Macroscopic Stability Research Program on Alcator C-Mod

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Alcator C-Mod PAC
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An important advantage of C-Mod’s high magnetic field is that we achieve high $n$, $T$, and plasma pressure without having to push $\beta$ limits.

Therefore, our high performance operation does not exhibit high-$\beta$ instabilities (NTMs, RWMs, etc.), and we do not carry on research in these areas.

However, there are several high-priority ITER-relevant MHD phenomena that C-Mod research does concentrate on.
Principal areas of MHD research on C-Mod

• Disruptions and disruption mitigation

• TAE’s, RSAE’s, fast particle instabilities, sawtooth stabilization (all closely tied to ICRF, since that is our primary generator of fast particles)

• **New ITER experiment**: test of proposed signal grounding scheme (common bonding network) [in Jim Irby’s presentation]

• Characterize and improve axisymmetric stability of ITER-like equilibria

• Effects of non-axisymmetric fields (mode locking, rotation damping)
C-Mod research on disruptions and disruption mitigation

Gas jet mitigation:
- toroidal asymmetry
- timing of thermal quench (TQ) after gas jet injection
- thermal footprint studies on divertor

Runaway electrons:
- characterization
- control & mitigation

ITPA database

Real-time prediction and mitigation
Spatial asymmetries of gas jet-induced radiated power

- A factor of 2 in the toroidal variation of radiated power during a disruption risks melting the beryllium PFCs in ITER

- ITER needs data on how multiple gas jet locations affect toroidal asymmetry

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1M. Sugihara et al. Nucl. Fusion. 47 337 (2007)
Diagnostics for studying temporal and spatial distribution of radiated power during disruptions

- **AXUV diodes (150 kHz)** view on the midplane towards (AXA) and away (AXJ) from the gas jet

- **AXUV diodes** view gas jet horizontally at +12.5 cm above (WB2) and -12.5 cm (WB3) below midplane

- **SXR diodes (150 kHz)** view on a single poloidal plane away from the gas jet

- **$T_e$ (ECE)** and $n_e$ (TCI) measured away from gas jet

**AXUV diode time histories averaged over shaded regions**

directed gas jet 2-3 cm from plasma edge, below midplane
1.3 ms puff, 7 MPa ~ $10^{25}$ atoms/s
Total radiated energy can also be toroidally asymmetric, but shot-to-shot variation is large.

- AXUV diode brightness integrated over full disruption
- plot ratio of chords looking at and away from gas jet
- asymmetry is at the 2.0 level predicted to cause Be melt damage in ITER

No clear correlation with target plasma conditions

\[
p \sim 70 \text{ [bar]}
\]

- 15:85 Ar:He
- 15:85 Ar:D\textsubscript{2}
- 15:85 Kr:He

30 < p < 70 \text{ [bar]}

15:85 Ar:He

Length of pre-TQ [ms]

Energy Loss Ratio (AXA/AXJ)

Ratio Range for DL/LM Disruption
Mirnov coils were used to examine MHD mode growth during the pre-thermal quench.

- There is a strong correlation between the growth time of the \( n=1 \) mode and the radiation asymmetry in gas jet mitigated disruptions.

- When this fitting is done at every time step, a coherent \( n=1 \) mode is always present. The \( n=2 \) modes are usually incoherent.

\[
RA \approx 0.47 \ln(\tau) + 0.06
\]
Upgrades and plans for gas jet disruption mitigation studies

• More detailed investigation of toroidal asymmetry, variability, and control of $P_{\text{rad}}$ in thermal quench
  - Install 2$^{\text{nd}}$ gas jet (~180° apart)
  - Install 4 – 5 additional AXUV (bolometer) arrays at different toroidal locations
  - Measure $P_{\text{rad}}$ at gas jet/plasma interface

• Thermal ‘footprint’ studies using the previously upgraded IR imaging of outboard divertor in mitigated and unmitigated disruptions

• Design halo/eddy current instrumentation for the new outer divertor

• Refurbish the currently installed halo current diagnostics
Disruption runaway electron studies

• At last year’s PAC meeting, we reported that initial experiments on LH-generated runaway electrons (RE’s) in normal C-Mod equilibria found a lack of RE’s in the disruption current quench.

• A survey of RE observations from a number of tokamaks led to the hypothesis that disruption RE’s are much more prevalent in low-elongation limiter devices compared to elongated diverted ones.

• An experiment to explicitly test this hypothesis was performed in C-Mod.
Normal-elongation, diverted vs Low-elongation, limited

$$\kappa = 1.65$$

$$\kappa = 1.03$$
Normal-elongation, diverted vs Low-elongation, limited

κ = 1.65, diverted

κ = 1.03, limited

RE dump at end of CQ
Normal-elongation, diverted vs Low-elongation, limited

\( \kappa = 1.65, \text{ diverted} \)  \hspace{1cm}  \kappa = 1.03, \text{ limited} 

\[ 1.03 \text{, limited} \]

Photo-neutrons
Normal-elongation, diverted vs Low-elongation, limited

Relativistic electrons (> 10 MeV) hitting Mo wall → γ’s → photo-neutrons

\[ \kappa = 1.03, \text{ limited} \]

Montalbetti et al. Phys. Rev. 91 (1953)

Photo-neutrons

Molybdenum

Graph showing the relationship between electron energy (MeV) and photo-neutron rate.
Acceleration of runaways to relativistic energies during current quench

• Photo-neutrons are observed at CQ dump, which requires relativistic electrons (> 10 Mev).

• Hard x-ray spectra observed at CQ dump have a much higher energy distribution than during LH (~100 keV) or during TQ.

• Conclude that LH seed electrons are being accelerated to relativistic energies during the CQ

Disruption loop voltage is of order 100 volts
During ~ 1 ms CQ, electron makes ~10^5 toroidal revolutions
RE energy gain ~ 10^5 × 10^2 ~ 10 MeV
Avalanche growth during current quench

- Little or no signals seen between TQ and the CQ dump
  - Conclude that RE’s are well-confined during the CQ (healed flux surfaces?)
- RE seed that survives TQ is small, and expected avalanching at $I_p = 0.6$ MA is too low to see macroscopic effects on $I_p$ or video camera

RE avalanche growth factor scales like\[^1\]:

$$\frac{I_{RE}}{I_{seed}} \sim \exp [2.5 \times I_p (MA)] \sim 4$$

\[^1\] Rosenbluth & Putvinski, Nuclear Fusion 37 (1997)
NIMROD modeling shows differences between high and low $\kappa$

At low $\kappa$, $n=1$ is not as dominant, and destruction of flux surfaces is not as extensive.
Near-term research plans on disruption runaways

Do we have a clear enough, quantifiable measure of RE’s in the C-Mod CQ that could be used to carry out quantitative RE mitigation studies?

Can we significantly increase RE population in CQ?

- Higher $I_p \ (\geq 1.0 \ \text{MA}) \Rightarrow$ more avalanche growth
- Increase $P_{\text{LH}} \ (\geq 1.0 \ \text{MW}) \Rightarrow$ larger suprathermal seed
- Increase current drive efficiency ($\text{lower } n_e$) $\Rightarrow$ larger seed

Separate co-dependence of elongation from diverted/limited configuration

Extend duration of CQ by optimizing radial position control (very difficult on C-Mod)
AE’s and fast particle instabilities

One of the primary reasons that Alfvén modes are of concern to ITER and future reactors is their potential to degrade heating efficiencies due to substantial fast particle losses (fusion $\alpha$’s, NBI, ICRF minority)

By modulating the amplitude of ICRF power at AE-relevant frequencies, the AE drive on C-Mod can be greatly increased compared to the active MHD antenna. The amplitude modulation frequency can be swept during a single discharge (D & E antennas)

ICRF antenna phasing (J antenna) can also affect AE’s

- Look for direct effects of the AE’s:
  - Fast particle transport & losses (CNPA, fast ion loss diagnostic, fast ion CX)
  - Degradation of ICRF heating efficiency (sawtooth reheat rate, neutron rate)
RF amplitude modulation technique

Possible coupling to Alfvén modes by ICRF modulation drive
Coherent MHD Activity is Observed During J-antenna Operation with +90 Phasing

- Magnetics detect coherent fluctuations at 250+ kHz and 700+ kHz
- Initially seems consistent with sawtooth-induced RSAEs
Observed Effects of RF Antenna Phasing on Instabilities and Transport

- Single discharge features -90 and +90 J-ant. phasing at different times
- +90 phasing period displays unique behavior compared to -90 phasing
  - lower neutron rate
  - appearance of coherent modes
  - outwardly peaked fast ion profile
- Fast ion stabilization of sawteeth
Scintillator detectors measure ICRH tail ion losses and resolve high frequency MHD activity

- Fast response scintillator features 2 MHz bandwidth
- Orbit modeling indicates LH-limiter as the ideal mounting position (counter-current facing)
Fast ion measurement via CXRS

- Studies of fast ion generation by RF wave deposition
- Observe diffusion of fast ion populations by Alfvén eigenmodes

Proof of principle:
Fully ID and simulate spectrum
Near-term MHD research schedule

2011-12  **Disruptions & mitigation**: install 2nd gas jet; effect on $P_{\text{rad}}$ asymmetry; RE characterization, control, mitigation; NIMROD modeling; real-time prediction; refurbish existing halo current instrumentation

Alfvén modes: characterize direct effects on fast particle loss & heating degradation; install fast ion diagnostics (confined & lost); benchmark AE mode structure & damping w/NOVA-K

**ITER CBN grounding experiments**: install & interface ITER hardware; confirm grounding scheme using actual magnetics signals

2012-  **Disruptions & mitigation**: $P_{\text{rad}}$ asymmetry studies; RE position control & deceleration; NIMROD modeling; real-time prediction; $D_2$ opacity studies; design and install disruption instrumentation on new divertor upgrade

Alfvén modes: fast particle loss & heating degradation; NOVA-K & other code modeling

**Non-axisymmetric fields**: upgrade A-coil power supplies; RMP ELM experiments; rotation physics

**NTMs**: explore LHCD profile effects & error field effects on NTMs (if present)
extra slides
Total RE loss fraction decreases as machine size increases.

100% RE loss
C-Mod (0.2 ms)

32% RE loss
DIII-D (0.77 ms)

0% RE loss
ITER (1.3 ms)