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

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

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

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LLNL-PRES-820764
This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under contract DE-AC52-07NA27344. Lawrence Livermore National Security, LLC

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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
  - LLNL hosts the 10th US-PRC Fusion Collaboration Virtual Workshop in 2021

Principal Activities

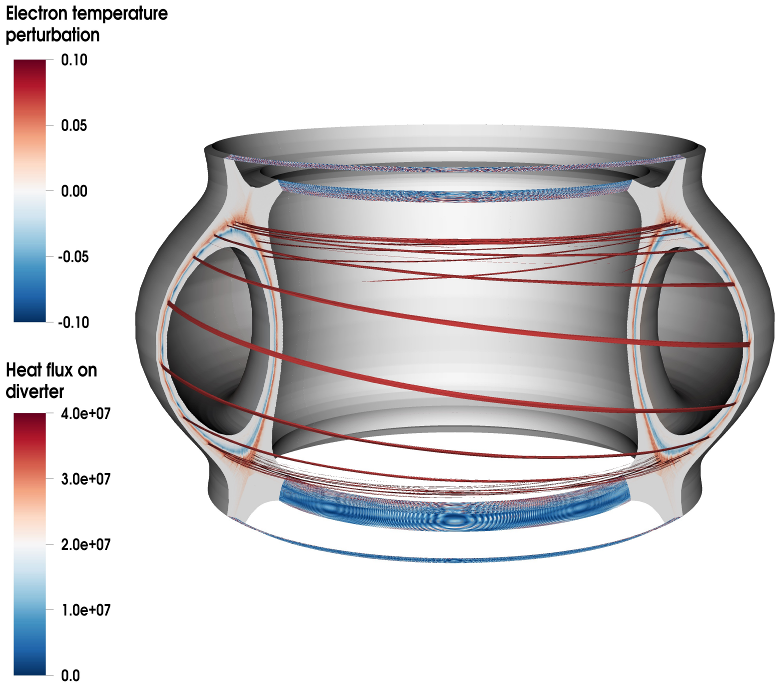
- A suite of two-fluid multiple-field models has been updated in BOUT++ with
  - flux driven sources from core plasmas
  - zonal flow & zonal field
    - ✓ 3D field solver to remove high-n ballooning approximation
  - Landau-fluid closures for parallel non-local transport
  - being refactored and optimized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

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

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

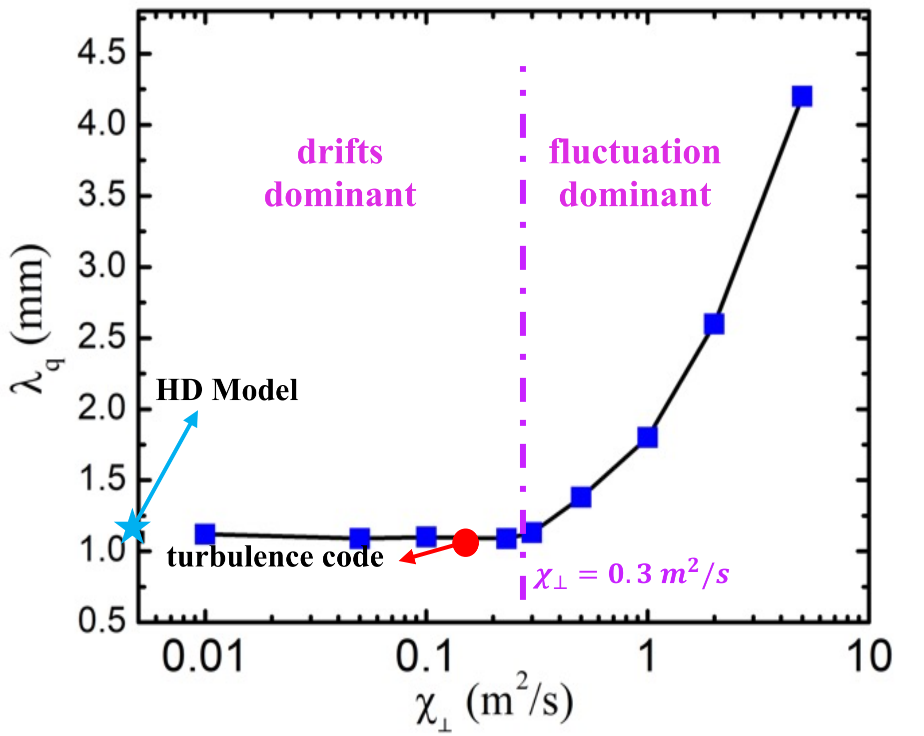
- Neutral & Impurity models for
  - SMBI, GAS puffing, Recycling
  - Pellet injections for fueling, ablation & ELM control & detachment

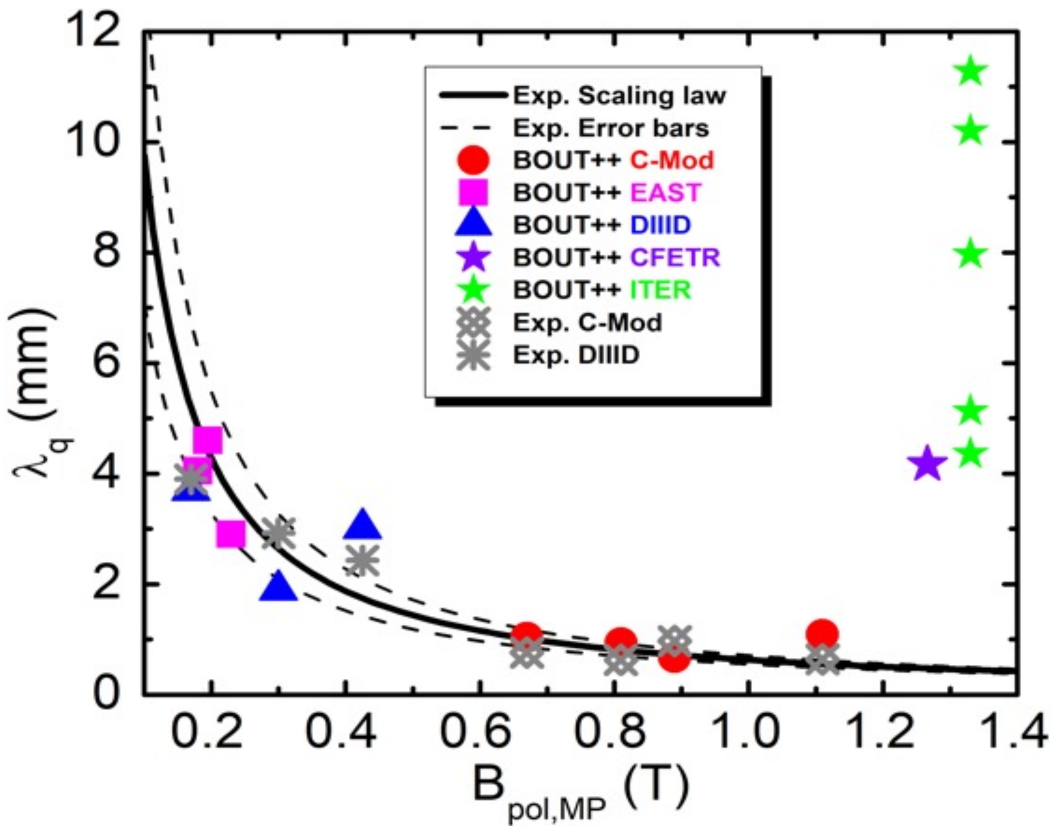
- A test particle module for
  - Impurity and dust-particle migration and transport
  - Modelling of alpha particle slowing down for burning plasmas



BOUT++ simulations predict that the divertor heat flux width of ITER & CFETR baseline target is broadened by ELMs

X.Q. Xu *et al* 2019 *Nucl. Fusion* **59** 126039

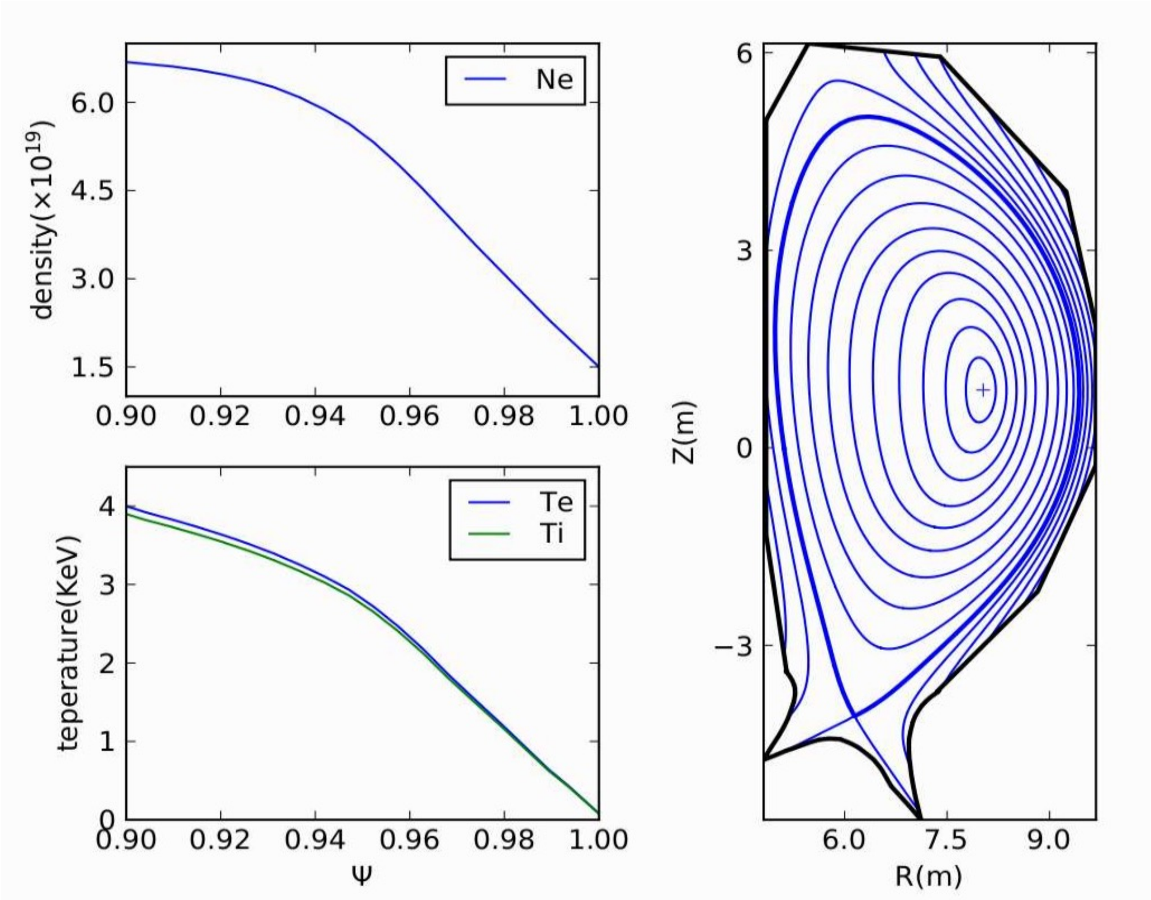




- **When $\chi > \chi_{crit}$, radial transport transits from a drift to a fluctuation-dominated regime**
  - **Bohm diffusion typically yields $\chi^{\mathrm{Bohm}} \gg \chi_{crit}$**
- **The divertor heat flux width is correlated with change in pedestal height**

BOUT++ simulations performed for CFETR scenarios SSO: high β_p, high q95

Pedestal profiles and magnetic configuration

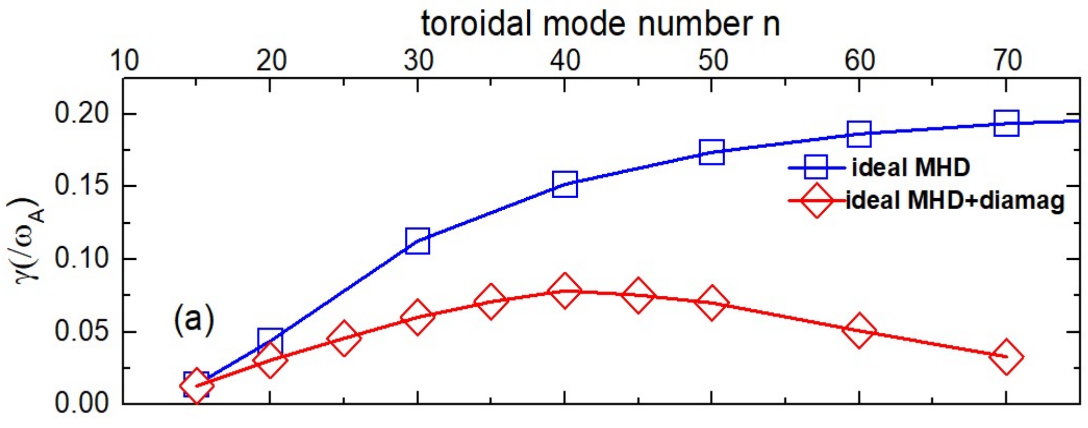


Parameters of current CFETR Steady State scenario

Parameters	CFETR Steady State Scenario
R	7.2m
a	2.2m
κ	2
δ	0.42
B_T	6.5T
I_p	11MA
β_N	2.81
β_p	2.2
q_{95}	7.34
n_{sep}/n_{ped}	0.25
ν_*	0.22

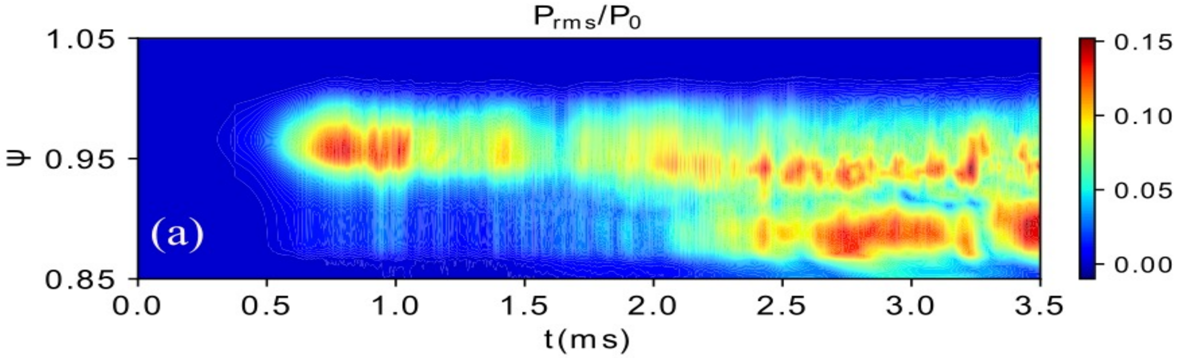
Near ballooning criticality, pressure gradient relaxes very little in non-linear steady state

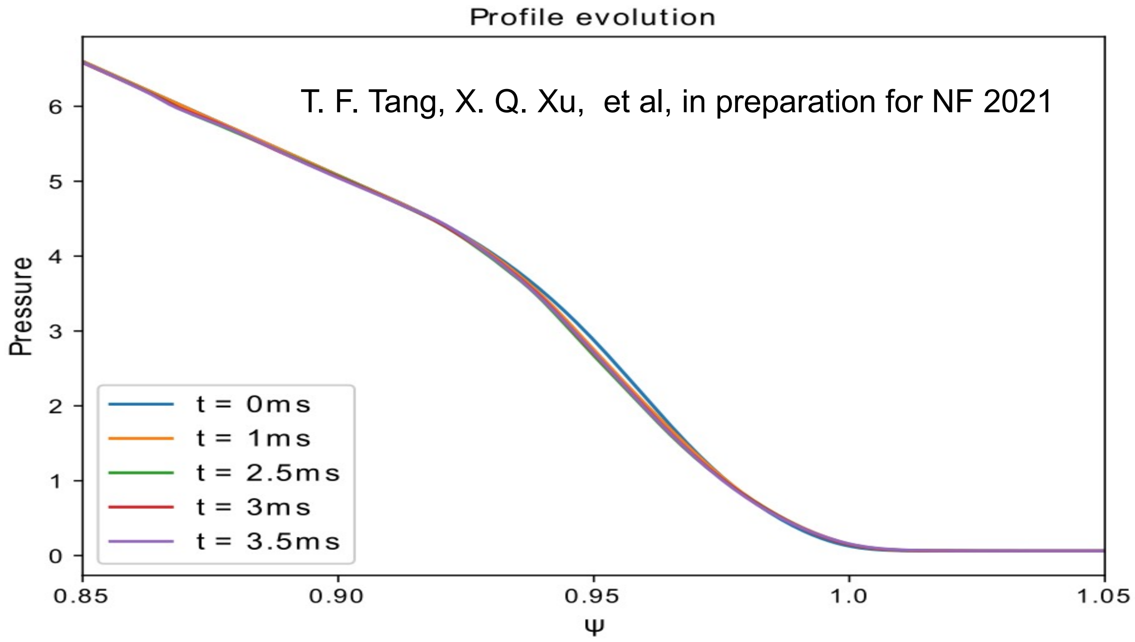
linear growth rate vs toroidal mode number



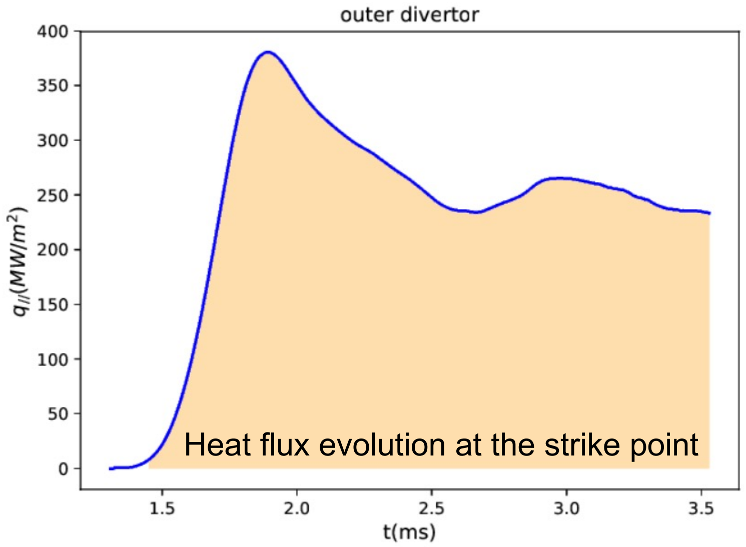
No large ELM collapses near the ballooning criticality, but large enough transport can be generated which broadens the SOL width

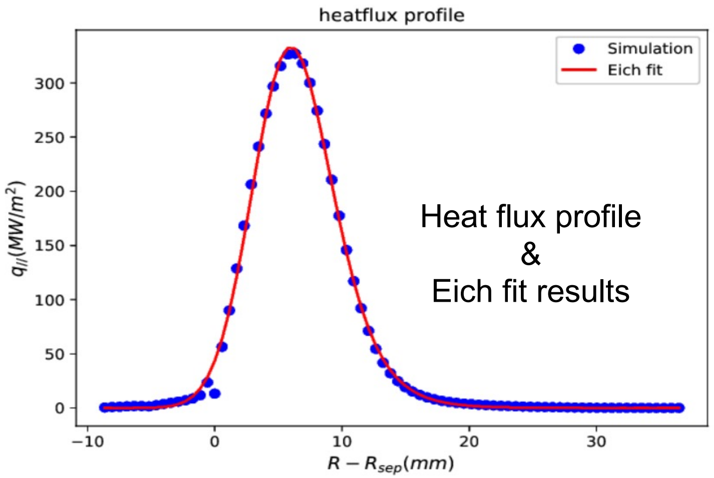
pressure fluctuation at the outer mid-plane





Divertor heat flux width broadening due to large electromagnetic fluctuation from the Grassy ELM





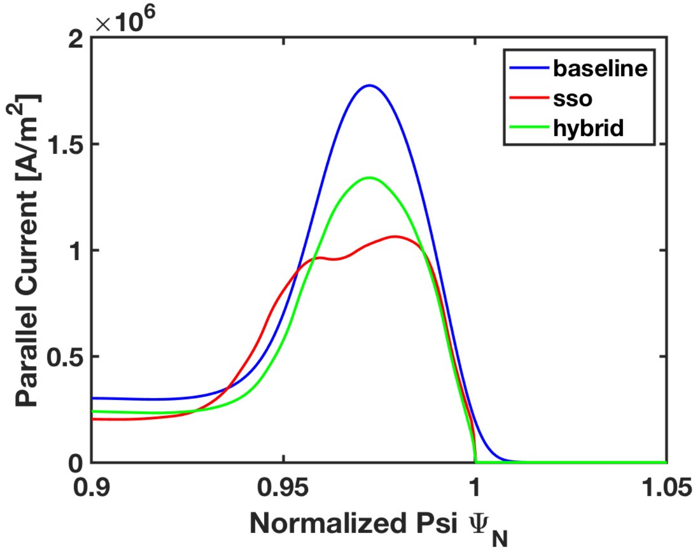
	formula	λ_q(mm)	λ_{int} (mm)
Simulation	/	2	8.33
Goldston HD model	$\frac{4a\sqrt{m_p T_{sep}/2}}{eB_pR} \frac{R < B_p >}{(RB_p)_{omp}}$	1.08	3.54
Eich Scaling law	$0.63B_{p,omp}^{-1.19}$	0.69	3.15
Eich turbulence	$0.59(1+3.6\alpha_t^{1.9})\rho_s$	1.17	3.63

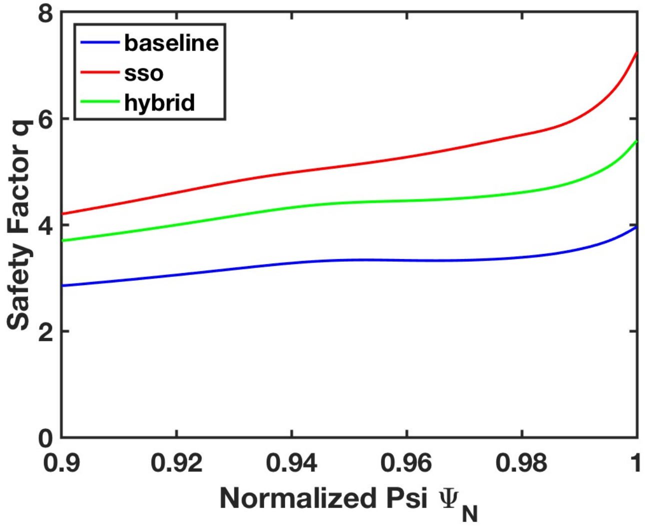
$$\chi_e^{sep,omp} \approx 0.5\, m^2/s \; > \; \chi_e^c \approx 0.2 m^2/s$$

T. F. Tang, X. Q. Xu, et al, in preparation for NF 2021

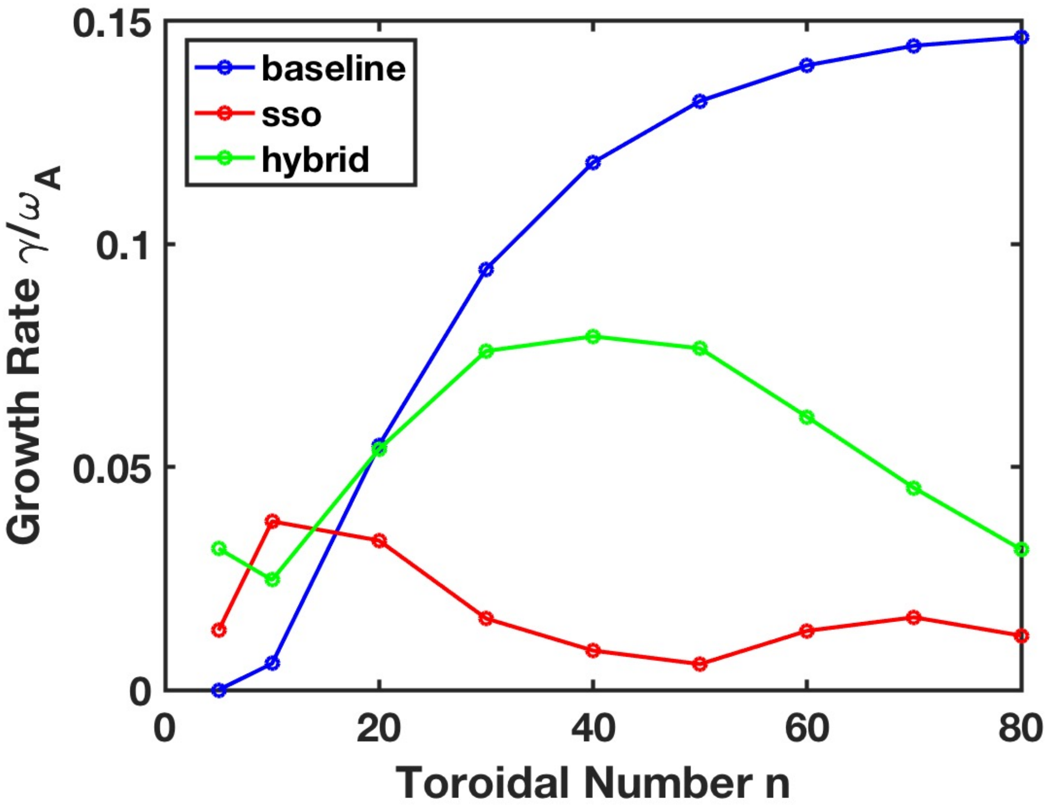
BOUT++ simulations also performed for ITER scenarios

SSO shows lower pedestal pressure & bootstrap current, but high β_p, high q95



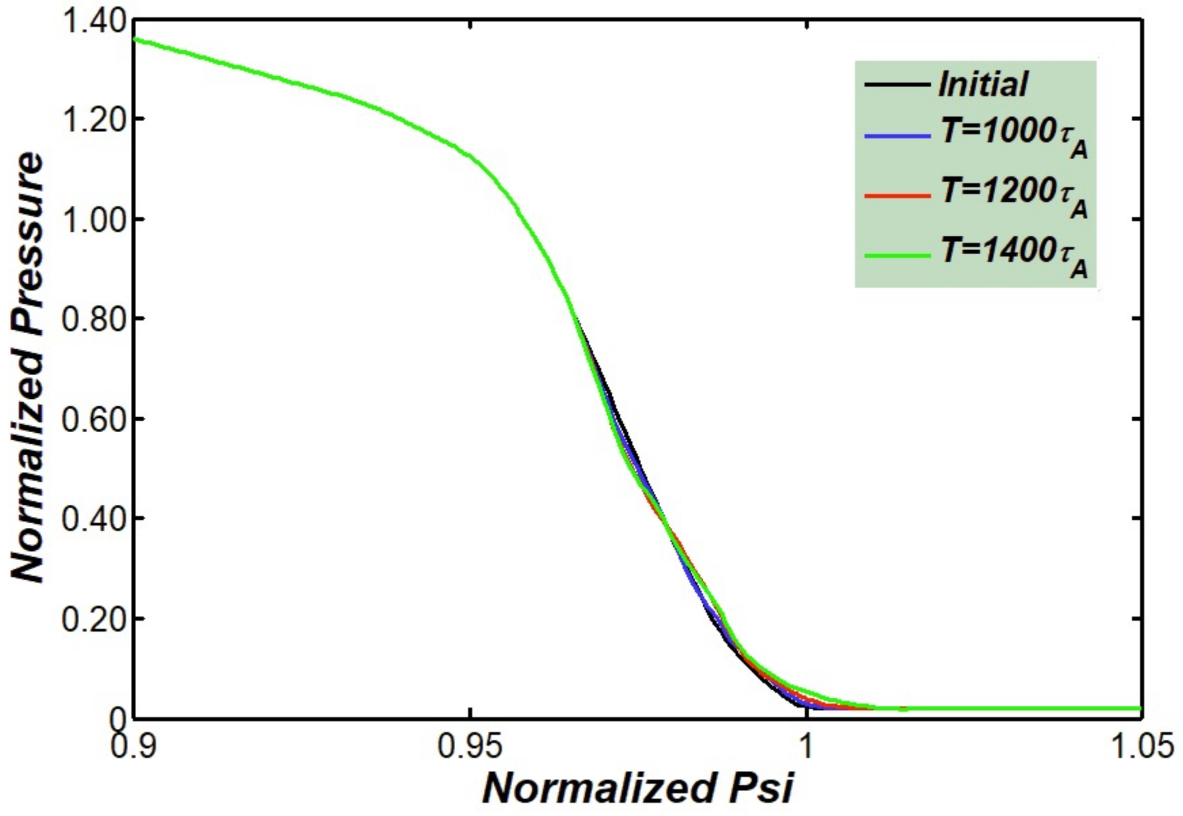


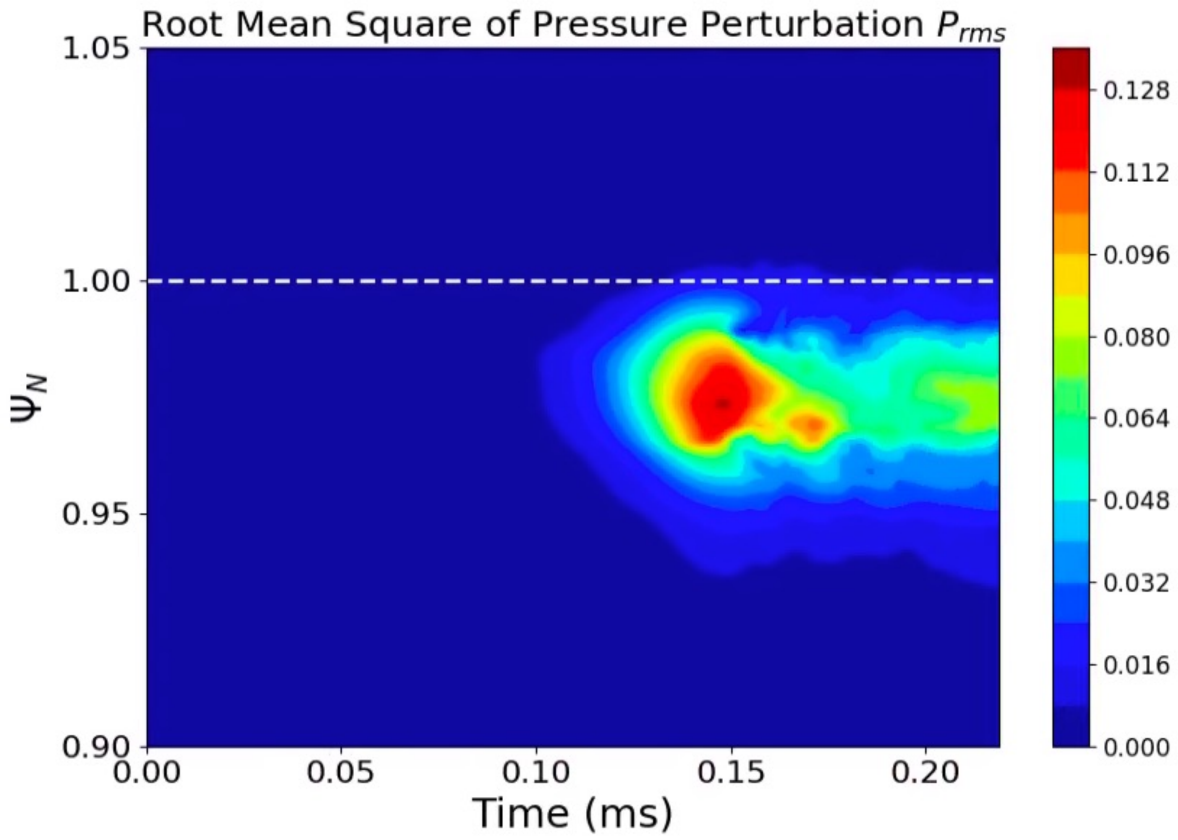
- **Baseline:**
  ballooning modes, most unstable toroidal mode numbers n=60~80
- **SSO:**
  peeling modes, most unstable modes n=10~20
- **Hybrid:**
  peeling-ballooning modes, most unstable modes n~40



X. Y. Wang, X. Q. Xu, et al, submitted to NF 2021

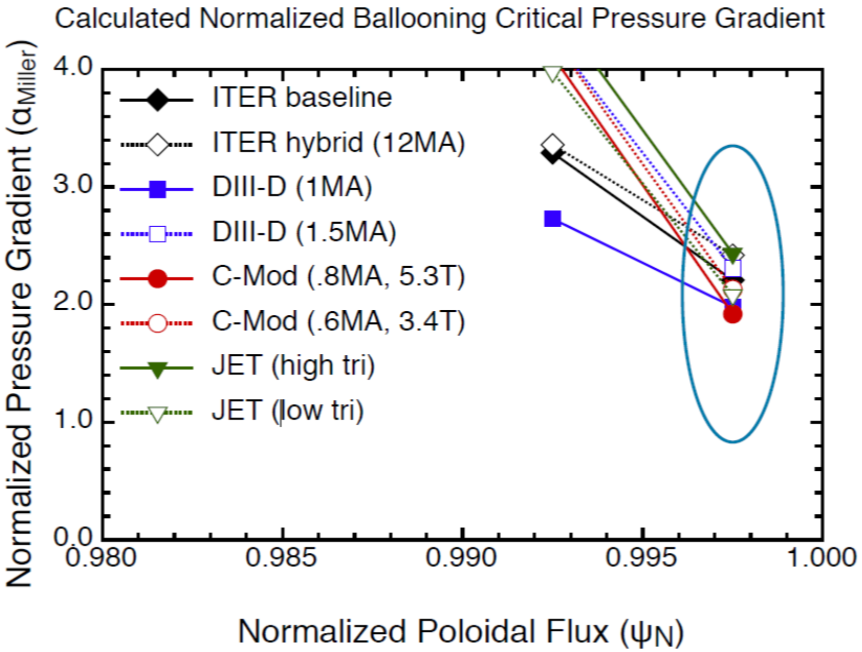
Near ballooning criticality, pressure gradient relaxes very little in non-linear steady state

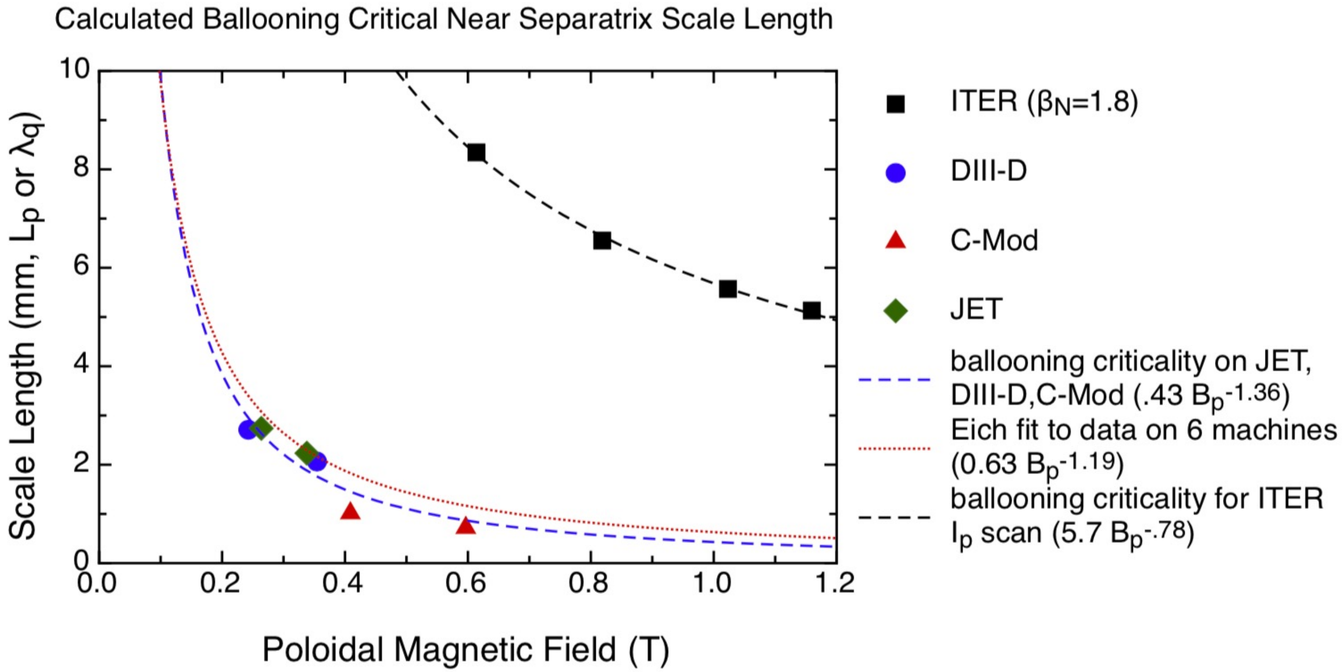




No large ELM collapses near the ballooning criticality, but large enough transport can be generated which broadens the SOL width

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

$$\alpha_{Miller} = -\frac{2\partial_\psi V}{(2\pi)^2}\left(\frac{V}{2\pi^2 R_0}\right)^{\frac{1}{2}} \mu_0 p' \sim 2.0 \qquad d\beta_p/d\psi_N \sim 2.5\text{-}3.5$$

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

X. Y.Y Wang et al, submitted to NF 2020

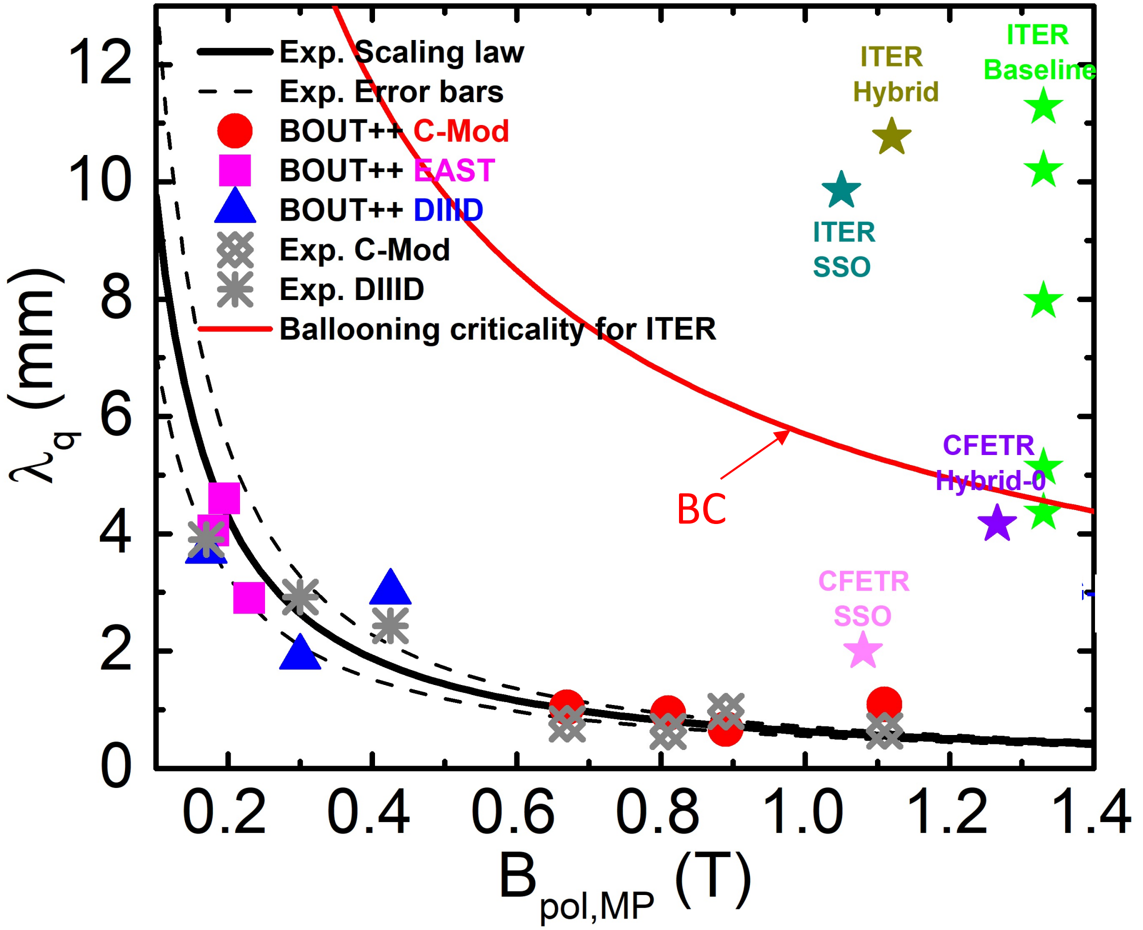
- For ITER baseline n_{sep}=3.7x10^{19}/m^3, $T_{e,sep}$=175eV, $T_{i,sep}$=300eV,

$$(dp/d\psi_N)_{crit} \sim 1.064\langle B_p^{1.6}\rangle_{edge} \longrightarrow L_{p,crit} \sim \text{5-6mm}$$

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

$L_{p,crit}=P/(dP/dx)=7.3mm$

Ballooning-critical pressure gradient is consistent with BOUT++ simulated divertor heat flux width at reduced pedestal height near marginal stability boundary for ELMs



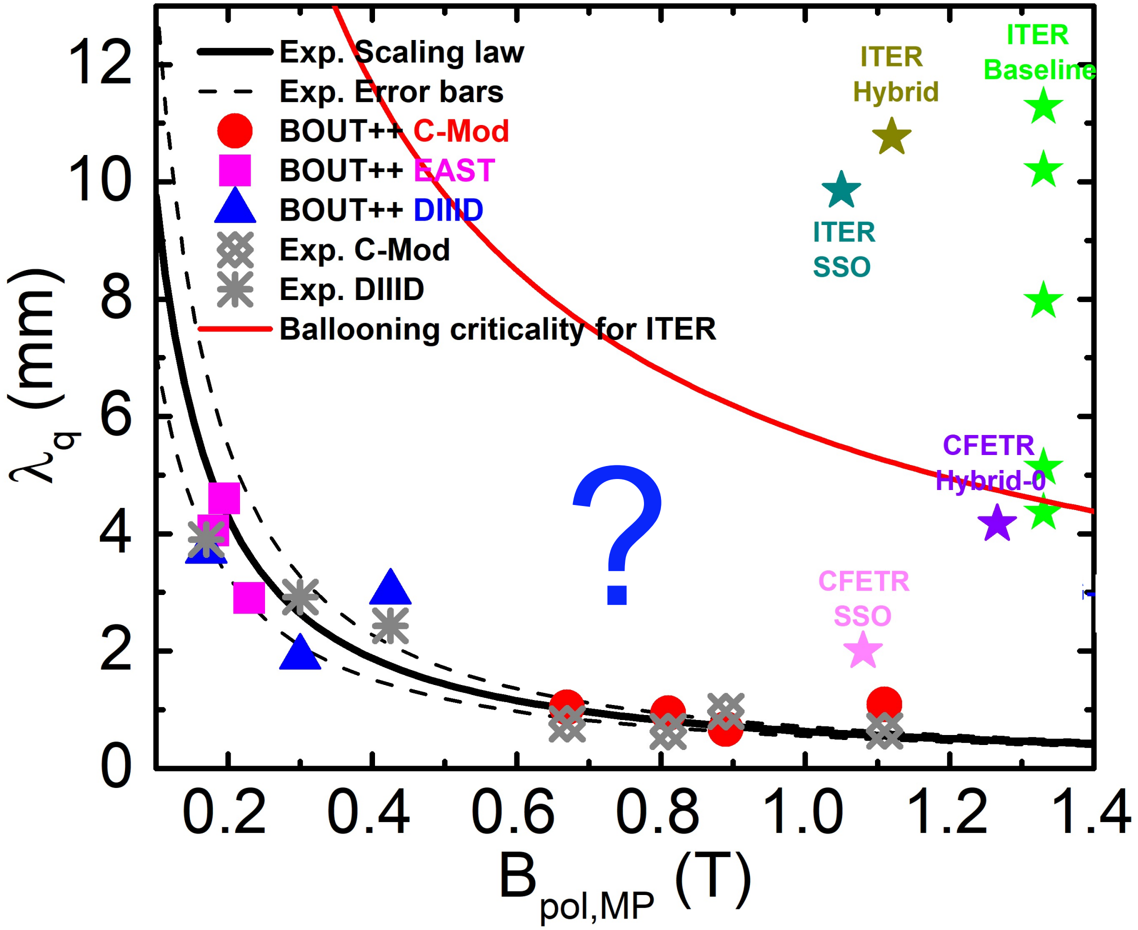
Near-Separatrix Ballooning criticality (BC)

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?



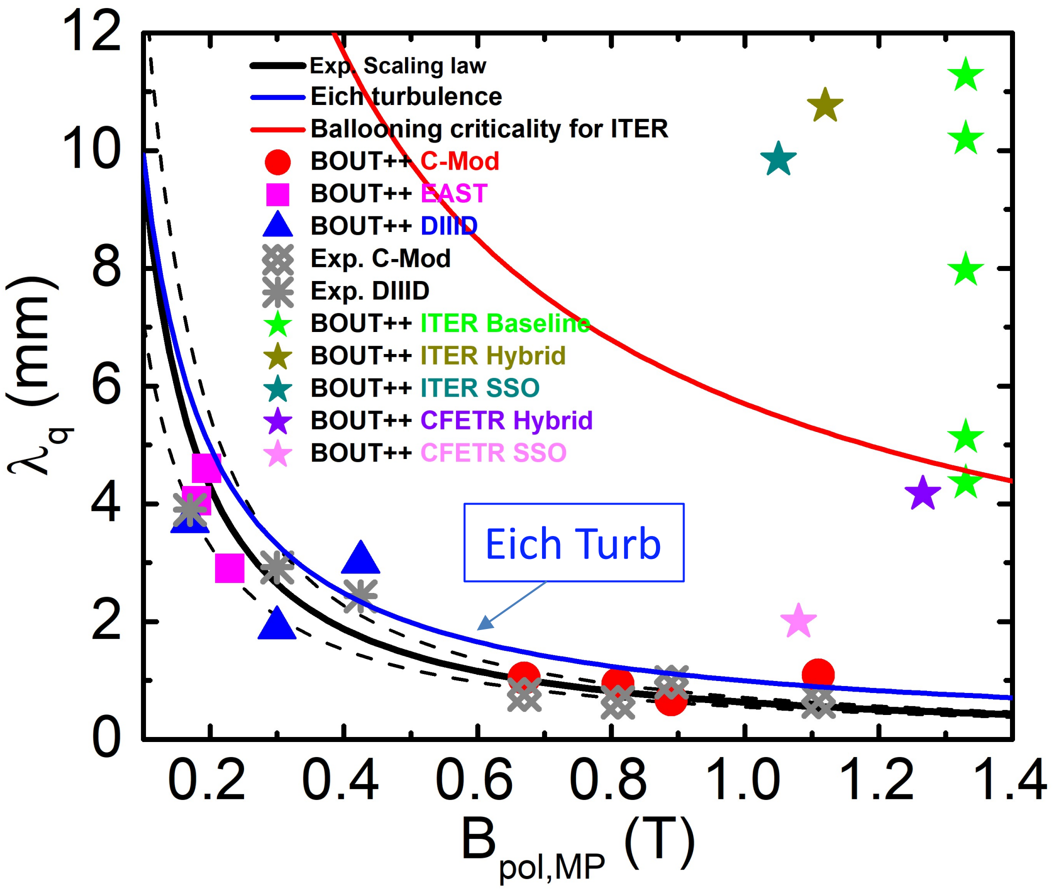
Near-Separatrix Ballooning criticality (BC)

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:

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

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

$$\alpha_t \simeq \frac{1}{100} \cdot \hat{q}_{cyl} \nu_e^* \qquad \nu_e^* = \frac{\pi \hat{q}_{cyl} R}{1.03 \cdot 10^{16}} \frac{n_e}{T_e^2} Z_{eff}$$

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

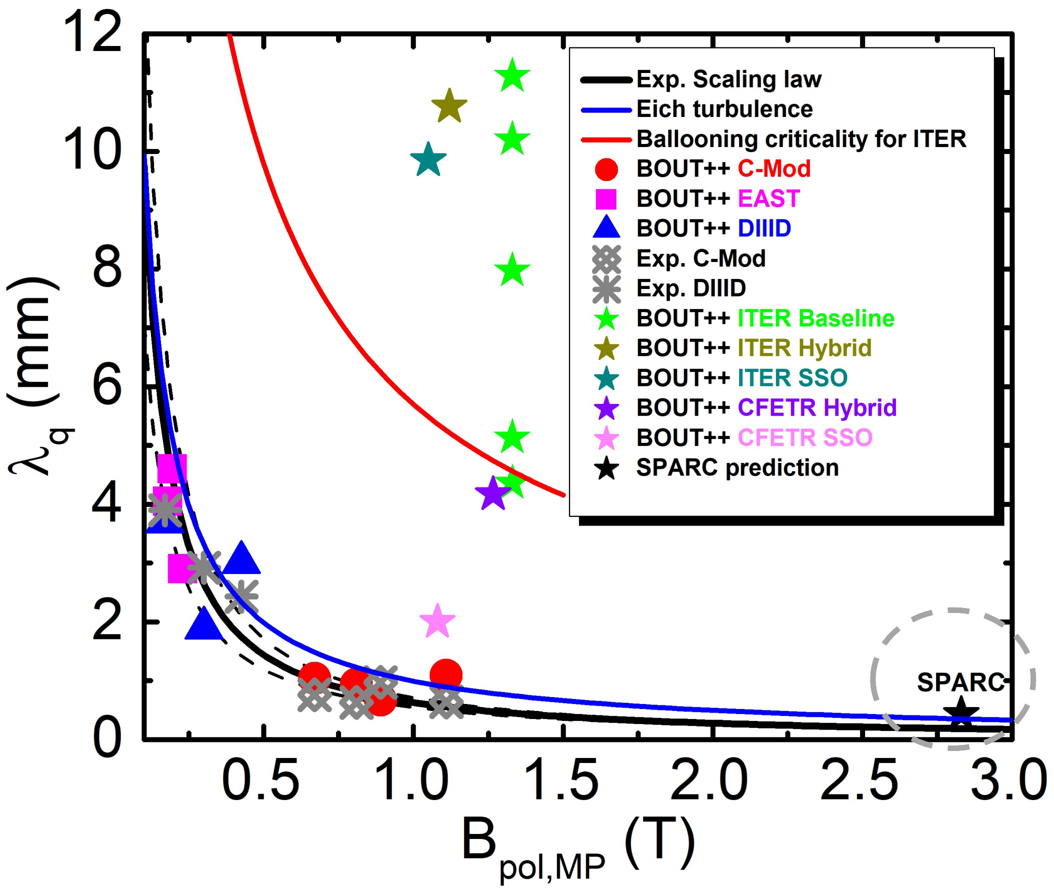
Based on ITER baseline parameters

- Low collisionality,

$$\nu_*^{ITER} \sim 1.8 \qquad \alpha_t^{ITER} \sim 0.02$$

- 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:

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

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

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- Based resistive interchange & drift Alfven turbulence
  - $\nu^*=0 \rightarrow \alpha_t=0$, no turbulence broadening
  - $\alpha_t>0.5$, H→L transition

Based on SPARC baseline parameters

- Low collisionality,

$$\nu_*^{SPARC} \sim 2.1 \qquad \alpha_t^{SPARC} \sim 0.05$$

- Eich turbulence predicts a 1.2% width broadening
- GHD model predicts a 2.6% width broadening

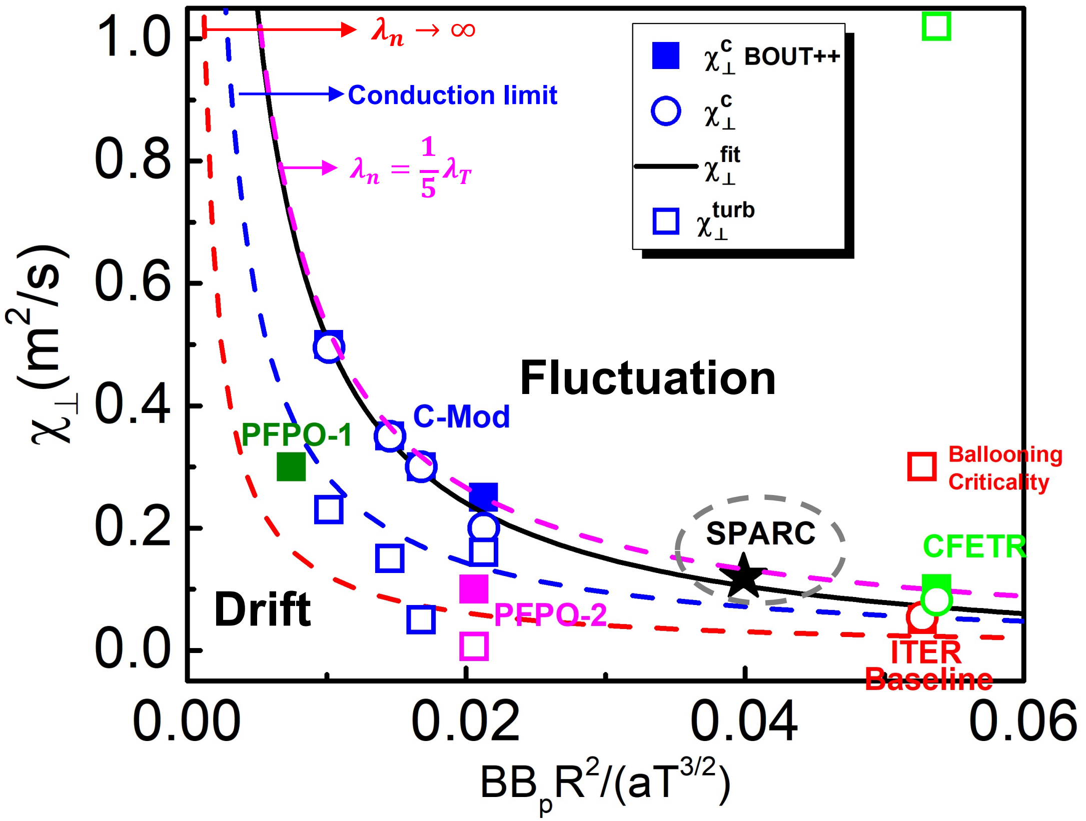
Dominant parameters for the transition from drift to fluctuation dominant regime

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

$$\chi_d^{eff} = v_d\lambda_q = \mathbf{C}v_d q\rho_s = \mathbf{C}\frac{A^{1/2}}{Z(1+Z^{1/2})}\frac{2T_{e,sep}^{3/2}}{BB_pR}\frac{m_p^{1/2}}{e^2}\frac{a}{R}$$

$$\chi_\perp^c = \chi_d^{eff} - D_\perp\left(\frac{\lambda_T}{\lambda_n}\right)$$

  - **C=26.5 is a fitting parameter to simulations for the transition**
  - **λ_q in χ_d^{eff} can be estimated using**
    - ✓ **HD λ_q**
    - ✓ **conduction limited λ_T, $\lambda_q = 2\lambda_T/7$**
    - ✓ **sheath limited λ_T :**
      - $\lambda_n \to \infty, \lambda_q = (1/\lambda_n + 3/2\lambda_T)^{-1} = 2\lambda_T/3$
      - $\lambda_n = \frac{1}{5}\lambda_T, \lambda_q = (1/\lambda_n + 3/2\lambda_T)^{-1} = 2\lambda_T/13$

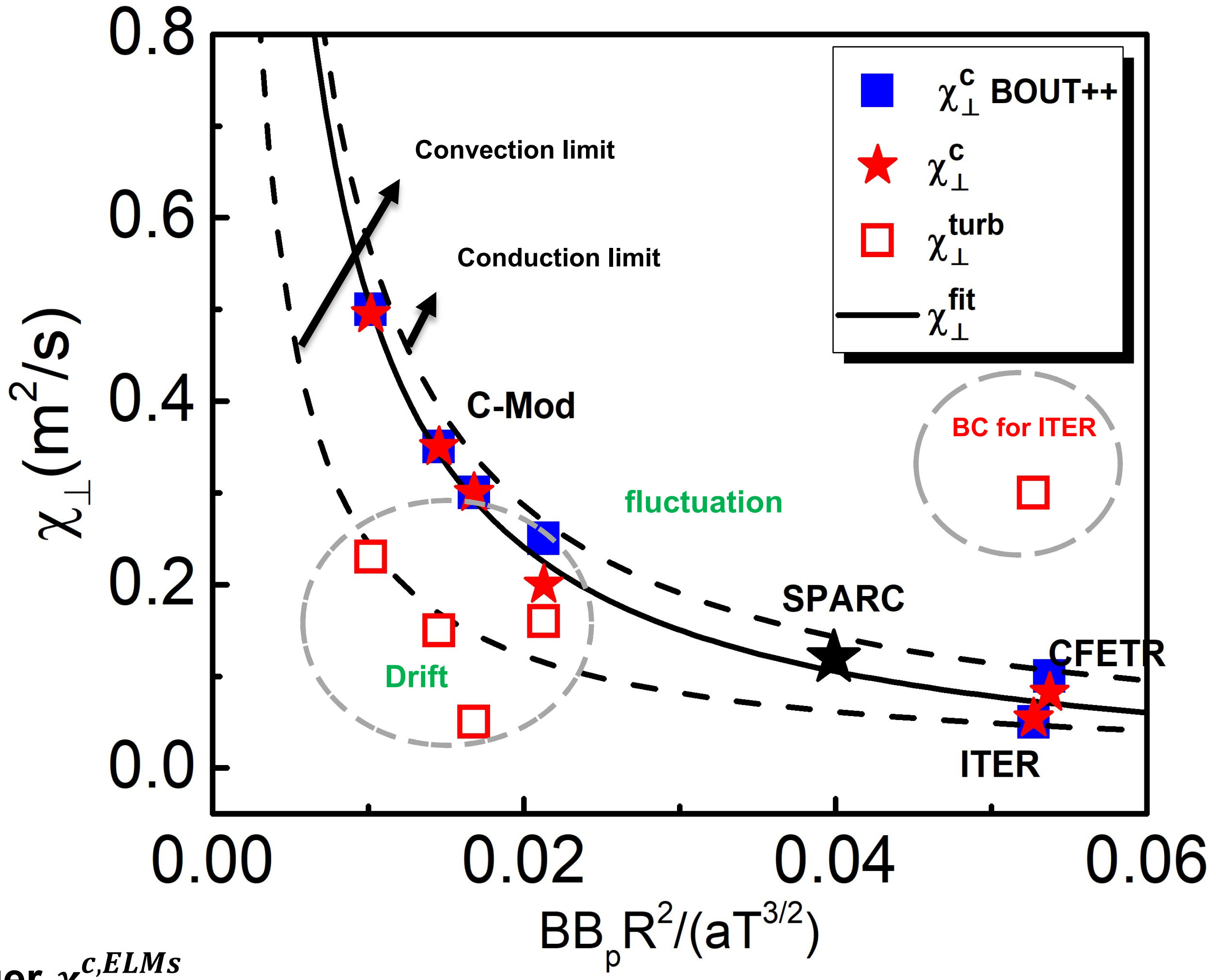


- **χ_d^{eff} decreases for strong magnetic field B, high current I_p (or B_{pol}), large machine size R, low T_{sep}.**

- $\chi_\perp^{c,SPARC} \sim 0.13\ m^2/s$, $\chi_\perp^{c,ITER} \sim 0.05\ m^2/s$

SPARC will possibly be in fluctuation dominant regime, because of strong magnetic field and relative low $\chi_\perp^c$

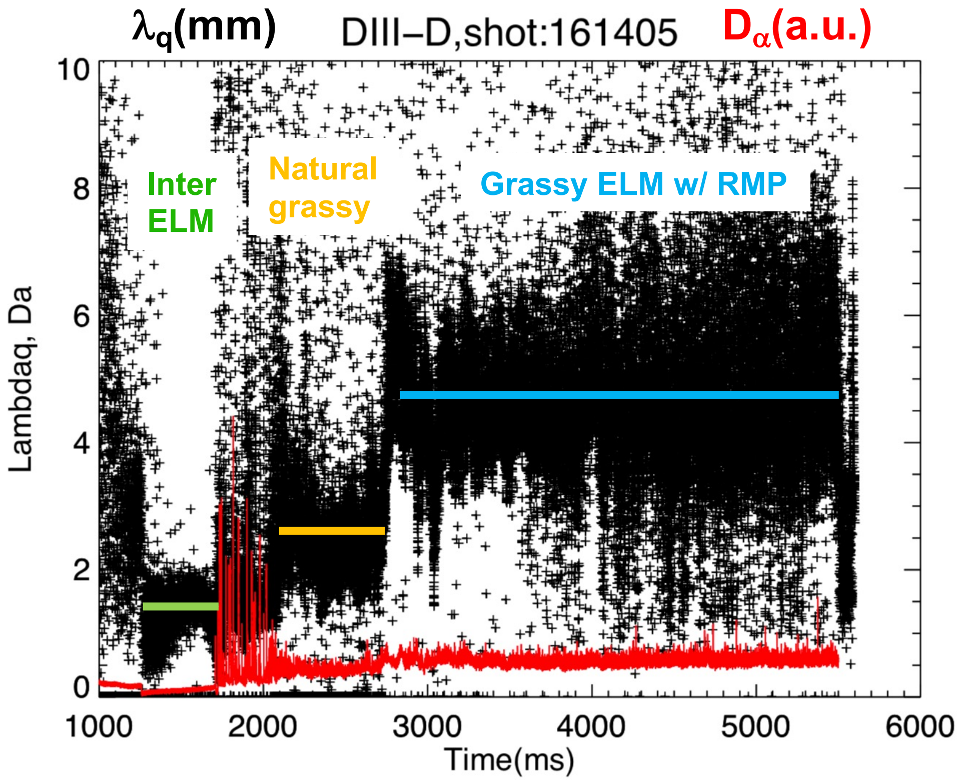
Fluctuation thermal diffusivity can be increased from Inter-ELMs to small/grassy ELM regime



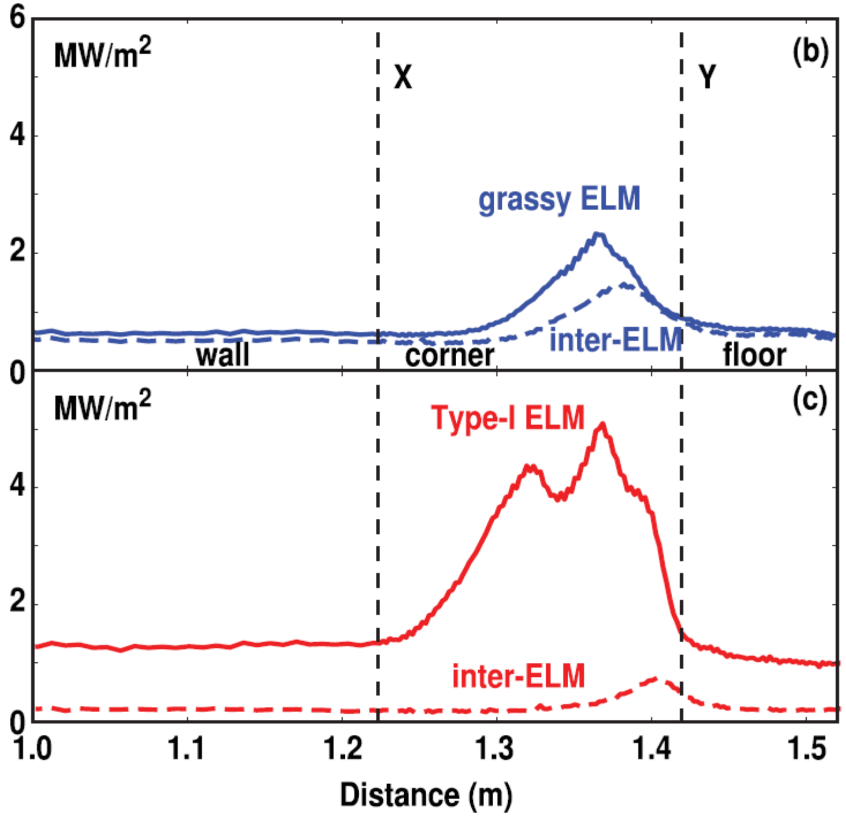
- **Broadening from micro-turbulence may not be effective**
  - ✓ **as Eich turbulence scaling indicates**
- **Ballooning criticality sets a threshold for ELMs with larger $\chi_\perp^{c,ELMs}$**

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



X.Q. Xu H Q Wang, et al, IAEA FEC 2020

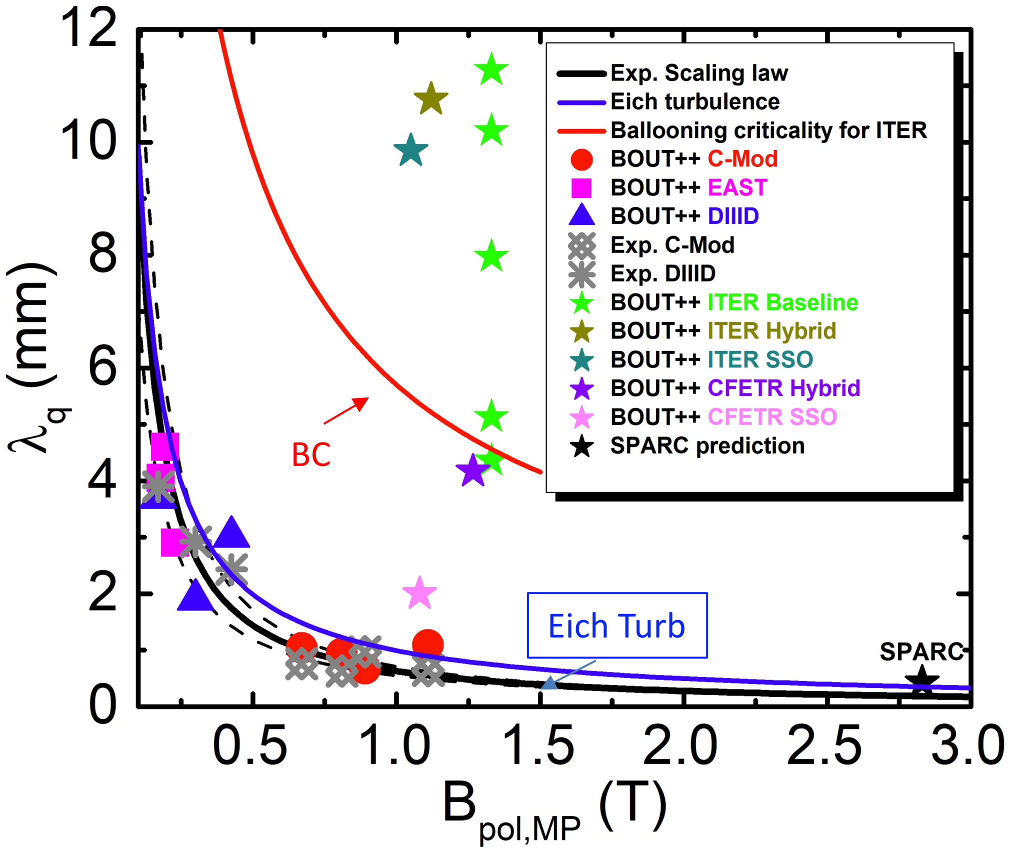


- **The D_α signal (RED) and inner divertor heat flux width (BLACK) from IR camera measurement, which shows mixed ELM activities.**
- **From inter-ELM phase to the grassy ELM phase,**
  - ✓ **The width increases about 2-3 times w/o RMP**
  - ✓ **The divertor heat flux width increases about 6 times w/ RMP**
- **The grassy-ELMs exhibit a reduced peak heat flux to the divertor similar to the inter-ELM heat flux with good confinement**

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

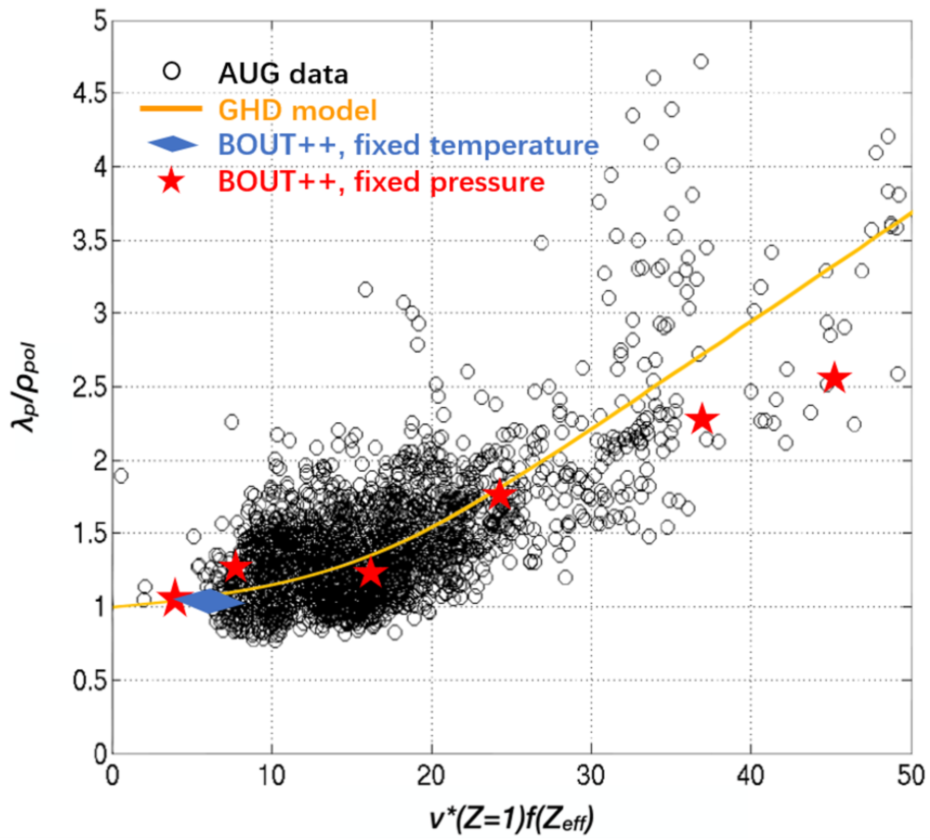


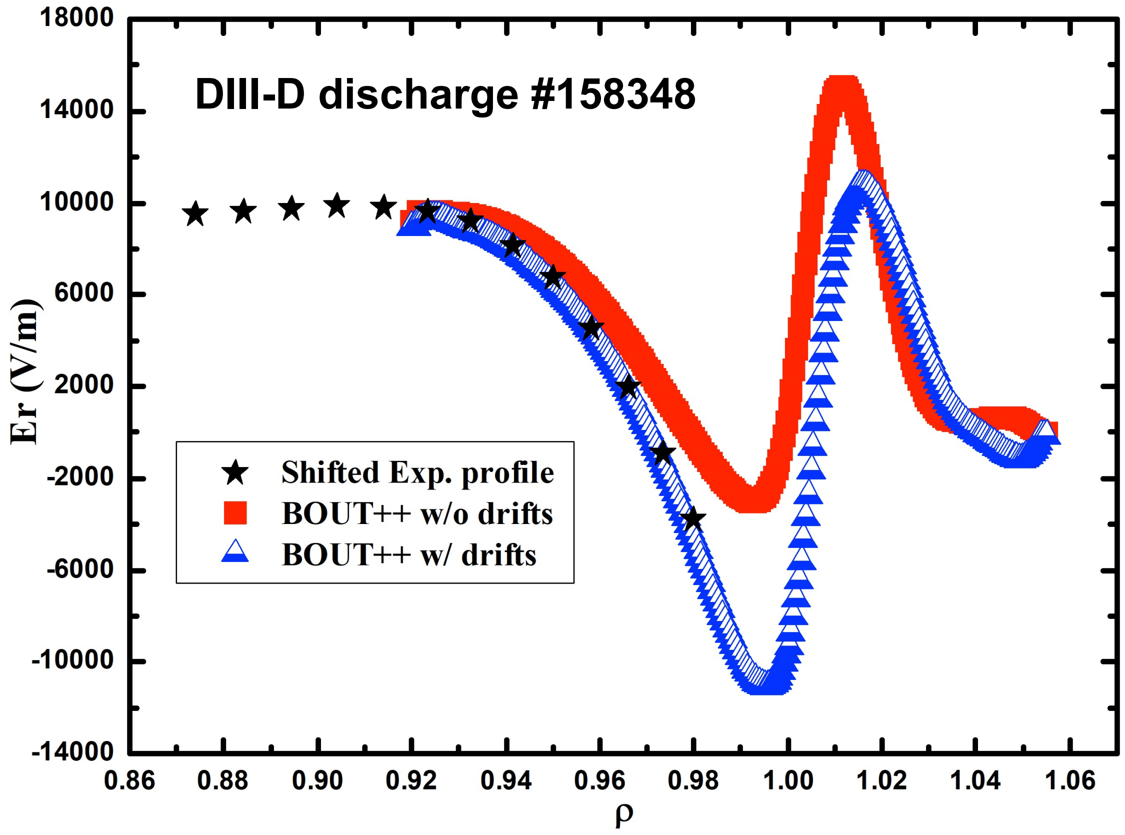
- Divertor heat flux will pose a significant challenge for compact pilot plant
  - SPARC is possibly in fluctuation dominant regime, due to strong magnetic field and lower $\chi_\perp^c$
  - A proper design for combination of B, Bp, R, T_{sep} could significantly alleviate the challenge

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.**



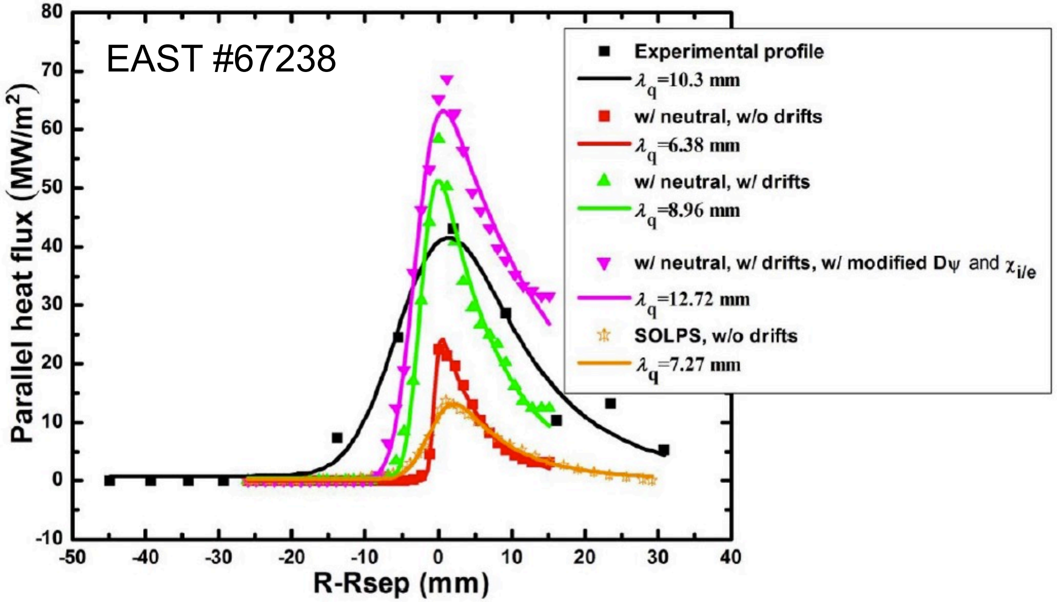


BOUT++ transport code is validated by the comparison of the simulated radial electric field Er with measured Er (shifted inward by 6.49mm)

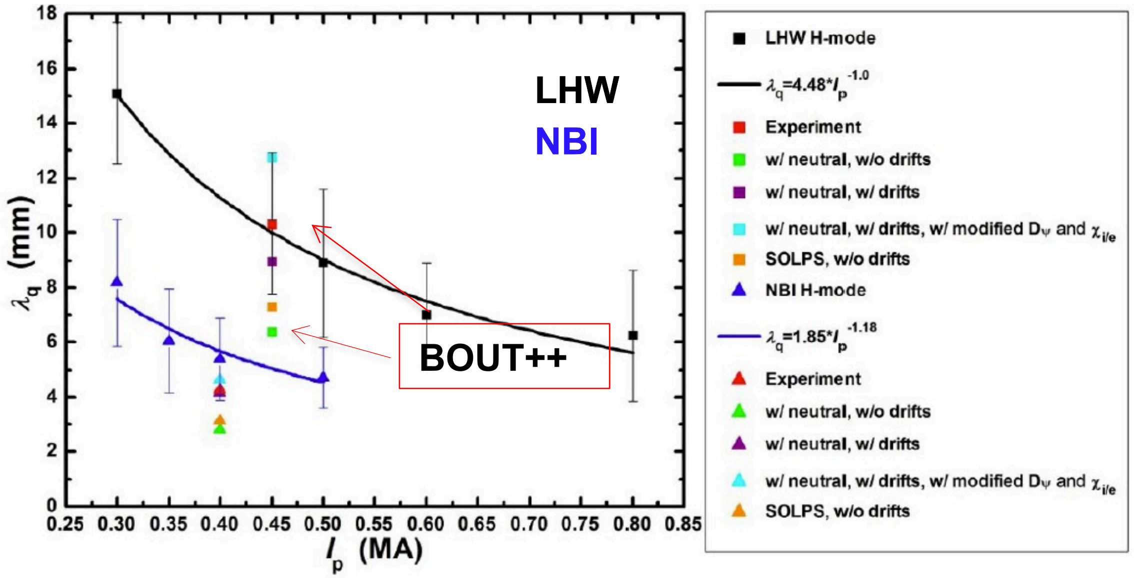
N.M. Li, X.Q. Xu, R.J. Goldston, *Nucl. Fusion* (2021)

BOUT++ Simulation of Divertor Heat Flux Width on EAST

Comparison of divertor heat flux and its width between simulations & experiments



Comparison of divertor heat flux width between simulations & experiments for LHW and NBI heating



- 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
T. Y. Xia, et al, *Nucl. Fusion* **59** (2019) 076043