Prediction of Divertor Heat Flux on ITER and CFETR Using BOUT++

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Outline

- **Background of SOL and heat flux width**
  - Current experiments, theory and simulation
  - BOUT++ simulation on heat flux width
  - Physics model of BOUT++ transport and turbulence model

- **BOUT++ transport module on predicting ITER $\lambda_q$**
  - ITER scenario and simulation setting
  - Anomalous thermal diffusivity ($\chi_{i,e}$) scan in SOL
  - Separatrix temperature Scan

- **BOUT++ turbulence module on predicting ITER $\lambda_q$**
  - Linear growth rate and turbulence spreading
  - Divertor heat flux width on ITER
  - Upstream pedestal structure impact

- **Recent progress on CFETR R7.2m hybrid scenario $\lambda_q$ study**

- **Summary**

This work was performed for USDOE by LLNL under DE-AC52-07NA27344 LLNL-PRES-750859 and supported under CSC1709180114 and ITER-CN No. 2014GB107004
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Background - Current experiment, theory and simulation of SOL and heat flux width

- Heat flux distribution on divertor target is becoming a main concern of future tokamak devices
  \[ q_{\text{peak}} \sim \frac{P_{\text{div}}}{A_w} \sim \frac{1}{\lambda_q} \]

- \( \lambda_q \) is determined by the competition between cross field and parallel transport in SOL \([1]\)

- Theory model “Heuristic Drift Model” matches well with current experiments \([3, 4]\)

- Some turbulence theory shows ITER might have a large \( \lambda_q \) with interchange mode; \([5]\)

- New gyro-kinetic simulation by XGC1 shows the ITER might violate the Eich’s Scaling \([6]\)

What would be the value of \( \lambda_q \) for ITER and CFETR?

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BOUT++ turbulence simulations are performed on C-Mod\textsuperscript{[1]}, EAST\textsuperscript{[2]} and DIII-D\textsuperscript{[3]}

Both transport and turbulence can roughly match with C-Mod experiments and Goldston’s HD model (with an outlier)

BOUT++ transport & turbulence would be performed on ITER and CFETR

\[ \lambda_q = 0.63 B_{pol}^{-1.19} \]

\begin{itemize}
  \item Eich’s Scaling
  \item BOUT++ 6f Turbulence
\end{itemize}

<table>
<thead>
<tr>
<th>Model</th>
<th>Dimension</th>
<th>Equation</th>
<th>ES/ EM</th>
<th>Time step</th>
<th>Turbulence</th>
<th>Cross Field Transport</th>
<th>Saturation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transport</td>
<td>2D</td>
<td>Braginskii</td>
<td>ES</td>
<td>$\sim 0.1 \frac{L}{C_s} \sim 10^{-5}$ s</td>
<td>No Turbulence</td>
<td>Drift + artificial transport coefficients</td>
<td>Both Ion and Electron (longer time scale)</td>
</tr>
<tr>
<td>Turbulence</td>
<td>3D</td>
<td>Braginskii</td>
<td>ES/ EM</td>
<td>$\sim 1 \tau_A \sim 10^{-7}$ s</td>
<td>PB mode, acoustic wave, drift wave instabilities</td>
<td>Drift + ExB turb. + Mag turb.</td>
<td>Only Electron</td>
</tr>
</tbody>
</table>

- Shed the light to future turbulence -> transport multi-timescale coupling
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ITER 15MA baseline Scenario (2015) \(^{[1]}\)

Simulation Domain (0.90-1.05)
256 x 64 x 64

Plasma Kinetic Profile

Transport Coefficients Setting

- Core: inverted from the initial profile to make core plasma profile unchanged
- SOL: consider constant coefficients from separatrix to far SOL
- Wide range 0.01~10.0
- Are considered the same for both ion and electron
- Simulation is done for both
  - w/o drift: Only $\chi T$
  - w/ drift: ExB and diamagnetic drift
Anomalous Transport Coefficient Scan In SOL

- **W/O Drift:**
  - $\lambda_q$ increases monotonically with $\chi_{i,e}$
  - Follows the $\lambda_q \sim \chi_{i,e}^{1/2}$ scaling

- **W/ Drift:**
  - $\chi_{i,e} < 0.1 \text{m}^2/\text{s} \Rightarrow \lambda_q$ is nearly unchanged
  - $\chi_{i,e} > 0.1 \text{m}^2/\text{s} \Rightarrow \lambda_q$ increases monotonically
Anomalous Transport Coefficient Scan In SOL

- 2.0x Drift shows a more clear flat region
- Value of flat $\lambda_q$ is doubled
- Turning point also increases (0.1->0.5)
- Two mechanisms may exist in determining perpendicular transport:
  - Drift vs. turbulence
Separatrix Temperature Scan

\[ v_{\text{grad+curv}} = \frac{2T}{BR} \]

Divertor Heat Flux Width

- Small average parallel flow (OMP->X-point, 0.3-0.4 Cs < 0.5 Cs)
- Large residence time in SOL
- Large \( \lambda_q \)

\[ \lambda_{q,\text{Goldston}} = \frac{4a}{eB_pR} \left( \frac{\tilde{A}m_pT_{\text{sep}}}{(1 + \tilde{Z})} \right)^{1/2} \]

Drift and turbulence dominate regimes are found

Goldston’s drift model can roughly match with drift dominate regime

In turbulence regime, we can have the relation: \( \lambda_q \sim \chi^{-1/2} \)

Different separatrix temperature impact on \( \lambda_q \)
- Smaller temperature \( \rightarrow \) smaller \( \lambda_q \) in drift dominate regime
- \( \lambda_q \) in drift regime roughly matches Goldston’s HD model

Drift vs. turbulence might bridge the gap between small and large \( \lambda_q \)

What determines the critical \( \chi_{-1} \) between drift and turbulence dominate regime?
Discussion on BOUT++ Transport Result

- By balancing the simple drift and turbulence term
  \[ \nu_{gradB+curlB}T \sim \chi_{crit} \nabla T \sim \chi_{crit} T / \lambda_T \]

- Turbulence

\[ \chi_{crit} \sim \frac{2T}{BR \lambda_T} \]

- Assuming Conv/Cond limit for parallel transport, we have:
  \[
  \lambda_q = \begin{cases} 
  \left( \frac{1}{\lambda_n} + \frac{3}{2} \frac{1}{\lambda_T} \right)^{-1} < \frac{2}{3} \lambda_T & \text{Convection} \\
  \frac{2}{7} \lambda_T & \text{Conduction} 
  \end{cases}
  \]

- Up to the critical \( \chi_\perp \) Goldston's model \( \lambda_q \sim \frac{4a}{BR} \left( \frac{m_p}{e} \right)^{\frac{1}{2}} T^{\frac{1}{2}} \)
  still valid, we have:
  \[
  \chi_{crit} \in \left[ \frac{12a}{B_p^2 R^2} \left( \frac{m_p}{e} \right)^{\frac{1}{2}} T^{\frac{3}{2}} T^{\frac{3}{2}} \right] \]

\[ T_{sep} \uparrow \rightarrow \chi_{crit} \uparrow \rightarrow \frac{B_p}{R} \uparrow \rightarrow \chi_{crit} \downarrow \]

- What is the typical \( \chi_\perp \) in real turbulence? → BOUT++ turbulence code!

[Graph showing \( T_{sep} \) and \( \chi_{crit} \) with a vertical line indicating the transition region.]
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Unstable for high-n ballooning mode

Large ELM crash would happen with the ITER scenario\[^1\]

Pedestal would crash to flat in ~0.3ms

A lot of energy would come out from core, similar to previous result\[^2\]

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\[^2\] C.S. Chang et al., 2017 Nucl. Fusion 57 116023
Turbulence is generated inside the pedestal and then spread into SOL

There would be a delay on saturation of turbulence in different position

Turbulence is generated in pedestal peak gradient position and then spreads into SOL, not local instability
Perpendicular thermal transport by ExB turbulence is:

\[ q_{ir,tur} = \left( n_i T_i \frac{b_0 \times \nabla \phi}{B_0} \right)_{\theta,\zeta}, \quad q_{er,tur} = \left( n_i T_e \frac{b_0 \times \nabla \phi}{B_0} \right)_{\theta,\zeta} \]

Effective perpendicular thermal diffusivity is defined by:

\[ \chi_{tur} = -\frac{\left\langle q_{tur} \right\rangle_{\theta,\zeta}}{\left\langle n\nabla T \right\rangle_{\theta,\zeta}}_t \]

Turbulence is quite strong for ITER baseline scenario

\[ \chi_{e,eff} = 4.71 m^2/s \] \( (t=[200,600]) \) may indicate the ITER might fall into turbulence dominate regime

What is the value of \( \lambda_q \)?
**Divertor Heat Flux**

- Electron heat flux width gets saturated after $600\tau_A$
- It would show a quite large, $\lambda_q = 11.28\, \text{mm}$, roughly consistent with Dr. Myra’s I-BWD case\(^\cite{1}\)
- ITER original pedestal profile might fall into the turbulence dominate regime
- What if without ELM? Change pedestal!

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\(^\text{1}\) J. R. Myra, Physics of Plasmas 22, 042516 (2015)
Both $P$ and $J_{\parallel}$ are scaled by a factor: density scale, temperature unchanged

Equilibriums are recalculated by CORSICA

Upstream pedestal condition would have a large impact on SOL physics, $\lambda_q$ in a wide range: 4mm~12mm

For lower pedestal height, ped0.8x and ped0.85x, probably in-between drift/turbulence dominate regime

For higher pedestal height, $\lambda_q$ increases with pedestal height increase, and finally get to a saturation
Small turbulence (0.8/0.85x) match well;

Large turbulence would show difference:

- Transport code remain H-mode, meanwhile turbulence crashed
- Poloidal asymmetry of turbulence heat flux (OMP)
Discussion on BOUT++ turbulence results

- ITER pedestal is unstable and would have a large ELM crash
- Turbulence is generated inside the pedestal and spreads into SOL
- ITER pedestal would probably fall in turbulence dominate regime
  - Might lead to a large $\lambda_q \sim 11.28\text{mm}$
- Pedestal structure is important in determining $\lambda_q$ of ITER
  - $\lambda_q$ is in the range of $4.0\text{mm} - 12.0\text{mm}$ for pedestal factor 0.8 to 1.0
- BOUT++ turbulence and transport have a similar trend, but have some deviation
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CFETR R7.2 Hybrid Scenario

\[ T_{e,sep} = 400 \text{eV} \]

Divertor Heat Flux for CFETR R7.2 Hybrid Scenario

- CFETR also has the drift vs. turbulence regime
- CFETR effective thermal diffusivity is close to unity
  - From scenario study (green star)
  - From BOUT++ turbulence code (red dot)
- Some small turbulence might be helpful to increase \( \lambda_q \), Eg. CFETR (\( \beta_p, q_{95}, v_{e*} \)) might perform like grassy ELM\(^1\)
- Grassy ELM might be favorable for achieving large \( \lambda_q \)

\[ \text{Larger } T_{e,sep}, \text{ smaller } B_p, \text{ similar } R \text{ makes } \chi_{\text{crit}} \text{ larger than ITER} \]

\(^1\) Zeyu Li, V.S. Chan et al. Nucl. Fusion 58 (2018) 016018
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Drift and turbulence would have a competition on determine perpendicular transport, which might bridge the gap between small and large $\lambda_q$

- Drift dominate regime, $\lambda_q$ roughly matches with Goldston’s model and experimental scaling
- Turbulence dominate regime, $\lambda_q$ would increase as the effective thermal diffusivity $\chi_\perp$

ITER pedestal from scenario study would probably fall in turbulence dominate regime and result in a large $\lambda_q$

Pedestal structure is important for determining $\lambda_q$ for ITER

BOUT++ transport and turbulence code can roughly match with each other

CFETR pedestal might lay in-between drift and turbulence regime, grassy ELM might be a promising scenario with a larger $\lambda_q$
Thanks For Your Listening!