DIII-D Research in Support of ITER

by
E.J. Strait and the DIII-D Team

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October 13-18, 2008
DIII-D Research Has Made Significant Contributions in the Design and Physics Basis for ITER

**Baseline Design**
- ELM Control
- Vertical Stability
- PF coil Capabilities

**Physics Basis**
- L-H Transition
- Pedestal Height
- Core Transport
- Plasma Rotation
- Fast Ions

**Scenario Development**
- Reference Scenarios
- ITER-relevant Startup
- High $\beta$ Scenarios

**Control Solutions**
- MHD Stability
- Disruption Mitigation
- Particle Control

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EJ Strait/IAEA/Oct2008 330-08/EJS/jy
Recent DIII-D Experiments Have Established Physics Criteria for Several Key ITER Design Choices

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DIII-D ELM Suppression Experiments Show Important Role of Resonant Magnetic Spectrum

- Width of island overlap region determines stochastic character of edge
- \(q_{95}\) operating window increases as width of stochastic layer increases
DIII-D ELM Suppression Experiments Show Important Role of Resonant Magnetic Spectrum

- Width of island overlap region determines stochastic character of edge
- q95 operating window increases as width of stochastic layer increases
ITER Coil Design Guided by DIII-D Experiments

- Maximum ELM size is correlated with width of island overlap region

![Graph showing correlation between ELM size and island overlap width](image)

- ELM control coils (schematic)

T. Evans, EX/4-1
V. Izzo, TH/P4-19
M. Jakubowski, EX/P6-2
ITER Coil Design Guided by DIII-D Experiments

- Maximum ELM size is correlated with width of island overlap region
- DIII-D results support the choice of internal, multi-row coils
  - Single I-coil row requires larger current
  - No suppression with external, large aperture C-coils
Control of ELM Frequency Achieved Using Oscillating \( n=3 \) Non-Resonant Magnetic Fields

- ELM frequency locked to twice frequency of I-coil modulation
- Energy loss from ELM scales inversely with driving frequency
- Minimum field perturbation required for pacing not yet determined
DIII-D Experiments Have Helped to Quantify ITER’s Capability for Vertical Control Performance

- **Experiments validate theoretical calculations of control capability**
  - Maximum controllable displacement is ~2x larger using inner + outer coils (like ITER VS1 + VS2)

- **Stability limits motivate addition of internal vertical stability coils in ITER**
DIII-D Experiments Have Helped to Quantify ITER’s Capability for Vertical Control Performance

- Experiments validate theoretical calculations of control capability
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\[
\begin{align*}
\Delta Z (\text{cm}) & \quad \gamma Z (\text{rad/s}) \\
\text{Inner + Outer Coils} & \quad \text{Model} & \quad \text{Outer Coils Only} & \quad \text{Uncontrollable} & \quad \text{Controllable}
\end{align*}
\]
DIII-D has Validated Performance Capabilities of ITER Startup and Operational Scenarios

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Control Solutions
- MHD Stability
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- Particle Control
DIII-D Experiments Have Achieved Fusion Performance at the Level Required for ITER Goals

- **Baseline**
  - Reference operating case
  - Q = 10 at 15 MA, $\beta_N \sim 1.8$, $q_{95} \sim 3$

$$ G = \frac{\beta_N H_{89}}{q_{95}^2} $$

![Graph showing performance metrics and reference operating case](image-url)

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E. Doyle, EX/1-3
DIII-D Experiments Have Achieved Fusion Performance at the Level Required for ITER Goals

- **Baseline**
  - Reference operating case
  - Q = 10 at 15 MA, $\beta_N \sim 1.8$, $q_{95} \sim 3$

- **Advanced inductive**
  - High fusion gain
  - Q = 30 at 15 MA, $\beta_N \sim 2.8$, $q_{95} \sim 3$

\[ G = \frac{\beta_N H_{89}}{q_{95}^2} \]

- Low $i(3)$ ⇒ changes in PF system

\[ \beta_{N} H_{89} \]

\[ q_{95} \]

\[ I_{i} (3) \]

\[ Q=10 \text{ in ITER} \]

\[ q_{95} = 3.1 \]

\[ q_{95} = 3.3 \]
DIII-D Experiments Have Achieved Fusion Performance at the Level Required for ITER Goals

**Baseline**
- Reference operating case
- $Q=10$ at 15 MA, $\beta_N \sim 1.8$, $q_{95} \sim 3$

**Advanced inductive**
- High fusion gain
- $Q=30$ at 15 MA, $\beta_N \sim 2.8$, $q_{95} \sim 3$

**Hybrid**
- Long pulse, high fluence
- $Q=5$ at 12 MA, $\beta_N \sim 2.5$, $q_{95} \sim 4$

\[ G = \frac{\beta_N H_{89}}{q_{95}^2} \]

- Low $l_i(3)$ \(\Rightarrow\) changes in PF system

\[
\begin{align*}
\text{Baseline} & \quad \text{ITER Design Range} \\
131499 & \quad G \\
Q=10 \text{ in ITER} & \quad q_{95} = 3.1 \\
\text{Advanced Inductive} & \quad \text{ITER Design Range} \\
133137 & \quad G \\
Q=10 \text{ in ITER} & \quad q_{95} = 3.3 \\
\text{Hybrid} & \quad \text{ITER Design Range} \\
131265 & \quad G \\
Q=10 \text{ in ITER} & \quad q_{95} = 4.1
\end{align*}
\]
DIII-D Experiments Have Achieved Fusion Performance at the Level Required for ITER Goals

- **Baseline**
  - Reference operating case
  - $Q=10$ at 15 MA, $\beta_N \sim 1.8$, $q_{95} \sim 3$

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  - $Q=30$ at 15 MA, $\beta_N \sim 2.8$, $q_{95} \sim 3$

- **Hybrid**
  - Long pulse, high fluence
  - $Q=5$ at 12 MA, $\beta_N \sim 2.5$, $q_{95} \sim 4$

- **Steady-state**
  - Fully non-inductive
  - $Q=5$ at 9 MA, $\beta_N \sim 3$, $q_{95} \sim 5$

\[ G = \frac{\beta_N \, H_{89}}{q_{95}^2} \]

- **Low $i(3)$**
  - Changes in PF system

ITER Design Range

\[ Q=10 \text{ in ITER} \]

\[ Q=10 \text{ in ITER} \]

\[ Q=5 \text{ in ITER} \]

\[ Q=5 \text{ in ITER} \]
Hybrid Scenario With Excellent Performance Accessed With Large Bore ITER Startup

- **Large Bore startup includes**
  - Initiation on outer limiter
  - Large cross-section early in limiter phase
  - Early x-point formation
  - No auxiliary heating until close to full current

- **Excellent plasma performance**
  - $\beta_N = 2.9$
  - $H_{98y2} = 1.6$
  - $G = 0.42 \rightarrow$ sufficient for $Q = 10$ in ITER at 11.6 MA

- At higher $q_{95}$, hybrid scenario achieved with $\sim 50\%$ bootstrap current and $\sim 100\%$ non-inductive current
Shape Optimization Leads to Higher $\beta$ and Higher Bootstrap Fraction

- Increased $\beta$ with shaped plasmas due to better stability and higher current at fixed $q_{95}$
- Pedestal and core stability improved leading to higher bootstrap fraction (up to 70%)
Further Optimization with q Profile Points Toward Steady-state Power Plant Goals of $\beta_N = 5$ and $f_{BS} > 0.8$

- Strong magnetic shear ($q_{min} \sim 1$) contributes to higher stability and good confinement
- Calculated bootstrap fraction is $\sim 90\%$ with $q_{min} \sim 1$

Access to $\beta_N > 3$ might be possible in ITER with this scenario without wall stabilization

- Ideal-wall limit
- No-wall limit
- Ballooning Limit

Calculated current fractions

- Total noninductive
- Bootstrap
- Neutral beam
- ECCD
DIII-D has Developed Control Solutions for Key Physics Issues

Baseline Design
- ELM Control
- Vertical Stability
- PF coil Capabilities

Physics Basis
- L-H Transition
- Pedestal Height
- Core Transport
- Plasma Rotation
- Fast Ions

Scenario Development
- Reference Scenarios
- ITER-relevant Startup
- High β Scenarios

Control Solutions
- MHD Stability
- Disruption Mitigation
- Particle Control

Real Time Control (Actuator)
- NTM Stabilization (ECCD)
- ELM Control (I-coil)
- Plasma β (P_{aux})
- Rotation Control (P_{co}, P_{ctr})
- RWM Stabilization (C-coil, I-coil)
- Current Profile (ECCD, ECH, NBI)
Resonant Amplification Increases the Sensitivity to Error Fields at High Beta

- n=1 “error field” is ramped up with time
  - At a critical amplitude, the plasma rotation locks, then an island grows

- Critical amplitude of applied field decreases with $\beta$

- Critical amplitude of plasma response is independent of $\beta$
  - Strong response by stable kink mode as $\beta$ increases

- Critical amplitude increases with NBI torque

- Plasma response must be considered in projections of error field correction
Active Stability Control Enables High Beta at Low Rotation

- Stable operation achieved by
  - Neoclassical tearing mode (NTM) stabilization by ECCD at q=2
  - Feedback-controlled error field correction

- Non-rotating instabilities at low NBI torque appear to be NTMs

- RWM stability at low $\Omega$ is consistent with theoretical predictions of kinetic stabilization

- Rotation is below values anticipated in ITER

Graph: Ideal-wall $\beta$ limit vs. plasma rotation at $q \sim 2$ (km/s)

- No feedback
- Rotating mode
- Non-rotating

2006 IAEA (no ECCD no feedback)

$C_\beta$ vs. $\beta_p$ with $q=2$

- 125709 (2006)
- 132270 (2008)

DIII-D

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M. Okabayashi, EX/P9-5
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Disruption Mitigation Requires Rapid Delivery of Low-Z Species

- Greatest remaining challenge is to achieve the “Rosenbluth density” for suppression of runaway electron avalanche: \( n_e \geq 10^{22} \text{ m}^{-3} \)
  - Several grams in DIII-D
  - ~100 g in ITER

- Gas injection studies show good assimilation of gas that arrives during thermal quench
  - favors low-Z species

- Studies of alternate delivery systems have started
  - Ar or B-filled capsules

Spectroscopy confirms delivery of payload

Particles delivered in TQ (10^{22} particles)

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<tr>
<th>Species</th>
<th>Nassim (10^{22} particles)</th>
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<tr>
<td>H2</td>
<td>100% assimilation</td>
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<tr>
<td>D2</td>
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<td>He</td>
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<tr>
<td>Ne</td>
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<tr>
<td>Ar</td>
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short gas pulse

Line brightness (a.u.)

C_V1 (18.2 nm) B_V (26.2 nm)

B-filled pellet

~ Several grams in DIII-D
~ 100 g in ITER
Particle Drifts Play a Critical Role in Predictions of Radiative Divertor Performance

Ion $\nabla B$ drift↓:
- Recycling and argon dominant in outer divertor
- Ar controlled by pumping

Argon injected into divertor follows $D_\alpha$ pattern

Ion $\nabla B$ drift↑:
- Inner leg detaches
- Ar leaks into the core plasma
Particle Drifts Play a Critical Role in Predictions of Radiative Divertor Performance

Ion $\nabla B$ drift↓:
- Recycling and argon dominant in outer divertor
- Drifts push ions to outer divertor

Argon injected into divertor follows $D_\alpha$ pattern

Ion $\nabla B$ drift↑:
- Inner leg detaches
- Drifts push ions to cold inner divertor

• Results suggest that drifts may play a key role in particle exhaust on ITER
DIII-D Research has Improved the Physics Basis of Projection of ITER Performance

- ELM Control
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- L-H Transition
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- MHD Stability
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Multiple Sources of Torque Will Affect ITER’s Rotation

- **Static non-resonant** n=3 fields apply a torque to the plasma
  - rotation accelerates for cases with small, negative rotation

- **Torque is consistent with prediction of Neoclassical Toroidal Viscosity theory**
  - drags rotation toward a non-zero “offset” rotation $\sim - \omega_i^*$

- **Torque from non-resonant part of ELM control field predicted to be $>> T_{NBI}$ in ITER**

- Other experiments show “intrinsic” torque consistent with thermal ion orbit loss
New Predictive Model for Pedestal Height Agrees Well with DIII-D Measurements

- EPED1 model uses peeling-ballooning theory
  - empirical scaling for pedestal width: \( \Delta_{\text{ped}} (\Psi_N) = 0.076 \sqrt{\beta_{p, \text{ped}}} \)
- Hydrogen plasma experiments confirm \( \Delta_{\text{ped}} \) is insensitive to \( \rho_i^* \)
  - favorable result for ITER
- Initial prediction for ITER: \( T_{\text{ped}} \sim 4.6 \text{ keV} \) (favorable for \( Q=10 \))
Quiescent H-mode (ELM-free) Achieved with Co-injection

- ELM-free operation for ~1 s
  - radiated power, core density and pedestal density are constant

- QH-mode cases have strong rotational shear at the edge
  - consistent with predicted stability of peeling - ballooning mode

Possible approach to ELM-free operation in ITER?
Detailed Diagnostic Measurements Test Gyrokinetic Transport Calculations

- GYRO predictions compared to simultaneous, localized measurements of $\delta n_e$ and $\delta T_e$
  - $\delta n_e$ measured with Beam Emission Spectroscopy
  - $\delta T_e$ measured with Correlation Electron Cyclotron Emission

- Addition of synthetic diagnostics to GYRO allows quantitative comparison
  - Good agreement in amplitudes, spectra, correlation lengths

- Good agreement of measured and predicted heat flux

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<th>$r/a = 0.5$</th>
<th>$Q_i$ (MW)</th>
<th>$Q_e$ (MW)</th>
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<td>Experimental</td>
<td>0.93 ± 0.16</td>
<td>0.74 ± 0.20</td>
</tr>
<tr>
<td>GYRO</td>
<td>1.1 ± 0.17</td>
<td>0.97 ± 0.14</td>
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- Key step in validation of GYRO code for ITER predictive capability
DIII-D Experiments Validate the Physics of Off-axis Neutral Beam Current Drive

- Experiments confirm prediction that off-axis NBCD efficiency depends on magnetic field alignment
  - Unfavorable alignment reduces current drive by ~40%
  - Proposed geometry for off-axis NBCD in ITER is unfavorable (~20% reduction)
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DIII-D Experiments Validate the Physics of Off-axis Neutral Beam Current Drive

- Planned modification of a DIII-D beam line will provide up to 200 kA of off-axis current drive
DIII-D Research Has Made Significant Contributions in the Design and Physics Basis of ITER

- **Physics criteria established for several key ITER design choices**
  - ELM suppression
  - Vertical stability margin
  - Operational envelope for H-mode operation → PF coil capabilities

- **Validated performance capabilities of ITER startup and operational scenarios**
  - $Q = 10$ (inductive) and $Q = 5$ (steady state) equivalent operation demonstrated

- **Developed control solutions for key physics issues**
  - High $\beta$ operation at near zero rotation
  - Massive gas delivery systems for disruption control
  - Effect of SOL drifts on particle control

- **Improved the physics basis for projection of ITER performance**
  - L-H transition
  - Turbulence code validation
  - Pedestal height
  - Offset rotation
  - Fast Ion Transport
## DIII-D Papers at This Conference

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