Experiment and Modeling of ITER Demonstration Experiment in DIII-D

Presented by

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In Collaboration with

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ORNL FED Seminar

Aug 13, 2010

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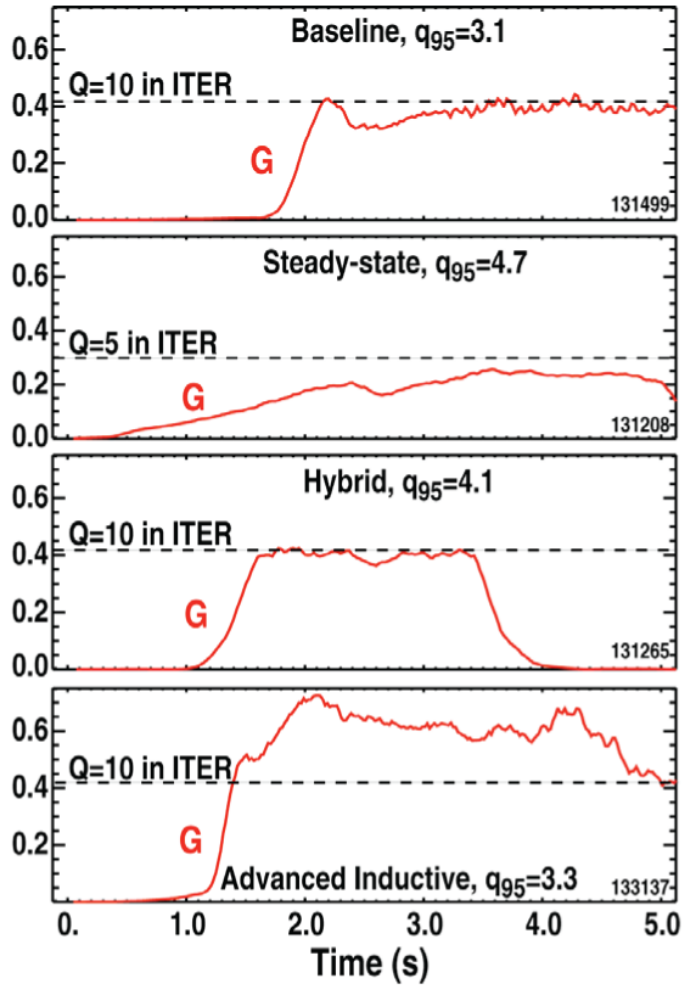
DIII-D Demonstration Discharges Meet ITER Normalized Performance Targets



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

- Four ITER missions addressed on DIII-D:

  Baseline scenario; Q=10 on ITER at I_p=15 MA, with conventional ELMy H-mode operation

  Steady-state scenario; full non-inductive operation with Q~5 at I_p ~9 MA

  Hybrid scenario; high neutron fluence at reduced current

  Advanced inductive scenario; Q≥20 and 700 MW fusion power production at I_p≥15 MA

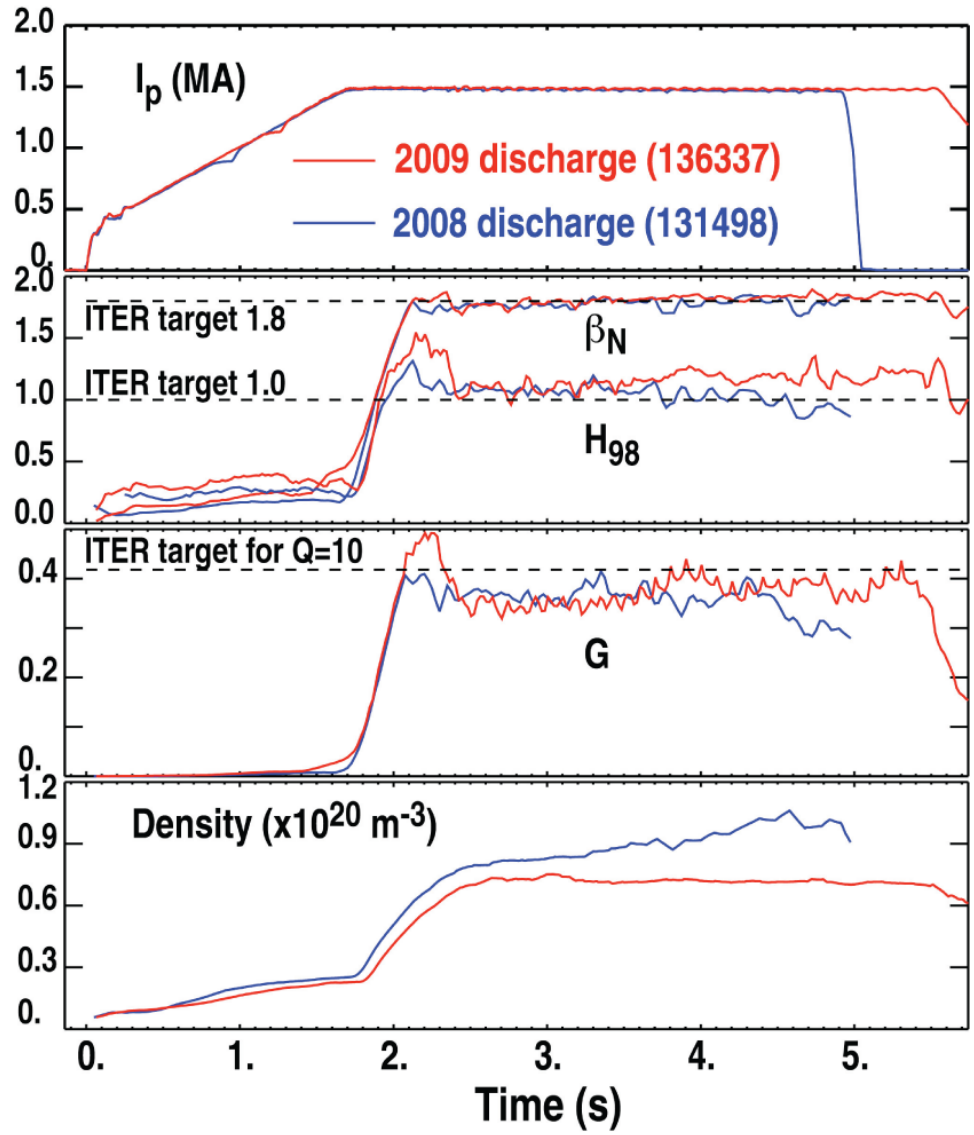
- Key ITER physics issues are discussed
- Projections to ITER

[E. Doyle, IAEA 2008]

Baseline Scenario

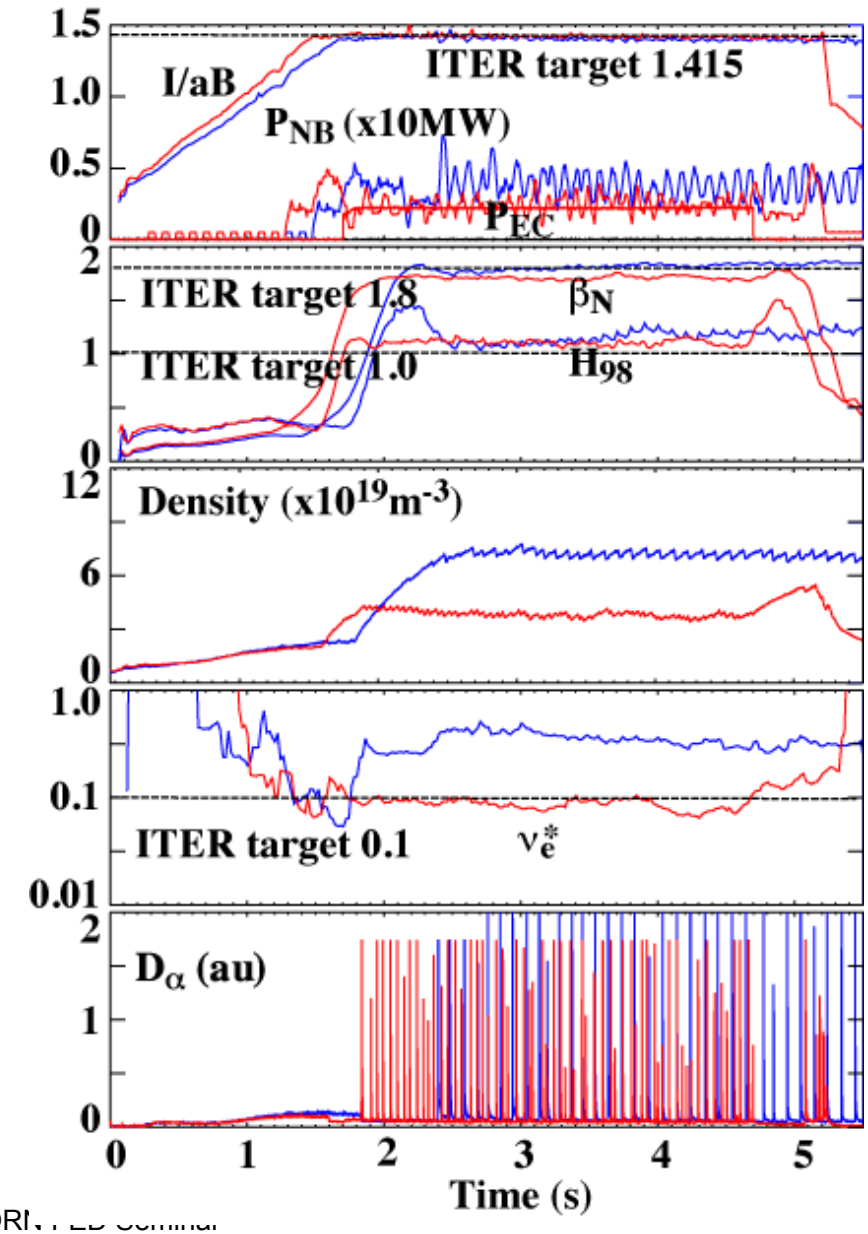
DIII-D Baseline Scenario Match ITER Performance Target

- **I/aB equivalent to 15 MA operation on ITER, q95 ~ 3.1**
- **Match ITER targets for β_N and H_{98}**
- **Performance projects to meet ITER Q=10 target**
  - $G = \beta_N H_{89}/q^2_{95}$: Measure of fusion performance
- **Absolute density up to ITER target of $1\times10^{20}m^{-3}$, n/n_{GW} ~ 0.65 (ITER 0.85)**
- **H-mode duration of ~$3\tau_R$, same normalization duration as ITER**
- **Density control and stationarity improved significantly**

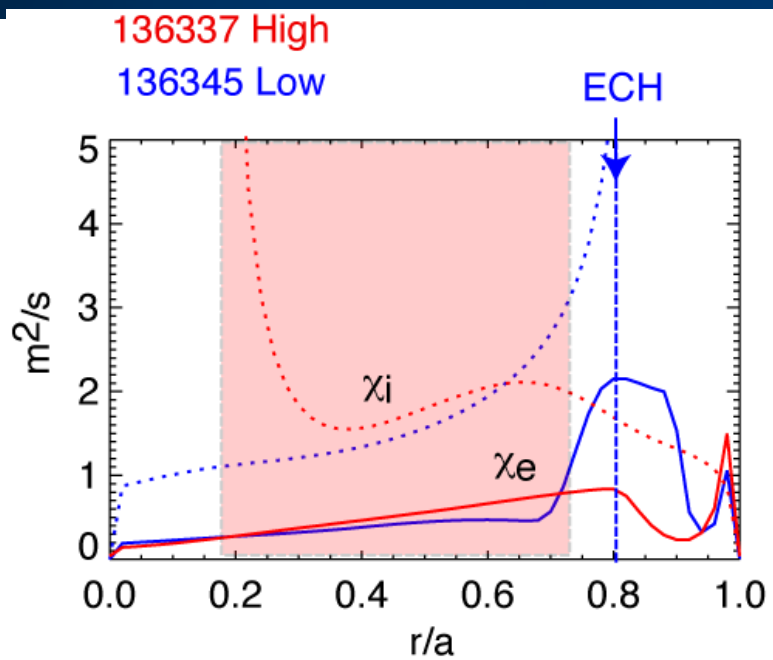


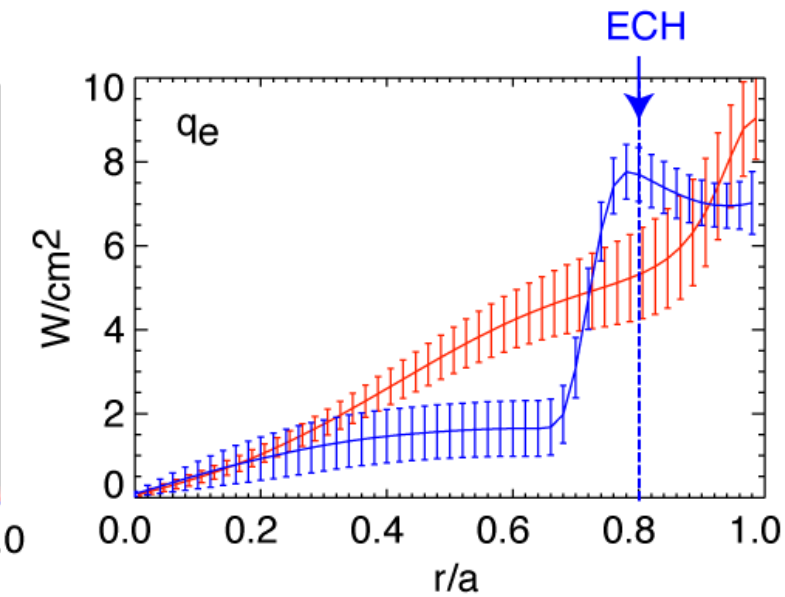
Lower Density Baseline Discharge Developed to Match Edge Pedestal Collisionality

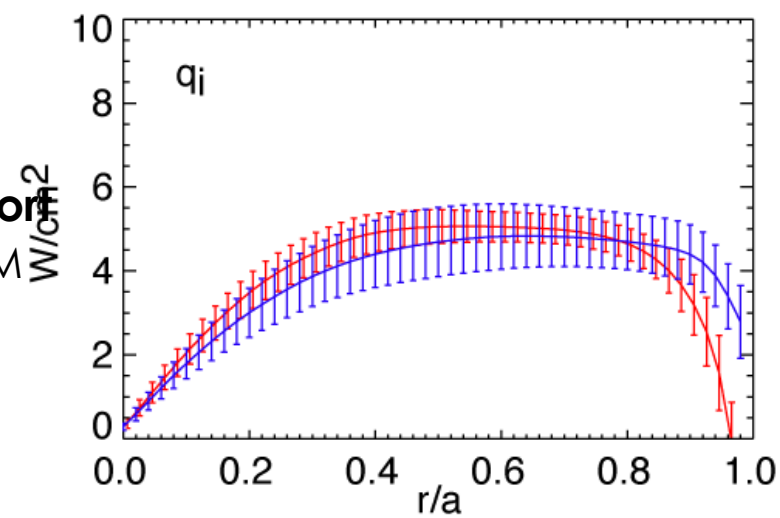
- **Density reduced by factor of ≥ 2 and temperature raised by:**
  - Lowering Ip
  - Application of ECH
- **Target Values for β_N and H_{98} maintained with lower collisionality/density operation**
  - **No loss in fusion performance**
- **Significant change in ELM characteristics**
- **ECH is dual purpose, also ECCD for NTM suppresion**



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



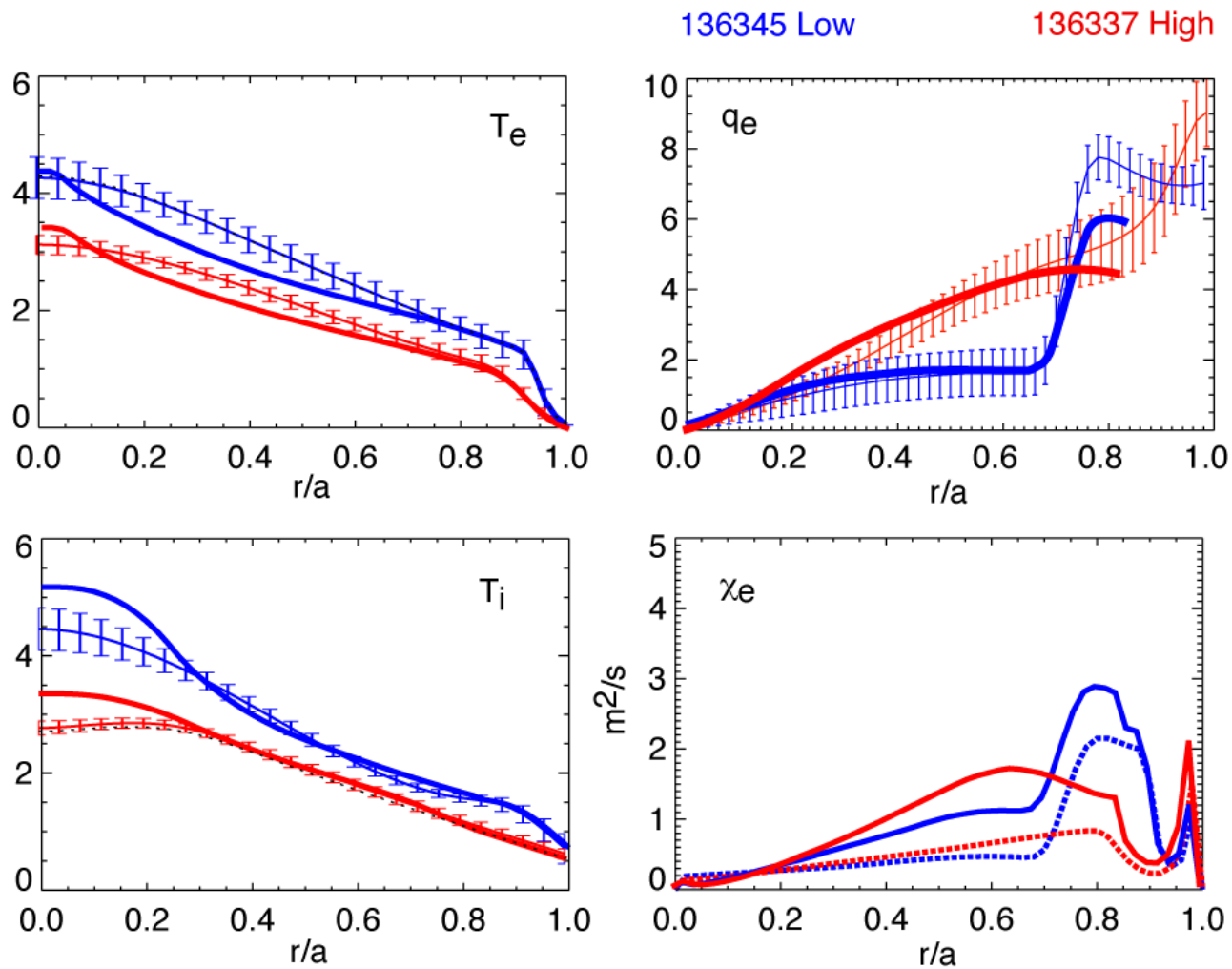




- **Significant change in local transport characteristics**
- **Collisionality plays a key role in transport**
  - Distinguish between ITG, ETG and TEM
  - Experiments indicate favorable Bτ
- **Dominant electron heating increases energy transport significantly**

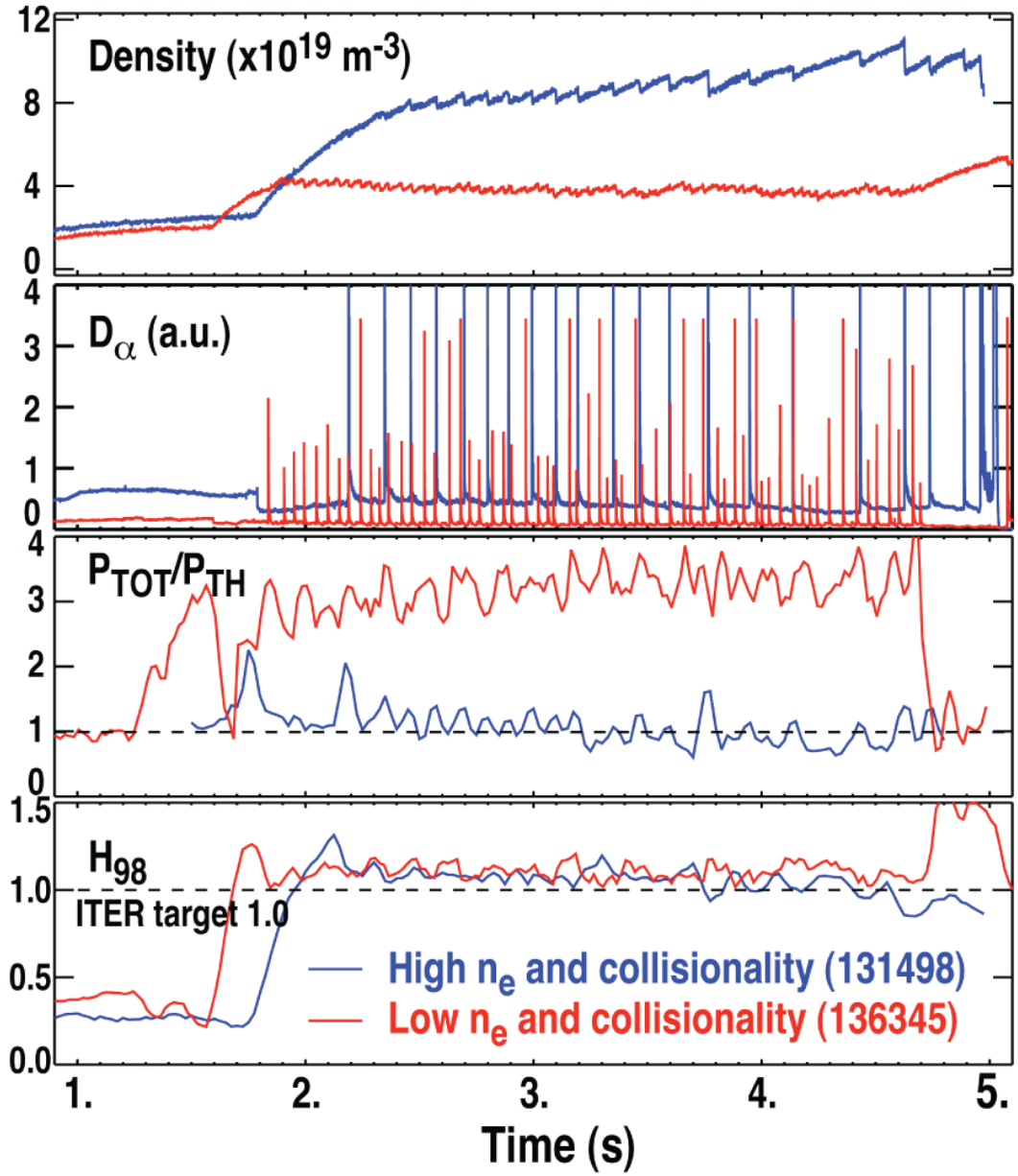
TGLF Reproduces Changes in Transport Processes As Observed in Experiments

- **TGLF modeling of T_e and T_i:**
  - Fixed density
  - Fixed pedestal
    - 40-60% ELM averaged profiles
  - ExB shearing from CER measurement
- **Agreement within typical range**
- **Overestimate electron transport**
- **FASTRAN transport solver**



Changes in ELM Characteristics with Change in Collisionality Probably Due to Change in P_{TOT}/P_{TH}

- **Empirical scaling used for L-H power threshold, P_{TH} (Y. Martin, et al., 2008)**
  - $P_{TH}=0.049*n^{0.72}B^{0.8}S^{0.9}$
- **High density discharges operate with P_{TOT}/P_{TH}~1 throughout H-mode phase**
  - Large, infrequent ELMs
- **Low density discharges have P_{TOT}/P_{TH}~3**
  - Smaller, more frequent ELMs
- **Initial ITER operation may correspond to P_{TOT}/P_{TH}~1 case**
  - Confinement is at target level, despite operation close to predicted L-H power threshold

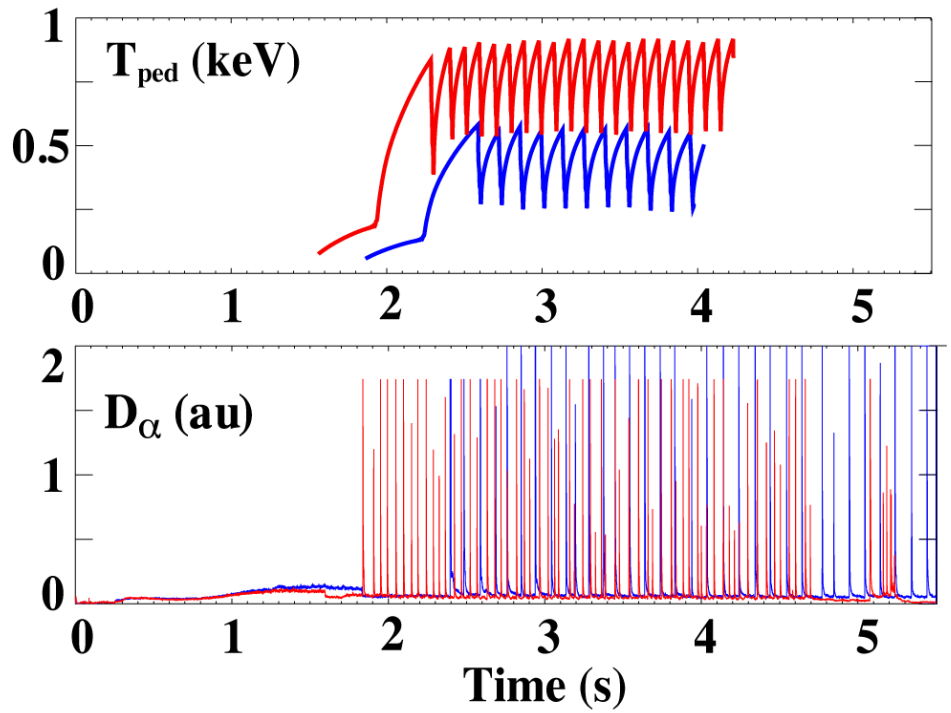


C2 Simulation Shows Changes in ELM Characteristics with P_{TOT}/P_{TH}

- **Two Dimensional Coupled Core-Edge-SOL modeling**
- **Simplified ELM trigger model**

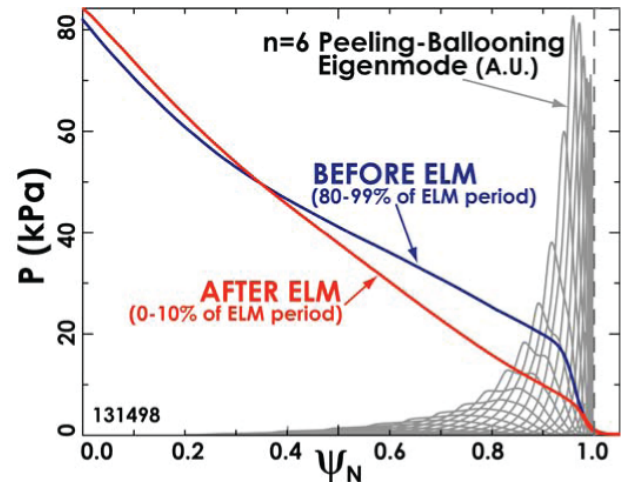
$$\alpha \equiv \frac{2\mu_0 R q^2}{B^2}\left(\frac{dp}{dr}\right) > \alpha_{cr}$$

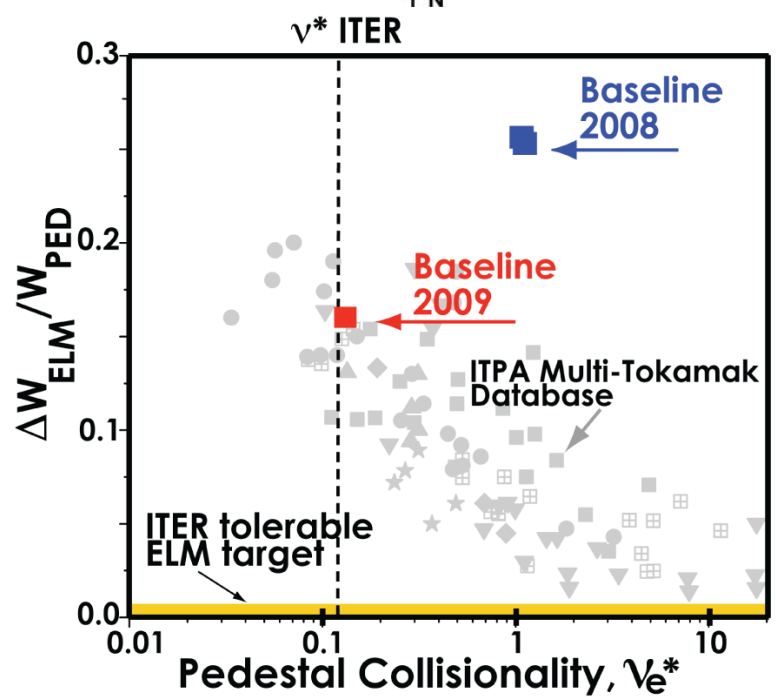
- **Detailed Peeling-Ballooning mode stability analysis needed**



Fractional Energy Loss at ELMs in Baseline Scenario Substantially Exceeds ITER Limit

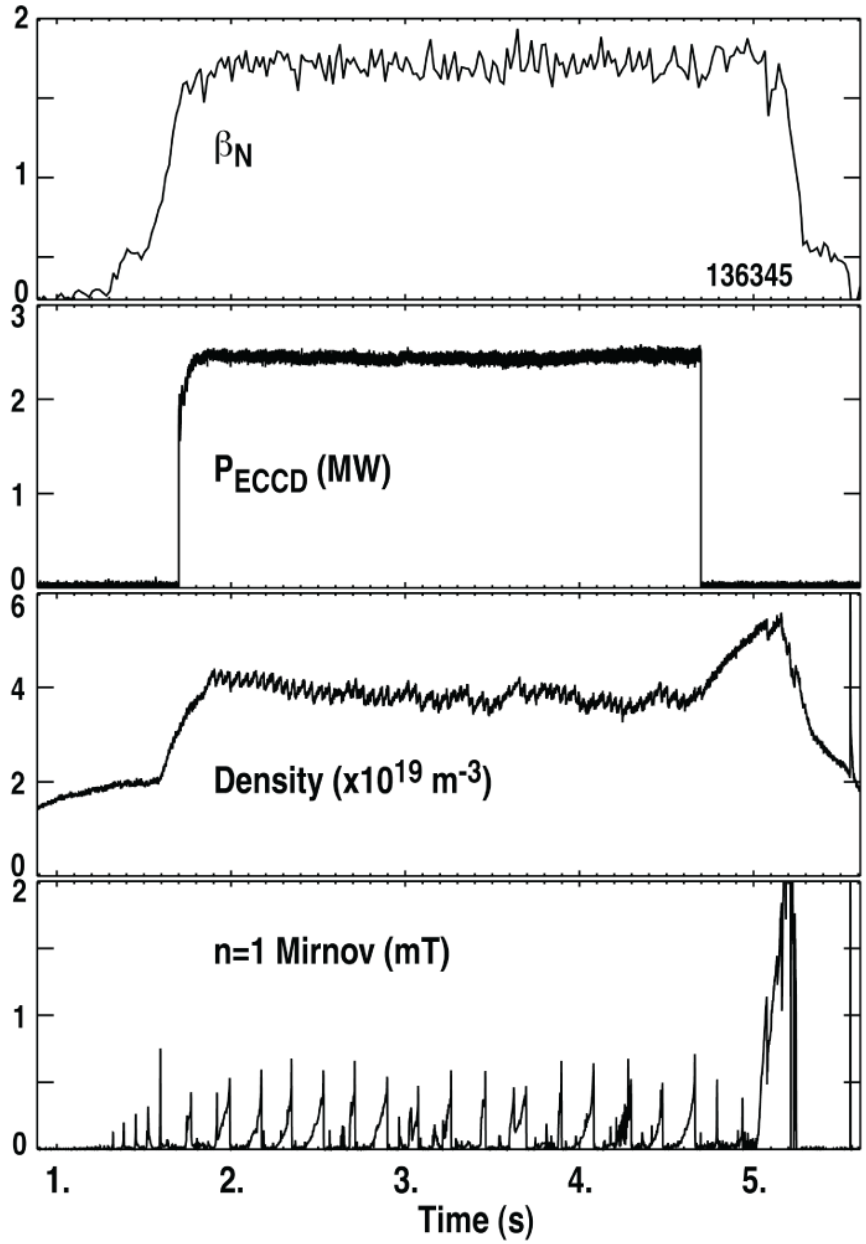
- **Type I ELMs in Baseline scenario plasmas have large radial extent**
- **Energy loss/ELM is > 10 % of total plasma stored energy, ~25 % of pedestal energy**
- **Fractional energy loss at ELMs exceeds ITPA scaling**
- **Reduction of energy loss in at lower collisonality discharges in counter to scaling observed in ITPA database**
  - Most discharges in database operate above P_{TH}





ECCD Provide First Demonstration of Preemptive Stabilization of 2/1 NTM in ITER Baseline Scenario Plasma

- **ECCD directed at q=2 surface successfully preempts destabilization of 2/1 NTM:**
  - Stationary ELMing H-mode with q_{95}~3, β_N~1.8
- **Four gyrotrons, delivering ~2.5 MW to the plasma**
  - More than 1.25 MW required
- **2/1 mode turns on when gyrotrons commanded off**



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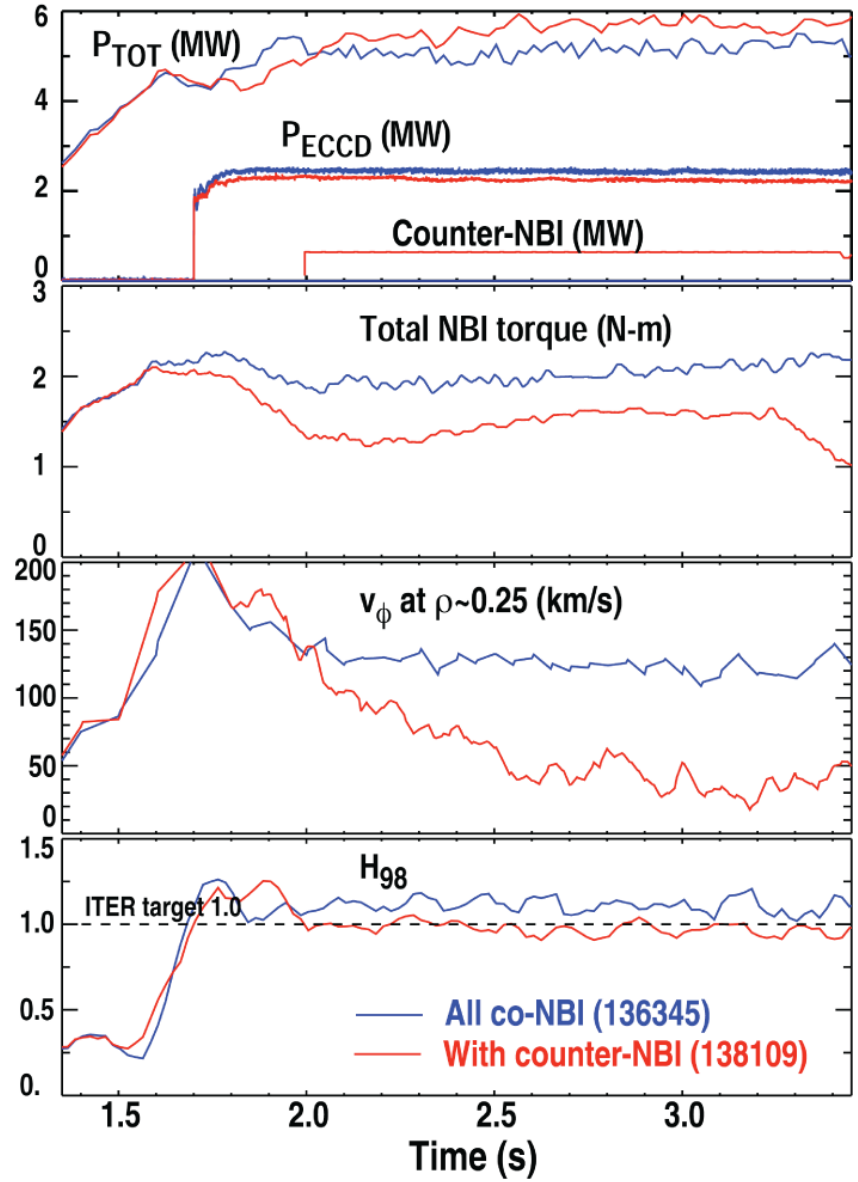
Reduced Plasma Rotation Reduces Confinement in Baseline Scenario

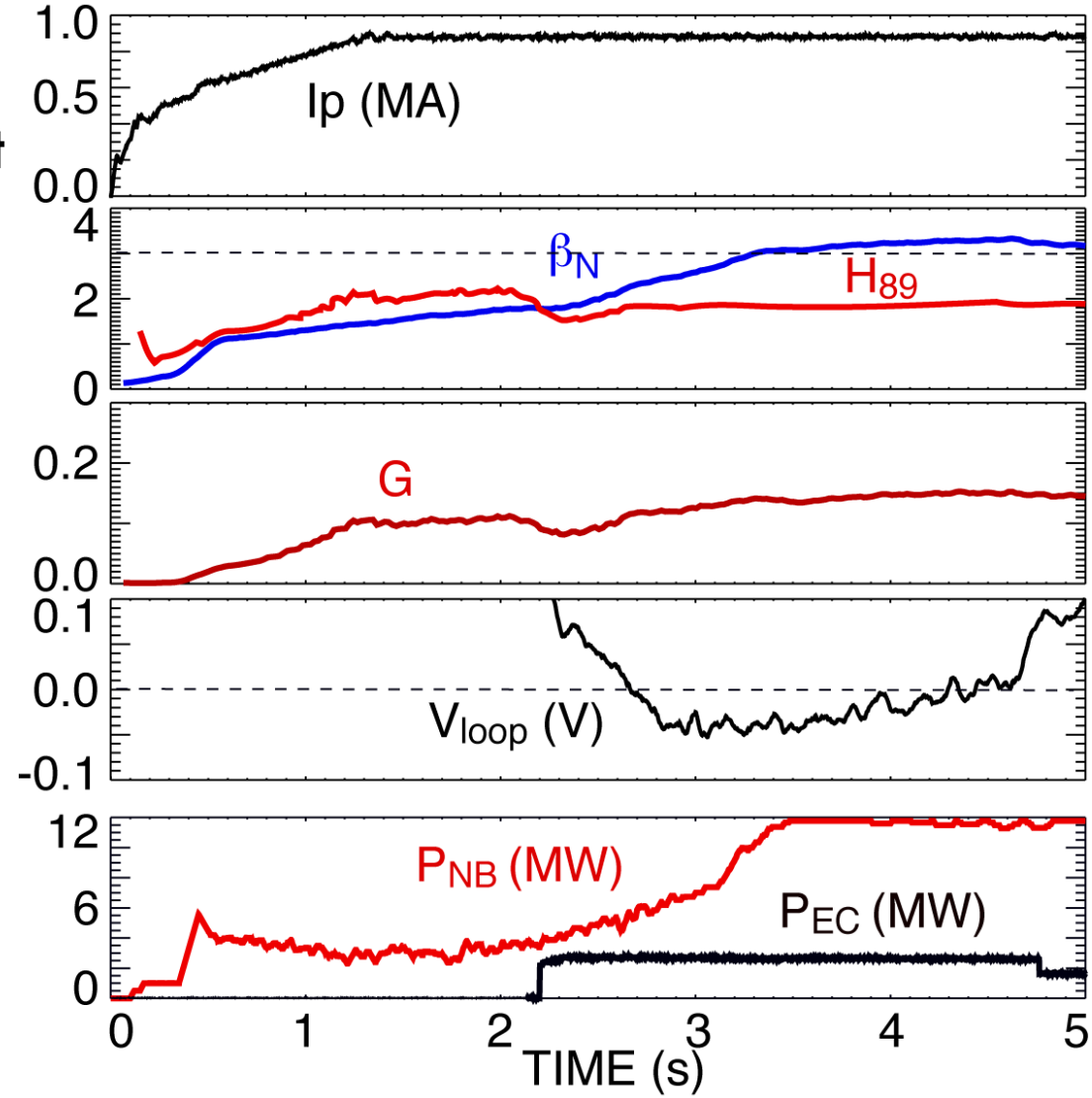
- **Plasma rotation reduced by adding counter-NBI in low collisionality case:**
  - Modest 1/4 counter-beam substantially changes rotation
  - ECH in these discharges also modifies rotation
- **Confinement factor H_{98} reduced by ~15%**
- **Indicates need for performance margin to account for effect of lower rotation, etc. in projecting to ITER**



Steady-State Scenario

Fully Non-inductive Operation Demonstrated in ITER Shape

- **Fully non-inductive operation obtained in 8.5 MA equivalent discharge with β_N = 3.1**
  - High bootstrap fraction (~70%)
- **Steady-state discharges utilize off-axis ECCD to maintain stable q-profile with $q_{min} \geq 1.5$**
- **$G = \beta_N H_{89}/q_{95}^2$**
  - Measure of fusion performance



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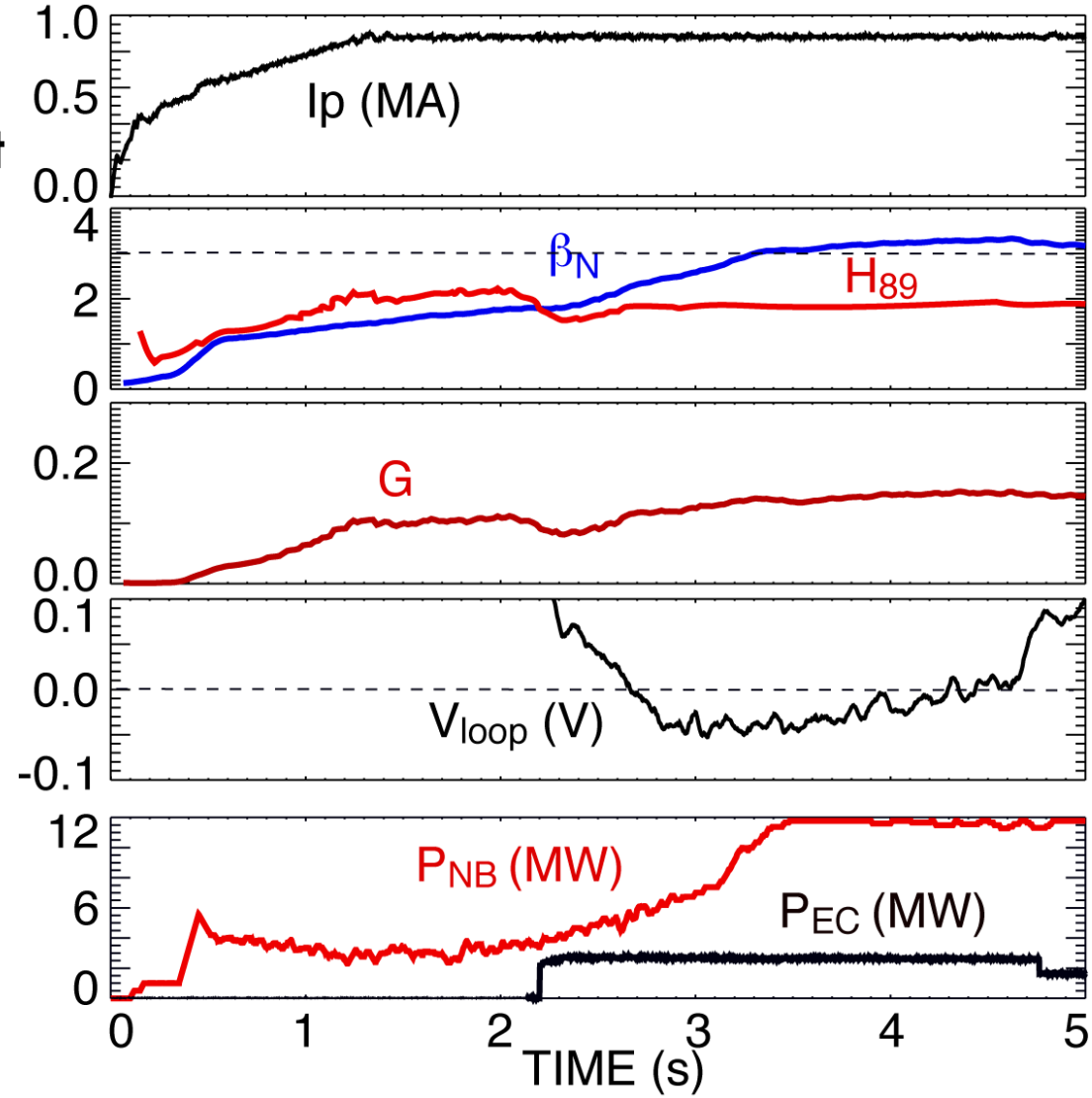
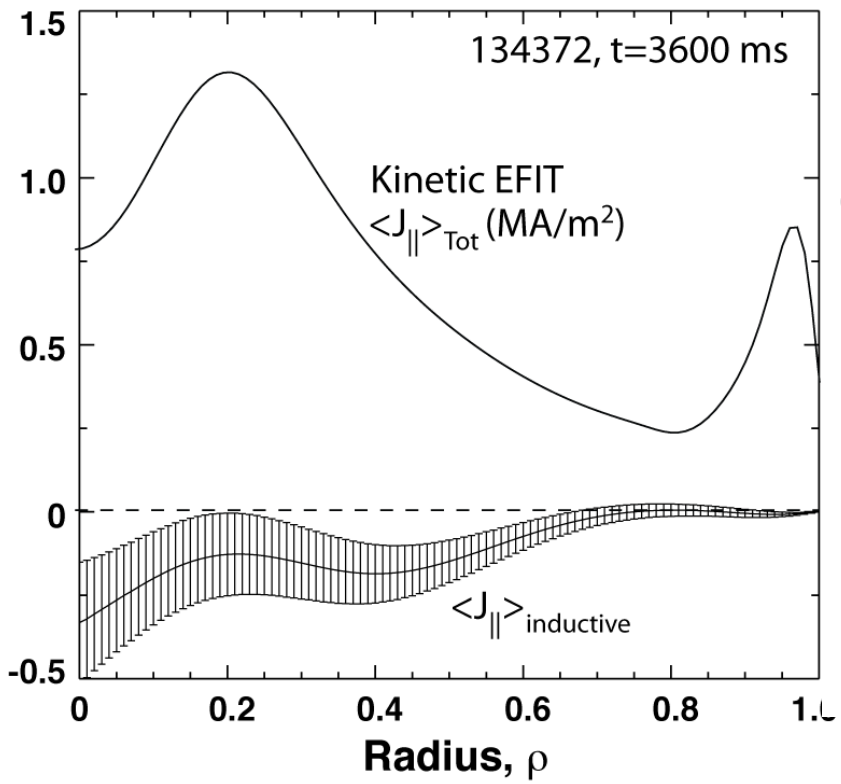
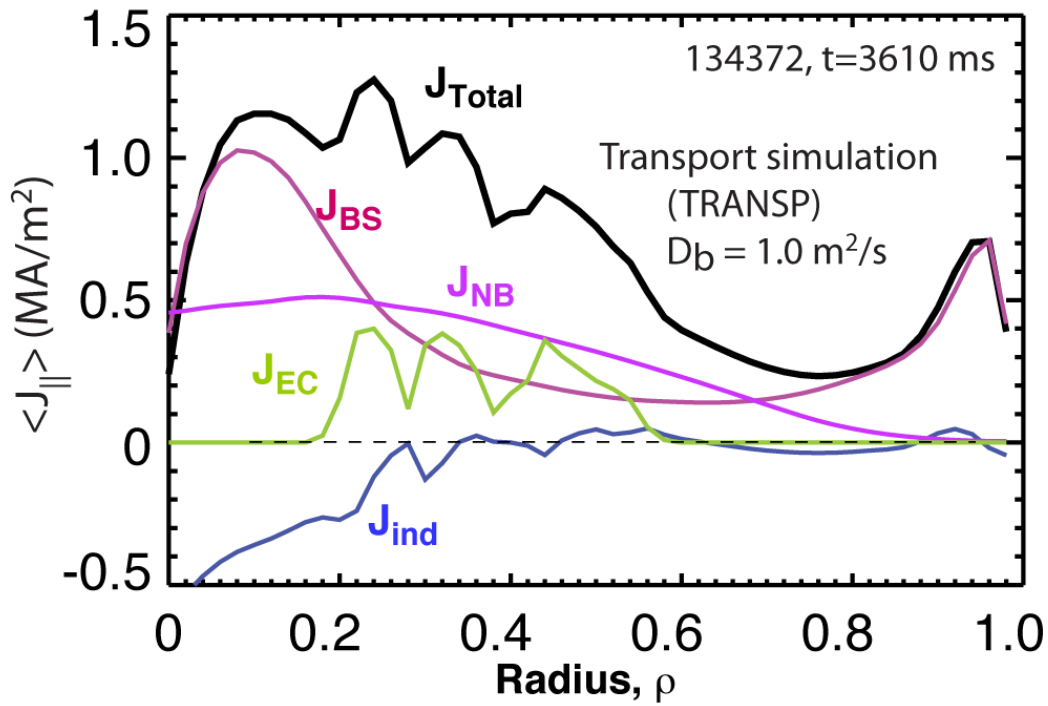


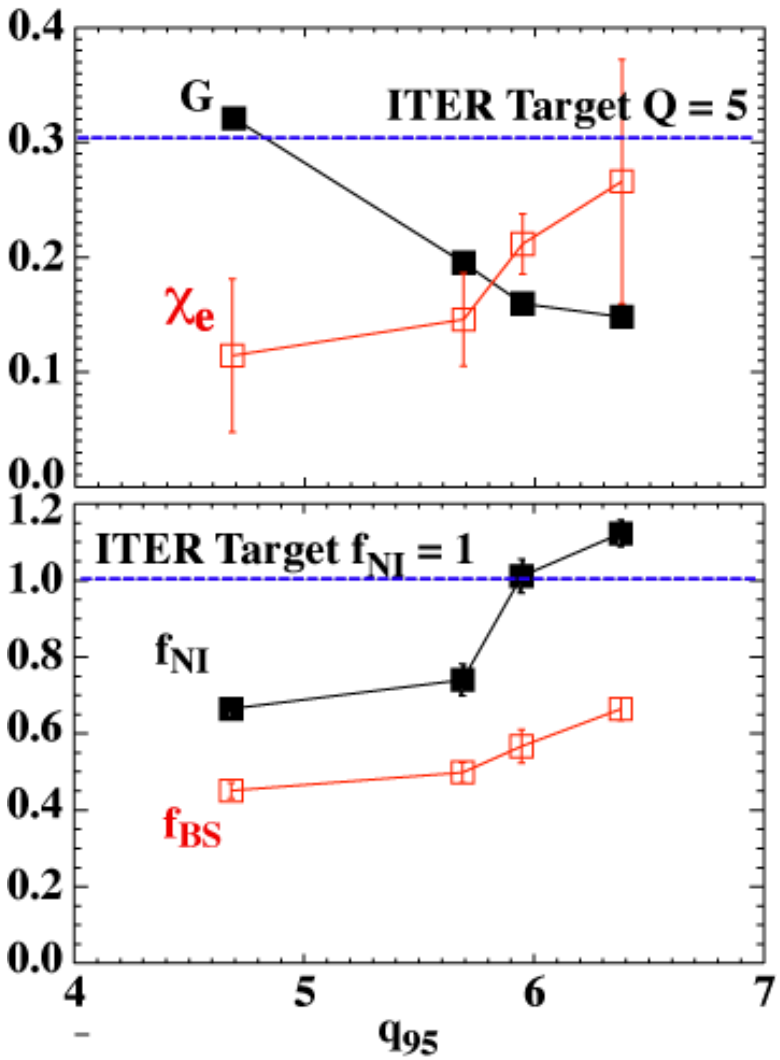
Measurement and Simulation Show the Inductive Current Density is Small Everywhere





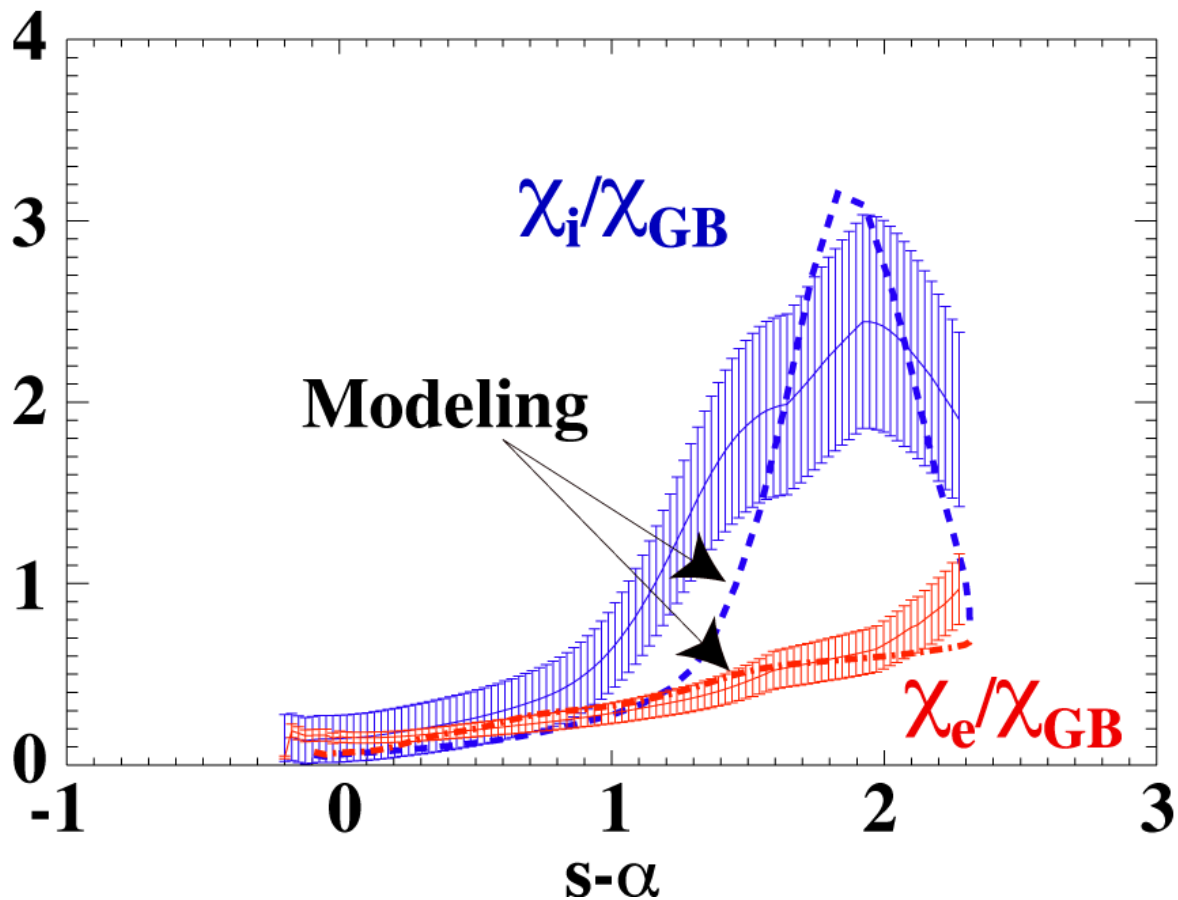
- **Measurement of inductive current density - loop voltage analysis**
- **Transport code simulation**

Trade-off Between Fusion Performance and Non-inductive Fraction Seen with Variation in q_{95}



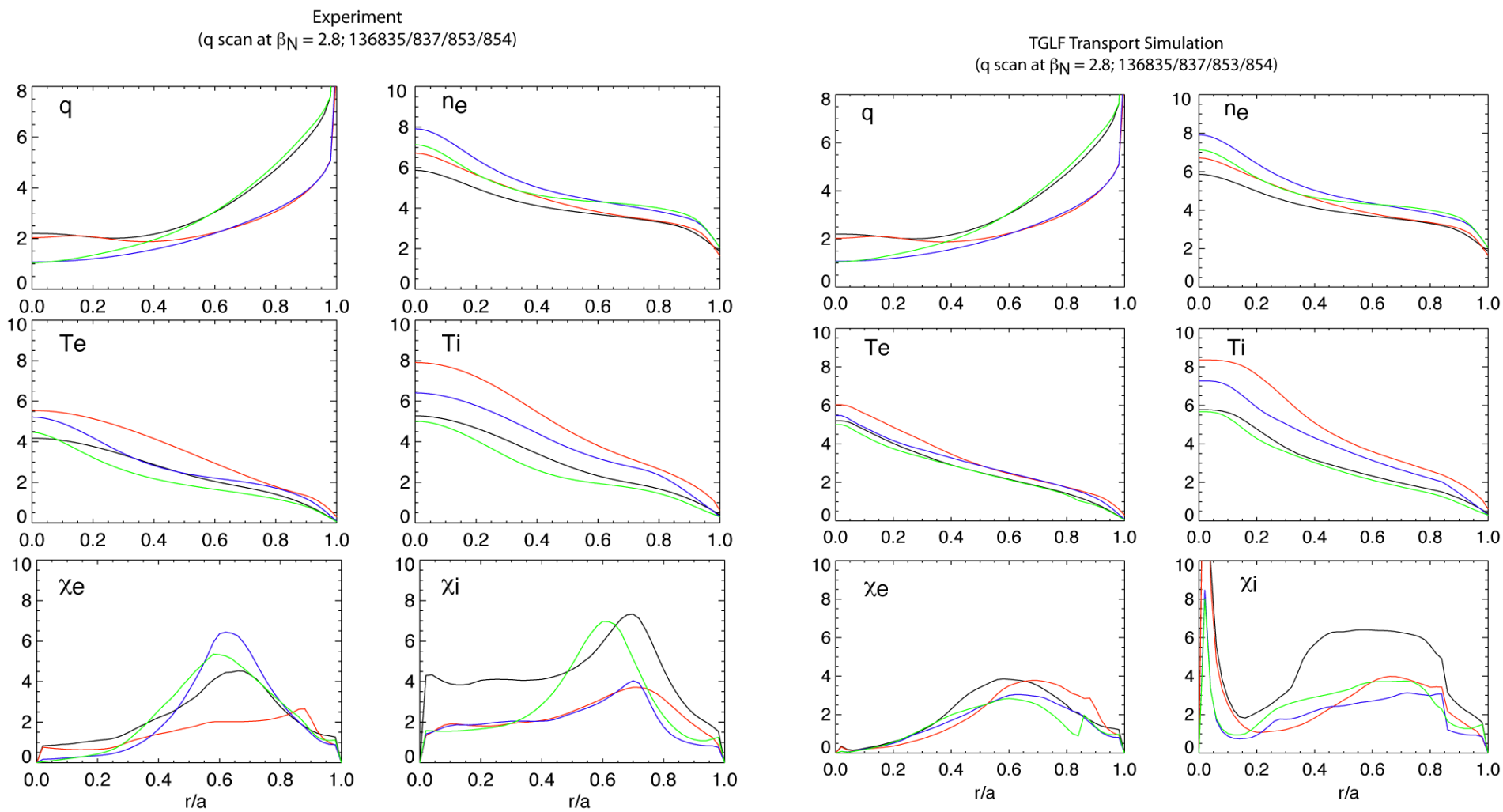
- **Strong dependency of plasma confinement on q95**
- **The thermal energy confinement time decreases with *q*95, generally following the scaling of *H*98**
- ***f*NI and *f*BS increase with βN*q*95.**
- **The edge pedestal provides typically ~40% of the total bootstrap current, and its height and width depend on *q*95,**
  - the pedestal plays a key role in optimizing the steady-state scenario.

The Electron and Ion Thermal Diffusivity Appear to Correlate Mainly with the Magnetic Shear

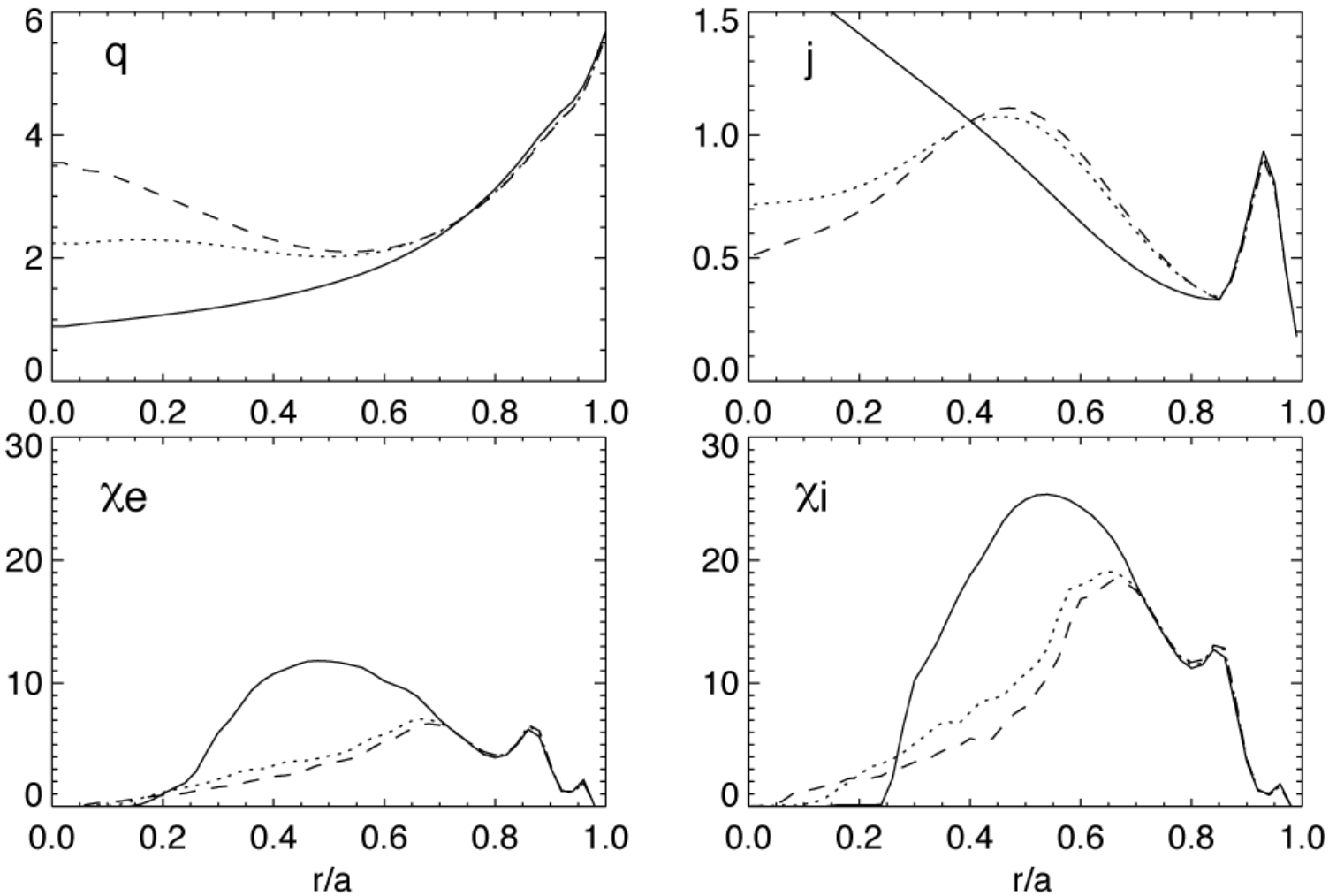


- **Optimizing q profile is critical to simultaneously achieving f_{NI}=1 and Q=5 goal**

TGLF Simulations Reproduce Strong Transport Dependency on q Profile



Predictive Simulation Suggests that a Larger Radius for the Minimum of *q* Helps to Increase both the Fusion Performance and f_{NI}



Summary

- **Match to Expected Conditions for ITER Baseline Scenario has been Significantly Improved**
  - Matched ITER collisionality target with no loss in performance
  - First demonstration of 2/1 NTM avoidance using ECCD under ITER-similar conditions
  - Improved stationarity and density control
  - Initial data on impact of reduced rotation on confinement
- **The demonstration discharges address many key ITER physics issues, e.g. transport, ELMs, optimum q profile, etc**
- **Data from these experiments have been used extensively to test and develop theory and modeling for realistic ITER projection and for further development of its optimum scenarios in DIII-D**
- **DIII-D Evaluations of ITER Scenarios Will be Further Extended by Applying New Tools: Off-axis NBI, Higher power EC, …**