Experiment and Modeling of ITER Demonstration Discharges in the DIII-D Tokamak

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OUTLINE

- **Recent progress on the ITER demonstration experiment made since 2008 IAEA and integrated theory-based modeling for ITER projection**
- **Baseline scenario:**
  - Improved match to the expected ITER parameters including:
    - Edge pedestal collisionality and rotation
  - Modeling implication for ITER:
    - Change in confinement, transport, and ELM characteristics in ITER regime of low collisionality and rotation
- **Steady state scenario:**
  - Demonstration of fully noninductive operation in ITER shape
    - Strong dependence of confinement, stability, and noninductive fraction on q_{95}
  - Modeling implication for ITER:
    - Optimizing q profile crucial to simultaneously achieving the fully noninductive (f_{NI}=1) and Q=5 goal

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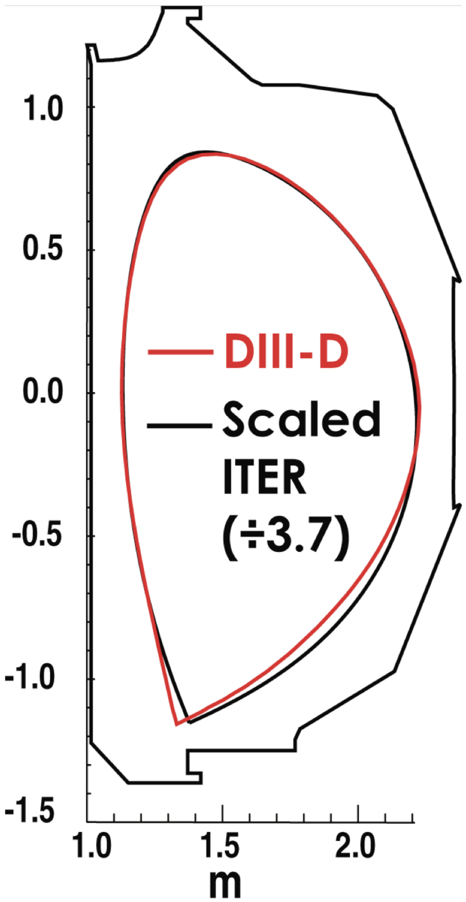
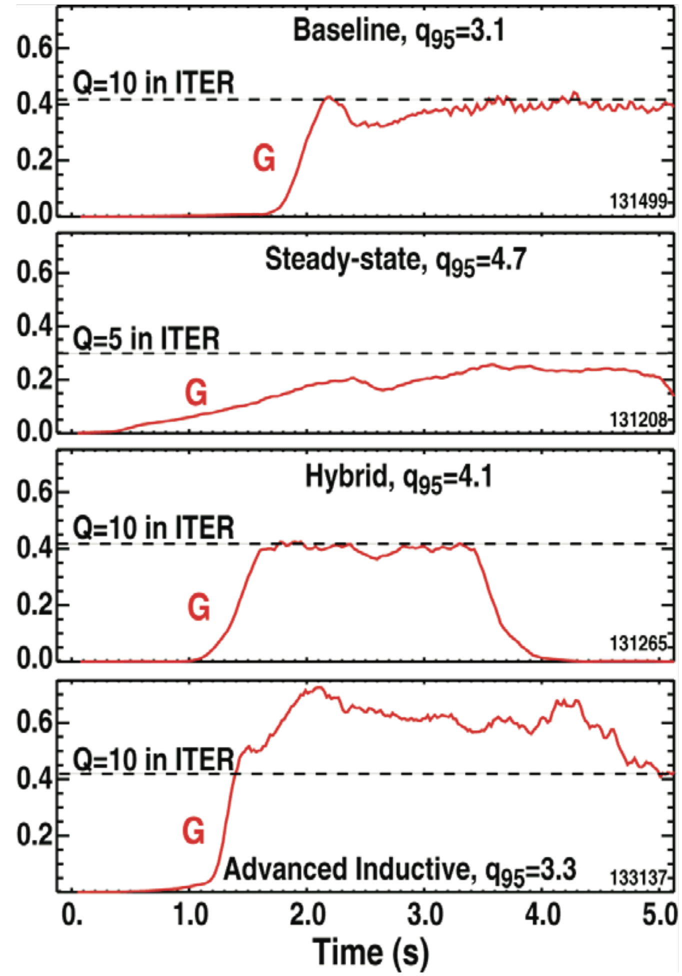
DIII-D Is Providing Suitably Scaled Experimental Evaluations of the Four Primary ITER Operational Scenarios



- **With size reduced by factor of 3.7, the DIII-D discharges match the ITER design values for**
  - Plasma cross-section
  - Aspect ratio
  - Normalized current I/aB

- **DIII-D demonstration discharges meet ITER normalized performance target**
  - Target values for β_N and H_{98} were matched or exceeded

[E. Doyle, IAEA 2008 (NF2010)]

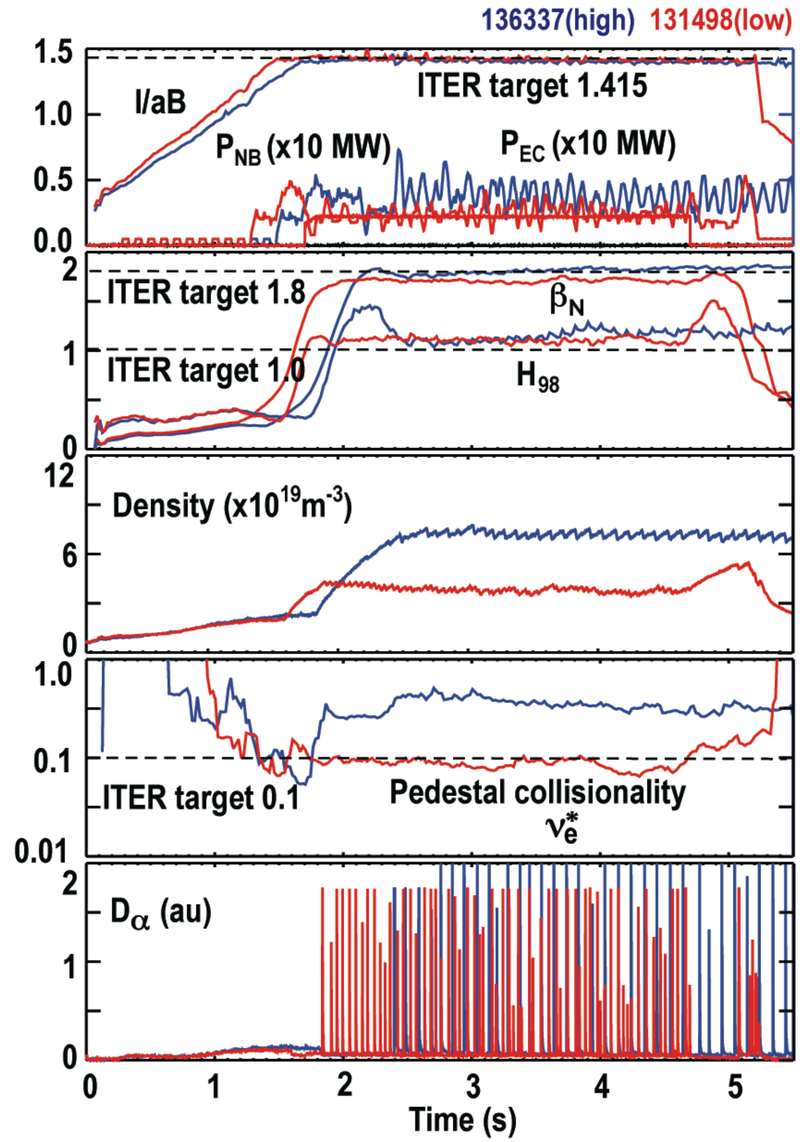


$G \equiv \beta_N H_{89}/q_{95}^2$ is a measure of fusion performance

BASELINE SCENARIO

Lower Density Baseline DIII-D Discharge Developed to Match Edge Pedestal Collisionality

- **Density reduced by more than factor 2 and temperature raised by:**
  - Lowering I_p (keeping I/aB=1.415)
  - Application of ECH
- **Target values for β_N and H_{98} maintained with lower collisionality/ density operation**
  - No loss in fusion performance
- **Significant change observed in ELM characteristics**
  - More frequent smaller ELMs
- **ECH is multi-purpose**
  - Suppressing 2/1 NTM by EC current drive
  - Electron dominant heating
- **Improved density control and stationarity**



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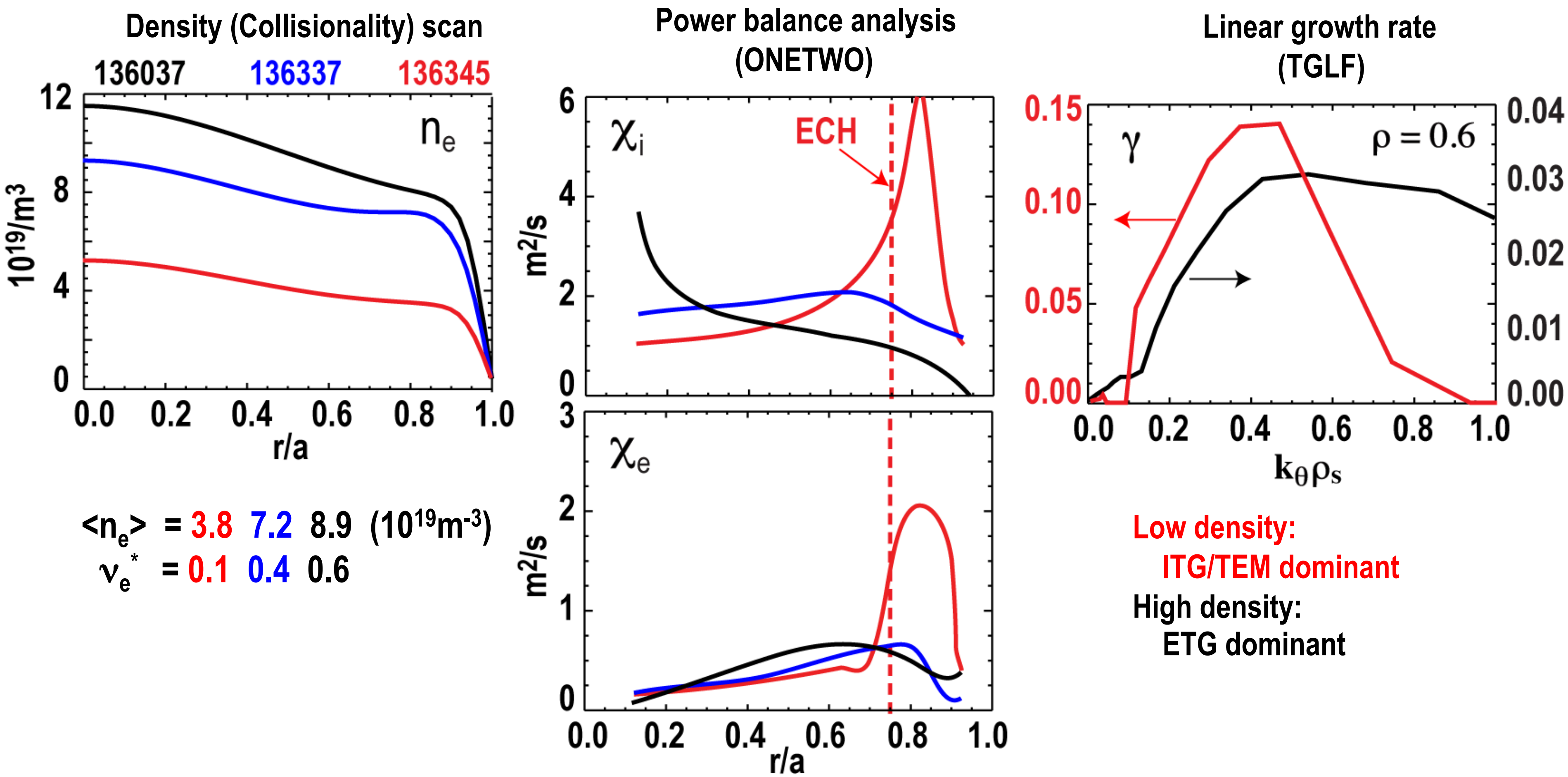
Transport Mechanism Changes Dramatically in ITER Regime of Low Collisionality and Localized Electron-Dominant Heating



$\langle n_e \rangle$ = 3.8 7.2 8.9 ($10^{19}m^{-3}$)
ν_e^* = 0.1 0.4 0.6

Low density:
ITG/TEM dominant
High density:
ETG dominant

- **Same normalized global energy confinement (H_{98}~1), but significant change in local transport characteristics**
  - Collisionality plays a key role in transport
- **Localized electron-dominant heating increases energy transport significantly**

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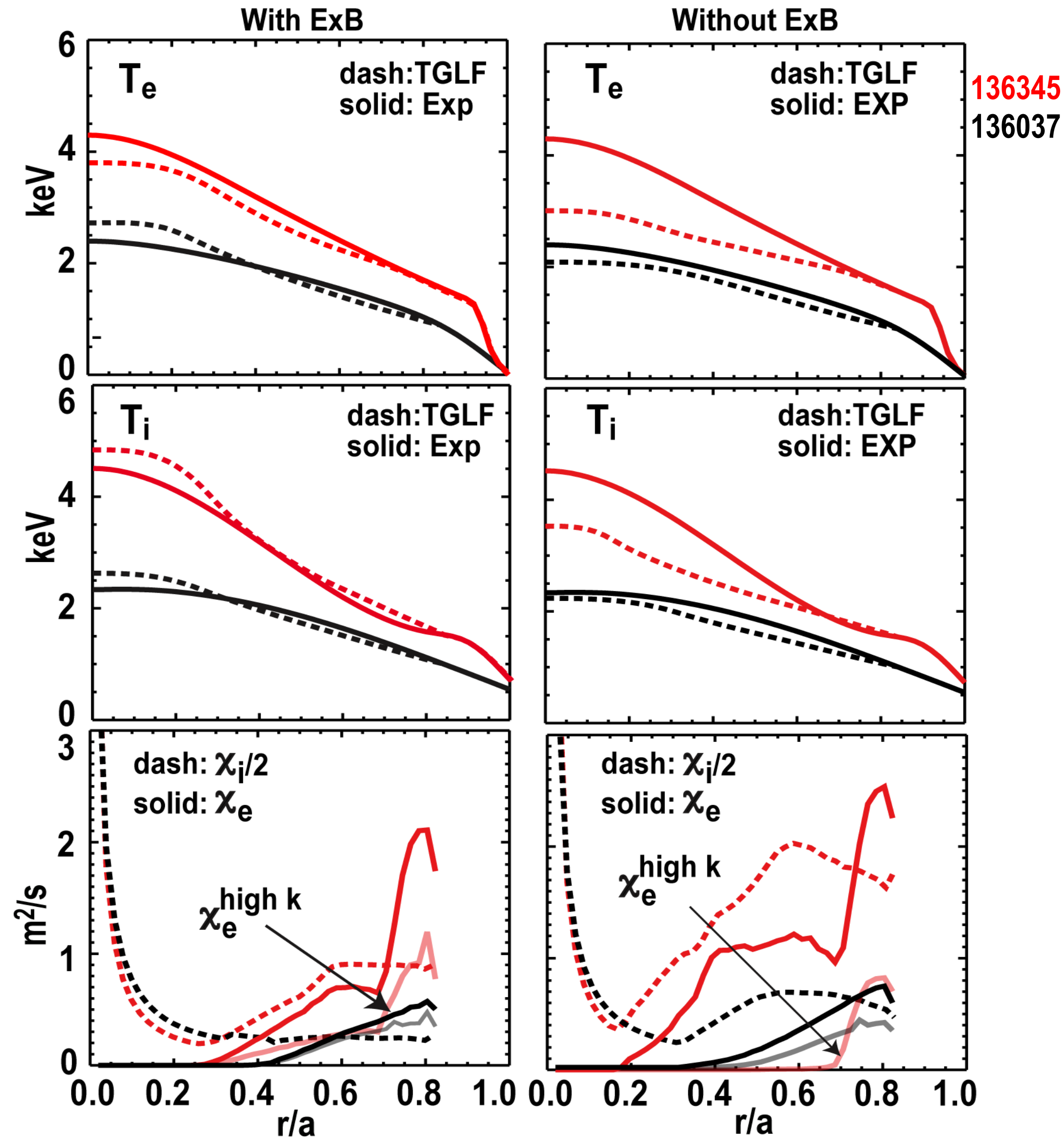
TGLF Transport Simulation Reproduces Change in Transport Processes As Observed in Experiment

- **TGLF modeling of T_e and T_i**
  - Used experimental density and pedestal
  - Profiles from 80-100 % of ELM cycles
  - Boundary condition at ρ= 0.84
  - Miller geometry, electrostatic
  - *E*×*B* shearing rate from CER measurement of rotation
  - FASTRAN transport solver
- **Low density**
  - ITG/TEM dominant (low *k* mode)
  - Good agreement only when the *ExB* shear stabilization included
- **High density**
  - ETG dominant (high *k* mode)
  - Relative small effects of *ExB* shear stabilization



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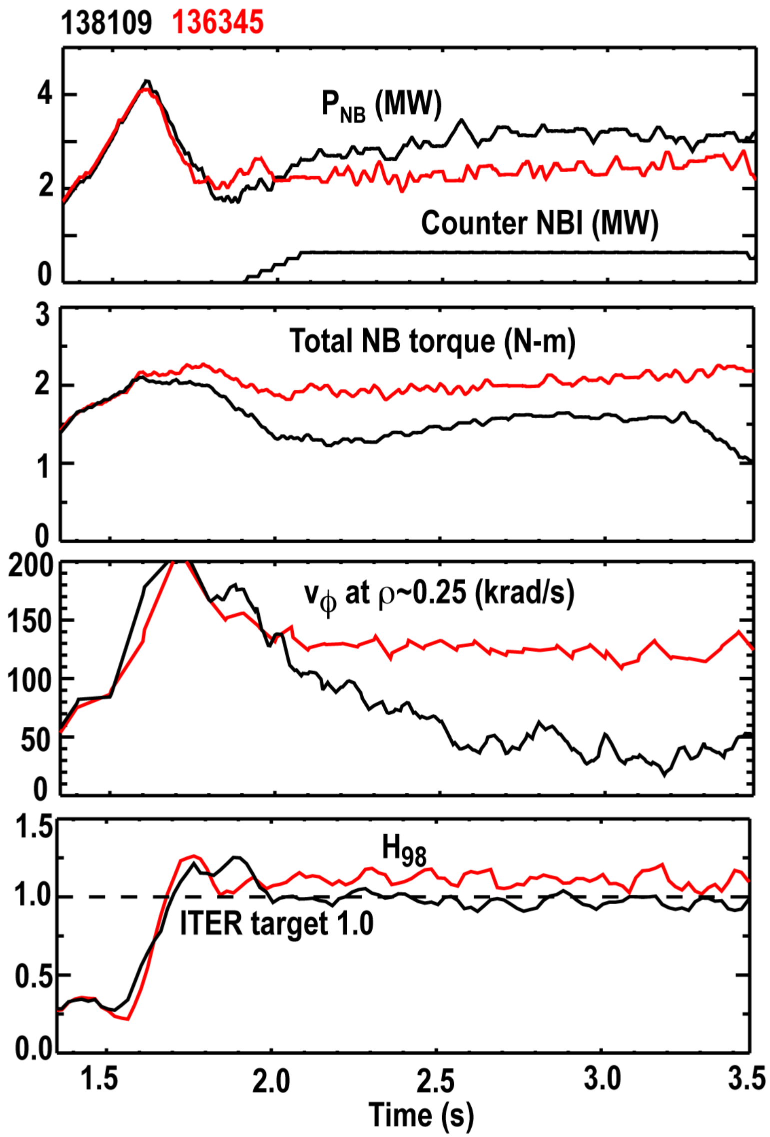
Plasma Rotation Reduced by Adding Counter-NBI in Low Collisionality Discharge



- Initiated study on effect of reduced plasma rotation on confinement
- Modest 1/4 counter-beam changes rotation substantially
- Confinement factor H_{98} reduced by ~15 %, but remains ITER target H_{98}~1

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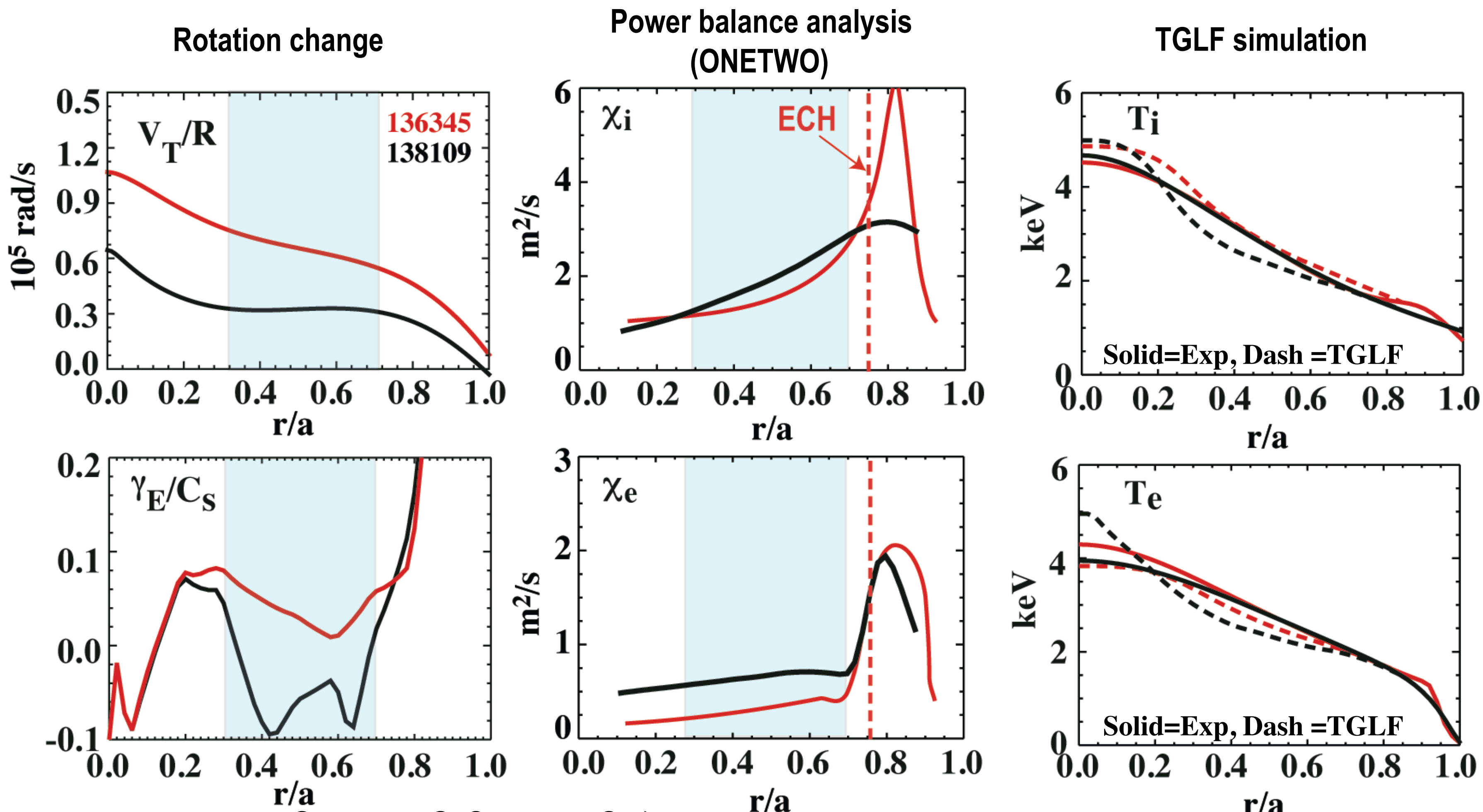
Initial Data Indicates that Reduced Plasma Rotation Reduces Confinement in Baseline Scenario



- γ_E ~ 0 over 0.3 < ρ <0.6
- **Thermal diffusivity increases with reduced rotation**
- **Indicate need for performance margin in projection to ITER**

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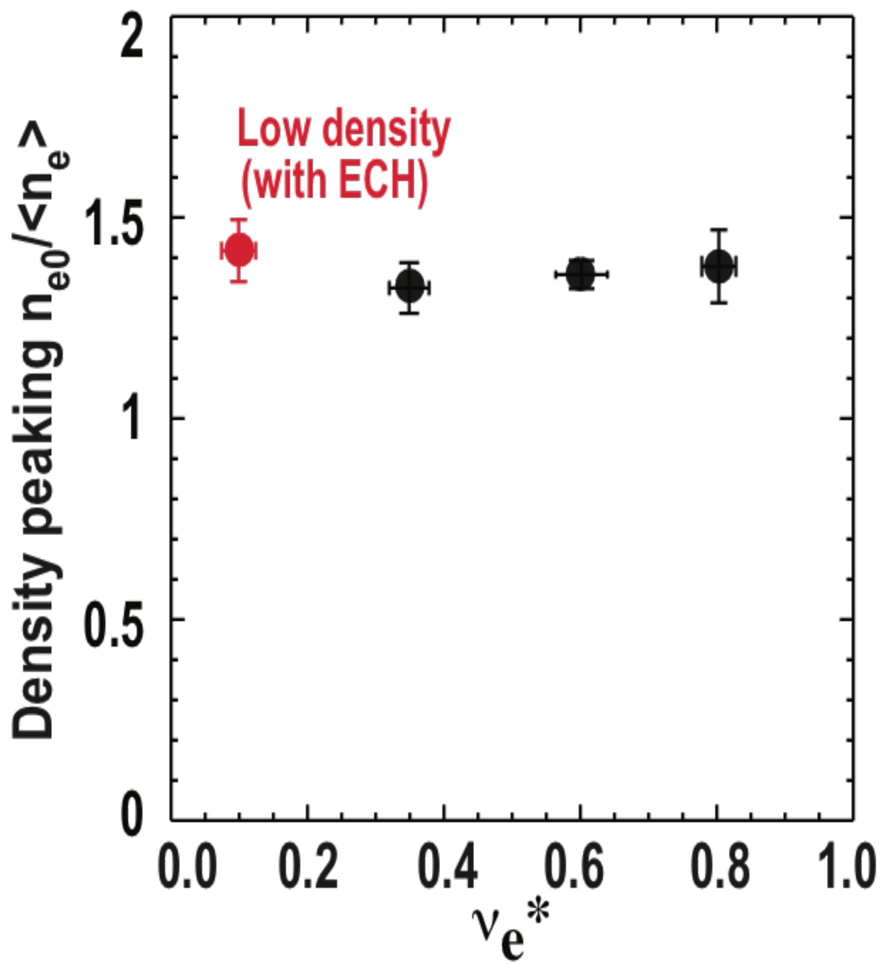
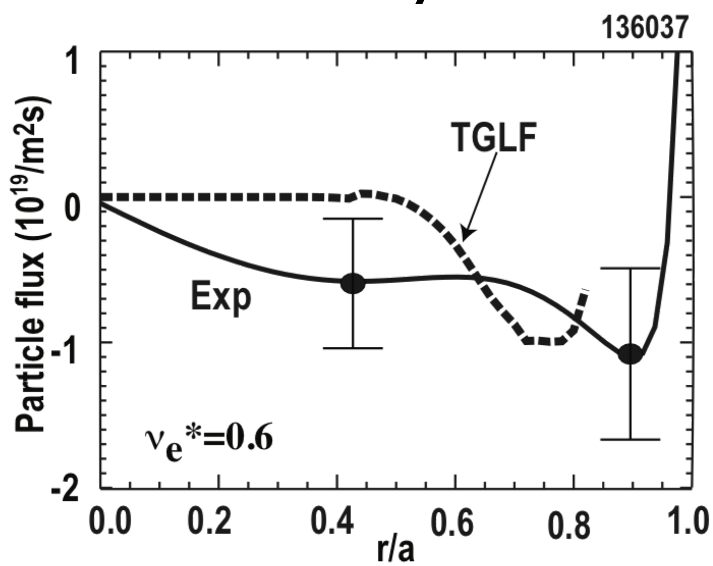
Density Profile Is Substantially Peaked for the Baseline Discharge while Insensitive to Collisionality

- **Less sensitive to the collisionality than recent AUG and JET observation, which do not use ECH at low density**



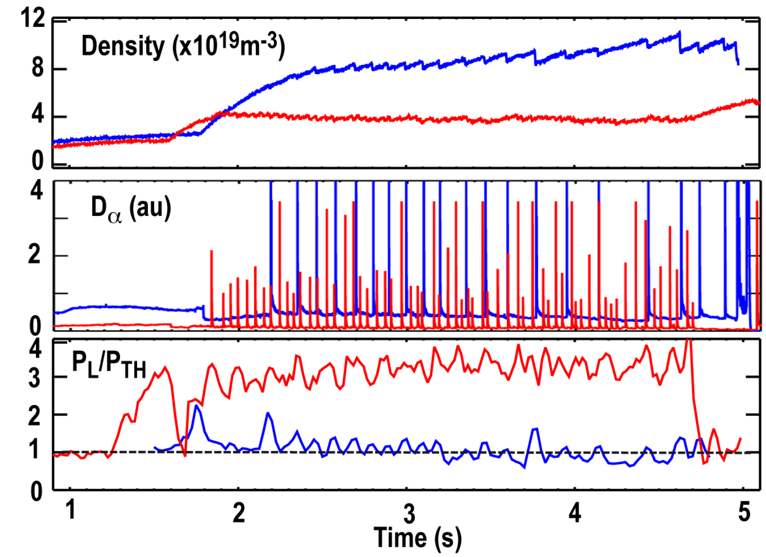


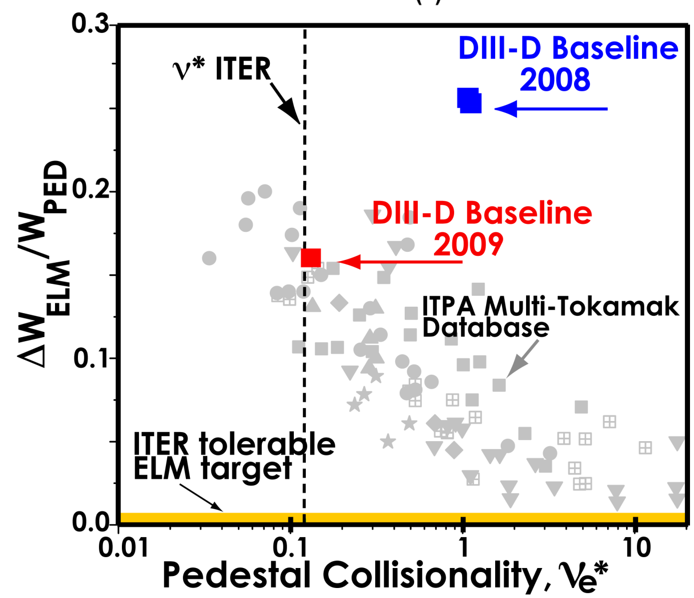
- **Density peaking affected by:**
  - NBI core fueling
  - ECH particle pumping
  - ELM characteristics
- **Particle balance analysis indicates inward particle flux**
  - Consistent with TGLF modeling

Lower Density Results in Smaller and More Frequent ELMs

- **Significant change in ELM characteristics**
  - More frequent smaller ELMs for low density discharges
- **The change in P_L/P_{TH} is likely to affect the ELM characteristics**
  - Empirical scaling for L-H power threshold (Y. Martin, et. al, 2008)

    $P_{TH} = 0.049 x n^{0.72} B^{0.8} S^{0.9}$
- **Reduction of energy loss at lower collisionality is counter to scaling obtained in ITPA database**
- **Fractional energy loss at ELMs substantially exceeds ITER limit**





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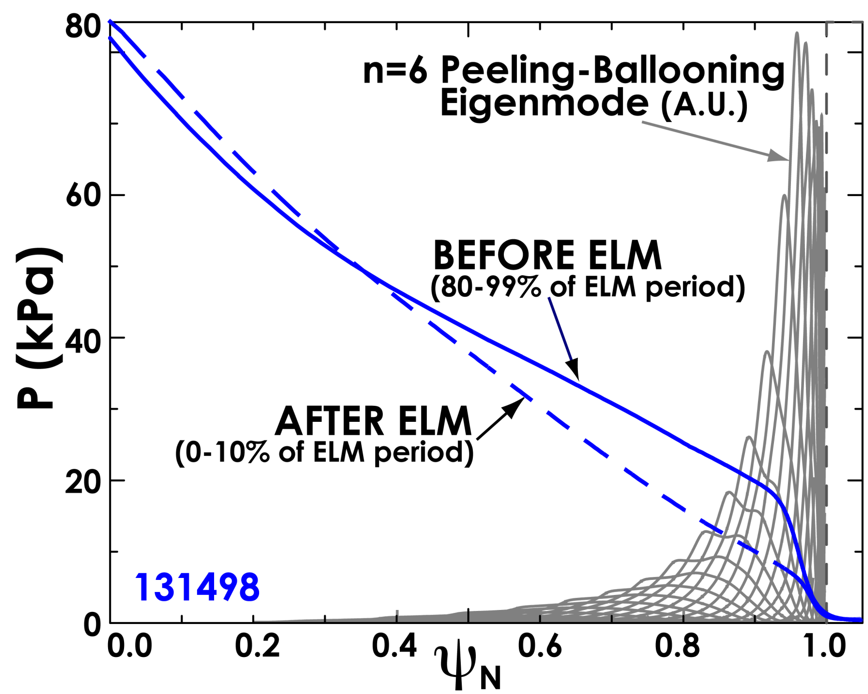
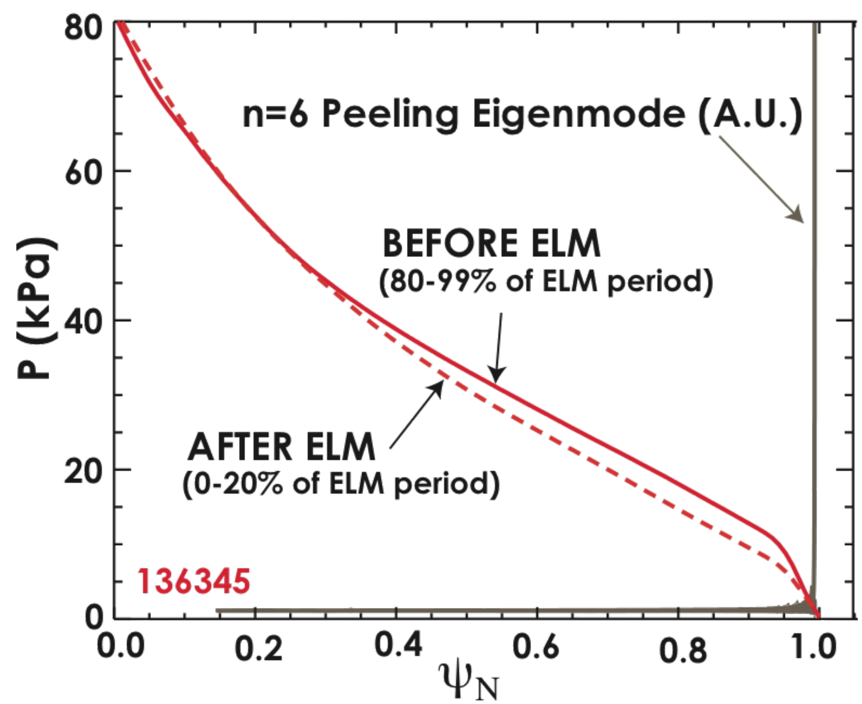
Magnitude of ELM Energy Loss Correlated With the Shape of Unstable Peeling-Ballooning Modes

- **High density**
  - Coupled peeling-ballooning mode
  - ELM-affected region extends deep into the plasma
- **Low density**
  - More peeling-like mode
  - Narrow mode structure
  - Smaller and more frequent ELM





- **Eigenmode structure calculated by ELITE stability code**

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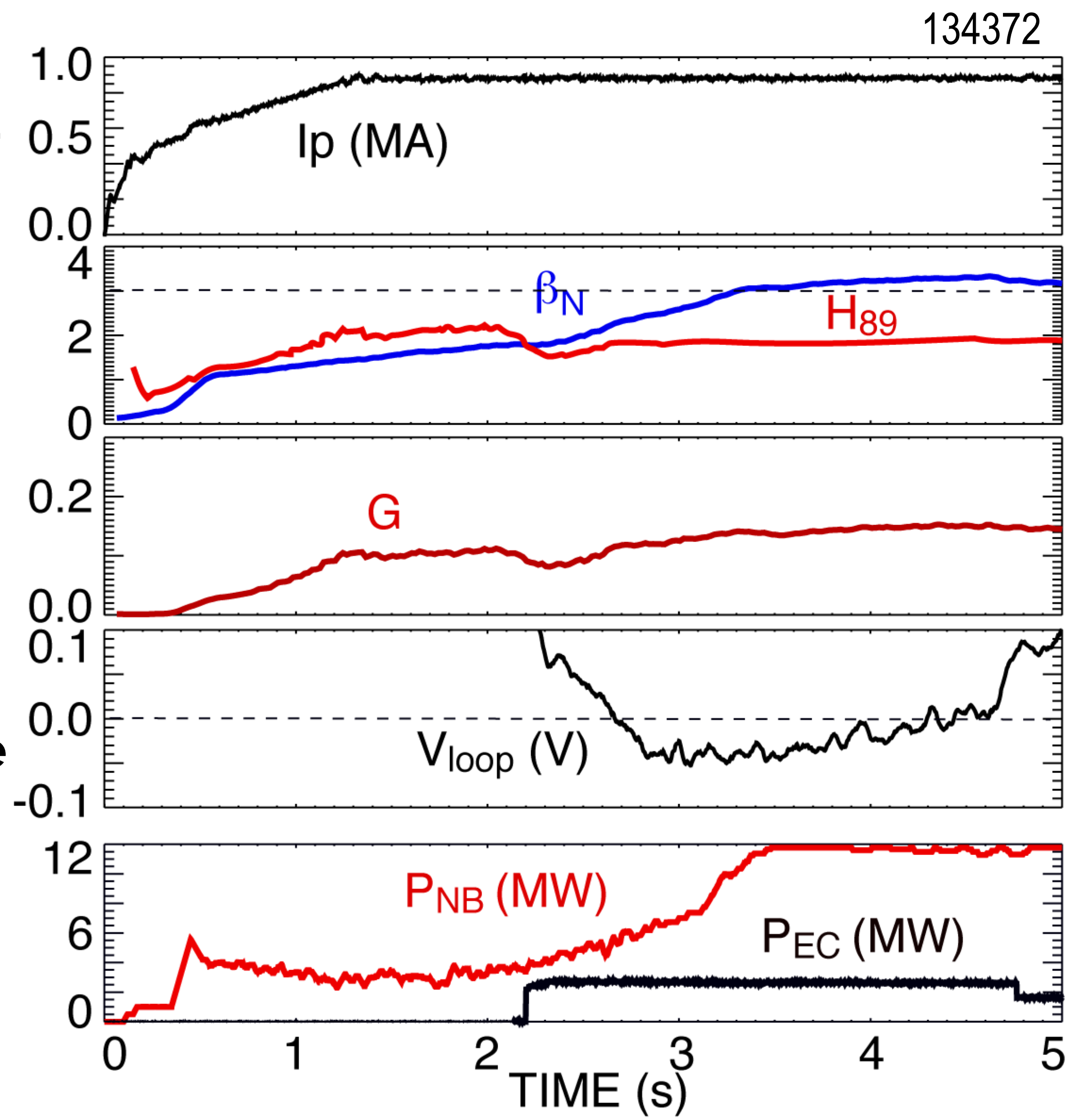
STEADY STATE SCENARIO

Fully Noninductive Operation Demonstrated in ITER Shape

- **Fully noninductive operation obtained in 8.5 MA equivalent discharge with β_N = 3.1**
  - q_{95} = 6.3
  - High bootstrap fraction (~70%)
  - Relatively low fusion performance
  - Not stationary
- **Standard DIII-D prescription**
- **Steady-state discharges utilize off-axis ECCD to maintain stable q-profile with q_{min} ≥1.5**
- **$G = \beta_N H_{89}/q_{95}^2$**
  - Measure of fusion performance



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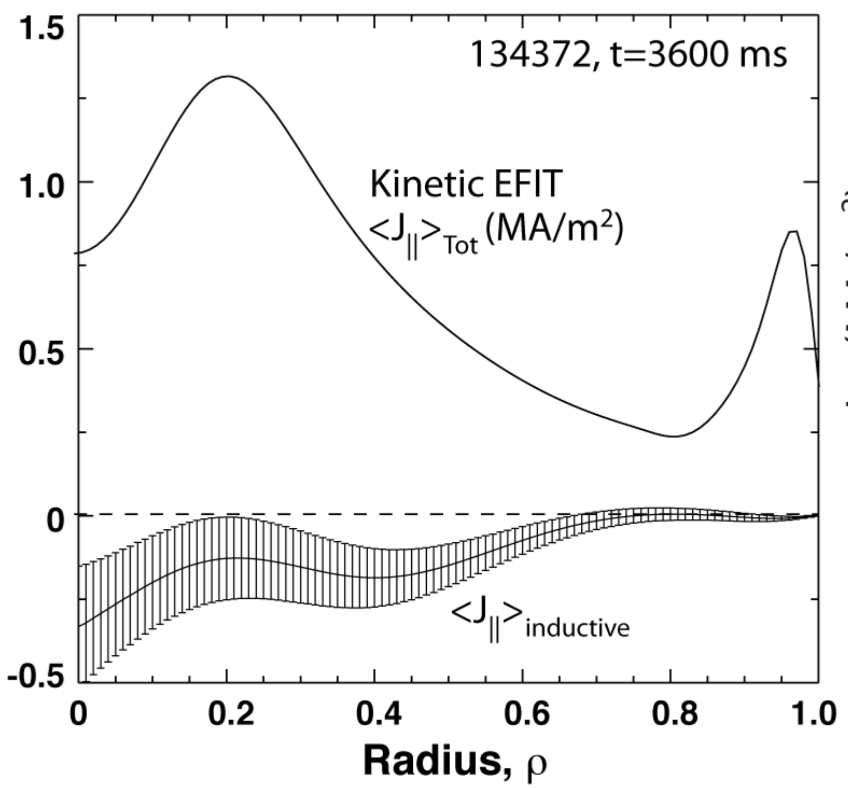
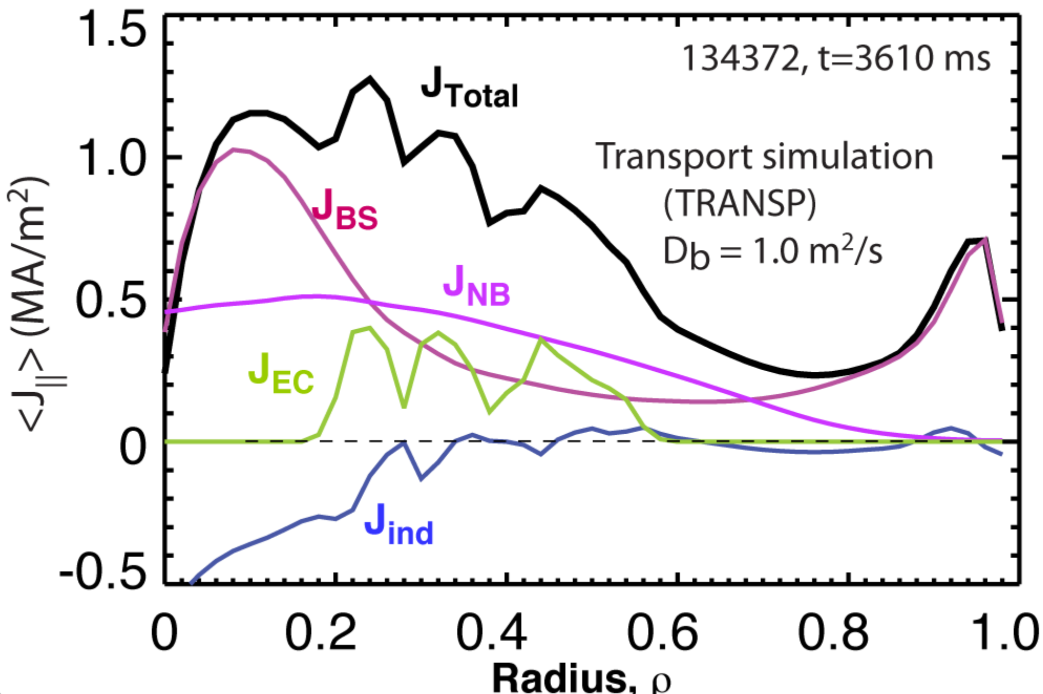
Measurement and Simulation Show that Inductive Current Density is Small Everywhere





- **Measurement of inductive current density - loop voltage analysis**
- **Transport code simulation**

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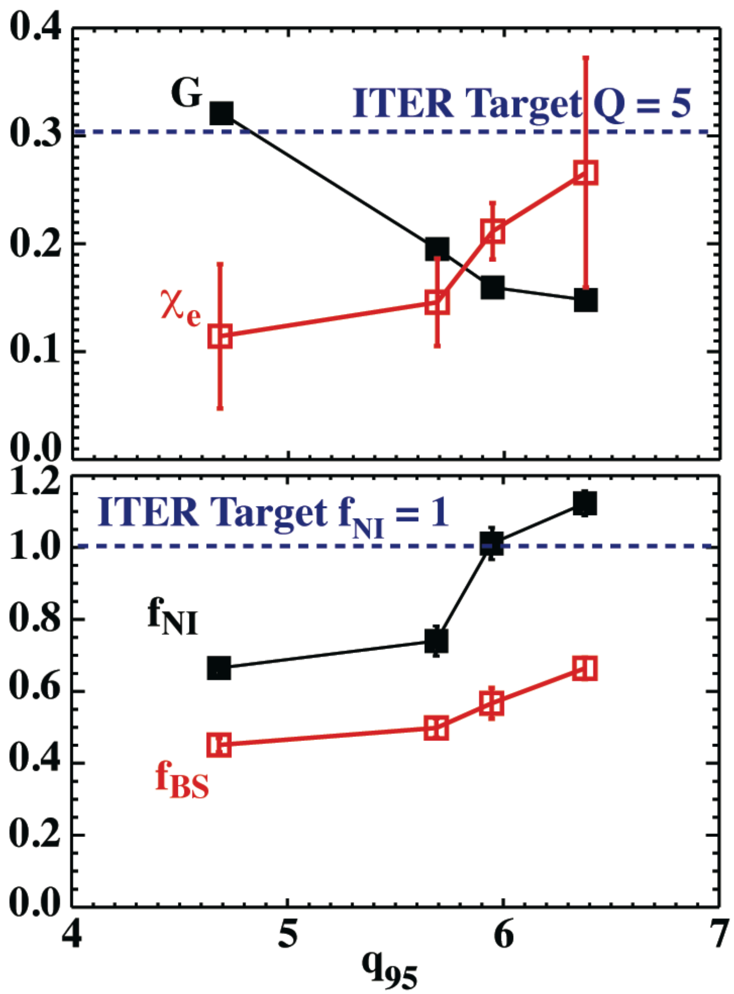
Noninductive Fraction Increases while Fusion Performance Decreases with q_{95}

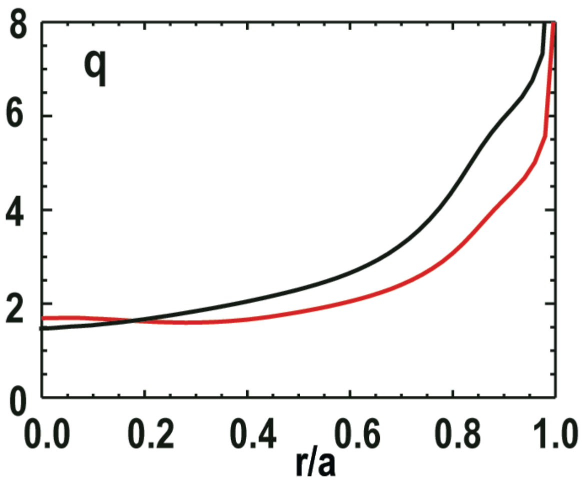


- **Thermal energy confinement time decreases with q_{95}**
  - Generally follow the scaling of H_{98}
- **f_{NI} and f_{BS} increase with $\beta_N q_{95}$**
- **Edge pedestal provides typically ~40% of the total bootstrap current**
  - Pedestal height and width depend on q_{95}
- **Theory-base (GLF23) projection using the scaled edge profiles shows the same trade-off between f_{NI} and Q with variation of q_{95} [M. Murakami: ITR P1-35]**

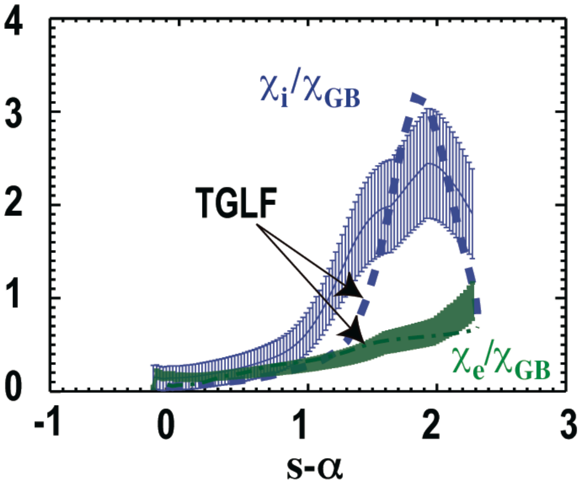
- **Indicate need for optimizing q_{95} in projection to ITER**

Electron and Ion Thermal Diffusivities Correlated Mainly with Magnetic Shear

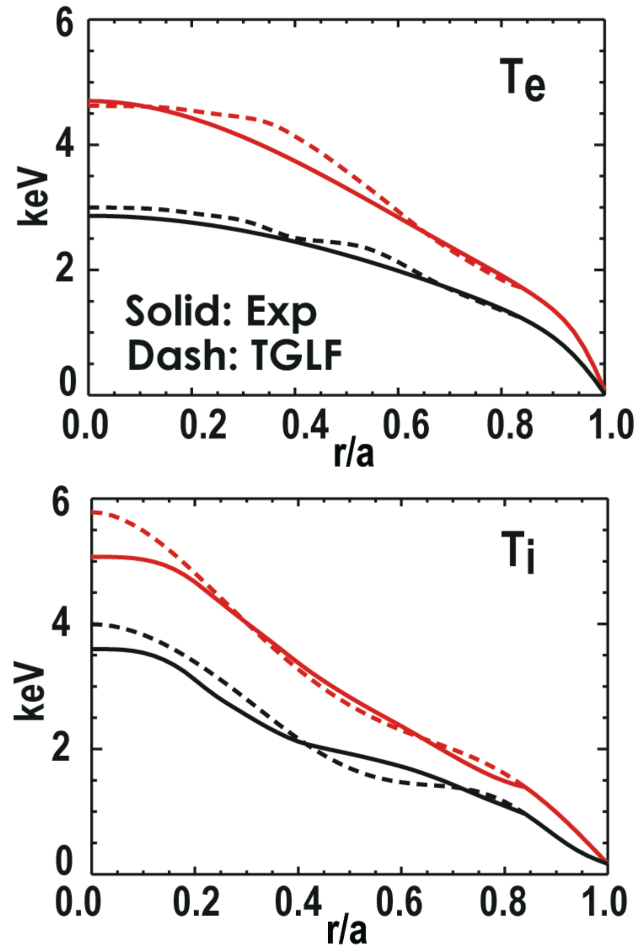
q_{95} scan



Power balance analysis



TGLF simulation



- **Electron and ion thermal diffusivities correlated mainly with magnetic shear both in the power balance analysis by TRANSP and in the TGLF modeling**
- **TGLF transport simulation reproduces the transport dependency on q_{95}**
- **Predictive simulation suggests that a larger radius of minimum q with weak magnetic shear can reduce turbulent transport significantly**

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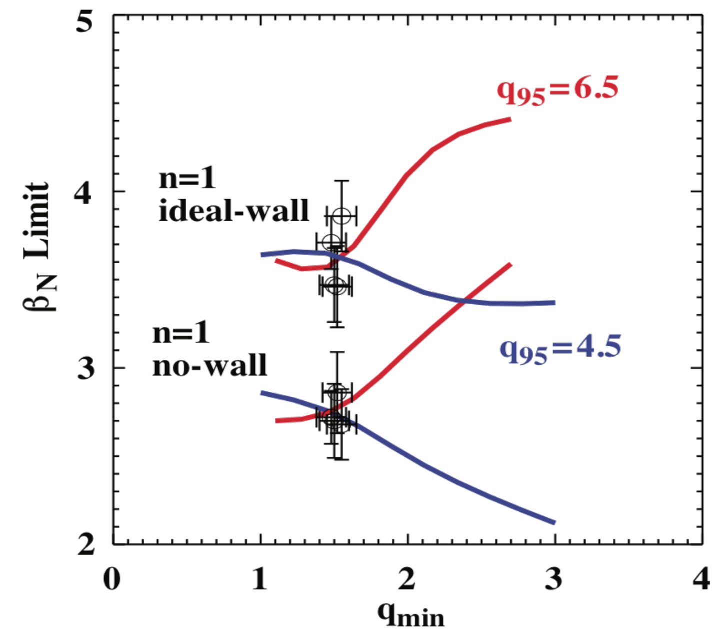
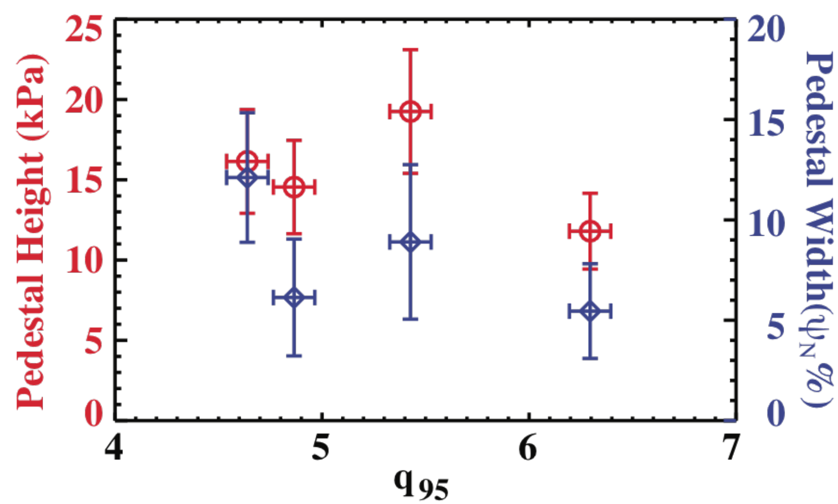
Experiment and Modeling Show Dependence of Stability and Edge Pedestal on q_{95}

- **Calculated ideal β_N limit using experimental profiles and equilibria**
  - n=1 no-wall ~ 2.8
  - n=1 ideal-wall ~ 3.7
- **Predictive modeling indicates:**
  - β_N Limit decrease (increase) with q_{min} at q_{95} = 4.5 (6.5)
  - Tradeoff between stability and confinement to achieve higher β_N at lower q_{95}
- **Edge pedestal provides typically ~ 40% of the total bootstrap current**
  - Key role in optimizing steady-state scenario
- **Pedestal height and width decrease with q_{95}**
  - Consistent with EPED prediction





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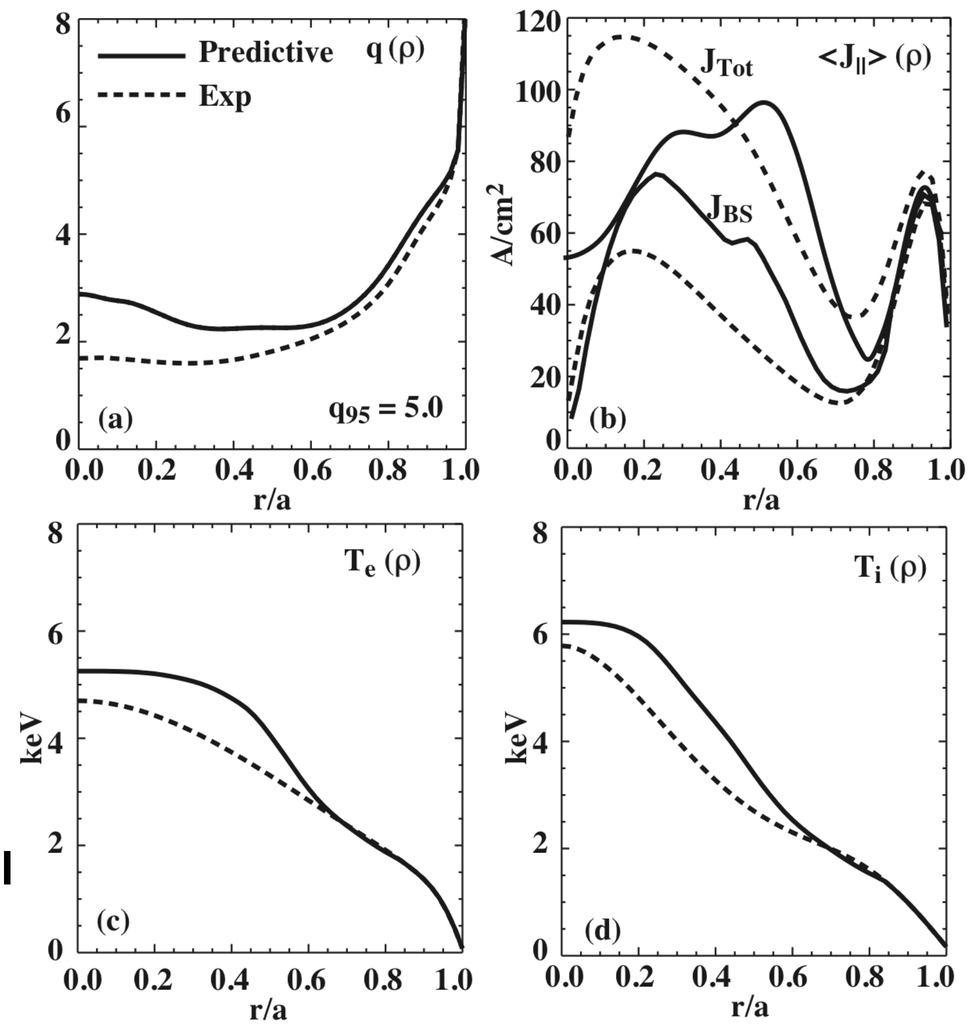
Optimum Scenario Studied by Integrated Theory-based Modeling to Achieve the f_{NI}=1 and Q=5 Goals Simultaneously

- **Newly developed iterative steady-state solution procedure:**
  - Iterative numerical method to find a steady state solution (d/dt=0) of core transport (TGLF) using FASTRAN with self-consistent calculation of equilibrium (EFIT) and heating/CD sources (NUBEAM, TORAY, CURRAY)
- **Predictive simulations suggest:**
  - A larger radius for q_{min} helps to increase both the fusion performance and f_{NI} at β_N limit calculated from ideal wall stability
- **Maximally utilize the benefits of low magnetic shear and higher pedestal pressure from the increased β_P**



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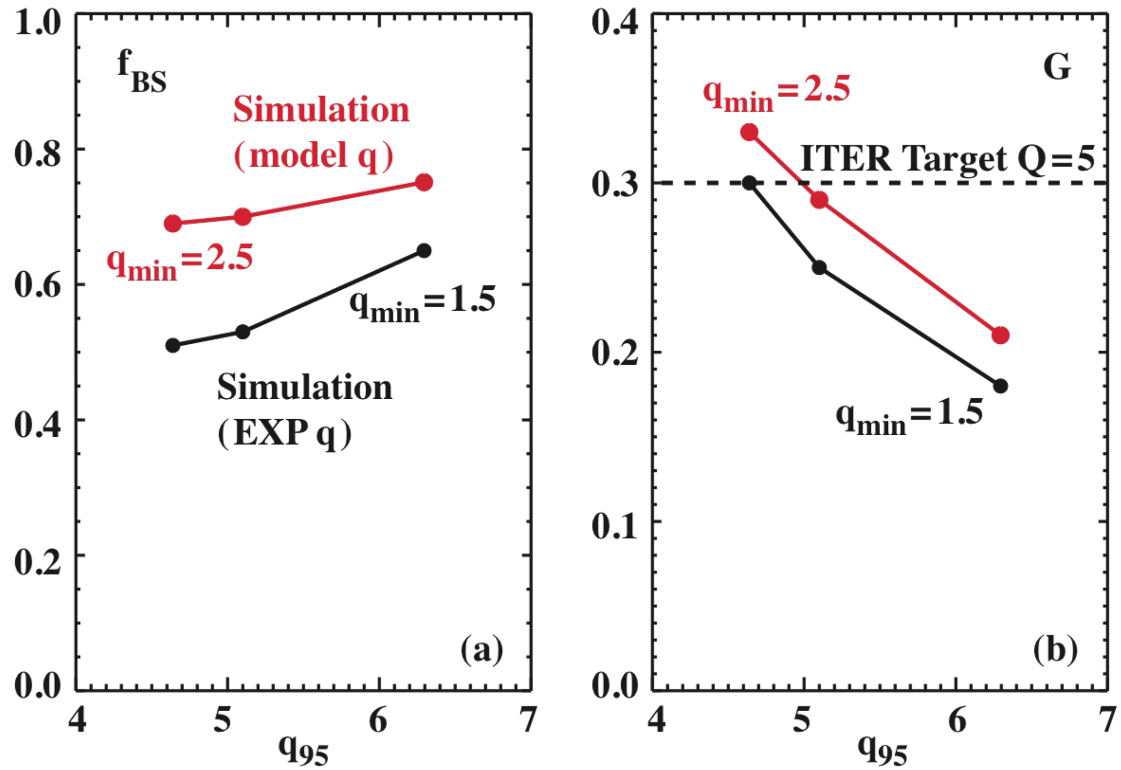
Low q_{95} (High I_p) Operation is Important to Reach the f_{NI}=1 and Q=5 Goals Simultaneously

- **Optimum q profile scan starting from the experimental condition:**
  - Modest improvement of fusion performance for $4.5<q_{95}<6.5$
- **Higher q_{95} (lower I_p)**
  - Maximum improvement of plasma confinement factor is not sufficient to reach G=0.3 for the Q=5 goal



- **Lower q_{95} (higher I_p)**
  - Significant increase of f_{BS} with a larger radius of q_{min}
  - At q_{95}=5.0 (q_{min}~2.5), reach f_{BS} = 0.72 with G=0.3 at the calculated ideal wall stability limit

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SUMMARY AND FUTURE WORK

- **Baseline scenario:**
  - Substantial progress made in improving the match to the expected ITER parameters including edge pedestal collisionality and rotation
  - Significant change in confinement and ELM characteristics in ITER regime of low collisionality and rotation indicates need for performance margin in ITER projection
- **Steady state scenario:**
  - Noninductive operation demonstrated but with relatively low fusion performance, indicating need for q_{95} optimization in ITER projections
  - Optimization of current profile is crucial to simultaneously achieving the fully noninductive (f_{NI}=1) and Q=5 goals
- **Future work:**
  - Apply new tools for better match to the ITER parameters
    (off-axis NBI, higher power EC, and FW current drive)
  - Develop steady state scenario with higher fusion performance and bootstrap fraction
  - Theory-based ITER projection using validated models against the DIII-D ITER demonstration discharges