Investigation of the origin of multi-scale MHD/turbulence and their role in setting the divertor heat flux widths for DIII-D wide-pedestal quiescent H-mode using BOUT++

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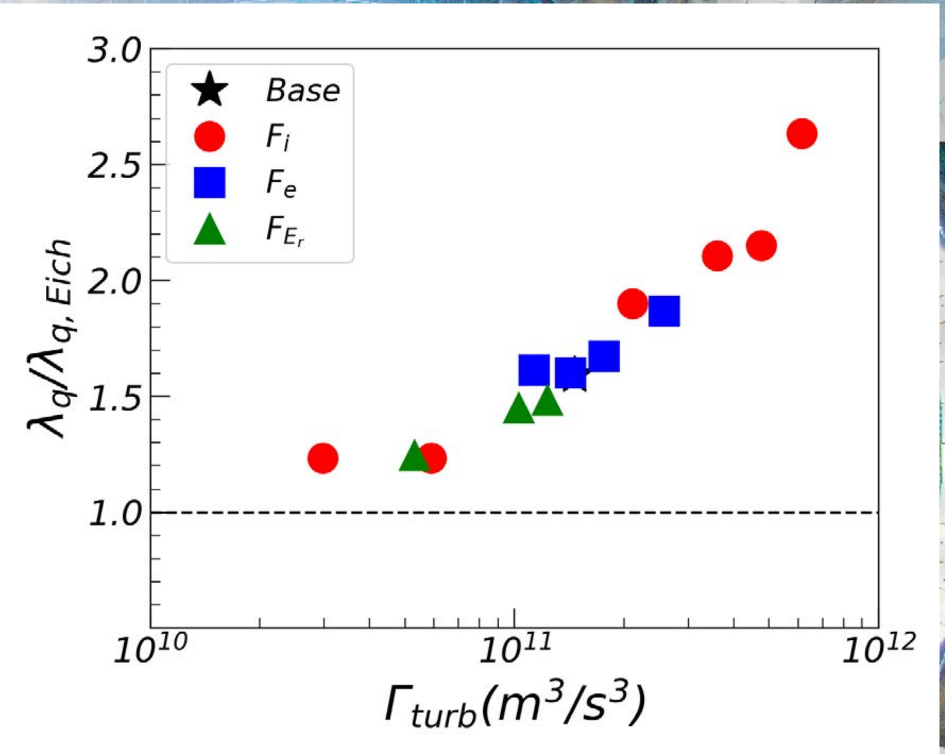


Present at BOUT++ workshop 2023
Jan. 10th, 2023

Work supported by US DOE under DE-FC02-04ER54698,DE-AC52-07NA27344, DE-SC0017992, DE-SC0019352, DE-FG02-08ER54999, DE-AC02-09CH11466 and LLNL-PRES-828728

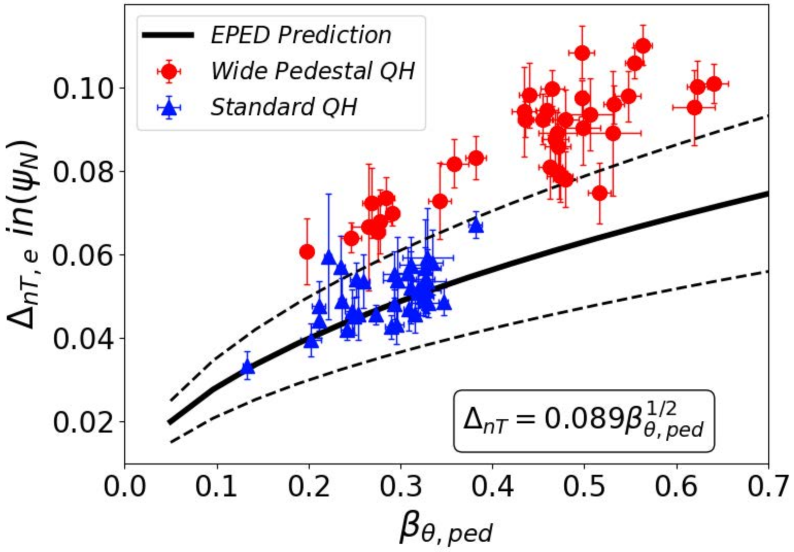
Outline

- Introduction of wide-pedestal QH mode (WPQH)
- Identification of the broadband turbulence in WPQH
- SOL: Divertor heat flux width and pedestal turbulence
- Summary

- Experiment
- Numerical Modeling
- Model/theory

Outline

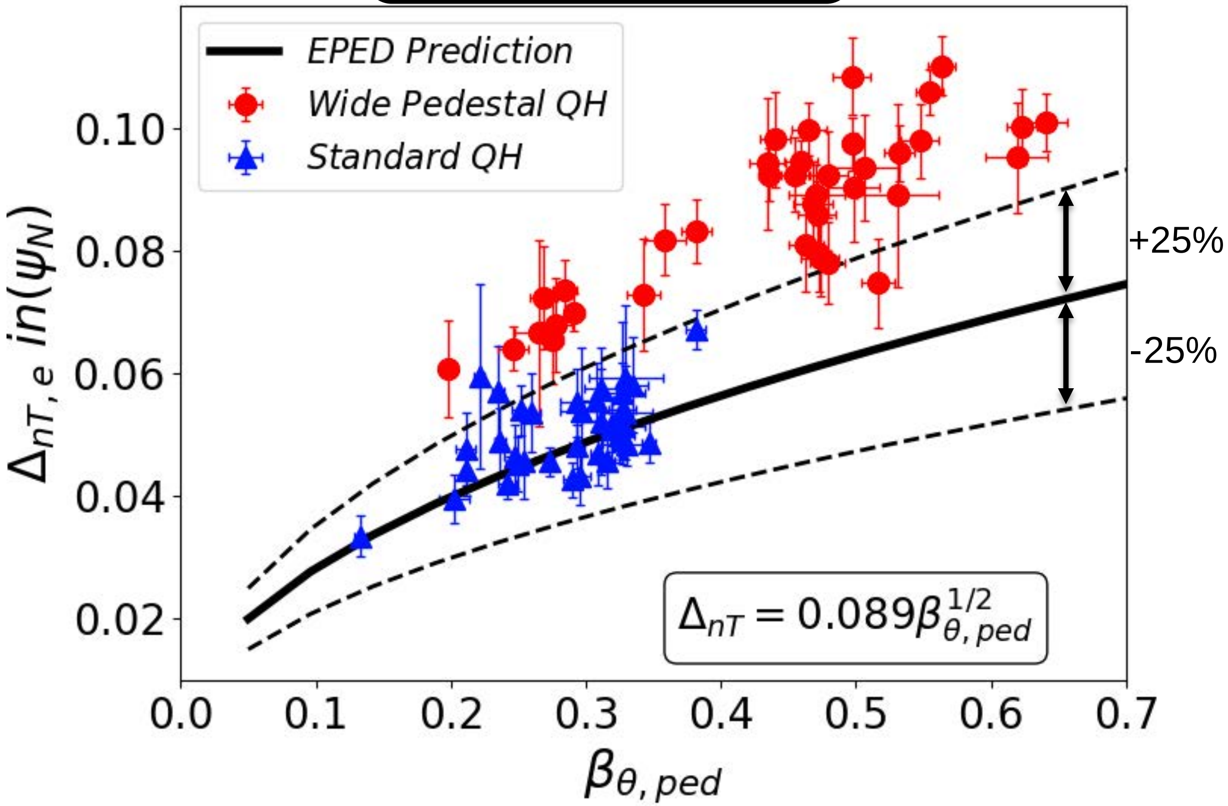
- Introduction
  - Wide-pedestal QH mode (WPQH)
  - Broadband turbulence in WPQH
  - Regulating of the pedestal profile
- Identification of the broadband turbulence in WPQH
- SOL: Divertor heat flux width and pedestal turbulence
- Summary



Experimental Characteristics of Wide Pedestal Quiescent H-Mode (WPQHM)

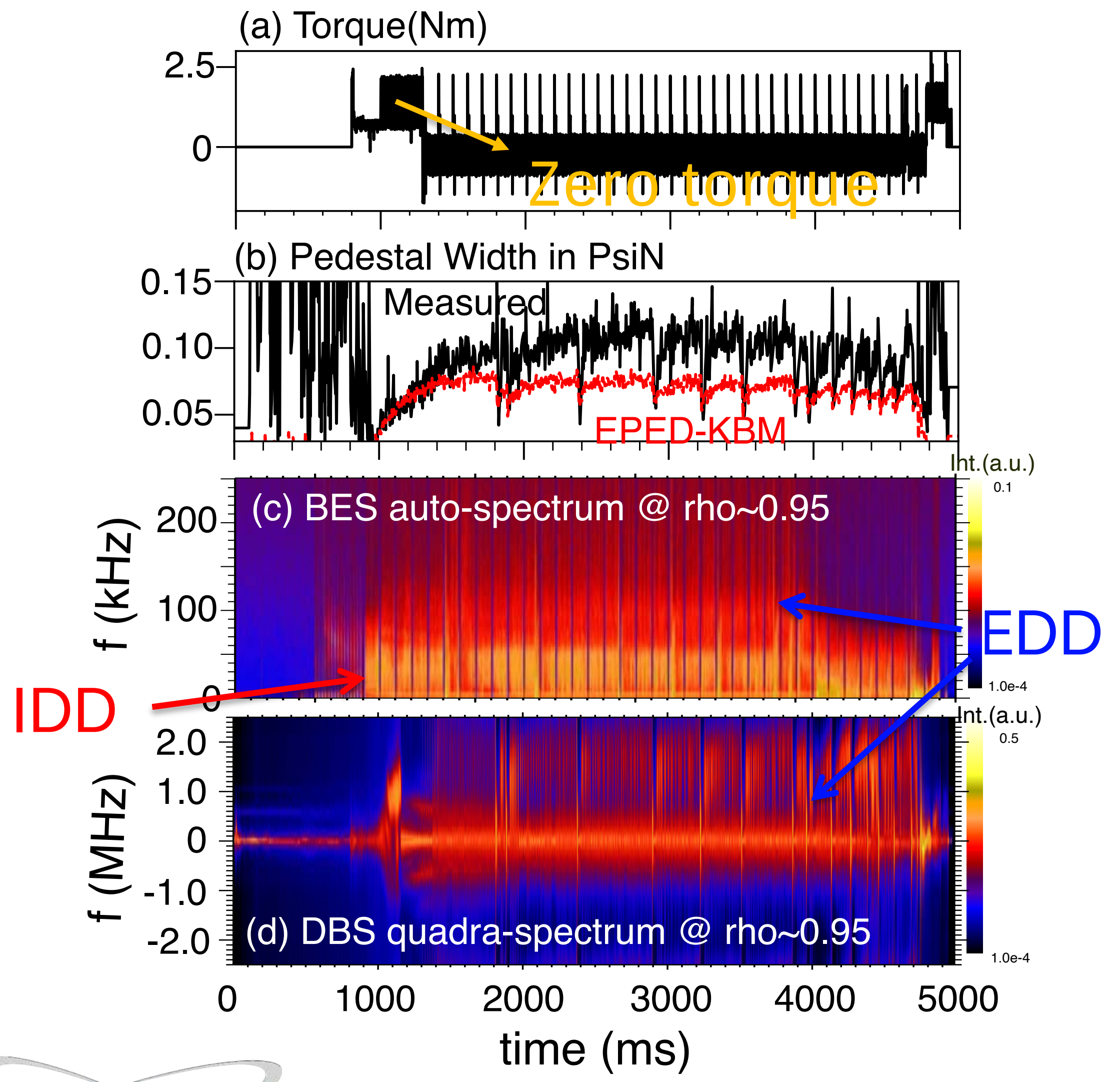
- Wide pedestal QH mode
  - Was first observed in DIII-D, 2015[1,2]
  - Achieved by reducing torque ~0Nm from QH mode[1,2]
  - Features:
    - Low edge rotation
    - Improved confinement, H_{98y2}~1.2-1.6
    - Naturally ELM-free
    - Future Reactors?
- Broadband[1-4] replace edge harmonic oscillations (EHO)
- Statistic about pedestal width[5]
  - Standard QH agrees well with EPED-KBM prediction[6]
  - WP QH pedestal width is larger by >25%
- New transport and stability limits are applied for wide pedestal QH
  - Below KBM limit

$$\Delta_{nT,e} = \frac{1}{2}(\Delta_{Te} + \Delta_n)$$



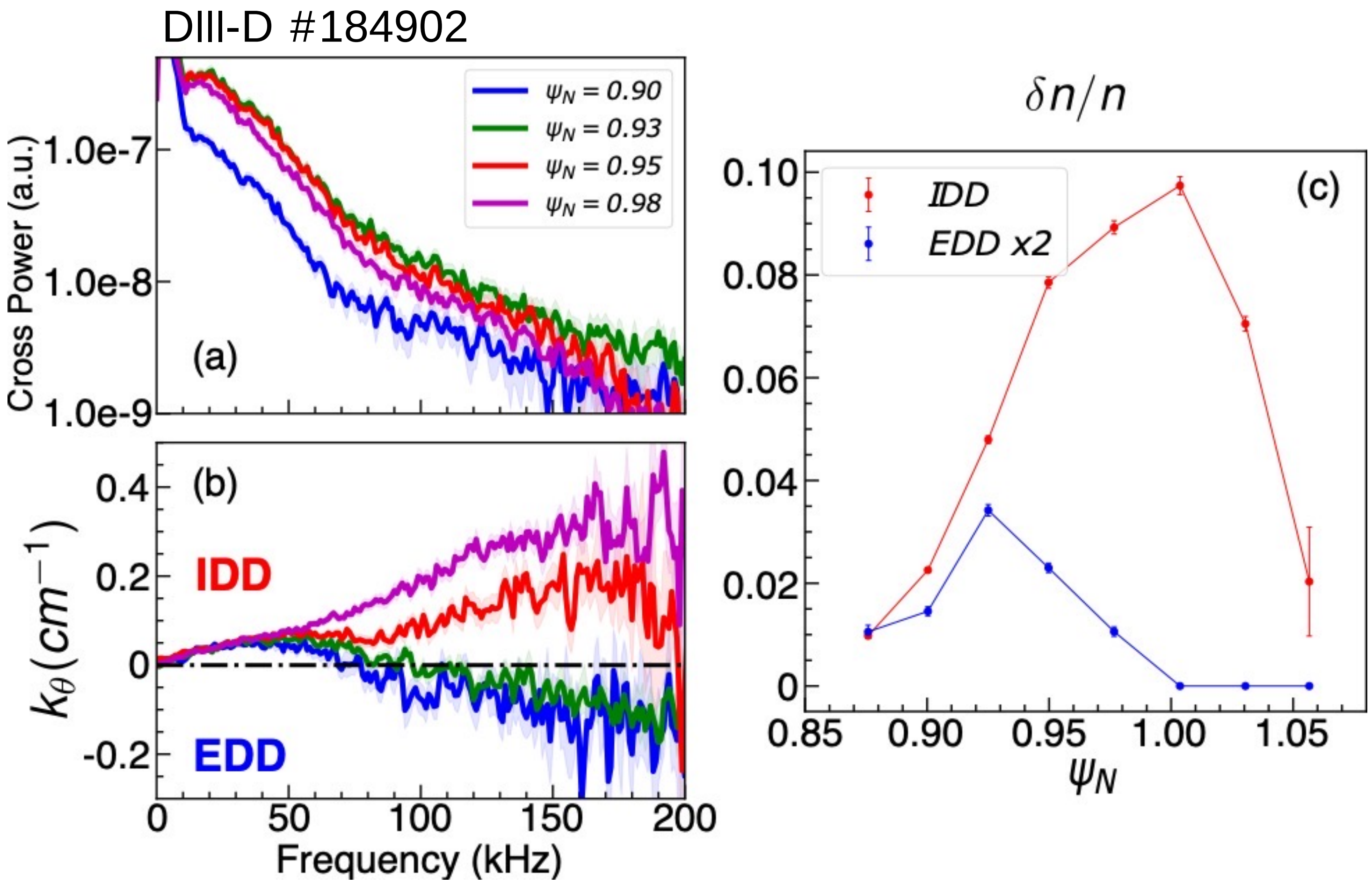
[1] K. H. Burrell, et al. Phys. Plasmas 23 (2016) 056103
[2] Xi Chen, et al. Nucl. Fusion 57 (2017) 022007
[3] Xi Chen, et al. Nucl. Fusion 57 (2017) 086008
[4] K. Barada, et al. PRL 120, (2018)135002
[5] Zeyu Li, et al., Nucl. Fusion 62 (2022) 076033
[6] P. B. Snyder et al. Nucl. Fusion 51 (2011)103016

Scale-separated Broadband Turbulence is Observed in WPQHM



- WPQH mode is achieved with net zero inject NBI torque
- Pedestal width is greater than EPED-KBM scaling
- Broadband turbulence is observed in WPQH
  - Broadband turbulence observed in BES/DBS
- Large-scale mode
  - Low-frequency 10-60 kHz
  - low k, $k_\theta < 0.3cm^{-1}$
  - ion diamagnetic direction (IDD)
- Small-scale mode
  - High frequency 60-2500 kHz
  - high k, $k_\theta < 4cm^{-1}$
  - electron diamagnetic direction (EDD)

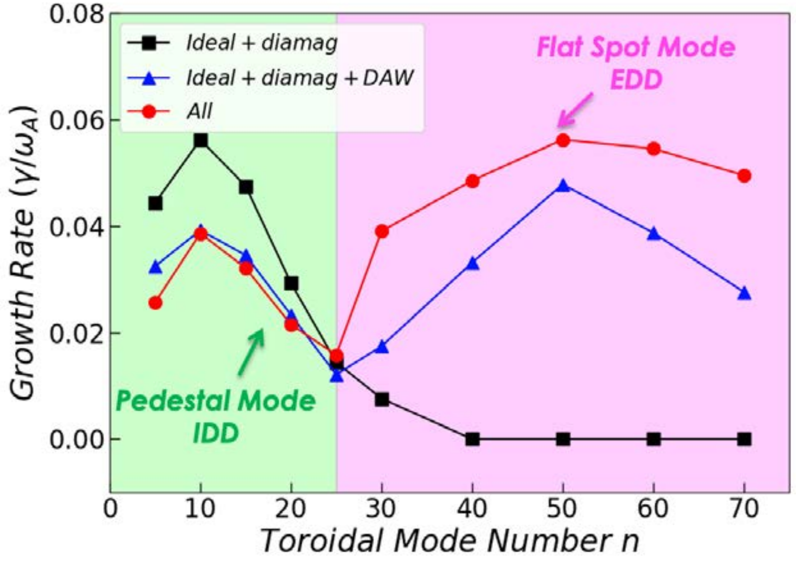
Characteristics of the Dual Bands of Broadband Turbulence: Frequency Ranges and Radial Mode Structure



- Dual bands in lab frame
  - IDD: ion diamagnetic direction
  - EDD: electron diamagnetic
- IDD mode:
  - Low frequency, large scale
  - Exist all over the pedestal
- EDD mode:
  - High frequency, small scale
  - Dominates in the upper pedestal
  - Rarely extended to the SOL

Outline

- Introduction
- Identification of the broadband turbulence in WPQH
  - BOUT++ linear simulation reveals two scale-separated modes
    - PBM: $\psi_N = 0.97$, peak gradient, low-intermediate n, most unstable at LFS, ion diamagnetic direction
    - DAW: $\psi_N = 0.93$, flat spot, high n, electron diamagnetic direction
  - Flat spot is successfully reproduced in electron temperature BOUT++ nonlinear simulation
  - Turbulence $\omega - k$ spectrum is consistent with BES diagnostic
- SOL: Divertor heat flux width and pedestal turbulence
- Summary



BOUT++ Six-field Turbulence Module with Carbon Impurity Contribution

$$\frac{\partial n_i}{\partial t} = -\left(\frac{1}{B_0}\boldsymbol{b}\times\boldsymbol{\nabla}_\perp\phi + V_{\parallel i}b\right)\cdot\boldsymbol{\nabla}n_i - \frac{2n_i}{B_0}\boldsymbol{b}\times\boldsymbol{\kappa}\cdot\left(\boldsymbol{\nabla}_\perp\phi + \frac{1}{Z_i e n_i}\boldsymbol{\nabla}P_i\right) - n_i B_0 \nabla_\parallel\left(\frac{V_{\parallel i}}{B_0}\right)$$

$$\frac{\partial n_{imp}}{\partial t} = -\left(\frac{1}{B_0}\boldsymbol{b}\times\boldsymbol{\nabla}_\perp\phi\right)\cdot\boldsymbol{\nabla}n_{imp} - \frac{2n_{imp}}{B_0}\boldsymbol{b}\times\boldsymbol{\kappa}\cdot\left(\boldsymbol{\nabla}_\perp\phi + \frac{1}{Z_{imp} e n_{imp}}\boldsymbol{\nabla}P_{imp}\right)$$

$$\frac{\partial T_i}{\partial t} = -\left(\frac{1}{B_0}\boldsymbol{b}\times\boldsymbol{\nabla}_\perp\phi + V_{\parallel i}b\right)\cdot\boldsymbol{\nabla}T_i - \frac{2}{3}T_i\left[\frac{2n_i}{B_0}\boldsymbol{b}\times\boldsymbol{\kappa}\cdot\left(\boldsymbol{\nabla}_\perp\phi + \frac{1}{Z_i e n_i}\boldsymbol{\nabla}P_i + \frac{5k_B}{2Z_i e}\boldsymbol{\nabla}T_i\right) + B_0\nabla_\parallel\left(\frac{V_{\parallel i}}{B_0}\right)\right] + \frac{2}{3n_i k_B}\nabla_\parallel(k_{\parallel i}\nabla_\parallel T_i) + \left(\frac{2m_e}{M_i}\right)\frac{T_e - T_i}{\tau_e}$$

$$\frac{\partial T_e}{\partial t} = -\left(\frac{1}{B_0}\boldsymbol{b}\times\boldsymbol{\nabla}_\perp\phi + V_{\parallel e}b\right)\cdot\nabla T_e - \frac{2}{3}T_e\left[\frac{2n_e}{B_0}\boldsymbol{b}\times\boldsymbol{\kappa}\cdot\left(\boldsymbol{\nabla}_\perp\phi - \frac{1}{en_e}\boldsymbol{\nabla}P_e - \frac{5k_B}{2e}\boldsymbol{\nabla}T_e\right) + B_0\nabla_\parallel\left(\frac{V_{\parallel e}}{B_0}\right)\right] + 0.71\frac{2T_e}{3en_e}B_0\nabla_\parallel\left(\frac{J_\parallel}{B_0}\right) + \frac{2}{3n_e k_B}\eta_\parallel J_\parallel^2 + \frac{2}{3n_e k_B}\nabla_\parallel(k_{\parallel e}\nabla_\parallel T_e) - \left(\frac{2m_e}{M_i}\right)\frac{T_e - T_i}{\tau_e}$$

$$\frac{\partial V_{\parallel i}}{\partial t} = -\left(\frac{1}{B_0}b\times\boldsymbol{\nabla}_\perp\phi + V_{\parallel i}\boldsymbol{b}\right)\cdot\boldsymbol{\nabla}V_{\parallel i} - \frac{\nabla_\parallel(P_i + P_e)}{n_i M_i}$$

$$\frac{\partial\varpi}{\partial t} = -\frac{1}{B_0}\boldsymbol{b}\times\boldsymbol{\nabla}_\perp\phi\cdot\nabla\varpi + B_0^2\nabla_\parallel\left(\frac{J_\parallel}{B_0}\right) + 2\boldsymbol{b}\times\boldsymbol{\kappa}\cdot\boldsymbol{\nabla}P + \mu_{i,\parallel}\nabla_{\parallel 0}^2\varpi - \frac{1}{2\Omega_i}\left[\frac{1}{B_0}\boldsymbol{b}\times\nabla P_i\cdot\nabla(\boldsymbol{\nabla}_\perp^2\boldsymbol{\phi}) - Z_i e B_0\boldsymbol{b}\times\nabla P_i\cdot\nabla\left(\frac{\nabla_\perp\phi}{B_0}\right)^2\right] + \frac{1}{2\Omega_i}\left[\frac{1}{B_0}\boldsymbol{b}\times\nabla\phi\cdot\nabla(\boldsymbol{\nabla}_\perp^2 P_i) - \boldsymbol{\nabla}_\perp^2\left(\frac{1}{B_0}\boldsymbol{b}\times\nabla P_i\right)\right] - \frac{1}{2\Omega_{imp}}\left[\frac{1}{B_0}\boldsymbol{b}\times\nabla P_{imp}\cdot\nabla(\boldsymbol{\nabla}_\perp^2\boldsymbol{\phi}) - eB_0\boldsymbol{b}\times\nabla P_{imp}\cdot\nabla\left(\frac{\nabla_\perp\phi}{B_0}\right)^2\right] + \frac{1}{2\Omega_{Imp}}\left[\frac{1}{B_0}\boldsymbol{b}\times\nabla\phi\cdot\nabla(\boldsymbol{\nabla}_\perp^2 P_{imp}) - \boldsymbol{\nabla}_\perp^2\left(\frac{1}{B_0}\boldsymbol{b}\times\nabla P_{imp}\right)\right]$$

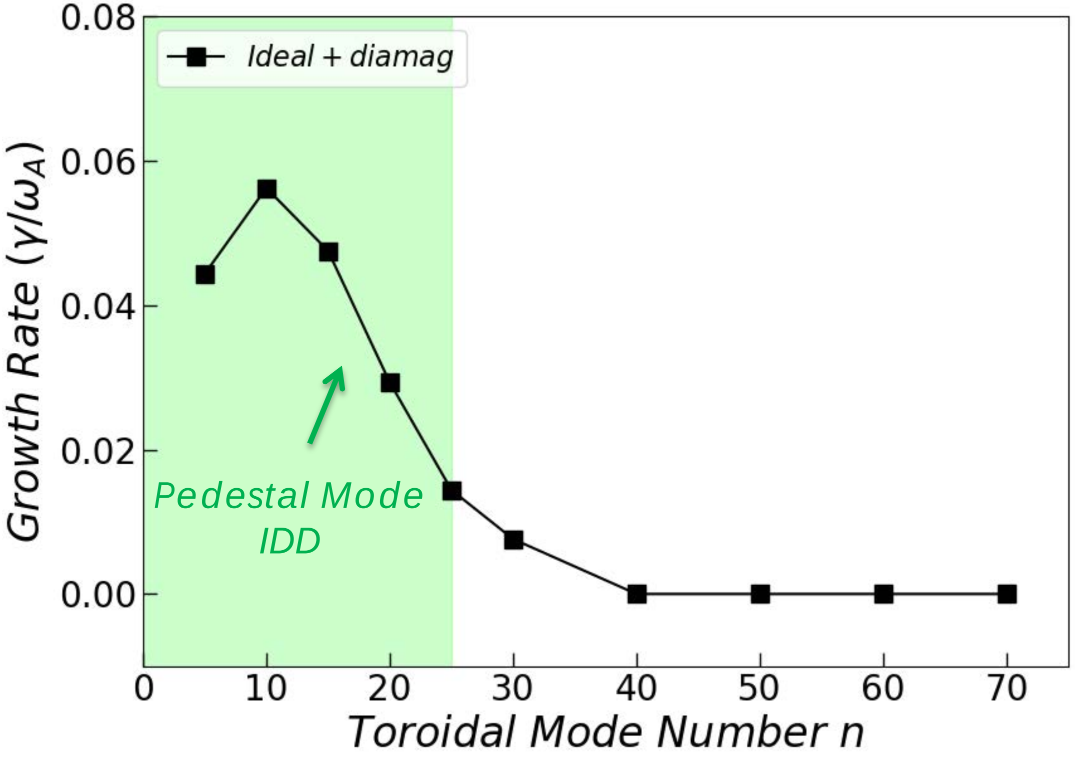
$$\frac{\partial\psi}{\partial t} = \frac{1}{B_0}\nabla_\parallel\phi + \frac{\eta}{\mu_0}\boldsymbol{\nabla}_\perp^2\psi + \frac{\eta_H}{\mu_0}\boldsymbol{\nabla}_\perp^4\psi + \frac{1}{en_eB_0}\nabla_\parallel P_e + 0.71\frac{1}{eB_0}\nabla_\parallel T_e$$

$$\varpi = \frac{N_iM_i}{B_0}\left(\nabla_\perp^2\phi + \frac{1}{Z_ieN_i}\nabla_\perp^2P_i + \frac{1}{N_i}\nabla_\perp N_i\cdot\nabla_\perp\phi\right) + \frac{N_{imp}M_{imp}}{B_0}\left(\nabla_\perp^2\phi + \frac{1}{Z_{imp}eN_{imp}}\nabla_\perp^2P_{imp} + \frac{1}{N_{imp}}\nabla_\perp N_{imp}\cdot\nabla_\perp\phi\right)$$

- BOUT++ ’*six*’-field module
- Relative High Zeff in WPQH
  - Impurity should be taken into consideration
- Impurity module:
  - Impurity density evolution equ.
  - Vorticity equs.
- Impurity is considered to be fully collisional with main ion
  - $T_{imp} = T_i$
- Carbon impurity C^{6+} is considered

BOUT++ Linear Modeling Finds Two Instabilities in Different Radial Locations

Generalized Ohm's law:
$\frac{\partial A_\parallel}{\partial t} = -\nabla_\parallel \phi + \eta J_\parallel$



IDD: ion diamagnetic drift direction

EDD: electron diamagnetic drift direction

- BOUT++ reduced 2-fluid 6(7?)-field module is performed
  - $N_i, N_{imp}, T_e, T_i, V_{i\parallel}, A_\parallel, \omega$
- Ideal MHD (PBM)
  - *only one unstable mode at lower pedestal ($\psi_N = 0.968$)*
  - *Ion diamagnetic drift direction*

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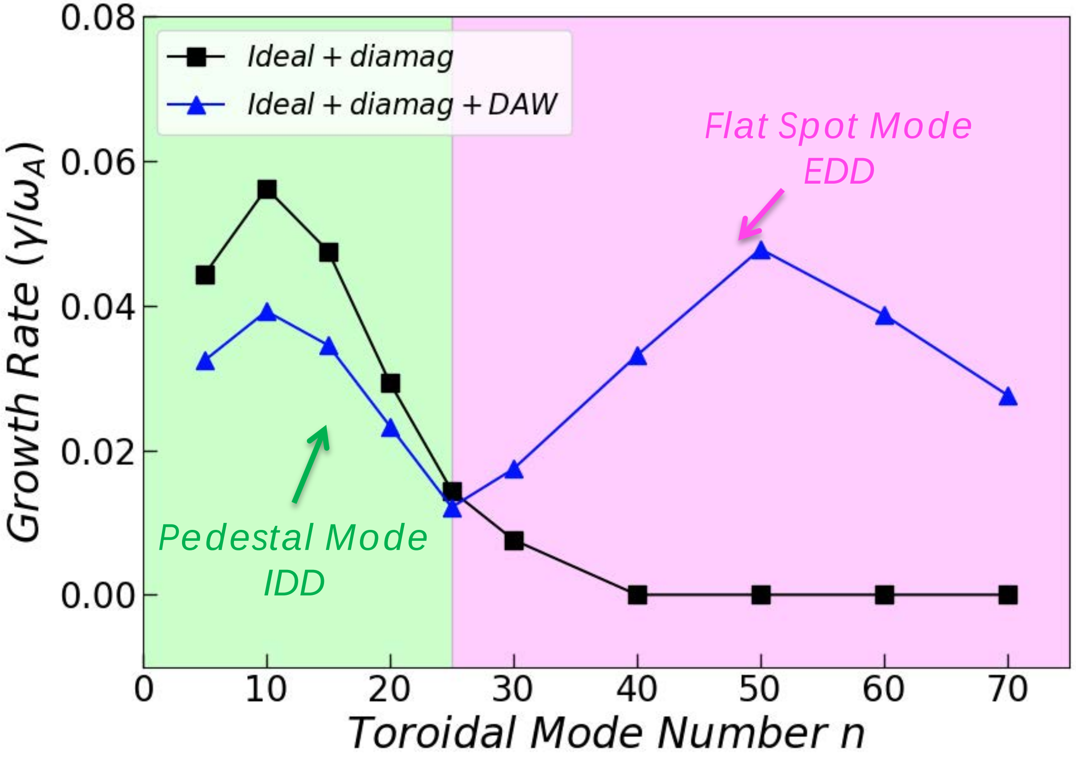

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- Ideal MHD (PBM)
  - *only one unstable mode at lower pedestal ($\psi_N = 0.968$)*
  - *Ion diamagnetic drift direction*
- Drift-Alfvén wave (DAW)
  - *By considering adiabatic electron response in generalized Ohm's law (∇P_e)*
  - *Another mode around at upper pedestal ($\psi_N = 0.93$)*
  - *Electron diamagnetic drift direction*
  - *EM version of electron drift wave in fluid*

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BOUT++ Linear Modeling Finds Two Instabilities in Different Radial Locations

Generalized Ohm's law:

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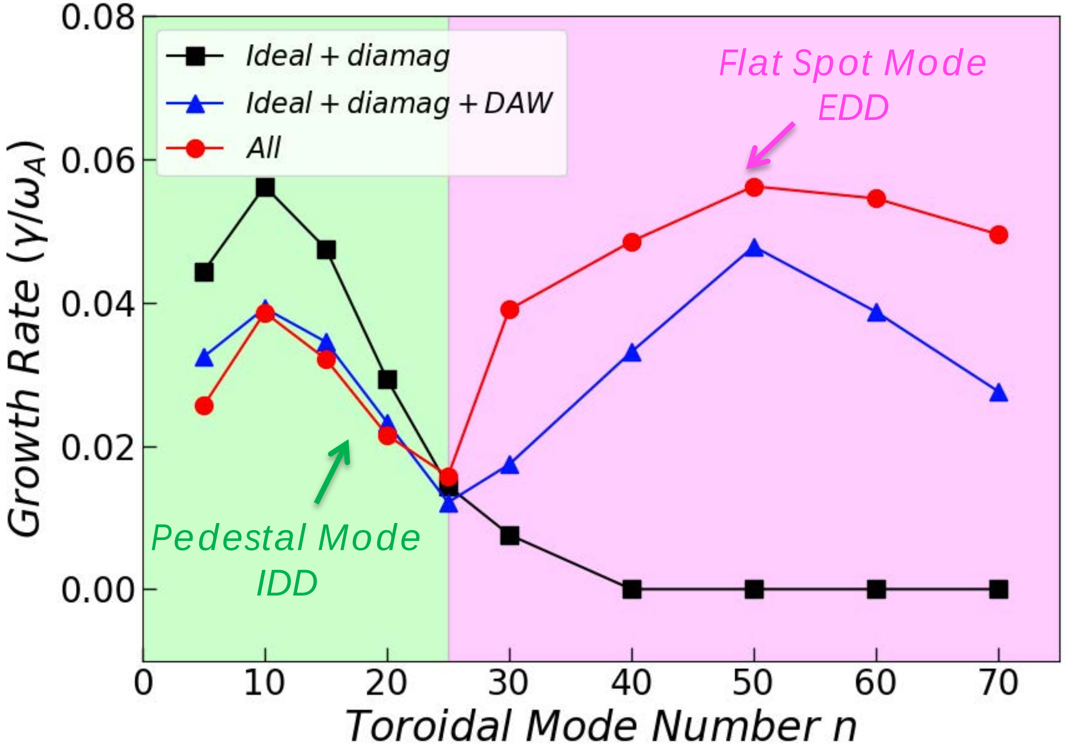

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  - *Another mode around at upper pedestal ($\psi_N = 0.93$)*
  - *Electron diamagnetic drift direction*
  - *EM version of electron drift wave in fluid*
- Full 6 fields terms:
  - *Ion-electron friction etc.*
  - *Destabilized the flat spot mode*

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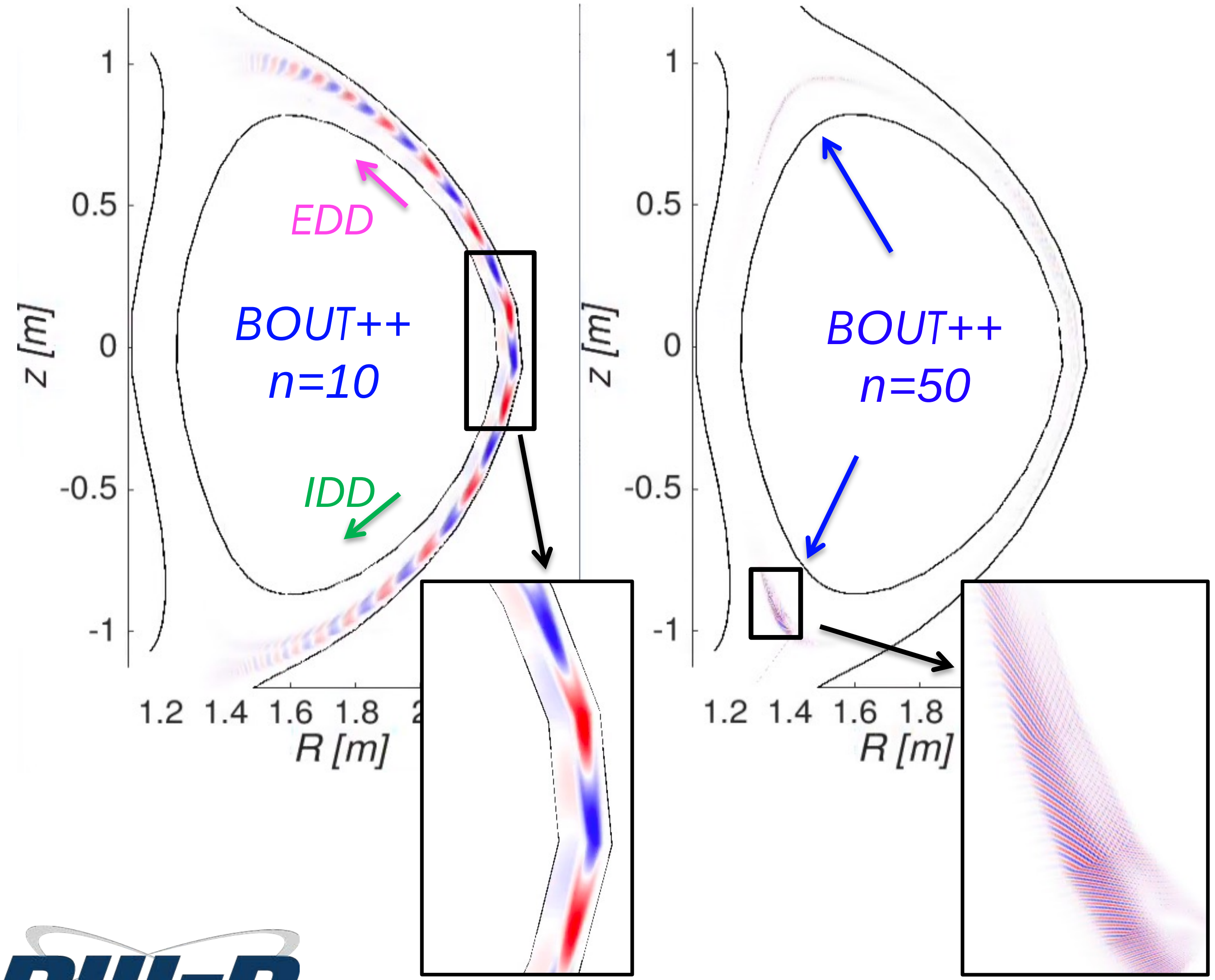
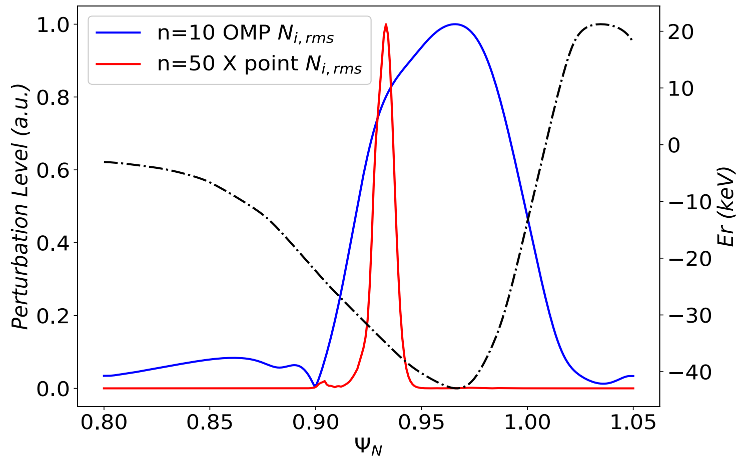
BOUT++ Linear Modeling Finds Two Instabilities in Different Radial Locations

Shot 169862 density perturbation $\tilde{n}$

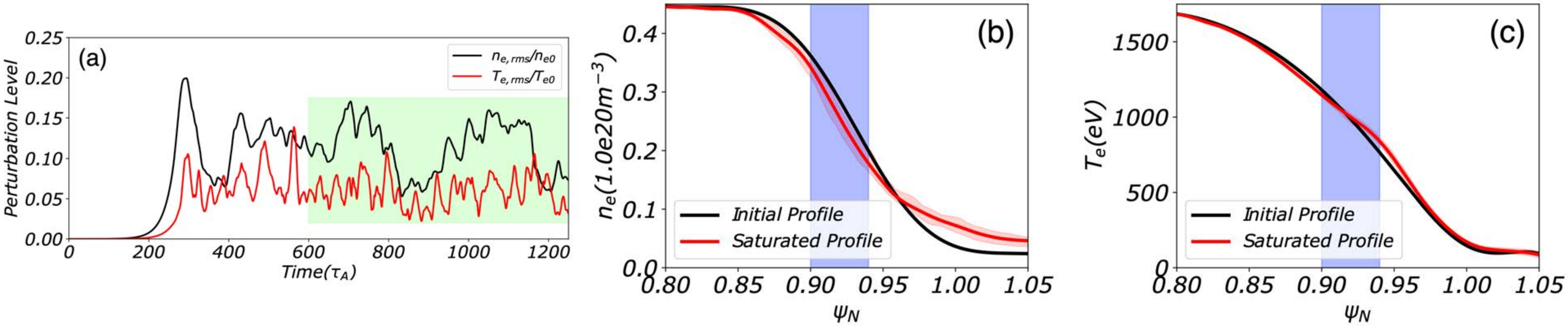




- Low n modes peak at low field side (LFS)
  - $\psi_N = 0.97$, *outboard mid plane (OMP)*
  - *Rotate in ion diamagnetic direction*
  - *Mild PB mode, which won't cause ELMs*
- High n modes peak at high field side (HFS)
  - $\psi_N = 0.93$, *near lower and upper X points*
  - *Drift Alfvén wave, large S and α makes the mode most unstable at HFS[1]*

[1] J. Wesson, Tokamak,2004

"Flat Spot" is Reproduced in Electron Temperature Channel with no ELM Crash for BOUT++ Nonlinear Simulation



- Perturbation is measured at ψ_N=0.95 in BOUT++ nonlinear simulation
- The low-n peeling-ballooning mode is mild – no ELM crash
- Flat spot is successfully reproduced in different channels (~ ψ_N=0.92)
  - *Electron density and temperature*

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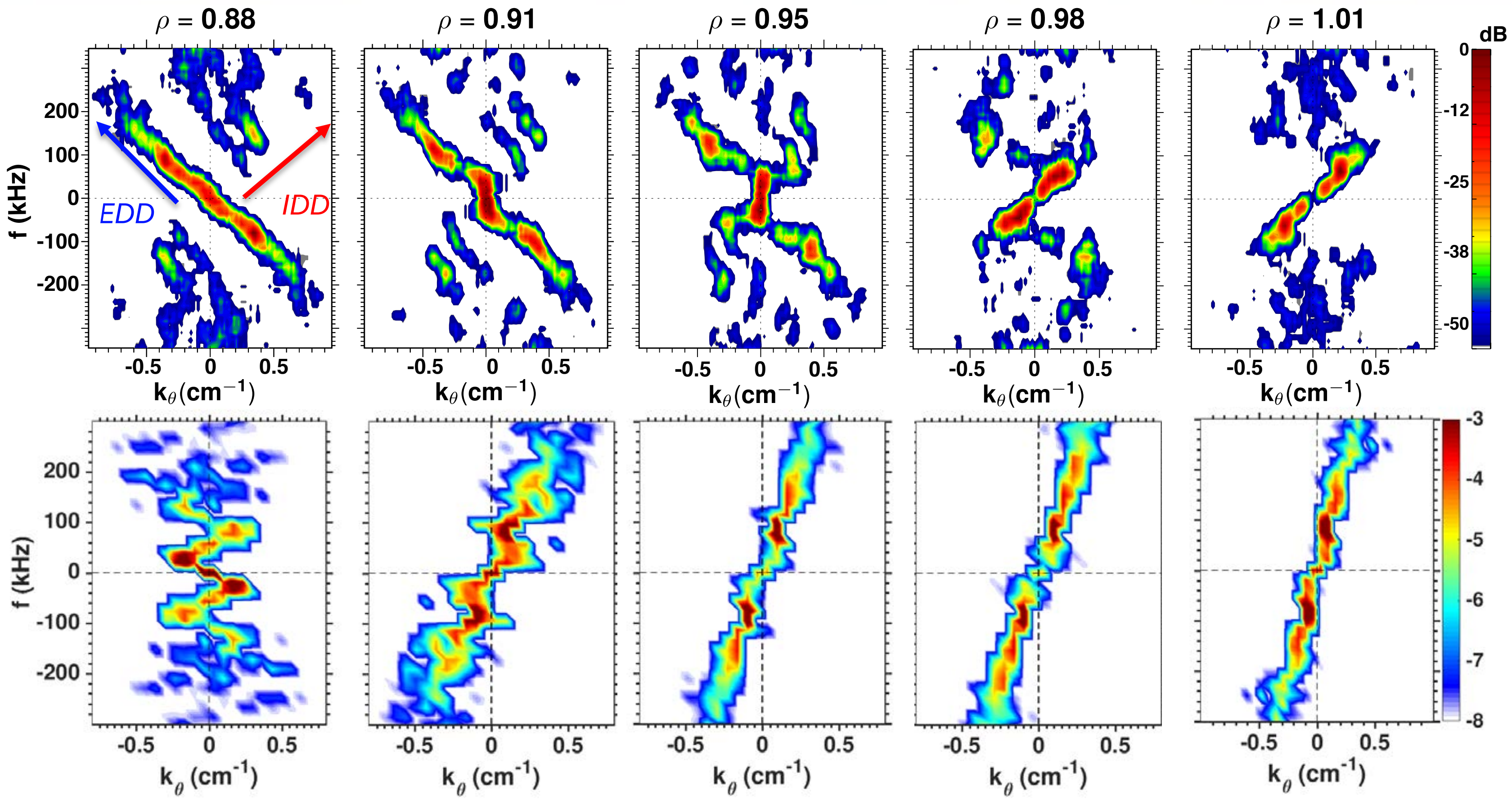
BOUT++ Nonlinear Modeling Successfully Captured the Two Counter-Propagating Modes Observed in BES Diagnostic

Shot 169862

BES Diagnostic

BOUT++ Nonlinear Simulation



- BOUT++ successfully captured the two counter-propagating modes observed in BES
  - *Didn't capture the High freq. EDD mode*
  - *Lack of <u>trapped electron</u> effects?*

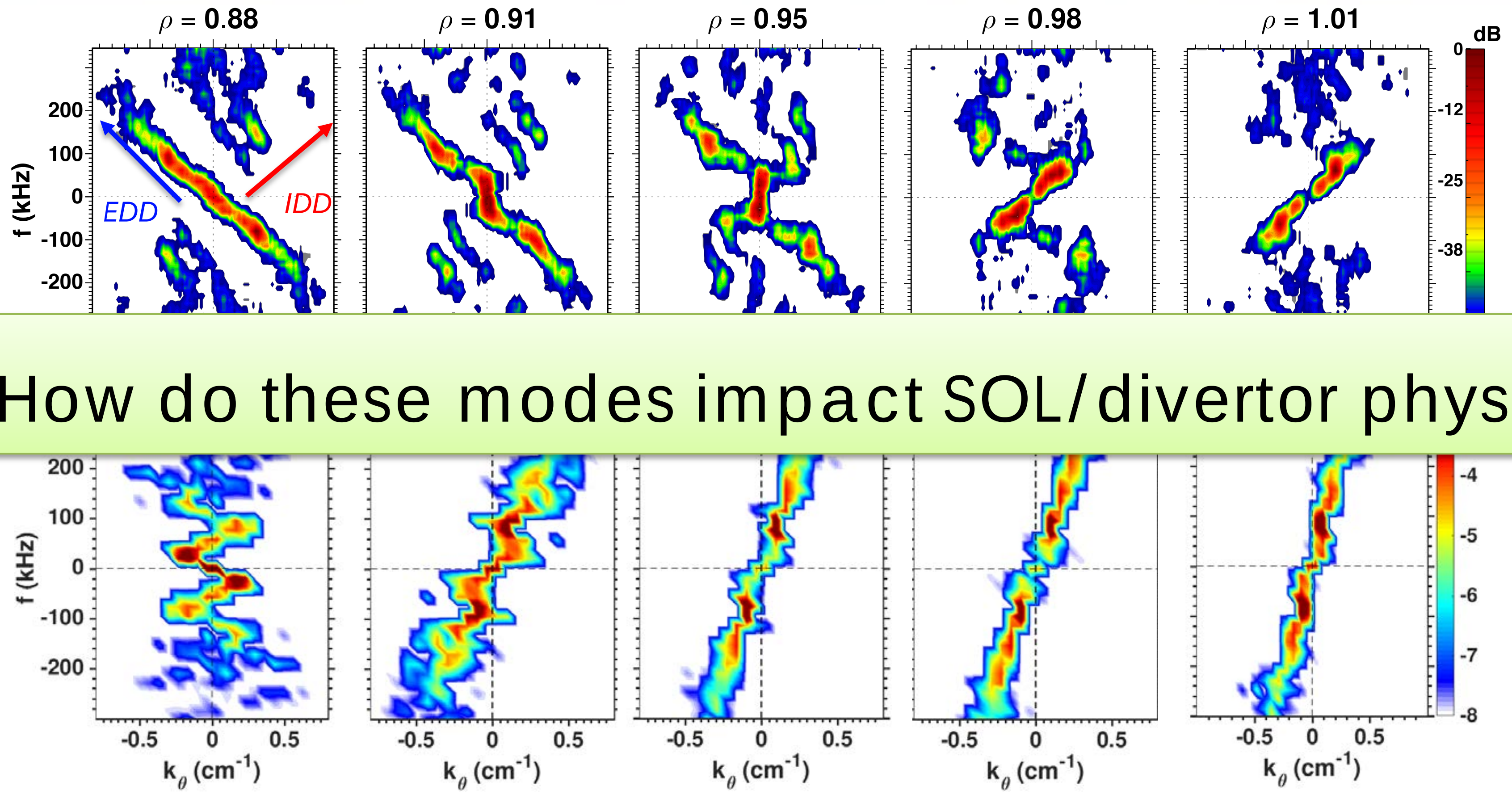
Zeyu Li, et al., Nucl. Fusion 62 (2022) 076033

BOUT++ Nonlinear Modeling Successfully Captured the Two Counter-Propagating Modes Observed in BES Diagnostic

Shot 169862

BES Diagnostic

BOUT++ Nonlinear Simulation

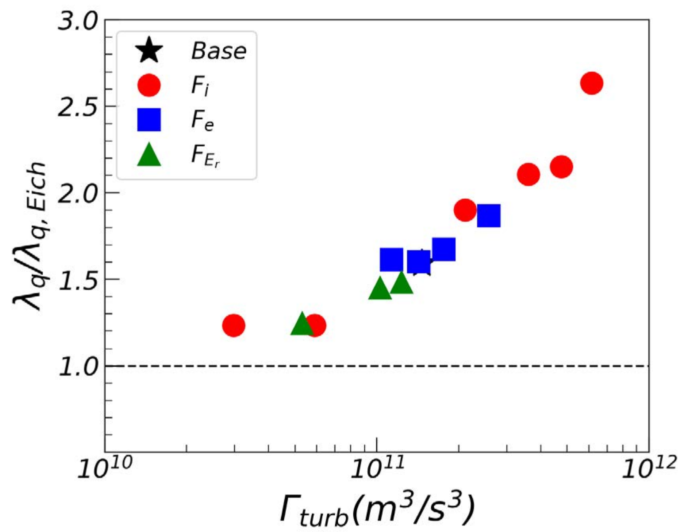


- How do these modes impact SOL/divertor physics?

- BOUT++ successfully captured the two counter-propagating modes observed in BES
  - *Didn't capture the High freq. EDD mode*
  - *Lack of trapped electron effects?*

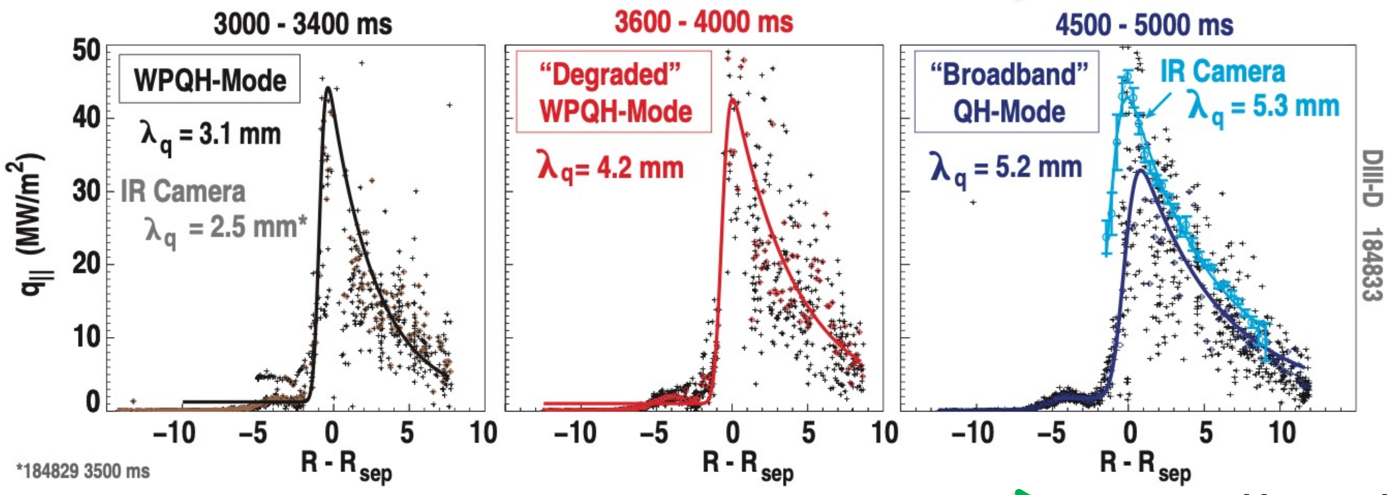
Outline

- Introduction
- Identification of the broadband turbulence in WPQH
- SOL: Divertor heat flux width and pedestal turbulence
  - Large scale IDD mode is extended to the separatrix, which could impact the heat flux width
  - Separatrix Er shear could suppress the turbulence spreading
  - Divertor heat flux width is correlated with the separatrix turbulence intensity flux
- Summary



Observation of divertor heat flux width widening in QH mode plasmas

Torque increase



WPQH

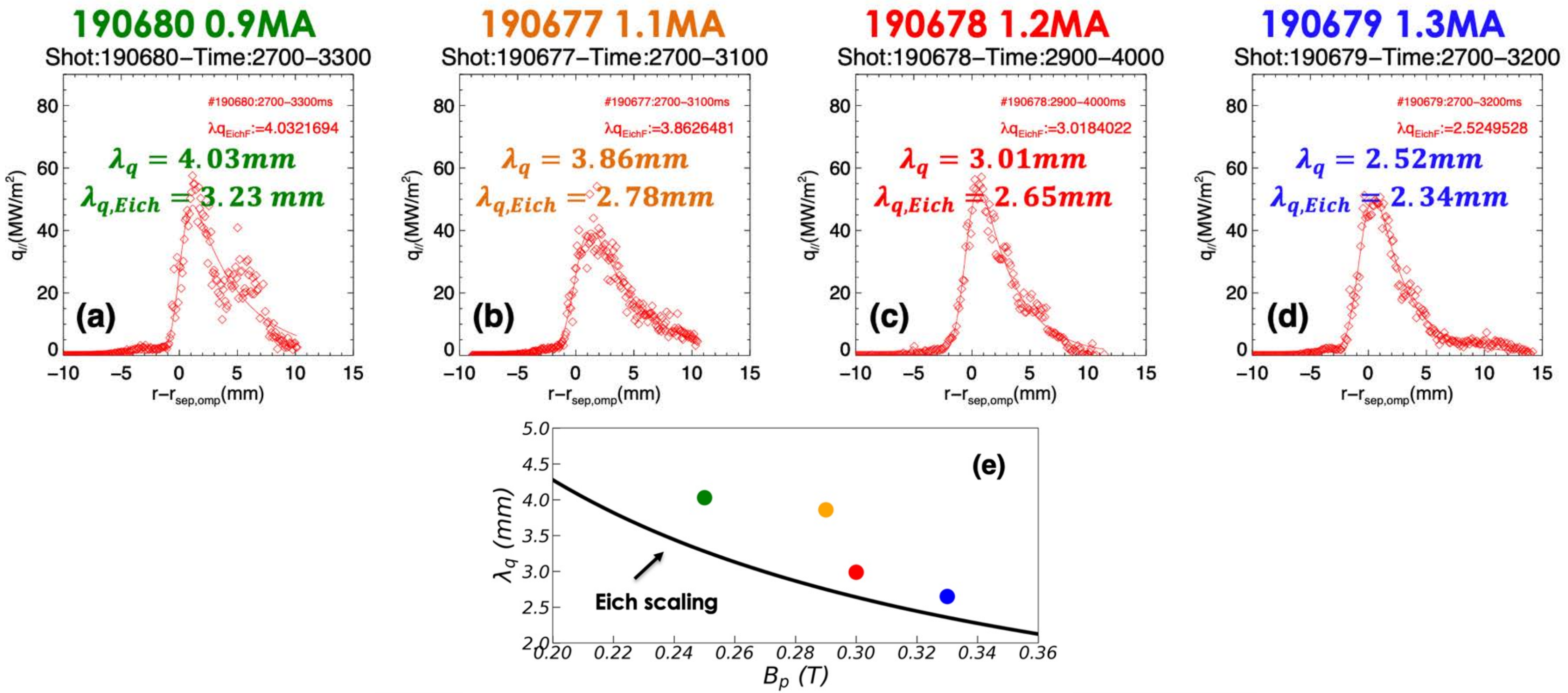
Both IDD/EDD amplitude increase

"Broadband" QH

- IDD vs. EDD
  - *IDD global, extended to SOL*
  - *EDD local, localized at pedestal top*
- IDD mode may lead to the heat flux width spreading in WPQH

D. Ernst TTF 2022
Private communication
Paper in preparation

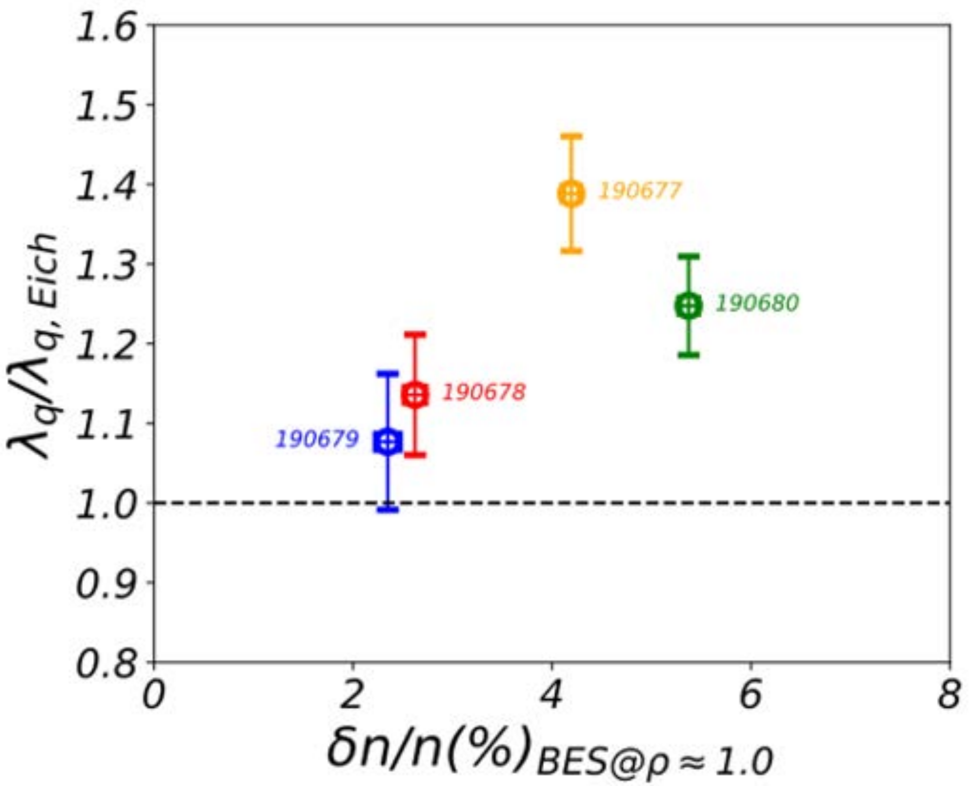
Broadened heat flux width is also observed in recent new campaign



➢ Heat flux width is generally greater than the typical H mode scaling with different Ip

Courtesy: H. Wang

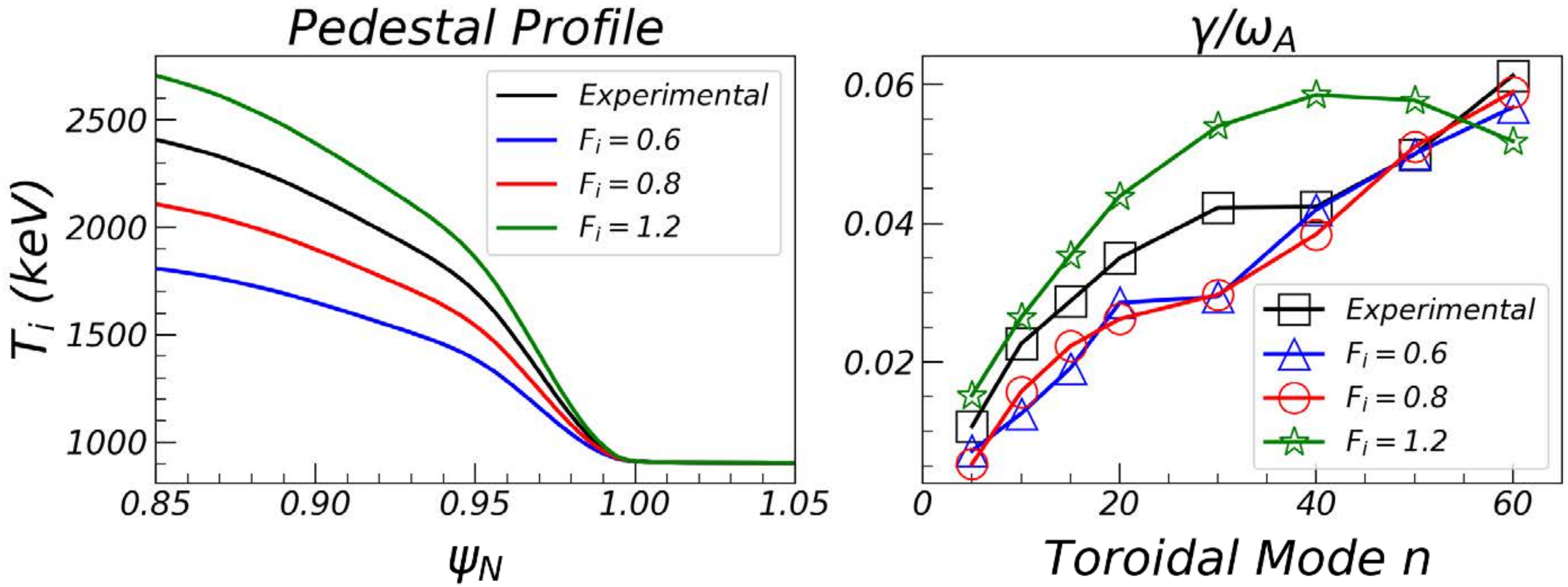
Divertor Heat Flux Width Correlates with the Edge Turbulence Intensity



- Edge turbulence intensity is measured by Beam Emission Spectroscopy (BES)
- Turbulence @ separatrix
  - Mainly IDD low freq. MHD
- General trend: heat flux width increases with turbulence intensity
  - Turbulence broadened, beyond Eich Scaling

Change Pedestal Profile to Change the Relative Amplitude of PBM and DAW: T_i -> PBM

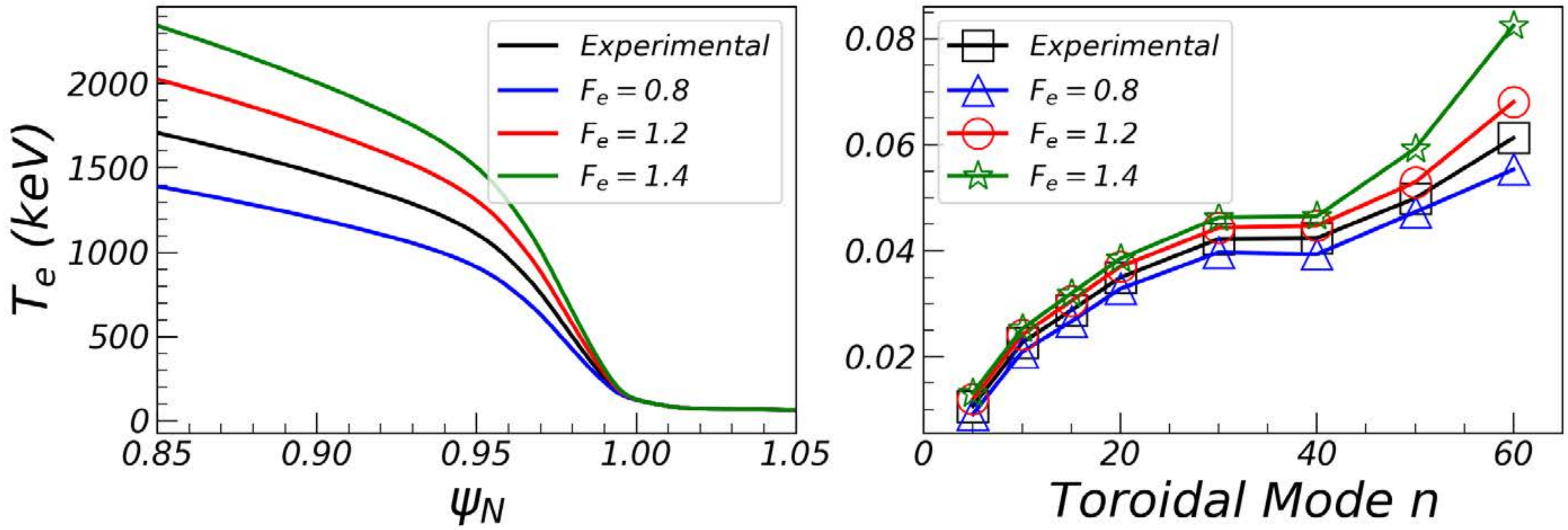
F_i: ion temperature scale factor



- Dominate mode transition happens at different n with different F_i
  - *F_i=0.6: pure EDD*; *F_i=0.8: n=30*; *F_i=1.0: n=40*; *F_i=1.2: pure IDD*
  - IDD mode changed accordingly; EDD mode nearly didn't change

Change Pedestal Profile to Change the Relative Amplitude of PBM and DAW: T_e -> DAW

F_e: electron temperature scale factor



- SOL profile is kept fixed
- DAW increase with $\boldsymbol{T_e}$
  - PBM also increase with total pressure

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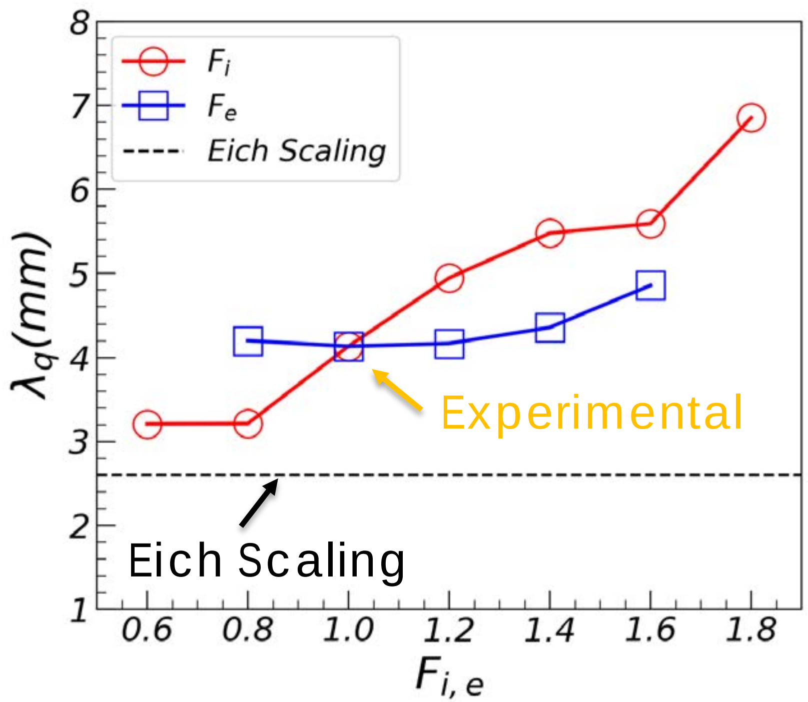
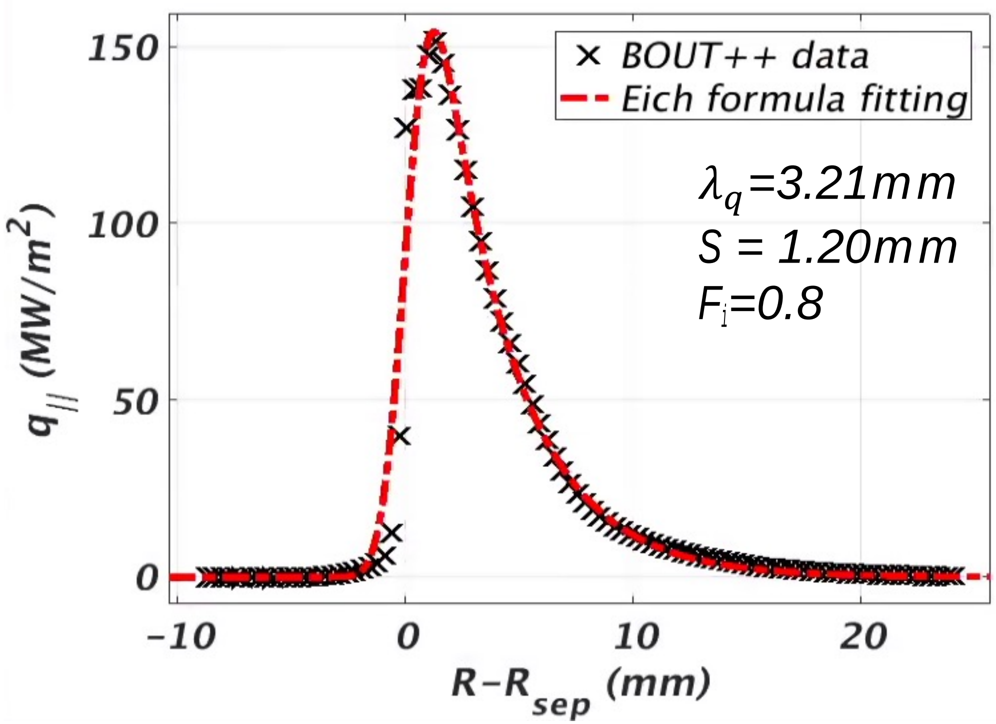
Divertor Heat Flux Width is More Sensitive to Ion Temperature and PBM

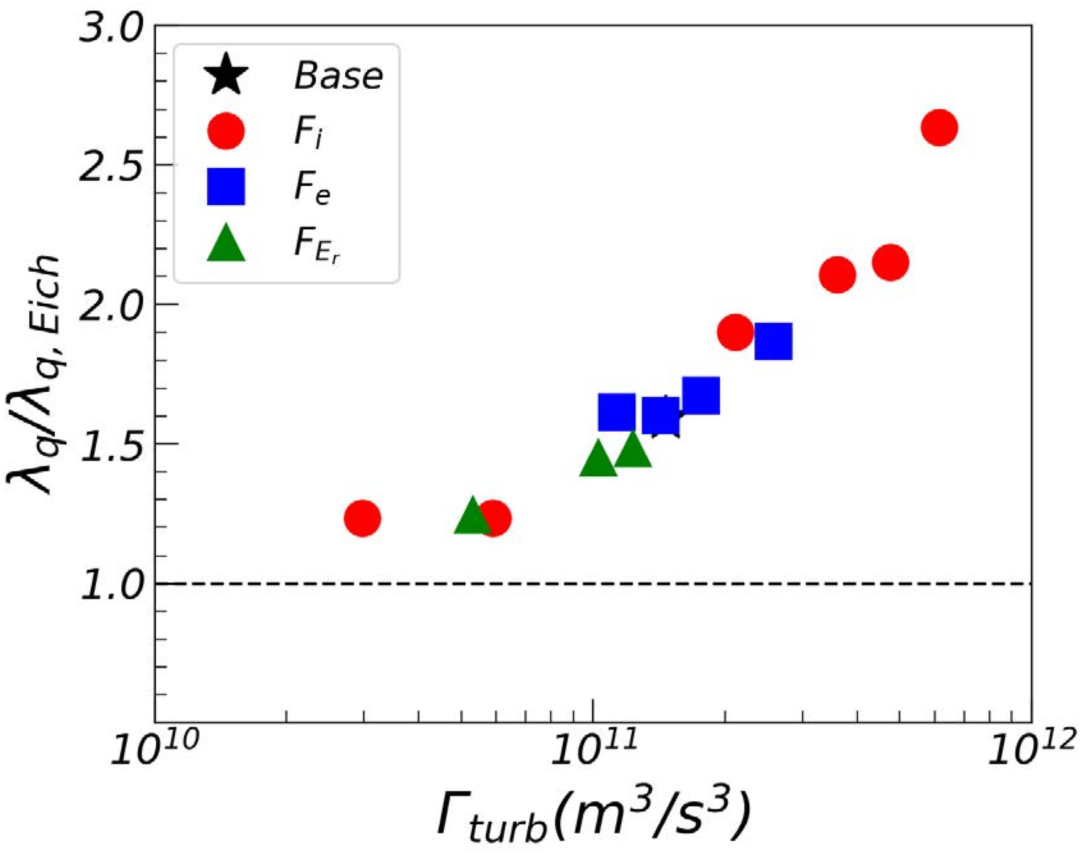




- BOUT++ could reproduce small λ_q=3.21mm when F_i<=0.8
  - *Slightly higher than Eich's scaling λ_q=2.5mm*
- Divertor heat flux width λ_q increases with the increase of ion mode (PBM)
  - *Not sensitive to the electron temperature and DAW*

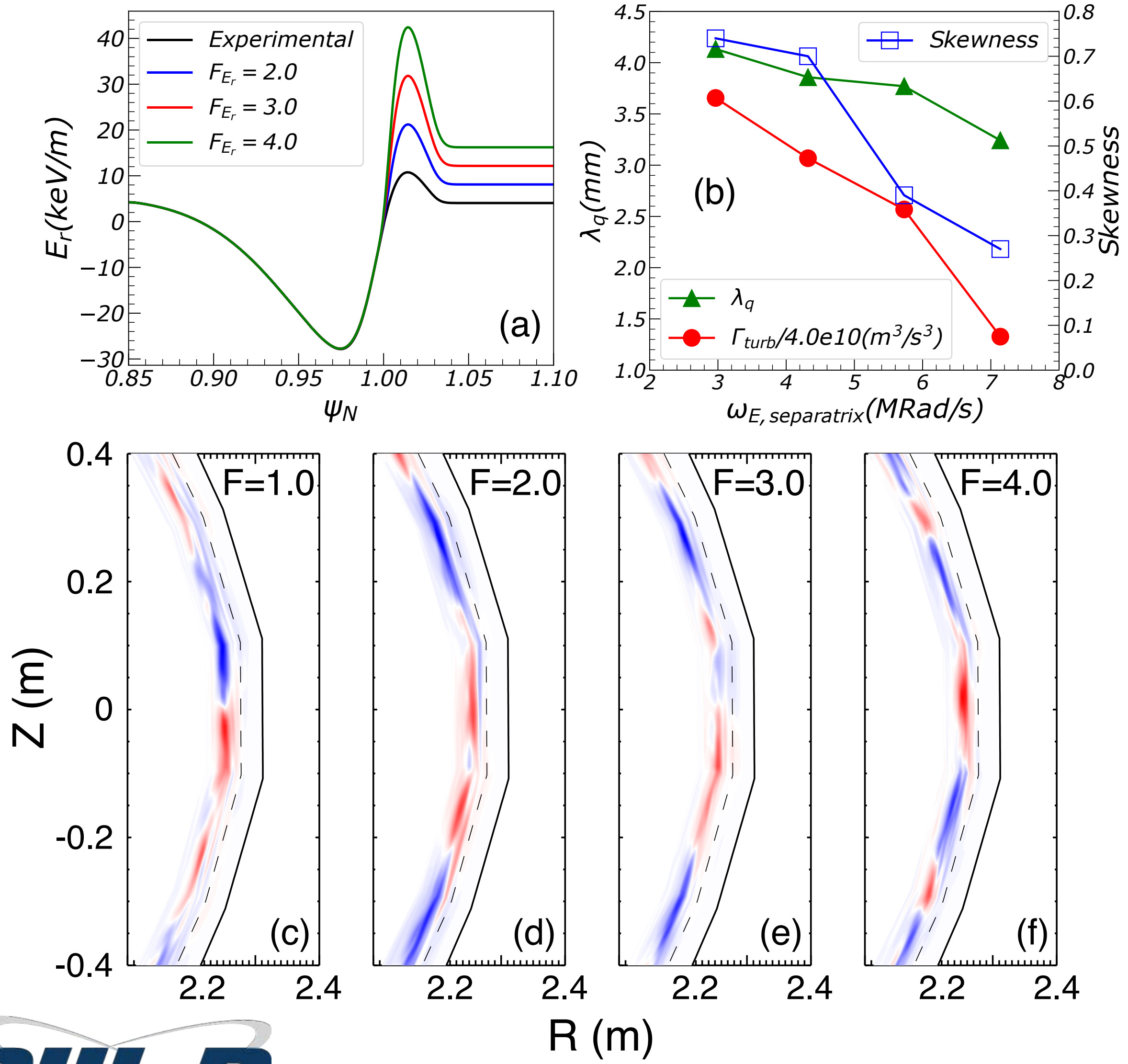
Divertor Heat Flux Width Increases with the Turbulence Intensity Flux

P. H. Diamond TTF 2022
P. H. Diamond AAPPS 2022



- Turbulence intensity flux[1]
  - $\Gamma_{turb} = c_s^2 \left\langle \left(\frac{\delta P}{P}\right)^2 \delta v_r \right\rangle_{\theta,\zeta,t}$
  - Turbulence intensity flux is measured at separatrix
  - Averaged over flux surface and time
- Different mechanisms:
  - IDD mode: strong effect, easy to change λ_q
  - EDD mode: little effect (but its own magnitude even changes just a little)
  - Er shear: suppresses the spreading and narrows the λ_q slightly

Separatrix ExB Shearing Rate Obscures Turbulence Spreading and Narrowing the Heat Flux Width



- Er profile inside separatrix is not changed to keep pedestal turbulence unchanged
  - *SOL potential is modified to check the ExB shearing at the separatrix*
- ExB shearing at the separatrix obscures the turbulence spreading
  - Reduce the skewness
  - Reduce the turbulence intensity flux
  - Edge eddies are sheared and broke into smaller size

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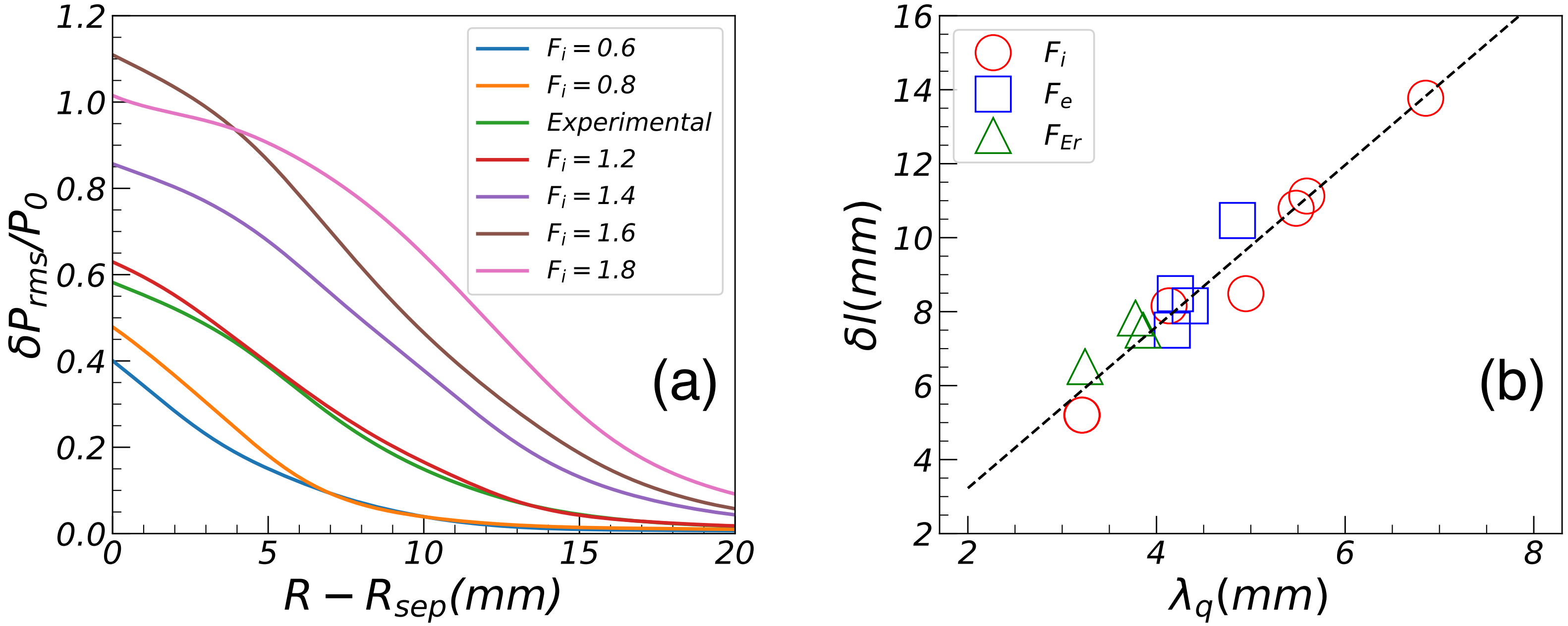
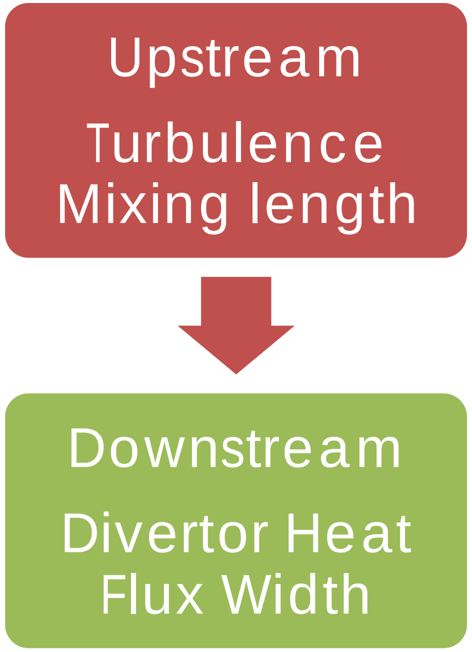
Upstream Turbulence Scale Length is Proportional to the Downstream Divertor Heat Flux Width





- Turbulence intensity scale length is measured at upstream OMP
  - Turbulence mixing length
- Shows good proportionality with divertor heat flux width

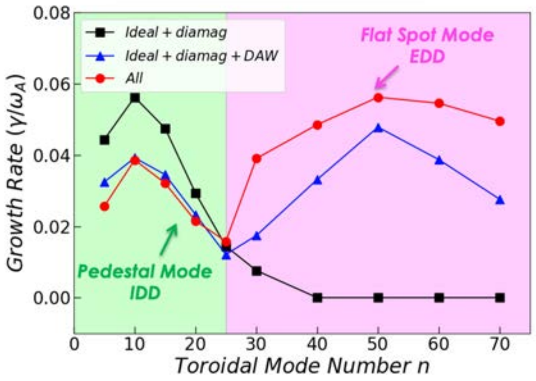
Zeyu Li, et al., in preparation

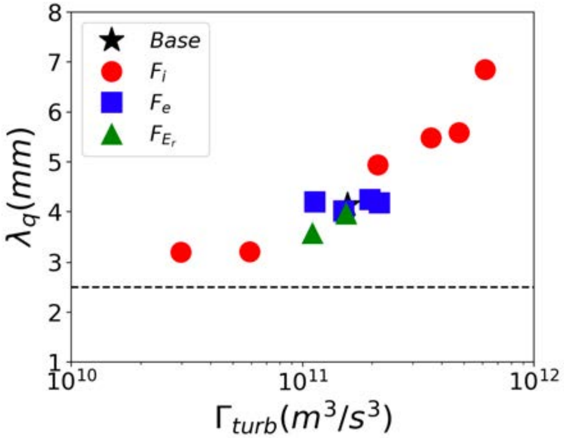
Outline

- Introduction
- Identification of the broadband turbulence in WPQH
- The interplay of scale-separated modes in WPQH
- SOL: Divertor heat flux width and pedestal turbulence
- Summary

Summary

- Wide-pedestal QH mode could be an attractive scenario for future reactors
  - Zero net inject torque, improved confinement, ELM-free
  - Turbulence-dominated pedestal, the potential to broaden heat flux width
- Identification of the different modes in WPQH
  - DAW: $\psi_N = 0.93$, flat spot, intermediate-high n, most unstable at HFS, EDD
  - PBM: $\psi_N = 0.97$, pedestal peak gradient, low n, most unstable at LFS, IDD
  - $\omega - k$ spectrum of modeled turbulences consistent with BES measurements
- Heat flux width
  - The large-scale PBM extended to SOL and could lead to heat flux width broadening
  - Divertor heat flux width increase with the turbulence intensity flux at separatrix
  - ExB shearing rate obscure the turbulence spreading
  - Upstream turbulence intensity scale length proportional to the downstream λ_q
- Future Reactors?





Thanks for your attention!

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