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

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Alcator C-Mod 5-year proposal review
13-14 May 2003
C-Mod’s Uniqueness in MHD Stability Research

High $n$, high $p$

Compact size

High field

Stability implications:
- Avoidance of high-$\beta$ core instabilities to date, but higher $\beta$ 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
# C-Mod’s role in MHD research

<table>
<thead>
<tr>
<th>Research area</th>
<th>Alcator C-Mod</th>
<th>Other tokamaks</th>
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<tbody>
<tr>
<td>Disruptions</td>
<td>Halo currents, asymmetries, scalings, structural strains, mitigation, avoidance</td>
<td>Lower $J \times B$ forces; Runaways (JET, JT60-U, DIII-D) Gas jet (DIII-D)</td>
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<tr>
<td>Pedestal stability</td>
<td>QC mode, small ELMs, peeling/ballooning, shaping, non-ideal MHD</td>
<td>Joint experiments to investigate similarities and differences</td>
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<td>High-$\beta$ instabilities (NTM’s, RWM’s)</td>
<td>No significant issues yet, but expected as $\beta$ is increased</td>
<td>Major emphasis on large tokamaks; Control coils (DIII-D)</td>
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<td>Locked modes</td>
<td>Non-axisymmetric control coils (A-coils)</td>
<td>Accepted scaling favors smaller tokamaks</td>
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<td>$J(r)$ control</td>
<td>Primarily LHCD; Reversed shear, ITB’s</td>
<td>RS, ITB’s on many tokamaks; Current holes (JET, JT60-U)</td>
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<tr>
<td>Active MHD spectroscopy</td>
<td>System designed for both Alfvén modes and global modes</td>
<td>Alfvén modes (JET)</td>
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## C-Mod MHD research and IPPA goals

<table>
<thead>
<tr>
<th>General Area</th>
<th>Specific Topic</th>
<th>C-Mod Contributions</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1.2 Macroscopic Stability</td>
<td>3.1.2.1 Stability Limits</td>
<td>Active MHD spectroscopy; Locked modes; no-wall $\beta$ limit</td>
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<td></td>
<td>3.1.2.2 Stability Control</td>
<td>A-coils; Active MHD of global modes</td>
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<td>3.1.4 Plasma Boundary</td>
<td>3.1.4.2 Edge and core coupling</td>
<td>Edge pedestal stability, ELMs; shaping; non-ideal MHD</td>
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<tr>
<td>3.3.2 High $\beta$ and Disruptions/</td>
<td>3.3.2.1 RWM control</td>
<td>Assess need and feasibility</td>
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<td>mitigation</td>
<td>3.3.2.2 NTM stabilization</td>
<td>LHCD, counter-FWCD, MCCD, ICCD (also: sawtooth control)</td>
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<td>3.3.2.4 Disruptions/ mitigation</td>
<td>Halo scaling, vessel forces, neutral point, gas jet, A-coils</td>
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MHD research highlights during previous 5-year period

MHD research on Alcator C-Mod has concentrated on:

- Disruption studies (halo currents, asymmetries & scalings; vessel wall flexing, neutral point behavior, killer pellets)
- H-mode edge pedestal stability and ELM behavior (peeling/ballooning, intermediate-$n$)
- Classical tearing modes (rotation velocity, wall torque)
- Alfvén eigenmodes
Recent disruption research

- Confirmed existence of neutral point behavior in C-Mod (Y. Nakamura, JAERI)
  \[ Z_{\text{neut pt}} = +2.7 \text{ cm} \]

- Laser ranging measurements of vessel wall flexing incorporated into design constraints of new inner wall girdle
MHD stability analysis of edge with grassy ELM’s

ELITE code used to analyze intermediate-\(n\) stability for high \(\nabla p\) discharge (P. Snyder, GA)

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

During the next 5 years, Alcator C-Mod’s capabilities will be significantly advanced:

MHD-specific:

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

General:

- 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 Stability
5-year research program

Continuing research topics:

• Disruption studies
• H-mode edge pedestal stability and ELM behavior

New MHD research topics enabled by enhanced C-Mod capabilities:

• Locked modes (characterization; machine scaling of $\tilde{B}_{mn}$ ; control)
• Active MHD determination of Alfvén and global mode resonances and stability
• NTM’s (provide C-Mod benchmark for scalings), core $\beta$-limiting modes
• RF stabilization of sawteeth/NTM’s
• Wall and feedback stabilization of RWM’s at high $\beta_N$
Non-axisymmetric control coils (A-coils) for locked mode studies

- Locked modes recently implicated in high current disruptions on C-Mod
- Prototype coils have been installed to begin locked mode studies (with pre-programmed waveform) — 8 coils arranged in 4 toroidal × 2 vertical locations
$m$-mode spectrum of non-axisymmetric control coils

- Predominantly $m = \pm 1$ and $\pm 2$; ratio adjustable
- Helicity adjustable
Non-axisymmetric control coils (A-coils) for locked mode studies

Very preliminary result (from initial run last week):

• The quadrupole configuration (red on previous page) has a reproducible effect on locked modes:
  — Negative polarity generates a locked mode in 1 MA discharge
  — Positive polarity suppresses a natural locked mode (lower density)
  — Other coil configurations had no effect
• Implications on $\tilde{B}_{mn}$ and machine scaling are being investigated
Active MHD spectroscopy

- Apply $\tilde{B}$ from ‘antenna’ coils to drive low amplitude, \textit{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
- $\gamma^{-1} \approx -80 \, \mu s$
New disruption instrumentation

Halo Rogowskis (10)

Tiles

Retro-reflectors (6)

Eddy Rogowskis (10)
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
VDE evolution

- Much of scrape-off layer misses new inboard divertor
- Important implications for divertor design in ITER/reactor
Relevance to reactor design (ITER)

Halo currents in this high-stress region could be reduced by pulling the blanket module further away from the plasma.
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

Sawtoothing 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 pressure profiles in BP support program
- Eliminate principal source of ‘seed’ island trigger of NTM’s, and provide C-Mod benchmark of NTM physics

  LHCD, MCCD, 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
RF control of sawteeth and NTM’s

Direct control of NTM’s

• Current drive stabilization using MCCD, LHCD, ICCD (strong coupling with RF physics program)
  — Amount of current required?
  — Radial localization required?
  — dc or phased?

• Provide C-Mod benchmark of NTM physics
  — Scaling of seed island size
  — Polarization current stabilization
Wall and feedback stabilization

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

We will assess what it would take to provide a stabilizing shell

- 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?

Based on these assessments, we will decide how to proceed.
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<th>Locked Mode Control</th>
<th>2003</th>
<th>2004</th>
<th>2005</th>
<th>2006</th>
<th>2007</th>
<th>2008</th>
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<tr>
<td></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></td>
<td>Incorporate measured J(r) into equilibrium and stability calculations</td>
<td>Stabilization by profile modification</td>
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<td>Wall and Feedback Stabilization</td>
<td>2003</td>
<td>2004</td>
<td>2005</td>
<td>2006</td>
<td>2007</td>
<td>2008</td>
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<tr>
<td></td>
<td>Investigate MHD stability near no-wall $\beta$ limit, Study RWM’s</td>
<td>Design stabilizing wall/feedback</td>
<td>Build/install stabilizing wall</td>
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<td></td>
<td>Study effects of higher $\delta$ on ELMs &amp; ped. stability</td>
<td>Compare pedestal modes to simulations</td>
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<tr>
<td>RF Stabilization of Sawteeth and NTM’s</td>
<td>2003</td>
<td>2004</td>
<td>2005</td>
<td>2006</td>
<td>2007</td>
<td>2008</td>
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<td></td>
<td>Sawtooth suppression in AT regime with LHCD</td>
<td>Sawtooth period control with ICRF</td>
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<td>Active MHD Spectroscopy</td>
<td>2003</td>
<td>2004</td>
<td>2005</td>
<td>2006</td>
<td>2007</td>
<td>2008</td>
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<td></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>Disruptions</td>
<td>2003</td>
<td>2004</td>
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<td>2006</td>
<td>2007</td>
<td>2008</td>
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<td></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)
  — Mitigation (gas jet)
  — Avoidance (active MHD)

• Control of MHD
  — Locked modes (A-coils)
  — NTM’s (sawtooth stabilization, RF current drive feedback)
  — Current profile (LHCD)
  — Resistive wall modes (A-coils; conducting structures)
  — Alfvén modes (active MHD)

• Edge pedestal
  — Extend shaping (triangularity); access to ELM regimes, QC mode, etc.
  — Computational modeling, simulations