Using 3D Fields to Control Islands, Aid ECCD-Stabilization and Measure Error-Fields in DIII-D

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with
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Disruptions, locked modes, NTMs and error fields are major concerns in ITER.

- We need profound understanding and effective controls.

- From 2007 Nuclear Fusion “Progress in the ITER Physics Basis”:
  “the NTM instability is predicted to lead to confinement deterioration… and possibly… disruption”

- Locked modes is one of the main causes of disruptions

- Stabilization by Electron Cyclotron Current Drive (ECCD) is well-developed in several tokamaks
  …but it becomes impossible if mode locks to the error field or to the wall in a position not accessible to ECCD.
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Magnetic control of toroidal phase aids understanding and control of

1) rotating islands,
2) locked modes,
3) the disruptions they cause,
4) the error fields that they are sensitive to.
3D fields were used to:

**Control island position**
- Locked mode stabilization by ECCD

**Control island rotation**
- Entrainment up to 300 Hz

**Measure error fields**
- Demonstration
**Highlights**

3D fields were used to:

- **Control island position**
  - Locked mode stabilization by ECCD
  
  ![Graph showing magnetic probe (G) vs time (ms)]
  - No ECCD, disruption
  - ECCD in O-point

- **Control island rotation**
  - Entrainment up to 300 Hz

  ![Graph showing magnetic probe (G) vs time (ms)]
  - B_p

- **Measure error fields**

  ![Graph showing phase (deg) vs time (ms)]
  - RMP, LM (meas.), RMP+EF

- **Demonstration**
Electrical circuits interact with magnetic fields (Ampere, 1822)

DITE [Morris 1990]
COMPASS-C [Hender 1992]
HBT-EP [Navratil 1998]
TEXTOR [Koslowski 2006]
DIII-D [Volpe 2009]
J-TEXT [Rao 2013]
Control-coils, magnetic diagnostics and ~3MW of steerable Gyrotron power were used at DIII-D.
Magnetic steering aligns locked mode O-point to stabilizing ECCD
Magnetic control of locking phase allowed ECCD deposition in O-point, suppressing locked mode.
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Furthermore,
- Key is ECCD > missing Bootstrap current
- Stabilization improves with power
Locked-mode-controlled discharges do not lose H-mode, or rapidly recover it.
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Energy confinement is largely recovered and comparable with discharges without NTMs (whether rotating or locked)
$\beta_n$ is recovered after locked mode suppression

ECCD at $q=2$ prevents reappearance of 2/1, whether locked or rotating
$\beta_N$ is recovered after locked mode suppression

Locked mode stabilized:
- High $\beta$ and no disruption

Locked mode not stabilized:
- Disruption at $\beta \sim 1.7$
3D fields were used to:

- Control island position
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- Measure error fields

**Highlights**

- **Control island rotation**
  - Entrainment up to 300 Hz

**Diagrams**

- No ECCD, disruption
- ECCD in O-point

- B_p Magnetic probe (G)
- I-coil freq (Hz)

- RMP, LM (meas.), RMP+EF
Rotating field sustains mode rotation up to 300 Hz ($\Omega \tau_w \approx 6$)

- **Without control**: 2/1 NTM grows and locks $\rightarrow \beta_N$ collapse and major disruption

- **Rotating $n=1$ I-coil field “entrains” slowing island**
  - Avoids disruption without using ECCD

- **Entrainment up to 300 Hz** ($\Omega \tau_w \approx 6$)
Magnetics array analysis and ECE diagnostic confirm entrainment and spin-up of 2/1 mode

- Magnetics arrays analyzed for modal shapes (eigspec code)
- \( m/n = -2/-1 \) mode tracks I-coil frequency
- Entrainment frequency is modulated by Error Field on sub-period timescale (not shown)
- Electron Cyclotron Emission (ECE) phase inversion across \( q = 2 \) surface, synchronous with I-coil
Improved confinement: edge pedestal forms during entrainment

At entrainment

At loss of entrainment
Loss of entrainment is more complicated than a simple loss of torque balance

- Entrainment lost at different times and frequencies in similar discharges.
  - Possibly due to MHD events.

- Entrainment depends not just on coil currents/frequency
Island dynamics (including entrainment stability) modeled by 3 differential equations in 3 unknowns

Island width (thus, $J_s$) assumed fixed

Synchronous frame (co-moving with $J_c$)

\[
\begin{align*}
\tau B_w &= -B_w + \alpha_s J_s \cos(\phi_2 - \phi_1) + \alpha_c J_c \cos(\phi_1) \\
\tau B_w \phi_1 &= -\tau B_w \omega_c + \alpha_s J_s \sin(\phi_2 - \phi_1) - \alpha_c J_c \sin(\phi_1) \\
\phi_2 &= -n\beta_1 y_1 B_w J_s \sin(\phi_2 - \phi_1)
\end{align*}
\]

(i) Find fixed points (torque balance)
(ii) Evaluate stability of points (i)
Entrainment can be lost due to failure of applied torque to counteract braking torque from the wall at high frequency.

$\textbf{l-coils: critical entrainment freq. [Hz]}$

$W = 4\text{cm}$

$l = 4\text{ kA}$

$l$-coils

Limit for stable entrainment

SPEED LIMIT 187
Entrainment can be lost due to failure of applied torque to counteract braking torque from the wall at high frequency.
Magnetic feedback can prevent locking and sustain NTM rotation at 15-60 Hz

**Feedback settings:**
- Low-pass filter, $\tau_p=40\text{ms}$
- Gain $G_p=60$

**Mode rotates at**
$\sim15$ Hz
Highlights

3D fields were used to:

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**Control island rotation**
- Entrainment up to 300 Hz

**Measure error fields**

- Demonstration
Locked Mode rotates non-uniformly in presence of uniformly rotating RMPs and static residual EF

Rotating NTM slows down and locks

I-coils apply slowly rotating \( n=1 \) resonant magnetic perturbation (RMP)

In the absence of Error Field (EF), Locked Mode (LM) should follow the RMP...

Due to EF, LM rotates non-uniformly→
Locked Mode rotates non-uniformly in presence of uniformly rotating RMPs and static residual EF

Rotating NTM slows down and locks

I-coils apply slowly rotating \( n=1 \) resonant magnetic perturbation (RMP)

EF is deduced from observed \( \Leftarrow \) LM dynamics, in a single-discharge
Simple model (time-evolving vector sum) explains non-uniform rotation and extracts error field

- Nodes \rightarrow phase of error field
- Amplitude of distortion \rightarrow amplitude of error field
Slowly accelerated LM always in torque balance. Unknown EF torque inferred from others, if known.

\[ \dot{I} \ddot{\phi} = T_{EF} + T_{MP} + T_{wall} + T_{NTM} + T_{NBI} + T_{visc} \]

e.m. torques \[ \bar{T} = \int \hat{\tau} \times d\vec{F} = \int \hat{\tau} \times (I \, d\hat{\ell} \times \bar{B}) \]
Slowly accelerated LM always in torque balance. Unknown EF torque inferred from others, if known.

\[ I_\phi = T_{EF} + T_{MP} + T_{wall} + T_{NTM} + T_{NBI} + T_{visc} \]

Calculated wall torque \( \tau_w = 3 \text{ms} \)

No other NTM

Balanced injection, Low rotation

\[ 0 = T_{EF} + T_{MP} \]

Rotating RMP and static EFC from I-coils and C-coils
Non-resonant torques sometimes needed to explain observed mode rotation

- e.g. in Ohmic discharges with EF-penetration locked modes (without rotating precursors)
  
  - Non-resonant torque $T_{NR} \sim |\delta B|^2$

- EF can still be fit
EF detection by steering of locked modes agrees with other techniques

- Forward calculation [Paz-Soldan 2014] use physical geometry of known intrinsic EF at DIII-D

![Diagram showing n=1 Correction Currents with LM Steering and Forward labels, and Intrinsic EF LH plasmas point]
EF detection by steering of locked modes agrees with other techniques

- Forward calculation [Paz-Soldan 2014] use physical geometry of known intrinsic EF at DIII-D

- Agreement over a variety of discharges
  - EFs were different because currents in EF sources were different
**Summary and conclusions**

3D fields were used to:

<table>
<thead>
<tr>
<th>Control island position</th>
<th>Control island rotation</th>
<th>Measure error fields</th>
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<td>Highlight: locked mode stabilization by ECCD</td>
<td>Highlight: entrainment up to 300 Hz</td>
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</table>

- Recovered high confinement and $\beta_N$
- In feed-forward and feed-back
- In single discharge
- Also at high $n_e$ or $\beta_N$
Applicability to ITER

- Magnetic control of locked mode demonstrated on 9 devices:
  - AUG
  - DIII-D
  - JET
  - J-TEXT
  - KSTAR
  - MAST
  - NSTX
  - LHD
  - EXTRAP-T2R

as part of International Tokamak Physics Activity (ITPA) effort

- Encouraging for ITER. Modeling under way.

- **EF detection by LM steering**
  - Not restricted to low density discharges
  - Independent of high beta or rotation
    - Early operation of ITER lacking full auxiliary power
Non-linear modeling of:

**Locking**
- Electrical phasor space

**Unlocking**
- Electrical phasor space

**Entrainment**
- Electrical phasor space

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Thank you for your attention

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*Add* locking

*Add* icoils - rampup*.swf

*Unlocking*

*Add* icoils - entrainment*.swf
"All truth passes through three stages. At first it is ridiculed or distorted. Then it is opposed. And finally it is accepted as being obvious."

Arthur Schopenhauer (1788-1860)
Extra Slides
Controlling toroidal phase of magnetic islands has numerous applications

Locked Mode and NTM Control, Disruption Avoidance:

- **In combination with ECCD:**
  - Re- or “pre”-position LM, to assist its ECCD stabilization (cw).
  - Pace island rotation in synch with modulated ECCD.

- **Without ECCD:**
  - Unlock island and spin it by NBI or magnetically.
  - Rotational stabilization?
    - Stabilizing effect of conducting wall on rotating mode [Fitzpatrick].
    - Stabilizing effect of flow and flow-shear [Buttery, La Haye, Sen et al.].

- Avoid locking altogether by entraining island while still slowing down.

All of the above can be done in f/back or f/fwd.

- f/back can also directly reduce island width, not just its phase [Hender, Lazzaro, Morris et al.]. Not our scope.

Other:

- Spatially spreading heat loads during disruptions.
- Assisting diagnosis of islands [Liang, Shaffer et al.].
- Disruption control (by massive gas injection) and disruption studies with controlled phase relative to mode [Pautasso, Izzo, Shiraki et al.].
Highlights

3D fields were used to:

Control island position

- Locked mode stabilization by ECCD

Control island rotation

- Entrainment up to 300 Hz

Measure error fields

Demonstration

---

**Control island position**

Locked mode stabilization by ECCD

No ECCD, disruption

ECCD in O-point

---

**Control island rotation**

- Entrainment up to 300 Hz

**Measure error fields**

Demonstration

---

**Graphs:**

- Bp Magnetic probe (G)
- I-coil freq (Hz)
- Phase (deg)
- RMP LM (meas.) RMP+EF

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**Diagram:**

- Time (ms)
- Phase (deg)
- RMP LM (meas.) RMP+EF
Magnetic perturbations control phase of locking. ECCD in O-point suppresses locked mode.
ECCD in X-point destabilizes locked mode. Deposition between O- and X-point has intermediate effects.
Stabilization improves with ECCD power, as expected
EC current drive is more stabilizing than heating. Key is (over-)compensating for missing Bootstrap.
Locked-mode-controlled discharges do not lose H-mode, or rapidly recover it.

(a) $P_{ECRH}$ (MW)

(b) $B_R$ (G)

(c) ELM Intens. (a.u.)

(time (ms))
By increasing NBI, $\beta_N=2.7$ is reached without disruptions.
3D fields were used to:

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**Entrainment up to 300 Hz**

![Graph showing entrainment up to 300 Hz](image-url)
EM torque injection formulation

- Torque balance equation:

\[ L_m \frac{d\omega}{dt} = L_m \frac{\omega}{\tau} + T_{NBI} + \int B_r^{n=1,EXT} \delta B_\phi R d\phi dl \]

- Torque balance in steady state:

\[ \frac{\omega}{\tau_{loss}} = Q_{NBI} - C_{EM} B_r^{n=1,FB}(t) \delta B_p^{n=1}(t) \cos(\phi_{BP}^{n=1}(t) - \phi_{EXT,FB}^{n=1}(t)) \]

[Strauss 1977, N.Logan 2010]
Feedback-backed Mode-rotation control -proper toroidal phasing with 3D coils-
Feedback-backed Mode-rotation control – simple model (T. Strait)

RWM control / DEFC ($\omega \sim 0$)

Feedback radial field
Cancels the RWM $\delta B_r$
Feedback-backed Mode-rotation control
- various phasing combination

Mode rotation control

\[
\frac{Gp}{1 + i\omega \tau_w}
\]

Wall time constant

\[
\frac{\Phi_0}{-G \delta B_r}
\]

Feedback sensor
Toroidal shift
“fake rotation”

\[
\frac{Gp}{1 + i\omega \tau_p}
\]

Feedback filtering
Feedback-backed Mode-rotation control - various phasing combination

DEFC
\( \omega \sim 0 \)

Mode rotation control
Torque. max = \( \delta B_p \) times\((-G\delta B_r)\)

\[ \text{DEFC Torque. max} = \delta B_p \times (-G\delta B_r) \]

\( \omega \sim 0 \)

\[ \Phi_0 \]

Feedback sensor Toroidal shift “fake rotation”

Feedback filtering

Wall time constant

Advantage: The system still preserves Dynamic Error Field Correction (\( \omega \sim 0 \)) when NTM quenched
Torque balance provides the stability condition of mode rotation by feedback-based approach

\[ f = - (\omega \tau_p)^3 (\tau_w / \tau_p) - (\omega \tau_p) (\tau_w / \tau_p) + G \sin(\phi_0) \left( 1 - (\omega \tau_p)^2 (\tau_w / \tau_p) \right) - G \cos(\phi_0) (\omega \tau_p) (1 + (\tau_w / \tau_p)) \]

\[ g > \text{positive definite} \]

Solutions \( f = 0 \) change sign: \( - \) \( \rightarrow \) \( - \) \( \rightarrow \)
with fake rotation phase shift \( \phi_0 \rightarrow - \phi_0 \)

(condition 1) Torque balance: \( f(\omega) = 0 \)
(condition 2) Stability of the torque balance: \( \partial A / \partial \omega < 0 \) \( \rightarrow \) \( \partial f / \partial \omega < 0 \)
Both conditions remain intact

\( \rightarrow \) toroidal shift \( \phi_0 \) preset determines the mode direction as was observed
The model predictions are consistent with key experimental observations.

\[ \frac{\omega \tau_p}{G(\tau_w/\tau_p)^{1/2}} \]

- Dotted line with \( \phi_0 = 0 \)
- Solid lines with \( \phi_0 = 30^0 \)

<table>
<thead>
<tr>
<th>Case</th>
<th>#1</th>
<th>#2</th>
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</thead>
<tbody>
<tr>
<td>( T_p )</td>
<td>10 ms</td>
<td>40 ms</td>
</tr>
<tr>
<td>( T_w/T_p )</td>
<td>0.3</td>
<td>0.075</td>
</tr>
<tr>
<td>( f ) (meas.)</td>
<td>60 Hz</td>
<td>20 Hz</td>
</tr>
<tr>
<td>( \omega T_p )</td>
<td>3.8</td>
<td>5.0</td>
</tr>
</tbody>
</table>

Calculation: \( \tau_w/\tau_p = 0.15 \)

\( \phi_0 = 0 \) advantage
Pre-programmed phase offset determines the direction of mode rotation

- Mode rotation reverses when sign of $\phi_0$ is reversed

- Only ~10ms delay in the plasma response $\Rightarrow$ small mode inertia
Highlights

3D fields were used to:

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Locked mode stabilization by ECCD

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Entrainment up to 300 Hz

Measure error fields

Demonstration
Larger error field increases non-uniformity of locked mode rotation

- Nodes \(\rightarrow\) phase of error field
- Amplitude of distortion \(\rightarrow\) amplitude of error field
Error field of different toroidal phase shifts “nodes” of locked mode rotation

- Nodes \(\rightarrow\) phase of error field
- Amplitude of distortion \(\rightarrow\) amplitude of error field
As RMP slowly rotates, LM locks to RMP+EF resultant. Measured LM phase = phase relative to displaced origin $\rightarrow$ EF

- Goal of EFC: identify displaced origin consistent with measured LM phases.
- Single trajectory is sufficient, but thoroughly “scanning” $I_x, I_y$ space is preferable.
  - Concentric circles, displaced circles, spiral.