Review of locked mode control techniques using 3D fields and ECCD

by
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D. Shiraki, R. Sweeney,
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Image by Guido Huijsmans, ITER Org.
Typically non-rotating
• Neoclassical Tearing Mode

It could also denote –but not here– non-rotating
• Resistive Wall Mode (NSTX Spherical Tokamak)
• Interchange Mode (LHD Heliotron)
• Tearing Mode (RFX-mod Reversed Field Pinch)

LM with rotating precursor a.k.a. “Locked Mode”
LM w/o rotating precursor a.k.a. “EF penetration mode”
    a.k.a. “Born Locked Mode”
Outline

- Motivation for LM control
- Techniques for LM control
- How to combine LM control techniques
- Timing of LM control
- LM control experiments in present devices
  - Static fields
  - Rotating fields
- Modeling for ITER
- LM control research needs
Motivation for LM control

Techniques for LM control

How to combine LM control techniques

Timing of LM control

LM control experiments in present devices
  - Static fields
  - Rotating fields

Modeling for ITER

LM control research needs

Disruptions
Degraded Confinement
Reduced Plasma Rotation
Locked islands cool plasma edge mostly by convection

F.C Schüller, PPCF 1995
Nearly all JET disruptions eventually exhibit Mode Locking

P. De Vries et al., NF 2011

R. Sweeney et al., NF 2017 (DIII-D)
LM degrades confinement and reduces plasma rotation

[Chang-Callen NF 1990]

[La Zzaro PoP 2002]

→ Reduced shear →
→ turbul. eddies → loss of H-mode?
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ECRH/ECCD, LHCD
NBI
3D Fields
$I_p$
Shaping, position
Self-healing
Electron Cyclotron Current Drive (ECCD) can replace missing Bootstrap Current

Resonant electrons:
\[ \frac{\omega - n \omega_{ce}}{\gamma} - k \parallel v \parallel = 0 \]
\[ k \parallel \neq 0 \text{ (oblique launch)} \]

Trapped cone

Heated electrons
less collisional \(\rightarrow\) less resistive \(\rightarrow\) net current
Lower Hybrid Current Drive stabilized NTMs in COMPASS

Compared to ECCD:
- Higher currents driven
- Less localized

LHCD in ITER?

Also, ICRH reduced EF penetration in C-mod

[Delgado-Apricio 2014]
While not LM control, ramping $I_p$ down also avoids LM disruption, if time permits.
Some LMs self-stabilize through minor disruptions. Typically $q_{\text{min}}>1.2$ and $q_0>2$ (Double 2/1 LM)

Double LM $\rightarrow$ Minor Disruption $\rightarrow$ $P$ profile reorganized $\rightarrow$ Neoclassical Drive removed

Classically stable.

[Sweeney, in preparation for NF, 2017]
NBI, $I_p$, plasma shape and position all help controlling LMs

- Increase NBI torque $\rightarrow$ Stabilization by rot.shear or rot.wall
- Drop in power (NBI and ECH) $\rightarrow$ Reduce $\beta$ $\rightarrow$ Neoclassical stability
- Full $I_p$ ramp down $\rightarrow$ Safe shutdown
- Partial $I_p$ ramp down $\rightarrow$ Reduce $q_{95}$. Increase $d_{\text{edge}}$, $I_i/q_{95}$
- Change in shape $\rightarrow$ Affect stability & rotation
- Some/all of the above
Electrical circuits interact with magnetic fields (Ampere, 1822)
NTM current filaments interact with various fields (applied by coils, from wall currents, or other NTMs)

\[ e.m. \text{ torques } d\vec{T} = \vec{r} \times d\vec{F} = \vec{r} \times (I \, d\vec{l} \times \vec{B}) \]
Modeling effect of rotating RMPs on locked or nearly-locked mode

\[ I \frac{d^2 \phi}{dt^2} = T_{wall} + T_{EF} + T_{RMP} + T_{TM} + T_{visc} + T_{NBI} \]

### E.M. Torques on Island

\[ I_h = \pm 2|B_R(b)|b \left( \frac{b}{r_{mn}} \right)^m \frac{1}{m \mu_0} \]

\[ T_{wall} = -\left[ \frac{2\pi R B_R(b) r_{mn}}{\mu_0 b} \right]^2 \left[ \frac{r_{mn}}{b} \right]^{2m-1} \frac{\Omega \tau}{1 + (\Omega \tau)^2} \]

\[ T_{EF} = -\pi^2 R^2 m \frac{a}{r_{mn}} I_{EF} B_R(a) \sin[n \phi(t)] \]

\[ T_{RMP} = -\pi^2 R^2 m \frac{b}{r_{mn}} I_{RMP} B_R(b) \sin[n \phi(t) - n \phi_{RMP}(t)] \]

\[ T_{TM} = -\pi^2 R^2 m \sum_{m', n'} \frac{r_{m'n'}}{r_{mn}} \sin[n \phi(t)] I_{m'n'} B_R[r_{m'n'}] \]
Equation of angular motion of mode can be simplified

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

Calculated wall torque 
\[ \tau_w = 3 \text{ms} \]

\[ I \dot{\phi} = T_{EF} + T_{MP} + T_{wall} \]

Simplified eq. of motion

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

Torque balance

~Uniform mode rotation

No other modes

Balanced injection, Low rotation

\[ \text{Torque balance} \]
\( \vec{r} \times \text{Single-fluid momentum equation} + \text{eq. for flux evolution} \) at island, wall & coils have several advantages

\[
\frac{d\hat{\Omega}_\phi}{dt} + \nu_* (\hat{\Omega}_\phi - \hat{\Omega}_\phi^{(0)}) = -\nu_* \hat{\Omega}_\phi \hat{\Psi}_a^2.
\]

\[
\frac{d^2 \hat{\Psi}_a}{dt^2} + (\nu_* - 2i\hat{\Omega}_\phi) \frac{d\hat{\Psi}_a}{dt} + \left[ (1 - \kappa)(1 - md) - \hat{\Omega}_\phi^2 - i\nu_* \hat{\Omega}_\phi \right] \hat{\Psi}_a = \sqrt{1 - (md)^2} \hat{\Psi}_w.
\]

\[
S_* \frac{d\hat{\Psi}_w}{dt} + (1 + md) \hat{\Psi}_w = \sqrt{1 - (md)^2} \hat{\Psi}_a + 2md\hat{\Psi}_c.
\]

- \( \Omega \) is plasma rotation, not mode rotation!
- Plasma partly frozen-in. Mode is non-rigid.
- Coupled rotation-stability problem
  - Growth/decay affects locking/unlocking
  - Rotation \( \rightarrow \) stabilization by rotation shear, effect of rotating wall, …
- Analogies with RWM dynamics [Fitzpatrick 02]
Proportional-integral controller controls LM phase in feedback with LM phase measurements

\[ \phi_{error} = \phi_{ref} - \phi_{mode} \]

\[ \phi_{correction} = \text{PI control} (\phi_{error}) \]

\[ \phi_{RMP} = \phi_{mode} + \phi_{corr.} \]

limit to \( \phi_{mode} \pm 90^\circ \) for max torque

applied to coils
Motivation for LM control
Techniques for LM control
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Static/rotating f-back/f-fwd cw/modulated
Some techniques control mode stability/amplitude, others mode phase/rotation

- **Stability** $dw/dt$, **Amplitude** $w$
  - ECRH/ECCD
  - LHCD
  - ICRH
  - NBI power reduction
  - $I_p$ reduction
  - Self-healing
  - Shaping
  - RMPs? Rotational stabilization by wall or shear.

- **Rotation** $d\phi/dt$, **Phase** $\phi$
  - RMPs
  - NBI torque
  - Shaping?
...but some tools might be unavailable in ITER or a reactor, or incompatible with its economic operation

- **Stability** $dw/dt$, **Amplitude** $w$
  - ECRH/ECCD
  - LHCD
  - ICRH
  - NBI power reduction
  - $I_p$ reduction \(\rightarrow\) Reactor to operate continuously at high performance
  - Self-healing *
  - Shaping *
  - RMPs? Rotational stabilization by wall or shear *

- **Rotation** $d\phi/dt$, **Phase** $\phi$
  - RMPs
  - NBI torque
  - Shaping? *
  
  * = under investigation
Most robust tools are ECCD and MPs, which can be combined in various ways.

<table>
<thead>
<tr>
<th>Phase control by RMPs</th>
<th>Amplitude control by ECCD</th>
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</thead>
<tbody>
<tr>
<td>f/fwd</td>
<td>Ampl. f/back</td>
</tr>
<tr>
<td>1</td>
<td>Static</td>
</tr>
<tr>
<td>2-4</td>
<td>Rotating</td>
</tr>
<tr>
<td>5-7</td>
<td>Rotating</td>
</tr>
<tr>
<td>8</td>
<td>Static</td>
</tr>
<tr>
<td>9-11</td>
<td>Rotating</td>
</tr>
</tbody>
</table>

Need metric: fastest, most complete stabilization? Highest $\tau_E$, $\beta$, $Q$?
Magnetic control aligns locked mode O-point to stabilizing ECCD
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Before onset
Before locking
Before disruption
During disruption
Staged approach to LM control, disruption avoidance and mitigation

Pre-emptive NTM control
Rotating NTM stabilization
Pre-emptive entrainment
LM stabilization
LM unlocking & spin-up
Compensate for $T_e$ drop in th. quench
Rotate LM to spread heat & radiation
Measurements & predictions of “slow-down time” and “survival time” indicate time available for LM control.
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5 tokamaks
2 STs
2 RFPs
1 heliotron
Static applied RMP make Locked Mode O-point accessible to stabilizing ECCD

Volpe et al., PRL 2015
Locked-mode-controlled discharges do not lose H-mode, or rapidly recover it.
Incomplete recovery of pre-locking confinement is probably due to ECCD and RMPs still on.

Best Disruption Avoidance should maintain high fusion gain Q.
$\beta_N$ is recovered after locked mode suppression

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

**Locked mode not stabilized:**
- Disruption at $\beta \sim 1.7$

ECCD at $q=2$ prevents reappearance of 2/1, whether locked or rotating.

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

Locked mode not stabilized:
- Disruption at $\beta \sim 1.7$
LM phase was magnetically controlled in 5 tokamaks, 2 spherical tokamaks, 2 RFPs and a helical device

Different Machines
- Sizes
- Aspect ratios
- Elongations
- Wall times

Different Coil sets
- Internal or external
- Narrow or broad in angular spread
- Dense or sparse arrays
- Partial/full toroidal/poloidal coverage
Static applied RMPs control phase of locked modes

• Born-locked $n=1$ modes (EF-penetration modes) in:
  – AUG, DIII-D, JET, KSTAR, MAST, NSTX

• $m/n = 2/1$ LMs with rotating precursors in:
  – DIII-D, J-TEXT, KSTAR

• $m/n = 1/-15$ LMs with rotating precursors in
  – EXTRAP-T2R

• QSH, Interchange, LM for EF detection by non-unif.rot.
  – MST, LHD, DIII-D
Static applied RMPs control phase of locked modes

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- **QSH, Interchange, LM for EF detection by non-unif.rot.**
  - MST, LHD, DIII-D
AUG (currently 2x8 internal coils)

Flipping $n=1$ RMP by $180^\circ$ changes $n=1$ LM phase by $\Delta \phi \neq 180^\circ$. 

M. Maraschek
Error-field penetration Locked Modes form at phase of strong applied MP.

T. Hender
MAST (2x6 internal, 1x4 ext. coils)

Locked mode phase observed to change when EFC phase is changed.

A. Kirk
Static applied RMPs control phase of locked modes

- **Born-locked** $n=1$ modes (EF-penetration modes) in:
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- QSH, Interchange, LM for EF detection by non-unif.rot.
  - MST, LHD, DIII-D
J-TEXT (3x4 internal +1x2+1x3 ext. coils)

\[ F = -70^\circ \]

\[ F = +110^\circ \]

\( n=1 \) RMPs applied with different phases cause pre-existing rotating TM to lock with different phases
Static applied RMPs control phase of locked modes

- Born-locked $n=1$ modes (EF-penetration modes) in:
  - AUG, DIII-D, JET, KSTAR, MAST, NSTX

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- QSH, Interchange, LM for EF detection by non-unif.rot.
  - MST, LHD, DIII-D
n= -15 TM locks with different phases if n= -15 RMP is applied, with $\phi_{\text{RMP}}=0^\circ$ (left) or only intrinsic n= -15 EF is present (right).

L. Frassinetti
Static applied RMPs control phase of locked modes

- **Born-locked** $n=1$ modes (EF-penetration modes) in:
  - AUG, DIII-D, JET, KSTAR, MAST, NSTX
- $m/n = 2/1$ LMs with rotating precursors in:
  - DIII-D, J-TEXT, KSTAR
- $m/n = 1/-15$ LMs with rotating precursors in
  - EXTRAP-T2R
- **QSH, Interchange, LM for EF detection by non-unif.rot.**
  - MST, LHD, DIII-D
At MST, 38x1 external coils align dominant $m=1$, $n=5$ mode (Quasi Single Helicity) to any phase of choice.
LHD (2x10 external coils)

Rotating 1/1 interchange island locks to EF, or to different positions if different EF corrections are used.

Y. Takemura, NF 2012
DIII-D (2x6 internal + 1x6 ext. coils)

Locked mode phase is controlled at DIII-D for ECCD stabilization & EFC studies.

- On LM with/without rot. precursor
- Int./Ext. coils
- Static/rotating MPs (up to 300 Hz)
- Preprogrammed/feedback
- With/without ECCD (cw or modulated)

Shiraki, NF 2014
Strait, NF 2014
Volpe, PoP 2009
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Initially locked islands were entrained by applied rotating RMPs at AUG, DIII-D, J-TEXT.

AUG, Maraschek et al., Paccagnella et al., EPS 2016

DIII-D, Volpe et al., PoP 2009

J-TEXT, Jin et al., PPCF 2015

Earlier entrainment studies (of initially rotating or initially locked islands):
Rotating fields applied in feedforward entrained mode at up to 300 Hz ($\Omega \tau_w \approx 6$), thus preventing disruption.
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
Improved confinement: edge pedestal forms during entrainment

In contrast with applied EF typically degrading confinement
Entrainment can be lost due to failure of applied torque to counteract braking torque from the wall at high frequency.

**l-coils**: critical entrainment freq. [Hz]

Max frequency increases with coil current and decreases with island width.

K.E.J. Olofsson PPCF 2016
Decelerating island can be “preemptively entrained” by rotating fields applied in feed-forward.
Phase controller locked mode where desired and entrained it at 20 Hz as desired.
Feedback phase-controller enables easier (pre-programmed) ECCD modulation in phase with O point
Amplitude feedback can prevent locking and sustain NTM rotation at 15-60 Hz

Mode rotates at ~15 Hz

Feedback settings:
- Low-pass filter, \( \tau_p = 40 \text{ms} \)
- Gain \( G_p = 60 \)
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With available power supplies, NSTX-U 1x6 ext. coils could entrain modes at ~350 Hz ($\Omega \tau_w \approx 11$)

- major radius: 0.86 m
- wall time: 5 ms
- density: $3 \times 10^{19}$ m$^{-3}$
- $B_t$: 0.18 T

Low $R$ $\rightarrow$ small $T_{wall}$ $\rightarrow$ high entrainment frequency

Similar modeling for J-TEXT and KSTAR not shown for brevity
ITER 2/1 mode entrained by external coils

- **coils:**
  - External coils: 3 sets of 6
  - Internal coils: 3 sets of 9
- **major radius:** 6.2 m
- **wall time:** 188 ms
- **density:** $7.2 \times 10^{19}$ m$^{-3}$
- **$B_t$:** 5.3 T

larger island results in stronger torque
ITER model – NTM slows and locks in about 7 seconds

5 cm island slows from 420 Hz and locks in 7 seconds

Agrees with La Haye NF2009

ITER treated with 2 walls:
1) vacuum vessels
2) tiled Be first wall

5 Hz entrainment with 10 kA in external coils
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Under which conditions do LMs cause:

1. **Disruptions**?
   a) Edge stochastization by large island close to edge?
   b) Radiative losses by impurities eroded from wall and accumulated in island.

2. Decrease in confinement and $\beta_N$?
   a) “Belt model”?

3. Loss of H-mode?
   a) Stop plasma rotation $\rightarrow$ no rotation shear $\rightarrow$ no breaking of turbulent eddies?

Can we partly stabilize the LM and/or entrain it just fast enough to prevent its negative effects?
Can we trade LM for lesser problem?

4. **Unlocked, rapidly rotating NTM?**
   - Competition between stabilization by ECCD and unlocking by NBI or viscous torque (partly assisted by ECCD).

5. **QSM?**
   - QSMs spread heat. Are they also less disruptive than LMs? Why?
Some sensors and actuators will not be available in DEMO. Focus on alternative sensors and actuators needed today.

• **Sensors**
  
  – **Optical and neutral-beam-based** diagnostics, including MSE
    
    • Should use other diagnostics (magnetics? Microwaves?) to constrain equilibrium reconstructions

• **Actuators**
  
  – **Internal coils**
    
    ➔ Should use External coils

  – **NBI torque**
    
    ➔ Should use off-axis tangential NBI, when available, to simulate limited penetration in DEMO
Further considerations

- Reactor should be efficient and operate at max performance for as long as safely possible
- LM control actuators (RMP and ECCD) degrade confinement → should be turned off after LM suppression, for full recovery of pre-locking confinement
- Reactor will have to be robust and easy to operate
- “Low tech” techniques?
  - Pre-emptive f/fwd rotating fields
  - Static fields
Summary and Conclusions

- Several techniques control locked mode amplitude and phase.
- Most efficient and reactor-relevant are ECCD and RMPs from external coils, respectively.
- Their combination completely stabilized LM in DIII-D.
- RMPs alone shown to control LM phase in 5 tokamaks, 2 spherical tokamaks, 2 RFPs and 1 helical device.
- Slow entrainment proven in at least 3 recent and 4 earlier tokamak experiments.
- Entrainment predicted possible in ITER at 10 Hz with planned PSs.
- Fast entrainment might rotationally stabilize LM, and appears to improve confinement.
Future work

• Predict LM effects, and only apply enough control to prevent them
• Trade LM for unlocked NTM or QSM
• Use reactor-compatible sensors and actuators
• Max confinement: turn control off when not needed
• Robustness: “low tech” techniques