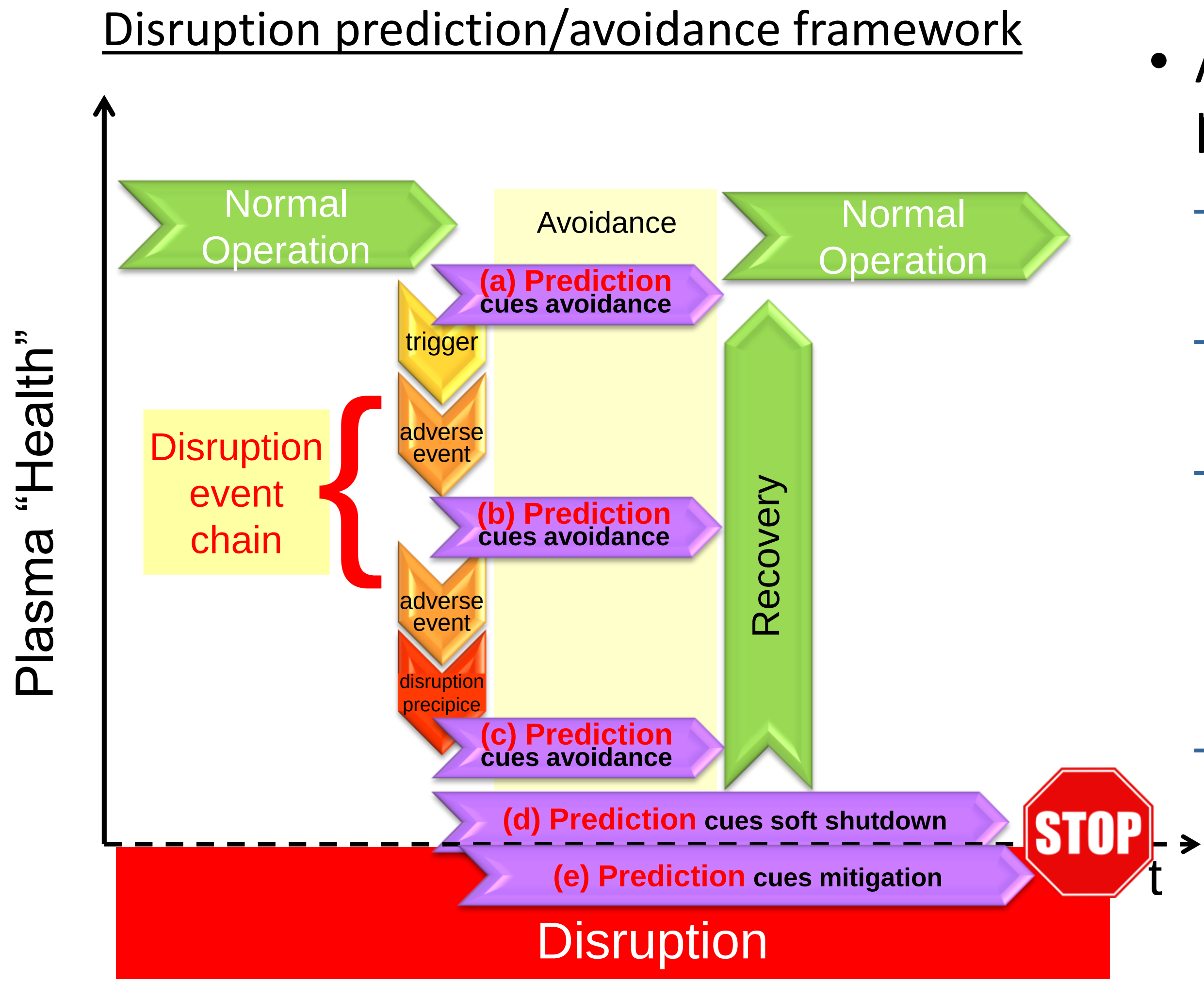
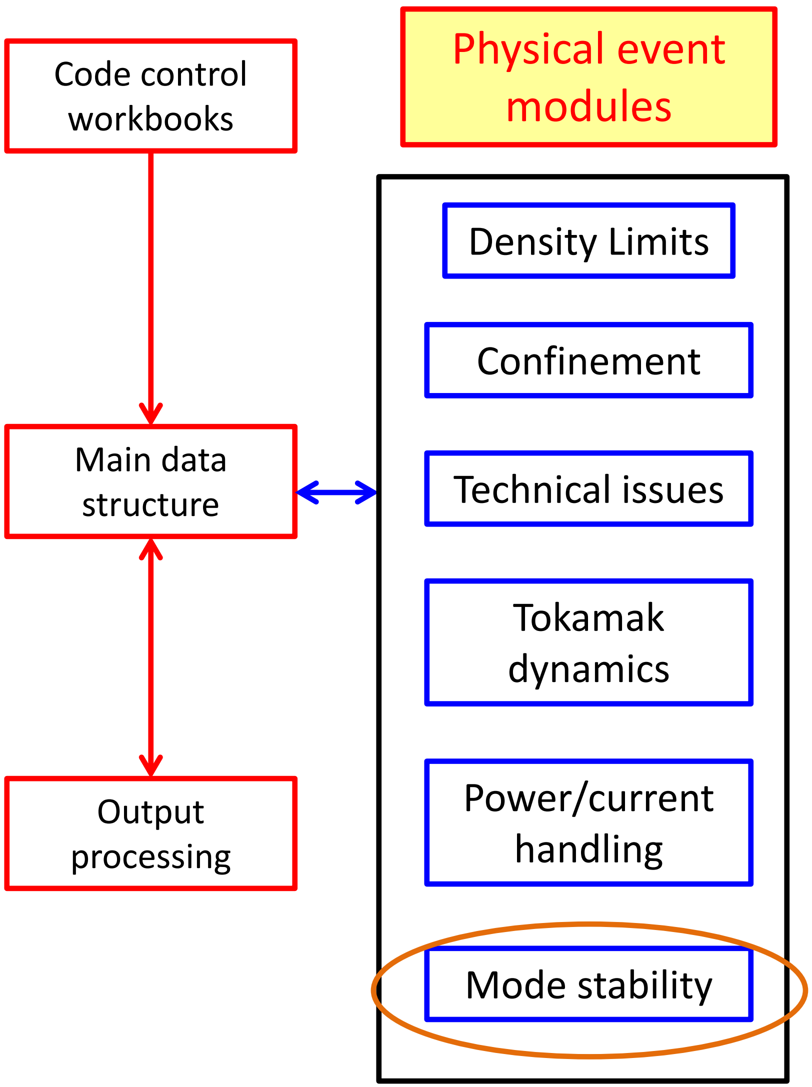
Disruption event chain characterization capability started as next step in disruption avoidance plan



[DOE report on Transient events (2015)]

- Approach to disruption prevention
  - Identify disruption event chains and elements
  - Predict events in disruption chains
  - Cues disruption avoidance systems to break event chains
    - Attack events at several places with active control
  - Builds upon both physics and control successes of NSTX

Disruption Event Characterization And Forecasting (DECAF) code is structured to ease parallel development



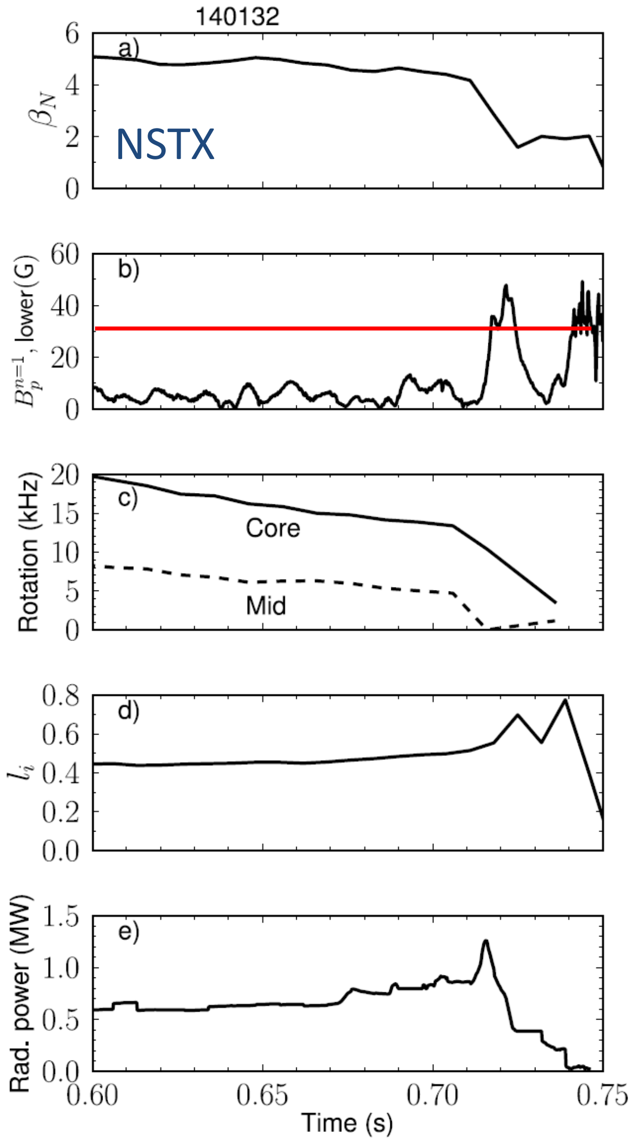
- Physical event modules
  - Present grouping follows work of deVries [P.C. de Vries et al., Nucl. Fusion 51, 053018 (2011)]
  - BUT, easily appended or altered
- Warning algorithms
  - Present approach follows [S.P. Gerhardt et al., Nucl. Fusion 53, 063021 (2013)]
  - More flexible: arbitrary number of tests, thresholds, and user-defined levels and warning points

Kinetic RWM analysis used as a reduced stability model in DECAF

Examples of some threshold tests currently included in DECAF

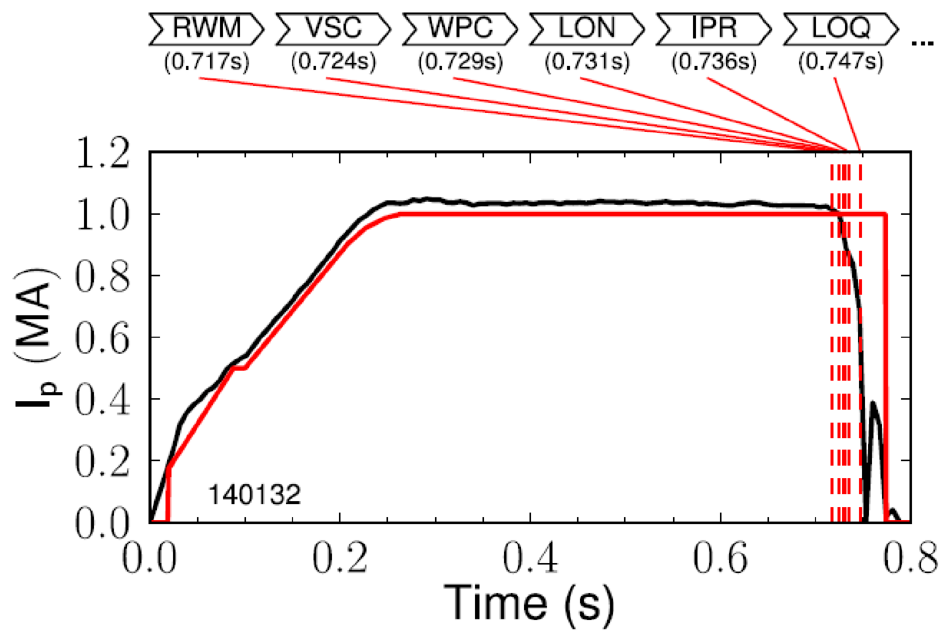
Group	Disruption chain event		Points	Test Criteria	Test Thresholds	Points
NL	Greenwald limit	GWL	3	Greenwald density limit	[0.90,0.95,0.99]	[1,2,3]
	Low density (error field)	LON	3	Decrease in line density (10^{14} cm^3/s) too large	[-10.0,-20.0,-30.0]	[1,2,3]
				Line density (10^{14} cm^3) too low	[0.3,0.2,0.1]	[1,2,3]
MS	Vertical stability control	VSC	5	Axis position (m)	[0.05,0.075,0.10]	[1,2,3]
				Axis velocity (m/s)	[3.93,6.54,9.01]	[1,2,3]
				Excessive ZdZdt (m/s^2)	[0.20,0.41,0.84]	[1,2,3]
	Resistive wall mode	RWM	3	$B_p^{n=1}$ lower component (G) too large	[10,20,30]	[1,2,3]
	Low edge q	LOQ	3	Safety factor $q*$ too low	[3.0,2.5,2.0]	[1,2,3]
				Safety factor q_{95} too low	[3.0,2.5,2.0]	[1,2,3]
	Sawtooth	SAW	3	Safety factor q_0 too low	[1.05,1.00,0.95]	[1,2,3]
	High pressure peaking	PRP	3	Excessive $p_0/\langle p\rangle$	[3.5,4.0,4.5]	[1,2,3]
TD	Plasma current request	IPR	3	$\|I_p^{req} - I_p\|/I_p^{req} >$	[0.05,0.10,0.15]	[1,2,3]
	Wall proximity control	WPC	3	Inner gap (m) too small	[0.03,0.02,0.01]	[1,2,3]
				Outer gap (m) too small	[0.03,0.02,0.01]	[1,2,3]
				Upper gap (m) too small	[0.03,0.02,0.01]	[1,2,3]
				Bottom gap (m) too small	[0.03,0.02,0.01]	[1,2,3]
PC	High heat/radiation load	HHL	3	Radiated power fraction too high	[0.2,0.3,0.4]	[1,2,3]

DECAF uses threshold tests and more sophisticated models to declare events and event chains

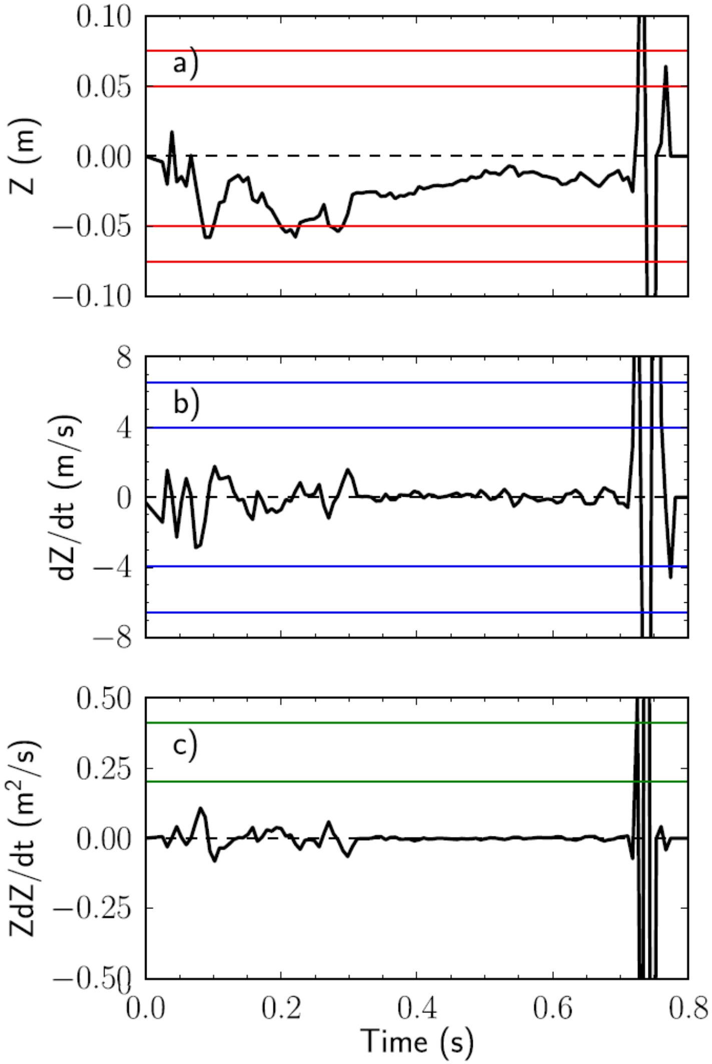


- Example DECAF analysis on single NSTX discharge
  - Ex: RWM $B_p^{n=1}$ threshold 30G ($\delta B/B0 \sim 0.67\%$)

<u>Disruption Events and Chain</u>

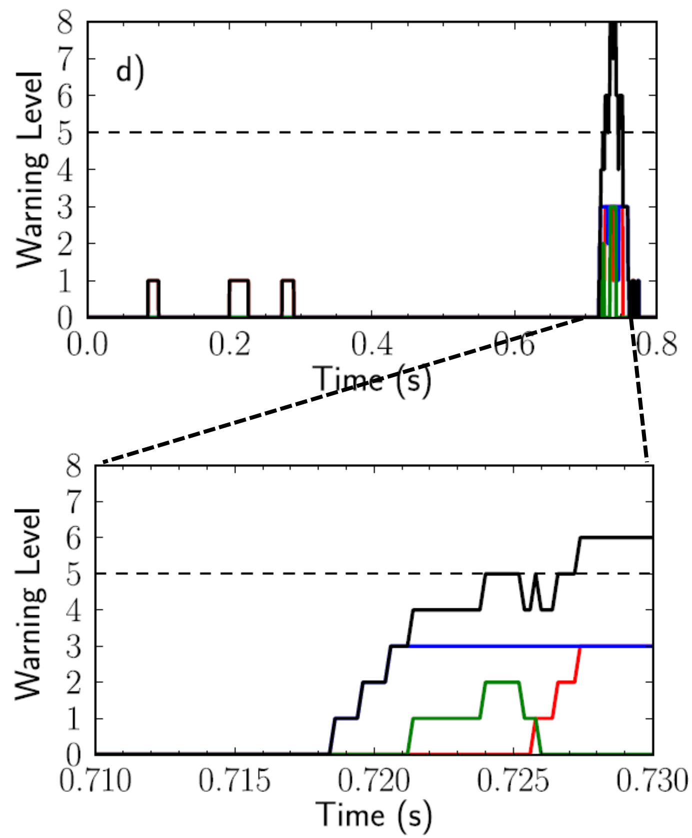


Tests can be combined with “warning points”



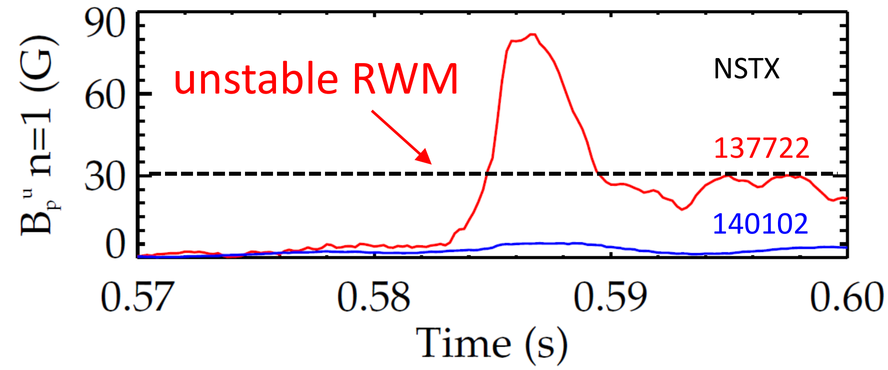
Example DECAF analysis on single NSTX discharge

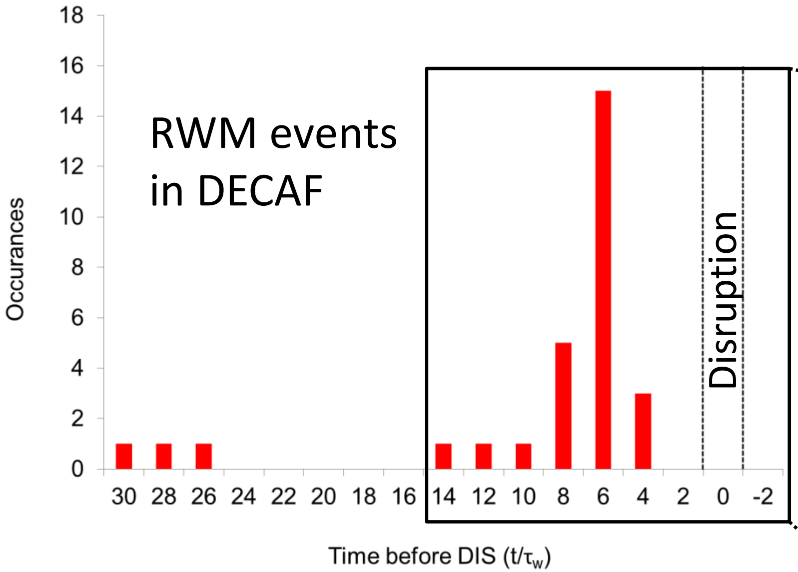
– Ex: VSC uses Z, dZ/dt, and ZdZ/dt

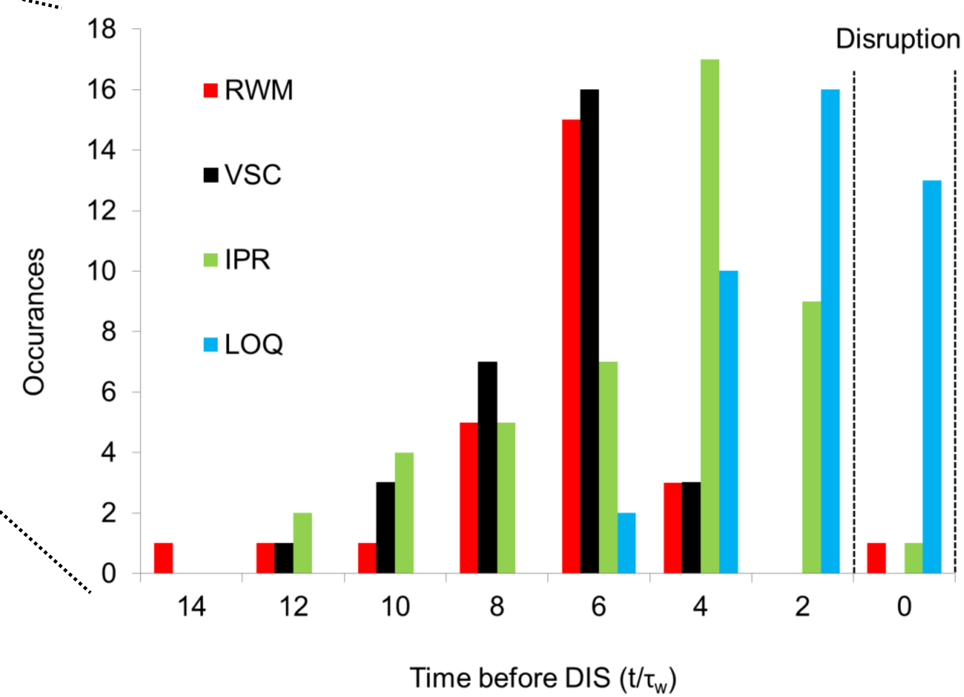


Initial DECAF results detects disruption chain events when applied to dedicated 45 shot NSTX RWM disruption database

- RWM $B_p^{n=1}$ threshold 30G ($\delta B/B_0$ ~ 0.67%)
- ~58% within 20 τ_w of disruption time (τ_w = 5 ms)







RWM: RWM event warning

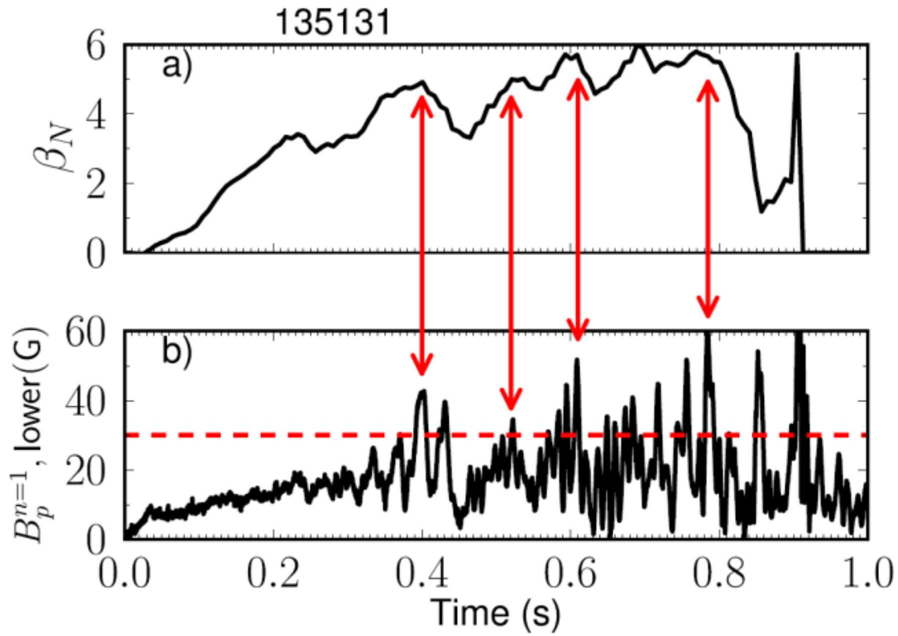
VSC: Vertical stability control

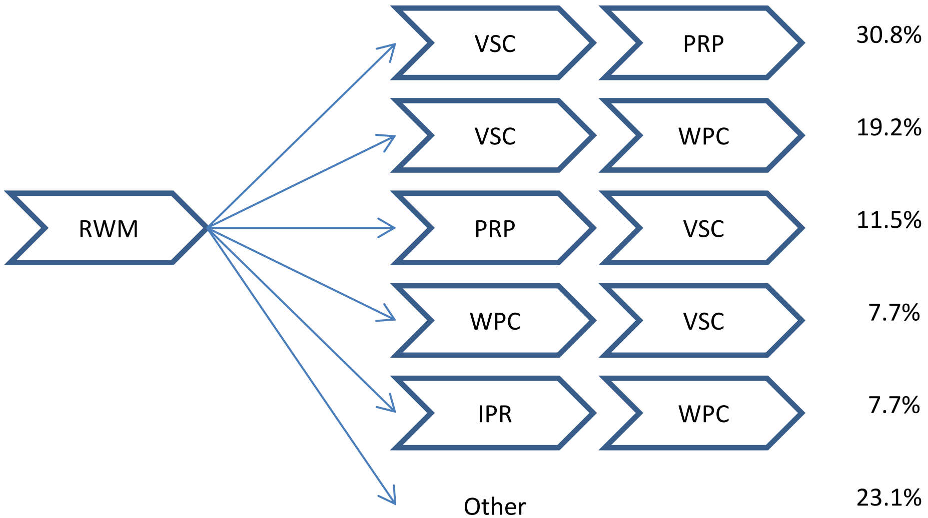
IPR: Plasma current request not met

LOQ: Low edge q warning

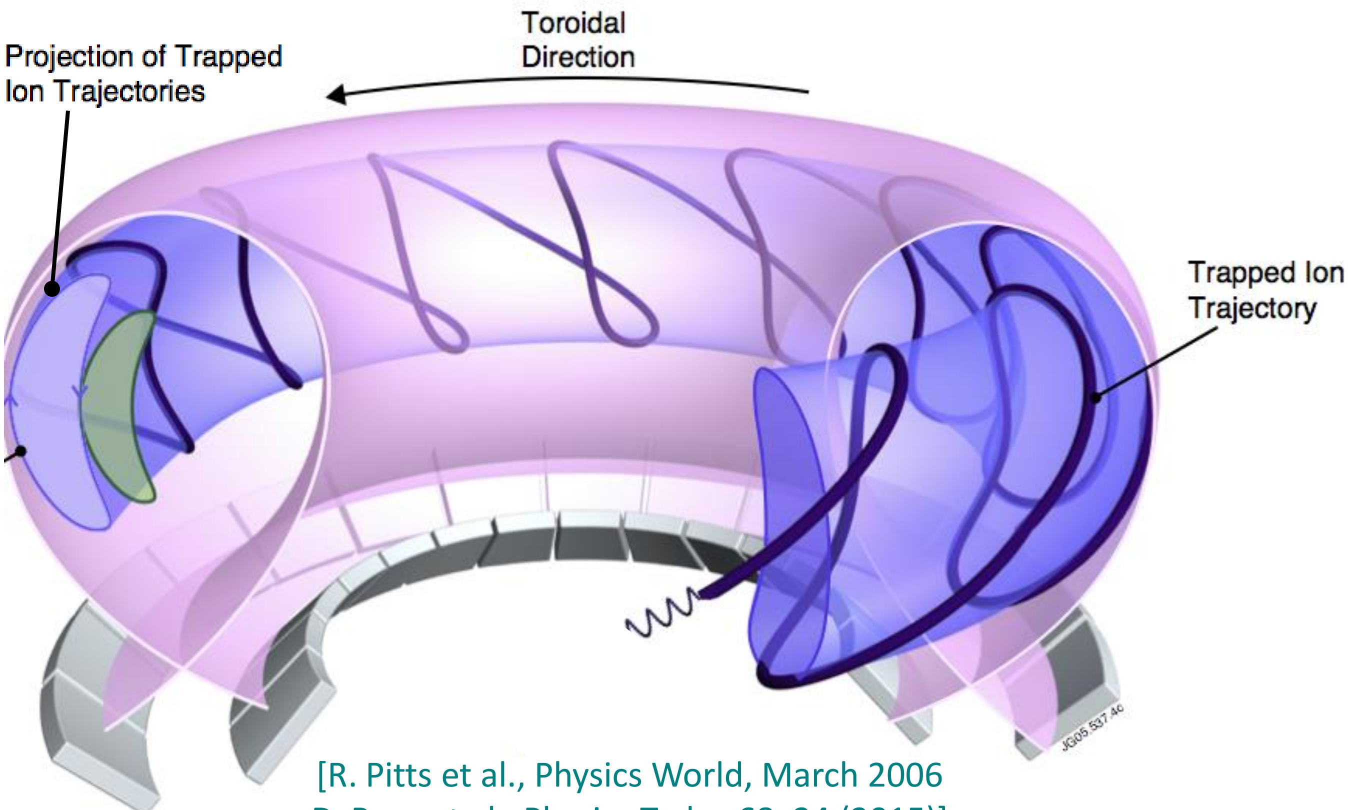
Initial DECAF analysis finding common disruption event chains, giving new insight

- Earlier RWM events *not* false positives
  - cause large decreases in β_N and stored energy with subsequent recovery (minor disruptions)
- Identifying common chains of events can provide insight into how to cue avoidance systems
  - 5 (out of theoretically 56) two-event combinations followed 77% of RWM cases (that occurred within $20\tau_w$ of DIS)





DECAF now incorporates a reduced kinetic MHD stability model for global MHD



[R. Pitts et al., Physics World, March 2006
D. Pace et al., Physics Today 68, 34 (2015)]

MISK code

- Solves for RWM growth rate
- δW_K is solved by using $\tilde{f}$ from the drift kinetic equation

Precession Drift

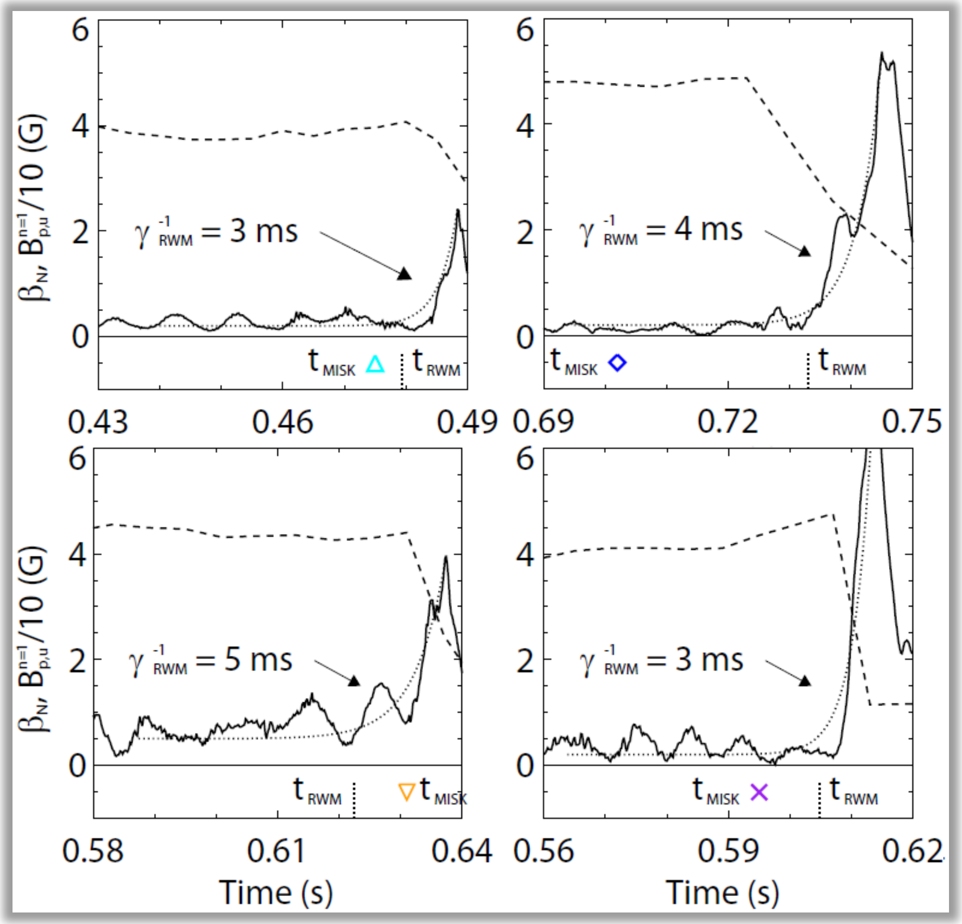
~ Plasma Rotation

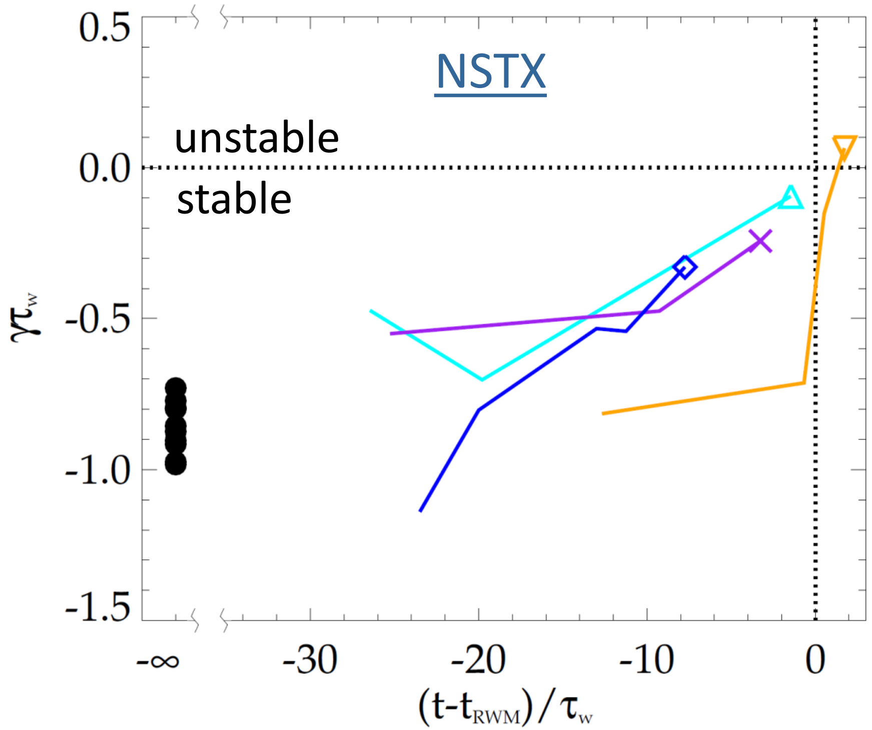
Rotational resonance effect

$$\delta W_K \sim \frac{1}{\langle\omega_D\rangle + \omega_E - i\nu}$$

[J. Berkery et al., Phys. Rev. Lett. 104, 035003 (2010)]

MISK calculations validated against unstable experimental plasmas; reproduce approach towards marginal stability





[J. Berkery et al., Nucl. Fusion 55, 123007 (2015)]

- MISK calculations including kinetic effects have been tested against many marginally stable NSTX experimental cases

Physics understanding from previous research using full model, used to construct a reduced kinetic model

- Goal is to forecast γ in real-time using parameterized reduced models for δW terms
- Need δW_K as a function of the most important, real-time measurable quantities

$$(\gamma - i\omega_r)\,\tau_w = -\frac{\delta W_\infty + \delta W_K}{\delta W_b + \delta W_K}$$

$$\delta W_K \sim \frac{1}{\langle\omega_D\rangle + l\omega_b - i\nu_{\rm eff} + \omega_E}$$

MISK[2] Calculations

Fluid terms[10]

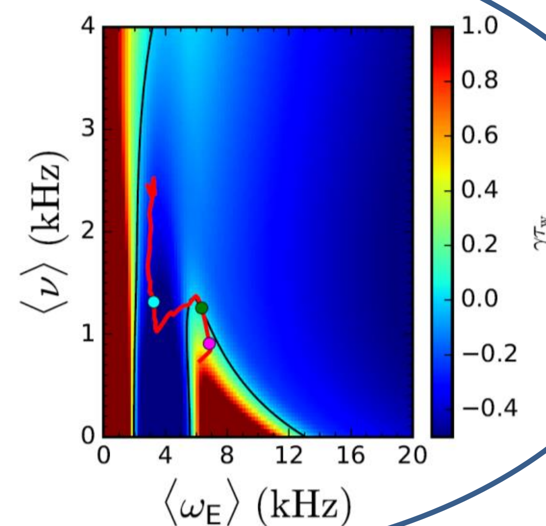
Kinetic effects[1]: Collisionality[5] Rotation[3]

+ Energetic Particles[4]

Benchmarked[8]

Compared to Experiments[3,4,6,7,9]

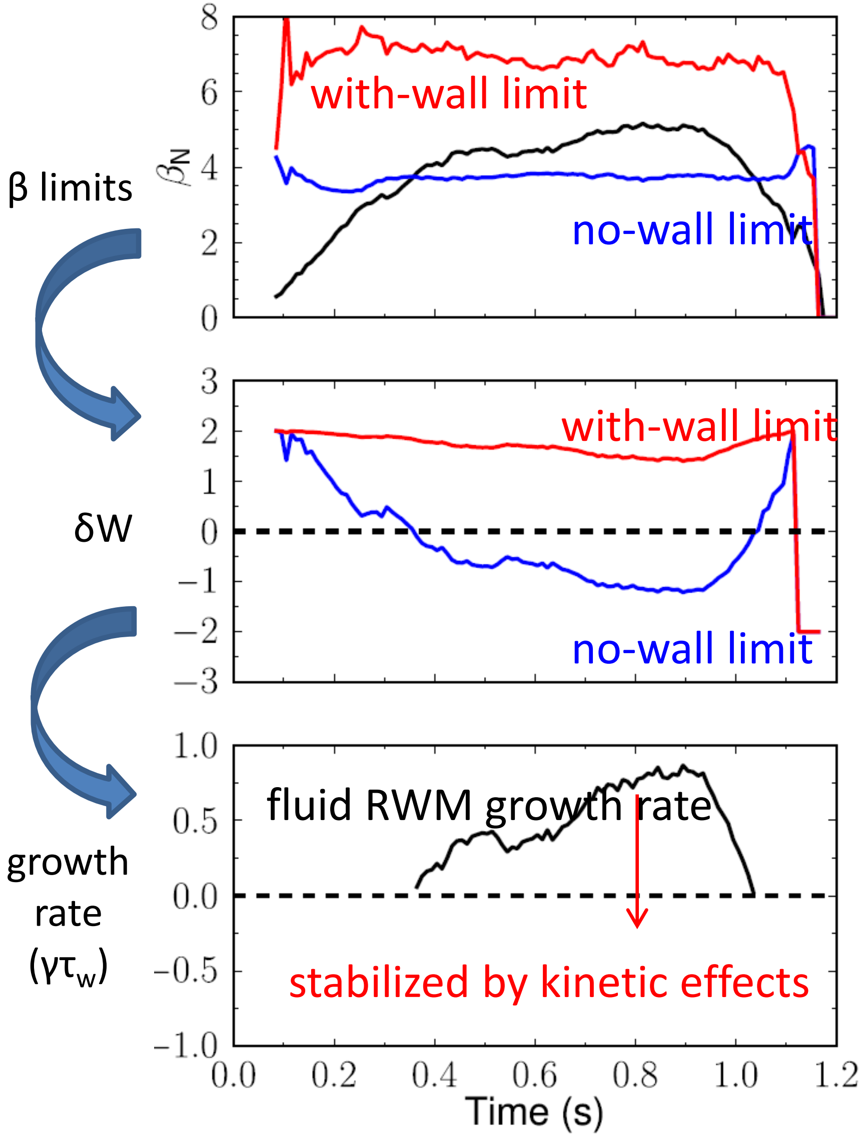
Reduced Kinetic Model



References

[1] B. Hu et al., Phys. Rev. Lett. 93, 105002 (2004)
[2] B. Hu et al., Phys. Plasmas 12, 057301 (2005)
[3] J. Berkery et al., Phys. Rev. Lett. 104, 035003 (2010)
[4] J. Berkery et al., Phys. Plasmas 17, 082504 (2010)
[5] J. Berkery et al., Phys. Rev. Lett. 106, 075004 (2011)
[6] H. Reimerdes et al., Phys. Rev. Lett. 106, 215002 (2011)
[7] J. Berkery et al., Phys. Plasmas 21, 056112 (2014)
[8] J. Berkery et al., Phys. Plasmas 21, 052505 (2014)
[9] S. Sabbagh APS invited (2014)
[10] J. Berkery et al., Nucl. Fusion 55, 123007 (2015)
… more

Goal is to forecast mode growth rate in real-time using parameterized reduced models for δW terms



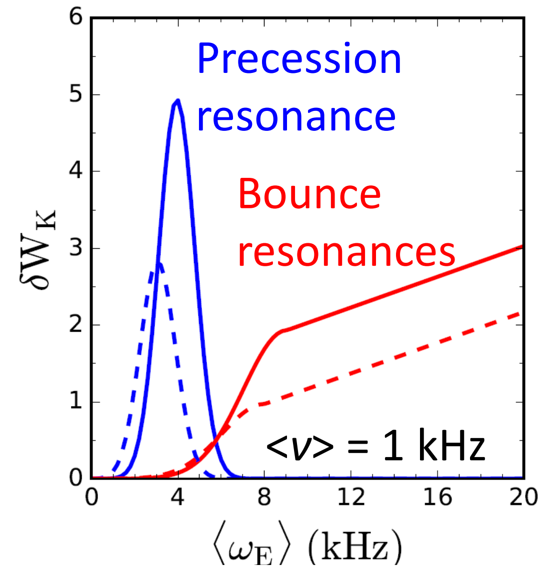
RWM dispersion relation

Growth rate — Fluid terms — Kinetic effects

$$(\gamma - i\omega_r)\,\tau_w = -\frac{\delta W_\infty + \delta W_K}{\delta W_b + \delta W_K}$$

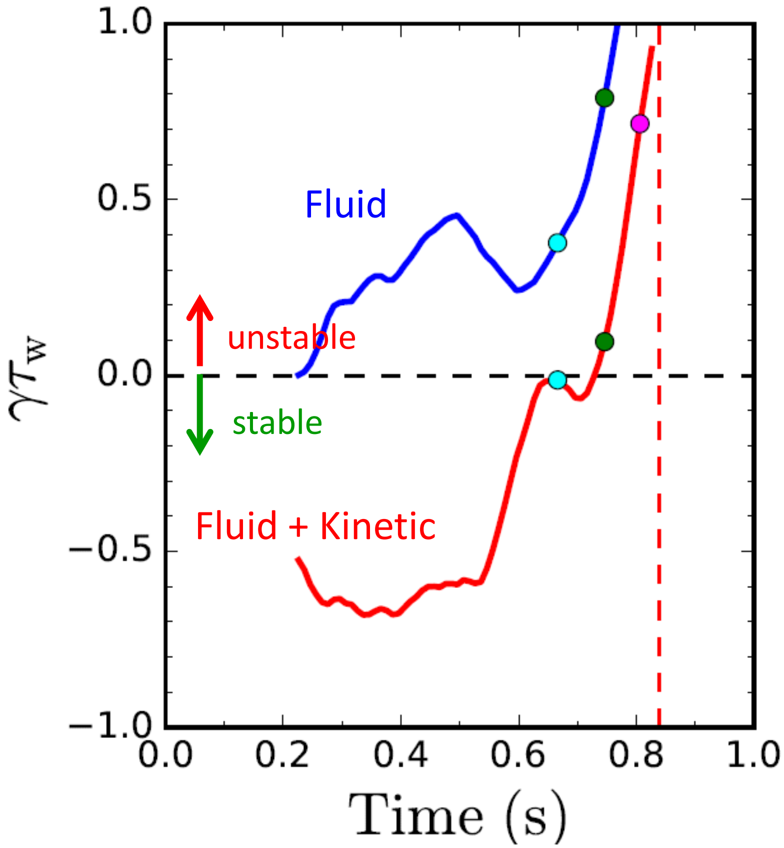
[B. Hu et al., Phys. Rev. Lett. 93, 105002 (2004)]

- Gaussian functions are used for resonances
  - Coefficients selected to reflect NSTX experience

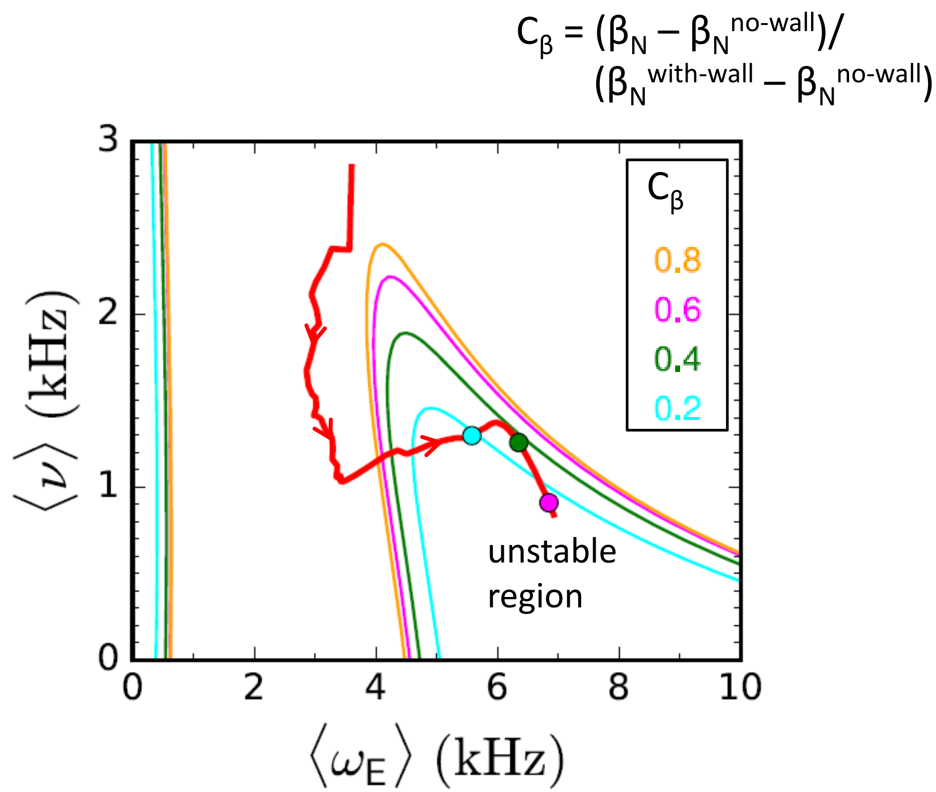


DECAF contains modeled kinetic quantities for generation of stability maps

Normalized growth rate vs. time

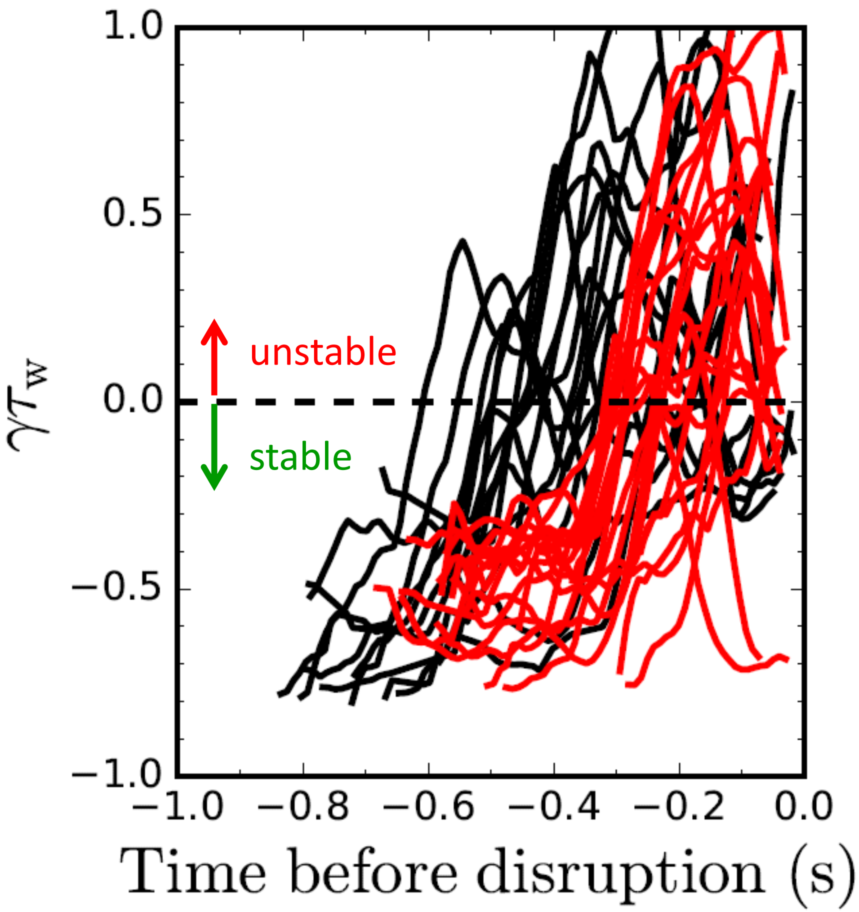


- Stability diagram shows trajectory of a discharge towards unstable regions

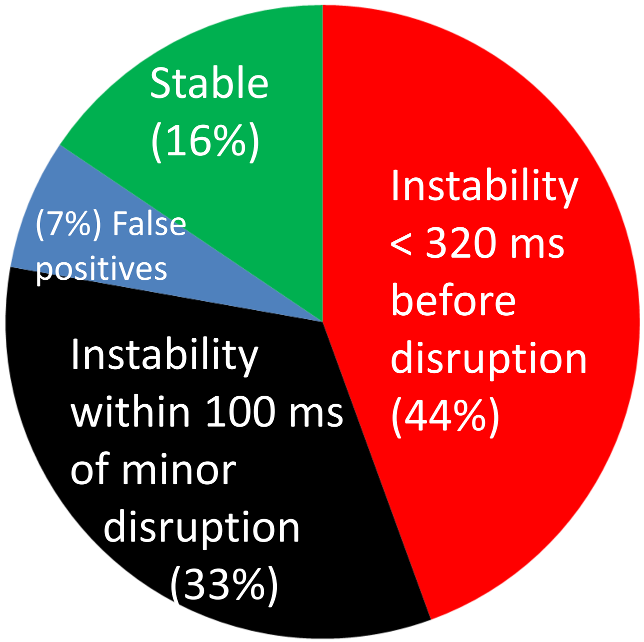


DECAF reduced kinetic model results initially tested on a database of NSTX discharges with unstable RWMs

Normalized growth rate vs. time

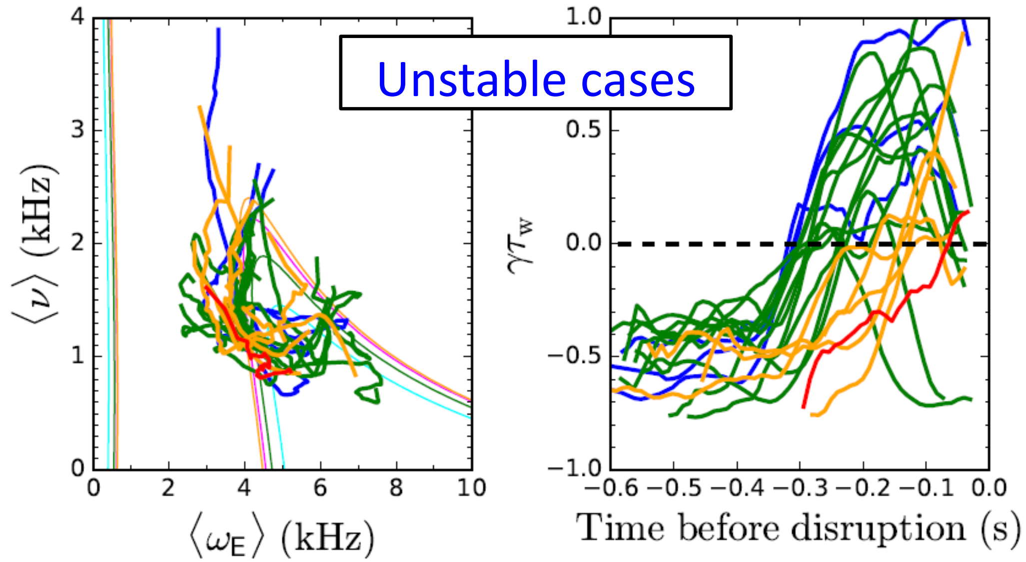


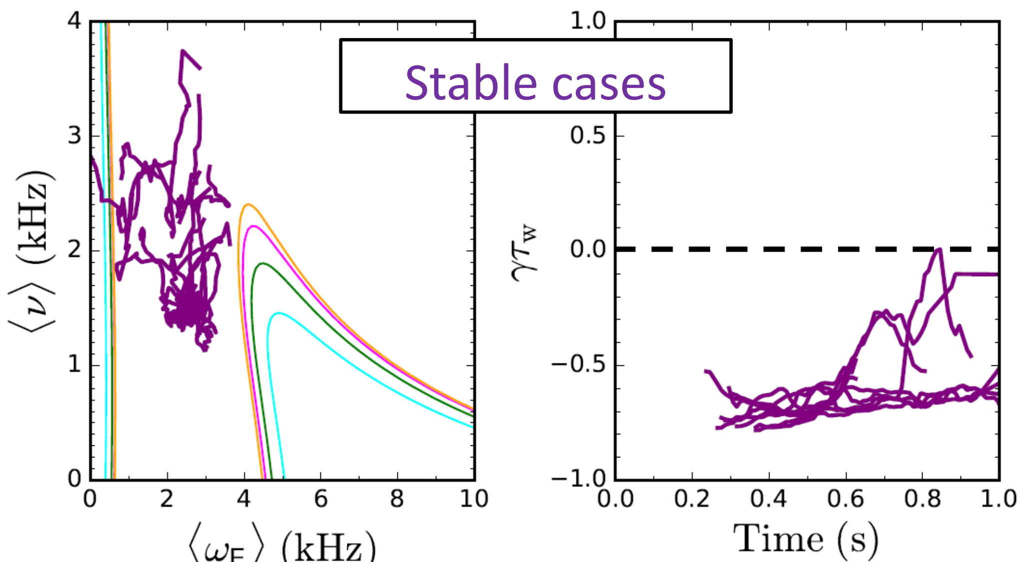
Predicted instability statistics (45 shots)



- 84% of shots are predicted unstable
- 44% predicted unstable < 320 ms (approx. 60τ_w) before current quench
- 33% predicted unstable within 100 ms of a minor disruption

Reduced kinetic model distinguishes between stable and unstable NSTX discharges





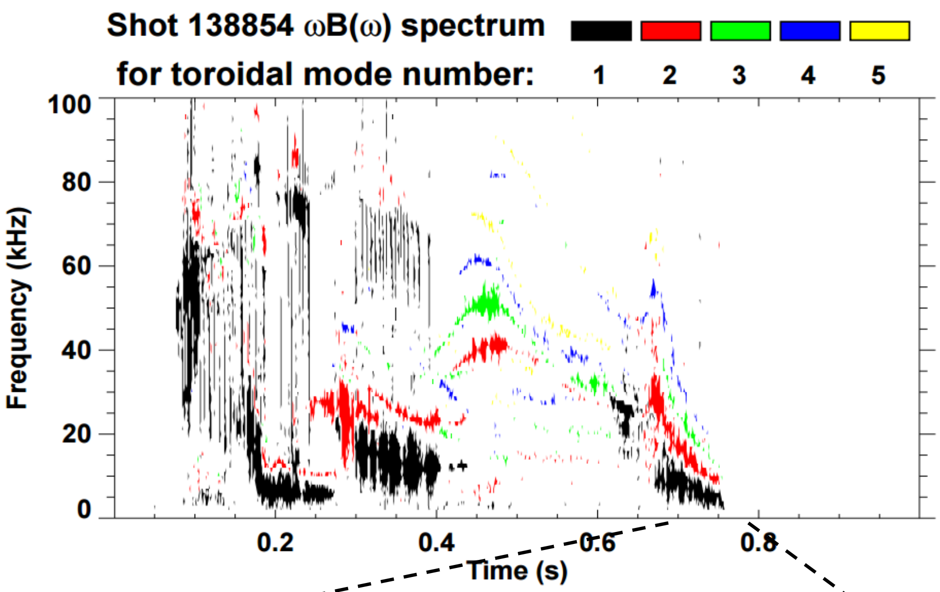
- If $<\omega_E>$ ~ 0 warnings are eliminated, 10/13, or 77%, of stable cases are stable in the model
- Model is successful in first incarnation - development continues to improve forecasting performance

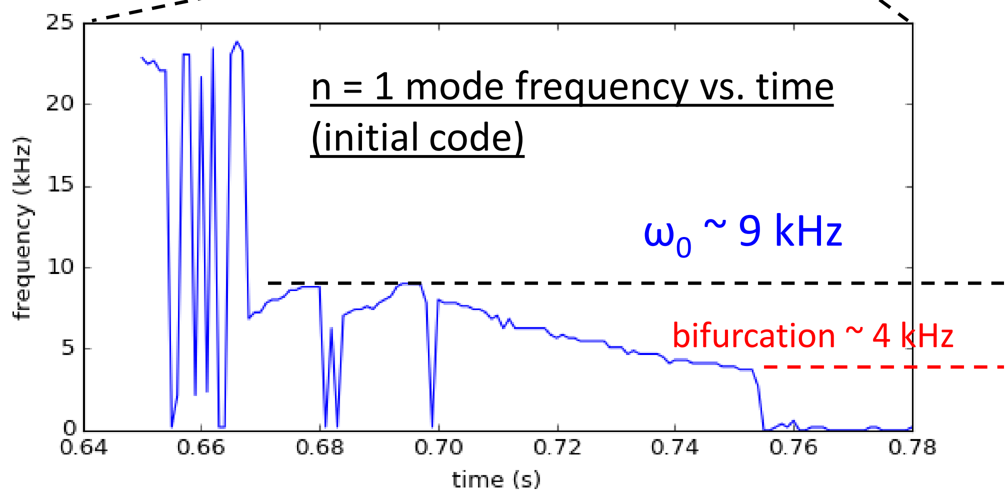
Tradeoff: missed vs. early warnings

Essential new step for DECAF analysis of general tokamak data: Identification of rotating MHD (e.g. NTMs)

- Initial goals
  - Create portable code to identify existence of rotating MHD modes
  - Track characteristics that lead to disruption
    - e.g. rotation bifurcation, mode lock
- Approach
  - Apply FFT analysis to determine mode frequency, bandwidth evolution
  - Determine bifurcation and mode locking

Magnetic spectrogram of rotating MHD in NSTX

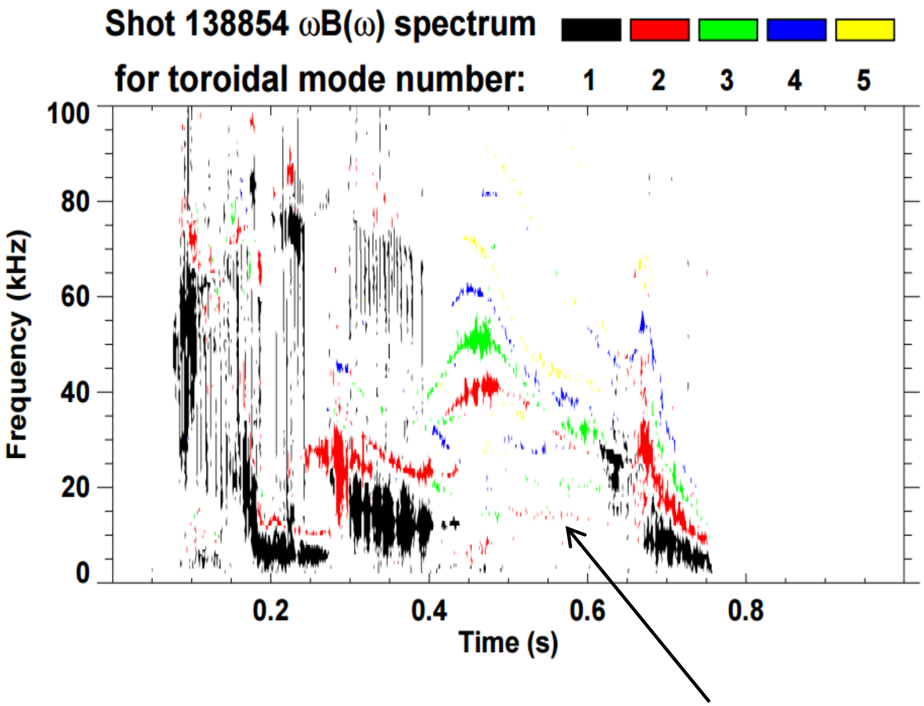




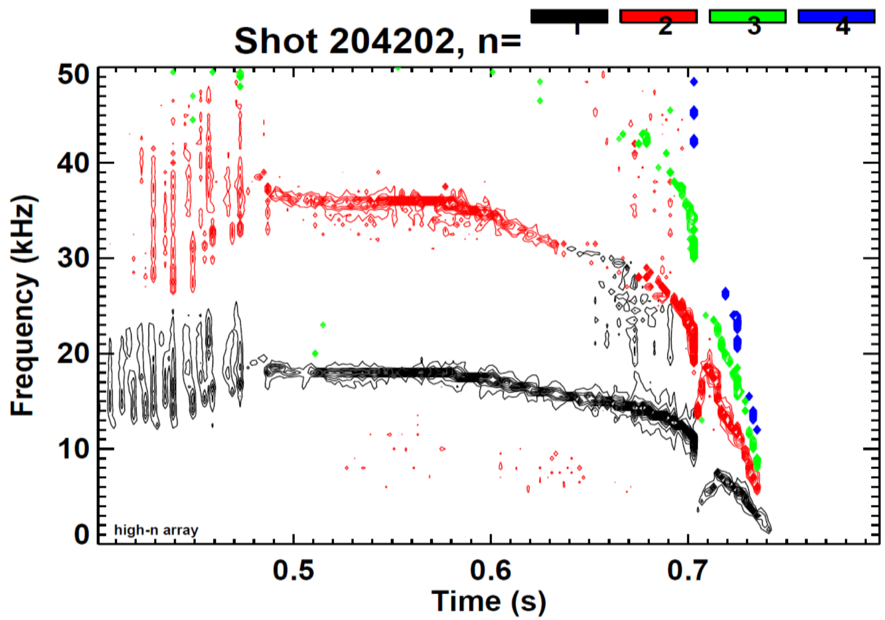
Many shots with rotating MHD (e.g. NTMs) examined for NSTX and NSTX-U – two illustrated here

Magnetic spectrogram of rotating MHD mode locking termination

NSTX 138854

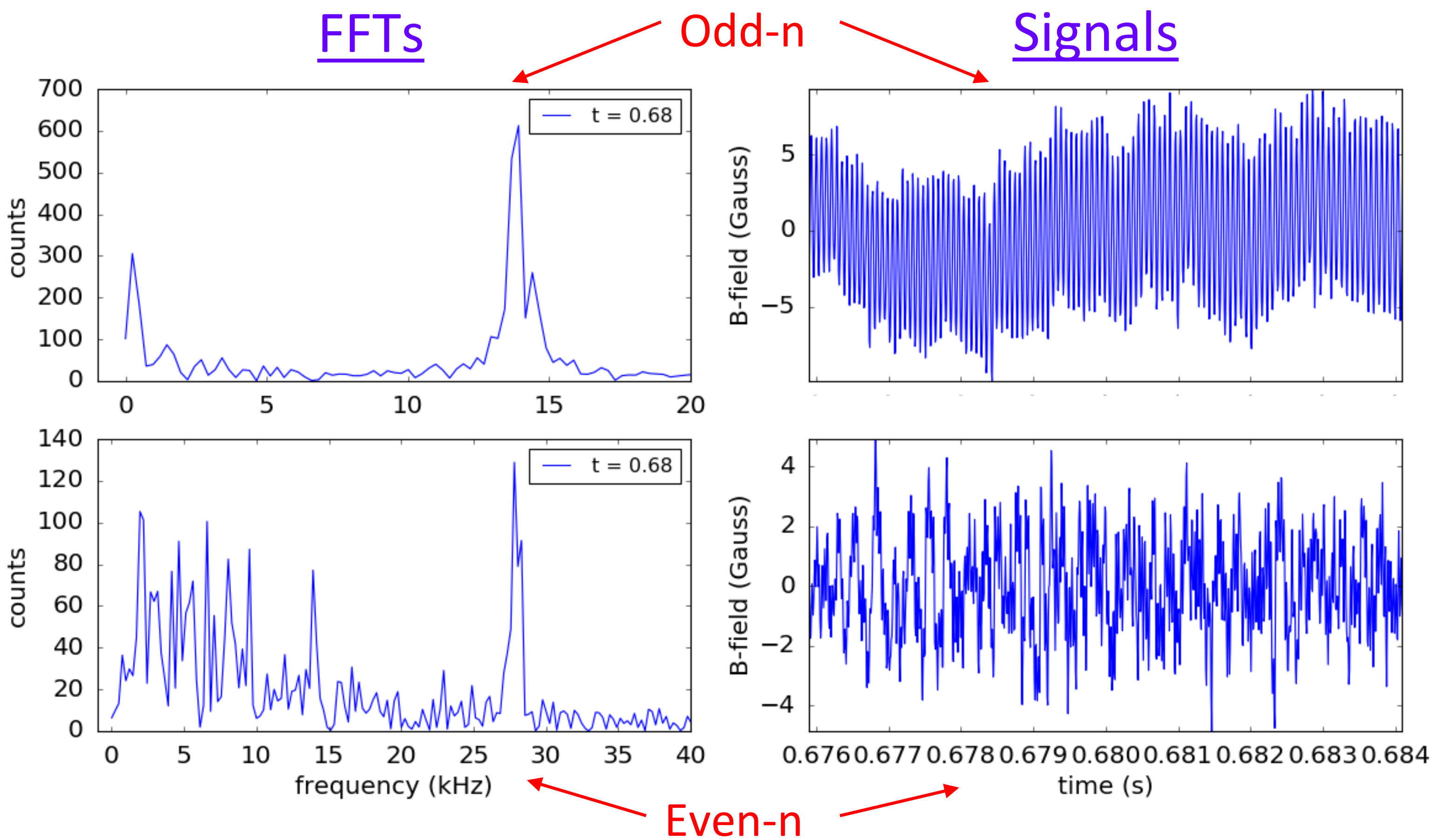


NSTX-U 204202



- NSTX "stable periods" – enhanced by high elongation (κ ~ 2.7), lithium wall conditioning
- NSTX-U: rotating MHD more common (so far, lower (κ ~ 2.3) , no Li wall conditioning)

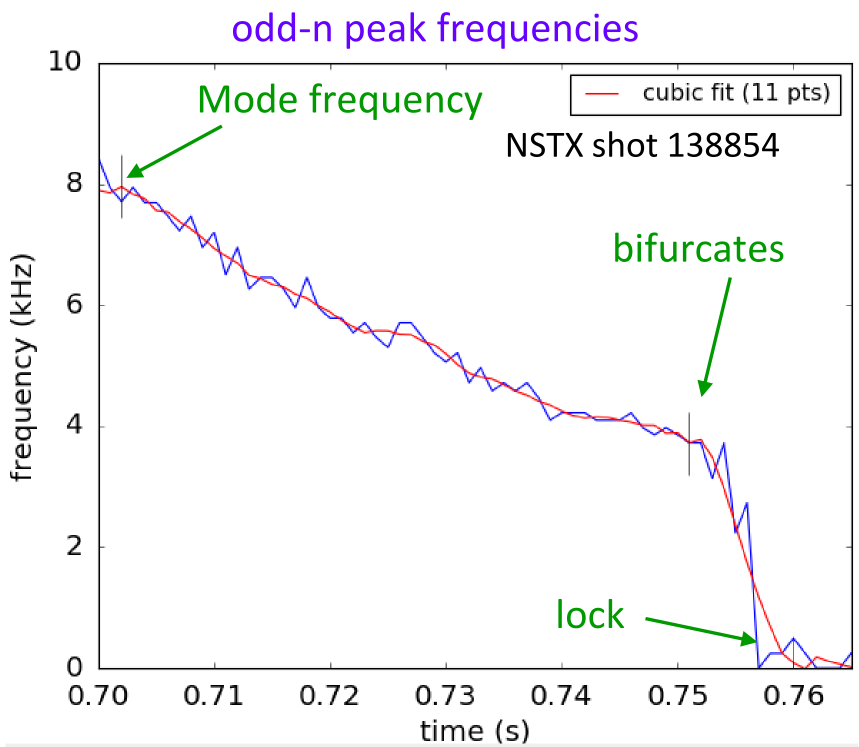
Fast Fourier transforms used to find mode peak frequency within a time interval

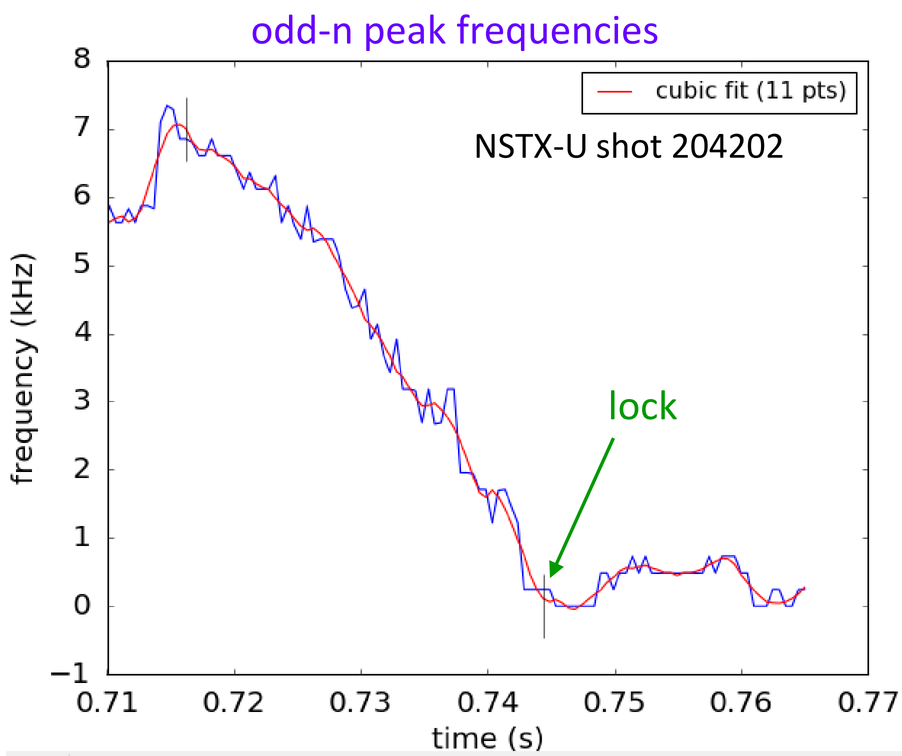


- Reveals potential issues handling multiple frequency peaks
- Now adding processing of toroidal array / *n* number discrimination

The characterization algorithm shows that the expected bifurcation and locking events can be found

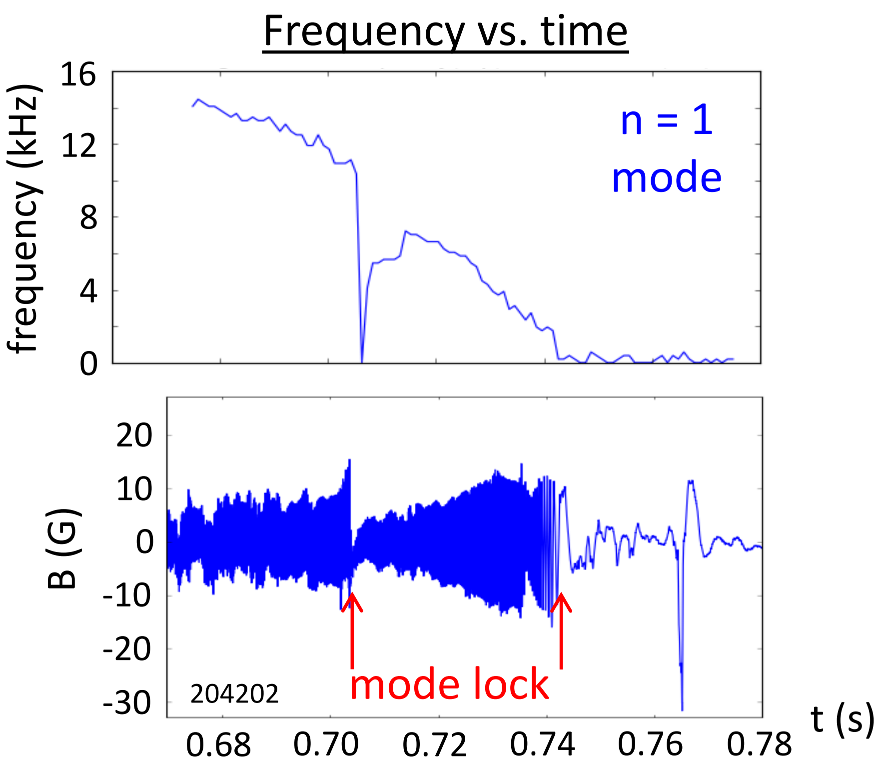
- Algorithm written looks for a “quasi-steady state” period, a potential bifurcation, and possible mode locking

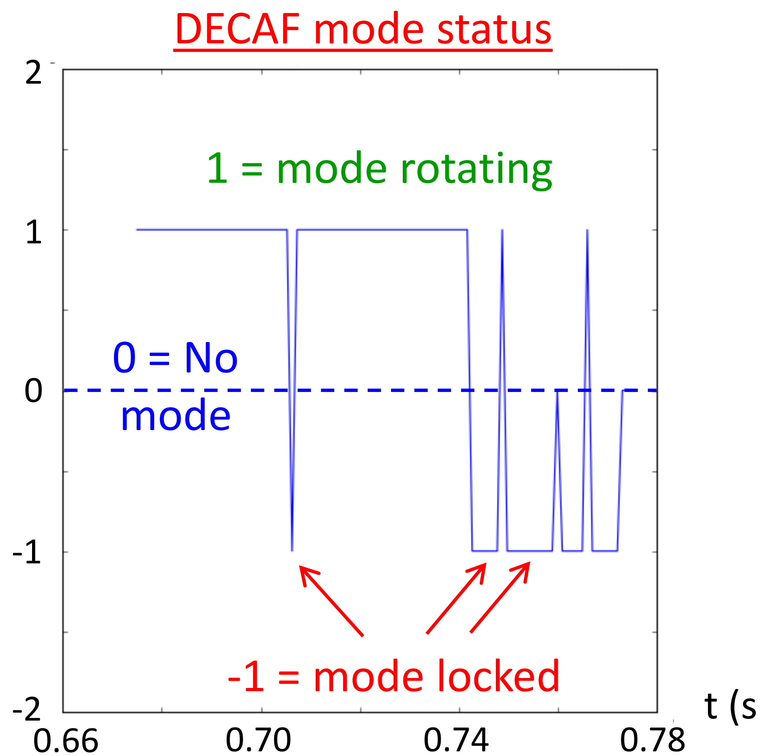




DECAF rotating MHD analysis identifies the state of the modes found (n = 1)

Magnetic signal / analysis (mode locking / unlocking)

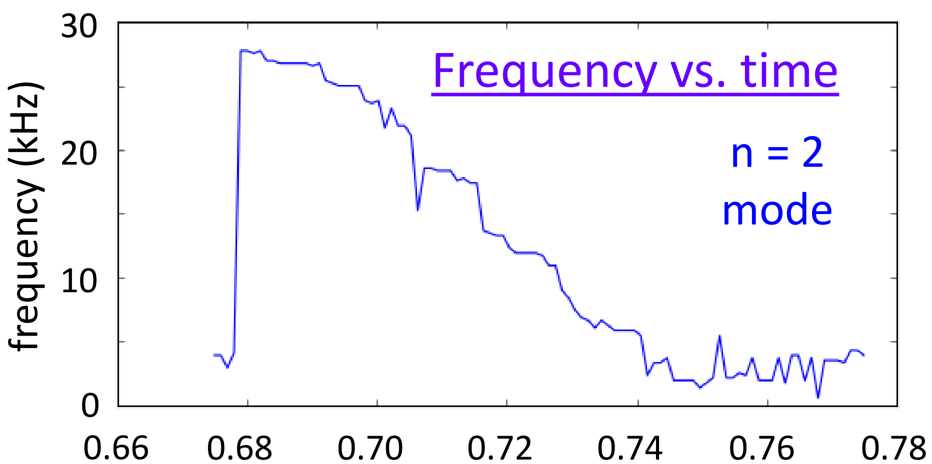


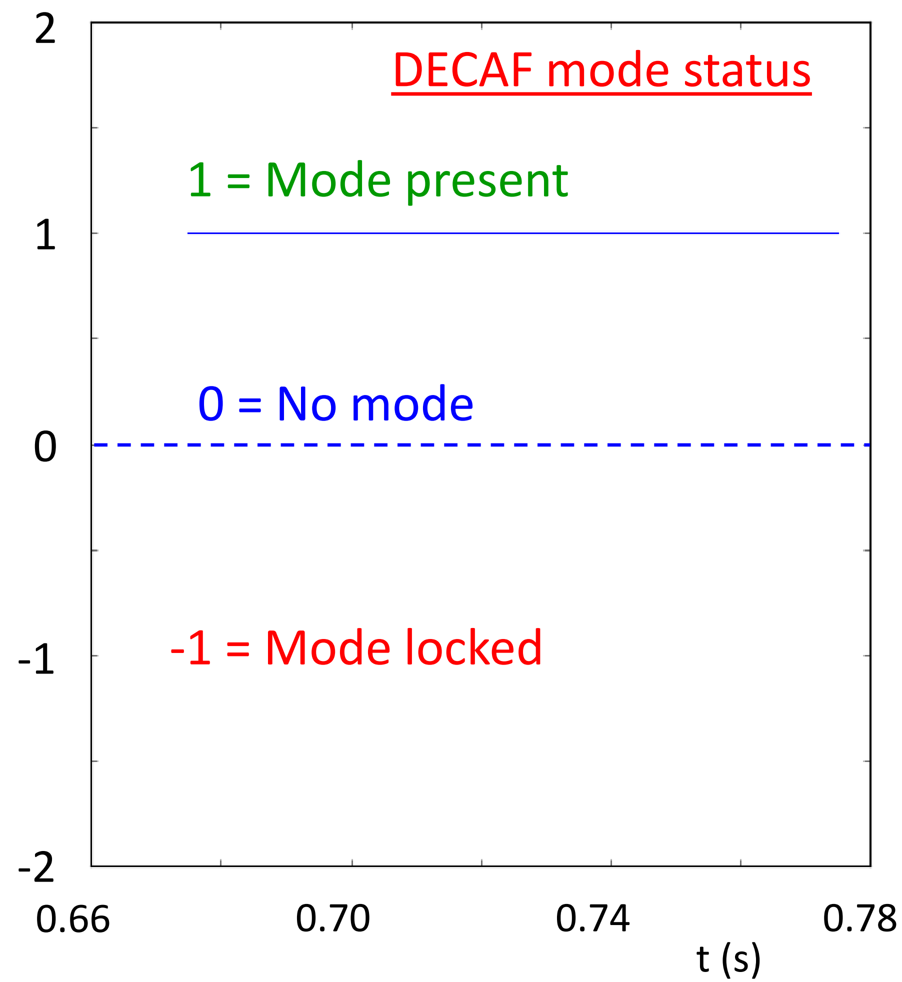


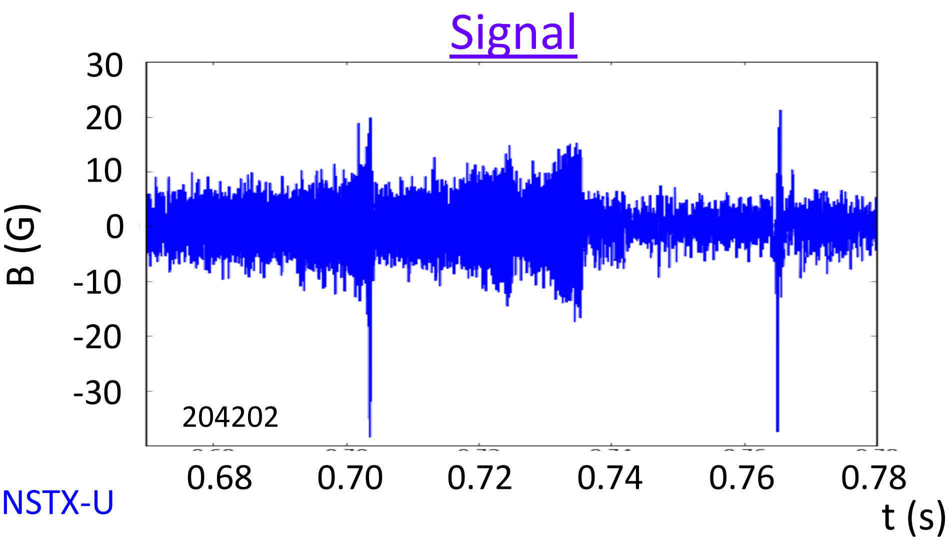
NSTX-U

DECAF rotating MHD analysis identifies the state of the modes found (n = 2)

Magnetic signal / analysis (mode present, not locked)







NSTX-U

Summary and next steps

- The Disruption Event Characterization and Forecasting code (DECAF)
  - Focuses on quantitative statistical characterization of the chains of events which most often lead to disruption of plasmas
  - The ultimate goal is to provide forecasts which integrate with a disruption avoidance system and are utilized in real-time during a device's operation
- Reduced kinetic model for disruption avoidance is implemented
  - Success rate is surprisingly high given its initial state and relative simplicity
- Rotating MHD is ubiquitous; Identification is essential
  - Characterization algorithm utilizes FFT, finds expected bifurcation and locking
- Next steps to the development and usage of DECAF include:
  - Continued improvement of accuracy of event determination
  - Significant expansion of events and event chains
  - Expansion of the dataset to multiple devices (including DIII-D., KSTAR)

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NSTX-U

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Characterization and Forecasting of Global and Tearing Mode Stability for Tokamak Disruption Avoidance

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