The Energy Confinement Evolution at Very High Edge Pedestal in Super H-mode Experiments

by
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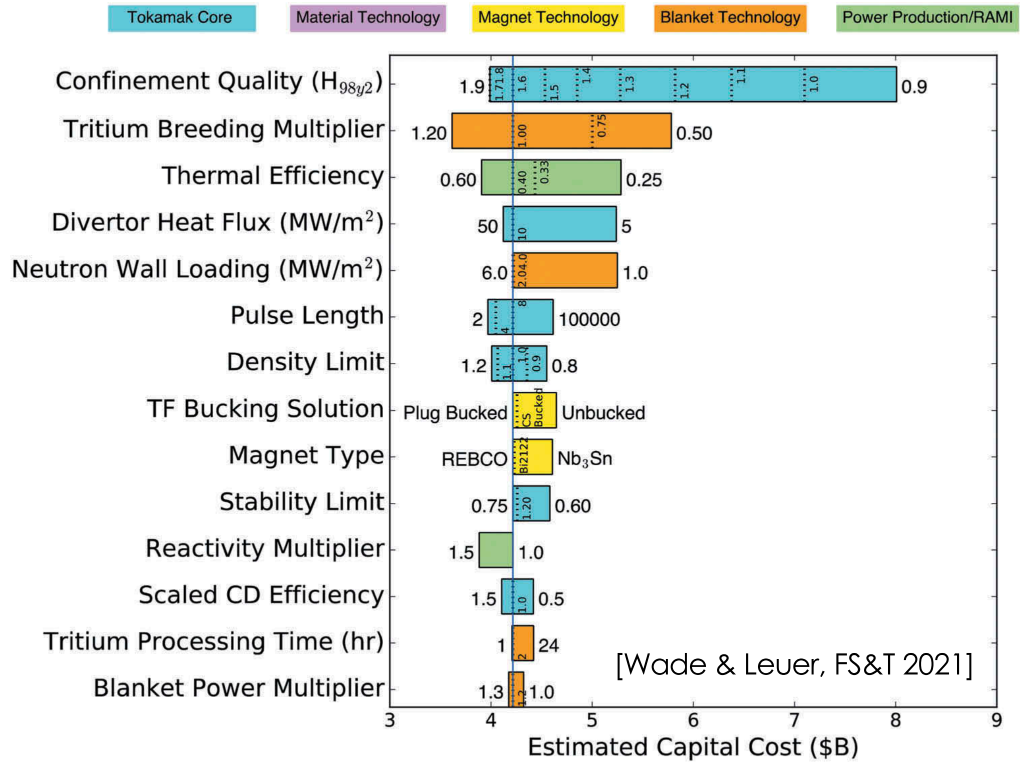
GENERAL ATOMICS

Energy Confinement Quality the Highest Leverage Parameters for Fusion Capital Cost

- **Strong sensitivity of fusion reactor capital cost to variations in the assumed energy confinement quality**
- **Use normalized energy confinement time (H_{98y2}) to compare energy confinement quality**
  - For discharges with diverse parameters
  - Across devices



$$H_{98y2} = \tau_E /(0.0562\, I_P^{0.93} B_T^{0.15} n_e^{0.41} P_H^{-0.69} M^{0.19} R^{1.97} \varepsilon^{0.58} \kappa^{0.78})$$

[ITER Physics Basis Chapter 2, NF 1999]

Sensitivity in capital cost as each parameter is independently varied over the range indicated

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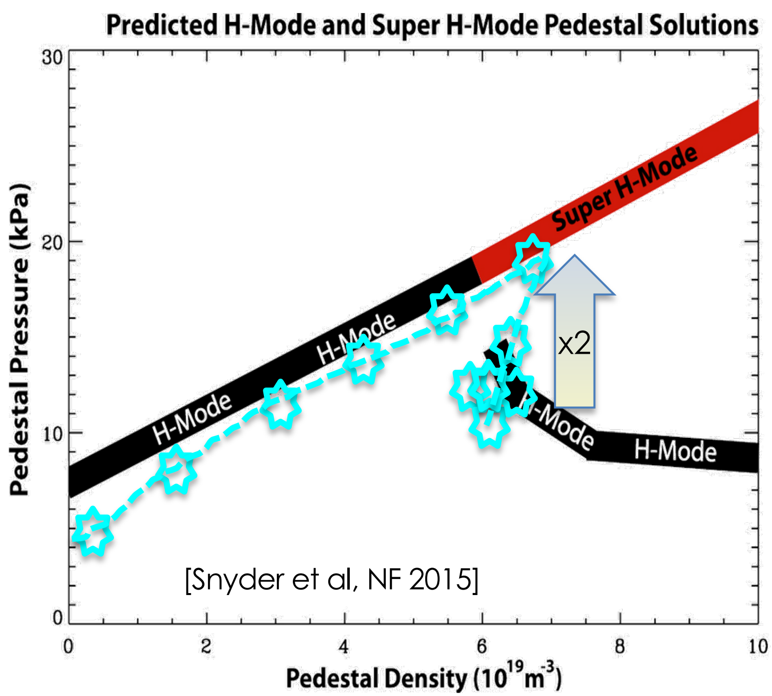
Higher Pedestal ≠ Higher Confinement

"Super H-mode" plasmas exploit strong plasma shaping to achieve high edge pedestal pressure at high density

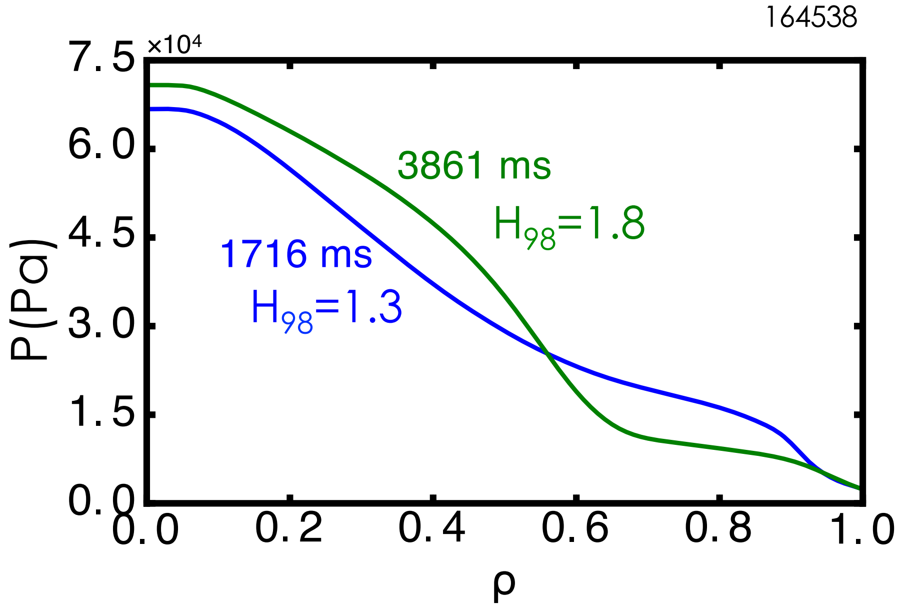


- **Higher pedestal is not identical to higher confinement**
  - i.e. higher pedestal does not necessarily lead to higher confinement
- **"higher pedestal → higher confinement" may be an intuitive expectation, and there may be cases that satisfy this expectation**
- **There are many cases that clearly violate this expectation**

Higher Pedestal ≠ Higher Confinement (1)

High β_P scenario

- Same shot,
- same plasma shape,
- same I_P and B_T,
- same beta,
- same density



[McClenaghan et al, NF 2019]

Lower pedestal leads to higher confinement

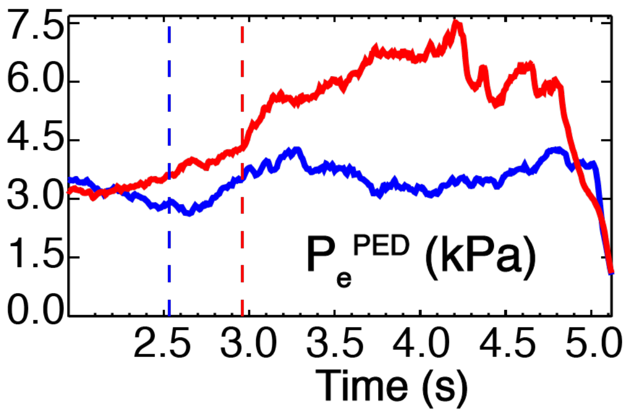
L. Wang (oral), Fri EX/7

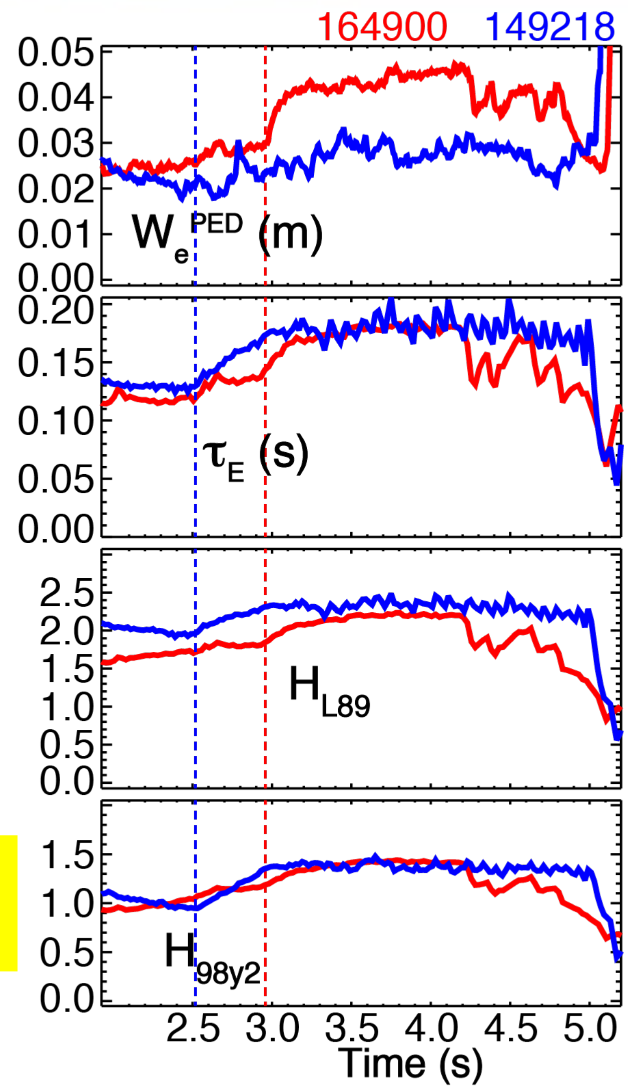
S. Ding (oral), Tue EX/1

Higher Pedestal ≠ Higher Confinement (2)

Wide Pedestal QH-mode
vs.
Standard QH-mode

- **Same I_P,**
- **same β_N,**
- **same NBI torque,**
- **similar B_T**





Much higher pedestal does not yield any higher confinement

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Higher Pedestal ≠ Higher Confinement (3)

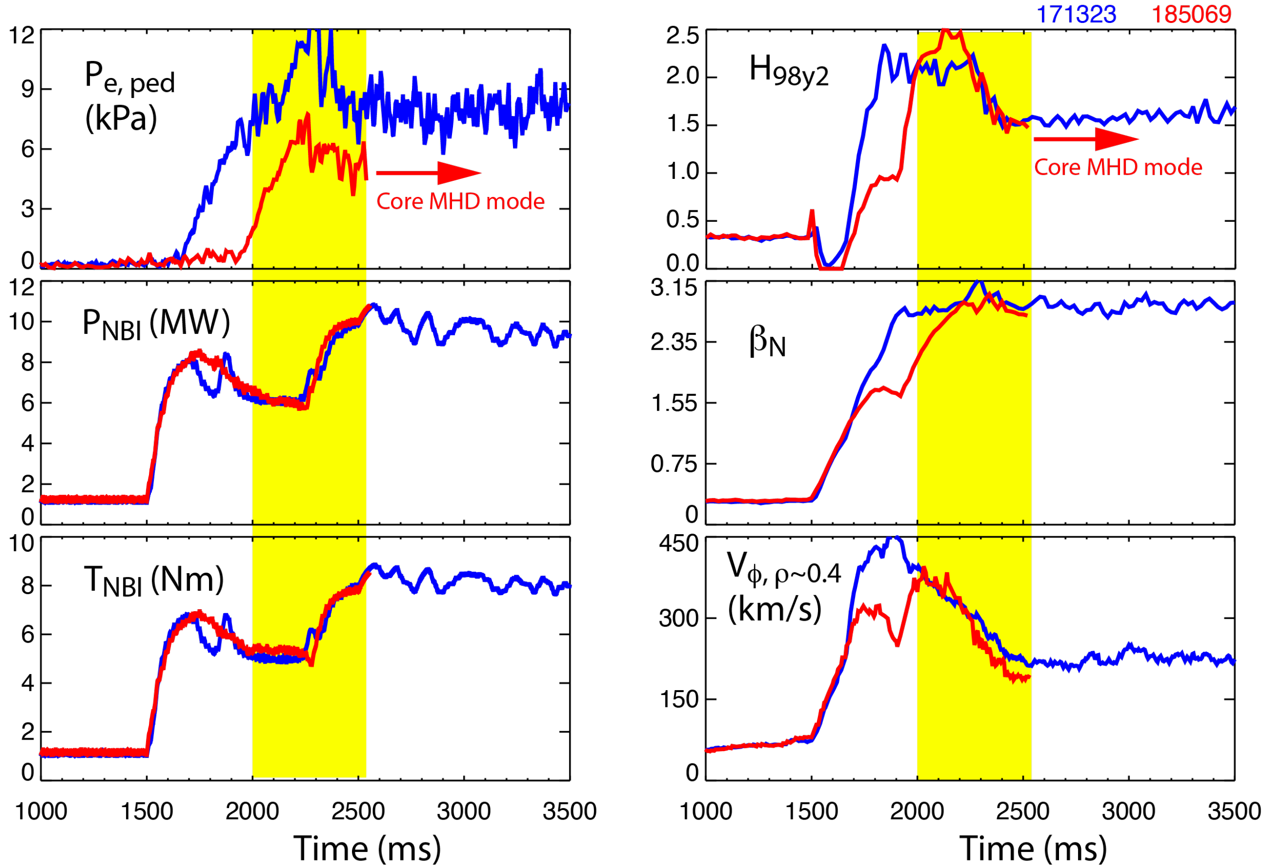
Recent Super H-mode experiments

High triangularity

vs.

Low triangularity

- **Lower triangularity → lower pedestal (consistent with EPED predictions)**



Lower pedestal → same confinement (until n=2 mode)

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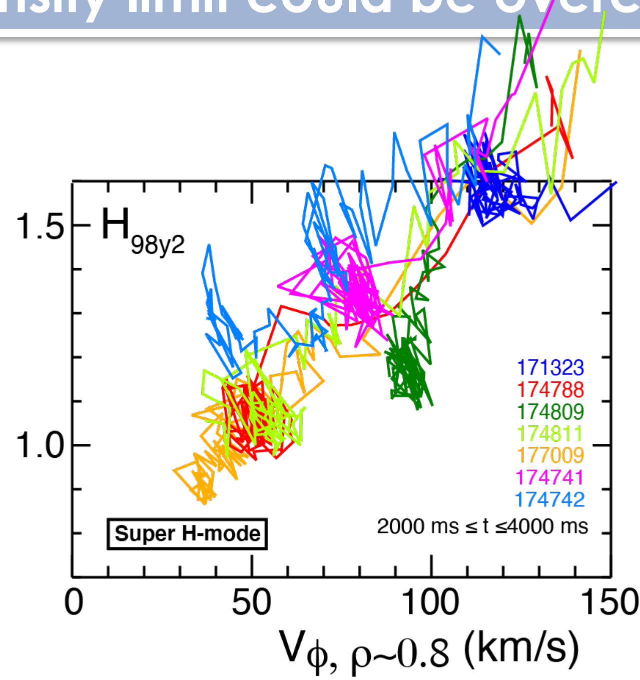
High Rotation (and Related ExB Shear), not High Pedestal, Enables H_{98}>>1 in Super H-mode Experiments

Correlation observed experimentally: energy confinement quality correlates with toroidal rotation, not with pedestal pressure

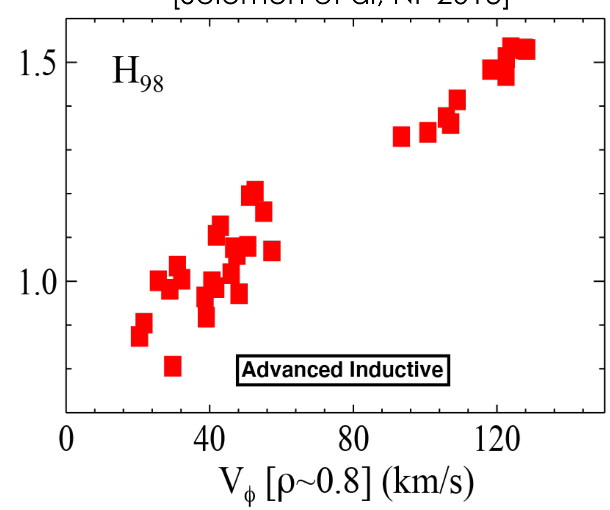
Causality is revealed by modeling, confirmed by new experiments

Modeling of Super H-mode in ITER predicts H_{98y2} ~ 1.0-1.1, Q>10 if Greenwald edge density limit could be overcome

- **Like AI scenario, Super H-mode discharges lose attractive confinement at ~standard rotation**



[Solomon et al, NF 2013]



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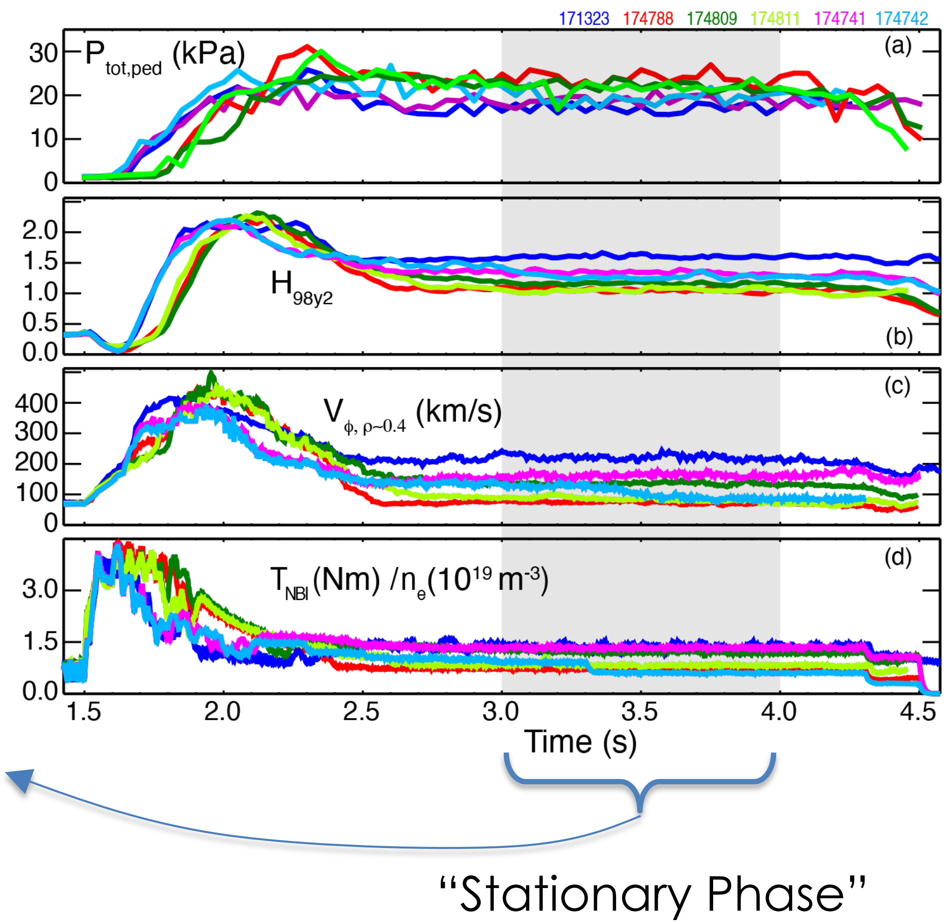
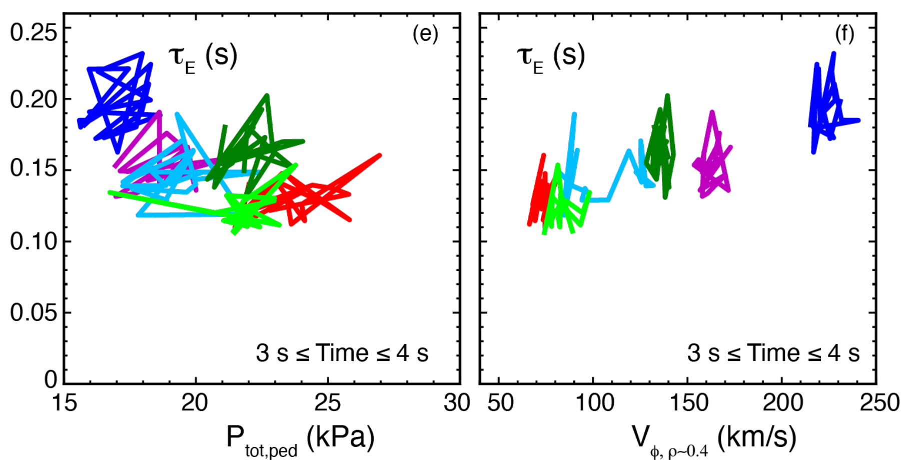
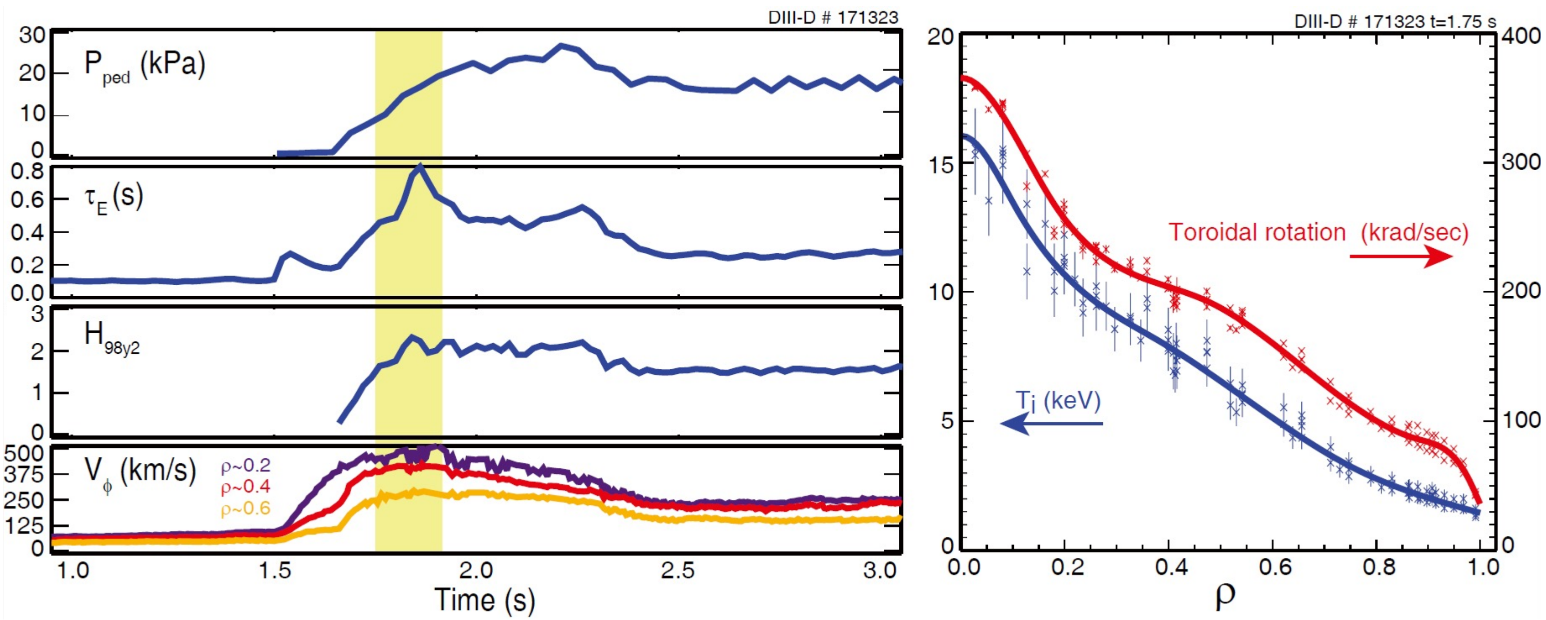
Energy Confinement Does Not Correlate with Pedestal Height

- **Typical super H-mode discharge waveforms**
  - Fixed plasma shape
  - Some variation in torque, density, Ip, core MHD
- **Large torque/particle drives high rotation**
- **H_{98y2} follows rotation, not pedestal**





Very High Confinement Obtained in the Early Phase with Low Pedestal, following Rotation Build-up

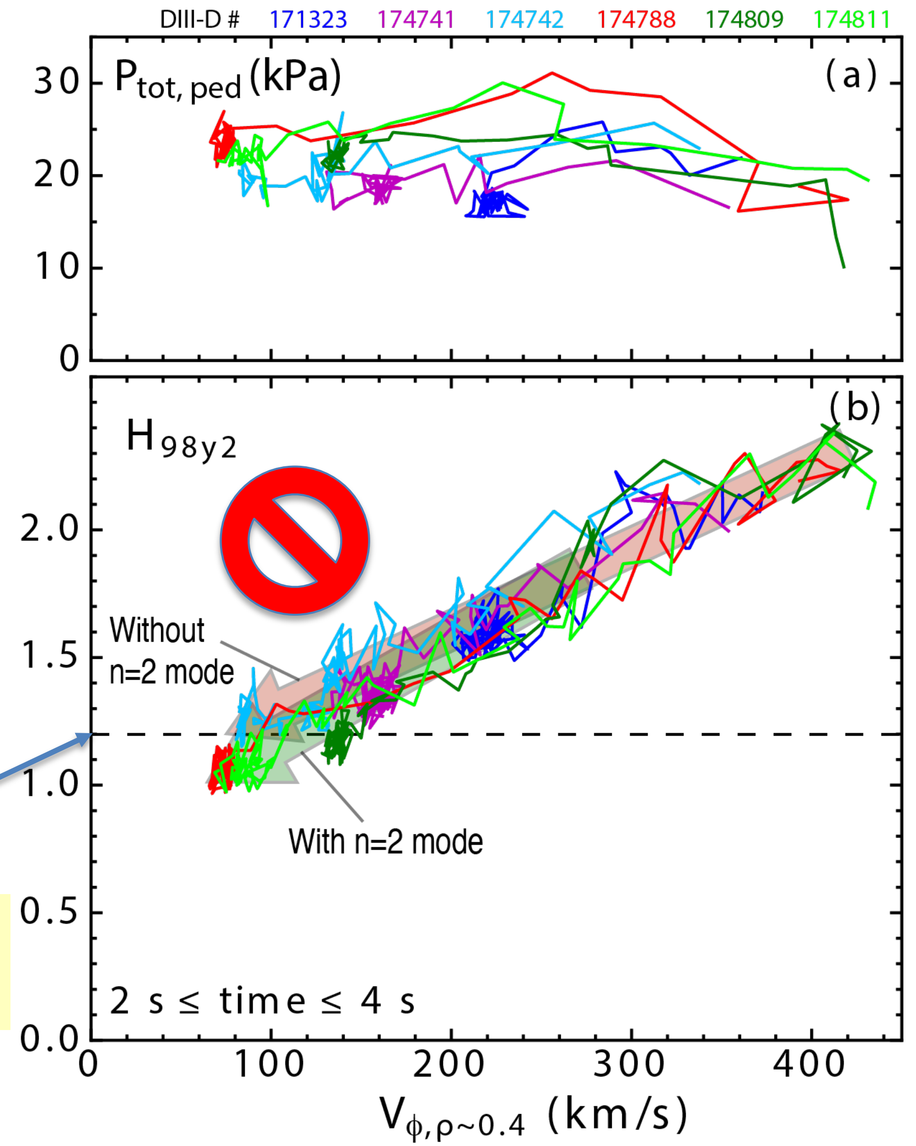


- **Very high confinement is reached with low pedestal pressure compared to its maximum and follows a strong rotation build-up**
- **Very peaked profiles of rotation and ion temperature are measured**
  - Confinement decreases as $T_{i,ped}$ increases (1.8 keV@1.75 s → 2.2 keV @ 2.5 s)

Confinement Quality is Linearly Correlated with Core Toroidal Rotation

- **Higher rotation, higher confinement quality**
  - Pedestal pressure is similar while rotation varies
- **No observation of very high confinement at low rotation in any DIII-D super H-mode experiment**
- **n=2 mode with saturated amplitude in some cases**
  - Higher amplitude with lower rotation
  - "Belt model" [Chang & Callen, NF 1990] predicts 13% reduction of confinement in good agreement with empirical observed difference

Empirical low-rotation extrapolation:
H_{98y2} ~ 1.2, without core tearing mode



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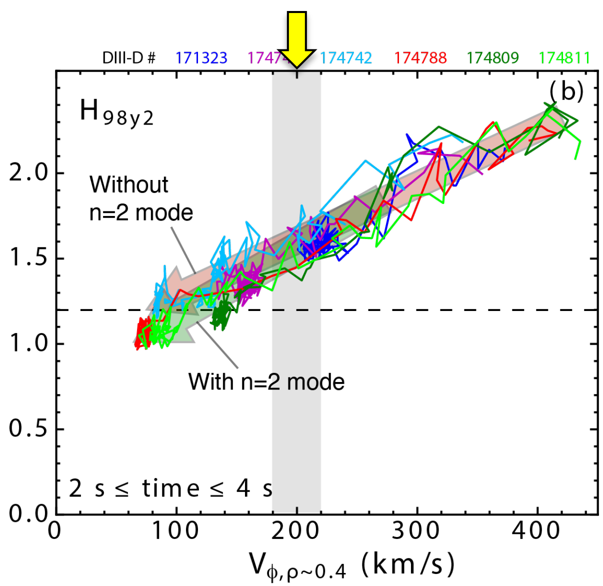
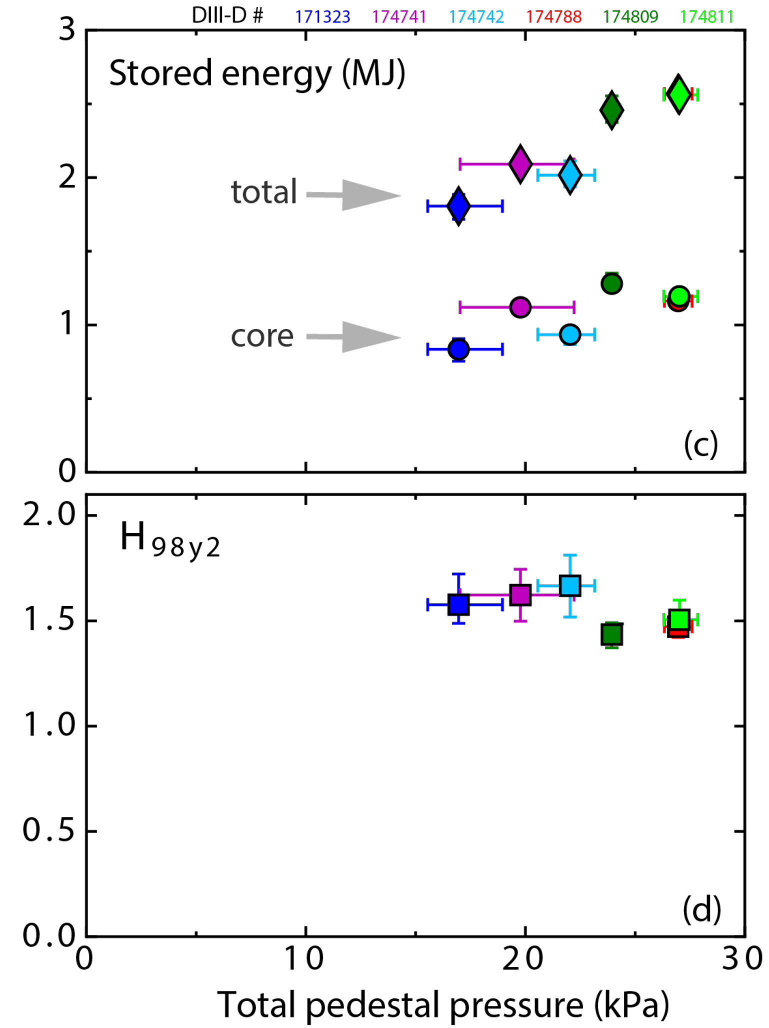
At ~Same Toroidal Rotation: Higher Stored Energy but ~Same H_{98y2} at Higher Pedestal Pressure

- **Look at core rotation $V_{\phi,\,\rho\sim0.4}$ = 200±20 km/s**
- **Higher pedestal → same confinement quality**
  - Cannot increase the pedestal "for free" in experiment
  - Other parameters have changed to increase pedestal height, resulting in ~constant H_{98y2}





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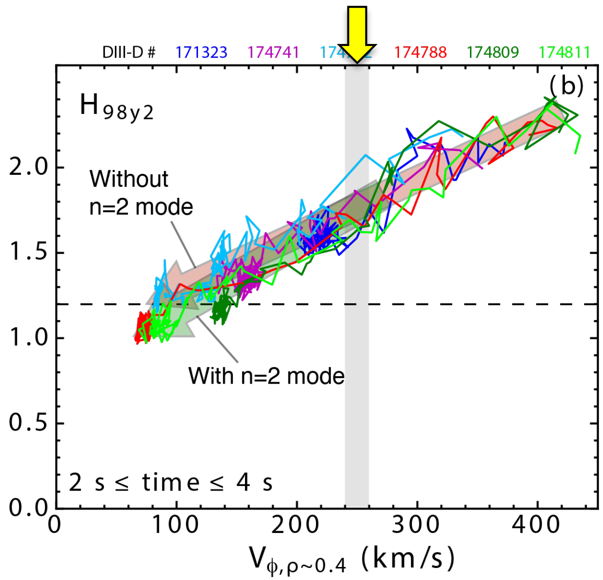

Compare two plasmas at **the same V_ϕ** (~250 km/s) and shape:

DIII-D #	174788	171323
P_{ped} (kPa)	31	23
W_{MHD} (MJ)	2.69	1.78
τ_E (s)	0.238	0.19
I_p (MA)	**1.95**	**1.58**
n_e (10^{19} m^{-3})	**6.9**	**6.0**
P_{inj} (MW)	**11.2**	**9.6**
H_{98}	1.66	1.66

- **At fixed rotation, τ_E changes in ways that are captured very well by H-factor definition**
- **H_{98y2} is constant (at fixed rotation)**

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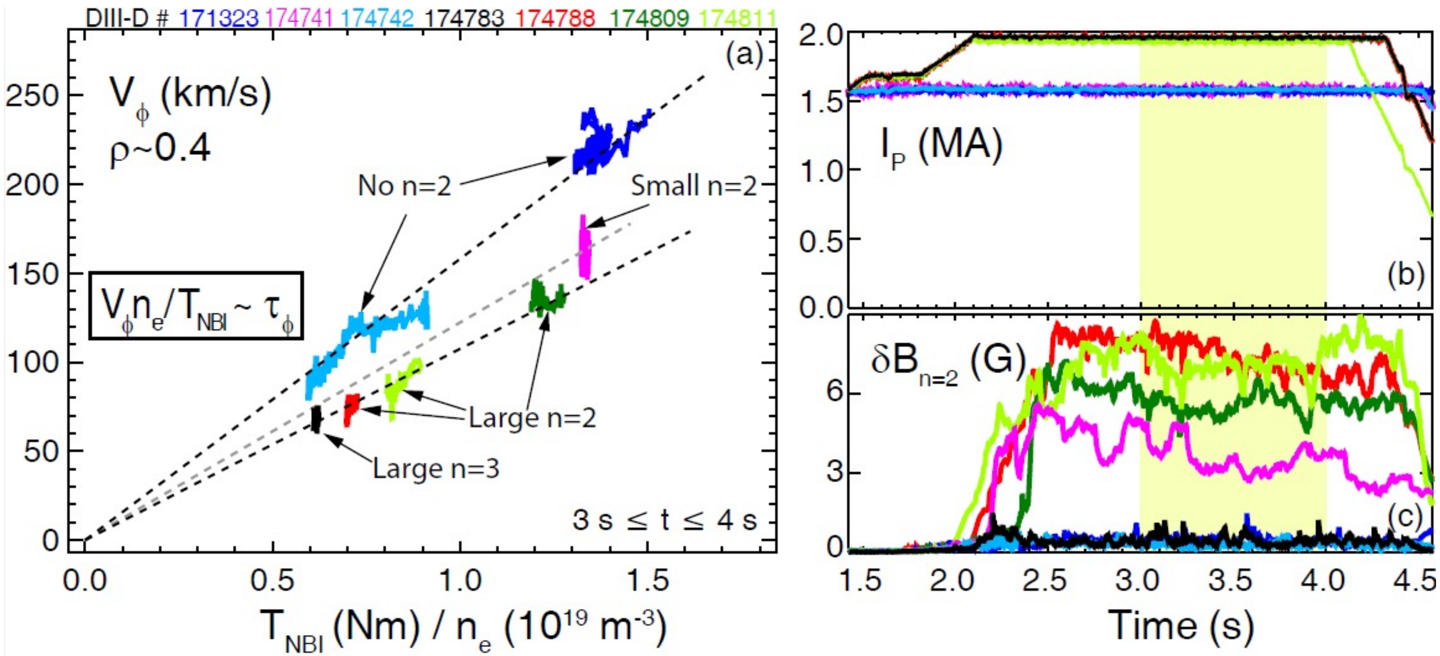
Core Toroidal Rotation is Linearly Correlated with Torque per Particle, Depending on TM Amplitude (Stationary Phase)



- A rotating tearing mode can exert a significant drag on the plasma rotation
- Discharges with similar MHD amplitude have similar τ_ϕ
- Core MHD impact on V_ϕ: ~30-40%
- T_{NBI}/n_e impact on V_ϕ: ~300-350% (stationary phase)

Rotation is mostly governed by external actuator

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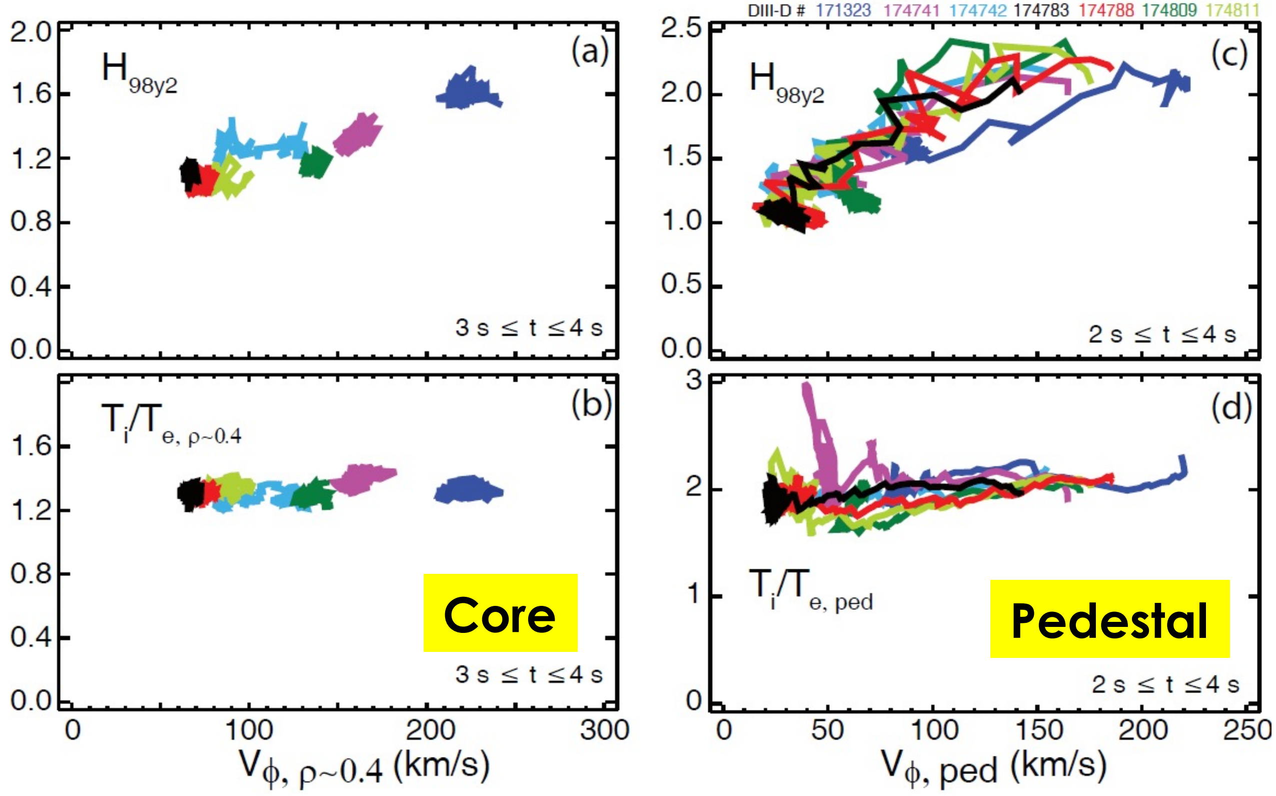
The Physics of T_i/T_e is Not Responsible for the Observed Thermal Energy Confinement Quality Change (Stationary Phase)

- **T_i/T_e is usually an important parameter in the turbulence and transport study**
  - The critical gradient $R/L_{Ti,e} \sim 1+T_{i,e}/T_{e,i}$
- **H_{98y2} decreases with reduced rotation both in the core and at the pedestal, while T_i/T_e stays nearly constant**



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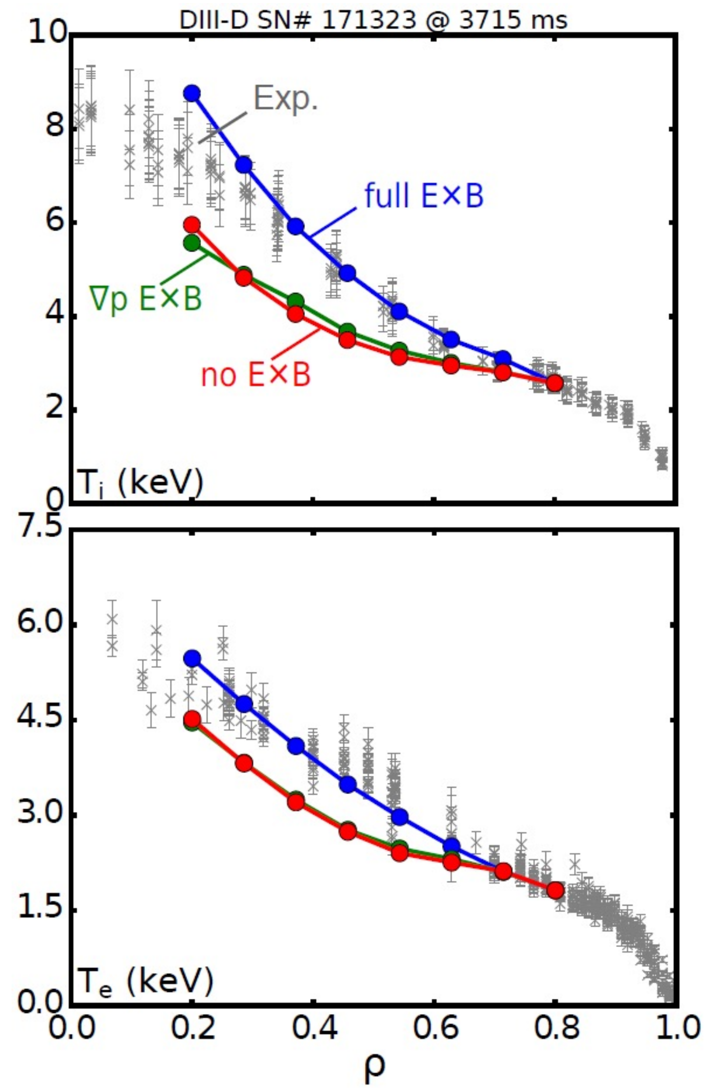
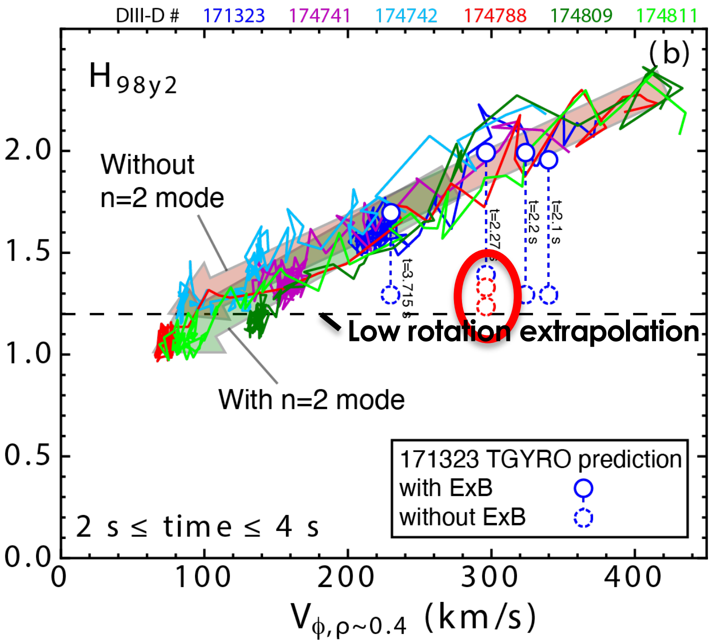
TGYRO Modeling Shows Removing E × B Effect Significantly Reduces Energy Confinement

- **TGYRO: a transport solver using gyrofluid code TGLF for turbulent transport, NEO for neoclassical transport**
- **Predicts temperature profiles using experimental fluxes**
  - Using full E × B can reproduce experiment temperature profile
  - Turning off E × B leads to a significant drop in the predicted profiles
  - Leaving only ∇p term of E x B has similar result to E × B off case
- **Confinement quality drops without E × B**
  - H_{98y2} ~1.7 with E × B
  - H_{98y2} ~ 1.3 without E × B
- **Same effect when also evolving density**

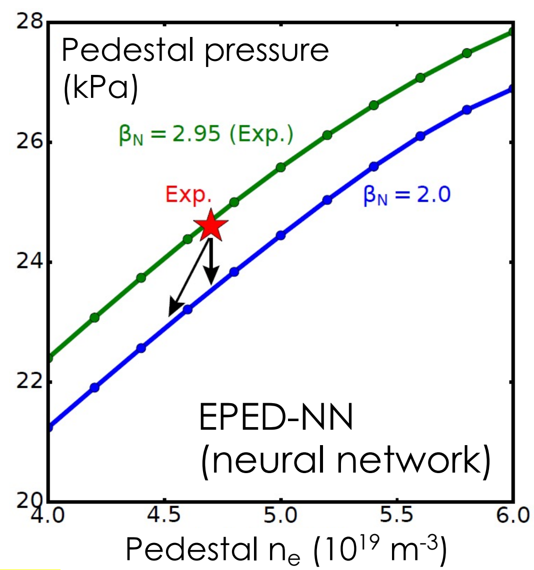


TGYRO Analysis Supports Empirical Low Rotation Extrapolation



- **H_{98y2} predicted with no E × B is reduced towards the empirical limit (dashed line) in self-consistent TGYRO-EPED modeling**
  - TGYRO: Drop in predicted profiles with no E × B → lower β_N
  - EPED: Lower β_N → Lower pedestal pressure ➔ TGYRO

- **P_{ped} decreases 5-7% due to predicted decrease of β_N with no ExB**



- **Predicted effect of E × B on H_{98} nearly completely accounts for empirical observations => Other physics effects play small role**

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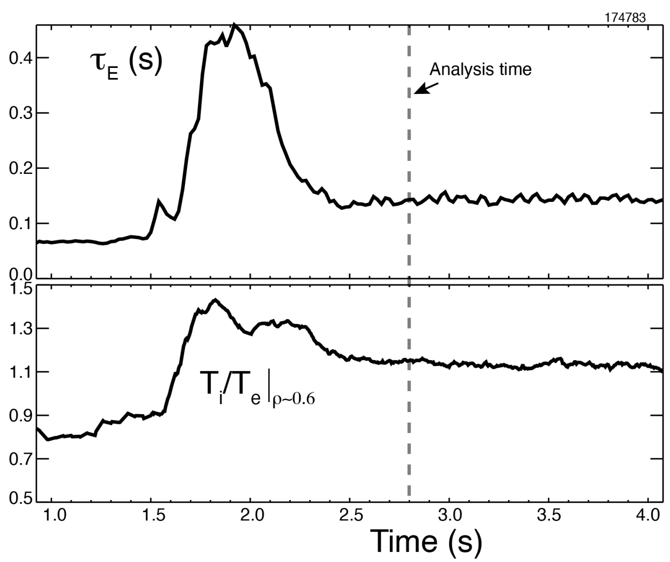
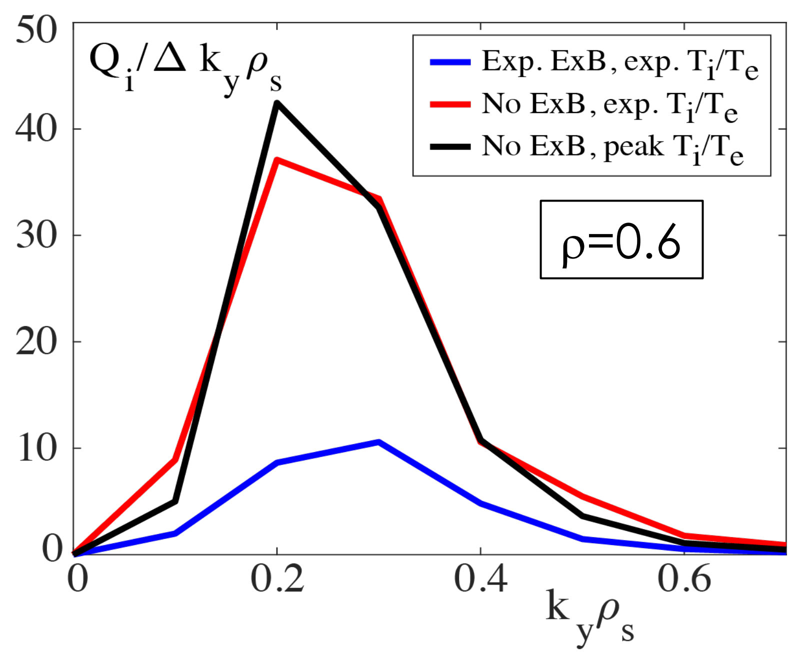
CGYRO Nonlinear Modeling also Shows Large Effect of ExB and Small Effect of T_i/T_e

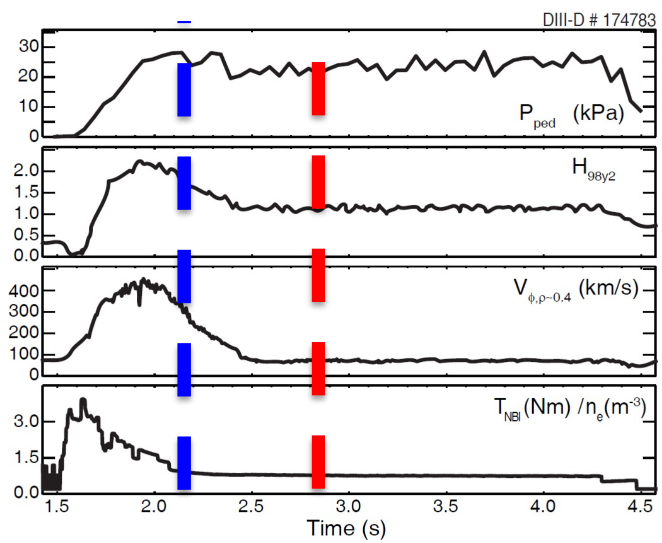
- **Large change in normalized ion energy flux is predicted when the E × B effect is removed**
- **Little effect is predicted when the T_i/T_e ratio is increased from the experimental value, ~1.15, to peak value achieved in discharge, ~1.35**
- **Other effects, such as fast ion or electromagnetic effects are also predicted to be much smaller than the E × B effect** [Xiang Jian et al, to be submitted]





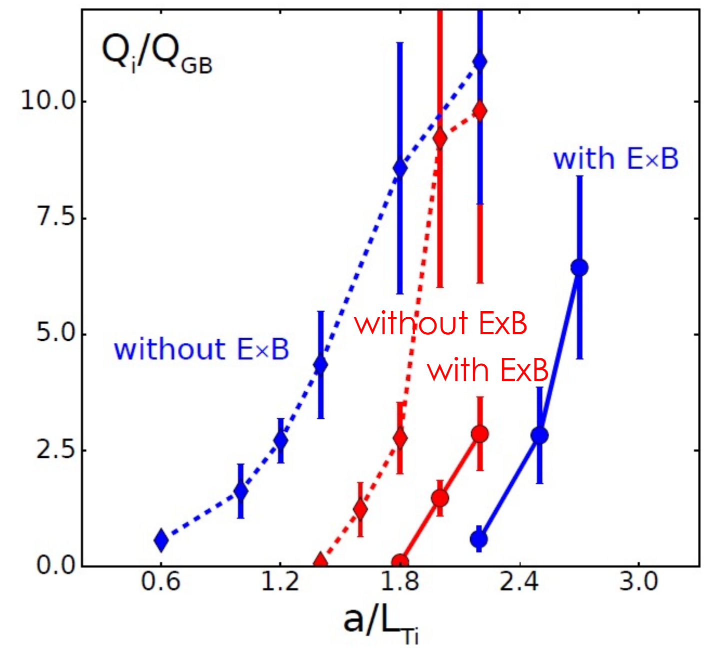
Large Upshift of Nonlinear Critical Gradient for ITG Identified by CGYRO with E × B

- **CGYRO: a gyrokinetic code for turbulence simulations**
- **Target plasma: at low rotation and high rotation**
- **Other physics effects (T_i/T_e, fast ions and EM stabilization) have smaller impact on γ and Q_i**



Enable E × B Shear in the simulation, $a/L_{Ti,crit\text{-}NL}$

- **increases 30% in low rotation case**
- **increases 300% in high rotation case**
- **Higher rotation, larger upshift by E × B**

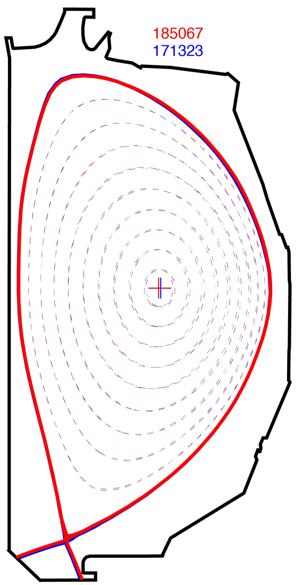


Higher critical gradient → higher a/L_{Ti} at given heat flux → higher confinement

New Experiments with Low torque Throughout Exhibit the Predicted Low-rotation Confinement, H_{98y2} ~1.2

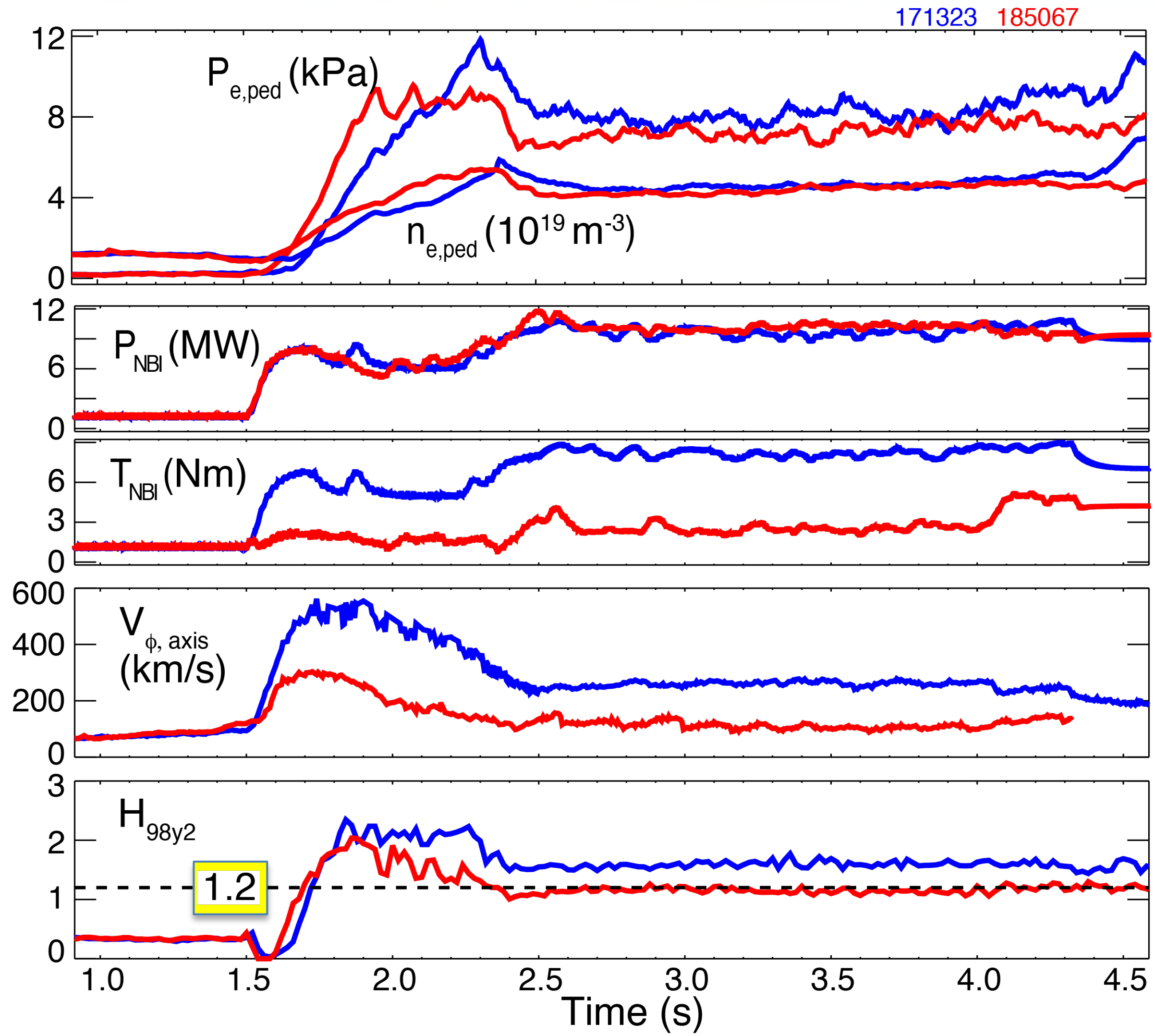
- **Same shape, density, power, lower torque (and rotation)**
- **Pedestal pressure slightly lower because of lower β_N, as predicted**

→ lower confinement, as predicted



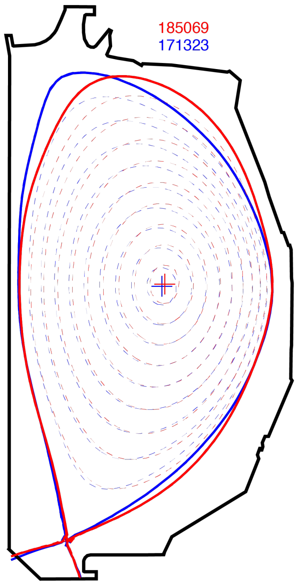
β_N ~2.8

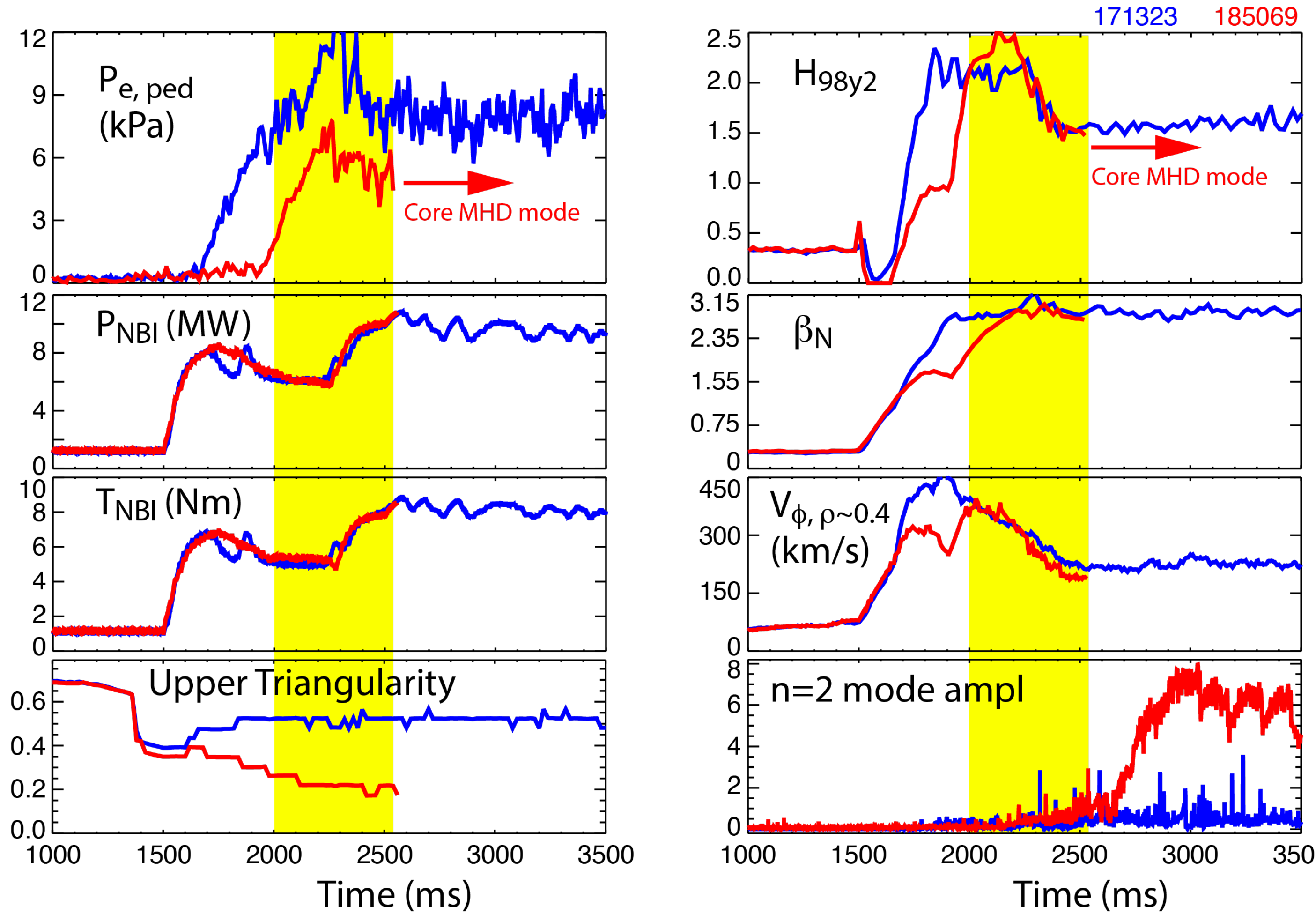
β_N ~2.1



New Experiments with Lower Shaping (Lower Pedestal) Exhibit Same High Confinement at Matching High Rotation

- **Lower triangularity → lower pedestal (consistent with EPED predictions)**
- **Lower pedestal → same confinement, until n=2 mode**





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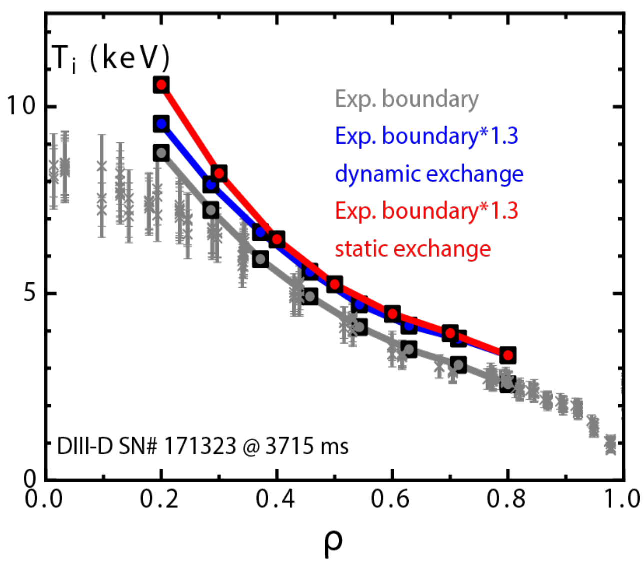
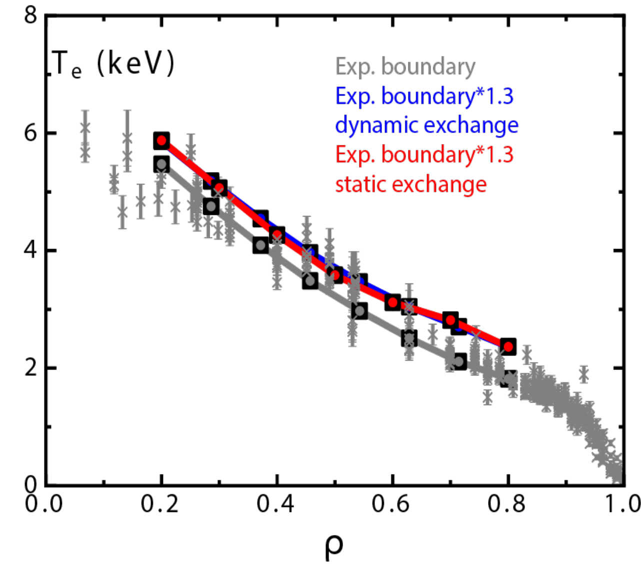
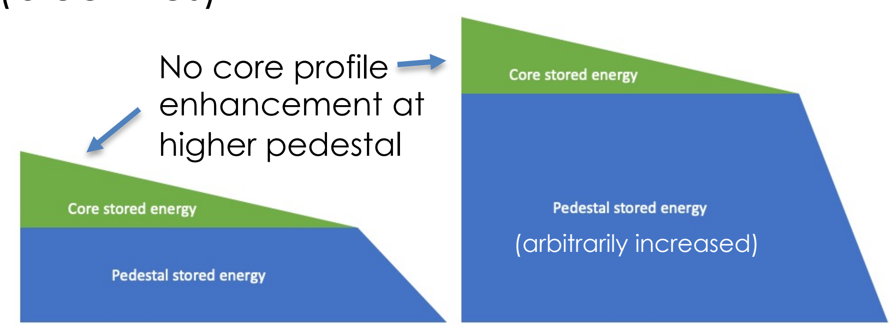
Pedestal Temperature Scan in TGYRO Modeling Shows No "Core Amplification" from Stiff Transport

- **Artificially change temperature boundary condition in TGYRO modeling**
  - $T_{i,e,ped} \times 1.3$
  - Pedestal density is not changed
  - Experimental $E \times B$
- **Dynamic ion-electron exchange (standard):**
  - Temperature increases uniformly: $\delta T = \delta T_{BC}$ (blue lines)
  - No core confinement improvement
- **Static ion-electron exchange:**
  - Weak core amplification of the boundary (red lines)
  - Could be analogous to experimental cases with very weak ion-electron coupling, for example at low density







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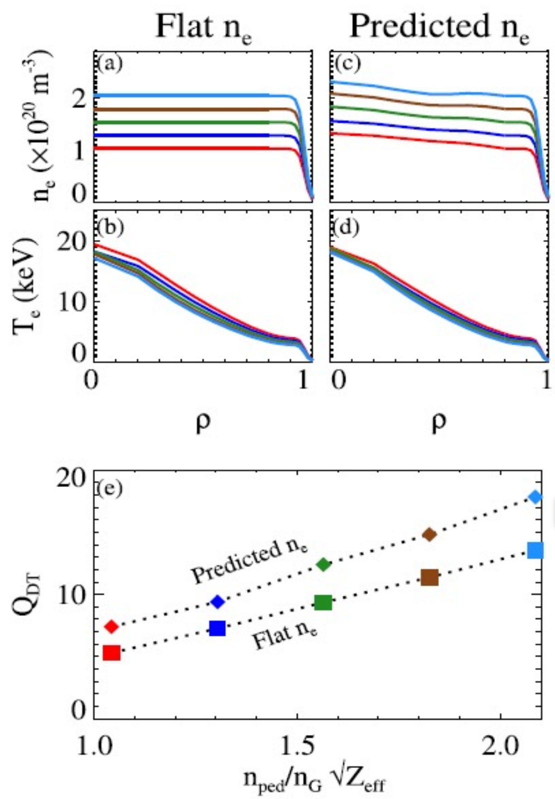
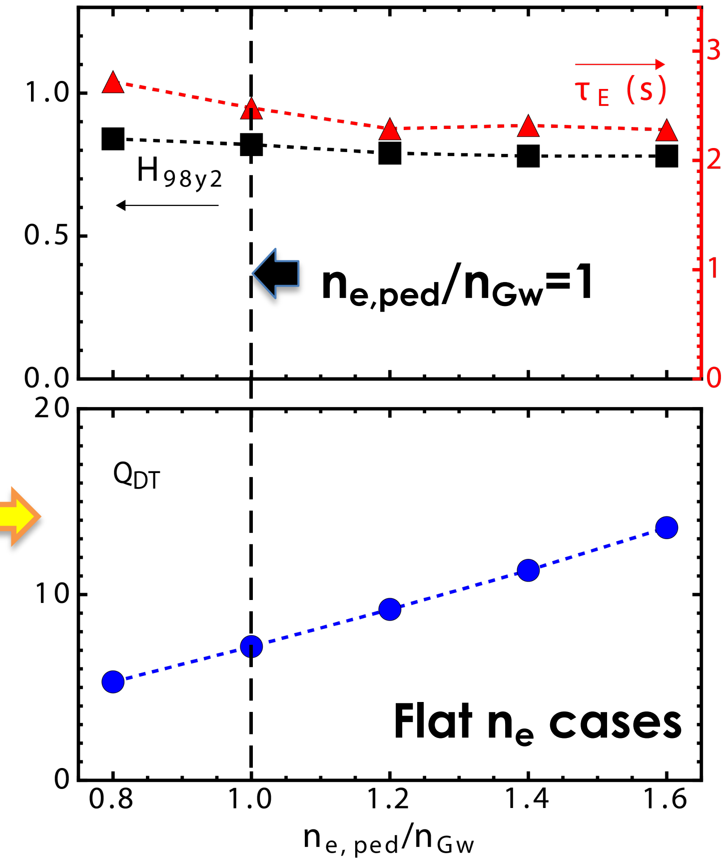
ITER Super H-mode Modeling Shows Q>10 at Pedestal Density above Greenwald Fraction, but $H_{98} \leq 1.1$

- **Q≤10 predicted within the pedestal density Greenwald limit**
- **H_{98y2}~0.8-0.85 for flat n_e cases**
- **Predicted n_e cases have ~30% higher Q, thus may have H_{98y2}~1.0-1.1**



[Solomon et al, PoP 2016]



Improvement in Q at higher pedestal density due to higher core density, NOT to higher energy confinement time

High Rotation (and Related ExB Shear), not High Pedestal, Enables H_{98y2}>>1 in Super H-mode Experiments

- **Correlation observed experimentally: energy confinement quality correlates with toroidal rotation instead of pedestal pressure in super H-mode experiments on DIII-D**
- **Causality is revealed by modeling**
  - Without E × B, TGYRO predicts similar confinement quality to empirical low rotation limit
  - Large upshift of nonlinear critical gradient for ITG identified by GK modeling with E × B, showing the governing physics in the core
  - E × B effect explains most confinement variation observed in Super H-mode experiments
- **Dedicated experiment to test role of pedestal, shows excellent agreement with "predict first" calculations (H_{98y2} = 1.2 at low rotation)**
- **Self-consistent transport/equilibrium modeling predicts ITER operating in Super H-mode could achieve Q~10 and H_{98y2} ~ 1.1 with pedestal density at Greenwald limit**
  - Q>10 by exceeding the pedestal density Greenwald limit (still with H_{98y2} ~ 1.1)