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 $\beta_N$ flattop phase [Turco and Luce, Nucl. Fusion (2010)]

- Can stable operation be found without requiring ECCD tearing control?
Sustained Pulses Have Been Achieved Without ECCD for Tearing Mode Stabilization

- $\ell_i$ evolved until TMs terminated the $\beta_N$ flattop phase [Turco and Luce, Nucl. Fusion (2010)]

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

YES!
Initial Campaign Produced Stationary Pulses, but Near Stability Limits

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

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

### Diagram

- Axes: $n_e / I_p \times 10^{13} \text{A}^{-1} \text{m}^{-3}$ vs. $j_{95N,av}$
- Stable and Unstable regions
- Detailed data points and trend lines

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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 $\Delta'$ is destabilizing, triggering a m/n=2/1 TM

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
- $\ell_{i,\text{start}}$ (controlled by varying $I_p$ ramp rate), covers the range expected for ITER
- Confinement is reduced by 15% at low torque (0.36 Nm)
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 ($\rho < 0.3$) 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 ($q \approx 3/2$) provides TM mitigation at lower $n_e$ typical of n=3 I-coil operation
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
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 $\beta_N = 1.8$ achieved with $H_{98y,2} \approx 1.2$

• Future work focused on achieving all these aspects simultaneously