DIII-D: Recent Physics Results, Implemented and Planned Hardware Upgrades

Presented by
Peter I. Petersen
for the DIII-D Team

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OutLine

• **Physics**
  - Tokamak scenarios
  - Plasma instabilities
    • Resistive Wall Modes (RWMs)
    • Edge Localized Modes (ELMs)
    • Neoclassical Tearing Modes (NTMs)
    • Disruption Mitigation

• **Hardware**
  - Plasma Control System (PCS)
  - Long Torus Opening Activities
Conventional, Hybrid and Advanced Tokamak Scenarios

Conventional ($\beta_N < \beta_{N,\text{no-wall}}$, $H_{89} \sim 2$, $f_{BS} << 1$)
- Pluses: High Fusion Gain, Physics Appears to Be Robust, Passive Control
- Minuses: High Plasma Current Required for High Fusion Gain

Hybrid ($\beta_N \sim \beta_{N,\text{no-wall}}$, $H_{89} > 2$, $f_{BS} \sim 0.5$)
- Pluses: Longer pulses (OH-drive), High Fusion Power Density at Reduced Engineering Parameters, Passive Control
- Minuses: Physics not yet fully established

Advanced ($\beta_N > \beta_{N,\text{no-wall}}$, $H_{89} > 2$, $f_{BS} \sim 1$)
- Pluses: Steady-State, High Fusion Power Density
- Minuses: Significant physics issues remain, Active Control of MHD Instabilities Required

$\beta_{N,\text{no-wall}}$ is the theoretical plasma pressure limit if there was no wall
Hybrid Scenario: Experiments Have Demonstrated Truly Stationary (> 9 $\tau_R$), High Performance Operation

- $I_P$ (MA)
- $P_{\text{NBI}}$ (MW/10)
- $\beta_T \approx 4\%$
- $\beta_N \approx 2.7$
- $H_{89p} = 2.3$
- $H_{98y2} = 1.3$
- No growing MHD

- $n = 1 \tilde{B} \text{ rms}$
- $n = 2 \tilde{B} \text{ rms}$
- $Z_{\text{eff}} = 2.0$

- $\langle n_e \rangle (10^{19} \text{ m}^{-3})$
- $D_\alpha$

Time (s)
Progress Toward High Performance Advanced Tokamak Scenario:  
\[ \beta_N \geq 50\% \text{ above the no-wall limit maintained for } 2 \text{ s with elevated } q \text{ profile} \]

- \[ \beta_N > 6\ell_i \text{ for } \sim 2 \text{ s} \]
  - Relies on wall stabilization of the \( n=1 \) external kink mode (no-wall stability limit \( \sim 4\ell_i \))

- High energy confinement, \( H_{89} > 2.5 \text{ for } \sim 2 \text{ s}, \) leads to high fusion gain factor, \( G \)

- High \( q_{\text{min}} \) leads to high bootstrap current fraction, \( f_{BS}, \) up to 70%

\( f_{BS} \) is the bootstrap fraction, the fraction of plasma current driven by the plasma itself

\( \ell_i \) is the plasma internal inductance
DIII-D Has a Mix of Tools To Minimize Error Fields, Resistive Wall Modes At High Plasma Pressures And ELMs

6 section, external C-coil
12 section, internal I-coil
5 C-supplies each @5 kA, 350 V or 7kA at lower voltage tap
4 Low Speed Switching Power Amplifiers (SPAs) each @5 kA, 300 V, ~ 4 - 5 s
6 audio amplifiers (200 A, 0.1 – 20 kHz)

System provides for both rotational stabilization of RWM (error field correction) and feedback stabilization of the RWM. System is also used to reduce or eliminate ELMs.
Independent Operation of Dynamic Error Field Correction (External Coils) and RWM Direct Feedback (Internal Coils) is Efficient and Effective

- D.E.F.C: larger current with low frequency
- Direct feedback: lower current with higher frequency

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**Diagram:**
- Magnetic sensor
- I-coils
- C-coils
- 1:2 Transformer optional
- High Pass Filter
- Low Pass Filter
- PID
- High-speed actuators (audio amplifier)
- Switching Power Amplifier
- Pre-programmed Error Field Correction

**Graph:**
- External current (kA) vs. time (ms)
- Internal current (kA) vs. time (ms)

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**Logos:**
- DIII-D National Fusion Facility
- General Atomics
The Internal I-Coils Also Provide A Flexible System For ELM Control

Small islands might be responsible for the ELM suppression

Relatively small impact on core confinement

Enhance magnetic and density fluctuations with no indication of increased stochasticity

Even parity is better than odd
ELMs are eliminated below a critical pedestal density using I-coils.

Recent experiments performed at pedestal collisionalities close to those anticipated in ITERS showed ELM suppression.
Neo-classical Tearing Modes $m/n = 3/2$ and $2/1$ Have Been Stabilized by ECCD.

Wider ECCD Is Less Effective Neo-classical Tearing Mode Suppression

The gyrotrons are modulated to give same current density

Island width compared to ECCD width

Misalignment of ECCD with island compared to ECCD width

Island width decreases most in blue case; meaning more effective stabilization

Blue case: Sys 1

Red case: Sys 2,3 and 4
Successful Disruption Mitigation on DIII–D Using Massive Gas Puffing

Recent experiments investigated neutral penetration

Fast camera picture confirms little neutral penetration during thermal quench (radial view toward injection port)

1 ms after jet hits Plasma

Gas: Argon

When the cold front reaches sufficiently far into the plasma core, typically around $q=2$, an explosive growth of MHD instabilities occurs.

Most of the plasma thermal energy is radiated away.
DIII-D Plasma Control System Upgrades

• **Control algorithm improvements**
  – Introduced Kalman Filter (to discriminate against RWMs & ELMs, increases S/N)
  – Integrated Audio amps into the RWM suppression algorithm.
  – 3/2 and 2/1 q-surface reconstruction for NTM control.
  – 2 point feedback control of $T_e$
  – Development of feedback control of q-profile using NBI, ECCD (and FW begun)
  – Advanced shape controller (MIMO) demonstration

• **Hardware Upgrades**
  – Total PCS processors increased from 9 to 13
  – Total More CPUs dedicated to Real-Time EFIT, with and without MSE
  – Remote CPUs in Thomson (32 ch), MSE (32 ch) and ECE (32 ch) labs
  – Dedicated RWM control CPU and new ADCs reduce latency (to 35 µs)
Several Major Tokamak & Facility Upgrades Are Foci of Long Torus Opening Activities

- Rotate the 210 neutral beam line
- Install new high triangularity lower divertor
- Buy 3 long pulse 1 MW gyrotrons
- Refurbish and build equipment for new gyrotrons
- Conditioning new gyrotrons
- Install 2 new cooling towers
- Upgrade TF-coil system to 10 s

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- Fast Wave Upgrade
- Plasma Control System Upgrade
- ...

The Long Torus Opening Period is 4/18/05 – 5/8/06
Rotation of 210° Beamline Opens New Regimes for Physics Studies and Improved Plasma Measurements

**New Physics**
- QH-mode (ELM-free) regime with central co-rotation
- Understanding physics of rotation
- RWM stability with low rotation
- NTM stabilization with modulated RF
- Transport barrier control (separate ExB and Shafranov shift effects)
- Fast ion physics
- Physics of neutral beam current drive

**Diagnostics**
- MSE measurement viewing co- and counter beam allows separation of $E_r$ and $j$
- Co and Counter CER view allow direct measurement of cross section corrections
New Divertor Modification Provides Physics Capability and Maintains Shape Flexibility

- Density control at high performance
  - SN and DN AT and QH-mode
- Pedestal physics with range of $v^* (n_e)$
- Mass transport physics (tritium uptake)
  - Microbalance diagnostics
  - Reduced carbon source from tile edges
- Optical access to the inner divertor leg
- Detachment control via pumping
Motivation for Upgrading the ECH System

**Enables**
- Current profile control
- Sustainment of high performance
- Tearing mode stabilization or avoidance
- Transport barrier studies
- Modulated transport and critical gradient studies
- Electron heating
Cooling System Upgrade Will Meet the Expanded Long Pulse, High Power Needs of the DIII-D Program

- Two aging cooling towers are being replaced
- Heat exchangers for ECH are being upgraded
Milestones

• 1/30/06 Complete installation of the lower divertor
• 3/31/06 Close DIII-D Vessel
• 4/10/06 Start Power Supply testing
• 4/26/06 Start NB conditioning
• 5/8/06 Start Plasma Physics Operation
  - NB should be ready with 7 sources
  - ECH should be ready with 4 – 6 gyrotrons
  - Fast Wave should be ready with 3 transmitters