Magnetic Control of Locked Modes in Present Devices and ITER (WG-11)

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5 tokamaks, 2 spherical tokamaks, 2 RFPs and LHD are involved in WG-11

<table>
<thead>
<tr>
<th>AUG</th>
<th>DIII-D</th>
<th>JET</th>
<th>J-TEXT</th>
<th>KSTAR</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image1.png" alt="AUG" /></td>
<td><img src="image2.png" alt="DIII-D" /></td>
<td><img src="image3.png" alt="JET" /></td>
<td><img src="image4.png" alt="J-TEXT" /></td>
<td><img src="image5.png" alt="KSTAR" /></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>MAST</th>
<th>NSTX</th>
<th>LHD</th>
<th>EXTRAP-T2R</th>
<th>MST</th>
</tr>
</thead>
<tbody>
<tr>
<td><img src="image6.png" alt="MAST" /></td>
<td><img src="image7.png" alt="NSTX" /></td>
<td><img src="image8.png" alt="LHD" /></td>
<td><img src="image9.png" alt="EXTRAP-T2R" /></td>
<td><img src="image10.png" alt="MST" /></td>
</tr>
</tbody>
</table>
WG-11 tests robustness of magnetic control of LMs in different devices, for different coil geometries → Extrapolation to ITER

### Table 1. Geometry of devices considered and their control coils.

<table>
<thead>
<tr>
<th>Coil geometry:</th>
<th>AUG</th>
<th>DIII-D</th>
<th>EXTRAP-T2R</th>
<th>JET</th>
<th>J-TEXT</th>
<th>KSTAR</th>
<th>LHD</th>
<th>MAST</th>
<th>NSTX</th>
</tr>
</thead>
<tbody>
<tr>
<td>No. internal coils (pol.×tor.)</td>
<td>3×8</td>
<td>2×6</td>
<td>none</td>
<td>none</td>
<td>3×4</td>
<td>3×4</td>
<td>none</td>
<td>2×6</td>
<td>none</td>
</tr>
<tr>
<td>No. turns per internal coil</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>1</td>
<td>2</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>No. external coils (pol.×tor.)</td>
<td>none</td>
<td>1×6</td>
<td>4×32</td>
<td>1×4</td>
<td>1×2+1×3</td>
<td>none</td>
<td>2×10</td>
<td>1×4</td>
<td>1×6</td>
</tr>
<tr>
<td>No. turns per external coil</td>
<td>-</td>
<td>4</td>
<td>40</td>
<td>16</td>
<td>1</td>
<td>-</td>
<td>-</td>
<td>2</td>
<td>-</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Device:</th>
<th>AUG</th>
<th>DIII-D</th>
<th>EXTRAP-T2R</th>
<th>JET</th>
<th>J-TEXT</th>
<th>KSTAR</th>
<th>LHD</th>
<th>MAST</th>
<th>NSTX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Major radius R(m)</td>
<td>1.65</td>
<td>1.66</td>
<td>1.24</td>
<td>2.96</td>
<td>1.05</td>
<td>1.8</td>
<td>3.9</td>
<td>0.85</td>
<td>0.86</td>
</tr>
<tr>
<td>Aspect ratio A</td>
<td>3.3</td>
<td>2.5</td>
<td>6.7</td>
<td>2.96</td>
<td>3.96</td>
<td>3.6</td>
<td>8.3</td>
<td>1.3</td>
<td>1.3</td>
</tr>
<tr>
<td>Elongation κ</td>
<td>1</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Internal/external coils
- Angularly narrow/broad coils
- Dense/sparse arrays of coils
- Partial/full toroidal/poloidal coverage
- Different sizes, aspect ratios, elongations
Electrical engineering and physics are also different and will improve our understanding and predictive capabilities

<table>
<thead>
<tr>
<th>Power supply limits:</th>
<th>AUG</th>
<th>DIII-D</th>
<th>EXTRAP-T2R</th>
<th>JET</th>
<th>J-TEXT</th>
<th>KSTAR</th>
<th>LHD</th>
<th>MAST</th>
<th>NSTX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Max coil current $I$ (kA)</td>
<td>1.2</td>
<td>4.5 (SPA)</td>
<td>0.02</td>
<td>6</td>
<td>6 (int.)</td>
<td>5</td>
<td>1.92</td>
<td>3.3</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.5 (AA)</td>
<td></td>
<td>8 (ext.)</td>
<td>30</td>
<td>22</td>
<td>61</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max $B_r$ (G) at plasma edge</td>
<td></td>
<td></td>
<td></td>
<td>6 (int.)</td>
<td>0.01</td>
<td>7</td>
<td>dc (ext.)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max frequency $f$ (kHz)</td>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Other frequency limits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coil inductance limit (kHz)</td>
</tr>
<tr>
<td>Wall shielding limit (kHz)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Typical $n=1$ EFC settings:</th>
<th>AUG</th>
<th>DIII-D</th>
<th>EXTRAP-T2R</th>
<th>JET</th>
<th>J-TEXT</th>
<th>KSTAR</th>
<th>LHD</th>
<th>MAST</th>
<th>NSTX</th>
</tr>
</thead>
<tbody>
<tr>
<td>Amplitude (kA)</td>
<td>0</td>
<td>0.02-0.04</td>
<td>0</td>
<td>0.1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Tor. phase $\phi$ (deg)</td>
<td>-</td>
<td>-</td>
<td>-126</td>
<td>300</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Estimated intrinsic EF (G)</td>
<td>1-5</td>
<td>6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max $B_T$ (T) on axis</td>
<td>2</td>
<td>2.2</td>
<td>3.5</td>
<td>3</td>
<td>0.55</td>
<td>0.45</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\tau_W$ (ms)</td>
<td>2.5-3</td>
<td>10</td>
<td>3.1</td>
<td>20</td>
<td>15</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Rapidly/slowly varying or rotating MPs
- Strong/weak Magnetic Perturbations (MPs). Requirement: MP $\geq$ EF
- Different $\tau_W$
- KSTAR has very small EF
- Island in LHD is interchange mode, not NTM
From a casual conversation with colleagues about locked modes and disruptions: “What would you do if you were driving against a wall?”

- **Turn around** (change scenario, stay away from stability boundary)
- **Brake** (early benign discharge termination, “safe landing”)

- **Destroy the wall** with a high-power microwave beam (ECCD) or **Move the wall away**
  
  Both require magnetic control of phase of locking (WG-11)

- **Hope in the air-bag** (disruption mitigation by massive gas injection)
Controlling the toroidal phase of locking, in f/fwd or f/back, has numerous applications

Locked Mode (LM) and NTM Control, Disruption Avoidance:

• In combination with Electron Cyclotron Current Drive (ECCD):
  – Re- or “pre”-position LM to assist its cw ECCD stabilization.
  – Controlled rotation, in synch with modulated ECCD.

• Without ECCD:
  – Unlock island and spin it by NBI or magnetically.
  – Rotational stabilization by conducting wall, flow and flow-shear.

• Avoid locking by entrainment.

Other:

• Spread heat during disruptions.
• Assist diagnosis of islands.
• Study radiation asymmetries in massive gas injection.

* Pursued by other MDCs. Not a WG-11 task.
Previous WG-11 reports showed experimentally that static applied RMPs control the phase of

- **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
- **Quasi-single Helicity** mode in MST
- **Initially rotating** $m/n = 1/1$ Interchange Modes in LHD
different locking positions for the 4 external fields:

- 90° shift of the external error field
- consistently 90° phase difference in the plasma response for 90° different coils
- re-arranging of phase with increasing error field
- coil amplitude at time of plasma response gives orientation of intrinsic error field
Additional experimental evidence desirable to conclude this part of WG-11 activities

- Born-locked* $n=1$ modes (EF-penetration modes) in:
  - J-TEXT
- $m/n = 2/1$ LMs with rotating precursors in:
  - AUG, JET, MAST, NSTX

* RMPs pre-exist to Born-locked mode.

Would be instructive for ITER to apply RMPs after Born-locked mode has appeared → Can we control its phase in
  - AUG, DIII-D, JET, J-TEXT, KSTAR, MAST, NSTX?
New activities: **modeling effect of rotating RMPs on locked or nearly-locked mode**

Solve equation of angular motion

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

\[ \text{e.m. torques } \mathbf{T} = \int \mathbf{r} \times d\mathbf{F} = \int \mathbf{r} \times \left( I \, dl \times \mathbf{B} \right) \]
New activities: modeling effect of rotating RMPs on locked or nearly-locked mode

\[ I \ddot{\phi} = T_{EF} + T_{MP} + T_{wall} + T_{NTM} + T_{NB1} + T_{visc} \]

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

No other NTM (strong assumption!)  Balanced injection, Low rotation

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

\[ 0 = T_{MP} + T_{wall} \]  
→ Find \( T_{wall} \) for given isl. width, rot.freq., etc.  
Find coil-current needed for \( T_{MP} = -T_{wall} \)
New activities: 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**

modelled by Interaction between Helical Currents:

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

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

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

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

\[ T_{TM} = -\pi^2 R^2 m \sum_{m', n'} \frac{r_{m'n'}}{r_{mn}} \sin[n \phi(t)] I_{m'n'} B_R[r_{m'n'}] \]

(Viscous Torques on resonant surface)

(NB: Island not exactly “frozen”: rotates at \( \leq \omega_{*s} \))
At DIII-D, rotating field drives mode rotation at 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 can be lost due to failure of applied torque to counteract braking torque from the wall at high frequency.

Max frequency increases with coil current and decreases with island width.
With available power supplies, NSTX-U 1x6 ext. coils could entrain modes at $\sim 350$ 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
RMPs in DIII-D compete with stronger $T_{\text{wall}}$, explaining slower entrainment

- coils: using 1x6 external coils (C-coils)
- major radius: 1.72 m
- wall time: 3 ms
- density: $2.2 \times 10^{19}$ m$^{-3}$
- $B_t$: 1.86 T
J-TEXT internal coils expected to entrain 2/1 modes at >600 Hz ($\Omega \tau_w \approx 11$)

- 3 sets of 4 internal coils treated as one set
- external coils ignored: DC only
- major radius: 1.05 m
- wall time: 3.1 ms
- density: $1 \times 10^{20}$ m$^{-3}$
- $B_t$: 3.5 T
Moment of Inertia

- Linear with radial location of island
- Quadratic with island width
- Linear with plasma density at island location
Non-linear modeling of:

<table>
<thead>
<tr>
<th>Locking</th>
<th>Unlocking</th>
<th>Entrainment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Add locking-event*.swf</td>
<td>Add icoils-rampup*.swf</td>
<td>Add icoils-entrainment*.swf</td>
</tr>
</tbody>
</table>

- **LM**
- **Non-mode \( B_x \)**
- **EF**
- **\( B_x + EF \)**
- **RMP**
- **B from eddy currents in wall**
Summary, conclusions and future work on LM control by static RMPs

• Static applied RMPs controlled toroidal phase of:
  – Locked modes with rotating precursors in DIII-D, EXTRAP-T2R, J-TEXT, KSTAR;
  – “Born locked” modes seeded by the applied MPs in AUG, JET, KSTAR, MAST, NESTX;
  – Interchange mode in LHD;
  – Dominant mode in quasi-single helicity plasmas in MST.

• Future work: show control of toroidal phase of:
  – Locked modes with rotating precursors also for AUG, JET, MAST, NSTX;
  – “Born locked” modes, after mode appearance.

• More future work:
  – Use filament model to calculate e.m. torques and compare with “competing” torques (e.g., NBI). Can torque balance be established for any $\phi_{lock}$?
  – Synthetic diagnostic of $\phi_{lock}$ in present devices.
  – If it agrees with measured $\phi_{lock}$, predict e.m. torque and $\phi_{lock}$ in ITER.
    Coils currents sufficient for full $\phi_{lock}$ control?
  – Contours of $\phi_{lock}$ as function of $A_{MP}$ and $\phi_{MP}$. 
Summary, conclusions and future work on LM control by *rotating* RMPs

- Island dynamics was modeled in DIII-D under effect of EF, RMP and wall torques.
- Modeling also started for J-TEXT, KSTAR and NSTX
  - Max entrainment frequencies achievable
  - Moment of inertia of island $\rightarrow$ responsiveness to torques applied
  - Need more time to implement peculiar KSTAR coil geometry
- Time-dependent results for locking, unlocking and entrainment presented for DIII-D
- Future work: extend both torque-balance and time-evolving simulations to AUG, EXTRAP-T2R, JET, MAST, MST.
  - In JET (1x4 coils), only simulate $n=1$ locking. No unlocking or entrainment.
About effectiveness of locked mode control at avoiding disruptions

• When combined with ECCD, effectiveness at DIII-D is 100%
  – Provided ECCD alignment is good, and power sufficient (same requirements as for NTM control)
  – Not many experiments carried out → 10-20 discharges, all successful, including at low $q_{95}=3.5$ and only using external coils.
  – Higher statistics desirable. “Low tech” pre-programmed techniques?

• Desirable if other devices contribute magnetic control of locked modes + their stabilization by ECCD
  – AUG and KSTAR only WG-11 devices with ECCD, besides DIII-D

• Disruption avoidance w/o ECCD?
  – Some evidence at DIII-D and J-TEXT.
  – Earlier results by DITE, COMPASS-C and TEXTOR
  – Analysis of ~22,000 DIII-D plasma discharges shows ~50 (~1080) disruptions due to rotating (locked) islands
  – All WG-11 colleagues, please check. We can provide routines for automatic build-up and analysis of database.
Back-up Slides
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
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
EXTRAP-T2R (4x32 external coils)

$n= -15$ TM locks with different phases
if $n= -15$ RMP is applied, with $\phi_{RMP}=0^\circ$ (left) or only intrinsic $n= -15$ EF is present (right)

shot 24776

- Coil current
- RMP
- TM velocity
- TM phase

shot 21604

- Coil current
- EF
- TM velocity
- TM phase

L. Frassinetti
Error-field penetration Locked Modes form at phase of strong applied MP.

T. Hender
n=1 RMPs applied with different phases cause pre-existing rotating TM to lock with different phases
KSTAR (3x4 internal coils)

Rotating NTMs rarely observed to lock. Ascribed to very small EF and wall torque. Low-density LMs lock to applied MPs.

Error Field Compass Scan
with MID-RMP coils only
(density normalized)

Excluded in 3 point circle fitting

Amp [Am²]: 35.1, phase [deg]: 70.7

Y. In
A locked mode in KSTAR is not frequently observed, likely thanks to a very low intrinsic error field.

- Rotating mode leads to a locked mode near t=0.8 sec, which is one of the rare events in KSTAR.
- AC power supply to be installed from 2015.
LHD detected $n=1$ EF by electron-beam mapping of vacuum flux surfaces

$m/n = 1/1$ island

T. Morisaki, FST 2010
LHD (2x10 external coils)

Rotating 1/1 interchange island locks to EF, or to different positions if different EF corrections are used.
MAST (2x6 internal, 1x4 ext. coils)

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

A. Kirk
At MST, 38x1 external coils align dominant $m=1$, $n=5$ mode (Quasi Single Helicity) to any phase of choice.

S. Munaretto
See poster PP8.022
NSTX (1x6 external coils)

When $n = 1$ fields are applied with different phases, $n = 1$ modes lock with different phases.

$n = 1$ applied field current, $\phi_{RMP} \approx 330^\circ$

LM amplitude

LM phase $\phi_{LM} \approx 300^\circ$

$n = 1$ applied field current, $\phi_{RMP} \approx 210^\circ$

LM amplitude

LM phase $\phi_{LM} \approx 180^\circ$

S. Sabbagh
KSTAR 2/1 mode

- Coils: internal 3 sets (upper, mid-plane, lower) of 4 coils
  - Currently projected as one set, centered at mid-plane
  - Unsure about wiring
- Major radius: 1.8 m
- Wall time: 20 ms
- Density: $1 \times 10^{20} \text{ m}^{-3}$
- $B_t$: 3.5 T