Cross-verification and validation of tokamak plasma evolution models

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Summary

• Validate Te/Ti predictors using state-of-the-art but general settings
  – Run on ~hundreds of cases automatically
  – Compare multiple independent implementations (TRANSP and ASTRA)
  – Compare against empirical (linear regressed) models to contextualize error

• Find no significant statistical difference in Te/Ti predictions between TRANSP, ASTRA, and empirical model
Predict core Te+Ti using ASTRA and TRANSP (w/ similar settings)

- **Inputs:**
  - EFIT01 (no kinetic constraint) \( q \)
  - ZIPFIT ne, rotation, Zeff profiles
  - Te and Ti boundary at \( \rho = 0.8 \)
- **900ms simulation**
- **TGLF SAT2, same settings except nky**

<table>
<thead>
<tr>
<th></th>
<th>TRANSP</th>
<th>ASTRA</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fast ions</td>
<td>NUBEAM</td>
<td>RABBIT</td>
</tr>
<tr>
<td>Equilibrium</td>
<td>(input directly)</td>
<td>SPIDER</td>
</tr>
<tr>
<td>Ion heat</td>
<td>+viscosity</td>
<td></td>
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<tr>
<td></td>
<td>+cold-neutral CX</td>
<td></td>
</tr>
<tr>
<td>Neoclassical diffusion</td>
<td>Modified Chang-Hinton</td>
<td>Angioni-Sauter (e)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Galeev-Sagdeev (i)</td>
</tr>
<tr>
<td>TGLF nky</td>
<td>12</td>
<td>19</td>
</tr>
</tbody>
</table>
Verification: ASTRA and TRANSP yield similar results

shot 191577, time=2.70s
Semi-randomly selected 219 DIII-D shots, created automated workflow

- **Exclude**
  - wave-heating
  - 3D field perturbations
  - Non-D2 gas
  - Rampup and rampdown
  - Shots before year 2010

- **OMFIT modules**
  - ASTRA: compiled + debugged + user-interface for GA (Iris) cluster
  - AGGregate: automatically mass prepare + launch TRANSP/ASTRA jobs
ASTRA and TRANSP converge in ~half of cases, runs take ~hrs (wall-clock). ASTRA less robust, TRANSP higher runtime.
Metrics to consider: $T_e$, $T_i$, and $W_{MHD}$

$$W_{MHD} = \int \left( p_{\text{thermal}} + p_{\text{fast ions}} \right) dV$$

ITER standard figures of merit used to measure accuracy

**Te and Ti**

$$\epsilon(\rho) = T^{\text{sim}}(\rho) - T^{\text{exp}}(\rho)$$

$$\sigma = \sqrt{\frac{\sum \epsilon(\rho)^2}{\sum T(\rho)^2}}$$

$$\bar{\sigma} = \sqrt{\langle \sigma^2 \rangle}$$

**$W_{MHD}$**

$$R_W = \frac{W^{\text{sim}}}{W^{\text{exp}}}$$

$$\Delta R_W = R_W - 1$$

$$\Delta \bar{R}_W = \sqrt{\langle \Delta R_W^2 \rangle}$$
Baseline for comparison:

\[ W_{\text{MHD}} = P_{\text{tot}} \tau_{H\{89,98\}} \]

\[ P_{\text{tot}} = P_{NBI} + 0.55MW \]

"Nondimensionalization"°1°°

\[ \frac{\dot{W}_{\text{MHD}}}{\dot{W}_{\text{H89}} \tau_{H\{89,98\}}} = \frac{P_{\text{tot}}}{P_{\text{NBI}} + 0.55MW} \]

"Profile Consistency"°3

\[ T_{\text{edge}} = \frac{P_{\text{core}}}{\rho_{\text{core}} - \rho_{\text{edge}}} \ln \left( \frac{T_{\text{core}}}{T_{\text{edge}}} \right) \]

"Sawteeth"°2

\[ T_{\text{core}} = mT_{\text{edge}} + b \]
TRANSP and ASTRA qualitatively capture time-dependent changes

\[ \rho = 0.3 \]

shot 191577 at 2.7s

\[ \text{sim boundary} \]
Full database: TRANSP/ASTRA within ~5%
Empirical Te/Ti also within ~5%, but $W_{MHD} > \sim 10\%$ worse
Conclusions and next steps: as we know, codes just one component to predict

- Developers are aware of models’ limitations: primarily used not predictively but for
  - Qualitative scaling
  - Physics understanding
  - Extrapolation to unexplored regimes
- BUT similar transport prediction workflows still used to plan
  - Reactors
  - Scenarios
  - Machine upgrades
- In practice, code outputs are combined with experience + empirical scalings
- Use machine learning to try a task humans have always done:
  - More rigorously understand where and when to trust codes vs empirical data
  - Maintain extrapolability to new regimes with power of empirical models
- Start by predicting difference from code to experiment value (w/ database we made)
What is shot 191577?

- Expt title: “Effects of upstream power and heat flux width on the SAS-VW heat flux profile; influence of radiative and neutral heating”
  - Detachment studies
- Al Hyatt (shot log): “Very strange behavior. \(\beta_{\text{tan}}\) and density and \(I_i\) all seem to oscillate at a few hertz until the plasma density reaches about 4-5+13. Strike is almost perfect, maybe a little (~1 mm) too far out.”
Detailed heat source comparison

shot 191577, time=2.70s
Detailed TGLF settings

- `sat_rule`: 2
- `use_bper` but not `bpar`
- `kygrid_model`: 1
- `wdia_transp`: 1
- `xnu_model`: 3
- `alpha_quench`: 0
- `n_species`: 3 (electrons, ions, impurity)
- `n_modes`: 3
- `ibranch` = -1
- `etg factor`: 1.25
- `gaussian width`: 1.65
- `growth rate search for max width from 0.3 to 21`
- `units`: cgyro