Overview of Recent DIII-D Experimental Results

by
M.E. Fenstermacher
for the DIII-D Team

Presented at the
52nd Annual Meeting of
the APS Division of Plasma Physics
Chicago, Illinois

November 8-12, 2010

This work was performed under the auspices of the U.S. Department of Energy by Lawrence Livermore National Laboratory under Contract DE-AC52-07NA27344, and under Contracts DE-FC02-04ER54698, DE-FG02-07ER54917, DE-FG02-05ER54809.
Ensuring the success of ITER

Critical issues for the design and operation of ITER

Improving predictive capability
Validation studies of physics-based models of burning plasma behavior

Developing sustained operational scenarios
Advanced inductive, steady-state
TBM: Perturbation From TBM Had Negligible Effect at ITER Target $\beta$ – Modest Effect at Higher Values

• Rotation Effect Can be Large at Largest TBM Perturbations

Simulated on DIII-D

• Little effect observed on L-H transition power threshold and fast ion confinement
ELM CONTROL: Observations Suggest RMP Fields Directly Modify Particle Transport; Also Can Affect L-H Power Threshold

- Density decrease observed over a range of $q_{95}$
- Particle transport correlated with increased fluctuations at higher I-coil current
- $P_{L-H}$ increases for RMP above threshold strength

(Density (BES $\rho=0.85$)

(ELMs remain suppressed throughout the period shown)
ELM CONTROL: First Demonstration of Pellet ELM Pacing in ITER Baseline Scenario Discharge

- 14 Hz pellets $\rightarrow$ ~25 Hz ELMs
- $\Delta W_{ELM}/W$ decreases by $\times 3-4$

\[\frac{\Delta W_{ELM}}{W} \approx 3\%\]
\[\frac{\Delta W_{ELM}}{W} \approx 11\%\]

- Planned upgrade: 30 Hz pellet injection

L. Baylor this session

Ensuring the success of ITER
ELM CONTROL: QH-mode Maintained Without NBI Torque – May Be a Viable Scenario Without ELMs For ITER

- QH-mode attractive due to natural absence of ELMs
  - Previously required strong NBI torque

- Use NTV counter offset velocity
  - Driven by nonresonant fields (I-coil plus C-coil)

- NTV provides E×B shear to maintain QH-mode even after NBI torque ramped to zero

- Plan extension to ITER level of weak co-torque

A. Garofalo this session

Ensuring the success of ITER
DISRUPTION CONTROL: Achieved Record DIII-D $n_e$ with SPI and Control of Runaway Electron Current and Position

- Position control of RE beam and energy dissipation by loop voltage control

![Diagram of Massive Gas Injection (MGI) and Shattered Pellet Injection (SPI)]

![Graph showing toroidal current and $\int n_e d\ell$ over time]

A. James Thurs 3:12, D. Humphreys Thurs 2:00, T. Jernigan, Parks, V. Izzo Thurs pm
L-H THRESHOLD: Characteristics of He Plasmas Examined in Support of ITER Research Plan for Non-nuclear Phase

- L-H threshold higher by up to a factor of two in He plasmas (compared to D plasmas)
  - Similar results in ECH (shown) and NBI heated plasmas
- Energy confinement reduced by 30% in He relative to D

---

P. Gohil Thurs 3:36

Ensuring the success of ITER
T-RETENTION: Techniques for Controlling Hydrogenic Inventory in Carbon Walls have been Developed

- Thermal oxidation removes hydrogenic bearing co-deposits
- Full tokamak performance (Hybrid scenario) rapidly re-established

E. Unterberg this session, C. Chobak, K. Umstadter Tues am

Ensuring the success of ITER
Ensuring the success of ITER
Critical issues for the design and operation of ITER

Improving predictive capability
Validation studies of physics-based models of burning plasma behavior

Developing sustained operational scenarios
Advanced inductive, steady-state
**PEDESTAL**: Detailed Experimental Tests Support Predictive Capability of First-principles Pedestal Model

- Measured pedestal height on several devices consistent with EPED1.6 model, combining
  - Non-local Peeling-Ballooning
  - Local kinetic ballooning mode (KBM) – initial experimental indications from BES data
  - Both directly calculated… *No Free Parameters*

- Model used to predict and optimize the pedestal in ITER:
  - $\beta_{\text{Nped}} = 0.6-0.8$
  - Joint EPED1.6 and TGLF simulations indicate $Q = 15$ and $P = 450$ MW is achievable
FAST IONS: 2D Electron Cyclotron Imaging (ECE-I) Data Allow Us to Validate Alfvén Eigenmode Physics Models

Gyrofluid simulation (TAE/FL)

Measured electron temperature fluctuations

Ideal MHD...

Fast ion contribution to mode structure included

ECE-I
FAST IONS: New Measurements Confirm Direct Fast Ion Loss From Alfvén Eigenmodes

- Fast Ion Loss Detector (FILD) measures energy and pitch of expelled ions
- Coherent losses at AE frequencies observed

Energy and Pitch of Loss

NBI Prompt Loss
FAST IONS: New Measurements Confirm Direct Fast Ion Loss From Alfvén Eigenmodes

- Fast Ion Loss Detector (FILD) measures energy and pitch of expelled ions
- Coherent losses at AE frequencies observed

Energy and Pitch of Loss

NBI Prompt Loss
Ensuring the success of ITER
Critical issues for the design and operation of ITER
Improving predictive capability
Validation studies of physics-based models of burning plasma behavior

Developing sustained operational scenarios
Advanced inductive, steady-state
HYBRIDS: DIII-D/JET Experiments Confirm Common Physics Basis for Projecting Advanced Inductive Plasmas to ITER

- Dimensionless parameter profiles match in “identity” discharges → Same physics governs both devices
- Overall confinement observed to scale in roughly Bohm-like fashion
  - Not all dimensionless parameters matched to ITER… more work needed for projection
AT: Profile Broadening at High $q_{\text{min}}$ and $\beta_N$ Points Out Importance of Transport in Attainable Bootstrap Fraction

- Steady-state operation requires bootstrap fraction $f_{BS} \geq 70\%$
  - $f_{BS} \propto q \beta_N f_p$

- But, observations indicate $f_p$ depends strongly on both $q$ and $\beta_N$
Steady-state operation requires bootstrap fraction $f_{BS} \geq 70\%$

- $f_{BS} \propto q \beta_N f_p$

But, observations indicate $f_p$ depends strongly on both $q$ and $\beta_N$

- At fixed $\beta_N$, $f_p$ decreases with $q_{min}$ increases

Developing sustained operational scenarios
AT: Profile Broadening at High $q_{\text{min}}$ and $\beta_N$ Points Out Importance of Transport in Attainable Bootstrap Fraction

- Steady-state operation requires bootstrap fraction $f_{BS} \geq 70\%$
  - $f_{BS} \propto q \beta_N f_p$

- But, observations indicate $f_p$ depends strongly on both $q$ and $\beta_N$
  - At fixed $\beta_N$, $f_p$ ↓ with $q_{\text{min}}$ ↑
  - At fixed $q_{\text{min}}$, $f_p$ ↓ with $\beta$ ↑

- Experimental $\chi_e$ and $\chi_i$ scale differently with $q_{\text{min}}$ and $q_{95}$
**UPGRADES:** DIII-D Upgrades In 2011 Continue to Address the Challenges of Future Burning Plasma Devices

**Challenges**
- Understand transport in regimes dominated by electron heating
- Provide off axis current drive necessary for steady state scenarios

**2011 Upgrades**
- 4 MW ECH/ECCD
- 5 MW off axis NBI

**Progress toward developing regimes for ITER & DEMO**

T. Taylor, J. Lohr, R. Prater Thurs pm, V. Chan Weds am
Talks In This Session Present DIII-D Research Supporting ITER, Steady-State High Performance and Fusion Science

• Ensuring the Success of ITER
  - E. Unterberg  CO4.07 : Fuel Retention and Removal from the Carbon First-Wall in DIII-D
  - R. Moyer  CO4.12 : Impact of RMPs on Turbulence Drive, Damping, and Transport
  - L. Baylor  CO4.13 : Pellet ELM Pacing Results from DIII-D

• Improving Predictive Capability
  - M. Choi  CO4.05 : Finite Orbit Monte Carlo Simulation with Full Wave Fields for ICRF Wave Heating Experiments in DIII-D, NSTX, KSTAR and ITER
  - W. Heidbrink  CO4.06 : New Measurements of Fast-ion Transport
  - C. Lasnier  CO4.08 : Investigation of Divertor Heat Flux Width in DIII-D for 2010 Joint Research Target
  - G. McKee  CO4.09 : Variation of Turbulence & Transport with the $T_e/T_i$ Ratio in H-mode Plasmas
  - J. deGrassie  CO4.10 : Thermal Ion Orbit Loss and Intrinsic Toroidal Velocity Near the LCFS
  - B. Hudson  CO4.11 : Dependence of ELM Size on Rotation at High-Triangularity and High Beta-Poloidal in the DIII-D Tokamak
  - R. Buttery  CO4.15 : A New Resistive Response to 3-D Fields in Low Rotation H-modes

• Developing Sustained Operational Scenarios
  - T. Luce  CO4.02 : Confinement in Advanced Inductive Plasmas – Gyro-radius and Rotation
  - F. Turco  CO4.03 : Impact of Current Profile on Transport and Stability in High Noninductive Fraction DIII-D Discharge
  - R. Pinsker  CO4.04 : High-Power Fast Wave Coupling Experiments in Advanced Regimes in DIII-D
DIII-D Program Much Broader Than Can Be Described Here – See Invited and ITER Talks Plus Two Poster Sessions

<table>
<thead>
<tr>
<th>Time</th>
<th>Speaker</th>
<th>Topic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Thurs 2:00</td>
<td>Humphreys</td>
<td>ITER current channel control under disturbances and disruptions - implications from DIII-D experiments</td>
</tr>
<tr>
<td>Thurs 3:12</td>
<td>A. James</td>
<td>Generation and Stability of Runaway Electrons During Rapid-Shutdown in DIII-D</td>
</tr>
<tr>
<td>Thurs 3:36</td>
<td>Gohil</td>
<td>L-H Transition Studies on DIII-D to Determine H-mode Access for Ops Scenarios in ITER</td>
</tr>
</tbody>
</table>

UO4 Oral Session on Research in Support of ITER-I

<table>
<thead>
<tr>
<th>Time</th>
<th>Speaker</th>
<th>Topic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fri 9:42</td>
<td>Strait</td>
<td>Error Field Measurement Techniques for ITER Using Plasma Response</td>
</tr>
<tr>
<td>Fri 10:06</td>
<td>Kramer</td>
<td>Fast Ion Effects During Test Blanket Module Simulation Experiments in DIII-D</td>
</tr>
<tr>
<td>Fri 10:18</td>
<td>Orlov</td>
<td>Numerical Analysis of Resonant Magnetic Perturbations ELM Control in ITER</td>
</tr>
</tbody>
</table>

XO4 Oral Session on Research in Support of ITER-II

<table>
<thead>
<tr>
<th>Time</th>
<th>Speaker</th>
<th>Topic</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mon 9:30</td>
<td>Schaffer</td>
<td>ITER Test Blanket Module Error Field Simulation Experiments</td>
</tr>
<tr>
<td>Mon 10:00</td>
<td>Lanctot</td>
<td>Measurement and Modeling of 3D Equilibria in DIII-D</td>
</tr>
<tr>
<td>Tues 10:00</td>
<td>Tobias</td>
<td>Electron Cyclotron Emission Imaging of MHD Activity on the DIII-D, TEXTOR, ASDEX-U, and KSTAR Tokamaks</td>
</tr>
<tr>
<td>Tues 11:00</td>
<td>Z. Yan</td>
<td>Pressure-Gradient-Limiting Instability Dynamics in the H-mode Pedestal on DIII-D</td>
</tr>
<tr>
<td>Tues 11:30</td>
<td>Beurskens</td>
<td>H-Mode Pedestal Scaling in DIII-D, AUG and JET</td>
</tr>
<tr>
<td>Weds 11:30</td>
<td>Holland</td>
<td>Advances in Validating Gyrokinetic Turbulence Models in L and H mode Plasmas</td>
</tr>
<tr>
<td>Weds 2:00</td>
<td>J-K Park</td>
<td>Response of Tokamaks to Non-axisymmetric Magnetic Perturbations</td>
</tr>
<tr>
<td>Weds 3:00</td>
<td>Muller</td>
<td>Evidence of an Edge Momentum Source in DIII-D H-mode Plasmas and Role of the Reynolds Stress for Intrinsic Rotation</td>
</tr>
<tr>
<td>Weds 3:30</td>
<td>Staebler</td>
<td>Discoveries From the Exploration of Gyrokinetic Momentum Transport</td>
</tr>
<tr>
<td>Weds 4:00</td>
<td>Cole</td>
<td>Peak Neoclassical Toroidal Viscous Force in DIII-D</td>
</tr>
<tr>
<td>Thurs 9:30</td>
<td>Van Zeeland</td>
<td>Alfvén Eigenmodes and Fast Ion Loss in the DIII-D and ASDEX-Upgrade Tokamaks</td>
</tr>
<tr>
<td>Thurs 11:30</td>
<td>Okabayashi</td>
<td>Off-axis Fishbone-like Instability and Excitation of Resistive Wall Mode (RWM) in JT-60U and DIII-D Devices</td>
</tr>
</tbody>
</table>

DIII-D Posters Tuesday Morning and Thursday Afternoon