Demonstration of ITER Operational Scenarios on DIII-D

E.J. Doyle¹,
for R.V. Budny², J.C. DeBoo³, J.R. Ferron³, G.L. Jackson³,
T.C. Luce³, M. Murakami⁴, T.H. Osborne³, J.-M. Park⁴,
P.A. Politzer³, H. Reimerdes⁵, T.A. Casper⁶, C.D. Challis⁷,
R.J. Groebner³, C.T. Holcomb⁶, A.W. Hyatt³, R.J. La Haye³,
J. Kinsey³, G.R. McKee⁸, T.W. Petrie³, C.C. Petty³,
T.L. Rhodes¹, M.W. Shafer⁸, P.B. Snyder³, E.J. Strait³,
M.R. Wade³, G. Wang¹, W.P. West³, and L. Zeng¹

1 University of California, Los Angeles
2 PPPL
3 General Atomics
4 ORNL
5 Columbia University
6 LLNL
7 Euratom/UKAEA Fusion Association, Culham, Oxon, UK
8 University of Wisconsin, Madison

Presented at
22nd IAEA Fusion Energy Conference
Geneva, Switzerland
October 13-18, 2008
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
  - **Advanced inductive scenario:** $Q \geq 20$ and 700 MW fusion power production at $I_p \geq 15$ MA

• Key ITER physics issues are discussed

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

Doyle/IAEA/Oct2008
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 $\beta_N$ and $H_{98}$ were matched or exceeded:
  - Evaluations concentrate on flat-top phase
  - Dominant co-NBI used throughout study

Doyle/IAEA/Oct2008
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 \( \frac{P_{\text{Loss}}}{P_{\text{th}}}=1 \) throughout H-mode phase

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

Doyle/IAEA/Oct2008
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, ~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

Doyle/IAEA/OCT2008
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 $q_{\text{min}} \geq 1.5$

Doyle/IAEA/Oct2008
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

$B_p$ (n=1) plasma response $f_{ext}=25$Hz

Plasma-wall outer gap (cm): 13.5 134351
- 8.5 134363

Time (s)
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
Doyle/IAEA/Oct2008
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, $H_{98}=1.5$

- $I/\alpha B$ 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
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, H/2-2; Change to ITER design, Hawryluk, H/1-2

Doyle/IAEA/Oct2008
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

Doyle/IAEA/Oct2008
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*

Doyle/IAEA/Oct2008
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 $P_{\text{fus}}$ 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)

<table>
<thead>
<tr>
<th></th>
<th>Baseline</th>
<th>Hybrid</th>
<th>Al</th>
<th>Steady-state</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_N$ (DIII-D)</td>
<td>1.8</td>
<td>2.8</td>
<td>2.8</td>
<td>3.1</td>
</tr>
<tr>
<td>$P_{\text{fus}}$ (ITER)</td>
<td>400</td>
<td>400</td>
<td>700</td>
<td>350</td>
</tr>
<tr>
<td>Fusion Gain (Q)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>89P</td>
<td>10.3</td>
<td>5.8*</td>
<td>13.5</td>
<td>2.7*</td>
</tr>
<tr>
<td>98y2</td>
<td>22.4</td>
<td>23.3</td>
<td>$\infty$</td>
<td>5.8*</td>
</tr>
<tr>
<td>DS03</td>
<td>$\infty$</td>
<td>$\infty$</td>
<td>$\infty$</td>
<td>19.8</td>
</tr>
<tr>
<td>ITER target</td>
<td>10</td>
<td>5</td>
<td>$\geq20$</td>
<td>5</td>
</tr>
</tbody>
</table>

* $P_{\text{aux}}$ 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 performance
  - Extend demonstration to startup and ramp-down phases