Impact of pedestal operation modes and machine design on the divertor heat flux width scaling

10th US-PRC Magnetic Fusion Collaboration Workshop (MFCW 2021)

March 22 - 26, 2021, Virtual-WeBex, Livermore, USA

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Xueqiao Xu
US-PRC International Collaboration work strengthens both sides of Fusion Development Program

a great example of win-win strategy

- LLNL US-PRC fusion collaborations include
  - Theory
  - Code development
  - Verification & Validation
  - Tokamak reactor designs

- Under these auspices in last 5 years we ...
  - Hosted ~ 45 visitors
  - Published 47 papers in peer-reviewed journals
  - Held weekly and monthly video conferences
    - Weekly Webex video conference with EAST & PKU
    - Monthly Webex video conference with CFETR
  - Contributed to the FY 2016 FES Theory and Simulation Performance Target
  - Hosted 2015 and 2018 BOUT++ workshop, [https://bout.llnl.gov/workshops](https://bout.llnl.gov/workshops)
  - LLNL hosts the 10th US-PRC Fusion Collaboration Virtual Workshop in 2021
Principal Activities

• A suite of two-fluid multiple-field models has been updated in BOUT++ with
  o flux driven sources from core plasmas
  o zonal flow & zonal field
    ✓ 3D field solver to remove high-n ballooning approximation
  o Landau-fluid closures for parallel non-local transport
  o being refactored and optimized on hybrid CPU-GPU architectures

• A suite of gyro-fluid models is also developed for
  o pedestal kinetic turbulence and transport
    ✓ Developing ML surrogate models for kinetic closures

• A transport model with all drifts has been implemented in BOUT++ for
  o Initial 2D plasma profiles & Er across separatrix for turbulence simulations
  o Coupling turbulent & transport

• Neutral & Impurity models for
  o SMBI, GAS puffing, Recycling
  o Pellet injections for fueling, ablation & ELM control & detachment

• A test particle module for
  o Impurity and dust-particle migration and transport
  o Modelling of alpha particle slowing down for burning plasmas
BOUT++ simulations predict that the divertor heat flux width of ITER & CFETR baseline target is broadened by ELMs

- When $\chi > \chi_{crit}$, radial transport transits from a drift to a fluctuation-dominated regime
  - Bohm diffusion typically yields $\chi^{Bohm} \gg \chi_{crit}$
- The divertor heat flux width is correlated with change in pedestal height

X.Q. Xu et al 2019 Nucl. Fusion 59 126039
BOUT++ simulations performed for CFETR scenarios
SSO: high $\beta_p$, high q95

Pedestal profiles and magnetic configuration

Parameters of current CFETR Steady State scenario

<table>
<thead>
<tr>
<th>Parameters</th>
<th>CFETR Steady State Scenario</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R$</td>
<td>7.2m</td>
</tr>
<tr>
<td>$a$</td>
<td>2.2m</td>
</tr>
<tr>
<td>$\kappa$</td>
<td>2</td>
</tr>
<tr>
<td>$\delta$</td>
<td>0.42</td>
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<tr>
<td>$B_T$</td>
<td>6.5T</td>
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<tr>
<td>$I_p$</td>
<td>11MA</td>
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<tr>
<td>$\beta_N$</td>
<td>2.81</td>
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<tr>
<td>$\beta_p$</td>
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</tr>
<tr>
<td>$q_{95}$</td>
<td>7.34</td>
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<tr>
<td>$n_{sep}/n_{ped}$</td>
<td>0.25</td>
</tr>
<tr>
<td>$v_\star$</td>
<td>0.22</td>
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Near ballooning criticality, pressure gradient relaxes very little in non-linear steady state

No large ELM collapses near the ballooning criticality, but large enough transport can be generated which broadens the SOL width
Divertor heat flux width broadening due to large electromagnetic fluctuation from the Grassy ELM

<table>
<thead>
<tr>
<th></th>
<th>formula</th>
<th>$\lambda_q$ (mm)</th>
<th>$\lambda_{int}$ (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulation</td>
<td>/</td>
<td>2</td>
<td>8.33</td>
</tr>
<tr>
<td>Goldston HD model</td>
<td>$\frac{4a\sqrt{m_pT_{sep}/2}}{eB_pR} \frac{R &lt; B_p &gt;}{(RB_p)_{omp}}$</td>
<td>1.08</td>
<td>3.54</td>
</tr>
<tr>
<td>Eich Scaling law</td>
<td>$0.63B_p^{1.19}$</td>
<td>0.69</td>
<td>3.15</td>
</tr>
<tr>
<td>Eich turbulence</td>
<td>$0.59(1 + 3.6\alpha_t^{1.9})\rho_s$</td>
<td>1.17</td>
<td>3.63</td>
</tr>
</tbody>
</table>

$$\chi_{e_{sep,omp}}^{\ast} \approx 0.5 \text{ m}^2 / \text{s} > \chi_c^e \approx 0.2 \text{ m}^2 / \text{s}$$

BOUT++ simulations also performed for ITER scenarios
SSO shows lower pedestal pressure & bootstrap current, but high $\beta_p$, high $q_{95}$

- **Baseline:**
  - ballooning modes, most unstable toroidal mode numbers $n=60\sim80$
  - SS0: peeling modes, most unstable modes $n=10\sim20$
  - Hybrid: peeling-ballooning modes, most unstable modes $n\sim40$

X. Y. Wang, X. Q. Xu, et al, submitted to NF 2021
Near ballooning criticality, pressure gradient relaxes very little in non-linear steady state

No large ELM collapses near the ballooning criticality, but large enough transport can be generated which broadens the SOL width
BOUT++ simulated near-separatrix pressure gradient is consistent with ballooning critical gradient model (BC)

- Pressure gradient should be marginally unstable for local ballooning mode near Separatrix

\[ \alpha_{Miller} = - \frac{2 \beta \psi' V}{(2\pi \rho_r)^2} \left( \frac{V}{2\pi^2 R_0} \right)^2 \mu_0 p' \sim 2.0 \quad d\beta_p/d\psi_N \sim 2.5-3.5 \]

- For ITER baseline \( n_{sep} = 3.7 \times 10^{19}/m^3 \), \( T_{e,sep} = 175 \text{eV}, T_{i,sep} = 300 \text{eV}, \)

\[ (dp/d\psi_N)_{crit} \sim 1.064 (B_p^{1.6})_{edge} \rightarrow L_{p,crit} \sim 5-6 \text{mm} \]

- In BOUT++, saturated near-separatrix pressure gradient scale length is consistent with the BC model

\[ L_{p,crit} = P/(dP/dx) = 7.3 \text{mm} \]

Philip B. Snyder. ITPA Pedestal and Div/SOL meeting, 2012.

X. Y.Y Wang et al, submitted to NF 2020
Ballooning-critical pressure gradient is consistent with BOUT++ simulated divertor heat flux width at reduced pedestal height near marginal stability boundary for ELMs

Near-Separatrix Ballooning criticality (BC) for ITER baseline target

\[ \lambda_q = 5.7 \times B_{pol,MP}^{-0.78} \]

X.Q. Xu, N. M. Li, Z. Y. Li, et al Nucl. Fusion 59 126039 (2019); Z. Y. Li, X.Q. Xu, N. M. Li, et al., Nucl. Fusion 59, 046014 (2019); X. Y. Wang et al., submitted to NF (2021)
What is about micro-turbulence broadening?

Near-Separatrix Ballooning criticality (BC) for ITER baseline target

\[ \lambda_q = 5.7 \times B_{pol,MP}^{-0.78} \]
Collisionality broadening factor is very little for ITER

T. Eich et al., NF2020

Eich turbulence regression:

\[ \frac{\lambda_p}{\rho_{s,pol}} = (1 + (3.6 \pm 0.19)\alpha_t^{1.9\pm0.14}) \cdot (1.2 \pm 0.05) \]

\[ \lambda_q \sim 0.5 \lambda_p = 1.986/B_{p,omp} \]

\[ \alpha_t \sim \frac{1}{100} \cdot \hat{q}_{cyl} \nu_e^* \]

\[ \nu_e^* = \frac{\pi \hat{q}_{cyl} R}{1.03 \cdot \nu_e T_e^{16} n_e Z_{eff}} \]

- Based on resistive interchange & drift Alfven turbulence
  - \( \nu^*=0 \rightarrow \alpha_t=0 \), no turbulence broadening
  - \( \alpha_t>0.5 \), H\( \rightarrow \)L transition, a maximum of factor 2 broadening

Based on ITER baseline parameters

- Low collisionality,
  - \( \nu_e^{ITER} \sim 1.8 \)
  - \( \alpha_t^{ITER} \sim 0.02 \)

- Eich turbulence predicts a 0.27% width broadening
- GHD model predicts a 3.6% width broadening
Divertor heat flux will pose a significant challenge for SPARC

Eich turbulence:

\[
\lambda_p \rho_{s, pol} = (1 + (3.6 \pm 0.19)\alpha_t^{1.9 \pm 0.14}) \cdot (1.2 \pm 0.5)
\]

\[
\lambda_q \sim 0.5 \lambda_p = 1.986/B_{p,omp}
\]

\[
\alpha_t \simeq \frac{1}{100} \cdot \hat{q}_{Cyl} \nu_e^* \quad \nu_e^* = \frac{\pi \hat{q}_{Cyl} R}{1.03 \cdot 10^{16} \frac{n_e}{T_e^{1/2}} Z_{eff}}
\]

- Based resistive interchange & drift Alfvén turbulence
  - \( \nu^* = 0 \rightarrow \alpha_t = 0 \), no turbulence broadening
  - \( \alpha_t > 0.5 \), H\( \rightarrow \)L transition

Based on SPARC baseline parameters

- Low collisionality,
  \( \nu^{SPARC} \sim 2.1 \quad \alpha_t^{SPARC} \sim 0.05 \)

- Eich turbulence predicts a 1.2% width broadening
- GHD model predicts a 2.6% width broadening
Dominant parameters for the transition from drift to fluctuation dominant regime

- The effective thermal diffusivity $\chi_{\parallel}^c$ from the magnetic drift-based radial transport can be estimated as:

$$\chi_{\parallel}^c = \chi_{\parallel}^{\text{eff}} = v_d \lambda_q = \frac{C v_d q \rho_s}{Z(1 + Z^{1/2})} \frac{A^{1/2}}{BB_p R} \frac{2T_{e,\text{sep}}^{3/2} m_p^{1/2} a}{e^2} \frac{\lambda_T}{\lambda_n}$$

- $C=26.5$ is a fitting parameter to simulations for the transition
- $\lambda_q$ in $\chi_{\parallel}^{\text{eff}}$ can be estimated using
  - HD $\lambda_q$
  - conduction limited $\lambda_T$, $\lambda_q = 2\lambda_T/7$  
  - sheath limited $\lambda_T$
    - $\lambda_n \rightarrow \infty$, $\lambda_q = (1/\lambda_n + 3/2\lambda_T)^{-1} = 2\lambda_T/3$
    - $\lambda_n = \frac{1}{5} \lambda_T$, $\lambda_q = (1/\lambda_n + 3/2\lambda_T)^{-1} = 2\lambda_T/13$
- $\chi_{\parallel}^{\text{eff}}$ decreases for strong magnetic field $B$, high current $I_p$ (or $B_{\text{pol}}$), large machine size $R$, low $T_{\text{sep}}$.
- $\chi_{\perp}^{\text{SPARC}} \sim 0.13 \, \text{m}^2/\text{s}$, $\chi_{\perp}^{\text{ITER}} \sim 0.05 \, \text{m}^2/\text{s}$
SPARC will possibly be in fluctuation dominant regime, because of strong magnetic field and relative low $\chi^c_{\perp}$

Fluctuation thermal diffusivity can be increased from Inter-ELMs to small/grassy ELM regime

- Broadening from micro-turbulence may not be effective as Eich turbulence scaling indicates
- Ballooning criticality sets a threshold for ELMs with larger $\chi^c_{ELMs}$

![Graph showing fluctuation thermal diffusivity and convection limit](image)
Recent DIII-D grassy ELM experiments show a consistent divertor heat flux width broadening and amplitude reduction, just as BOUT++ simulations demonstrated in the grassy ELM regime.

X.Q. Xu – 10th US-PRC MFCW virtual
Summary

- BOUT++ turbulence simulation shows that peeling-ballooning modes dominate in the linear stage for CFETR & ITER scenarios and eventually evolve into various type ELMs.

- The divertor heat flux width broadens with fluctuations
  - Small/grassy ELM broadening is much effective
    - Ballooning critical gradient scale length near separatrix is a good proxy for heat flux width in small ELMs
  - Micro-turbulence broadening is very little for ITER & CFETR

- Divertor heat flux will pose a significant challenge for compact pilot plant
  - SPARC is possibly in fluctuation dominant regime, due to strong magnetic field and lower $\chi$.
  - A proper design for combination of $B$, $B_p$, $R$, $T_{sep}$ could significantly alleviate the challenge.
Back up slides
BOUT++ Simulations Were Validated on Other ITPA Machines

- BOUT++ simulations agree with the GHD model and AUG data.
- The broadening width at high collisionality is due to the transitions of SOL residence time from the particle flow time to the energy confinement time.

BOUT++ transport code is validated by the comparison of the simulated radial electric field $E_r$ with measured $E_r$ (shifted inward by 6.49mm)

N.M. Li, X.Q. Xu, R.J. Goldston, *Nucl. Fusion* (2021)
BOUT++ Simulation of Divertor Heat Flux Width on EAST

- Simulated two EAST discharges of the steady-state H-mode plasmas heated by low hybrid wave (LHW) and neutral beam (NB)
- Both the amplitude and width of the divertor heat flux are found to increase significantly by including drifts
- Simulated heat flux width w/ drifts for the two discharges shows reasonable agreement with the experiments
- Width from the simulation and experiment for the LHW is much larger than that of the NB heated discharge.
  - Turbulence may have played a more important role in LHW heated discharges
  - The magnetic topology and the equilibrium may be changed

Deng, Xu, Li, et al., *Nucl. Fusion* 60 (2020) 082007