Statistical Survey of Mode Locking at DIII-D

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Motivation

• Neoclassical Tearing Mode (NTM) – one of the principal limits to high $\beta$ operation in tokamaks

• Locked Modes (LMs) can lead to disruptions

• 20,000 DIII-D discharges analyzed for LM database

• Better understanding of LM physics

• LM Control & ITER
Outline

- Categories of Mode Locking
- Quantitative definition of Mode Locking
  - NTM locking
  - Born-locked
  - Disruptive LM
- Statistical results
- Characterization of typical mode locking
  - Typically locks ~30ms after $f<2$kHz (control programming)
  - Preferential locking phase (control design)
- Disruptive LMs
  - General correlation: bigger modes disrupt more rapidly
  - Grow in amplitude before saturation and disruption (pertinent to control)
Categories of Mode Locking

- **With rotating precursor (NTMs)**
  - 2/1 mode, most abundant and deleterious
  - Locking to EF, resistive wall

- **Without rotating precursor (born-locked modes)**
  - EF penetration

- **After onset LM can:**
  - Evolve into Quasi-stationary mode (QSM)
  - Cause disruption
  - Controlled by:
    - Neutral beam injection (NBI)
    - electron cyclotron current drive (ECCD)
    - Magnetic perturbation (MP)
Mirnov Coils are Used to Flag NTMs and LMs with Precursors

- $B_{p,n=1}$: $n=1$ mode amplitude
- $f_{n=1}$: $n=1$ mode frequency

(obtained after Fourier Analysis)

- “Finite amplitude NTM”: $B_{p,n=1} > 2$ Gauss for 100 ms
- “Alarm”: $f_{n=1} < 2$ kHz for 30 ms
- Locking:
  - $B_{p,n=1} > 2$ Gauss for 100 ms
  - $f_{n=1} > 0$ consistent with zero within ± 3 s for 20 ms
LM Amplitude and Phase are Inferred from External Saddle Loop Differences (ESLDs)

After applying:

- Baseline Subtraction before locking
- Low-pass filter (f<100Hz)
Born-locked Modes have No Rotating Precursors but are Recognized from ESLDs

With rotating n=1 precursor

Without rotating n=1 precursor

B_r (G)

B_r (G)

φ (deg)

φ (deg)
Born-locked Modes have No Rotating Precursors but are Recognized from ESLDs

No \( n=1 \) rotating precursor →

Born-locked Modes visible in ESLD, sensitive to \( f<100\text{Hz} \) →

- Criterion: \( A_{\text{ESLD}} > 5\text{G} \) for \( t >50\text{ms} \), not visible on Mirnov
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Disruption Database

- Typical time-sequence of a disruption

![Graph showing disruption database with time-sequence](image)

- Energy conf. time (100ms)
- Programmed ramp down
- No. of shots
- Cumulative distribution
Outline

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Statistic Analysis of 20000 Shots

20,000 shots
Statistic Analysis of 20000 Shots

13003 plasma shots*

2342 disruptions

137 Disruptive born LM (23%)

586 born-locked

658 NTM locking

182 Disruptive LM (28%)

* = IP > 100kA for at least 100ms
Statistic Analysis of 20000 Shots

8460 high $b_N (>1.5)$ plasma shots

- 1433 disruptions
  - 369 born-locked
  - 378 NTM locking
  - 134 Disruptive LM (35%)
  - 101 Disruptive born LM (27%)

Test shots $\beta_N < 1.5$ or not available
Statistic Analysis of 20000 Shots

11,000 plasma shots without control*

107 Disruptive born LM (22%)

498 born-locked

435 NTM locking

142 Disruptive LM (33%)

1959 disruptions

* = w/o reducing NBI power (thus, $\beta_n$) in response to LM detector
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• Qualitative definition of Mode Locking
• Statistical results

• **Characterization of typical mode locking**
  – Typically locks ~30ms after $f<2\text{kHz}$ (control programming)
  – Preferential locking phase (control design)

• Disruptive LMs
Typically Mode Locks ~30ms After $f<2\text{kHz}$

Bigger Modes at Alarm Lock More Rapidly
Locking to EF Dominates over Locking to Resistive Wall in the Final Stage

Magnetic dipole of the rotating mode

Static Error Field
Locking to EF Dominates over Locking to Resistive Wall in the Final Stage

Locking without rot. precursor

- EF penetration
  - $f = 195 \pm 28$ deg
  - (141 events)

Locking with rot. precursor

- Over-corrected EF (434 events)
  - $f = 202 \pm 20$ deg
  - (Empirical EFC 230 deg)

- Consistent with EF phase (224 events)
  - $f = 315 \pm 86$ deg

$\pm$ values in degrees (deg.)
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- Disruptive LMs
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  - Grow in amplitude before saturation and disruption (pertinent to control)
LMs Survive ~200-700ms Before Disruption (if any)
Bigger Modes Disrupt More Rapidly

Upper limit for survival time
Average survival time

No. of Disruptive LM

Survival Time (ms)

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LM Continues to Grow in Amplitude
Saturates in ~100ms
Identikit for Mode-locking

If born rotating:
- Locks ~30ms* after f<2kHz
- Locks at f ≈ 200° or 310°
- Keeps growing for the first 100ms after locking
- 28% of the time it disrupts, typically after 500ms*
- Disruptivity reduced if control in use

If born locked:
- Locks at f ≈ 200° or 340°
- 23% of the time it disrupts
- Disruptivity reduced if control in use

*or faster/slower depending if larger/smaller than normal
Summary

- Magnetic Diagnostics are used to recognize LMs
- Bigger modes lock more rapidly
- Preferential locking position
- LM grows in amplitude to saturation before disruption
- Bigger modes disrupt more rapidly
Mode Rotation and Locking are Described by Torque Balance

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

**E.m. Torques on Island**

modelled by Interaction between Helical Currents:

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

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

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

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

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

**Viscous Torques on resonant surface**

(NB: Island not exactly “frozen”: rotates at \( \leq \omega_{*s} \))

- \( I_h \) is the helicity current.
- \( T_{wall} \) is the wall torque.
- \( T_{EF} \) is the E.M. force on the island.
- \( T_{RMP} \) is the resonant magnetic perturbation force.
- \( T_{TM} \) is the toroidal magnetic moment force.
Other Causes for Disruptions

- high plasma density
- β-limit
- low q(a) profile
- vertical instability
- current rise
- fragments of the impurity

2342 disruptions
586 born-locked
658 NTM locking
Statistic Analysis of 20000 Shots

2003 plasma shots with dud

- 30 Disruptive born LM (34%)
- 88 born-locked
- 383 disruptions
- 223 NTM locking
- 40 Disruptive LM (18%)
More on Disruptivity

Disruption/disruptivity and
(1) betaN
(2) Mode amplitude (no general correlation)
(3) proximity to wall Hugill/Troyon diagram

![Disruptivity Chart]

![Mode Amplitude Chart]
More on Locking

Big picture: 26% of NTMs lock (729 out of 2809)

(1) Dud (anti-correlation)
(2) q95
(3) Mode amplitude
Fit Locking Timescale to Simplified Torque Balance Model

AUTOMATE THE FITTING?

- 2-parameter model:

\[
\frac{d\omega}{dt} = \frac{\omega_0 (\tau_M/\tau_{M0}) - \omega}{\tau_M} - \frac{C_1 (w/a)^3}{2\omega \tau_{A0}^2 \tau_w} \\
\frac{\tau_M}{\tau_{M0}} = \frac{1}{1 + C_2 (w/a)}
\]

- Critical island width for locking

\[
\left(\frac{w}{a}\right)^3 \left(1 + \frac{C_2 w}{a}\right) = \frac{\omega_0^2 \tau_{A0}^2}{2C_1}\left(\frac{\tau_w}{\tau_{M0}}\right)
\]

- Critical island width for unlocking

\[
w_{\text{marg}} \approx 2\epsilon^{1/2} \rho_{\theta i}
\]

\[
\rho_{\theta i} = (2m_i k_B T/e^2 B^2_\theta)^{1/2} \quad \epsilon = r/R_0
\]