MHD Stability Research Program on Alcator C-Mod
2003-2008

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Alcator C-Mod PAC
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C-Mod’s Uniqueness in MHD Stability Research

High \( n \), high \( p \)

Compact size

High field

Stability implications:
- Low core \( \beta \) to date, but higher expected
- High \( \alpha \) (normalized \( p' \)) in pedestal

Disruption implications:
- Very high current density
- Fast timescales
- Large halo currents, eddy currents
- Very high \( J \times B \) forces
- High local heat flux
- High energy density (hard to kill)
- No runaways
Stability research status on C-Mod

To date, $\beta$-limiting global MHD modes are rare (NTM’s, RWM’s)

Most MHD research on Alcator C-Mod has concentrated on:

• H-mode edge pedestal stability and ELM behavior (peeling/ballooning, intermediate-$n$)

• Disruption studies (halo currents, asymmetries & scalings; vessel wall flexing, neutral point behavior, killer pellets)

• Classical tearing modes (rotation velocity, wall torque)

• Alfvén eigenmodes
MHD stability analysis of edge with grassy ELM’s

ELITE code used to analyze intermediate-\(n\) stability for high \(\nabla p\) discharge

- Spatial structure of \(n = 30\) mode is shown
- At high \(\nabla p\) (high \(P_{RF}\)), coupled peeling/ballooning modes become unstable

\[ n = 30 \quad \gamma / \omega_A = .05 \]
Recent disruption research

- Confirmed existance of neutral point behavior in C-Mod
  
  $z = +2.7 \text{ cm}$

- Laser ranging measurements of vessel wall flexing incorporated into design constraints of new inner wall girdle
During the next 5 years, Alcator C-Mod’s capabilities will be significantly advanced:

- More heating power; higher $\beta$, higher $\nabla p$
- LHCD; profile control
- New inner divertor shape, allowing increased triangularity (installed last campaign)
- BP support program, with $I_p$ up to 2 MA, $B_T$ up to 8 T
- AT plasmas with ITB’s, lower $v^*$, high $f_{BS}$, high $\beta_N$, self-consistent profiles

**MHD-specific:**

- Installation of non-axisymmetric control coils
- Installation of active MHD antennas (initial phase began last campaign)
MHD Stability research program

In addition to past areas of emphasis, we expect that these enhanced capabilities will result in a number of new MHD research topics to be addressed, including:

- Locked modes (characterization, control)
- Active determination of Alfvén and global mode resonances and stability
- NTM’s, core $\beta$-limiting modes
- RF stabilization of sawteeth/NTM’s
- Wall and feedback stabilization of RWM’s at high $\beta_N$

Continuing research topics:

- H-mode edge pedestal stability and ELM behavior
- Disruption studies
Non-axisymmetric control coils for locked mode studies

- Locked modes recently implicated in high current disruptions on C-Mod
- Prototype coils immediately installed to begin locked mode studies (with pre-programmed waveform) — 8 coils arranged in 4 toroidal $\times$ 2 vertical locations
Active MHD spectroscopy

• Apply $\tilde{B}$ from ‘antenna’ coils to drive low amplitude, stable modes
  – Low frequencies (1–50 kHz) for global MHD
  – High frequencies (100–900 kHz) for Alfvén eigenmodes

• Measure plasma response with Mirnov coils

• Sweep applied frequency to determine damping rate, $\gamma$
  – Width of resonance = $\gamma$

• Monitor proximity to stability limits in real time
  – Feedback on power and/or profiles to avoid instabilities.
Active MHD spectroscopy

- C-Mod system will eventually consist of two antenna pairs, straddling the midplane
  - First pair was installed last campaign
  - Second pair operational in FY2004 (180° apart toroidally)
- Power supplies over broad frequency range
  - 1 kHz – 900 kHz
  - 10 – 20 amps
Proof-of-principle test of active MHD spectroscopy

• Drive frequency held fixed (420 kHz)

• $B_T$ ramped to sweep through Alfvén resonance

• $\gamma \approx -80 \mu s$
Disruption studies

Extensive halo current, eddy current, and laser ranging instrumentation embedded in new inner divertor/girdle region

• Characterize halo currents, toroidal asymmetries, empirical scalings, up to $I_p = 2$ MA and $B_T = 8$ T

• Measure toroidal eddy currents, asymmetries for first time

Combine the halo and eddy current measurements, vessel strain data, and engineering structural modelling to get a fully integrated picture of the dynamical behavior of disruption forces, so we can extrapolate to reactor regimes with confidence.
Halo current scaling with new divertor

$I_p/q_{95}$ Scaling Law for Halo Current
(for downward disruptions)

Previous scaling
• Much of scrape-off layer misses new inboard divertor
• Important implications for divertor design in ITER/reactor
Disruption mitigation and avoidance

- **High-pressure gas jet (with D. Whyte)**
  
  Study physics of jet penetration into C-Mod’s high-pressure core, as well as thermal quench

- **Locked modes**
  
  Use upgraded non-axisymmetric perturbation coilset and feedback control to avoid locked modes

- **Disruption avoidance:**
  
  Use active MHD real-time measurements of growth rates to avoid approaching unstable regimes
Pedestal Stability

Triangularity and $\nabla p$ (heating power) are known to affect edge MHD behavior and access to different ELM/EDA regimes. The ranges of both of these parameters are being extended to higher limits

- Explore edge stability, MHD modes, and ELM regimes at:
  - larger values of triangularity afforded by the new inner divertor ($\delta_L \geq 0.75$ vs $0.55–0.6$ previously)
  - higher $P_{RF}$ (12 MW source vs 8 MW previously)
  - double null

MHD theory in the pedestal region is complicated by non-ideal physics (scale length $\sim \rho_{pol}$, separatrix geometry, rotation, neutrals, etc).

- Compare experimental results with stability codes, including non-ideal physics, to gain an understanding of their importance

- Look for theoretically-predicted 3-wave coupling of QC mode to other modes (Alfvén, geodesic acoustic)
RF control of sawteeth and NTM’s

Sawtooothing may need to be controlled:

- Compatibility with ITB’s in AT program
  (Note: C-Mod ITB discharges produced by off-axis ICRF continue to sawtooth)

- Control of peaked profiles in BP support program

- Eliminate principal source of ‘seed’ island trigger of NTM’s, and provide C-Mod benchmark of NTM physics

  LHCD or counter-FWCD: Keep $q_0 > 1$

  ICRF (by controlling deposition radius and phasing): Shorten sawtooth period $\Rightarrow$ small seed islands $\Rightarrow$ below trigger threshold

- Current drive stabilization using MCCD, LHCD, ICCD

  Strong coupling with RF physics program
Wall and feedback stabilization

The AT plasmas currently planned for C-Mod will go to the no-wall limit ($\beta_N = 3$)

To increase $\beta_N$ further, we will need to assess what it would take to provide a stabilizing shell, and then install it.

- Is the present vessel wall sufficient? (non-conformal and relatively far from plasma surface, $b/a \geq 1.7$)
- Do the RF antenna and waveguide surfaces provide significant stabilization?
- How large a fraction of the toroidal circumference is necessary?
- Can feedback coils for RWM stabilization be integrated into an upgraded wall structure?

This assessment activity will quite likely involve collaboration with outside expertise.
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<th>Year</th>
<th>2003</th>
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<th>2007</th>
<th>2008</th>
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<tbody>
<tr>
<td><strong>Locked Mode Control</strong></td>
<td>Study effects of prototype correction coils</td>
<td>Upgrade power supplies; Develop active feedback</td>
<td>Upgrade coilset; control locked modes</td>
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<td><strong>Stability of AT Plasmas</strong></td>
<td>Incorporate measured J(r) into equilibrium and stability calculations</td>
<td>Stabilization by profile modification</td>
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<td><strong>Wall and Feedback Stabilization</strong></td>
<td>Investigate MHD stability near no-wall β limit, Study RWM’s</td>
<td>Design stabilizing wall/feedback</td>
<td>Build/install stabilizing wall</td>
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<td><strong>Pedestal Stability</strong></td>
<td>Study effects of higher δ on ELMs &amp; ped. stability</td>
<td>Compare pedestal modes to simulations</td>
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<td><strong>RF Stabilization of Sawteeth and NTM’s</strong></td>
<td>Sawtooth suppression in AT regime with LHCD</td>
<td>Sawtooth period control with ICRF</td>
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<td><strong>Active MHD Spectroscopy</strong></td>
<td>Initial studies of global MHD &amp; Alfvén modes</td>
<td>Operate with 2nd antenna pair</td>
<td>Active feedback to avoid large amplitude instabilities</td>
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<td><strong>Disruptions</strong></td>
<td>Study disruption halo and eddy currents with new inner divertor diagnostics</td>
<td>Extend halo current scalings &amp; disruption characterization up to 2 MA</td>
<td>Use active MHD spectroscopy to avoid disruptions</td>
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Summary of MHD Stability research plans

• Disruptions
  — Halo currents, forces, strains, finite-element modeling (2 MA, 8 T)
  — Locked mode control
  — Mitigation (gas jet)
  — Avoidance (active MHD)

• MHD at high $\beta$
  — NTM’s (sawtooth stabilization, RF current drive feedback)
  — Resistive wall modes
  — Alfvén modes (active MHD)

• Edge pedestal
  — Extend shaping (triangularity); access to ELM regimes, QC mode, etc.
  — Computational modeling, simulations
Support for C-Mod Thrusts

MHD stability will become an increasingly important aspect of our AT and BP programs.

• AT-specific issues:
  — Low $\nu^*$, high $f_{BS}$, high $\nabla p$ at ITB $\Rightarrow$ NTM’s
  — $\beta_N \rightarrow$ no-wall limit, RWM’s

• BP-specific issues:
  — Disruption halo currents and forces
  — Edge pedestal (ELM’s, QC mode)