Transport at High β_p and Development of Candidate Steady State Scenarios for ITER

by

Joseph McClenaghan

with

A.M. Garofalo[1], J. Huang[2], G. M. Staebler[1], S.Y. Ding[2,3], D.B. Weisberg[1], L.L. Lao[1], X. Gong[2], J. Qian[1], Q. Ren[1], C.T. Holcomb[4], O. Meneghini[1], B.C. Lyons[1], S.P. Smith[1]

1. General Atomics
2. Institute of Plasma Physics, Chinese Academy of Sciences
3. Oak Ridge Associated Universities
4. Lawrence Livermore Nation Lab

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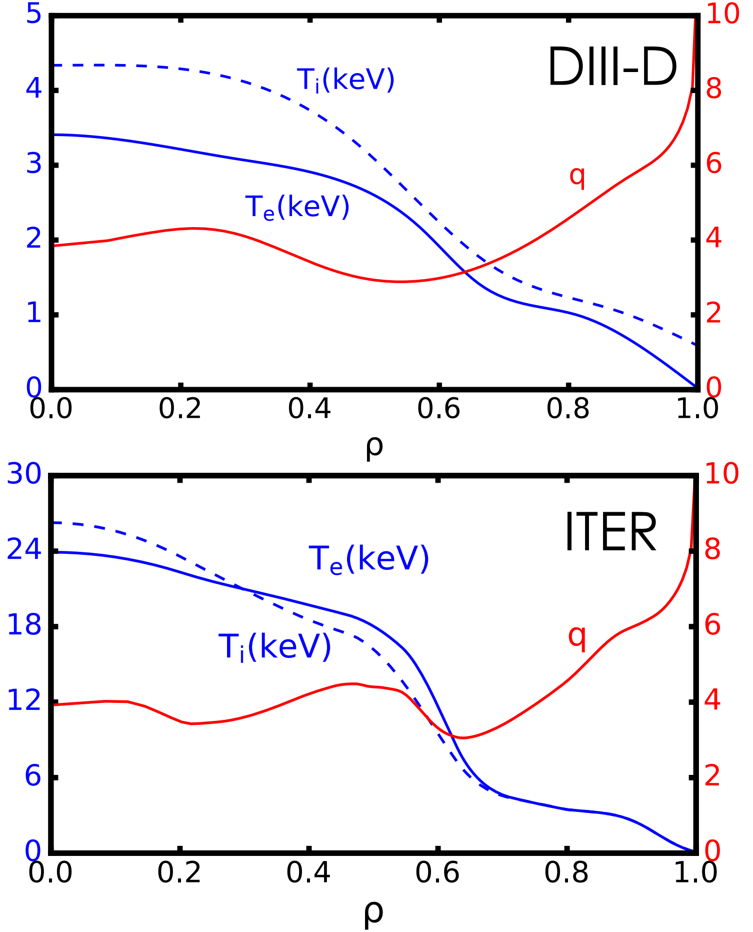
High β_p~2 ITB scenario is a promising candidate for ITER steady-state

- **Shafranov shift causes bifurcation in turbulent transport at high q_{95}~10**
- **ITB and enhanced normalized confinement ($H_{98,y2}$~1.8) maintained at q_{95}~6 on DIII-D with help of reverse magnetic shear**
- **Modeling suggests only modest reverse shear is needed for ITB prediction in ITER**



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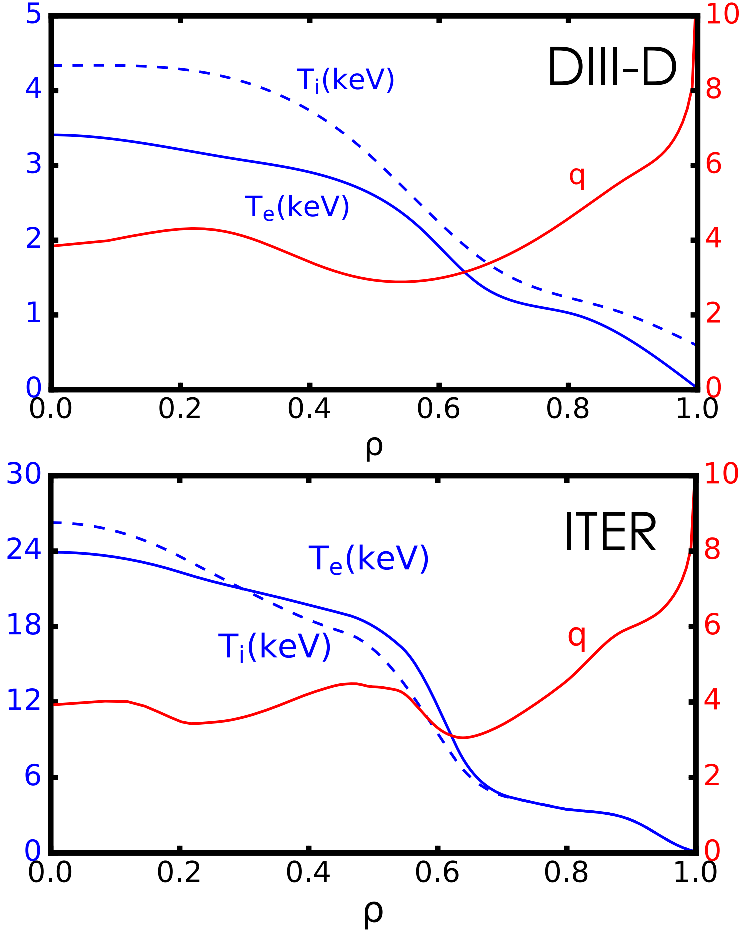
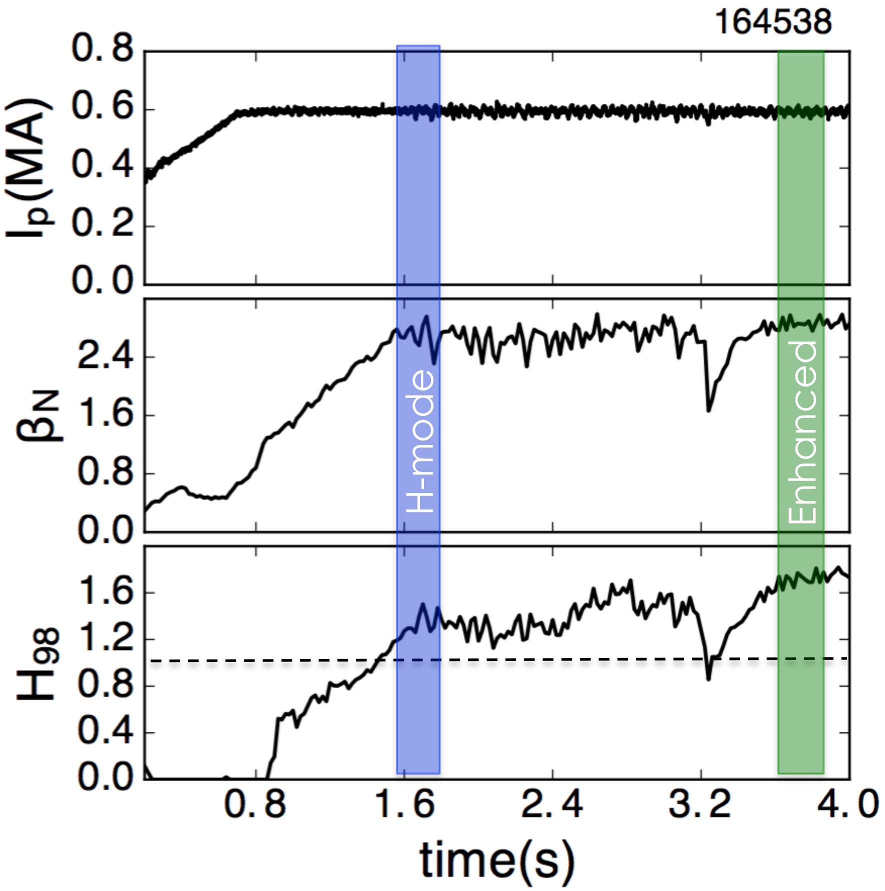


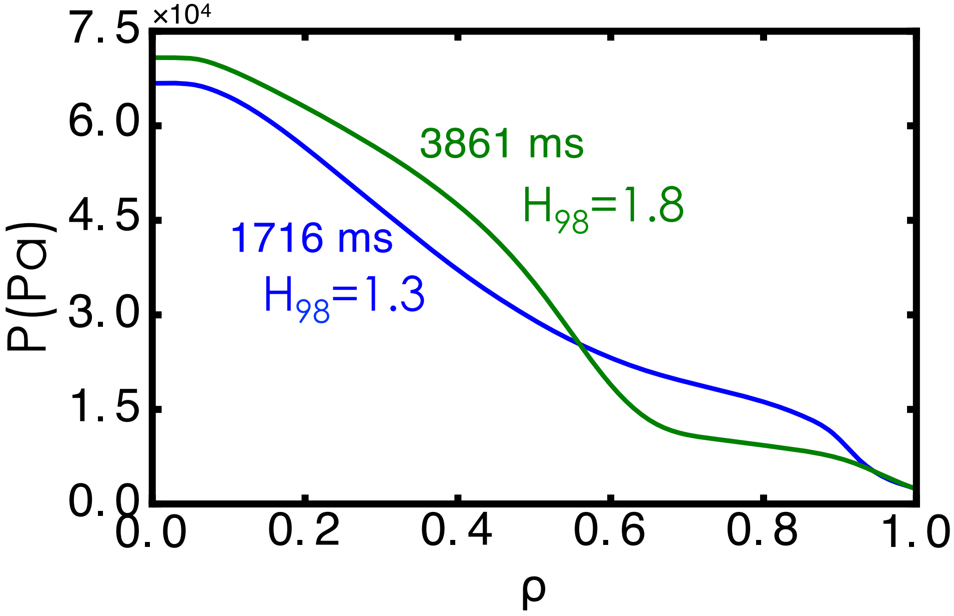
The high q_{95} high β_p scenario transitions to high confinement at fixed β

- **High performance typical operation:**
  - $\beta_p \sim \beta_N \sim 3$, $f_{gw} \sim 1$, $f_{bs} \sim 0.8$, $q_{95} \sim 10\text{-}12$
  - $H_{98} > 1.5$ even at low torque
- **Multiple confinement states**
  - H-mode ($H_{98}=1.3$)
  - Enhanced ($H_{98}=1.8$)
- **What is the difference between confinement states?**



H-mode and enhanced confinement states have very different pressure profiles

- **Enhanced confinement state has lower pedestal height**
- **Large radius transport barrier improves confinement**



Simple model predicts Shafranov shift and magnetic shear creates bifurcation in transport

- **For circular flux surface large aspect ratio limit, the drift frequency is:**

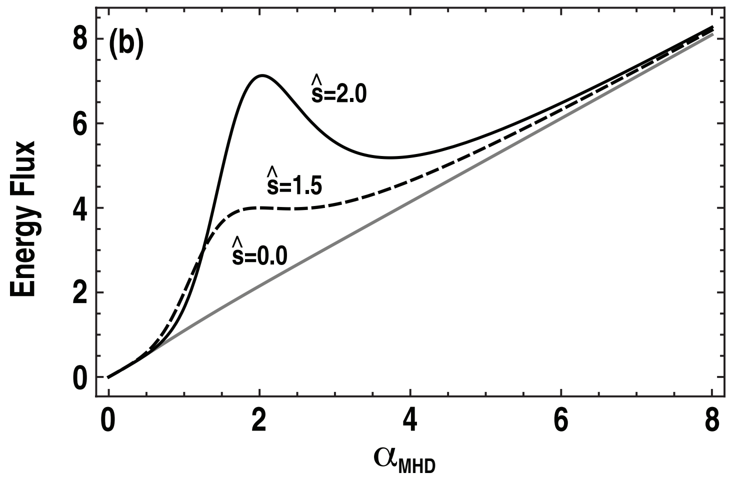
$$\bar{k}_\perp \cdot \bar{\mathrm{v}}_{da} \cong k_\theta \frac{m_a\left(2\mathrm{v}_\parallel^2 + \mathrm{v}_\perp^2\right)}{2e_a R_0}\left[1+\left(-\frac{1}{2}+\hat{s}-\alpha\right)\theta^2\right]+\ldots$$

Magnetic shear

$$\hat{s} = \frac{r}{q}\frac{dq}{dr}$$

Shafranov shift

$$\alpha = -R_0 q^2 \frac{d\beta}{dr}$$



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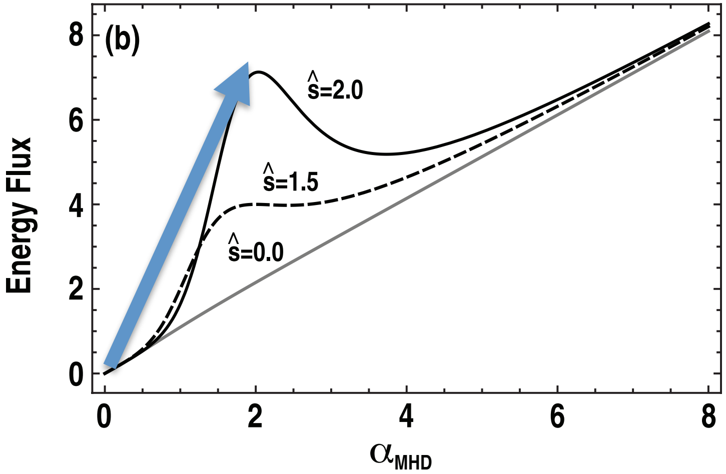

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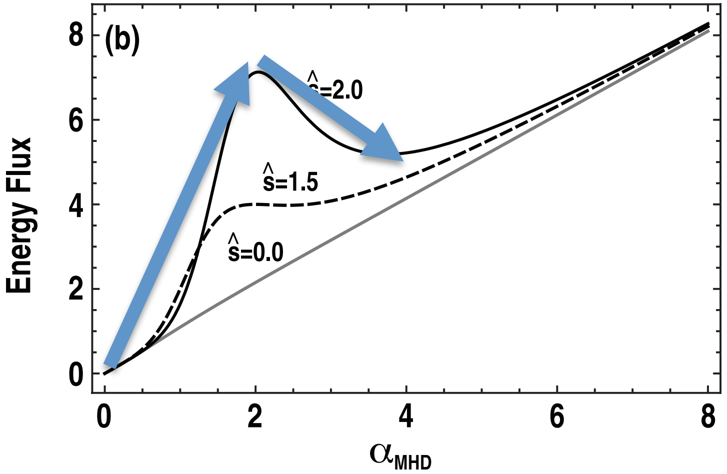

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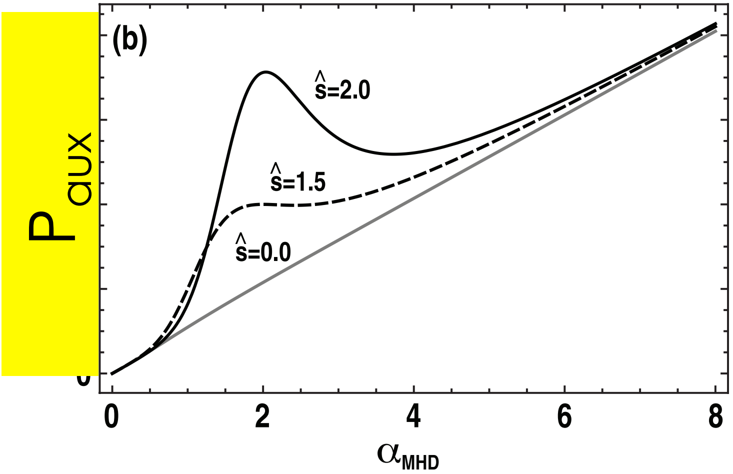

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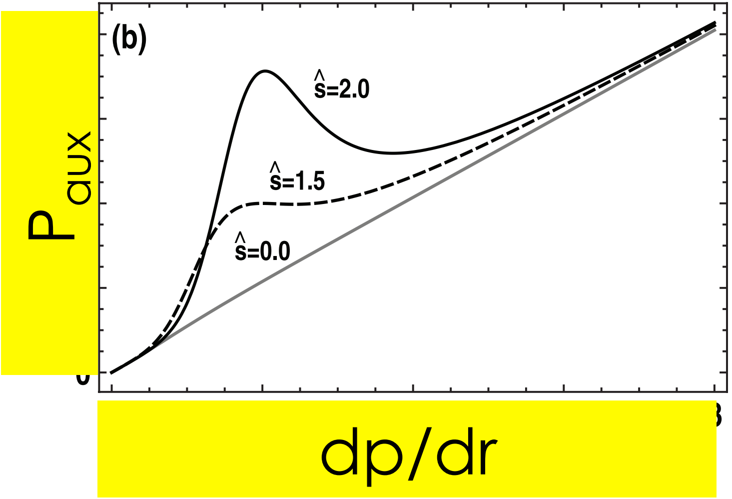

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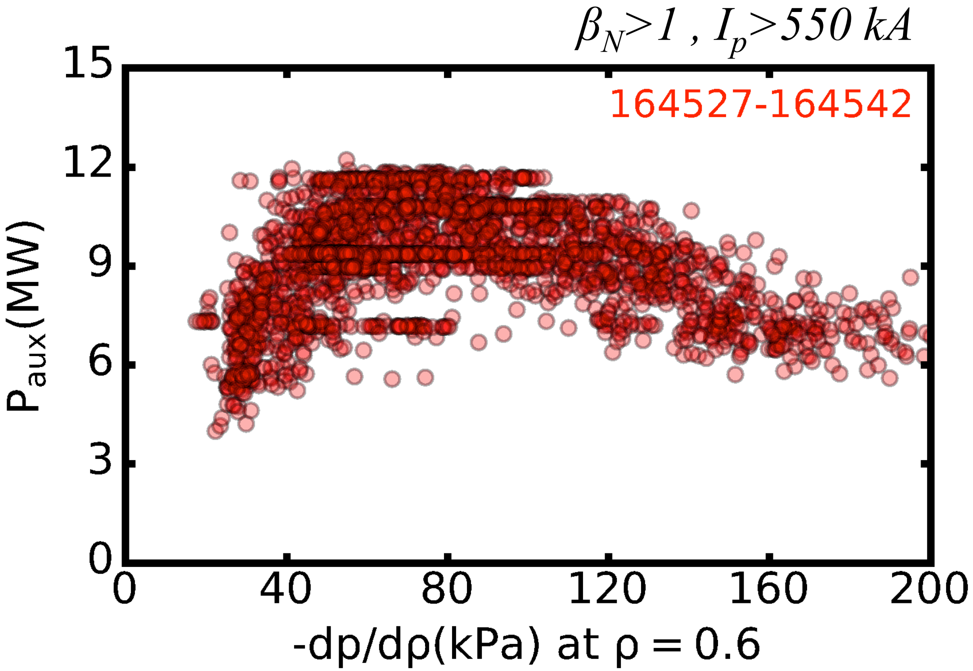
Bifurcation of transport with mid-radius pressure gradient observed when plasma is in β_N feedback

- **β_N feedback**
  - P_{aux} is dependent on p



Bifurcation of transport with mid-radius pressure gradient observed when plasma is in β_N feedback

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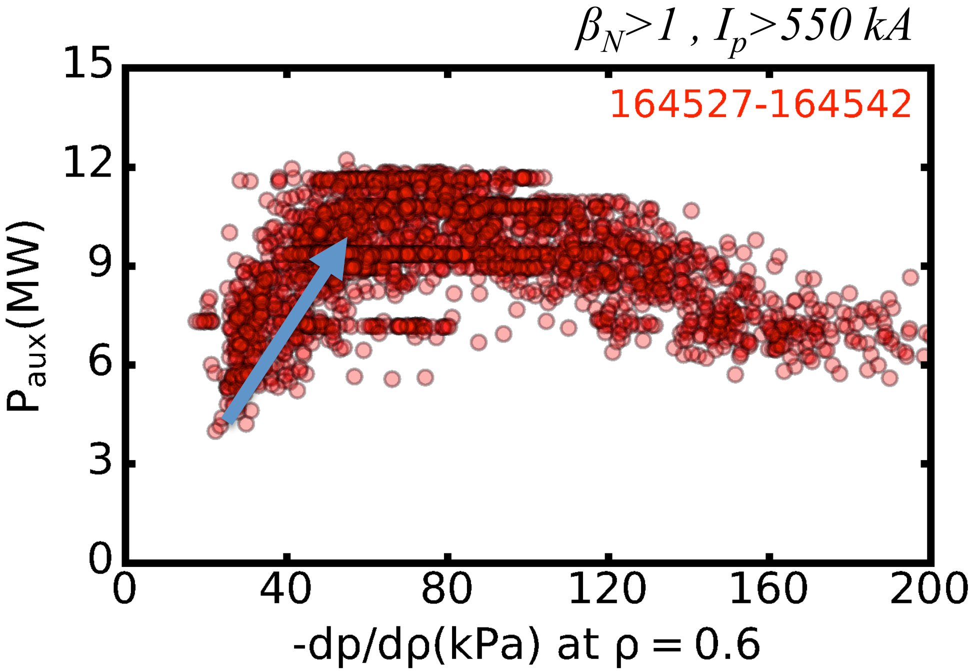
- **Small dp/dρ**
  - Increasing pressure gradient increases required P_{aux}



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- **β_N feedback**
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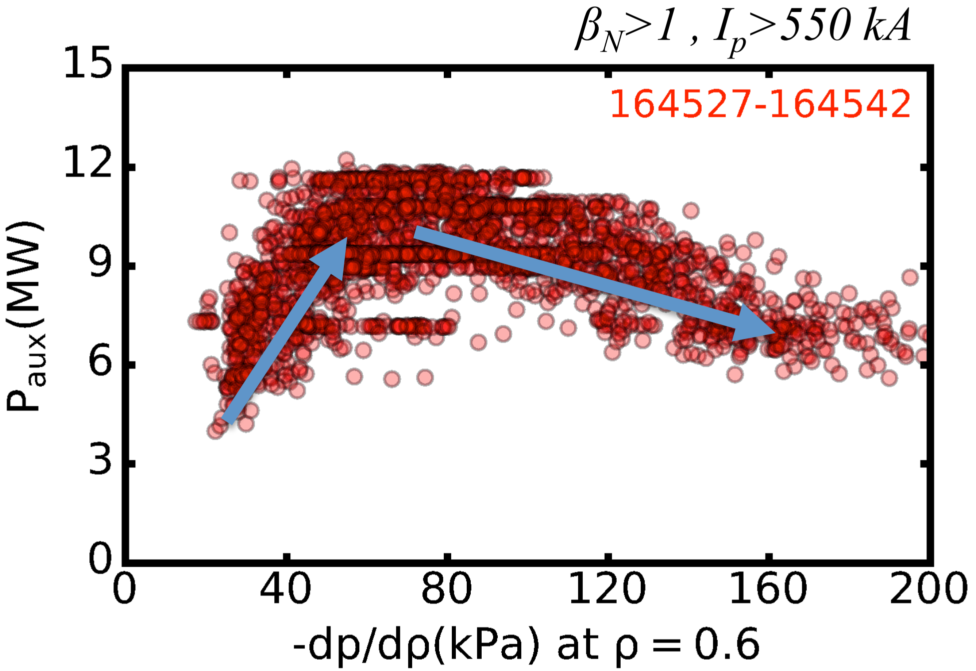
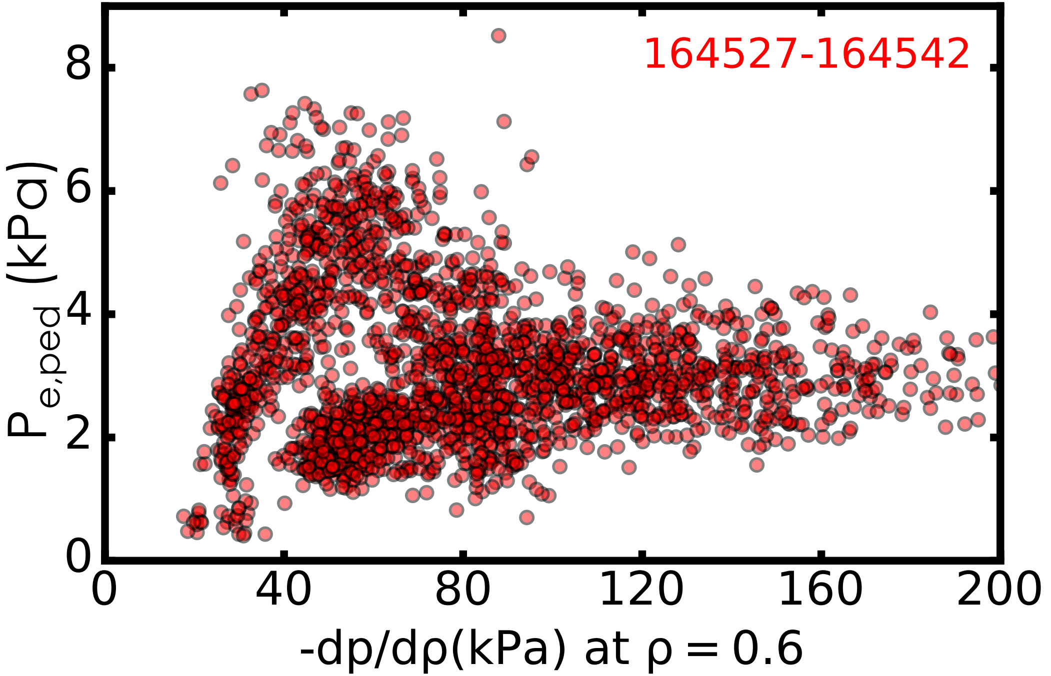


Two distinct pedestal states are observed in high β_p scenario



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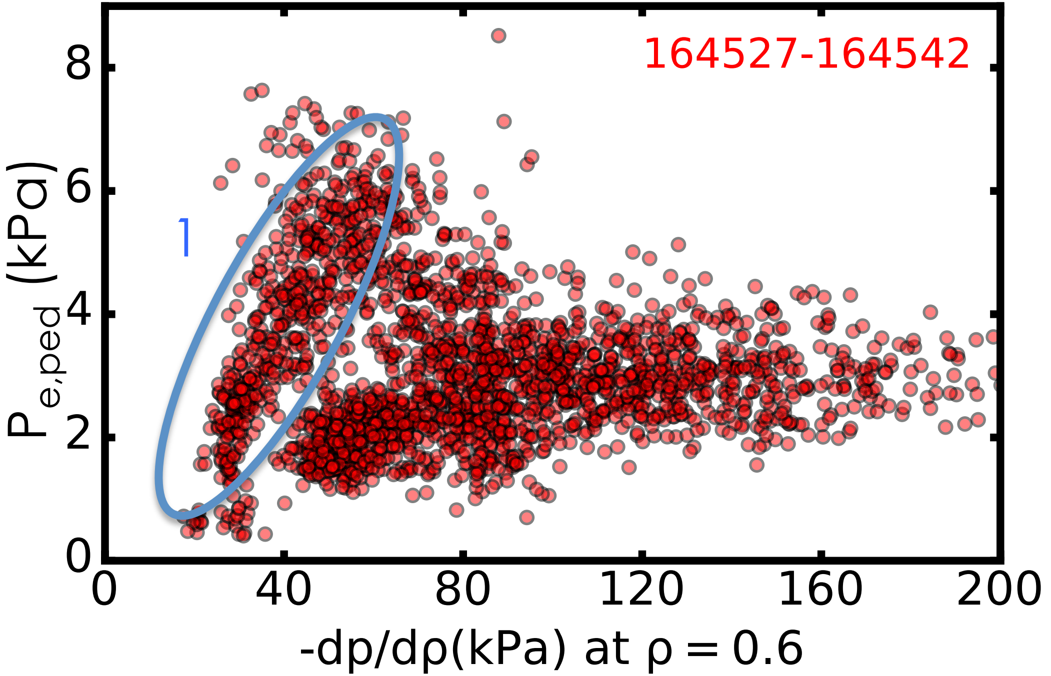

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- **High pedestal, low mid-radius pressure gradient state**
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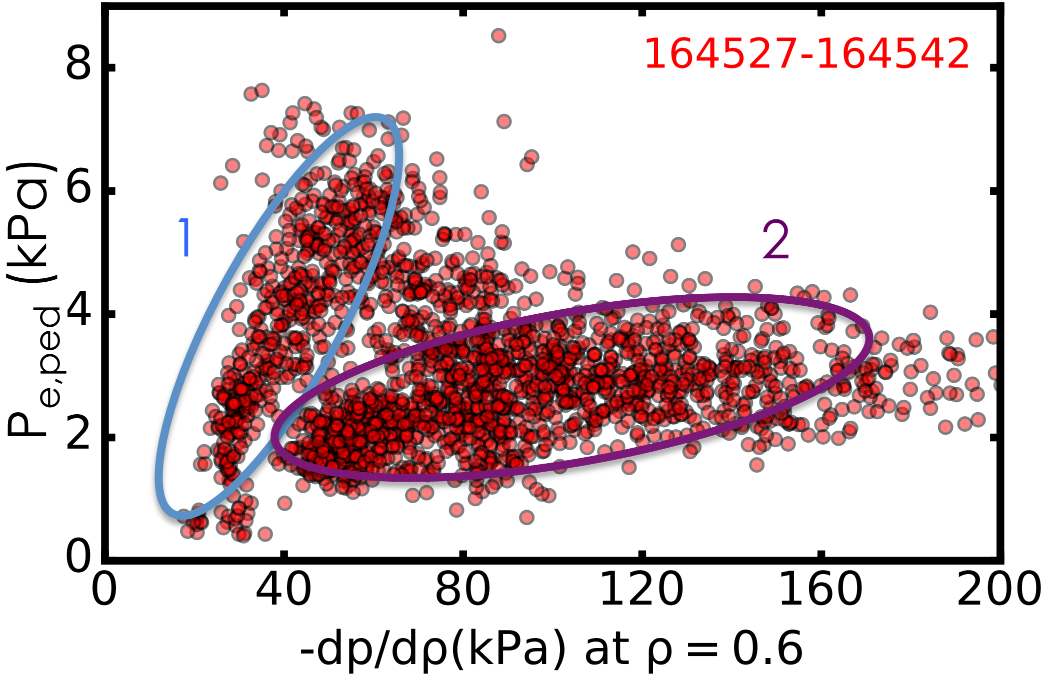
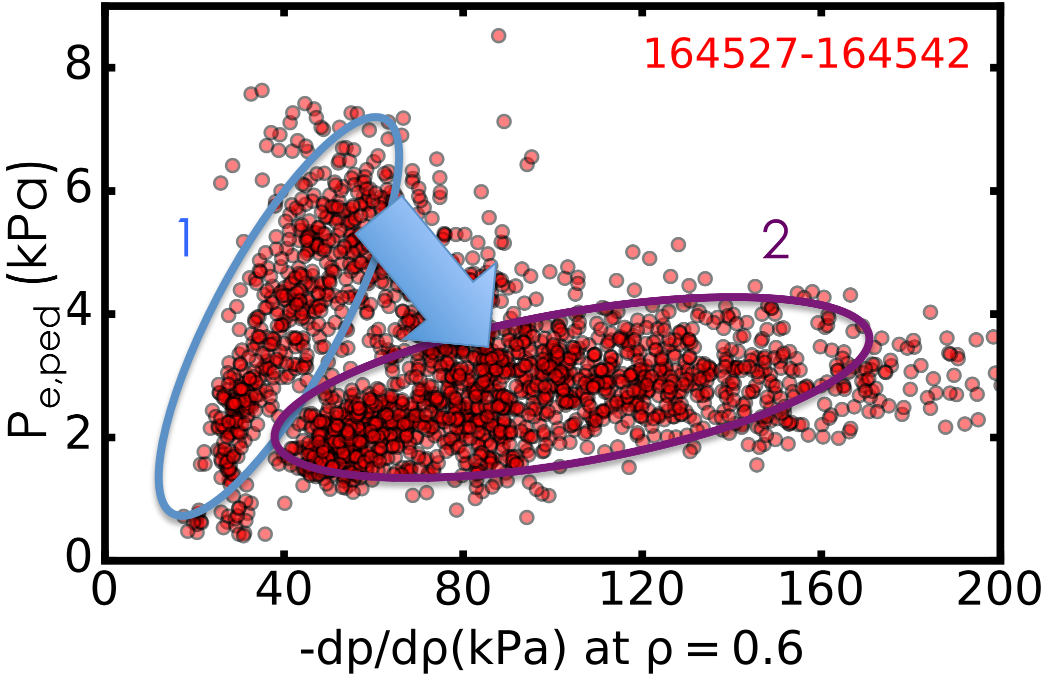


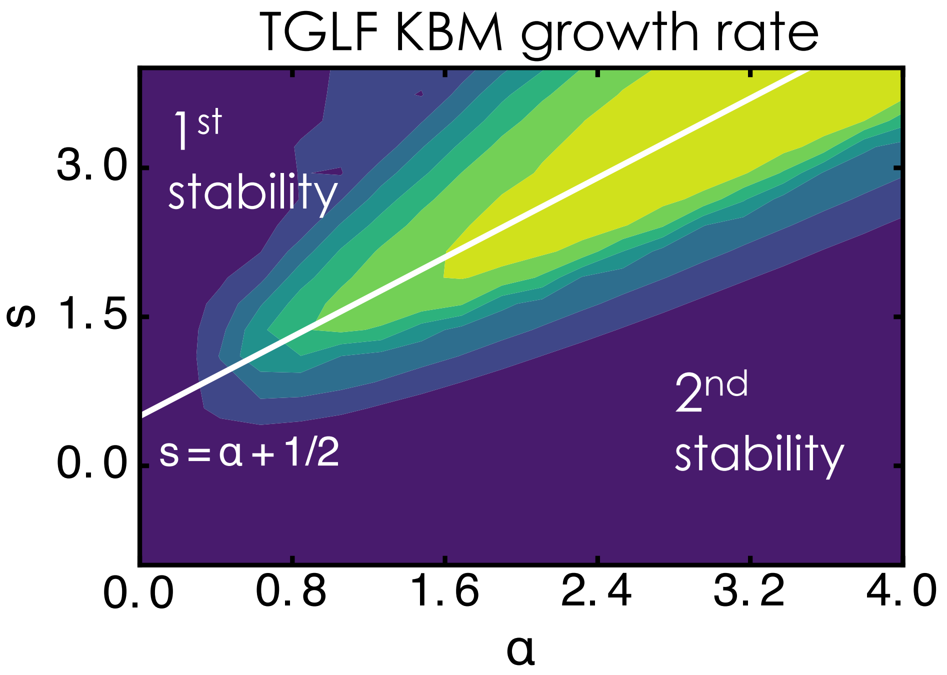
Two distinct pedestal states are observed in high β_p scenario

- **High pedestal, low mid-radius pressure gradient state**
- **Low pedestal, high mid-radius pressure gradient state**
- **Transition between states is usually triggered by ELM**



TGLF transport code used to analyze core transport

- **Quasilinear gyro-Landau fluid code fit to non-linear gyrokinetic turbulence simulations**
- **Recent correction to Ampere's Law leads to prediction of KBM mountain, which is important in predicting high β_p ITB plasmas**



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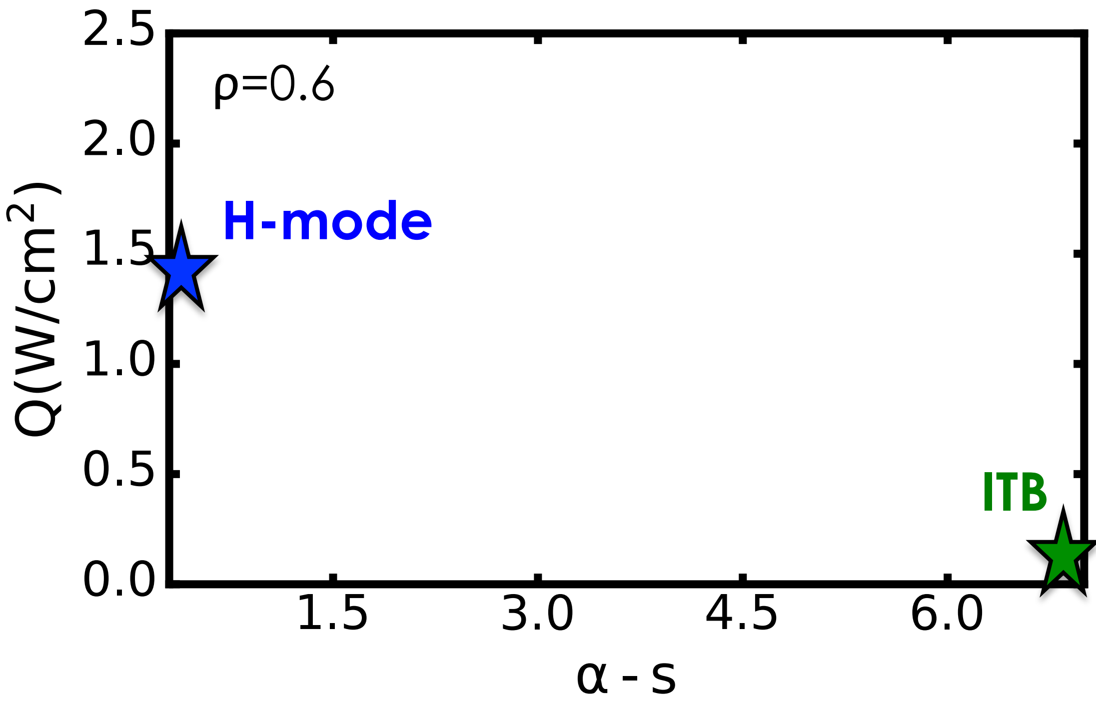
TGLF predicts transport at ρ=0.6 decreases as ITB forms

- **Predicted flux greater for H-mode state**



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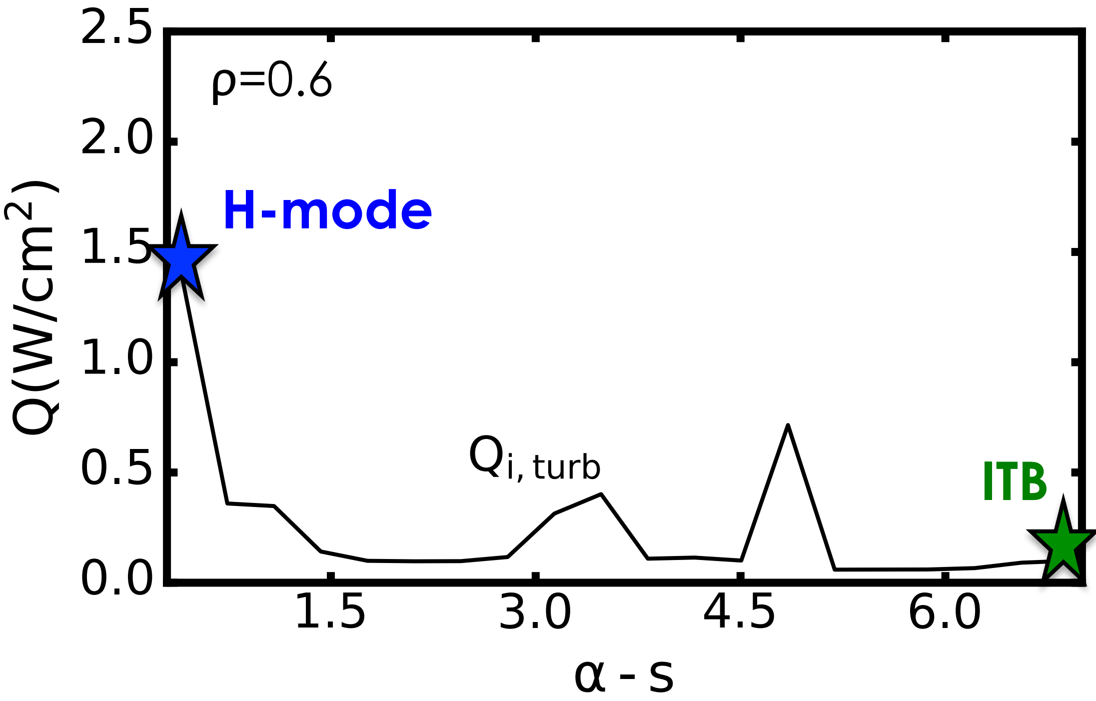
- **Predicted flux greater for H-mode state**
- **TGLF input linear interpolated for intermediate state**
- **At ρ=0.6, turbulence is stabilized as α-s increases**



Large electromagnetic transport in between two states at large radius ρ=0.8

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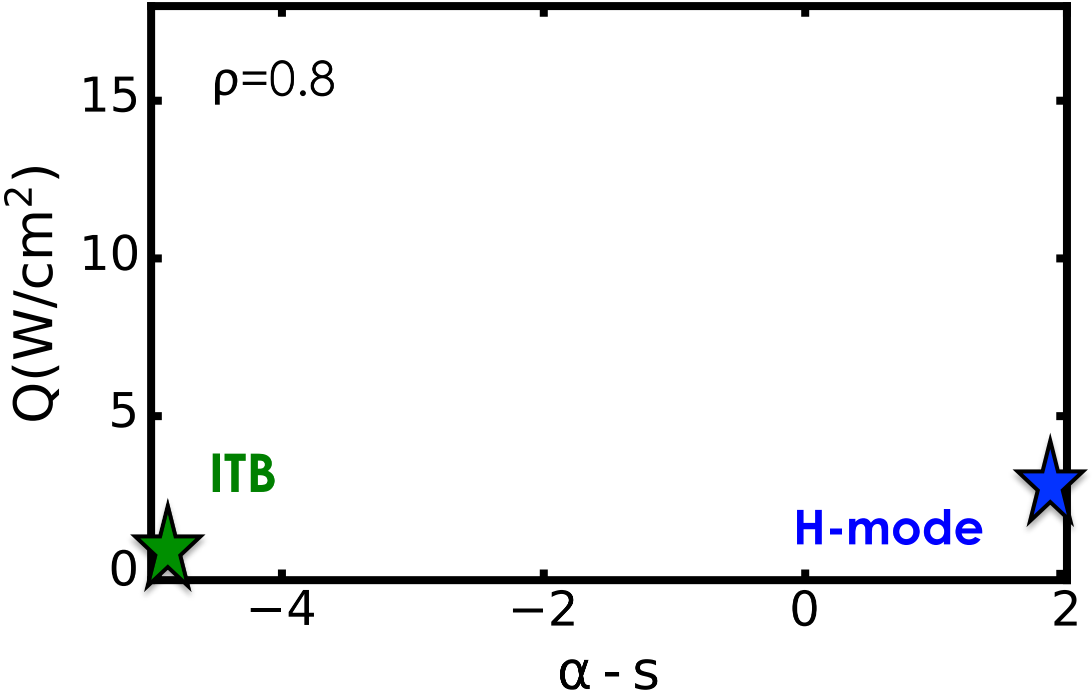

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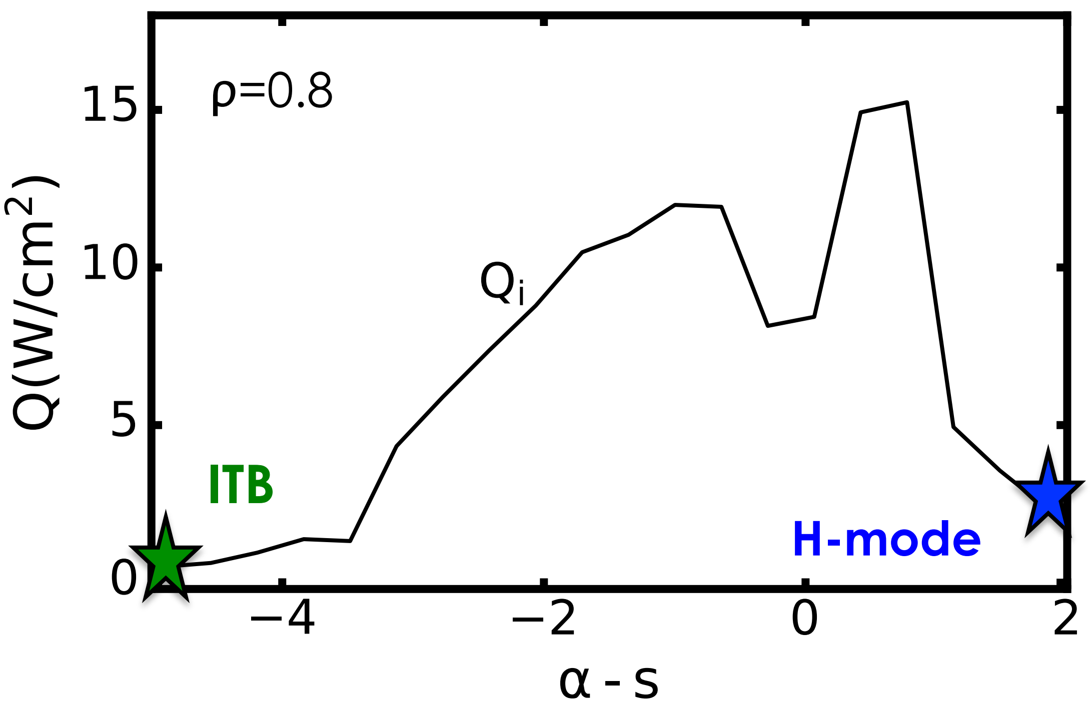
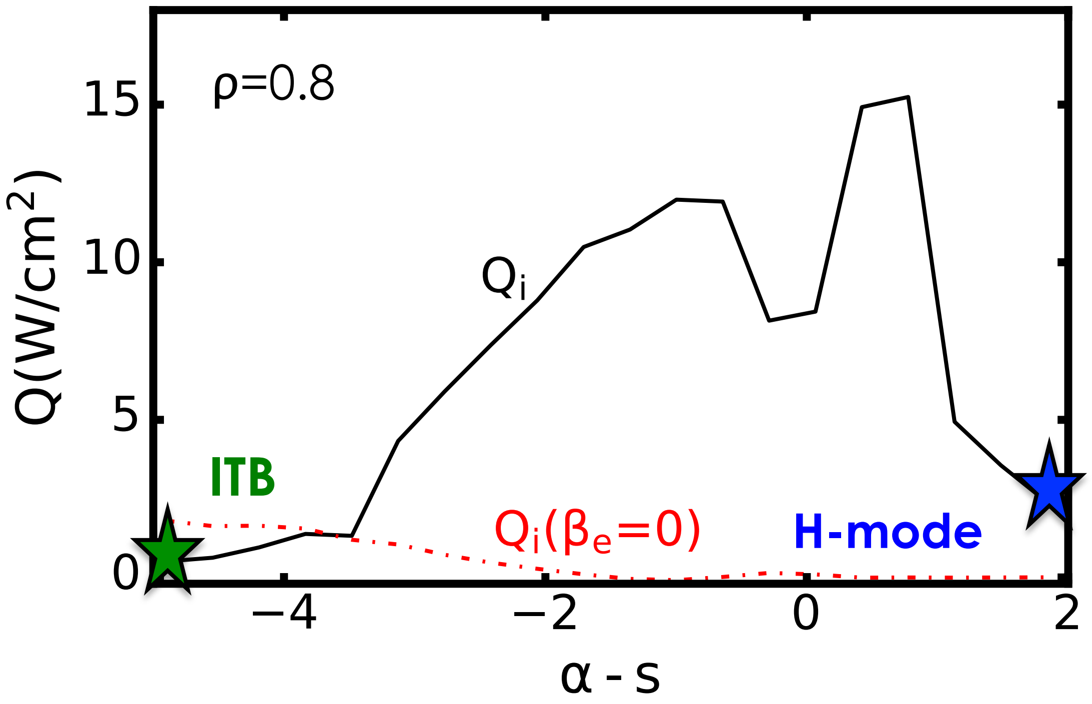


Large electromagnetic transport in between two states at large radius ρ=0.8

- Predicted flux greater for H-mode confinement state
- When β_e=0 (i.e. electrostatic), increasing α -s is stabilizing
- How does plasma cross the KBM mountain?



Large ELM could help plasma across KBM mountain

- **Large ELM that occurs 50 ms before ITB begins to form**
- **Allows transition from H-mode to ITB state**
  - ELM lowers edge T_e and increases mid-radius p'
  - Transiently lowers β_e at edge

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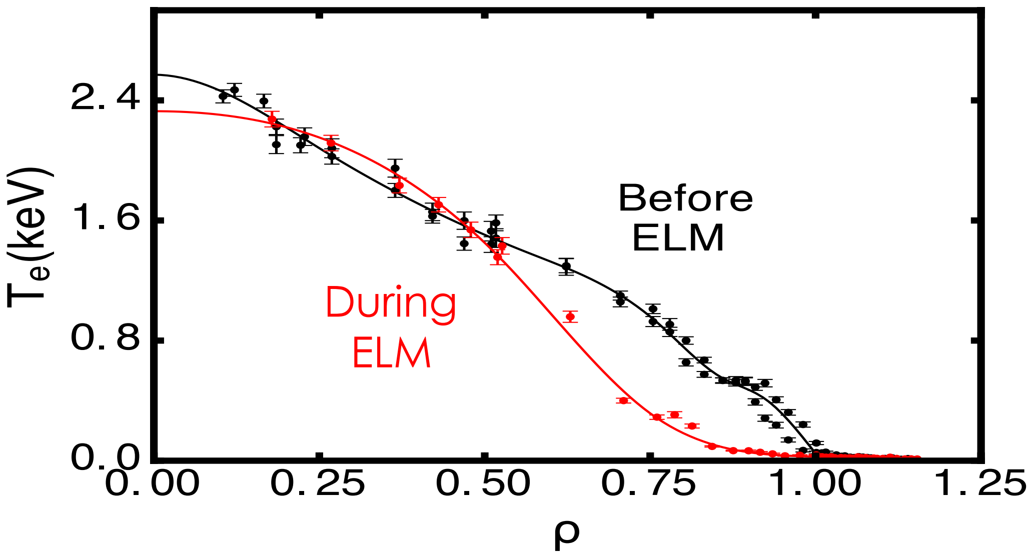

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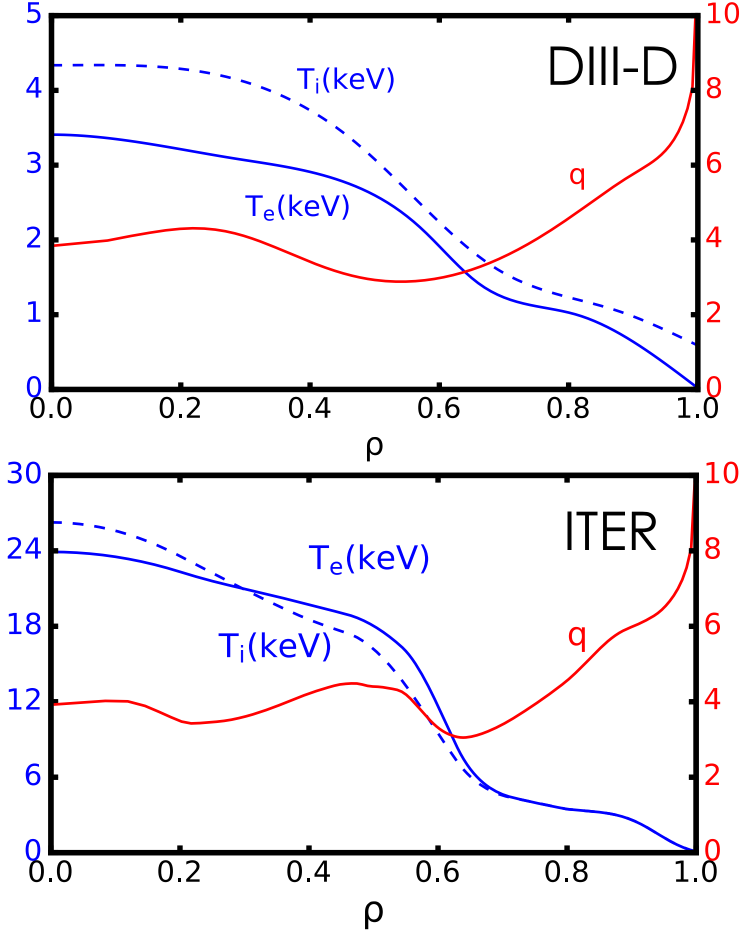

q dependence of Shafranov shift makes sustainment of ITB at lower q_{95} more difficult

Local measure of Shafranov shift:

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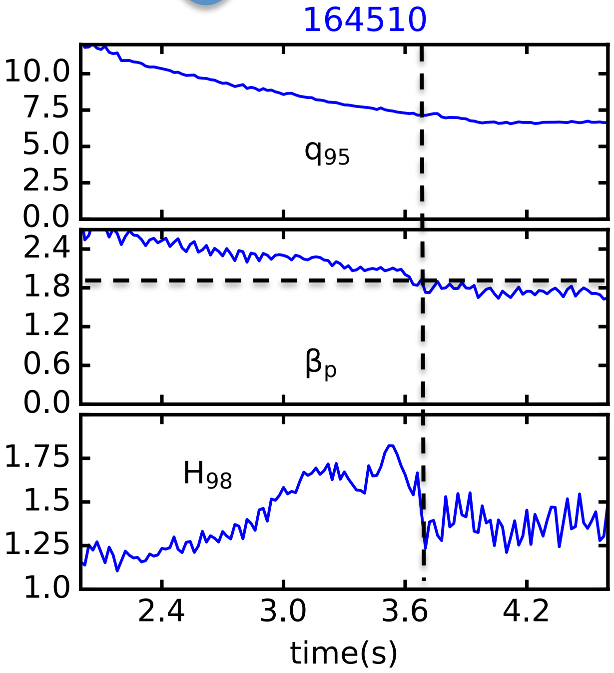

- **Plasma extended to lower q_{95}~6 via second current ramp**
  - allows plasma to get to near ITB conditions before going to lower q_{95}
- **Threshold β_p~1.9**

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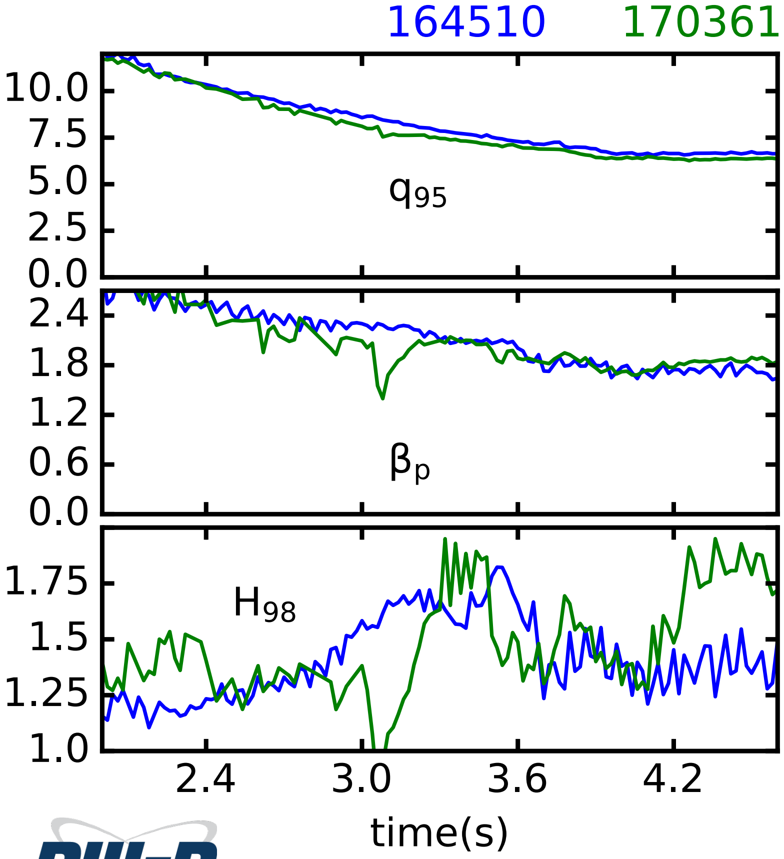
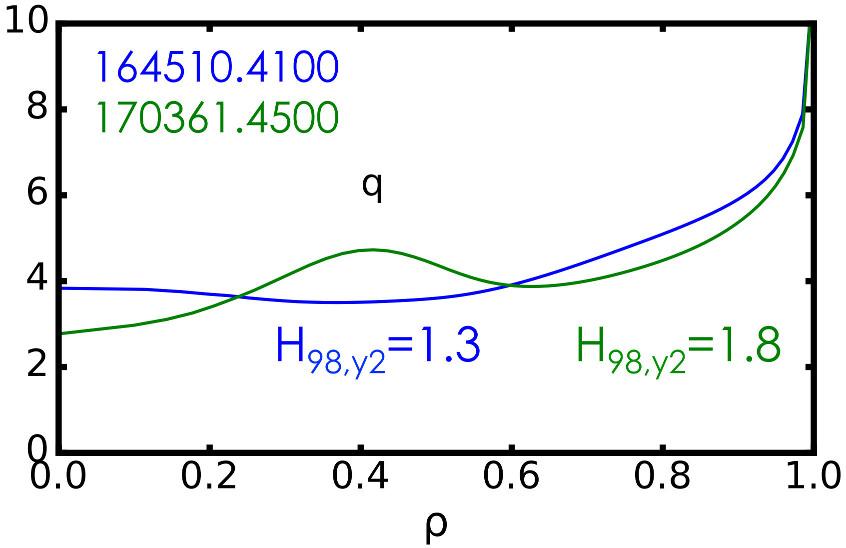
Enhanced confinement at q_{95}~6 has been achieved with reverse shear

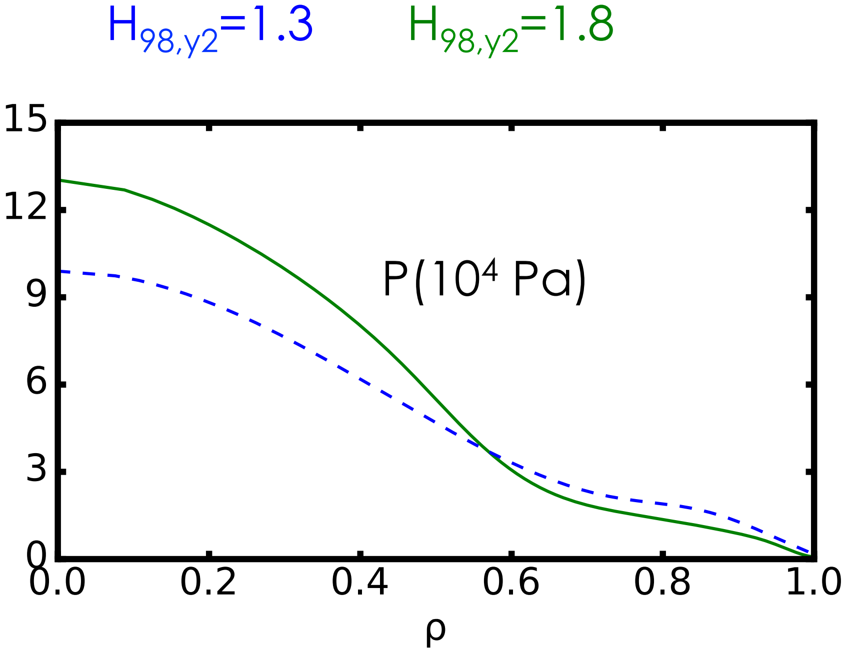


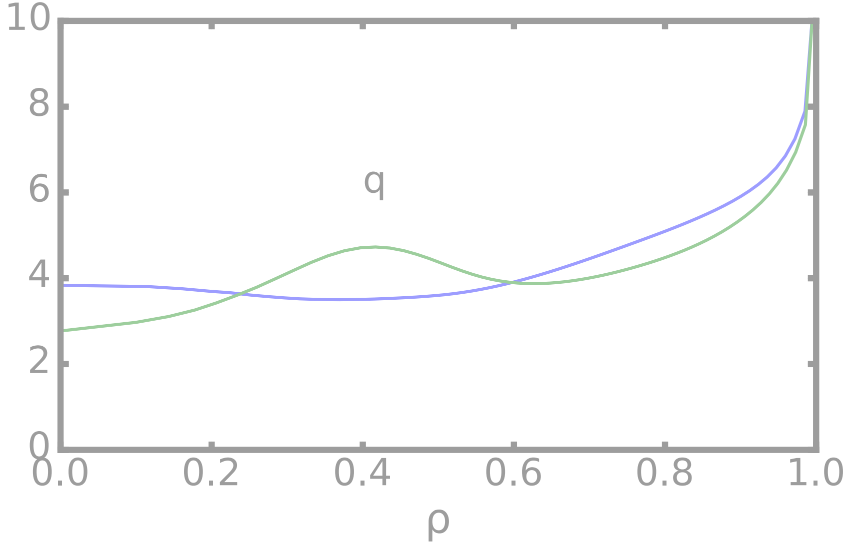
Reverse shear produced with use of off-axis beams



Simple model: α,s

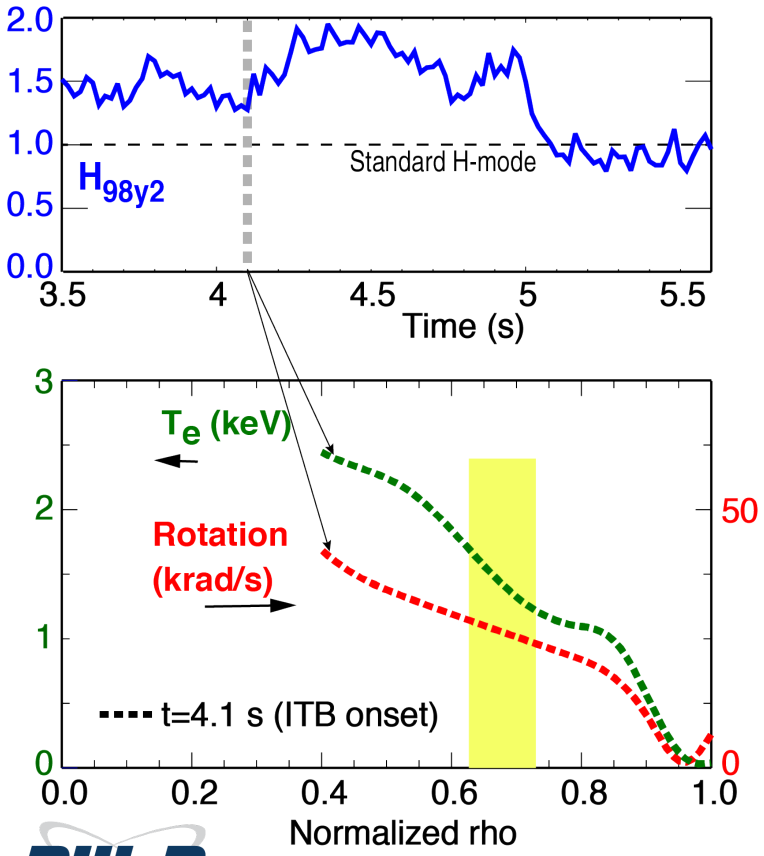
Lower pedestal observed with ITB (same as high q_{95}!)





Simple model: α,s

Rotation ITB does not align with temperature ITB, suggests that ExB shear not important for energy confinement



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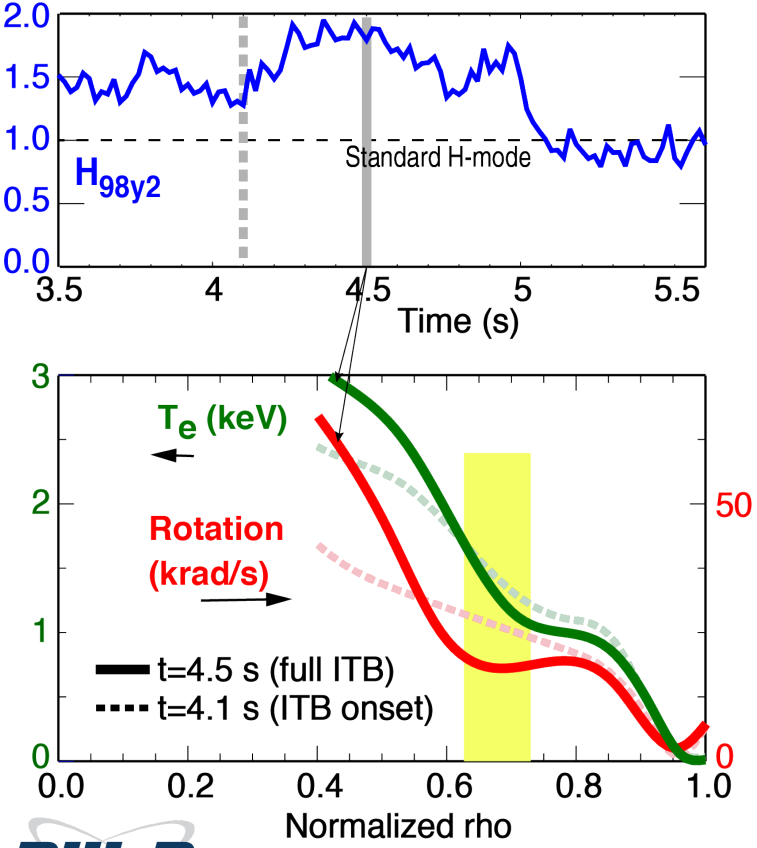

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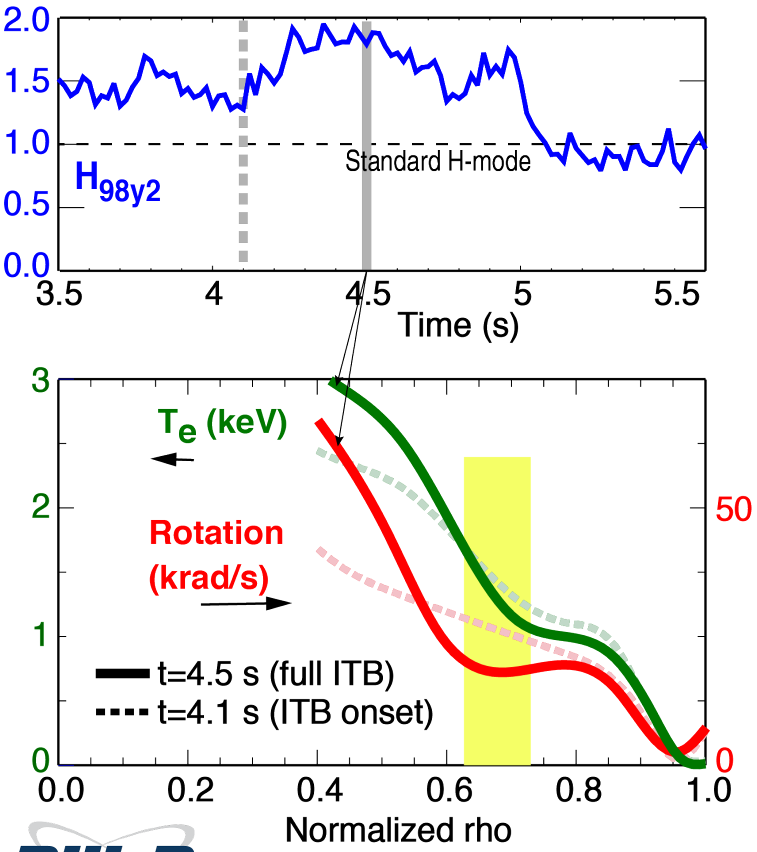
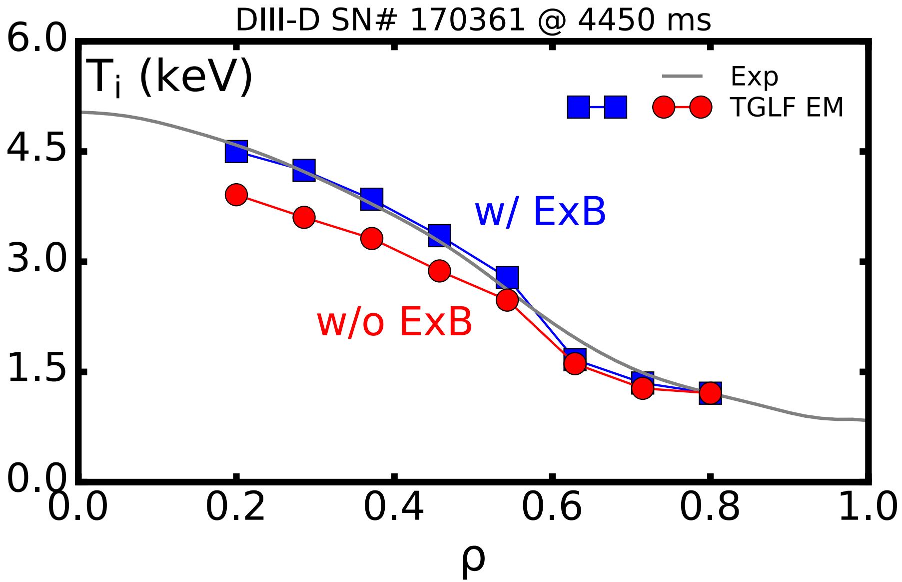


- TGYRO predictive simulation suggests ITB exists w/o ExB shear



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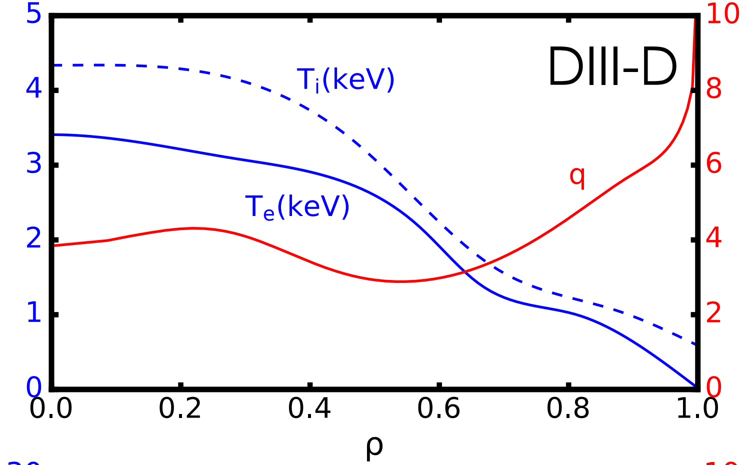
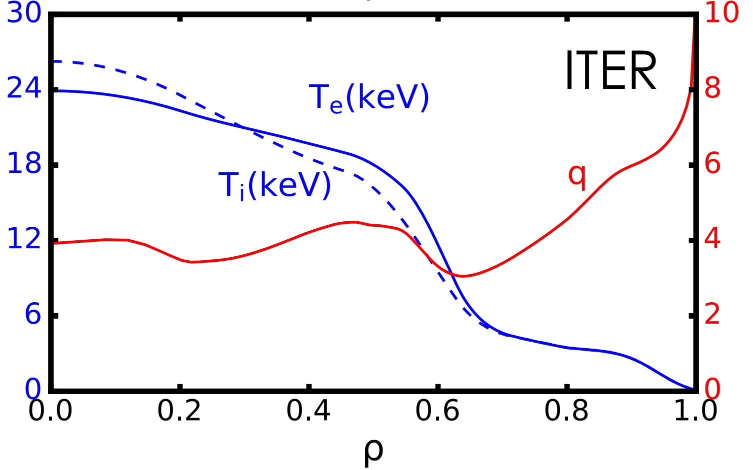
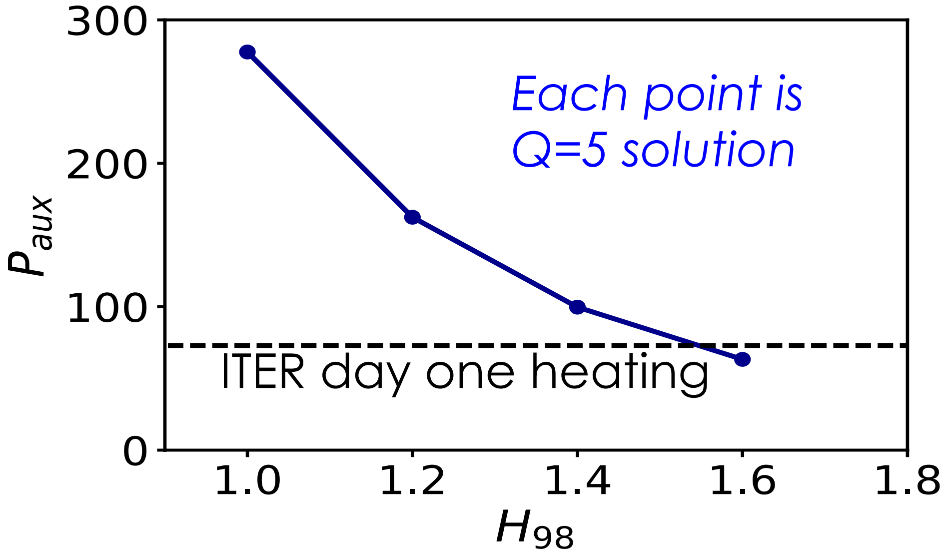




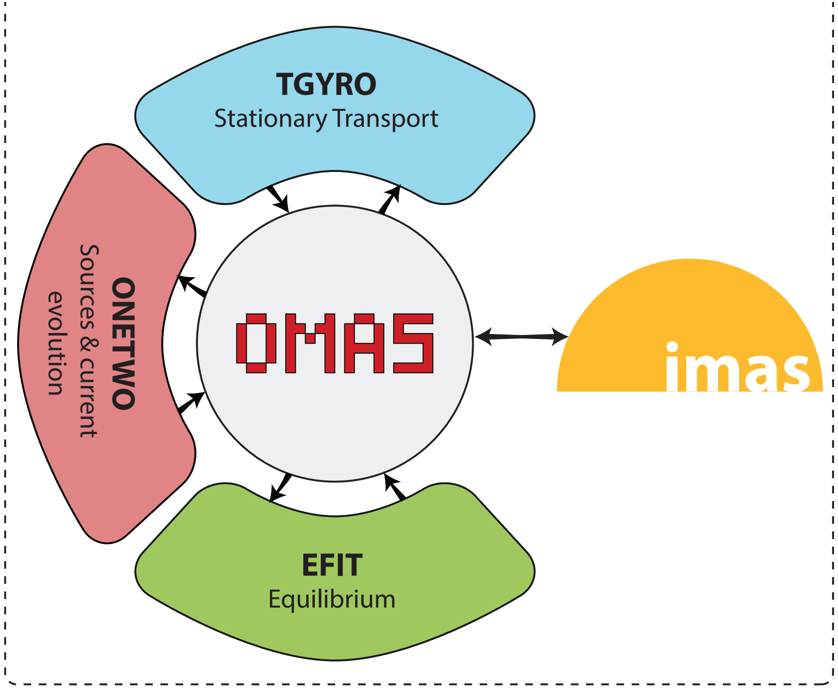
High confinement required to achieve ITER steady-state goal of Q=5 with day one heating

- **0D modeling using GA Systems Code**
- **Constraints include:**
  - f_{gw}=1, H_{98y2} , f_{NI}=1, Q=5
- **H_{98}~1.5 is required to achieve Q=5 with P_{aux} = 73 MW**



Iterative loop for integrated modeling is used to find self-consistent steady-state solution

- **Self-consistent modeling loop**
  - Iterate between kinetic evolution (TGYRO) current evolution (ONETWO), and magnetic equilibrium solver (EFIT)
- **T_i, T_e, n_e, q are evolved**
  - Day 1 heating: 33MW NNBI, 20MW ECCD, 20MW ICRF
  - ExB=0, $T_{e,ped}$=3.25 keV, I_p= 8 MA, f_{gw}~1.2

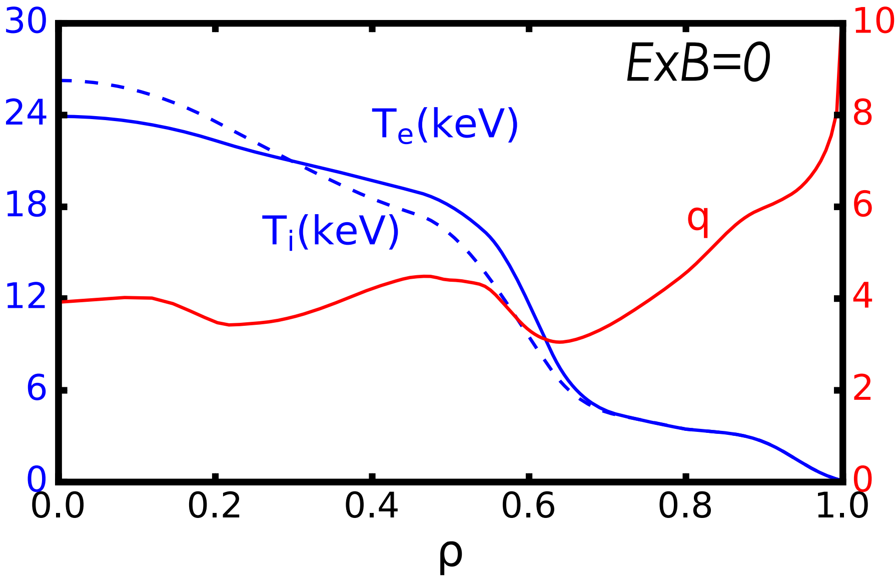


Meneghini TH/P6-16

Self-consistent modeling suggests that ITER ITB could be sustained with day one actuators

- **Converged prediction shows Q~6 solution with ITB and reverse shear**
  - However, Q is very sensitive to height of ITB

- **Predicted n=1 no-wall stable by GATO at β_N~3.2**



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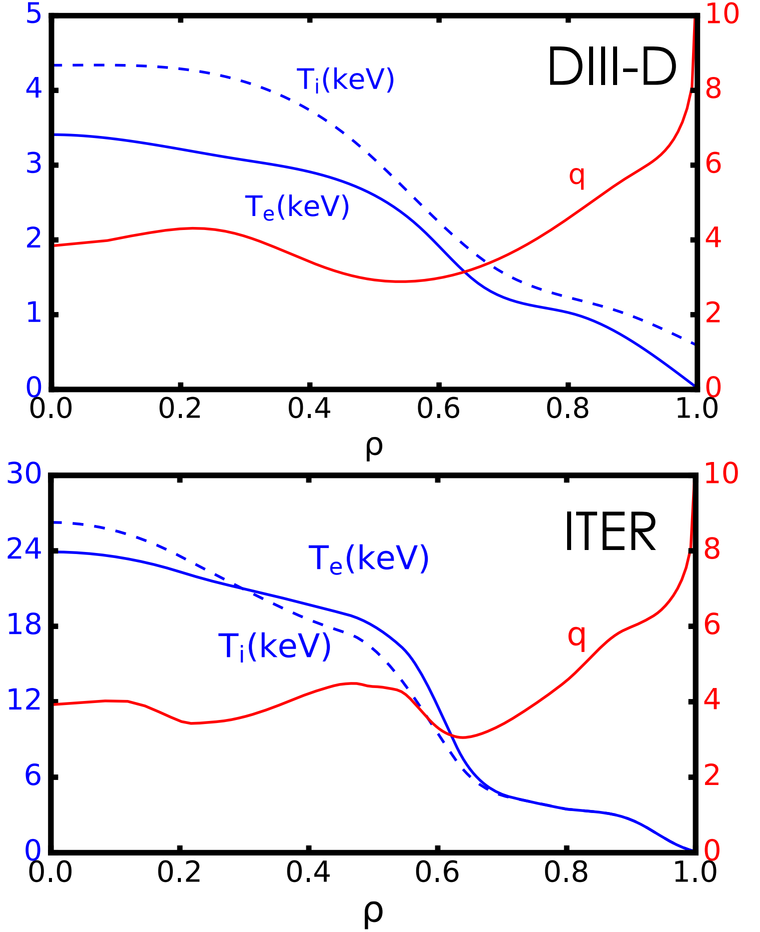
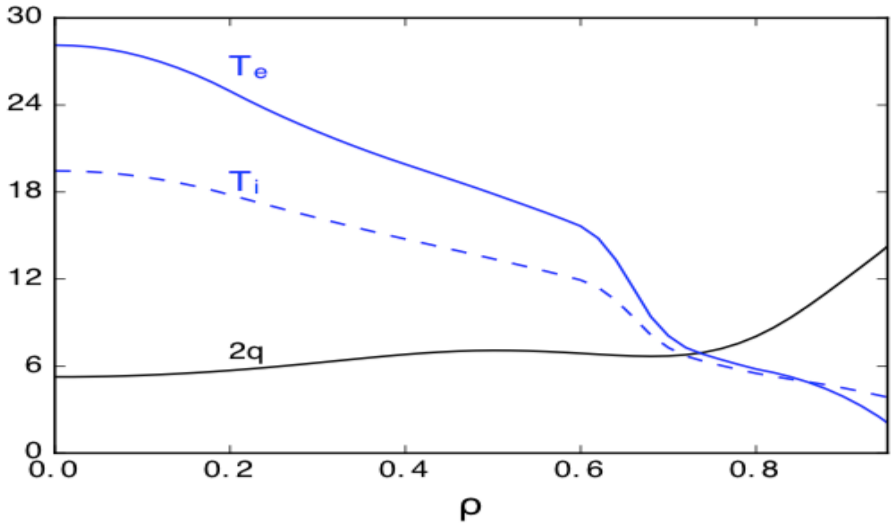


Recent correction to EM effects predicts ITB without need for large NCS

- **Prediction of T_i is roughly what is needed for Q=5**
- **q-profile not consistent with evolved kinetic profiles.**

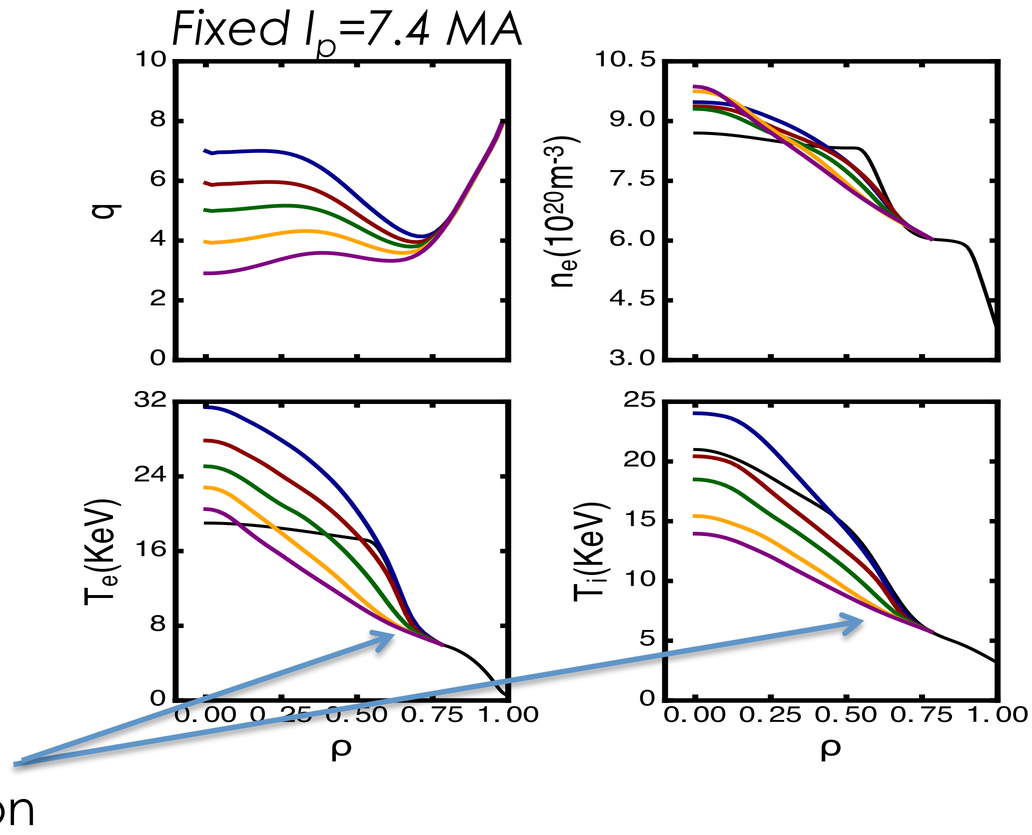
ExB=0



evolve Ti,te,ne profiles
fixed q profile

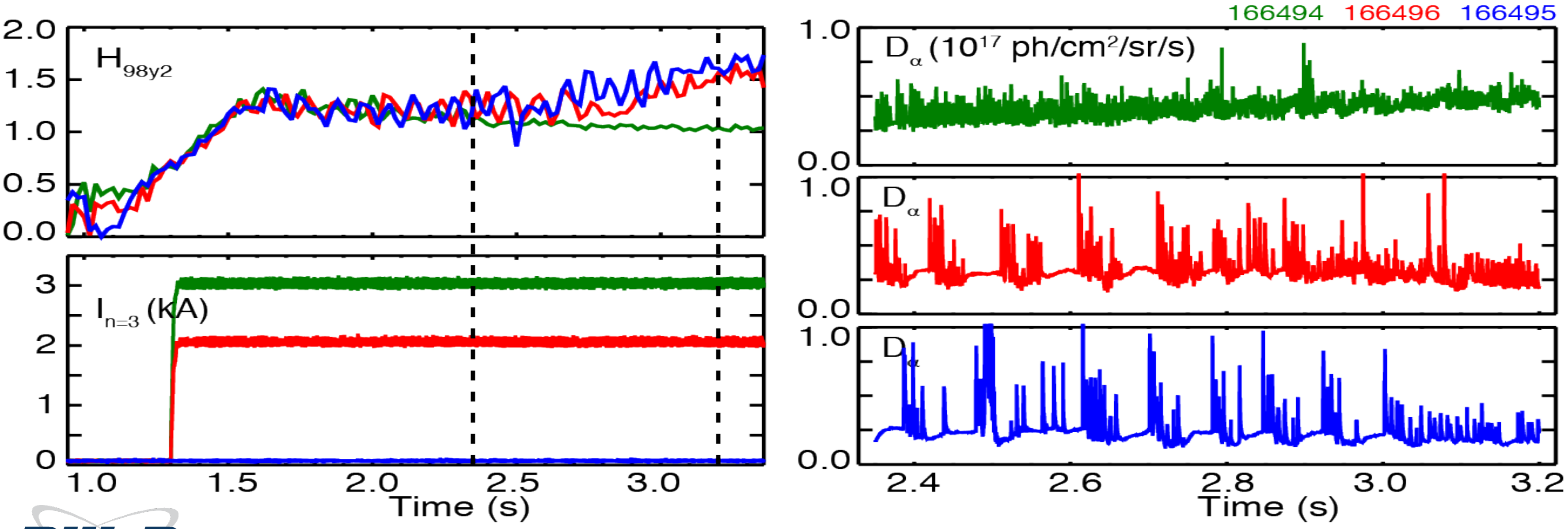
Previous TGYRO predictive modeling suggested large NCS required for ITB formation

- **TGYRO predict n_e, T_e, T_i profiles by matching predicted flux from TGLF, NEO to power balance**
- **n_e, T_e, T_i profiles needed for Q=5 approximately q_0=7**



When there are no large type-I ELMs, and there is no ITB formation, consistent with ELM hypothesis

- **Three extended high β_p discharges with varied RMP I-coil perturbations**
  - Largest I-coil perturbation(green) has no Type-I ELMs and no ITB



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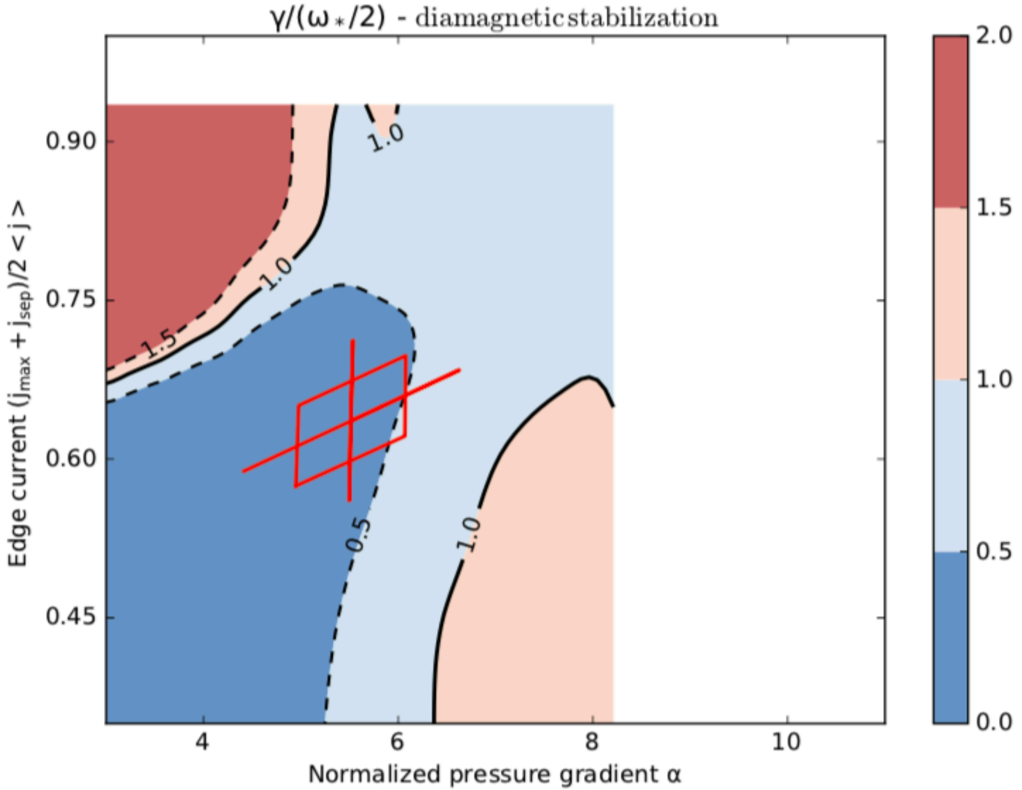
Low pedestal state stability not near instability threshold

- **Stability analysis performed using the ELITE code**

- **Gap in right corner**



High pedestal state is inside the right corner gap

- **State current gradient peeling limited**