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

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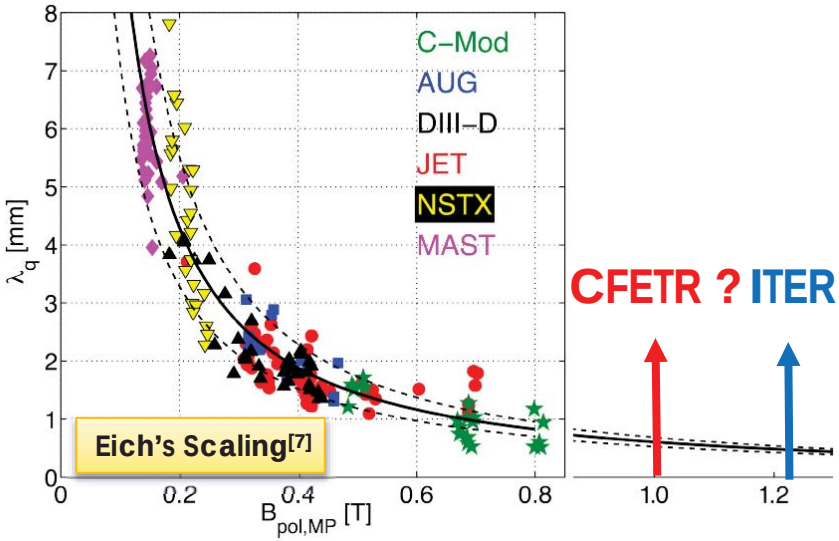
Background – Current experiment, theory and simulation of SOL and heat flux width



- Heat flux distribution on divertor target is becoming a main concern of future tokamak devices

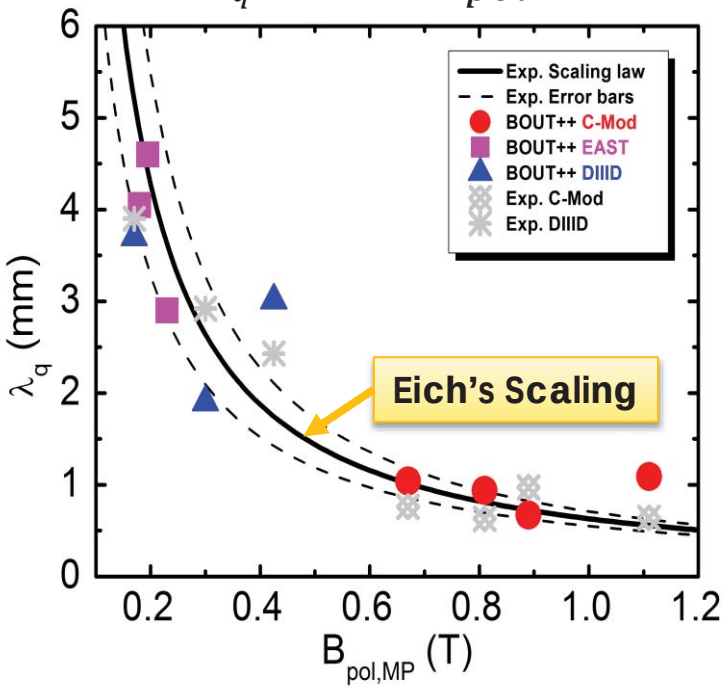
$$q_{peak} \sim {}^{P_{div}}/_{A_w} \sim {}^{1}/_{\lambda_q}$$

- λ_q is determined by the competition between cross field and parallel transport in SOL[1]
- $\lambda_q \propto {}^{1}/_{B_{p,omp}^{\gamma}}$ scaling law is founded on multi-machines[2,4]
- Theory model "Heuristic Drift Model" matches well with current experiments[3,4]
- Some turbulence theory shows ITER might have a large λ_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 λ_q for ITER and CFETR?

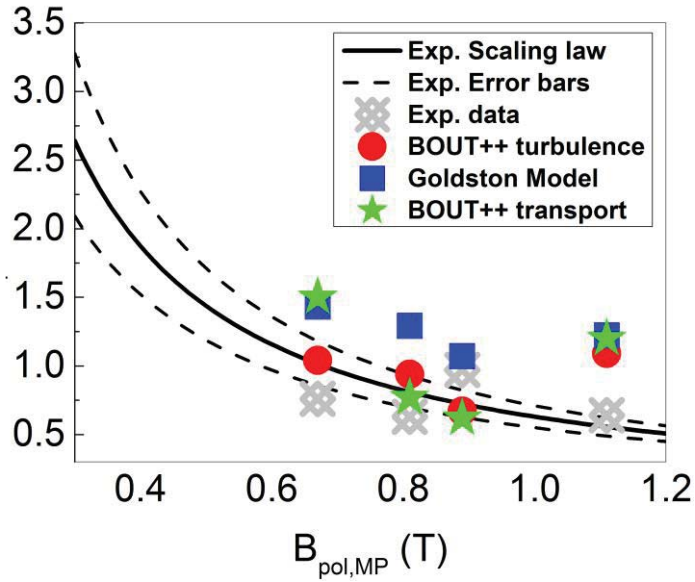
[1] P.F. Stangeby, The Plasma Boundary of Magnetic Fusion Devices, 2000
[2] T. Eich, B. Sieglin, A. Scarabosio, et al., J. Nucl. Mater. (2013)
[3] Goldston R.J. 2012 Nucl. Fusion 52 013009
[4] T. Eich, et al. Phys. Review Lett. 107, 215001 (2011)
[5] J. R. Myra, Physics of Plasmas 22, 042516 (2015)
[6] C. S. Chang et al. Nucl. Fusion 57 116023 (2017)
[7] D. Brunner et al. October 23, 2017 at APS DPP Milwaukee, WI

Background – BOUT++ simulation

$$\lambda_q = 0.63 B_{pol}^{-1.19}$$



BOUT++ 6f Turbulence



BOUT++ Turbulence & Transport on C-Mod Discharges

- BOUT++ turbulence simulations are performed on C-Mod[1], EAST[2] and DIIID[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

[1] B. Chen, X. Q. Xu, et al, Phys. Plasmas 25, 055905 (2018)
[2] T.Y. Xia, et al, 2017, Nucl. Fusion, 57, 116016.
[3] T.F. Tang, et al, 2017, submitted to Phys. Plasmas;.

BOUT++ Transport vs. Turbulence

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

- Shed the light to future turbulence -> transport multi-timescale coupling

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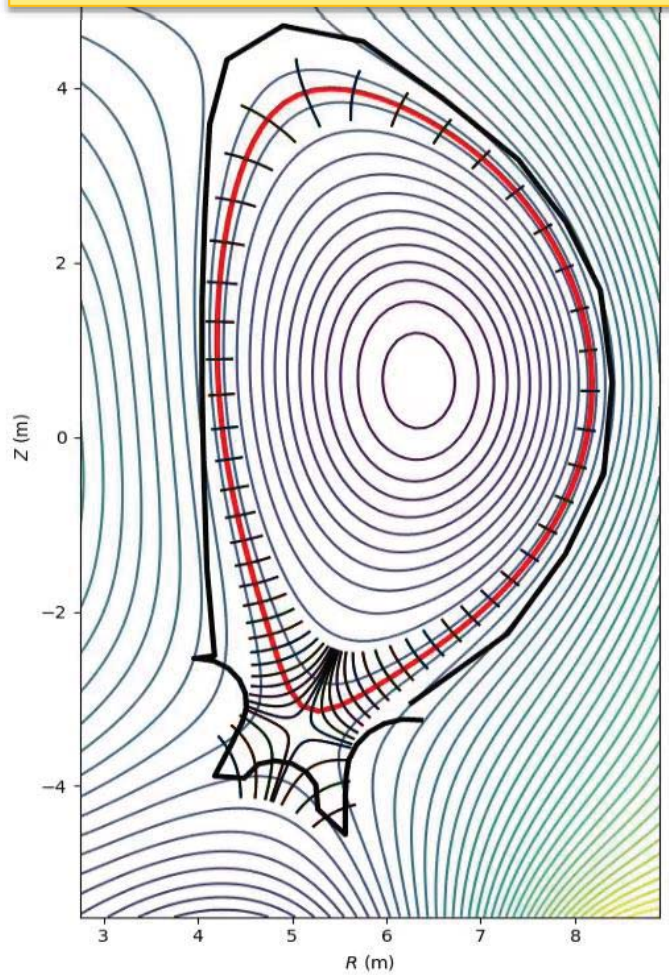
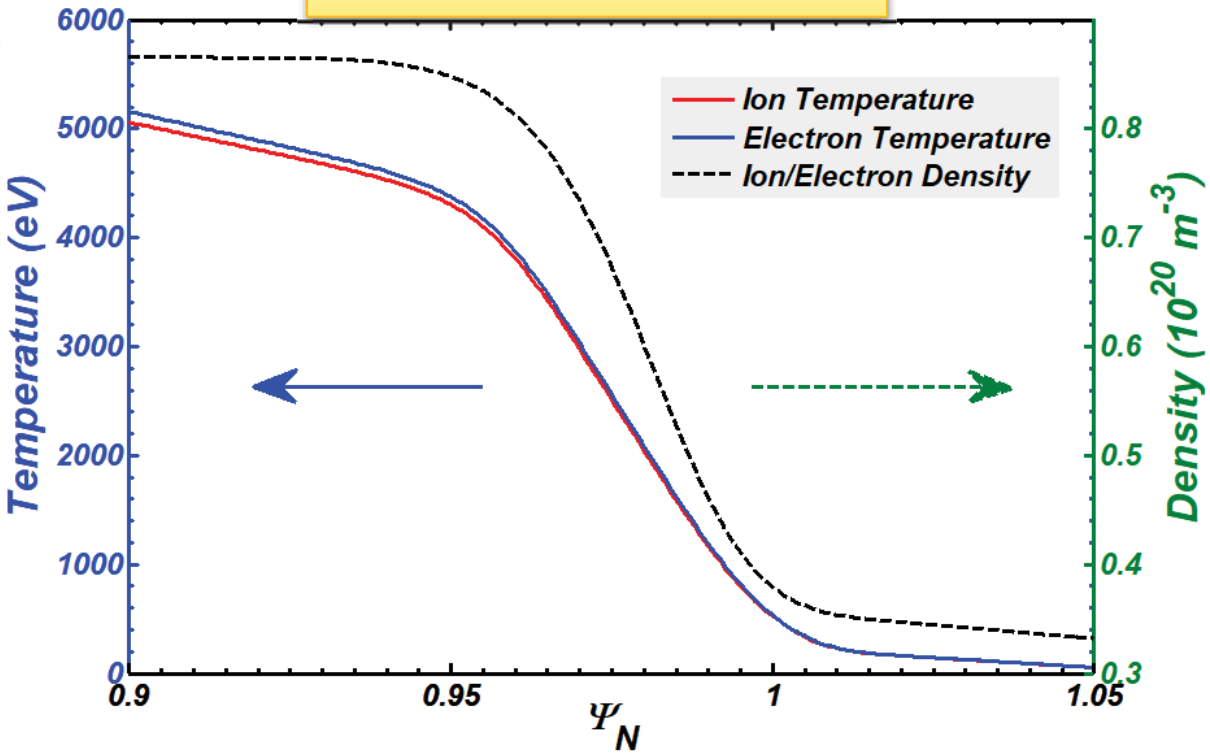
ITER 15MA baseline Scenario(2015)[1]

Simulation Domain (0.90-1.05)
$256 \times 64 \times 64$

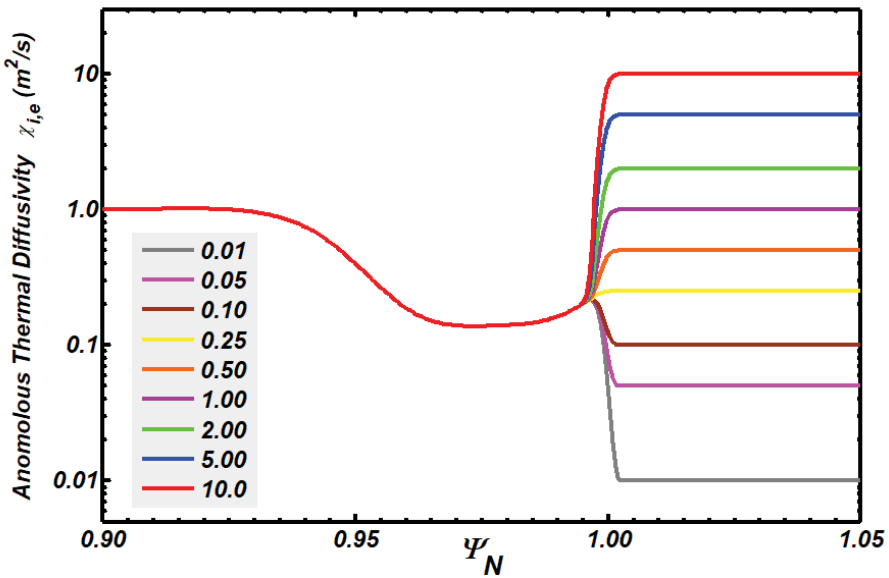


Plasma Kinetic Profile



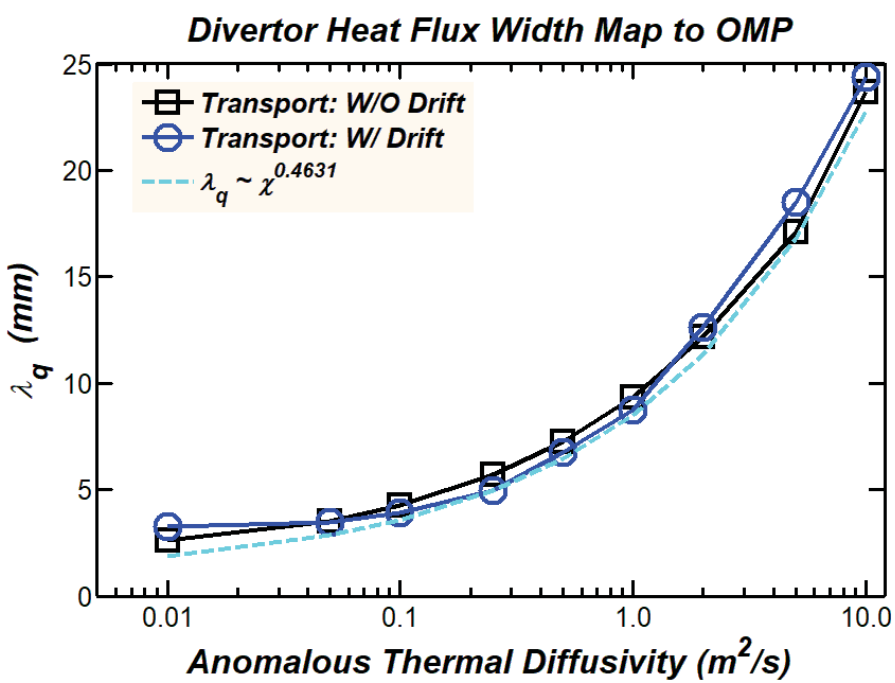
[1] S.H. Kim et al. "Simulating Burning Plasma Operation in ITER", EPS, Lisbon, 2015

Transport Coefficients Setting



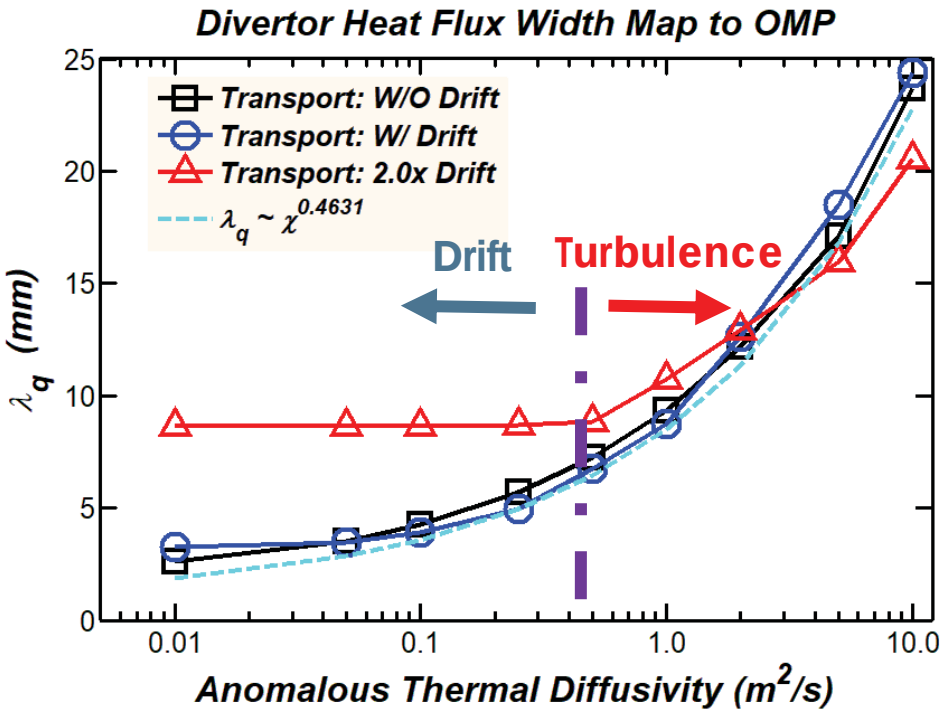
- Core: inverted from the initial profile to make core plasma profile unchanged
- SOL: consider constant coefficients from separatrix to far SOL
- Wide range 0.01~10.0
- Are considered the same for both ion and electron
- Simulation is done for both
  - w/o drift: Only $\chi_\perp \nabla_\perp T$
  -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

Anomalous Transport Coefficient Scan In SOL



- **W/O Drift:**
  - λ_q **increases monotonically with** $\chi_{i,e}$
  - **Follows the** $\lambda_q \sim \chi_{i,e}^{1/2}$ **scaling**
- **W/ Drift:**
  - $\chi_{i,e}$**< 0.1m²/s** λ_q **is nearly unchanged**
  - $\chi_{i,e}$**> 0.1m²/s** λ_q **increases monotonically**

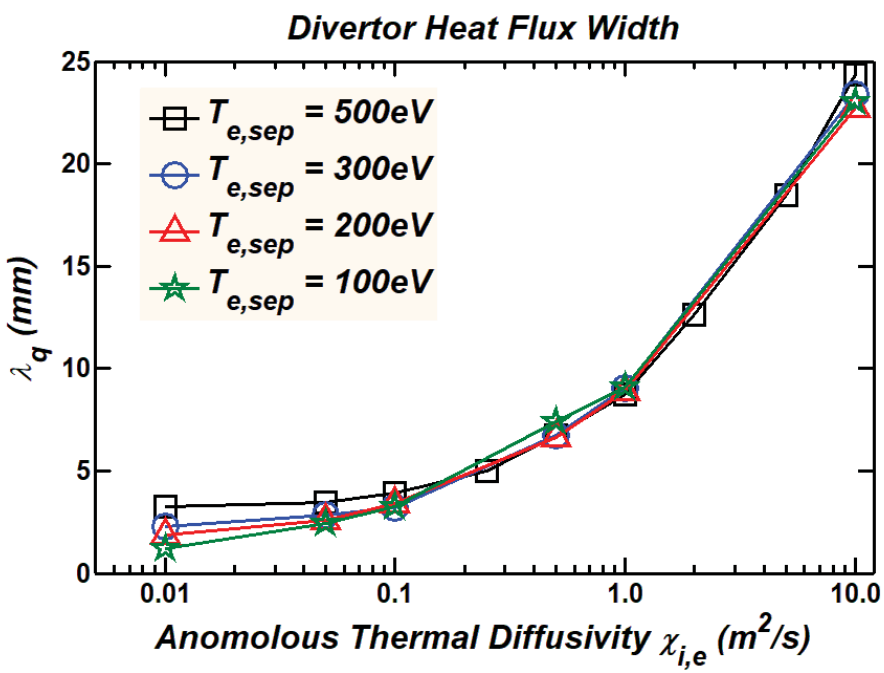
Anomalous Transport Coefficient Scan In SOL

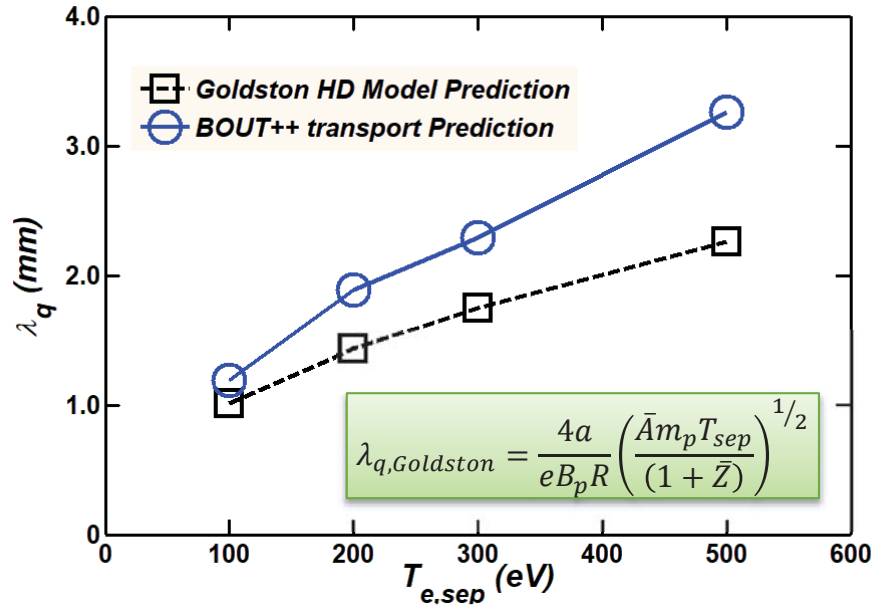


- 2.0x Drift shows a more clear flat region
- Value of flat λ_q is doubled
- Turning point also increases (0.1->0.5)
- Two mechanisms may exist in determining perpendicular transport:
  - Drift vs. turbulence

Separatrix Temperature Scan

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





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

[1] Goldston R.J. 2012 Nucl. Fusion 52 013009

Discussion on BOUT++ Transport Result

- **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: $\lambda_q \sim \chi_\perp^{1/2}$**
- **Different separatrix temperature impact on λ_q**
  - Smaller temperature → smaller λ_q in drift dominate regime
  - λ_q in drift regime roughly matches Goldston's HD model
- **Drift vs. turbulence might bridge the gap between small and large λ_q**
- **What determines the critical $\chi_\perp$ between drift and turbulence dominate regime ?**

Discussion on BOUT++ Transport Result

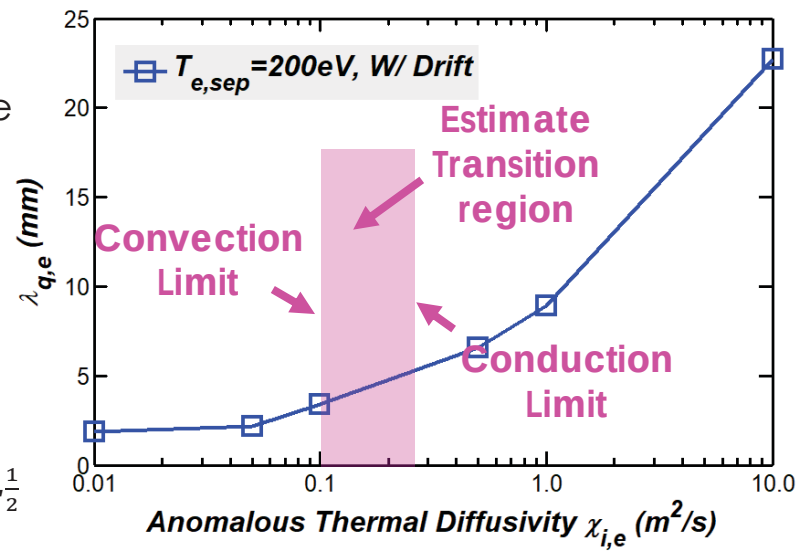
- By balancing the simple drift and turbulence term

Drift → $\boxed{v_{\mathrm{gradB+curlB}} T} \sim \boxed{\chi_{crit} \nabla_{\perp} T \sim \chi_{crit} T / \lambda_T}$ ← Turbulence

$$\chi_{crit} \sim \frac{2T}{BR} \lambda_T$$

- Assuming Conv/Cond limit for parallel transport, we have:

$$\lambda_q = \begin{cases} \left(\frac{1}{\lambda_n} + \frac{3}{2} \frac{1}{\lambda_T} \right)^{-1} < \frac{2}{3} \lambda_T & \leftarrow \text{Convection} \\ \frac{2}{7} \lambda_T & \leftarrow \text{Conduction} \end{cases}$$



- Up to the critical $\chi_{\perp}$ Goldston's model $\lambda_q \sim \frac{4a}{BR} (\frac{m_p}{e})^{\frac{1}{2}} T^{\frac{1}{2}}$ still valid, we have:

$$\chi_{crit} \in \left[\frac{12a}{B_p^2 R^2} \left(\frac{m_p}{e} \right)^{\frac{1}{2}} T_{sep}^{\frac{3}{2}}, \quad \frac{28a}{B_p^2 R^2} \left(\frac{m_p}{e} \right)^{\frac{1}{2}} T_{sep}^{\frac{3}{2}} \right]$$

← $T_{sep} \uparrow \rightarrow \chi_{crit} \uparrow$
$B_p, R \uparrow \rightarrow \chi_{crit} \downarrow$

➢ **What is the typical $\chi_{\perp}$ in real turbulence? → BOUT++ turbulence code !**

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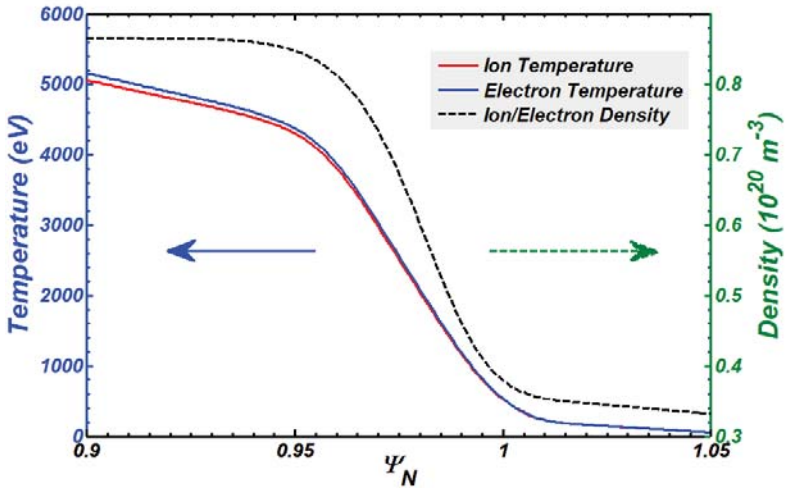
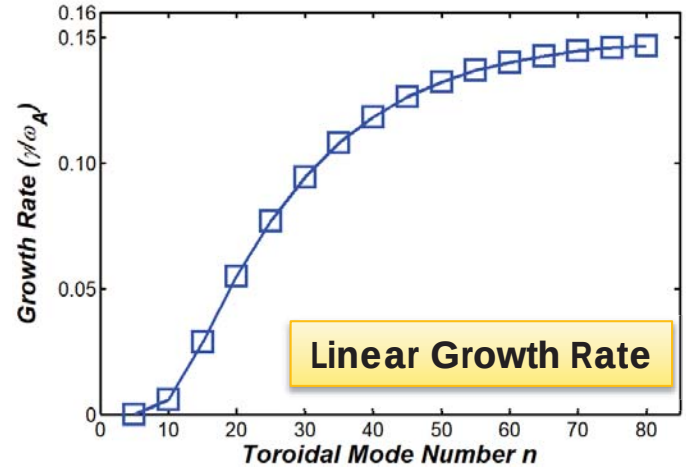
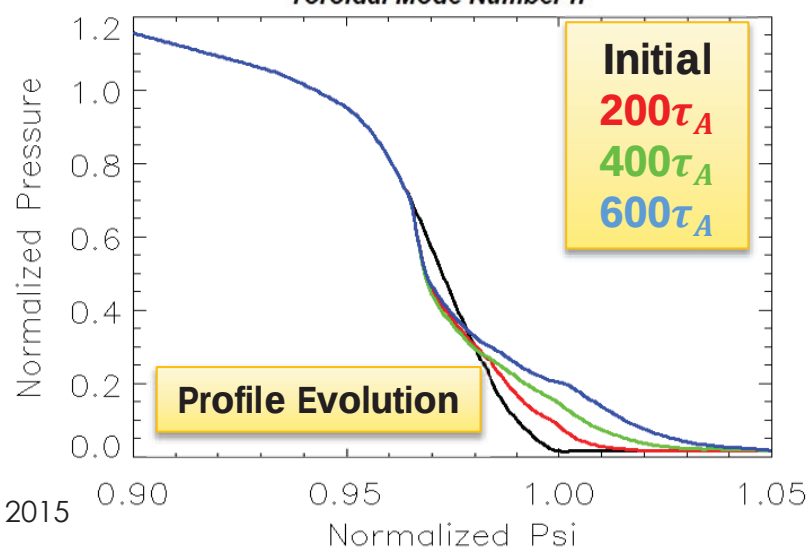
ITER Instability and profile evolution



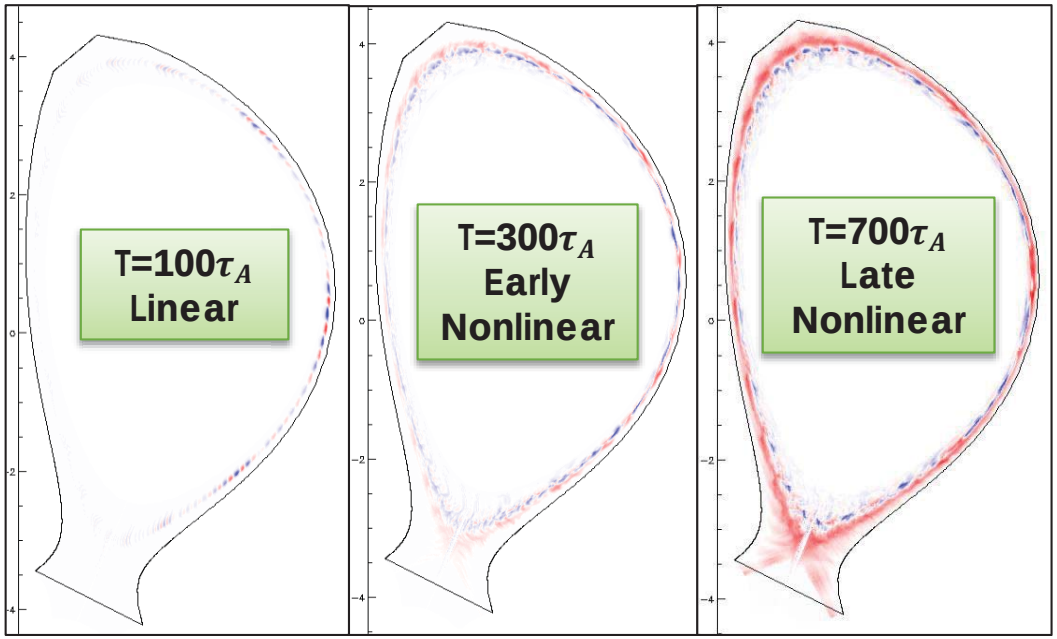


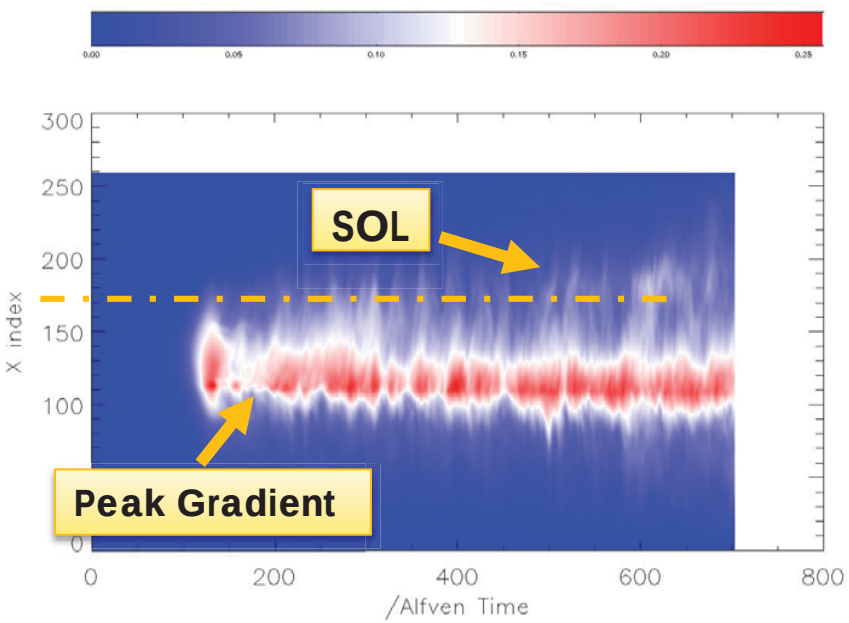
- Unstable for high-n ballooning mode
- Large ELM crash would happen with the ITER scenario[1]
- Pedestal would crash to flat in ~0.3ms
- A lot of energy would come out from core, similar to previous result[2]



[1] S.H. Kim et al. "Simulating Burning Plasma Operation in ITER", EPS, Lisbon, 2015
[2] C.S. Chang et al., 2017 *Nucl. Fusion* 57 116023

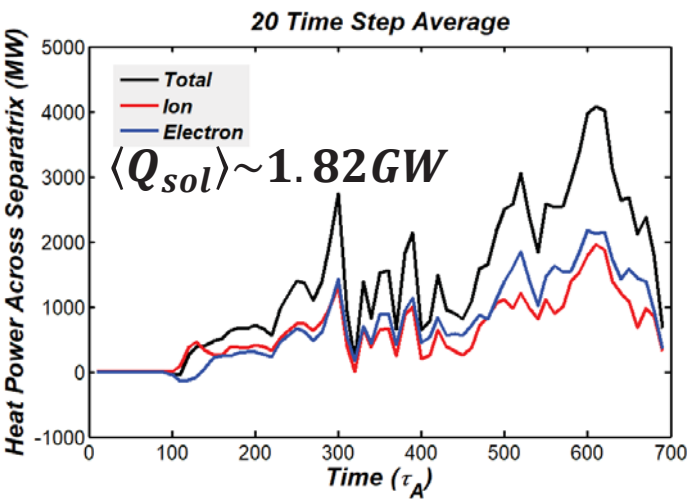
Turbulence is generated inside the pedestal and then spread into SOL

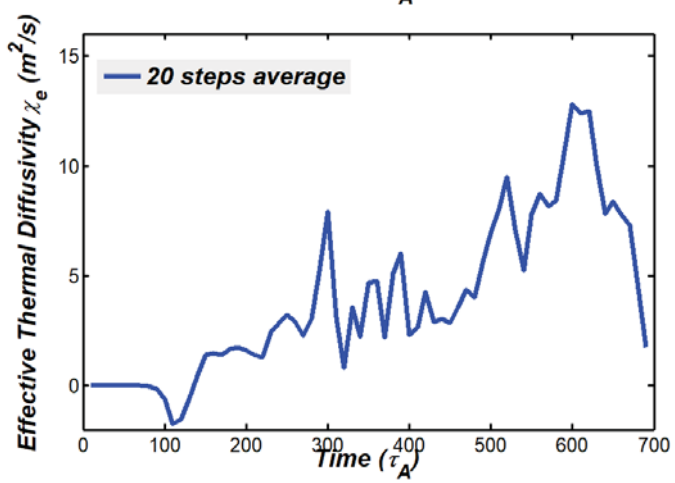




- There would be a delay on saturation of turbulence in different position
- Turbulence is generated in pedestal peak gradient position and then spreads into SOL, not local instability

Heat Flux Across Separatrix





- Perpendicular thermal transport by ExB turbulence is:

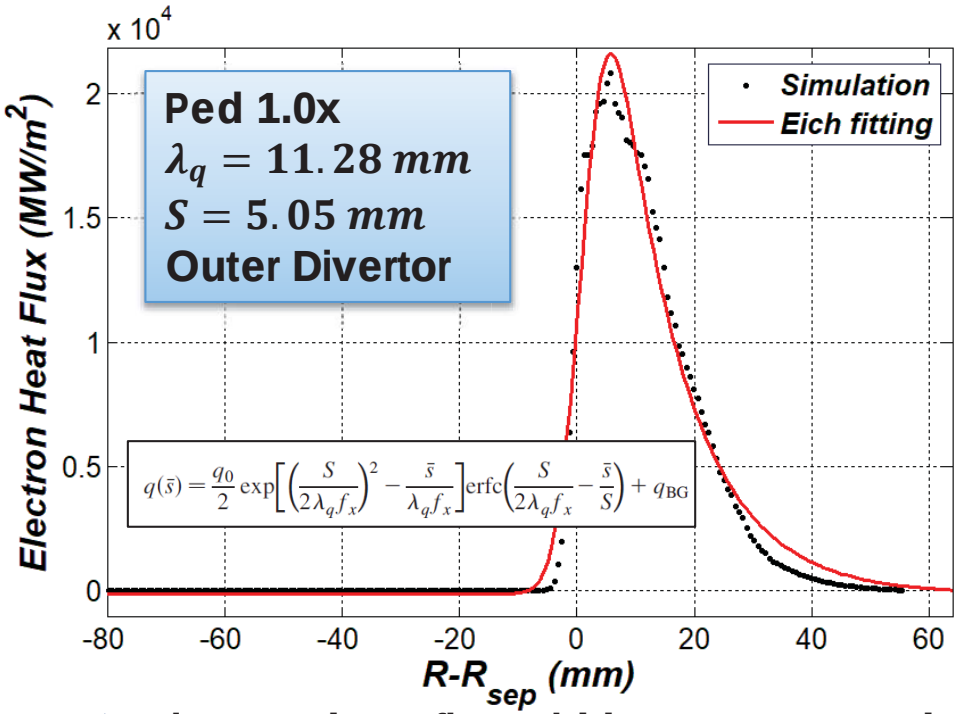
$$q_{ir,tur} = \left\langle n_i T_i \frac{(b_0 \times \nabla\phi)_r}{B_0} \right\rangle_{\theta,\zeta}, q_{er,tur} = \left\langle n_i T_e \frac{(b_0 \times \nabla\phi)_r}{B_0} \right\rangle_{\theta,\zeta}$$

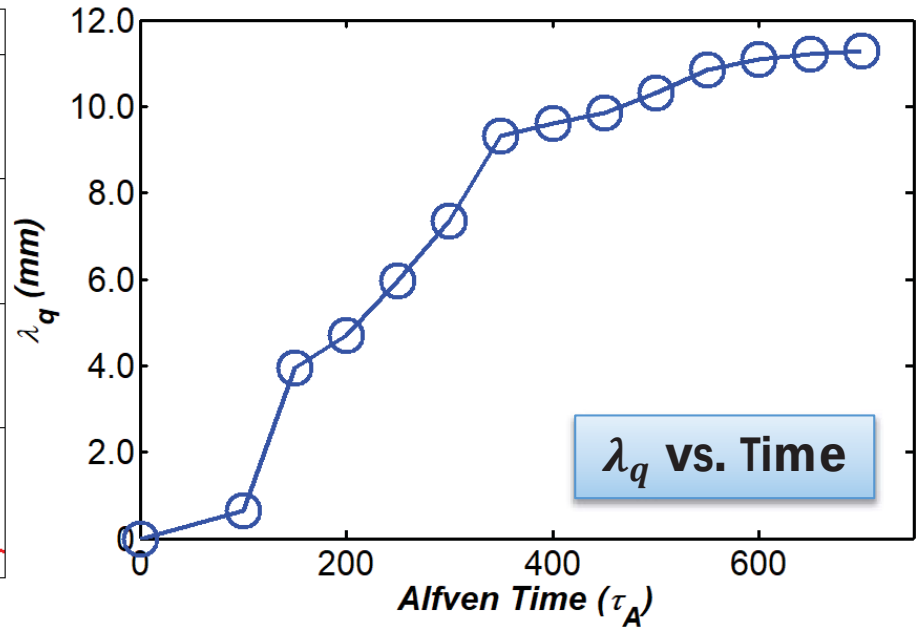
- Effective perpendicular thermal diffusivity is defined by:

$$\chi_{tur} = -\left\langle \frac{\langle q_{tur} \rangle_{\theta,\zeta}}{\langle n \nabla T \rangle_{\theta,\zeta}} \right\rangle_t$$

- 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 λ_q?

Divertor Heat Flux

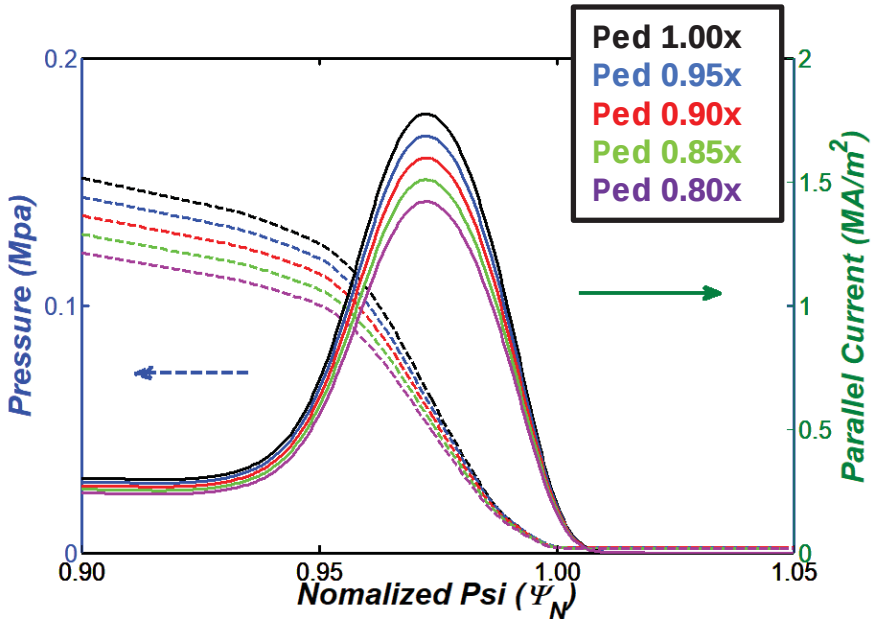


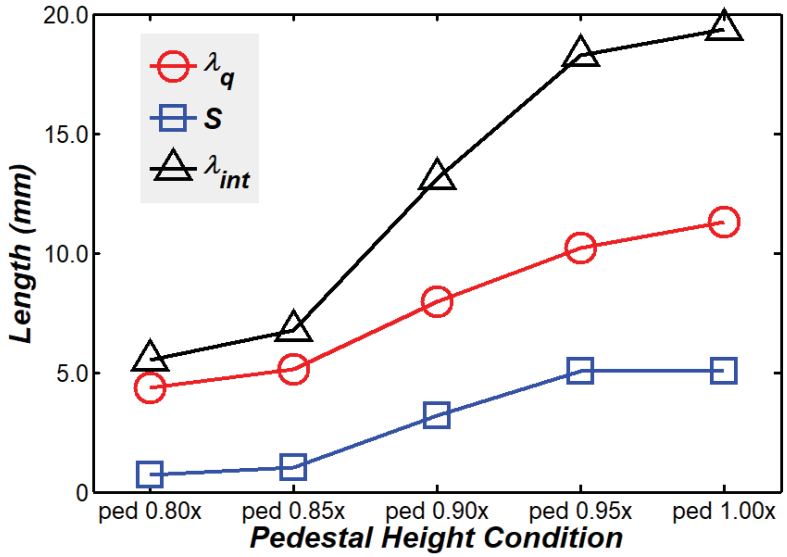


- Electron heat flux width gets saturated after 600τ_A
- It would show a quite large, λ_q=11.28mm, roughly consistent with Dr. Myra's I-BWD case[1]
- ITER original pedestal profile might fall into the turbulence dominate regime
- What if without ELM ? Change pedestal !

[1] J. R. Myra, Physics of Plasmas 22, 042516 (2015)

Different Pedestal Structure

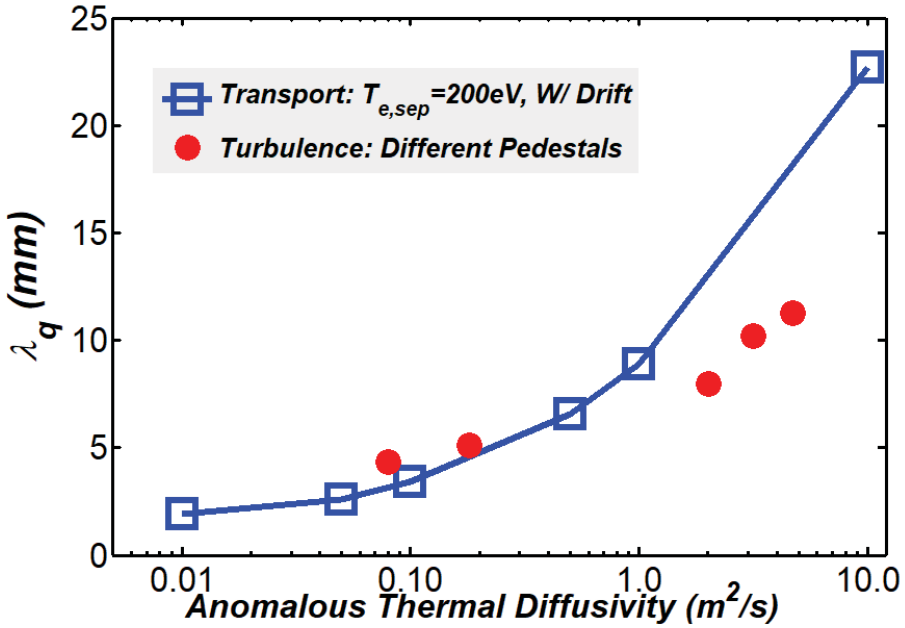




Weak turbulence → Strong turbulence

- Both P and Jpar are scaled by a factor : density scale, temperature unchanged
- Equilibriums are **re-calculated** by CORSICA
- Upstream pedestal condition would have a large impact on SOL physics, λ_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, λ_q increases with pedestal height increase, and finally get to a saturation

BOUT++ Turbulence - Transport Comparison



- **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 λ_q ~11.28mm
- **Pedestal structure is important in determining λ_q of ITER**
  - λ_q is in the range of 4.0mm – 12.0mm for pedestal factor 0.8 to1.0
- **BOUT++ turbulence and transport have a similar trend, but have some deviation**

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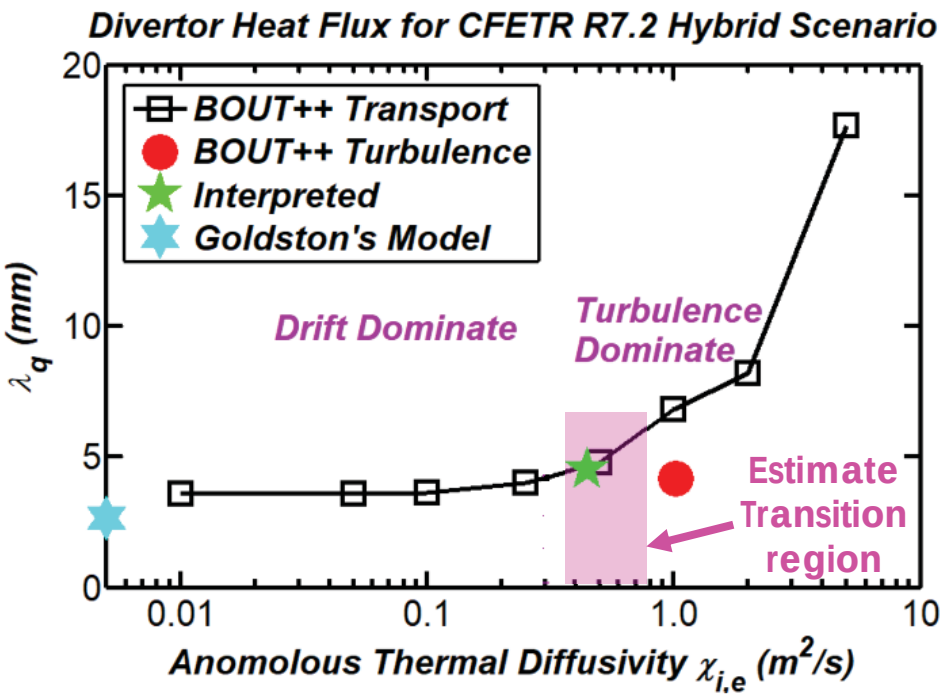
CFETR R7.2 Hybrid Scenario

$T_{e,sep} = 400eV$



Larger $T_{e,sep}$, smaller B_p, similar R makes χ_{crit} larger than ITER

- **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 λ_q, Eg. CFETR ($\beta_p, q_{95}, \nu_{e*}$) might perform like grassy ELM[1]**
- **Grassy ELM might be favorable for achieving large λ_q**

[1] Zeyu Li, V.S. Chan et al. *Nucl. Fusion* 58 (2018) 016018

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Summary

- **Drift and turbulence would have a competition on determine perpendicular transport, which might bridge the gap between small and large λ_q**
  - Drift dominate regime, λ_q roughly matches with Goldston's model and experimental scaling
  - Turbulence dominate regime, λ_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 λ_q**
- **Pedestal structure is important for determining λ_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 λ_q**

Thanks For Your Listening !