NSTX

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Overview of Neoclassical Tearing Mode Studies in NSTX

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APS-DPP Meeting, 2008

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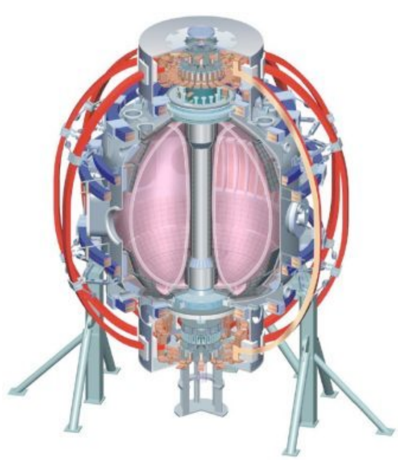

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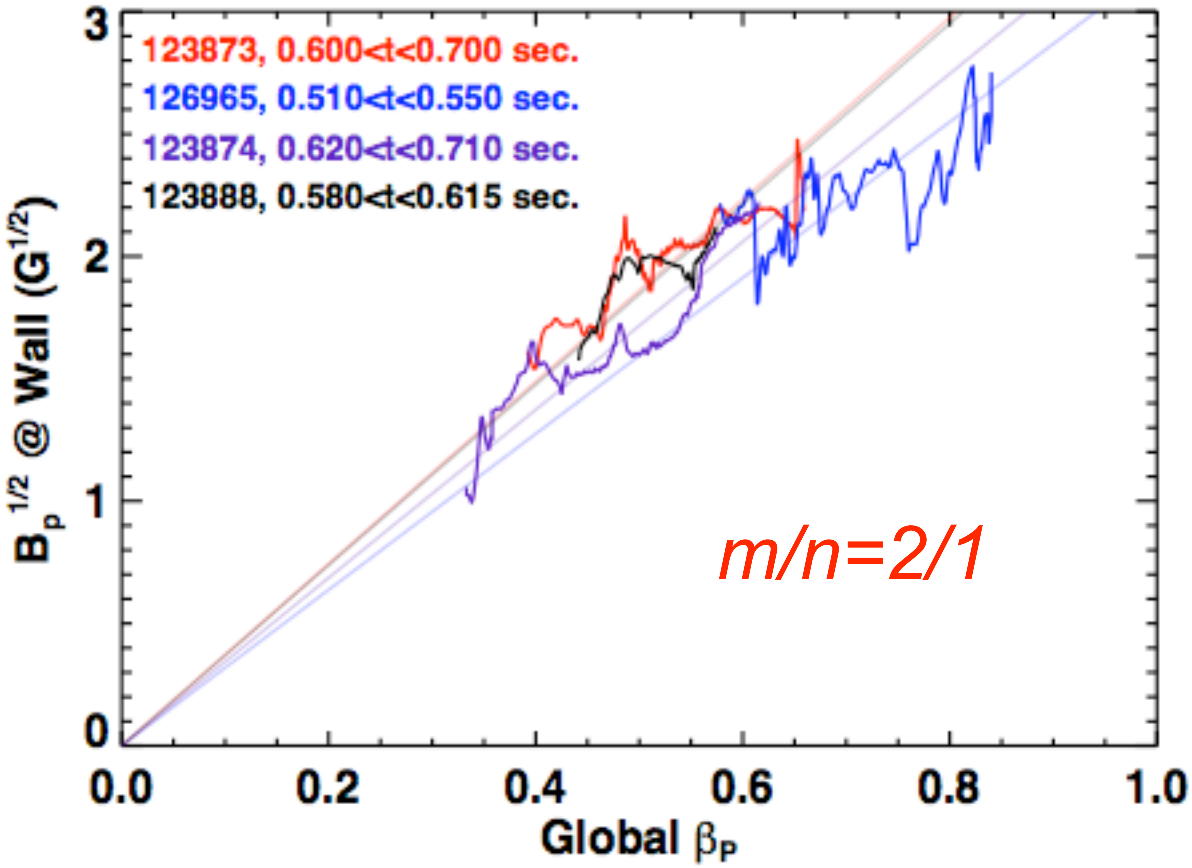
Part 1: Introduction

- Modes have the expected island width dependence on β_P.
- Modes lead to severe discharge degradation.
- Modes can be restabilized when β_P is sufficiently reduced.

Islands Have Expected $w \propto \beta_P$ dependence

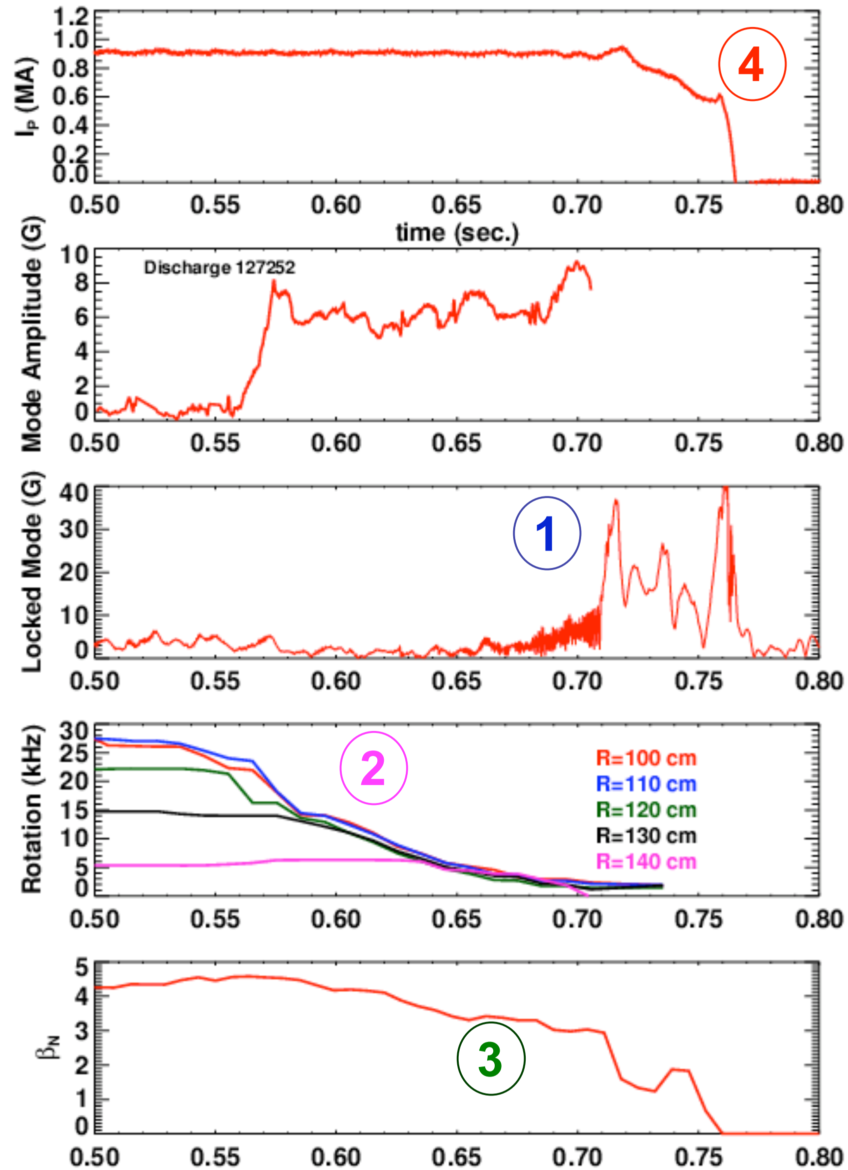
In β_p rampdown experiments, $w \propto \beta_P$



Global Performance Severely Impacted By Growth of Rotating MHD

Deleterious Effects of the m/n=2/1 Mode

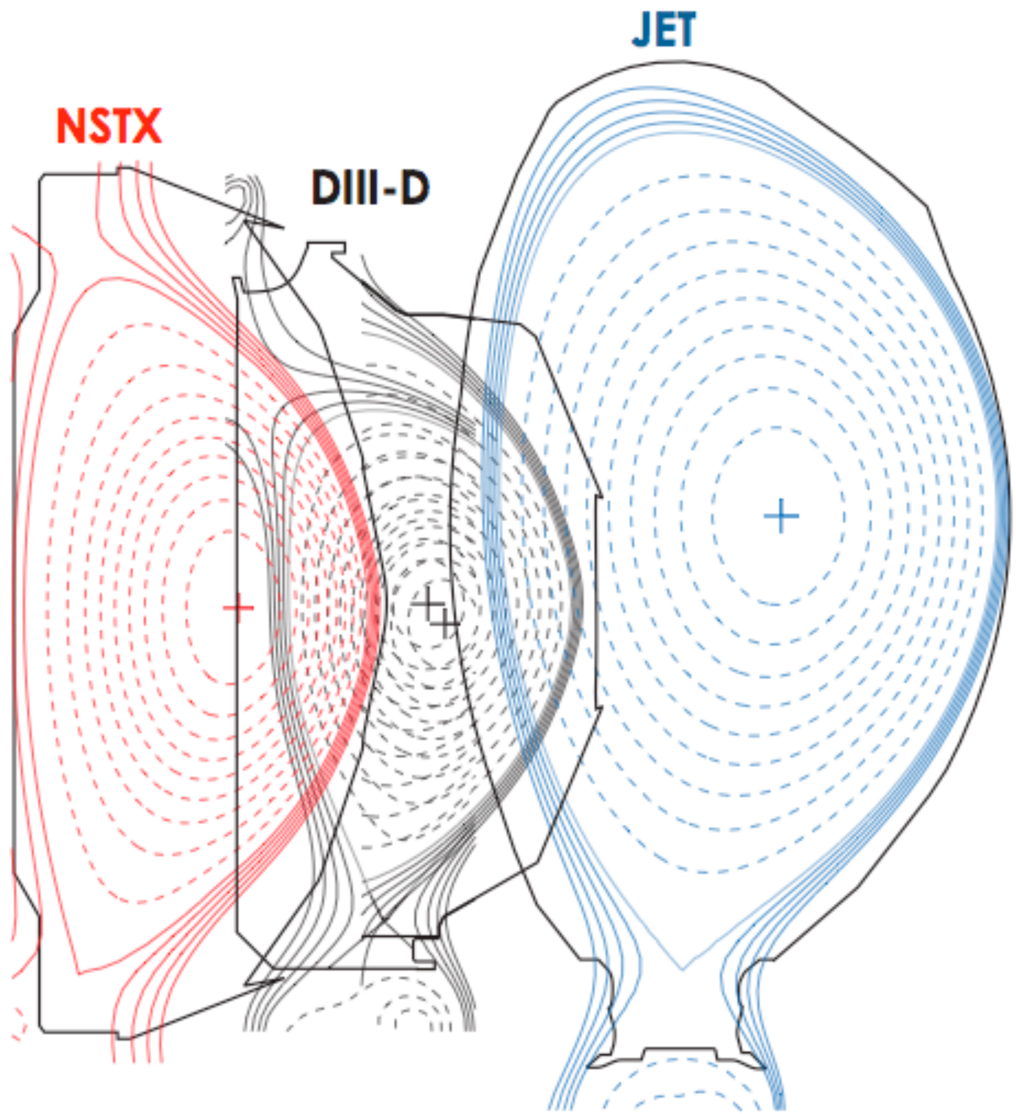
1) Mode Locking
2) Rotation Damping
3) Confinement Degradation
4) Disruption



DIII-D, NSTX, and JET m/n=2/1 Comparison Allows Study of Aspect Ratio Effects on Marginal Stability

- All ELMing H-mode
- Aspect ratio and size vary
- q_{95} matched:
    - ~7 in NSTX and DIII-D
    - ~4 in DIII-D and JET

Study the island width and Δ' at the restabilization point.



Analysis By R. J. La Haye

Appraising marginal Island Width and Δ' in DIII-D for m/n=2/1 Neoclassical Tearing Modes

- **Helically perturbed bootstrap current balanced by negative Δ' in MRE**

★ $\Delta' r \approx -\varepsilon^{1/2} (L_q/L_{pe}) (r/w_{sat}) \beta_{\theta e}$

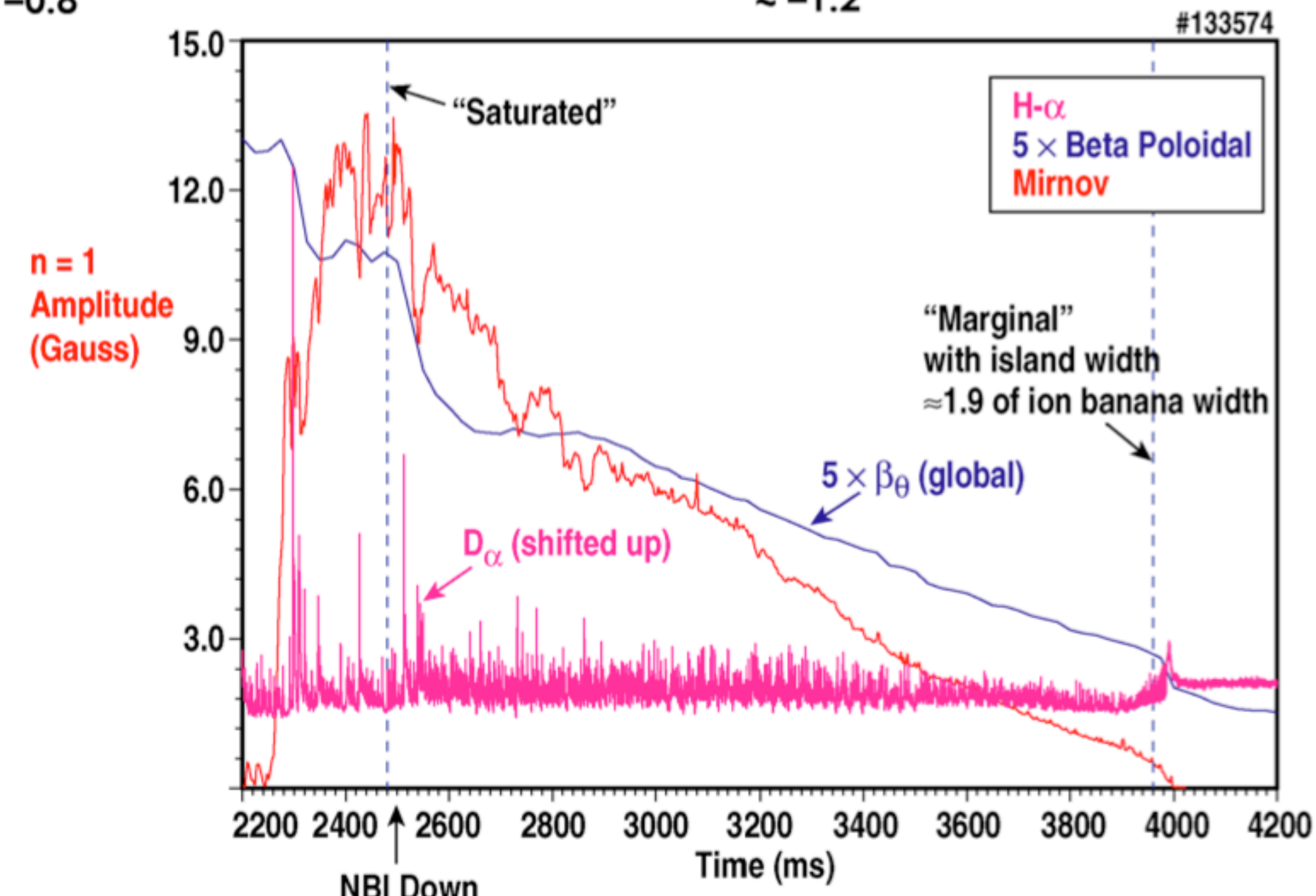
$\approx -0.42\ (0.116/0.323)\ (0.308/0.074)\ 0.92$

≈ -0.8

★ $\Delta' r \approx -(2/3)\, \varepsilon^{1/2} (L_q/L_{pe}) (r/w_{marg}) \beta_{\theta e}$

$\approx -0.667 * 0.41\ (0.165/0.169)(0.282/0.019)0.30$

≈ -1.2



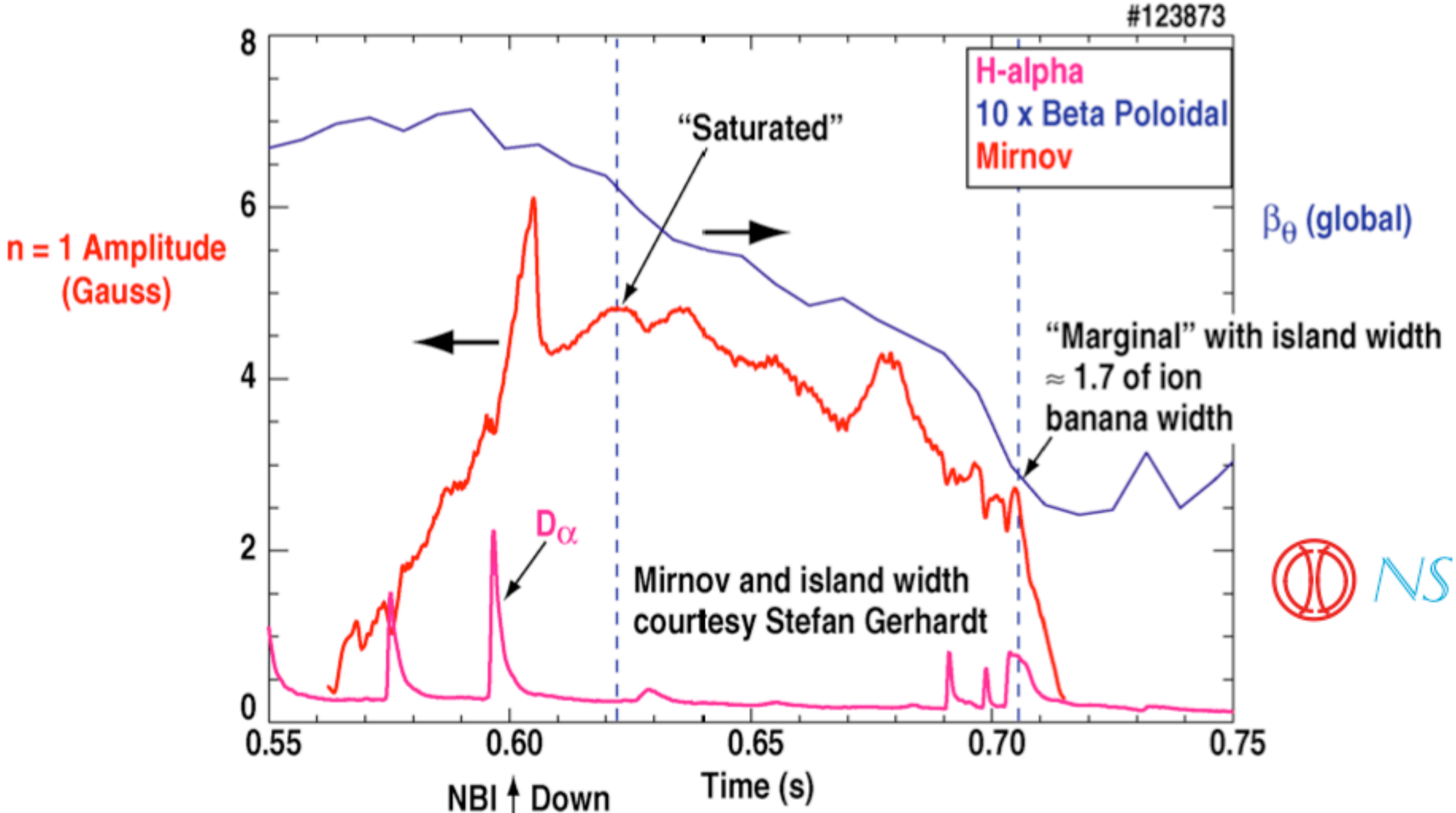
Analysis By R. J. La Haye

Appraising Marginal Island Width and Δ' in NSTX for m/n=2/1 Neoclassical Tearing Modes

- **Helically perturbed bootstrap current balanced by negative Δ´ in MRE**

★ $\Delta' r \approx -\varepsilon_B^{1/2}\,(L_q/L_{pe})\,(r/w_{sat})\,\beta_{\theta e}$
$\approx -0.65\ (0.083/0.158)\ (0.447/0.060)\ 0.22$
≈ -0.6

★ $\Delta' r \approx -(2/3)\,\varepsilon_B^{1/2}\,(L_q/L_{pe})\,(r/w_{marg})\,\beta_{\theta e}$
$\approx -0.667 * 0.65\ (0.128/0.081)(0.436/0.045)0.135$
≈ -0.9



Analysis By R. J. La Haye

Appraising Marginal Island Width and Δ' in JET for m/n=2/1 Neoclassical Tearing Modes

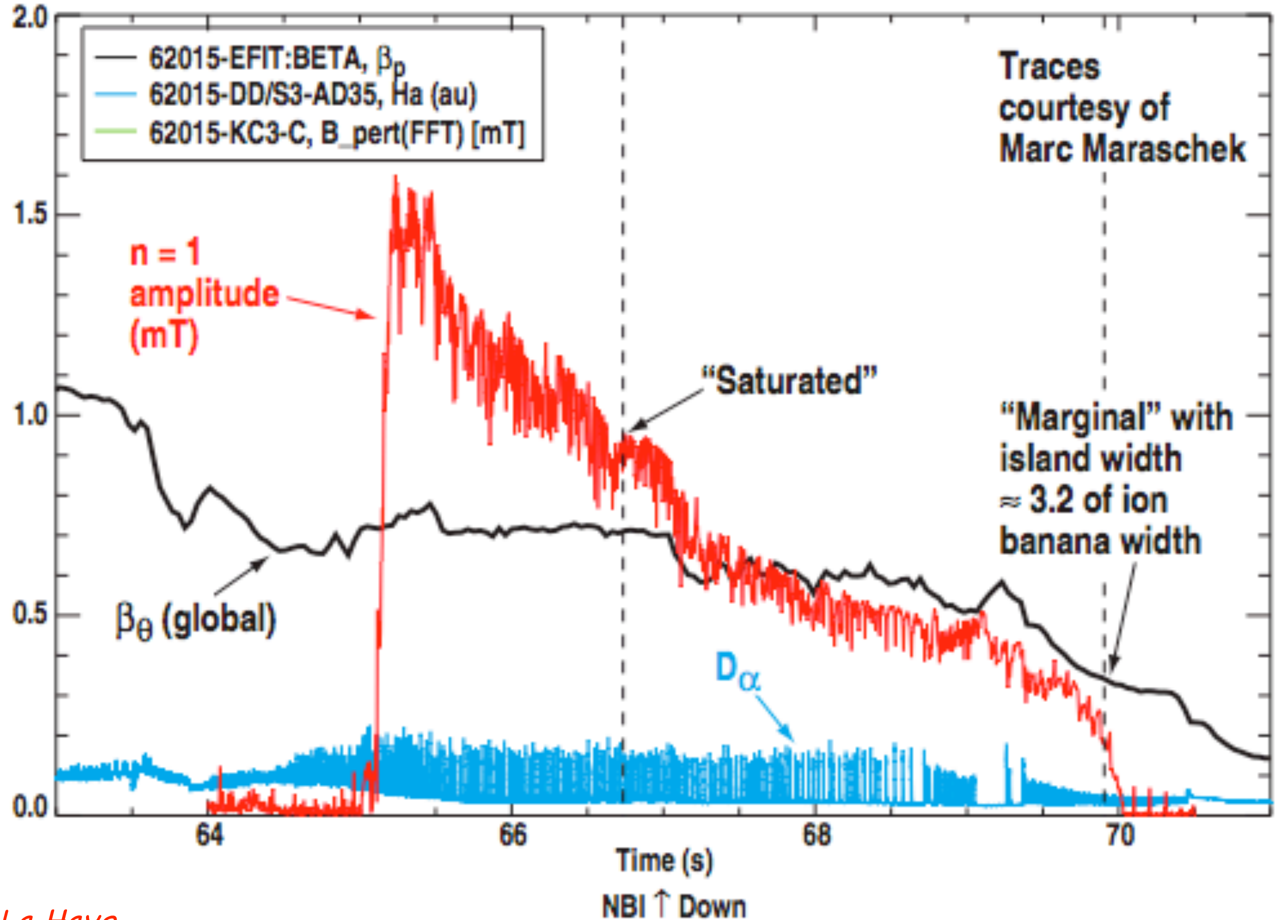
- **Helically perturbed bootstrap current balanced by negative Δ´ in MRE**

★ $w_{marg}/\varepsilon^{1/2}\,\rho_{\theta i} \approx 3.2$

★ $\Delta' r \approx -(2/3)\,\varepsilon^{1/2}\,(L_q/L_{pe})\,(r/w_{marg})\,\beta_{\theta e}$

$\approx -0.667 * 0.46\,(0.556/0.492)(0.628/0.037)0.137$

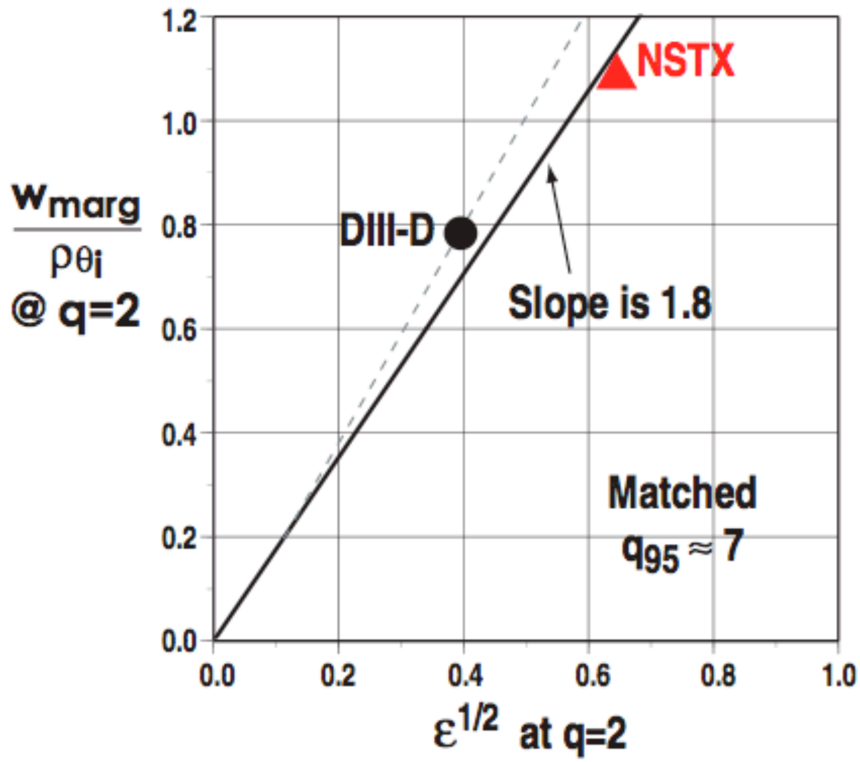
≈ -0.8

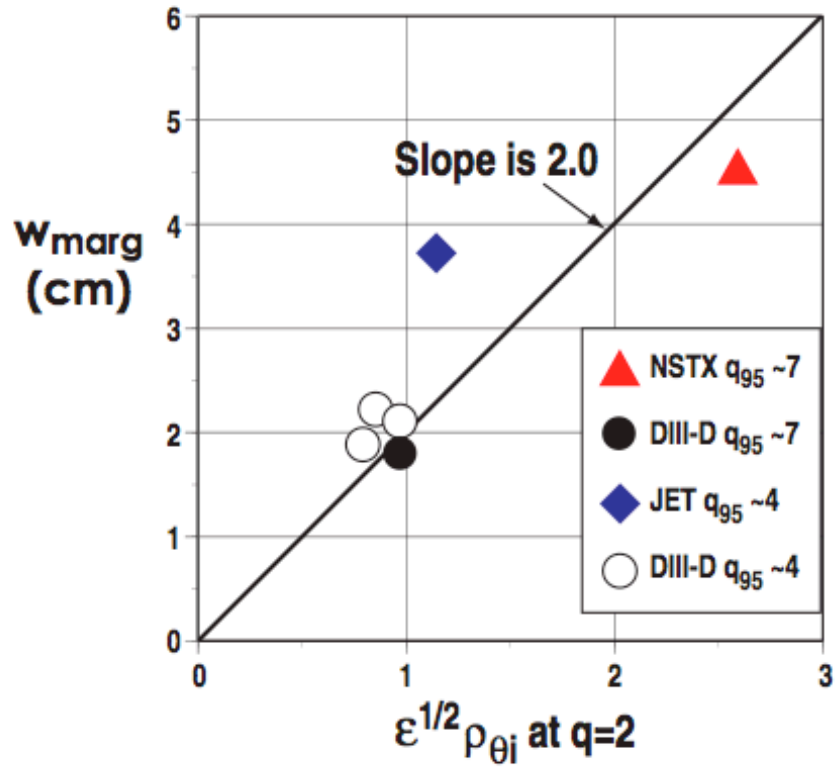


Analysis By R. J. La Haye

Marginal Island Widths Are a Few Ion Banana Widths at q=2

- **Marginal island width a few times the ion banana width at q = 2**





- **$\Delta'(w_{marg})r$ ranges from –1 to –2**

335-08/RJL/jy

Analysis By R. J. La Haye

Part 1: Mode Triggering

- *Slowly Growing Modes With No Clear Trigger*
- *Modes With Clear EPM Triggers*
- *Modes with ELM Triggers*
- *Modes born from Locked Modes*

Common Characteristics Lead to "Rules" for Mode Identification

1: Mode should have n=1, as determined by Mirnov array phase analysis
   - Toroidal mode number identification.

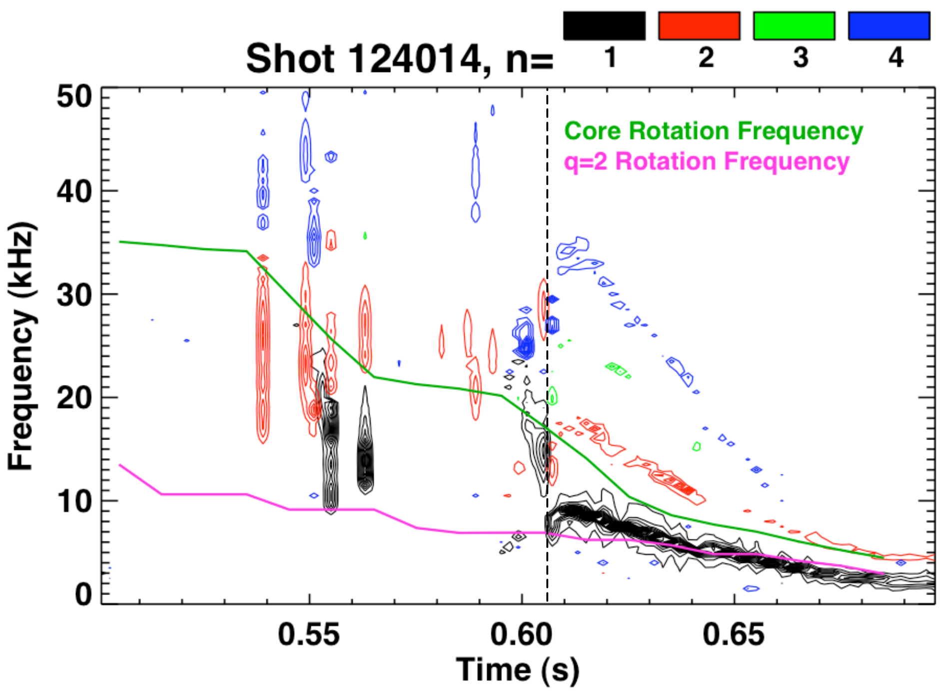
2: Flat spots visible in T_e profile in the vicinity of q=2 for saturated mode (less strict for short-lived modes).
   - Indicative of an island & poloidal mode number

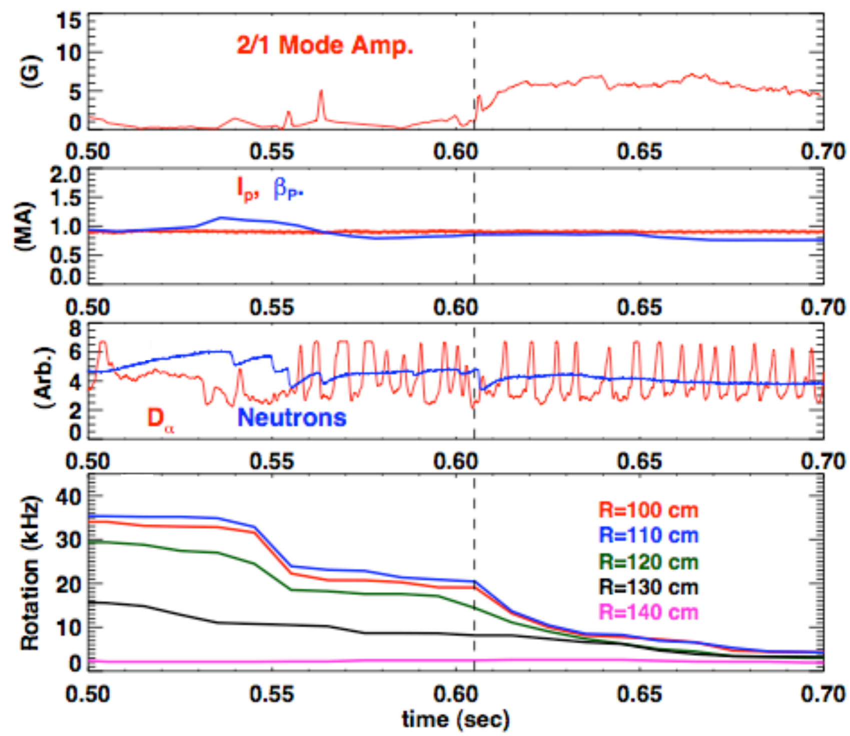
3: Mode frequency (Mirnov) should quickly approach the q=2 frequency once formed
   - Poloidal mode number identification.

4: Mode should lead to a flattening of rotation at q=2, followed by collapse to flat rotation inside q=2
   - Provides additional confirmation of similarity.

Modes Are Sometimes Triggered By EPMs

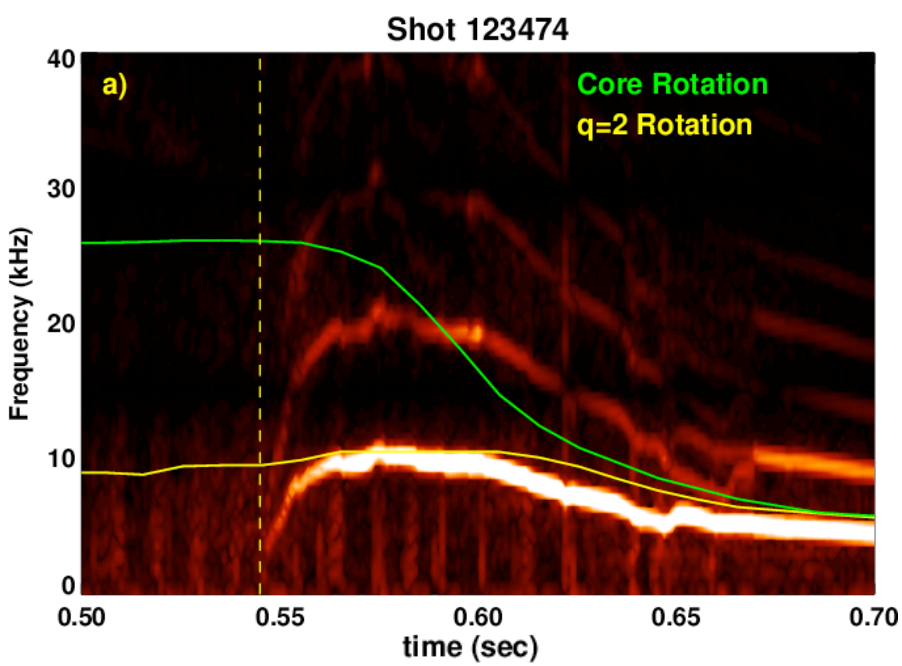
- Chirping EPMs result in rapid drop in the D-D neutron rate (fast particle loss) and slowing of the plasma rotation.
- Some EPMs have strong n=1 components, including the triggering mode at t=0.605.
- Significant rotation drop once mode strikes.

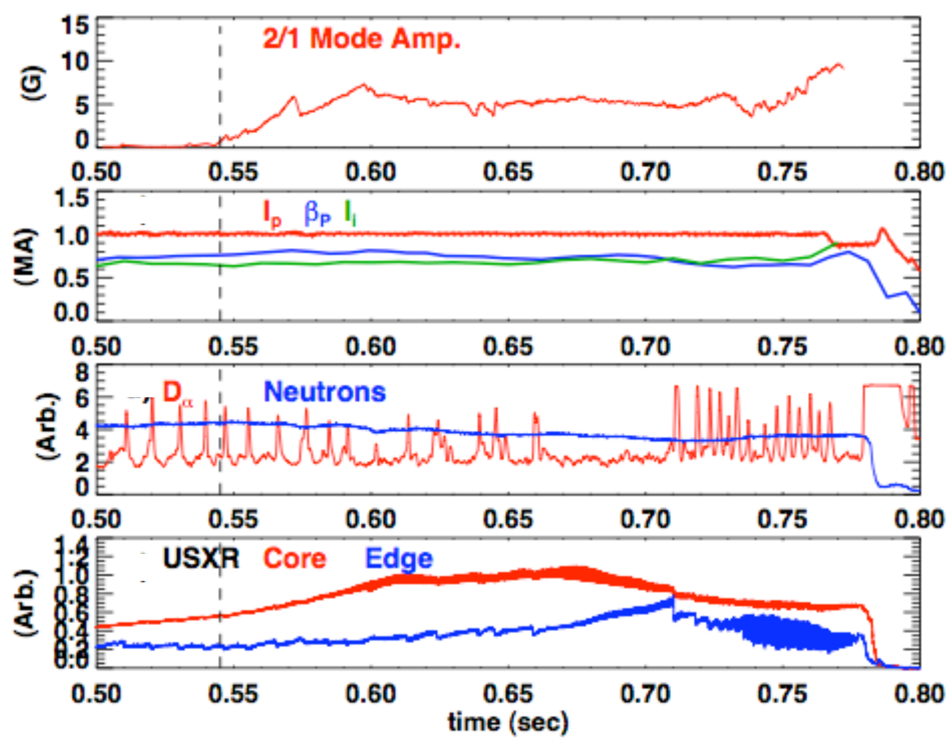




Other Modes Are Triggered By ELMs

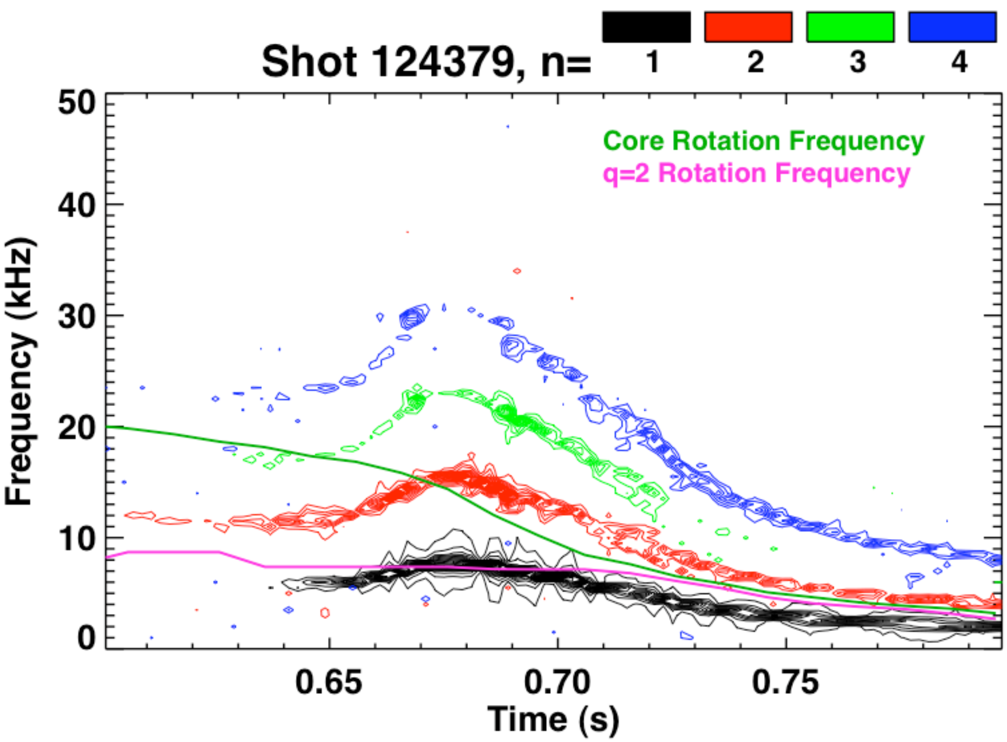
- The ELM at 0.545 strikes the mode.
- Initial mode frequency is much less than the q=2 rotation frequency.
- Triggering ELMs don't appear to be "special"…likely the plasma is evolving toward a less stable state.

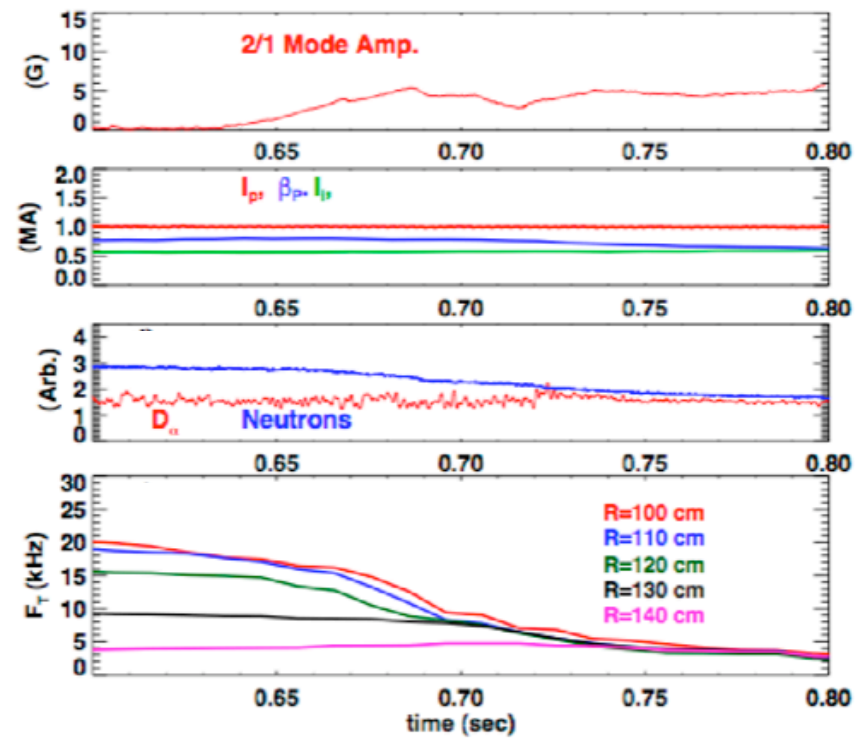




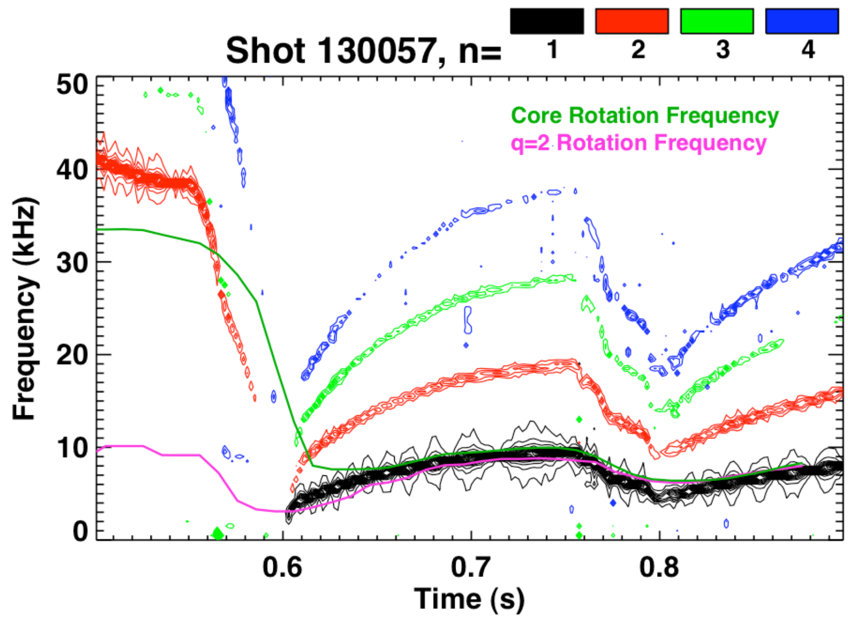
Finally, Some Modes Have No Apparent Trigger

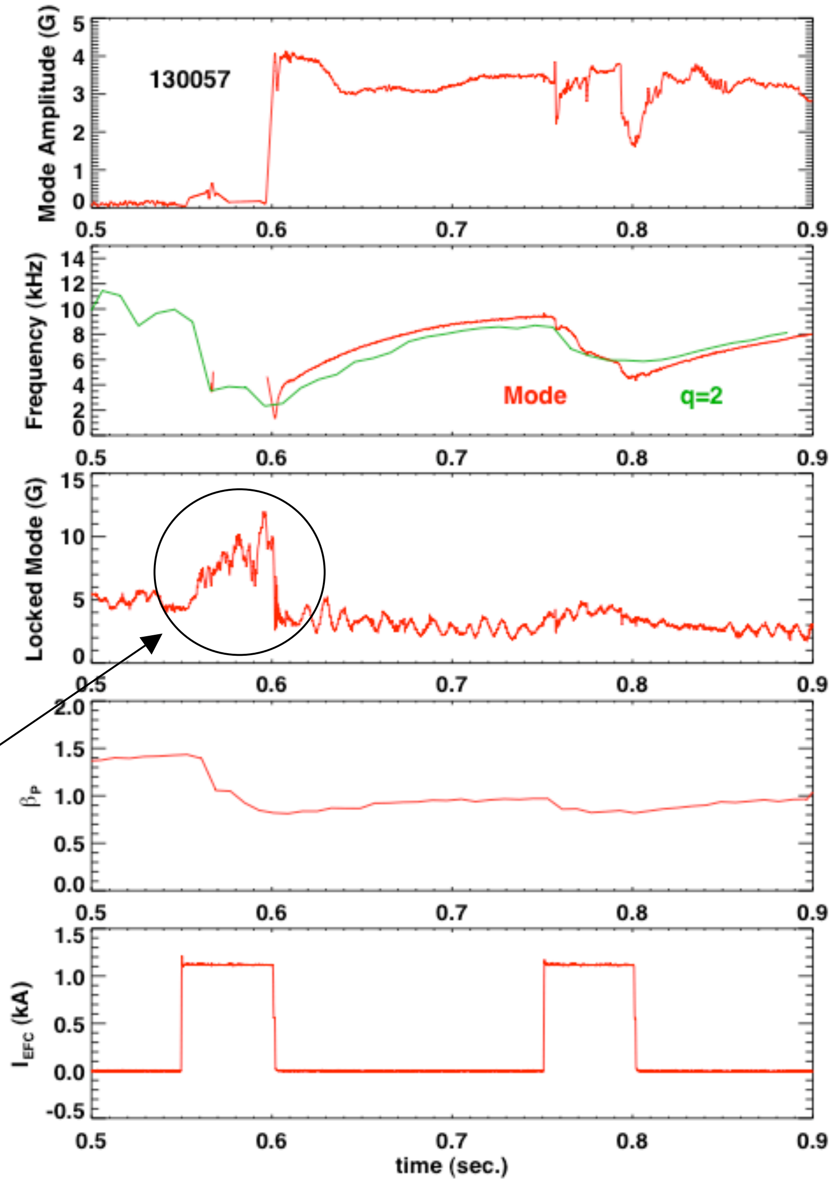
- No triggering MHD apparent in the USXR, D_α, or neutrons.
- Mode grows smoothly from very low amplitude, with frequency near that of the q=2 rotation.
- Is it linearly unstable at onset?…calculations underway for a similar shot.
- USXR signature of this shot to be analyzed in next section.





Triggering of Rotating 2/1 Mode From Initially Locked Mode also Observed





- Two pulses of n=3 non-resonant braking used to slow plasma rotation.
- Locked mode grows during 1st braking pulse.
- Plasma spins up and mode begins to rotate.
- Note: Disruption prone scenario.

Part 2: Eigenfunction Analysis From USXR Measurements

- Multichord USXR system is the only internal measurement of the mode structure.
- The measured emission is consistent with a 2/1 mode for mid-radius chords, but not for core chords.
- Addition of a coupled 1/1 ideal kink improves agreement between measured and simulated emission.

JHU USXR System Utilized to Study Mode Eigenfunction

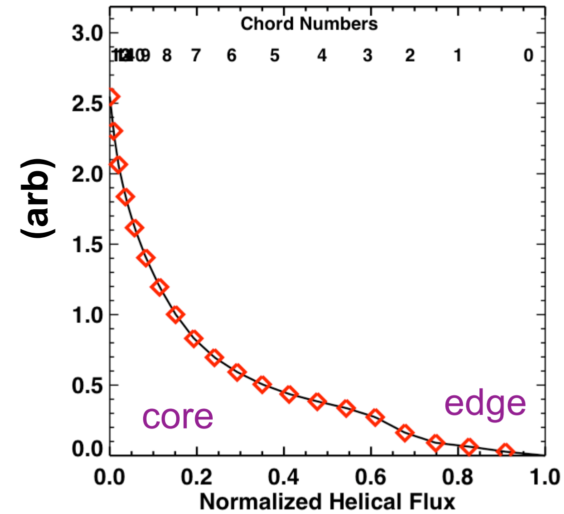
The Diagnostic

- Two arrays of 15 USXR detectors.
- Adjustable filters for each array: 5μm, 10 μm, 100μm, no filter (bolometer).

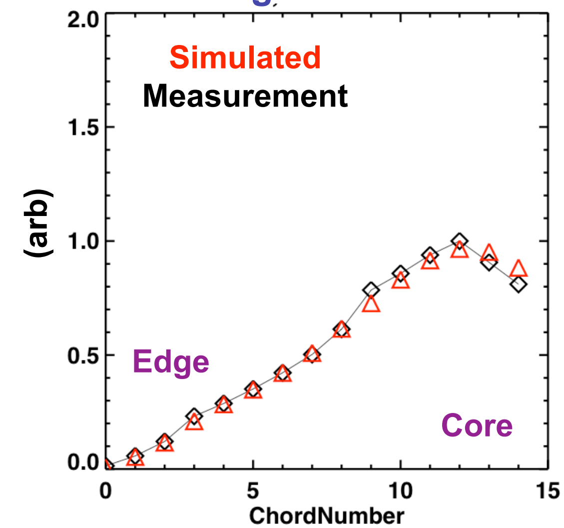
Analysis Method

- Compute axisymmetric helical flux ($\psi_{h,0}$).
- Invert emission as a function of $\psi_{h,0}$
  Regularized inversion using the "Phillips-Twomey" method, Numerical Recipes in C, Section 18.5, 1992
- Generate equilibrium with modes.
- Integrate emission through the eigenfunction for multiple mode toroidal phases (simulating rotation).
- Compare to measurements.

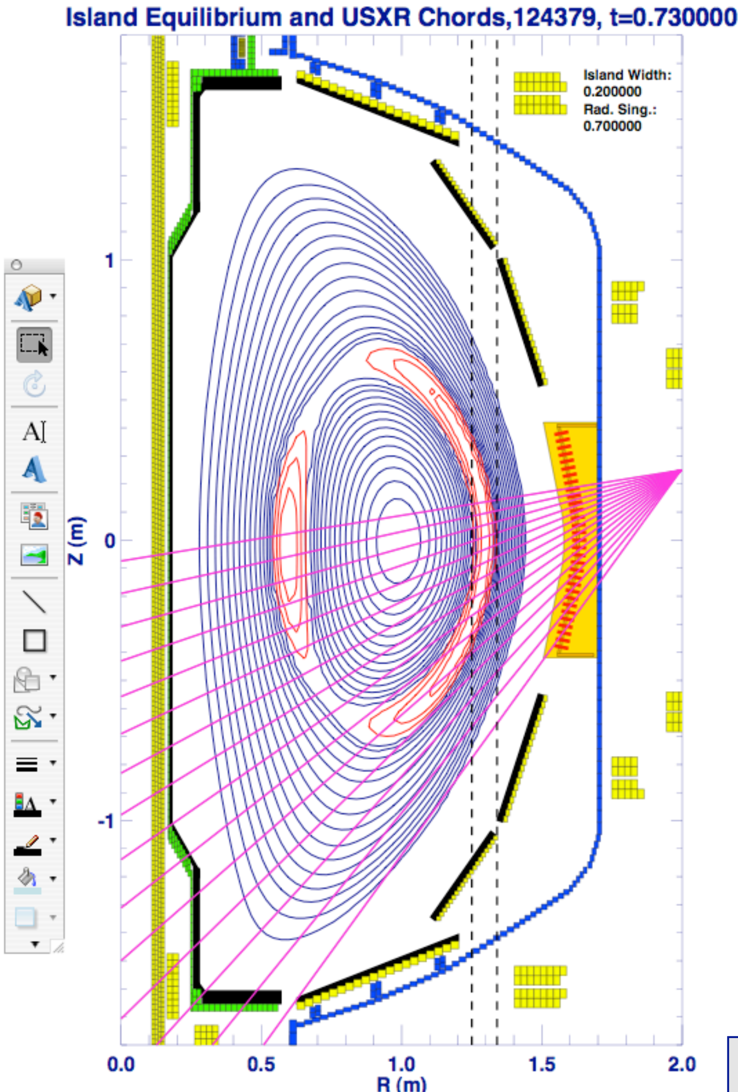
Inverted Emission Profile



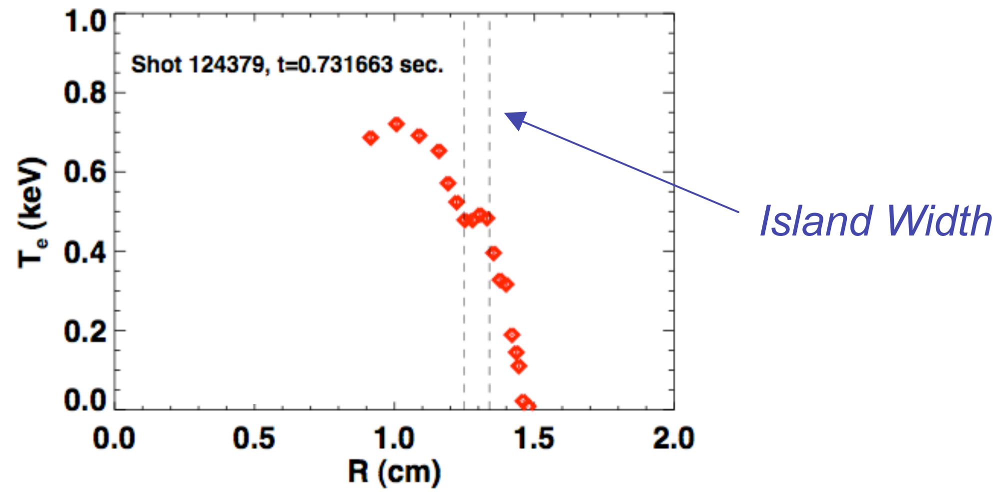
Line Integrated Emission



Constrain The Island Model By Reconstructions and Flat-Spots in the Electron Temperature Profile



- Typical to find outboard flat-spots when the mode persists >~100 msec.
- Two model parameters are constrained:
  - ➢ Rational surface radius by reconstruction and T_e profile
  - ➢ Island width by T_e profile.

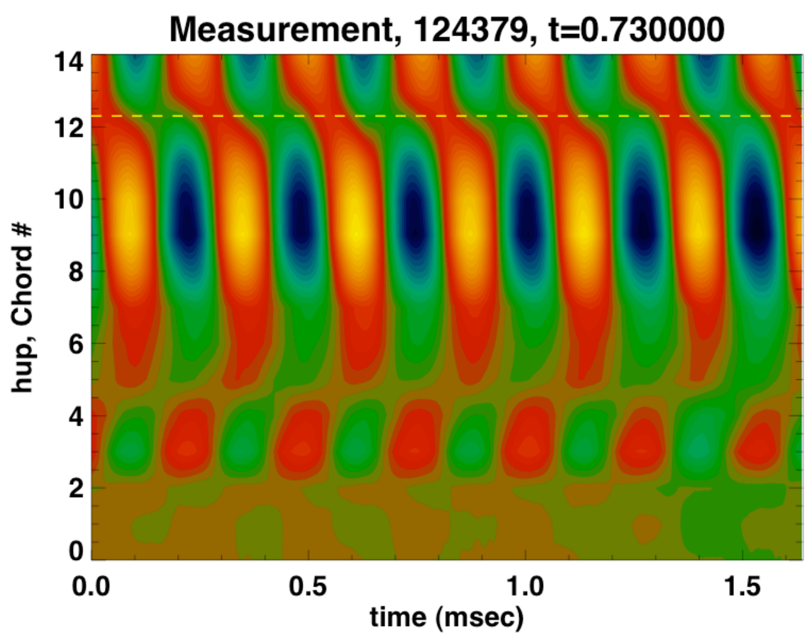


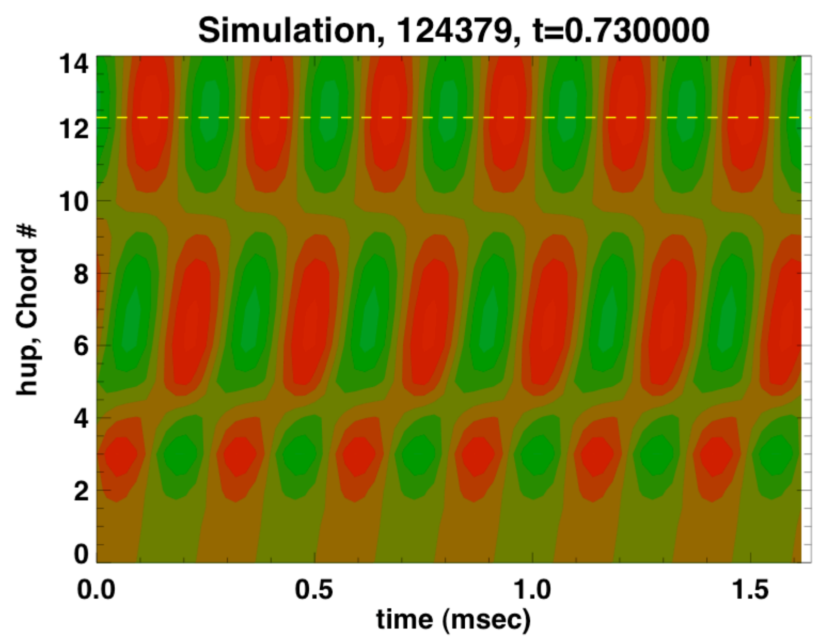
All Island Model Free Parameters Constrained by These Measurements

For details regarding the 2/1 island model, see Menard, et al, NF **45**, 539 (2006)

Edge USXR Chords and T_e Profile Consistent With q=2 Island, But Core Chords Inconsistent

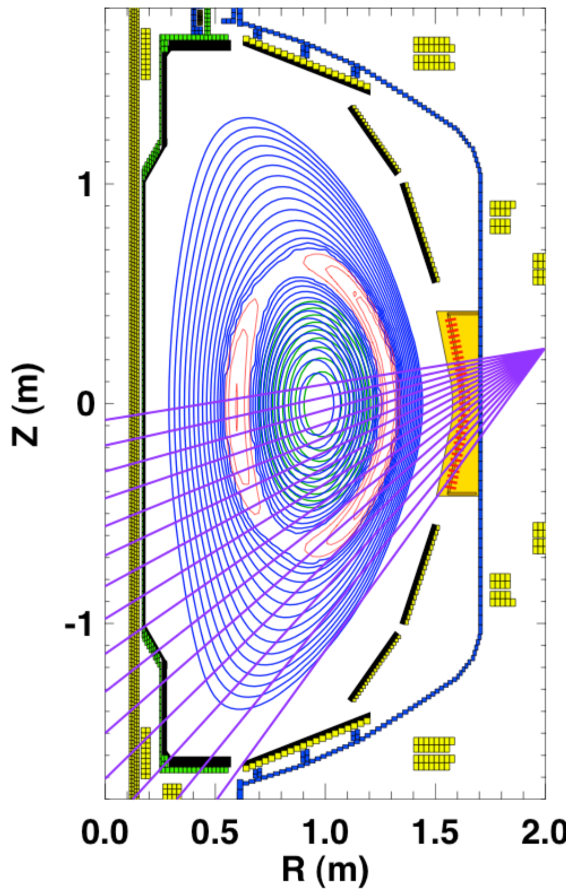
- Reasonable agreement for chords 0-7
    - Good agreement in the location of inversion layer and magnitude of oscillation
    - Confirms the island structure at q=2
- Poor agreement for core chords
    - Measurement has inversion layer across the magnetic axis, incompatible with a pure even-m mode.
    - Likely a non-resonant core 1/1 mode, phase locked to the m/n=2/1 mode.

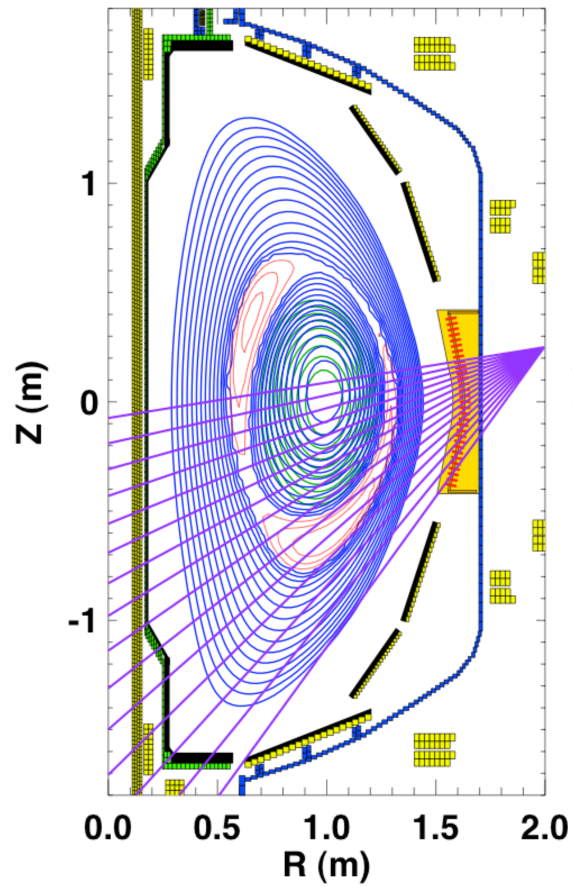


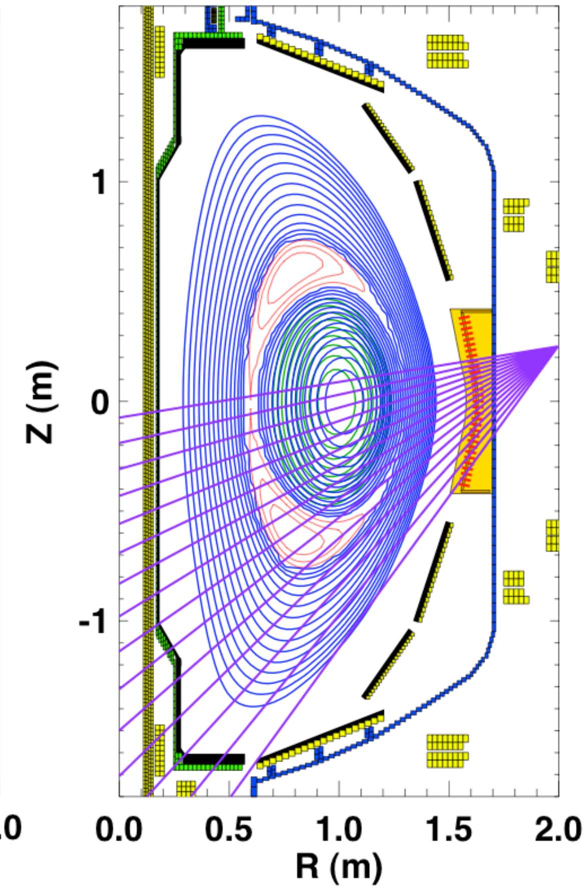


Now Add an Ideal m/n=1/1 Perturbation to the 2/1 Island

Unperturbed Core Surfaces **Nested Surfaces with Island and Kink** **Island Surfaces**



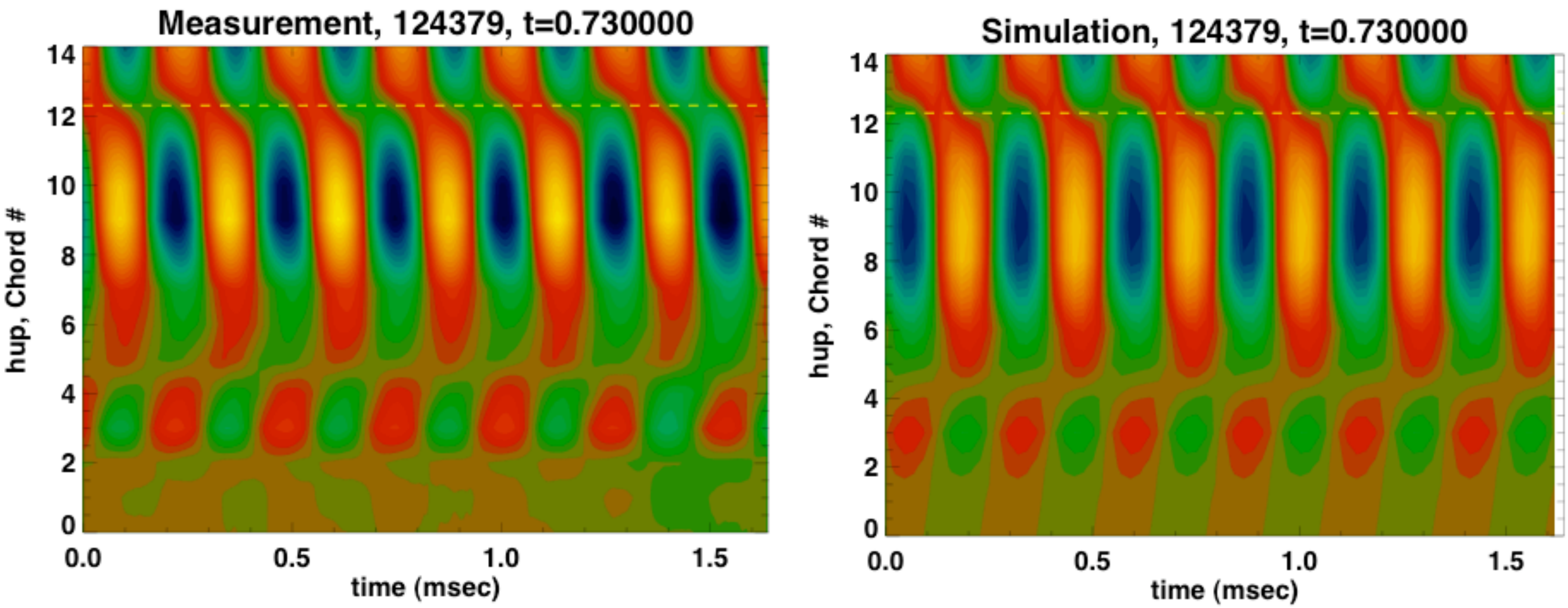




- 1/1 mode "rotates" around magnetic axis twice as fast as the 2/1 mode.
- Ballooning phase between 1/1 and 2/1 perturbations.

$$\xi_{1,1} = \begin{cases} \xi_0 & r < r_c \\ \xi_0 e^{-\left[(r-r_c)/r_f\right]^2} & r > r_c \end{cases}$$

Simulation and Measurement Agreement Improved Substantially By Inclusion of Additional Core Perturbation



- *2/1+1/1 coupling observed in essentially all 2/1 modes.*
- *Core non-resonant 1/1 modes previously observed in NSTX*

  J.E. Menard, et al, Nuclear Fusion (2005)
- *Coupling of m/n NTM to m-1/n kink observed in AUG and TFTR*

  *A. Gude, et al, Nuclear Fusion **39**, 127 (1999)*

  *E. Fredrickson, Phys. Plasmas **9**, 548 (2002)*

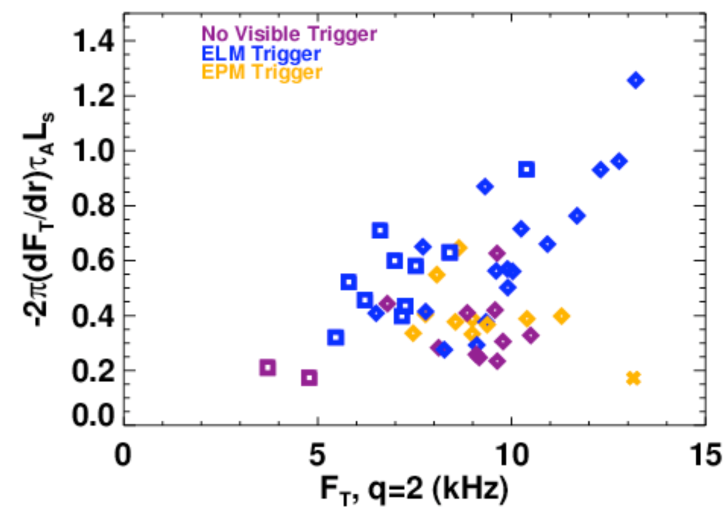
Database Analysis

- Examine if rotation or rotation shear changes the onset threshold for 2/1 modes.
- Determine the applicability of previous onset scaling laws $\beta_N\left(\rho^*_{tor},\nu^*\right),\beta_P\left(\rho^*_\theta,\nu^*\right)$ to NSTX modes.

Data Analyzed to Ascertain Scaling of Onset Threshold with Rotation and Rotation Shear

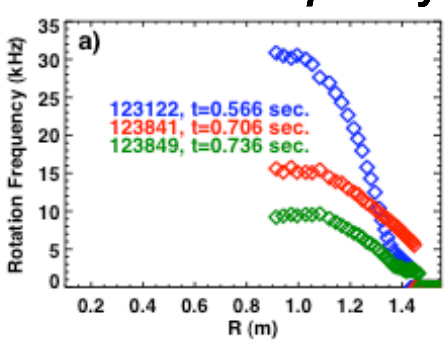
- Include different beam timing and n=3 braking levels.
- Consider limited range of shapes, plasma current and toroidal fields:
  - $2.05<\kappa<2.5$
  - $0.57<l_i<0.8$
  - $0.5<\delta_l<0.83$
  - $900kA<I_p<1000kA$
  - $B_T=0.45T$
  - $0.05<\nu_i<0.11$
  - $6.5<q_{95}<9$

Signify the Trigger Type
With Symbol Color
"Spontaneous"
EPM Trigger
ELM Trigger

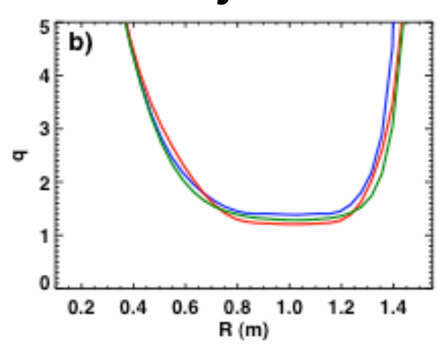


Example Profiles Showing Rotation Variation With All Else Fixed

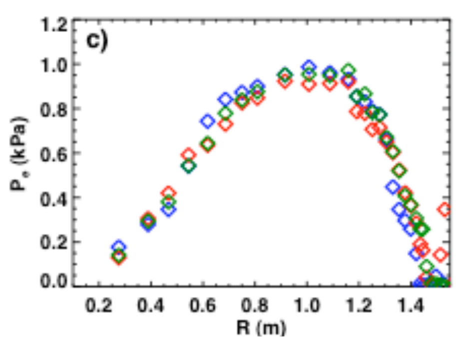
Rotation Frequency



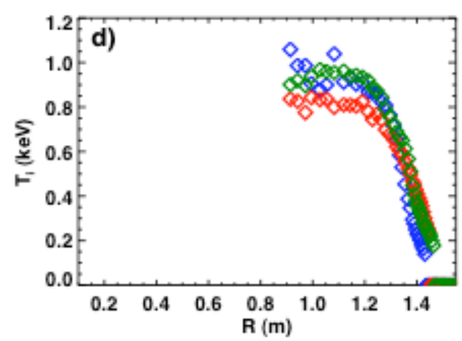
Safety Factor



Electron Pressure



Ion Temperature



Use the Modified Rutherford Equation to Study the Mode Dynamics

$$\frac{\tau_R}{r_s^2}\frac{dw}{dt} = \Delta' - \frac{6D_R w}{w^2 + w_d^2} + D_{BS}\left(\frac{w}{w^2 + w_d^2} - \frac{w w_{pol}^2}{w^4 + w_b^4}\right)$$

For Saturated Large Islands: $0 = \Delta' + \dfrac{D_{BS} - 6D_R}{w}$

1: Neoclassical Bootstrap Drive:
δj_{BS} can be calculated from various models

$$D_{BS} = \frac{C_{BS}\mu_0 L_q}{B_\theta}\delta j_{BS}, \quad C_{BS} = 16$$

2: Curvature Term: $D_R \propto \beta$, not β_P, and so can be important in an ST

3: Classical Tearing: May introduce various additional dependencies

$$\Delta' = C_0 - C_W w + C_2\left(-\frac{d\Omega_\phi}{dr}\right)L_S\tau_A + C_3\left[1 - \left(\frac{\pi\beta}{\beta_N}\right)\cot\left(\frac{\pi\beta}{\beta_N}\right)\right] + f(q_{\min}) + \ldots$$

4: Small Island Terms: Prevent growth of arbitrarily small islands.

Three Definitions of Drive Generally Agree Quite Well

Choices for the Coefficient on the Bootstrap Term

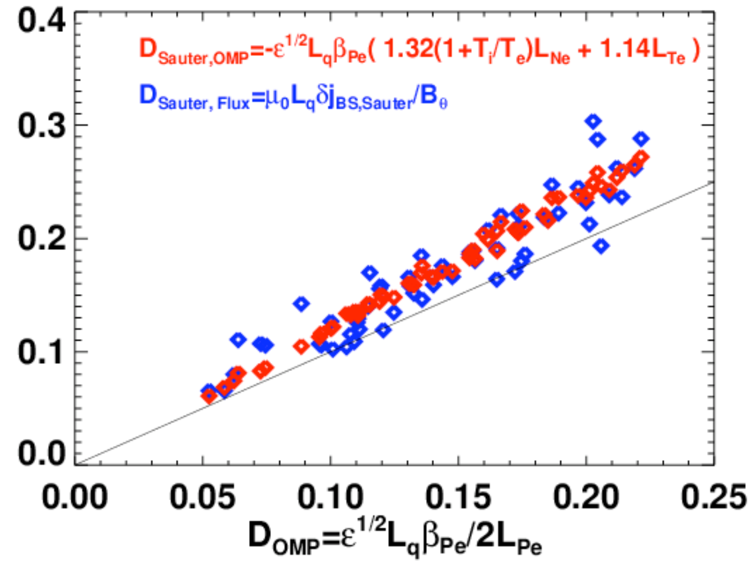
1) $$D_{OMP} = -\frac{\sqrt{\varepsilon_{OMP}}\beta_{Pe,OMP}}{2}\frac{L_{q,OMP}}{L_{Pe,OMP}}$$

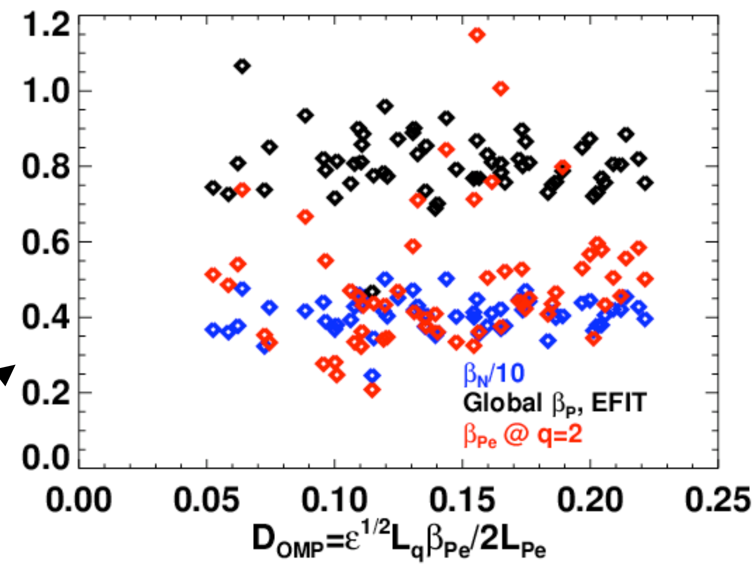
2) $$D_{Sauter,OMP} = -\frac{\sqrt{\varepsilon_{OMP}}\beta_{Pe,OMP}}{2}L_{q,OMP}(A+B)$$

$$A = 1.32\left(1+\frac{T_i}{T_e}\right)(1/L_{ne.OMP}) \quad B = 1.14/L_{Te.OMP}$$

3) $$\delta j_{BS,Sauter} = \frac{I(\psi)p_e\left(L_{31}\frac{1}{p_e}\frac{dp_e}{d\psi} + L_{32}\frac{1}{T_e}\frac{dT_e}{d\psi}\right)}{\sqrt{\langle B^2\rangle}}$$

$$D_{Sauter,Flux} = \frac{\mu_0 L_q}{B_\theta}\delta j_{BS,Sauter}$$



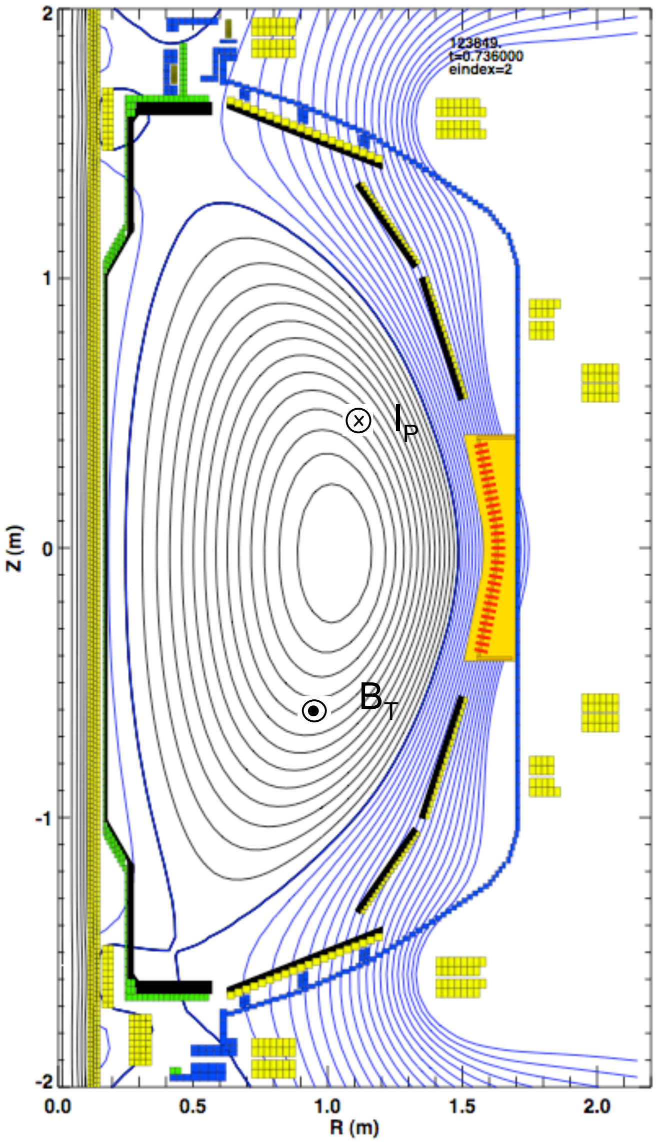


However, global parameters don't map well to relevant local quantity…profiles aren't self-similar in the large data set.

Rotation or Rotation Shear May Change Onset In a Number of Ways:

- Coupling to Triggers or Wall
  - Rotational shielding may cause decoupling of trigger from NTM rational surface.
  - *Look for onset to be correlated with differential rotation or absolute value of rotation.*
- Polarization Threshold
  - Depends on the sign and magnitude of the island rotation in the E_R=0 plasma frame.
  - *Look for onset to be correlated with velocity in the E_r=0 frame*.
- Classical Tearing Stability
  - Explanation used to explain DIII-D results.
  - Modifications to both Δ' and inner-layer physics are possible.
  - *Look for onset to be correlated with flow shear (rotation plays no role).*

Measure the Island Frequency in the E_R=0 rest Frame Immediately After Striking

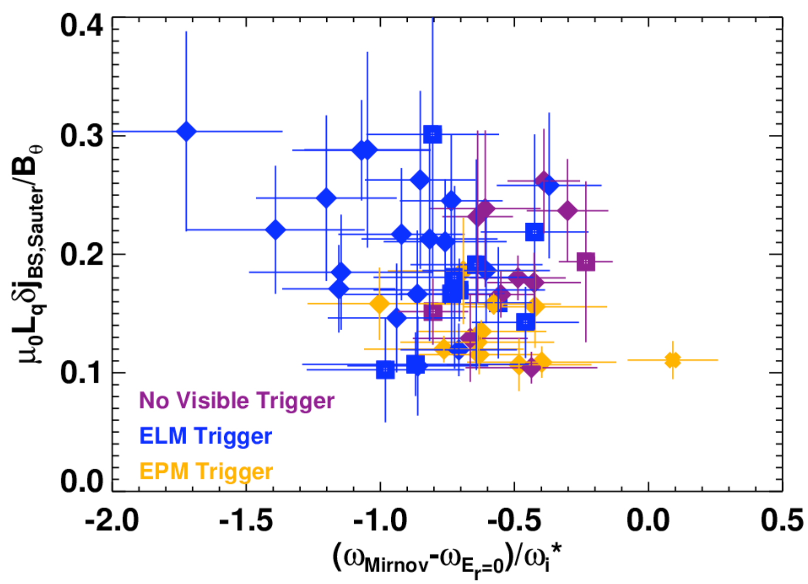


Polarization Term is Stabilizing If

$$0 < \frac{\omega_{Mirnov} - \omega_{E_r=0}}{\omega_i^*} < 1, \quad \omega_j^* = \vec{k} \cdot \vec{V}_D = \left(\frac{m\langle B_\phi \rangle}{r} - \frac{n\langle B_\theta \rangle}{R} \right) \frac{dp_j}{dr} \frac{1}{Z_j n_j B^2}$$

$$f_{E_R=0} = \frac{\omega_{E_r=0}}{2\pi} = -\frac{nV_{\phi,j}}{2\pi R} + \frac{n}{2\pi R Z_j e n_j B_\theta} \frac{dp_j}{dr}$$

Poloidal rotation term excluded, but expected to be small.



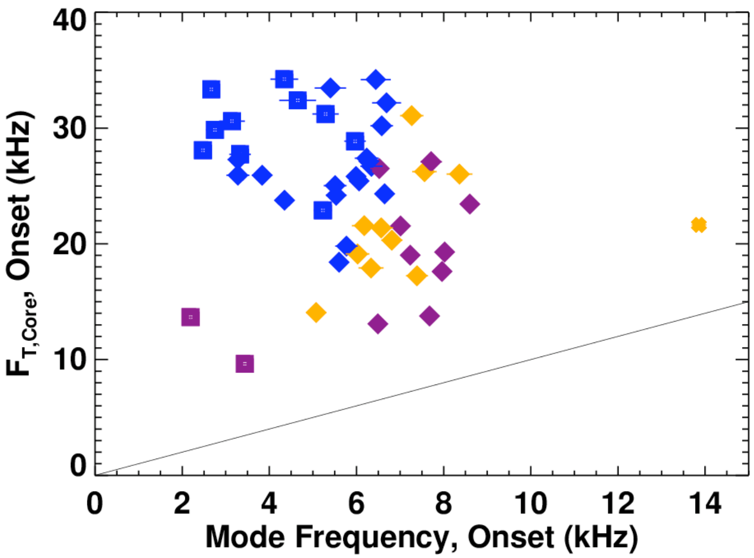
However, NTM Drive at Onset Uncorrelated with Normalized Frequency Difference

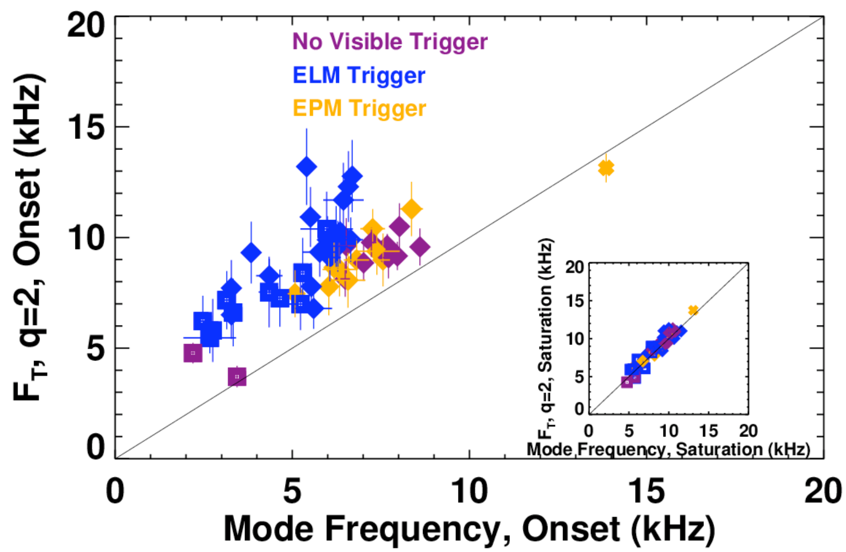
Modes Generally Rotate More Slowly Than Plasma at q=2

Measure Mode Frequency at Earliest Possible Time,
Using Zero Crossings of Filtered Odd-n Mirnov

Core rotation frequency is uncorrelated with mode onset frequency for all trigger types

Mode Frequency at Onset is Close to q=2 Rotation, but Depends on Trigger Type



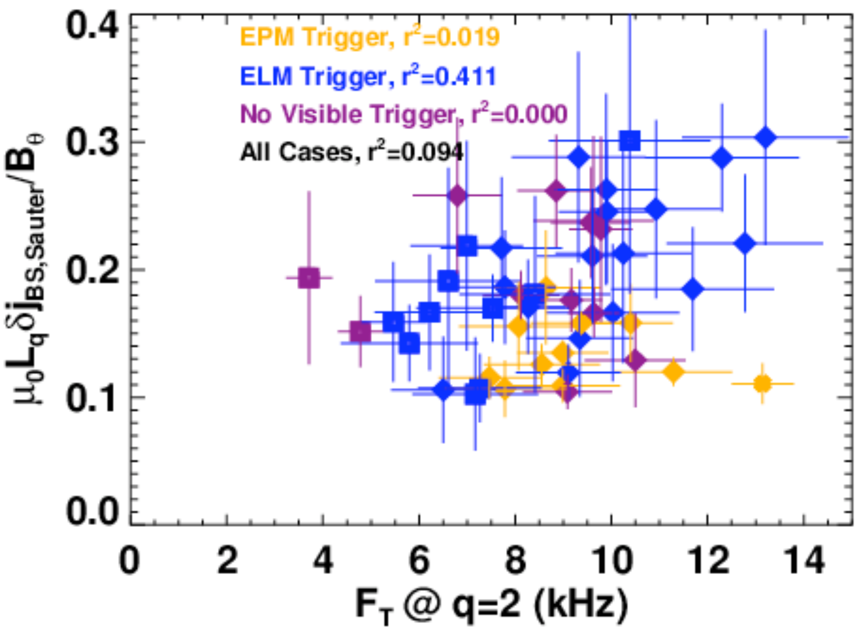


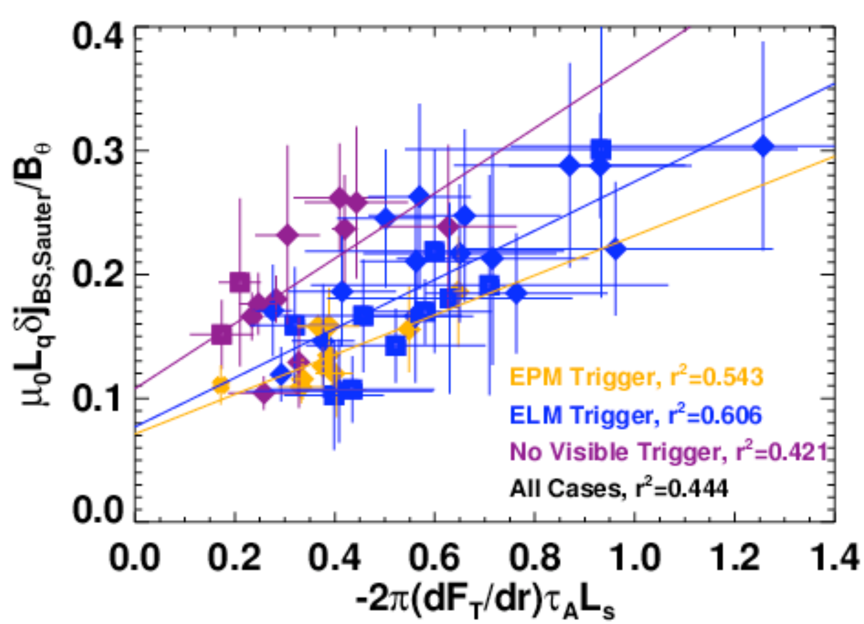
ELM Trigger: Much Slower than q=2
No Trigger: Typically Slightly Slower
EPM Trigger: Faster or Slower

Strongest Correlation Found between Mode Drive and Flow Shear

- *NTM drive at onset only poorly correlated with q=2 (carbon) rotation*
- *Essentially no correlation for EPM and "Triggerless" cases*

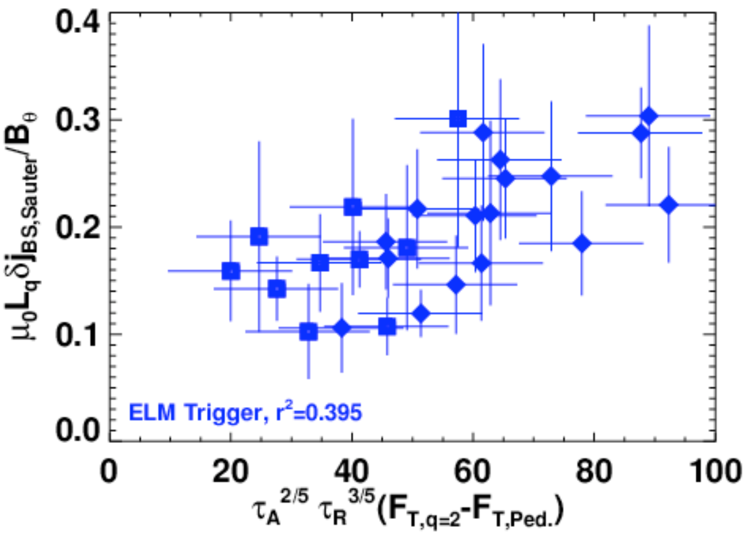
- Strongest correlation is between "noise-prone" parameters
  Provides confidence that this is the correct physics.
- Slopes of lines are similar within error
  The physics is likely not related to triggering, but rather the underlying tearing stability.





Differential Rotation Is Unlikely to be Playing the Dominant Role

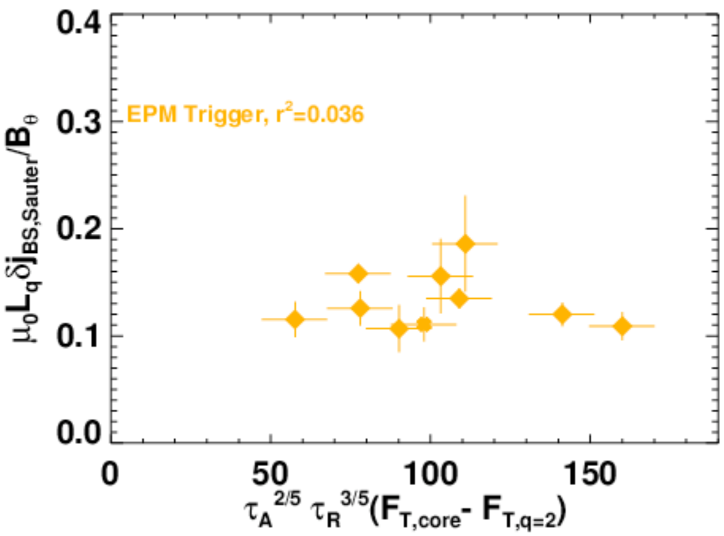
Normalize differential rotation by the tearing time [La Haye 2000]

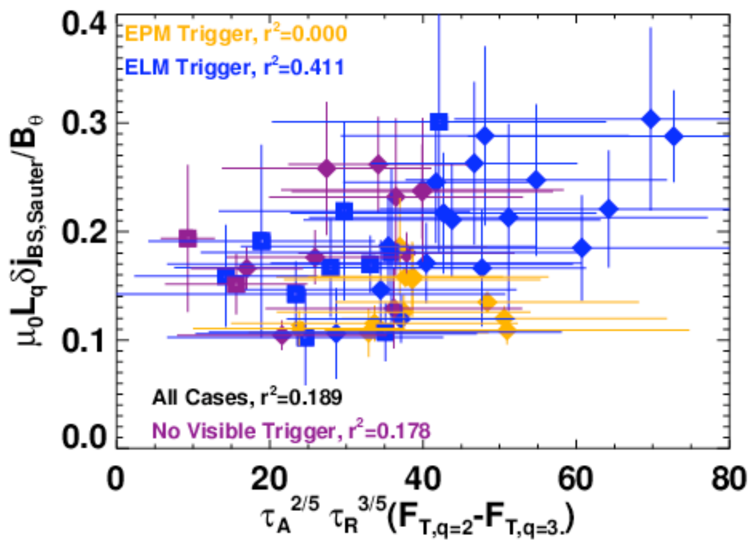


- For *ELMs* triggers, look for correlation with q=2/edge differential rotation.
- Correlation is weaker than with local rotation shear.

- For all cases, look for correlation with q=2/q=3 differential rotation.
- Correlations are better than with flow, but worse than with local flow shear.

- For *EPMs* triggers, look for correlation with q=2/core differential rotation.
- No correlation found.





Statistically, Local Flow Shear has the Best Correlation

	All Cases	EPM Triggers	ELM Triggers	No Visible Trigger
$F_{T,q=2}$	0.09	0.02	0.41	0.00
dF_T/dr @ q=2	.059	0.00	0.14	.024
$L_S\tau_A(dF_T/dr)$ @ q=2	**0.44**	**0.543**	**0.606**	**0.421**
$(F_{T,q=2}- F_{T,q=3})$	.015	0.00	0.411	0.177
$\tau_A^{2/3}\tau_R^{3/5} (F_{T,q=2}- F_{T,q=3})$	0.189	0.00	0.41	0.19
$\tau_A^{2/3}\tau_R^{3/5} (F_{T,q=2}- F_{T,Ped})$	----	----	0.395	----
$\tau_A^{2/3}\tau_R^{3/5} (F_{T,core}- F_{T,q=2})$	----	0.04	----	----

EPM Cases

- The ONLY correlation is with rotation shear.
- Typically the lowest onset threshold (largest seed island?)

ELM Cases:

- Lots of colinearity in the data (flow vs. flow shear. vs differential rotation), but best correlation is with flow shear.
- Intermediate onset threshold

"Triggerless" Cases:

- More scatter in data, and often the highest onset threshold, but….
- Additional physics likely playing a role, including q_0~1 and β_N near ideal kink limit

Appears Likely That Classical Tearing Stability, Modified by Flow Shear, is Responsible For Observed Trends

- As in DIII-D[1], polarization term and wall interaction unlikely to play the dominant role in setting threshold.
  - *Poor correlations with absolute or E_r=0 frequency*
- Differential rotation shielding of triggers is likely excluded.
  - *Correlation of onset with differential rotation to triggering location is poor.*
  - *All trigger types have a similar onset scaling with rotation shear.*
- Differential rotation between adjacent rational surfaces can be a stabilizing effect.[2]
  - Cannot be excluded, but correlation is worse than with local rotation shear.
- Interplay between magnetic and rotation shear is a candidate mechanism.
  - Toroidal flow shear has been found to be stabilizing in cylindrical geometry for large viscosity.[3]
  - Heuristic model by La Haye[4] has flow shear adding to magnetic shear, in order to stabilize the TM.
  - Implies that a reduction in flow shear can be accommodated by changes to the current profile.
- Additionally, flow shear may change the inner-layer dynamics.

1) R. Buttery, et al, Phys. Plasmas **15**, 056115 (2008), 2) D. Chandra, et al, Nuclear Fusion **45**, 524 (2005); A. Sen et al, 32nd EPS Conference on Plasma Physics, 3) R. Coelho and E. Lazzaro, Phys. Plasmas **14**, 012101 (2007), 4) La Haye, et al, Submitted to Phys. Plasmas, abstract JP6.00087 at this meeting.

Scaling Laws Exist for the 2/1 Mode Onset From DIII-D and JET.

Evaluate Collisionality and Gyroradius:
(for consistency, all at OMP)

$$\nu_i^* = \frac{520 n_e\left(10^{19} m^{-3}\right) q R_0}{\varepsilon^{3/2} T_i^2 (eV)}, \qquad \beta_{Pe} = \frac{2\mu_0 P_e}{B_\theta^2}$$

$$\rho_{\theta,i}^* = \frac{2\times 10^{-4}\sqrt{T_i(eV)}}{r_s B_\theta}, \qquad \rho_{tor}^* = \frac{2\times 10^{-4}\sqrt{T_i(eV)}}{r_s B_t}$$

Use a larger database of shots, with wider ν^*_i range, than in rotation studies

For JET/DIII-D ELMy H-Mode

Hender et al, NF **44** (2004)

1) $\beta_N = 550\left(\rho_{tor}^*\right)^{1.01\pm 0.16}\left(\nu_i^*\right)^{0.19\pm 0.03}$

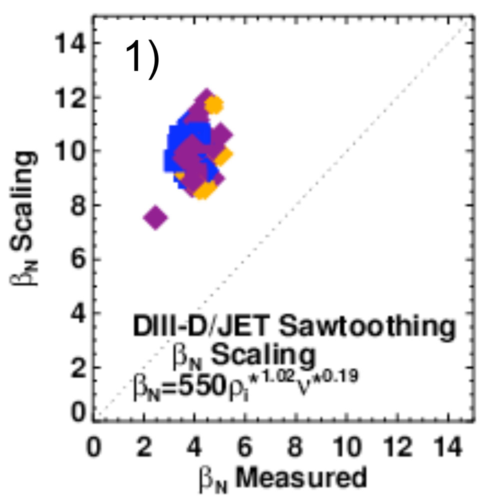
2) $\beta_{Pe} = 101\left(\rho_\theta^*\right)^{1.59\pm 0.12}\left(\nu_i^*\right)^{0.37\pm 0.05}$

For DIII-D Hybrid Mode

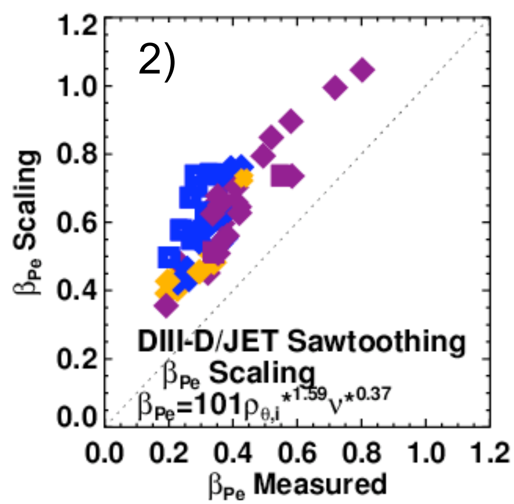
La Haye et al, NF **48** (2008)

3) $\beta_N = 12\left(\rho_{tor}^*\right)^{0.335\pm 0.014}\left(\nu_i^*\right)^{-0.024\pm 0.014}$

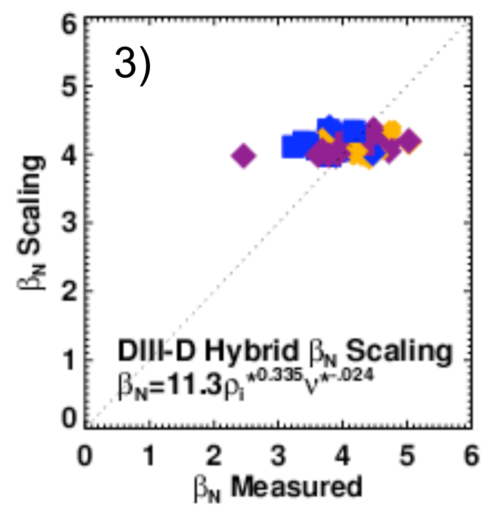
Overestimates the β_N Value



Not So Bad



Scaling is Apparently Too Weak

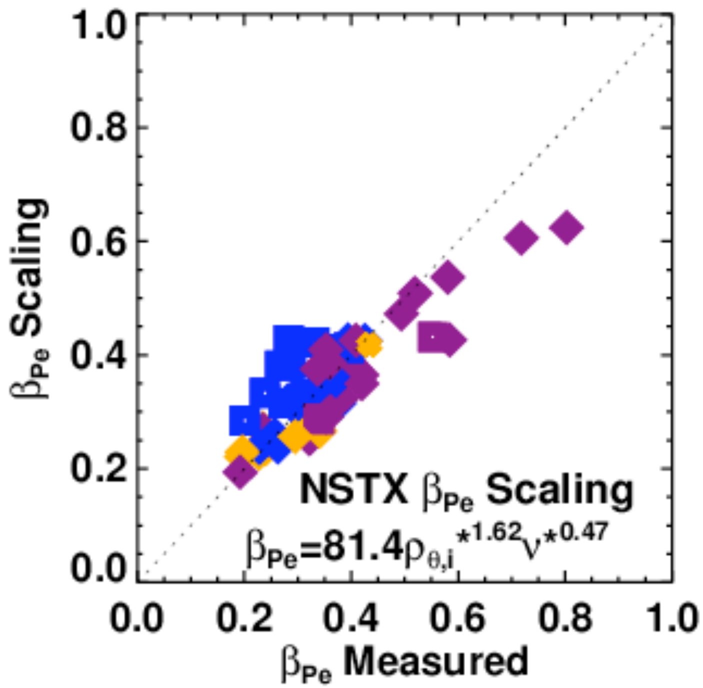


Likely Unwise to Use These Scaling Laws For NSTX Predictions

Scaling From Full NSTX Database

$$\beta_{Pe} = 81.4\,\rho_{\theta,i}^{*\ \ 1.62}\,\nu^{*\,0.47}$$

Similar to the DIII-D/JET Scaling

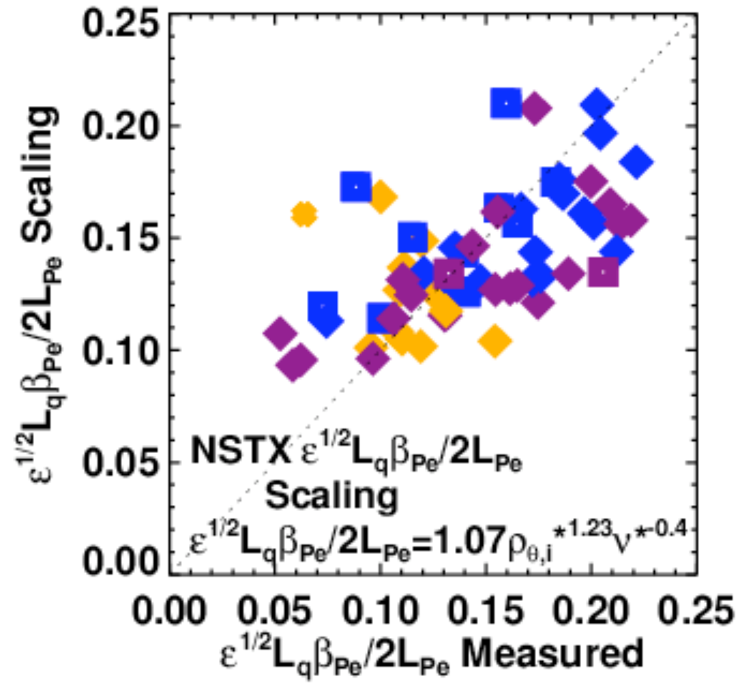


However, strong $\rho_{\theta,i}$ scaling is expected

$$\beta_{Pe} \propto \rho_{\theta,i}^{*\ \ 2}\,n_e$$

Scaling From Full NSTX Database

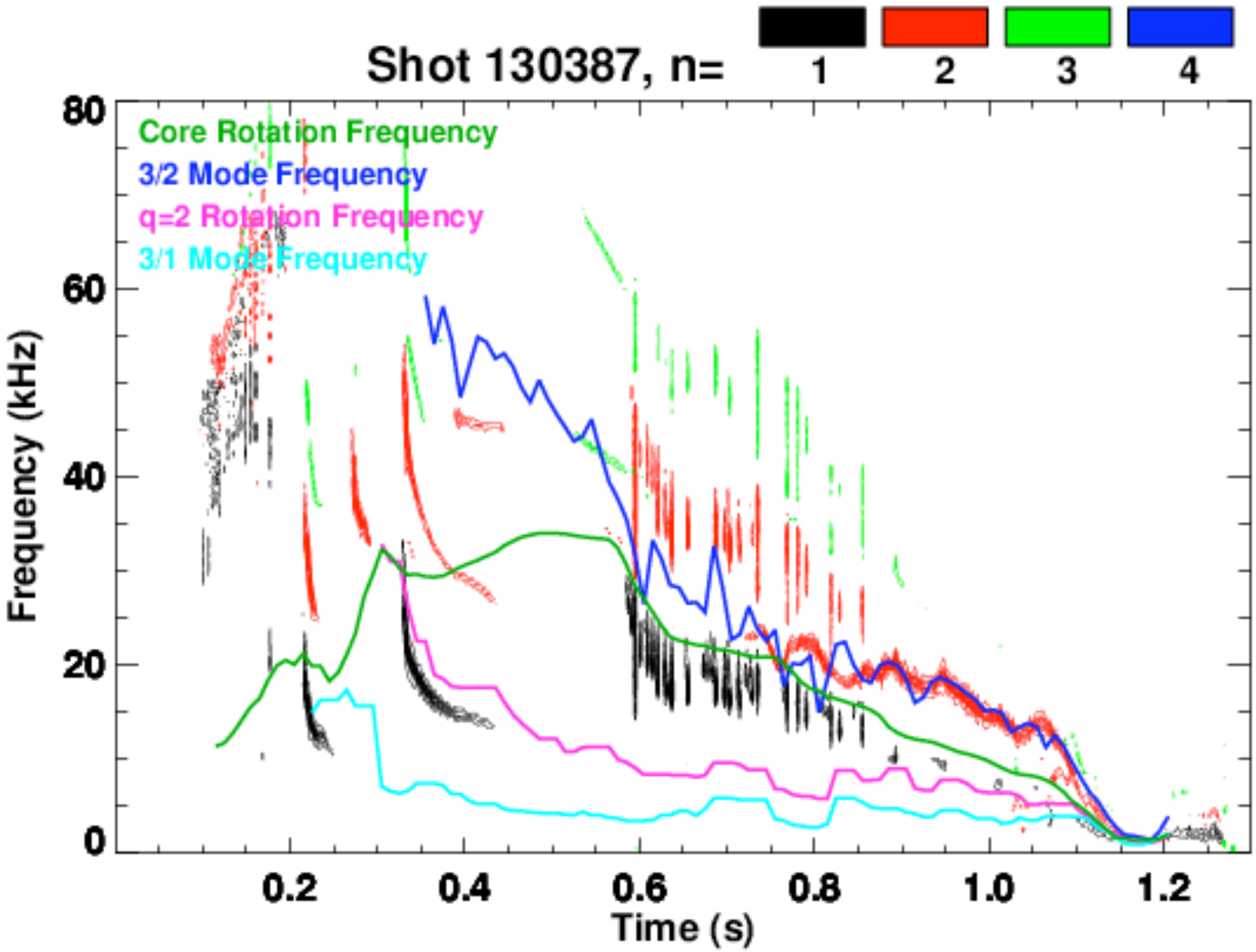
$$\varepsilon^{1/2}\frac{L_q\beta_{Pe}}{2L_{Pe}} = 1.07\,\rho_{\theta,i}^{*\ \ 1.23}\,\nu^{*\,-0.4}$$



Derived scaling law is apparently not useful in predicting the onset of the 2/1 mode.

The remainder is old useless crap.

3/2 Modes Observed in Some Cases

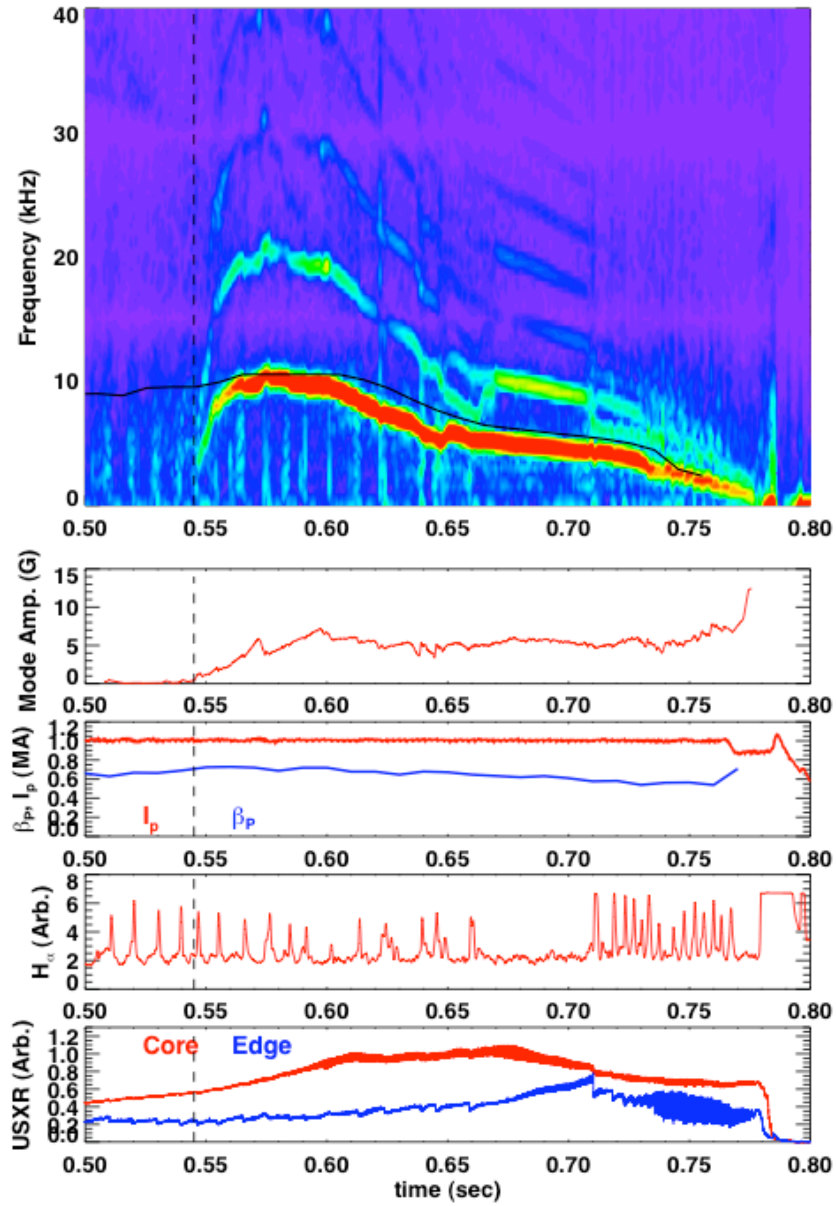


Also 130379,130384,130386,130387

ELMs Also Observed to Trigger Mode

- Rapid ELMs visible on D_α & edge USXR
- Frequency is initially much below the q=2 frequency.
- Mode spins up to and tracks q=2.

When ELMs are present, they typically lead to this behavior.

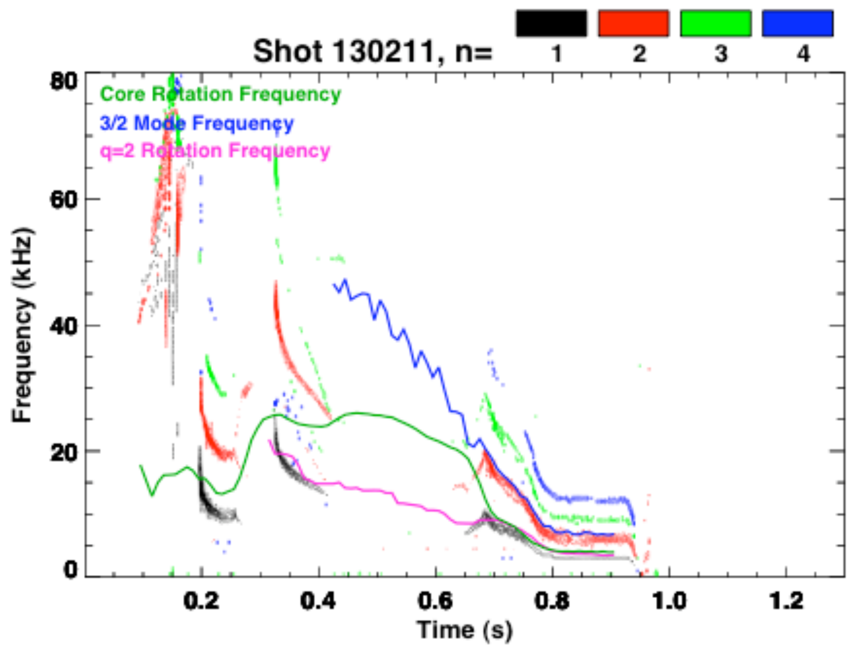


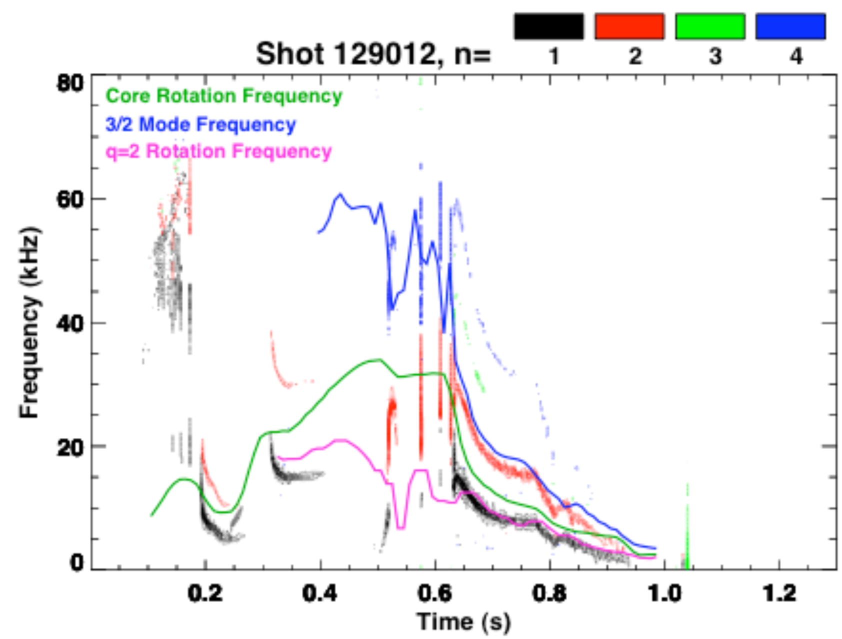
Two Common Early Evolution Trends Observed For the 2/1 Mode (I)

Similar Spectrograms…to first appearances.

1: Growth From Vanishing Small Amplitude (130211)

2: Struck Near Full Amplitude (129012)



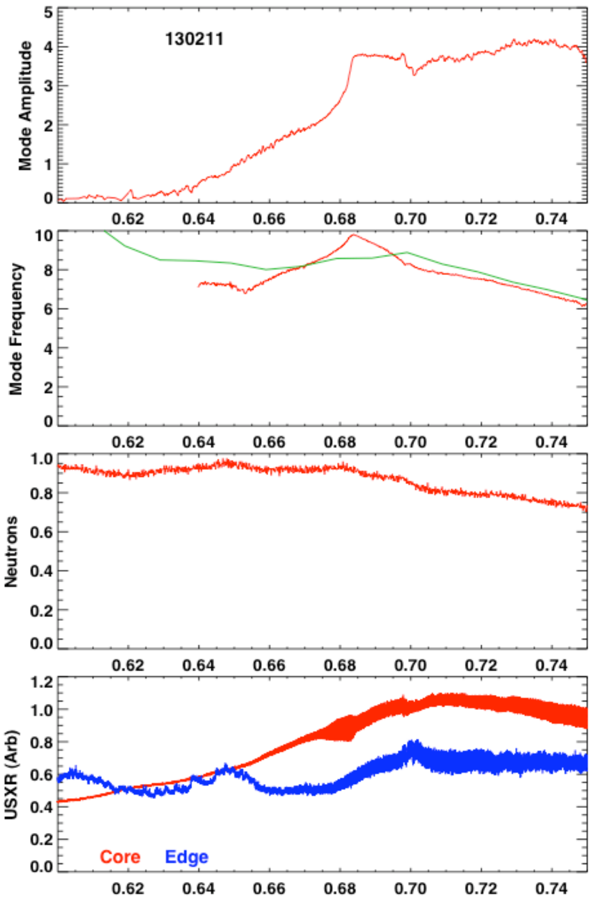


Mode frequency matches the q=2 carbon frequency

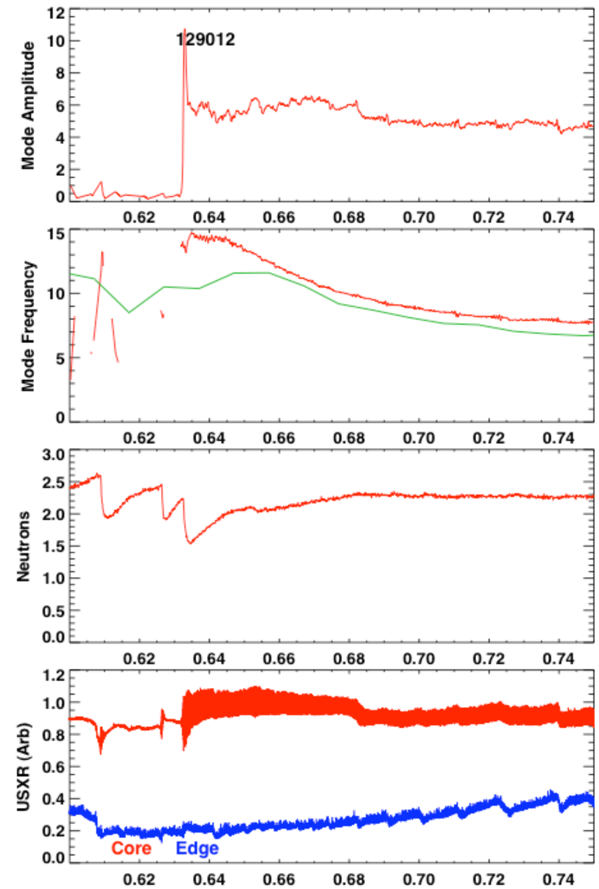
Two Common Early Evolution Trends Observed For the 2/1 Mode (II)

Different Triggering Behavior!

1: Growth From Vanishing Small Amplitude (130211)



2: Struck Near Full Amplitude (129012)



Different time-scales for growth

Mode frequency close to q=2 from CHERS and LRDFIT

Neutron collapse in case of full amplitude trigger…EP seeding event?

No large drops in core or edge USXR

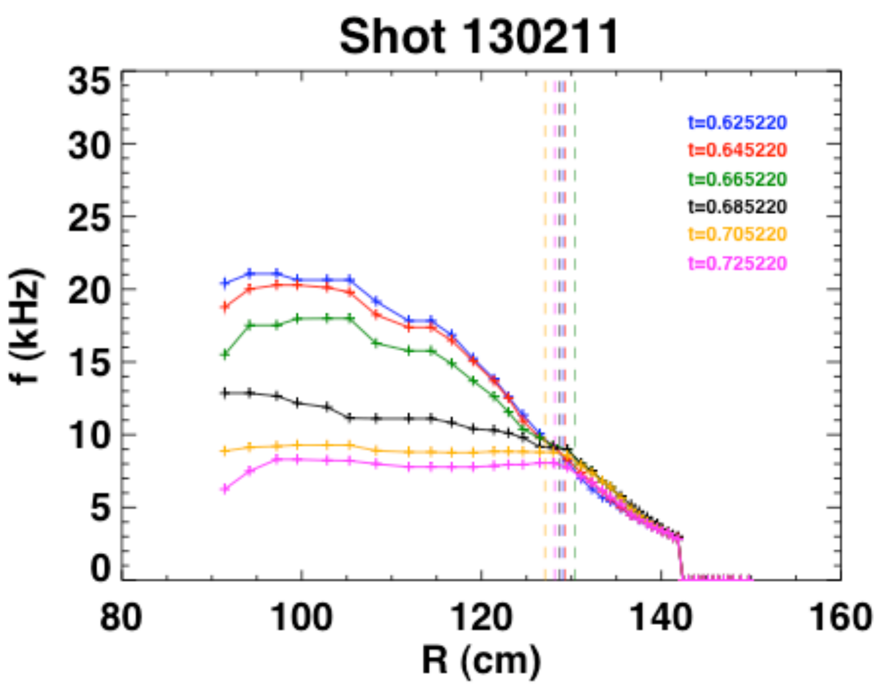
Both figures are 15msec wide.

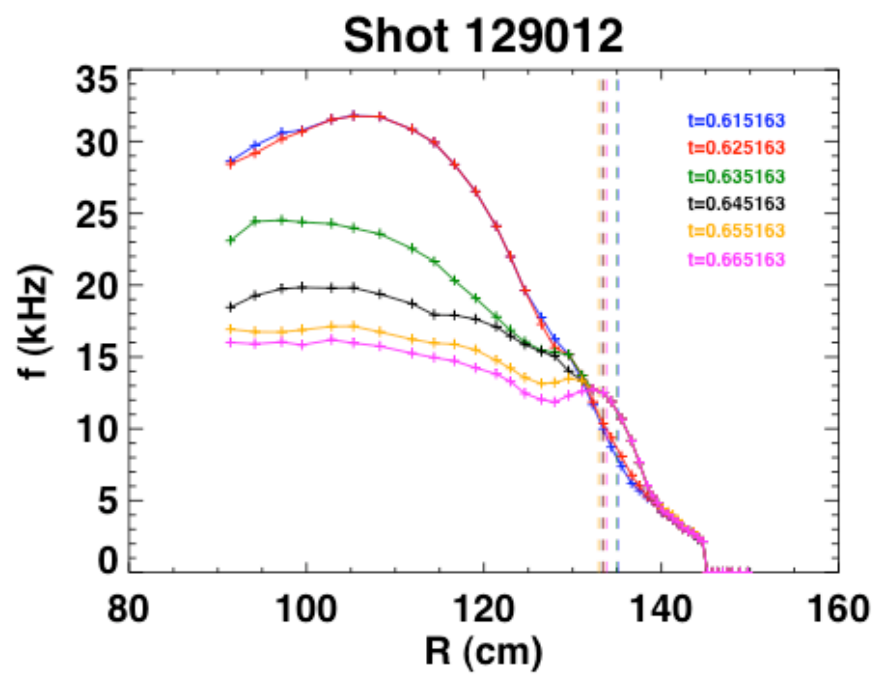
Two Common Early Evolution Trends Observed For the 2/1 Mode (III)

Both Lead to Large Rotation Damping

1: Growth From Vanishing Small Amplitude (130211)

2: Struck Near Full Amplitude (129012)





Initially: Flat region develops near q=2, core rotation collapses
Final State: rigid body rotation inside of q=2.

Define Quantities at Outboard Midplane, or after Mapping to Flux: Other Definitions

Outboard Midplane @ q=2

Directly Calculated From Data and Equilibrium:
$T_{e,OMP}$, $T_{i,\ OMP}$, $B_{P,OMP}$, $n_{e,OMP}$, Ω_{OMP}, $(d\Omega/dR)_{OMP}$

$$L_{q,OMP} = \frac{2}{(dq/dR)_{q=2}}$$

$$L_{S,OMP} = 2L_{q,OMP}/\varepsilon_{OMP}$$

$$\varepsilon_{OMP} = \frac{R_{OMP,q=2} - R_{IMP,q=2}}{2R_{OMP,q=2}}$$

$$\rho_{\theta i,OMP} = 2\times10^{-4}\sqrt{T_{i,OMP}}\Big/B_{P,OMP}, \quad \rho^{*}_{\theta i,OMP} = \rho_{\theta i,OMP}/r_s$$

$$\tau_{A,BT,OMP} = \frac{R_{axis}\sqrt{\mu_0 2n_{e,OMP}m_H}}{B_{centr}}$$

$$(\textbf{Norm. Flow Shear})_{OMP} = \left(\frac{d\Omega}{dR}\right)_{OMP} L_{S,OMP}\tau_{A,BT,OMP}$$

$$\beta_{Pe,OMP} = 2\mu_0 P_{e,OMP}/(B_{P,OMP})^2$$

Mapped To Flux @ q=2

Directly Calculated From Data and Equilibrium:
T_e, T_i, B_P, n_e, Ω, $(d\Omega/dr)$

$$\frac{df}{dr} = \frac{1}{a}\frac{df}{d\rho} \qquad \rho =$$

Use the Modified Rutherford Equation to Study the Mode Dynamics (I)

1. 2. 3.

$$\frac{\tau_R}{r_s^2}\frac{dw}{dt} = \Delta' - \frac{6D_R w}{w^2 + w_d^2} + D\left(\frac{w}{w^2 + w_d^2} - \frac{w w_{pol}^2}{w^4 + w_b^4}\right)$$

$$D = \frac{16\mu_0 L_q}{B_\theta}\delta j_{BS}$$

w_{pol}^2

1: Curvature Term

2: Bootstrap Term

$$D = \frac{C_{BS}\mu_0 L_q}{B_\theta}\delta j_{BS}, \quad C_{BS} = 16$$

3: Polarization Threshold

$$w_{pol}^2 = \frac{a_{pol}}{D}\beta_{Pol}, \quad a_{pol} \propto \left(\frac{L_q}{L_P}\right)^2 g(\varepsilon,\upsilon)\rho_{i,\theta}^2 \frac{\Omega\left(\Omega - \omega_i^*\right)}{\omega_e^{*2}}$$

if $\delta j_{BS} = \frac{\sqrt{\varepsilon}}{B_\theta}\frac{dP}{dR}$ and $g(\varepsilon,\upsilon) = \varepsilon^{3/2}$ then $w_{pol} = \frac{1}{\sqrt{8}}\sqrt{\varepsilon}\sqrt{\frac{L_q}{L_P}}\rho_{\theta,i}$