Bifurcation of Quiescent H-mode to a Wide Pedestal Regime in DIII-D and Advances in the Understanding of Edge Harmonic Oscillations

by

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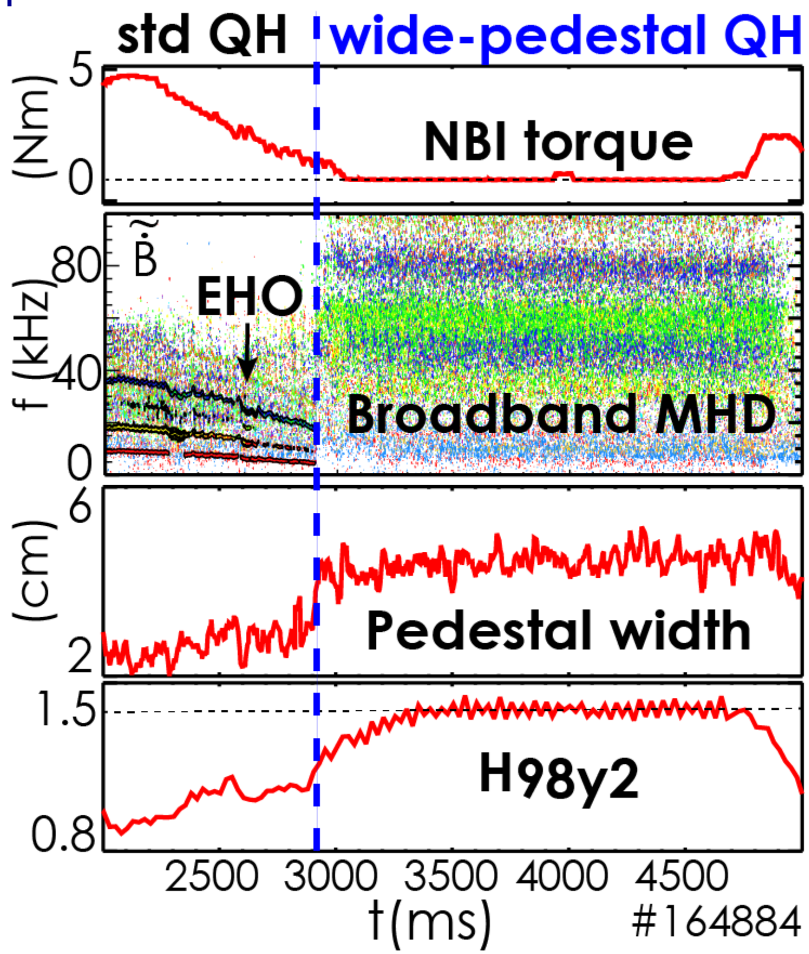

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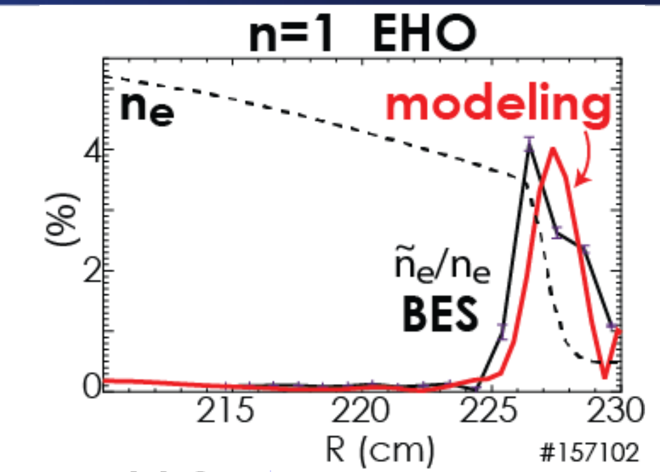
Quiescent H-mode is a Good Candidate for ELM-stable, High Performance Operation Regime in ITER and Beyond

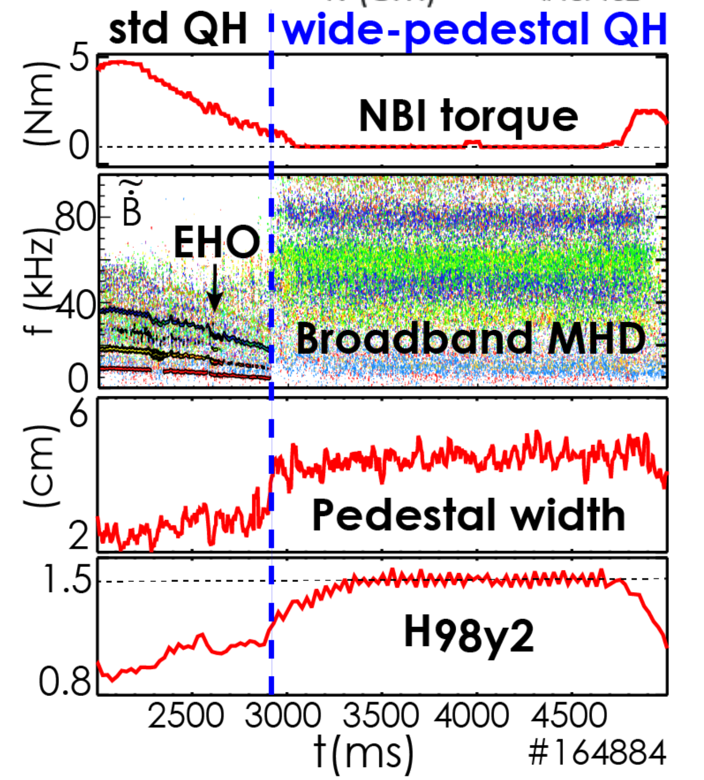
- **QH-modes operate at ITER-like low collisionality with H-mode confinement but without ELMs**

- **Two approaches to run QH at ITER-like low-torque:**

1. **Apply 3D fields to provide the strong edge *ExB* rotation shear ($\omega_{E\times B}$) required for edge harmonic oscillations (EHO) that regulate standard QH edge**
   – *New modeling finds linear eigenmode structure closely matches the measurements, confirms the importance of $\omega_{E\times B}$ in destabilizing low−n EHO*[1]

2. **New wide-pedestal QH-mode at low rotation with edge regulated by broadband MHD**
   – *Increased edge turbulent transport at low torque (thus low $\omega_{E\times B}$) reduces pedestal gradients and allows higher pressure*[2]

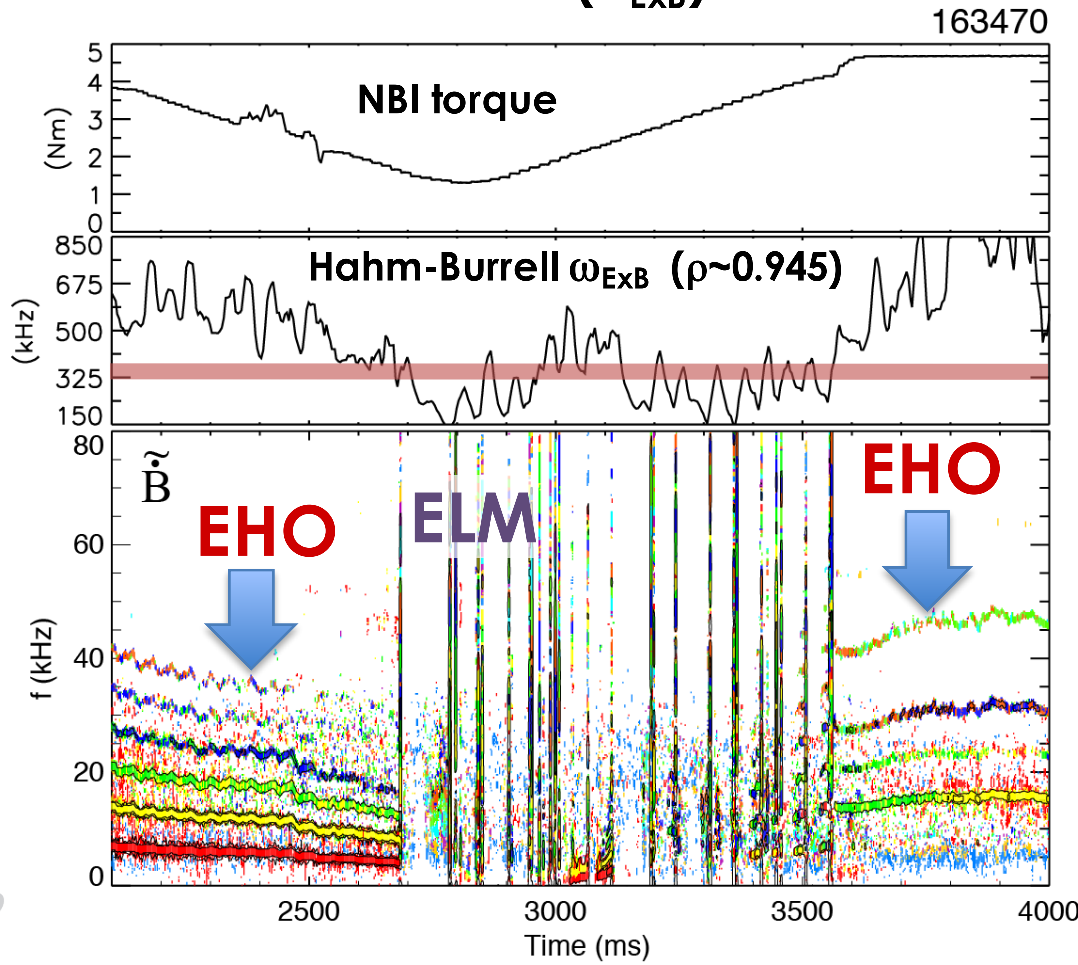




[1] Xi Chen, *et al.*, NF 56, 076011 (2016)
[2] K.H. Burrell, *et al.*, POP 23, 056103 (2016); Xi Chen, *et al.*, NF 57, 022007 (2017)

Strong Edge Rotation Shear is Required to Excite and Sustain EHO in Experiments

- **Theory and previous data analysis suggest EHO is a low-n kink/peeling mode destabilized by *ExB* rotation shear[1,2]**
- **A series of NBI torque ramp QH-mode experiments were carried out to investigate the critical *ExB* shear (ω_{ExB})**



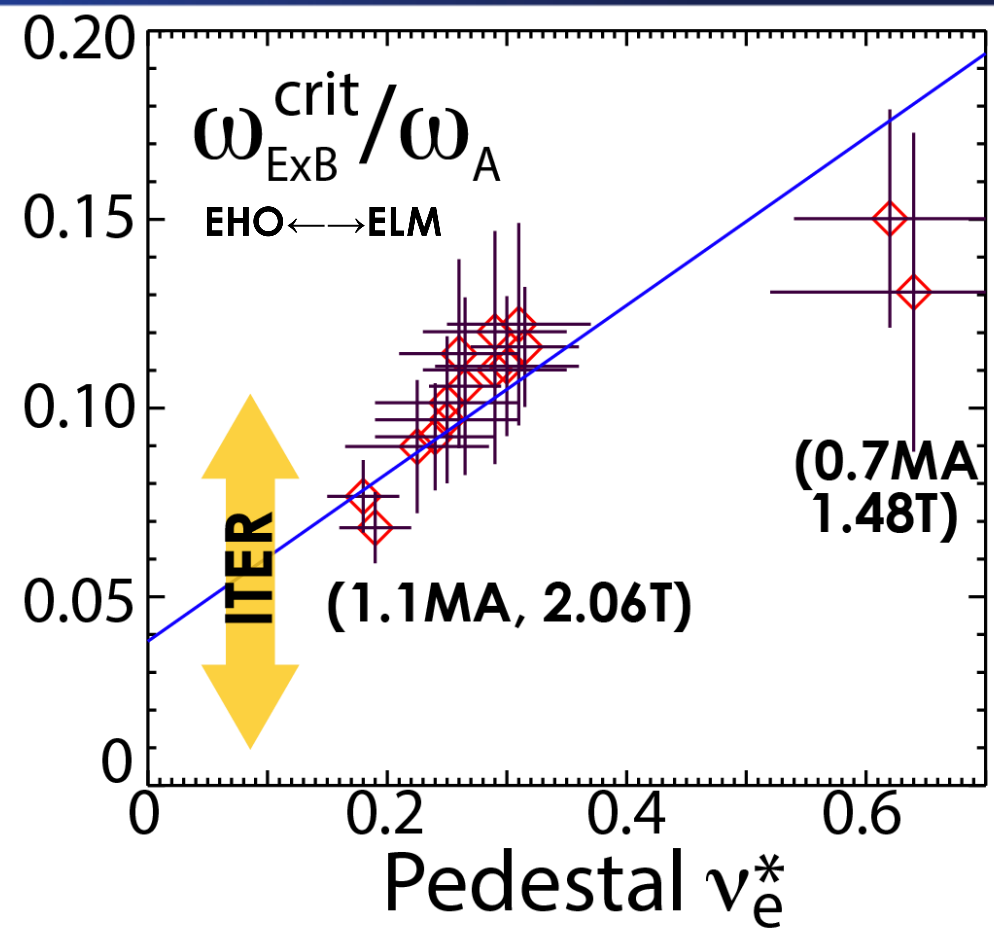
EHO appears when $\omega_{ExB} > \omega_{crit}$

EHO disappears, ELMs appear when $\omega_{ExB} < \omega_{crit}$

[1] P.B. Snyder, *et al.*, NF 47, 961 (2007)
[2] A.M. Garofalo, *et al.*, NF 51, 083018 (2011)

Positive Correlation between Critical *ExB* Shear and Pedestal Electron Collisionality Observed

- **Preliminary analyses of 15 EHO → ELM or ELM → EHO data points from 10 discharges**
- **$\omega_{\mathbf{E\times B}}^{crit}$ decreases with pedestal υ_e^***
  - No clear dependence on n_e^{ped} seen
  - υ^* effects on J_{BS} might be related
- **Favorable scaling for exciting EHO in machines where low edge collisionality and rotation are expected, such as ITER**



linear least-square fit considering uncertainties in both axes:

$$\omega_{\mathbf{E\times B}}^{crit} = 0.038 + (0.22 \pm 0.06)\,\nu_e^*$$

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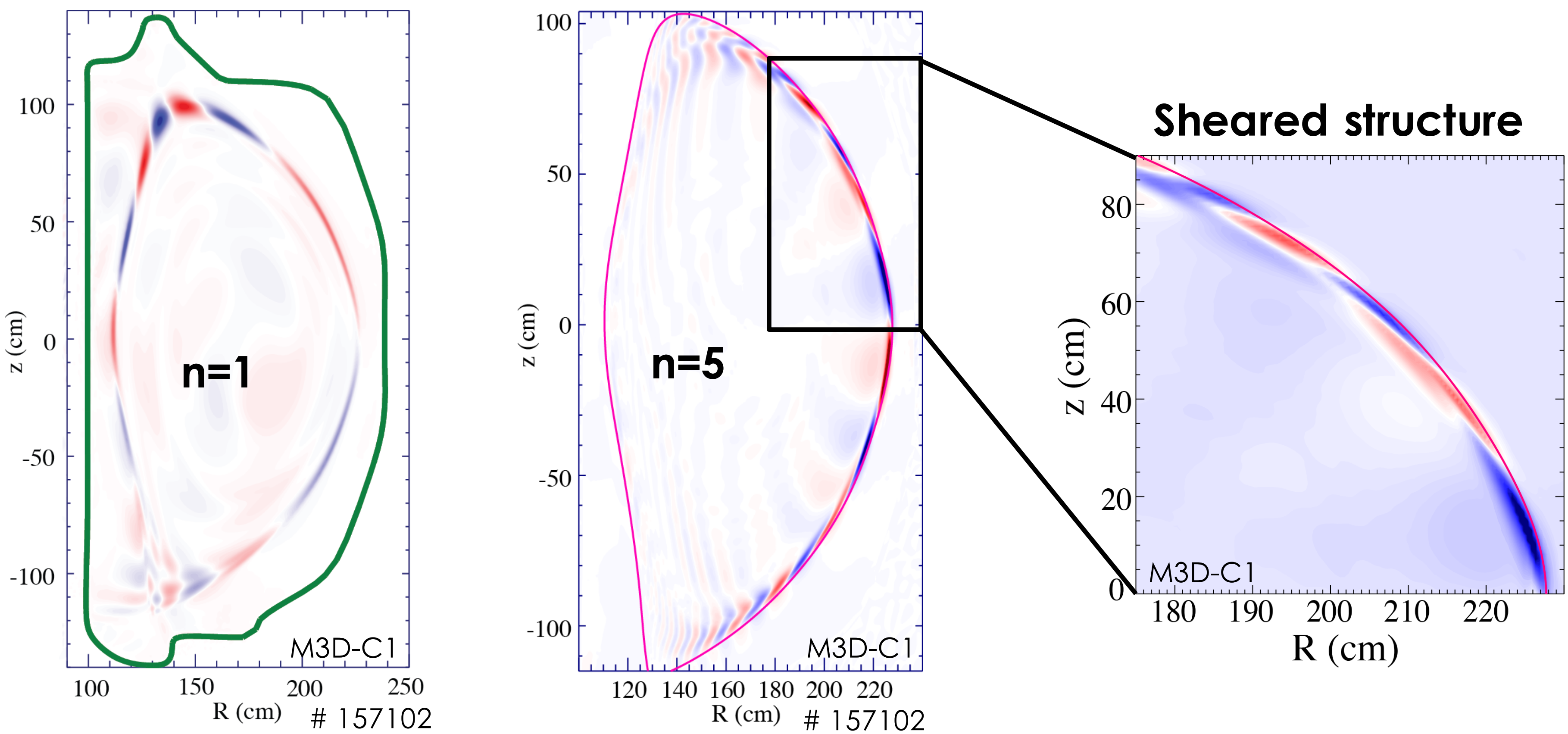
Sheared Mode Structure Observed in M3D-C1 Simulation with Rotation in Line with Experiments

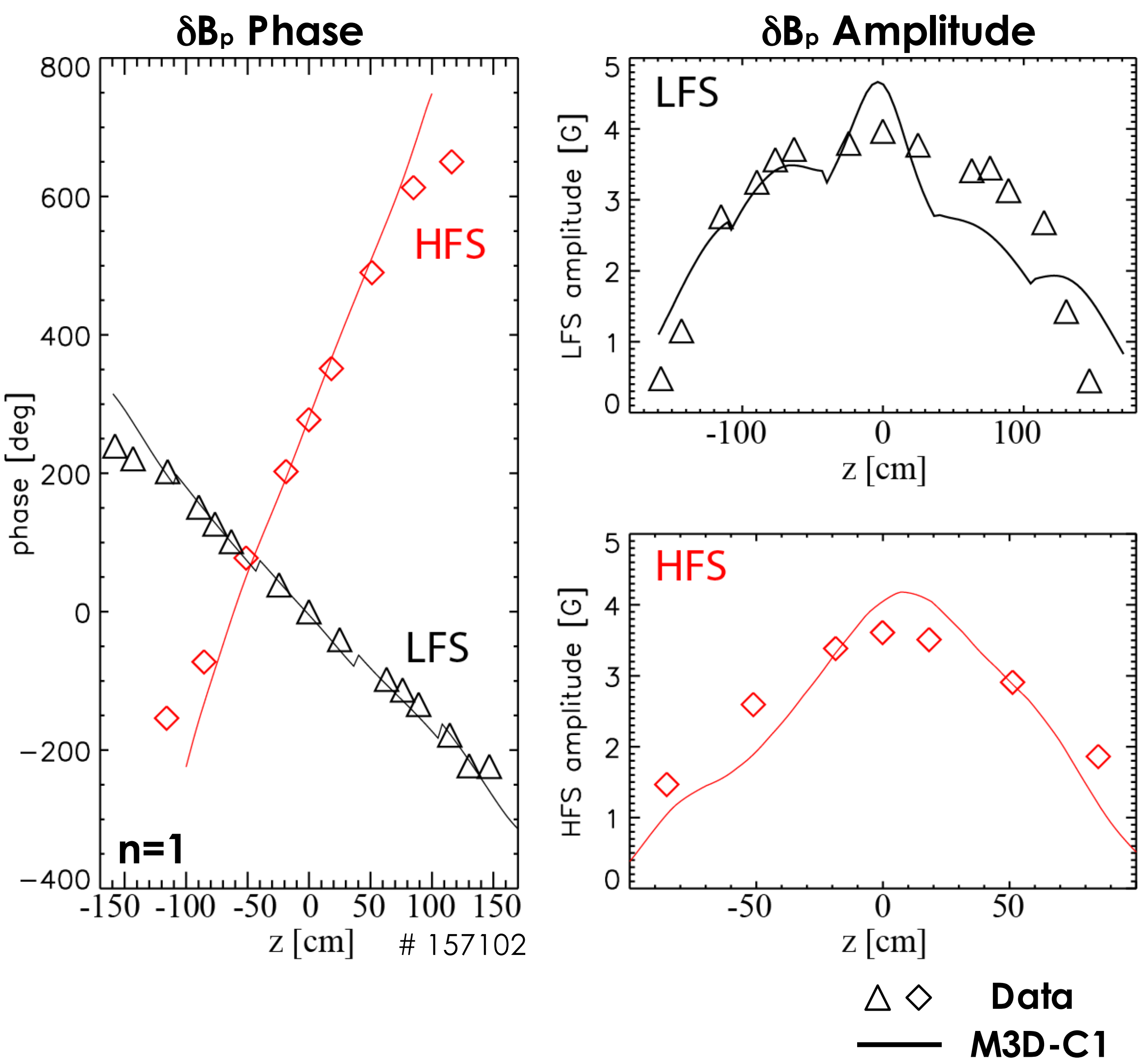
- **M3D-C1 is 3D resistive initial-value extended fluid MHD code[1]**
  - Real X-point geometry
  - Low-n (n≤5)
  - Rotation shear effects (experimental rotation profile)



[1] N.M. Ferraro, *et al.*, J. Comput. Phys. 228, 7742 (2009)
+ Xi Chen, *et al.*, NF 56, 076011 (2016)

Calculated Edge Magnetic Perturbations Match Well with External Magnetics Measurements

- **Calculated perturbation amplitudes are scaled to measurements by least-squares fit**
- **Stochastic edge appears in modeling with experimental perturbation amplitude ($\delta B/B \sim 2\times10^{-4}$ at midplane vessel wall)**
  - Similar to nonlinear simulation results of JOREK [Liu TH/P1-9] and NIMROD [King TH/1-542]



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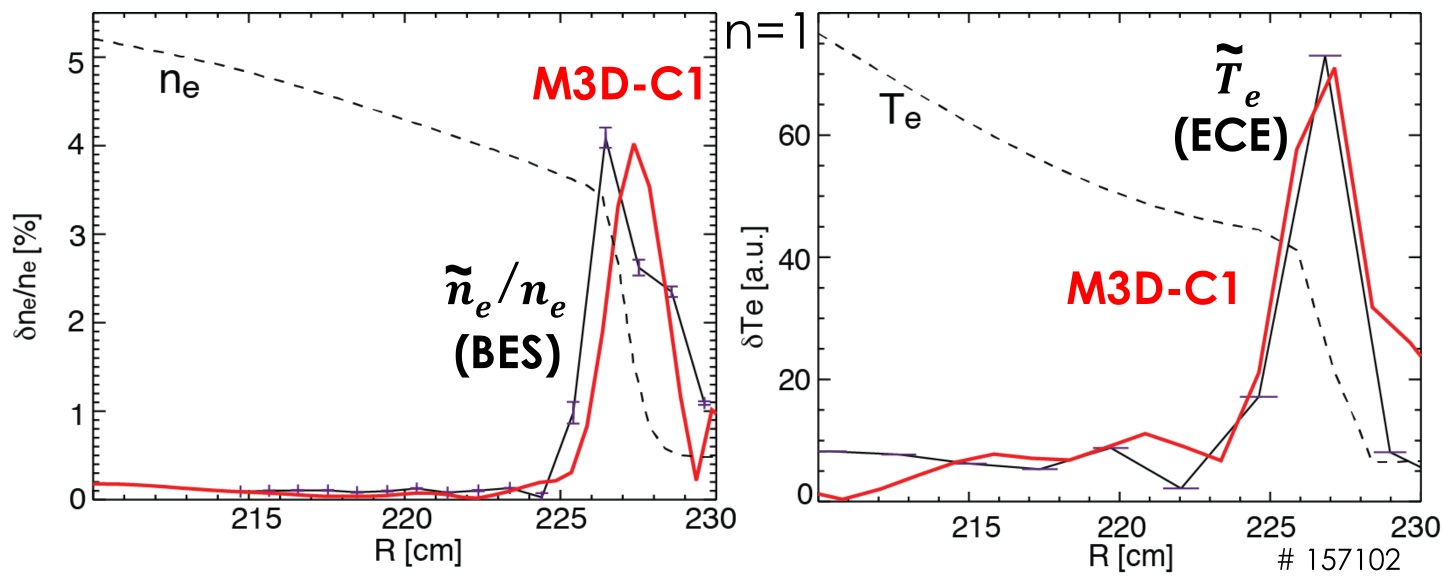
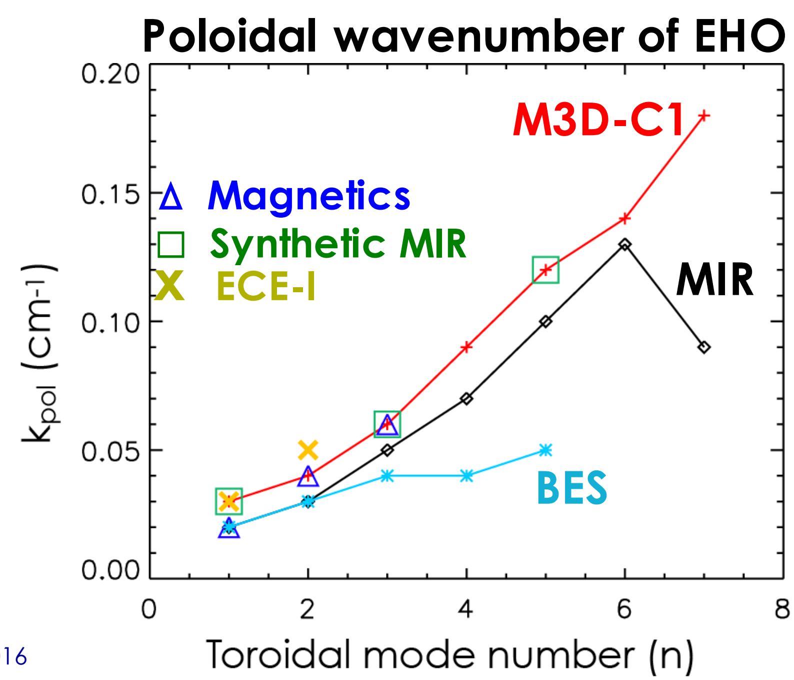
Calculated Mode Structures Closely Match Internal Density and Temperature Fluctuation Measurements

- **General features:**
  - Extends over the whole pedestal (~2.5cm radial width)
  - Peaks in the steep gradient region



- **Agreement is found in the more stringent test of modeling: comparison of wavenumber**
  - k_{pol} of EHO (0.02-0.2cm^{-1}) increases linearly with toroidal mode number



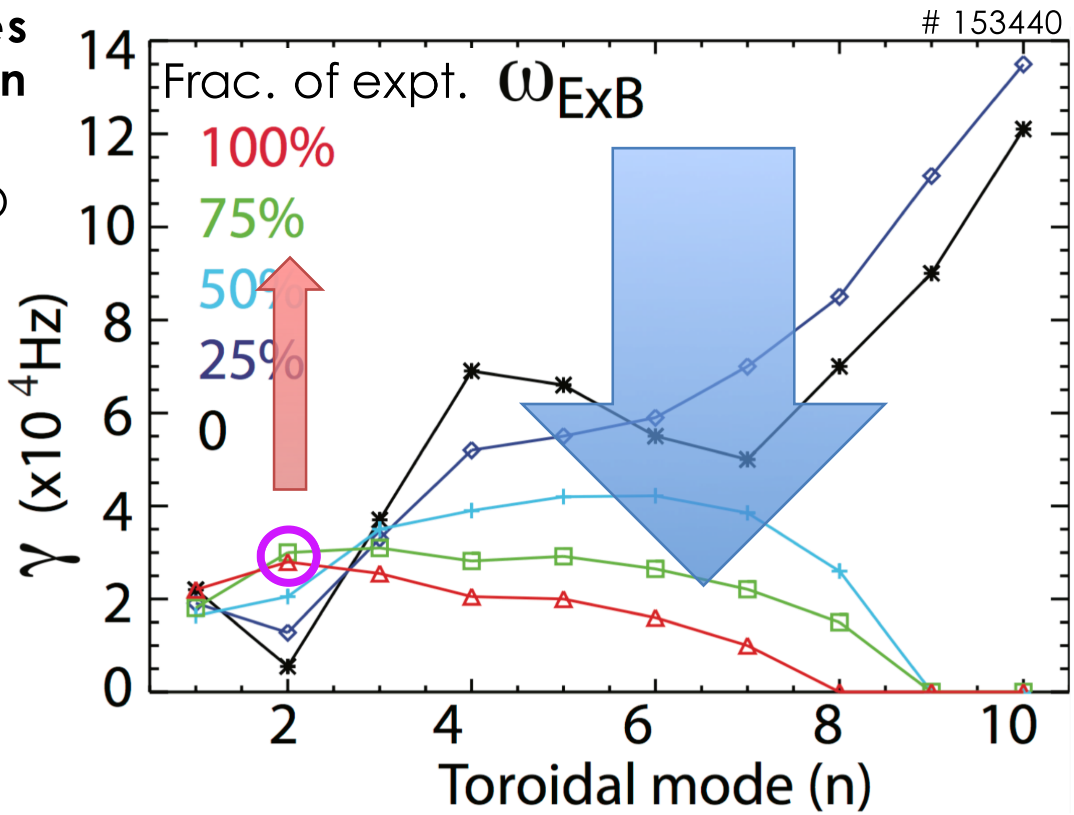
+ Xi Chen, *et al.*, NF 56, 076011(2016)

M3D-C1 Modeling Shows *ExB* Rotation Shear Destabilizing Low-n Modes while Stabilizing Higher-n Modes

- ***ExB*** **rotation shear (ω_{ExB}) profile was scanned in a series of linear M3D-C1 modelings of QH plasma # 153440 (n=2 EHO dominates)**

- **Linear growth rates of low-n modes increase with ω_{ExB} while that of higher-n modes decrease**
  - Consistent with the loss of low-n EHO and onset of higher-n ELMs at too low ω_{ExB}

- **n=2 is the least stable mode at the experimental ω_{ExB} level**
  - Consistent with detected dominant EHO component

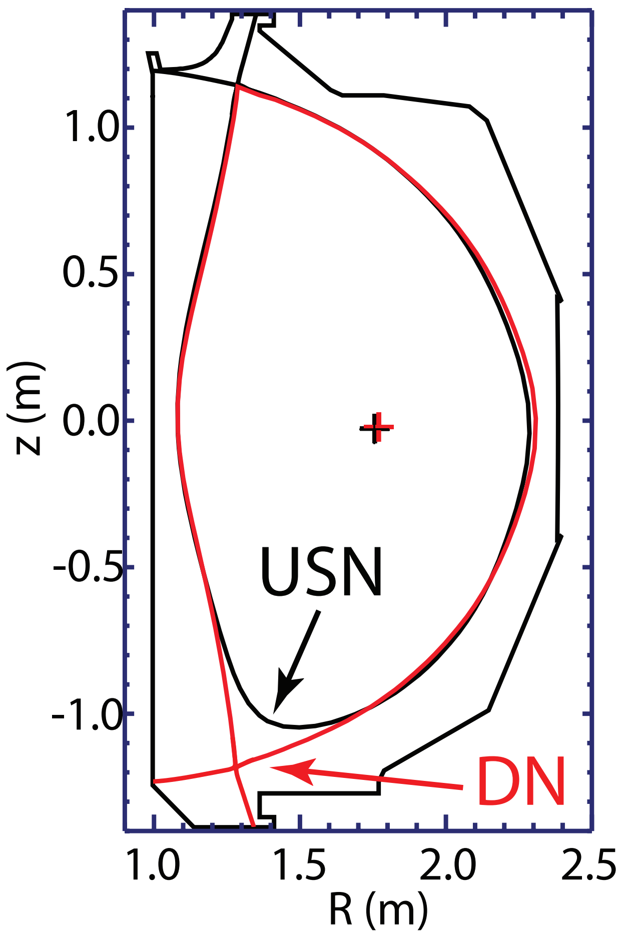


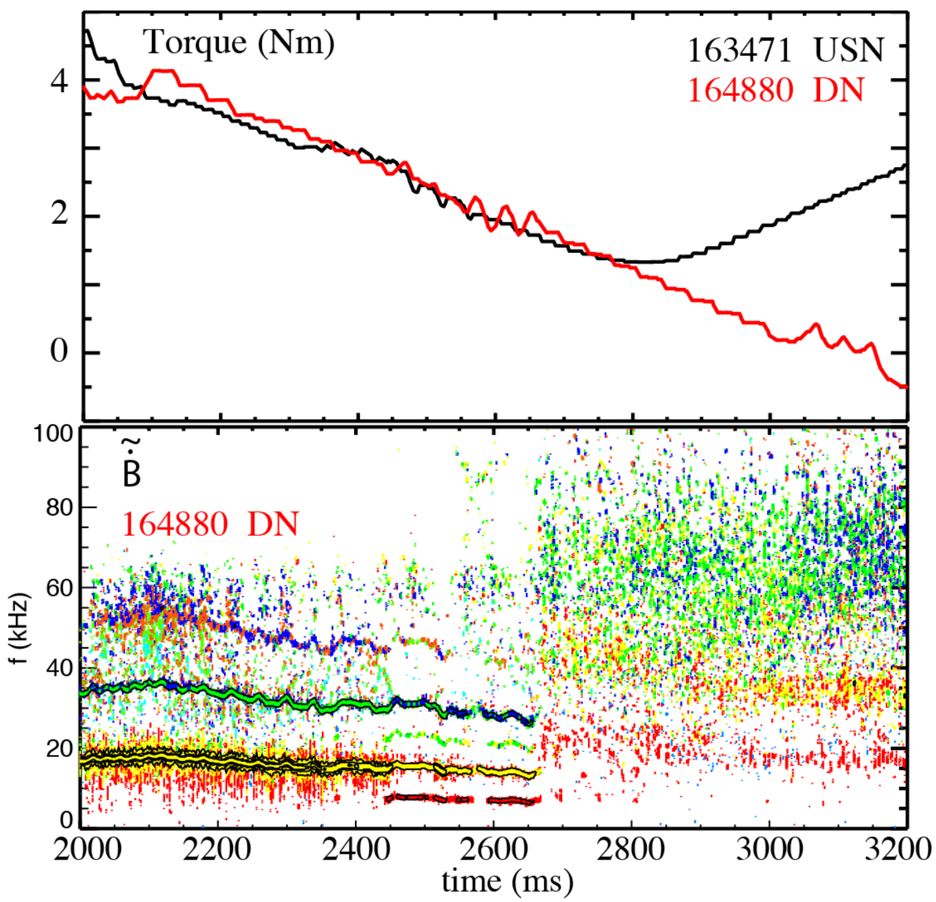
Xi Chen/IAEA/Oct. 2016

⁺ Xi Chen, *et al.*, NF 56, 076011(2016)

Discovery of Wide-Pedestal QH-mode in NBI Torque Ramp Experiments In Double-null Plasma Shape

- **EHO is lost and ELMs onset at too low torque in USN plasmas**
- **EHO ceases and broadband MHD rises at low torque in DN plasmas[1]**

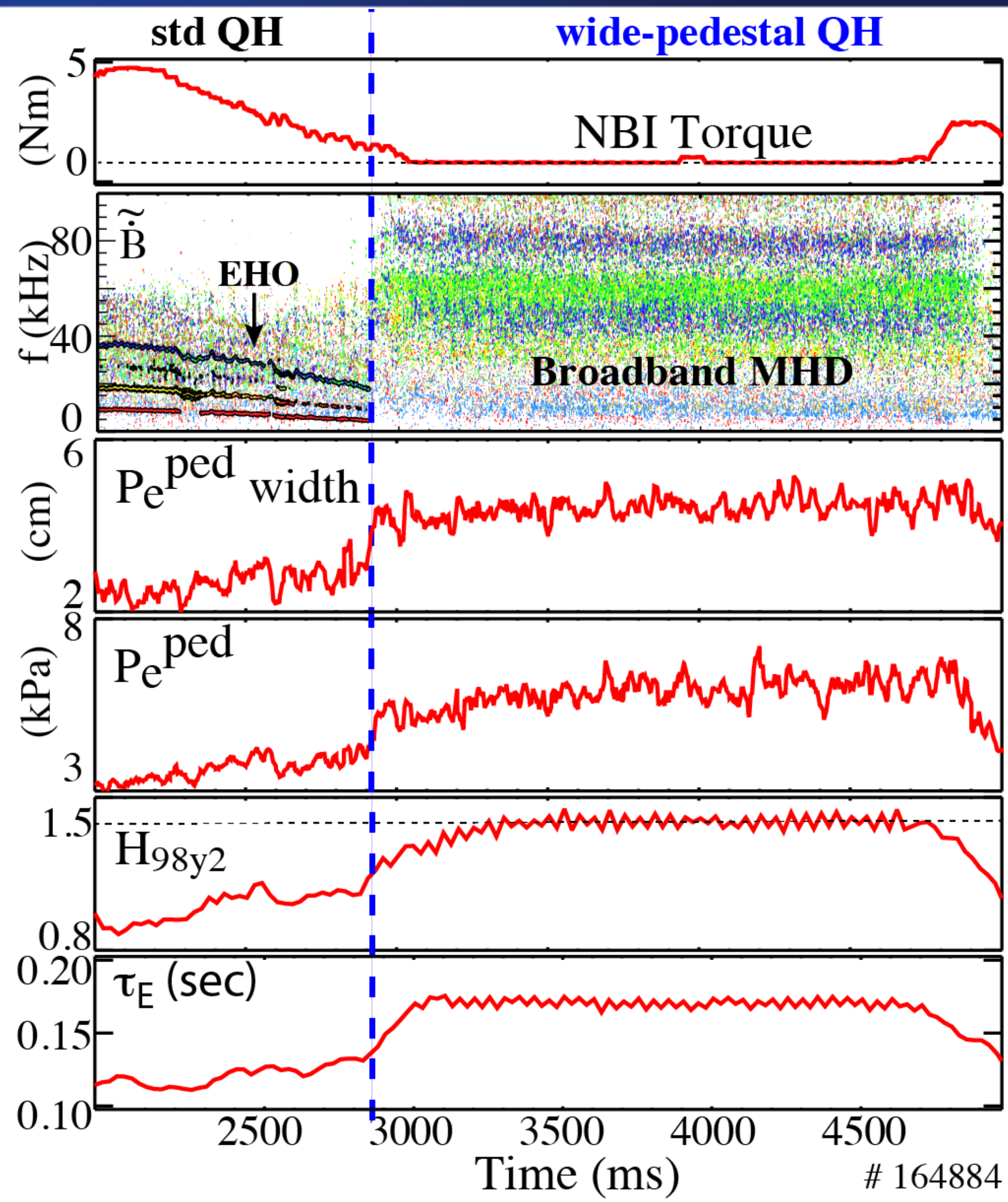




[1] K.H. Burrell, *et al.*, POP 23, 056103 (2016); Xi Chen, *et al.*, NF 57, 022007 (2017)

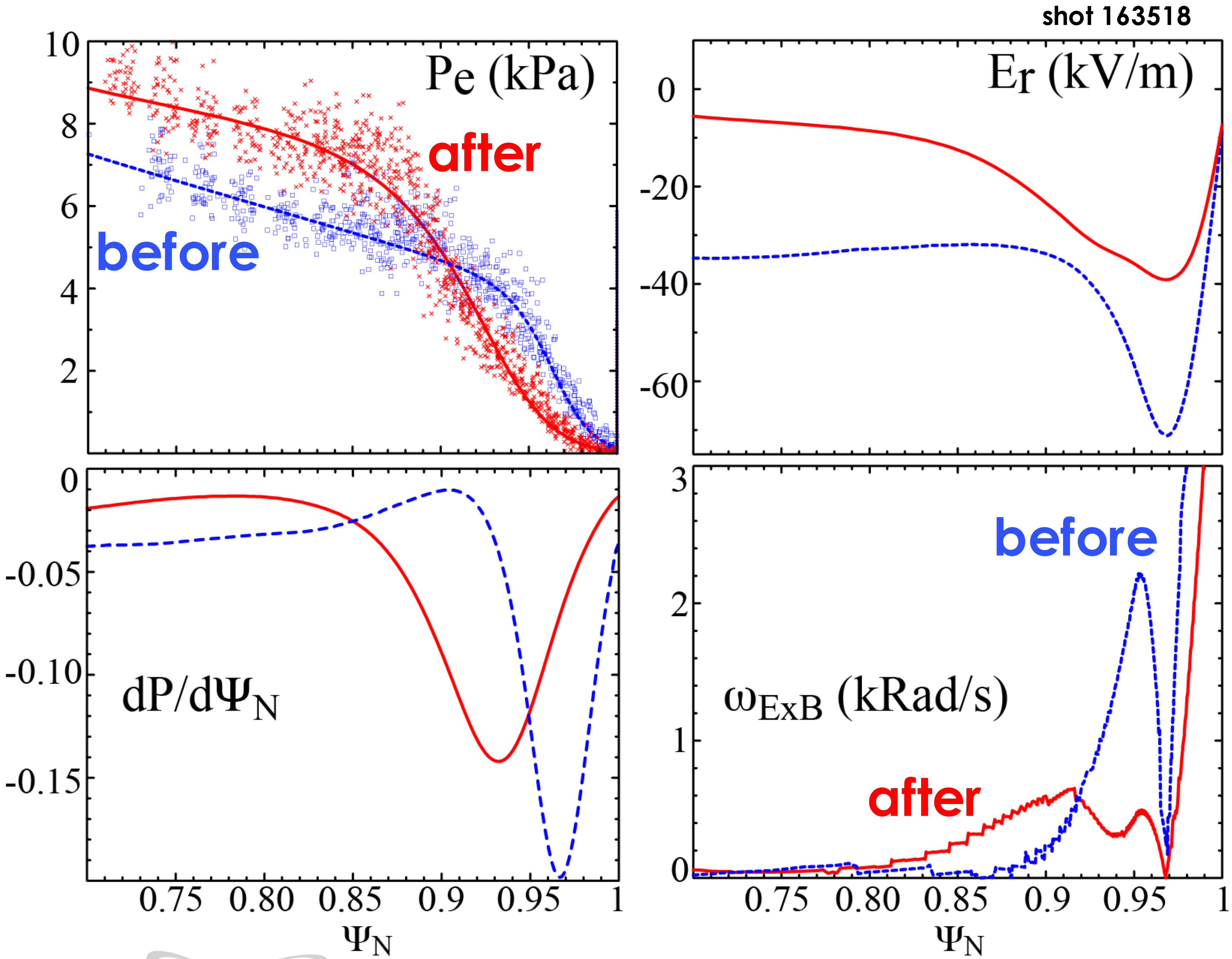
Bifurcates to Wide-Pedestal State and Stationary High Confinement Operation with Net-zero Injected Torque

- **Rapid transition to improved pedestal conditions as neutral beam torque is reduced to zero**
  - P_e^{PED} ↑ 60%, $Width_e^{PED}$ ↑ 50%, τ_E ↑ 40%
- **Improved pedestal achieved with reactor-relevant plasma parameters**
  - β_N =1.5-2.3, H_{98y2}=1.2-1.6, ν^*_e (PED)=0.2-0.4
- **Transition is associated with**
  - Changes in E_r well and ExB shear profiles
  - Increased edge density and broadband MHD fluctuations
- **Working hypothesis: Wider pedestal is due to changes in turbulent transport caused by altered *E* x *B* shear**



[+] K.H. Burrell, *et al.*, POP 23, 056103 (2016); Xi Chen, *et al.*, NF 57, 022007 (2017)

Substantial Increase in Pedestal Height and Width and Decrease in Pedestal Gradients and Edge *ExB* Shear

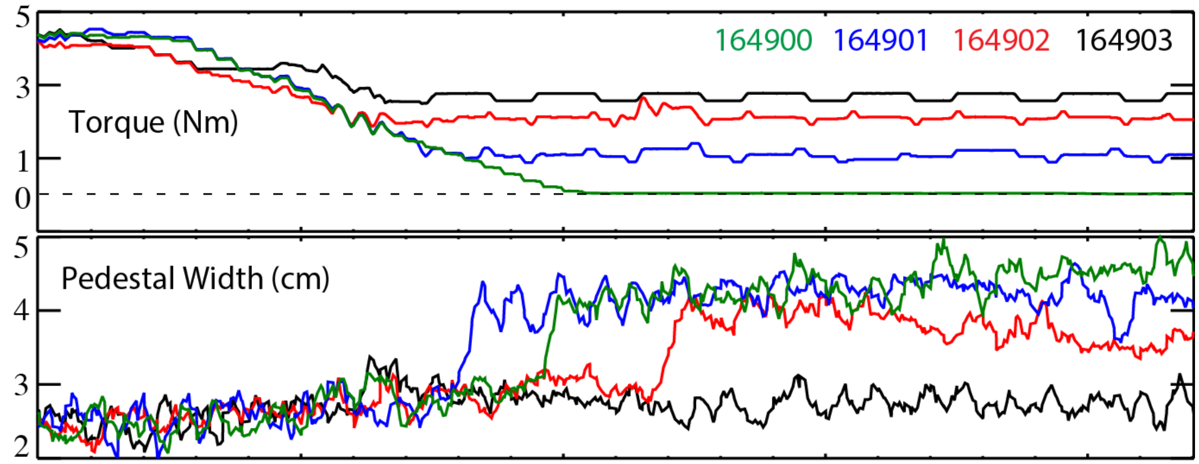


Pedestal pressure gradient decreases and peak P' moves away from the separatrix

E_r well becomes shallower and *ExB* shear decreases outside Ψ_N~0.9

Torque Needs to be Reduced Sufficiently to Access the Wide-Pedestal QH

- **Torque was ramped down and held at 0, 1, 2, 2.7 Nm (ctr-I_p)**
- **Transition into wide-pedestal occurred except in 2.7 Nm case**



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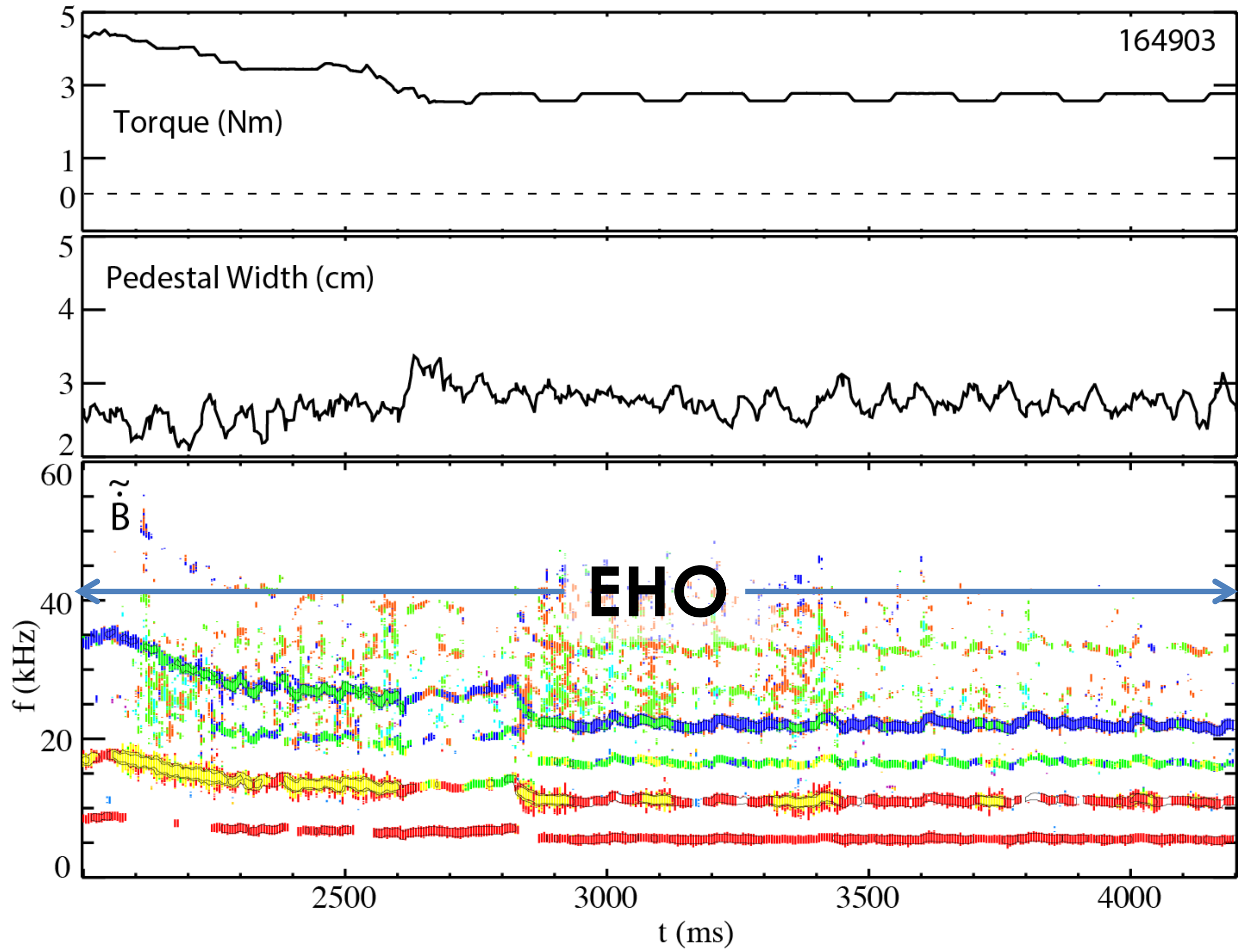
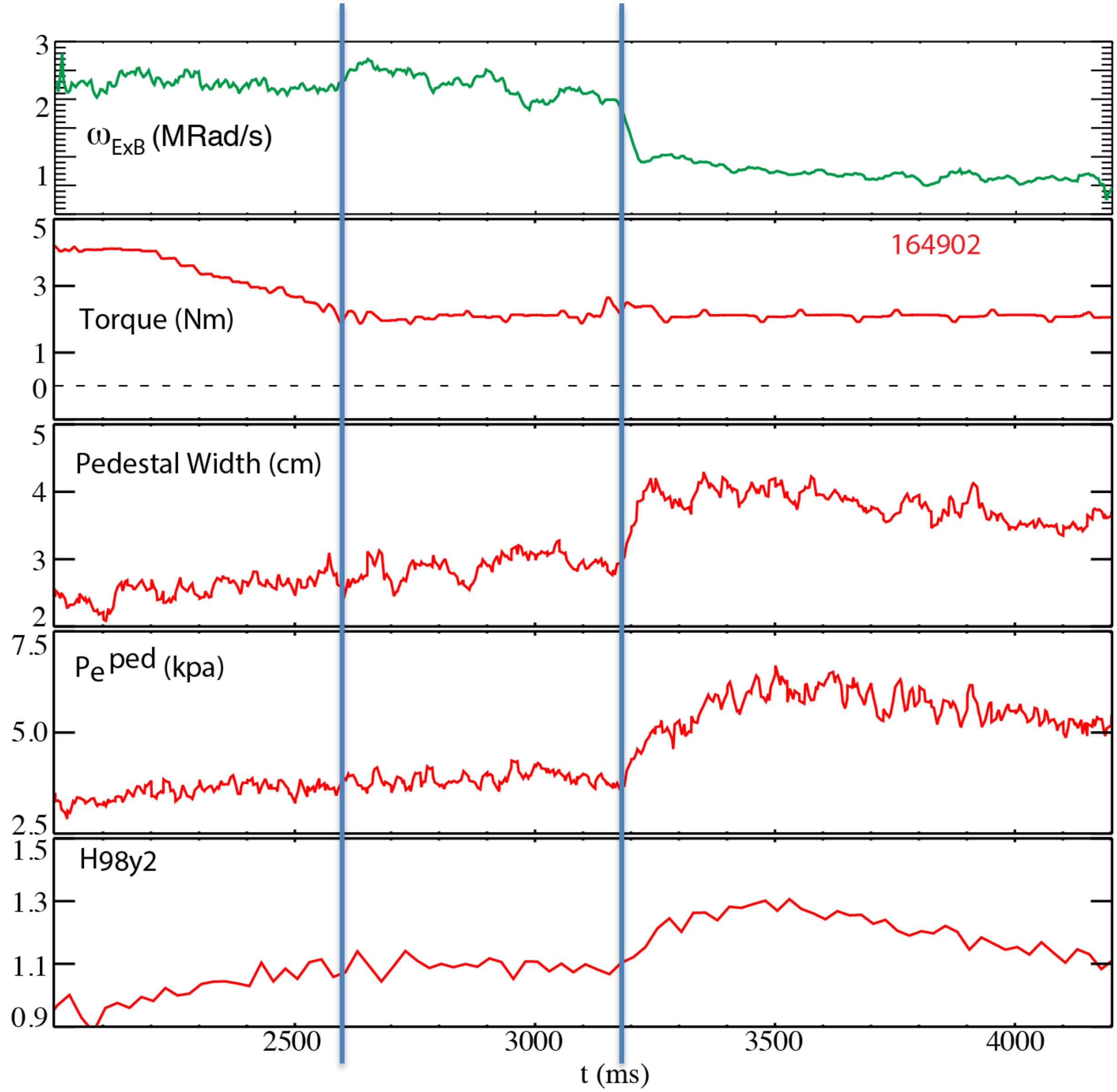
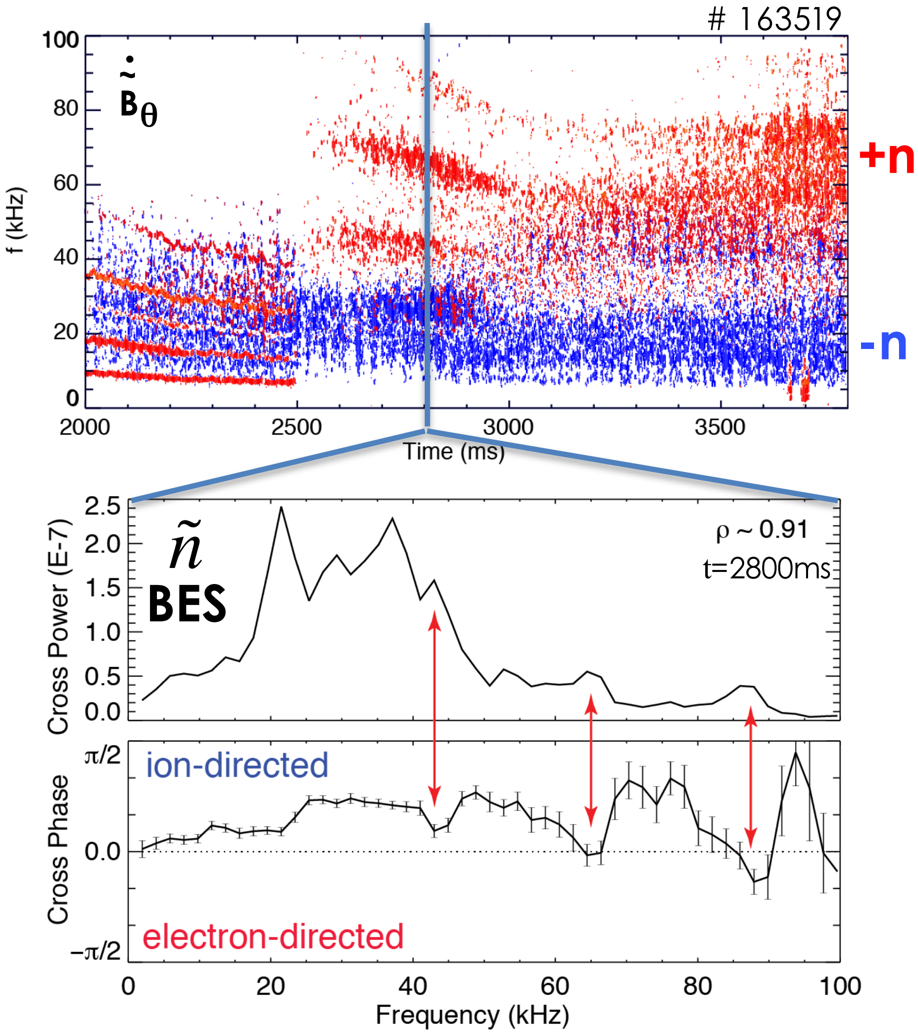


Edge *ExB* Shear Seems to be the Key

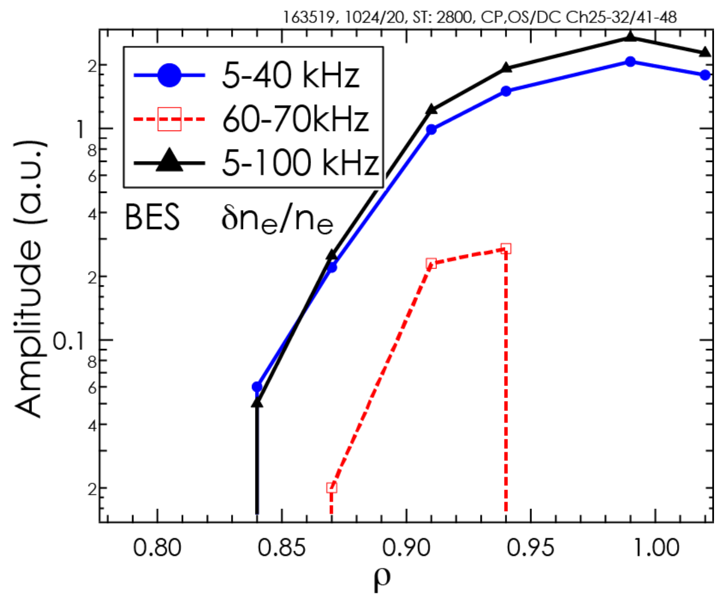
- **Torque was ramped down and held at 0, 1, 2, 2.7 Nm (ctr-I_p)**
- **Transition into wide-pedestal occurred except in 2.7 Nm case**
- **2.7 Nm case: discharge stays in std. QH-mode with EHO**
- **2 Nm case: the transition occurs in flat torque phase when the edge *ExB* shear decreased sufficiently**



Magnetic and Low-k Broadband Fluctuations Increase after Transition

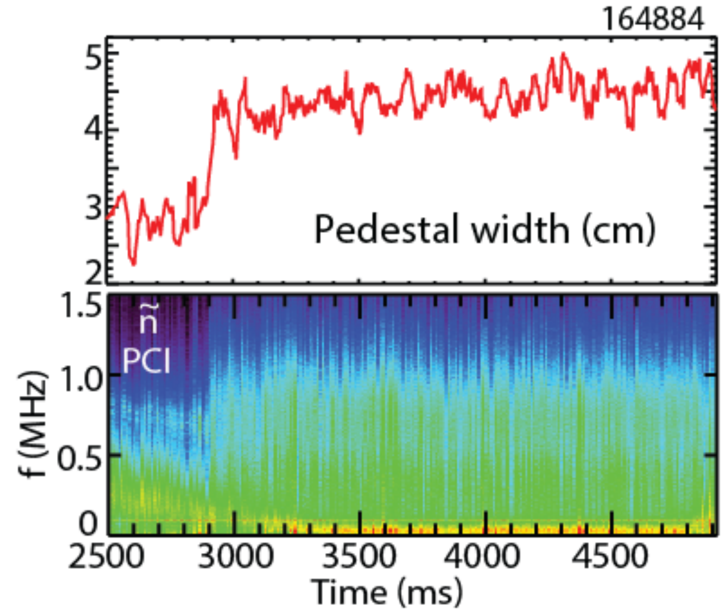


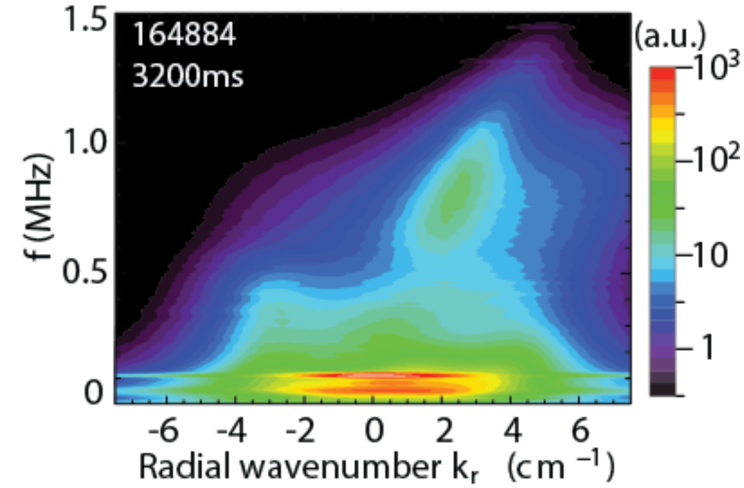
- **Edge magnetics reveal two counter-propagating spectrally overlapping branches**
- **Low-k ($k_\theta \rho_s \leq 0.5$) density fluctuation spectra detected by BES and MIR in wide-pedestal QH are superposition of two counter-propagating branches**
  - Mode amplitudes peak at different locations



Intermediate-*k* Turbulence in the Pedestal after Transition is also Enhanced

- **Phase Contrast Imaging (PCI) system detects high frequency (f > 500kHz, lab frame) intermediate-k (0.3< $k_\theta \rho_s$ < 1.2) turbulence in the pedestal of wide-pedestal QH**
  - Absent in L-mode and high-torque QH
  - Similar to that in standard ELM-free H-mode





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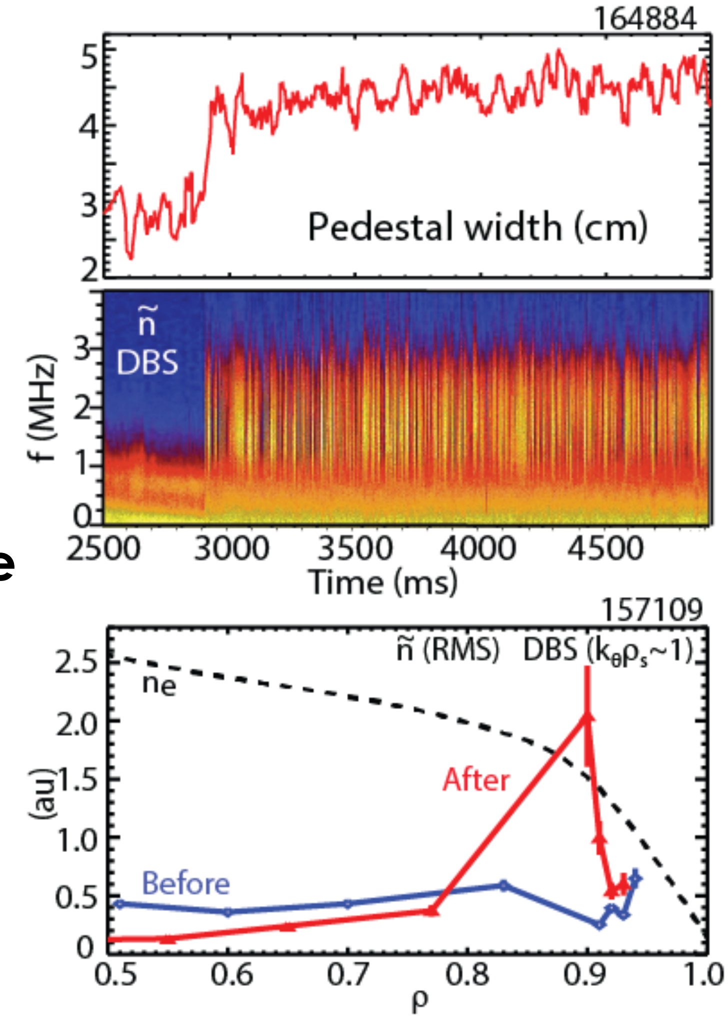
  - Absent in L-mode and high-torque QH
  - Similar to that in standard ELM-free H-mode

- **Doppler Back-Scattering (DBS) system detects broadband lab-frame electron-directed mode ($k_\theta\rho_s$ ~ 1) peaking near the pedestal top**
  - Significantly weaker at $k_\theta\rho_s$ ~ 2 or when the EHO is present



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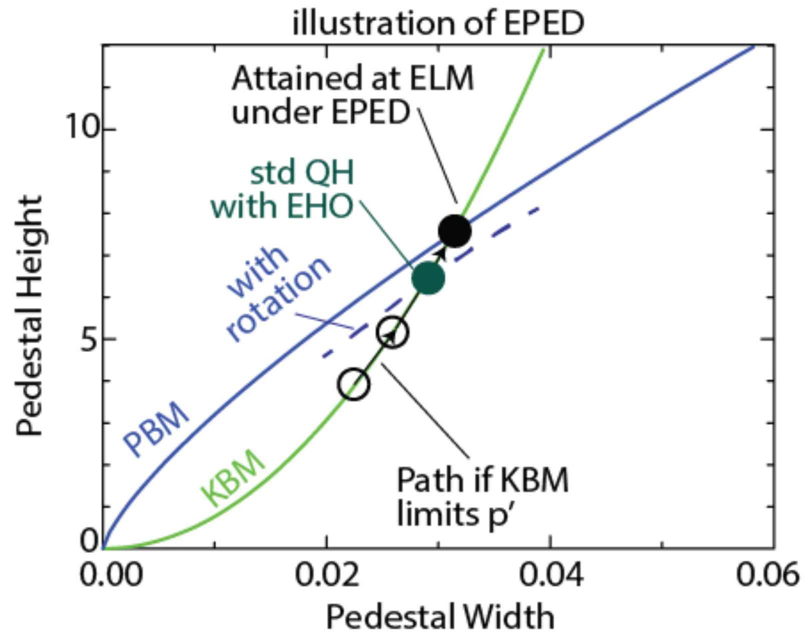
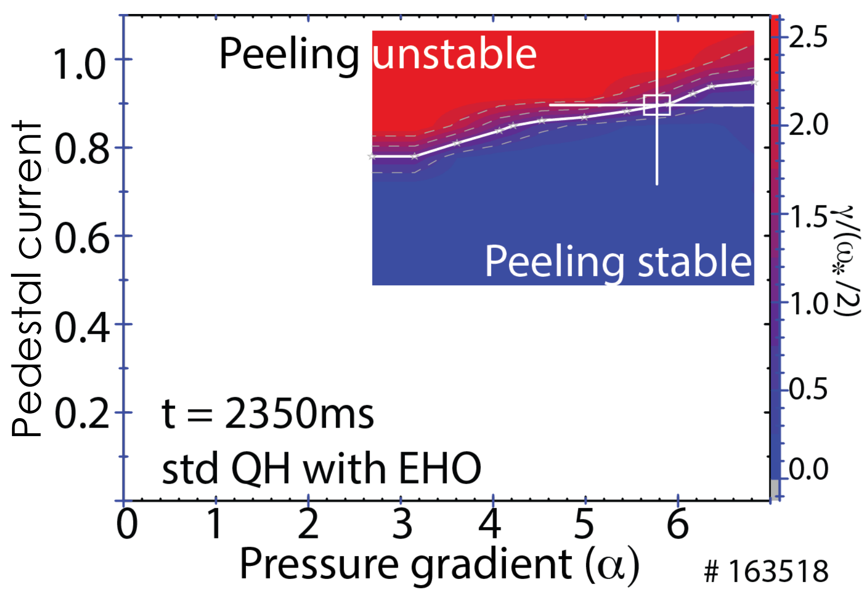
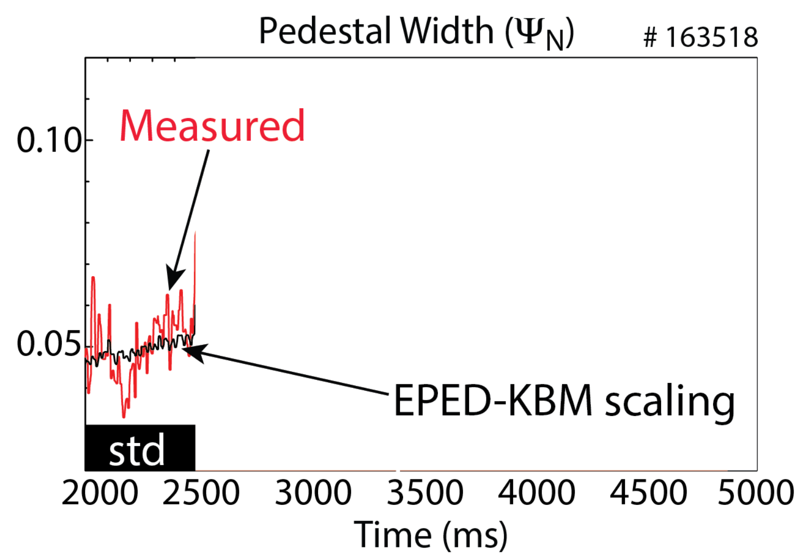
Operating Point of QH-mode with EHO is Near but Below the ELM Limit

- **Intersection of PBM and KBM constraints determines pedestal height and width in EPED[1]**
  - PBM: $P' \propto W^{-0.25}$
  - KBM: $P' \propto W$
- **ELITE[2] calculations statistically show std. QH edge sits just below the no-rotation PBM boundary**
- **Pedestal width well described by EPED-KBM limit**





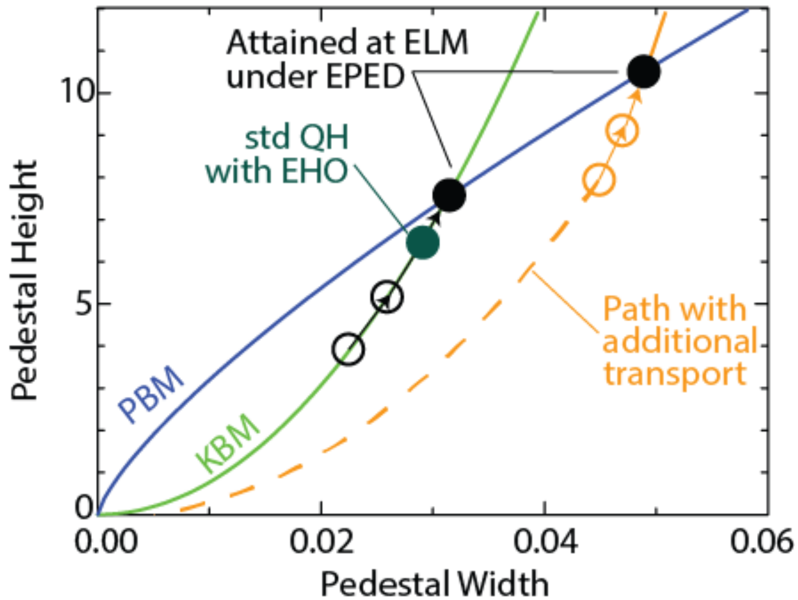


[1] P.B. Snyder, *et al.*, NF 51, 103016 (2011)
[2] P.B. Snyder, *et al.*, POP 9, 2037 (2002); H.R. Wilson, *et al.*, POP 9, 1277 (2002)

Higher Pedestal Pressure Expected at Reduced *P'*

- **Additional transport can reduce *P'***
- **PBM and KBM intersect at higher P_{ped} at reduced *P'* due to the weaker width dependence of PBM**
- **Higher P_{ped} is allowed within ELM limit when peak *P'* (α_{max}) moves away from separatrix**
  - Seen in lithium induced pedestal bifurcation on DIII-D[1]

illustration of EPED

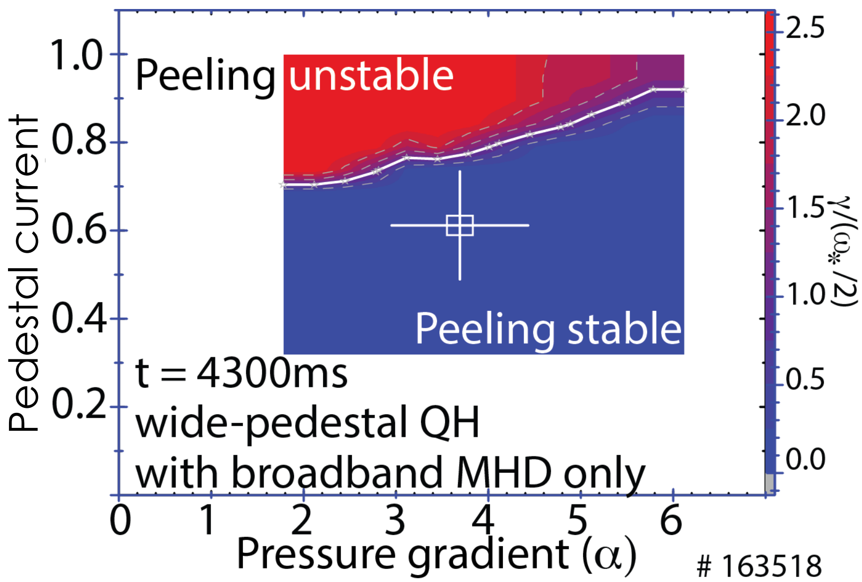


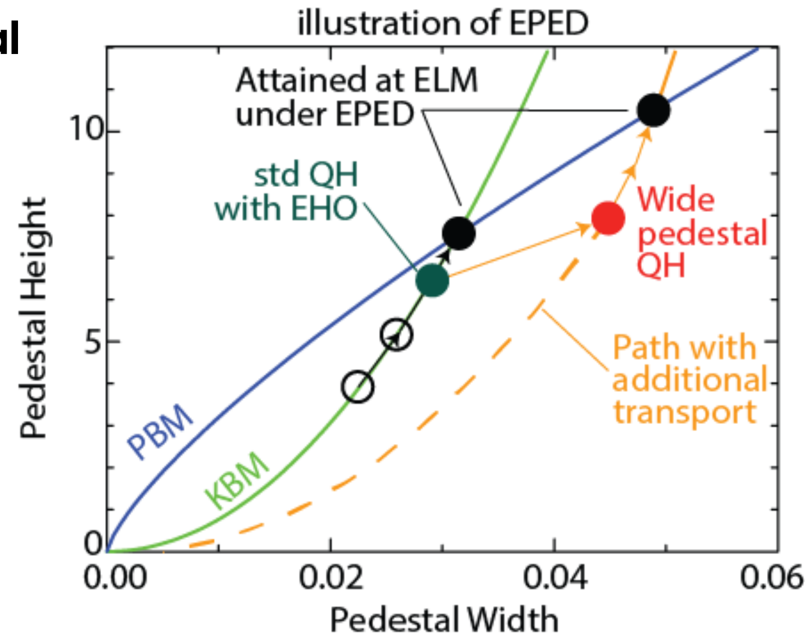
[1] T.H. Osborne, *et al.*, NF 55, 063018(2015)

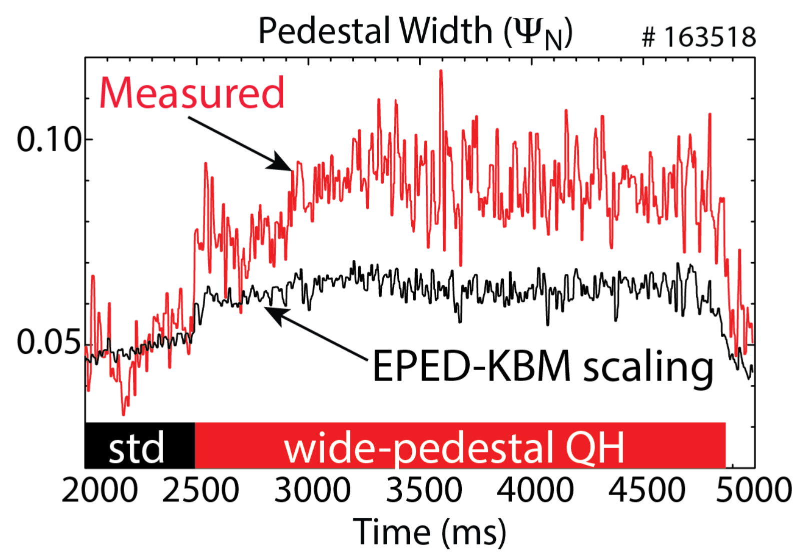
Increased Edge Transport in Wide-Pedestal QH Reduces *P'* Allowing Higher P_{ped} while Remaining Below ELM Limit

- **ELITE calculations consistently show wide-pedestal QH edge sits far below the PBM boundary**

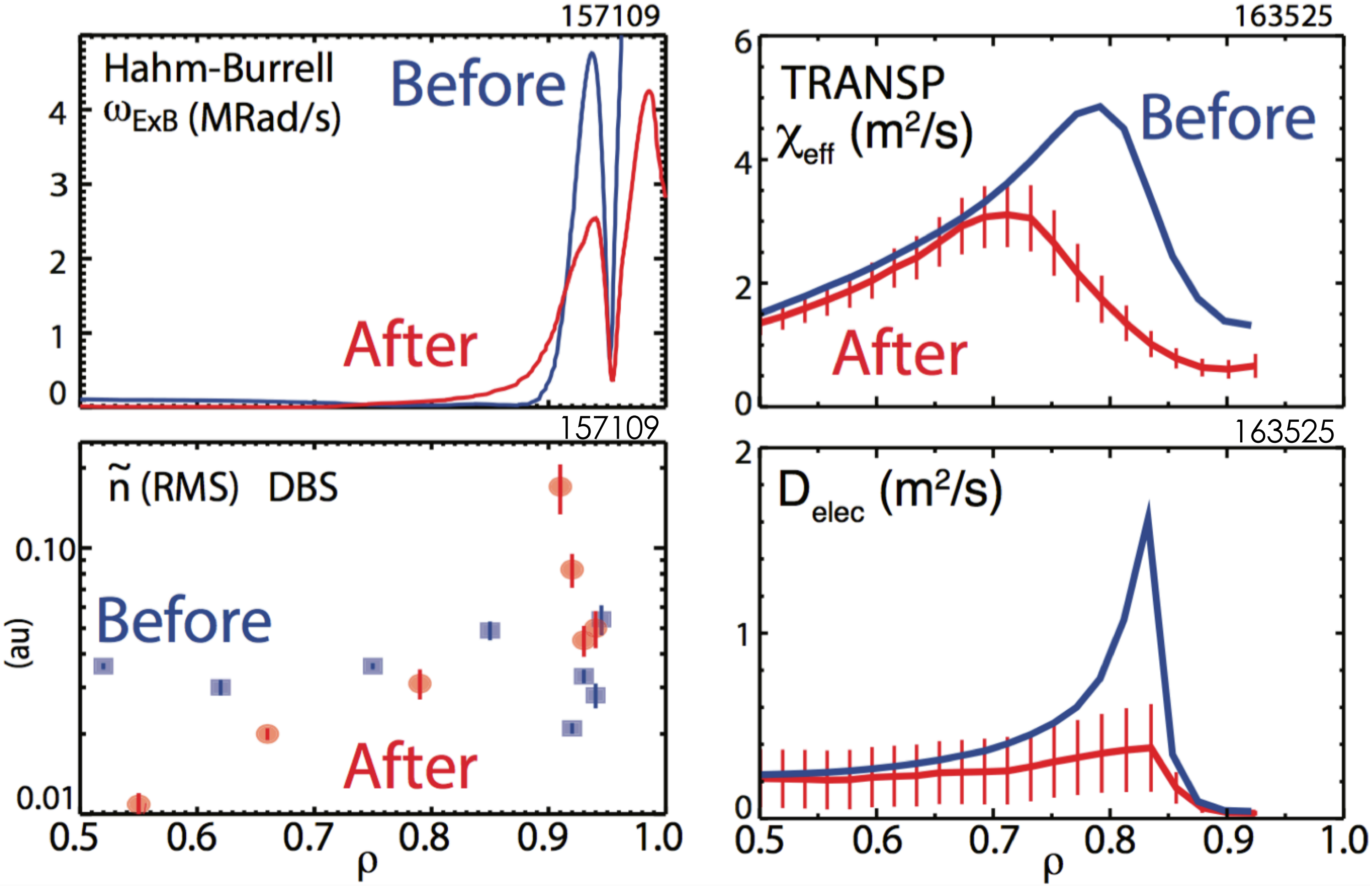
- **Pedestal width exceeds (by 50%) the EPED-KBM scaling**







Transport Improvement in Outer-Core Region Consistent with Global Confinement Improvement



- In outer-core region, ExB shearing rate increases and transport is reduced
- Similar to previous finding of reduced outer-core transport in low rotation QH-mode using NTV torque from applied 3D fields[1]

[1] A.M. Garofalo, *et al.*, NF 51, 083018 (2011)

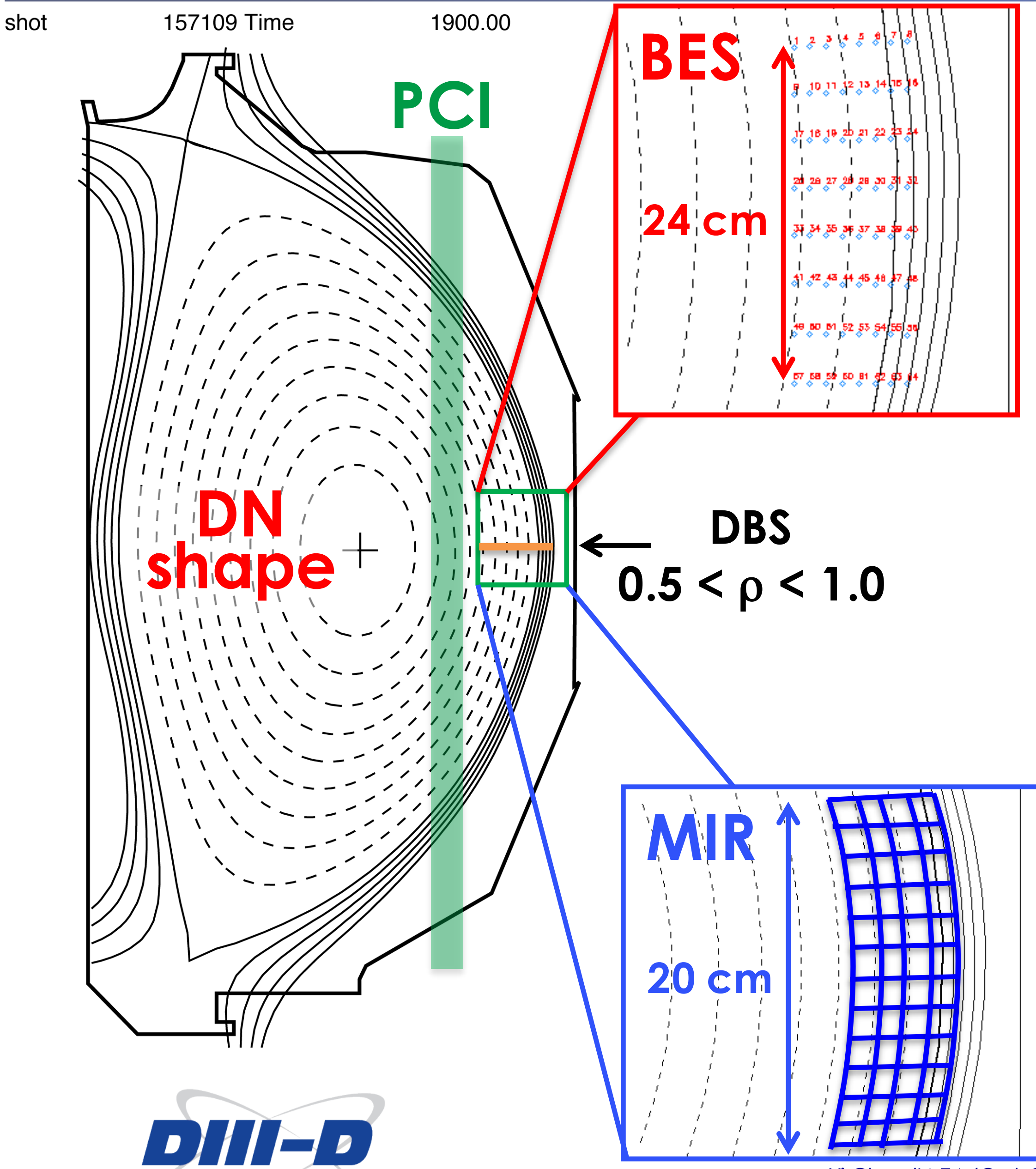
We are Developing Predictive Confidence in QH-mode as Low Rotation ELM Free Regime for Future Reactors

- **M3D-C1 modeling predicts *ExB* rotation shear ($\omega_{E\times B}$) destabilizes EHO**
  - Consistent with theory and experiment, including measured eigenmode structure
  - Experimentally, lower $\boldsymbol{\omega_{E\times B}}$ for exciting EHO correlates with lower pedestal υ_e^*

- **New wide-pedestal QH state discovered at low torque where Increased edge turbulence reduces pedestal gradients allowing higher pressure**
  - Stationary ELM-free operation at net-zero torque with excellent confinement (H_{98y2} ~ 1.5, β_N ~ 2) for 12 τ_E

- **Standard QH with EHO (assisted by NTV at low torque) and new wide-pedestal QH are exciting candidates for high confinement ELM-stable operating modes for ITER and future machines where torque, rotation and collisionality are expected to be low**

Plasma Shape, Diagnostics Coverage and 'Directions'

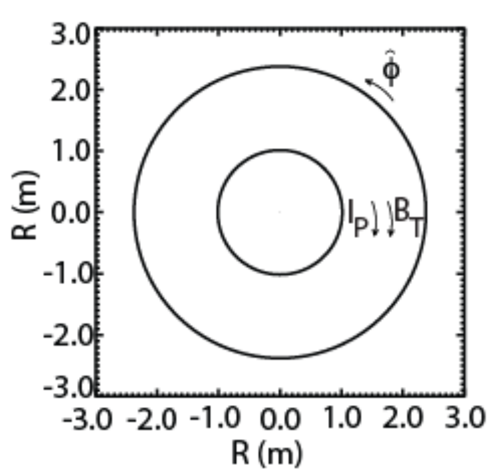


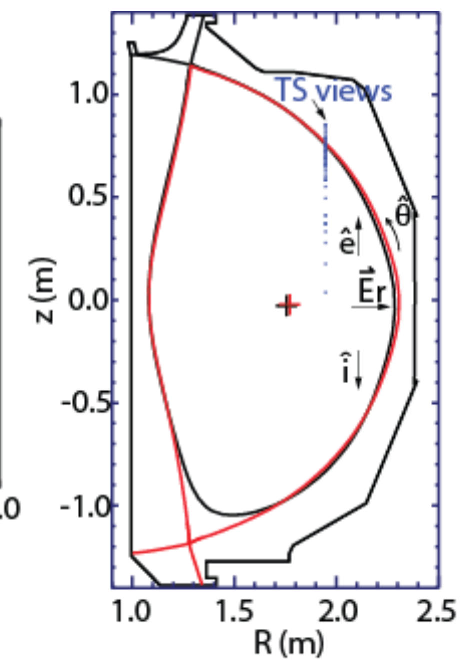
Low-k $\tilde{n}_e$ disgnostics
Beam Emission Spectroscopy (BES)
Microwave Imaging Reflectrometry (MIR)

Intermediate-k $\tilde{n}_e$ disgnostics
Doppler-Back Scatter (DBS)

Low- to high-k $\tilde{n}_e$ disgnostics
Phase Contrast Imaging (PCI)

Low-k $\tilde{T}_e$ disgnostics
Correlation Electron Cyclotron Emission (CECE)





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