Tearing Under Stress — The Collusion of 3D Fields and Resistivity at Low Rotation

by
R.J. Buttery

with
A.H. Boozer, N.M. Ferraro, S. Gerhardt, R.J. La Haye,
Y.Q. Liu, J.-K. Park, H. Reimerdes, S. Sabbagh,
E.J. Strait, J.H. Yu, and the DIII-D and NSTX Teams

1 General Atomics, USA
2 Columbia University, USA
3 Princeton Plasma Physics Laboratory, USA
4 EURATOM/CCFE Fusion Association, UK
5 EPFL, Switzerland
6 UCSD, USA

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3D Fields Have Long Been Known to Pose a Limit to Low Density Ohmic Operation

- 3D “error” fields from asymmetries in tokamak construction
  - Fields resonate with rational surface to drive formation of magnetic island

DIII-D
R.J. Buttery/APS/November 2011
3D Fields Have Long Been Known to Pose a Limit to Low Density Ohmic Operation

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- 3D “error” fields from asymmetries in tokamak construction
  - Fields resonate with rational surface to drive formation of magnetic island
  - Fields must brake plasma rotation first to stop natural screening currents
    - Lower density plasmas more readily stopped
  - Basis for error field correction system in ITER
    - H mode plasmas expected to be fine
  - High density

[Scoville, PoP 1992]
3D Fields in H Mode Found to Trigger Rotating Modes

- Less 3D field needed to induce modes than that required in Ohmic plasmas

- How does a static 3D field cause a rotating mode to appear?
  - Changes to natural mode stability

- Why is H mode so sensitive?
  - Answer lies in the plasma response

Need to understand how fields interact & what governs mode formation

[Buttery & Liu, NF 2011]
Contents

• The plasma response to 3D fields
  – Ideal and Resistive MHD

• Interaction of 3D field with tearing stability
  – Braking action of 3D fields is key

• Reducing the 3D “error” fields in ITER
  – Need for more than one mode of correction

• Conclusion
  – 3D fields a key concern for H modes
The Plasma Response to 3D Fields
The Starting Point to Understand 3D Field Interactions is Through Ideal MHD

- Plasma displacement transforms internal field
  - Plasma is an electromagnetically interconnected structure
  - Resists some displacements, accepts others
  - Preferred distortion – least stable ideal mode

Applied field

Displacement

DIII-D

[Laclctot & Chu]
The Starting Point to Understand 3D Field Interactions is Through Ideal MHD

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    - Preferred distortion – least stable ideal mode
  - Perturbed current paths give order (1) change to field

FIELD COMPONENT AT GIVEN SURFACE

<table>
<thead>
<tr>
<th>Radial ordinate, $\psi_p$</th>
<th>Field component at vacuum</th>
<th>Field component with response</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>amplifies here</td>
<td>reduces here</td>
</tr>
<tr>
<td>1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Applied field $\text{MARS-F}$

Displacement $\text{DIII-D}$

[Figure: Graph showing field component at given surface]

[Lanctot & Chu]

R.J. Buttery/APS/November 2011

113-11/RJB/rs
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**Graph:**
- Field component at given surface $G/kA$
  - $m=1$ harmonic
  - $m=2$ harmonic
  - $m=3$ harmonic
  - $m=4$ harmonic
  - $m=5$ harmonic

[Image: Illustration of plasma displacement and field interaction]

[Lanctot & Chu, Buttery & Liu NF 2011]
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![Graph showing field component at given surface](image)

- Field component at given surface $G/kA$
- Radial ordinate, $\psi_p$
- $m=2$

Note the field goes to zero at the resonant $q$ surface...

[Buttery & Liu, NF 2011]
The Starting Point to Understand 3D Field Interactions is Through Ideal MHD

- Plasma displacement transforms internal field
- Plasma shields out field components resonant with rational q surfaces
  - Flux conservation: image currents driven to prevent tearing of flux surface

\[ \phi_{q=2} \text{ flux surface} \]

Image currents on surface

Field line

\[ \delta i \]

\[ \theta \]

+ magnetic shear between surfaces
The Starting Point to Understand 3D Field Interactions is Through Ideal MHD

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- But with resistivity image currents start to decay
  - Enables formation of small islands

![Image](image.png)
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- But with resistivity image currents start to decay
  - Enables formation of small islands
- However, rotating plasma past 3D field helps it shield out the field
  - Viscosity $\rightarrow$ flows in island $\rightarrow$ re-generates the currents that keep the island small

[ Fitzgerald Phys Fluids 1991 ]
The Starting Point to Understand 3D Field Interactions is Through Ideal MHD... but resistivity modifies perspective

- Plasma displacement transforms internal field
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- However, rotating plasma past 3D field helps it shield out the field
  - Viscosity → flows in island → re-generates the currents that keep the island small
    - Decreasing rotation enables resistive response

[Buttery & Liu, NF 2011]
Resistivity & Rotation Cause a Torque Balance to be Established with the 3D Field

- **Island dragged round by rotating plasma**
- **Island less phase aligned → less driven by 3D field**

**Torque balance:** *viscous coupling vs electromagnetic forces*
- Low field/high rotation: island out of phase, suppressed → plasma slips past
- High field/low rotation: island aligns to 3D field → grows → stops rotation

**Resistive response depends on island phase, & so torque balance**
- Process is highly nonlinear → can bifurcate to a locked state

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[Fitzpatrick Phys Fluids 1991]

R.J. Buttery/APS/November 2011
Recap — The Plasma Response to 3D Fields

Degree of Tearing

depends on

amount image currents decay

Torque on plasma & modes

“Drive” to Tear – amount of imaging current

3D field + ideal MHD \(\Rightarrow\) imaging currents

Measure by the component of B at edge that induces these currents

Inclination to Tear

How much plasma tears for given field resonant B

Resistivity + \(\Delta'\)

Resilience to Tearing

- Flows inside island renew image currents
- Flows outside island drag it out of phase from field

[Park IAEA 2010]
Measurements of Plasma Magnetic Response Show Ideal and Resistive Components

Measure response to 3D probing field

– Repeat at different beam torques and $\beta$'s

![Graph showing 3D field, Rotation, Magnetics spectrogram, and Locked mode.](image)
Measurements of Plasma Magnetic Response Show Ideal and Resistive Components

Measure response to 3D probing field

- Repeat at different beam torques and $\beta$'s

[Graphs and data plots showing magnetic response to probing fields with labels indicating different modes and frequency responses.]
Measurements of Plasma Magnetic Response Show Ideal and Resistive Components

Measure response to 3D probing field

- Repeat at different beam torques and $\beta$'s
- Clear $\beta_N$ dependence:
  - Characteristic of ideal response
  - Kink mode more readily driven at high $\beta_N$

[Buttery & Liu, NF 2011]
Measurements of Plasma Magnetic Response Show Ideal and Resistive Components

Measure response to 3D probing field

- Repeat at different beam torques and $\beta$'s

- Clear $\beta_N$ dependence:
  - Characteristic of ideal response
  - Kink mode more readily driven at high $\beta_N$

- Rotation dependence indicative of resistive response
  - An ideal response would maintain shielding, irrespective of rotation
    \[ \Rightarrow \text{Developing response indicates breakdown of screening} \]

- Resistive response may be an important element of how 3D fields couple to plasma at low torque

Response to 10 Hz probing field

[Buttery & Liu, NF 2011]
Need to Focus Further on Resistive Response…

**Degree of Tearing**
- depends on:
  - amount image currents decay

**Torque on plasma & modes**

**“Drive” to Tear – amount of imaging current**
- Measure by the component of B at edge that induces these currents
- 3D field + ideal MHD $\rightarrow$ imaging currents

**Inclination to Tear**
- How much plasma tears for given field resonant B
- Resistivity $\Delta' + \Delta$

**Resilience to Tearing**
- Flows inside island renew image currents
- Flows outside island drag it out of phase from field
Need to Focus Further on Resistive Response…

- **Plasma tearing stability**
  - Governs response of plasma to applied 3D field
  - Size of island for given field
  - Sets threshold for natural tearing mode instability

**Inclination to Tear**

How much plasma tears for given field resonant $B$

Resistivity + $\Delta'$
Interaction of 3D Field with Tearing Stability

- Rotation dependence
- Braking action of fields

=> 3D field limits in H mode
H Mode Plasmas are Close to Natural Tearing Instability

- Tearing modes can come out the noise
  - If $\beta$ too high or current profile unstable

![Magnetic spectrogram graph]
H Mode Plasmas are Close to Natural Tearing Instability, ...which depends on plasma rotation

- Tearing modes can come out the noise
  - If \( \beta \) too high or current profile unstable
  - Or if rotation too low...

- Rotation thought to act through flow shear
  - Changes field structure and so field line bending and compression energy

Flow shear: Viscous forces couple into island to change its structure

Flow shear
normalized to Alfven speed & magnetic shear scale length

What is action of 3D Fields?
3D Fields Brake Plasma to Trigger Rotating or Stationary Modes

- 3D field ramps trigger modes in NSTX

Midplane field coils on NSTX
3D Fields Brake Plasma to Trigger Rotating or Stationary Modes

- 3D field ramps trigger modes in NSTX

- With enough braking, mode born locked
  - Lower levels of braking → rotating modes
  - Action through inherent stability changes

- Resonant ($n=1$) and non-resonant ($n=3$) fields act similarly on braking & modes
  - Braking action through NTV?
  - Resonant part of interaction may be weak in these high rotation plasmas

- Mode onset is not due to resonant interaction of the 3D field
  - Mode not directly driven by field
  - It is an inherent stability change through braking of rotation
At Low Torque 3D Fields Pose Greater Concern

- Consider cases close to tearing instability at low torque in DIII-D

- Tearing $\beta_N$ limit falls with rotation (no 3D field)

![Diagram showing $\beta_N$ ramp to induce mode and Neutral Beam Torque vs. $\beta_N$ for DIII-D with co-rotation increasing.]
At Low Torque 3D Fields Pose Greater Concern

- Consider cases close to tearing instability at low torque in DIII-D

- Tearing $\beta_N$ limit falls with rotation (no 3D field)
- 3D field torque brakes plasma, decreasing stability $\rightarrow$ mode grows & locks

DIII-D 139571

- Co-rotation increasing
A 3D Field Limit is Observed in $\beta$ and Torque

- Field thresholds reach optimal intrinsic error correction of 1.3 G as $\beta_N$ rises
- Torque dependence observed

Component of field at boundary that drives $q=2$ imaging currents

[Buttery & Liu, NF 2011, Park IAEA 2010]
3D Field Limit Depends on Proximity to Natural Tearing Limit

- Field thresholds reach optimal intrinsic error correction of 1.3 G as $\beta_N$ rises.

- Torque dependence observed — **Explained by proximity to natural tearing $\beta$ limit**
  - $\beta_{N\text{-TM-limit}} = 2.2 + 0.32 T_{\text{NBI}}$

![Graph showing relationship between torque and field limit](image)

Optimal intrinsic error correction $\beta_{N\text{-TM-limit}} = 2.2$ at zero torque.
ITER Prediction

• ITER heating systems inject much less torque per MW
  – Approximate this to zero for a worst case scenario

• For torque-free plasmas can treat rotation as a “hidden” parameter
  – Plays an important role...
  – But self generated – a part of the scaling

• Measure field thresholds to trigger modes in torque free H modes
  – Extrapolate in $\rho^*$ and $\nu$ by measuring toroidal field and density scaling

Required precision $\frac{\delta B}{B_T}$
ITER Prediction: 3D Field Limits in H Mode are Even More Stringent than in Ohmic Regimes

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- Measure field thresholds to trigger modes in torque free H modes
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\[
\frac{\delta B}{B_T} = \left(1.3 - [\beta_N - 1.8]\right) \times \frac{\left(n_e / 10^{20} m^{-3}\right) \left(R / 6.2m\right)^{0.725} \left(q_{95} / 3.1\right)^{0.83*}}{\left(B_T / 5.3T\right)^{1.02}} \times 10^{-4}
\]

- Predicts $\delta B/B < 1.3 \times 10^{-4}$ to avoid modes in ITER $Q=10$ baseline
  - 40% lower than Ohmic regime scaling, even though H mode 5x higher density
Reducing 3D “Error” Fields in ITER
Updated ITER Error Field Predictions Suggest Significant Error Field Correction Required

• Monte Carlo analysis of error field sources updated for ideal response formalism
  – Sum up sources – conservative to allow for lack of magnetic optimization in ITER plans
  – Total possible: $\delta B/B \sim 2.8 \times 10^{-4}$
    cf expected limit of $1.3 \times 10^{-4}$

• Must remove 55% of error field in ITER baseline, or more for higher $\beta$ regimes
  – This task is planned for ITER error field correction coils

<table>
<thead>
<tr>
<th>Source</th>
<th>$\delta B/B/10^{-5}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>TF, CS, PF misalignments</td>
<td>4.3</td>
</tr>
<tr>
<td>TBM</td>
<td>4.3</td>
</tr>
<tr>
<td>Ferromagnetic inserts</td>
<td>1.5</td>
</tr>
<tr>
<td>NBI*</td>
<td>5.2</td>
</tr>
<tr>
<td>TF, CS, PF feeds &amp; joints*</td>
<td>4.3</td>
</tr>
<tr>
<td>Ferromagnetic saturation*</td>
<td>4.3</td>
</tr>
<tr>
<td>Bioshield*</td>
<td>4.3</td>
</tr>
<tr>
<td>Tokamak Complex*</td>
<td>0.2</td>
</tr>
<tr>
<td><strong>Possible total</strong></td>
<td><strong>2.8 \times 10^{-4}</strong></td>
</tr>
</tbody>
</table>

*scaled vacuum calculation

Can this level of correction be met?
– Assistance needed from internal ELM coils?
Experience with Error Field Correction Has Shown Limited Benefits

- Typically performed in Ohmic plasmas
- Benefits measured by density access
  - Low density limit proportional to error field
  - 3D coil currents optimized to lower limit
- Single array correction achieves improvements from ~0 to 50%

\[ \delta B (G) \cdot f(B_T, q_{95}) \]

Experience with Error Field Correction Has Shown Limited Benefits

- Typically performed in Ohmic plasmas
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- Single array correction achieves improvements from ~0 to 50%
  - Improved with more coils, best ~70%
  - Design of coils matter – some offer little improvement, poloidal pairs do better
    - eg. JET EFCCs seem orthogonal to error field

Key questions
- Do multiple field harmonics play a role?
- Is plasma response more complex than through a single dominant ideal mode?
- Is there an inherent stability limit?
Proxy Error Field Study Shows Correction Limits Arise Through Higher Order n=1 Ideal Modes

- Use DIII-D I coils to correct proxy error field from C coils
  - Well above usual machine error & density limits
  - Pure n=1 – no n=0,2,3,4
- Optimal correction yields only 50% improvement in density limit
  - Confirms correction limits arise from additional components in n=1 field
  - Must couple through more than one ideal MHD mode

Coils have very different spectra making large residual field at boundary
Interpretation: Error Field Interacts through Multiple Modes and Surfaces, Requiring Multiple Coil Correction

- With a single ideal mode, perfect correction should be possible
  - Additional ideal modes enable residual field to pass through to core plasma

- But if braking is resonant with a single surface, perfect correction is still possible
  - Braking must be at multiple surfaces

- Correction must minimize ideal response or minimize internal braking
  - *Outstanding*: Important to resolve how and where braking manifests in the plasma

- For ITER 3D field coils must have flexibility to adapt to error field structure and the modes it couples through
  - Multiple arrays needed (& planned) to push down drives present while not raising others
Conclusions

• 3D fields collude with the plasma resistive response at low rotation to cause tearing modes
  – Flow shear places incipient tearing mode “under stress”, decreasing free energy available to drive the mode
  – 3D fields decrease flow shear to access instability

• This leads to a limit for tolerable 3D fields in ITER’s baseline low rotation H mode
  – Scalings obtained, field error predictions updated…
  – Substantial error correction needed

• Experience with error field correction shows interaction through more than one mode
  – Multiple coil arrays needed for good correction
    • Planned in ITER; additional internal ELM coils provide important margin

Understanding the processes of 3D fields and tearing is fascinating physics of crucial importance to resolving development of low rotation regimes
For Poster:

Survey of Experience with Error Correction across the world
Experiments Suggest More to Plasma Response Than Coupling Through a Single Ideal Mode

- DIII-D C-Coils access lower density
  - But correction imperfect: ~50%

[Scoville, APS 2003]
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DIII-D pre-B-fix Error Field

[Scoville, APS 2003]
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- JET saddle coils measure 1.2 G error*
  - Correction $\rightarrow$ 35% lower density

* vacuum 2/1 measure

[Buttery, NF 2000]
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  - But JET’s EFCC offered little benefit
  - Do couple to plasma to induce tearing but don’t “see” intrinsic error

*JET EFCC measurement of intrinsic error*:

*vacuum 2/1 measure* [Howell, APS 2003]
Experimental Experience with Error Field Correction

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- MAST EFCCs offer 30%+ benefit
- C-Mod A coil 2x4 array gives over 60% improvement in density

[Wolfe, PoP 2005]
Experiments Suggest More to Plasma Response Than Coupling Through a Single Ideal Mode

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Observations

- Correction benefits depend on shape of EF and coils
- More coils improve correction
- Internal twin arrays have been most effective
- Coils can couple orthogonally to machine error
  - Is this intrinsic instability?
  - Is this all through n=1?
  - Where does error field couple to plasma to cause braking?