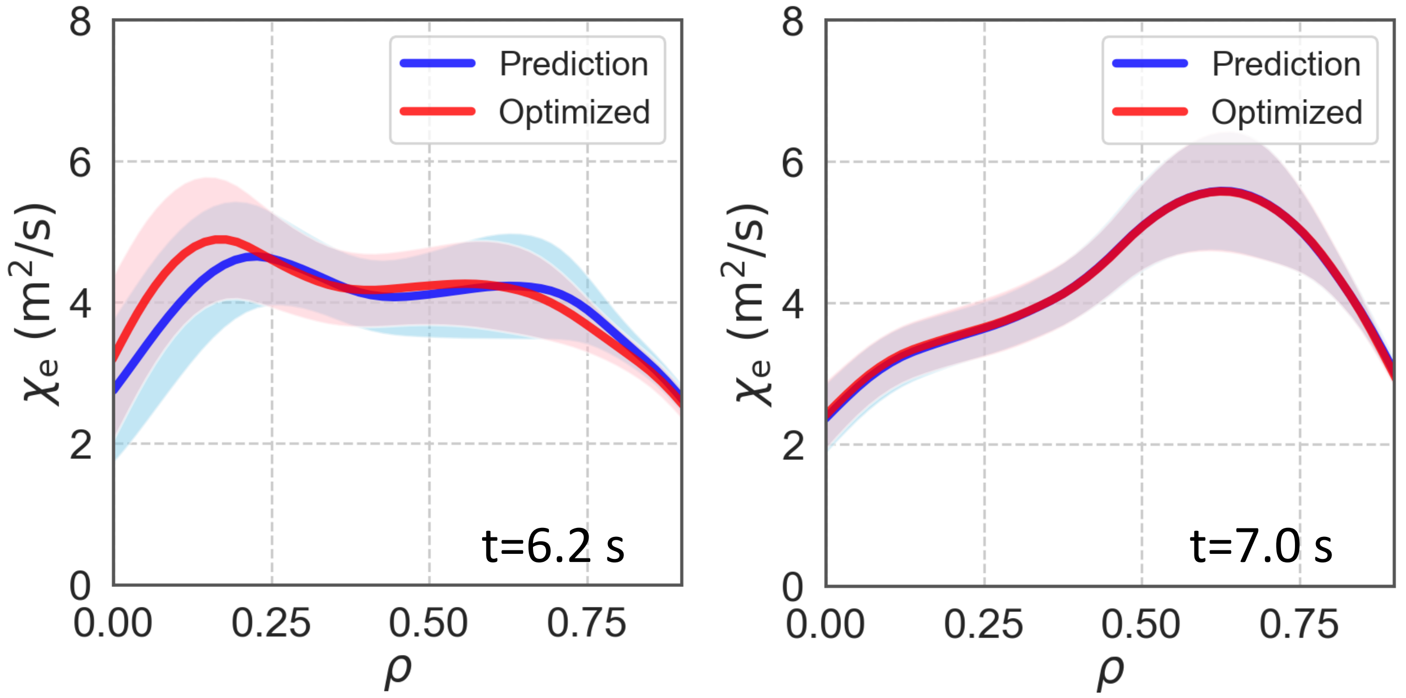
State variable		Dim	
T_e	Electron temperature	11	Obs, Target
T_i	Ion temperature	11	Target
n_e	electron density	11	Obs
C_e	Factor for thermal diffusivity (electron)	11	
C_i	Factor for thermal diffusivity (ion)	11	
v_c	Parameter in NBI model (critical velocity)	11	
P_{ECH}	ECH power	2	Actuator
P_{NBI}	NBI heating power	1	Actuator



Radial Profiles of T_e and T_i

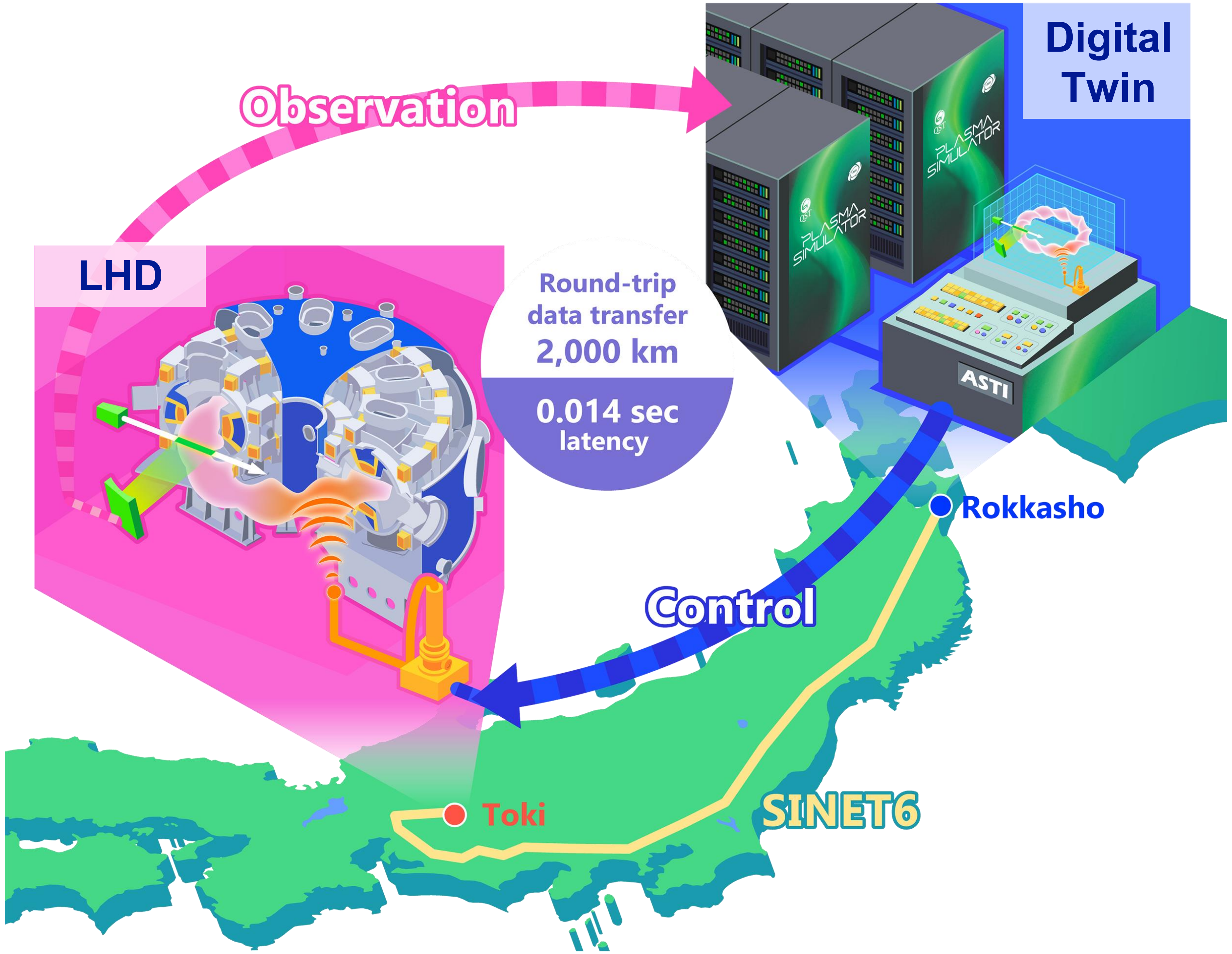
- Both electron and ion temperatures meet the conditions of the target state with high accuracy.
- The model parameters (e.g., thermal diffusivities) are adjusted using the real-time observations.
- Control of ion temperature without real-time observations has been realized through the digital twin.





Plasma control by a remote supercomputer

- The supercomputer, ***Plasma Simulator***, was replaced with a new one installed at the Rokkasho site.
- To explore advanced control using the particle filter, which requires significant computational resources, we connected the LHD to the new Plasma Simulator, located 1000 km away.
- Real-time LHD control by ASTI on the Plasma Simulator was achieved with a latency of only 0.014 s.
- For the control experiment, 20,000 CPUs of the Plasma Simulator were assigned, allowing ASTI to utilize up to 40,000 ensemble members.



Summary

- We have developed the data assimilation system ASTI to predict and control the behavior of fusion plasmas in real time.
- Extending the general DA framework, we have introduced a framework for adaptive predictive control that integrates system model updates and optimal control-input estimation.
- In LHD, the ECH, gas-puff, NB, and real-time Thomson scattering measurement systems have been successfully connected to ASTI. We have conducted some demonstration experiments and successfully controlled T_e profile, n_e, and T_i.
- Real-time LHD control by ASTI on the Plasma Simulator, which is located 1,000 km away, was achieved with a latency of only 0.014 s.
- ASTI is being further developed toward comprehensive control of tokamak plasmas.
- The digital twin control applying data assimilation can become a key technology for solving challenging control problems in future fusion reactors.

LHD experiments in 2025 (Oct.-)

- We will conduct further experiments to demonstrate real-time multivariate control of electron and ion temperatures and density, using the extended ASTI control system.
- The ASTI system will be operated on the new Plasma Simulator in Aomori Prefecture.