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

- Disruptions and disruption mitigation, including runaway electrons
- Characterize and improve axisymmetric stability of ITER-like equilibria
- TAEs and fast particle instabilities
- Effects of non-axisymmetric fields
- Neoclassical tearing modes (NTMs)
Using LHCD to create runaway seed for disruption studies

\[ I_{LH} \approx 0.10 - 0.15 \text{ MA} \]
Study runaway physics of avalanching and losses 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)
  - Knobs for steering wall deposition of runaway energy?
Runaways in C-Mod are lost at thermal quench

no LHCD

with LHCD

no avalanche growth
What about other tokamaks?

Some tokamaks tend to observe RE’s during some current quenches:

- FTU, Tore-Supra, TEXTOR 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 RE’s 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 generation of runaways during a disruption.
Why don’t we see RE’s 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 RE’s?

This hypothesis can be tested:

Val Izzo has just started working on NIMROD/KPRAD modeling of a low-elongation C-Mod shot.

Gas jet disruption experiments with LHCD on low-elongation equilibria are planned on C-Mod.
Preliminary 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.
Used AXUV diodes to measure emission at equivalent toroidal and poloidal locations

- Prior to TQ (pre-TQ), power loss local to gas/plasma interface
- During disruption (TQ and CQ) radiated power loss much higher, but more symmetric

**Future plans**
- Increase diagnostic set
  - fast visible spectroscopy, Ly-a emissivity, more AXUV coverage.
- Statistics of toroidal symmetry
  - variation, average over a large #?
- What controls the duration of the pre-TQ
  - $W_{th}$, $p_{gas}$, depth of q=2 surface?

M.L. Reinke et al. Nucl. Fusion. 48 1-7
Research on disruptions and mitigation

- Study runaway electron physics during disruptions and mitigation using unique C-Mod tools (LHCD, hard x-ray and synchrotron diagnostics, error-field coils)

- Study toroidal variation of radiated power with gas jet 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 D2 opacity conditions and study radiation rates and spatial uniformity
Maximum controllable displacement $\Delta z_{\text{max}}$ [1]:

- The loop is open at $t_0$;
- The plasma drifts vertically;
- A saturated command of the proper sign is sent to the vertical stabilization power supply (chopper) at $t_0+\Delta t$;
- The plasma either turns around or does not: the maximum controllable displacement is the maximum displacement for which the plasma motion is reversed;
- Non-linear stability metric, quantifies if the vertical stabilization power supplies are dimensioned to handle sudden vertical displacements from minor disruptions, ELMs, etc.

Experimental Measurement of $\Delta z_{\text{max}}$ (k=1.72)
$\Delta z_{\text{max}}$: Experimental results and simulations

Results from ITPA joint experiments have shown that $\Delta z_{\text{max}}/a > 5\%$ is required for minimally robust control.

ITER's VS system needed to be upgraded.
"Multi purpose" in vessel coils:
- ELM control
- Vertical Stability control
- Resistive Wall Mode (RWM) control
Research on axisymmetric stability of ITER-like equilibria

- Develop advanced controllers for stability at higher elongation
- Characterize effects of noise on feedback and develop noise rejection/suppression algorithms
- Develop ‘safe scenarios’ and adaptive algorithms in case of power supply saturation/failure
TAE stability increases with moderate RF in some shots

- The decrease in TAE damping rate when RF is applied reflects excitation by RF generated fast particles.
- Interestingly, in some cases the effect of the fast particles is to increase the TAE damping rate.
In qualitative agreement with NOVA-K modeling, i.e. fast particles with energies below the TAE-particle resonance contribute to *stabilizing* the TAE.
RSAEs excited during sawteeth give $q_{\text{min}}$ to $\sim 1\%$

- RSAEs excited in both L-mode and H-mode with ICRH
- Up-chirping RSAEs
  - imply $q < 1$
  - reversed shear $q$ profile
- Down-chirping RSAEs
  - imply $q > 1$
  - local maximum in $q$
- RSAEs used for “MHD Spectroscopy”

\[ f_{RSAE} \sim \frac{1}{q_{\text{min}}} \]

“Phase contrast imaging measurements of reversed shear Alfvén eigenmodes during sawteeth in Alcator C-Mod”

NOVA results are compared to experiment with a synthetic PCI analysis

Radial Displacement Eigenfunction

2D density perturbation

Best fit solution
Research on TAEs and fast particle instabilities

- Characterize dependence of intermediate-n TAE damping rate on plasma parameters and ICRF
- Benchmarking codes (NOVA-K, AORSA/CQL3D) against experiment
- Study TAE-induced fast ion loss (ICRF-generated ions)
- Combine measurements and modeling of reversed shear AEs (Alfven cascades) to provide information on q-profile modification by LHCD
- Diagnostic upgrades (re-position antennas; CNPA array, fast ion loss diagnostic, fast ion H diagnostic, 2nd PCI)
Fast Ion Charge Exchange (FICX)

- FICX (UT-FRC) provides fast ions spatial profile info.
- A typical set of view chords intersect with the neutral beam to collect emission from the fast neutrals that are formed by the interaction of fast ions with the neutral beam.
- A state-of-the-art high-throughput imaging spectrometer provides spectral analysis of the emission which is detected and digitized with a fast, high-sensitivity camera.
- Validate the physical models for RF deposition via minority ions.
- Investigate Alfvén eigenmodes via the diffusive effect of these plasma waves on the fast ion population.
- For analysis of CNPA, FICX (UT-FRC) contributes spatial profile of the fast ions.
RMP ELM control experiment: Null result

Same current

Same density

Same ELMs!

Same RF power

A-coils on

A-coils off
Used ‘JFT-2M’ shape to get ELMs in C-Mod

$q_{95}=3.7-3.9, \nu^*=0.5-0.6$

A-coils in standard $n=1$ configuration (usually for controlling locked modes) at maximum current

No effect on pedestal profiles nor plasma rotation observed either

At lower $q_{95}$ and lower $\nu^*$ there was a hint of an effect on ELMs

Chirikov parameter, $\sigma_{CH} \sim 1.0$ at $q_{95}=3.0$, i.e. just marginal

Proposed upgrade to A-coilset and power supplies would improve chances of affecting ELMs
Research on effects of non-axisymmetric fields

- Re-measure intrinsic error fields after current reassembly (near term)
- Magnetic braking of rotation; tests of NTV theory (JET identity experiments gave null result)
- Explore resonant magnetic perturbations for affecting/controlling edge pedestals and ELMs
- Upgrade A-coil power supplies and coilset
Numerous personnel changes

**Staff:**

Joe Snipes joined ITER team in Cadarache (TAE/FP, mode analyses)

**Grad students:**

Marco Ferrara recently graduated (advanced controllers, vertical stability, Kalman filters, etc.)

Jason Sears is graduating soon (active MHD, RF/FP/TAE interaction)

Eric Edlund is graduating soon (RSAEs, Nova-K, $q$-profiles)

A new grad student will be working on TAE/fast particle research, supervised by Steve Wukitch
| Disruption mitigation, including runaway electrons | Study physics of runaway electron physics during disruptions and mitigation using unique C-Mod tools (LHCD, hard x-ray and synchrotron diagnostics, error-field coils) |
| Study toroidal variation of radiated power with gas jet 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 D₂ opacity conditions and study radiation rates and spatial uniformity |
| Characterize and improve axisymmetric stability of ITER-like equilibria | Develop advanced controllers for stability at higher elongation |
| Characterize effects of noise on feedback and develop noise rejection/suppression algorithms |
| Develop ‘safe scenarios’ and adaptive algorithms in case of power supply saturation/failure |
| TAEs and fast particle instabilities | Characterize dependence of intermediate-\( n \) TAE damping rate on plasma parameters and ICRF |
| Benchmarking codes (NOVA-K, AORSA/CQL3D) against experiment |
| Study TAE-induced fast ion loss (ICRF-generated ions) |
| Combine measurements and modeling of reversed shear AEs (Alfven cascades) to provide information on \( q \)-profile modification by LHCD |
| Diagnostic upgrades (re-position antennas; CNPA array, fast ion loss diagnostic, fast ion \( \mathrm{H}_\alpha \) diagnostic, 2\textsuperscript{nd} PCI) |
| Study effects of non-axisymmetric fields | Re-measure intrinsic error fields after current reassembly (near term) |
| Magnetic braking of rotation; tests of NTV theory (JET identity experiments gave null result) |
| Explore resonant magnetic perturbations for affecting/controlling edge pedestals and ELMs |
| Upgrade A-coil power supplies and coilset |
| Neoclassical tearing modes (NTMs) | LHCD stabilization of NTMs by modification of \( \Delta' \) |
| ICRF stabilization of NTMs by eliminating sawtooth seed islands |
Motivation for studying disruption REs

• Study physics of runaway electrons (RE)
  — Quenching avalanching by density buildup alone requires gas loads of order $10^5$ 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)
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
ITER needs to be confident of axisymmetric control when operating close to machine limits

- ITER’s post-EDA design is not as conservative, leading to considerable concern about the stability of high-$\ell_i$ plasmas.

- Desire smart adaptive control algorithms beyond those available today. Algorithm development and practical experience should be pursued on existing tokamaks in the next few years.

ITER also has stringent limits on measurement noise and fluctuations in the feedback loop.

- Current machines, such as C-Mod, can address the issue of noise and how to suppress/reject it.
Ongoing and future research related to axisymmetric control issues in ITER

• Continue work on vertical stability metrics
  — Stability margin, $m_s$ (linear, open-loop)
  — Gain and phase margin, $m_g$, $m_\omega$ (linear, closed-loop)

• Analysis of noise and pickups. Estimation of their effects on axisymmetric control (control precision, power supply and PF coil requirements, etc.).
  — Particularly important with controllers using high order derivatives
  — Sources; frequency spectra
  — Noise suppression through model-based (Kalman) filters
Ongoing and future research related to axisymmetric control issues in ITER

- Design and experimental validation of high order controllers to improve controllability of high-$\kappa$, high-$\ell_i$ plasmas.
  - Develop and investigate effectiveness of Kalman filtering for high-frequency noise rejection
- Design and experimental validation of "safe scenarios" and adaptive interpolation algorithms to be deployed in case of power supply saturation.
  - Adaptive pulse rescheduling (interpolate to a less demanding compatible target equilibrium)
Energetic Particle and TAE 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.
  – 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
Observations of RSAEs constrain the evolution of the $q$ profile during sawteeth

- Post-reconnection $q$ profile has a local maximum
- Pre-reconnection $q$ profile has reversed shear in the region $r/a < 0.2$
- Sawtooth cycle models require a self-consistent
  - relaxation process
  - reconnection process
MHD Induced Fast Ion Loss Diagnostic

- A magnetic spectrometer using the TF images lost fast ions onto a scintillator plate as a function of their energy (gyroradius) and pitch angle.

- The high time resolution (1 MHz) will allow measurements of the ICRF heated fast ions lost due to Alfvén eigenmodes to better quantify fast particle transport and compare with modeling.

\[ v_{tot} = v_\perp + v_{\parallel} \]
Higher $\beta_N$ and lower $\nu^*$ planned in our program over the next 5 years are expected to destabilize NTMs. NTM physics could then be studied at C-Mod conditions and parameters, including:

- Threshold $\beta_N$ scalings
- Critical seed island physics (by ramping $\beta_N$ down)
- Rotation effects on NTM threshold $\beta_N$

And in particular:

- Effect of non-axisymmetric fields on NTM threshold
- NTM stabilization by external current drive (LHCD for C-Mod)
A potential application of LHCD on ITER is for NTM stabilization

- LHCD efficiency is higher than ECCD
- Stabilization physics is different:
  - ECCD stabilization works mainly by driving current centered on the island (to replace missing bootstrap current)
  - LHCD stabilization works mainly through the $\Delta^\prime$ term, i.e. by modifying the current profile near the resonant surface
We have successfully demonstrated the use of LHCD to stabilize and destabilize classical tearing modes.

- The same Δʿ modification with LHCD should carry over directly to NTM stabilization.

**NTM stability studies using LHCD (cont.)**

Destabilization

\[ n_// = 2.3 \]

Stabilization

\[ n_// = 1.6 \]