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Integrated Transport Simulation of LHD Plasma Applying Data Assimilation Technique

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ABSTRACT

Data assimilation techniques are applied to the integrated transport simulation (TASK3D) in Large Helical Device (LHD). We employ the ensemble Kalman filter (EnKF) and the ensemble Kalman smoother (EnKS) as data assimilation methods. The time series data of experimentally measured temperature and density profiles are assimilated into the particle and heat transport simulation. The obtained temperature and density profiles and temporal variations agree well with measured ones due to the employed model parameters' optimization. These results indicate the effectiveness and validity of the data assimilation approach for accurate prediction of the behavior of fusion plasmas and the possibility of advanced transport modeling.

BACKGROUND

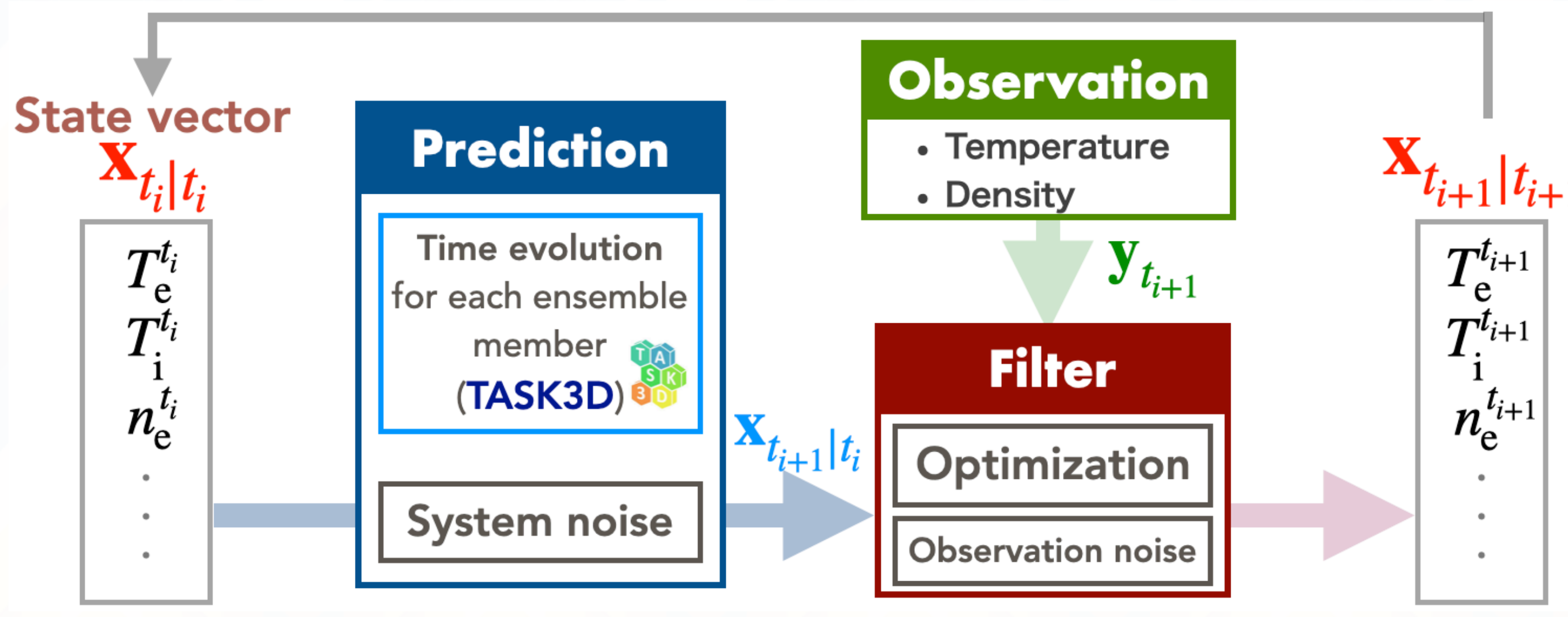
Integrated simulation codes for fusion plasmas have been developed in order to analyze, predict and control the behavior of the plasmas. The present integrated simulations of fusion plasmas have some problems.

- It has various uncertainties in each of the employed simulation models. Thus, the simulation results also have uncertainties and it is difficult to predict the behavior of fusion plasmas with high accuracy.
- More than one simulation model with each uncertainty can not be optimized simultaneously.

To solve these problems, we have introduced data assimilation techniques into the integrated simulation.

DATA ASSIMILATION SYSTEM

- We are developing a data assimilation system, **ASTI** based on the integrated transport simulation code, **TASK3D** to predict and control the behavior of fusion plasmas with high accuracy [Y. Morishita *et al.*, NF(2020) & PFR(2021)].
- ASTI can also be used to estimate the variables which can not be observed and the model parameters that can reproduce experimental time series data.



State vector $\mathbf{x}_{t_i|t_i}$

$T_e^{t_i}$, $T_i^{t_i}$, $n_e^{t_i}$, ⋮

Prediction

Time evolution for each ensemble member (TASK3D)

System noise

$\mathbf{x}_{t_{i+1}|t_i}$

Observation

- Temperature
- Density

$\mathbf{y}_{t_{i+1}}$

Filter

Optimization

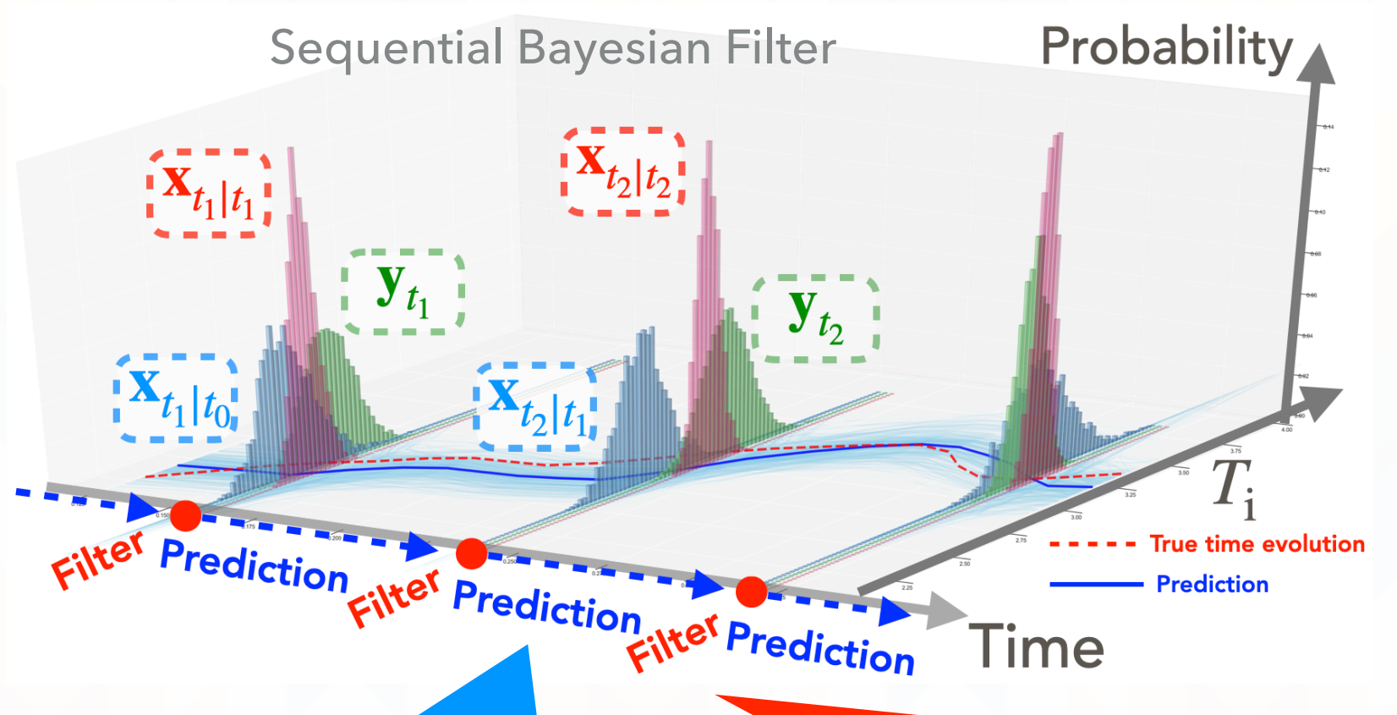
Observation noise

$\mathbf{x}_{t_{i+1}|t_{i+1}}$

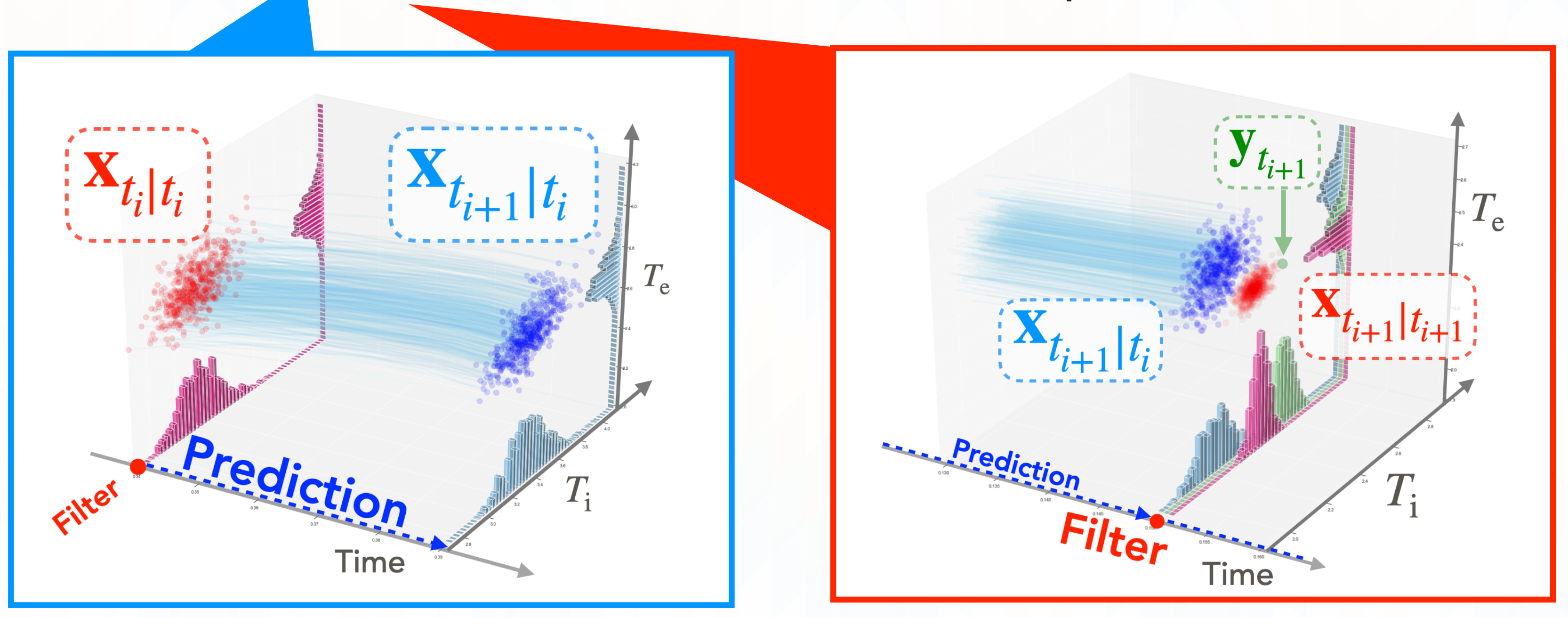
$T_e^{t_{i+1}}$, $T_i^{t_{i+1}}$, $n_e^{t_{i+1}}$, ⋮

Data Assimilation

- Data assimilation is one of the statistical estimation methods. It finds the optimum combination of a numerical model and observation to estimate the state of a system more accurately.
- The procedure of data assimilation (**Sequential Bayesian Filter**) is a loop of prediction and filtering.
- The filter optimizes the state vector to enhance the prediction capability and reproducibility of the simulation model based on the observation data.



- **Ensemble Kalman Filter** (EnKF) assumes a nonlinear system model and the Gaussian distribution as the probability distribution.
- The probability distribution of state vector is approximated by an ensemble.



- Temporal variations of the filtered estimates have a time delay from measured values, because the EnKF optimizes the state vector using only past data. **Ensemble Kalman smoother** (EnKS) corrects the filtered estimates of EnKF using future data (posterior to the time of filtering) [G. Evensen, Ocean Dynamics (2003)].

ASSIMILATION RESULTS

- We apply ASTI to particle and heat transport of NBI heated plasma in LHD.
- We define the state vector as the following table.
- This assimilation is performed with 1000 ensemble members for assimilation cycle 80 msec.

State variable			System noise
n	: Plasma density	Observed variables	10%
T_e, T_i	: Ion and electron Temperature		10%
d	: Particle turbulent diffusivity		20%
c_e, c_i	: Thermal turbulent diffusivity		20%
v	: Convection velocity	In transport model	15%
$f_{180\mathrm{keV}}$, $f_{40\mathrm{keV}}$	: Fast ion birth profile of NBI		5%
v_c	: Critical velocity		5%
t_{sd}	: Slow down time	In NBI heating model	5%
n_n	: Neutral density @ edge		10%
T_n	: Neutral temperature @ edge	In particle source model	10%

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

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

Variables in the state vector

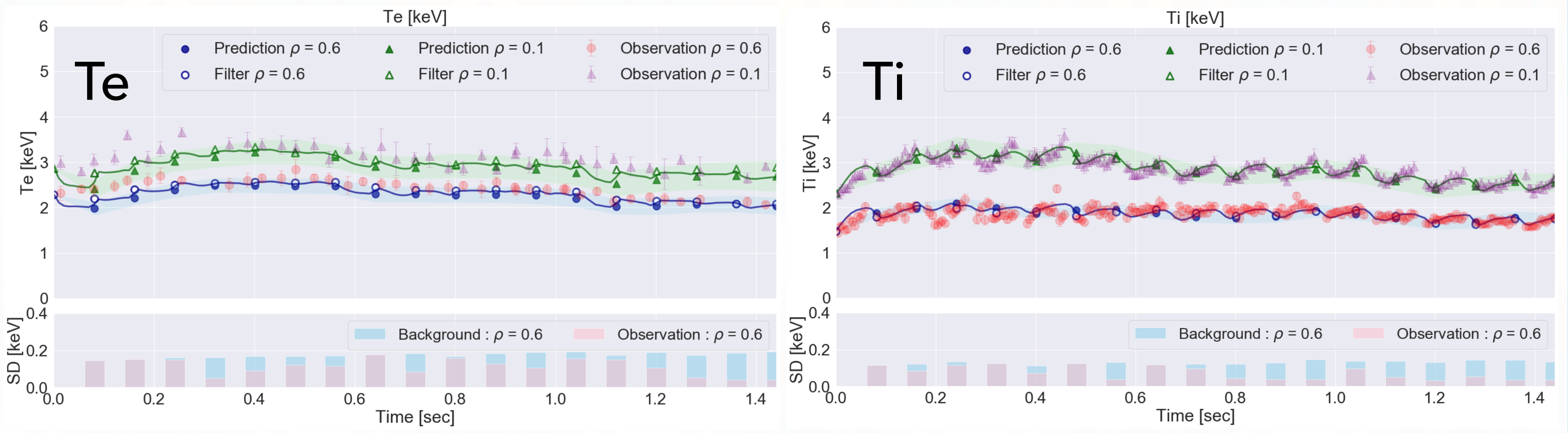
- **Theramal turbulent diffisivity**
  $\chi_s^{\mathrm{TB}*} = c_s \chi_s^{\mathrm{TB}}$
- **Particle turbulent diffusivity**
  $D^{\mathrm{TB}*} = d D^{\mathrm{TB}}$
- **Convection velocity**
  $V^* = V + v$

$\chi_e^{\mathrm{TB}} = C_e \frac{T_e}{eB}\frac{\rho_i}{a}$

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

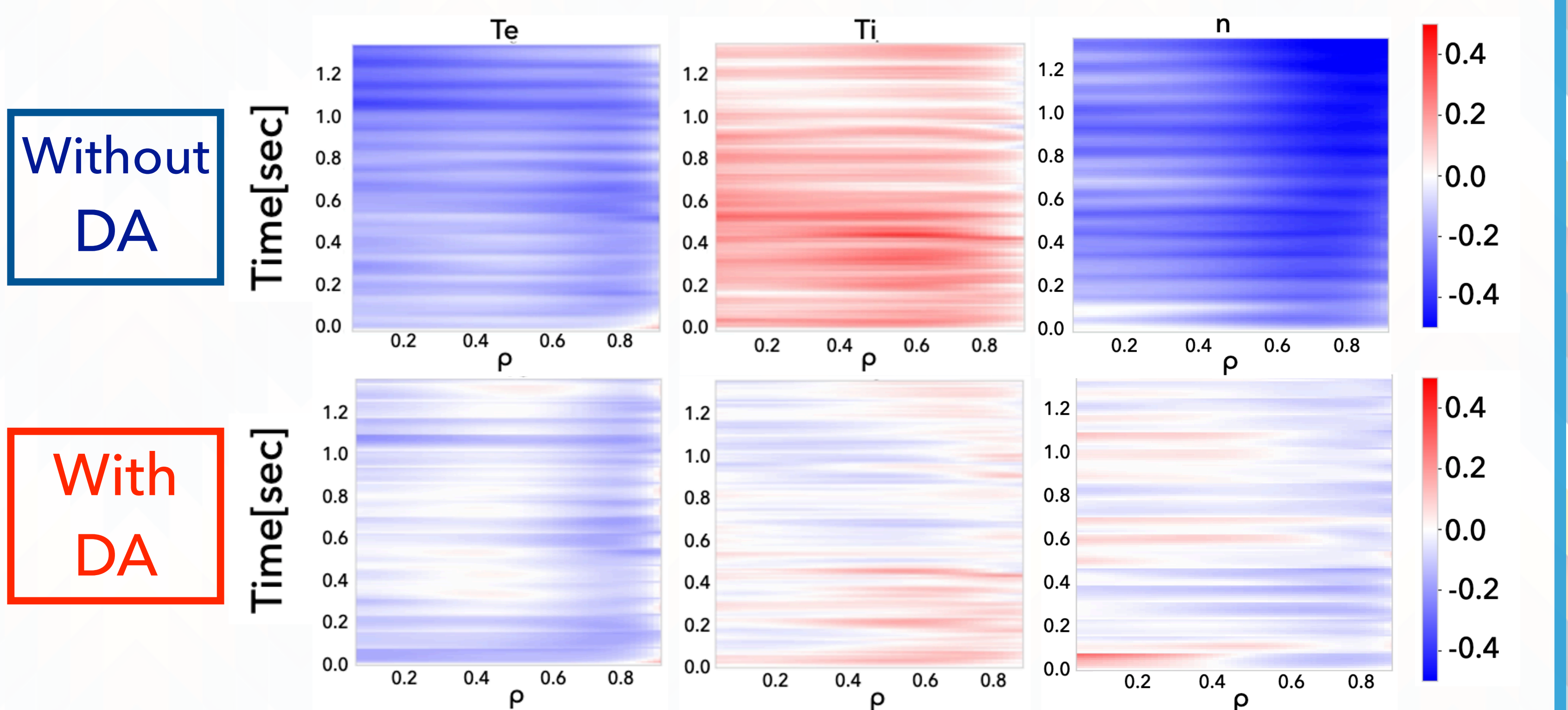
$D^{\mathrm{TB}} = \mathrm{constant}$

- The obtained temperature and density (not shown) profiles and temporal changes agree well with measured ones



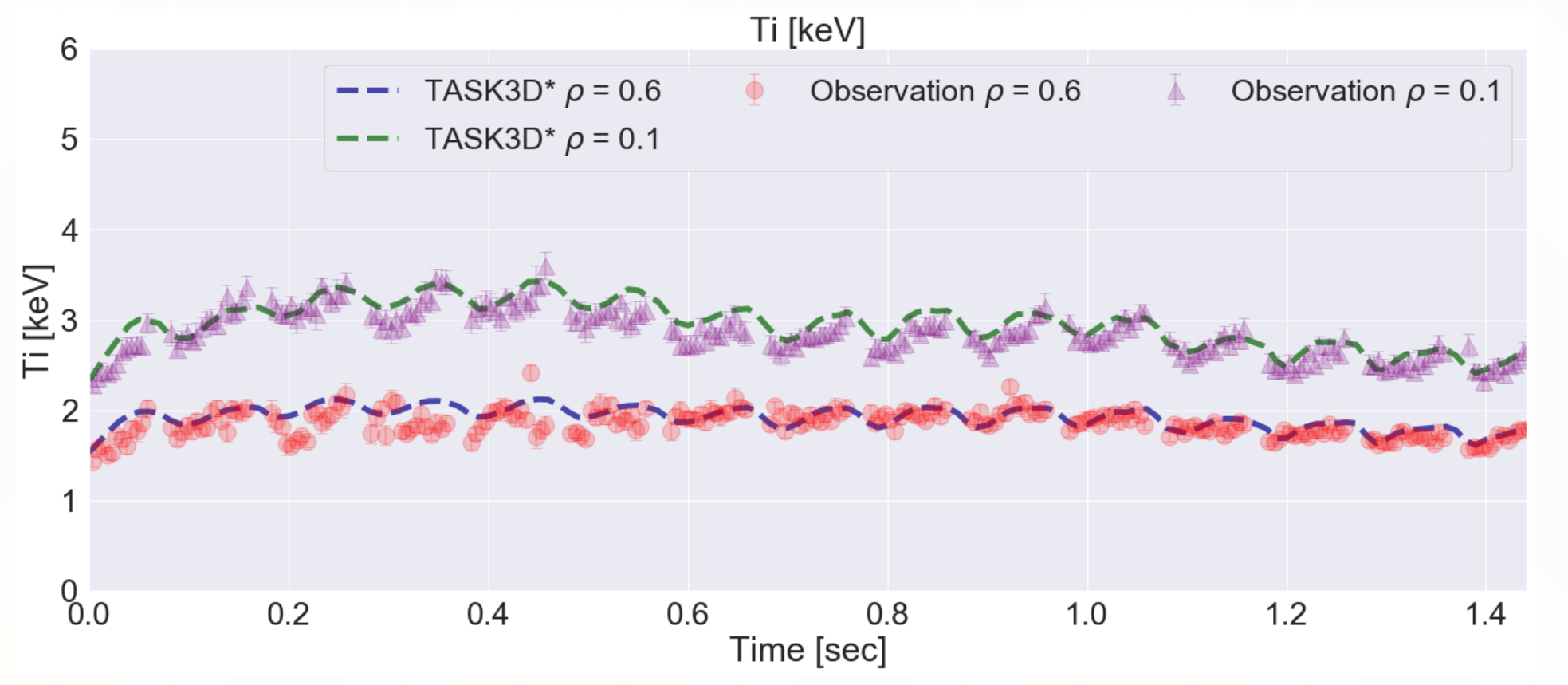
Prediction and filtered estimates of temperature for ρ=0.1 & 0.6 (normalized minor radius).

- At almost all times, the error rates of prediction by ASTI (row labeled 'With DA') are less than 0.1 in both temperature and density, while those by TASK3D ('Without DA') are greater than 0.3. (error rate = (prediction - obs.)/obs.)



Space-time distribution of prediction error rates of temperature and density.

- We can confirm that the TASK3D simulation using the smoothed estimates of model parameters by the EnKS can reproduce the experimental time series data with high accuracy. This indicates the validity of the EnKS estimation.



TASK3D simulation of T_i using the smoothed estimates of simulation model parameters.

CONCLUSION

- We have developed the data assimilation system, ASTI for the particle and heat transport simulation of LHD plasmas.
- We have applied ASTI to the experimental time series data of NBI heated plasma in LHD. The obtained density and temperature radial profiles and temporal variations have been agreed well with measured ones. Moreover, we have confirmed that the simulation using the smoothed estimates of model parameters can reproduce the observation time series data with high accuracy.
- These results indicate the effectiveness and validity of data assimilation (ASTI) for accurate prediction and analysis of fusion plasma behavior.

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