Plans for MHD control in DIII-D (2009-2013)

By
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MHD stability research in DIII-D addresses key issues of physics understanding and mode control

- Sawtooth physics
- Fast ion-driven modes
- Neoclassical Tearing Mode stabilization
- Resistive Wall Mode control
- ELM control
- Error Field Correction
- Disruption Mitigation
Planned Facility Upgrades are Aimed at Critical Issues for ITER

<table>
<thead>
<tr>
<th>Tool</th>
<th>Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inner wall RMP coils</td>
<td>ELM control</td>
</tr>
<tr>
<td>NBI vertical steering</td>
<td>Steady-state advanced scenarios</td>
</tr>
<tr>
<td>EC system expansion to 12 MW</td>
<td>NTM control, low-torque heating, $T_e/T_i \sim 1$</td>
</tr>
<tr>
<td>FW antenna upgrades</td>
<td>Stability and confinement at low torque</td>
</tr>
<tr>
<td></td>
<td>Coupling to ITER H-mode edge</td>
</tr>
<tr>
<td>RWM amplifier upgrade</td>
<td>RWM plus error field control</td>
</tr>
<tr>
<td></td>
<td>Simultaneous stabilization of $n=1, 2, 3$</td>
</tr>
<tr>
<td>TF coil connector upgrade</td>
<td>Error field control</td>
</tr>
<tr>
<td></td>
<td>RWM control</td>
</tr>
<tr>
<td>Additional F-coil choppers</td>
<td>Improved shape control for ITER startup</td>
</tr>
<tr>
<td>High-throughput pellet injector upgrade</td>
<td>ELM pacemaking</td>
</tr>
<tr>
<td></td>
<td>Core fueling</td>
</tr>
<tr>
<td>High-throughput gas injection, inverse jet, custom pellets, liquid jet</td>
<td>Disruption mitigation</td>
</tr>
<tr>
<td>Axisymmetric divertor coils</td>
<td>Divertor heat load reduction</td>
</tr>
<tr>
<td>Closed loop water/air cooling</td>
<td>Hot wall operation against Tretention</td>
</tr>
</tbody>
</table>
Sawtooth Experiments Will Study Linkage with Transport as well as Stability Issues

- **Research objectives for 2009-2013**
  - Examine role of shape and fast ions in sawtooth crash dynamics
  - Modify sawteeth to reduce NTM seeding
- **Verify models of sawtooth stability**
  - NIMROD (3-D effects)
  - Porcelli model
- **Control tools**
  - 12 MW ECH
  - Fast Waves
  - Shape flexibility
- **Key diagnostics**
  - ECE, ECE imaging, CER
  - MSE
  - BES, scattering, reflectometry

![ECE color map of sawtooth crash](image)
Alpha Physics Will Introduce New Scientific Challenges in ITER

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<thead>
<tr>
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</thead>
<tbody>
<tr>
<td>Physics:</td>
<td>linear stability</td>
<td>Fast ion transport</td>
<td>Instability control</td>
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<tr>
<td>Fast ion</td>
<td>ECH, FW, co/ctr NBI</td>
<td>Off-axis NBI</td>
<td>distribution:</td>
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- **Near-term DIII-D goal: validate models for fast ion-driven instabilities**
  - Rigorous tests of sawtooth models
  - Multi-field measurements of Alfven eigenmode structure
  - Detailed comparison to ideal and kinetic theory

- **5-year goal: understand and control fast ion transport**
  - Measurements of fast ion profile
  - Comparison to orbit codes, effects of mode mixing
  - ECH stabilization physics

- **Key hardware elements**
  - NPAs for phase space resolved confined fast ions
  - Poloidal scintillator probe array for fast ion loss
  - Heating and current drive upgrades: 12 MW ECH, 6 MW FW, off-axis NBI
DIII-D has the Diagnostic Set to Validate AE Stability Models for Future Burning Plasma Experiments

- **Research objectives for 2009-2013**
  - Make multi-field measurements to further explore mode structure
  - Assess high order (low velocity) resonances
- **New diagnostics**
  - Mode polarization, linear BES, high frequency CER, ECE imaging, polarimetry
- **Test multi-field codes (two fluid, gyrokinetic) being developed**
  - GTC, NOVA-2F
- **Collaborations**
  - UT, UCI, PPPL (NSTX), Frascati, SciDAC, JET
DIII-D Will Continue to Develop the Tools for Controlling AEs and Fast Ion Transport

- **Research objectives for 2009-2013**
  - Assess effect of ECH on a range of fast ion instabilities (TAEs, EAEs) at different radii
  - Investigate effect of ECH stabilization on fast ion loss
  - Determine mechanism for stabilization and extrapolate to ITER

- **Key tools**
  - 12 MW ECH
  - 6 MW FW power with multiple frequencies (60, 90 MHz)
    - Can effect AE stability by accelerating beam ions
  - Counter NBI & off-axis NBI
    - Alters mode drive and damping

![Graph showing ECH P1 and P3 with RSAEs and No RSAEs]
Off-axis NBCD Enables Near-Term Scenario Development

- High $q_{min}$ scenario development at high $\beta$ is limited at present by overdrive of the central current by the NBI required for heating.

- Off-axis NBCD is as efficient as off-axis ECCD and would allow the existing ECCD to be used for tailoring the current profile.

- Plan is for 2 beamlines to be modified for off-axis operation, retaining the capability for the present on-axis aiming.

![Graph comparing off-axis and on-axis CD efficiency](image_url)
Neoclassical Tearing Mode Control is Required in ITER’s Baseline Scenario

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<tr>
<td></td>
<td>Validate stabilization models</td>
<td>Apply in ITER-relevant plasmas</td>
<td>Multi-mode control</td>
<td>Real-time mirror steering</td>
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- **Near-term DIII-D goal:** validate the physics basis and power requirements for 2/1 mode stabilization by ECCD
  - Dependence on current drive width, alignment, modulation, ...

- **5-year goal:** develop control techniques for routine stabilization of high-performance plasmas in DIII-D and ITER
  - Simultaneous control of multiple islands (e.g. 3/2 and 2/1)
  - Robust control by island detection at the current drive location
  - “Unlocking” of locked islands in low-torque plasmas
  - Magnetic perturbations and ECCD

- **Key hardware elements**
  - Increased gyrotron power
  - Real-time mirror steering
  - Oblique ECE detection
DIII-D has the Tools to Advance Our Understanding of NTM Onset and Suppression

- **Research objectives for 2009-2013**
  - Assess mechanisms determining NTM seeding, onset threshold
  - Evaluate ECCD modulation for improved suppression

- **Control tools of NTM studies**
  - 12 MW ECH
  - Co/counter NBI
  - RMP coils
  - Multi-variable PCS

- **Key diagnostics**
  - ECE, ECE imaging, MSE
  - BES, high frequency CER

- **Collaborations**
  - AUG, JET, JT-60U, NSTX

Helical perturbations in $J_\phi$, measured by MSE, for a slowly rotating 2/1 mode
Understanding of Resistive MHD is Needed for Scenario Design, Extrapolation, and Control

- Ideal MHD calculations have been the cornerstone of scenario development of DIII-D
- Resistive MHD limits the range of current profiles available for steady-state operation
- Physics basis for extrapolation of the favorable effects of resistive MHD in the hybrid scenario does not exist
- Feedback control of access to advanced scenarios needs to incorporate a roadmap of resistive MHD stability
Resistive Wall Mode Control Will Allow Stable Operation of High-\(\beta\) Advanced Scenarios in ITER

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<tbody>
<tr>
<td>Feedback at low rotation</td>
<td>Multi-mode feedback</td>
<td>Simulate ITER’s RWM control</td>
<td>Internal vs. external coils</td>
<td>Validate feedback models</td>
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**Near-term goal:** provide input to ITER’s choice of coils for RWM stabilization
- Feedback control of \(n=1\) RWM in low-torque plasmas
- Direct comparison of internal vs. external control coils
- Validate control models for ITER coil design

**5-year goal:** establish the basis for optimized control of RWMs in ITER
- Validate models of rotational stabilization, including kinetic effects
- Simulate ITER’s control system (bandwidth, etc.)
- Role of \(n>1\) modes at high beta
- Optimal controllers for operation near the ideal-wall stability limit

**Key hardware elements**
- Additional amplifiers for the I-coil ⇒ simultaneous control of \(n=1, 2, 3\)
- Multiple toroidal locations for profile diagnostics (ECE)
- Reduction of known error field sources
Understanding of RWM Stabilization is Essential for Steady-state Operation Above the No-wall Limit

- Present understanding indicates rotational stabilization will be sufficient for scenario development in this five-year plan.

- The focus of the physics studies is to provide the physics basis for operating near the ideal wall limit in DIII-D and beyond:
  - Stability at low rotation
  - Development of feedback methods and requirements
  - Understanding stability for $n > 1$
Control of Edge-Localized Modes is Critical to the Lifetime of ITER’s Divertor

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<tr>
<th>Year</th>
<th>Event</th>
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<tbody>
<tr>
<td>2008</td>
<td>RMP physics basis</td>
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<tr>
<td>2009</td>
<td>Extend QH mode regime</td>
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<tr>
<td>2010</td>
<td>Inner Wall coils</td>
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<tr>
<td>2011</td>
<td>Pellet pacing</td>
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- **Near-term DIII-D goal:** provide input on choice of RMP coils for ITER
  - Dependence on mode spectrum
  - Braking of plasma rotation

- **5-year goal:** establish the physics basis for optimized ELM control in ITER
  - **RMP control:** optimization of RMP spectrum, physics of particle transport
  - **Pellet pacing:** optimization of pellet size and rate
  - **ELM-free QH mode:** extension to low torque plasmas
  - **Small-ELM regimes:** extension to ITER-like parameters
  - Dependence on plasma rotation

- **Key hardware elements**
  - Inner wall RMP coils (48)
  - Low field side “pellet dropper”
  - Diagnostic improvements: edge current density, edge gas puff imaging, fast IR cameras
Edge Stability Studies Will Focus on ELMs, Building Upon Previous Theory/Experiment Collaborations

- **Research objectives for 2009-2013**
  - Develop improved understanding of ELM crash
  - Assess tools for ELM suppression

- **Need to model nonlinear evolution and saturation of peeling-ballooning modes**
  - **BOUT, NIMROD**

- **Control tools**
  - RMP coils (internal, inner wall)
  - Co/counter NBI (QH-mode)

- **New diagnostics**
  - IR + visible TV periscopes
  - BES upgrade
  - Gas puff imaging

ELM mode structure calculated by ELITE showing filaments
The Proposed HFS Coil Provides Important New Physics Research Opportunities

- **HFS coil — physics opportunities (short list):**
  - Resonant and non-resonant flow damping variations with applied spectrum
  - Single/multi-row HFS coils versus single/multi-row LFS coils
  - ELM suppression at low $q_{95}$ with high $n$ spectrum
  - Physics of pedestal transport
  - ELM suppression in AT and Hybrid plasmas

- **HFS coil designed to increase RMP physics understanding**
  - Not intended as a reactor prototype
QH-Mode Offers an Alternative Path to ELM Stabilization

- Agreement of QH operating point with peeling ballooning theory suggest QH-mode possible in ITER

- Peeling-ballooning stability boundary independent of rotation direction
  - New result: QH-mode with co-injection

- Diagnostic improvements for physics understanding and ITER predictions
  - Main ion $T_i$ and $v_\phi$ measurement for MHD modeling
  - Routine edge current density measurement
  - Improved poloidal magnetics for EHO analysis
Error Field Control is Critical to ITER’s Performance at Low Rotation and High Beta

- Recent breakthrough: semi-quantitative agreement of experimental results with ideal perturbed MHD equilibrium theory
  - Shows importance of global plasma response to the error field
- Near-term DIII-D goal: improved error correction for low-torque experiments in DIII-D
  - Qualitative or quantitative guidance by theory
- 5-year goal: physics basis for error field control in ITER
  - Validate models of plasma response to error fields
    - Dependence on rotation, $\beta$, spatial mode spectrum
    - Optimize error field control techniques (possibly feedback-based)
- Key hardware elements
  - Additional amplifiers for the I-coil ⇒ control of $n=1$, 2, 3
  - Multiple toroidal locations for profile diagnostics (ECE)
  - Reduction of known error field: 30° TF feed

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<tr>
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<tbody>
<tr>
<td>2008</td>
<td>Error field physics at low torque</td>
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<tr>
<td>2009</td>
<td>Multi-mode error correction</td>
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<tr>
<td>2010</td>
<td>Validate models of plasma response</td>
</tr>
<tr>
<td>2011</td>
<td>Optimize error field control</td>
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Known DIII–D, 2006, $n = 1$

DIII–D Error + I-Coil Empirical Correction, 2006, $n = 1$

Poloidal Mode Number
Need to Understand How to Reduce Error Field Effects Using Realistic, Imperfect Coils

- **Research objectives for 2009-2013**
  - Improve understanding of plasma response to error field
- **3-D equilibria codes are critical**
  - EFIT3D
  - IPEC
- **Control tools**
  - Redesigned B-coil current feed at 30°
  - I-coil, C-coil
  - Inner wall coil
  - Co/counter NBI
- **New diagnostics**
  - 3-D magnetics
  - ECE at multiple toroidal locations
  - SXR at multiple toroidal locations
A Broad Physics Program in ITER Requires Predictive Capability for Consequences of Disruptions

- **Near-term DIII-D goal:** contribute to the specification of ITER disruption loads
  - Characterize asymmetric thermal and electromagnetic loads in DIII-D
  - Establish the scaling with $I_p$, $q_{95}$, ...

- **5-year goal:** establish the physics basis for prediction of ITER disruption loads
  - Expand disruption databases: DIII-D and international (ITPA)
  - Validate modeling of disruption dynamics (DINA, TSC)
  - Validate physics of runaway electron generation and deposition

- **Key hardware elements**
  - Halo current diagnostics
  - Diagnostics for horizontal vessel motion
  - Runaway electron diagnostics
A Broad Physics Program in ITER Requires a Reliable Disruption Protection System

- **Near-term DIII-D goal:** provide input to specifications of ITER gas jet and pumping systems
  - Establish physics basis for fast gas jet shutdown
  - Physics of impurity assimilation, role of MHD activity
  - Validation of nonlinear 3D models (NIMROD)

- **5-year goal:** develop mitigation of runaway electron avalanche
  - Validate physics of runaway electron multiplication
  - Shutdown with sufficient density for runaway suppression
  - Develop alternative methods of runaway suppression (e.g., RMP)
  - Validate nonlinear 3D models (NIMROD)

- **Key hardware elements**
  - Runaway electron diagnostics
  - Fast risetime gas delivery (rupture disk)
  - “Custom” impurity pellets, cryogenic liquid jet
  - Fast framing cameras

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**Argon Assimilation Increases with Plasma Energy and MHD Amplitude**
Operation of ITER Without Disruptions Will Require Multiple Levels of Protection

- **Plasma configuration**
  - Multivariable shape control
  - Current, pressure profile control
  - Rotation profile control

- **Detect & avoid operational limits**
  - Radiated power, density, q(r), ...
  - Real-time beta measurements
  - Real-time stability code

- **Actively suppress instabilities**
  - NTM stabilization (ECCD)
  - Rotation, error field control
  - RWM feedback (int/ext coils)

- **Off-normal condition: soft shutdown**
  - Action depends on plasma state
  - Change heating, fueling
  - Radiated power (small pellets)

- **Onset of disruption: fast shutdown**
  - High-pressure gas jet, liquid jet
  - Large pellets: High-Z, Low-Z
  - Magnetic perturbations

*These features must become integrated and routine!*
Long-term Goal is Disruption-Free Operation in DIII-D and ITER

Integrated stability control
  ⇒ avoidance of disruptions and other instabilities
  • Enable full use of machine capabilities through reliable operation near stability limits
  • Avoid the need to establish stability limits by trial-and-error
  • Disruption mitigation only as a last resort

Possible new elements over next 5 years include:
  • Real-time stability calculations (DCON)
  • Real-time measurements of MHD damping rates
  • Optimized coils for control of ELMs and RWMs
  • Fast steering mirrors for ECCD
  • Upgraded injectors for gas, pellets
  • Plasma control computer upgrades

Stability control in ITER must become as routine and reliable as shape control
DIII-D research in 2009-2013 will address key issues in MHD stability

- Physics understanding for prediction and avoidance of stability limits
- Mode control for suppression of instabilities
- Disruption mitigation to reduce the impact of instabilities
- Long-term goal: integrated stability control ➔ reliable, stable operation in DIII-D and ITER