MHD Stability Research Program on Alcator C-Mod

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Alcator C-Mod PAC
23-25 Feb 2004
MHD Stability research program

New MHD research topics being addressed:

- Locked mode characterization & control (T. Hender, JET/R. LaHaye, DIII-D)
- Active determination of Alfvén and global mode resonances and stability (C. Boswell, JET)
- NTM’s, core β-limiting modes (D. Brennan; R. LaHaye, DIII-D)
  - All-digital plasma control system

Continuing research topics:

- H-mode edge pedestal stability and ELM behavior (P. Snyder, DIII-D /JET)
- Disruption mitigation with high-pressure noble gas jet (D. Whyte, T. Jernigan)

 ITER/ITPA high priority
 Collaboration and/or joint experiments involved
Locked mode and error field studies

A-coils on Alcator C-Mod igloo
Mapping out locked mode threshold at 0.6 MA and $5 \times 10^{19}$ m$^{-3}$

- Applied 2/1 magnitude and toroidal phase have been varied over a wide range
- Finite region of non-locked discharges is found to exist in this parameter space (approx. circular)
- Offset of region gives intrinsic field perturbation ($\sim 0.35$ mT at $\phi \sim 45^\circ$)
- Size of region gives magnitude of locking threshold (which should depend on $I_p$ and $n_e$)
Error field correction expands C-Mod operational space

- Applying 2/1 field with proper toroidal phase allows operation at lower densities without locked mode disruptions
- Should also allow operation at higher plasma currents
C-Mod data contradicts LaHaye’s initial size scaling

- $1/R^{1.8}$ scaling derived by LaHaye based on theoretical arguments and measured thresholds in Compass-C, DIII-D, and JET (small, med, large)
- Very pessimistic for ITER
- **BUT** C-Mod data apparently disproves the strong size scaling
C-Mod/JET/DIII-D dimensionless scaling experiments are planned

Experiments will have:
- Same harmonic spectrum
- Same $na^2$, $Ba^{5/4}$, $q_{95}$, …
- Same shape
- High density, so $B_{pen} \gg B_{intrinsic}$

So far, C-Mod’s scaling is most similar to JET’s:

$$B_{pen}/B_t \propto n^{\alpha_n} B_t^{\alpha_B} q_{95}^{\alpha_q} R^{\alpha_R}$$

where $\alpha_n \approx 1$, $\alpha_B \approx -1$, $\alpha_q \approx 0 \Rightarrow \alpha_R = 2\alpha_n + 1.25\alpha_B \approx 0.75$
Known sources of non-axisymmetric fields in C-Mod

Asymmetric vessel structures

TF Bus Connection
TF bus/feed and OH1 winding are the dominant identified sources. Asymmetric structures and PF feeds are calculated negligible.

OH winding turn transitions
Additional error fields from PF coil tilts/shifts deduced experimentally

- Individual PF coils activated; $n=1 \ B_p$ fields measured; known asymmetries subtracted out (TF bus, OH winding)
- Tilts and shifts determined by least squares fit, weighted by guesstimates of reasonable engineering tolerances
- $\chi^2 \sim 1$; verifies consistency of model and engineering tolerances
- Implies that error fields evolve during discharge
Active MHD studies of Alfvén and global modes
Active TAE Resonances in Diverted Plasmas

- ITER relevant moderately high n ~ 20 antennas excite stable TAE’s
- Three TAE resonances as \( f_{TAE} \) crosses the active frequency in a diverted plasma with outer gap < 2.5 mm have \(|\gamma/\omega| \sim 1\%\)
ICRF fast particle driven Alfvén Cascades in the current rise indicate a flat or reversed shear q profile.

MISHKA modeling through a JET collaboration indicates a very flat shear q profile with $q_{\text{min}} = 3$ at the start of the Alfvén Cascade.
Active Low Frequency Sweeping at High $\beta$

- Active sweeping of a single antenna from 5 – 30 kHz at $\beta_N = 1.2$ in the presence of unstable n=3 modes
- No clear stable mode resonances were as yet observed
- New 6 kW audio stereo amplifier will drive both antennas
Future Active MHD Upgrades

• Power supply just upgraded to ±125 V, 25 A DC supply capable of driving 4 antennas simultaneously

• Amplifier being upgraded to provide
  - 6 kW audio stereo amplifier to excite low frequency MHD modes
  - automatic capacitor switching for high frequencies to maintain good matching to the changing antenna impedance

• New digital control computer for C-Mod operation will provide real-time feedback control of the TAE frequency

• Future plans for an additional set of 2 to 4 Active MHD antennas 180° away toroidally to provide even/odd toroidal mode selection as well as high n ~ 10 mode selection
Nimrod analysis of $\beta$–limiting MHD: Are these NTM’s?
β–limiting MHD in C-Mod

• 2/1 mode
• Is this an NTM?
Nimrod non-linear stability calculations (D. Brennan, GA: “very preliminary”)

- 1/1 always present, since discharge is sawtooothing ($q(0) < 1$)
- 2/1 driven unstable by non-linear coupling with sawtooth 1/1, which is a characteristic of NTM’s.

n=1 component only shown

Before 2/1 mode appears

After 2/1 mode appears
NTM dimensionless scaling experiment with DIII-D (R. LaHaye)

- Confirm underlying physics ($\rho_*, \nu_*, \ldots$) for critical beta of onset of 2/1 NTM
  - DIII–D/JET have already made non-dimensionally similar discharges on both machines at $\beta_N \approx 3.8$, $q_{95} \approx 3.6$
    - Low $B_T$ (1.0 T) low $\bar{n}_{13}$ (2.6) corner of JET op. space ($a = 92$ cm)
    - High $B_T$ (1.9 T), high $\bar{n}_{13}$ (6.7) corner of DIII–D op. space ($a = 53$ cm to match JET)
  - C–Mod fits into small ($a = 22$ cm), very high $B_T$ (5.3 T), very high $\bar{n}_{13}$ (39)
    - But reaching $\beta_N = 3.8$ difficult?
    - Match lower $\beta_N \approx 1.7$ DIII–D ($B_T \approx 1.6$ T, $\bar{n}_{13} \approx 3.2$, $a \approx 62$ cm, $q_{95} \approx 3.2$)
      - $\beta_N \approx 1.7$, 5.3 T, 22 cm, $\bar{n}_{13} \approx 25$
Additional NTM-related research

RF control of sawteeth and NTM’s

• 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
New all-digital plasma control system
New all-digital control system will replace our venerable Hybrid

• We have been using a ‘hybrid’ analog/digital computer for plasma control since the start of C-Mod

• The Hybrid computer can only implement linear control algorithms; 16 plasma quantities are estimated from linear combinations of 96 inputs; 16 outputs are linear combinations of PID-weighted errors

• Analog signals (inputs, errors, outputs) are subject to baseline offsets and saturation problems

• Ancient hardware, including a micro-VAX and bitbus communications; 1 ms clocking
All-digital system is being brought online in three steps

1) The all-digital system’s input and processing modules are now operating in parallel with the Hybrid
   — Same linear control algorithms are implemented
   — Outputs are being tested by comparing to Hybrid
   — Characterization of correctness, failure rates, etc.

2) After proper operation is verified, the outputs of the all-digital system will be connected to power supplies, valves, etc.

3) When all-digital system is fully operational, begin utilizing its new capabilities:
   — Can add extra inputs (128 vs 96) and outputs (32 vs 16)
   — Develop more advanced, non-linear control algorithms, possibly real-time EFIT’s
Disruption mitigation with high-pressure noble gas jet
Disruption mitigation with high-pressure noble gas jet

High-pressure noble gas jets can mitigate 3 problems arising from disruptions, without contaminating subsequent discharges.

These issues are particularly severe for ITER:

1) Surface thermal loading: concentrated heat loss ablates/melts divertor material
   **Solution:** Deliver large quantities of impurity into core plasma to dissipate ~100% of plasma energy by relatively benign, isotropic radiation

2) Halo currents: large mechanical J×B forces on vessel/first wall components
   **Solution:** Rapid thermal quench, resulting in a plasma that remains centered in vessel during current quench, substantially reducing vessel halo currents

3) Runaway electrons: Relativistic MeV electrons from avalanche amplification during current quench in large-scale tokamaks
   **Solution:** Suppression by large density of bound electrons in neutral gas atoms in plasma volume.
   (Note: C-Mod does not have problems with disruption-generated runaways)
Why do high-pressure noble gas jet experiments on C-Mod?

Physics of gas jet penetration into plasma is not yet well diagnosed nor understood.

1) It is postulated that the gas jet penetrates the DIII-D plasma because \( P_{\text{jet}} \) (20-30 kPa) \( \gtrsim \) \( P_{\text{plasma}} \) (8 kPa vol. avg, 30 kPa on axis)

2) Plasma pressure in C-Mod is roughly 10\( \times \) higher, and therefore provides a test of the penetration physics

3) C-Mod also has a fast-framing (4 \( \mu \)s), multiple-image (300) CCD camera looking at the midplane plasma edge

4) C-Mod also has 10\( \times \) higher energy density, providing a challenging test of the ability to radiate high enough power.
High-pressure noble gas jet experiments on C-Mod

• A gas tube with fast valve will be installed on the side of the A/B split limiter in C-Mod, where the fast camera is focused.

• The periscope optics for the camera will be modified to allow imaging of most of the plasma cross-section, rather than just the edge.

• A variety of noble gases will be tested (He, Ne, Ar) into stable plasmas.

• Thermal and $I_p$ quench times, radiated energy, plasma motion, halo currents, and surface IR will be monitored.

• Tests on reproducible plasmas (such as purposeful VDE’s) may also be tried.
Disruption mitigation and avoidance

- **High-pressure gas jet**
  
  Study physics of jet penetration into C-Mod’s high-pressure core, as well as thermal quench

- **Locked modes**
  
  Use non-axisymmetric perturbation coilset to avoid locked modes

- **Disruption avoidance:**
  
  Use active MHD real-time measurements of growth rates to avoid approaching unstable regimes
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.
C-Mod MHD research program:

- Focused on key issues in support of C-Mod’s BP and AT programs
- Strong collaborations through ITPA (locked modes, disruption mitigation, NTM’s)
  - Leverages C-Mod’s unique region of parameter space to better determine scalings to ITER
- Good connections with theory and modelling