Viability of Wide Pedestal QH-Mode for Burning Plasma Operation

by

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Oral 11:05 AM EX/2-2 Pedestal & ELM Optimization (24 Oct 2018, 10:45-12:30)
Poster (24 Oct 2018, 14:00-18:45)

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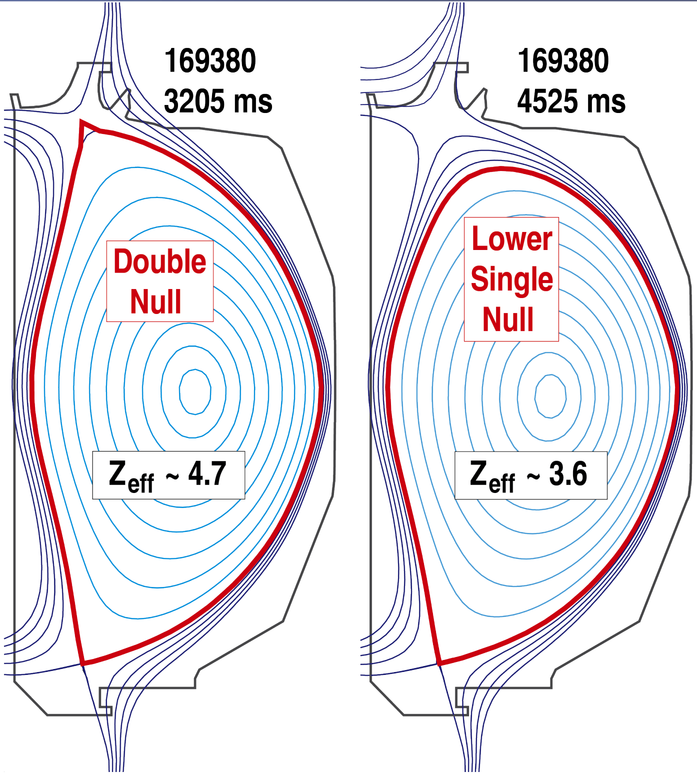
MIT PSFC Plasma Science and Fusion Center

Rapid Progress Suggests Wide Pedestal QH-Mode is Attractive Scenario for Burning Plasma Operation in ITER

- **New stationary ELM-stable regime in DIII-D**
- **QH-Mode transitions to Wide Pedestal at low E_r shear**
  - Pedestal pressure ⬆ 60%
  - Pedestal width ⬆ 65%
  - Global confinement time ⬆ 40%
  - H_{98y2} ⬆ 45%
- **Zero injected torque throughout discharge**
- **Sustained with up to 77% ECH power**
  - Confinement *improves* with electron heating
  - Promising for burning plasma: α-particles heat electrons



- **Wide Pedestal QH-Mode in LSN Shape**
  - Lower Z_{eff} implicates sources

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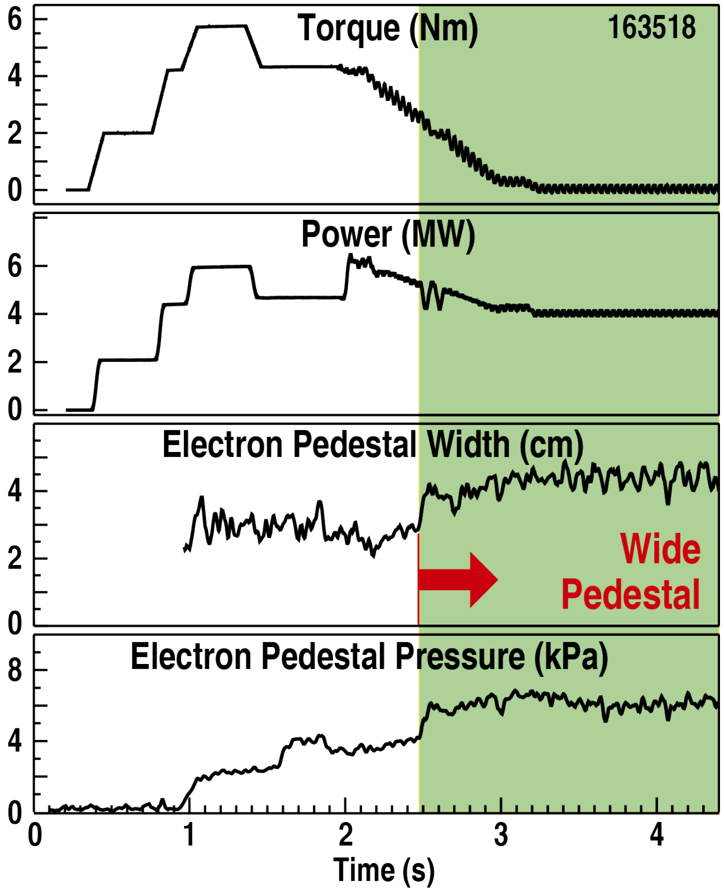
Transition to Wide Pedestal QH-Mode First Discovered While Ramping Counter-NBI Torque Toward Zero

- **Reduced Pedestal E_r shear**
- **Less drive for Edge Harmonic Oscillations (EHO) which regulate standard QH-Mode**
  - EHO replaced by shorter wavelength broadband fluctuations
  - Transition to 60% higher and 65% wider pedestal
  - Transport-limited pedestal – no ELMs
- **Core confinement improves with higher pedestal**

Burrell et al., Phys. Plasmas (2016)
Chen et al., Nucl. Fusion (2017)



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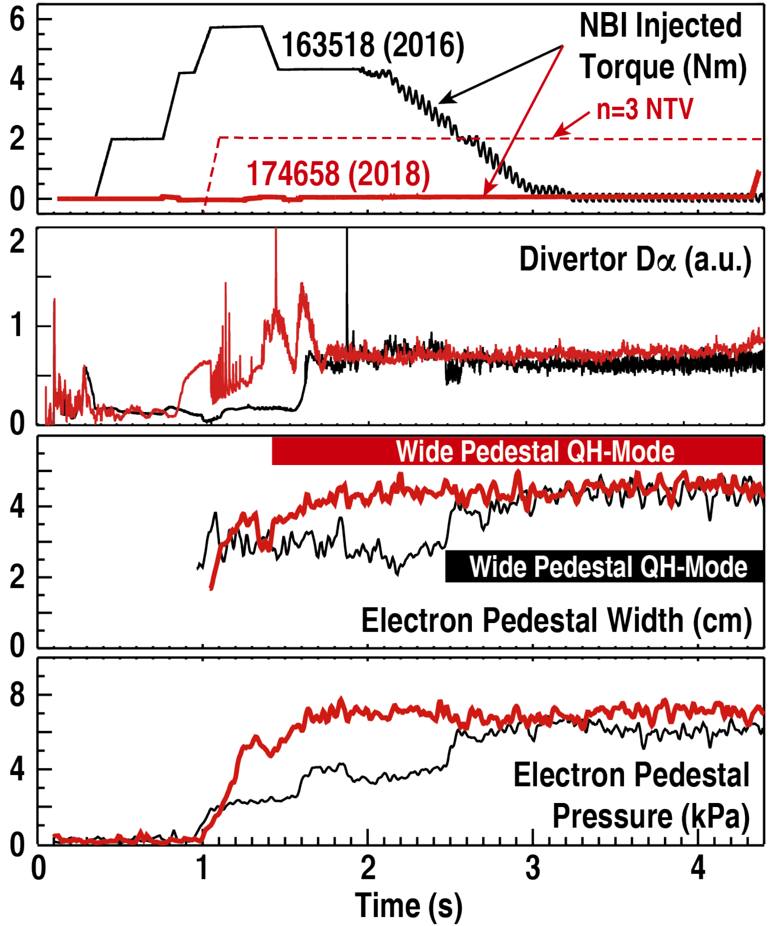
Creation of Wide Pedestal QH-Mode does not Require Injected NBI Torque

NBI Torque to Initiate and Sustain Wide Pedestal QH-Mode now Reduced to ~Zero Net Torque Injected Throughout

- **New zero torque startup**
- **Replace NBI counter torque with Neoclassical Toroidal Viscous (NTV) torque**
  - Use n=3 non-axisymmetric magnetic fields
  - NTV torque prevents early locked modes, tailor to avoid n=2 NTM
- **Same or better wide pedestal QH-Mode performance with zero injected NBI torque**

Burrell et al. (2018)



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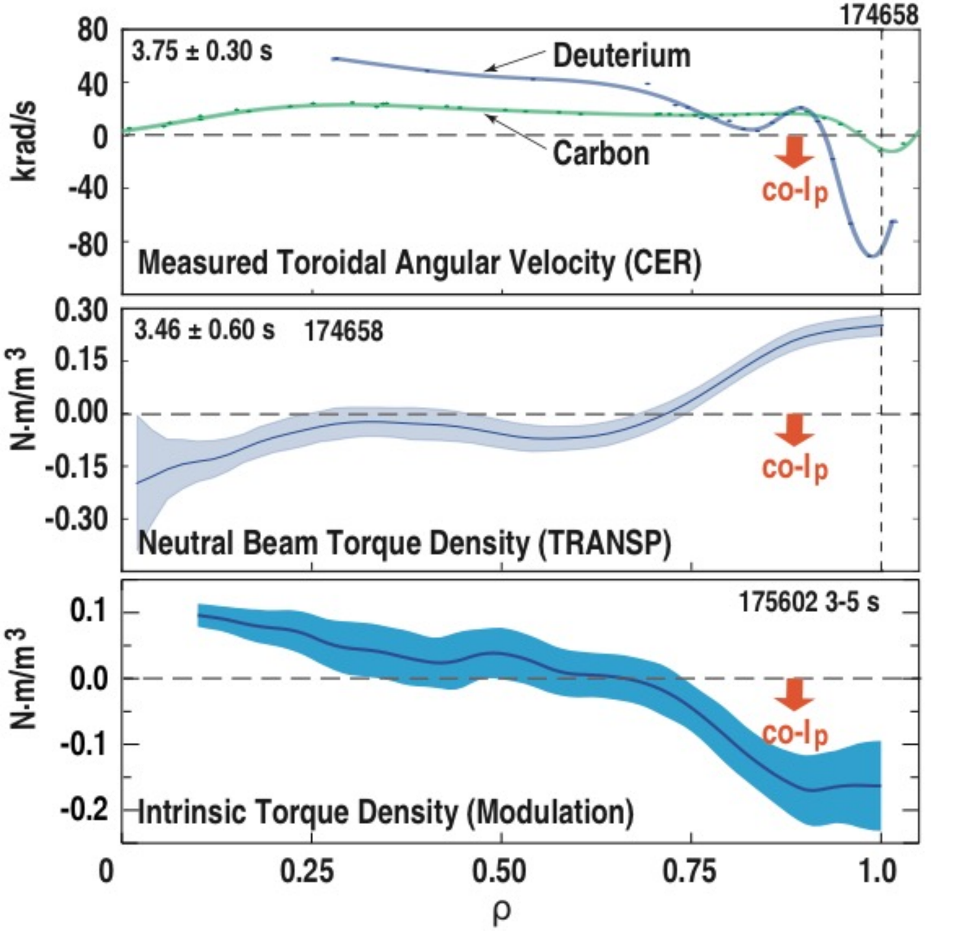
Measured Intrinsic Torque Dominates and Matches Direction of Rotation

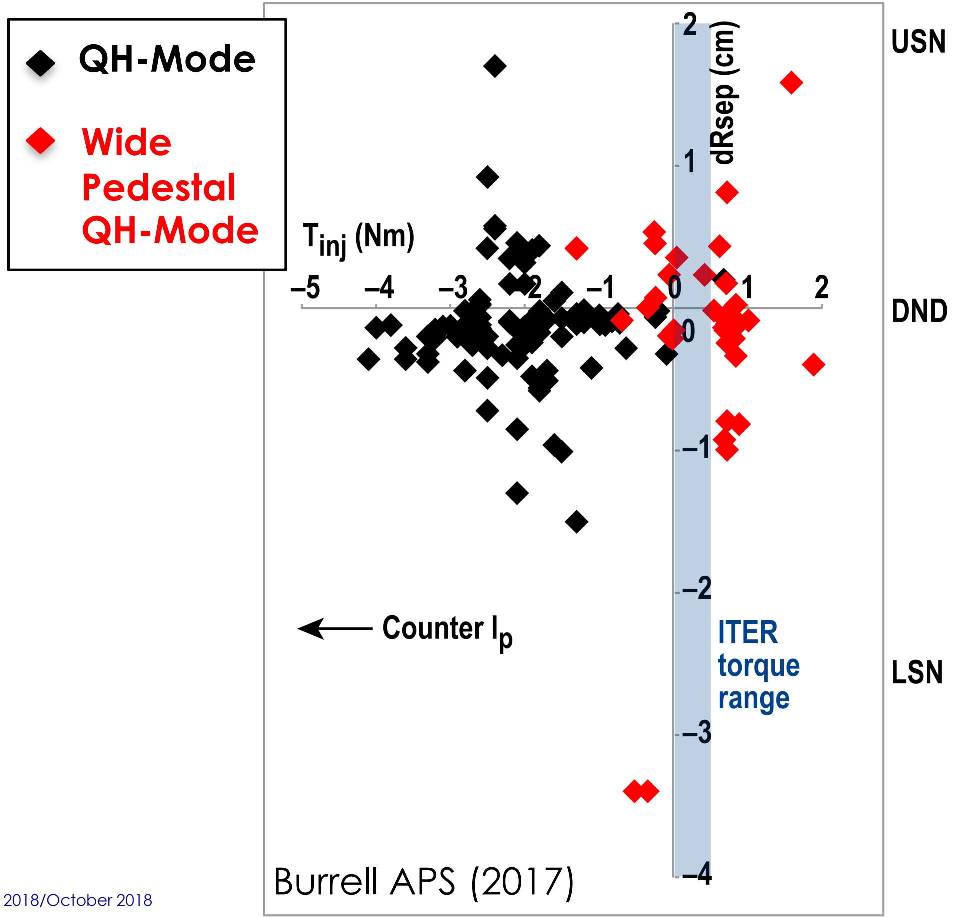
With ~zero injected NBI torque

- **Measured both carbon and deuterium toroidal rotation profiles**
- **Intrinsic torque density measured using beam torque modulation in similar discharge**
  - Includes thermal ion loss (co-)
  - Edge NTV not yet included (counter-)
- **Local beam torque density opposite rotation over most of profile**



Wide-Pedestal QH-mode Operation has been Extended to LSN and USN Shapes and a Wide Range of NBI Torque

- **Wide pedestal transition seen in range of discharge shapes over wide range of NBI torque**
  - Transition not seen yet for USN with dRsep ≥ 2 cm
- **Shape and torque ramps in wide pedestal conditions used to broaden parameter space further**
- **Range of wide pedestal accessible torques exceeds ITER equivalent range**



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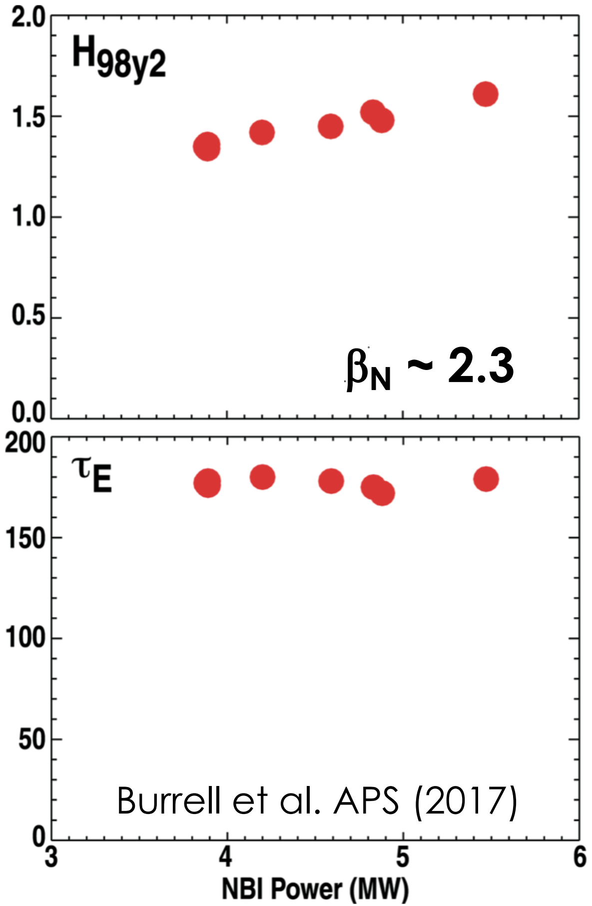
Approaching Dominant Electron Heated Wide Pedestal QH-Mode using Off-Axis ECH

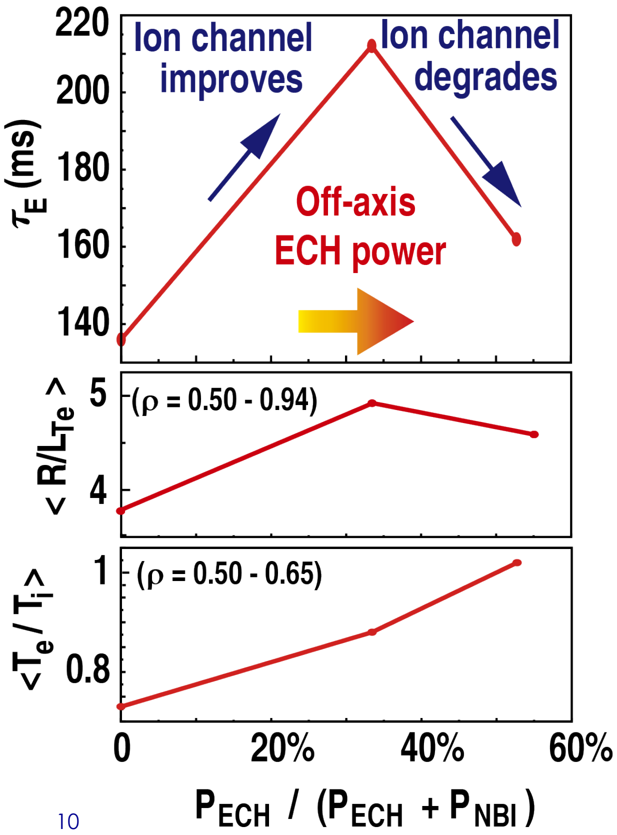
In Wide Pedestal QH-Mode, Confinement Improves further with Increasing Auxiliary Power

- H_{98y2} ~ 1.6 *increases* with power
- Global energy confinement time τ_E does not degrade with power as in usual H-Mode scaling
- These scans utilize NBI heating at zero injected torque

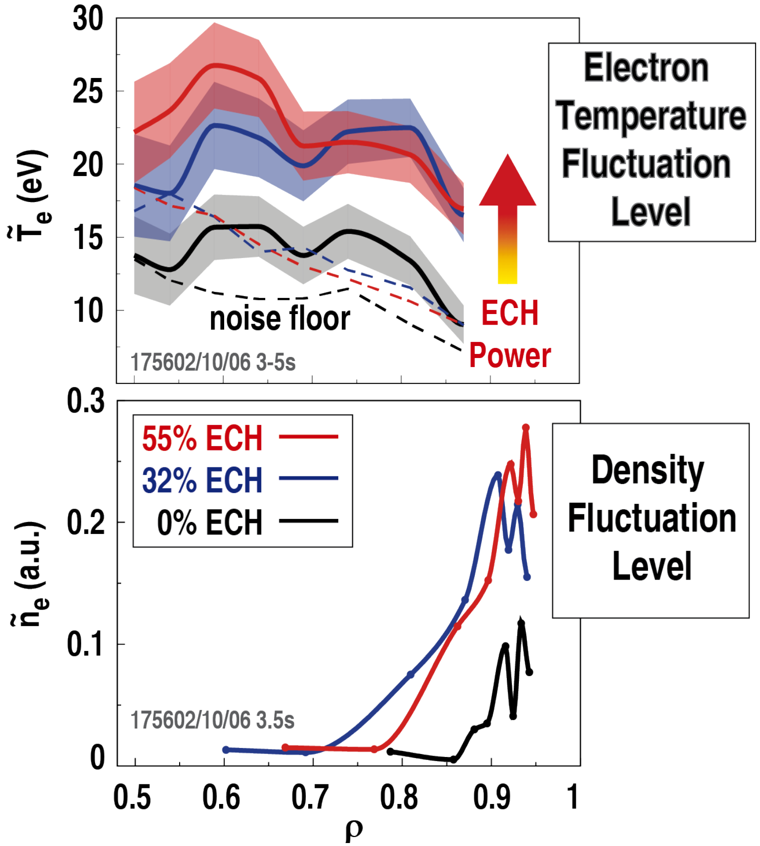


Electron Heating Improves Wide Pedestal QH-Mode Confinement, Unlike any Other DIII-D Regime — as $T_e/T_i \rightarrow 1$ at ITER Collisionality

Off-axis ECH at ρ=0.4



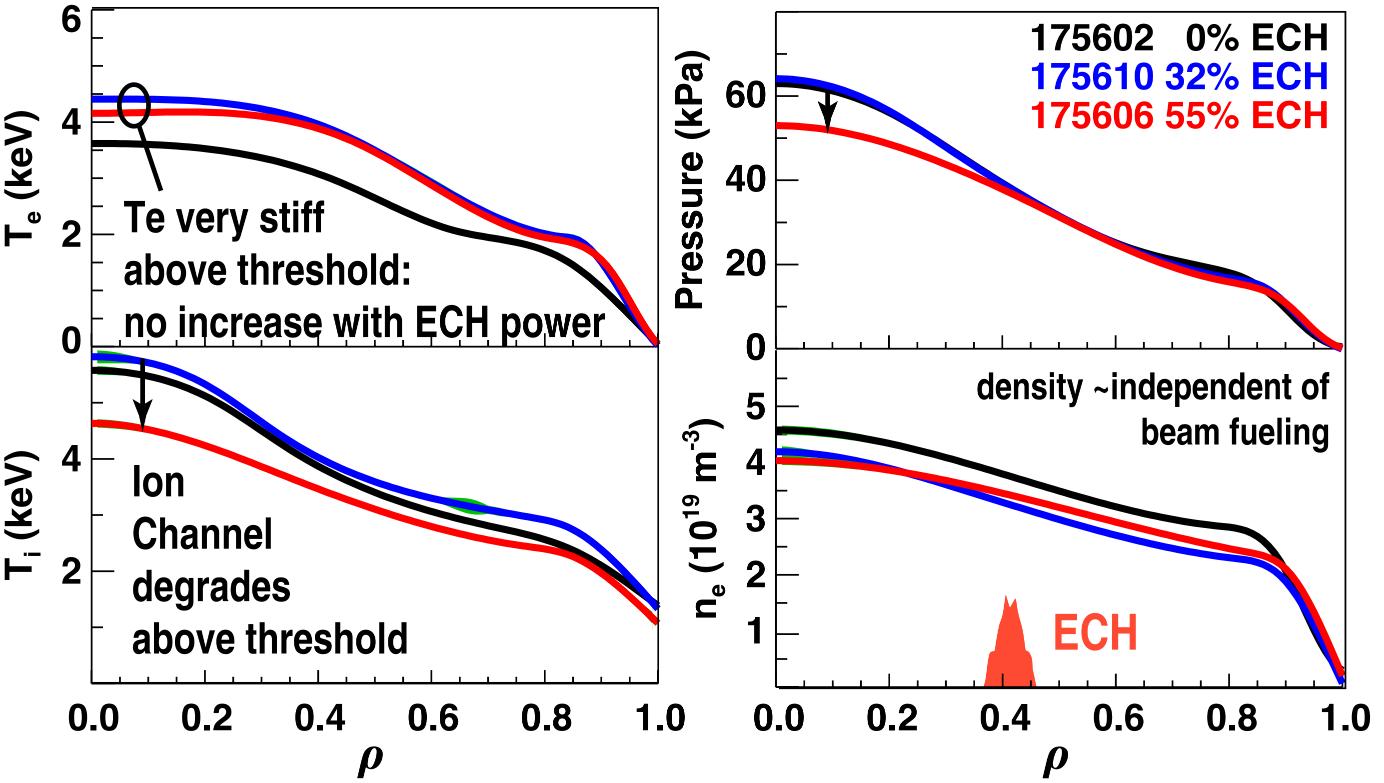
- τ_E **increased 60% with 1/3 ECH power**
  - Pedestal E_r well widens/deepens
- **With more ECH, T_e fluctuations intensify for ρ=0.5-0.7**
  - T_e profile stiffens
  - Ion channel degrades
- **Suggests T_e/T_i threshold crossed**



With ECH off-axis, Confinement Initially Improves but Shows Less Improvement at Higher ECH Power Fractions

Off-axis ECH at ρ=0.4

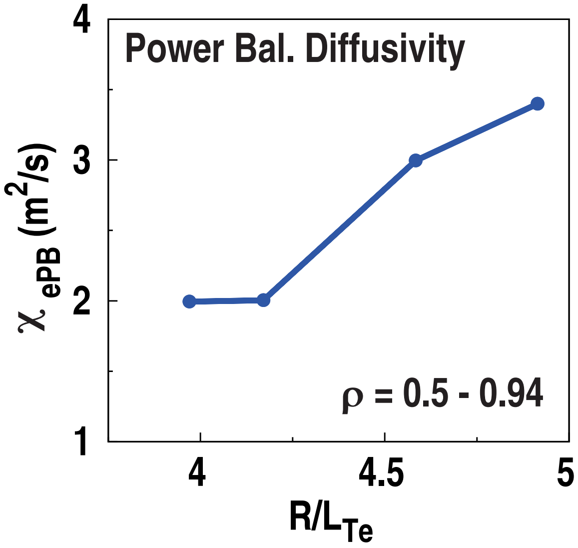
- τ_E increased 60% with 1/3 ECH power
- Encounter "stiff" response as increase ECH power further
- τ_E still 19% higher with equal ECH and NBI powers

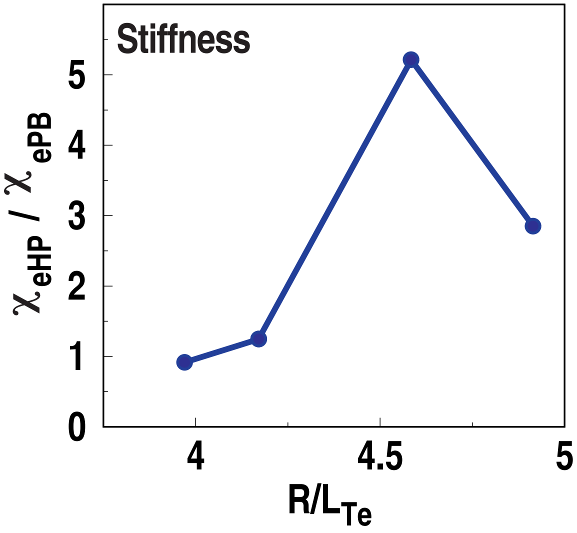


(Z_{eff} ~ 4.5 shows little change)

Fourier Analysis of Modulated ECH Shows Electron Thermal Diffusivity Increases Monotonically with Electron Temperature Gradient R/L_{Te}

Off-axis ECH at ρ=0.4





- **At highest ECH power fraction, stiffness with respect to R/L_{Te} decreases**
- **Consistent with crossing threshold in T_e/T_i or collisionality**

$$\chi_e^{HP} = \chi_e^{PB} + \frac{\partial \chi_e^{PB}}{\partial \nabla T_e} \nabla T_e$$

(heat pulse diffusivity[2])

$$S = \frac{\partial \ln Q_e^{PB}}{\partial \ln \nabla T_e} = \frac{\chi_e^{HP}}{\chi_e^{PB}}$$

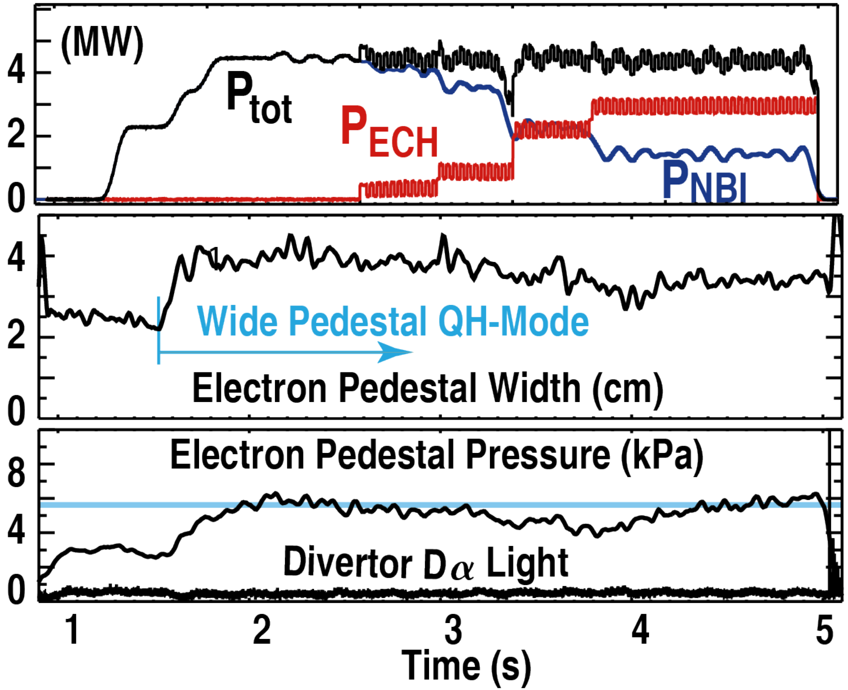
(stiffness[2])

[2]J. C. DeBoo, C. C. Petty et al Phys. Plasmas, **19**, 082518 (2012)

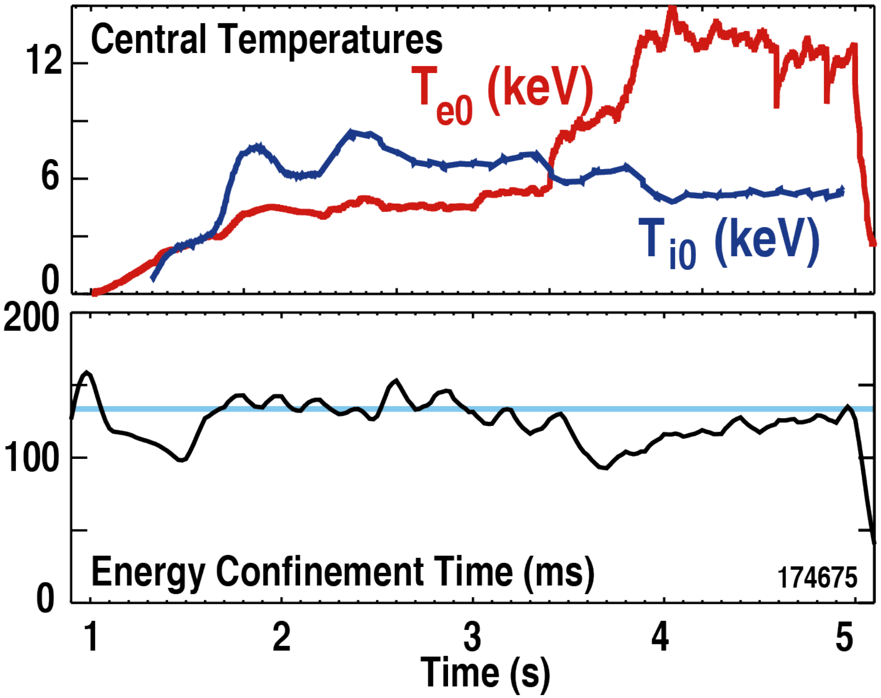
Dominant Electron Heated
Wide Pedestal QH-Mode using On-Axis ECH

Low Torque, Wide-Pedestal QH-mode Sustained with 77% ECH Power

On-axis ECH replacing beam power



- Confinement not degraded with ECH

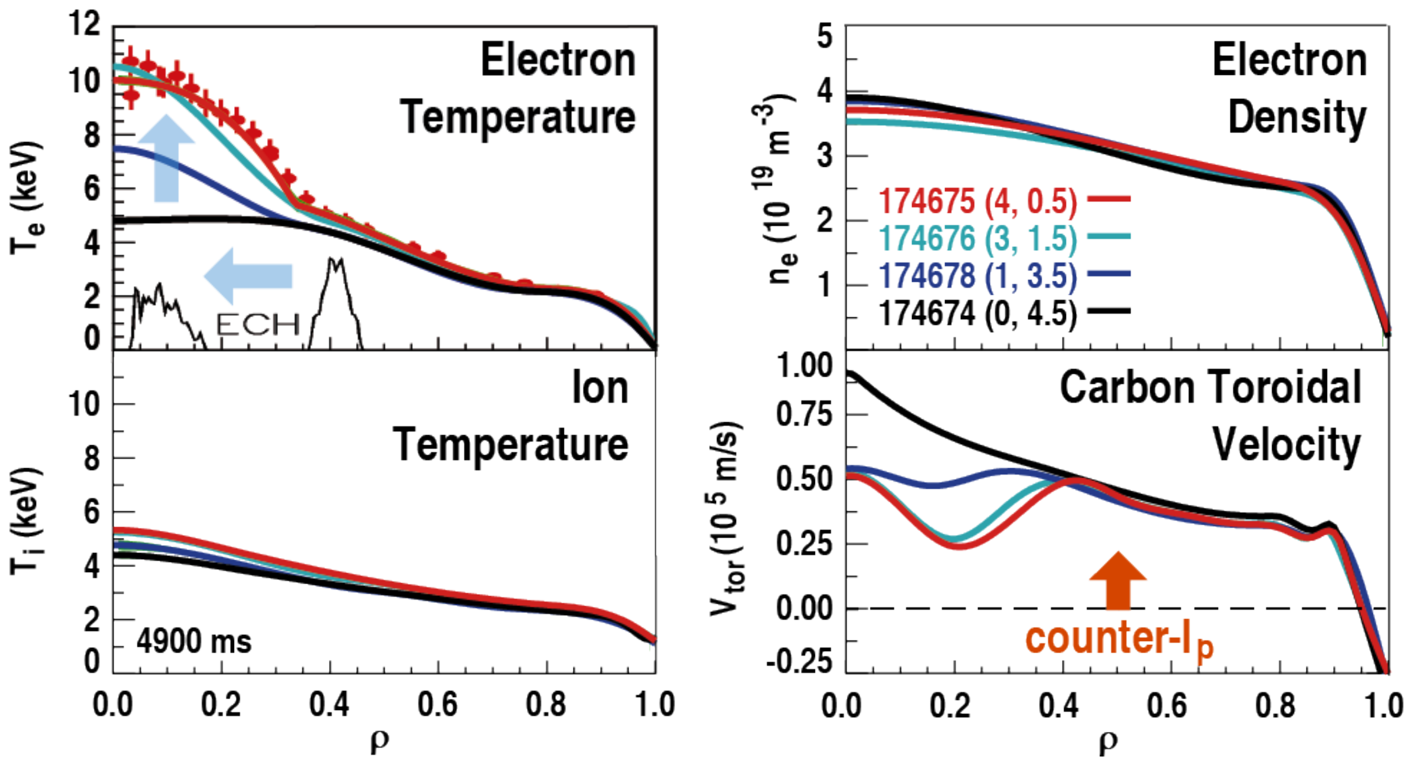


- Recovers from loss of beam core fueling
- New core T_e ITB forms without reverse shear

With ECH on-axis, New ITB Forms in Electron Temperature Despite Monotonic q-profile, Further Improving Confinement with ECH

ECH location scan

- **Move one gyrotron per discharge from ρ=0.4 → ρ=0.1**
- **Carbon toroidal velocity hollows in ITB**
  - Connected to e^- channel
  - *n* = 3 NTV torque: electron root?



- **T_e profile inside ITB controlled by ECH location**

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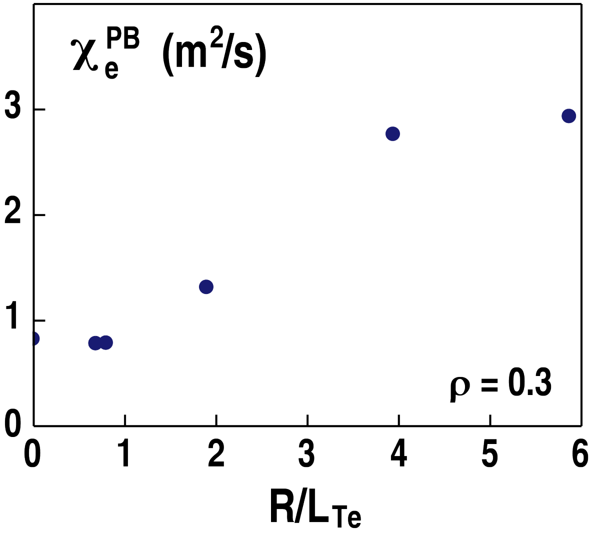
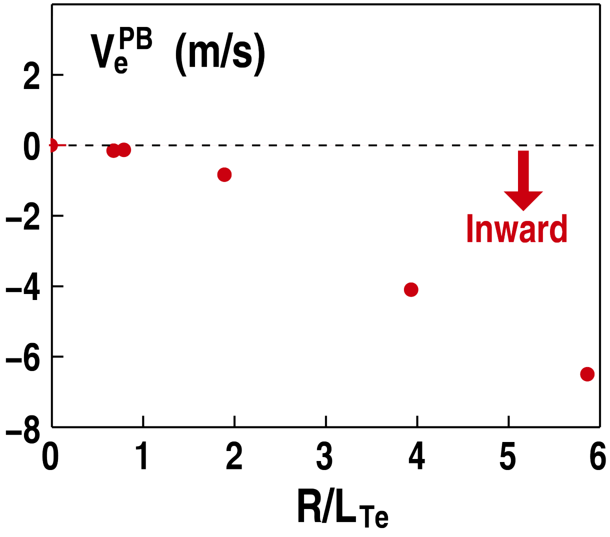
Role of Electron Heat Pinch Identified in T_e ITB Formation through ECH Location Scan and Fourier Analysis of Modulated ECH

ECH location scan

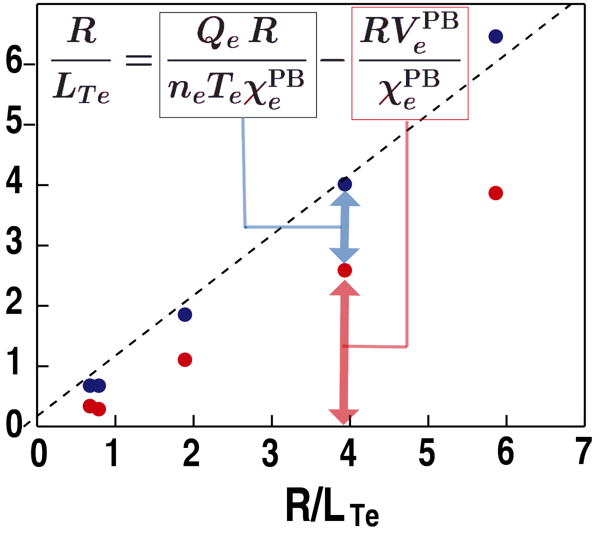
Electron Thermal Diffusivity (Power Balance)



Electron Convective Velocity (Power Balance)



Contributions to Electron Temperature Gradient



- Electron Heat Pinch increases R/L$_{Te}$ by factor 2.4

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Current Status of Wide Pedestal QH-Mode as Candidate Burning Plasma Regime for ITER Baseline Scenario

Demonstrated	Work in Progress	Not Yet Addressed
No ELMS	Reduce q_{95}	Radiative divertor
No reliance on NBI torque, fueling; zero torque throughout, torques spanning ITER equiv. range	Reduce high Z_{eff} (DIII-D specific sources)	Wall conditioning requirements
Dominant Electron Heating (77%) with Improved τ_E	Impurity confinement studies	
H_{98y2}~ 1.6 ⇧ with power, β_N ~ 2.3		
LSN Shape		
T_e ~ T_i		
Very low core MHD		
ITER collisionality		

- *Wide pedestal QH-Mode: low ExB shear – turbulence limited pedestal*
- *ITER at low ρ_* †, where* $E_r \simeq \nabla p/en$:

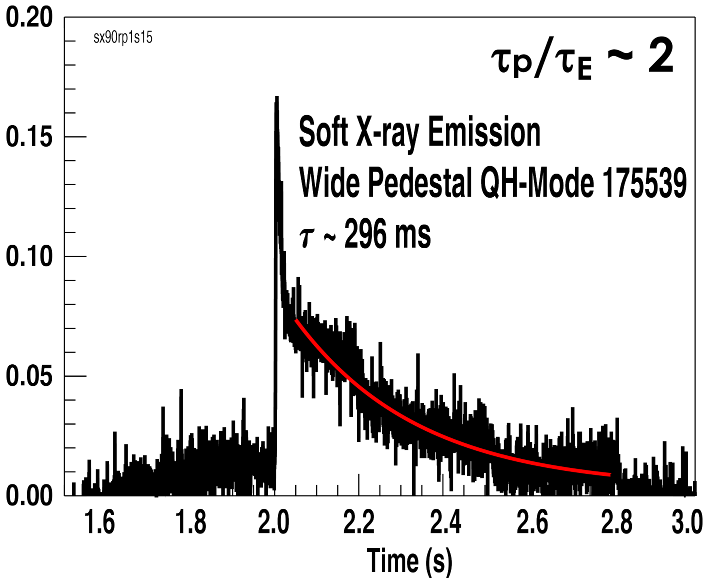
$$\frac{\omega_{\mathrm{E\times B}}}{\gamma} \propto \left(\frac{a}{w_{\mathrm{ped}}}\right) \rho_*$$

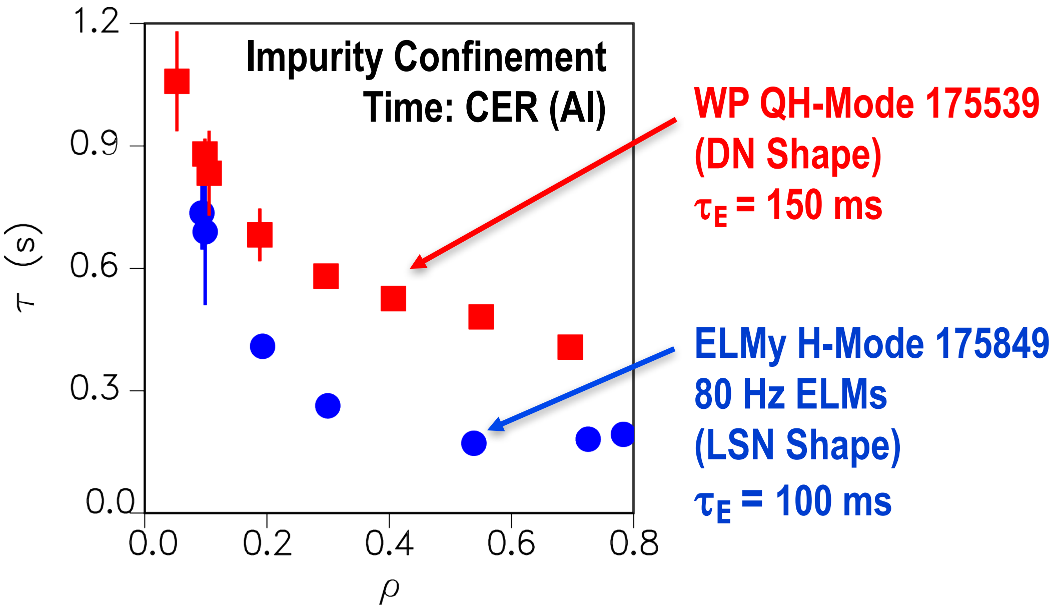
† Kotschenreuther et al. NF (2017)

Backup slides

Preliminary Results for Impurity Transport in Wide-pedestal QH-Mode

- **Impurity transport studied by injecting pulses of Aluminum using laser blow-off system**
- **WP QH has typical H-Mode ratio of particle to energy confinement time τ_p/τ_E ~ 2-3**
- **Unlike ELMy H-mode, Wide-pedestal QH-mode does not have inward impurity pinch**



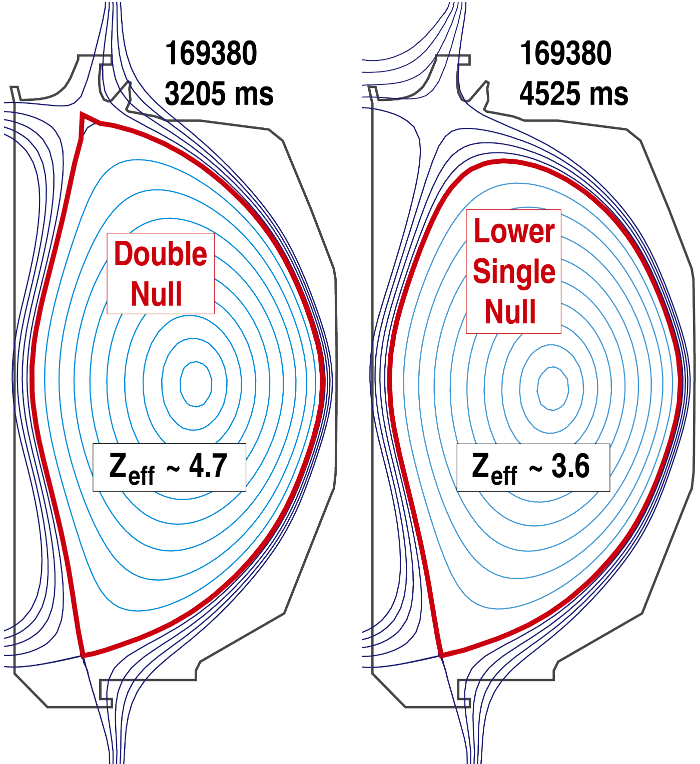


Xi Chen, C. C. Petty et al., APS (2018)

Impurity Concentrations Due (in part) to Stronger Sources of Carbon

- **Balanced double null (DN) configurations tend to have higher Z_{eff}**
- **Counter NBI orbit losses also increase carbon influx, but counter NBI is not needed**
- **Expect lower Z_{eff} Wide Pedestal QH-Mode without NBI and with ITER-relevant Lower Single Null (LSN) shape**
- **ECH does not appear to lower Z_{eff}**

- **Wide Pedestal QH-Mode in LSN Shape**
  - Z_{eff} reduced by 23% going from Double Null to Lower Single Null



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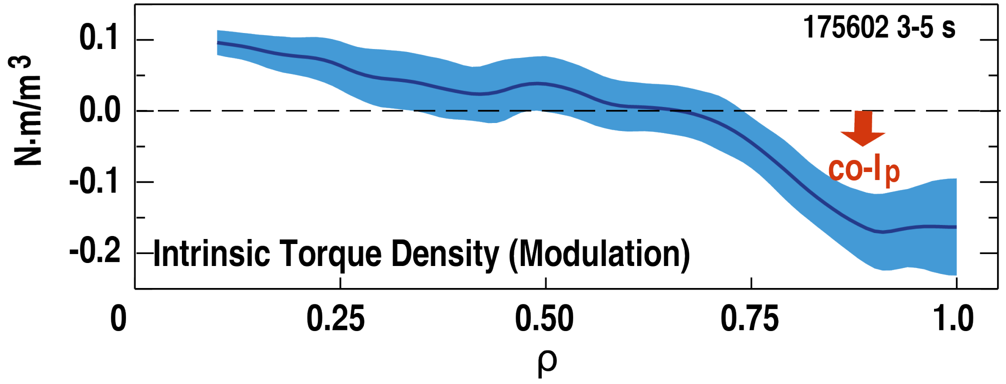
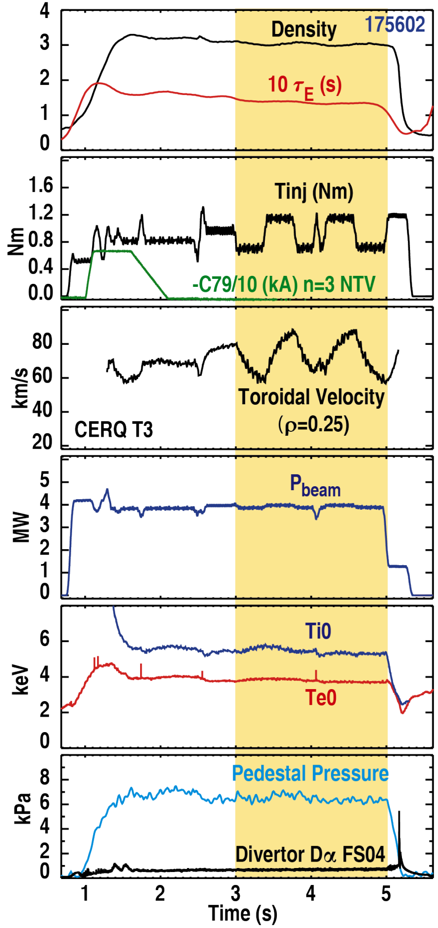
Use Beam Torque Modulation at Constant Power to Measure Intrinsic Torque

- **Vary torque by exchanging co- and counter- beams, keeping total power constant**
- **Mean counter-current NBI torque 0.9 Nm**
  - Modulated in 400 ms duration steps ±0.2 Nm
- **TRANSP with 250,000 particles to compute beam torque**
  - Use reflectometer density profile with high time resolution
- **Determine momentum confinement time at each radius; “peel the onion” to infer “intrinsic” torque density profile[1]**





[1]C. Chrystal, B. A. Grierson et al., Phys. Plasmas **24**, 056113 (2017)