Stability Boundaries and Development of the ITER Baseline Scenario

by

G.L. Jackson, F. Turco, W.M. Solomon, T.C. Luce, R.J. Buttery, A.W. Hyatt, J.S. deGrassie, E.J. Doyle, J.R. Ferron, R.J. La Haye, and P.A. Politzer

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Motivation and Goals

- **Experimentally demonstrate feasibility of the ITER baseline 15 MA scenario ($\beta_N \approx 1.8$, $I_p/aB_T \approx 1.42$)**
  - ITER equivalent torque
  - Dominant electron heating
  - ELM mitigation at $q_{95} \leq 3.2$

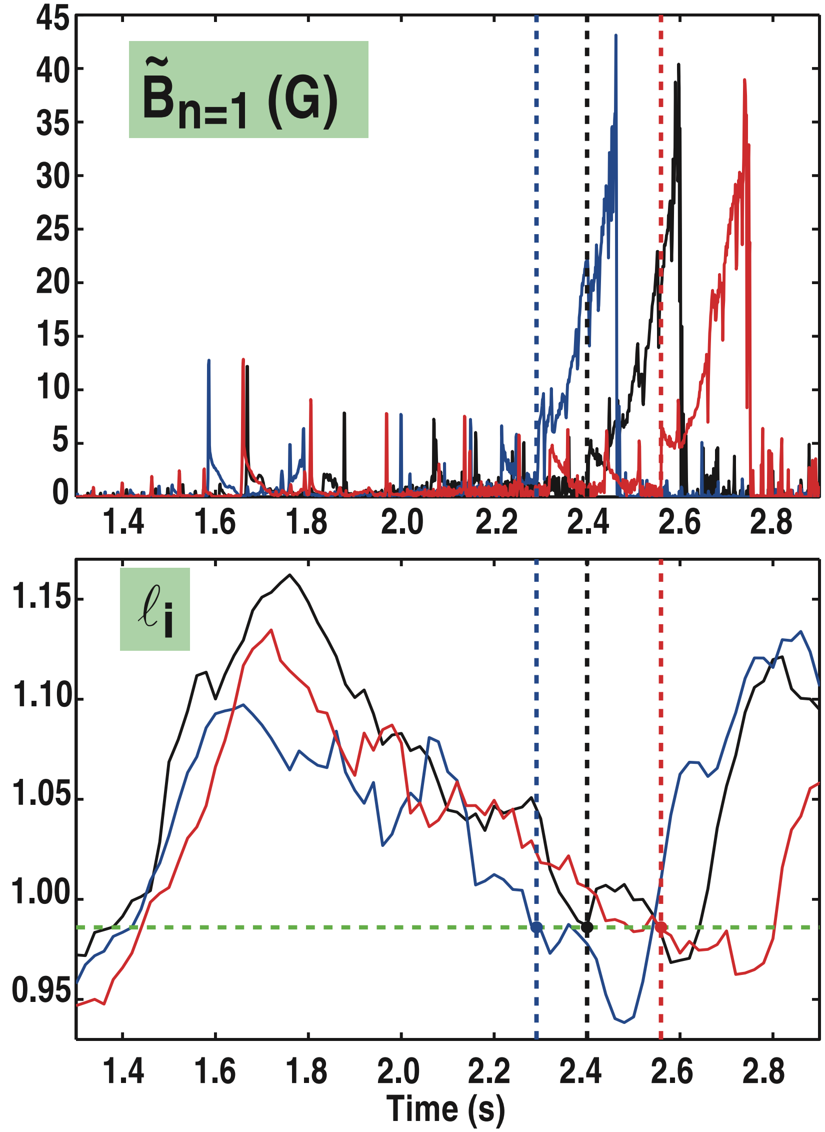
- **Demonstrate stationary, long duration pulses**

- **Understand tearing stability**

Previous Work Showed Limits to Sustained Operation in Pulses Without ECCD Stabilization

- ℓ_i **evolved until TMs terminated the β_N flattop phase** *[Turco and Luce, Nucl. Fusion (2010)]*

- **Can stable operation be found without requiring ECCD tearing control?**



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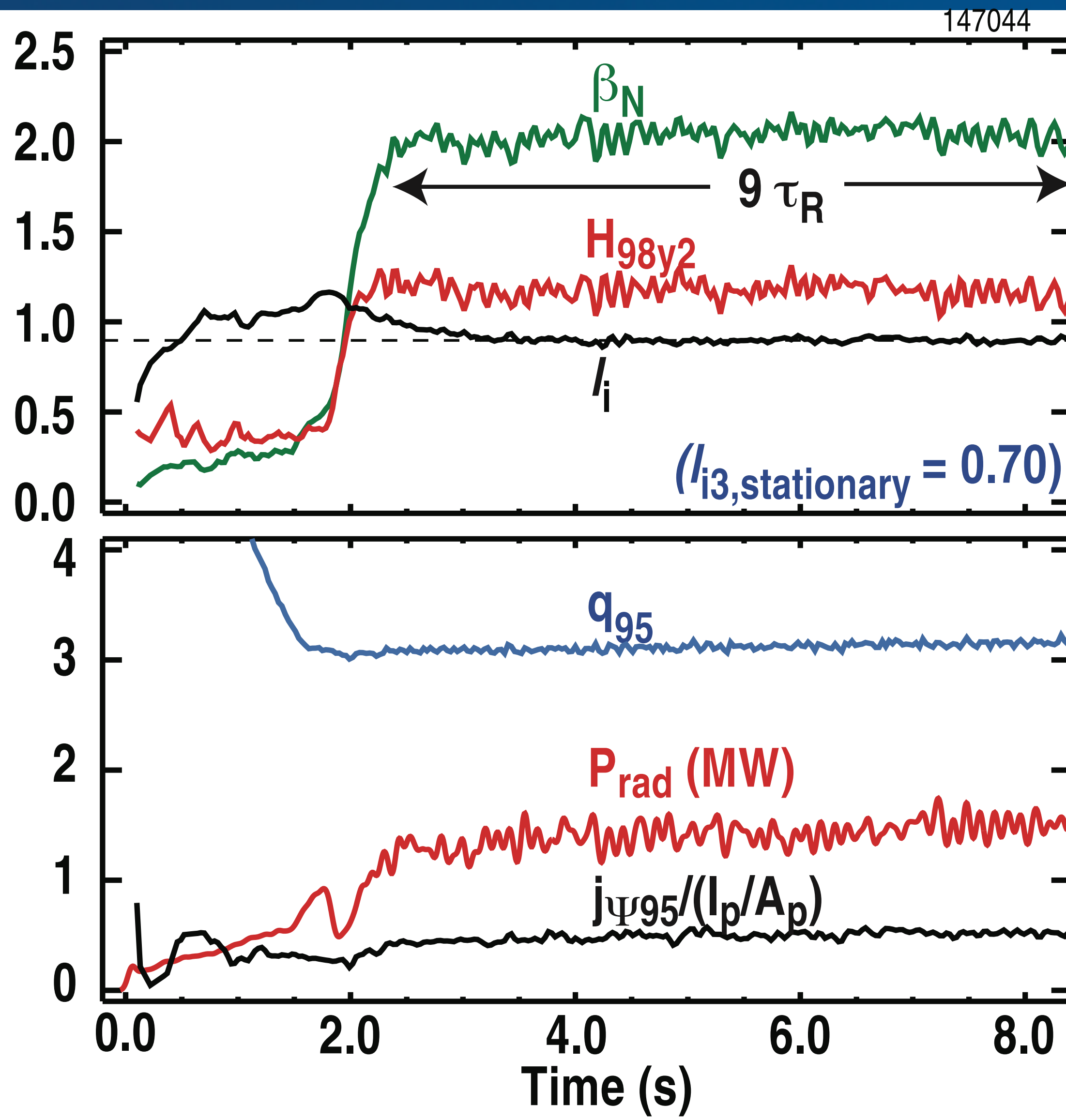
Sustained Pulses Have Been Achieved Without ECCD for Tearing Mode Stabilization

- ℓ_i evolved until TMs terminated the β_N flattop phase *[Turco and Luce, Nucl. Fusion (2010)]*

- **Can stable operation be found without requiring ECCD tearing control?**

YES!



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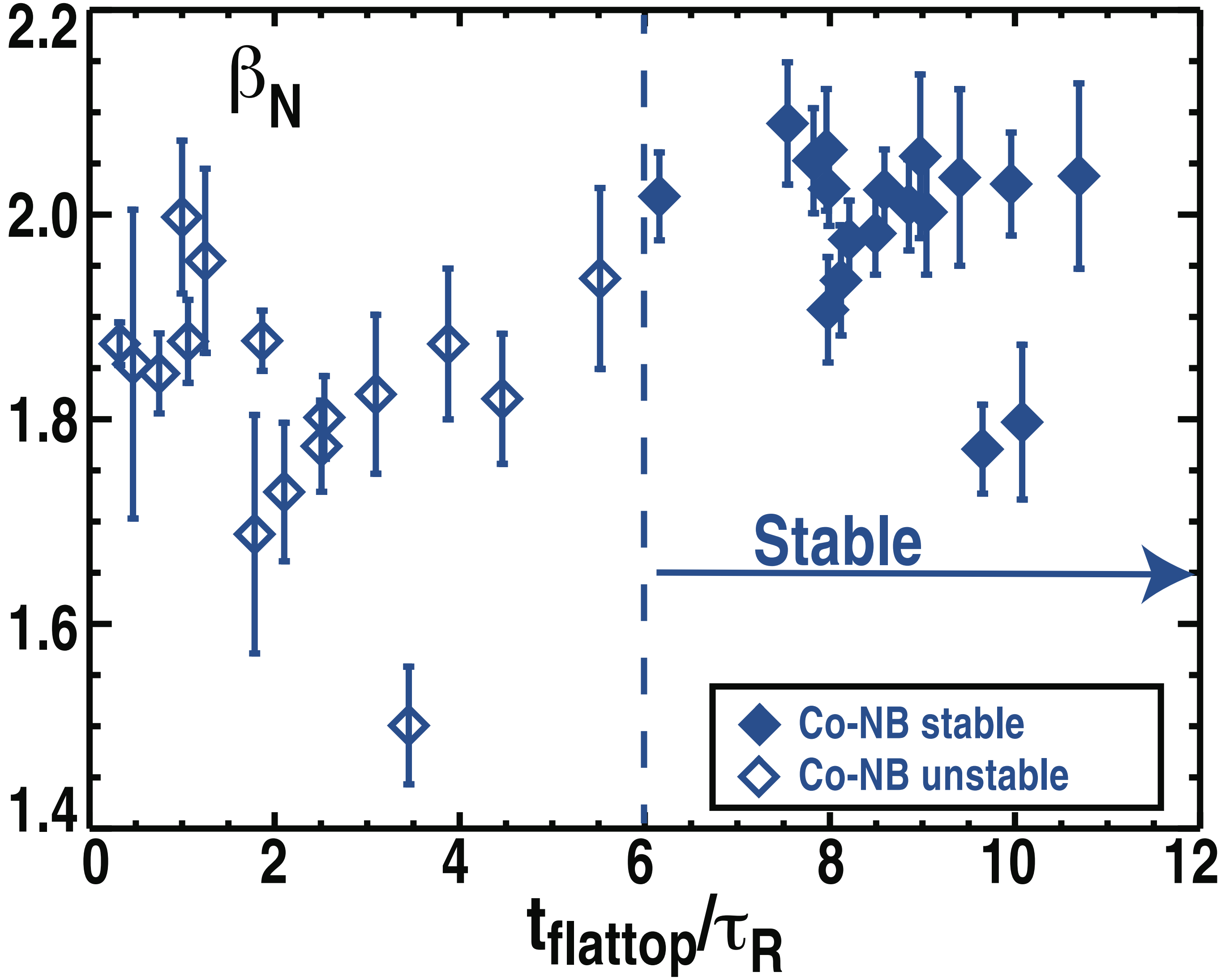
Initial Campaign Produced Stationary Pulses, but Near Stability Limits



- Even slightly reduced torque led to 2/1 TMs
- Good conditioning required for reliable operation

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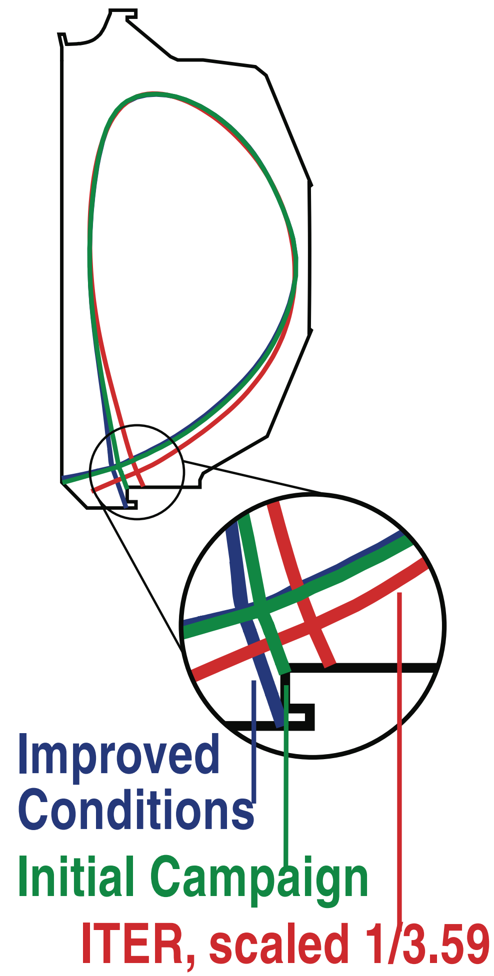
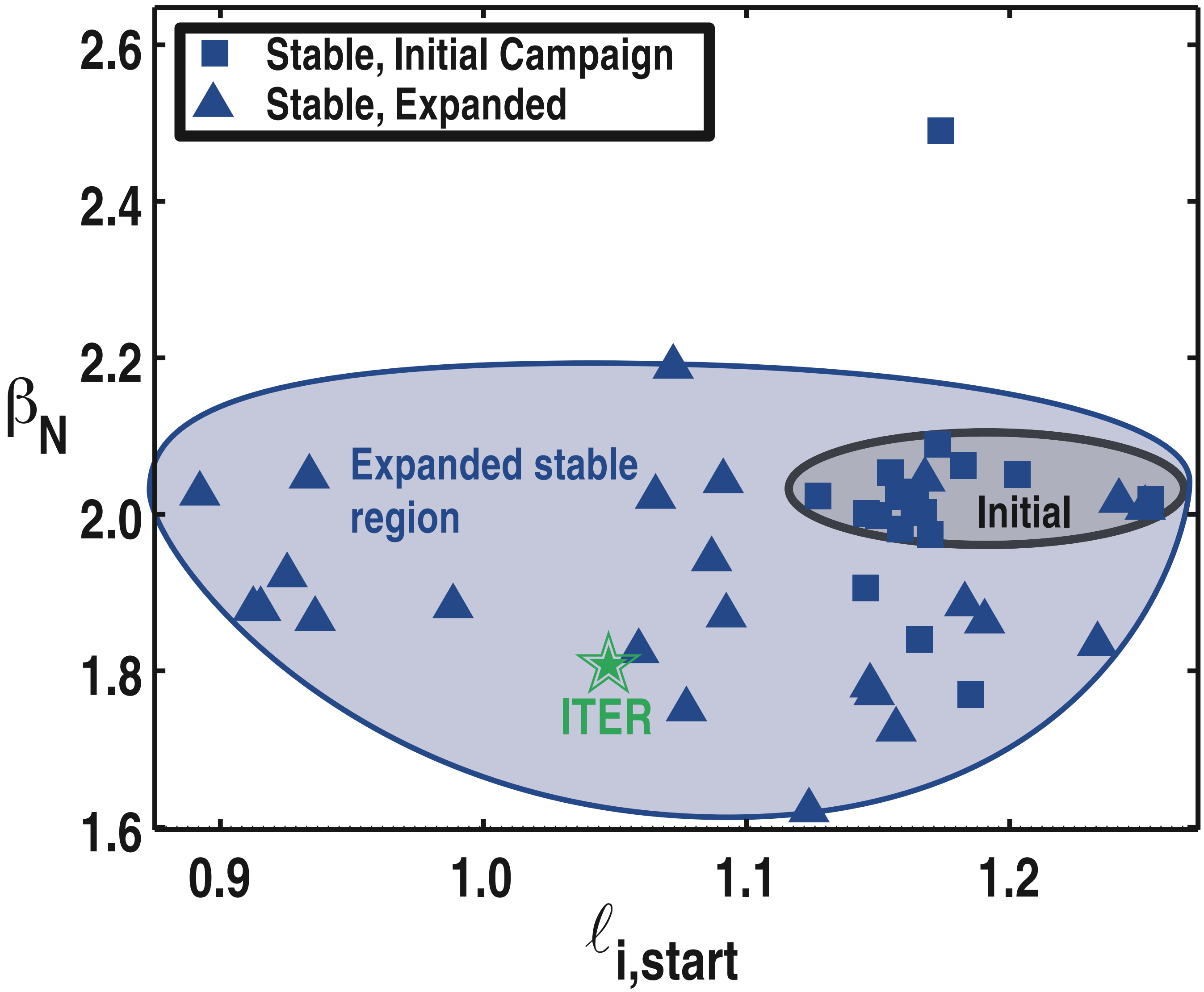
Subsequent ITER Baseline Campaign Expanded Operational Space by Careful Tuning

- **Operation at higher electron density**
- **Shape better aligned for DIII-D cryopumping**
- **Optimization of D_2 gas programing in I_p rampup**
- **"Soft landings" after TMs for better wall conditions**

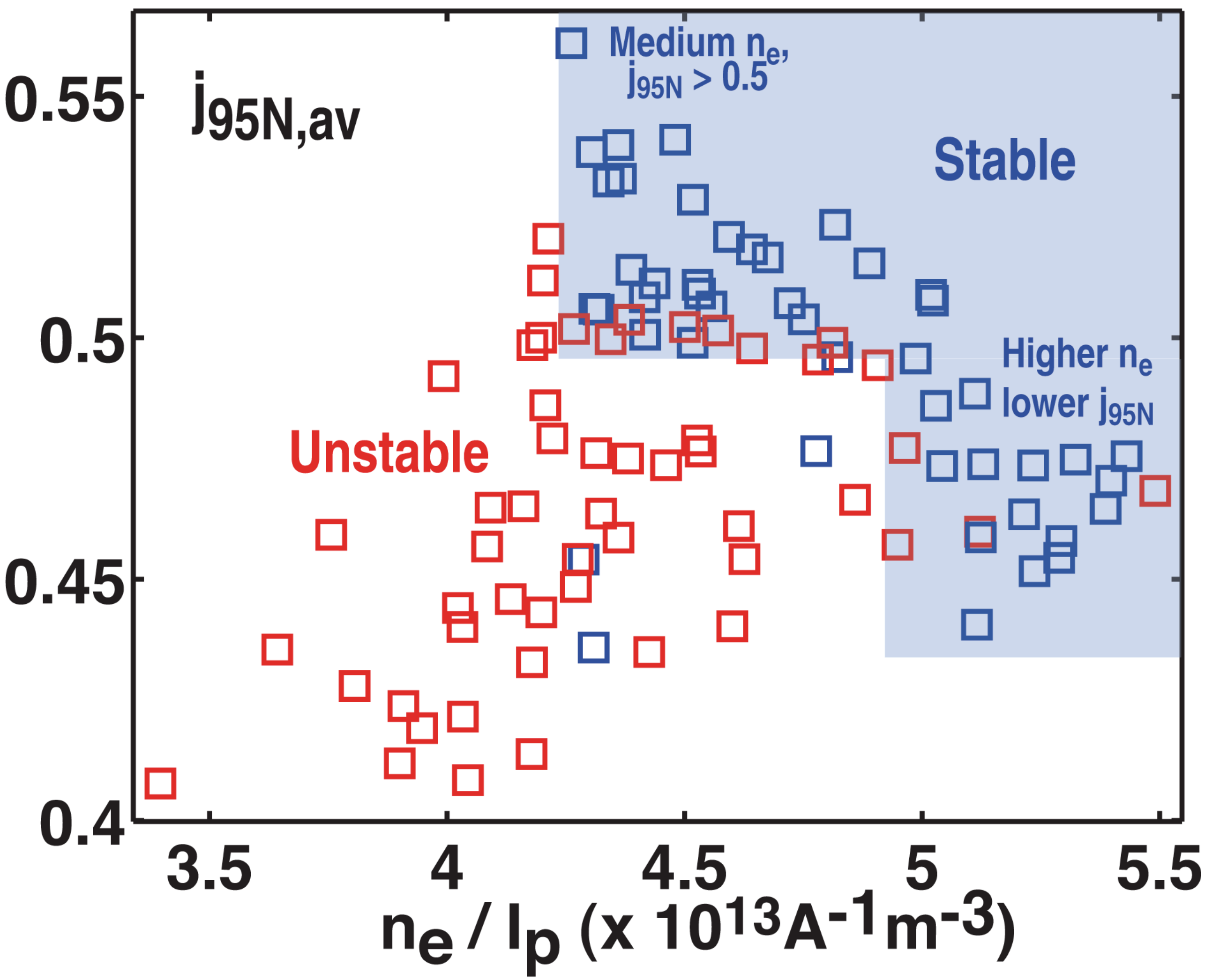


Subsequent ITER Baseline Campaign Expanded Operational Space by Careful Tuning

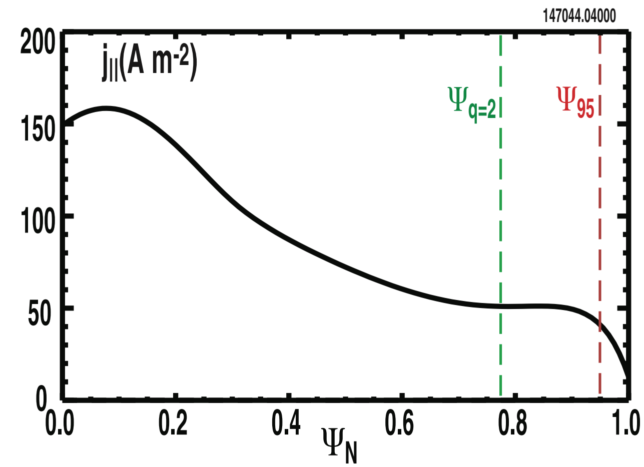


- **Expanded stable region achieved with improved pulse conditions**
- **Results obtained without ECCD for active 2/1 TM control**

Stable Pulses are Usually Above a Density Threshold, and Correlate with Normalized Pedestal Current Density



- $n_e^{Threshold} = 5.2 \times 10^{19}$ m^{-3} without ECCD
- (B_T = 1.62 T, I_p = 1.23 MA)
- $j_{95N,av}$ is normalized torodial current density at Ψ_N = 0.95, averaged over the flattop phase



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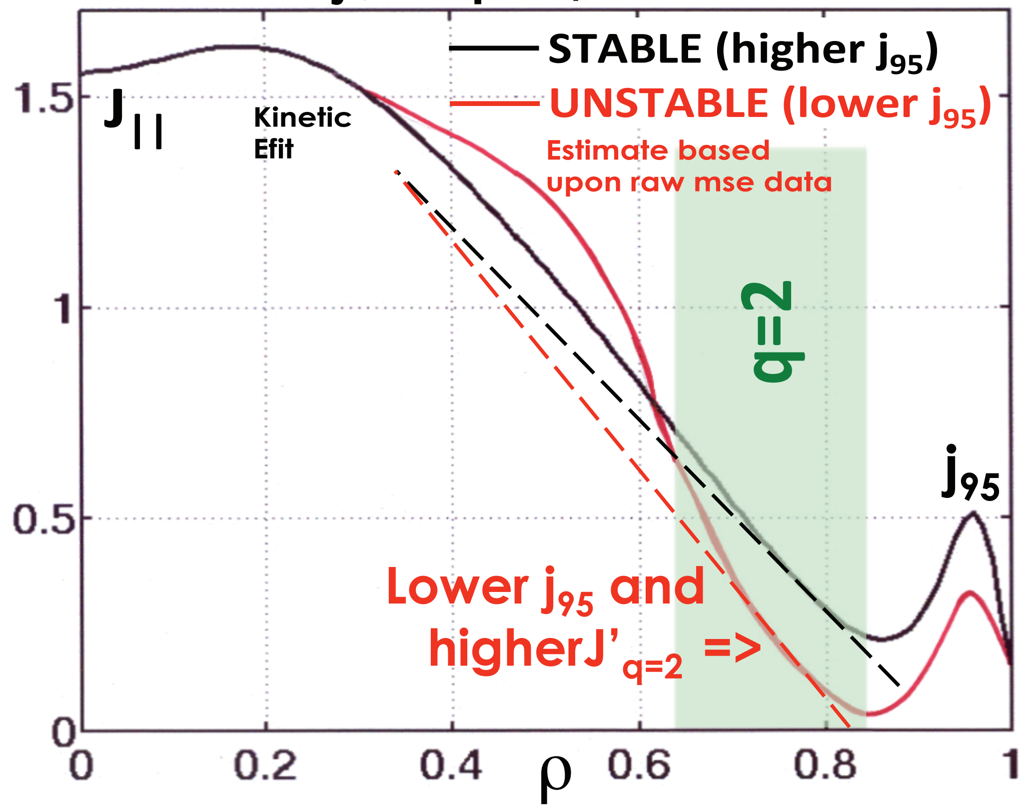
Why Might $j_{95N,av}$ be an Indicator of Stable/Unstable Pulses?

- **Hypothesis**

Lower j_{95N} leads to lower $j_{,q=2}$ and higher j in other regions (for same I_p) => Current deficit, modifies the current gradient, j′, at q = 2/1 => $j'_{q=2}$ increases until Δ′ is destabilizing, triggering a m/n=2/1 TM



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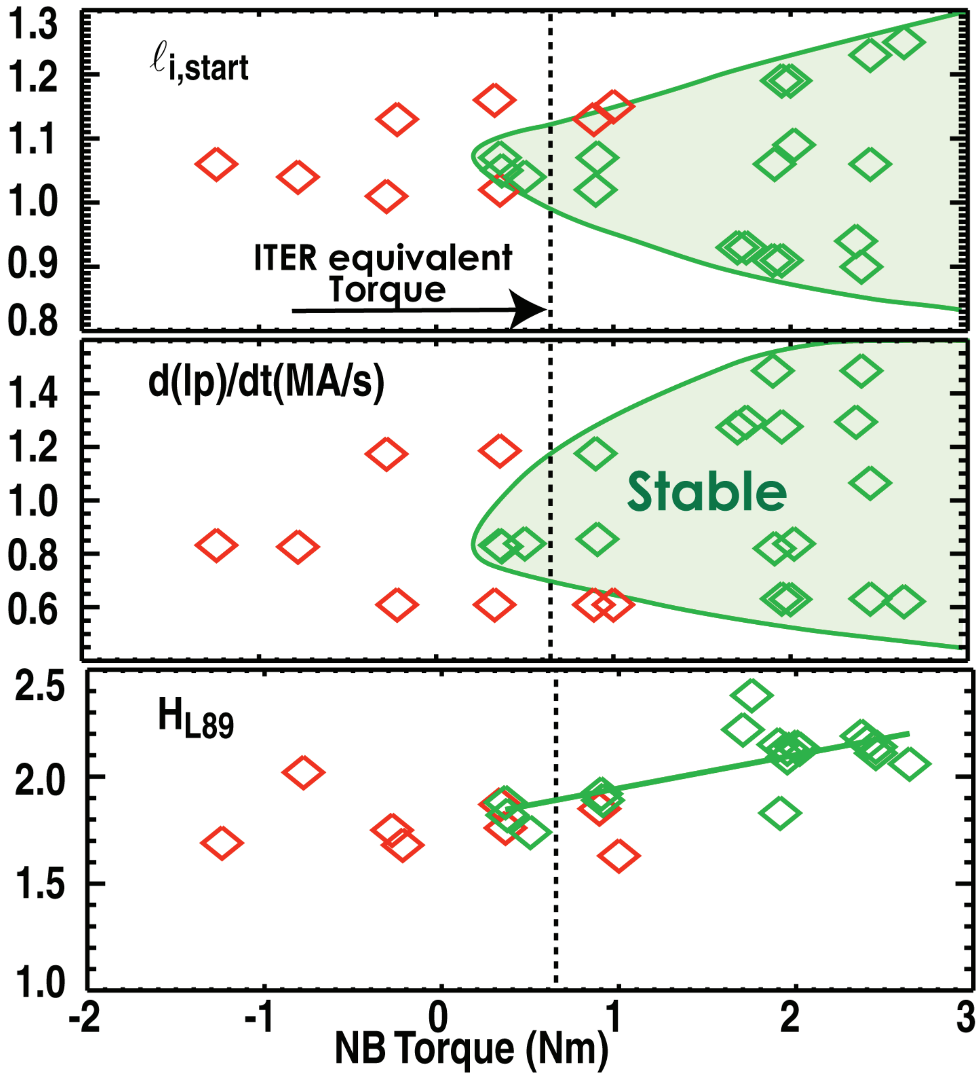
ITER Baseline Discharges (Without ECCD) Have Been Successfully Demonstrated at ITER Equivalent Torque



- Stable pulses obtained at ITER equivalent torque
- Operating space is reduced at lower torque
- $\ell_{i,start}$ (controlled by varying I_p ramp rate), covers the range expected for ITER
- Confinement is reduced by 15% at low torque (0.36 Nm)

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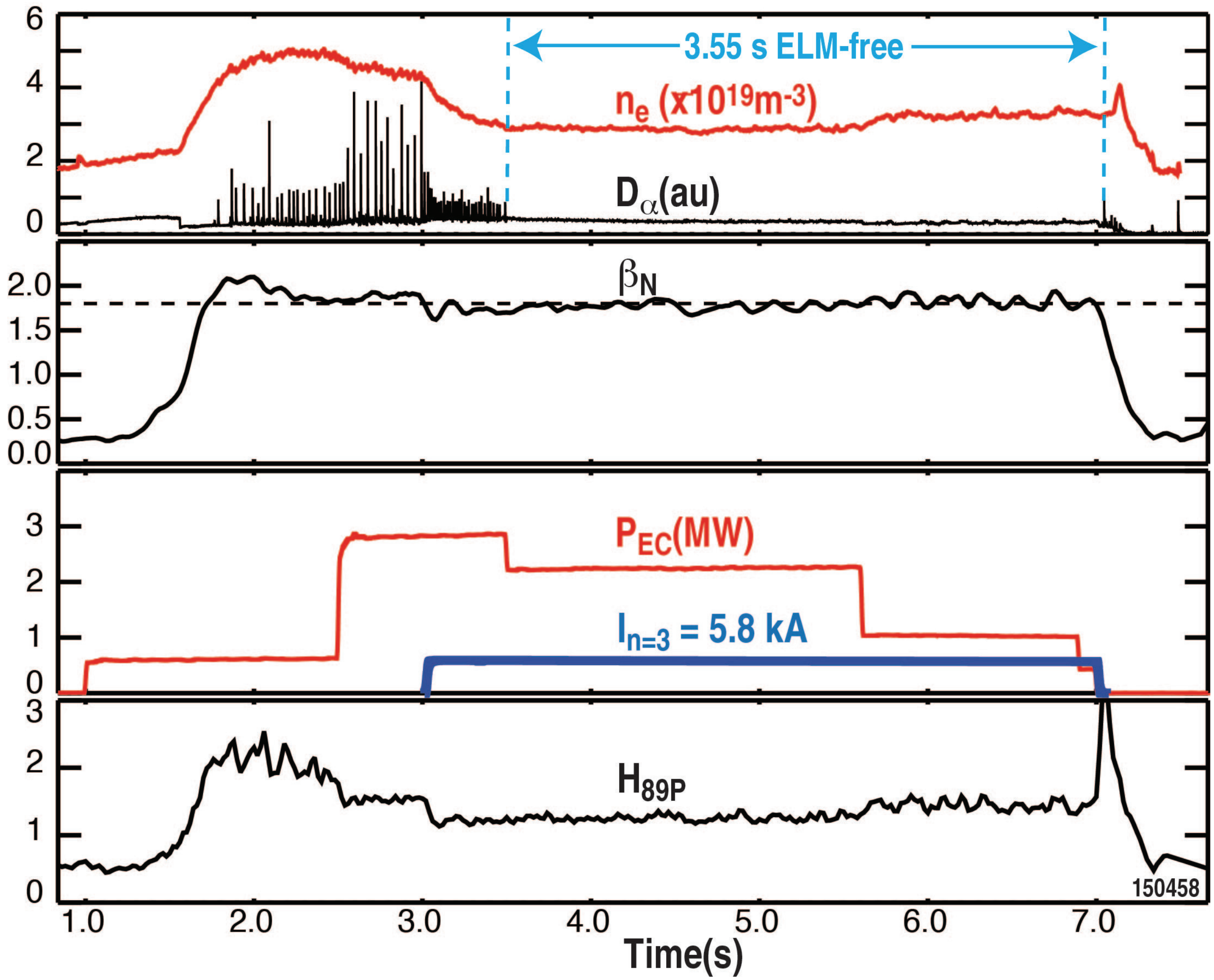
EC Can Expand the Stable Region by Allowing Stable Operation at Lower Density (and Collisionality)

- **ECCD for tearing control in RMP-ELM controlled discharges**

- **ECH (ρ < 0.3) for dominant electron heating**

ELM-Free Pulses in the ITER 15 MA Scenario Obtained With ECCD and a Single Row of Internal 3D Coils



- **Demonstrates ITER baseline compatibility (q_{95} = 3.19, (I_p/aB_T = 1.41)**
- **Single row of I-coils (n=3) provides a broader spectrum allowing lower q ELM suppression**
- **ECCD (q ≈ 3/2) provides TM mitigation at lower n_e typical of n=3 I-coil operation**

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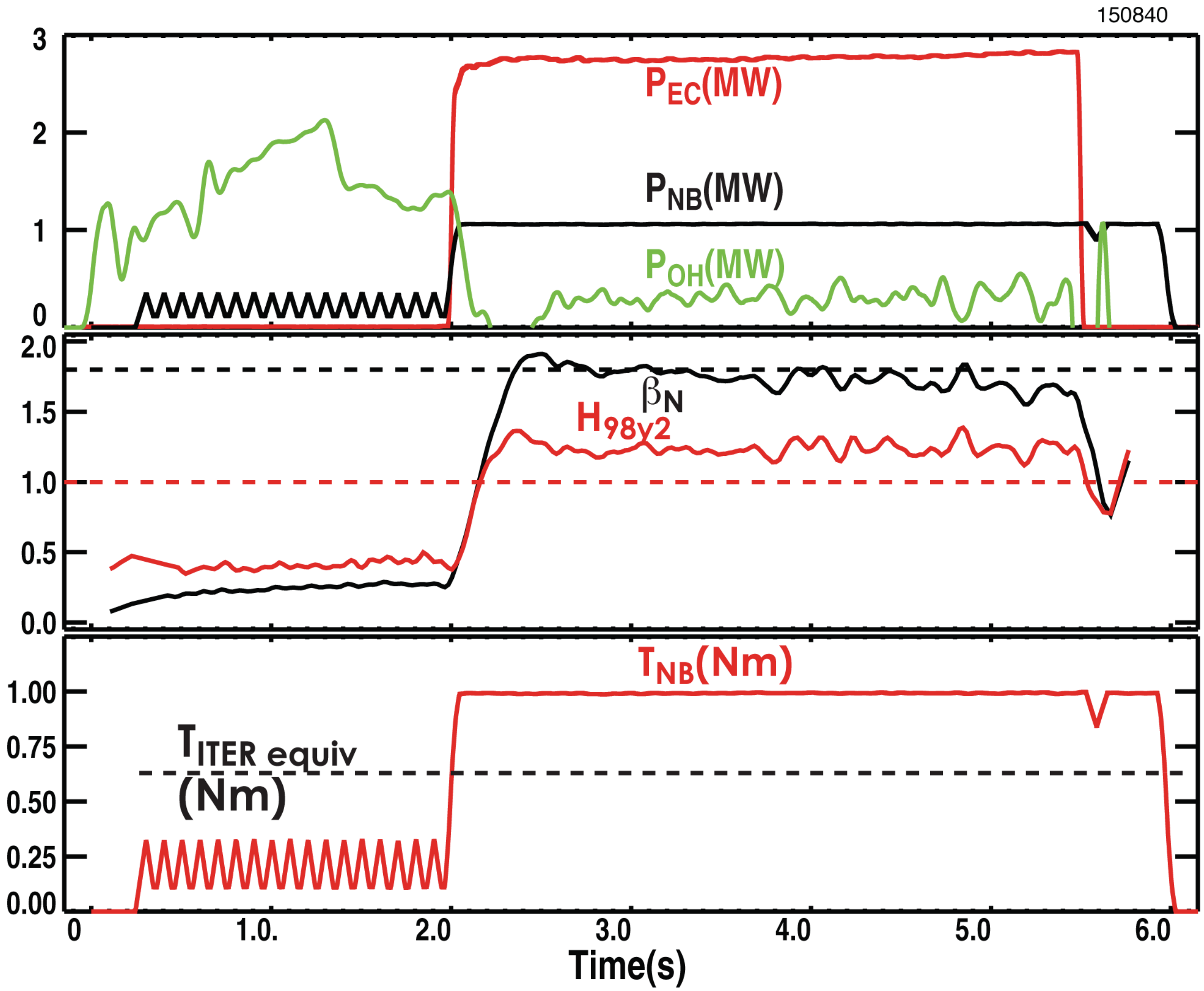
Stable Pulses Demonstrated Using Dominant Electron Heating (Heating Scenario for ITER)



- **Demonstrated at q_{95} = 4.2**
  - P_{EC}/P_{tot} = 0.67
  - $\beta_N \approx 1.8$
- **Core EC heating (not ECCD)**
- **No MHD**
  - No sawteeth
- **Confinement above H_{98y2}**
- **Applied external torque near ITER requirements**

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ITER Baseline Scenario Experiments in DIII-D Led to Successful Operation in a Variety of Conditions

- **Operation in the ITER baseline scenario is possible without active TM stabilization**
  - But pulses appear to be near the stability limit
- **Low torque achieved without TM stabilization**
  - ECCD can further expand the operating space
- **ELM suppression is possible with I-coils in the ITER scenario**
- **Dominant electron heating at β_N = 1.8 achieved with $H_{98y,2} \approx 1.2$**
- **Future work focused on achieving all these aspects simultaneously**