Macroscopic Stability Research
Program on Alcator C-Mod

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Alcator C-Mod PAC
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Principal areas of MHD research on C-Mod

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

However, there a number of 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

• Alfvén modes and fast particle instabilities

• Effects of non-axisymmetric fields (mode locking, rotation damping)

• Characterize and improve axisymmetric stability of ITER-like equilibria
C-Mod research on disruptions and disruption mitigation

Gas jet mitigation:
- timing of thermal quench (TQ) after gas jet injection
- toroidal asymmetry
- optimization of species mix

Runaway electrons
- characterization
- mitigation

ITPA database

Real-time prediction and mitigation

D$_2$ opacity for reactor first-wall survival
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\(^1\)

• ITER needs to decide how many gas jet locations are required

\(^1\)M. 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
Typical gas jet mitigated disruption

- radiating shell expanding at neutral sound speed @ gas jet, some faster transport of gas jet ions\(^1\)
- thermal quench triggered resulting in fast thermal energy loss, intense burst of radiation
- Plasma current decays on slower time scale, with less radiation

\(^1\)M. L. Reinke et al. Nucl. Fusion. 48 125004 (2008)
Large toroidal asymmetry observed in some disruption thermal quenches, but not on others

pre-TQ emission from plasma/gas jet interface

Viewing towards gas-jet
Viewing away from gas-jet
Symmetric during current quench
Observe shot-to-shot asymmetry variation in otherwise very repeatable mitigated disruptions
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.
Plans for future work on
gas jet disruption mitigation

• Understand cause of toroidal asymmetry and variability of $P_{rad}$
in thermal quench
  ─ Measure $P_{rad}$ at gas jet/plasma interface

• Install a 2nd gas jet on opposite side of torus and explore
disruption mitigation using multiple jets

• Continue size scaling studies of timing between gas jet
  injection and thermal quench (C-Mod, JET, JT60-U, DIII-D,
  ASDEX-U)
  ─ comparison of multi-machine dataset to NIMROD
  predictions in hopes of a physics-based prediction
Disruption Runaway Electrons

• Quenching avalanching by density buildup alone requires gas loads of order $10^5 \text{ Pa-m}^3$ (Rosenbluth criterion) in ITER.

  This has serious implications for the cryopump systems and the tritium handling plant, particularly with mixed noble gases.

• Present experiments suggest that other mechanisms may suppress avalanching by enhancing RE transport losses

  Suggests that huge gas loads may not be required.

• Confinement/loss of runaways can be studied in C-Mod
  - Use LHCD to generate a seed population prior to a disruption
  - Spatially-resolved HXR and synchrotron imaging diagnostics can study runaway transport in conjunction with different quenching mechanisms (for example: non-axisymmetric fields)

• ITPA MDC-16
LH-driven runaways on Alcator C-Mod

Relativistic runaways on C-Mod have been observed with LHCD during flattop.

Forward cone of emission is a signature of relativistic electrons.

This emission is also observed on the visible bremsstrahlung array.

Deleterious effects of runaway dumps in C-Mod have also been observed.
Study runaway physics of avalanching, losses, and position control in current quench

• Numerous ‘knobs’ can be varied:
  ➢ Applied non-axisymmetric fields (i.e. $\delta B$), including amplitude, $m$ and $n$, and resonant vs non-resonant
  ➢ LHCD parameters, such as power (varies the initial amount of seed electrons), and phasing (varies the spatial profile of seed electrons)
  ➢ Gas jet parameters, particularly total injected atoms, and gas atomic number (total injected electrons)
  ➢ Study position control; steering wall deposition of runaway energy
  ➢ OH inversion to extract RE energy?

• Proposed RE experimental program on C-Mod assumes that LH-driven runaways survive into the current quench
Runaways in C-Mod are lost at thermal quench

no LHCD

with LHCD

no avalanche growth
Some tokamaks tend to observe REs during some current quenches:

FTU, Tore-Supra, TEXTOR, TFTR, HT-7 all run circular, limited plasmas

JET ran only limited plasmas for a number of years before the installation of its first divertor. Disruption runaways were much more prevalent back then, compared to now.

JT-60U is diverted, with low elongation

Some tokamaks don’t see REs during the current quench (except perhaps during killer pellet experiments):

DIII-D, ASDEX-U, and C-Mod run diverted, elongated plasmas (vertically unstable)

This suggests that elongation and/or vertical stability might have something to do with observations of runaways during the CQ.
Why don’t we see REs and avalanching during C-Mod disruption current quench?

• We know from NIMROD/KPRAD simulations of C-Mod gas jet disruptions that large regions of stochastic field lines are formed, and this plays an important role in the effect of the gas injection on the plasma core.

• Could the stochastic regions also play an important role in the loss of REs?

This hypothesis can be tested both experimentally and theoretically:

Val Izzo is working on NIMROD/KPRAD modeling of low-elongation C-Mod gas jet disruptions.

Gas jet disruption experiments with LHCD on low-elongation equilibria are planned on C-Mod (on hold until LH is reinstalled).

Last month DIII-D ran low-elongation disruptions and found that REs did indeed survive into the current quench.
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.
Additional research plans on disruptions and mitigation

- Continue development of real-time disruption prediction and mitigation activation for additional types of disruptions, possibly using advanced controllers and/or Kalman filter techniques
- Continue collaboration with modelers on NIMROD/KPRAD simulations of gas jet disruption mitigation
- Continue participation in ITPA disruption database activities
- Achieve D$_2$ opacity conditions and study radiation rates and spatial uniformity (DEMO relevant, survival of first wall)
Alfvén eigenmodes and energetic particle studies: resources

• Active MHD system:
  – Active MHD antennas can measure the damping of ITER relevant moderate toroidal mode number ($n \sim 10$) Alfvén eigenmodes.
  – Two antennas excite stable Alfvén eigenmodes $|n| \leq 20$ FWHM.
• Diagnostics
  – Mirnov coils in toroidal and poloidal arrays
  – Phase contrast imaging diagnostic (PCI) to measure core density fluctuations.
  – Upgraded CNPA to measure distribution function of confined energetic ions.
  – Hard X-ray camera for measuring electron spatial and energy distribution.
• Sources of energetic particles:
  – Flexible ICRF system that produces primarily trapped fast ions.
  – LHRF system produces energetic electrons.
• Codes:
  – NOVA-K comparisons of AE damping, drive, ICRF distribution
  – TRANSP/TORIC models of ICRF wave solver and fast ions
  – AORSA/CQL3D ICRF fast particle distribution + orbit effects
Research to date on AEs and fast particle instabilities

• Characterize dependence of intermediate-\(n\) AE damping rate on plasma parameters and ICRF tail parameters

• Benchmarking of codes (NOVA-K, AORSA/CQL3D) against experiment

• Combine measurements and modeling of reversed shear AEs (Alfvén cascades) to provide information on \(q\)-profile evolution during sawteeth, and \(q\)-profile modification by LHCD
Research plans on AEs 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).

Experimental verification of this degradation due to AEs is lacking, perhaps because driven Alfvén modes to date have been relatively low amplitude. (C-Mod’s active MHD antennas produce $\delta B/B_T \sim 3 \times 10^{-7}$.)

We propose at least two schemes to increase the AE drive by using our high-power ICRF systems instead of active MHD system:

- Use beat wave generated by difference between D and E transmitters (nominally operated at 80.0 and 80.5 MHz)$^1$
- Modulate amplitude of ICRF power at AE-relevant frequencies

$^1$A. Fasoli et al, Nucl. Fus. 36 (1996) 258
Initial attempt at sweeping ICRF modulation in relevant AE frequency range

magnetics Fluctuations for Shot 1100122028

Channel = BP01_GHK
Research plans on AEs and fast particle instabilities, cont.

Once the ICRF drive technique is developed, two main goals will be pursued:

- Measure radial mode structure (PCI), mode \((m,n)\) spectra (magnetics), damping rate for the driven modes and benchmark against NOVA-K

- Look for direct effects of the AEs:
  - Fast particle losses (CNPA, future fast ion loss diagnostic)
  - Degradation of ICRF heating efficiency (sawtooth reheat rate, neutron rate)
Summary of MHD research schedule

2010-11  **Disruptions & mitigation**: scaling of quench timing; $P_{\text{rad}}$ asymmetry variation; REs w/LH vs elongation; NIMROD modeling; ITPA database

   **Alfvén modes**: develop ICRF drive; characterize AE mode structure & damping

2011-12  **Disruptions & mitigation**: install 2nd gas jet; effect on $P_{\text{rad}}$ asymmetry; RE characterization & error field effects; NIMROD modeling; real-time prediction

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

   **Non-axisymmetric fields**: upgrade A-coil power supplies

2012-    **Disruptions & mitigation**: D$_2$ opacity studies; RE position control & deceleration; NIMROD modeling; real-time prediction

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

   **Non-axisymmetric fields**: Retry RMP ELM experiments; rotation physics

   **NTMs**: explore LHCD profile effects & error field effects on NTMs (if present)