Demonstration of ITER Operational Scenarios on DIII-D

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DIII-D Demonstration Discharges Meet ITER Normalized Performance Targets

- 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 \( Q \sim 5 \) at \( I_p \sim 9 \) MA
  - **Hybrid scenario:** high neutron fluence at reduced current \( I_p \sim 12 \) MA, \( Q \geq 5 \)
  - **Advanced inductive scenario:** \( Q \geq 20 \) and 700 MW fusion power production at \( I_p \geq 15 \) MA

\[ G \equiv \beta_N H_{89}/q_{95}^2 \]

\( G \) is a measure of fusion performance

Key ITER physics issues are discussed

Projections to ITER

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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 $\frac{I}{aB}$ (normalized current)

- Target values for $\beta_N$ and $H_{98}$ were matched or exceeded
  - Evaluations concentrate on flat-top phase
  - Dominant co-NBI used throughout study

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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 $\sim 3\tau_R$,
  $\sim$ same normalized duration as ITER
  - However, plasma is non-stationary
- Absolute density $\sim$ same as ITER, $n/n_{GW} \sim 0.65$ (ITER 0.85)
- Operation limited to $\beta_N \leq 2$, with disruptions even at lower $\beta_N$ 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 \( P_{\text{Loss}} / P_{\text{th}} = 1 \) throughout H-mode phase

- L-H power threshold \( (P_{\text{th}}) \) calculated using latest scaling prediction
  - \( P_{\text{th}} = 0.049 n^{0.72} B^{0.8} S^{0.9} \)
  - 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 $\rho \sim 0.5$
  - Not due to synchronized ELMs and sawteeth
- Energy loss/ELM is $>10\%$ of total plasma stored energy, $\sim 25\%$ 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 $\beta_N=3.1$
  - High bootstrap fraction (~70%)

- Steady-state discharges utilize off-axis ECCD to maintain stable $q$-profile with $q_{\text{min}} \geq 1.5$

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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.
Wall Stabilization is Necessary for Steady-State Scenario Operation in ITER with $\beta_N > 3$

- Higher $\beta_N$ 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

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

- Advanced inductive scenario has sustained high performance at $\beta_N = 2.8$ 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 $l_i(3) = 0.7-1.0$ at 15 MA.

- Measured $l_i(3)$ 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

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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 the 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

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

- DIII-D discharges projected to ITER assuming same $\beta_N$ 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)

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<th>Baseline</th>
<th>Hybrid</th>
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<th>Steady-state</th>
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<td>$P_{fus}$ (ITER)</td>
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* $P_{aux}$ required is greater than Day-one value of 73 MW

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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 performance
  - Extend demonstration to startup and ramp-down phases