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

X. Q. Xu[1],

N. M. Li[1,2], Z.Y. Li[1,3], X. Y. Wang[1,3], T. Y. Xia[1,4], T. F. Tang[1,2], G. Z. Deng[1,4,7], C. Lasnier[1], H. Q. Wang[5], and R. Nazkian[6]

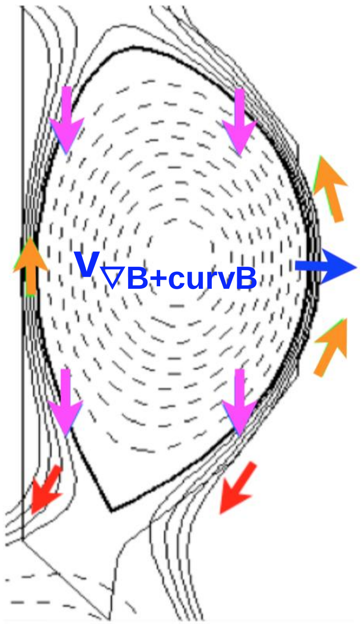
1) Lawrence Livermore National Laboratory, Livermore, CA 94550 USA
2) Dalian University of Technology, Dalian, China
3) Peking University, Beijing, China
4) Institute of Plasma Physics, Chinese Academy of Sciences, Hefei, China
5) General Atomics, San Diego, CA 92186 USA
6) Princeton Plasma Physics Laboratory, Princeton, NJ 08543-0451, USA
7) University of Science and Technology of China, Hefei, China

Acknowledgement: S. H. Kim and L L LoDestro for providing CORSICA simulation data for ITER 15MA baseline operation scenarios.

Presented at
Third IAEA Technical Meeting on Divertor Concepts
4-7 November 2019, Vienna, Austria

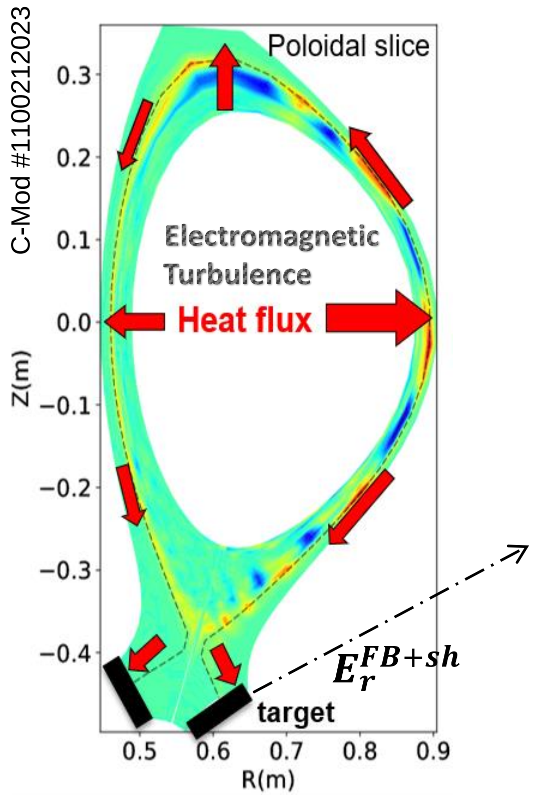
This work was performed under the auspices of the U.S. DoE by LLNL under Contract DE-AC52-07NA27344 , and is supported by the China NSF under Contract No.10721505, the National Magnetic Confinement Fusion Science Program of China under Contracts No. 2011GB107001 . LLNL-PRES-795856

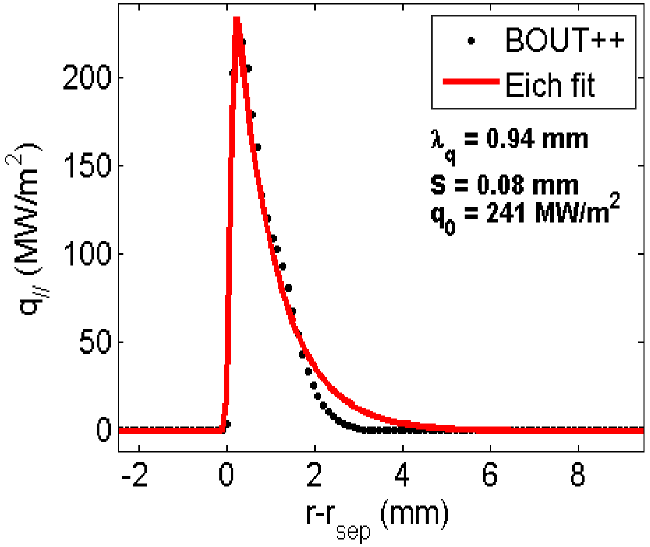
Both EM fluctuation & drifts provide anomalous radial transport, setting divertor heat flux width



Setting density channel width
$\lambda_n \sim v_{\nabla B+curvB}(L_{||}/c_s) \sim q\rho_s$

+



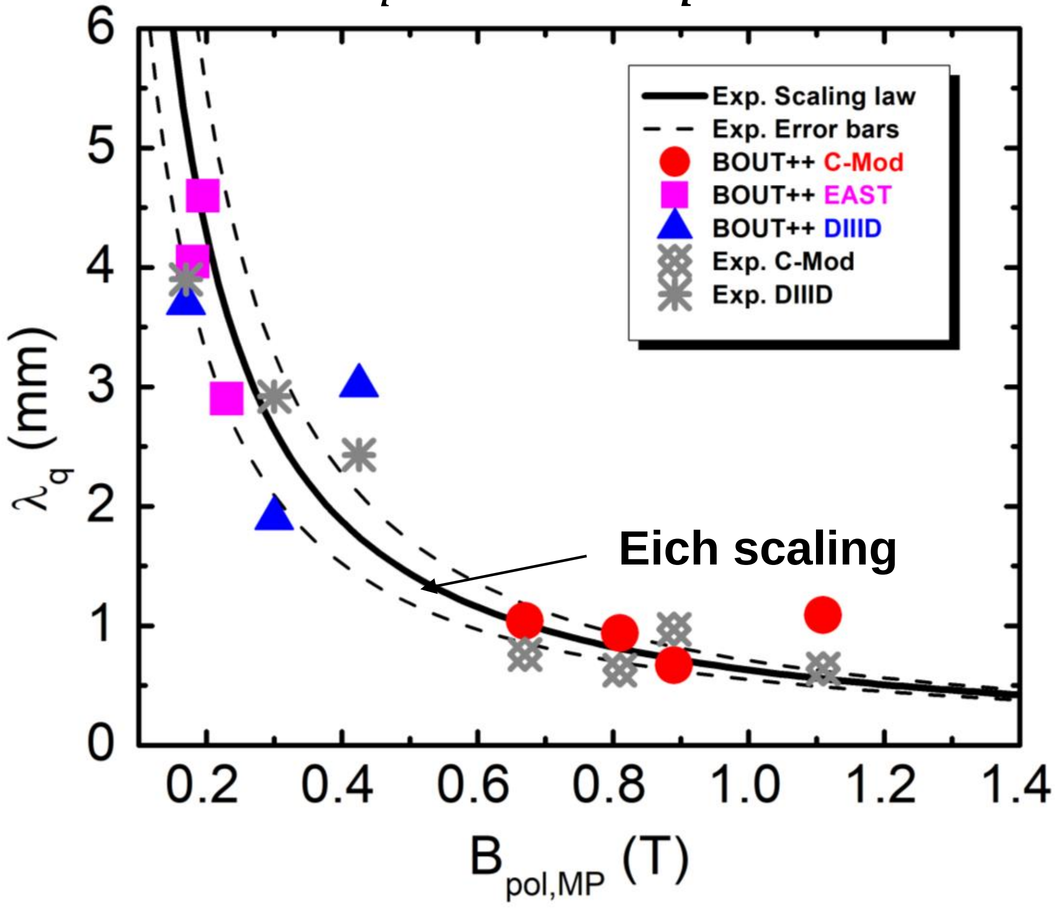


[1] B. Chen, X. Q. Xu, et al, Phys. Plasmas (2018)
[2] T.Y. Xia, et al, 2017, Nucl. Fusion, 57, 116016.
[3] Z.Y.Li, X.Q.Xu, 2019 Nucl. Fusion
[4] X. Q. Xu., N.M. Li, et al., 2019 Nucl. Fusion
[5] N. M. Li, et al. 2019 Phys. Plasmas
[6] T.F. Tang, et al, 2019, submitted to IEEE Trans. Plasmas.

- **Upstream:** Both EM fluctuations & drifts provide anomalous radial transport
- **SOL:** Parallel transport connect SOL to divertor
- **Divertor footprint:** Radial profile of divertor heat flux mapped to the outer midplane, showing a good agreement with Eich-fitting formula

The e^- heat flux width from BOUT++ turbulence simulations of C-Mod, DIII-D and EAST follows exp. "Eich" scaling

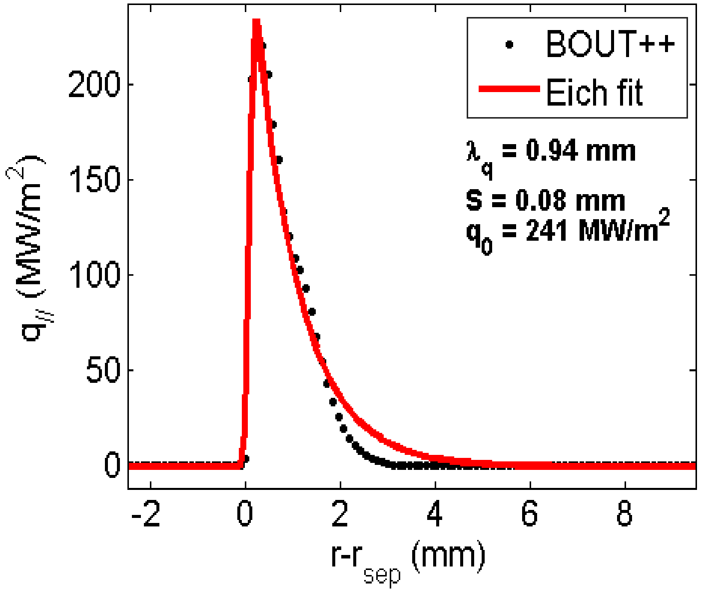
$$\lambda_q = 0.63 B_{pol}^{-1.19}$$



[1] B. Chen, X. Q. Xu, et al, Phys. Plasmas 25, 055905 (2018)

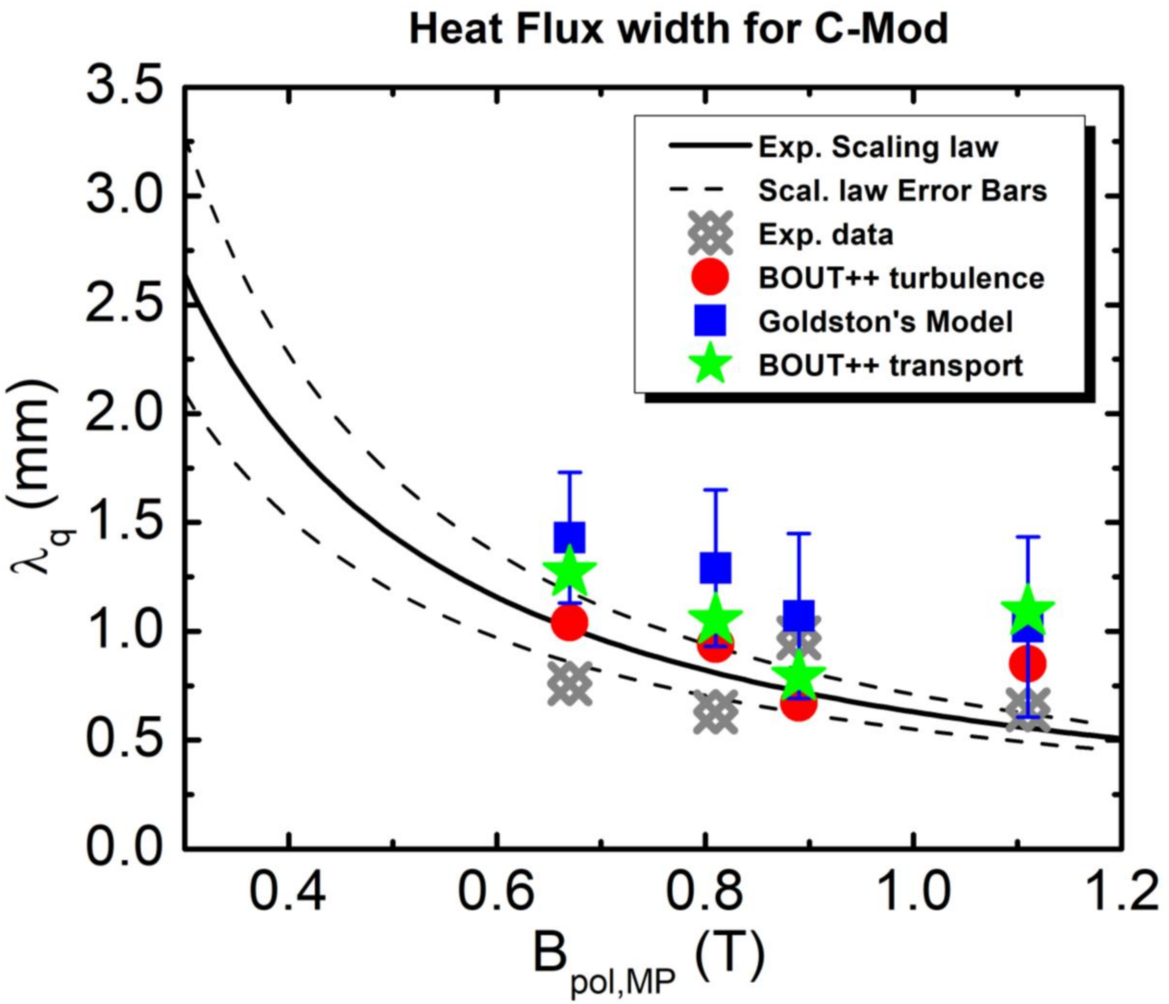
[2] T.Y. Xia, et al, 2017, Nucl. Fusion, 57, 116016.

[3]] T.F. Tang, et al, 2019, submitted to IEEE Trans. Plasmas



- **Dominant modes: EM RBMs+DAW**
- **EM turbulence originates inside the pedestal near ∇P_{peak} and nonlinearly, spreads across the separatrix into the SOL in simulations**
- **The simulated EM turbulence characteristics compared well with experiments**
- **The amplitude of the electron heat fluxes is within a factor of 2 compared to experiment**

Calculated heat flux width from BOUT++ transport is similar to Goldston's model and turbulence simulations



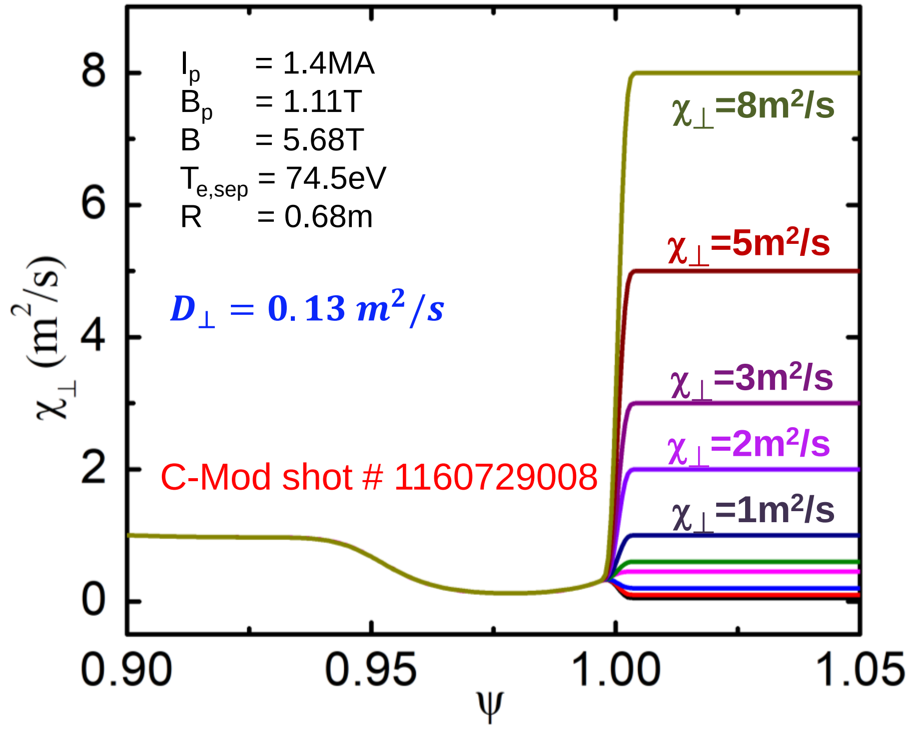
Goldston's HD formula

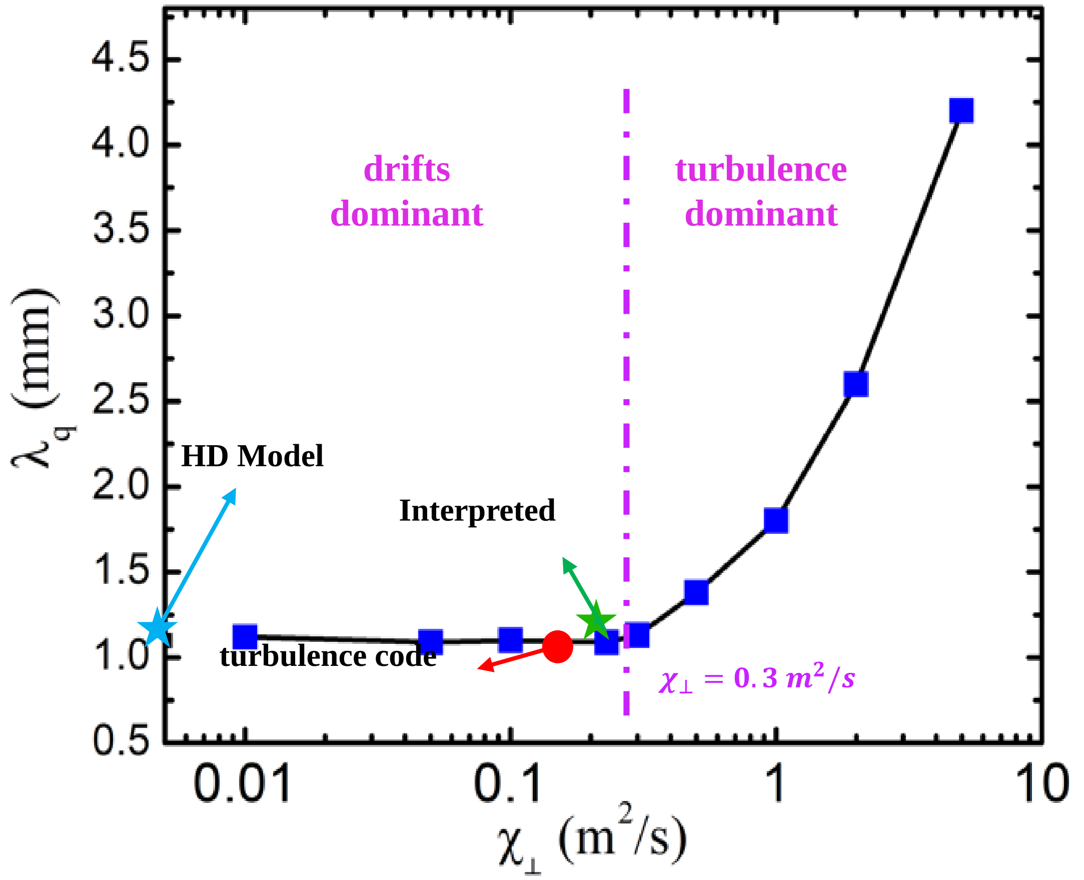
$$\lambda_q = \frac{4a}{\bar{Z}eB_pR}\left(\frac{\bar{A}m_pT_{sep}}{1+\bar{Z}}\right)^{1/2}$$

- **The transport simulations show a similar trend to the Goldston's HD model**
- **The electron and ion heat flux width on the divertor targets follow similar trends**
- **Large λ_q for B_p=1.1T is due to higher separatrix temperature measured from expt.**

N.M. Li, X. Q. Xu, J. W. Hughes, et al., submitted to Phys. Plasmas (2019)

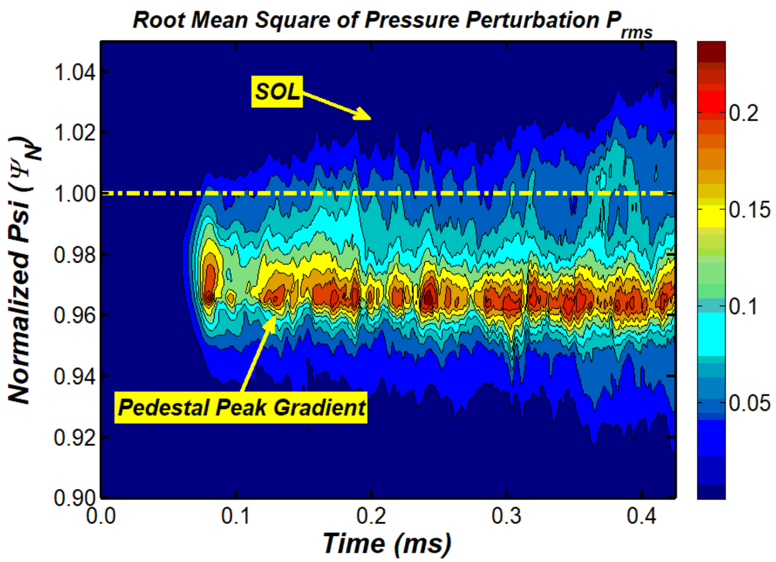
The drifts and turbulent transport compete in setting the divertor heat flux width for C-Mod



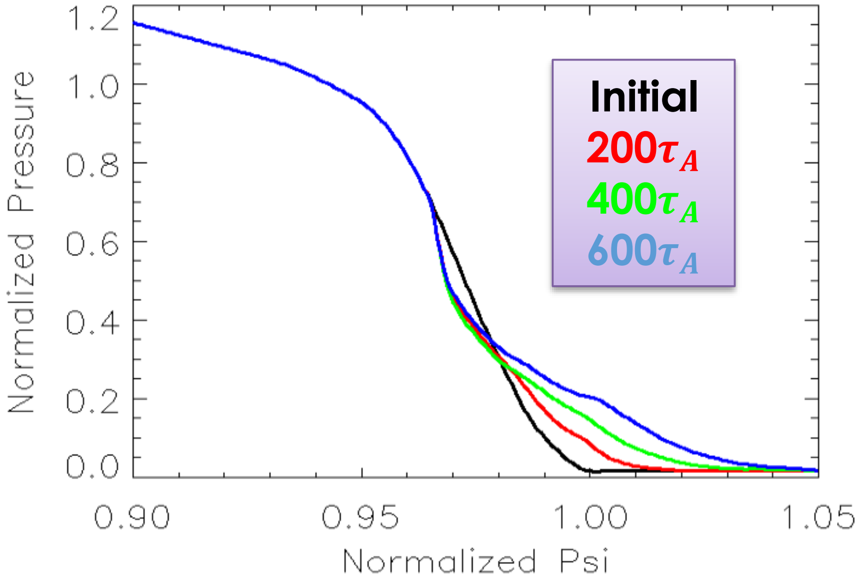


- Heat flux width is flat and then increases with the SOL thermal diffusivity
- $\chi_{\perp,\text{critical}}$ is found
  - $\chi_\perp < 0.3\ m^2/s$, drifts dominate cross-field transport
  - $\chi_\perp > 0.3\ m^2/s$, turbulence dominates cross-field transport
- Interpreted $\chi_\perp = 0.23\ m^2/s$ from experiments
- Calculated $\chi_\perp = 0.16\ m^2/s$ from 6field turbulent simulations

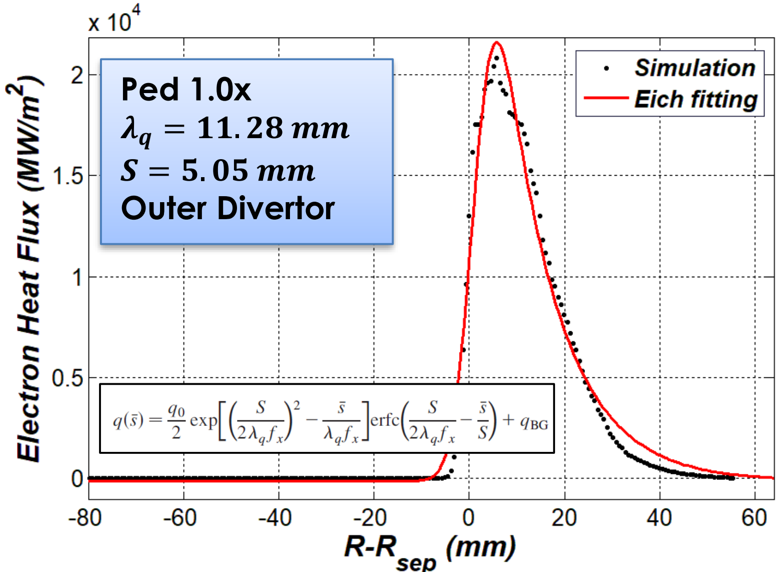
The ITER baseline target plasmas are in the type-I ELMy H-mode regime from turbulence simulations



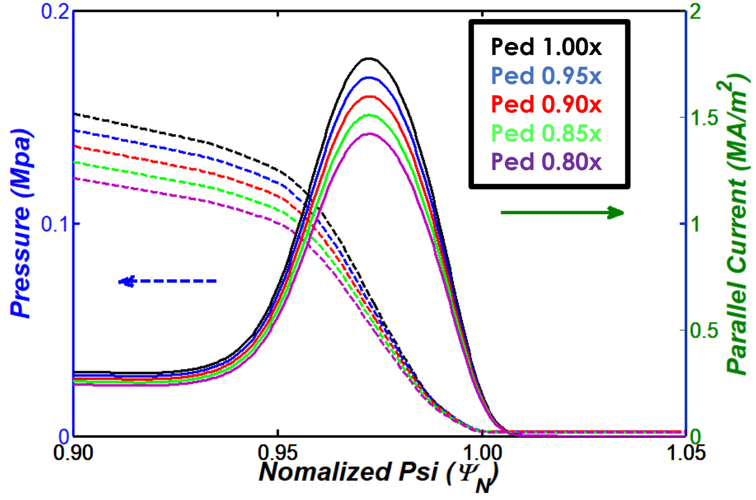
Li, Xu, et al. Nucl. Fusion **59**, 046014 (2019)

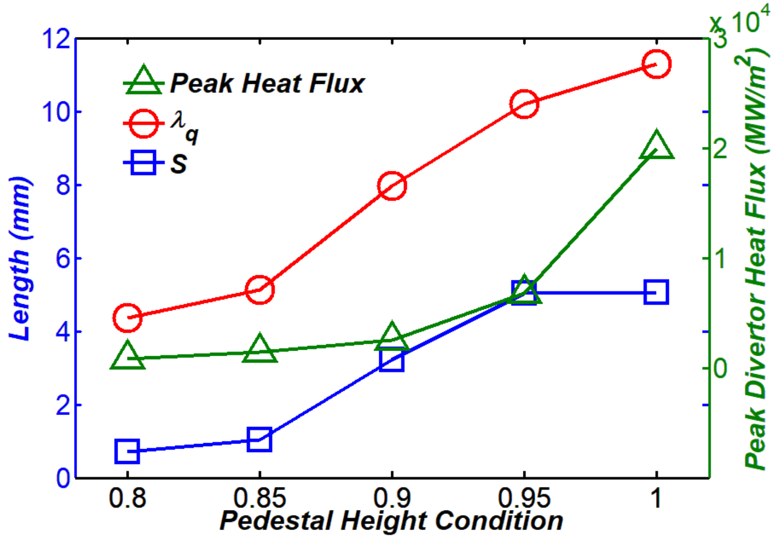


- **Unstable for high-n ballooning mode**
- **Dominant fluctuation is generated in pedestal peak gradient location and spreads into SOL**
- **ELM collapses to flatten pedestal pressure profile in ~ 300µs**
- **Unmitigated ELM parallel heat fluxes ~20 GW/m², leading to λ_q=11.28mm**



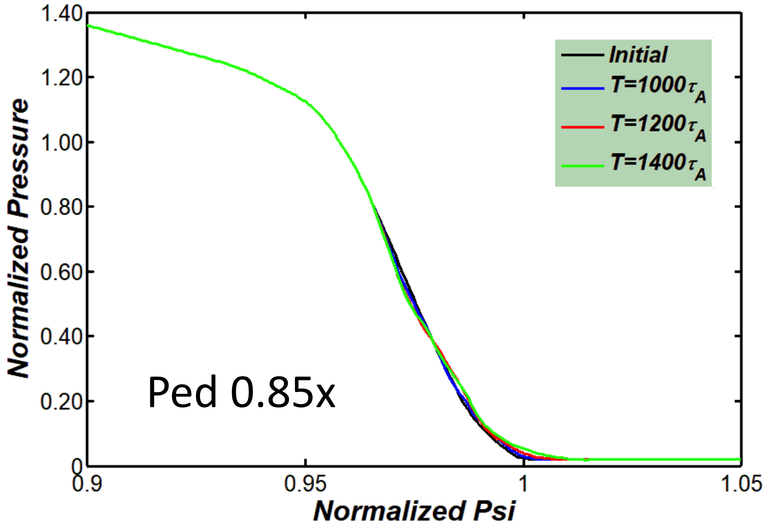
Decreasing of pedestal heights by ELM mitigation leads to smaller λ_q



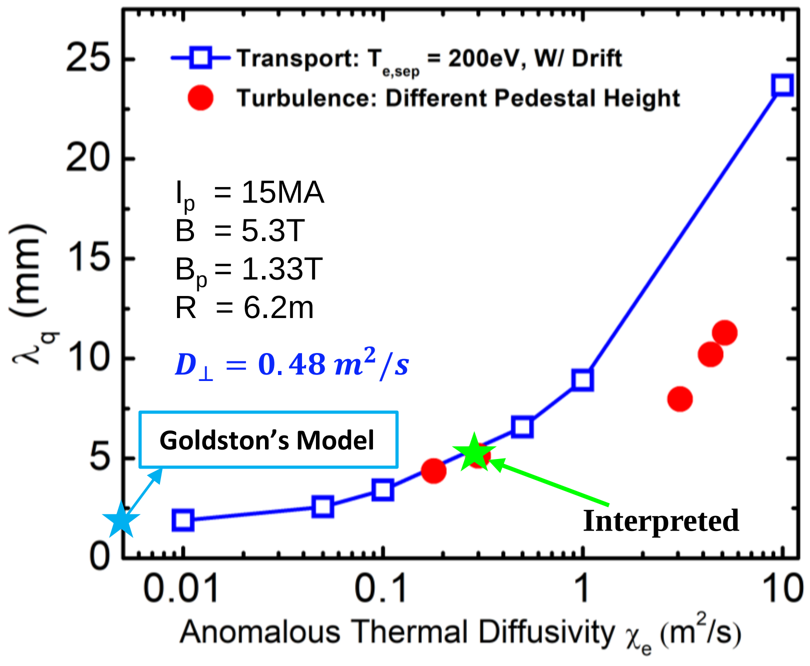


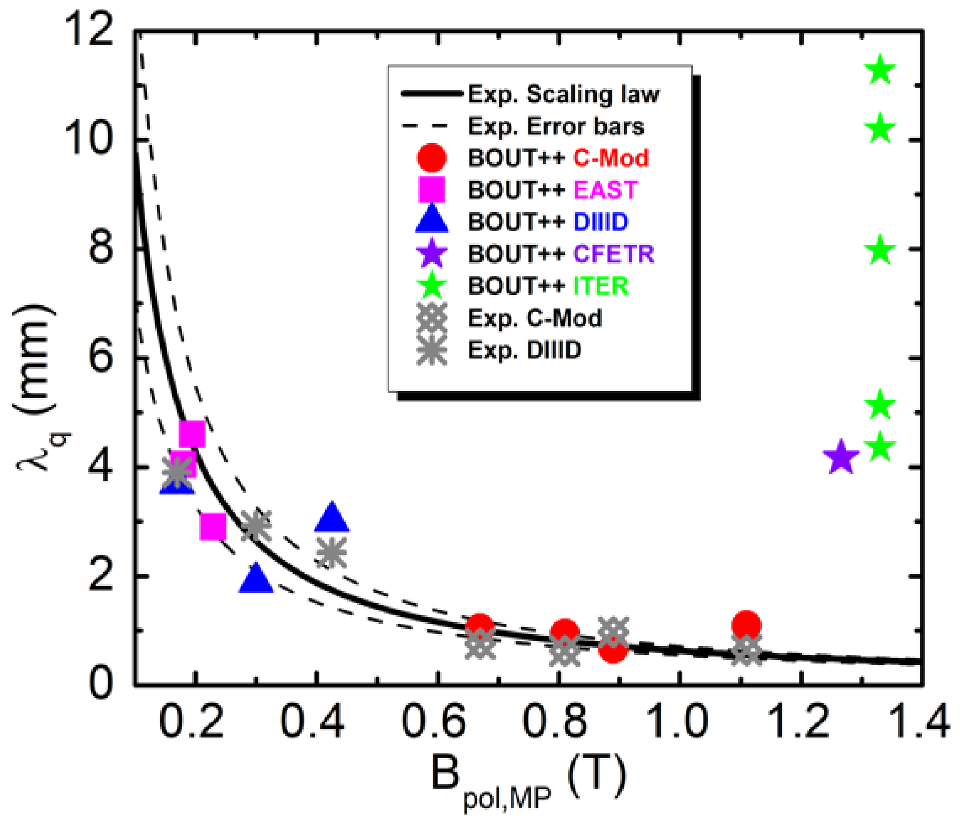
Weak turbulence → Strong turbulence

- Both P and $J_{||}$ are scaled by a factor : density scale, temperature unchanged
- Equilibria are re-calculated by CORSICA
- Upstream pedestal structures have a large impact on SOL physics
  - Decrease in pedestal heights by 20%
    → 3x decrease in λ_q,
    → 3x decrease in $q_{||, peak}$
  - λ_q in a wide range: 4mm~12mm
- No large ELM collapses at 0.85x pedestal



Both BOUT++ turbulence and transport simulations predict that ITER will possibly be in a turbulence dominant regime with large λ_q





- HD model sets the pessimistic limit of divertor heat flux width
- Drift becomes sub-dominant in ITER simulation due to large R
- Turbulent transport coefficients depends on pedestal structures inside the separatrix
- $\chi_\perp = 0.34\ m^2/s$ in scenario studies
- Added the ITER data point to the ITPA multi-machine scaling plot show
  - a transition from drift dominant regime to turbulence dominant regime
  - λ_q no longer follows the $1/B_{pol,MP}$ experimental Eich scaling law

Dominant parameters for the transition from drift dominant to turbulence dominant regime

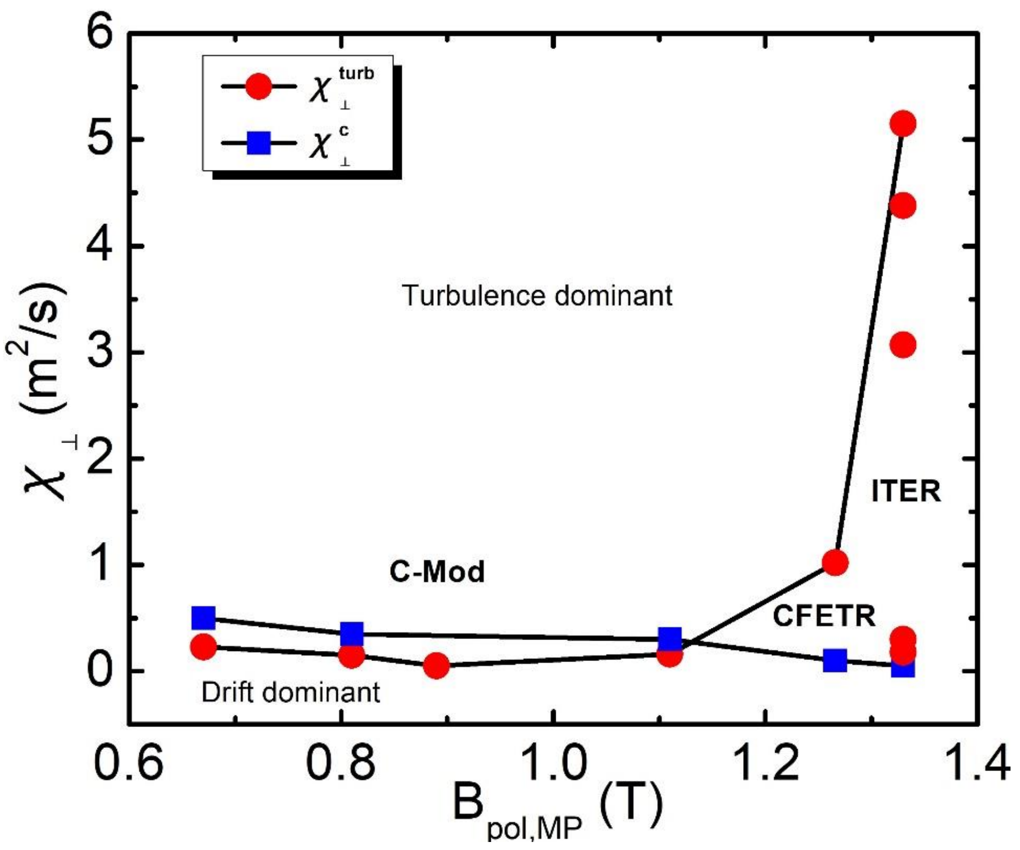
- **The effective diffusivity $\chi_\perp^c$ from the magnetic drift-based radial transport can be estimated as:**

$$\chi_\perp^c = v_d \lambda_T = \mathbf{C} v_d q \rho_s = \mathbf{C} \frac{2T_{e,sep}^{3/2}}{BB_pR}\frac{m_p^{1/2}}{e^2}\frac{a}{R}$$

C=26.5 is a fitting parameter to simulations for the transition

- **$\chi_\perp^c$ decreases for strong magnetic field B, high current I_p (or B_{pol}) and large machine size R.**
- **Turbulence thermal diffusivity can be increased from ELM-free H-mode to small/grassy ELM regime**
- **Even C-Mod is capable of operating at ITER-level B_p~1.3 T, because $\chi_\perp^c$ is high, the C-Mod high Bp shots are possibly still in the drift dominant regime**

X. Q. Xu, N. M. Li, Z.Y. Li, et al., Nuclear Fusion (2019)



Critical $\chi_\perp^c$ can be rewritten to be inversely proportional to B_p^2

$$\chi_\perp^c = \mathbf{C}\,\frac{2T_{e,sep}^{3/2}}{BB_pR}\,\frac{m_p^{1/2}}{e^2}\,\frac{a}{R}$$

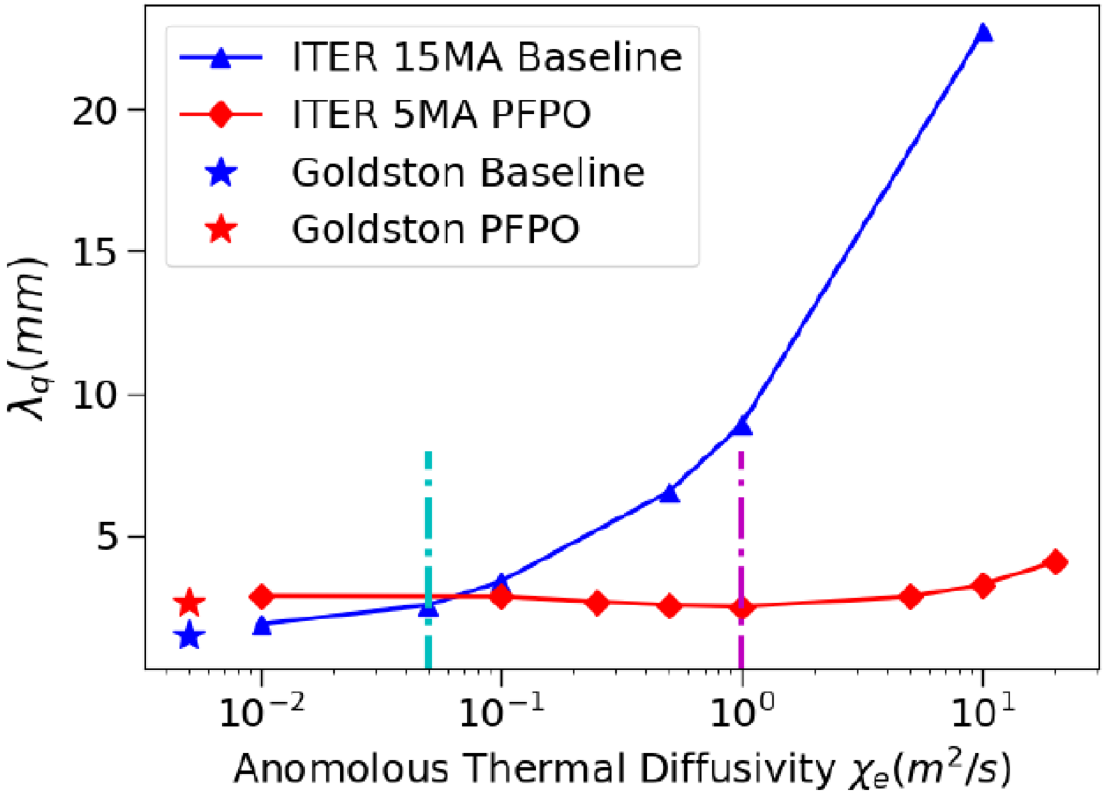
$$\Downarrow$$

B → $qB_p\,\frac{R}{a}$

$$\chi_\perp^c = \mathbf{C}\,\frac{2T_{e,sep}^{3/2}}{qB_p^{\,2}}\,\frac{m_p^{1/2}}{e^{1/2}}\,\frac{a^2}{R^3}$$

By fixing q_{95}, $T_{e,sep}$, (a/R), R, → $\chi^c \approx 1/B_p^2$

Critical $\chi_{\perp}^{c}$ for ITER PFPO-1 is 20x larger than baseline target due to reduced current I_p=5MA by fixing $q_{95}\approx 3$



$$\chi_{\perp}^{c} = C\,\frac{2T_{e,sep}^{3/2}}{qB_p{}^2}\,\frac{m_p^{1/2}}{e^{1/2}}\,\frac{a^2}{R^3}$$

Basic Parameters	ITER 15MA (BT)	ITER 5MA (PFPO-1)
a/R (m)	2.0/6.2	2.0/6.2
B_T (T)	5	1.97
$B_{p,omp}$ (T)	1.33	0.44
Ion	Deuterium	Hydrogen
HD λ_q-prediction (mm)	1.49	2.65
BOUT++ λ_q-prediction (mm) $\chi_e = 0.01\ (m^2/s)$	1.89	2.89
$\chi_{crit,}\ (m^2/s)$ prediction	0.05	1.0

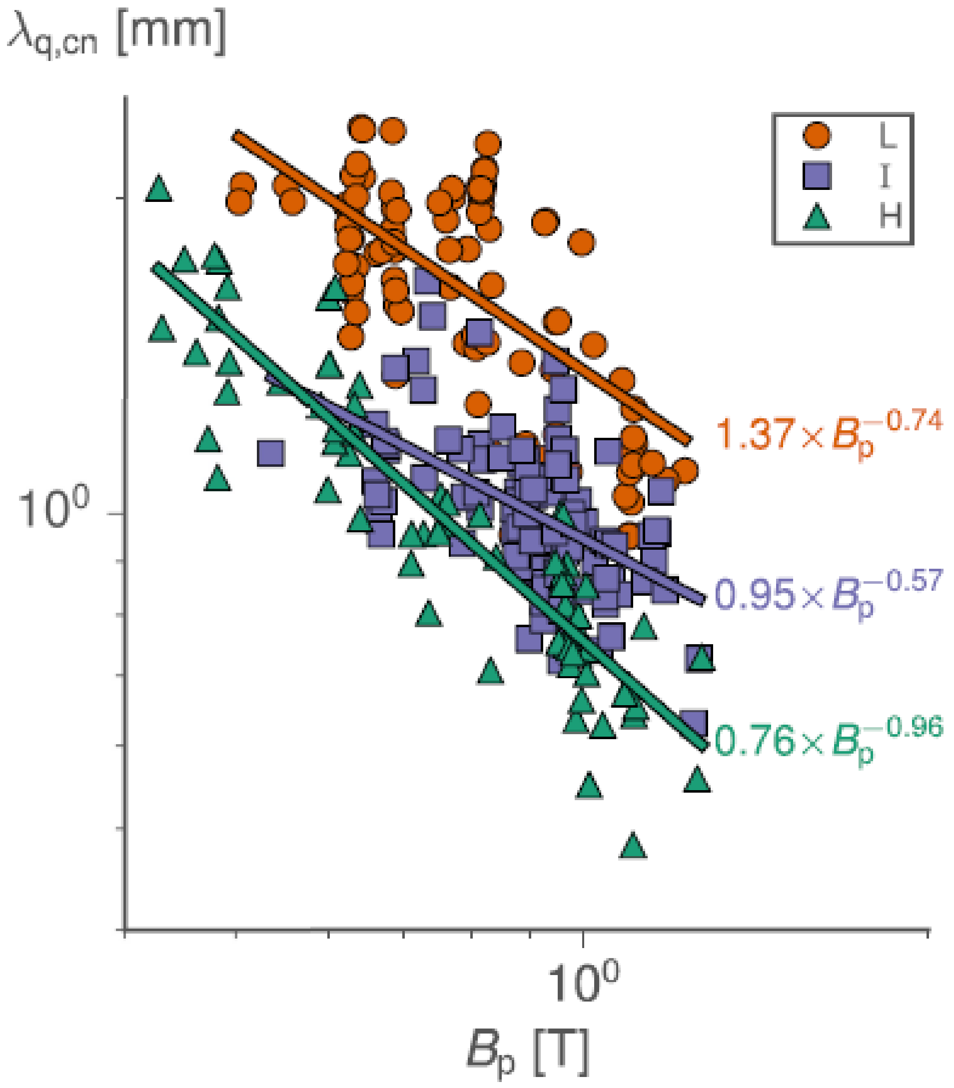
- ITER PFPO-1 scenario is possibly in a drift dominant regime
- Turbulence simulations for PFPO-1 is under way
- Critical thermal diffusivity $\chi_{e,crit}\sim 1.0\ m^2/s$, about 2 times larger than the prediction
  - Possibly because the flat density profile in PFPO-1 H123 case

What are the experimental evidences for

Impact of pedestal operation modes on the divertor heat flux width scaling?

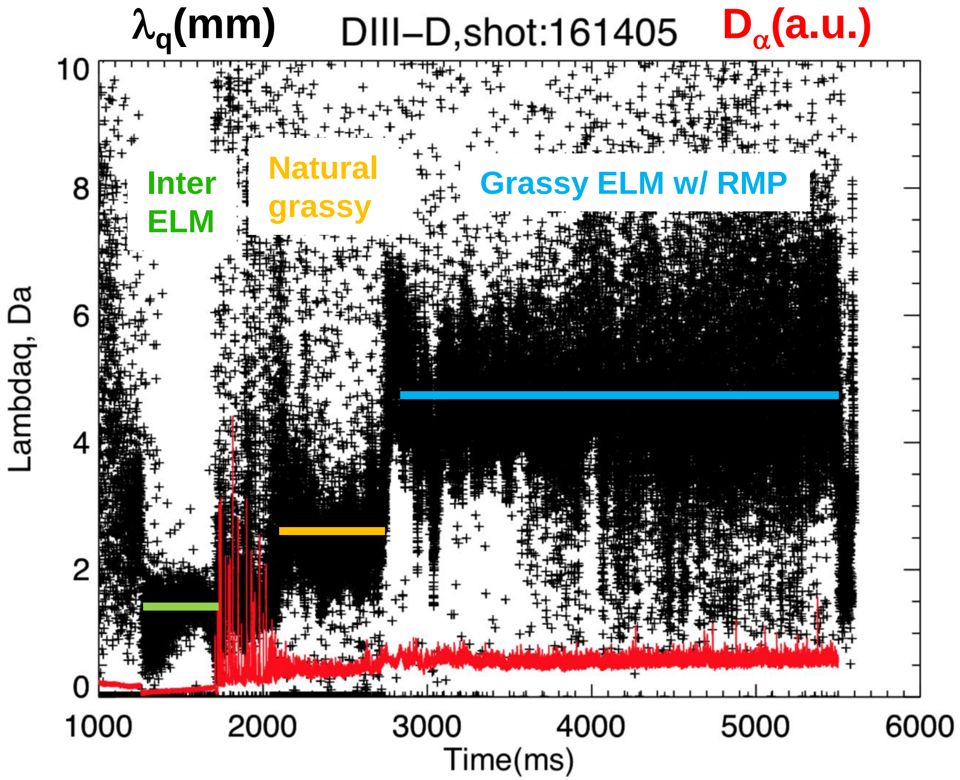
Turbulence transport does matter across confinement regimes on C-mod

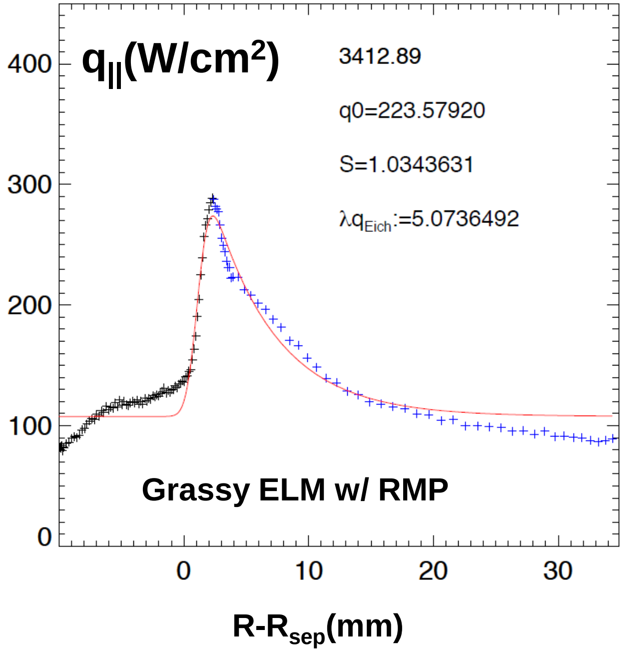
- **H-modes**
  - Purely Inverse Bp scaling
  - Narrowest width
  - Drift & turbulence competing to set the width
- **L-mode:**
  - ~ 2x wider than H-mode
  - Weaker Bp scaling
  - Turbulence transport broadening the width
- **I-mode:**
  - Scatted distribution bounded between L-mode and H-mode
  - WCM enhances the turbulence transport & broadening the width

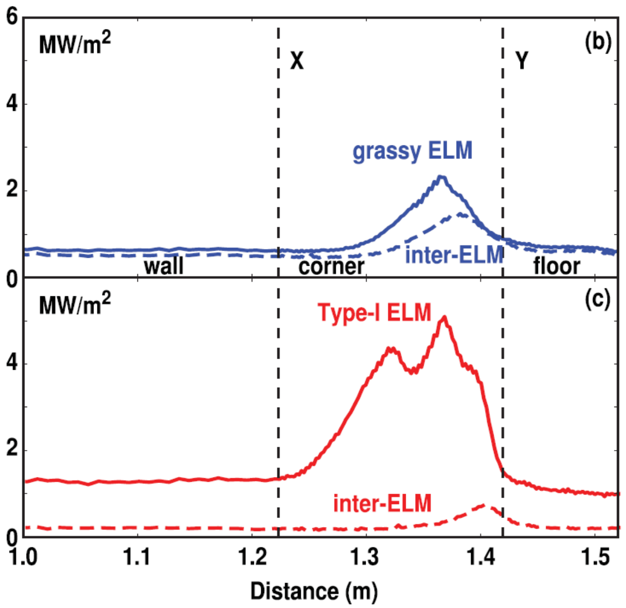


Recent DIII-D grassy ELM experiments show a consistent divertor heat flux width broadening and amplitude reduction, just as BOUT++ simulations demonstrated in the grassy ELM regime

Nazikian, et al. Nucl. Fusion **58** (2018) 106010

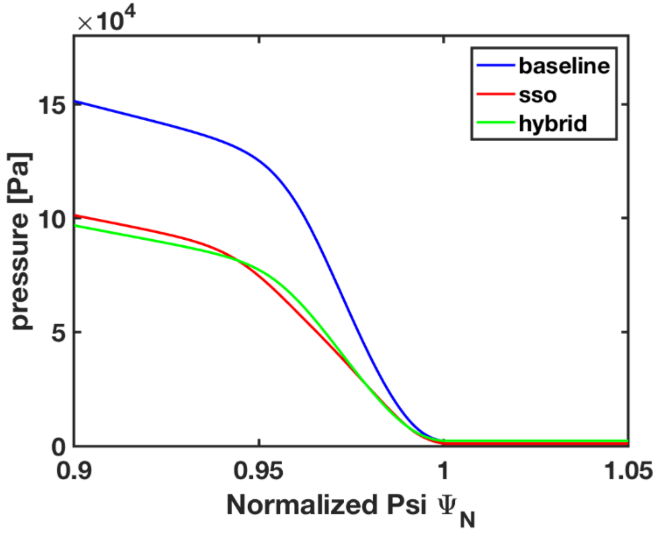


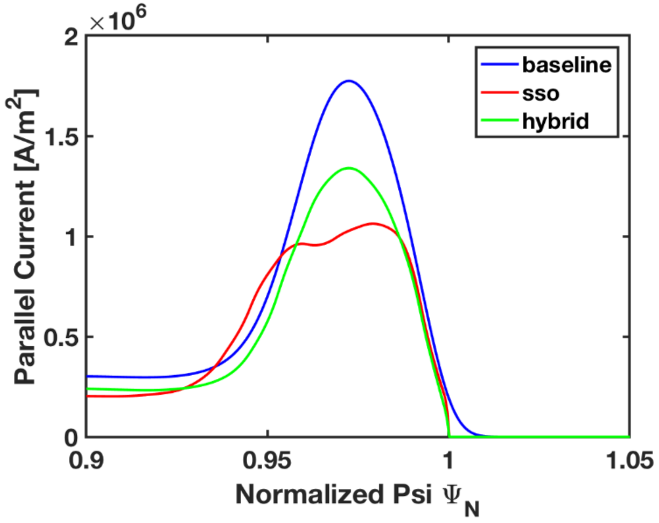


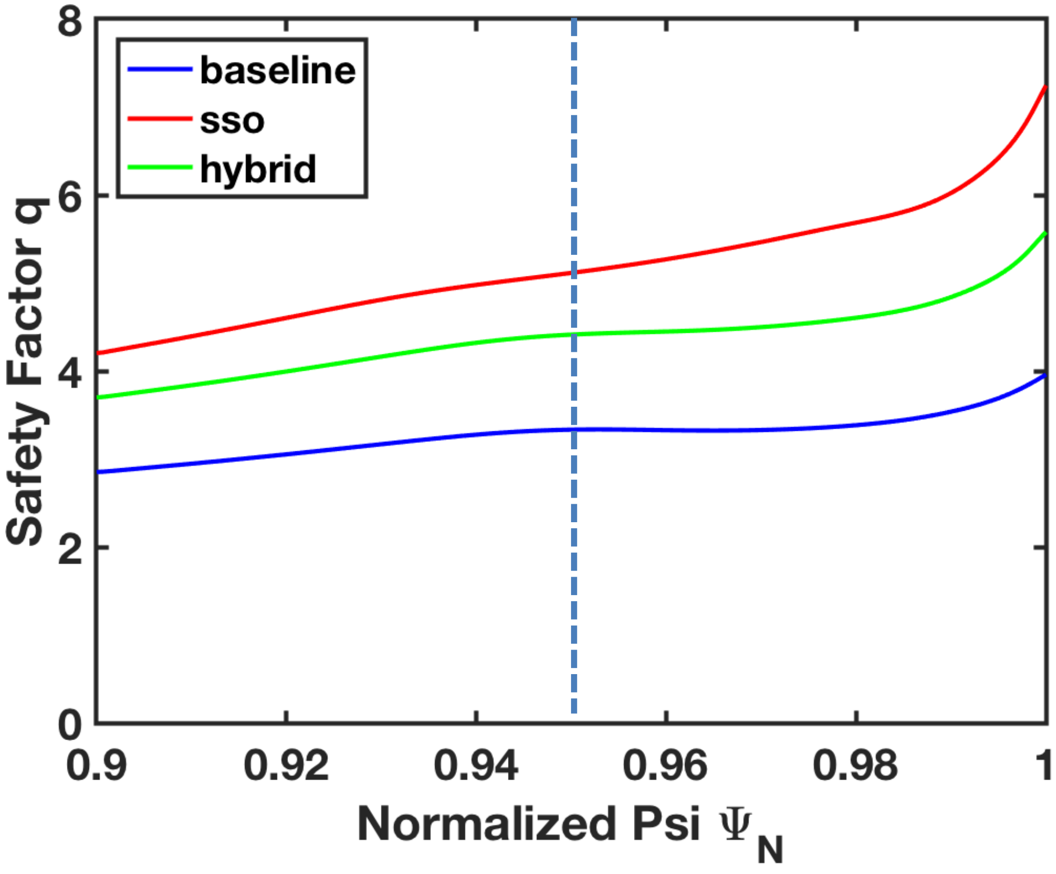


- The D_α signal (RED) and inner divertor heat flux width (BLACK) from the infrared IR camera measurement, which shows mixed ELM activities.
- From the ELM-free phase to the grassy ELM phase,
  - ✓ The divertor heat flux width increases about 6 times w/ RMP
  - ✓ The width increases about 2-3 times w/o RMP
- The grassy-ELMs exhibit a reduced peak heat flux to the divertor that can be as low as 1.2 times the ELM-free heat flux in plasmas with high $H_{98y2} \approx 1.1–1.3$

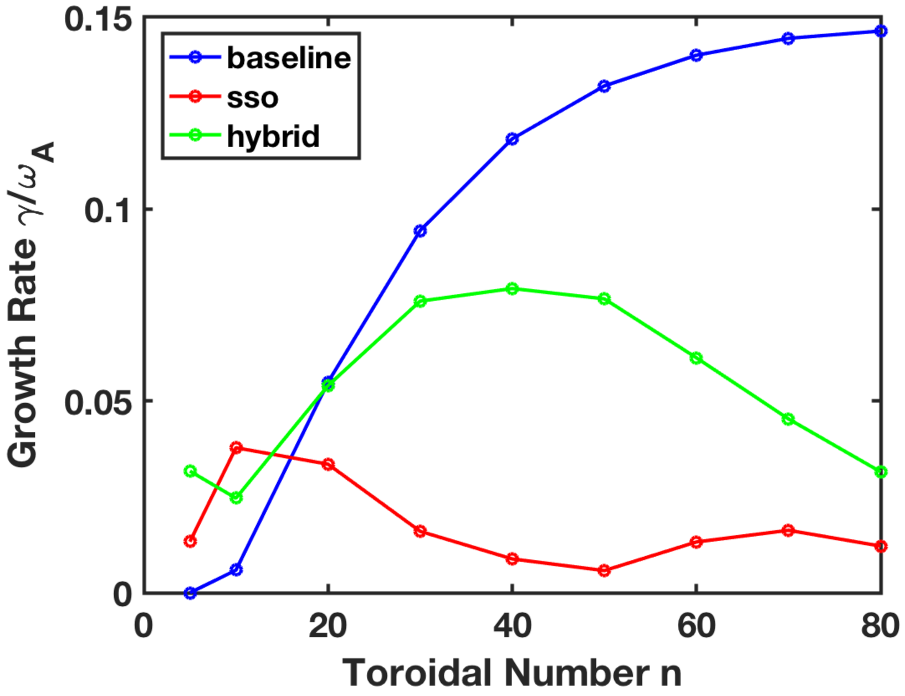
In comparison with ITER baseline scenario, ITER SSO scenario shows lower pedestal pressure and bootstrap current, but high poloidal beta, high q95

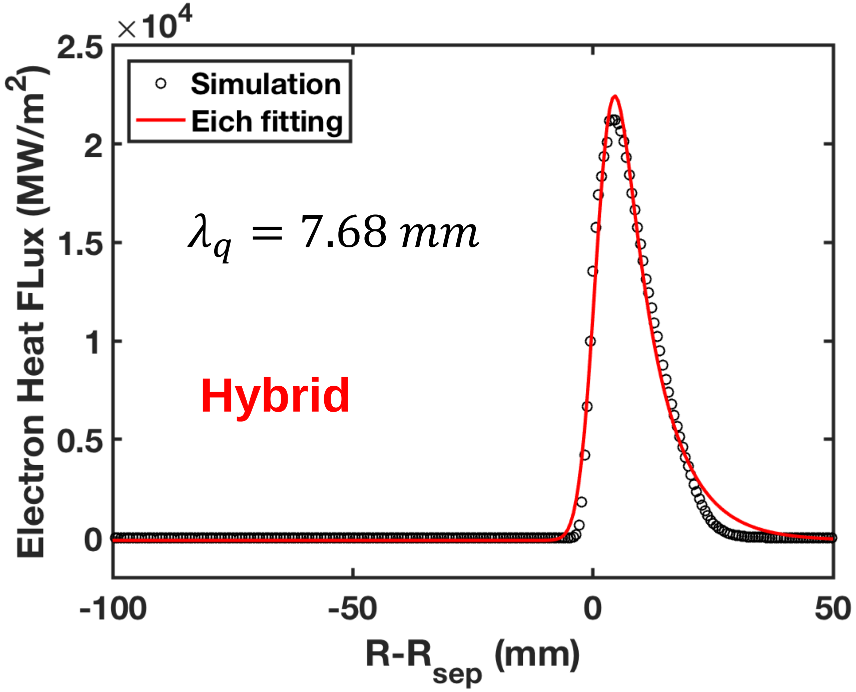






ITER SSO scenario shows high poloidal beta, high q95 which will possibly operates in grassy ELM regimes





- Grassy ELM operation yields H-mode level performance
- Operating in a grassy ELM regimes will help to
  - Reduce the divertor peak heat load
  - Broaden divertor heat flux width
- More researches need to be done to address these

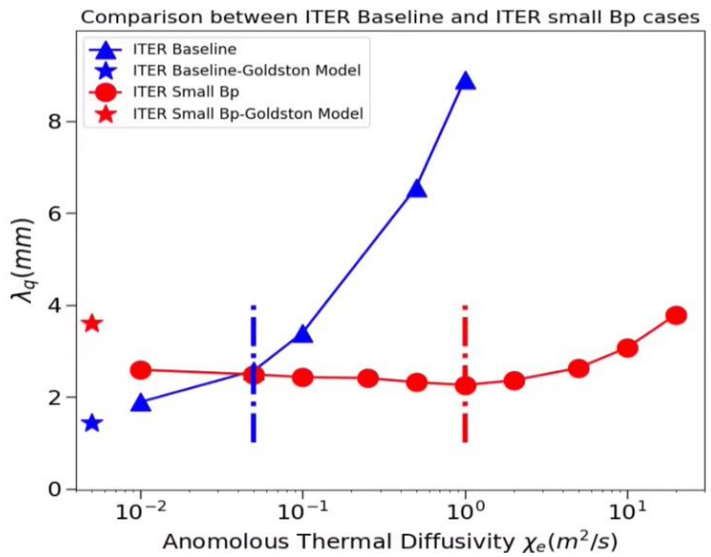
Principal Results

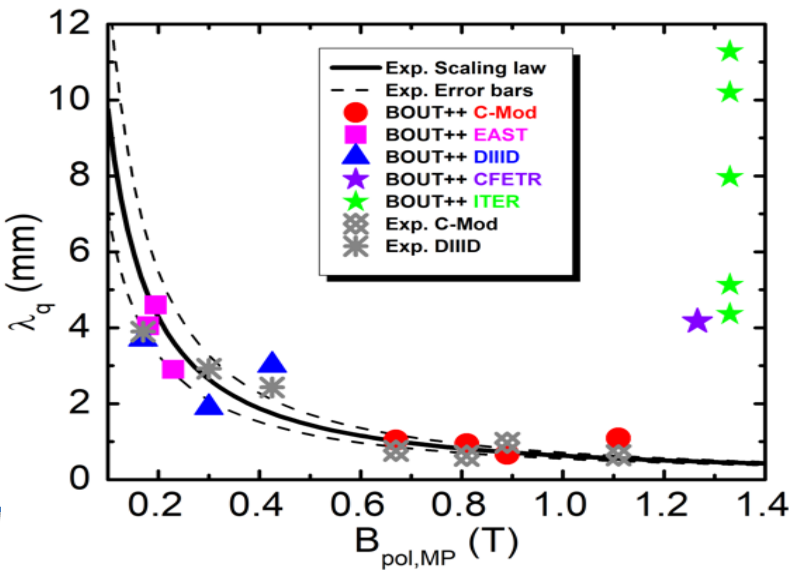
- **BOUT++ turbulence code is used to simulate the electron heat flux width λ_q, which is consistent with experimental Eich scaling**

- **ITER baseline target will possibly be in a turbulence dominant regime**
  - **HD model sets the pessimistic limit of divertor heat flux width λ_q**
  - **Drift effects decrease for strong magnetic field B, high current I_p (or B_{pol}) and large machine size R.**
  - **λ_q no longer follows the $1/B_{pol,MP}$ experimental Eich scaling law**

- **ITER PFPO-1 is possibly in a drift dominant regime**
  - **$\chi_{\perp,critical}$ is ~20x larger**

- **ITER SSO possibly in grassy ELMs → $q_{||}\downarrow$ & $\lambda_q \uparrow$**
  - **The best compromise between divertor solutions and H-mode performance operations**

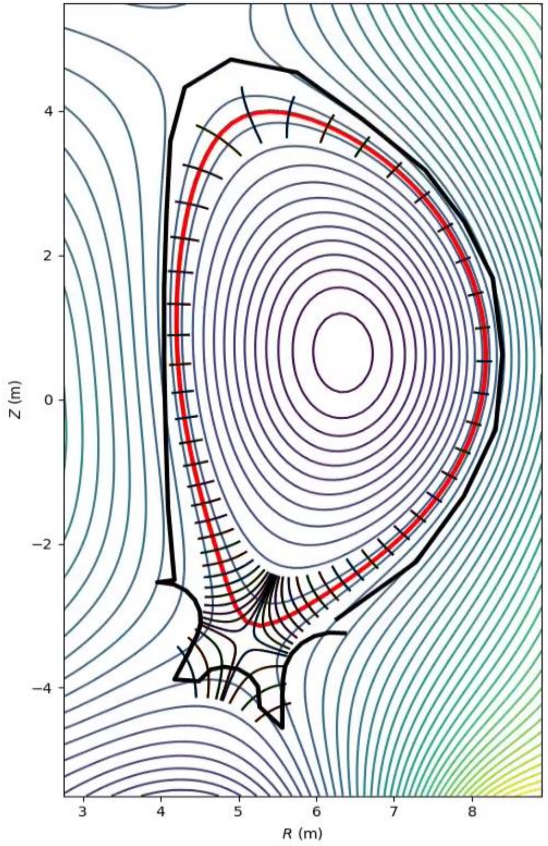




Backup slides

BOUT++ turbulence code is used to simulate the divertor electron heat flux width

- **BOUT++ 3D 6-field 2-fluid evolves**
  - ✓ **density n_i,**
  - ✓ **ion temperature T_i**
  - ✓ **electron temperature T_e**
  - ✓ **parallel velocity $v_{\|i}$**
  - ✓ **vorticity ϖ**
  - ✓ **perturbed magnetic vector potential $A_{\|}$ for turbulence**
- **To simulate tokamak divertor heat flux width**
  - ✓ **Special source inside the separatrix to maintain the experimentally measured plasma profiles inside the separatrix and let the SOL plasma profiles evolving**
  - ✓ **Flux-limited parallel thermal transport**
  - ✓ **Sheath boundary conditions**

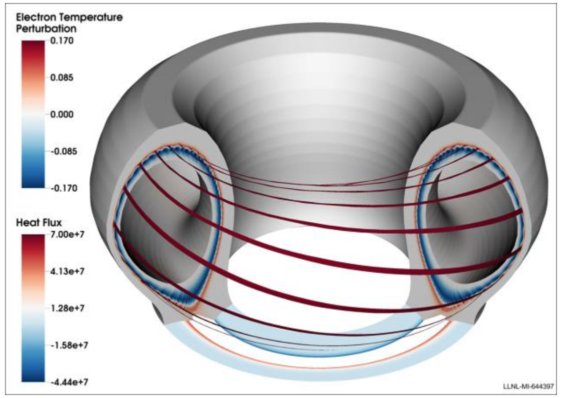


[1] X.Q.Xu et al., PoP **7**, 1951 (2000)
[2] X. Q. Xu et al., Commun. Comput. Phys. 4, 949 (2008)
[3] T. Y. Xia et al., 2013 Nucl. Fusion 53 073009
[4] T. Y. Xia et al., Nucl. Fusion 55, 113030 (2015)

Setup of BOUT++ simulations for the divertor heat load

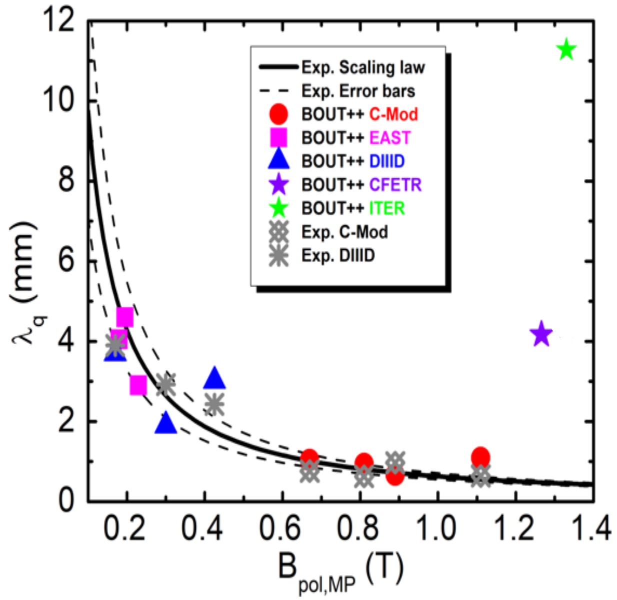
The inputs to BOUT++ simulations

- **The magnetic geometry**
- **Plasma profiles of each species up to separatrix**
- **This information is taken from**
  - **C-MOD, DIII-D, EAST experiments;**
  - **ITER scenario studies;**
- **Computation region across the magnetic separatrix**



The outputs from the BOUT++ simulations

- **Turbulence fluctuation across the separatrix**
- **Power across the separatrix**
- **Divertor heat flux amplitude and width**

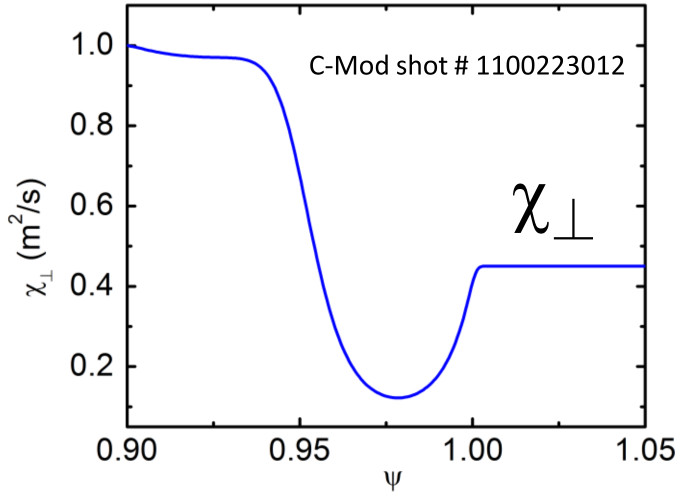


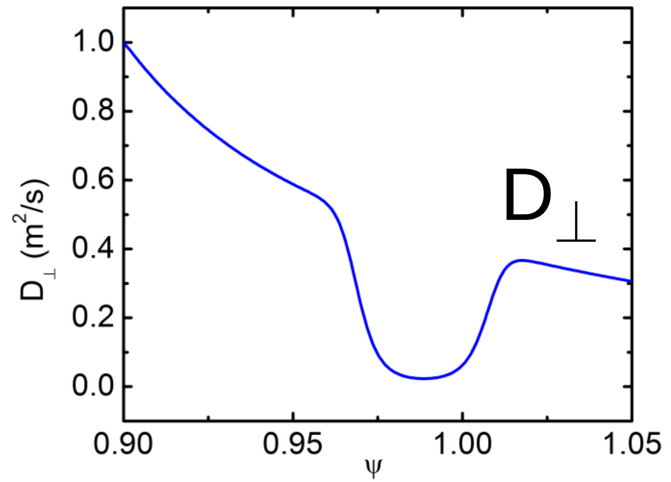
A new transport code with all drifts is developed for quick scoping studies in BOUT++ framework

- **BOUT++ 3D 6-field 2-fluid transport evolves**
  - ✓ **density n_i,**
  - ✓ **ion temperature T_i**
  - ✓ **electron temperature T_e**
  - ✓ **parallel velocity $v_{||i}$**
  - ✓ **vorticity ϖ for electric field**
  - ✓ **Ohm's law $j_{||}$ for current**

- **Fluid neutral and impurity models are under development and have not been used in this work**

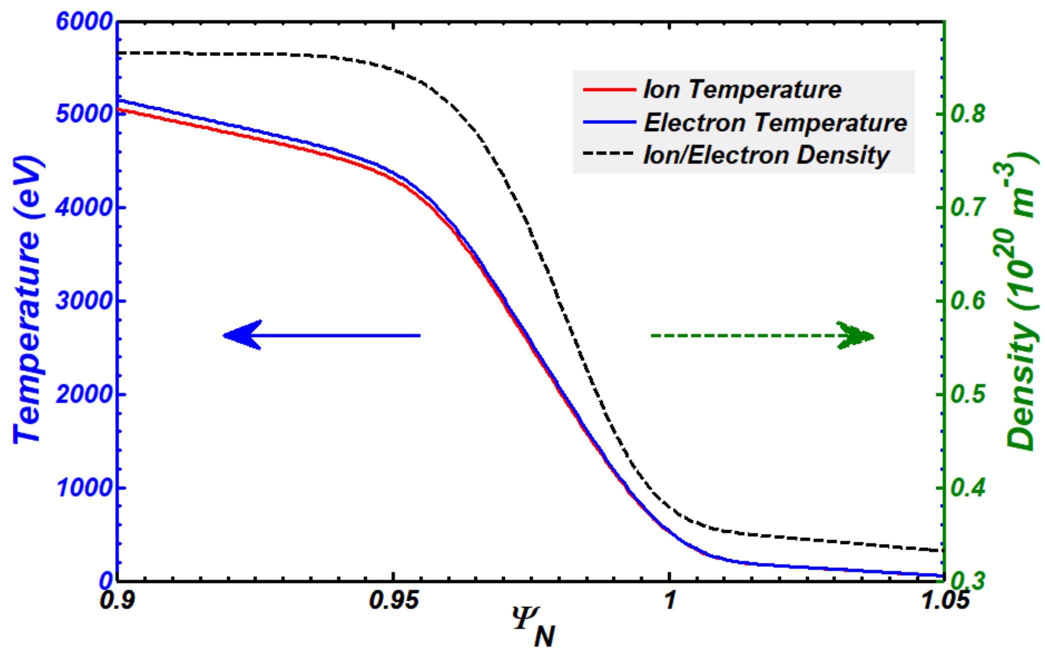
- **To simulate tokamak divertor heat flux width**
  - ✓ **Transport coef profiles inside the separatrix are prescribed in order to match the steady-state n & T profiles there**
  - ✓ **In the SOL, the value is consistent with the turbulence code calculation**

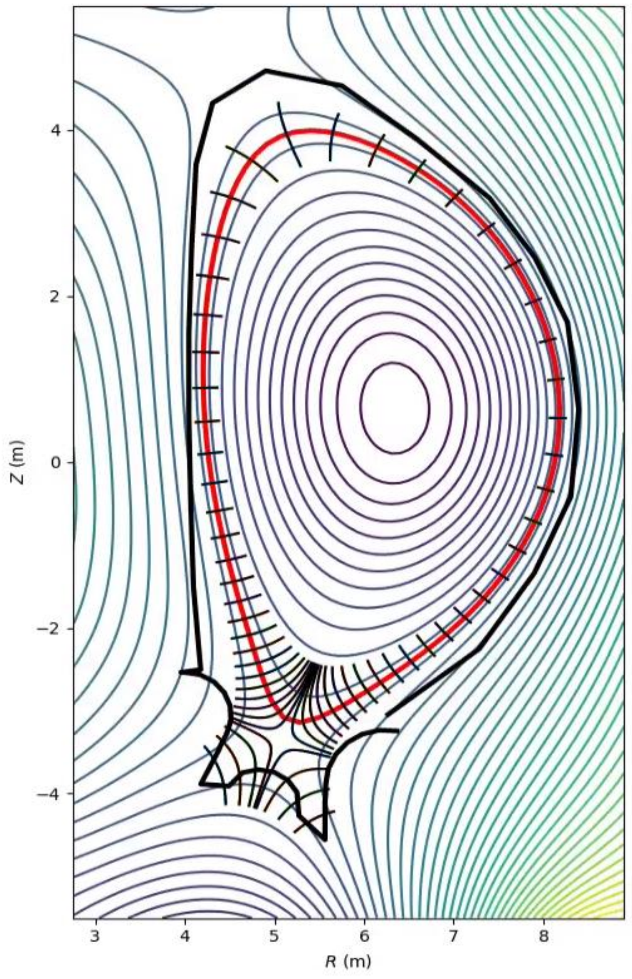




N.M. Li, X. Q. Xu, et al., CPC.(2018)

Divertor heat flux width prediction for ITER

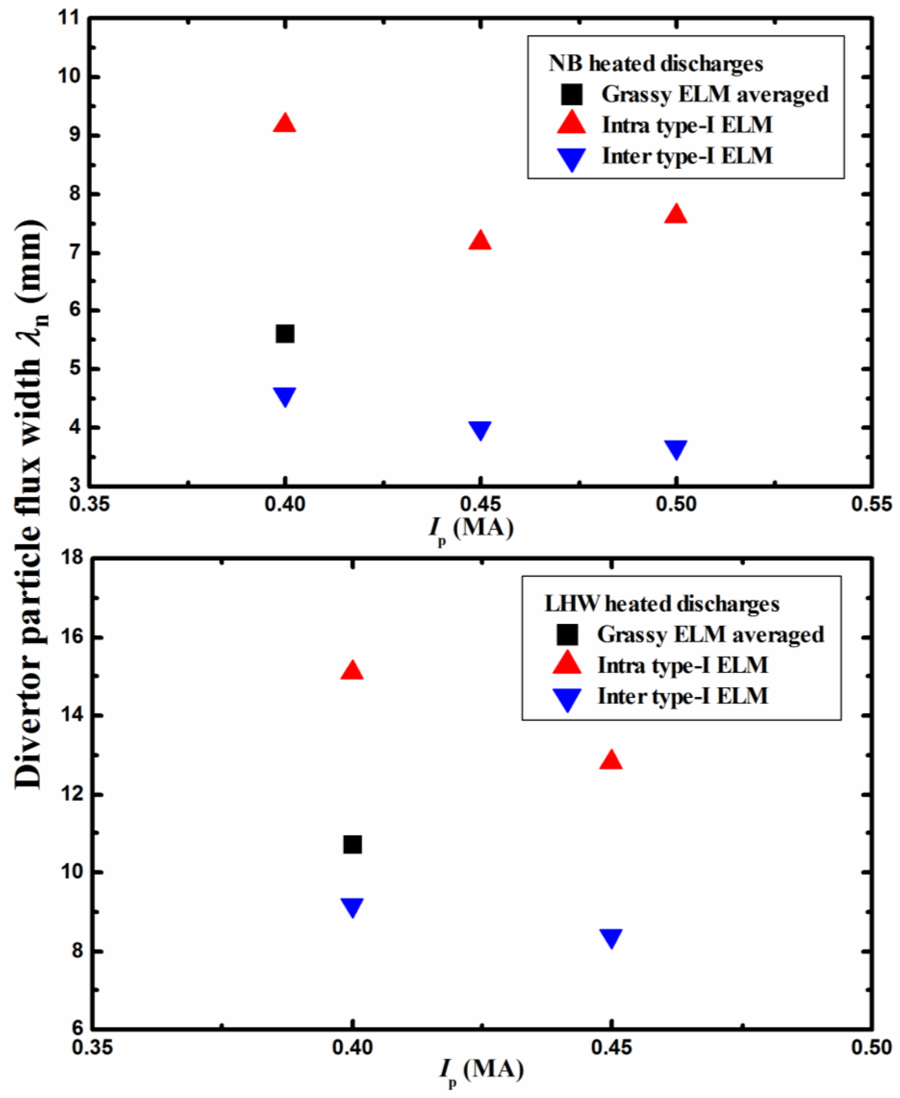




The simulated ITER plasma is generated from 15MA baseline operation scenarios using CORSICA with a high ratio of fusion power gain Q~10 by operating D-T plasmas in the type-I ELMy H-mode regime.

[1] Kim S.H. et al 2016 Nucl. Fusion 56 126002
[2] Kim S.H. et al 2018 Nucl. Fusion 58 056013

Turbulence transport does play an important role on EAST across confinement regimes



- **The averaged width for grassy ELMy discharges is broadened from that from Inter type-I ELMy discharges**
  - **Peak divertor fluxes are about at the similar level**
- **The particle flux width from intra type-I ELMy discharges is about 2 times larger than that from inter type-I ELMy discharges**
  - **Peak divertor fluxes is 10x larger**
- **Divertor heat flux width shows a similar trend**