Locked Mode Disruptions: Stability, Dynamics, Control

by
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Acknowledgments:
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Disruption Physics & Control

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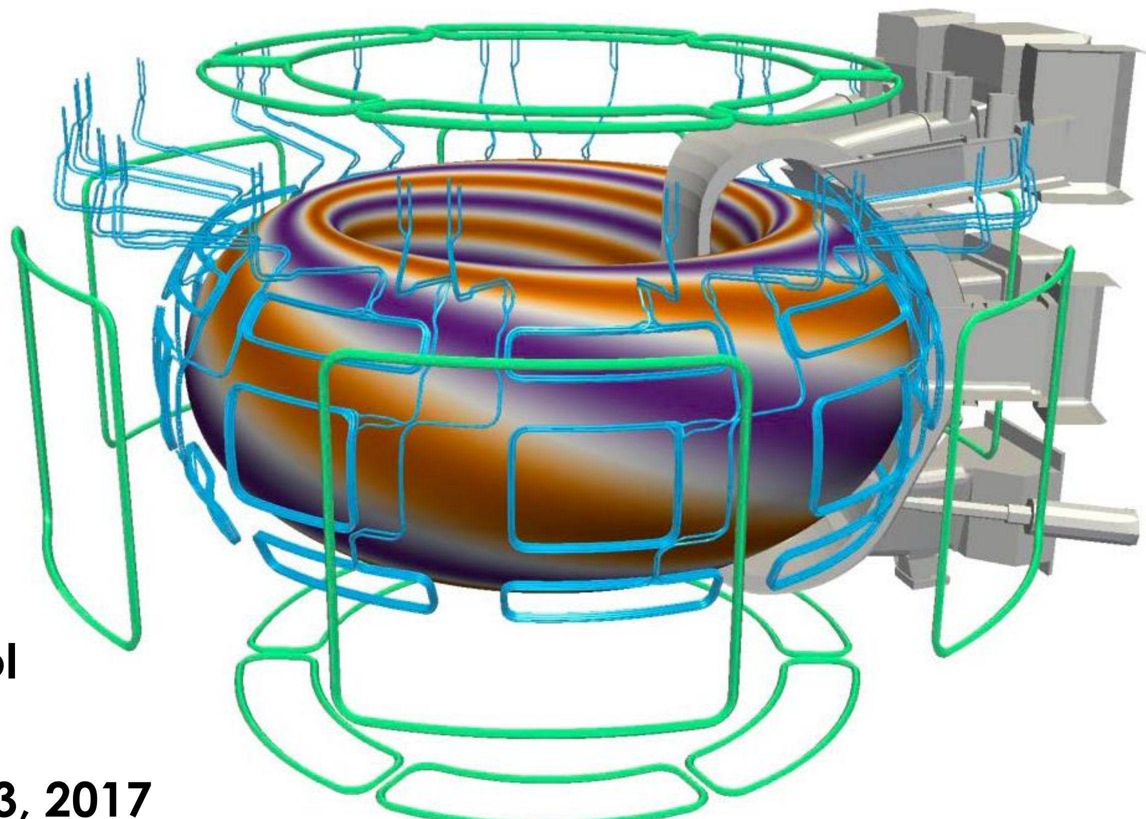

Image by Guido Huijsmans, ITER Org.

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Outline

- Why a lecture on *Locked* Modes in a summer school about Disruptions?
- ...and what is a Neoclassical Tearing Mode anyway?
- Why/how does it lock? → Eq.of motion, torques
- Why/how does a mode form w/o rotating precursors? → Error Field penetration
- Why/how/when does it cause a disruption? → Stochastization? When classically unstable?
- How can we avoid/control locking, and avoid the associated disruption? → Magn. Perturbations & Localized Current Drive

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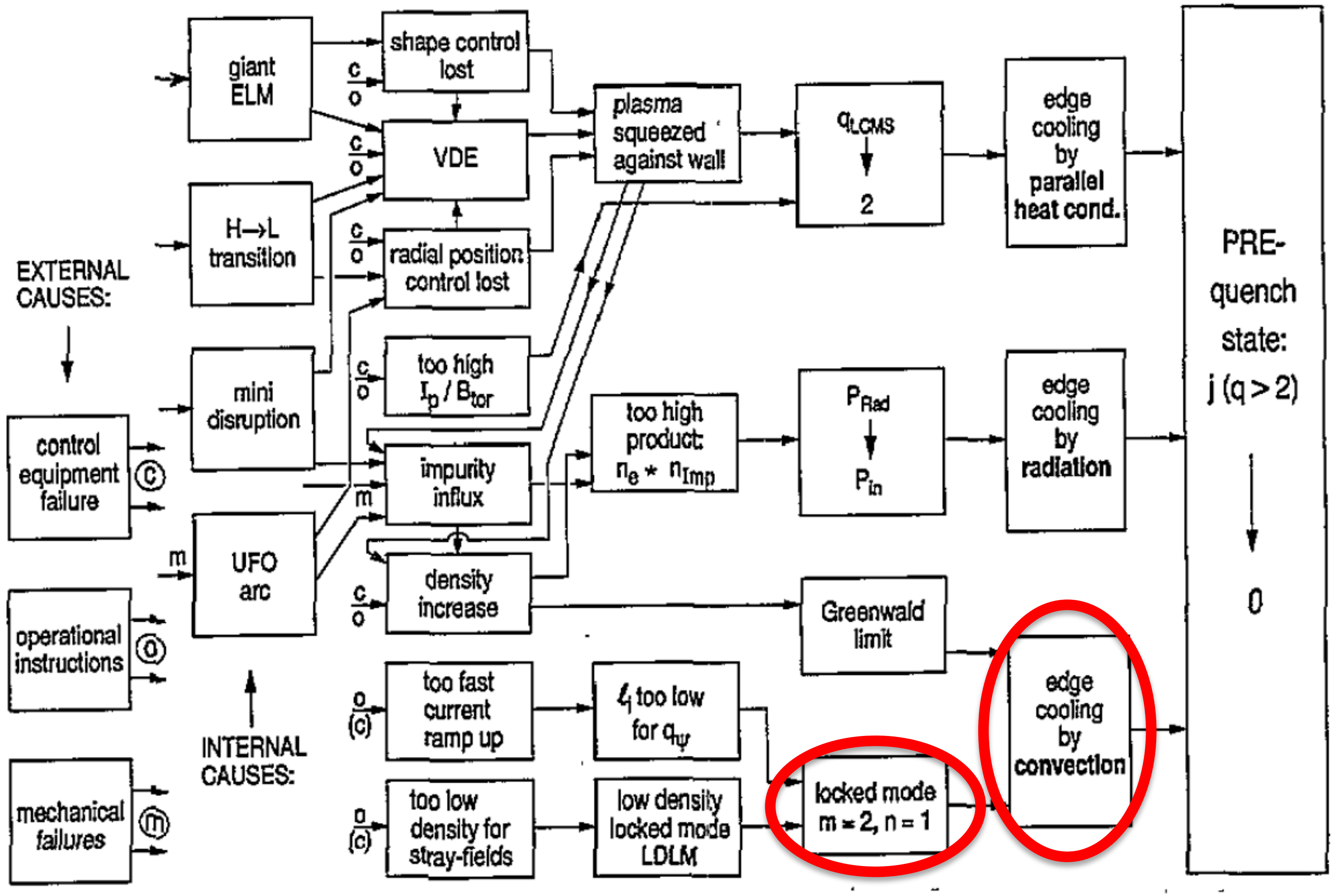
Locked islands cool plasma edge mostly by convection



F.C Schüller, PPCF 1995

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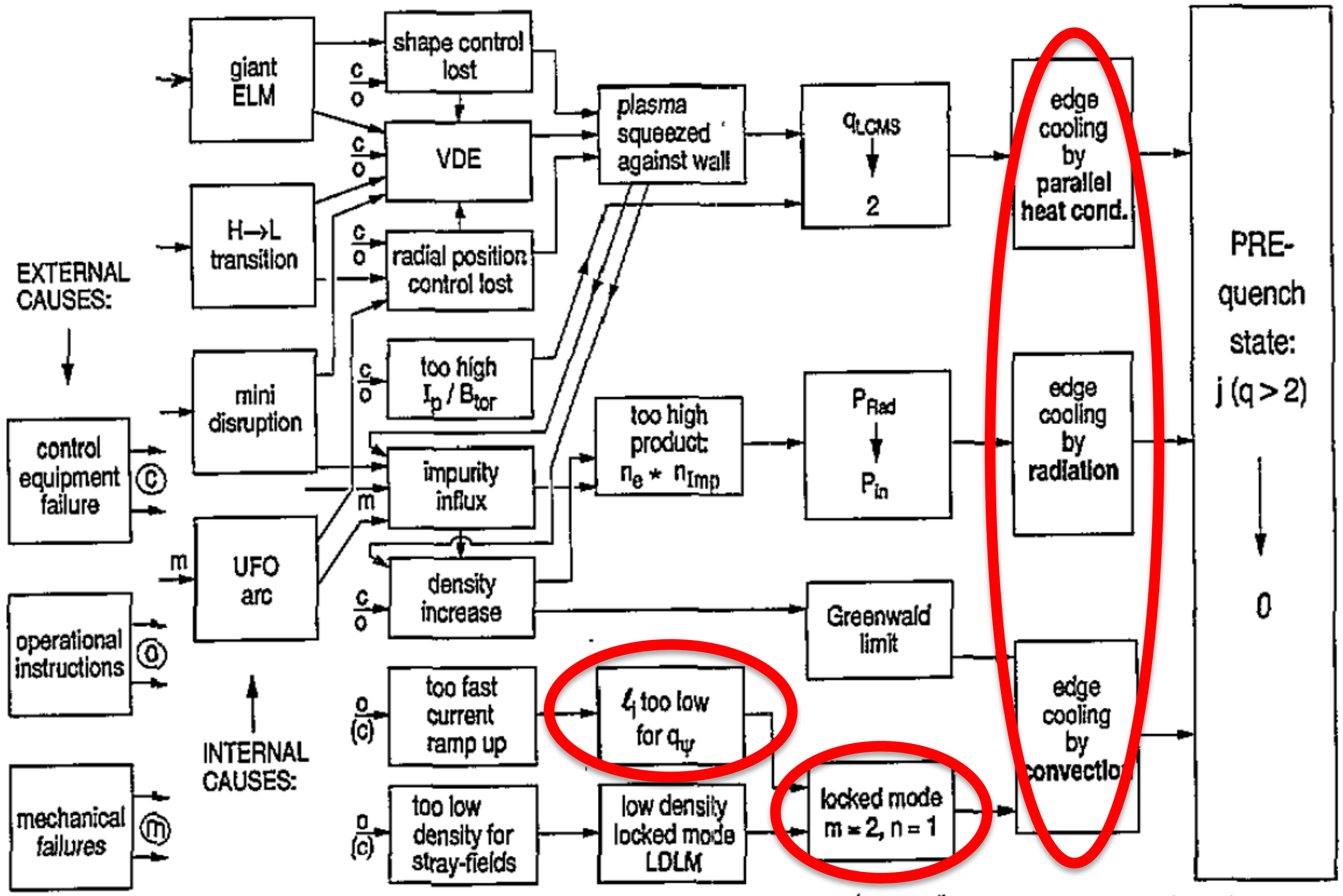
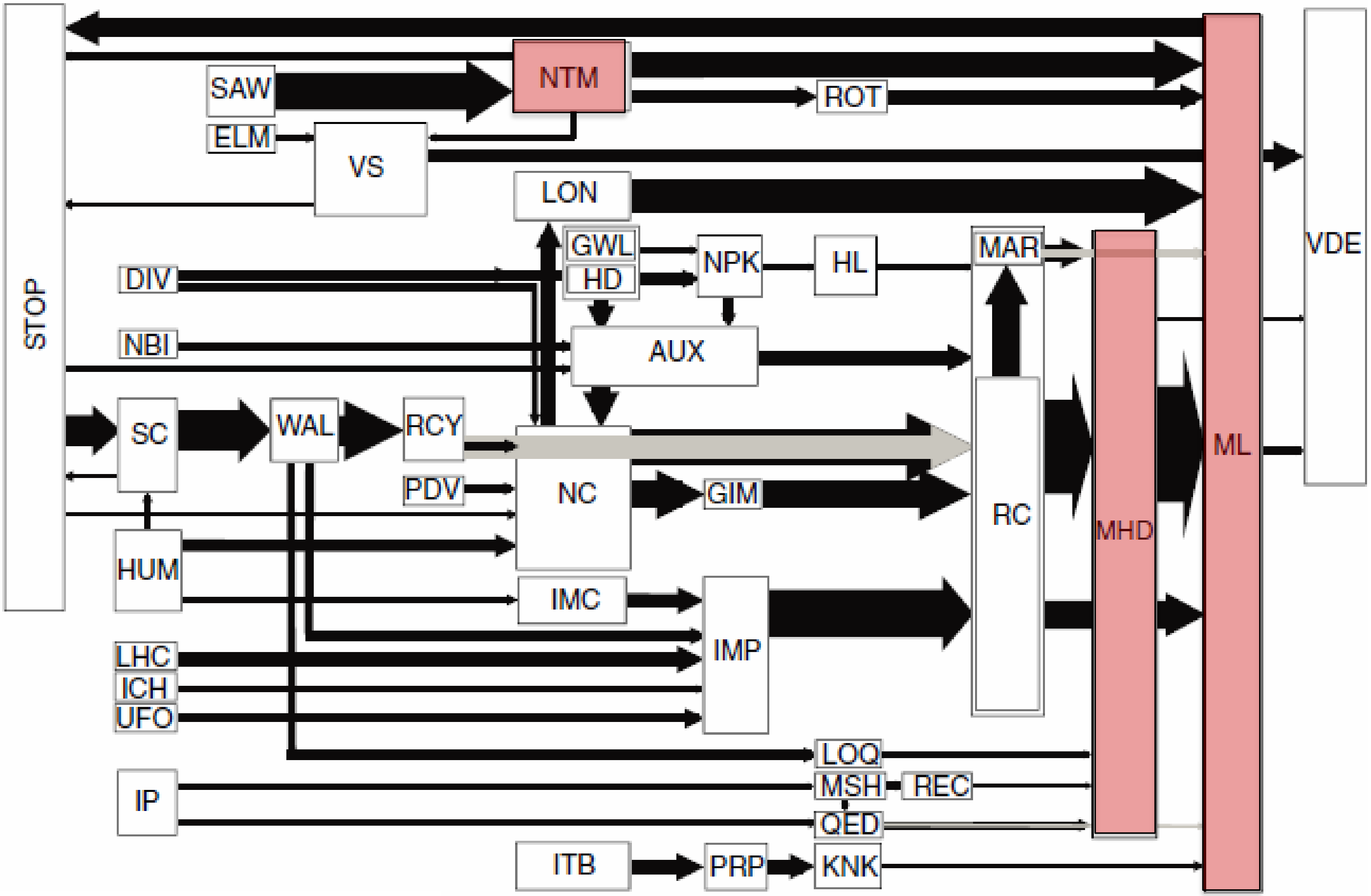


Too high β
Too low q_{95}. Proximity to wall
Too slow rotation

F.C Schüller, PPCF 1995

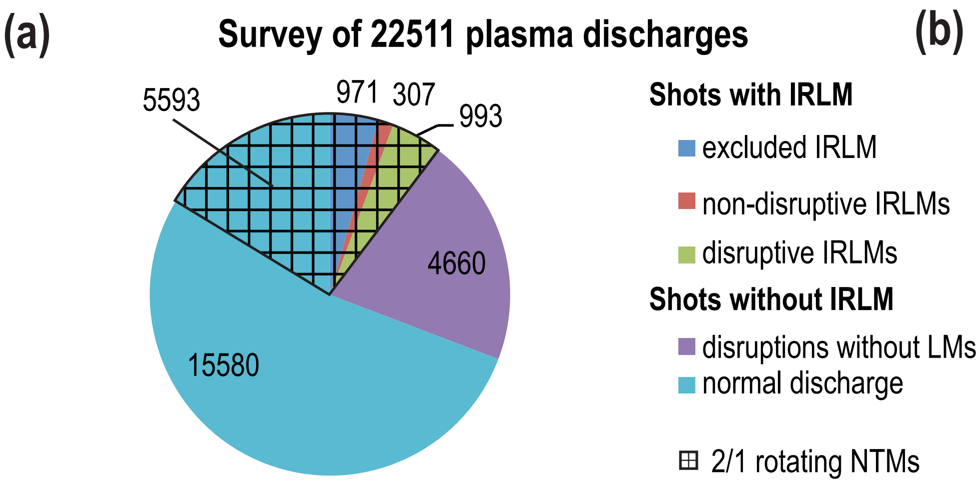
Nearly all JET disruptions eventually exhibit Mode Locking

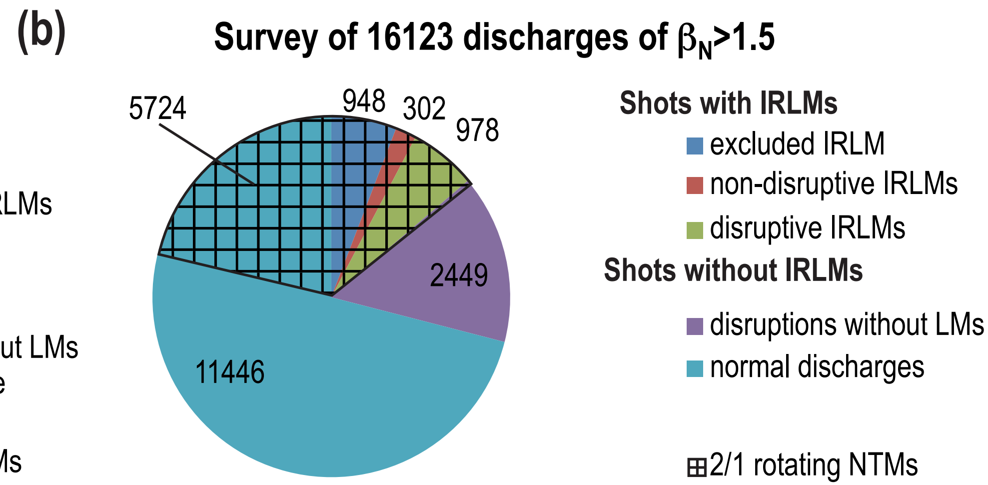


P. De Vries *et al*., NF 2011

About a quarter of DIII-D disruptions is due to LMs *with* rotating precursors

- **Study performed on shots 122000 to 159837 (2005 to 2014)**





- **18% of disruptions due to IRLMs** **28% of disruptions with β_N >1.5**

- **Fraction due to LMs *without* rotating precursors ("born locked modes") unknown, left as future work**

Locked Modes = non-rotating modes

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"

Could denote non-rotating

- **Resistive Wall Mode (NSTX Spherical Tokamak)**
- **Interchange Mode (LHD Heliotron)**
- **Tearing Mode (RFX-mod Reversed Field Pinch)**

Typically, non-rotating

- **Neoclassical Tearing Mode**

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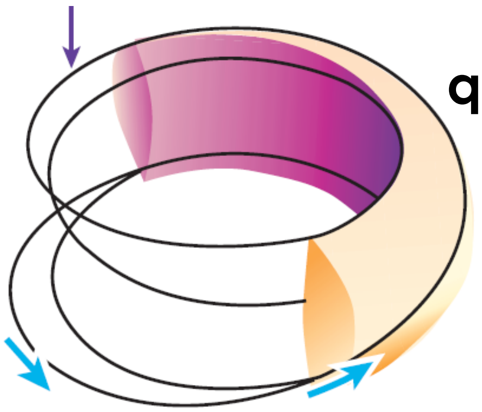
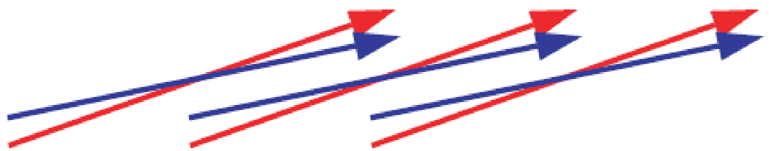
Reconnection creates Magnetic Islands

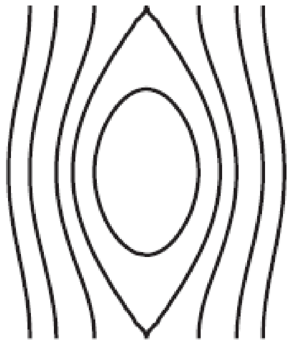
Field lines are helical



Field Lines on neighbouring surfaces have different helicity



Local B is sheared, relative to average



Current filamentation deforms, possibly reconnects field lines → magnetic island

Islands ubiquitous in tokamaks:

- Fast reconnection (sawteeth)
- Nonlinear saturation (tearing modes)
- Forced reconnection (error fields)
- Nonlinear filaments and mass ejection (edge-localized modes)

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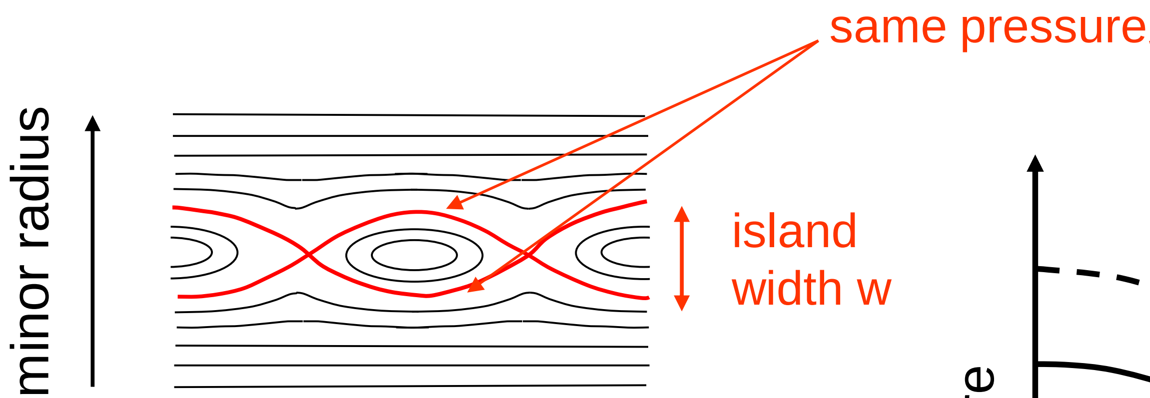
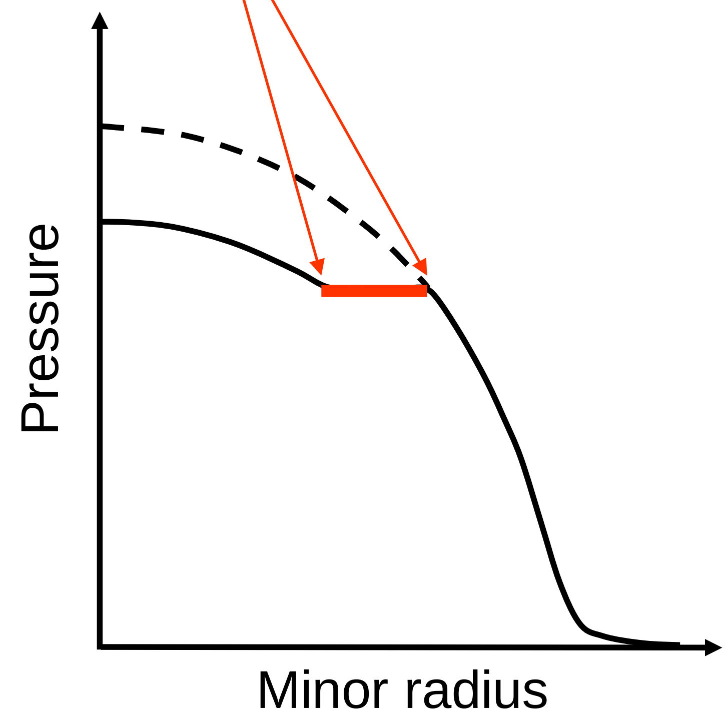
Neoclassical Tearing Modes form due to a lack of Bootstrap Current

For NTMs, filamented current
= <u>bootstrap current</u> deficit



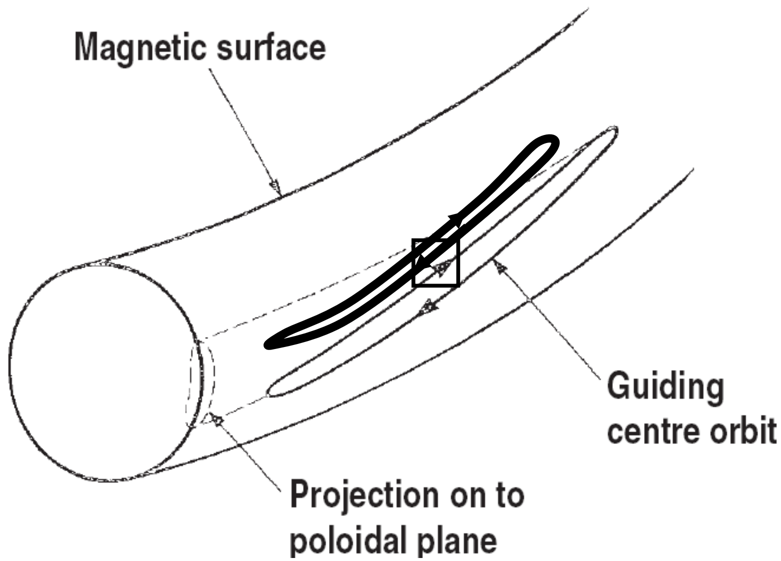


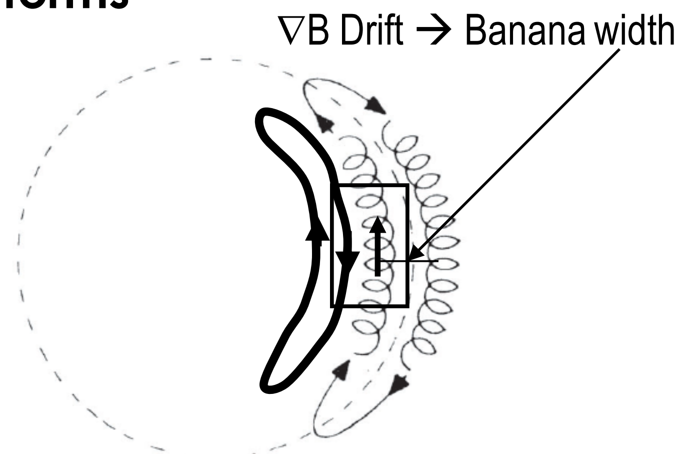
Island forms → flat P → less ∇P
→ less bootstrap current → reinforces the initial filamentation

Toroidal Effects produce a Pressure Gradient Driven "Bootstrap" Current

Guiding centre moves along field line, but

B changes along field line → magnetic mirror forms





Drift of guiding centres

Per se doesn't imply net toroidal current, because it involves trapped particles.

However, these collisionally transfer momentum to passing electrons → current

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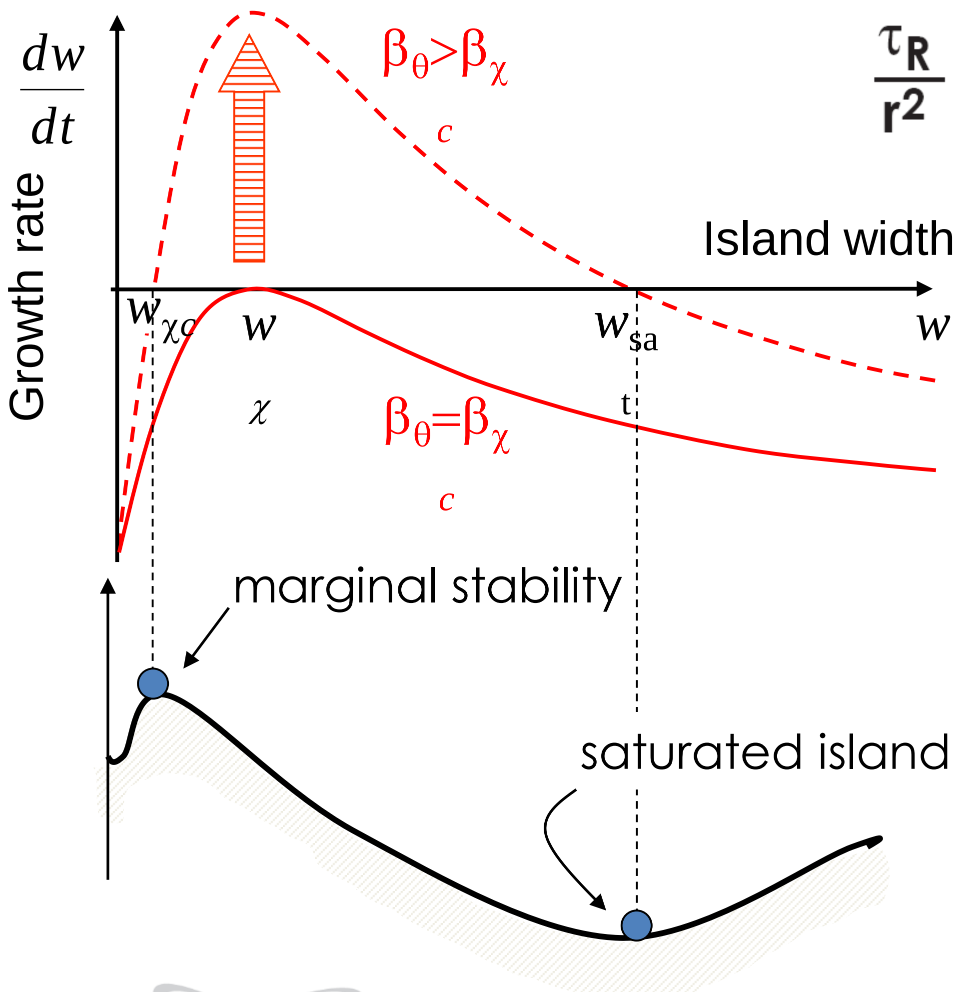
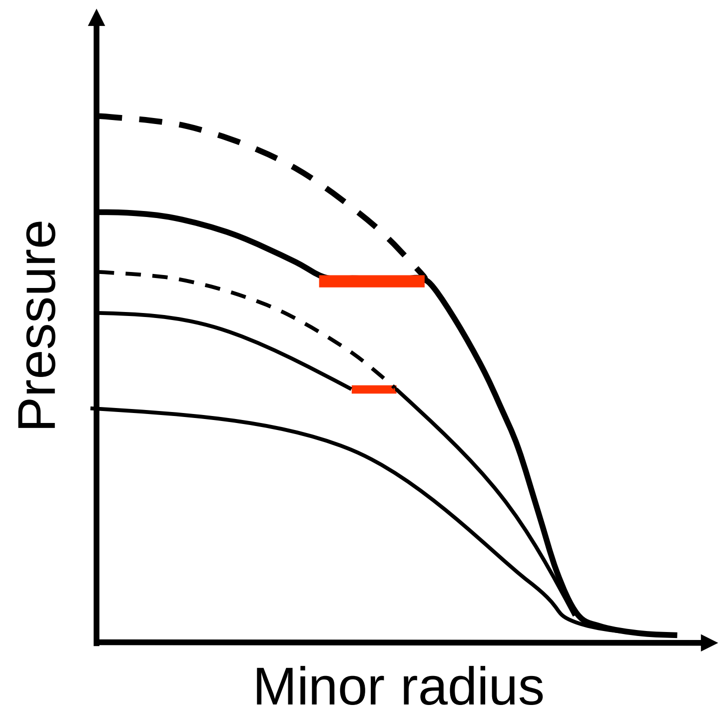
NTMs form at high pressure
…and limit pressure at inner radii

Modified Rutherford Eq.:

$$\frac{\tau_R}{r^2}\frac{dw}{dt} = \Delta' + \text{destab. BS curren term} \times \text{correction for small isl.}$$





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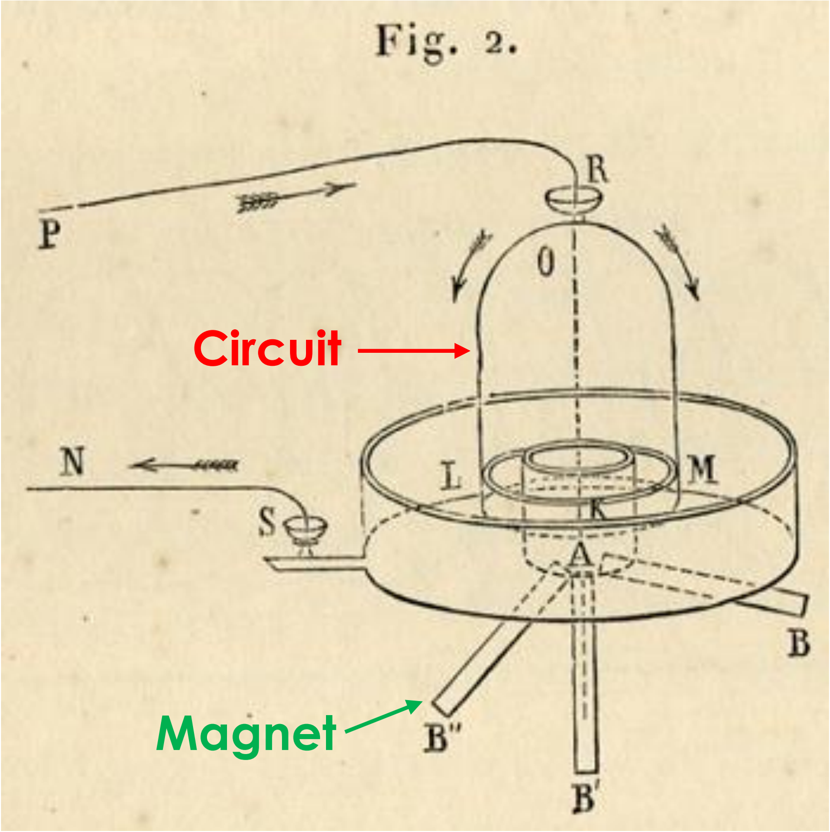
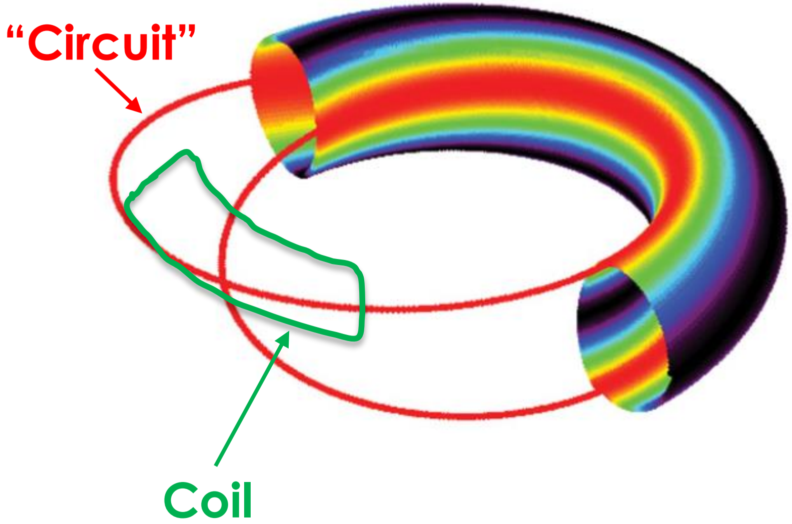
Electrical circuits interact with magnetic fields (Ampere, 1822)





DITE [Morris 1990]
COMPASS-C [Hender 1992]
HBT-EP [Navratil 1998]
TEXTOR [Koslowski 2006]
DIII-D [Volpe 2009]
J-TEXT [Rao 2013]

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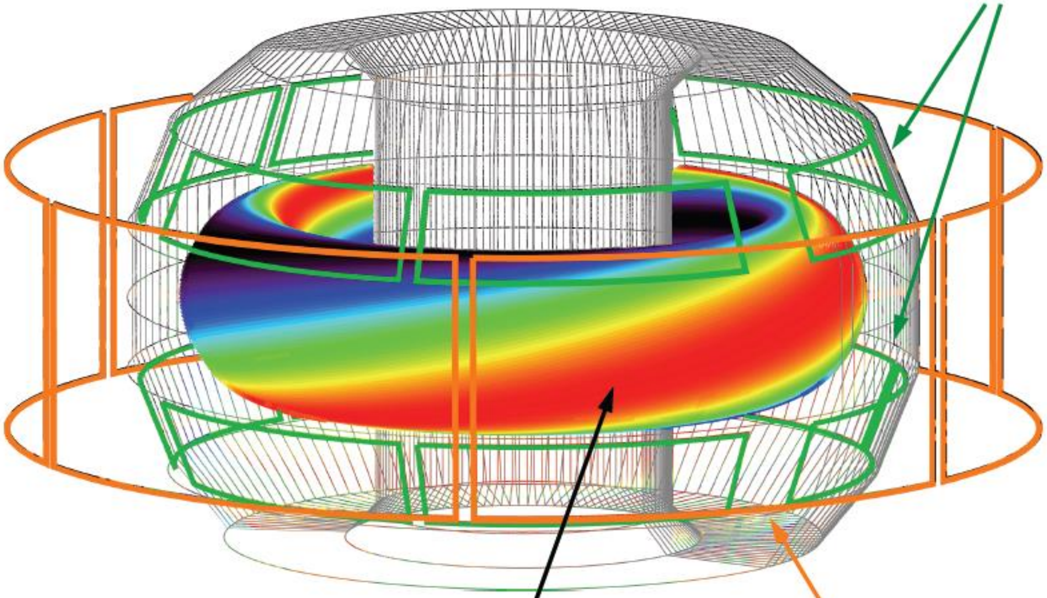
Currents (NTM) also interact with other currents (induced in wall, applied by coils, or other NTMs)



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Current-field and current-current interactions → electromagnetic torques on island

current in filament (island)

e.m. torques $d\vec{T} = \vec{r} \times d\vec{F} = \vec{r} \times (I\, d\vec{l} \times \vec{B})$

Current-field and current-current interactions → electromagnetic torques on island

- **Island(s)= non-axisymmetric distribution of $\vec{j}$ at rational surface(s)**
- **Wall = non-axisymmetric distribution of $\vec{j}$ at at the wall, resistively delayed w.r.t. $d\vec{\mathbf{B}}/dt$ that caused it (e.g. from rotating $\vec{j}$ at rational surface(s))**
- **EF**, **RMP = non-axisymmetric $\vec{B}$**

current in filament (island)

$$\text{e.m. torques } d\vec{T} = \vec{r} \times d\vec{F} = \vec{r} \times (I\, d\vec{l} \times \vec{B})$$

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current in filament (island)

$$\text{e.m. torques } \vec{T} = \int \vec{r} \times d\vec{F} = \int \vec{r} \times (I\, d\vec{l} \times \vec{B})$$

$$I\ddot{\varphi} = T_{EF} + T_{MP} + T_{wall} + T_{NTM} + \cancel{T_{NBI}} + \cancel{T_{visc}}$$

Moment of inertia of frozen-in plasma

non - e.m. torques on frozen-in plasma

Low NBI torque, Low rotation

All e.m. torques except wall torque are angle-dependent. Wall torque → magnetic braking, mimics viscous torque.

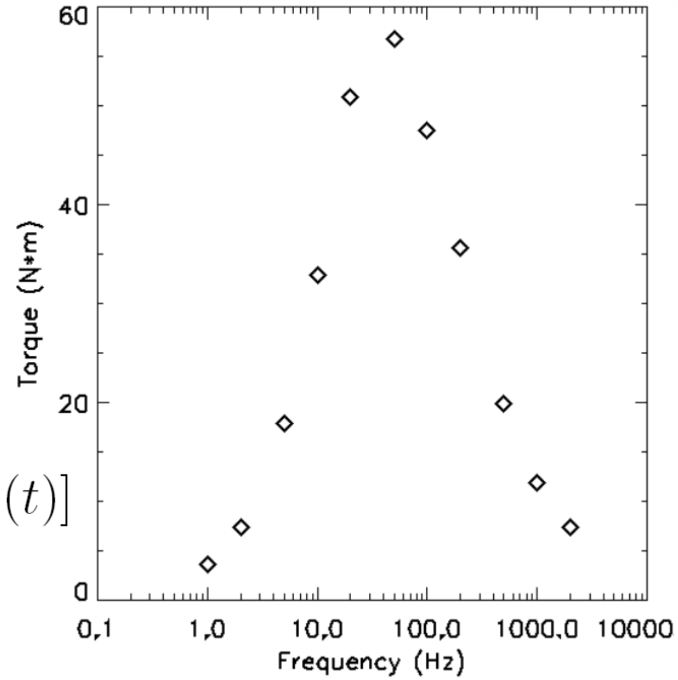
$$I_h = \pm 2|B_R(b)|b\left(\frac{b}{r_{mn}}\right)^m \frac{1}{m\mu_0}$$

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

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

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

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



- **Wall torque decelerates rotating island**
- **$T_{\text{wall}} \to 0$ as $\Omega \to 0$**
- **EF, RMP and other TMs cause final locking**
- **Final phase minimizes potential energy of multipole-multipole system (generalization of compass in terrestrial field)**

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

$$\frac{d\hat{\Omega}_\phi}{d\hat{t}} + \nu_*(\hat{\Omega}_\phi - \hat{\Omega}_\phi^{(0)}) = -\nu_* \hat{\Omega}_\phi |\hat{\Psi}_a|^2$$ +other torques/I

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

Or non-linear generalization

$$S_*\frac{d\hat{\Psi}_w}{d\hat{t}} + (1+md)\hat{\Psi}_w = \sqrt{1-(md)^2}\hat{\Psi}_a + 2md\hat{\Psi}_c$$

- **Inertia of and torques on *partly* frozen-in plasma**
  - Note: here Ω is *plasma* rotation, not mode rotation!
  - Non-rigidity
- **Coupled rotation-stability problem**
  - Growth/decay affects locking/unlocking
  - Rotation → stabilization by rotation shear, effect of rotating wall, …
- **Original model for RWM [Fitzpatrick 02] can be adapted to NTM**

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Simplest torque balance only admits finite solution if B_R(b) > threshold EF (or plasma rotation < threshold)

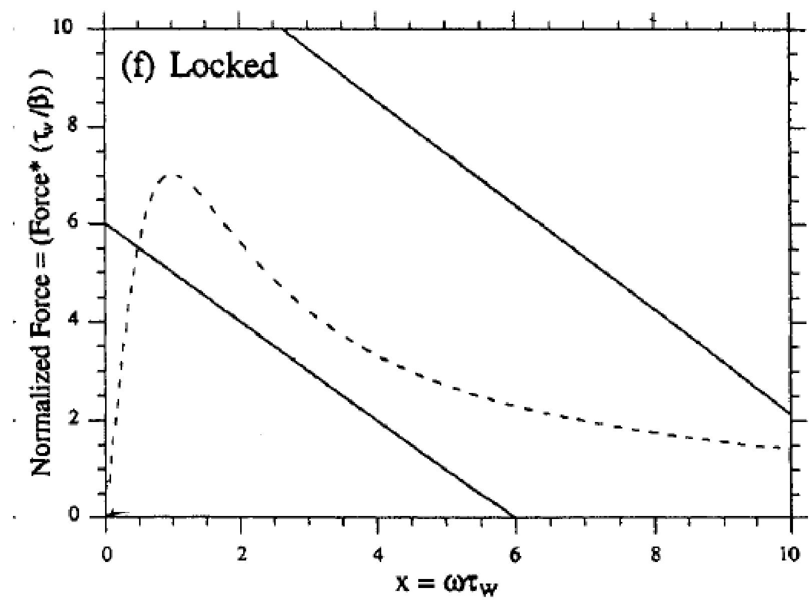
- …but when it does, born locked mode can form

$$\cancel{I\ddot{\phi}} = T_{EF} + \cancel{T_{MP}} + T_{wall} + \cancel{T_{NTM}} + \cancel{T_{NBI}} + T_{visc}$$

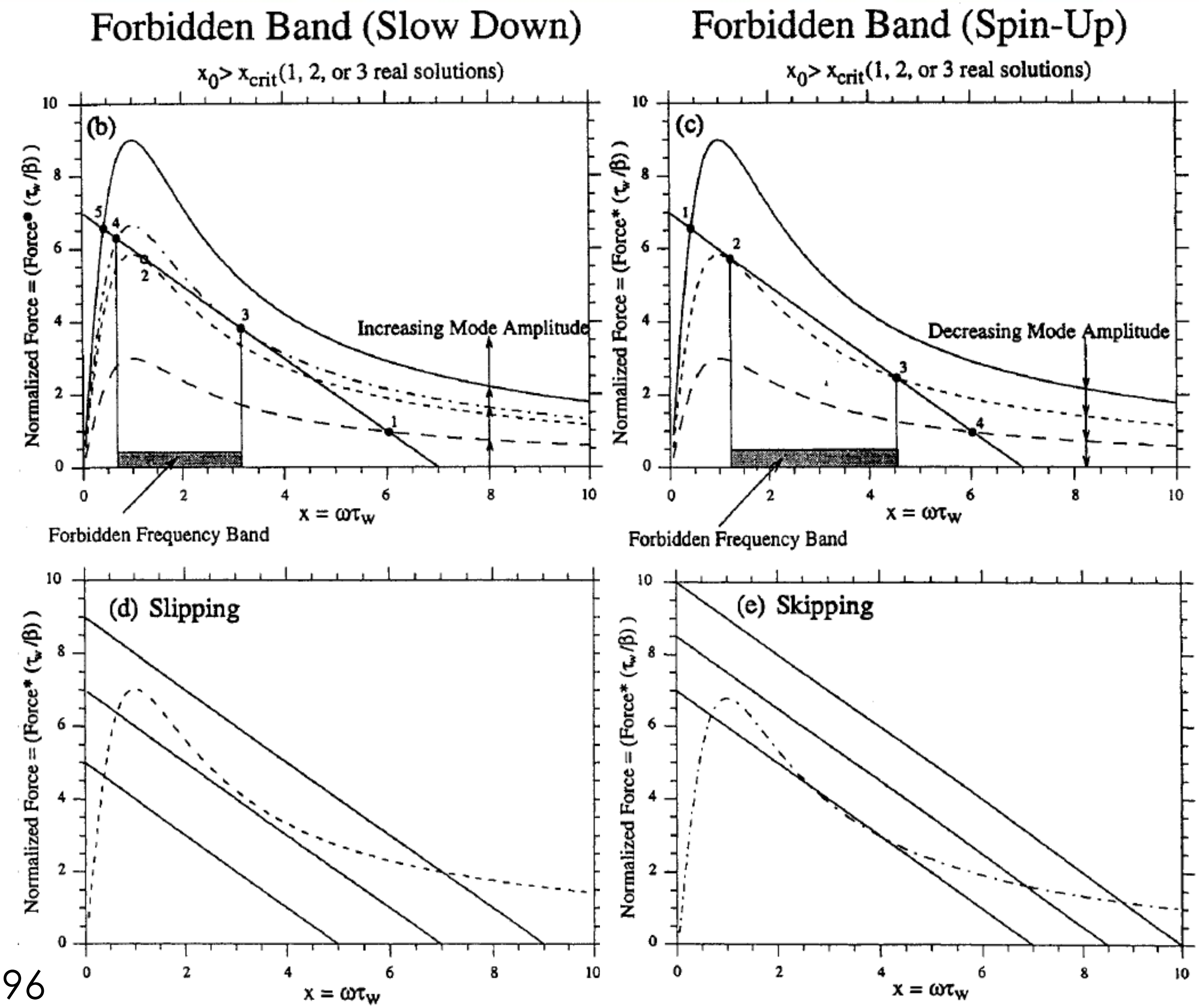
$$\propto \frac{\Omega\tau}{1+(\Omega\tau)^2} \qquad\qquad \propto (\Omega_0 - \Omega)$$

- T_{EF} moves line down
- Ω_0 moves line up

→ Bifurcation in B_R at mode location ("error field penetration")



Bifurcation, forbidden bands, slipping, skipping…



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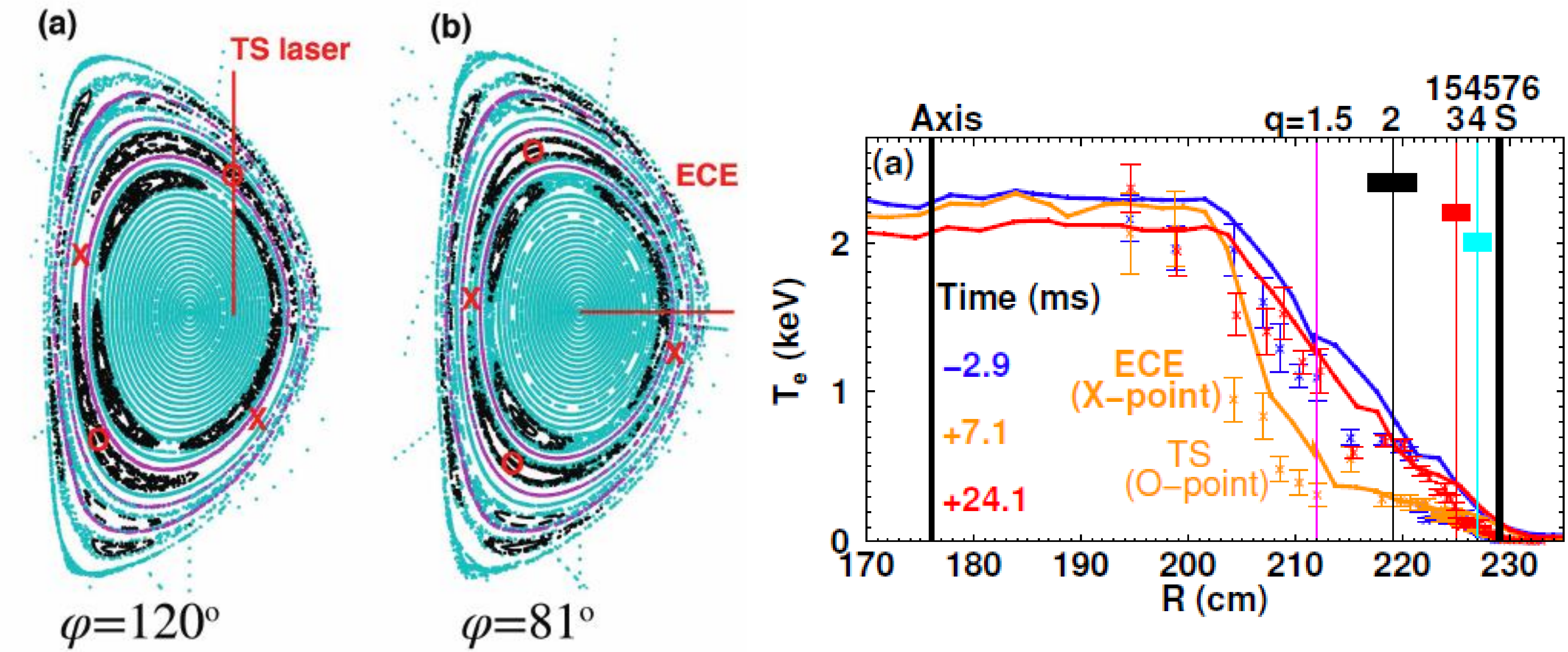
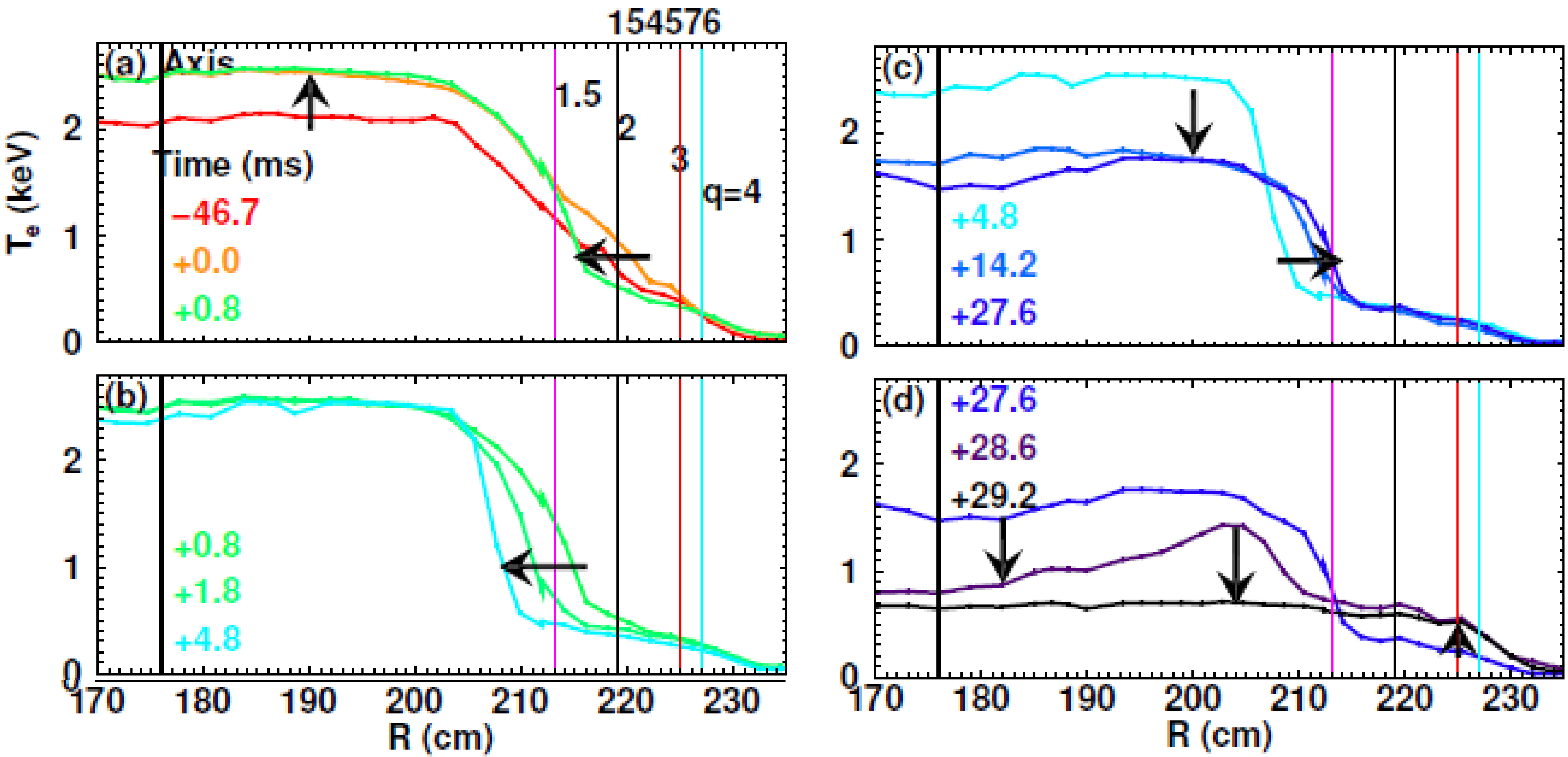
Locked overlapping islands cause edge thermal collapse. Sometimes plasma recovers (minor disr.)…

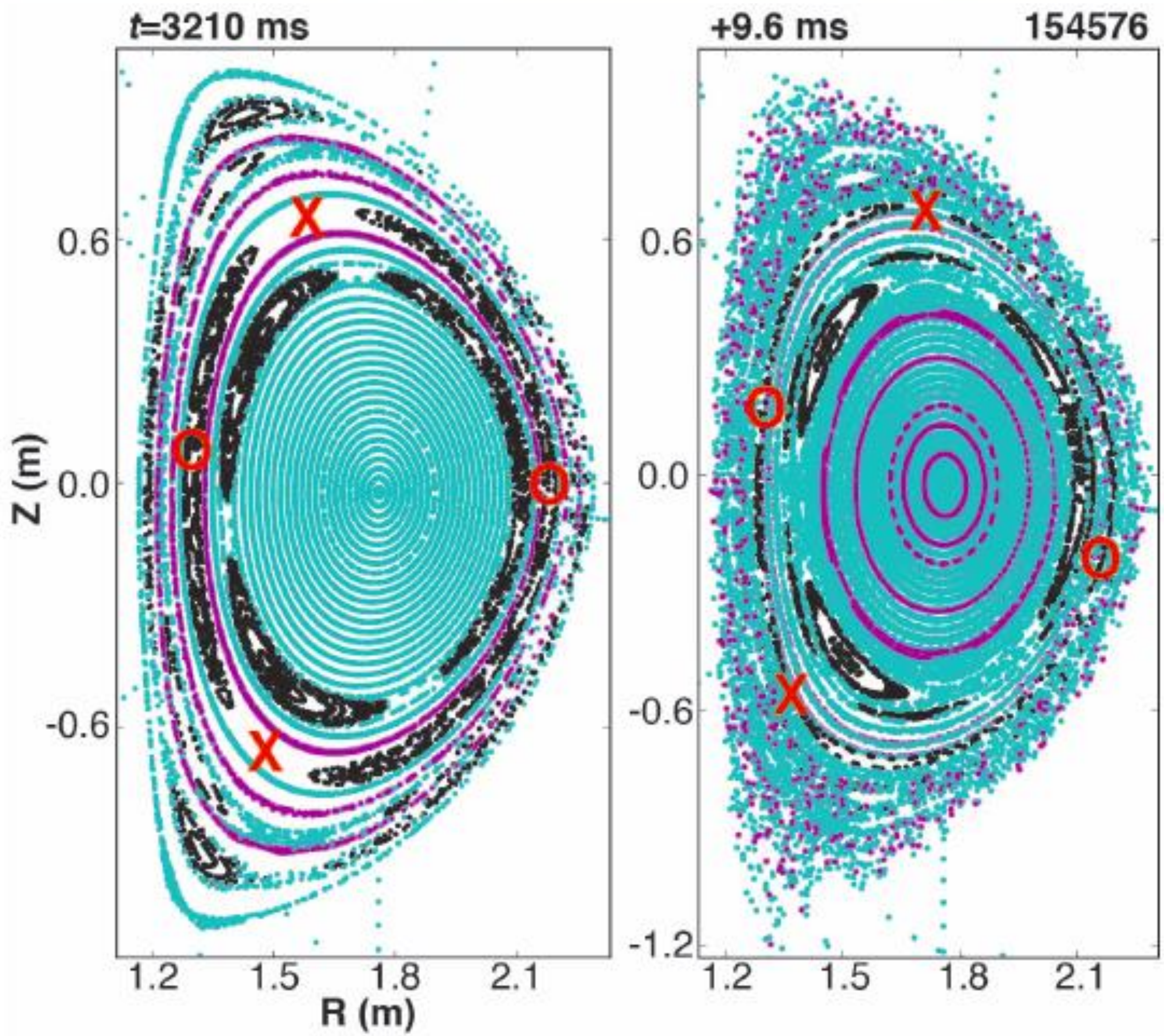


- TS and ECE at different toroidal locations allow simultaneous profile measurements at O-point and close to X-point
- Collapse is axisymmetrc

…and sometimes it does not (thermal quench, current quench, major disruption)



Nonlinear MHD simulations show that initial 3/2, 2/1, 3/1 and 4/1 islands grow, overlap and stochasticize B



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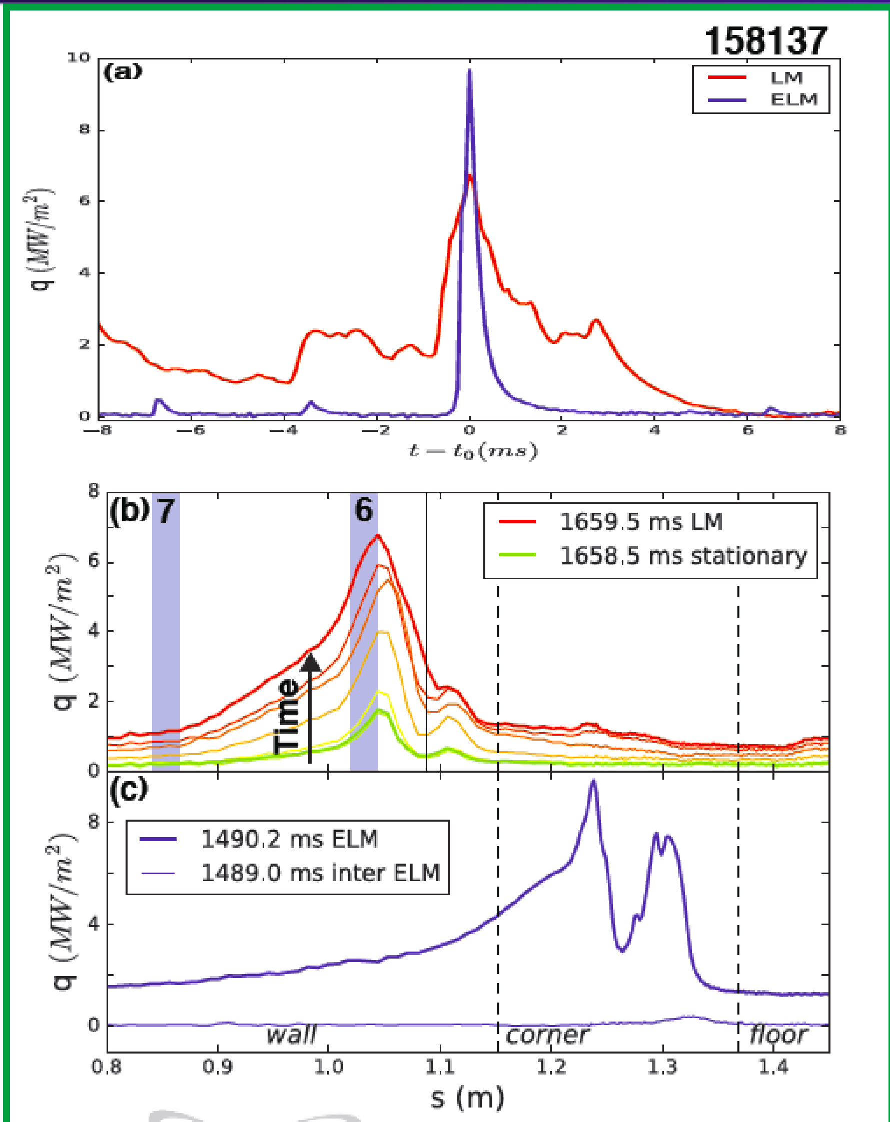
Energy loss is a combination of conduction, convection and radiation



Divertor infrared (IR) camera

1. **Total loss of ~32 kJ estimated using kinetic EFITs**
2. **~10 kJ of energy measured by divertor infrared camera**
3. **25 ± 5 kJ of energy measured by bolometers, localized in divertor**

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Example of an initially rotating locked mode (IRLM)

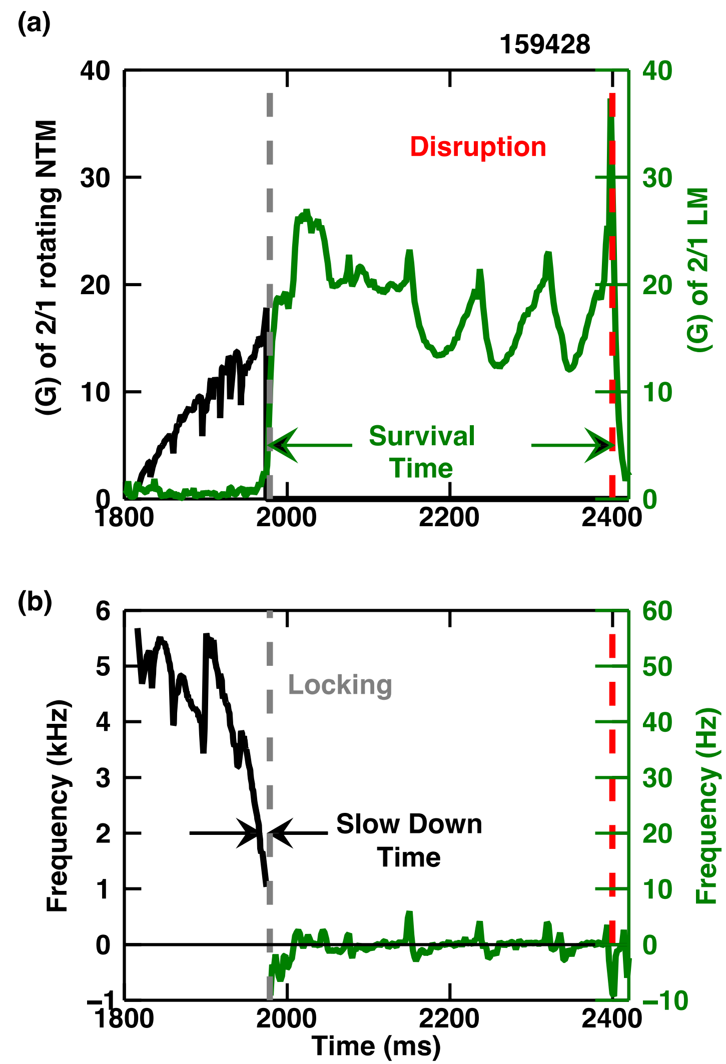
1. ***m/n* = 2/1 rotating mode**

2. **Mode locks**

3. **Exists as locked mode**
   - Few to thousands of milliseconds
   - Referred to as ***survival time*** for disruptive IRLMs

4. **Disrupts or…**

   …ceases to be a locked mode
   - decays
   - or spins up



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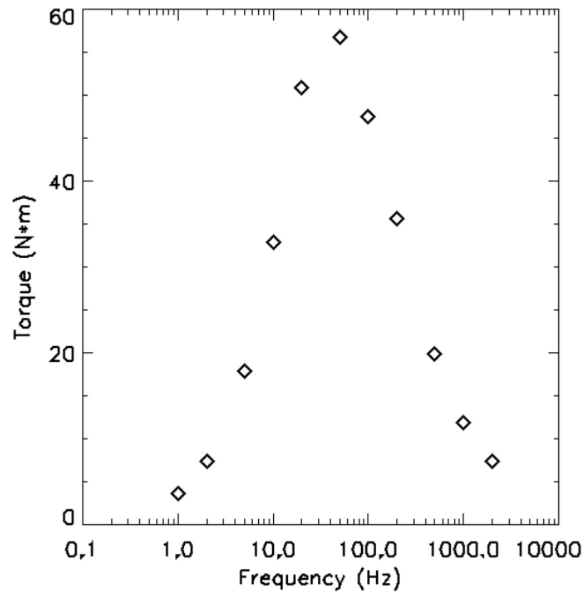
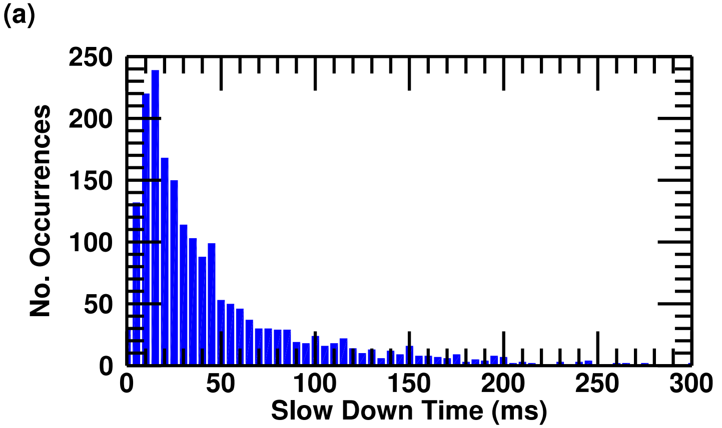
66% of 2/1 NTMs rotating at 2 kHz will lock in 45 ± 10 ms

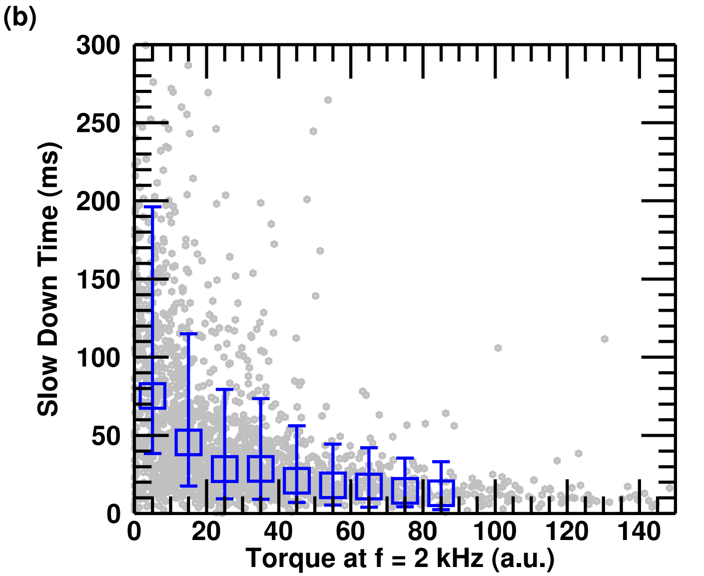
- *Slow down time* = time between 2 kHz rotation and locking



- Indication of time available to prevent locking

- Larger T_{wall} results in shorter slow-down time





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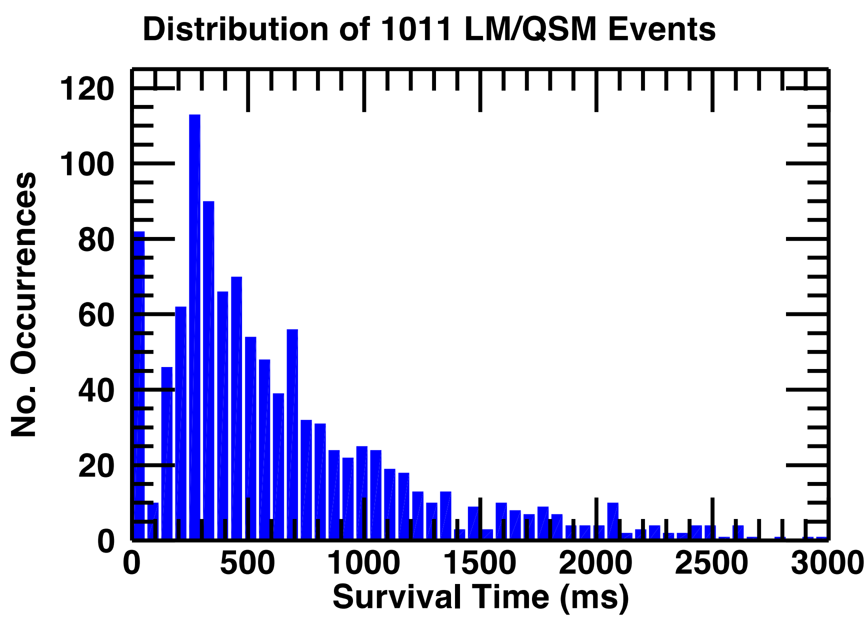
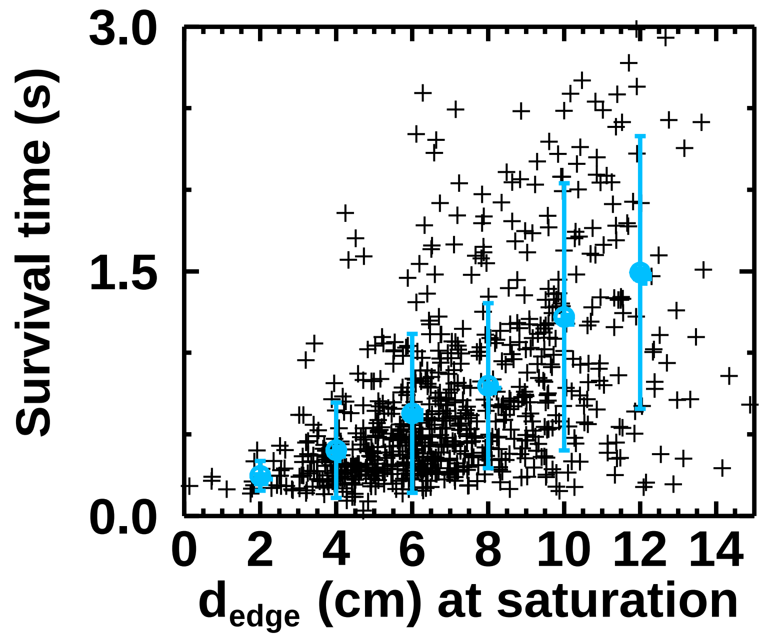
LMs "survive" 270 ± 60ms before causing a disruption. Survival correlates inversely with proximity to edge.

- *Survival time* = time between locking and disruption
- 66% of disruptive modes terminate between 150 to 1010 ms





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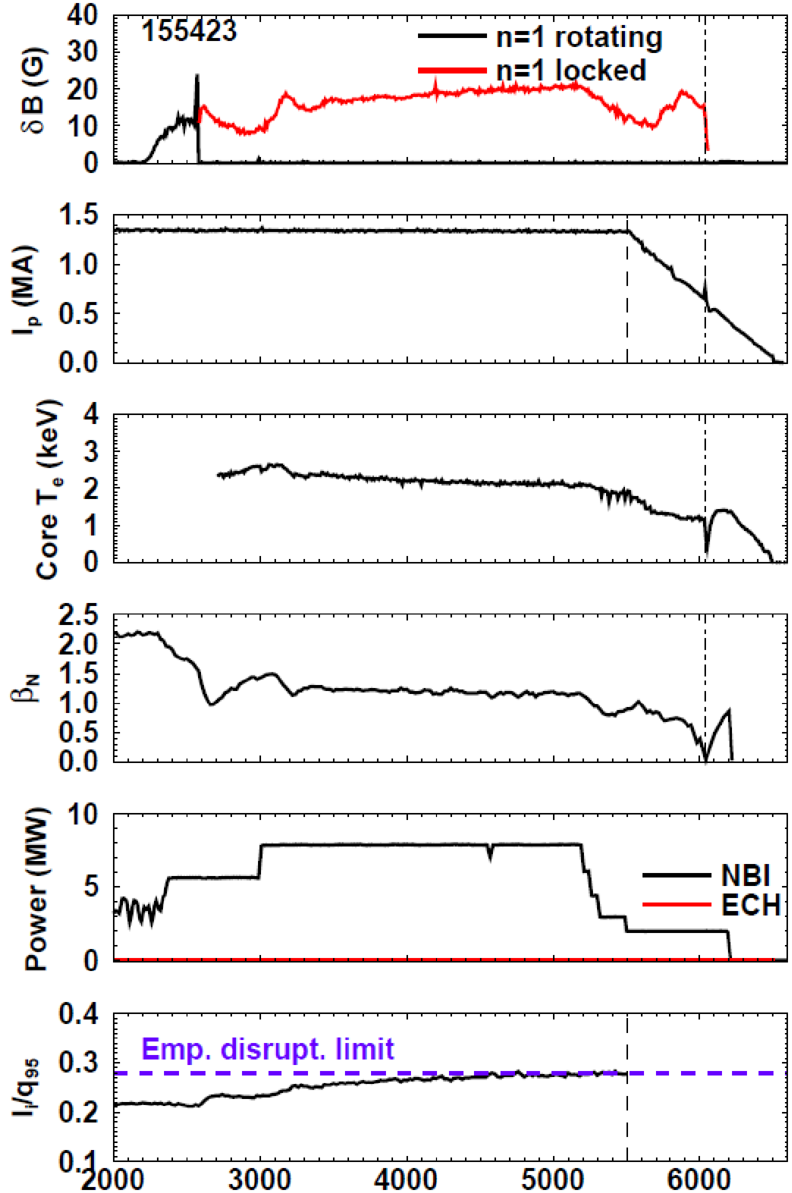
Long survival gives time to safely ramp discharge down



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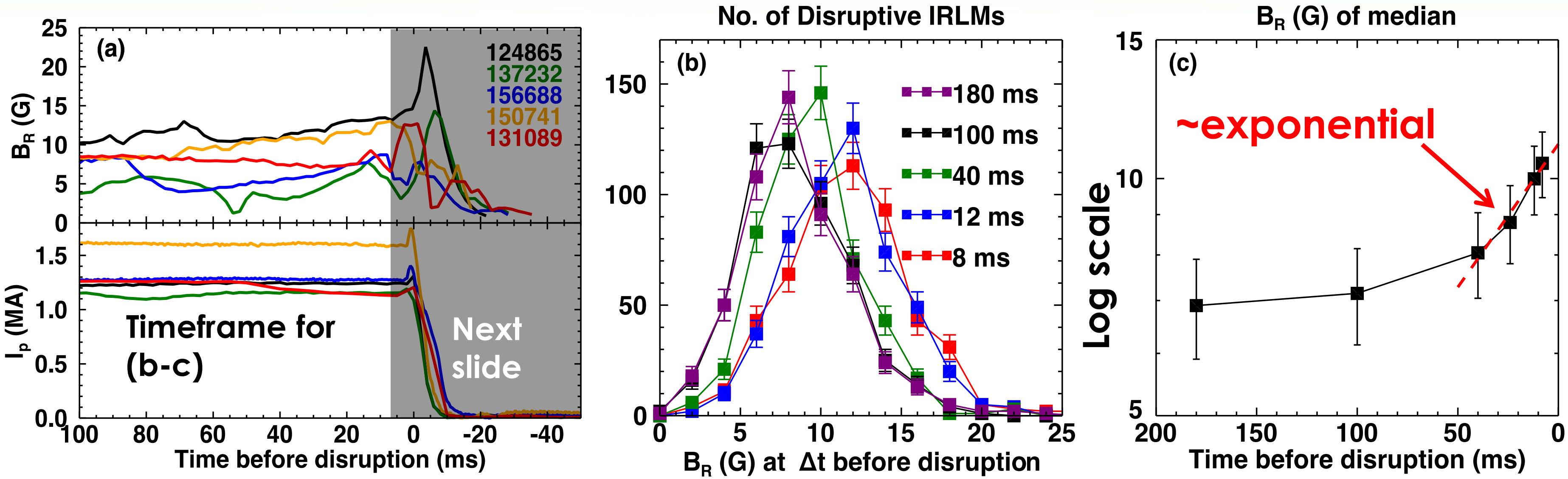
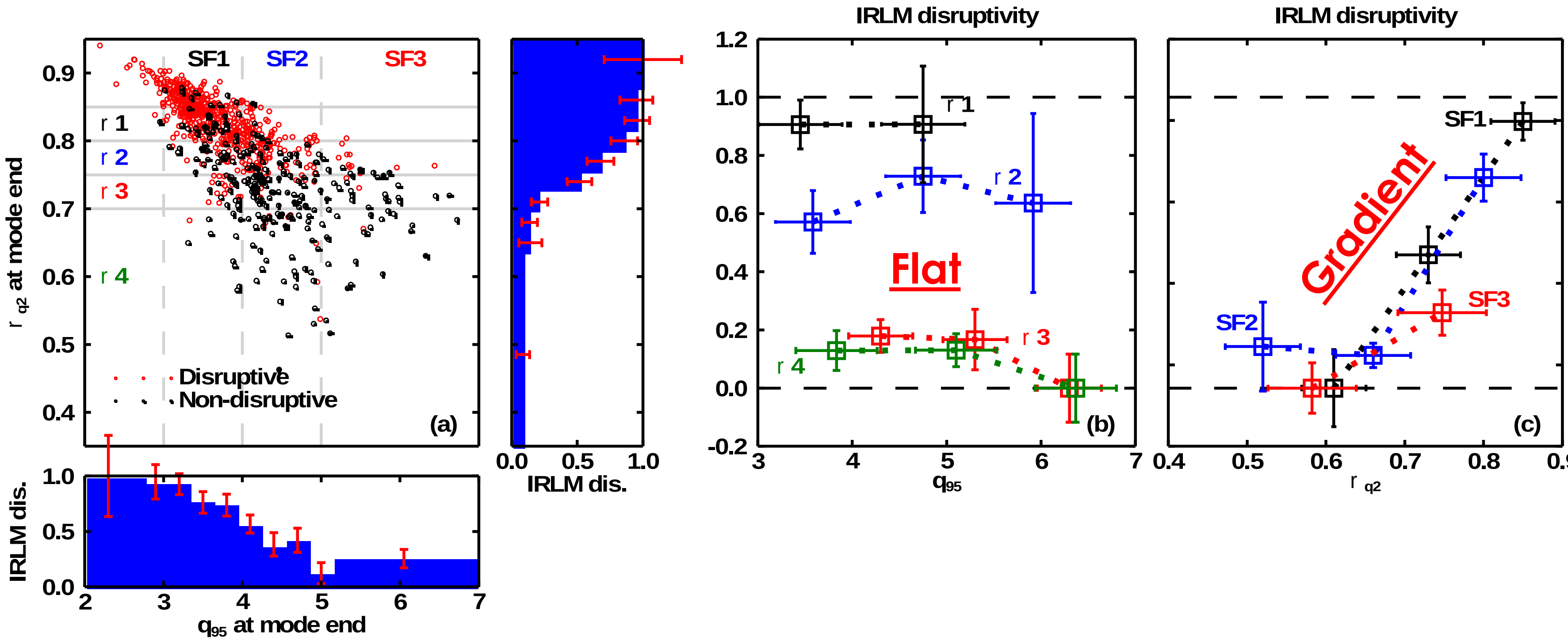
From 100 to a few milliseconds before the thermal quench, the *n*=1 field typically grows



- **(a)** Most IRLMs show increasing *n*=1 field within 100 ms of disruption (5 random IRLMs)
- **(b)** Distributions of *n*=1 field shift higher as disruption approached
- **(c)** Median of (b) grows exponentially in last 50 ms
- Preliminary results suggest *m* is often even during growth

IRLM disruptivity scales strongly with normalized q=2 radius ρ_{q2} (fixing q_{95}), and weakly with q_{95} (fixing ρ_{q2})



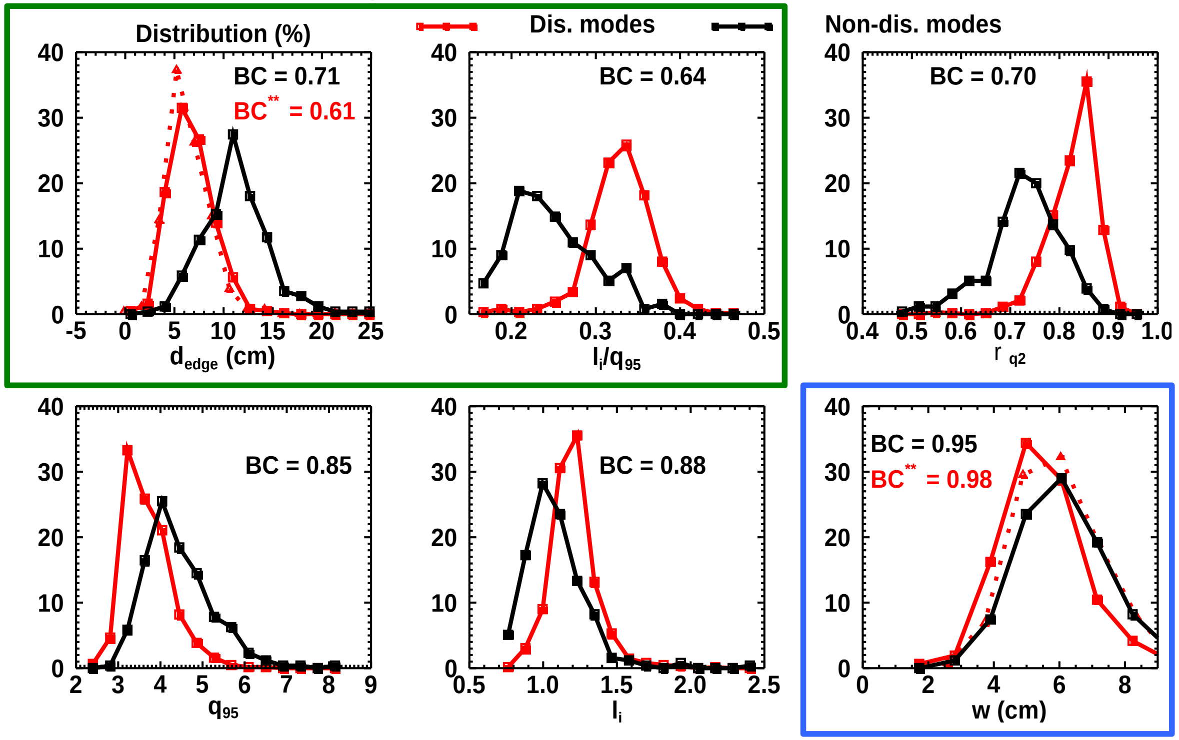
(a) In 1D projections (blue histograms), IRLM disruptivity appears to depend on both ρ_{q2} and q_{95}

(b) Fixing ρ_{q2} shows that IRLM disruptivity scales weakly with q_{95}

(c) Fixing q_{95} shows IRLM disruptivity depends strongly on ρ_{q2}

Bhattacharyya Coefficient informs on best and worst separators

Best performing



Poor separation
(solid 100 ms prior to disruption, dotted is 20 ms prior)

For discrete probability distributions *p* and *q* parameterized by x, the *BC* value is given by,

$$BC = \sum_{x \in X} \sqrt{p(x)q(x)}$$

- *BC*=0: *p* and *q* do not overlap
- *BC*=1 means *p* and *q* are identical (completely overlapping)

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IRLM disruptions might be explained by Δ' becoming marginal, or unstable, as a result of the increasing l_i

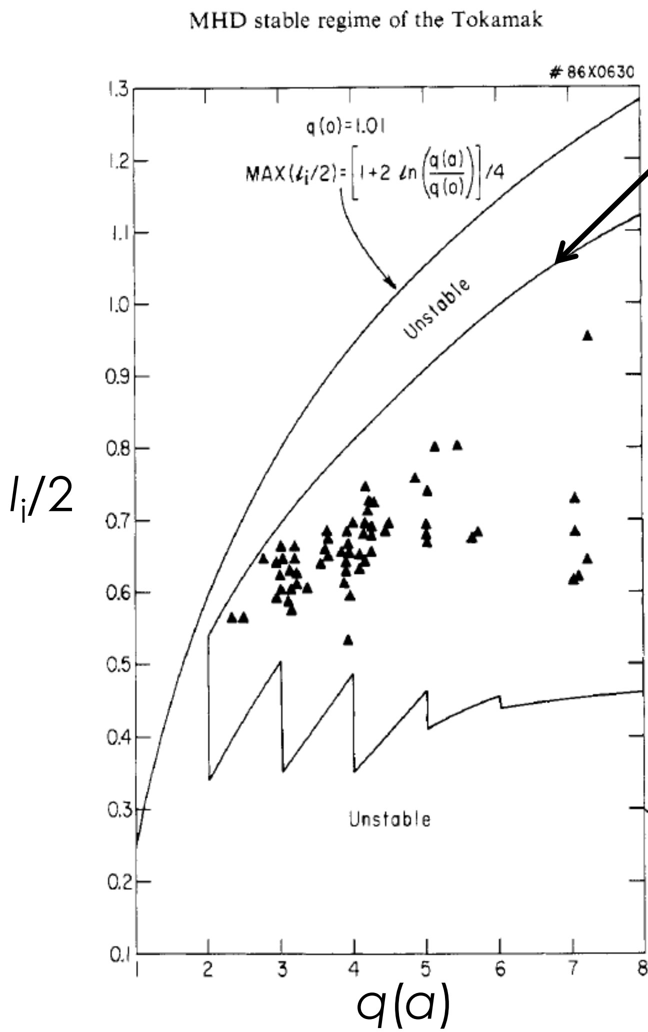
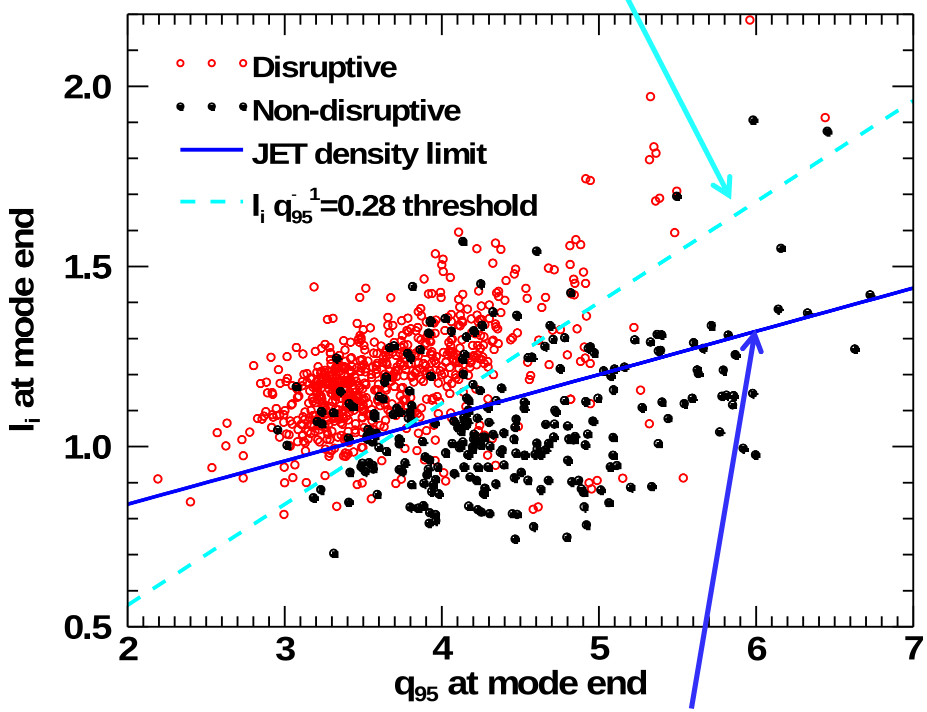


FIG. 4.—The range of permissible internal inductance $l_i/2$ as a function of $q(a)$ for $q(0) = 1.01$ is contained by a jig-saw boundary. The maximum $l_i/2$, which corresponds to a uniform current profile up to $r/a = [q(0)/q(a)]^{1/2}$, is also shown. Steady-state data from TFTR operations are found to fall inside the permissible domain.

- Theoretical stability limit for tearing mode onset [*Cheng, Furth, Boozer PPCF 1987*]
- Limit for IRLM disruptions in DIII-D



- Limit for high-density disruptions in JET [Wesson, NF 1989]

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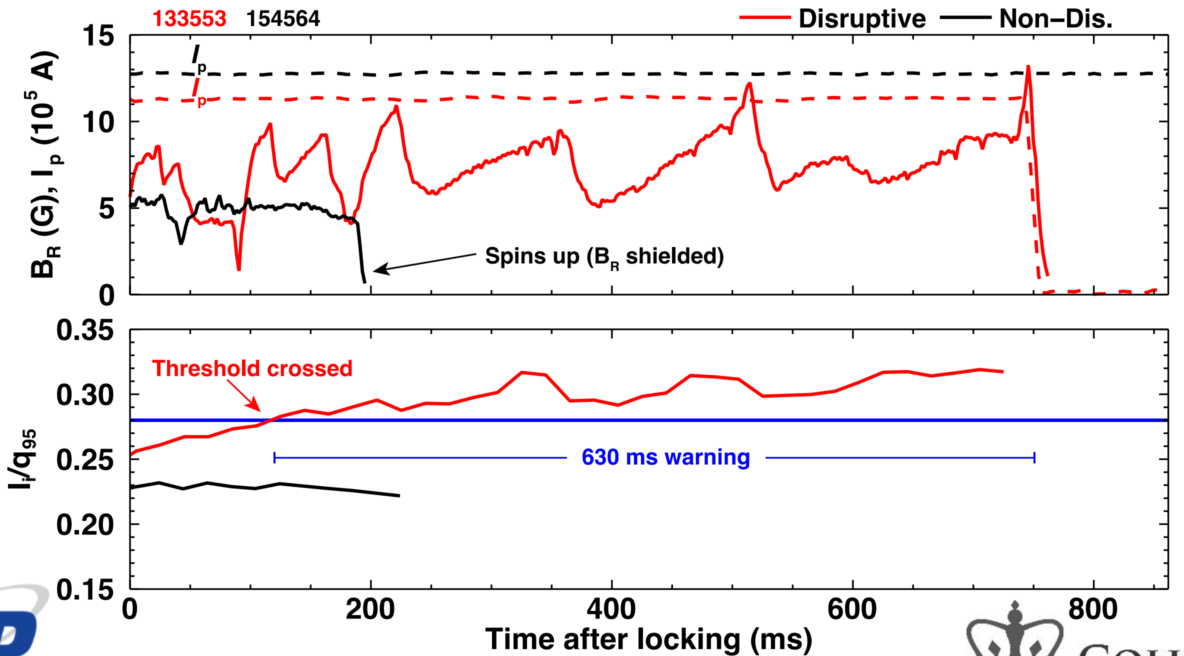
l_i/q_{95} and d_{edge} can be used for disruption prediction

Condition with IRLM	Missed disruptions (%) at 100 [20] ms	False alarms (%)
$\frac{l_i}{q_{95}} > 0.28$	6 [6]	13
$d_{edge} < 9$ cm	6 [4]	14
None (i.e. all LMs assumed disruptive)	0 [0]	29



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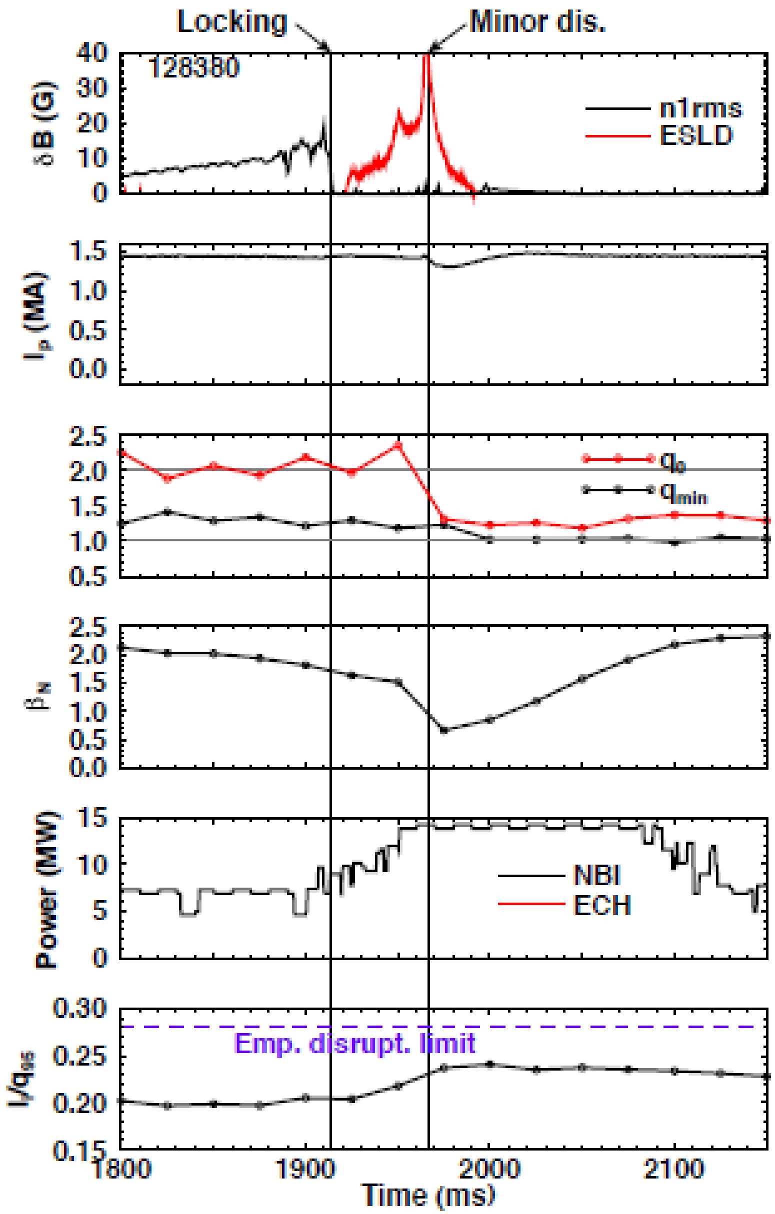
Some LMs self-stabilize through minor disruptions. Typically q_{min}>1.2 and q_0>2 (Double 2/1 LM)



Classically stable.
Change in pressure profile makes it neoclassically stable too?

- "Hiccup" in I_p
- q_0 drops at minor disruption
- Significant drop in β_N
- Beams appear in feedback
- l_i/q_{95} below empirical disruption limit

Outline

- Why a lecture on *Locked* Modes in a summer school about Disruptions?
- ...and what is a Neoclassical Tearing Mode anyway?
- Why/how does it lock? → Eq.of motion, torques
- Why/how does a mode form w/o rotating precursors? → Error Field penetration
- Why/how/when does it cause a disruption? → Stochastization?
- **How can we avoid/control locking, and avoid the associated disruption? → *Static* Magn. Perturbations & cw Localized Current Drive**

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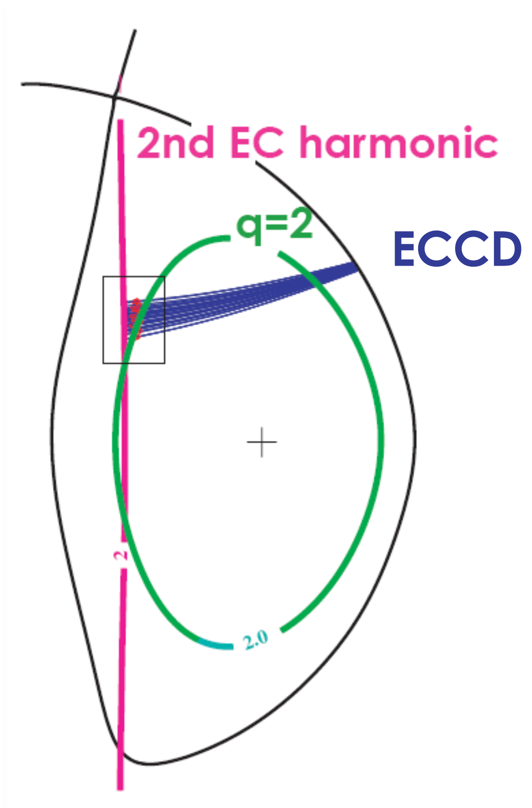
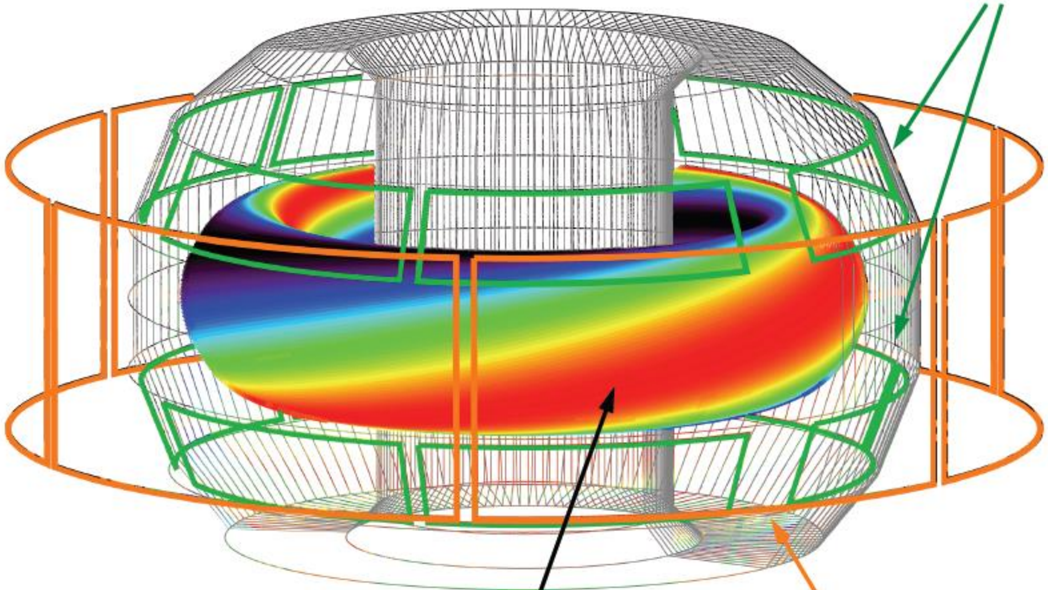
Control-coils, magnetic diagnostics and ~3MW of steerable Gyrotron power were used at DIII-D





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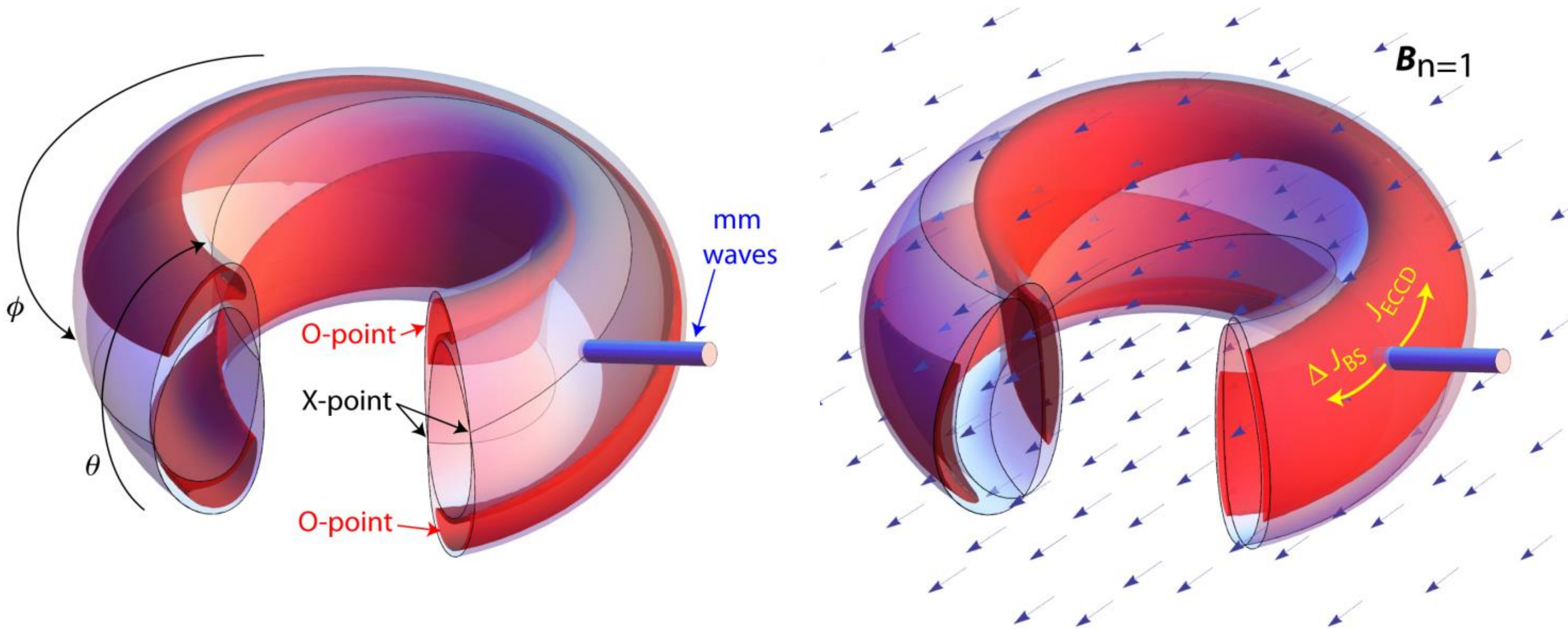
Magnetic steering aligns locked mode O-point to stabilizing ECCD



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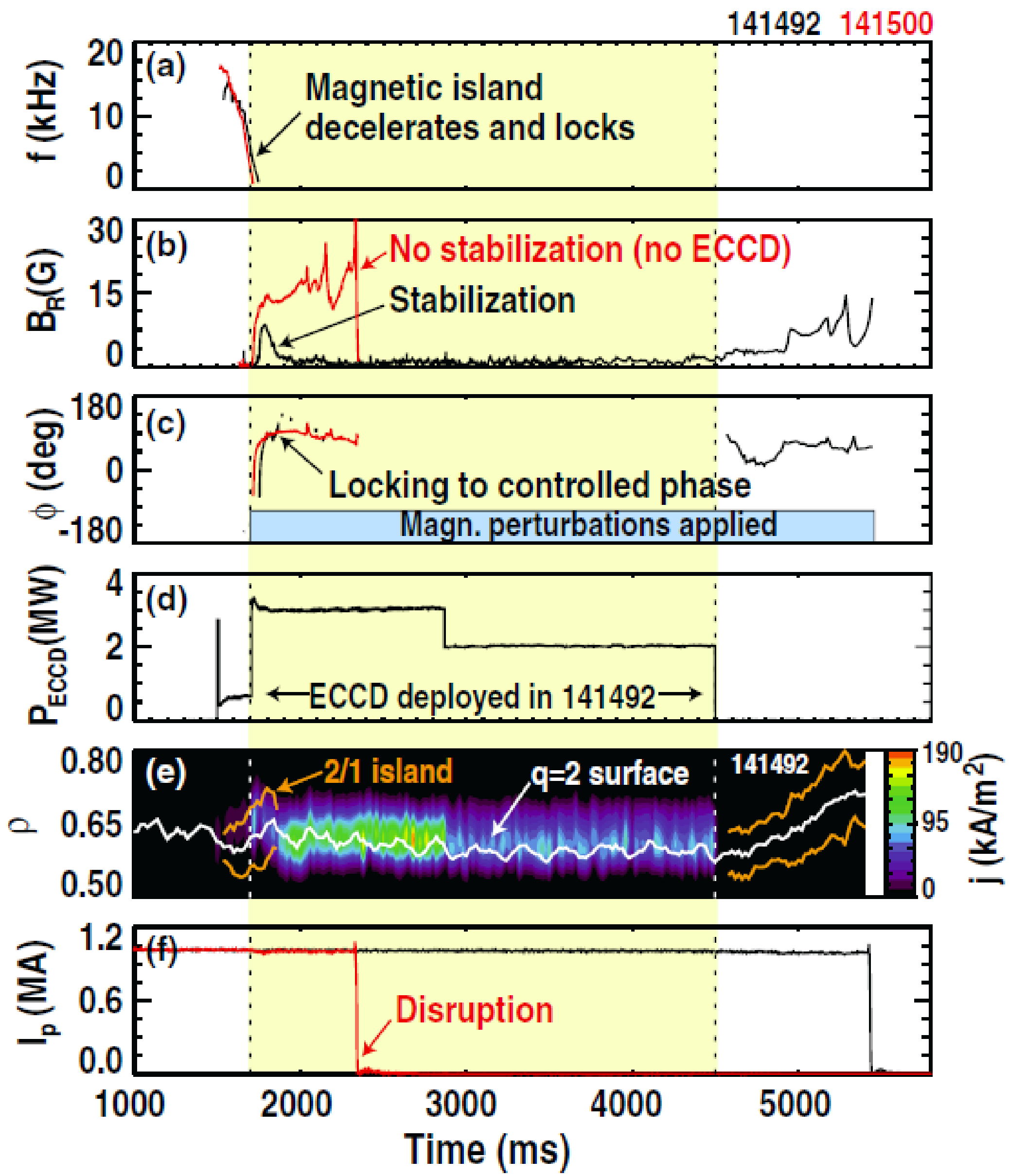
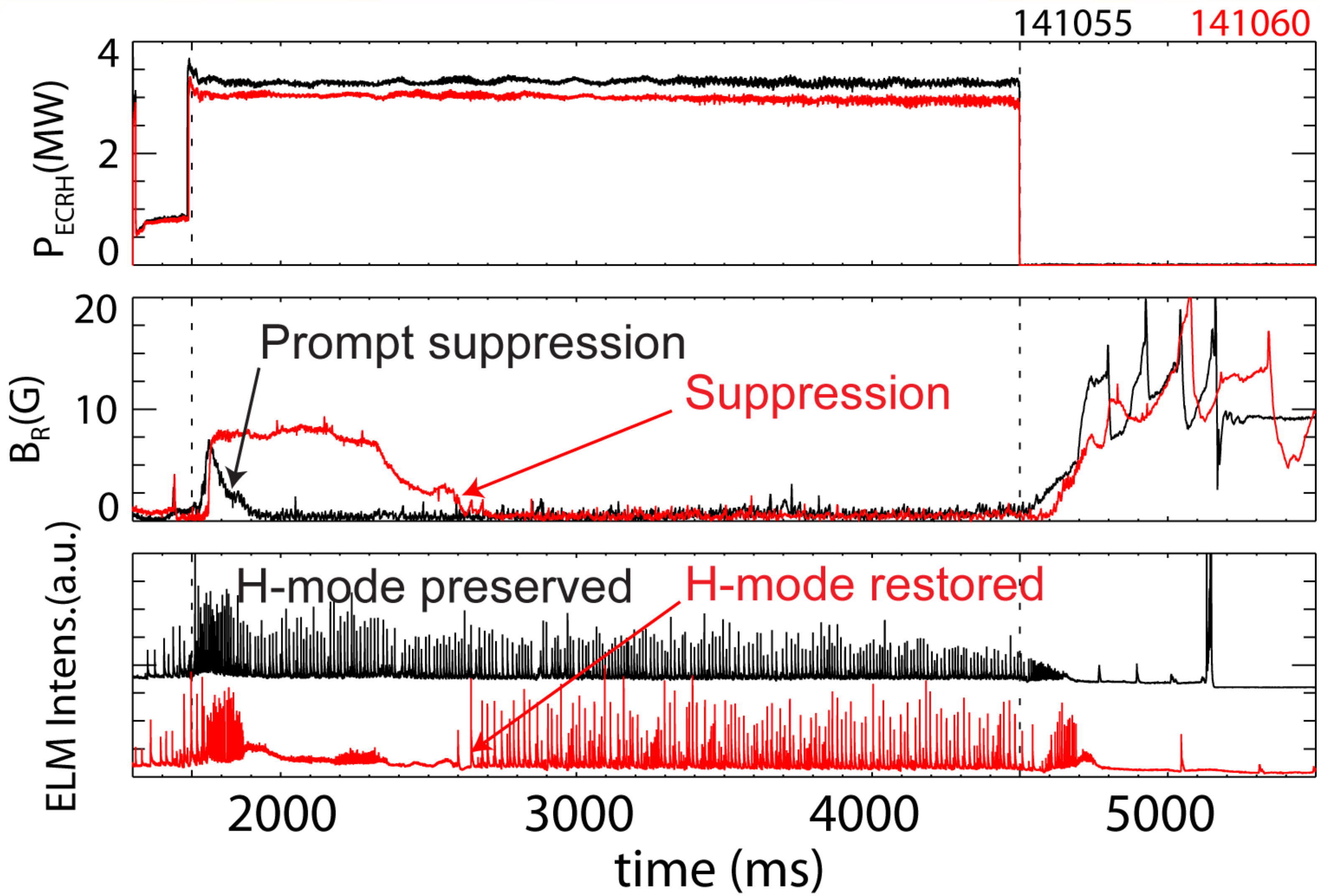
Static applied RMP make Locked Mode O-point accessible to stabilizing ECCD



Locked-mode-controlled discharges do not lose H-mode, or rapidly recover it



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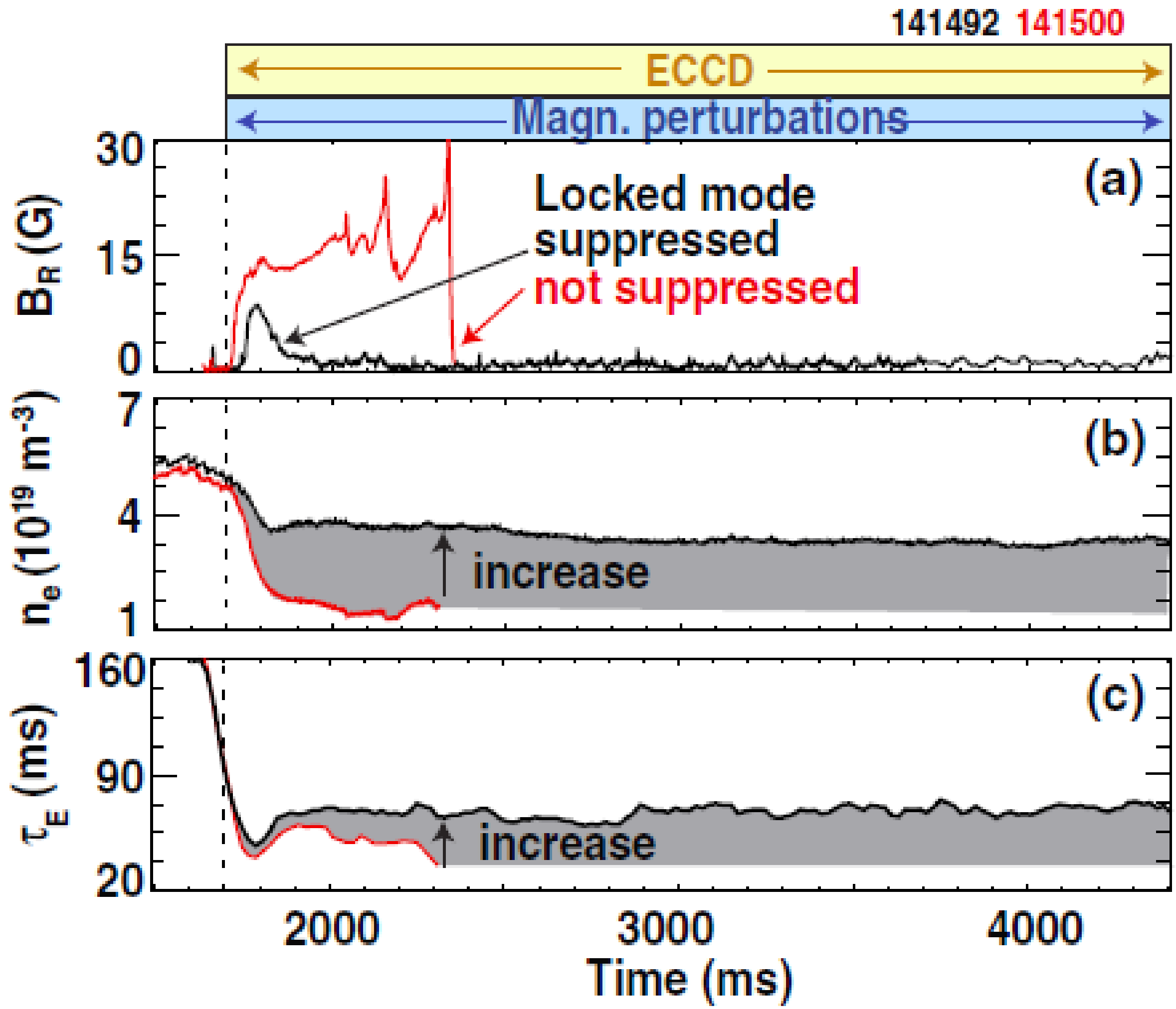
Incomplete recovery of pre-locking confinement is probably due to ECCD and RMPs still on



Best Disruption Avoidance should maintain high fusion gain Q

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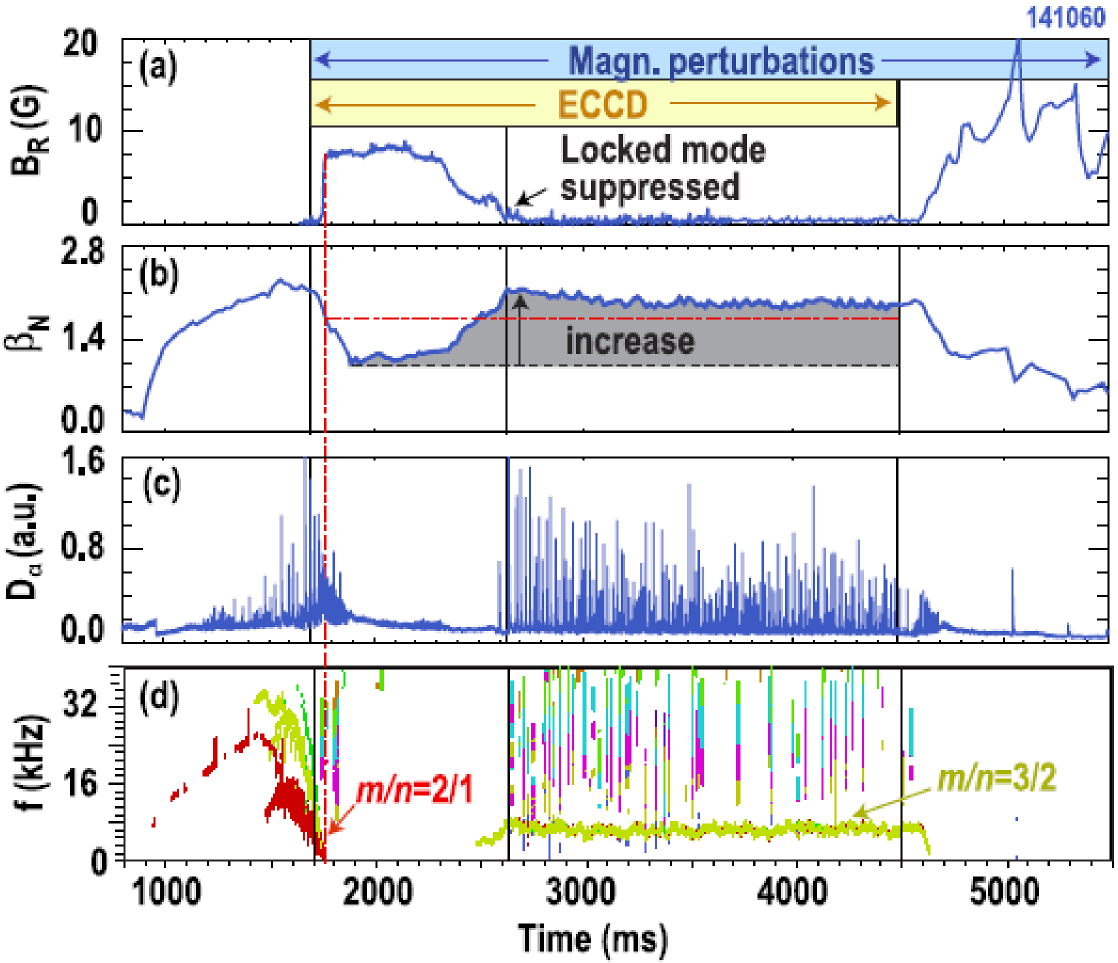
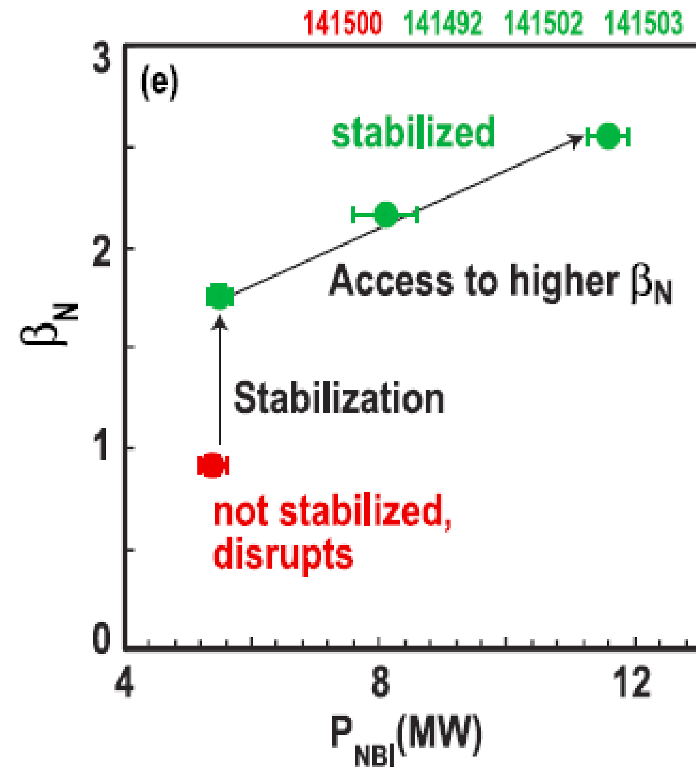
β_N is recovered after locked mode suppression



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



Locked mode stabilized:

- High β and no disruption

Locked mode not stabilized:

- Disruption at β~1.7

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Outline

- Why a lecture on *Locked* Modes in a summer school about Disruptions?
- ...and what is a Neoclassical Tearing Mode anyway?
- Why/how does it lock? → Eq.of motion, torques
- Why/how does a mode form w/o rotating precursors? → Error Field penetration
- Why/how/when does it cause a disruption? → Stochastization?
- **How can we avoid/control locking, and avoid the associated disruption? → *Rotating* Magn. Perturbations & *Modulated* Localized Current Drive**

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Modeling effect of rotating RMPs on locked or nearly-locked mode

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

E.M. Torques on Island **Other Torques**

Simplified equation of motion

$$I\frac{d^2\phi}{dt^2} = T_{wall} + T_{EF} + T_{RMP}$$

Smooth entrainment

$$0 = T_{wall} + T_{RMP}$$

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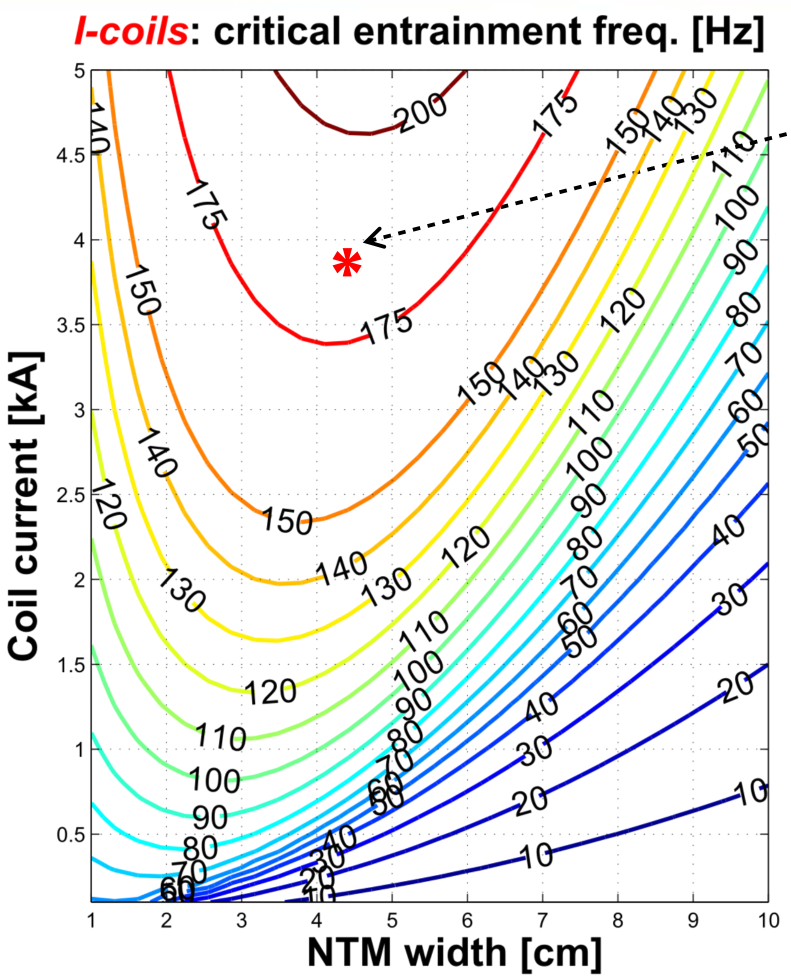
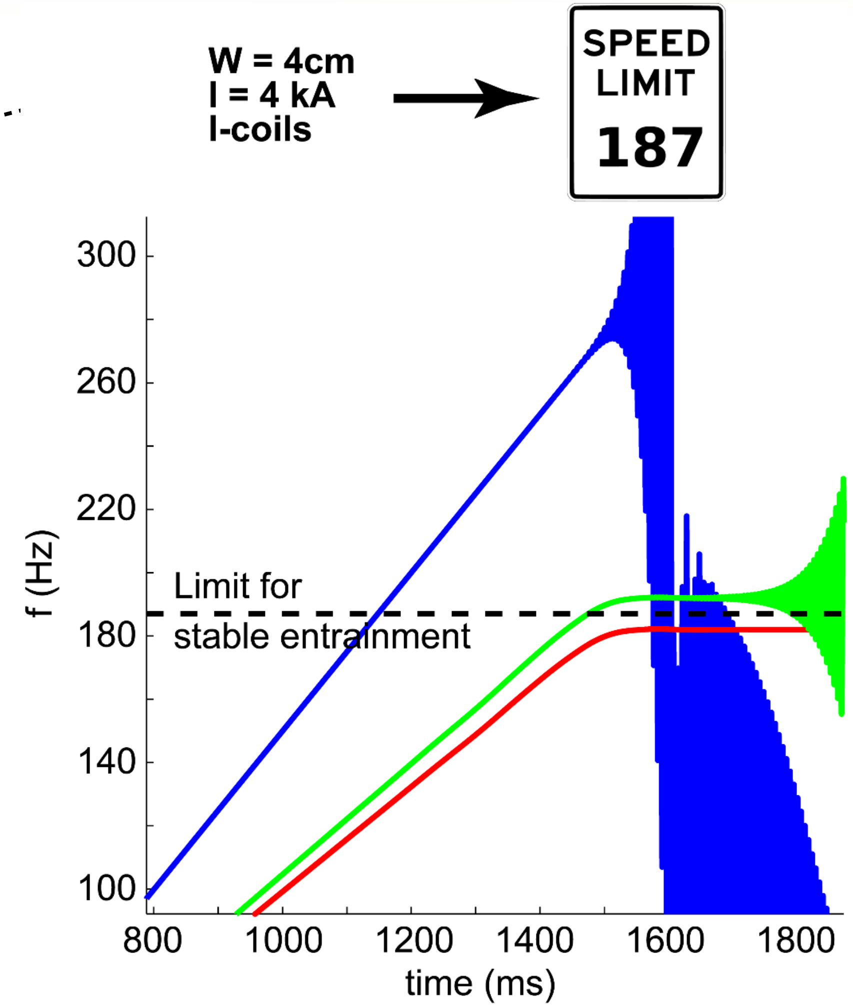
Entrainment can be lost due to failure of applied torque to counteract braking torque from the wall at high frequency





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

K.E.J. Olofsson PPCF 2016

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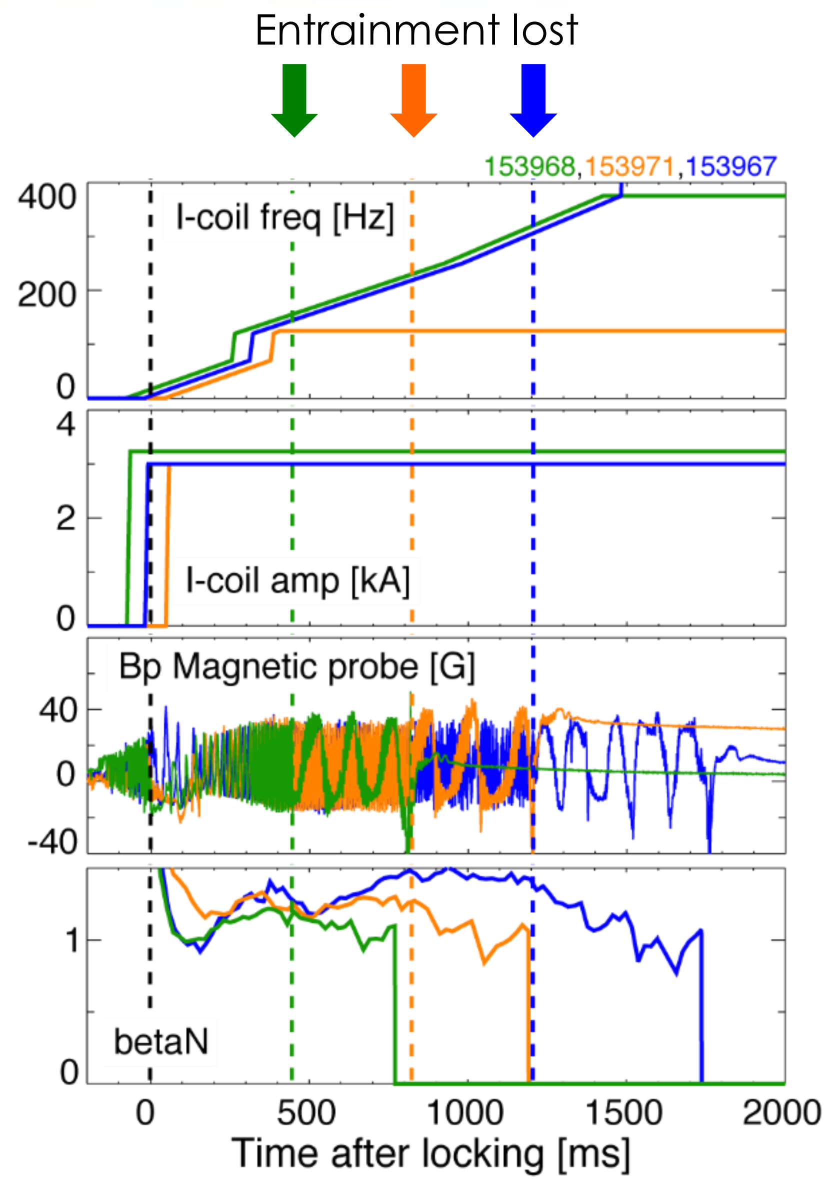
Loss of entrainment is more complicated than loss of torque balance

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

- **While it lasts, it avoids disruptions w/o using ECCD**



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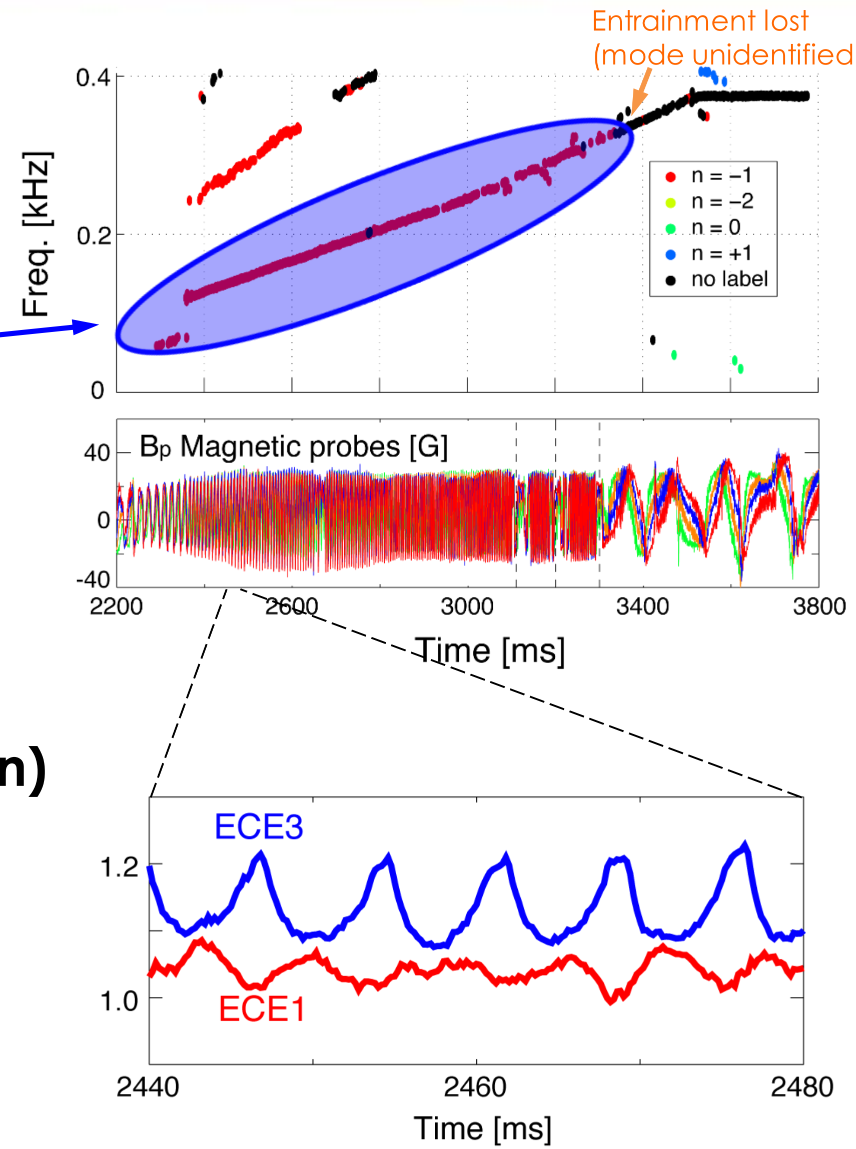
Magnetics array analysis and ECE diagnostic confirm entrainment and spin-up of 2/1 mode

- ***m*/*n*=-2/-1 mode tracks I-coil frequency**

- **Entrainment frequency is modulated by EF on sub-period timescale (not shown)**



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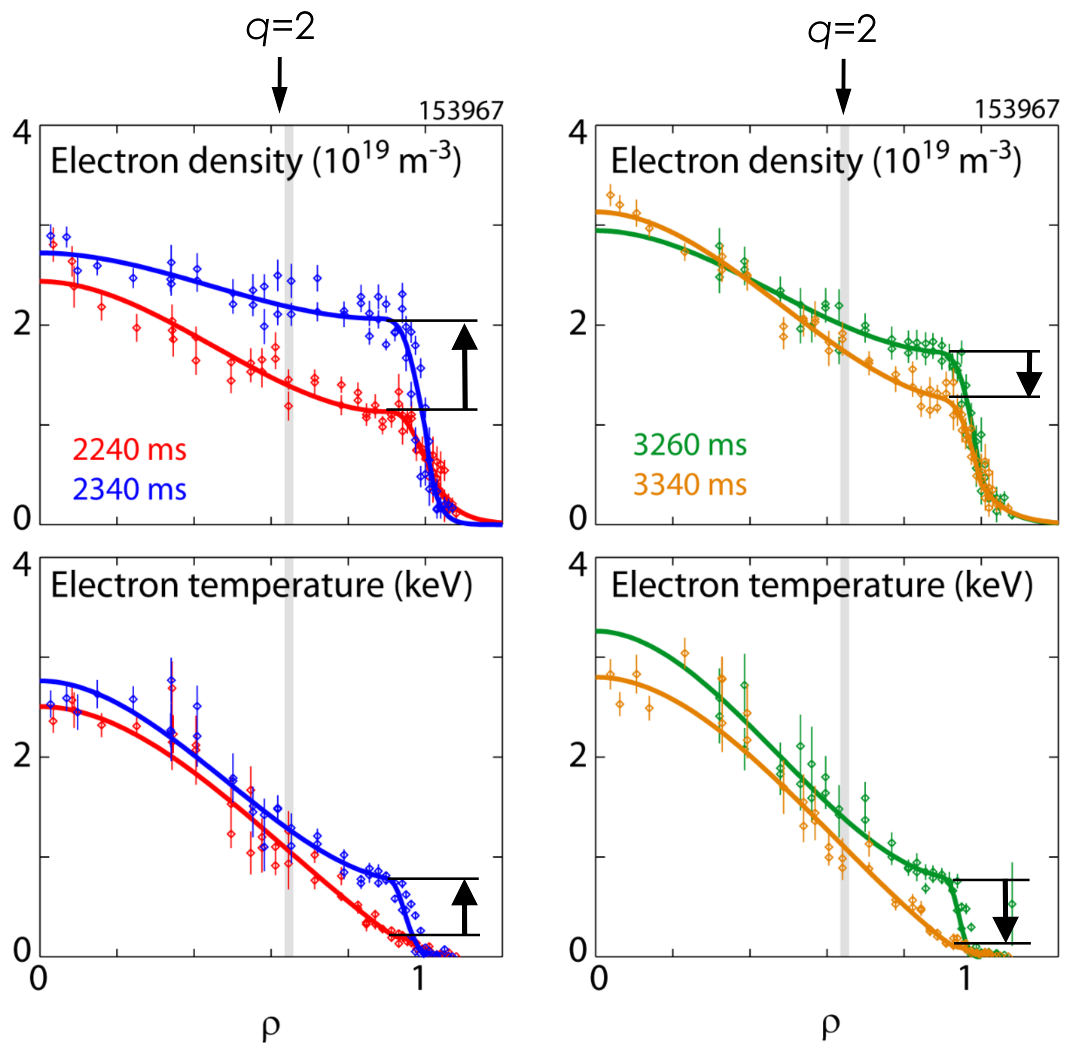
Improved confinement: edge pedestal forms during entrainment

At entrainment



At loss of entrainment

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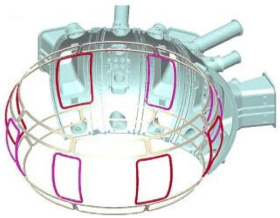
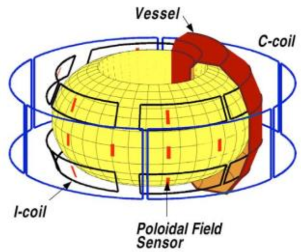
5 tokamaks, 2 spherical tokamaks, 2 RFPs and a helical device are involved in WG-11

AUG

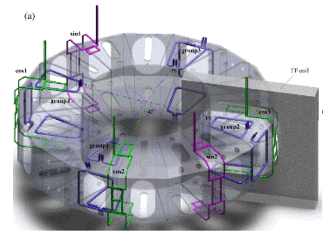


DIII-D

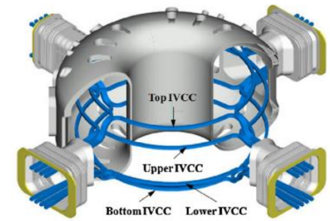


JET

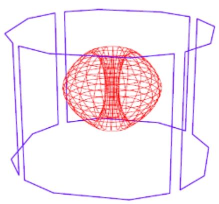
J-TEXT



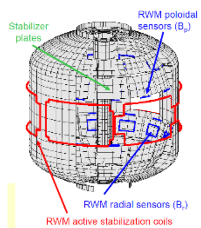
KSTAR



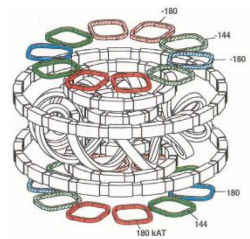
MAST



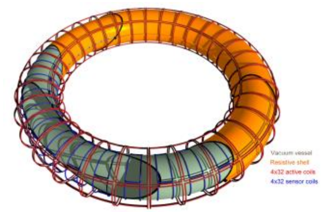
NSTX



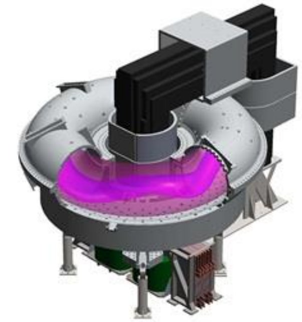
LHD



EXTRAP-T2R



MST



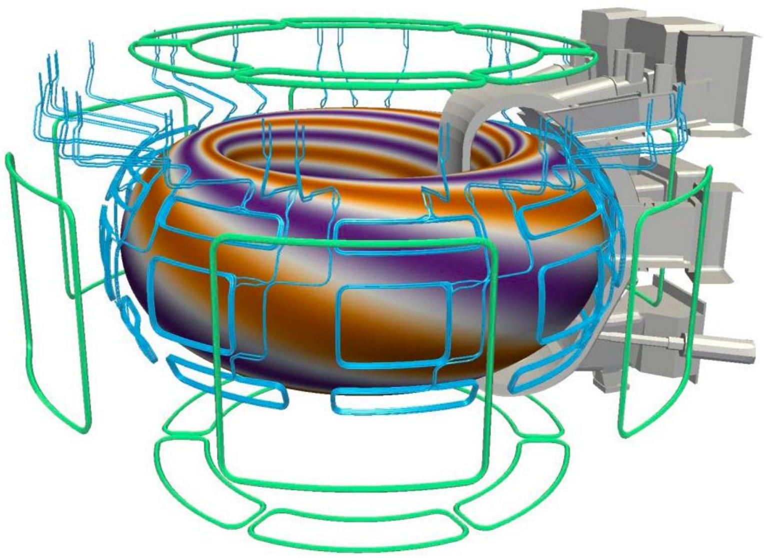
Different Machines

- Sizes
- Aspect ratios
- elongations
- wall times

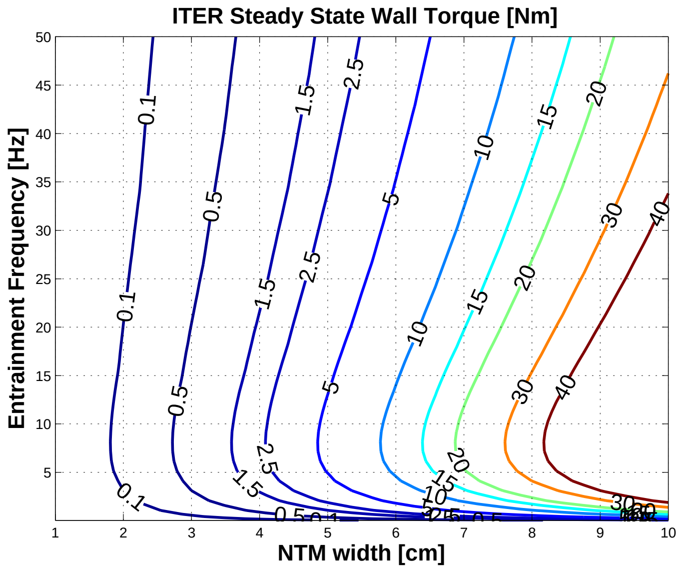
Different Coil sets

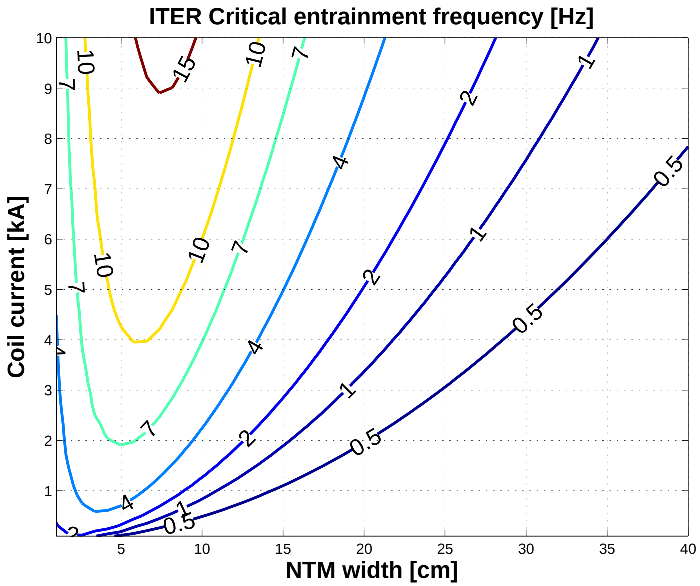
- Internal or external
- narrow or broad in angular spread
- dense or sparse arrays
- partial/full toroidal/poloidal coverage

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: 7.2×10^{19} m^{-3}**
- **B_t: 5.3 T**





larger island results in stronger torque

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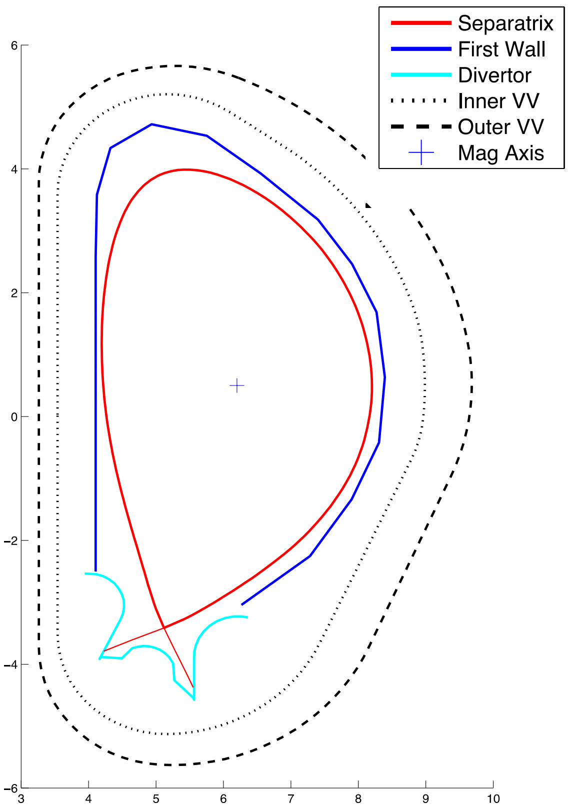
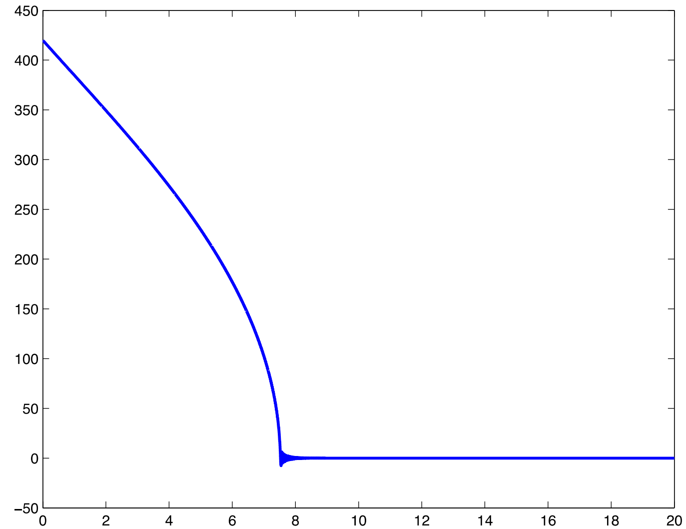
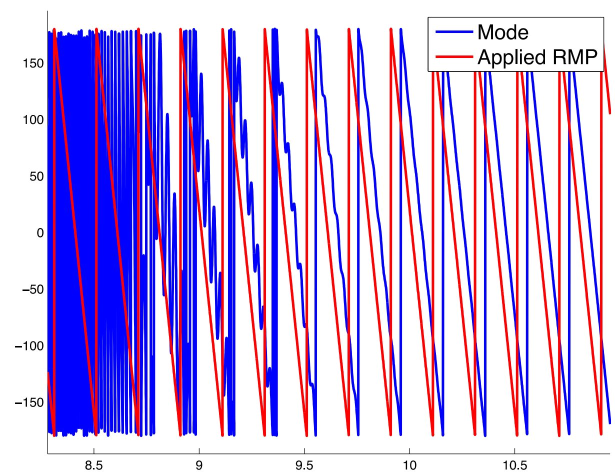
ITER model – NTM slows and locks in about 7 seconds



ITER treated with 2 walls:

1) vacuum vessels
2) tiled Be first wall





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

Agrees with La Haye NF2009

5 Hz entrainment with 10 kA in external coils

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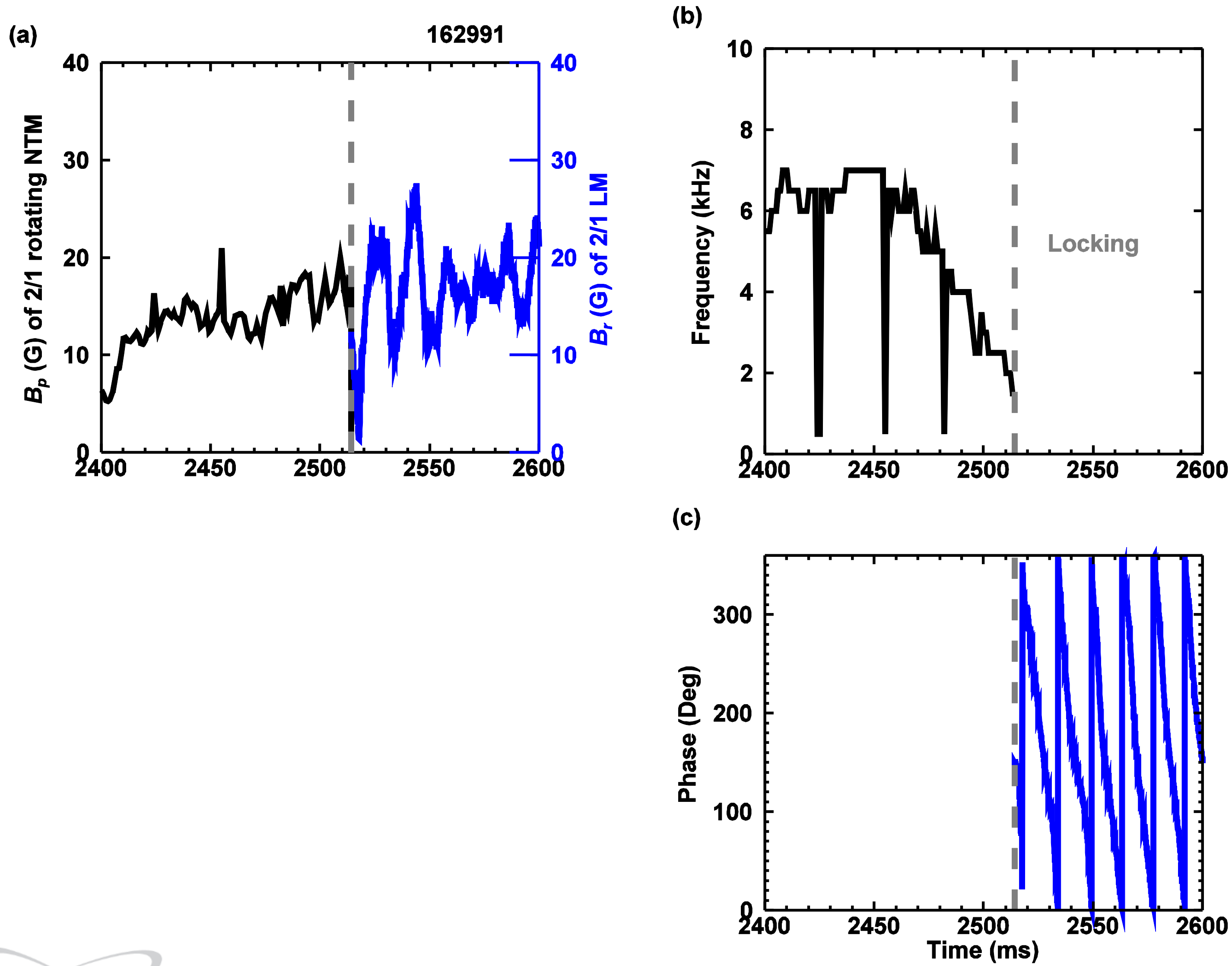
Decelerating island can be "preemptively entrained" by rotating fields applied in feed-forward



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Proportional-integral controller controls LM phase in feedback with LM phase measurements

$\Phi_{reference}$ requested →

Φ_{mode} from magnetic signals →

$$\Phi_{error} = \Phi_{ref} - \Phi_{mode}$$

$$\Phi_{correction} = \text{PI control}\,(\Phi_{error})$$

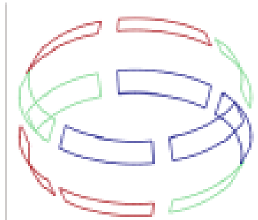
↓ $\Phi_{corr.}$

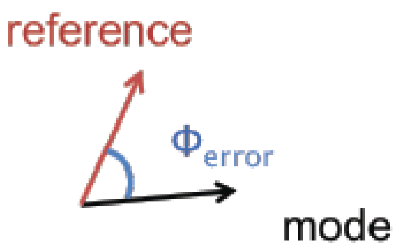
$$\Phi_{RMP} = \Phi_{mode} + \Phi_{corr.}$$

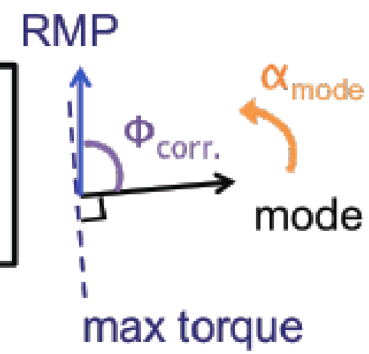
limit to Φ_{mode} $\pm 90°$ for max torque

↓ Φ_{RMP}

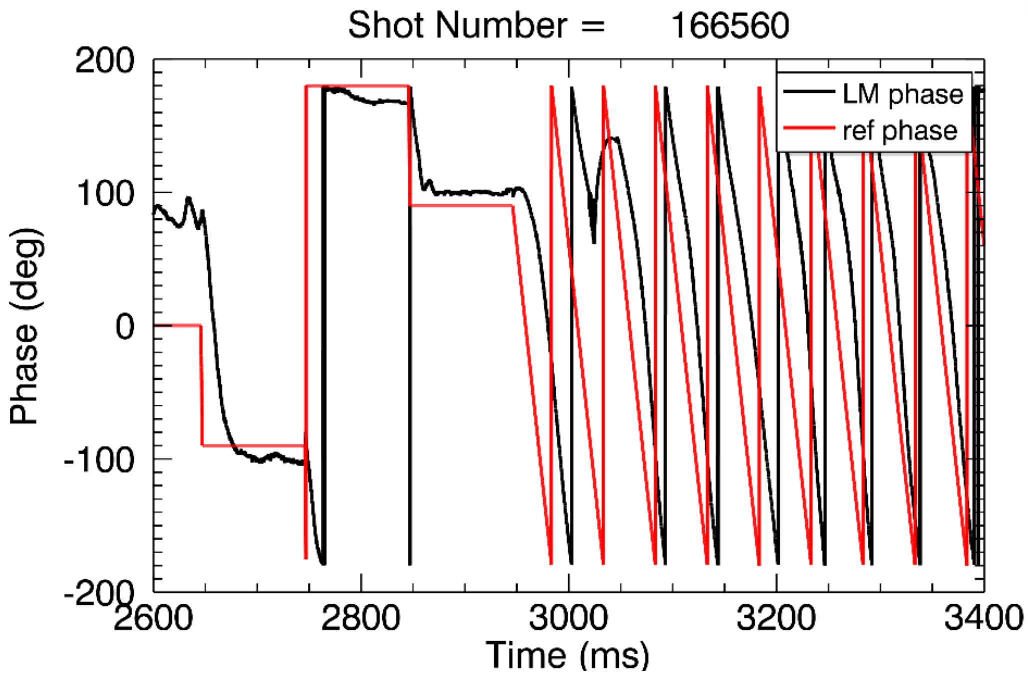
applied to coils

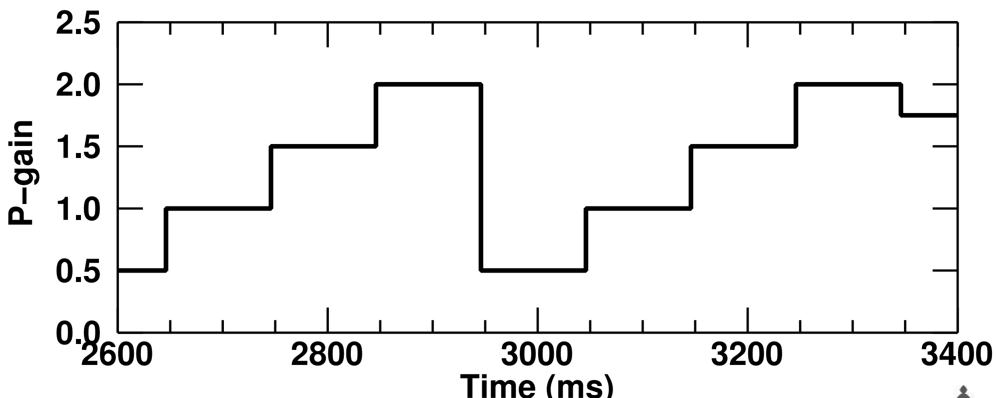






Phase controller locked mode where desired and entrained it at 20 Hz as desired





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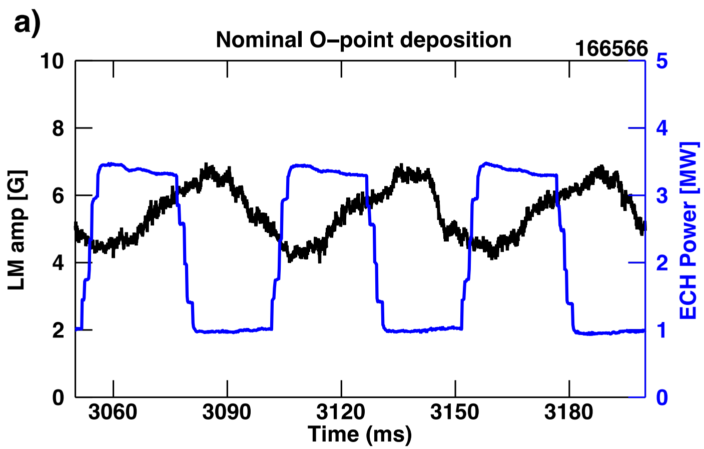
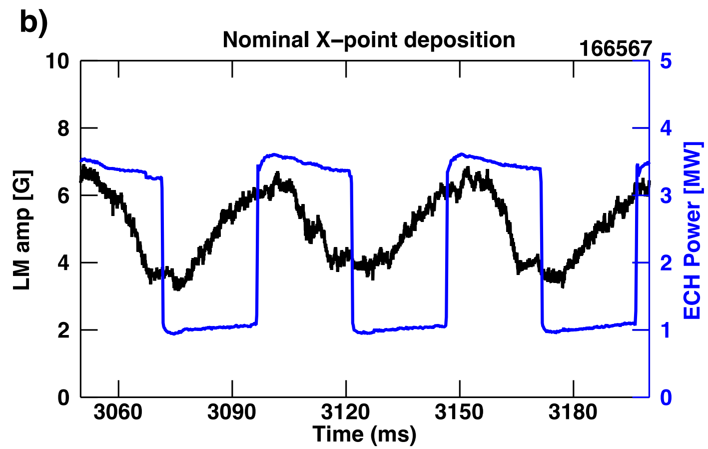
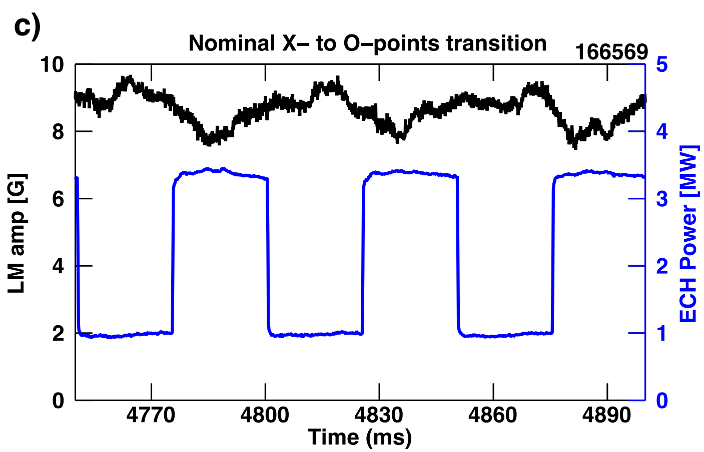
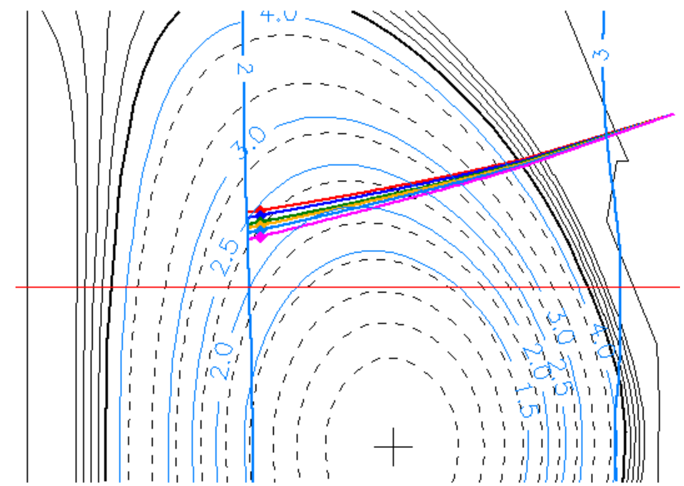
Different phasing gives different behavior. Deposition slightly outside q=2 location.

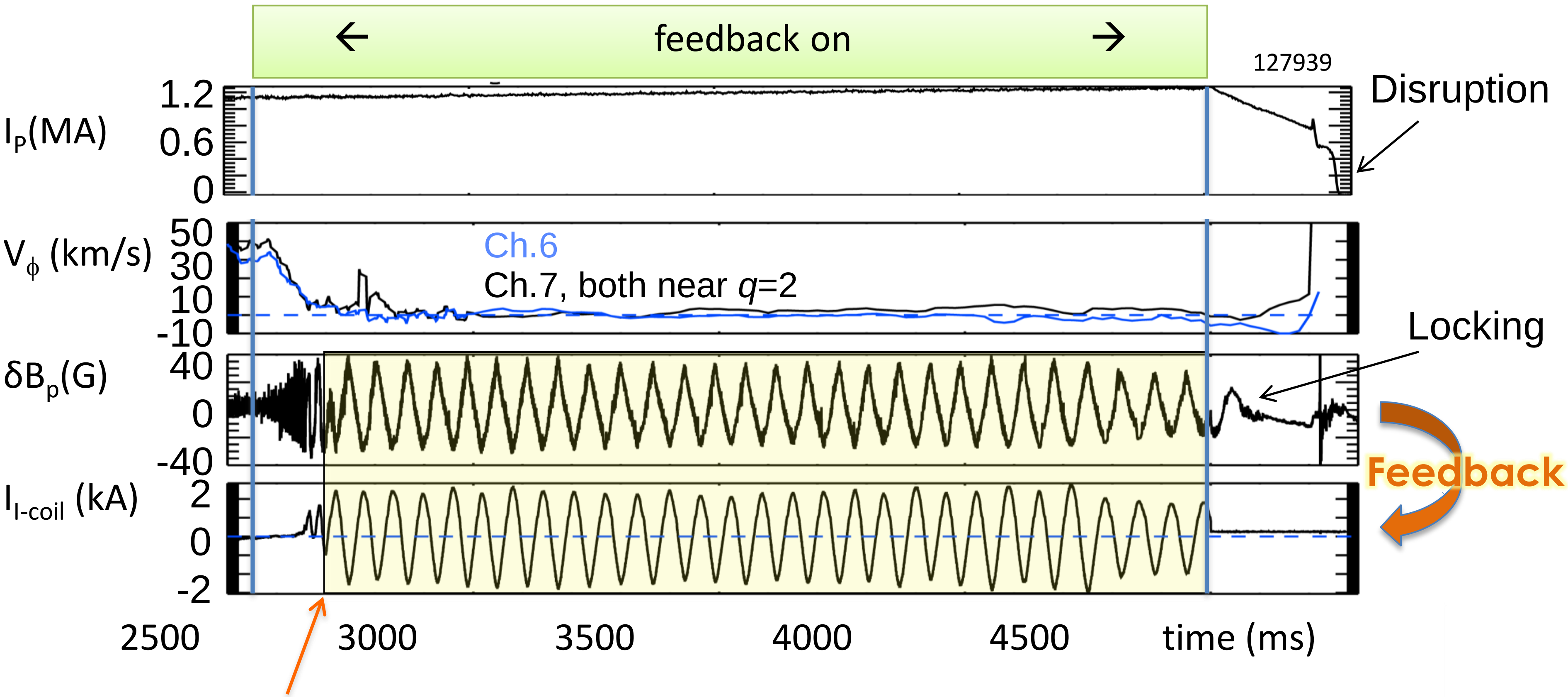








Amplitude feedback can prevent locking and sustain NTM rotation at 15-60 Hz



Mode rotates at ~15 Hz

Feedback settings:

- Low-pass filter, τ_p=40ms
- Gain G_p= 60

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.

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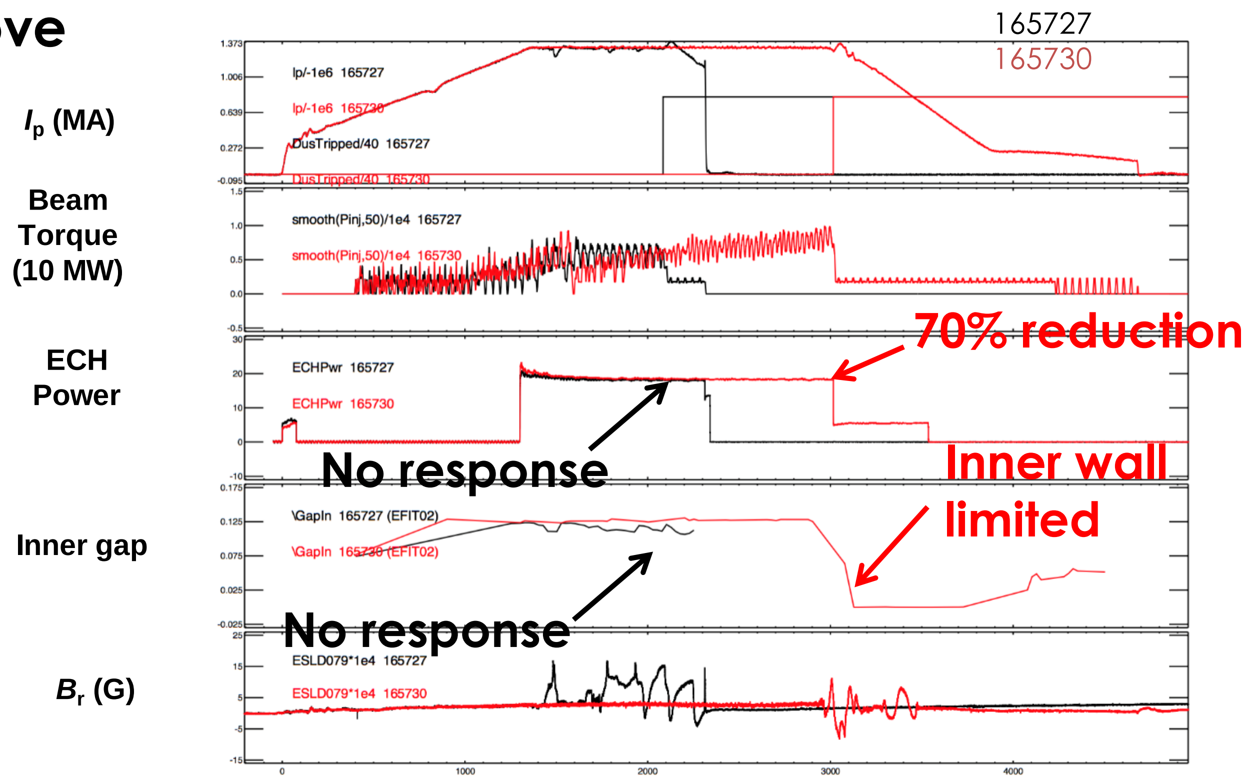
Locked modes can also be controlled non-magnetically, or w/o ECCD

- Increase NBI torque → Stabilization by rot.shear or rot.wall
- Drop in power (NBI and ECH) → Reduce β → Neoclassical stability
- Full I_p ramp down → Safe shutdown
- Partial I_p ramp down → Reduce q_{95}. Increase d_{edge}, l_i/q_{95}
- Change in shape → Affect stability & rotation
- Some/all of the above



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Summary & Conclusions on Locked Modes

- Locked modes are non-rotating (growing or saturated) plasma instabilities, typically NTMs.
- Without the benefits of rotation, they grow to the point of significantly degrading confinement.
- One of the main causes of disruptions.
- Ubiquitous, also in disruptions initiated by other phenomena.
- Simple model: helical current-filaments at rational surface, subject to e.m. and non-e.m. torques.
- Advanced model: coupled single-fluid momentum eq. + flux evolution at island location and wall.
- Rotating precursor decelerates due to wall torque, and locks to resultant of EF + applied MP + other TMs.
- Even w/o precursor, above-threshold EF or below-threshold rotation leads to a bifurcation in B_R → EF penetration, born LM.

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Summary & Conclusions on LM Disruptions

- **Overlap of several islands locked to each other and to EF+MP → Stochastization → Enhanced convection, conduction (and radiation) → Partial thermal quench (TQ) → Full TQ → CQ**
- **Database analysis suggests that proximity to edge & classical stability determines LM "disruptivity".**
- **Real-time monitoring of these parameters could help predicting locking.**
- **If locking occurs, applied MPs control LM phase, applied ECCD controls LM amplitude.**
  - Static/rotating, cw/modulated, in f/fwd, two types of f/back.
  - LM stabilized in DIII-D and entrained in several devices, in agreement with modeling. 5 Hz entrainment possible in ITER.
  - Changes in NBI, I_p and plasma shape also affect locking and disruptivity.

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