Non-axisymmetric Field Effects on Alcator C-Mod

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on behalf of

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Error field induced locked modes can limit tokamak performance

- Resonant error fields of the order of $10^{-4}B_T$ can destabilize non-rotating tearing modes, leading to loss of confinement, disruptions.

- ITER may be susceptible, particularly the low-density ohmic target plasma, due to low rotation, uncertain size and field scaling.

- Experiments on C-Mod improve predictive capability, demonstrate mode suppression.
2/1 stationary mode typically observed

- Theory predicts sensitivity to resonant (2,1) field $\frac{B_{mn}}{B_T} \propto \omega_0 \tau_A \left(\frac{\tau_{rec}}{\tau_v}\right)^{1/2}$
- $m = 1, 3$ Sidebands contribute through toroidal coupling, viscous effects

Island growth seen on magnetics, $T_e$ Profile

Flattening observed on $T_e$ near $q=2$
C-Mod Non-axisymmetric coil set used to investigate locking physics, extend operation

- Mounted on concrete igloo above and below midplane horizontal ports
- Location chosen for accessibility for quick installation in 2003
  Affects mode spectrum and penetration time.
- Seven (of 8) coils installed for 2003, 2004 Campaigns
A-coil can be configured to vary mode spectrum

Helical mode structure defined in straight field line geometry

\[ B_{mn} = \frac{1}{2\pi^2} \int_0^{2\pi} d\phi \int_0^{2\pi} d\hat{\theta} B_\perp(\phi, \hat{\theta}) e^{-i(n\phi + m\hat{\theta})}, \]

\[ \hat{\theta} = \frac{1}{q} \oint dl \frac{B_\phi}{RB_p} \]

- Can obtain \( B_{21} \sim B_{11} \) but typically (1,1) component dominates
- Positive m resonant helicity
  - Either handedness configurable
- \( B_{31} \ll B_{21} \), higher modes negligible
- 2/1 complex phase (toroidal orientation) varies with configuration
- Sideband orientation basically aligned with 2/1
Locking boundary in complex $B_{21}$ plane identifies threshold and intrinsic error field

For constant plasma conditions, use different A-coil configurations to map stable vs unstable values of applied field

- A circle fit to the boundary of the unlocked (stable) region has radius equal to the effective threshold $|B_{\text{lock}}|$, and center opposite $B_{\text{intrinsic}}$

- For $B_T = 4.1$ T, $I_p = 0.6$ MA, $\bar{n}_e \approx 5 \times 10^{19} m^{-3}$ we find $B_{\text{lock}} \approx B_{\text{intrinsic}} \approx 0.35 mT$, $\phi_{\text{intrinsic}} \approx -135^\circ$
Locked mode suppression and generation by A-coil

- Ohmic 1MA 5.4T plasmas
- Intrinsic locked mode threshold (magenta) at $\bar{n}_e \approx 1.1 \times 10^{20} m^{-3}$
- A-coil allows stable operation (black) to $\bar{n}_e < 0.4 \times 10^{20}$
- Reduction in density implies good error field cancellation
- In opposite polarity (green) locking induced at $1.7 \times 10^{20}$

Identifies error field in third quadrant
Sources of Intrinsic Error Fields

Initial Experiments with the non-axisymmetric correction coils indicated the presence of 2/1 error fields in the range of a few $10^{-4}$T oriented to the third quadrant. A number of possible sources of this error field have been considered.

- **“Designed-in” non-axisymmetric current paths**
  Effects calculated for:
  - TF Bus
  - OH Solenoid Layer-to-Layer Transitions
  - EF (Ring Coil) Current feeds – local fields at sensors, negligible at plasma
  - OH bus system ($<10\%$ of winding effect)
  - The D- and E-port ICRF antennas short circuit ($\sim 1$cm thick Inconel) path across adjacent horizontal ports ($\lesssim 10^{-5}$ T)

- **Inadvertent Positioning or Manufacturing Errors in the PF System**
  - Infer from measurements
Calculations based on “As Built” Drawings indicate that the TF Bus and Layer-to-Layer radial transitions in the OH1 Solenoid each contribute 1 to $2 \times 10^{-4}$T of 2/1 field perturbation for typical currents.

- 2/1 perturbations all in the third quadrant
- TF bus perturbation strongly in resonant helicity
- OH1 sideband phase in first quadrant
Analysis of PF Coil Displacements (Tilts and Shifts)

- Individual PF coils energized on successive shots
- Toroidal asymmetries measured using *difference signals* of standard equilibrium diagnostics (BP loops)
- PF positioning errors modeled as rigid (n=1) shifts and tilts of each PF coil*
- Need to fit differential loop gains to better than original calibration uncertainty ±0.5%
- Discrepancies in placement or orientation of the sensor loops mimic PF coil position errors. *Differential* displacements and tilts of sensor pairs in the poloidal plane also fitted as part of the model.

The final analysis consists of a $663 \times 248$ linear least-square regression

Data: 13 pulses $\times$ 51 difference signals between toriodally spaced loops

Model: 11 PF Coils $\times$ 4 tilt and shift parameters ($\sin$ and $\cos$ components)
51 Gain/Calibration discrepancies
3 $\times$ 51 relative sensor displacement and tilt discrepancies ($R, Z, \theta$).
Solved by Truncated SVD, with 240 of 248 principal vectors being retained.
$\chi^2 = 347$ for 423 degrees of freedom.

- Results plausible with respect to assembly tolerances
- Inferred mis-position of OH1, EF3L, EF2L coils produce a few $\times 10^{-4}$T of $m = 1 - 3$ on a typical shot
Intrinsic error field based on source analysis is in the mTesla range

- Sideband orientations are not aligned with 2/1 mode (1/1 is nearly opposite)
- A-coil sidebands are aligned, so not possible to compensate full intrinsic spectrum
- Error field orientations are relatively constant over a wide range of operating conditions.
Suppression of Locked Modes Observed with Applied field counter to inferred Intrinsic Error

- Intrinsic error increases in time due to OH1 terms
- A-coil reduces net $|B_{21}|$ from 0.6 to $\sim 0.2\text{mT}$ (and reverses its polarity)
- Experiment consistent with model of source terms, locking threshold around 0.4 mT
Overcompensating the intrinsic error field induces transitory locked mode

- Mode locks shortly after maximum of $|B_{21}|$
- Increasing oppositely-directed intrinsic 2/1 field reduces net 2/1 below threshold
- Net 1/1 field is large and parallel to 2/1
Locking map determines density dependence of threshold perturbation

• Data at 5.4 T, 1 MA, \( q_{95} = 3.9 \) fit to \( B_{21} \approx C \bar{n}^{\alpha_n} \)
• Fit \( C, \alpha_n, \bar{B}_{\text{intr}} = (\bar{B}_{21} - \bar{B}_{\text{app}}) \)
• Exponent \( \alpha_n \approx 1 \) same as previous experiments
• \( C \approx 4.8 \times 10^{-24} \) somewhat smaller than would be extrapolated from JET, DIII-D

\[
\frac{B_{\text{lock}}}{B_T} \propto n^{\alpha_n} B^{\alpha_B} q^{\alpha_q} R^{2\alpha_n + 1.25\alpha_q}
\]

• Coordinated experiments (matching shape, sidebands,…) undertaken
C-Mod data spans the ITER field

- Locking threshold $B_{21}/B_T \sim 10^{-4}$ similar to larger (and smaller!) lower field experiments*

- C-Mod field scaling $(\alpha_B \approx -0.6 \pm 0.6)$ uncertain, may be weaker than JET/DIII-D, definitely not as strong as old Compass results

- Projection to ITER indicates proposed error field compensation system (correction to $2 \times 10^{-5}$) should be adequate

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R. J. Buttery, *et al.*, Nucl. Fusion **39** 1999

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* Solid: $nR/B = (0.2 \pm 0.3)$
Non-dimensional identity experiment carried out with JET, DIII-D*

- Match non-dimensional plasma parameters
  - $na^2$, $Ba^{5/4}$ constant
  - Ohmic heating constraint causes $Ta^{1/2}$ to also scale
  - Geometry matched (LSN), $q = 3.2$

- C-Mod parameters
  $B = 6.3T$, $I_p = 1.3MA$
  $1 < \bar{n}_e < 4 \times 10^{20}m^{-3}$

- Match poloidal mode spectrum of JET EFCC coil
- Helical mode spectrum in second and fourth quadrant
- Significant misalignment with (model) intrinsic error field
Comparison with JET/DIII-D tests
non-dimensional identity

Identity experiments† (same $\rho^*, \nu^*, q_\psi, \beta$) should have identical $B_{21}/B_T$, validating extrapolation in size to ITER by $\alpha_R = 2\alpha_n + 1.25\alpha_B$

- Total C-Mod $B_{21}$ including intrinsic field from source model consistent with bounds from raw data
- JET points (scaled to C-Mod units) agree within error bars
- DIII-D data disagree by factor $\sim 2$
  Reasons under investigation

†See Howell: CP1.020 (M pm); Also Scoville: NP1.008(Th am)
A-coils have significantly expanded C-Mod operating space

- Without error field correction, locked modes limit operation

![C-Mod Operating Space](image)

Locked - No Acoil
Unlocked - No Acoil

\[
\bar{n}_e \approx 0.04
\]

Enables extension of physics studies to higher \(\beta\) (high current, \(I_N\)), lower \(\nu^*\) (low density)
A-coils have significantly expanded C-Mod operating space

- Without error field correction, locked modes limit operation
- Use of A-coil to compensate intrinsic 2/1 field results in increase in current to 2MA
- Minimum locking-stable density at 1MA reduced from $\sim 1.2$ to $< 0.3 \times 10^{20}m^{-3}$ ($\frac{\bar{n}}{(I/\pi a^2)} \approx 0.04$)
- Enables extension of physics studies to higher $\beta$ (high current, $I_N$), lower $\nu^*$ (low density)
Suppression of locked modes allows increase in current to 2MA†

- A-coil programmed to compensate calculated intrinsic (2/1) error field
- No locked mode signatures through current flattop
- Locked mode appears in rampdown, after A-coil ramps down

†See Hutchinson JO3.002 W pm
Summary

- Comparison of C-Mod results with larger (and smaller) tokamaks indicates relatively weak scaling of effective error field sensitivity with size, field.

- Test of non-dimensional identity in threshold should permit more confident extrapolation to ITER.

- Evaluation of intrinsic error fields using *in situ* equilibrium magnetics diagnostics consistent with results of plasma experiments.

- Successful error field correction using simple external coilset substantially expands accessible operating space.