# Development of the turbulence-transport coupling simulation framework for the edge plasma

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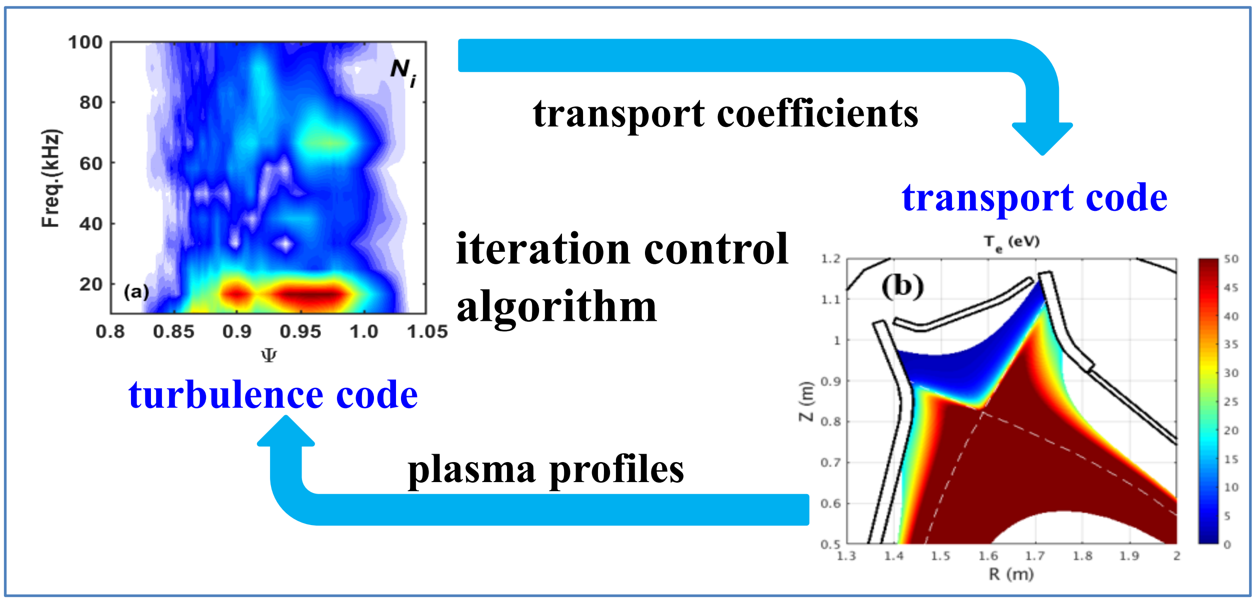
# Outline

# Motivation

- It is essential to perform **self-consistent** turbulence-transport simulation of the edge plasma in predicting the performance of fusion devices

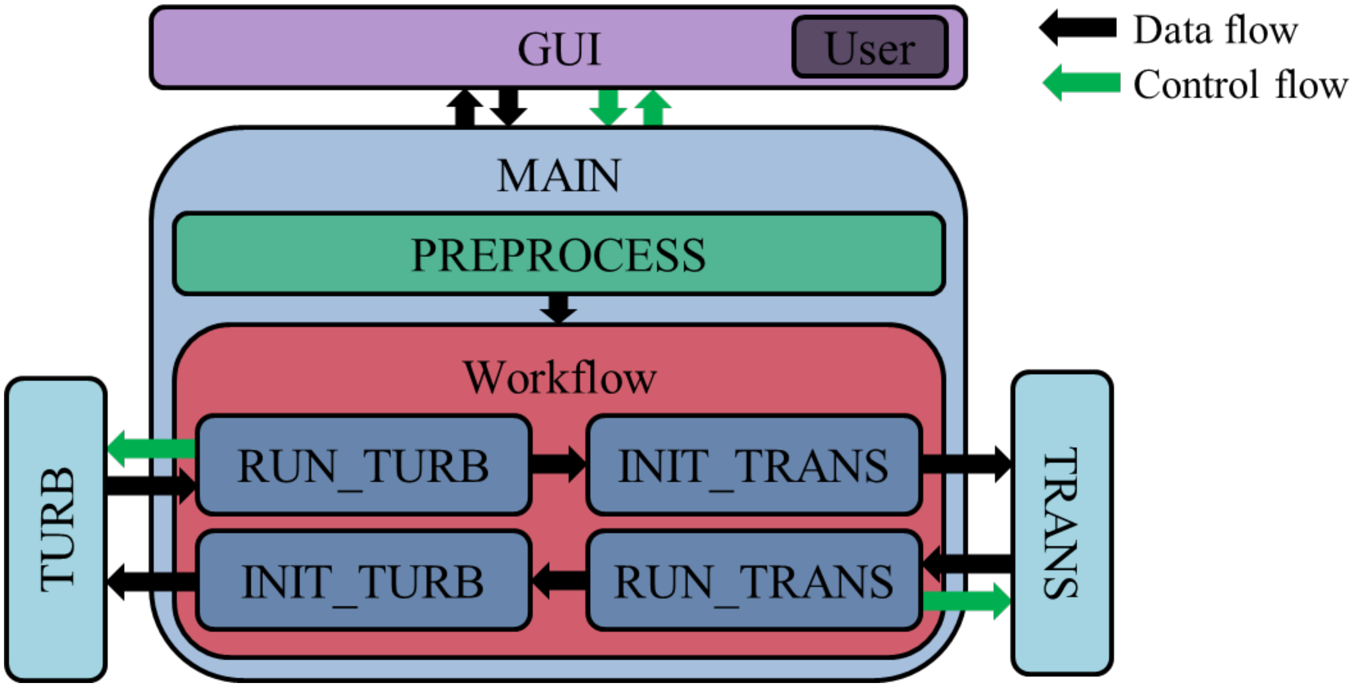
**An efficient and flexible way:**

**Coupling the turbulence (like BOUT++) and transport (like SOLPS-ITER) codes inside a framework with well developed interfaces and acceleration algorithms**



# Outline

# Turbulence-transport coupling simulation framework




**A multiscale simulation framework is developed to build complex workflows**

**Components：**

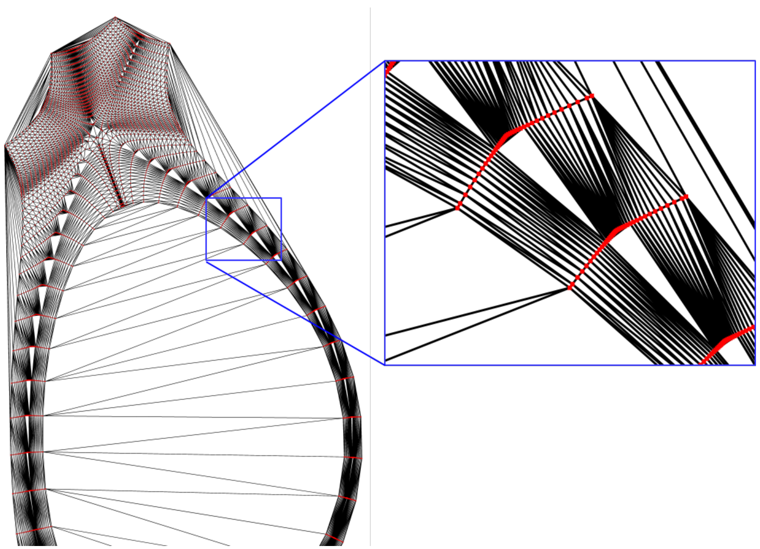
- **2 fundamental modules (TURBulence module and TRANSport module): basic file I/O interfaces and data processing routines**
- **4 core modules: data transfer interfaces (INIT_TRANS and INIT_TURB) and code running drivers (RUN_TRANS and RUN_TURB)**
- **PREPROCESS module: generate initial inputs for core modules based on user configurations**
- **MAIN function: turbulence-transport coupling workflow using core modules**

# Spatial scale coupling

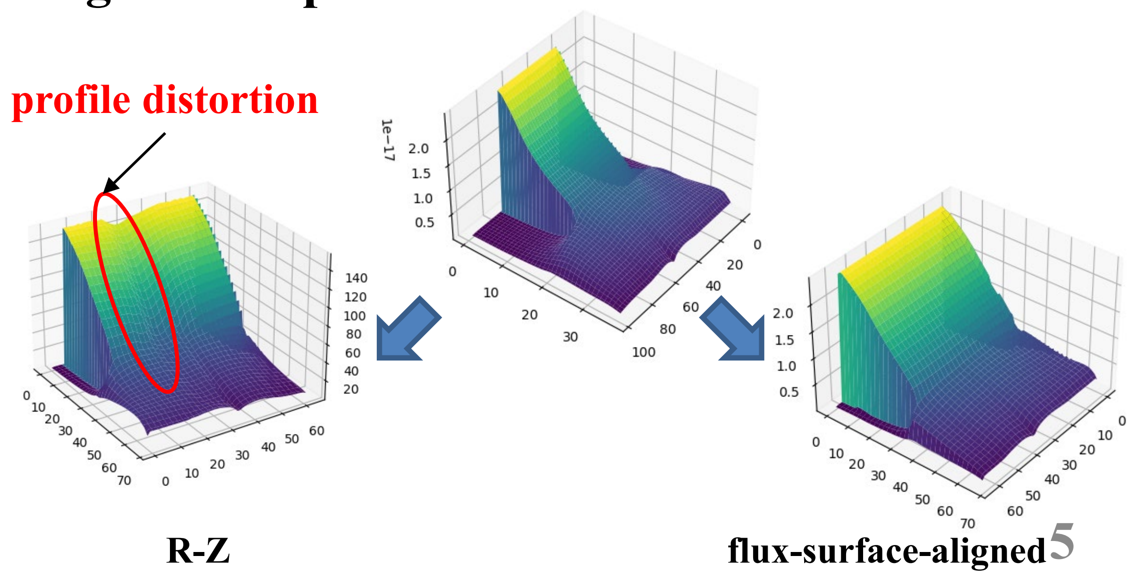
**Due to the different spatial scales of turbulence and transport processes, the resolution of computing grid varies greatly among different codes. Thus, it is necessary to develop a grid interpolation algorithm**

- **Unstructured grid: based on triangulation algorithm**
- **Structured grid: based on Breadth-First Search (BFS) algorithm**
  - **Use flux-surface-aligned coordinate to improve the accuracy of interpolation**
  - **Use higher-order interpolation algorithm to improve the robust of simulation**

**triangulation on SOLPS grid**

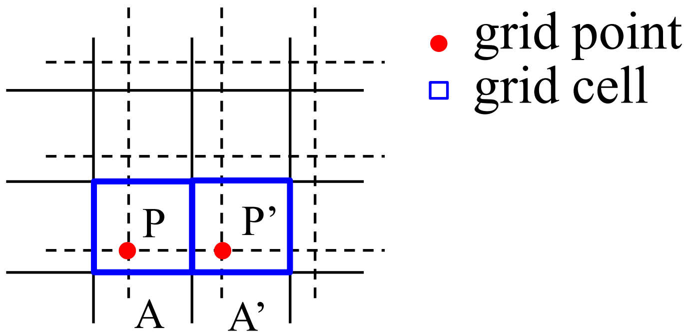


**grid interpolation under different coordinates**



# Structured grid interpolation

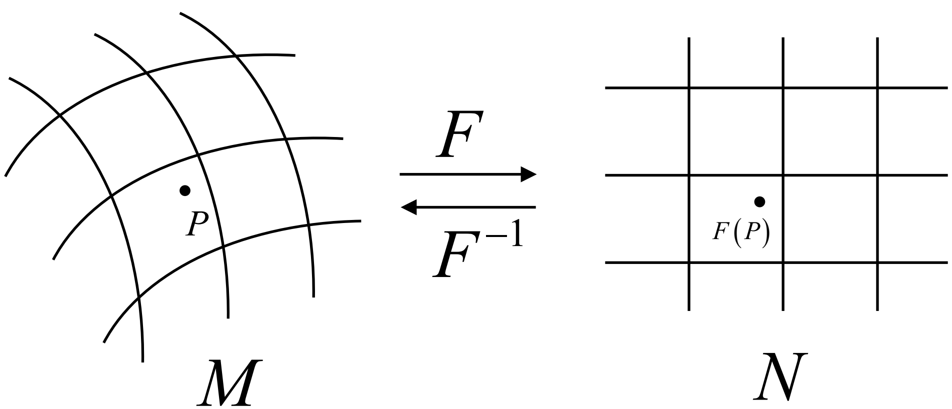
- **BFS algorithm**

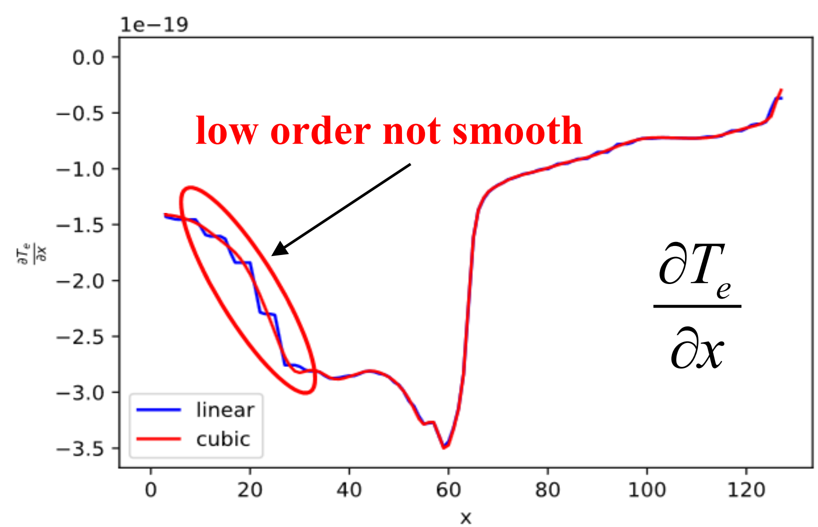



| Topology | SOLPS grid | BOUT++ grid | Elapsed time (per 100 times) |
|---|---|---|---|
| USN | 36×96 | 68×64 | 8.3s |
| | | 128×64 | 12.5s |
| | | 260×64 | 20.8s |
| LSN | 36×64 | 200×64 | 14.6s |

- **Higher-order interpolation algorithm**

- **Use higher-order regular grid interpolation to define a smooth function $F^{-1}$**
- **Use BFS algorithm above and root-finding method to get function $F$**



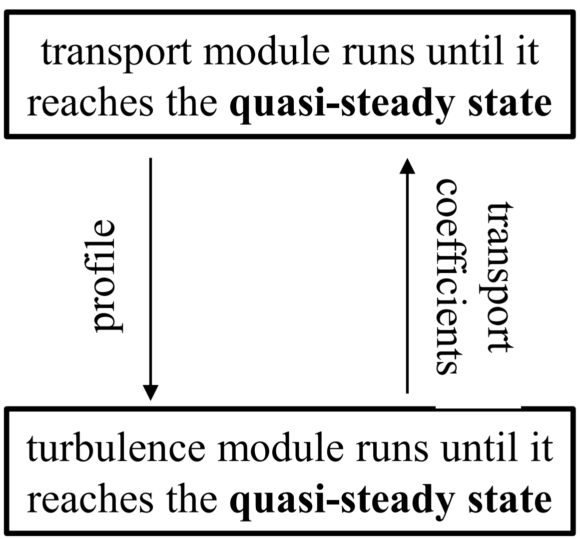
# Temporal scale coupling

**Different temporal scale coupling schemes can be implemented by designing different workflows using the component-based approach**

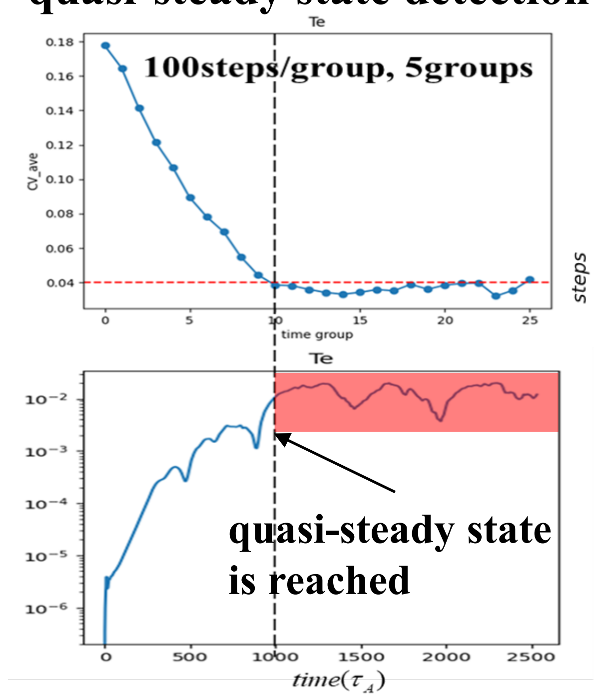
**Computation speedup for turbulence simulation：**

- **Develop a quasi-steady state detection method to terminate the simulation**
- **Use the state from the end of the previous iteration as the initial condition**

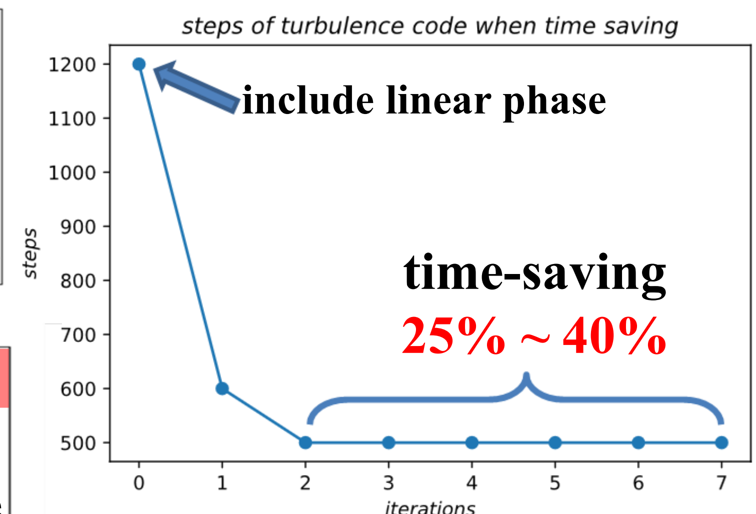
**steady state coupling workflow**



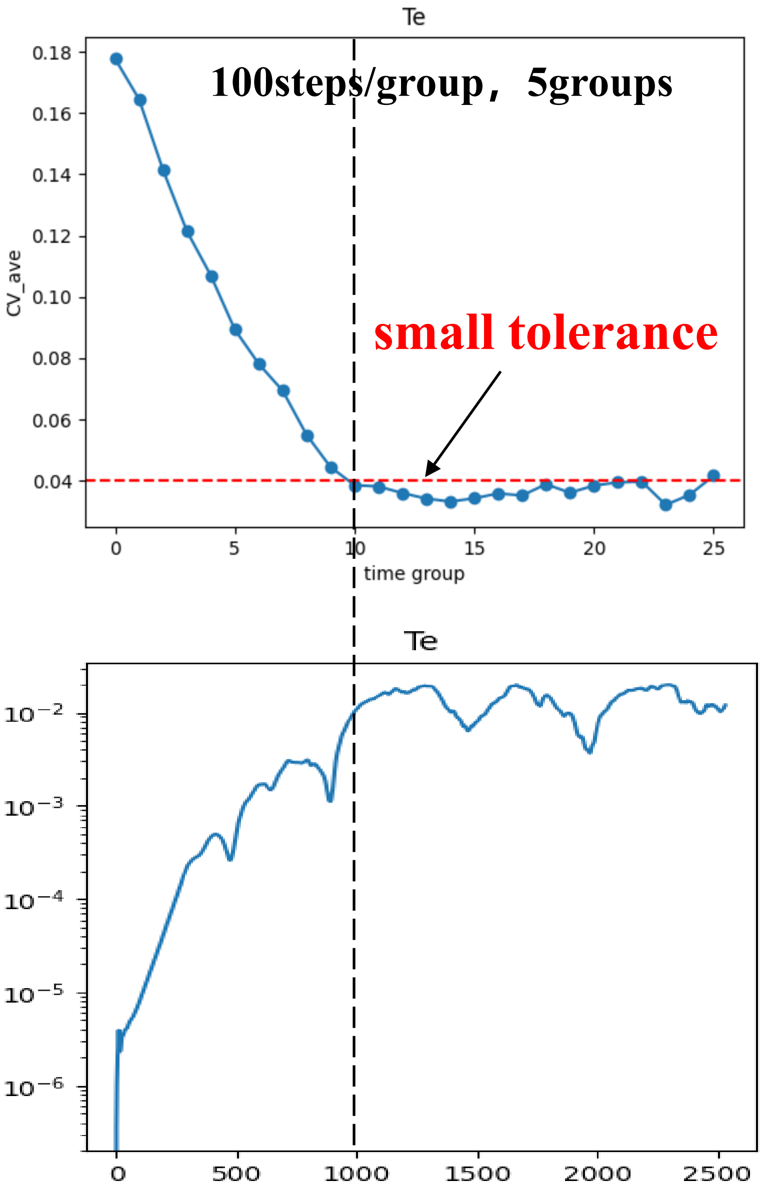

**quasi-steady state detection**




**computation speedup**



# Quasi-steady state detection




$$\textit{Coefficient of Variation} \equiv \frac{\textit{Standard Deviation}}{\textit{Mean}}$$

- **When turbulence simulation reaches nonlinear quasi-steady state, CV falls within some small tolerance**
- **CV is calculated from the latest time-step groups, each group contains several time steps**

# Outline

1 Motivation

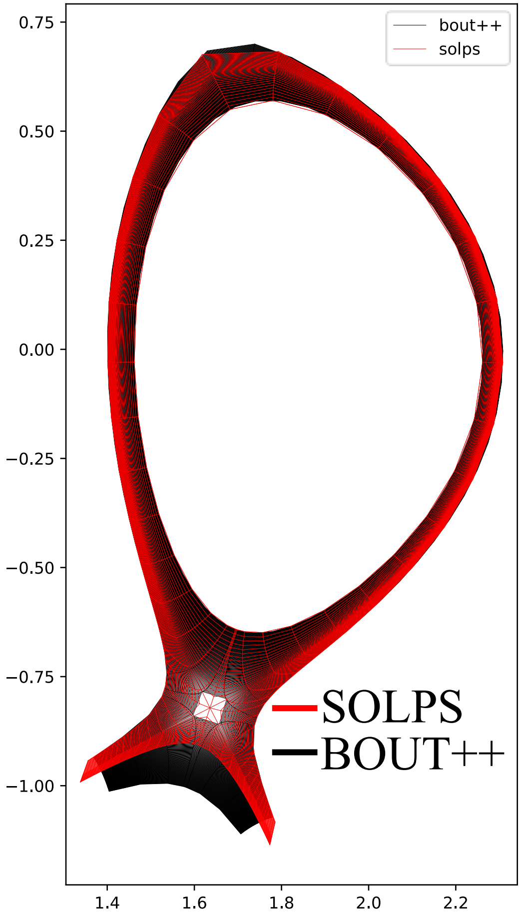
2 Development of the framework

3 **Validation for steady state coupling workflow**

4 Summary

# Simulation setup

- Transport: SOLPS-ITER; Turbulence: BOUT++ 6-field model
- According to Zhang et al.'s work [1, 2], The steady state coupling workflow is validated based on EAST H-mode (Shot#56129 t=5551ms )




Normalized poloidal flux $\psi = 0.85 \sim 1.05$

transport:

plasma profiles $n_i, T_i, T_e, J_{//}, \phi$

grid (radial×poloidal) 36 × 64

turbulence:

transport coefficients $D_i, V_r, \kappa_i, \kappa_e$

grid (radial×poloidal) 200 × 64

start from constant transport coefficients

$$D_i = 0.5, V_r = 0.0, \kappa_i = 1.0, \kappa_e = 1.0$$


[1] D.R. Zhang, Y.P. Chen, X.Q. Xu, et al. Nuclear Fusion, 2020, 60(10).
[2] D.R. Zhang, Y.P. Chen, X.Q. Xu, et al. Physics of Plasmas, 2019, 26(1): 012508.

# Transport coefficients

$$\tilde{\Gamma}_{\alpha}^{r}=\left\langle n_{\alpha}\tilde{V}_{E}^{r}\right\rangle+\left\langle n_{\alpha}V_{\alpha,//}\tilde{b}^{r}\right\rangle$$

$$\tilde{q}_{\alpha}^{r}=\frac{5}{2}\left\langle n_{\alpha}\tilde{T}_{\alpha}\tilde{V}_{E}^{r}\right\rangle+\frac{5}{2}\left\langle n_{\alpha}V_{\alpha,//}\tilde{T}_{\alpha}\tilde{b}^{r}\right\rangle-\left\langle\kappa_{\alpha,//}\nabla_{//}T_{\alpha}\tilde{b}^{r}\right\rangle$$

**$E\times B$** drift

magnetic fluttering

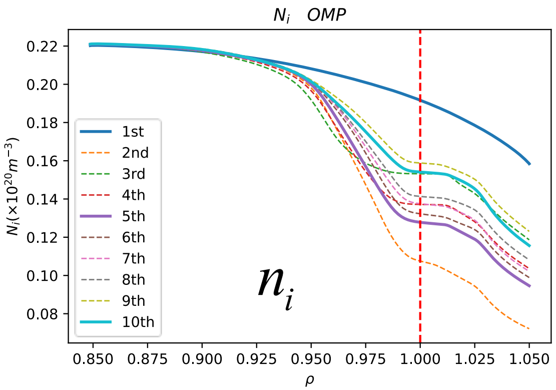
<>: time and toroidal average

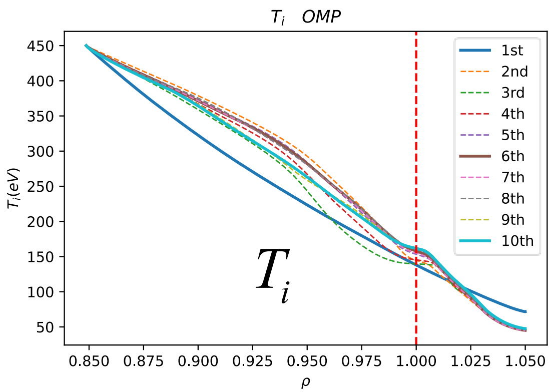
$$D_{i}=-\frac{\left(\tilde{\Gamma}_{i}^{r}\right)_{+}}{\nabla^{r}\overline{n}_{i}}\qquad V_{r}=\frac{\left(\tilde{\Gamma}_{i}^{r}\right)_{-}}{\overline{n}_{i}}\qquad \kappa_{\alpha}=-\frac{\tilde{q}_{\alpha}^{r}}{\overline{n}_{\alpha}\nabla^{r}\overline{T}_{\alpha}}$$

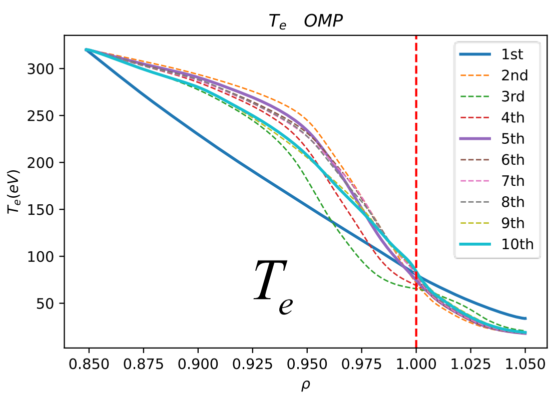
$$\tilde{\Gamma}_{i}^{r}=-D_{i}\nabla^{r}\overline{n}_{i}+\overline{n}_{i}V_{r}$$

# Profiles and transport coefficients

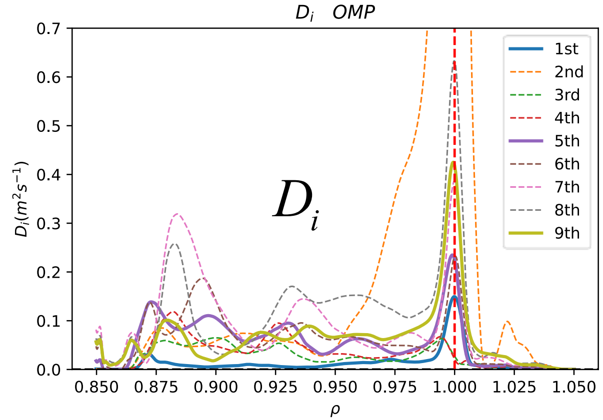
## plasma profiles

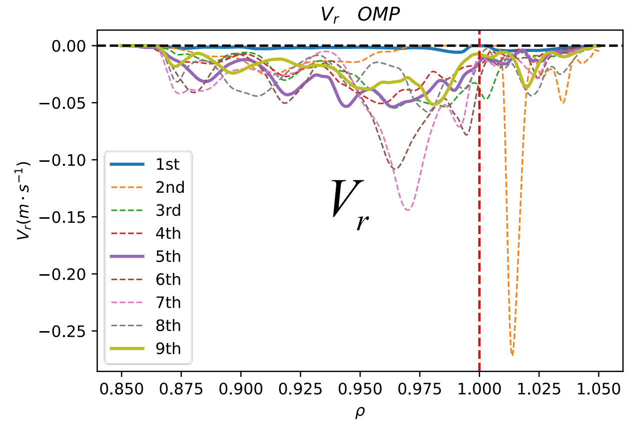


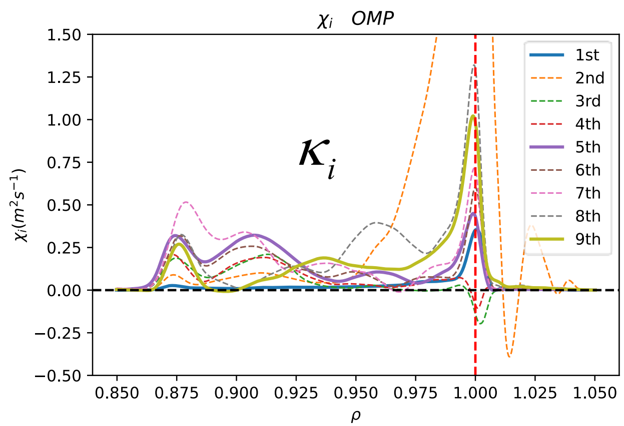



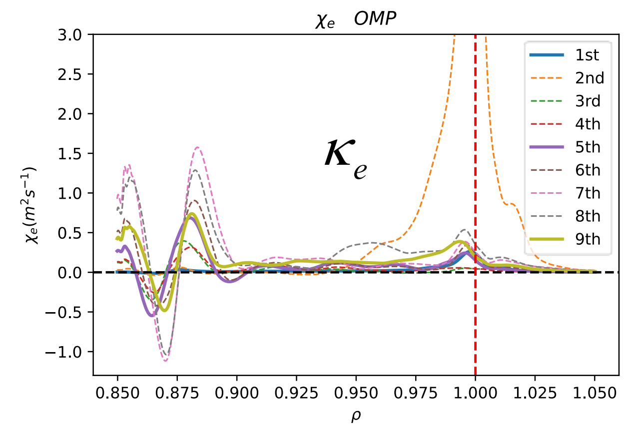




## transport coefficients



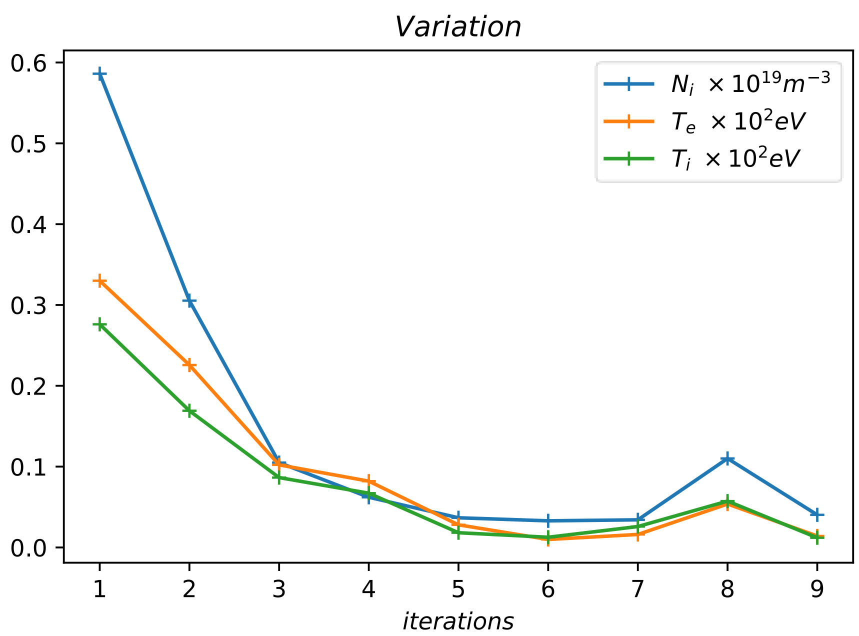



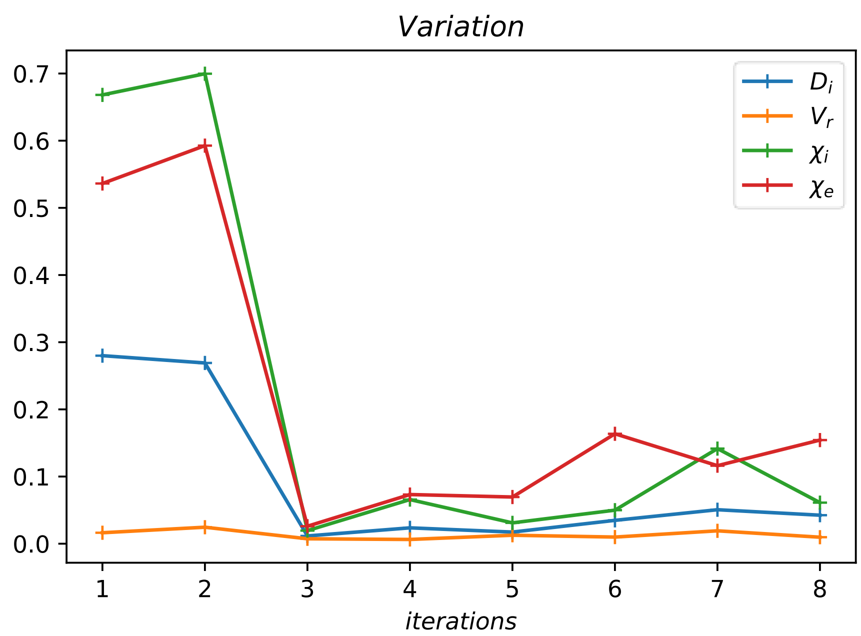




**After 10 coupling iterations, the plasma profiles and transport coefficients at the Outer Mid-Plane (OMP) were obtained**

# tendency of convergence

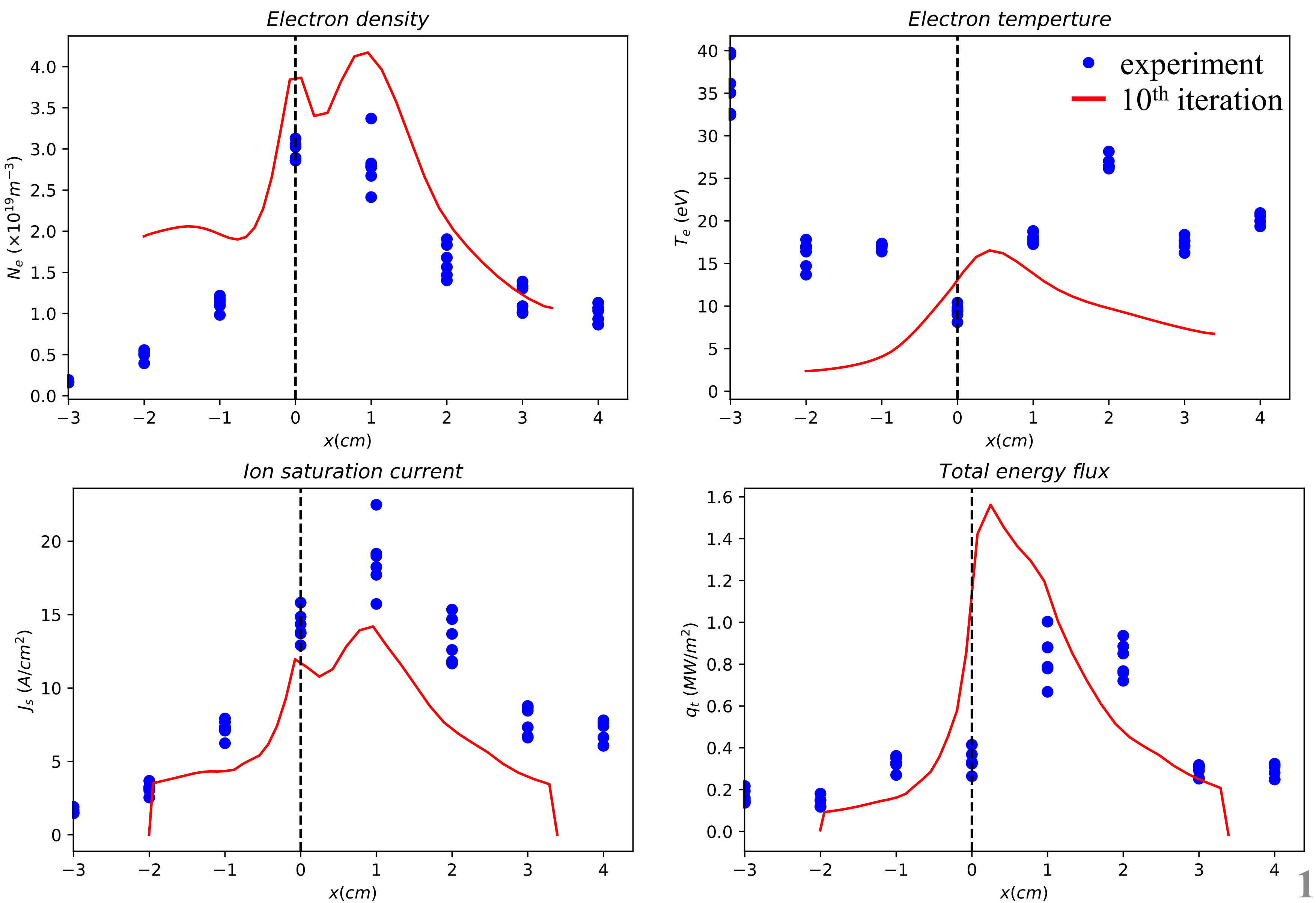



$$\text{Variation: } V_k \equiv \frac{1}{n}\sum_{j=1}^{n}\left|N_{j,k+1}-N_{j,k}\right|$$

**The variation between the adjacent two iterations gradually decreases, showing the tendency of convergence**

# Validation with experiment



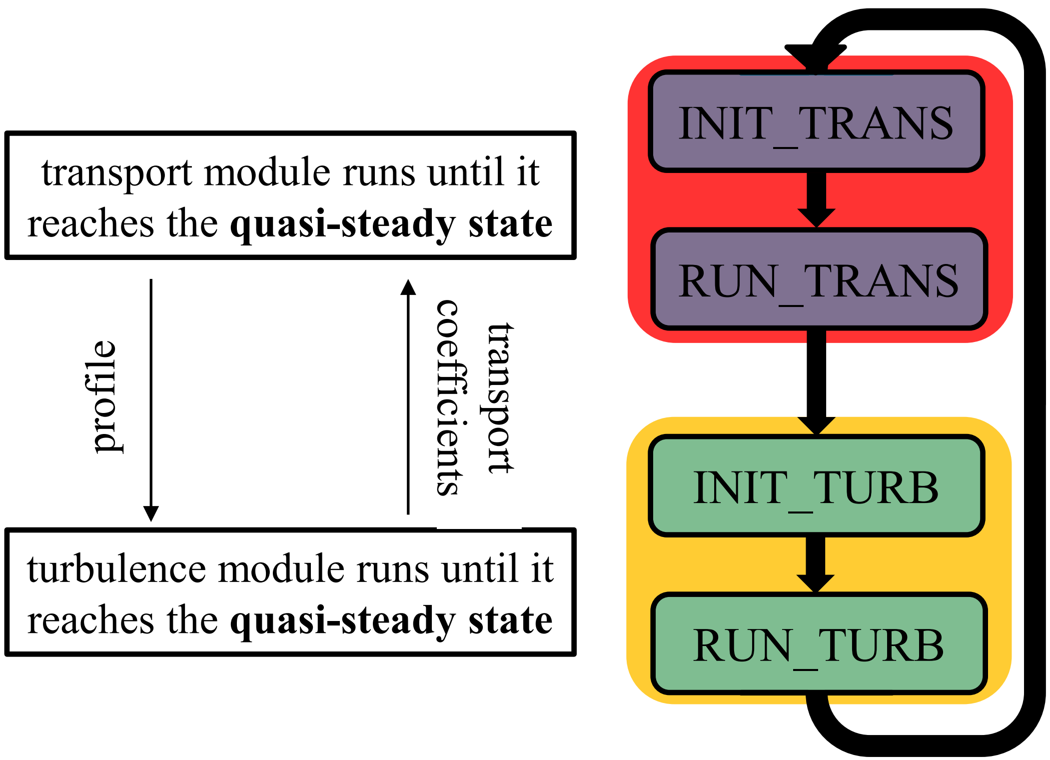
# Outline

# Summary

- A multiscale simulation framework is developed which integrates the simulation codes, data processing routines, data transfer interfaces and code running drivers.
- Based on the framework, the steady state coupling workflow for the edge plasma is developed using SOLPS-ITER and BOUT++.
- Based on the EAST experiment, the steady state coupling workflow shows the tendency of convergence and the computational divertor profiles of last iteration provide good match with measurement.
- A transient state or time-dependent coupling workflow has been developed based on this framework, which still need further research.

# Thanks!

# Steady state coupling workflow




- grid interpolation
- write data files

- quasi-steady state detection
- get plasma profiles

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