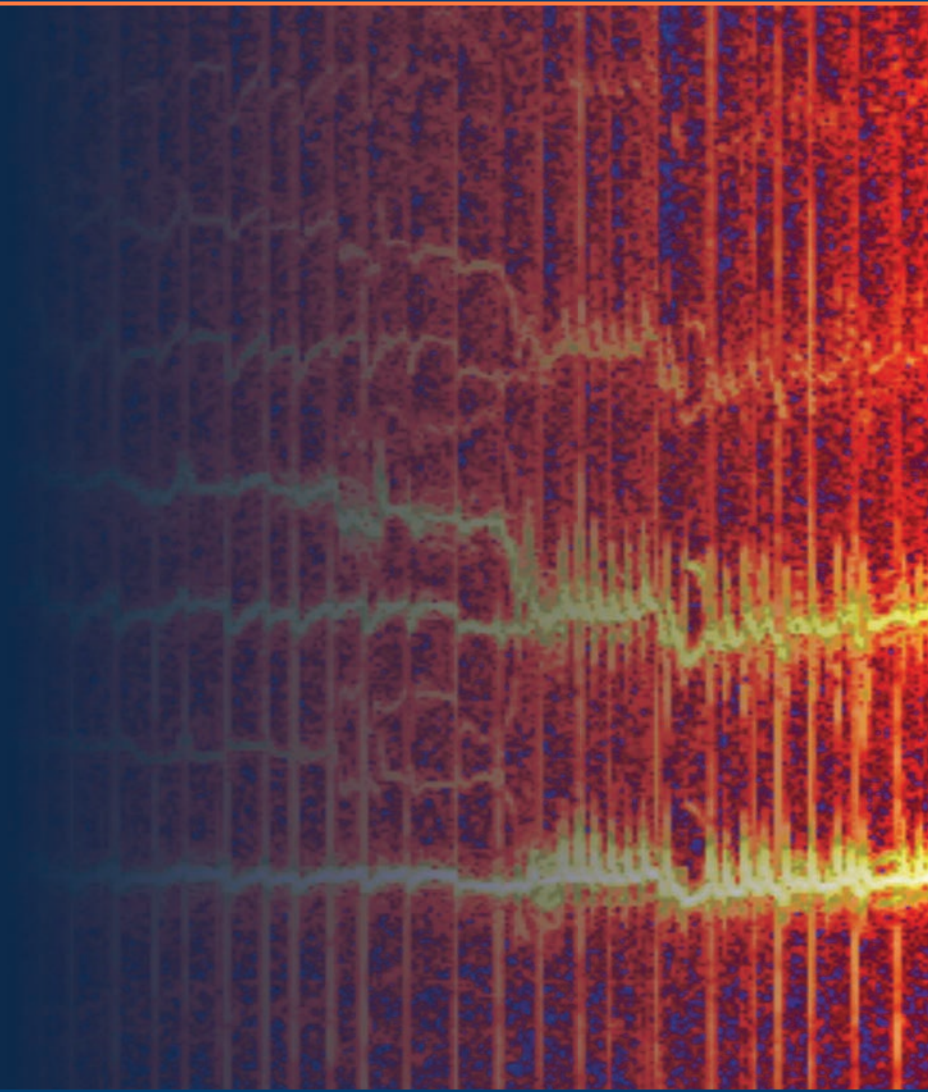
Phase-locking of NTMs on DIII-D



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FSM, General Atomics
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Dynamics of stochastic collapse (1)

- **Two islands couple and exchange momentum through linear processes:**
  - $\cos^2$ form of the 2/1 island separatrix produces a 4/2 ‘harmonic’ fluctuation
  - toroidicity induces m±1 sidebands and linear JxB interaction with a 3/2 island chain
  - mutual inductive currents damp the rotation of the magnetic islands
  - viscous torques damp differential flow between the plasma surfaces

Dynamics of stochastic collapse (2)

- **Nonlinear mixing of the plasma responses to each NTM produces a 3rd wave, $\omega_3=\omega_1+\omega_2$**
- **This 3rd wave might be resonant with an otherwise stable mode at a 3rd rational surface**
  - i.e., rotation at the 4/3 surface is also damped, 4/3 helical currents resonate with $<\omega_3, k_3>$
- **Islands destabilized by penetration of the 3-wave product experience a nonlinear torque associated with 3-wave mixing**

Dynamics of stochastic collapse (3)

- **EM torques overcome momentum of the system and the viscous forces transferring that momentum to modes**
  - higher order surfaces are destabilized
  - a cascade of tearing instabilities
  - island overlap and stochastic collapse
- **If this model is valid, it suggests that by preventing phase-locking, one avoids thermal quench and prevents disruption**

Principle of disruption mitigation by prevention of NTM phase-locking

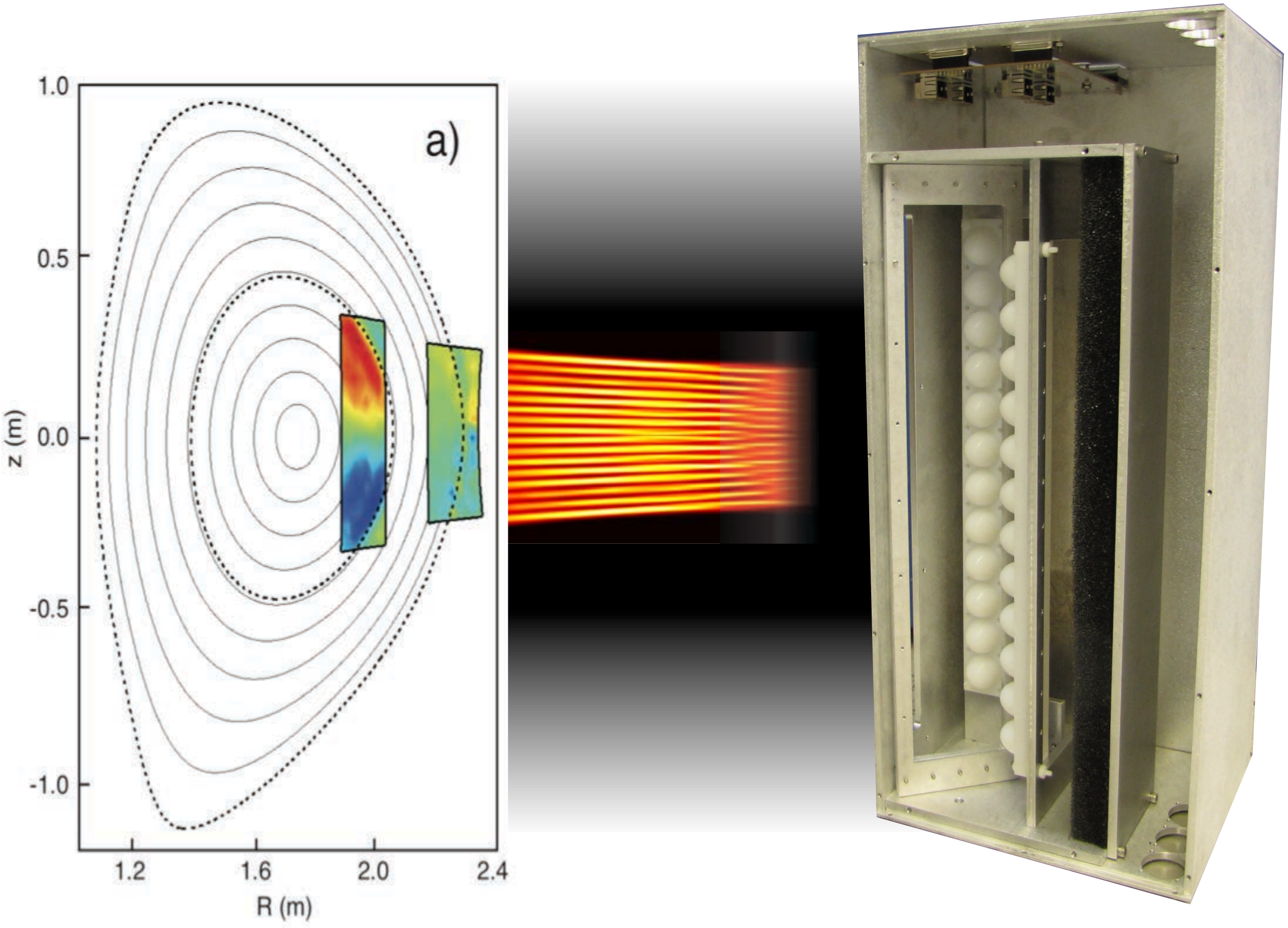
- **Phase-locking dynamics often include an evolution of mode structure ($k_{poloidal}$)**
  - localization of the island (current profile)
  - structure of the plasma response (pitch-resonant vs. kink-like spectra)
- **If either of these processes has a sufficient energetic barrier, phase-locking cannot proceed and flow shear is maintained**

Phase-locking: an energetically favorable alignment of propagating phase fronts

- **In general, it is an agreement in phase velocity**
- **In tokamaks, it is the synchronous rotation of internal magnetic islands as they traverse the outboard midplane**

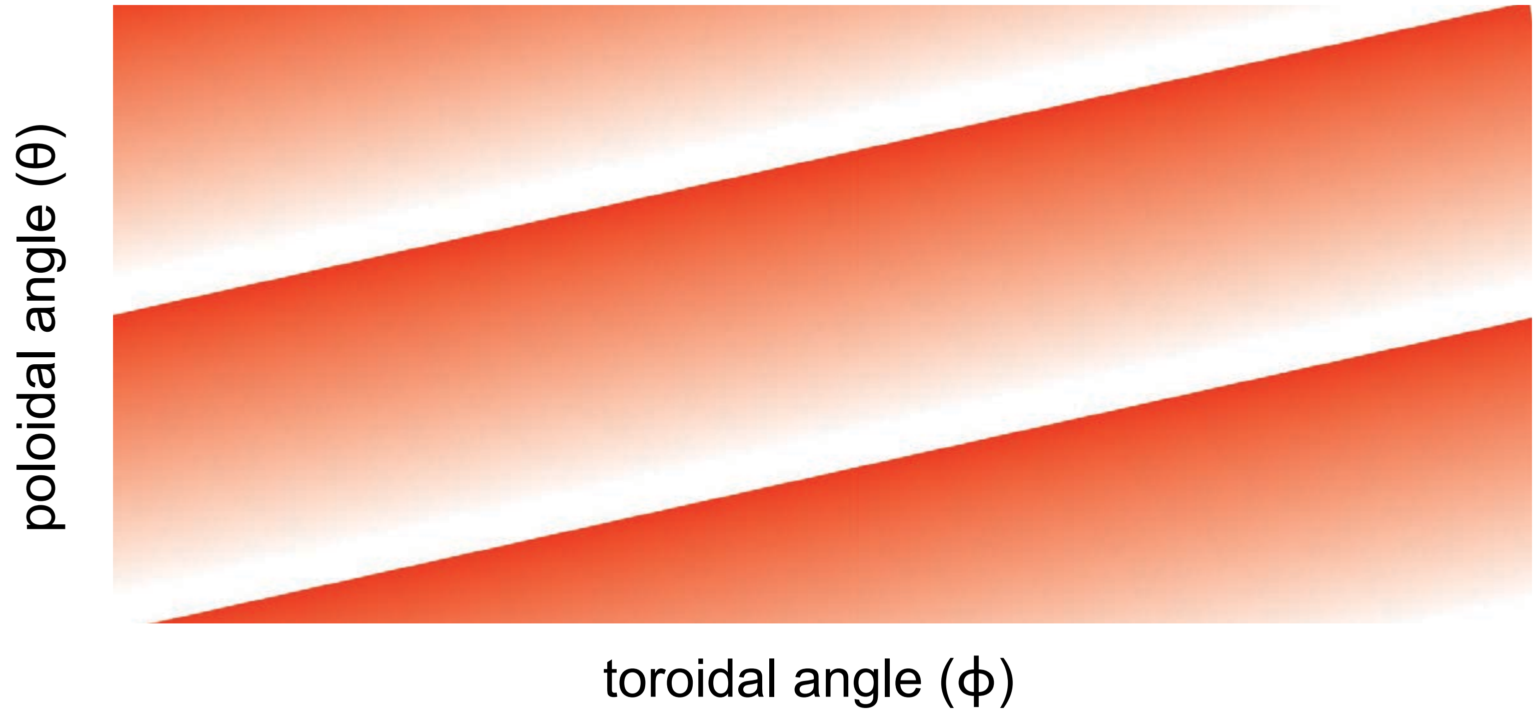
- **Phase-locking exacerbates the impact of NTMs**
  - flattens rotation across multiple rational surfaces
  - contributes to a further degradation of confinement
  - makes the core more susceptible to external perturbation
- **Inter-NTM torques may be manipulated to hold up flow shear**
  - some NTMs simply cannot phase-lock
  - forces that otherwise cause phase-locking accelerate the edge plasma and invert the rotation profile

Viewing geometry of ECE-Imaging



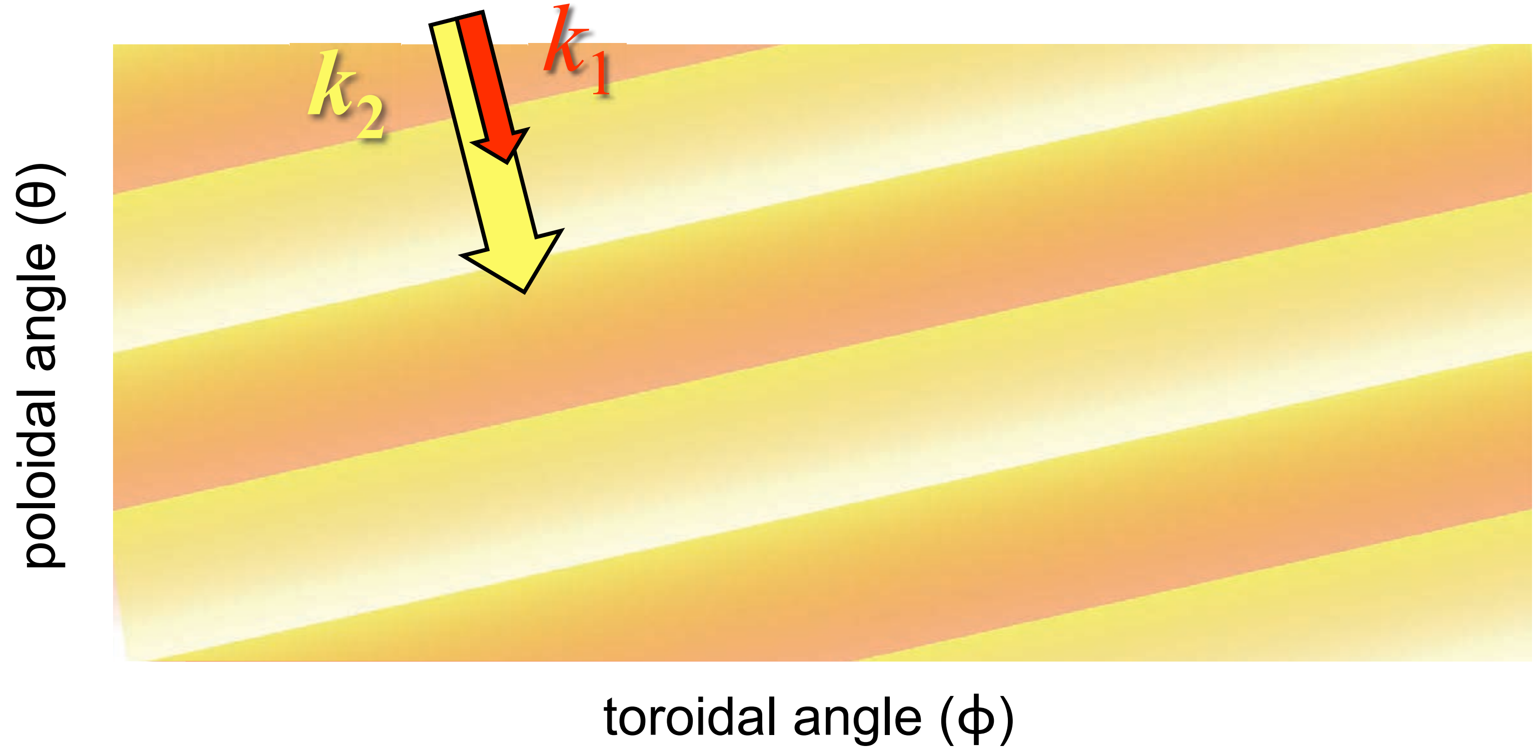
Simplified model of the n=1 mode, as seen from the outboard midplane

$n=1$



Overlay a second mode, same pitch, i.e. having harmonic wavenumber, $k_2 = 2k_1$

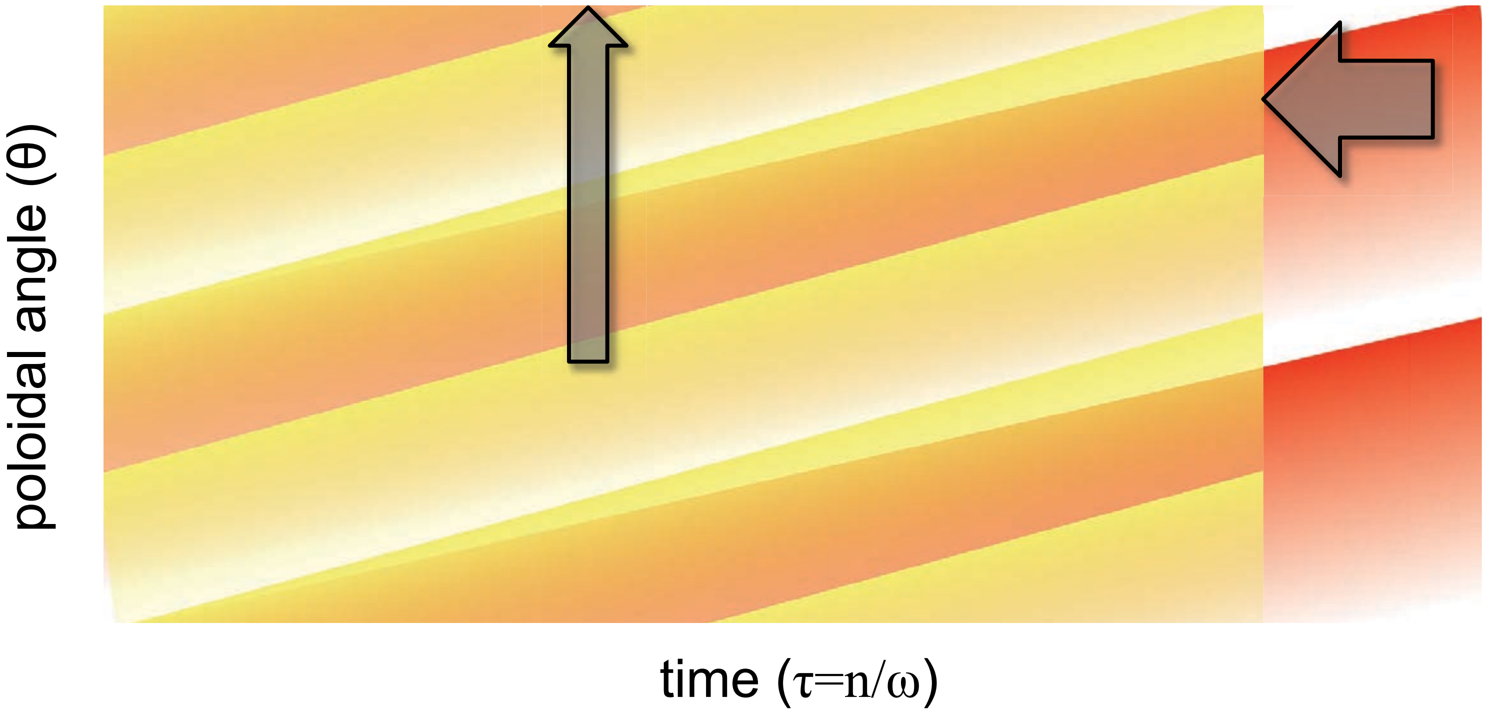
n=1 + *n*=2



Doppler shift due to differential rotation (faster n=2)

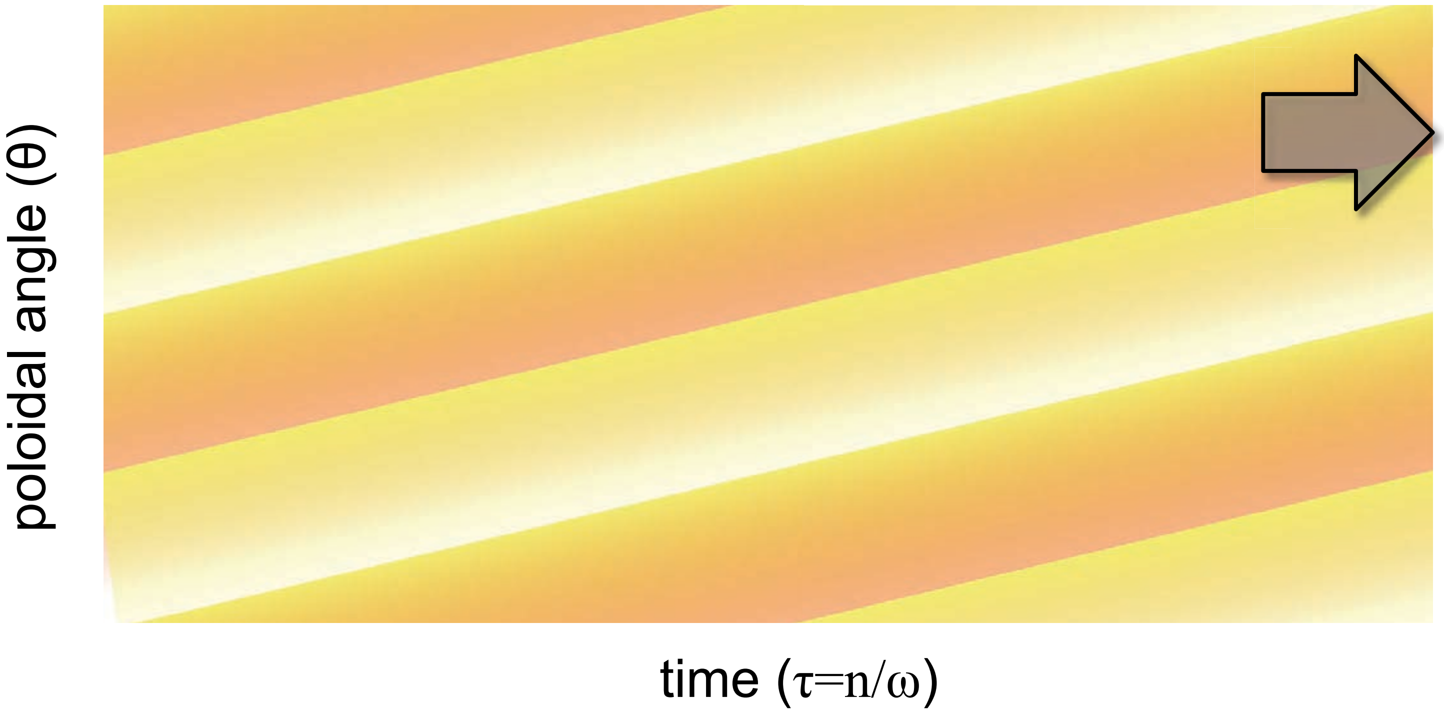
$$\Delta v_{phase,\theta} = \Delta\omega / k_\theta$$

$$\tau_n = n\frac{2\pi R}{v_{tor}}$$



Toroidal ion fluid rotation adjusts so as to re-establish phase-locking

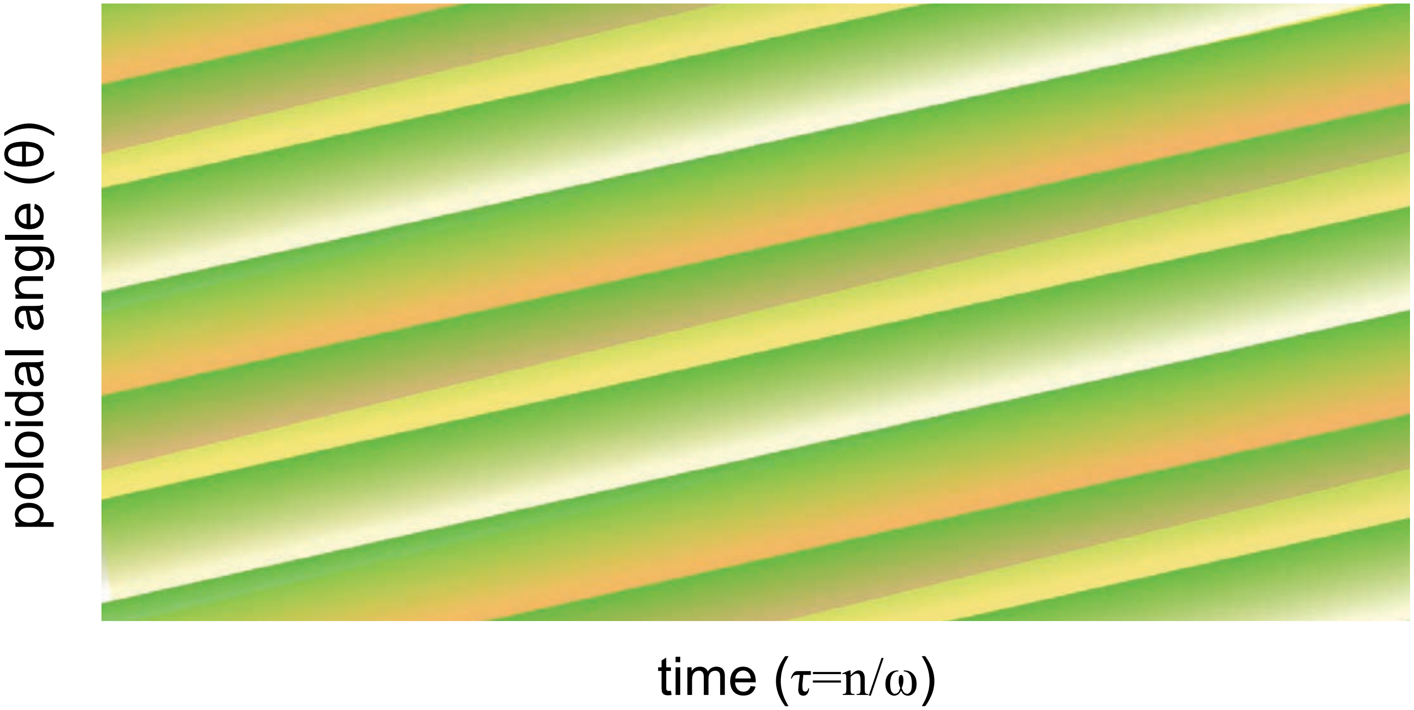
$$v_{tor}\downarrow,\quad \tau_n\uparrow$$



n = 1,2, 3, compose a set of harmonic modes

$$k_3 = k_1 + k_2 = 3k_1$$

$$\omega_3 = \omega_1 + \omega_2 = 3\omega_1$$



Internal measurements are necessary to identify phase-locking and/or 3-wave coupling

3-wave selection criteria

$$\langle \omega , \omega ' , \omega - \omega ' \rangle$$

Simply the laboratory frame mode frequency, as measured by any diagnostic

$$\langle k , k ' , k - k ' \rangle$$

Should be evaluated in both toroidal and poloidal dimensions

$$\langle n , n ' , n - n ' \rangle$$

A good metric—toroidal mode is a good quantum number

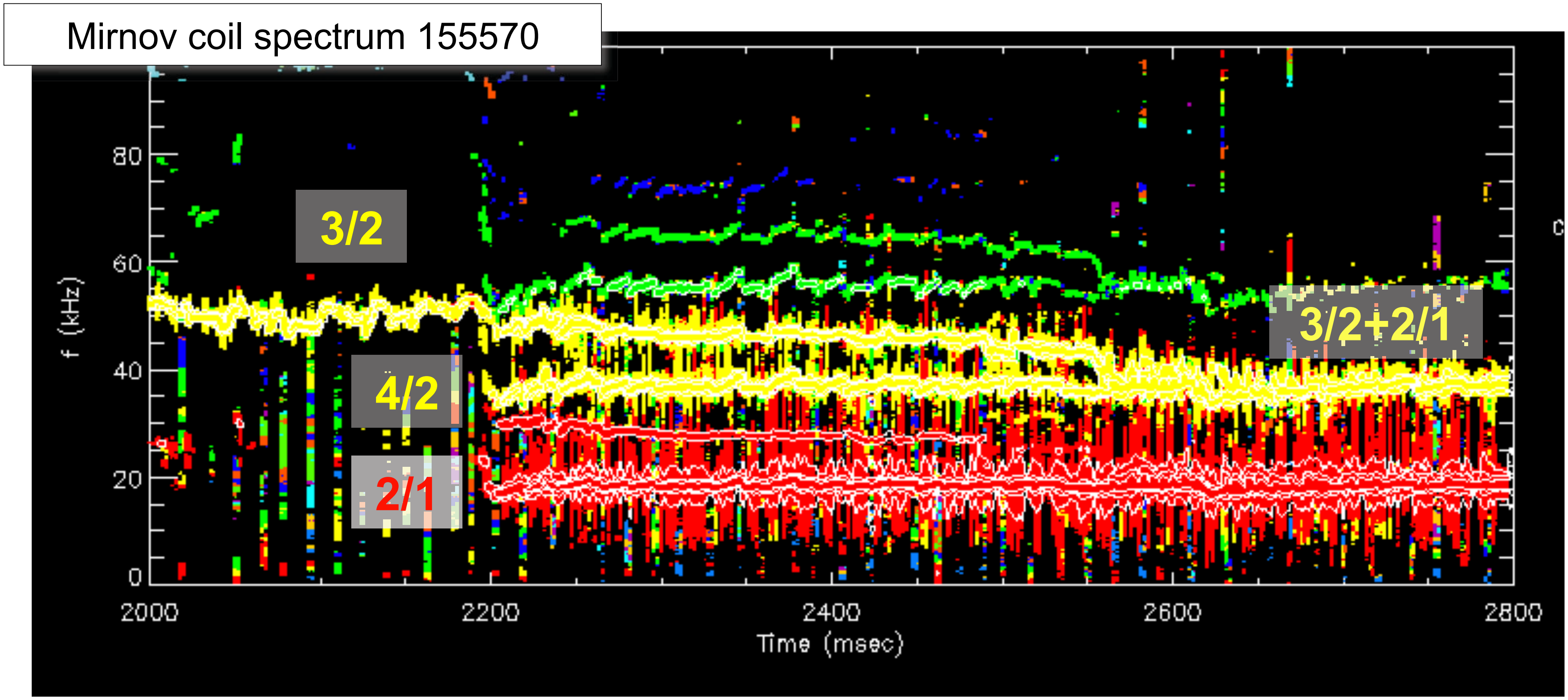
$$\cancel{\langle m , m ' , m - m ' \rangle}$$

Need a local quantity.

$$m/n = \langle 3/2 \, , \, 2/1 \, , \, 4/3 \rangle$$

Example: modes that are observed to phase-lock in 155570 (and similar)

Synchronous toroidal phase propagation: coalescence of the 3/2 and 4/2 fluctuations

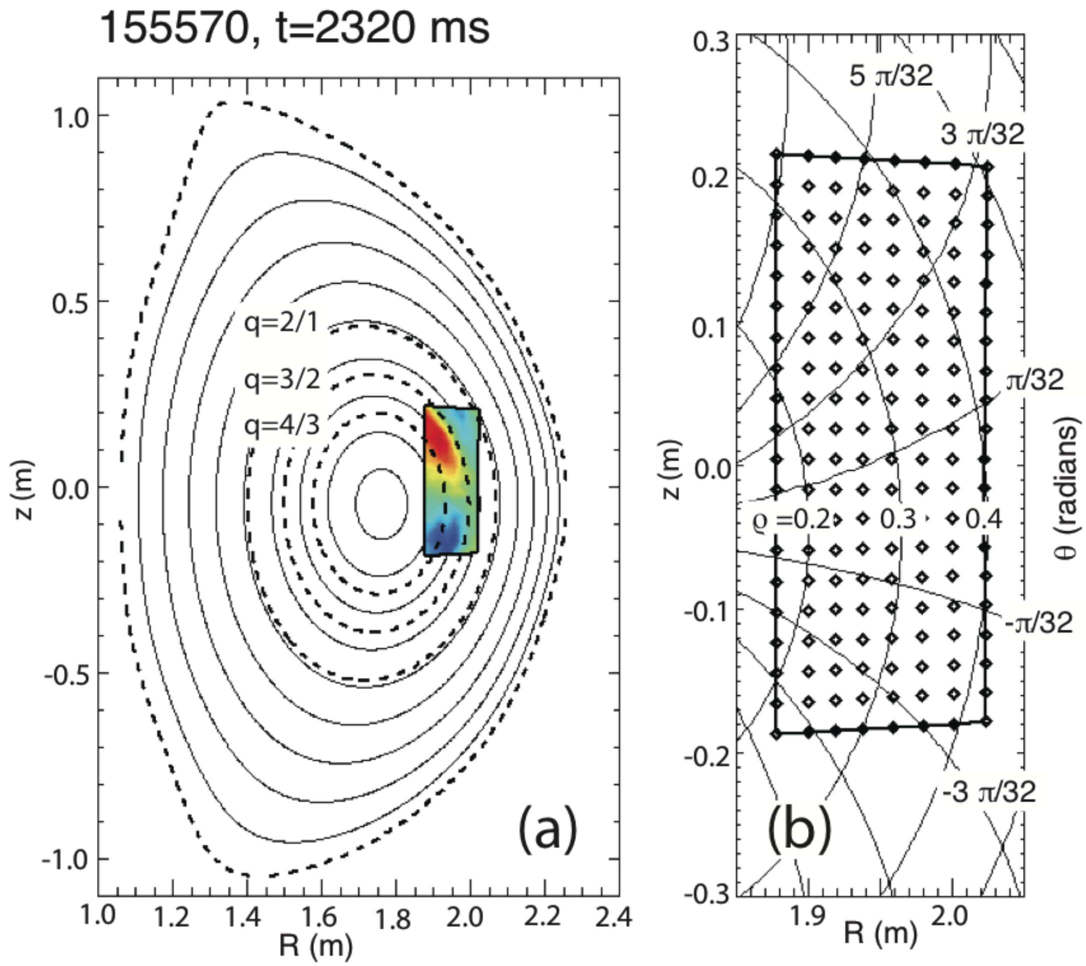


Begs, 'do phases propagate in sync poloidally?'

Dynamics of phase-locking are studied in non-disruptive discharges

- **'Hybrid' scenario attempted**
  - early 3/2 mode a key element
- **Onset of 2/1 mode spoils the scenario**
  - islands saturate in amplitude
- **A region of the rotation profile flattens**
  - islands rotate together, further degrading confinement
- **But, discharge does not disrupt**
  - 'bulk' rotation stays elevated
  - locking to external fields does not occur
  - an *opportunity* to probe the underlying mechanisms as they take hold over a localized region, without the threat of a global collapse in confinement

2D imaging data provides a local, 2D power spectral density, $S(\omega,k_{\mathrm{pol}})$, at each radius



M linearly independent time records X *N(N-1)* channel pairs, each contributing a two-point measurement, *j*:

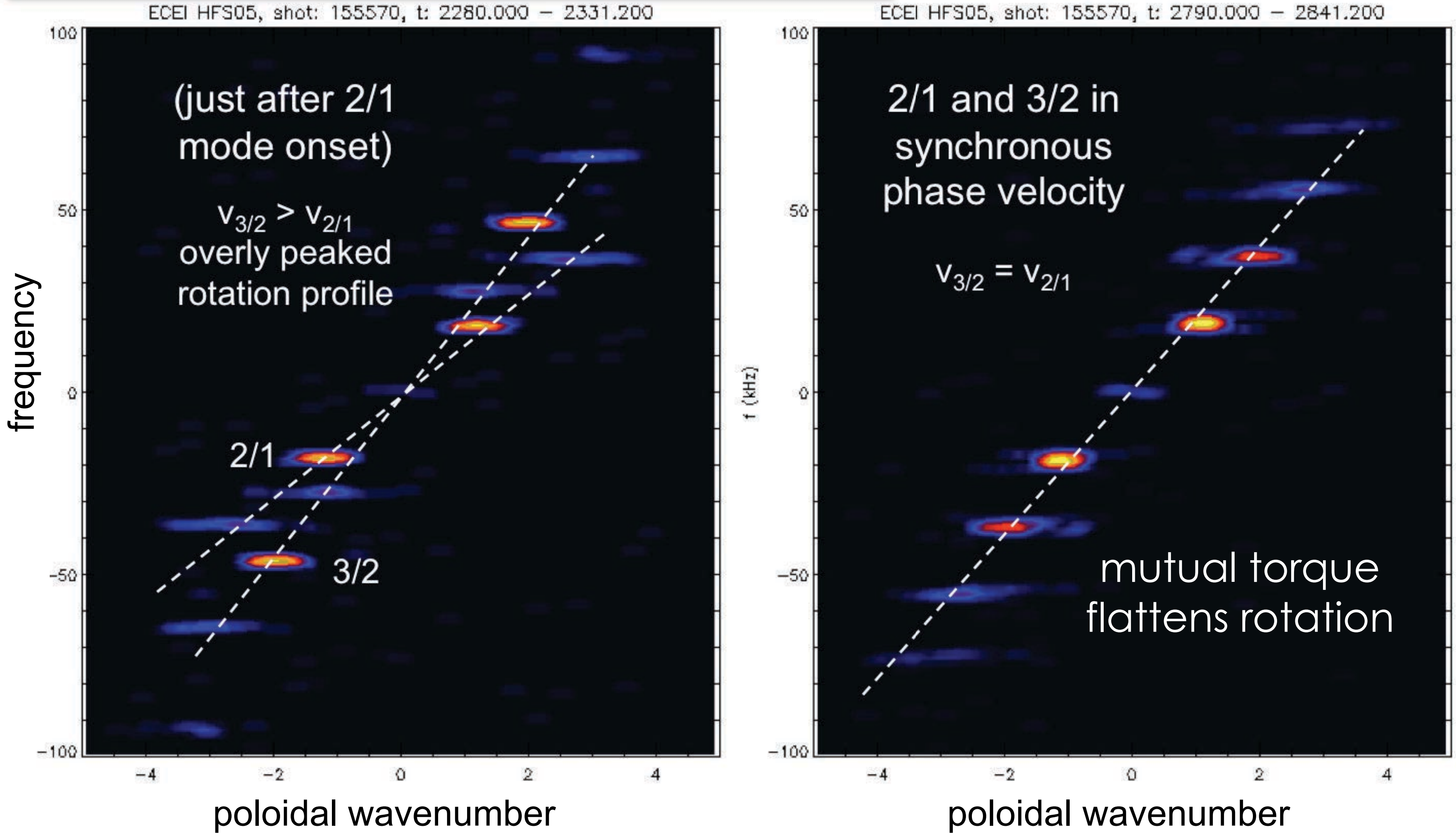
$$K^{j}(\omega)=\theta^{j}(\omega)\big/\Delta x$$

$$\theta^{j}(\omega)=\arg\left[\Phi^{j*}(x_1,\omega)\Phi^{j}(x_2,\omega)\right]$$

*M***N*(*N*-1) ~3800 measurements, binned to divisions in wavenumber (k_{pol} 0.4-150 m^{-1}) and frequency (0-400 kHz)

Internal, local measurements reveal synchronous poloidal phase propagation

Core-localized ECE-Imaging data 155570



(just after 2/1 mode onset)

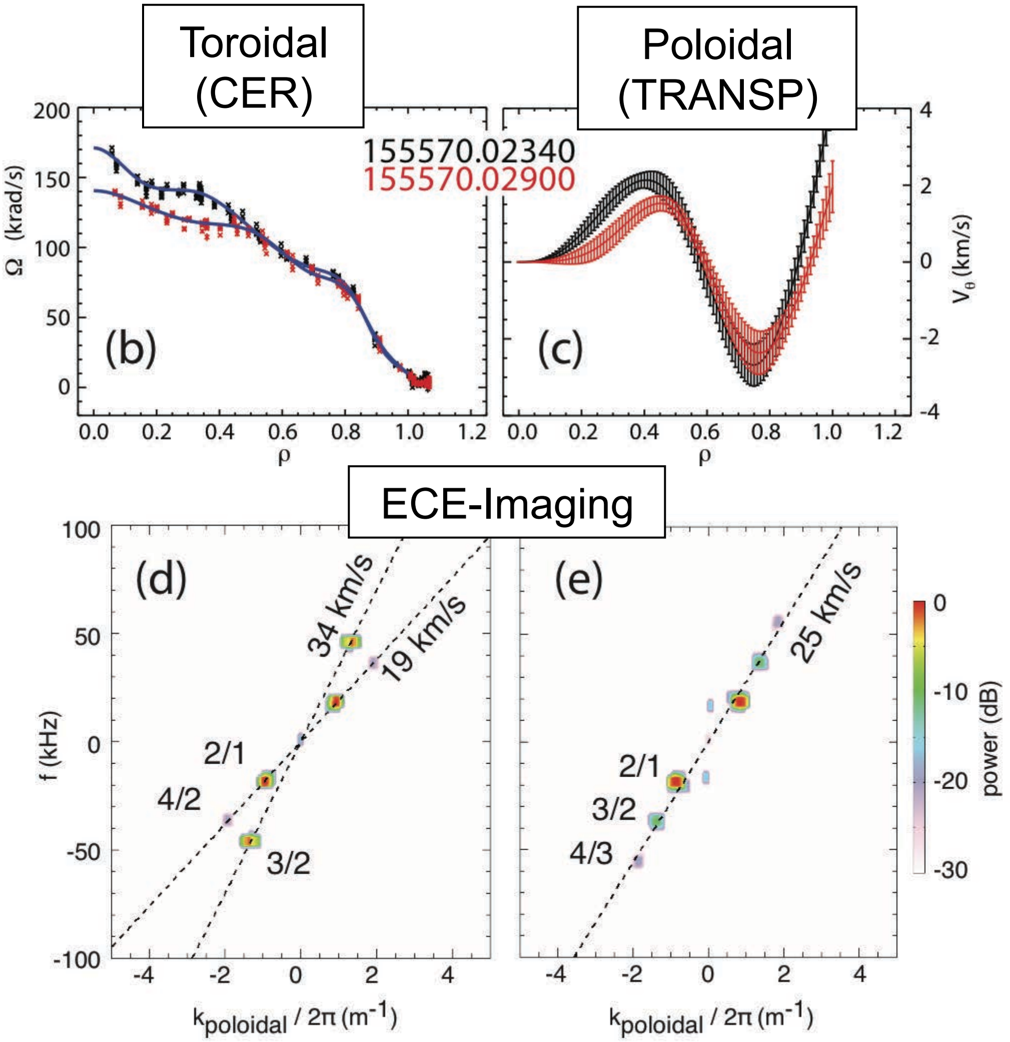
$v_{3/2} > v_{2/1}$
overly peaked rotation profile

2/1 and 3/2 in synchronous phase velocity

$v_{3/2} = v_{2/1}$

mutual torque flattens rotation

In this regime, changes in MHD frequency reflect changes in fluid rotation



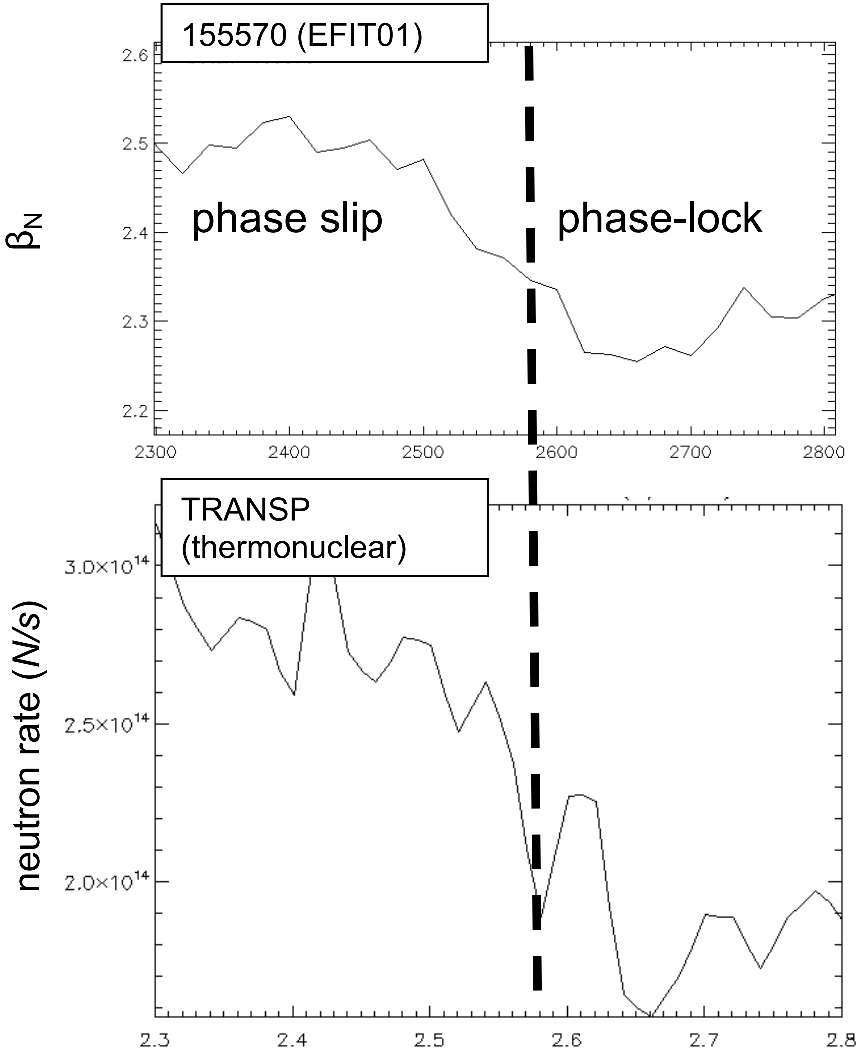
- **Observed velocities agree with CER and TRANSP fitting**

$$\omega = k_{pol}\left[v_{Doppler}\right] + \omega_0 + \varepsilon(\omega,k)$$

$$v_{Doppler} \equiv v_{pol} - \gamma v_{tor}$$

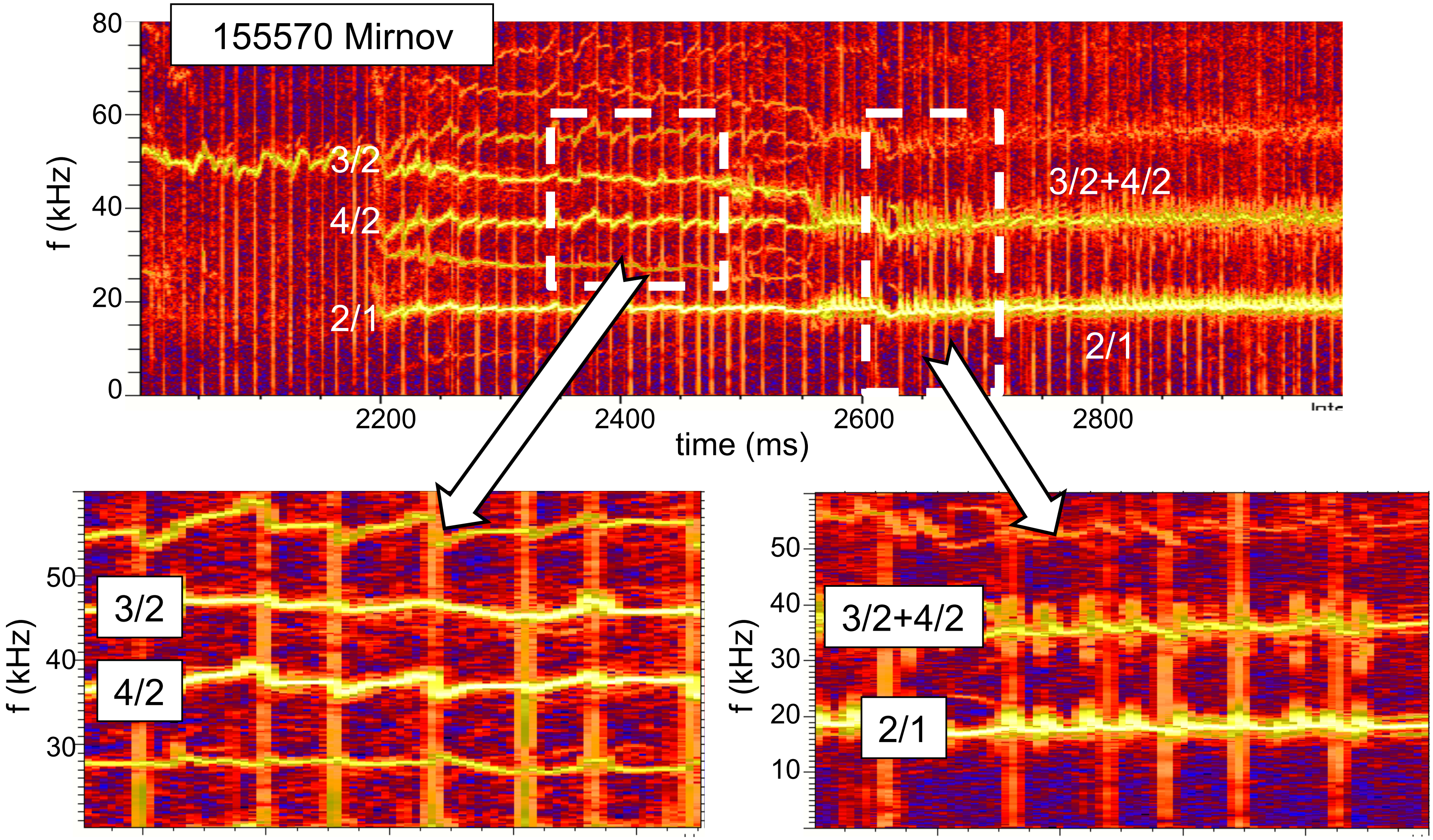
- **Toroidal rotation adjusts 'spontaneously'**
  - no identifiable 'trigger'
  - NBI power (and torque) held constant

Reduction in β_N (and neutrons) at phase-locking



- **Confinement is degraded as a consequence of phase-locking**
- **Neutron rates also fall (thermal plasma effect)**

Once phase-locked, modes behave dynamically as a single structure



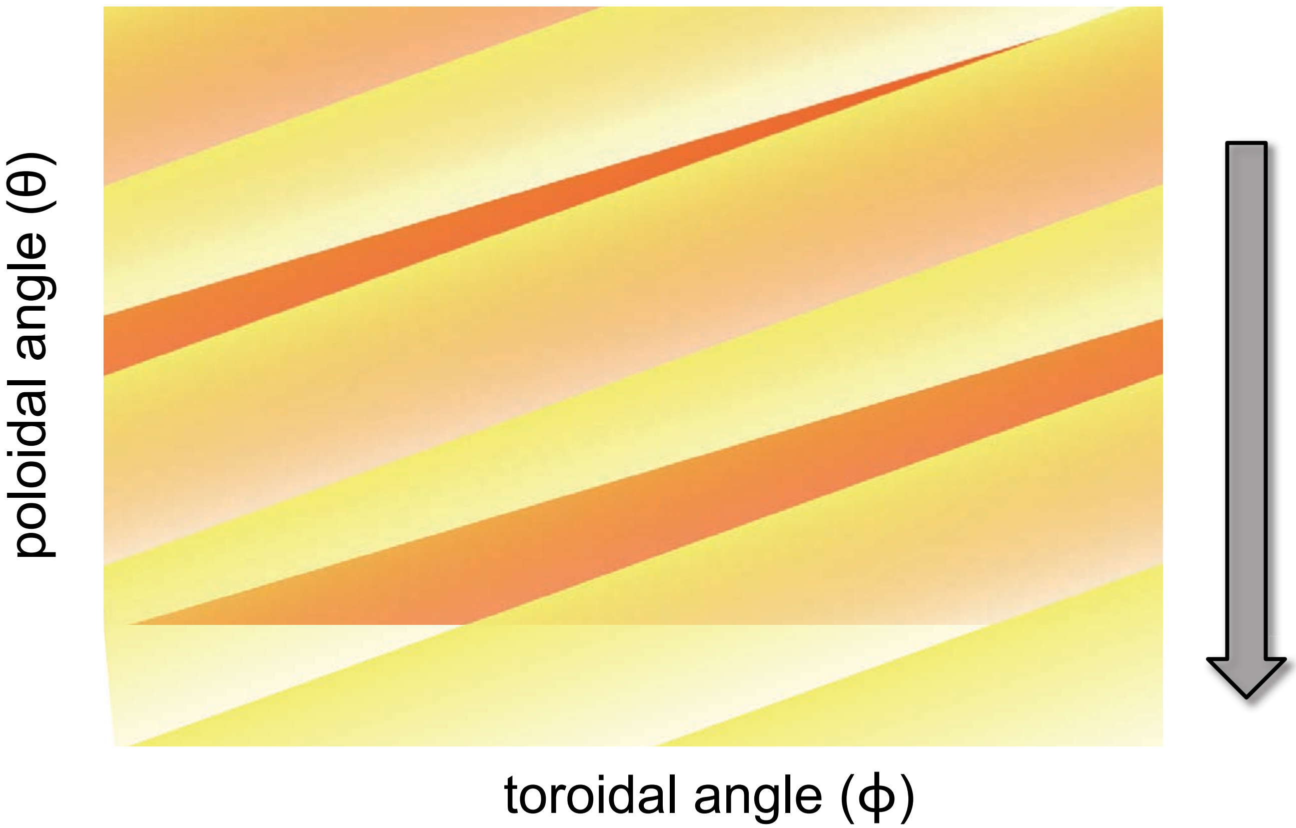
Tobias—July 18th, 2014

How does one prevent phase-locking?

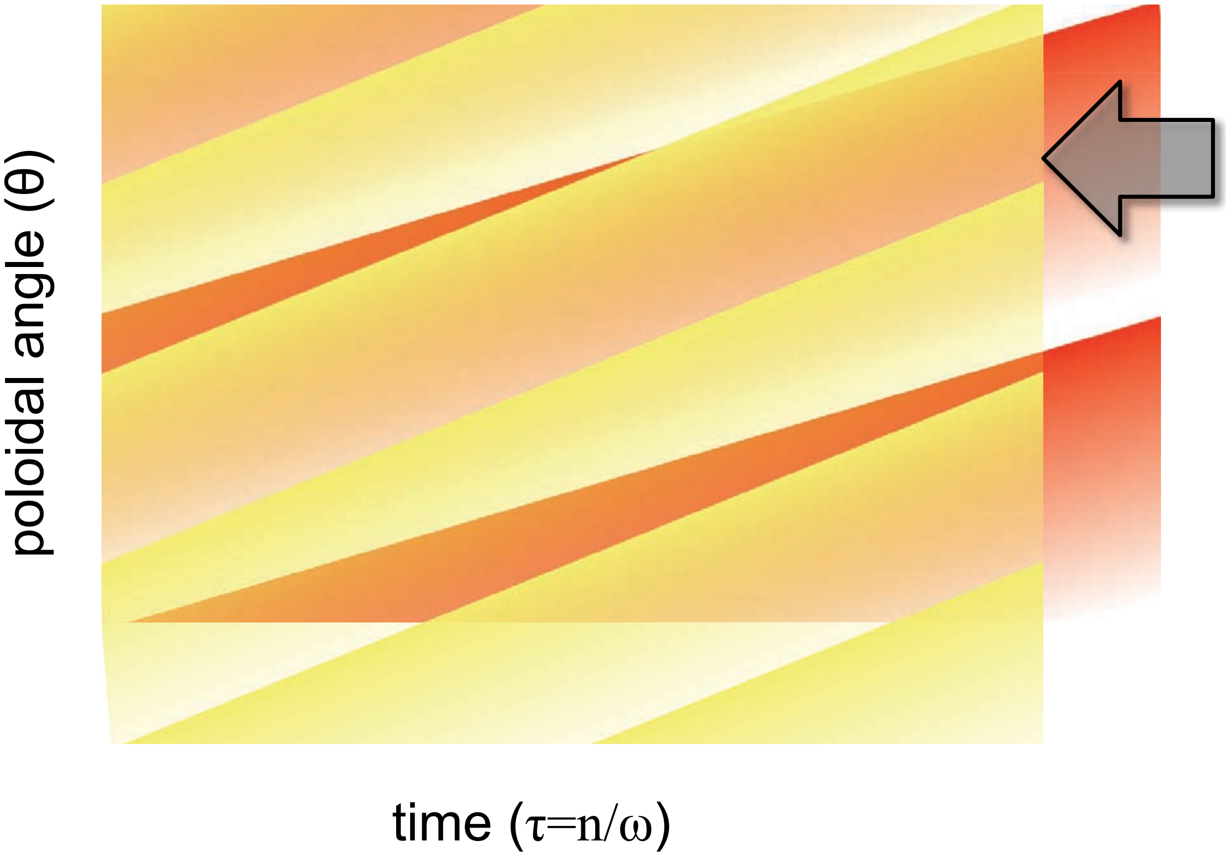
- **Forces between islands (irrespective of *n*-number) act to reduce/eliminate flow shear**
- **These forces are significant enough to impact discharge dynamics (and control schemes)**
  - rotation profile prediction/control
  - orderly shutdown/disruption avoidance
  - shot recovery/island suppression
- ***Poloidal and toroidal phase-locking torques may be made to counter each other, with toroidal EM and viscous torques in the same sense***

Destabilize two modes which, by design, have different pitch of phase:

$$\Delta v_{phase,\theta} = \omega \Delta \lambda_{\theta} \equiv \omega / \Delta k_{\theta}$$

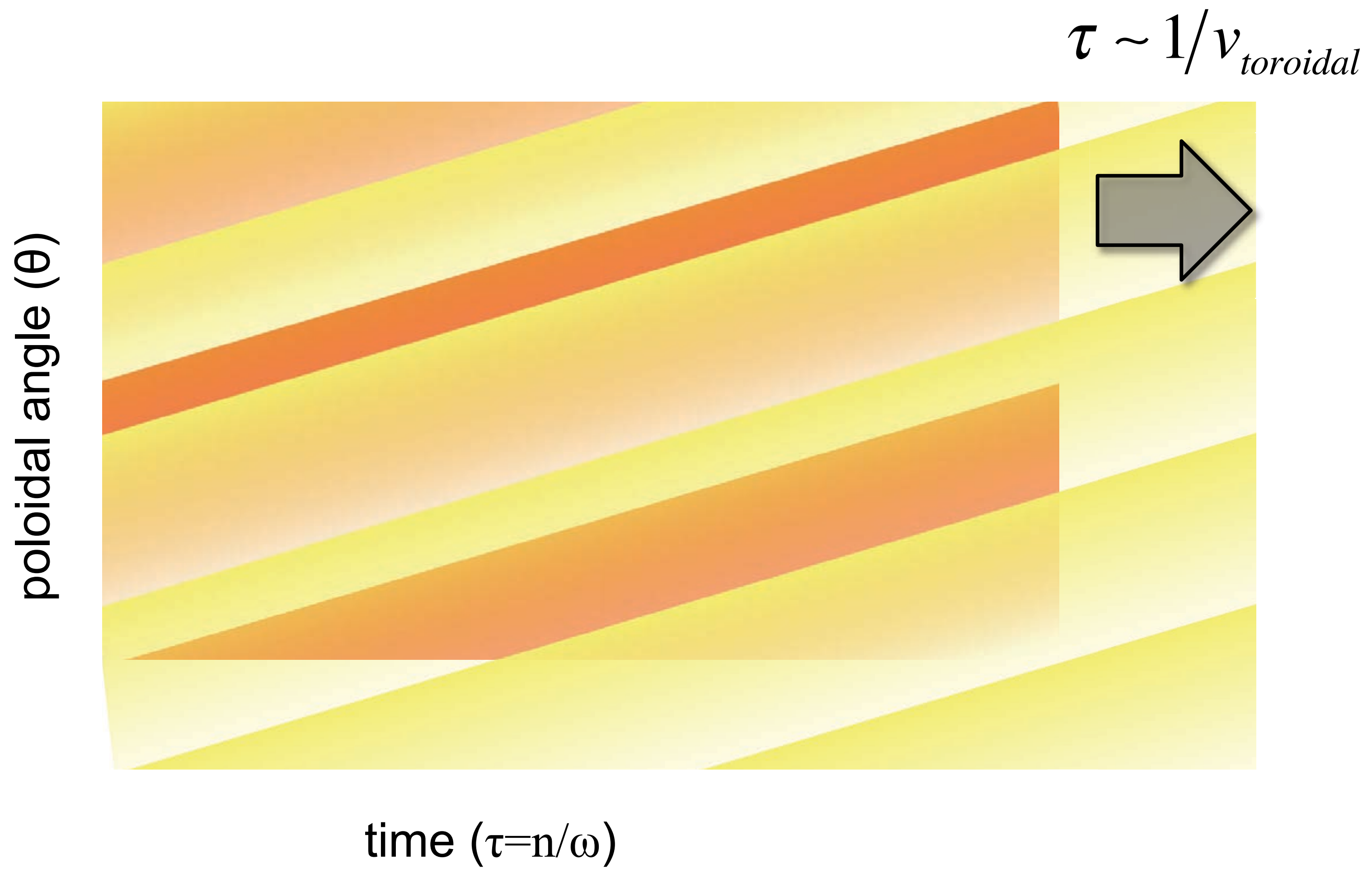


Again, the rotation profile at the onset of the modes exacerbates phase slip

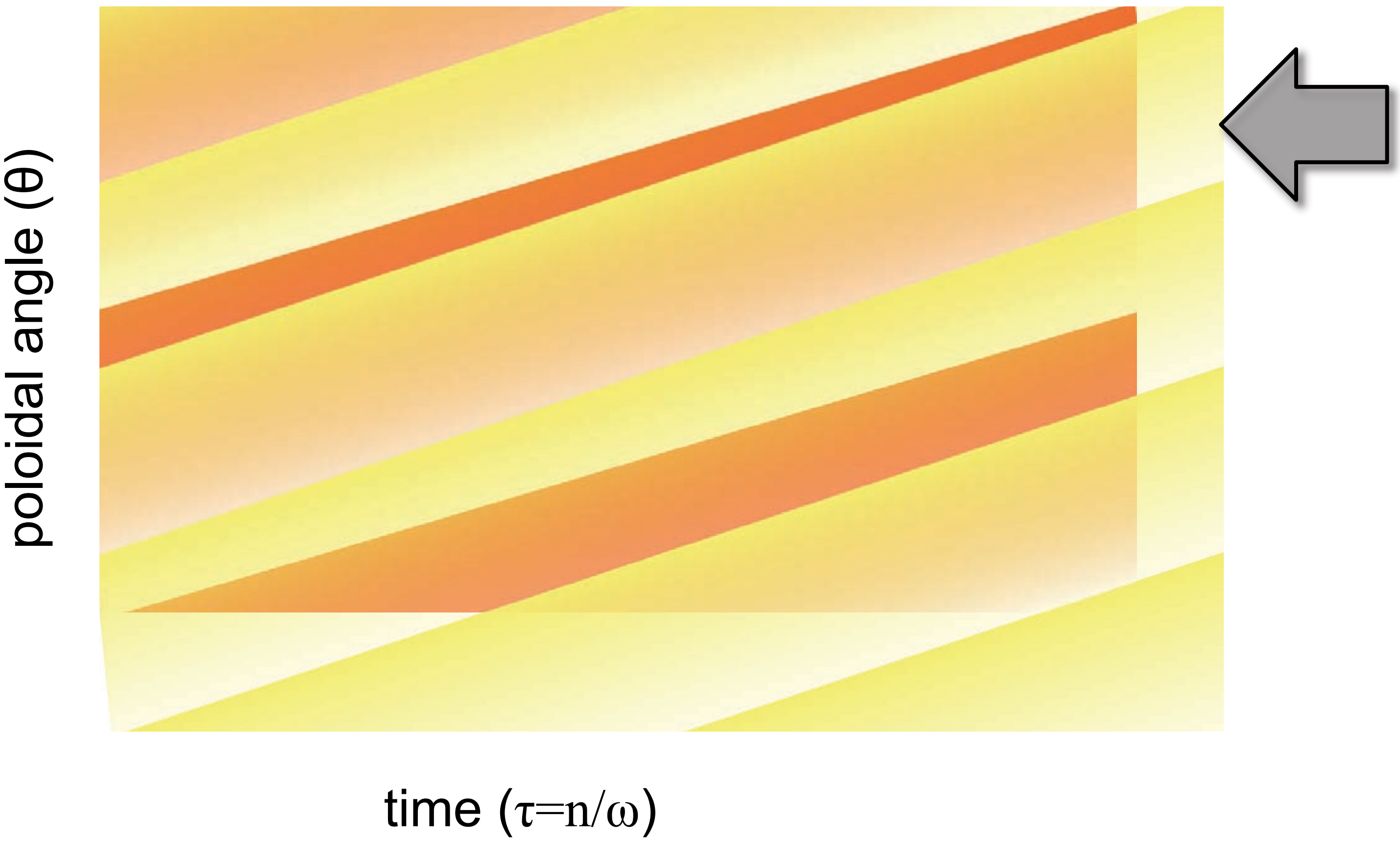


$$\tau_n = n\frac{2\pi R}{v_{tor}}$$

Changes in rotation act to align phase fronts, but at the expense of frequency matching

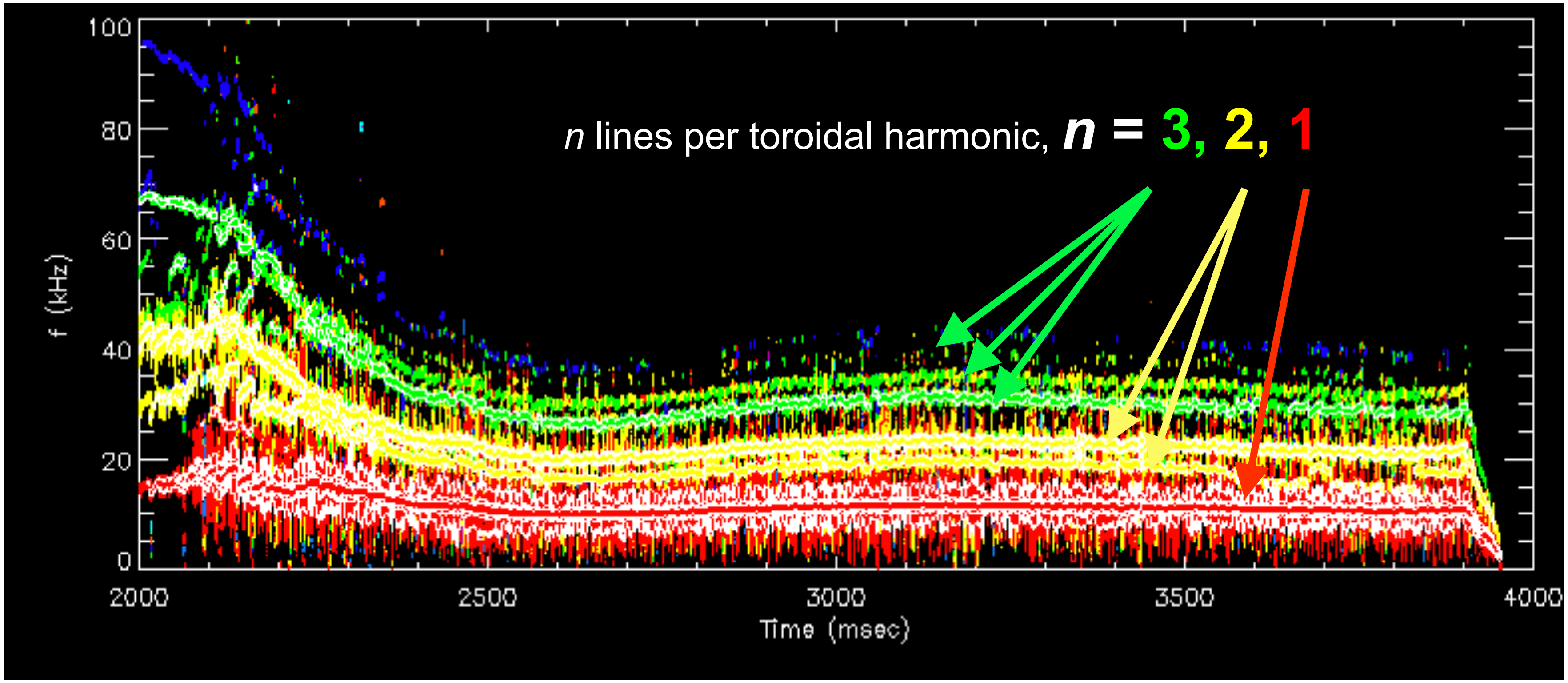

$\tau \sim 1/v_{toroidal}$

After rotation profile inversion, momentum diffusion opposes the alignment of phase fronts



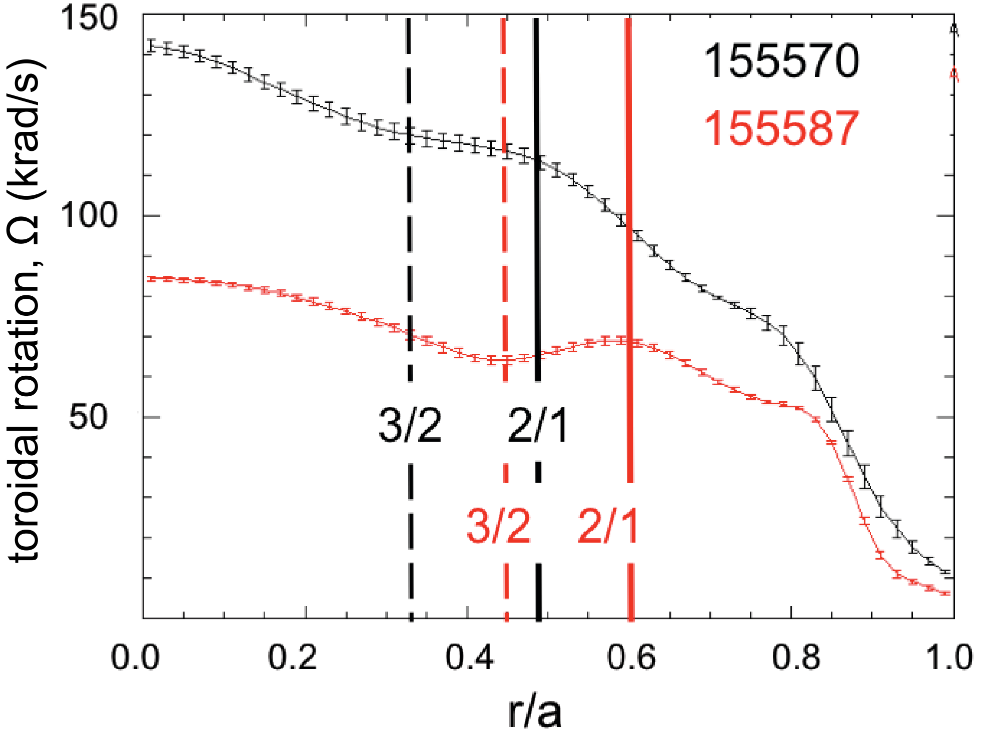
Shot 155587: Phase-locking does not occur

- **Mode pitch makes phase-locking impossible**
- **Viscous forces separate both phase velocities**

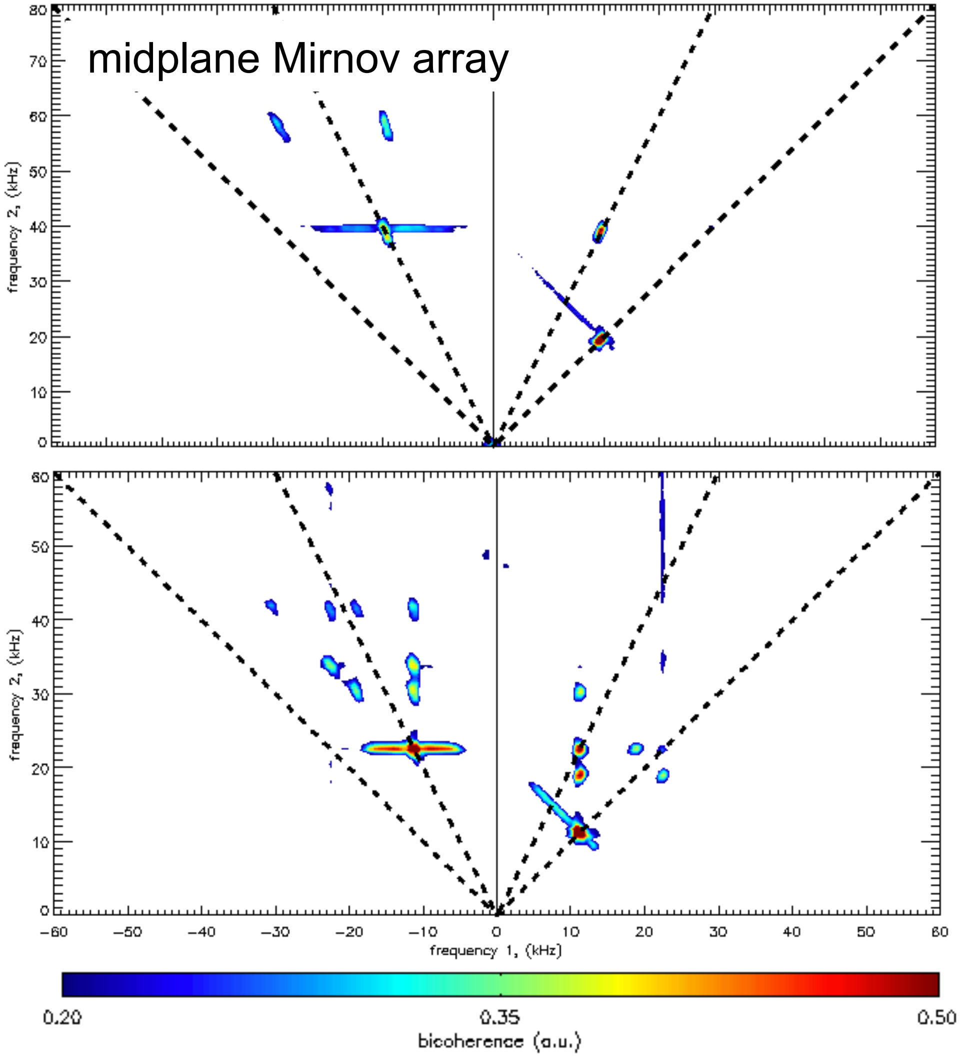


Without phase-locking, the discharge takes on a very different character

- **Modes are larger, and nearer the edge**
- **Core rotation cut nearly in half**
  - 20% decrease in angular momentum
- **Gradient in the region between the modes is reversed**
  - shearing rate held up by differential torques



Bicoherence reflects sustained quadratic nonlinearities (nonlinear mixing products)



Nonlinear coupling leads to coherent mixing

$$B(\omega_1,\omega_2)=\lim_{T\to\infty}\frac{1}{T}E\left[X(\omega_1)X(\omega_2)X^*(\omega_1+\omega_2)\right]$$

$$b^2=\lim_{T\to\infty}\frac{1}{T}\frac{\left|B(\omega_1,\omega_2)\right|^2}{P(\omega_1)P(\omega_2)P(\omega_1+\omega_2)}$$

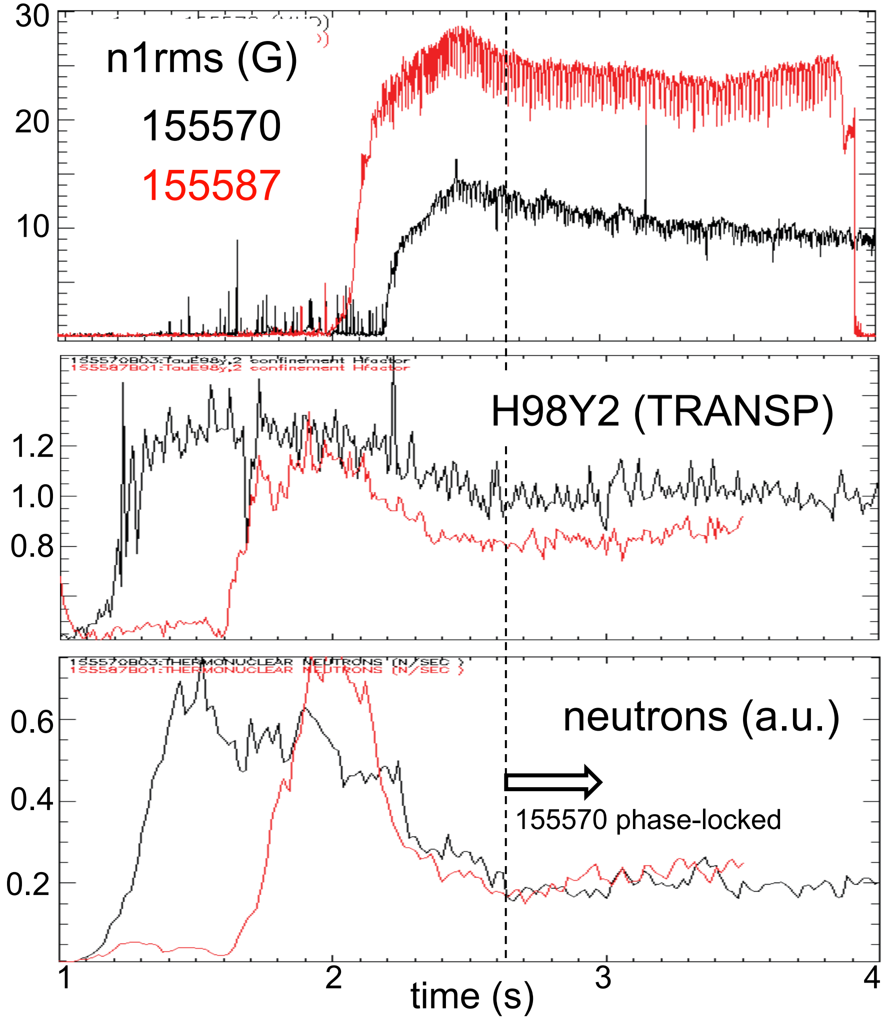
$$k_{pol,3}=k_{pol,1}+k_{pol,2}$$

$$\sum_{n=3}P=P(3\omega_1)+P(\omega_1+\omega_2)\ldots$$

distribution of harmonics reflects the mixer response function

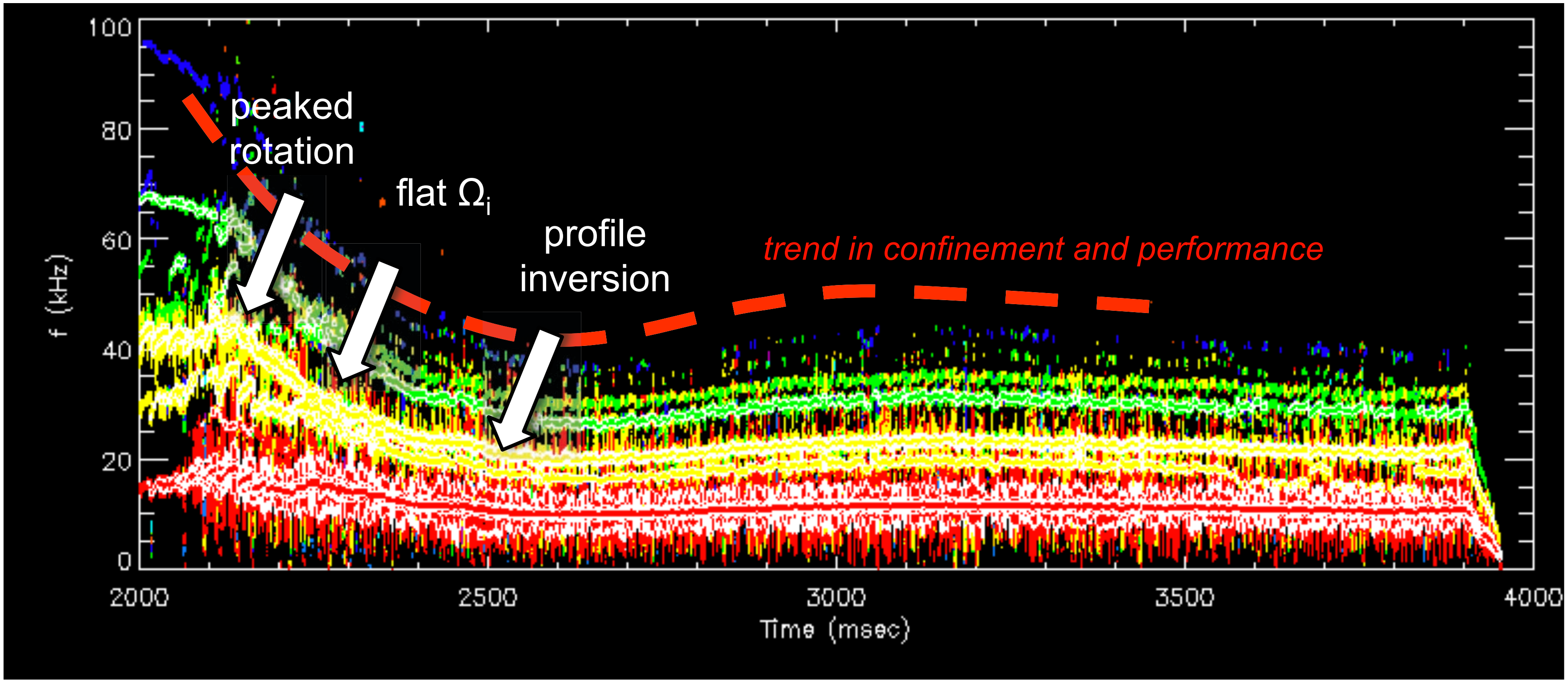
Differential rotation lessens the impact of the modes on thermonuclear performance

- **Larger modes:**
  - Increase from 10 to 25 Gauss at the wall
- **Worse confinement:**
  - H98Y2 down 20%
  - β_N, 2.3 → 2.0
  - (lost fast particles)
- **The same measured neutron rate**
  - improved thermal production (partly due to mode location)



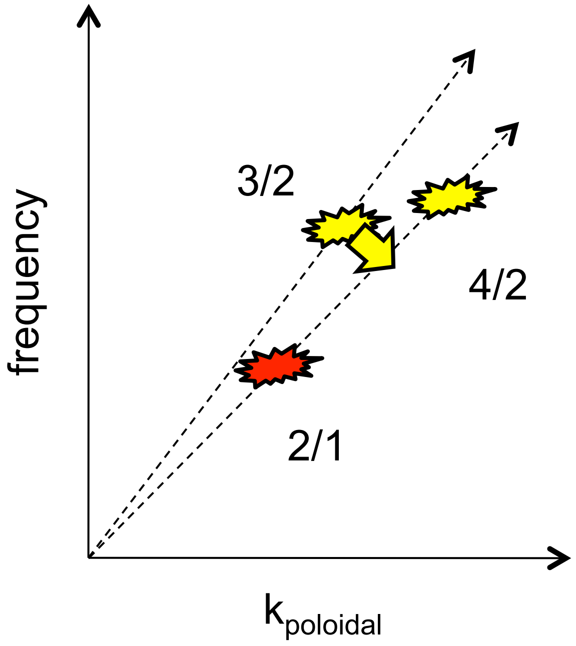
Further evidence of resonant effects

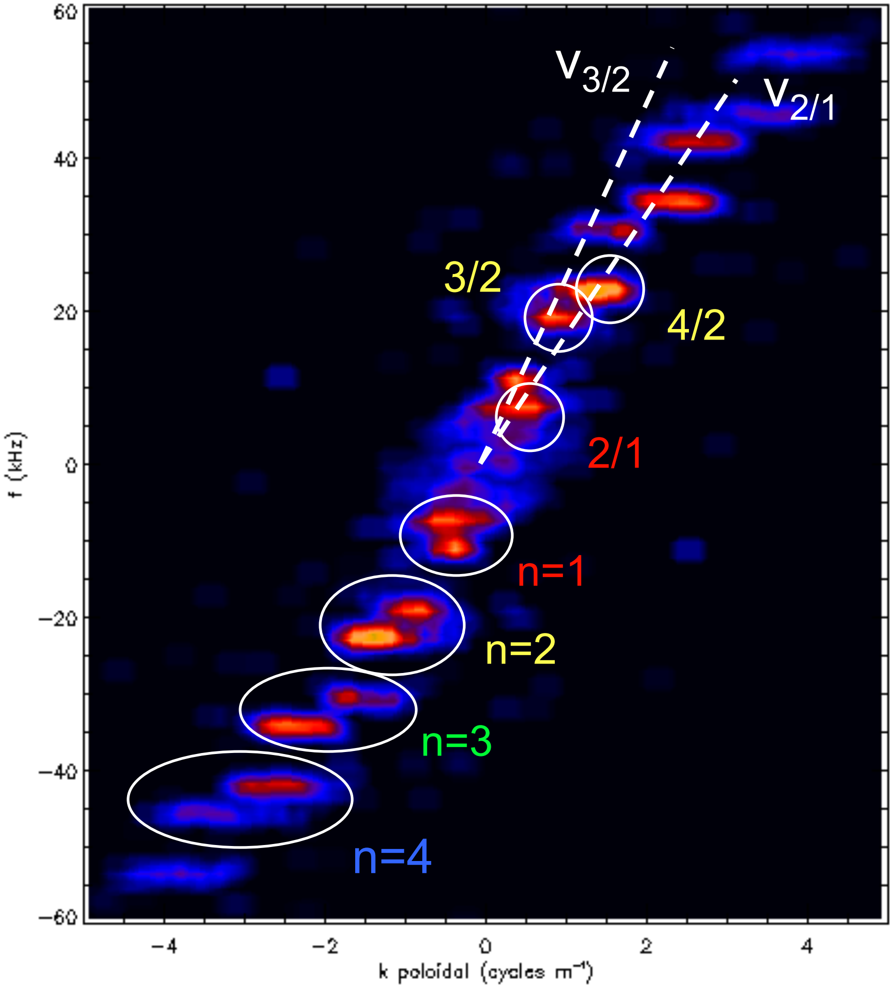
- **Rotation evolves slowly toward torque balance**
- **Confinement trends upward after profile inversion**



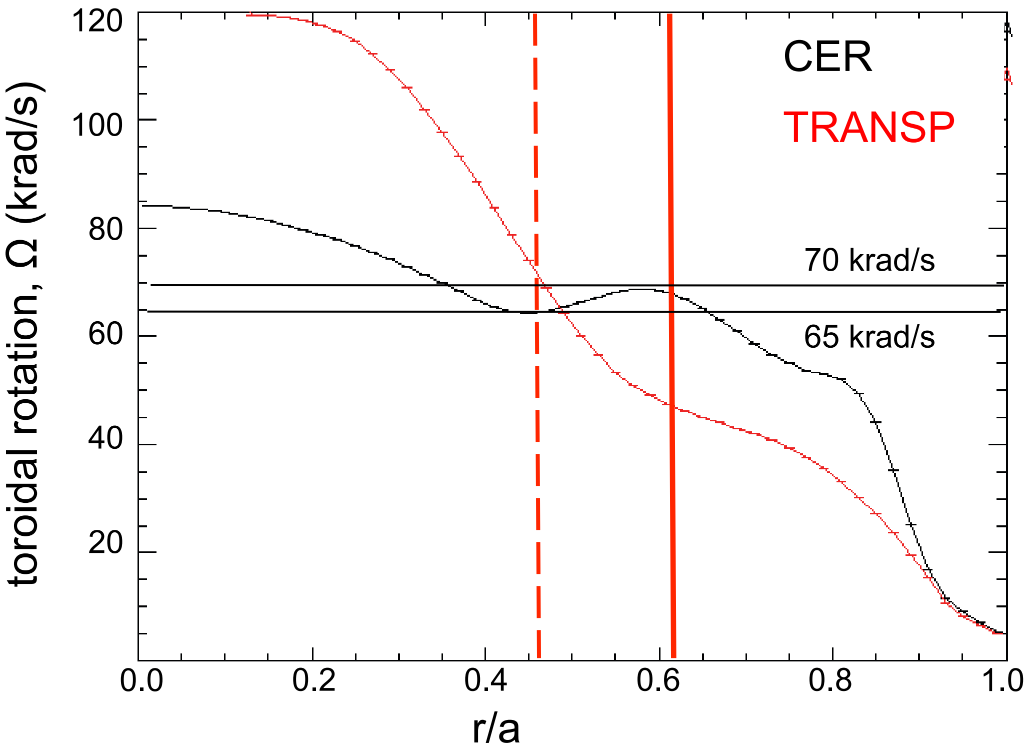
Poloidal velocity: 3/2 > 2/1

Poloidal EM torque is decelerating--toroidal rotation profile is already inverted





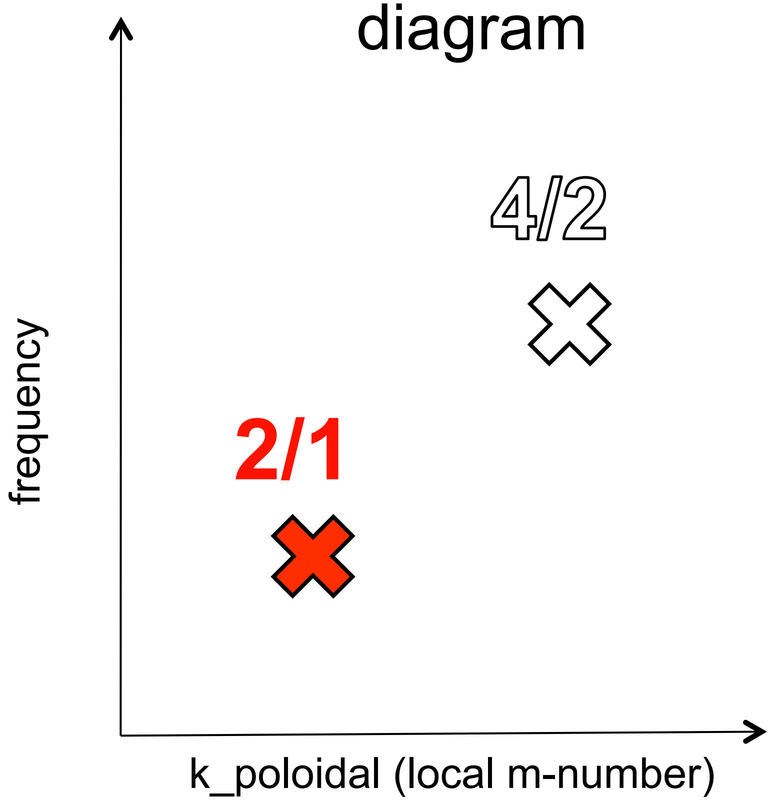
Toloidal velocity: 3/2 < 2/1



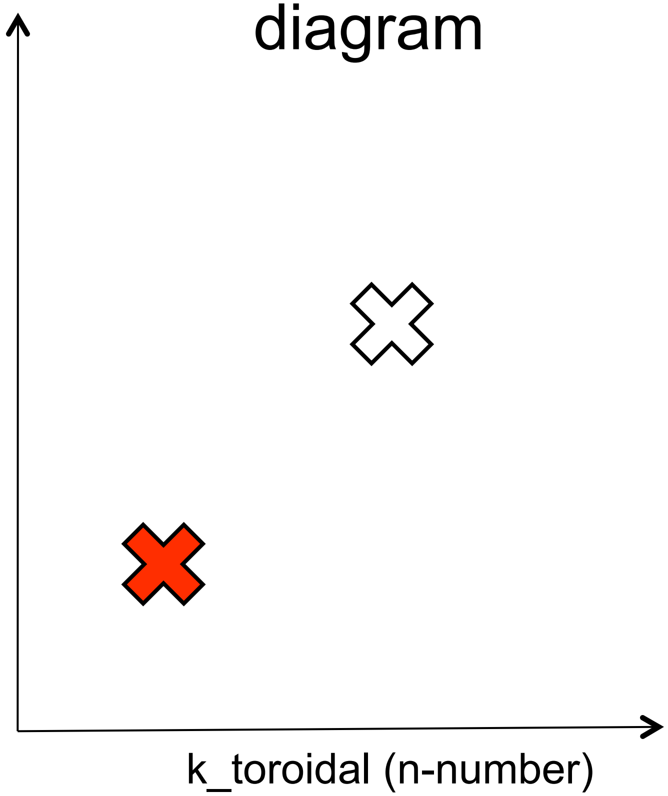
- **Toroidal rotation profile inverted**
  - 2/1 accelerated
- **TRANSP has an unbiased approach to MHD—it includes none of it**

A generic prescription to avoid phase-locking

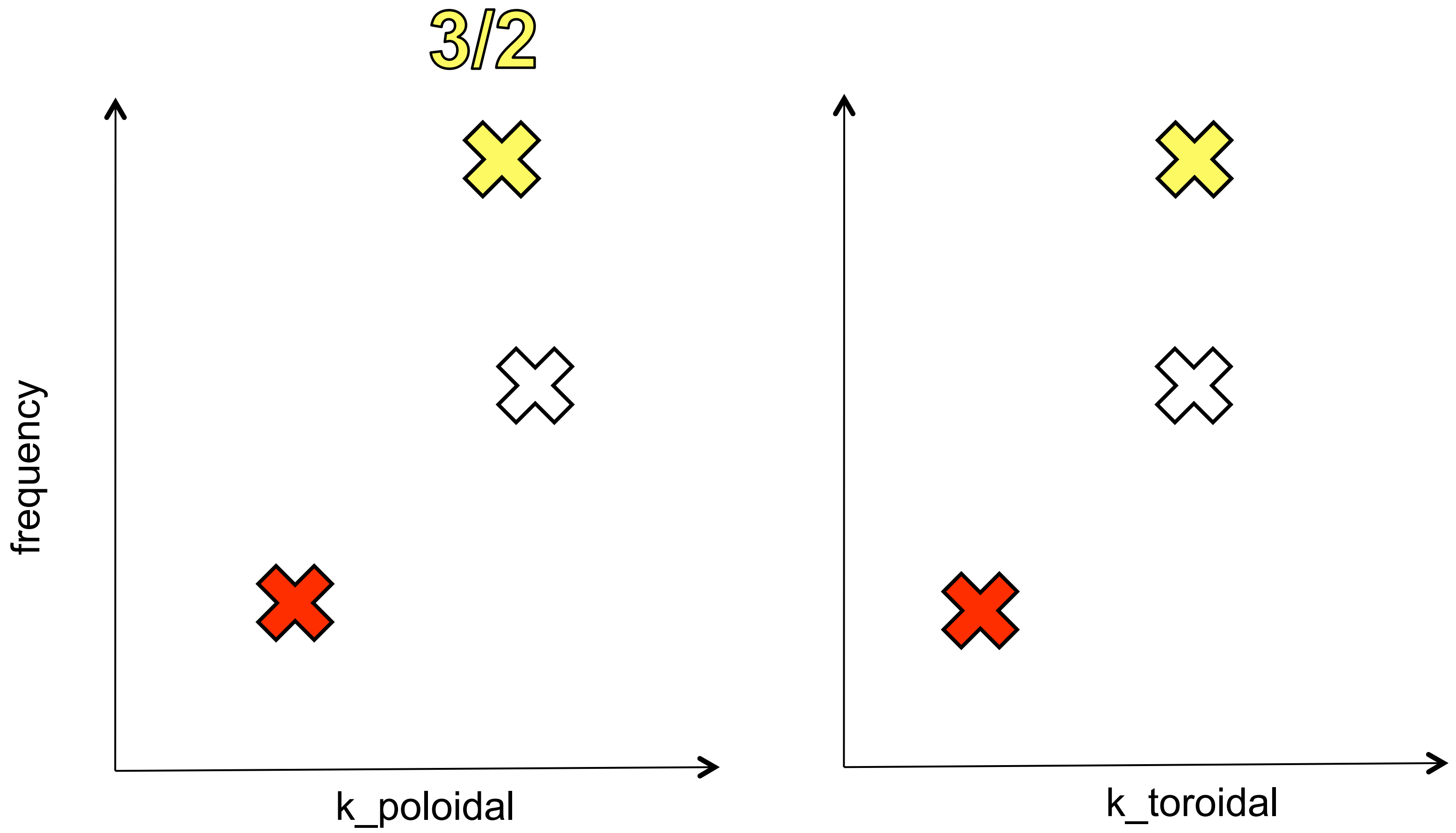
Poloidal phase diagram



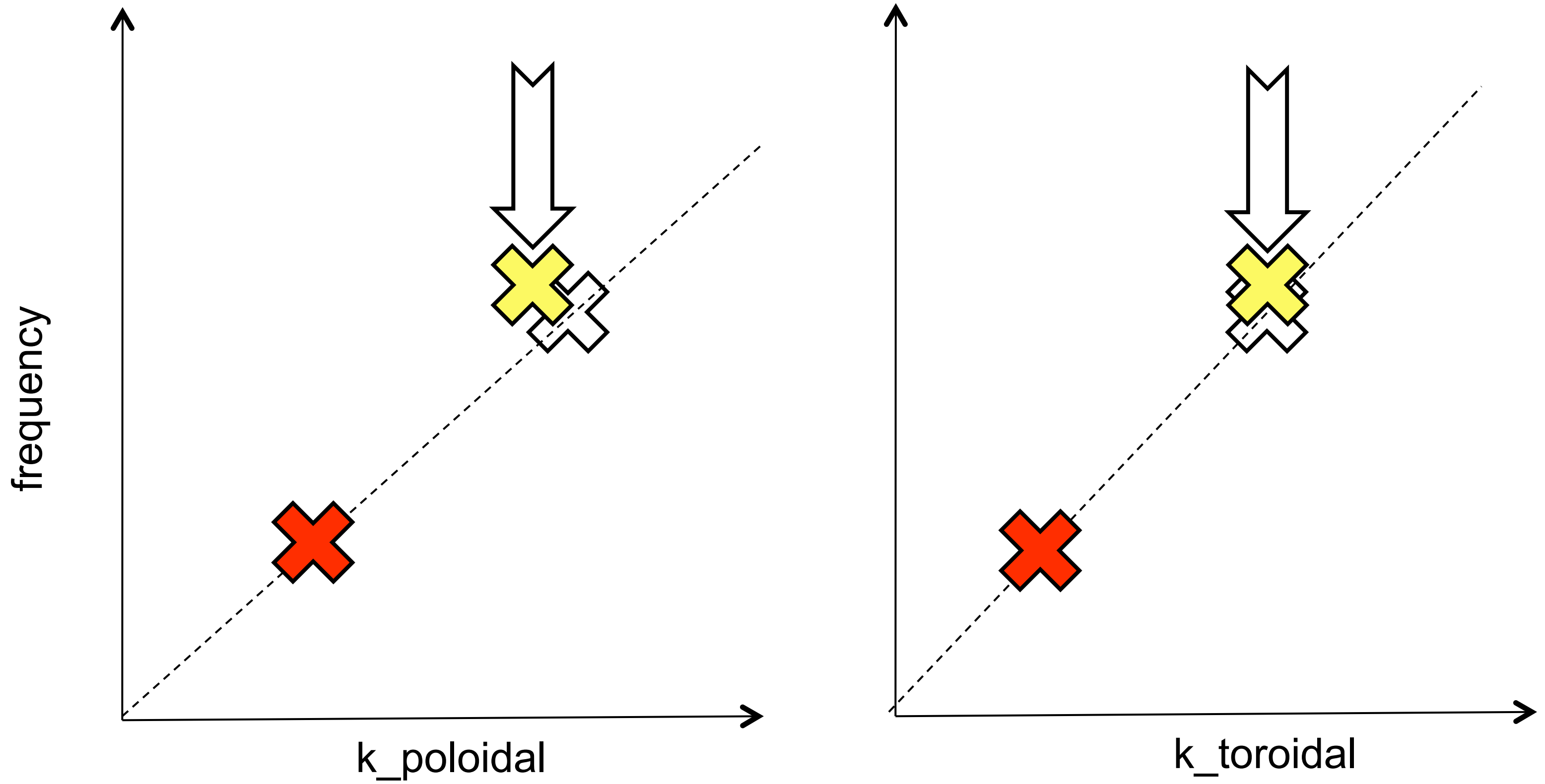
Toroidal phase diagram



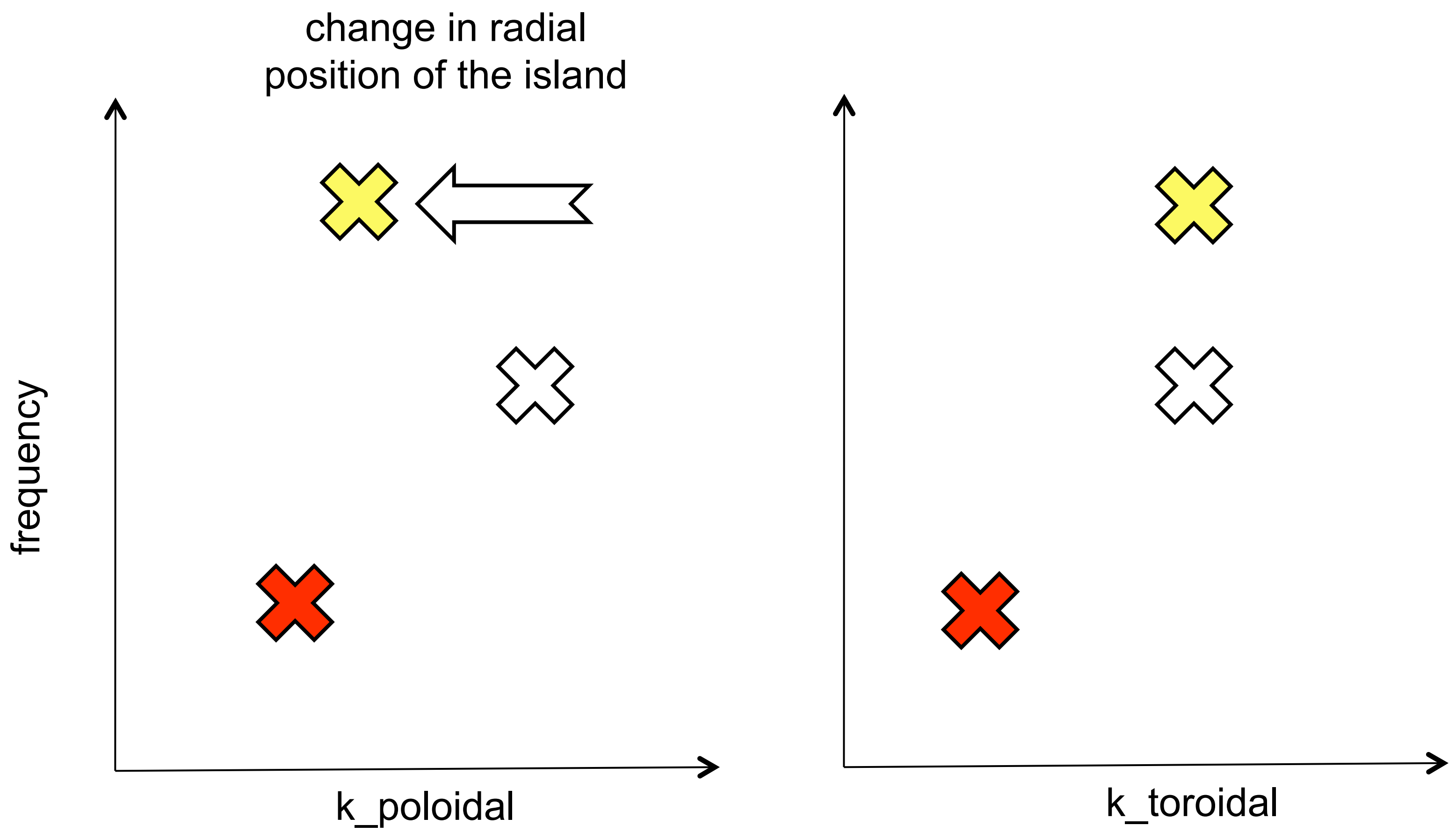
Modes initially separated by toroidal rotation



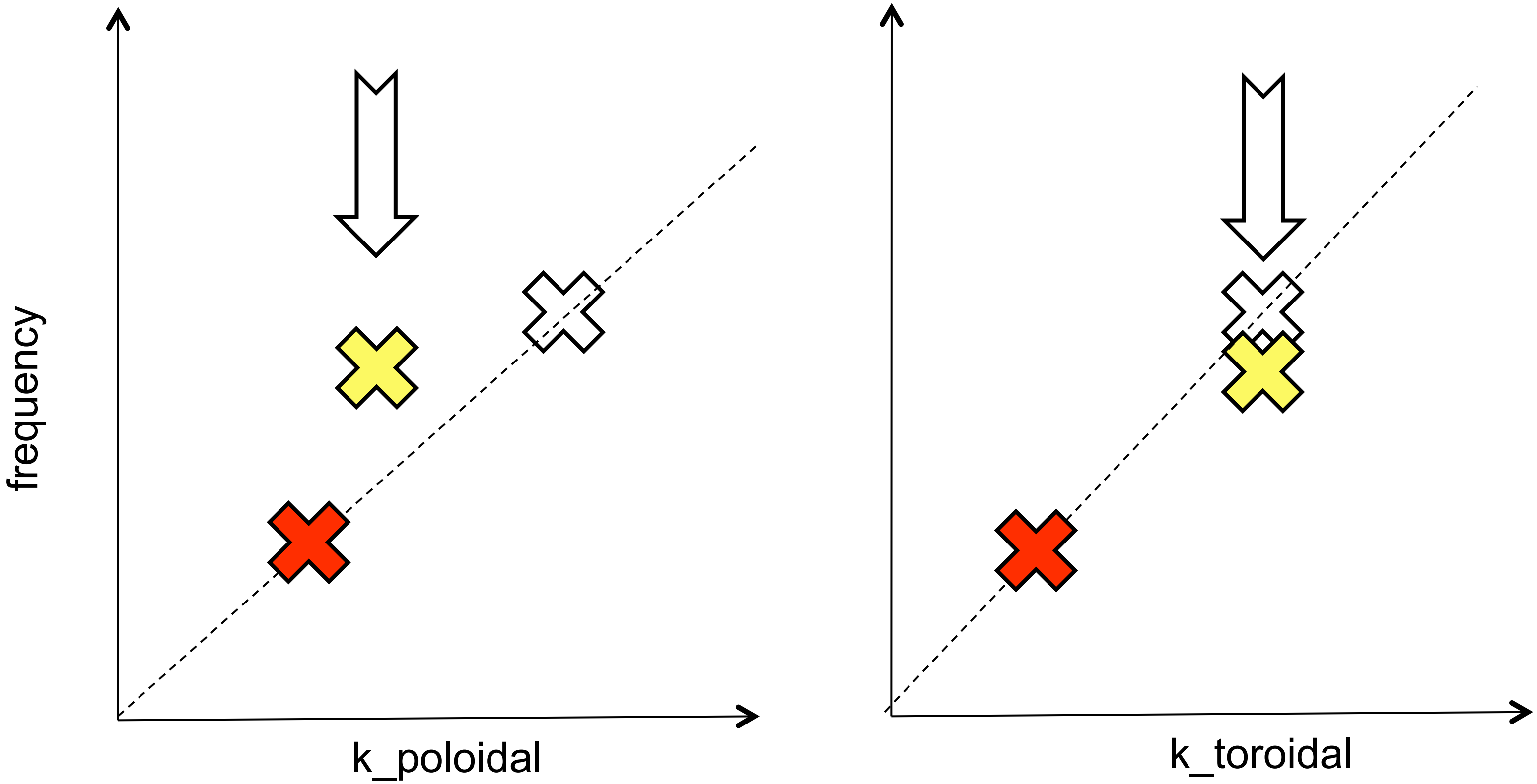
Electromagnetic and viscous torques are brought into balance near phase-lock



'Mode pitch,' a function of the current profile and radial location of the island

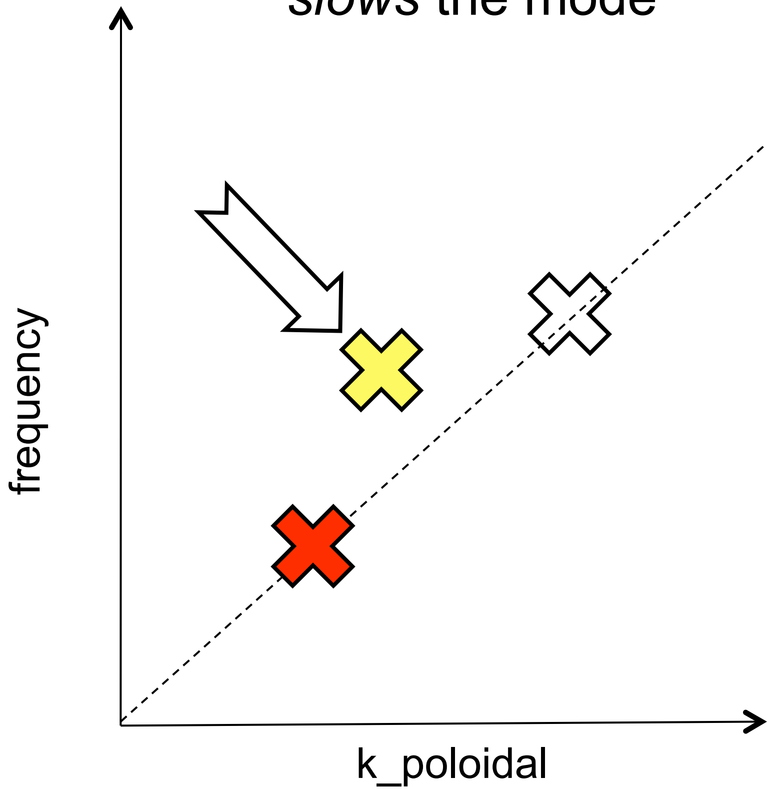


Rotation decays toward torque balance

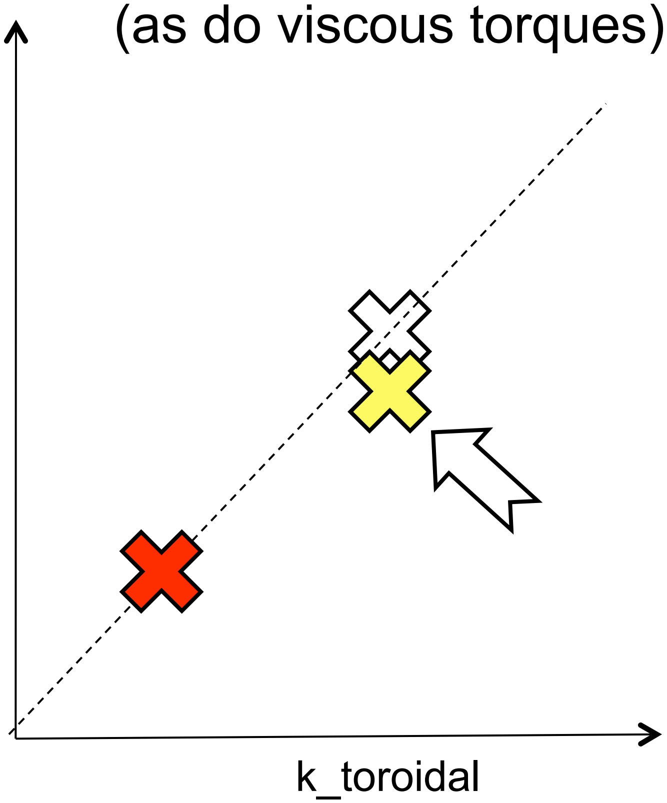


Poloidal and Toroidal torques are opposed

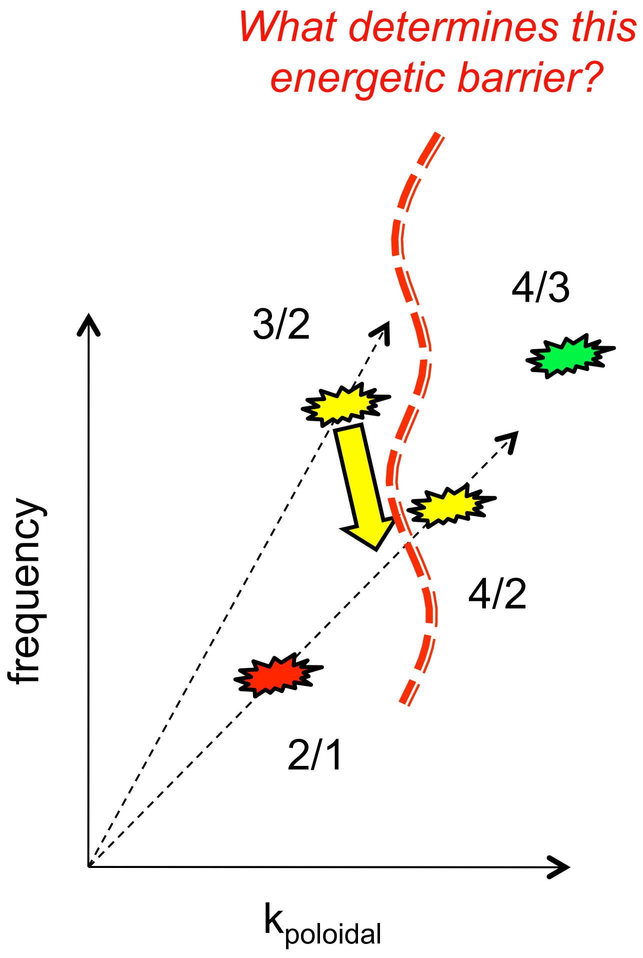
Poloidal EM torque
slows the mode



Toroidal EM torque
accelerates the mode
(as do viscous torques)



Stiffness of mode structure prevents matching of poloidal wavenumbers



- **3/2 mode frequency drifts down past that of the 4/2, without evolving in wavenumber**
  - $k_{3/2} \neq k_{4/2}$
- **Change in $k_{poloidal}$ remains energetically unfavorable**
  - Localization: current profile and flux surface shape
  - Response: dependence on other parameters (e.g. β_N) of structure in ideal MHD region

Concluding remarks

- **Differential rotation, induced by the structure of the MHD, appears to lessen the impact of the islands**
  - impact of large, slipping = smaller, locked islands
  - phase-locking can be avoided, if not universally prevented
- **Questions for dedicated experiments:**
  - Can the process of phase-locking be reversed? Can islands be unlocked and the discharge restored? Can EM torque heal higher-order islands and 3-wave mixing products?
  - Does the prevention of phase-locking delay the onset of thermal quench? Can a disruption be mitigated by interrupting the 'tearing cascade?'