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

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Outline

1. Motivation
2. Development of the framework
3. Validation for steady state coupling workflow
4. Summary
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.

- Zhang et al.'s work (POP2019, NF2020) shows the feasibility to do steady-state simulation based on BOUT++-SOLPS-ITER coupling.

- 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.

![Diagram showing turbulence, transport coefficients, iteration control algorithm, and plasma profiles.]

- It is hard to achieve a fully-resolved turbulence simulation at transport scales due to highly disparate spatiotemporal scales.
- A multiscale approach will be necessary by coupling turbulence code and transport code.
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Turbulence-transport coupling simulation framework

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

A multiscale simulation framework is developed to build complex workflows
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

- 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 $F$

<table>
<thead>
<tr>
<th>Topology</th>
<th>SOLPS grid</th>
<th>BOUT++ grid</th>
<th>Elapsed time (per 100 times)</th>
</tr>
</thead>
<tbody>
<tr>
<td>USN</td>
<td>36×96</td>
<td>68×64</td>
<td>8.3s</td>
</tr>
<tr>
<td></td>
<td>128×64</td>
<td>12.5s</td>
<td></td>
</tr>
<tr>
<td></td>
<td>260×64</td>
<td>20.8s</td>
<td></td>
</tr>
<tr>
<td>LSN</td>
<td>36×64</td>
<td>200×64</td>
<td>14.6s</td>
</tr>
</tbody>
</table>

- low order not smooth
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**
- Transport module runs until it reaches the quasi-steady state.
- Turbulence module runs until it reaches the quasi-steady state.

**quasi-steady state detection**
- Profile coefficients.
- Computation speedup: steps of turbulence code when time saving.
- Include linear phase.
- Time-saving: 25% ~ 40%.
Quasi-steady state detection

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.

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

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

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

Transport coefficients

\[ \tilde{\Gamma}_\alpha^r = \langle n_\alpha \tilde{V}_E^r \rangle + \langle n_\alpha V_{\alpha,//} \tilde{b}^r \rangle \]

\[ \tilde{q}_\alpha^r = \frac{5}{2} \langle n_\alpha \tilde{T}_\alpha \tilde{V}_E^r \rangle + \frac{5}{2} \langle n_\alpha V_{\alpha,//} \tilde{T}_\alpha \tilde{b}^r \rangle - \langle \kappa_{\alpha,//} \nabla_{//} T_\alpha \tilde{b}^r \rangle \]

\(<> : \text{time and toroidal average}\)

\[ D_i = - \frac{\left( \tilde{\Gamma}_i^r \right)_+}{\nabla^r \bar{n}_i} \quad V_r = \frac{\left( \tilde{\Gamma}_i^r \right)_-}{\bar{n}_i} \quad \kappa_\alpha = - \frac{\tilde{q}_\alpha^r}{\bar{n}_\alpha \nabla^r \bar{T}_\alpha} \]

\[ \tilde{\Gamma}_i^r = -D_i \nabla^r \bar{n}_i + \bar{n}_i V_r \]
After 10 coupling iterations, the plasma profiles and transport coefficients at the Outer Mid-Plane (OMP) were obtained.
Variation: $V_k \equiv \frac{1}{n} \sum_{j=1}^{n} |N_{j,k+1} - N_{j,k}|$

The variation between the adjacent two iterations gradually decreases, showing the tendency of convergence
Validation with experiment

Electron density

$N_e \times 10^{19} \text{ m}^{-3}$

$x (\text{cm})$

$0 \quad 1 \quad 2 \quad 3 \quad 4$

$-3 \quad -2 \quad -1 \quad 0$

Electron temperature

$T_e (\text{eV})$

$x (\text{cm})$

$0 \quad 1 \quad 2 \quad 3 \quad 4$

$-3 \quad -2 \quad -1 \quad 0$

Ion saturation current

$I_s (\text{A} \cdot \text{cm}^{-2})$

$x (\text{cm})$

$0 \quad 1 \quad 2 \quad 3 \quad 4$

$-3 \quad -2 \quad -1 \quad 0$

Total energy flux

$q_t (\text{MW/m}^2)$

$x (\text{cm})$

$0 \quad 1 \quad 2 \quad 3 \quad 4$

$-3 \quad -2 \quad -1 \quad 0$
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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
- grid interpolation
- write data files
- quasi-steady state detection
- get transport coefficients

transport module runs until it reaches the **quasi-steady state**

- profile
- transport coefficients

- turbulence module runs until it reaches the **quasi-steady state**

RUN_TURB

- INIT_TURB
- quasi-steady state detection
- get transport coefficients

RUN_TRANS

- INIT_TRANS
- quasi-steady state detection
- write data files

- grid interpolation

grid interpolation
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