Development in the DIII-D Tokamak of Advanced Operating Scenarios and Associated Control Techniques for ITER

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for
The DIII-D Team

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DIII-D's Research Program is Aimed at Maximizing the Scientific Benefit from ITER

DIII-D Research Elements are:

- Ensuring the success of ITER through development of physics solutions to key ITER issues

- Enriching the physics program on ITER through the development and characterization of advanced operating scenarios

- Advancing the physics understanding of issues critical to the success of ITER
DIII-D Has Advanced the Physics Basis and Confidence in ITER Achieving Its Physics Objectives

**DIII-D**
- Plasma Control
  - NTM stabilization
  - ELM suppression
  - RWM stabilization
  - Profile Control

**Advanced Scenario Integration**
- High $\beta$, steady-state ($Q=5$)
- Hybrid ($Q \geq 10$)

**Improvement of Scientific Understanding**
- Energetic particles
- Turbulence-driven transport

**ITER**
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- **ITER**
Real-Time Control of Key Plasma Properties Enabled by Extensive Set of Control Tools

- NTM Stabilization (ECCD)
- ELM Control (I-coil)
- Neutral Beam Injection
- Plasma $\beta$ ($P_{aux}$)
- Rotation Control ($P_{co}, P_{ctr}$)
- RWM Stabilization (C-coil, I-coil)
- Density Control (Divertor Cryopumps)

* New Lower Divertor Hardware Provided by ASIPP

Each control tool is implemented in the DIII-D Plasma Control System, allowing real-time integrated control.
Sustained Operation at $\beta = \beta_{\text{no-wall}}$ Without $m=2/n=1$ NTM Demonstrated Using Real-Time Positioning of ECCD

- Optimal location for NTM suppression found by real-time searching and maintained by tracking of $q=2$ surface using real-time equilibrium reconstructions including MSE (every 6 ms)

Prater, EX/4-2, Thurs a.m.  Humphreys, IT/2-6, Sat a.m.
Complete ELM Suppression Achieved in an ITER-like Shape and Collisionality Using n=3 Resonant Magnetic Perturbations

- Type I ELMs suppressed when n=3 RMP is applied

\[ \kappa = 1.8, \delta_{\text{top}} = 0.36, \delta_{\text{bot}} = 0.71 \]

Moyer, EX/9-3, Fri. p.m.  Snyder, TH/4-1, Fri. p.m.
Complete ELM Suppression Achieved in an ITER-like Shape and Collisionality Using n=3 Resonant Magnetic Perturbations

- Type I ELMs suppressed when n=3 RMP is applied
- RMP reduces pressure gradient below peeling-ballooning stability limit
- Pressure gradient reduction due to changes in particle transport
Reconfigured NBI System Provides Fine Control of Plasma Rotation

- Re-orientation of beamline allows 5 MW counter-NBI and 12.5 MW co-NBI
Reconfigured NBI System Provides Fine Control of Plasma Rotation

- Simultaneous feedback control of $\beta_N$ and toroidal rotation demonstrated
Transport and NTM Physics Shown to be Sensitive to Applied Torque and Resulting Rotation

- Hybrid discharges with $\beta_N = 2.6$
  - $q_{95} = 4.0$ (closed) $q_{95} = 4.5$ (open)

- $\beta_N$ limit for $m=2/n=1$ onset decreases as torque decreases

Petty/Politzer, EX/P1-9, Tues. p.m.
Threshold for Rotational Stabilization of RWM Found to Be Comparable to Expected Rotation in ITER

- Previous measurements using magnetic braking suggested a high rotation threshold for RWM stabilization (~ 1-2% of $\Omega_A$ at $q = 2$)

Predicted rotation at $\rho = 0.6$ in ITER:
$\Omega_{\text{ITER}} = 0.003 \Omega_A$

Garofalo, EX/7-1Ra, Fri. a.m.
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ITER
Performance Routinely Achieved Above Requirements for Q=5 Steady-state Scenario in ITER

- **$G > G_{Q=5}^{\text{ITER}}$** achieved in two separate lines of research
  1. Weak negative central shear utilizing current drive tools compatible with steady state
  2. Moderate negative central shear through continuous ramps in $I_p$ and $B_T$

- Both methods utilize:
  - Highly shaped, double-null configurations
  - Rotational and feedback stabilization of RWM

Greenfield, EX/1-2, Mon. p.m.
Nearly Fully Noninductive Plasmas Achieved with $\beta_N \approx 4$

- High triangularity double null operation allows operation 25% above no-wall limit
- Future availability of higher ECCD power should allow fully non-inductive operation

Greenfield, EX/1-2, Mon. p.m.
Sustained High Performance ($\beta_N \approx 4$ for $\sim 2$ s) Achieved in Discharges with an Internal Transport Barrier

- $\beta_N = 3.8$ is approximately 50% above conventional no-wall limit
- Broad current density profile obtained by early heating, off-axis ECCD, and ramps in $I_p$ and $B_T$
- Excellent confinement ($H_{89} \approx 2.5$) maintained throughout
Sustained High Performance ($\beta_N \approx 4$ for $\sim 2$ s) Achieved in Discharges with an Internal Transport Barrier
Plasma Performance Shown to be Sensitive to Details of the Plasma Shape

- Stability analysis indicates n=1 stability limit has a narrow optimum in plasma "squareness"

- Measured long pulse $\beta$ limit shows similar dependence

\[
\delta = 0.65 \\
\kappa = 1.9
\]

\[
\beta_N \text{ Limit}
\]

\[
\begin{align*}
\beta_N = 0.65 \\
\beta_N = 1.9
\end{align*}
\]
Details of the Plasma Shape Near the ITER Design Shape are Important

- In ITER shape, significant change in edge pressure gradient associated with change in squareness
  - Factor of 2 in measured pressure gradient
  - 50% in calculated stability boundary (ELITE)

![Diagram showing calculated stability boundary and normalized peak pressure gradient against average pedestal current density.]

Leonard, EX/P8-3, Sat. a.m.
Performance Above ITER Q=10 Baseline Scenario Achieved in Low-Rotation Hybrid Plasmas

- $q_{95} = 4.5$
- $\beta_N = 2.6$
- $G = 0.8 \, G_{\text{ITER}}$

- $q_{95} = 3.2$
- $\beta_N = 2.6$
- $G = 1.25 \, G_{\text{ITER}}$

Projected Q for 15 MA ITER
- 89P: $Q = 10.3$
- 98y2: $Q = 10.2$
- DS03: $Q = \infty$

Petty, Politzer, EX/P1-9, Tues. p.m.
Comparison of Measured Profiles with GLF23
Confirm Importance of ExB Shear on Transport

• With high toroidal rotation, ExB shear required in GLF23 to reproduce measured profiles
• At low rotation, ExB shear is much less important

• H98y2 = 1.5 – excellent confinement!
• H98y2 = 1.2 – good overall confinement still maintained

Petty, Politzer, EX/P1-9, Tues. p.m.
Compatibility of Hybrid Regime with Radiative Divertor Demonstrated Using “Puff and Pump” Technique

- Upstream gas puffing and divertor exhaust induce strong SOL flow
- Very high enrichment value obtained

\[
\frac{P_{\text{rad}}}{P_{\text{NBI}}} \approx 60\% \text{ with } Z_{\text{eff}} \approx 2.0
\]

\[
\beta_N = 2.6, \ H_{89} = 2.0, \ G = 0.4 \text{ maintained}
\]
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New Diagnostic Capabilities Enable Detailed Comparisons with Alfvén Eigenmode Theory

- Diagnostics probing different regions of plasma observe different MHD activity
- Measured radial structure consistent with theoretical predictions (NOVA)

\[
\begin{align*}
\rho &= 0.64 \\
\rho &= 0.45 \\
\end{align*}
\]

\[
\begin{align*}
ECE & \quad f (kHz) \\
\text{Local } \delta T_e & \quad \text{Global } \delta B \\
\text{Mirnov} & \quad \text{Line-integrated } \delta n_e \\
\text{CO}_2 \text{ interf.} & \quad \text{Local } \delta n_e \\
\text{BES} &
\end{align*}
\]

\[
\begin{align*}
\delta T_e (eV) & \\
\text{Measurement} & \quad \text{Theory} \\
n=3 \text{ RSAE} & \\
n=3 \text{ TAE} &
\end{align*}
\]

Heidbrink, EX/6-3, Thurs. p.m.
High Sensitivity BES Measurements Enable Detailed Characterization of Zonal Flow Structure and Dynamics

- Geodesic acoustic modes (GAMs) dominant near edge \((r/a > 0.85)\)
- Zero-mean-frequency (ZMF) zonal flow dominant in core \((0.6 \leq r/a \leq 0.85)\)
- GAMs couple energy to high frequency turbulence

\[
\text{Turbulent Energy Transfer} = -\Re \langle n(f)V_y (f-f') \frac{\partial n(f')}{\partial y} \rangle
\]

McKee, EX/2-3, Tues. p.m.
Recent Experiments Suggests Tritium Uptake in Carbon Facing Surfaces May be Controllable

- DiMES experiments show large reduction in C and D deposition on heated materials

Non-Heated Mirror

Heated Mirror

Deuterium co-deposition profile in tile gap

Non-heated

Heated x 10!
Access to High Performance Regimes on Graphite Tiles Does Not Require Frequent Wall Conditioning

- Results are distinctly different from recent results indicating the need for frequent wall conditioning of metal walls from Alcator C-Mod and Asdex-Upgrade

- Access to high $\beta$ demonstrated after $\sim 6000\ s$ of plasma operation without boronization

- Demonstrated reproducible hybrid discharges without between-shot wall conditioning

- No systematic degradation observed in daily reference shots
The DIII–D Research Program has:

- Developed physics solutions to issues key to the success of ITER
  - NTM stabilization using ECCD $\implies$ Sustained $\beta_N > 3$ operation
  - ELM suppression via n=3 RMPs $\implies$ Longer divertor lifetime
  - Low RWM rotation threshold $\implies$ High $\beta$ operation for Q=5 steady-state

- Developed and characterized advanced operating scenarios that offer significant potential benefit to the ITER physics program
  - Fully noninductive operation with $\beta_N = 3.5$
  - Demonstrated $\beta_N = 3.8$ for ~2 s with internal transport barriers $\implies$ Increased confidence in Q=5 steady-state scenario
  - Demonstrated $G > G_{\text{ITER}}$ at low rotation
  - Demonstrated compatibility of radiative divertor operation and hybrid performance $\implies$ Potential for Q > 10
The DIII–D Research Program has:

- Advanced the physics understanding of issues critical to the success of ITER
  - Energetic particles: Documented structure and impact of Alfvén eigenmodes on fast-ion distribution
  - Turbulence-driven transport: Characterized zonal flow structure and impact on ITB formation

Future research will continue to focus on resolving near-term ITER design issues, qualifying advanced scenarios for use in ITER, and advancing the understanding of fusion plasmas.
The Success of DIII-D Is Made Possible by the Hard Work of Many Scientists, Engineers, and Technicians