Demonstration of ITER Operational Scenarios on DIII-D

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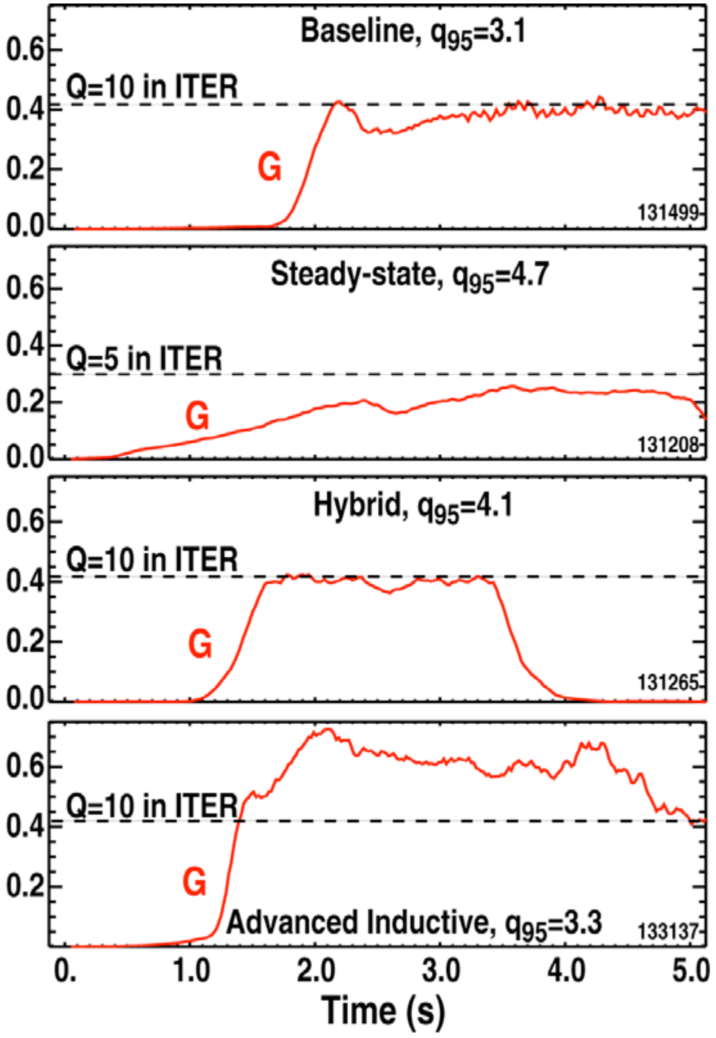
DIII-D Demonstration Discharges Meet ITER Normalized Performance Targets



$G \equiv \beta_N H_{89}/q_{95}^2$ 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**

DIII-D NATIONAL FUSION FACILITY SAN DIEGO

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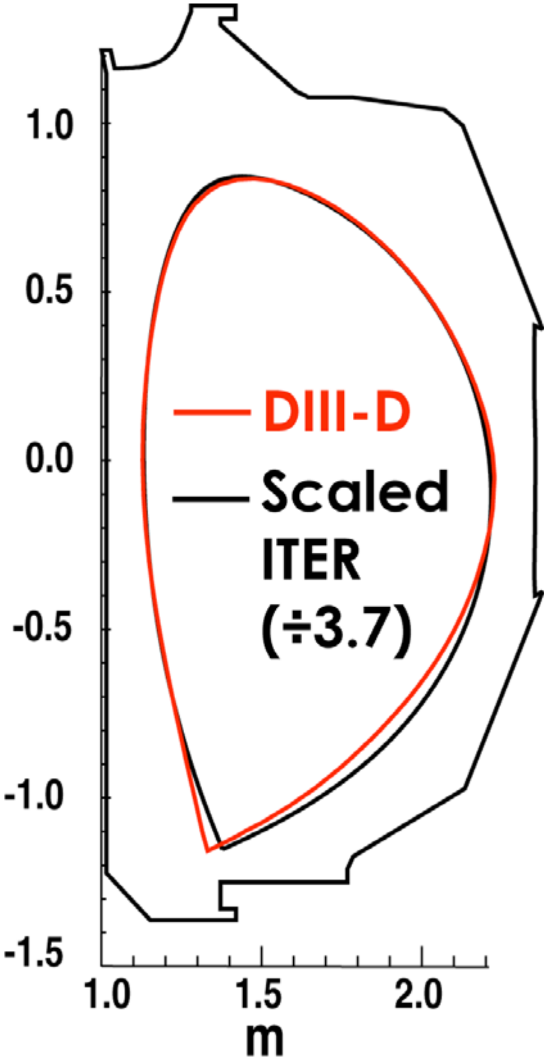
DIII-D has Unique Capability to Evaluate ITER Scenarios While Matching Design Shape and Aspect Ratio

- **With size reduced by factor of 3.7, the DIII-D discharges match the ITER design values for**
  - Plasma cross section
  - Aspect ratio
  - Value of I/aB (normalized current)
- **Target values for β_N and H_{98} were matched or exceeded**
  - Evaluations concentrate on flat-top phase
  - Dominant co-NBI used throughout study



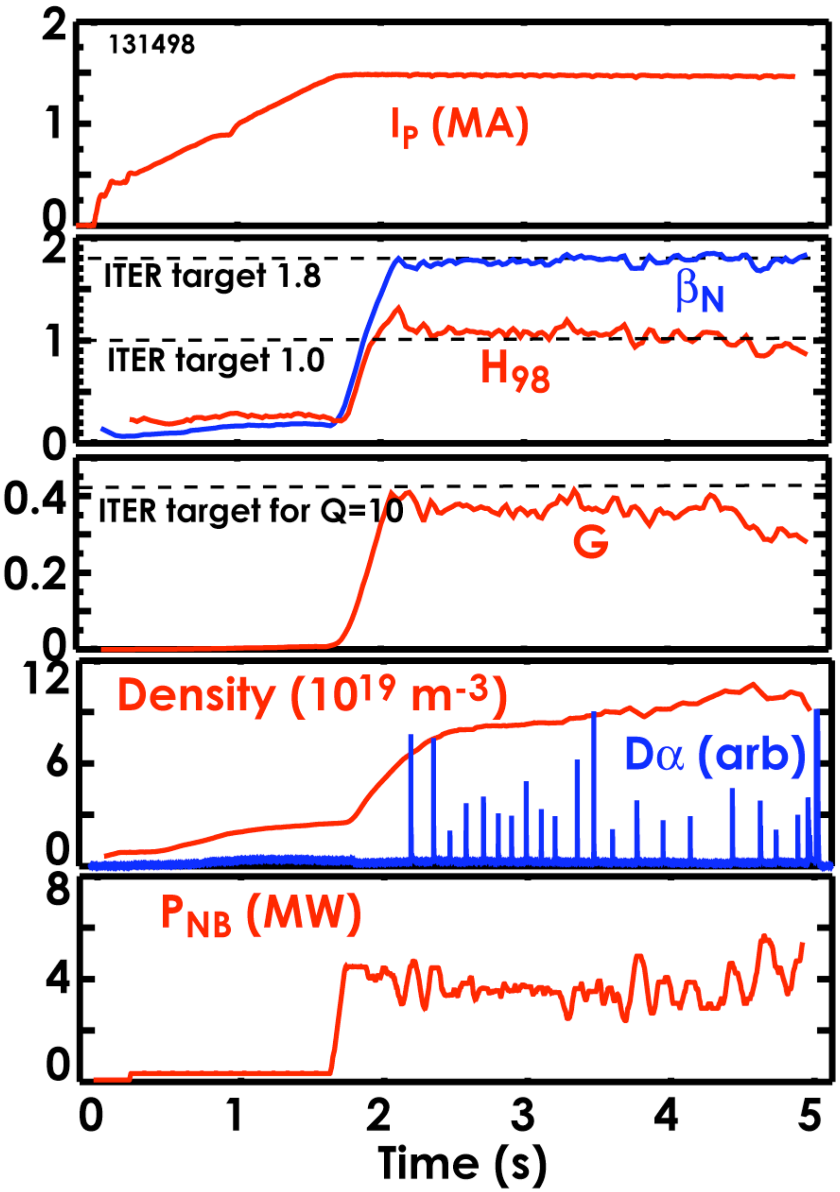
ITER Baseline Scenario Performance Matched on DIII-D

- **I/aB equivalent to 15 MA operation on ITER, q_{95} of 3.1**

- **3 s H-mode period is ~3τ_R, ~ same normalized duration as ITER**
  - However, plasma is non-stationary

- **Absolute density ~ same as ITER, n/n_{GW}~0.65 (ITER 0.85)**

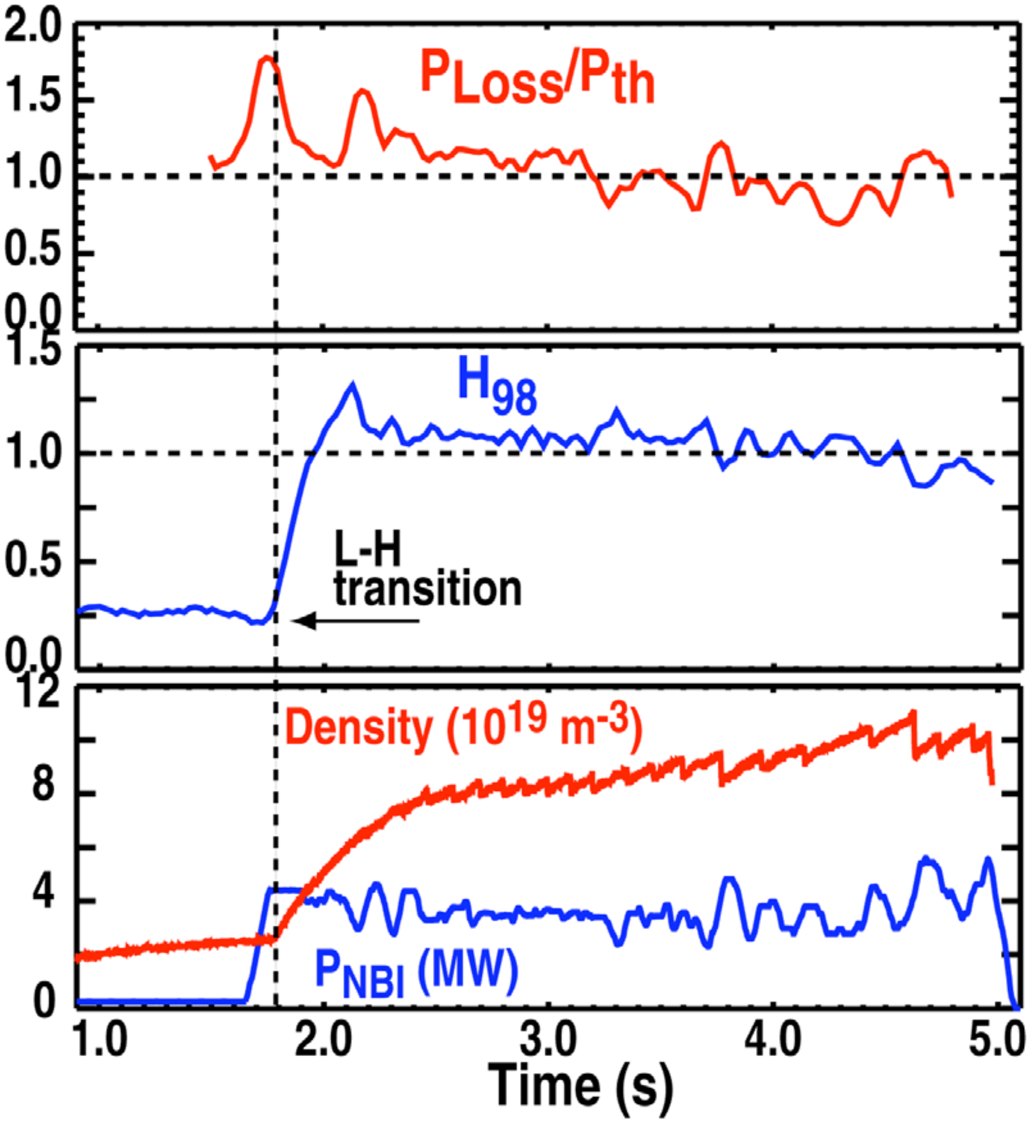
- **Operation limited to $\beta_N \leq 2$, with disruptions even at lower β_N when 2/1 tearing modes appear**



Confinement is at ITER Target Level Despite Operation Close to Predicted L-H Power Threshold

- **Baseline discharges operate close to or below P_{Loss}/P_{th}=1. throughout H-mode phase**

- **L-H power threshold (P_{th}) calculated using latest scaling prediction**
  - $P_{th}=0.049*n^{0.72}B^{0.8}S^{0.9}$
  - Y. Martin, et al., 2008



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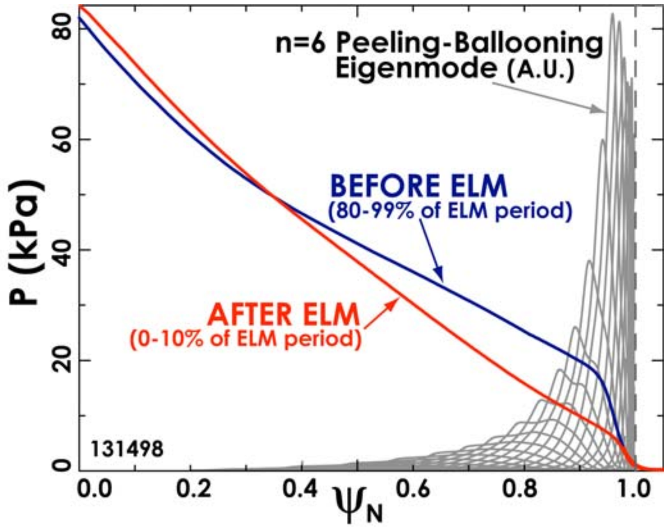
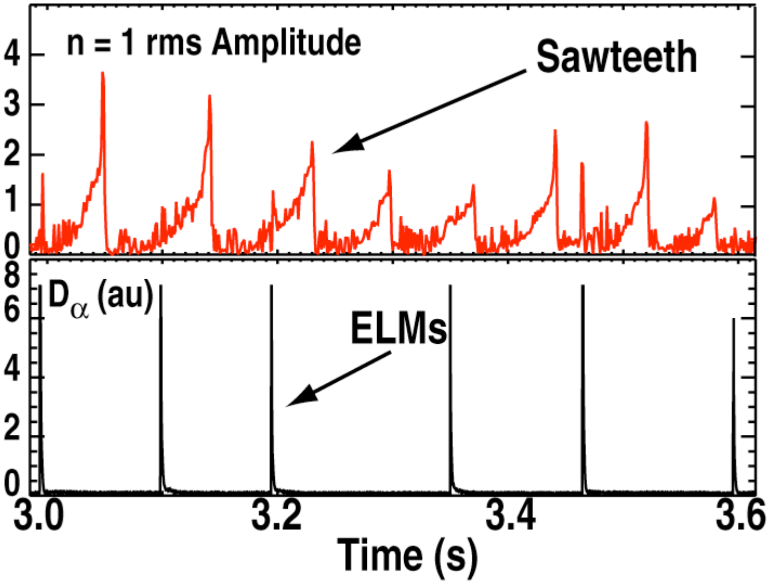
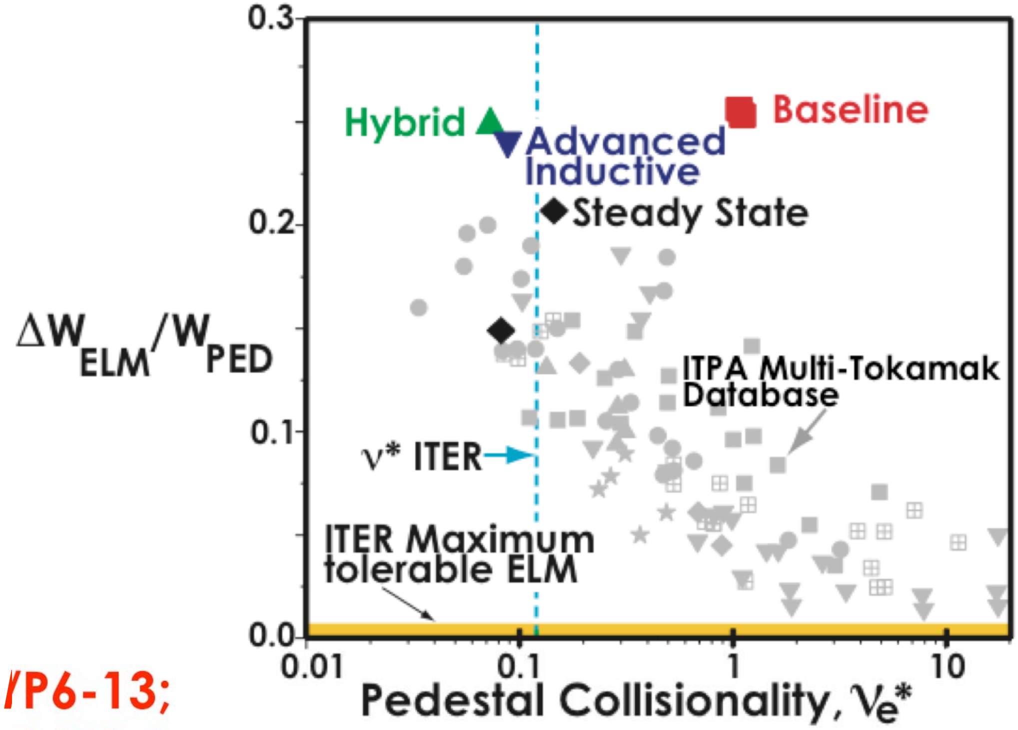
Fractional Energy Loss at ELMs in Baseline Scenario Substantially Exceeds ITER Limits



- **Type I ELMs in Baseline scenario plasmas have large radial extent, to ρ~0.5**
  - Not due to synchronized ELMs and sawteeth
- **Energy loss/ELM is >10% of total plasma stored energy, ~25% of pedestal energy**
- **Further motivates need for ELM control system on ITER**





ITER limits, Loarte, IT/P6-13; ELM control, Evans, EX/4-1

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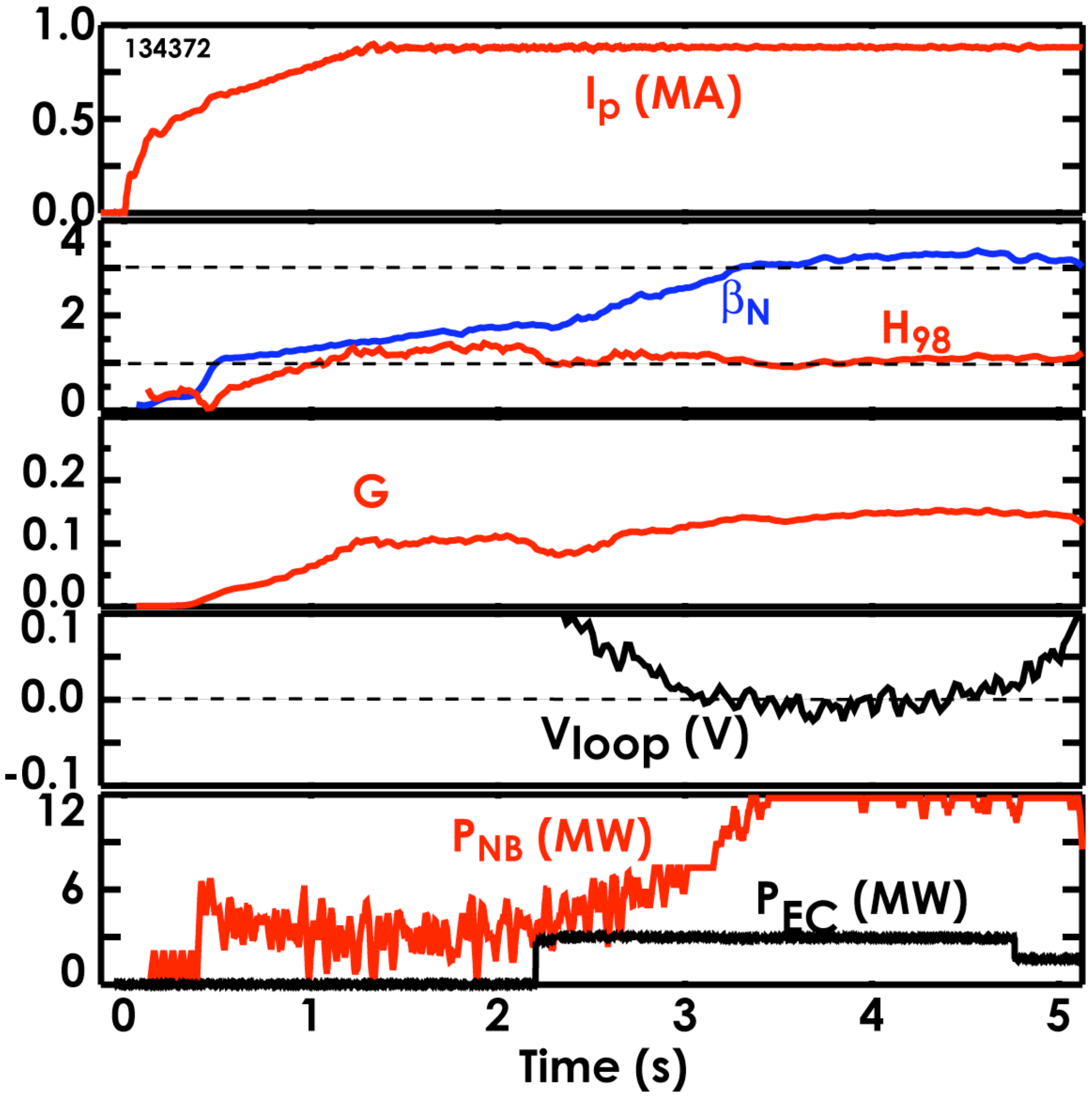
Steady-State Scenario: Fully Non-inductive Operation Demonstrated in ITER Shape

- **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}≥1.5**



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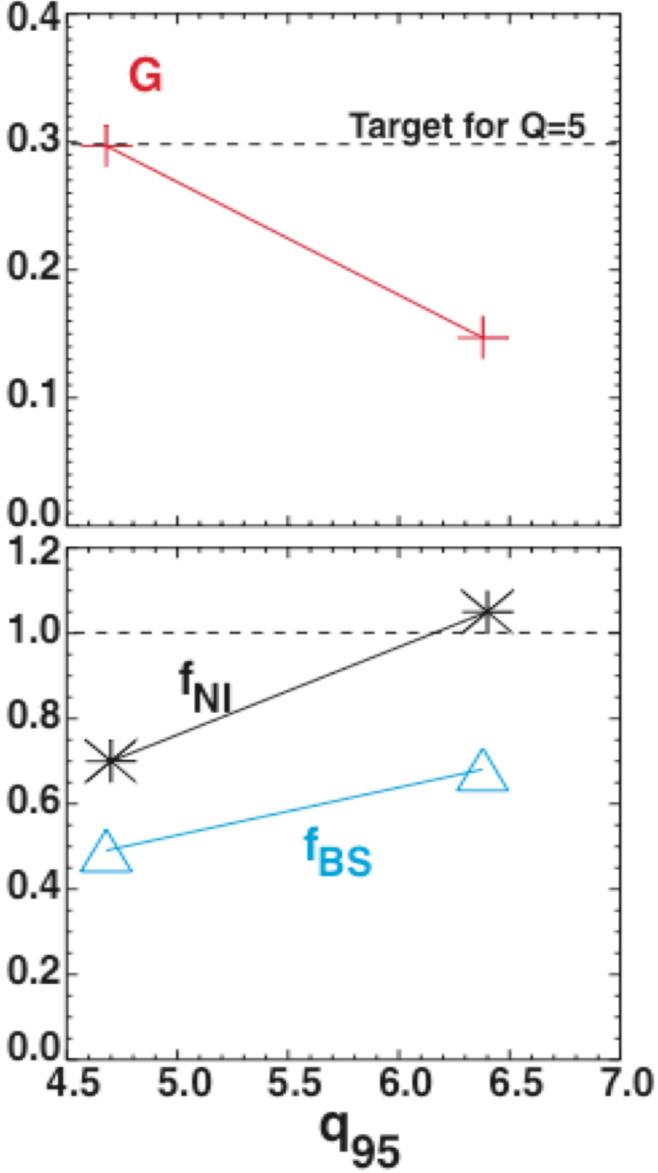
Trade-off Between Fusion Performance and Non-inductive Fraction Seen with Variation in q_{95}

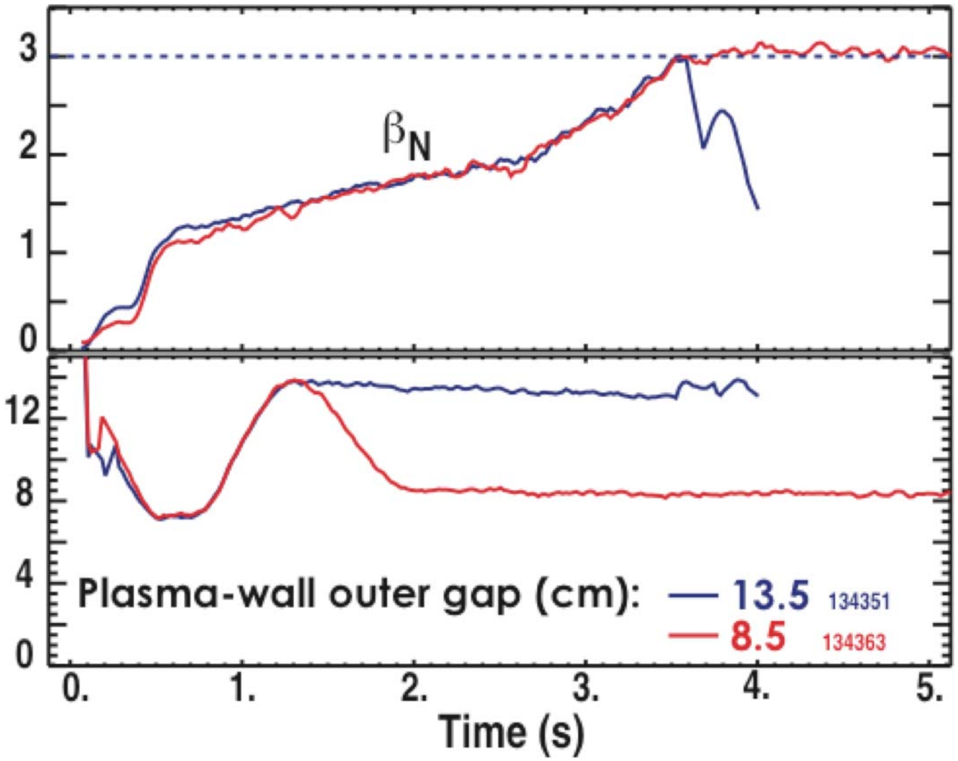
- **Detailed analysis performed for discharges at ends of q_{95} range**
- **At higher currents (q_{95}=4.7), G=0.3 for Q=5 target was matched**
- **At lower current (q_{95}=6.3), 100% NI (or overdriven) operation was achieved, but with lower fusion performance**



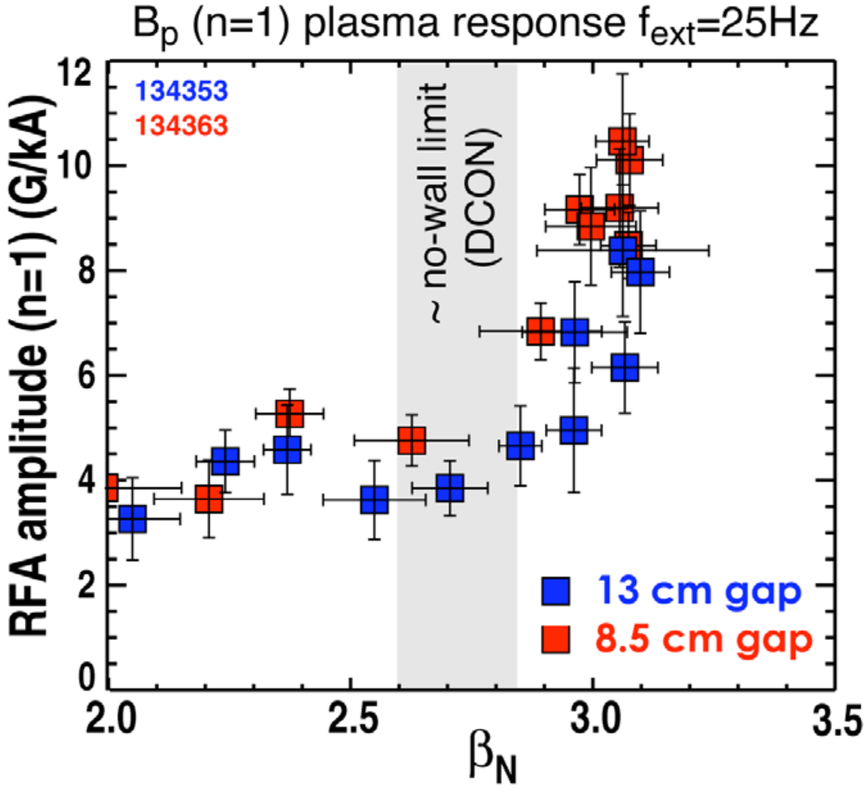
DIII-D steady-state scenario development, Ferron EX/P4-24

Wall Stabilization is Necessary for Steady-State Scenario Operation in ITER with β_N>3

- **Higher β_N achieved with smaller plasma-wall gap**



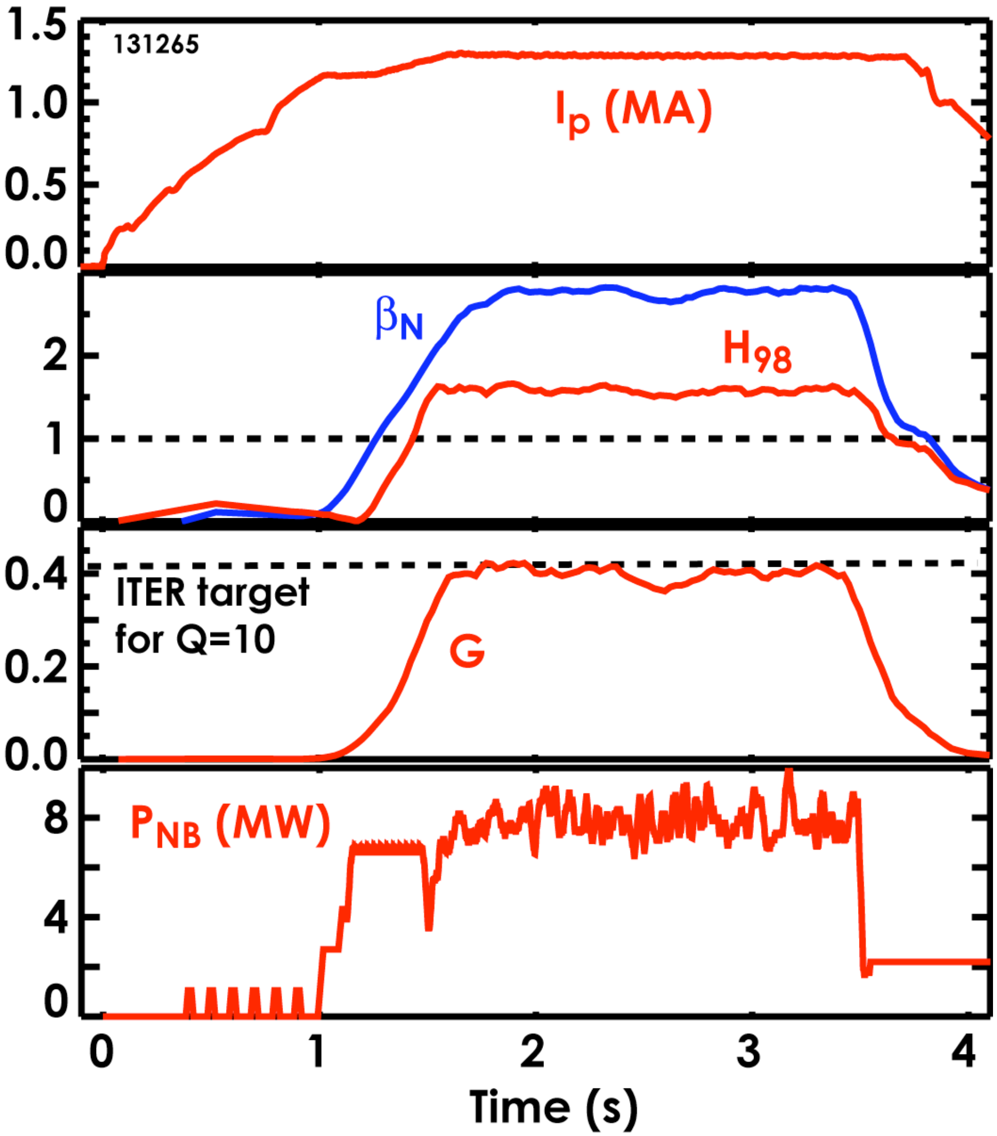
- **This change is not due to variation of the no-wall limit**



- **Difficult to simultaneously match ITER shape and plasma-wall separation**

Excellent Confinement and Stability in the ITER Shape Obtained in Hybrid Scenario Discharges

- Example shown utilized ITER large bore plasma startup scenario (Jackson, IT/P7-2)
- I/aB equivalent to 11.6 MA operation on ITER, q_{95} of 4.1
- Alternative route to Q=10 mission, at lower I_p and with lower disruptivity
- Issues: Requirements for access in ITER, performance with more ITER relevant conditions



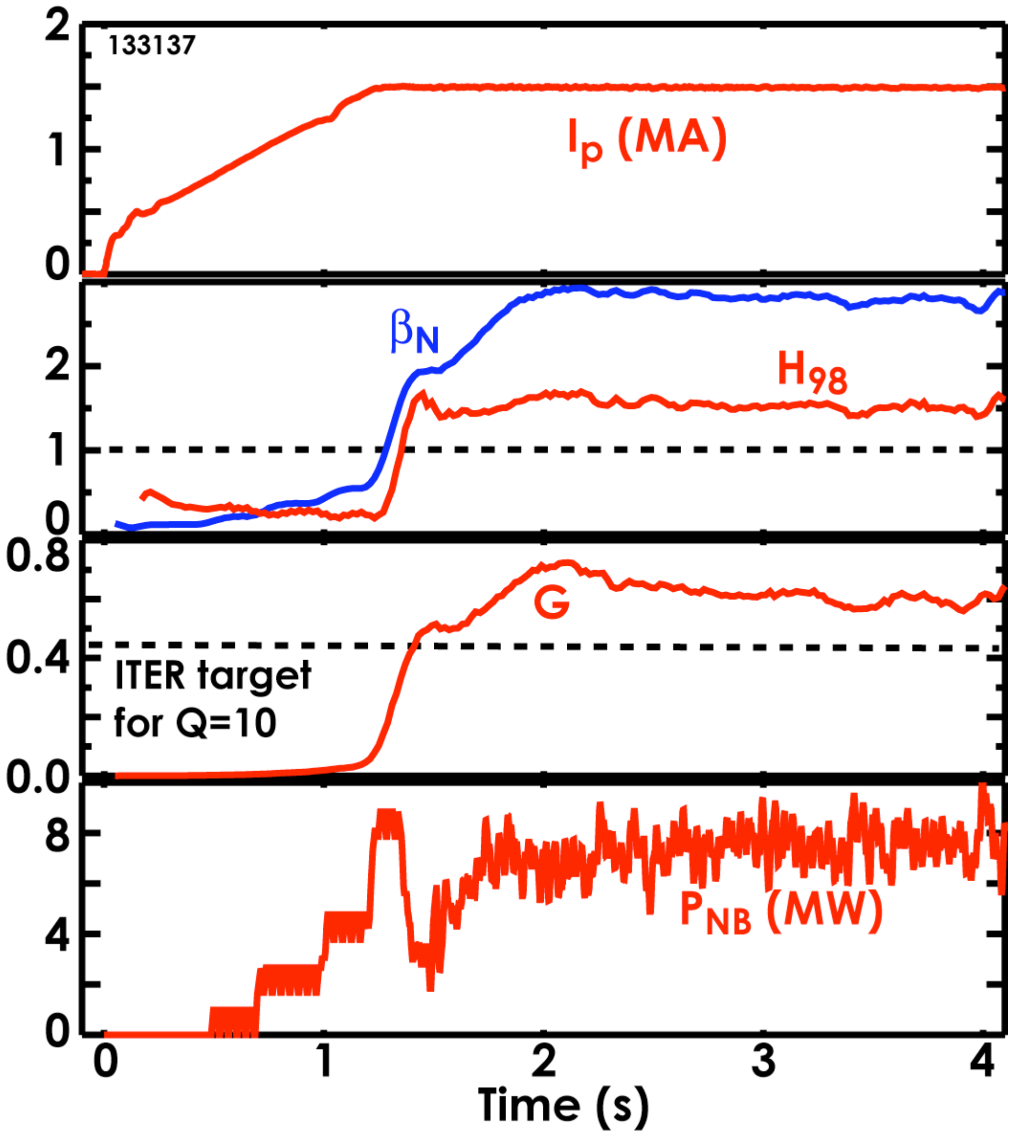
DIII-D hybrid research, Petty EX/1-4Rb

Excellent Confinement and Stability are also Obtained in Advanced Inductive Scenario Discharges

- **Advanced inductive scenario has sustained high performance at β_N=2.8 with excellent confinement, H_{98}=1.5**

- **I/aB equivalent to 14.8 MA operation on ITER, q_{95} of 3.3**

- **Issues for advanced inductive scenario are similar to those for hybrid, except operation is at a higher current**



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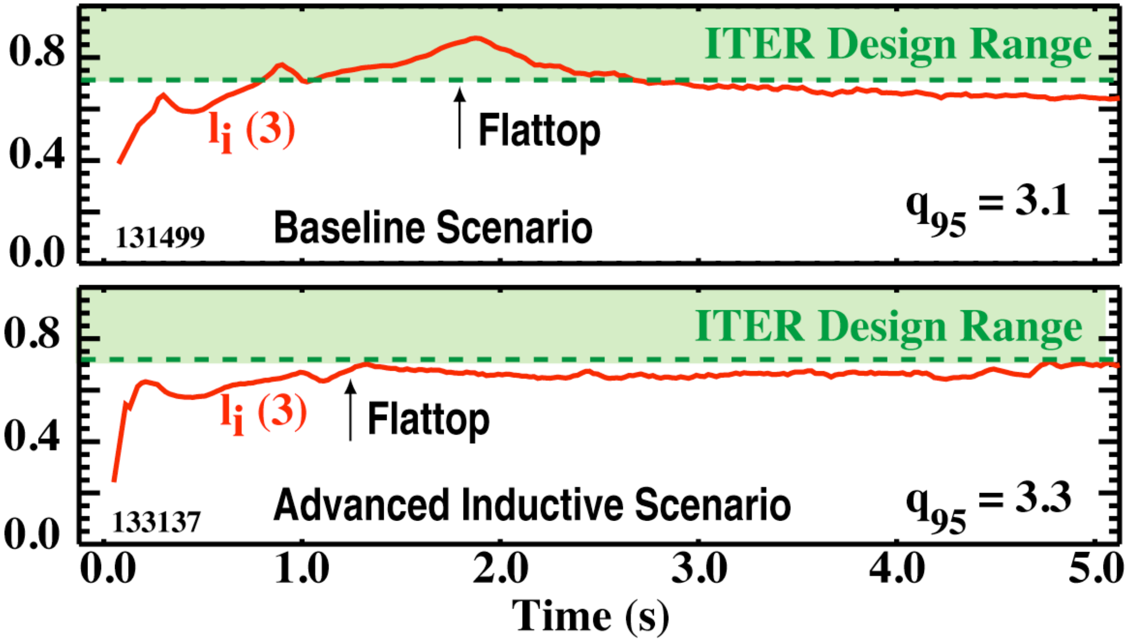
DIII-D Results Have Impacted the ITER Design, e.g., Increase in Operating Range for ITER Shape Control System

- **ITER shape control was designed for internal inductance in the range of $\ell_i(3)$ = 0.7-1.0 at 15 MA**

- **Measured $\ell_i(3)$ on DIII-D during flattop phase are outside this range**
  - Would lead to loss of plasma shape control



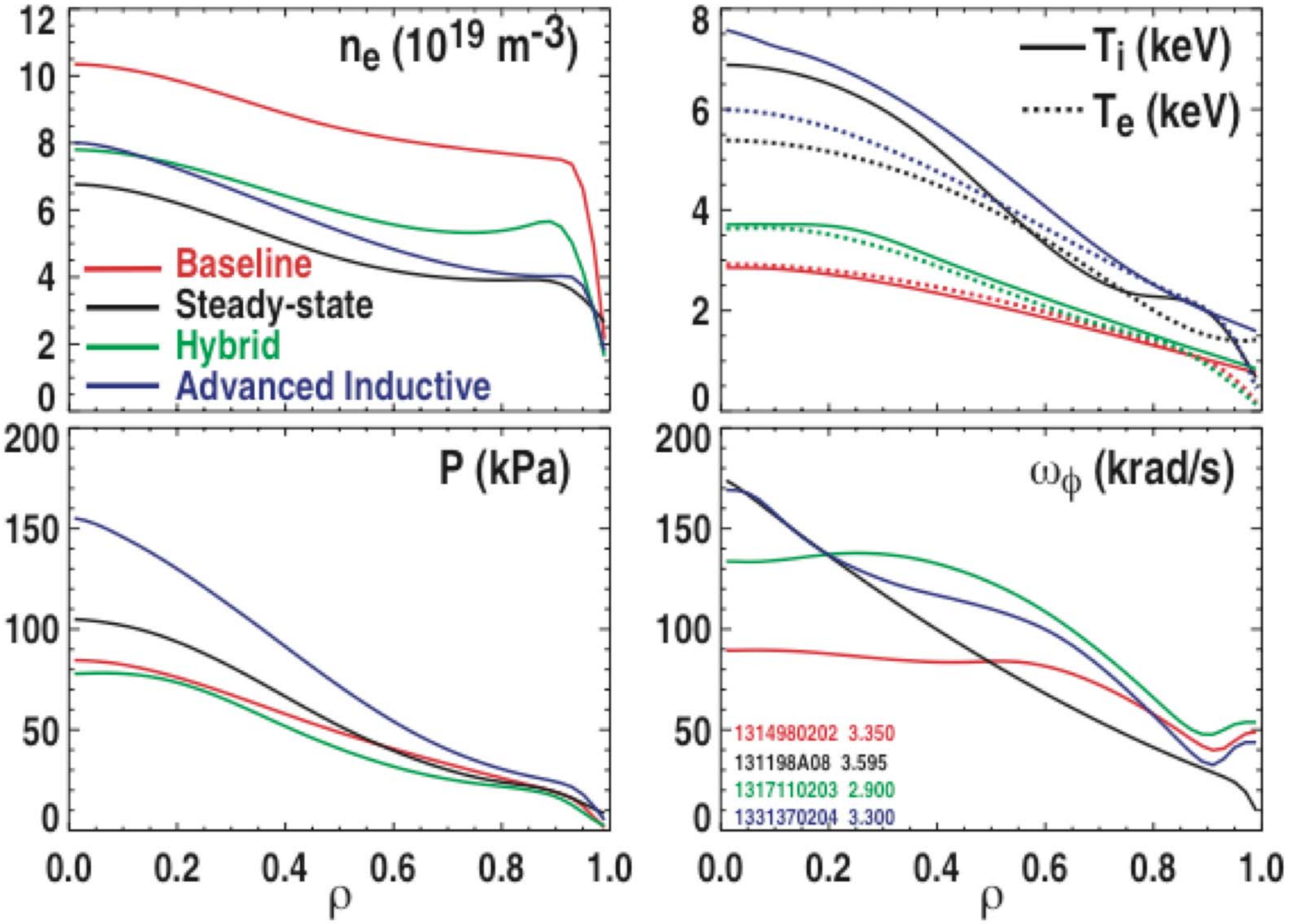
- **The design range for ITER has been increased, based on results from DIII-D and other machines**

Results from multiple devices, Sips, IT/2-2;

Change to ITER design, Hawryluk, IT/1-2

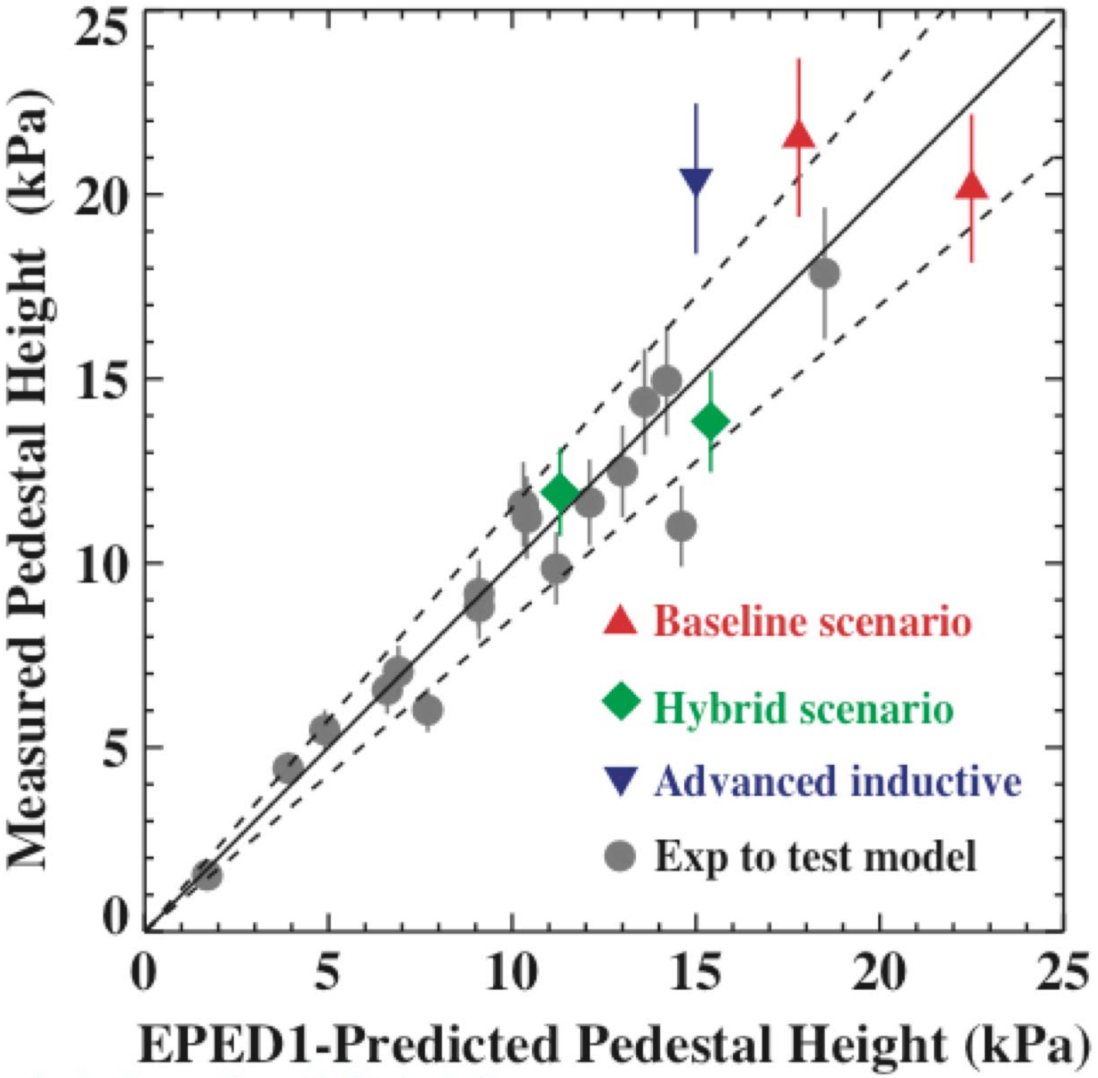
DIII-D Experimental Profiles are Utilized for Both Transport Modeling and ITER Performance Projections

- Baseline and hybrid scenarios have $T_e \sim T_i$
- At 1.9 T, advanced scenarios have same pressure as baseline scenario at lower I_p, or higher pressure at equal I_p
- All discharges have co-NBI



Good Fit to Pedestal Conditions in the ITER Scenarios Obtained from Predictive Model

- **Data from the ITER scenarios are being added to the database used to test the EPED1 predictive pedestal model**



EPED1 model, Snyder IT/P6-14;
Experimental tests, Groebner EX/P3-5

Performance Projections Support ITER Reaching its Physics and Technology Objectives, with Margin

- **DIII-D discharges projected to ITER assuming same β_N and H, with n_e/n_{GW}=0.85, using range of confinement scalings:**
  - ITER-89P, Bohm-like,
  - IPB98y2, intermediate,
  - DS03, gyroBohm-like

- **ITER P_{fus} target met or exceeded in all cases**

- **Margin can cover differences due to quantities not matched to ITER, e.g. plasma rotation**

- **For details of projection method see T.C. Luce, Phys. Plasmas 11, 2627 (2004)**

	Base-line	Hybrid	AI	Steady-state
β_N (DIII-D)	1.8	2.8	2.8	3.1
P_{fus}(ITER)	400	400	700	350
Fusion Gain (Q)				
89P	10.3	5.8*	13.5	2.7*
98y2	22.4	23.3	∞	5.8*
DS03	∞	∞	∞	19.8
ITER target	10	5	≥20	5

*** P_{aux} required is greater than Day-one value of 73 MW**

Summary: DIII-D Has Demonstrated the Performance Required to Meet ITER Goals for Four Key Scenarios

- **The demonstration discharges address many key ITER physics issues, e.g. ELMs, L-H transition, pedestal scaling, beta limits, etc.**

- **DIII-D results have impacted the ITER design, e.g., the required operating range of the plasma shape control system**

- **DIII-D evaluations of ITER scenarios can be extended and improved:**
  - Vary NBI power and torque to operate with reduced plasma rotation
  - Extend $T_e=T_i$ operation to more scenarios
  - Determine sensitivity of performance to shape
  - Assess impact of ELM suppression on perfromance
  - Extend demonstration to startup and ramp-down phases