Statistical Survey of Mode Locking at DIII-D

By
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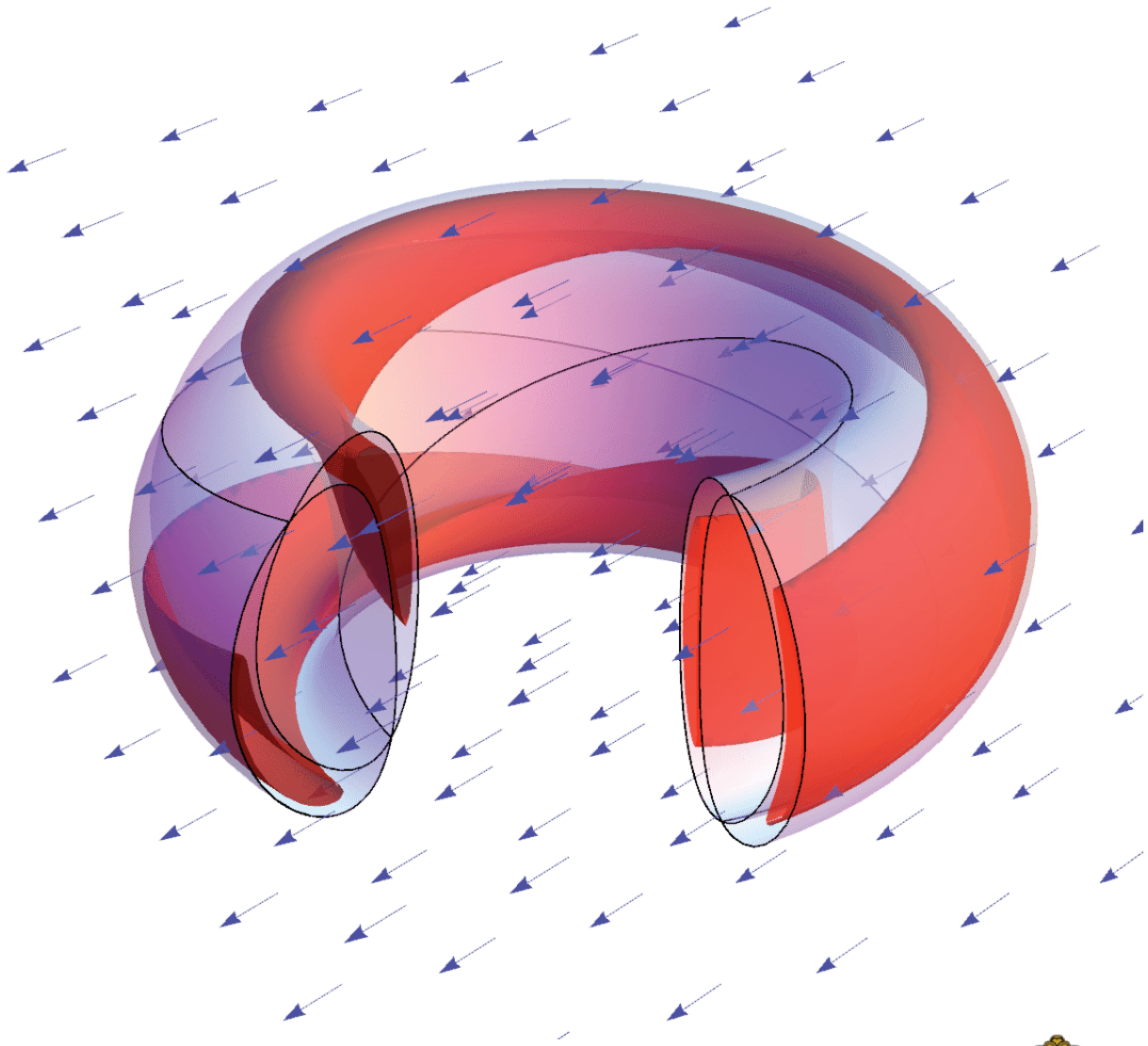

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Motivation

- Neoclassical Tearing Mode (NTM) – one of the principal limits to high β 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

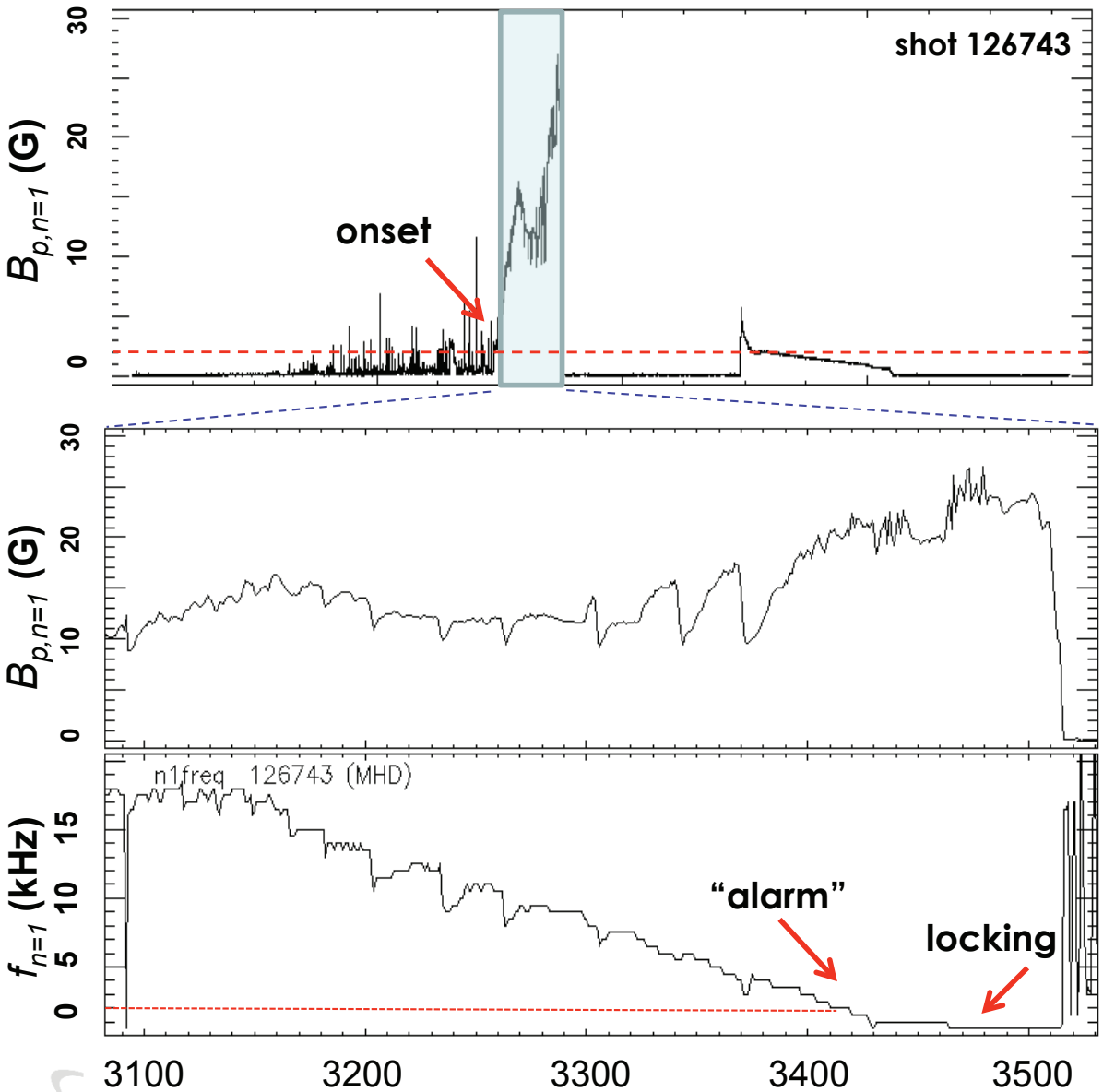
- **Categories of Mode Locking**
- **Quantative definition of Mode Locking**
  - NTM locking
  - Born-locked
  - Disruptive LM
- **Statistical results**
- **Characterization of typical mode locking**
  - Typically locks ~30ms after f<2kHz (control programming)
  - Preferential locking phase (control 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



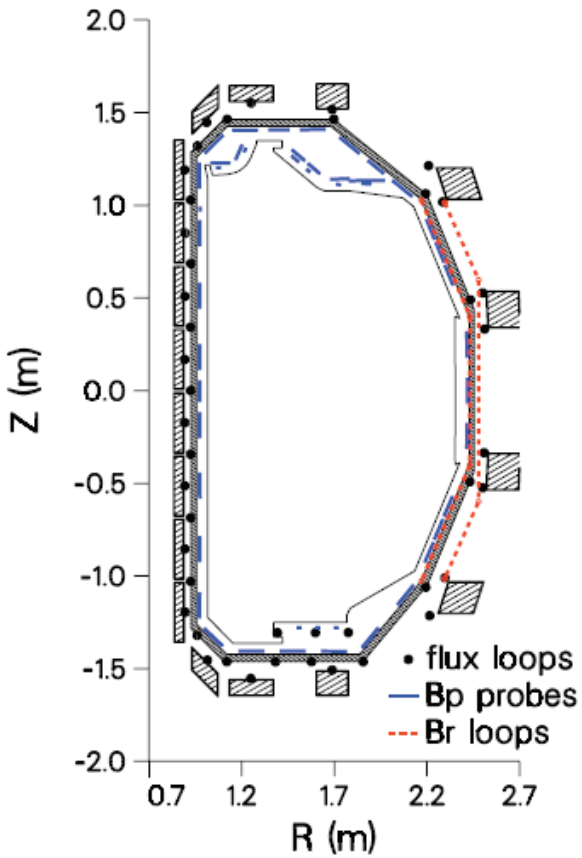
- $B_{p,n=1}$: n=1 mode amplitude
- $f_{n=1}$: n=1 mode frequency

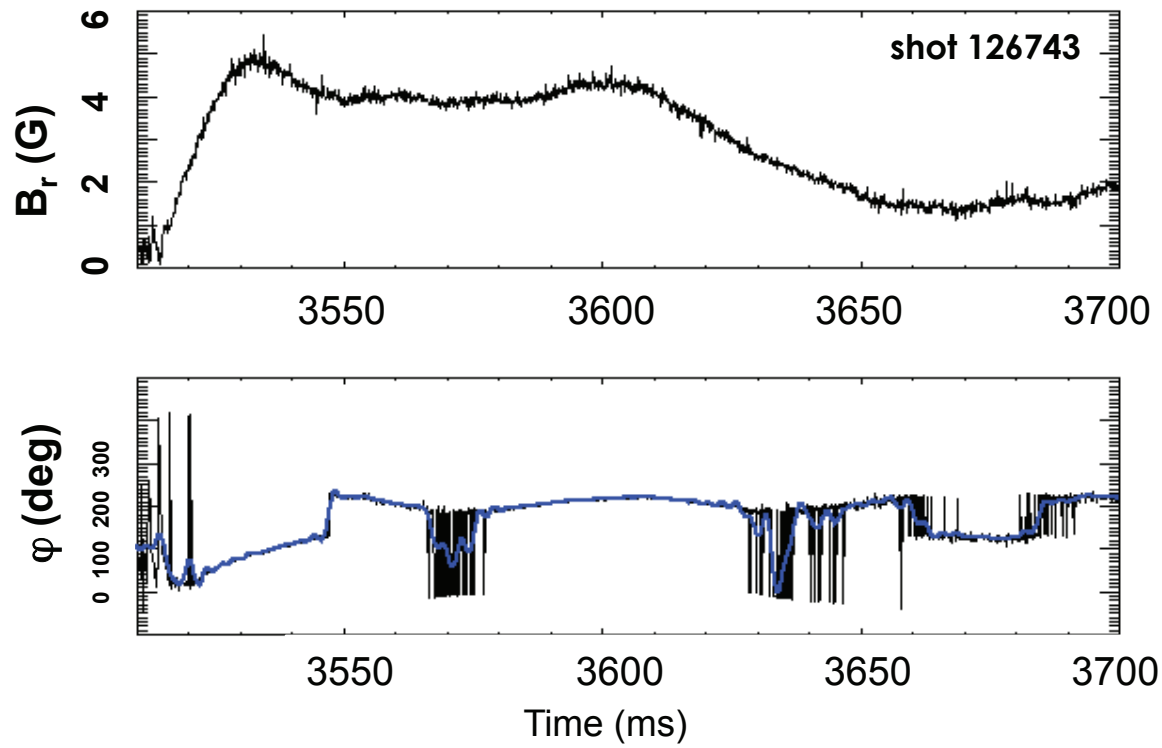
  (obtained after Fourier Analysis)

- **"Finite amplitude NTM":**
  $B_{p,n=1}$ >2Gauss for 100ms
- **"Alarm":**
  $f_{n=1}$ <2kHz for 30ms

- **Locking:**
  $B_{p,n=1}$ >2Gauss for 100ms
  $f_{n=1}$ consistent with zero within ± 3s for 20ms

LM Amplitude and Phase are Inferred from External Saddle Loop Differences (ESLDs)

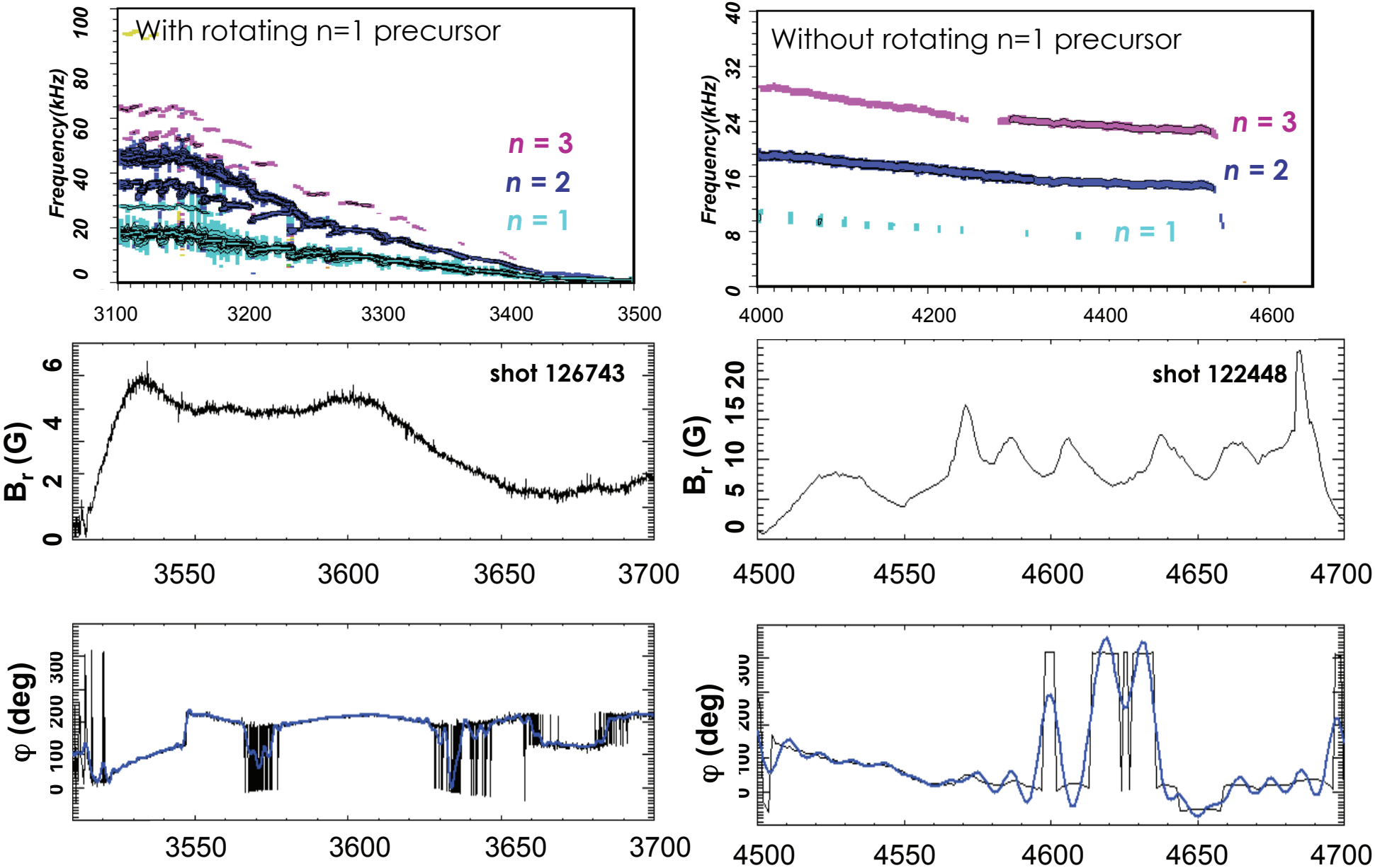




After applying:

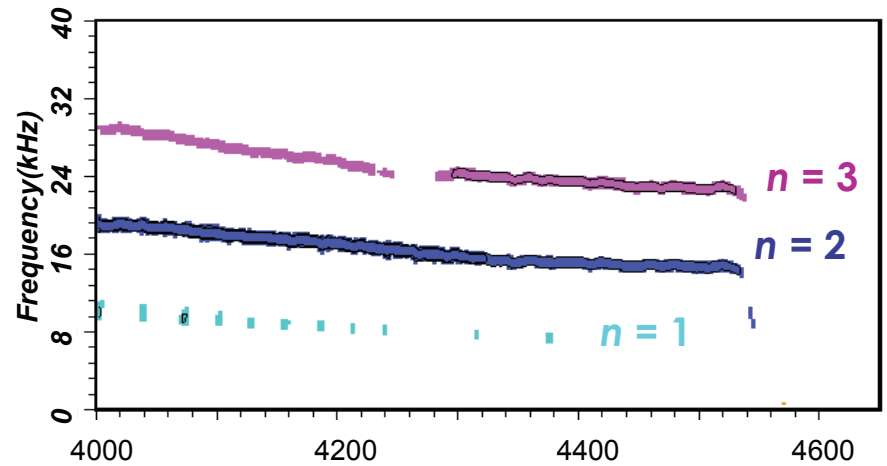
- **Baseline Subtraction before locking**
- **Low-pass filter (f<100Hz)**

Born-locked Modes have No Rotating Precursors but are Recognized from ESLDs

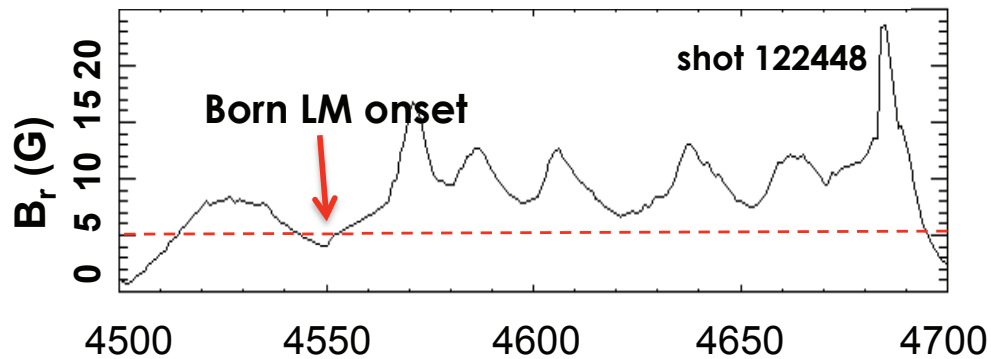


Born-locked Modes have No Rotating Precursors but are Recognized from ESLDs

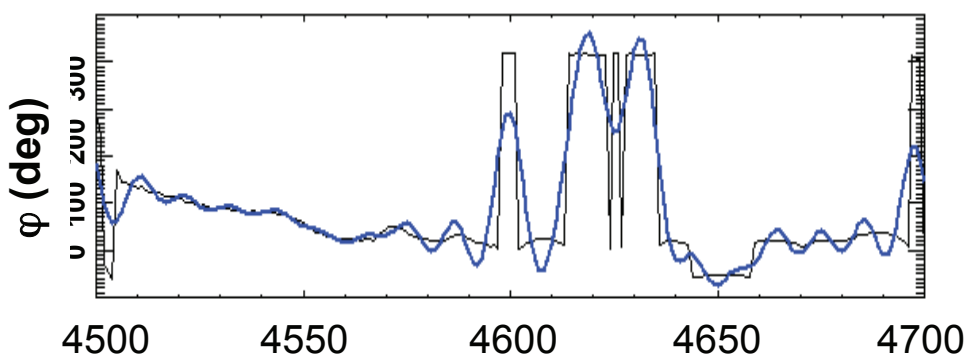
No n=1 rotating precursor →



Born-locked Modes visible in ESLD, sensitive to f<100Hz →



- Criterion: A_{ESLD} > 5G for t >50ms, not visible on Mirnov

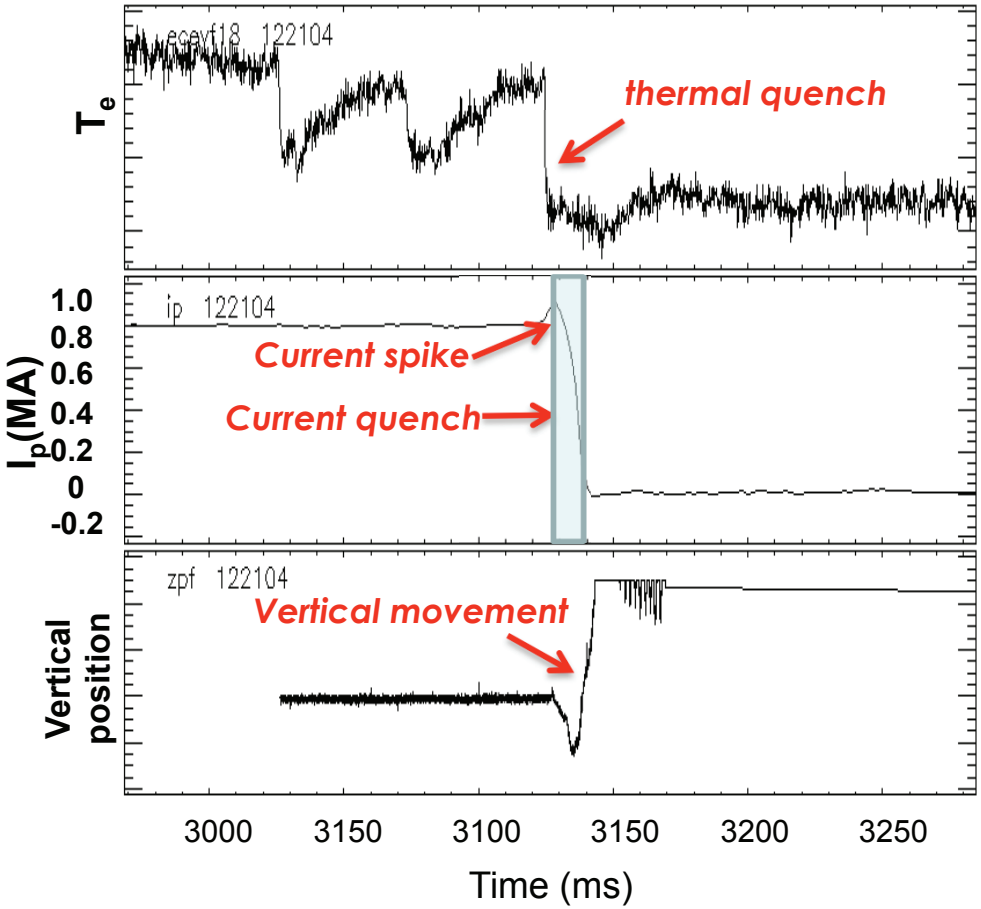


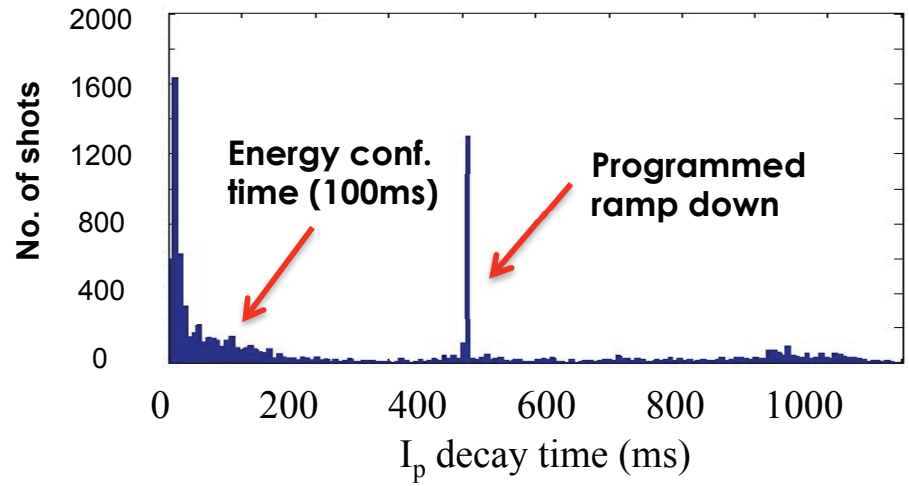
Outline

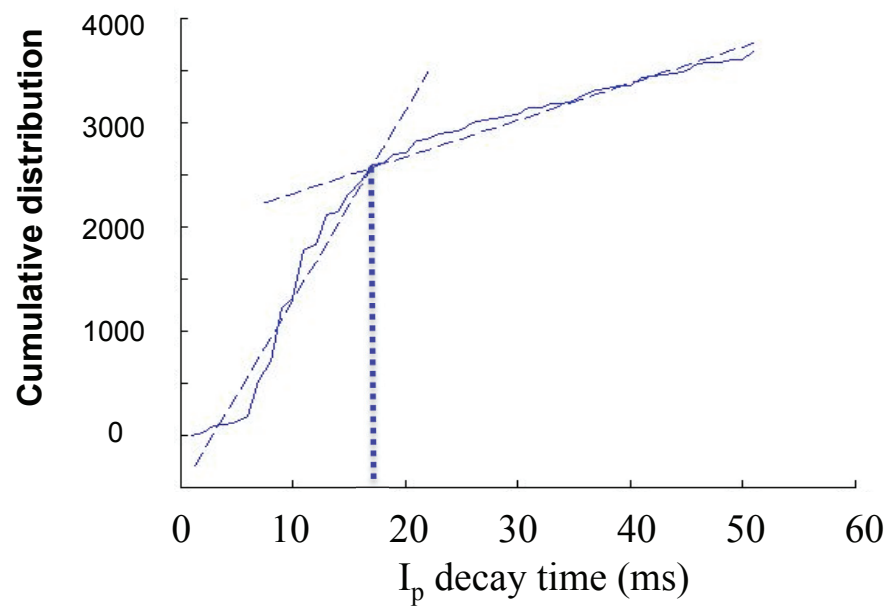
- Time sequence of Mode Locking
- Qualitative definition of Mode Locking
  - NTM locking
  - Born-locked
  - Disruptive LM
- Statistical results
- Characterization of typical mode locking
- Disruptive LMs

Disruption Database

- **Typical time-sequence of a disruption**







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- Categories of Mode Locking
- Quantitative definition of Mode Locking

- **Statistical results**
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Statistic Analysis of 20000 Shots

20,000 shots

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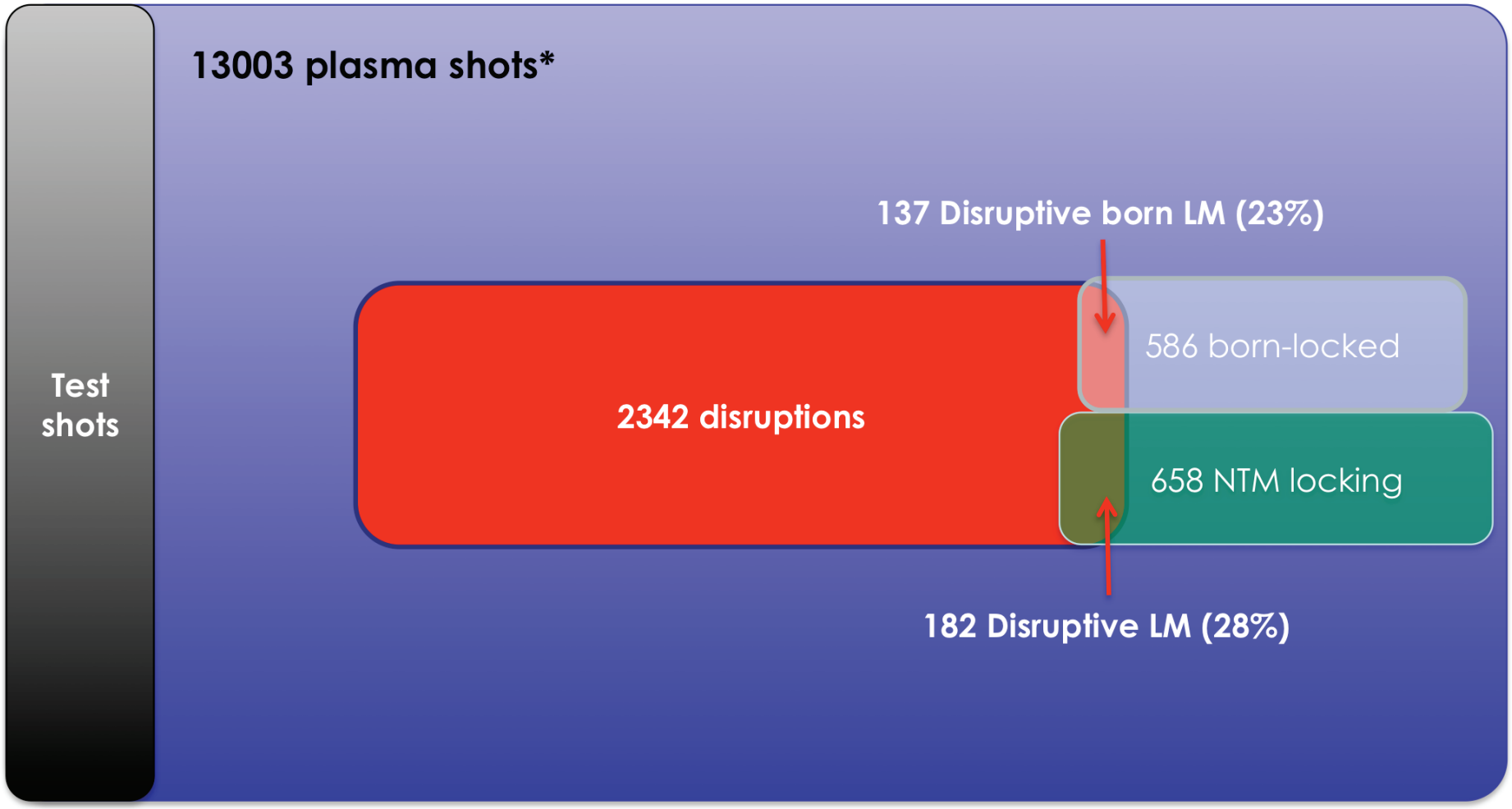
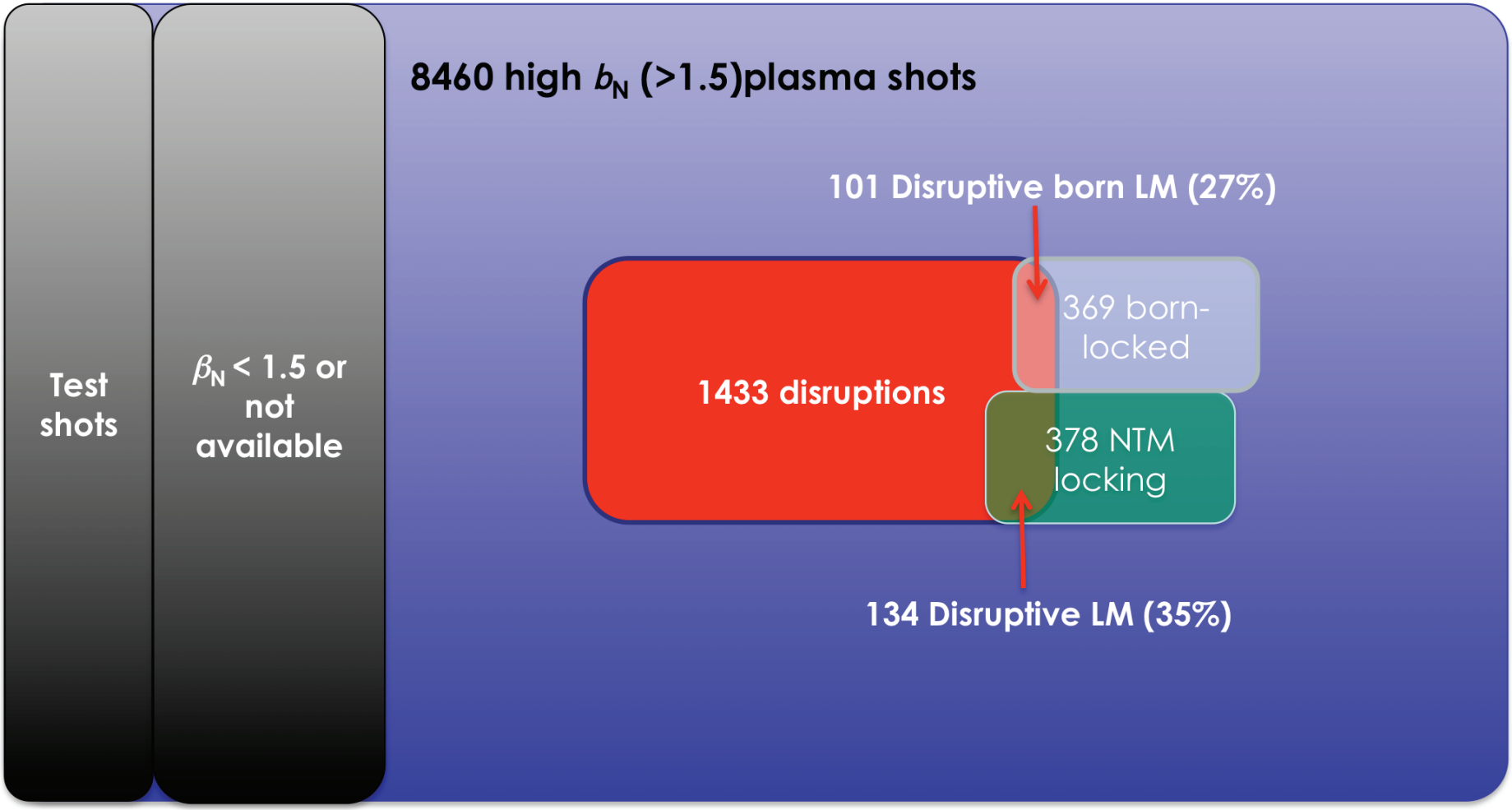


* = IP > 100kA for at least 100ms

Statistic Analysis of 20000 Shots



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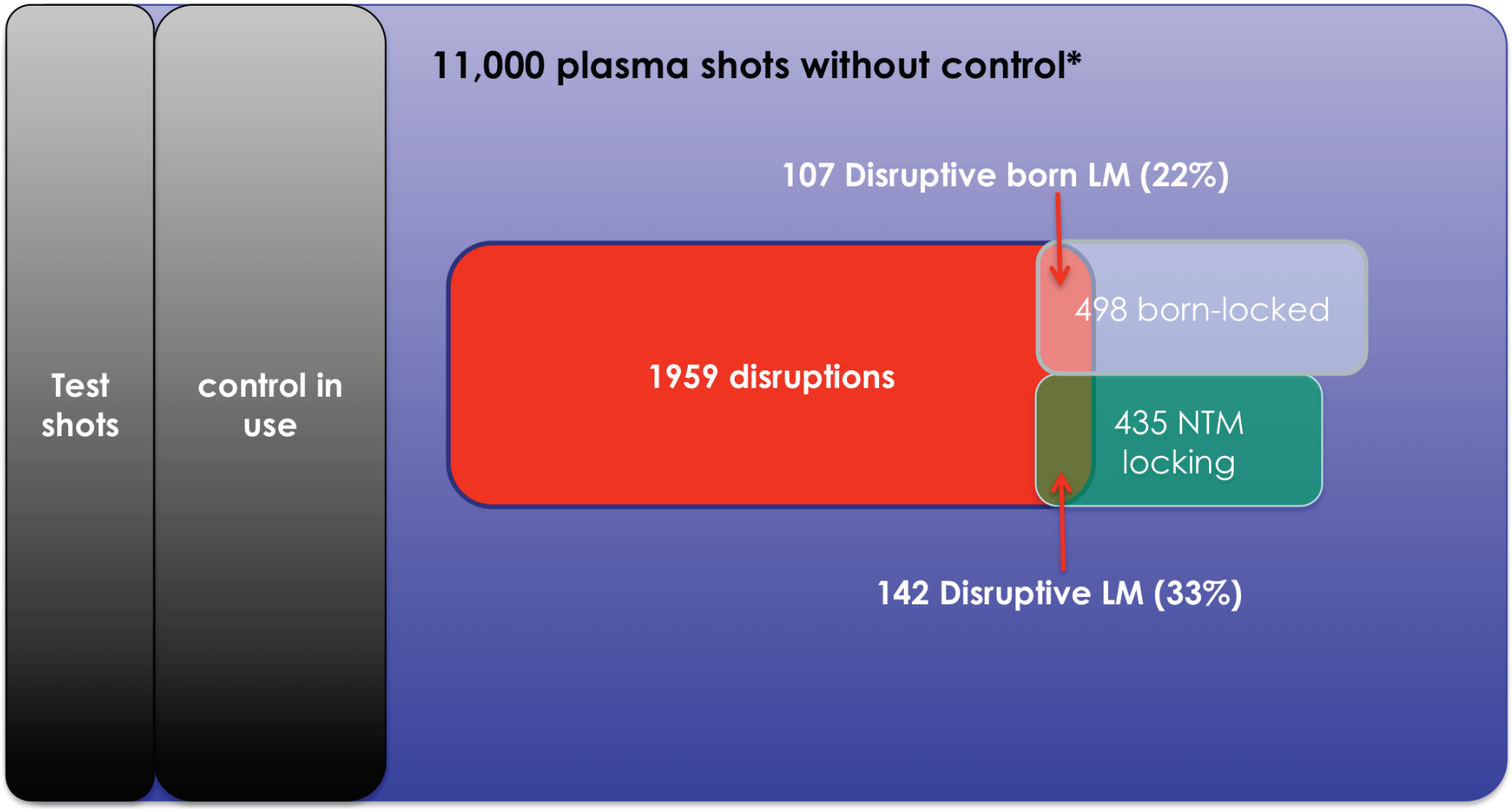

* = w/o reducing NBI power (thus, β_N) in response to LM detector

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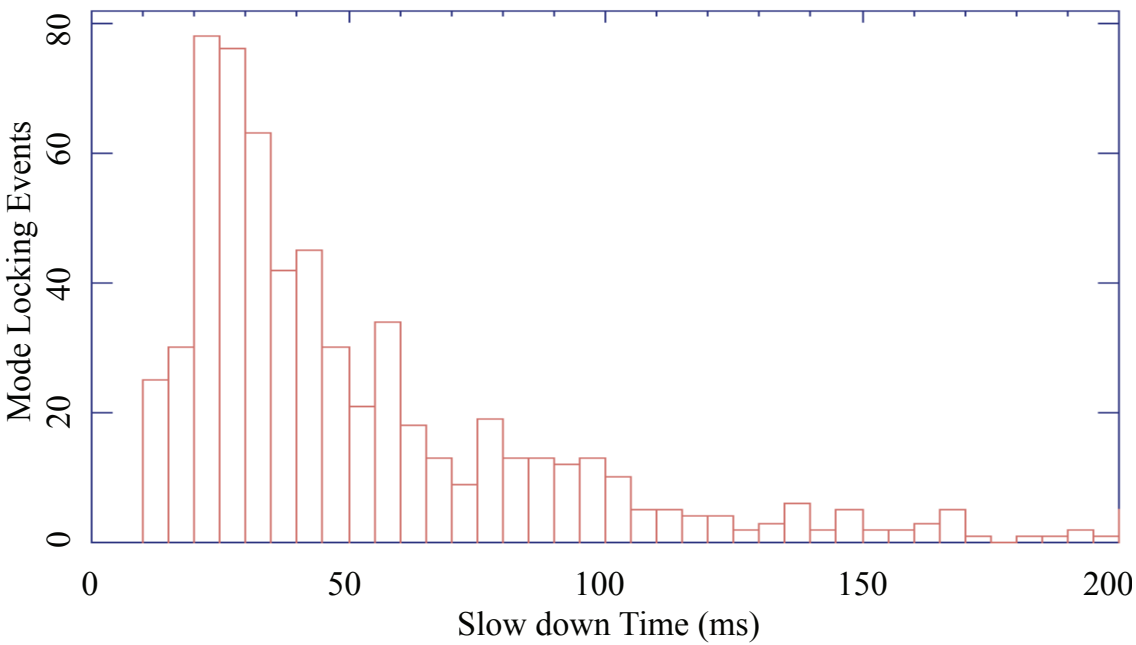
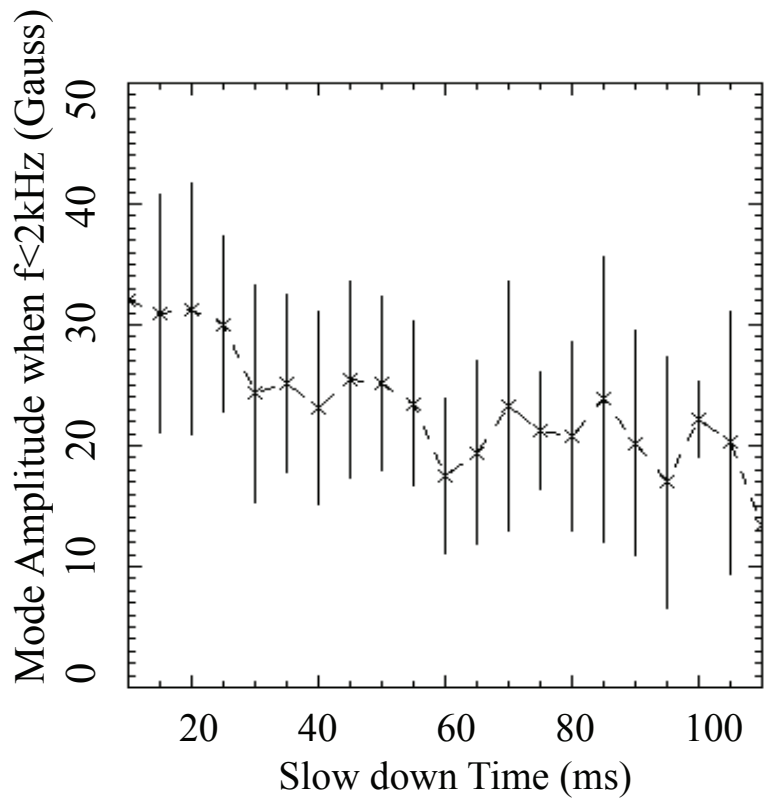
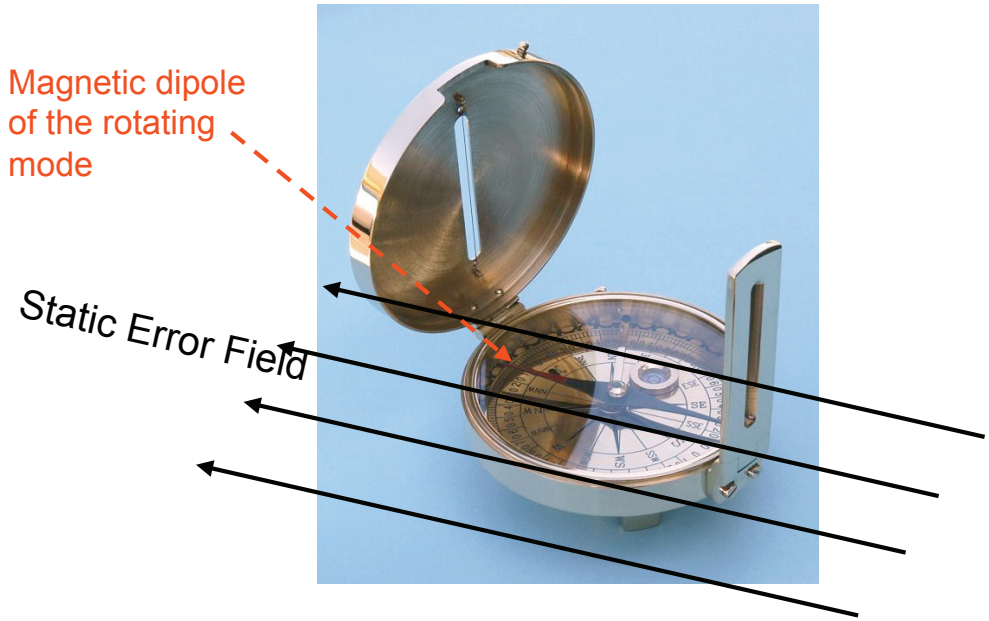
Typically Mode Locks ~30ms After *f*<2kHz
Bigger Modes at Alarm Lock More Rapidly





Locking to EF Dominates over Locking to Resistive Wall in the Final Stage



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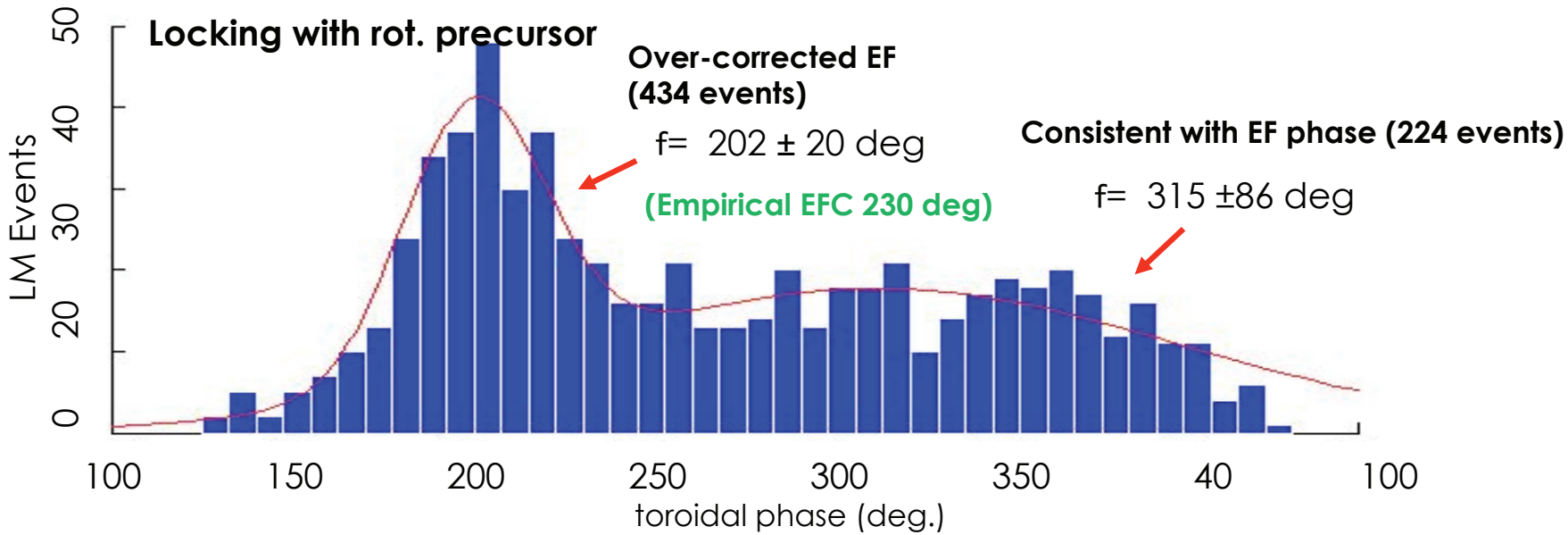

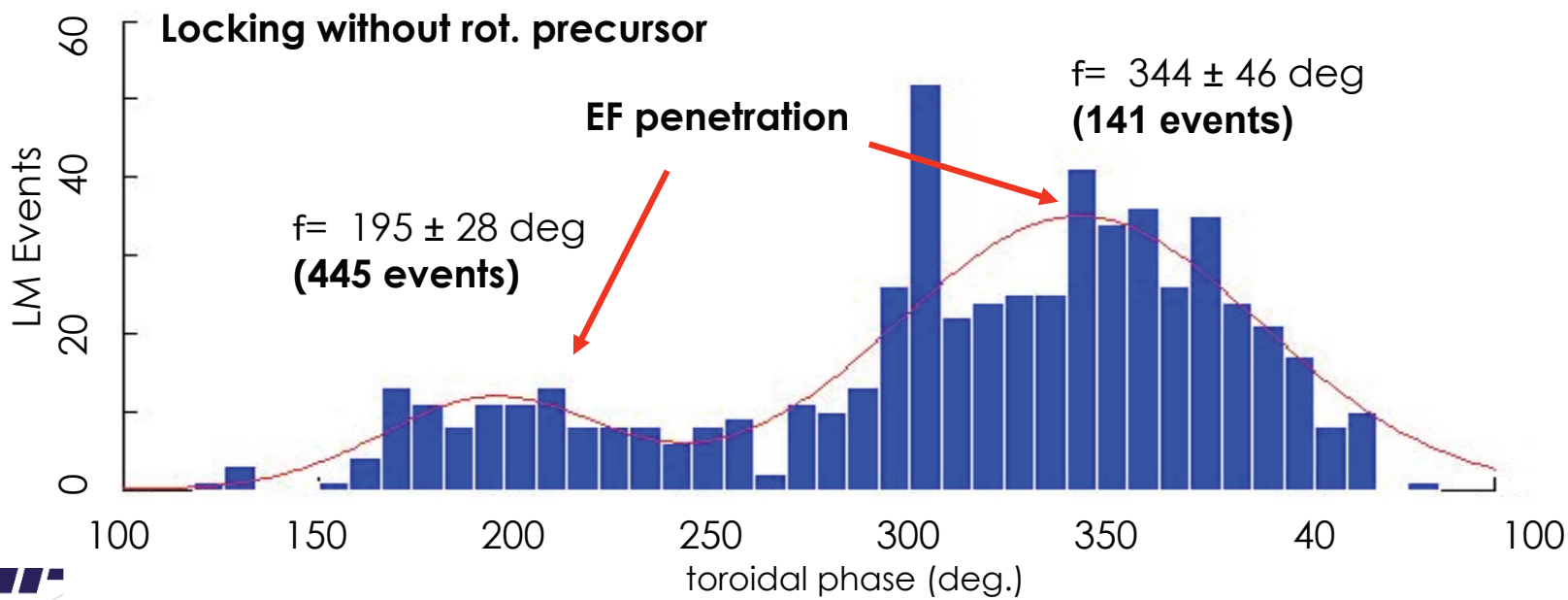

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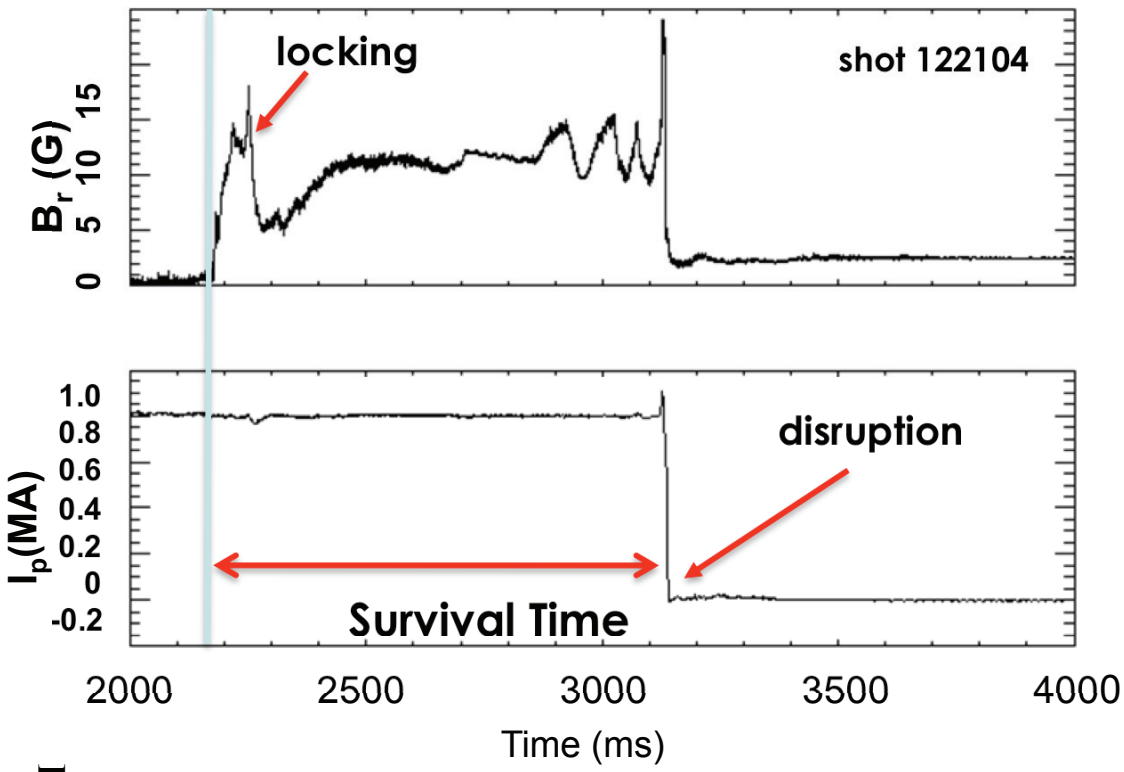
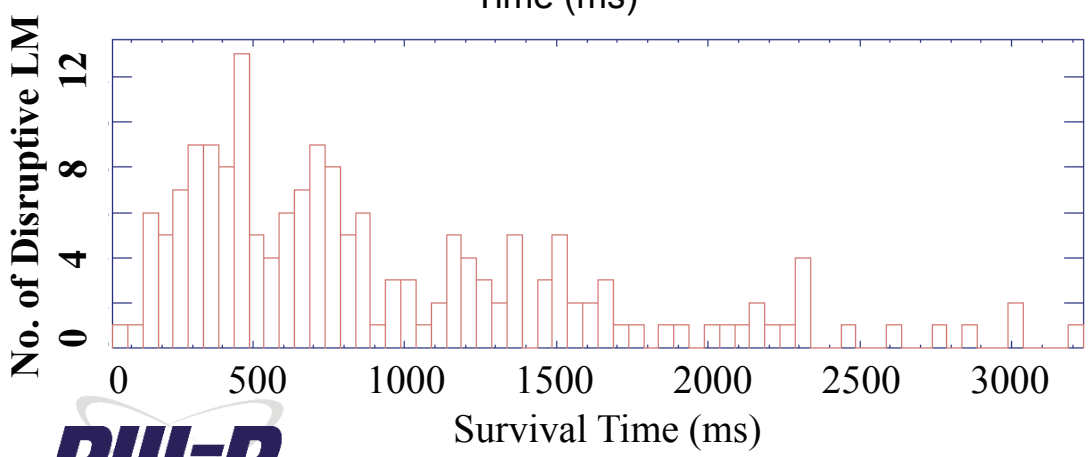
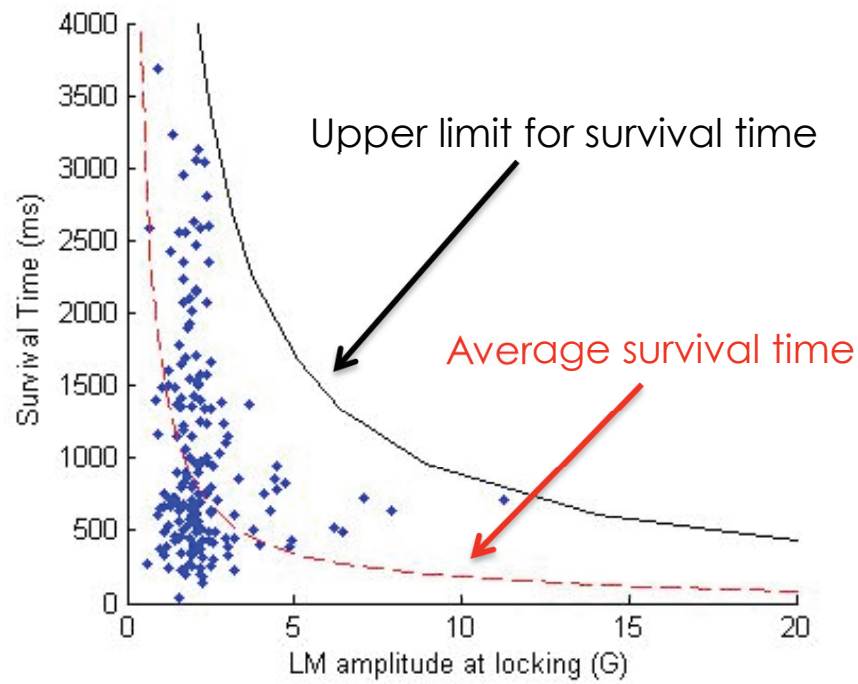
LMs Survive ~200-700ms Before Disruption (if any) Bigger Modes Disrupt More Rapidly







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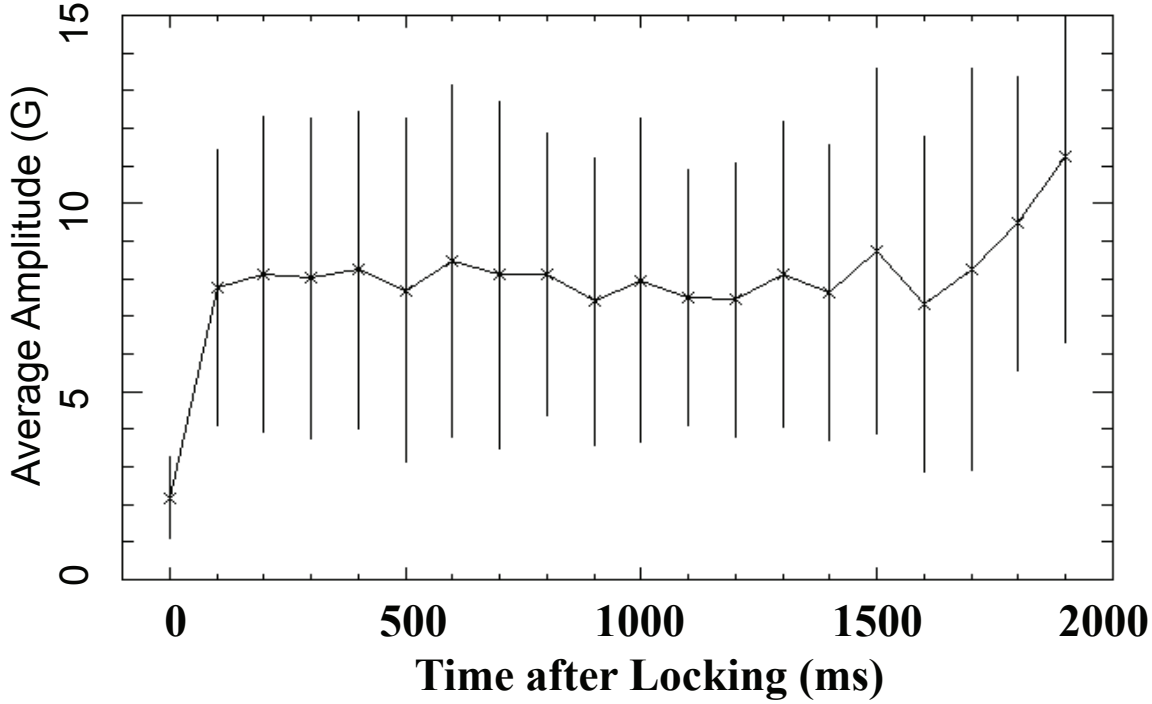
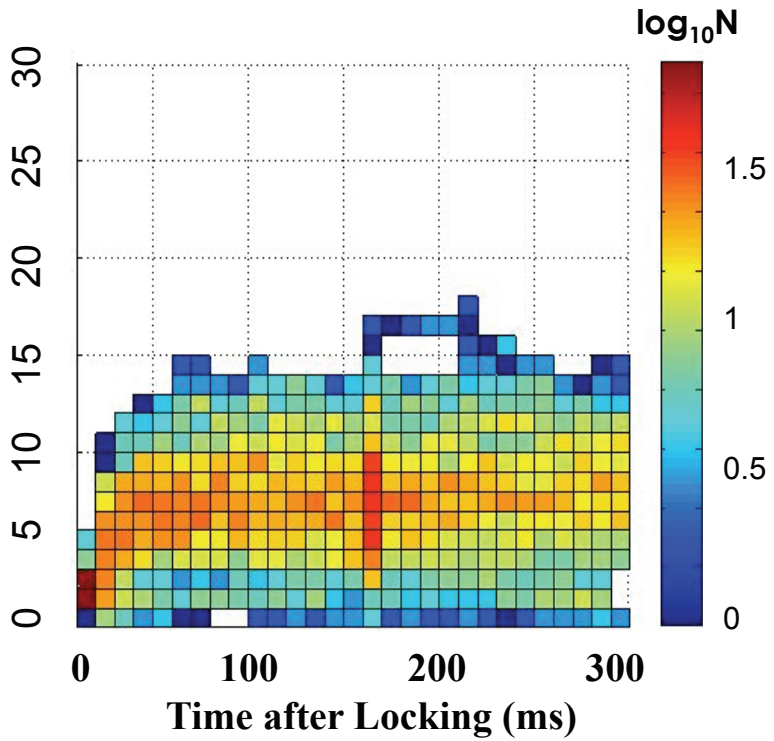
LM Continues to Grow in Amplitude Saturates in ~100ms





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

Back-up Slides

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:

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

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

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

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

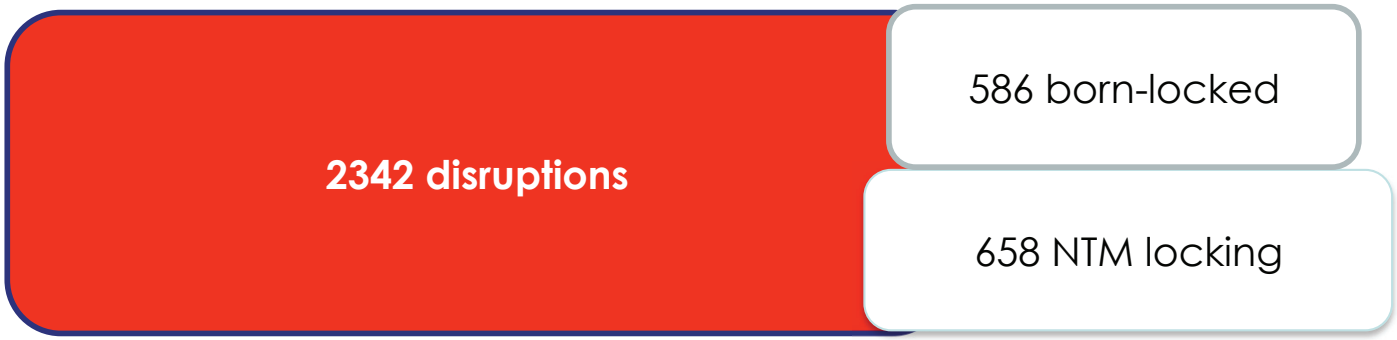
$$T_{TM} = -\pi^2 R^2 m \sum_{m',n'} \frac{r_{m'n'}}{r_{mn}}\sin[n\phi(t)] I_{m'n'} B_R[r_{m'n'}]$$

Viscous Torques on resonant surface

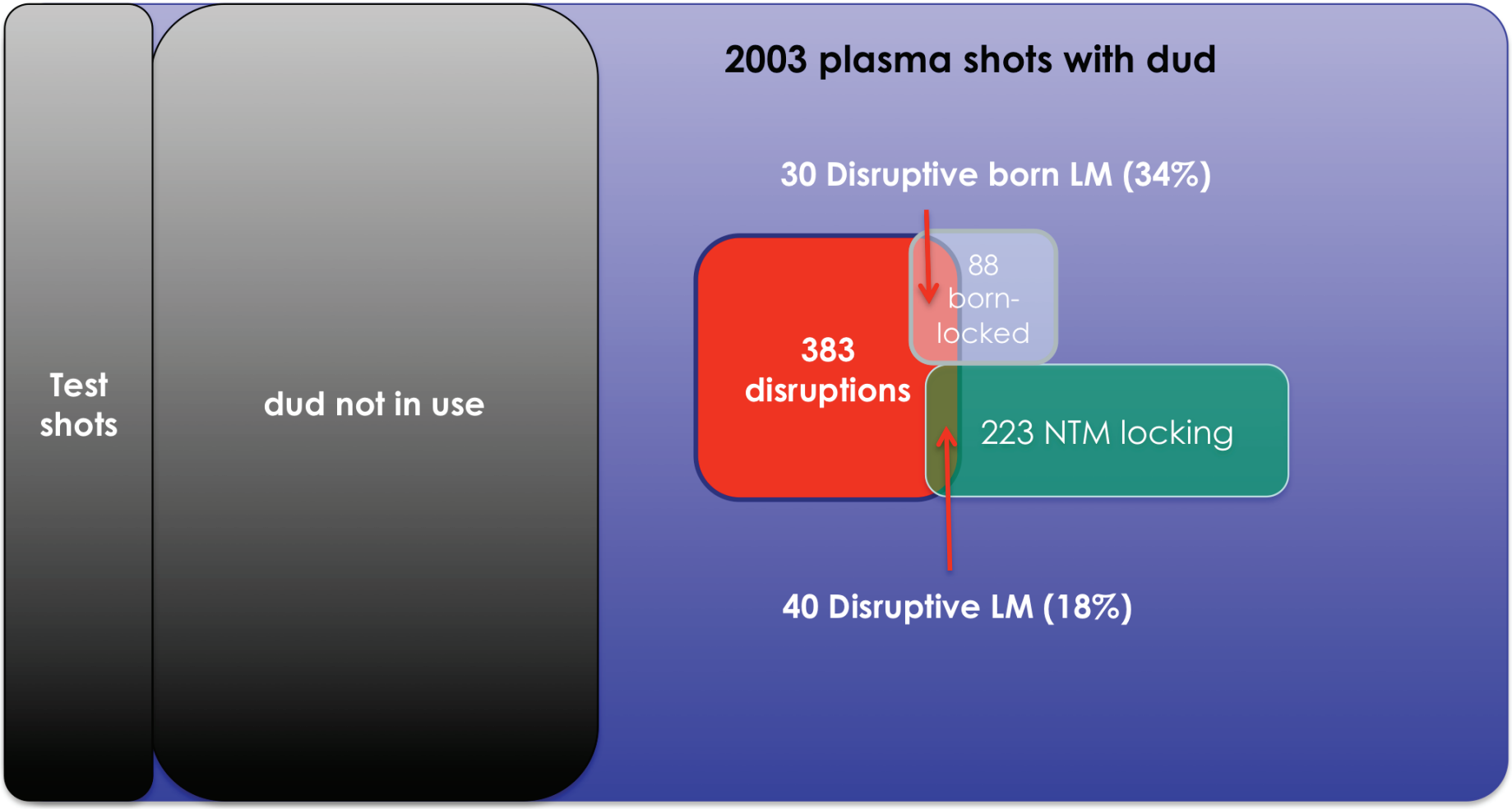
(NB: Island not exactly "frozen": rotates at $\leq \omega_{*s}$)

Other Causes for Disruptions

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

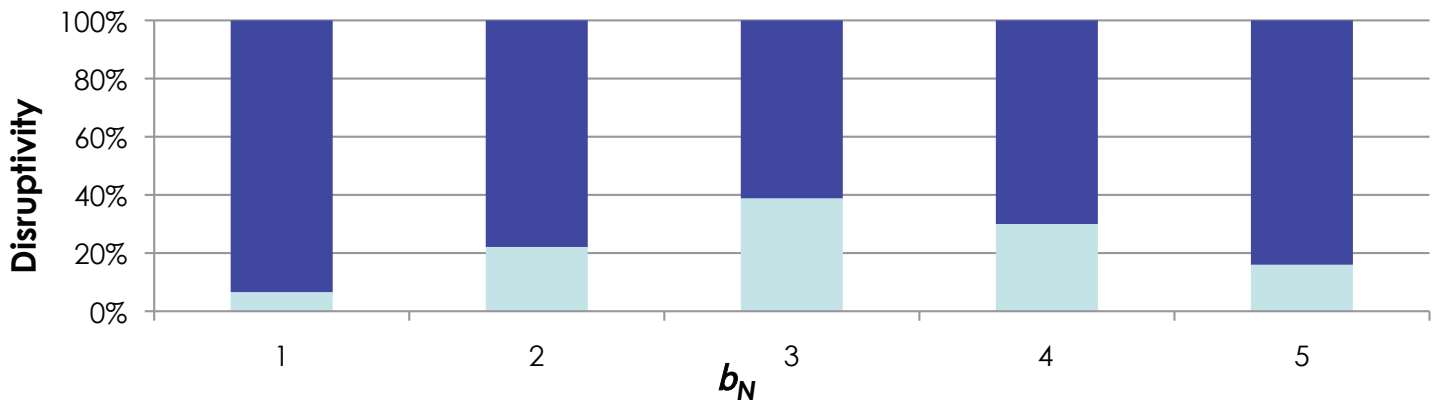


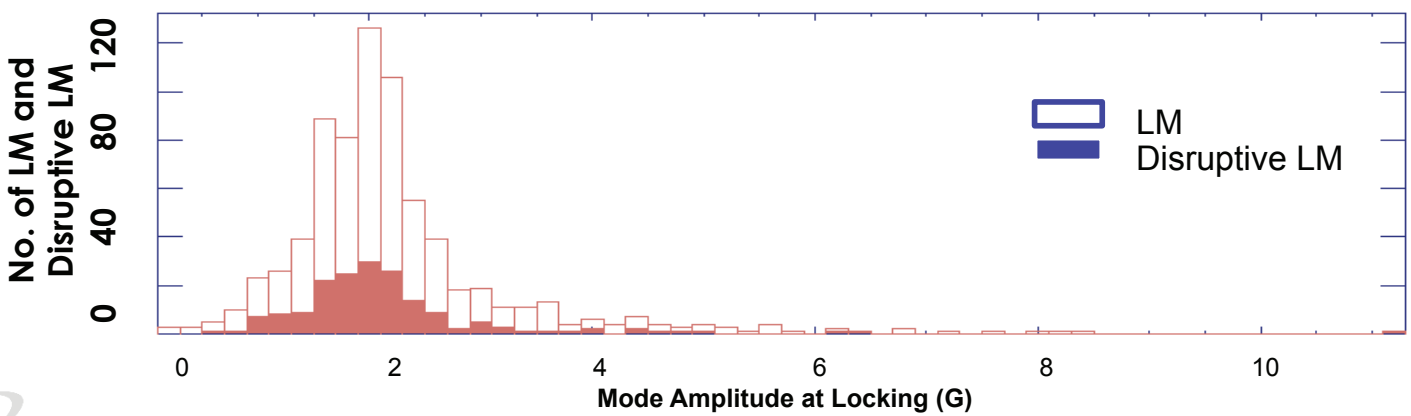
Statistic Analysis of 20000 Shots



More on Disruptivity

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

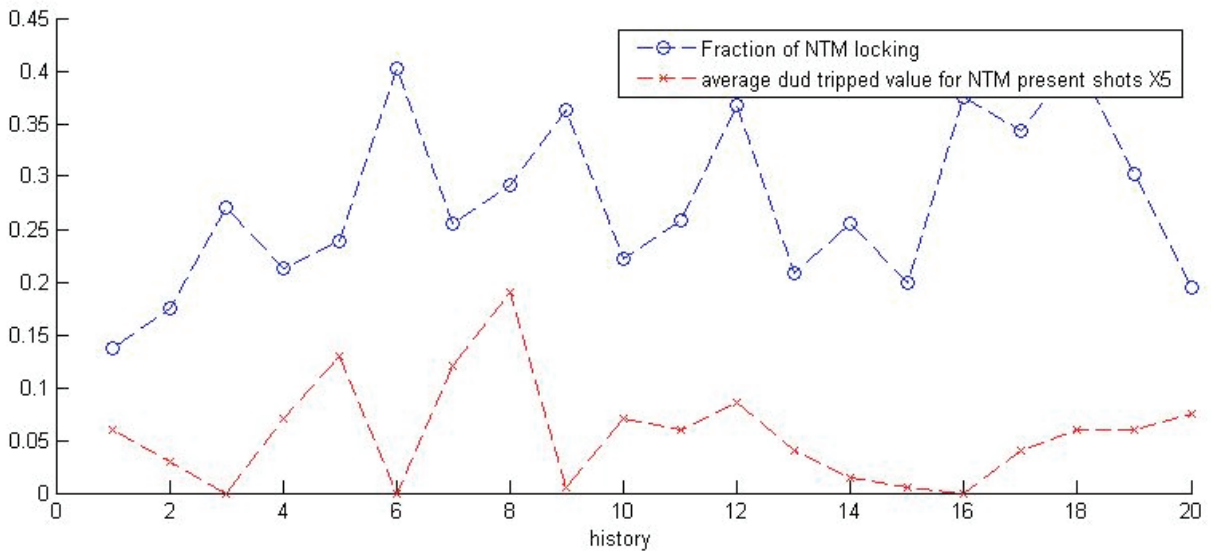




More on Locking

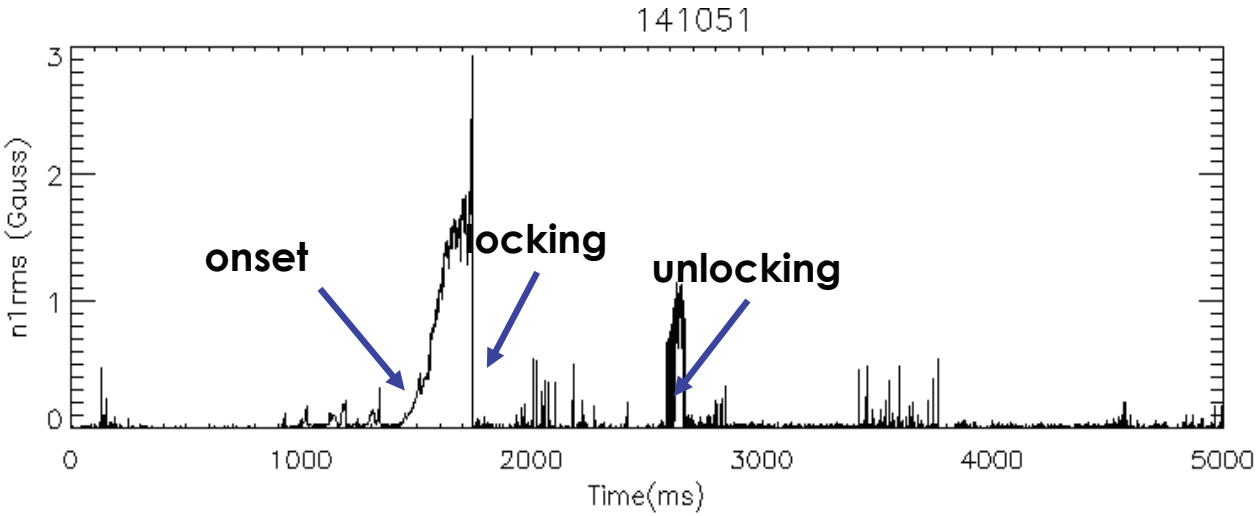
Big picture: 26% of NTMs lock (729 out of 2809)

(1) Dud (anti-correlation)
(2) q95
(3) Mode amplitude



Fit Locking Timescale to Simplified Torque Balance Model

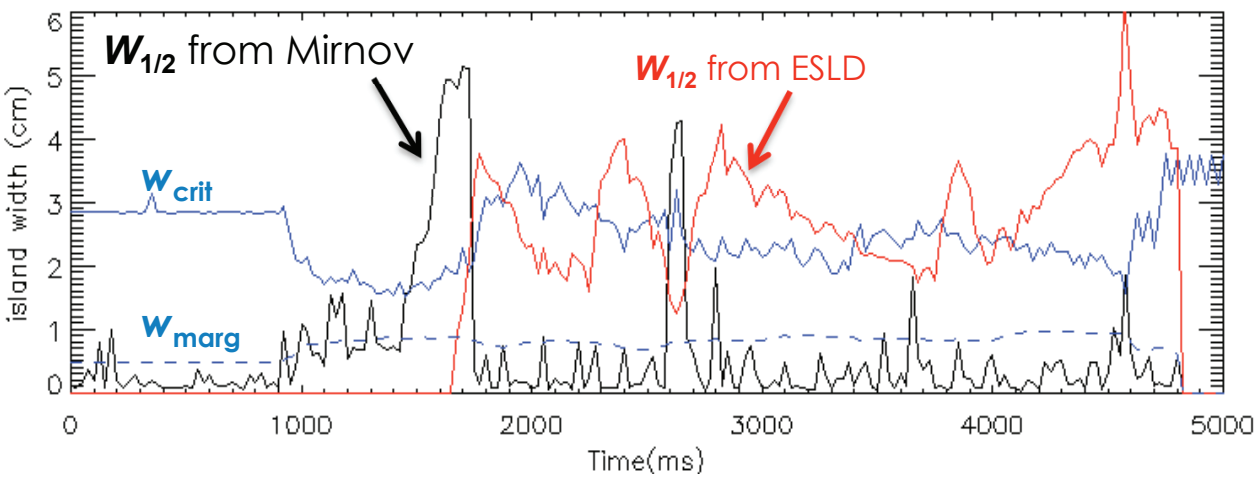
AUTOMATE THE FITTING?



- 2-paramater model:

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

$$\frac{\tau_M}{\tau_{M0}} = \frac{1}{1 + C_2(w/a)}$$



- 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 locking

$$w_{marg} \approx 2\varepsilon^{1/2}\rho_{\theta i}$$

$$\rho_{\theta i} = (2m_i\kappa_B T_i/e^2 B_\theta{}^2)^{1/2} \qquad \varepsilon = r/R_0$$