NSTX-U

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Disruption event characterization and forecasting of global and tearing mode stability for tokamaks

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COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

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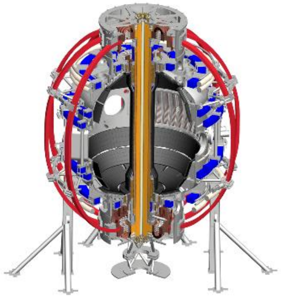
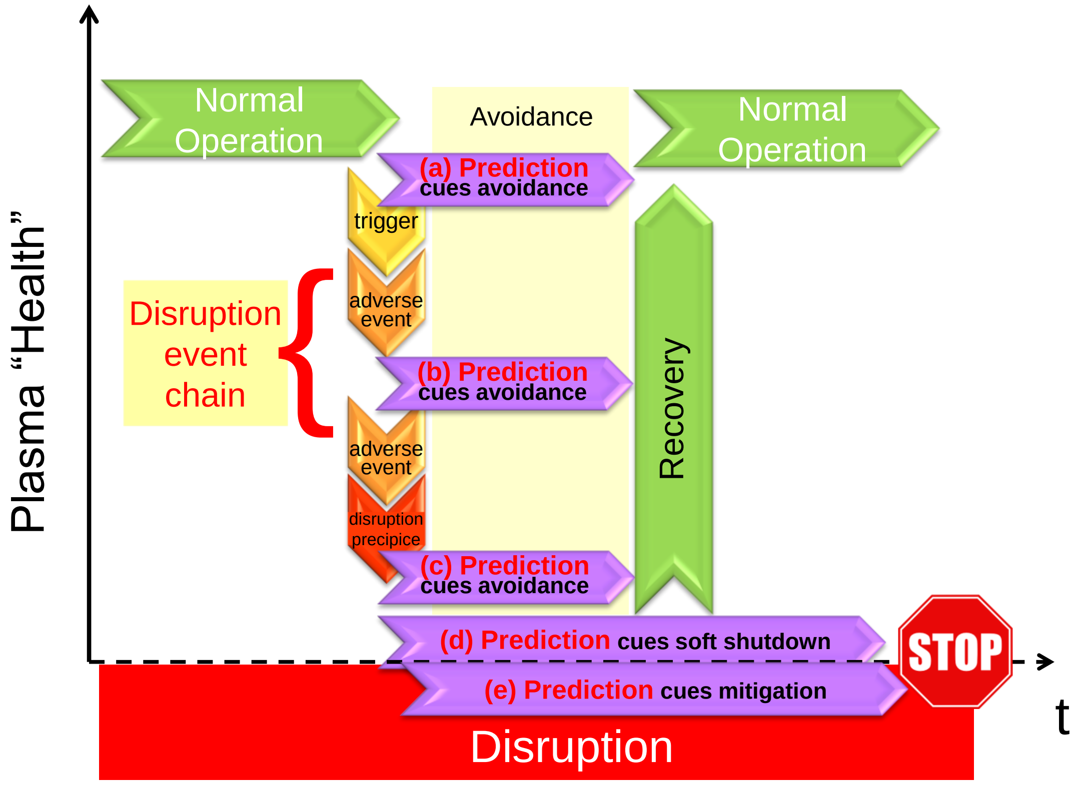


**This work is supported by the US DOE contracts DE-AC02-09CH11466 and DE-FG02-99ER54524*

Outline

- **The Disruption Event Characterization And Forecasting (DECAF) code**
  - Contains various physical event modules with warning algorithms
- **A reduced kinetic model for resistive wall mode stability**
  - Complex calculation reduced for speed, performs well
- **Identification of rotating MHD**
  - Tracks characteristics that lead to disruption: rotation bifurcation, mode lock

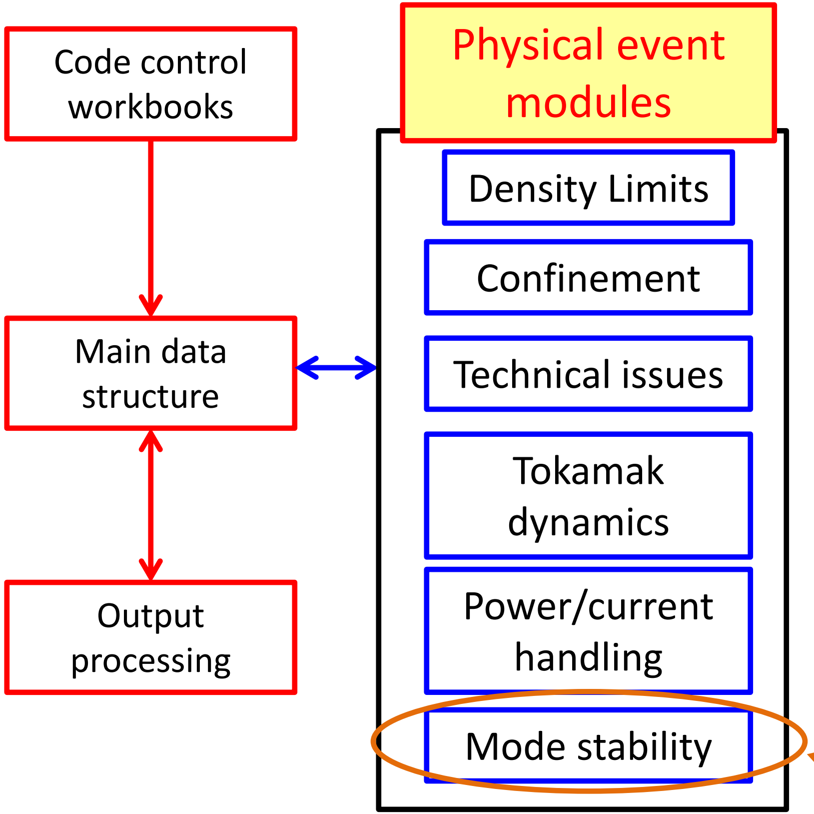
Disruption event chain characterization capability started as next step in disruption avoidance plan



[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



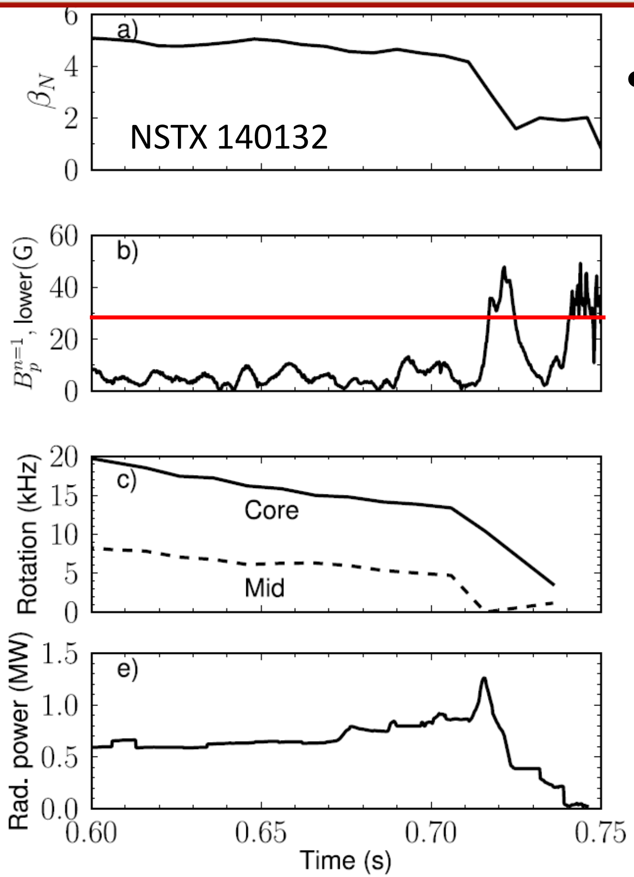
- Physical event modules
  - Present grouping follows work of deVries [P.C. de Vries et al., Nucl. Fusion 51, 053018 (2011)]
  - BUT, easily appended or altered
- Warning algorithms
  - Present approach follows [S.P. Gerhardt et al., Nucl. Fusion 53, 063021 (2013)]
  - More flexible: arbitrary number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

RWM and tearing mode stability

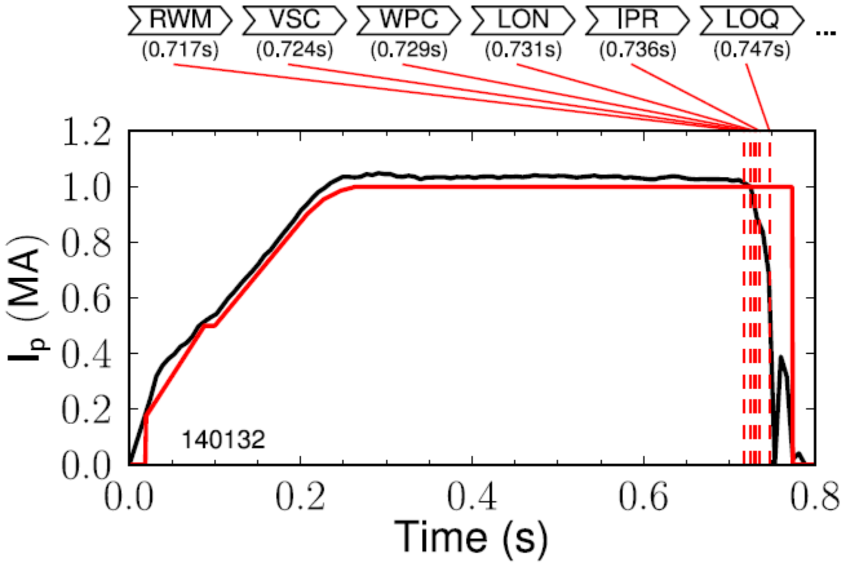
Several threshold tests are currently included in DECAF

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]

Example DECAF analysis on single NSTX discharge



- DECAF uses simple threshold tests and more sophisticated models to declare events
  - Ex: RWM $B_p^{n=1}$ threshold 30G ($\delta B/B0$ ~ 0.67%)



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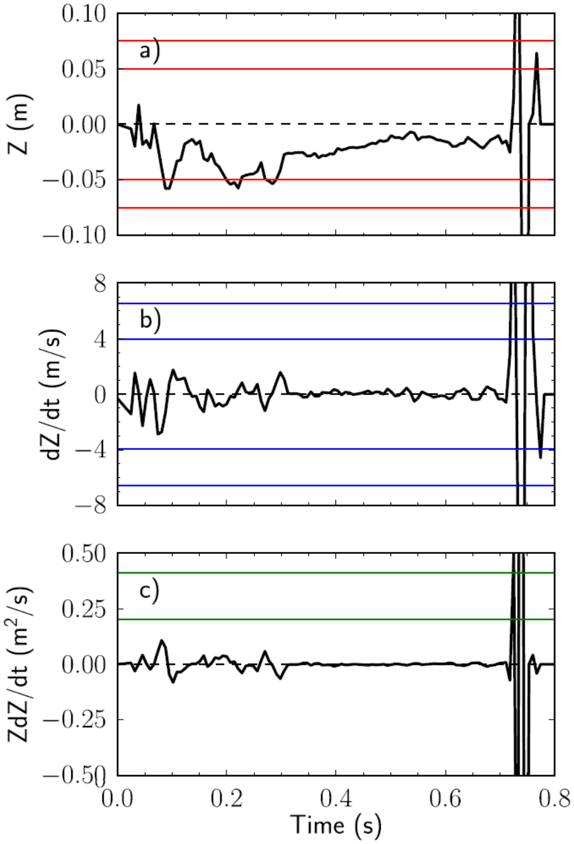
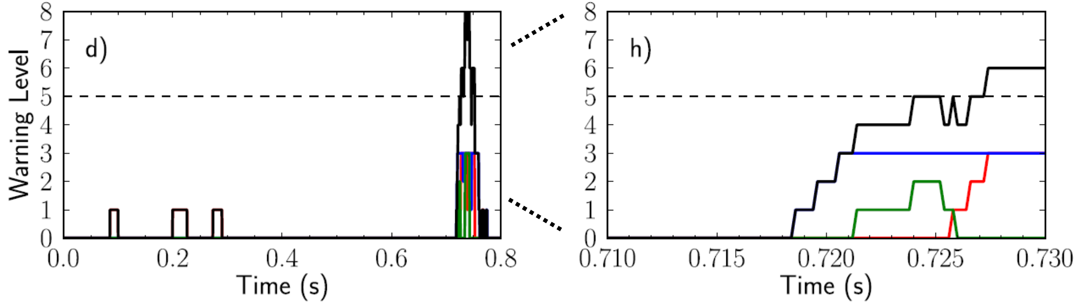
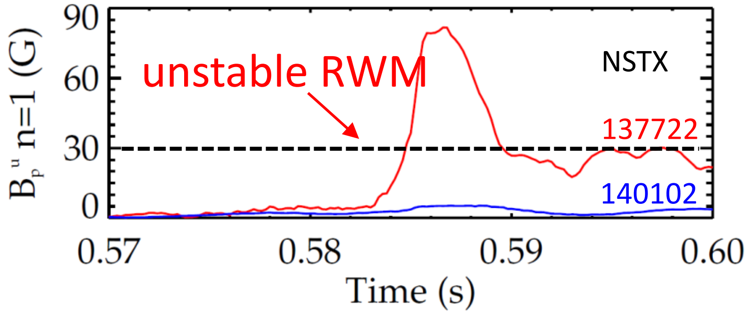


- DECAF uses simple threshold tests and more sophisticated models to declare events
  - Ex: RWM $B_p^{n=1}$ threshold 30G (δB/B0 ~ 0.67%)
- Tests can be combined with "warning points"
  - Ex: VSC uses Z, dZ/dt, and ZdZ/dt

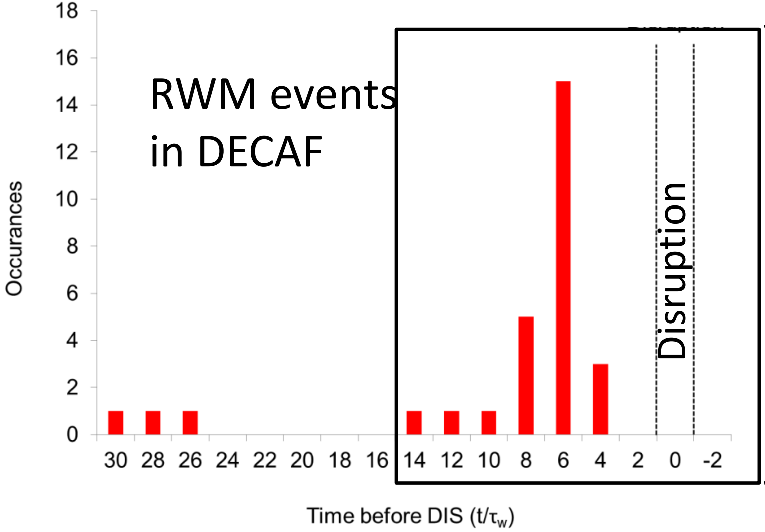
Vertical stability control	VSC	5	Axis position (m)	[0.05,0.075,0.10]	[1,2,3]
			Axis velocity (m/s)	[3.93,6.54,9.01]	[1,2,3]
			Excessive ZdZdt (m/s²)	[0.20,0.41,0.84]	[1,2,3]

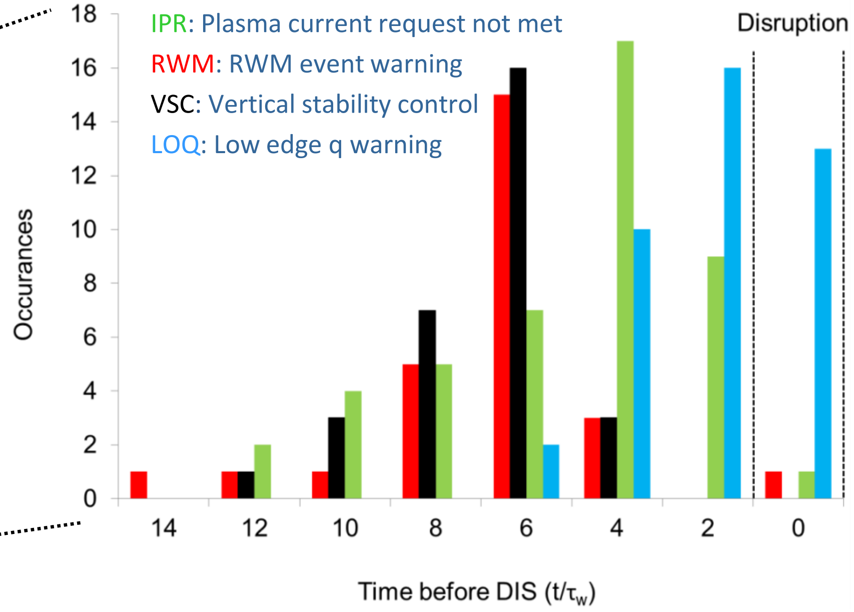


Initial DECAF results detects disruption chain events when applied to dedicated 45 shot NSTX RWM disruption database



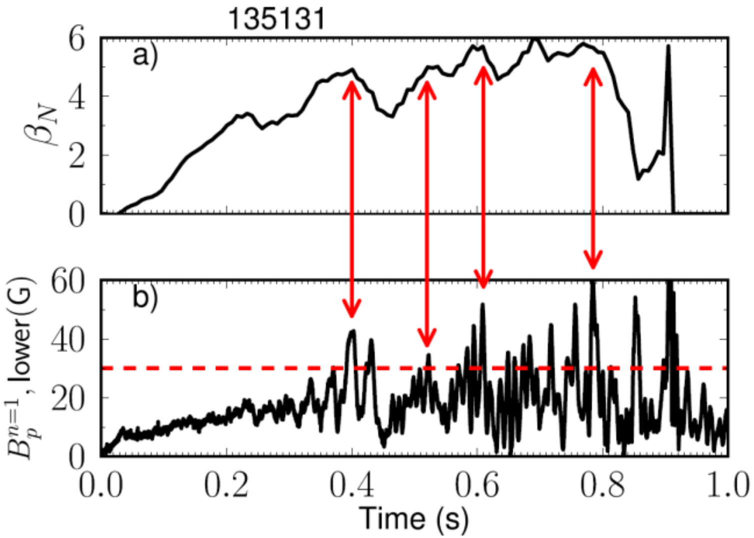
- RWM $B_P^{n=1}$ threshold 30G ($\delta B/B_0 \sim 0.67\%$)
- 60% within 14 τ_w of disruption time (τ_w = 5 ms)



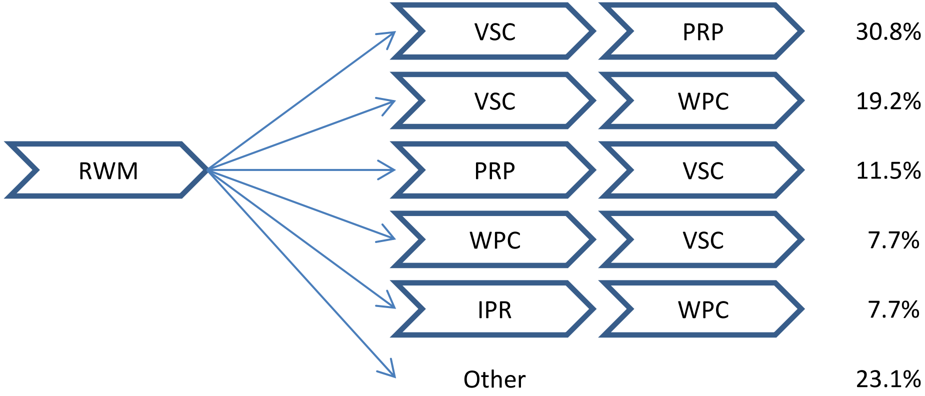


Initial DECAF analysis already finding common disruption event chains, giving new insight

- 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 to cue avoidance systems
  - 5 (out of theoretically 56) two-event combinations followed 77% of RWM cases (those that occurred within $14\tau_w$ of DIS)



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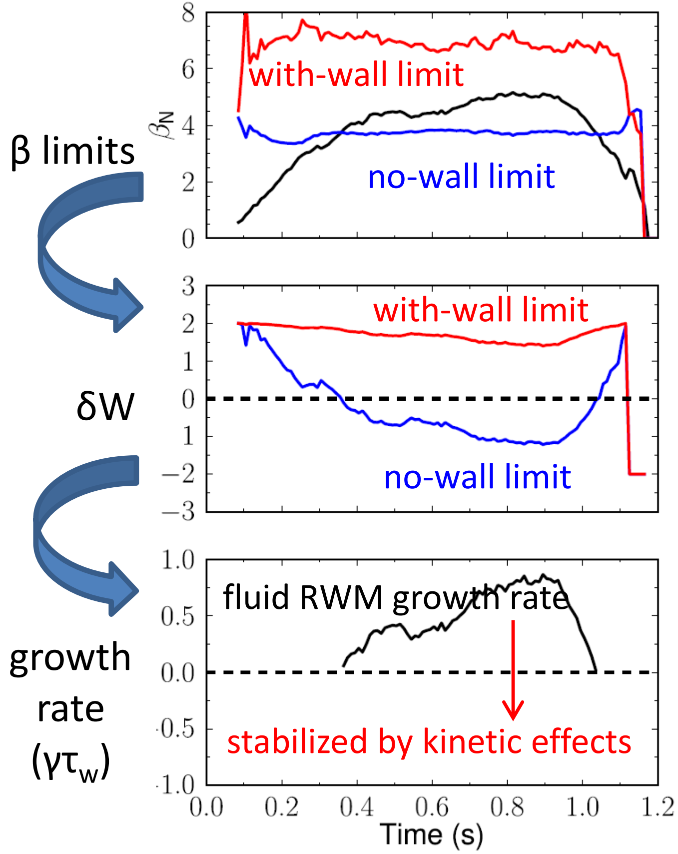
Goal is to forecast mode growth rate in real-time using parameterized reduced models for δW terms



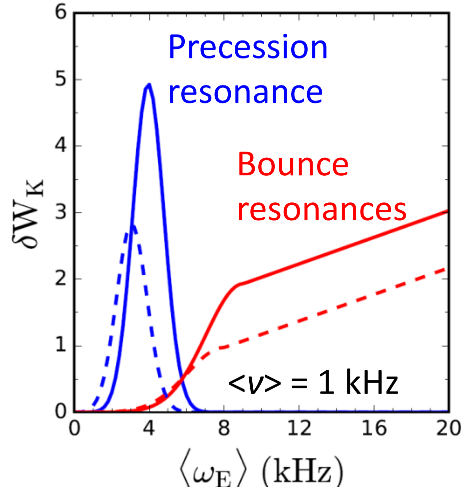
RWM dispersion relation

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

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

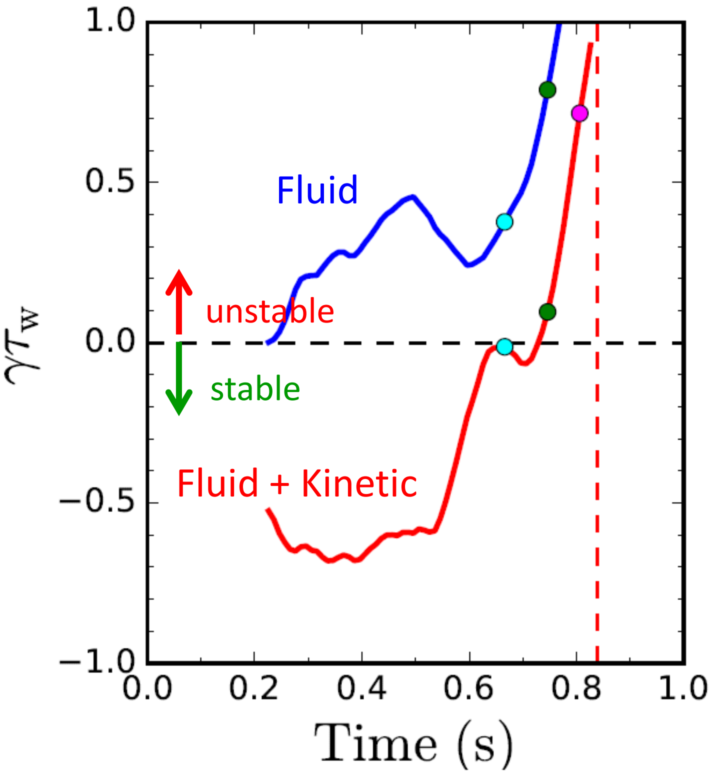
Fluid terms   Kinetic effects: Collisionality   Rotation

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

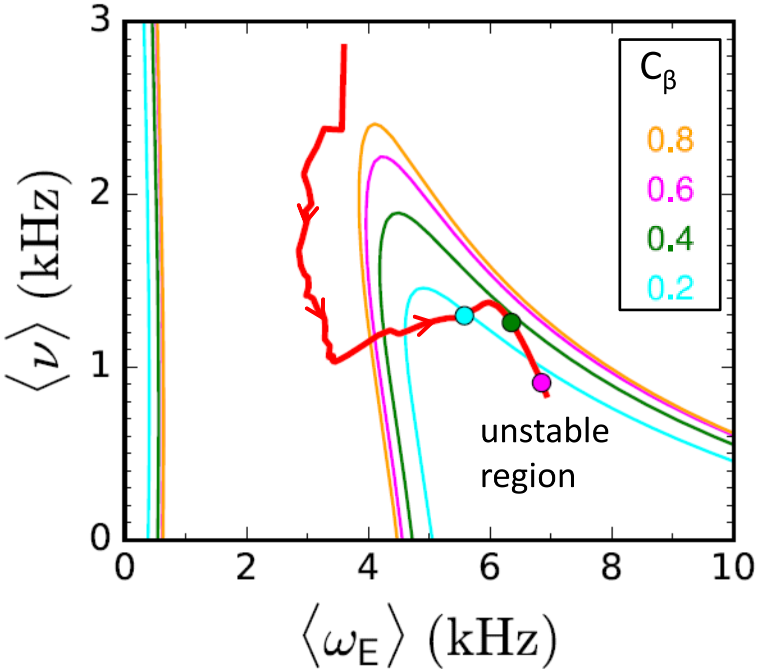


DECAF contains modeled kinetic quantities for generation of stability maps

Normalized growth rate vs. time



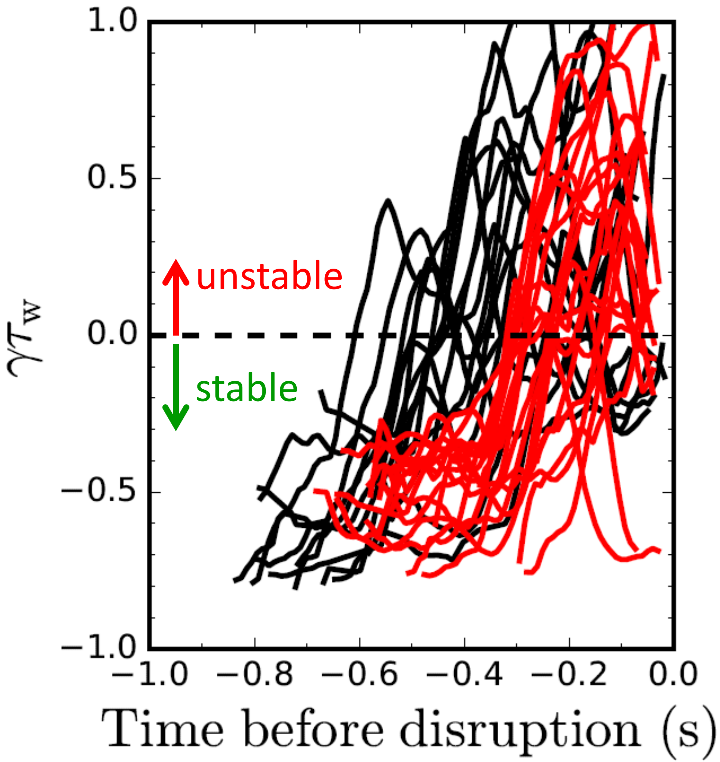
- Stability diagram shows trajectory of a discharge towards unstable regions



$C_\beta = (\beta_N - \beta_N^{\text{no-wall}}) / (\beta_N^{\text{with-wall}} - \beta_N^{\text{no-wall}})$

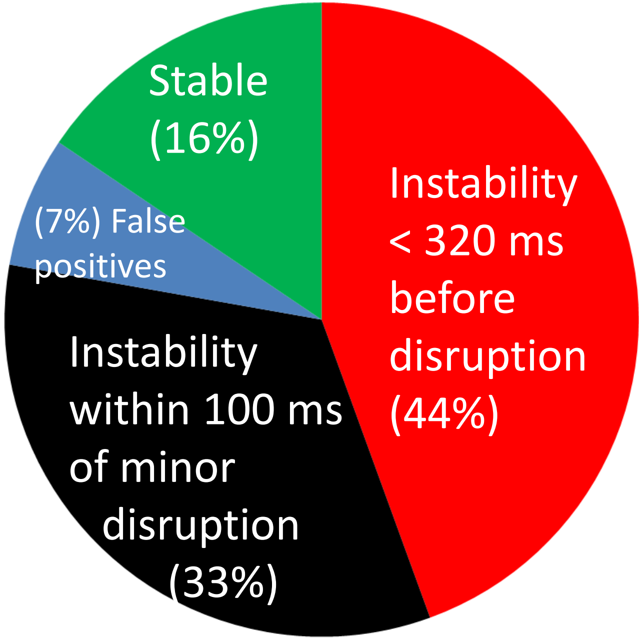
DECAF reduced kinetic model results initially tested on a database of NSTX discharges with unstable RWMs

Normalized growth rate vs. time

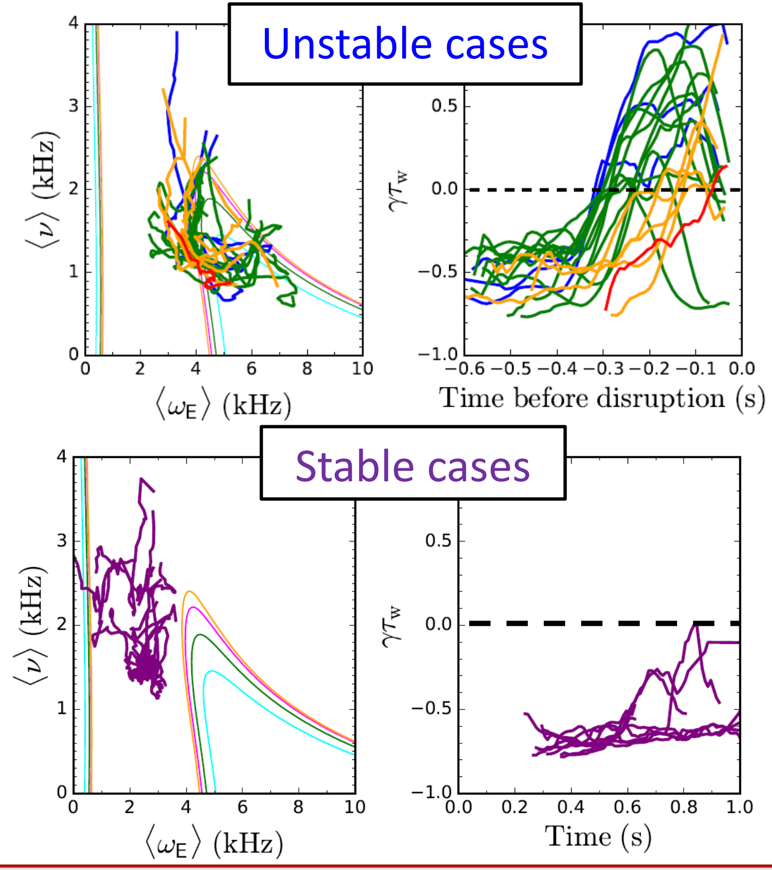


- 44% predicted unstable < 320 ms (approx. $60\tau_w$) before current quench
- 33% predicted unstable within 100 ms of a minor disruption

Predicted instability statistics (45 shots)



Reduced kinetic model distinguishes between stable and unstable NSTX discharges



- If <ω$_E$> ~ 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

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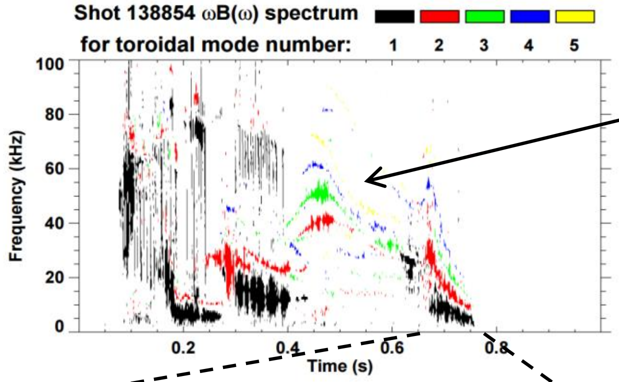
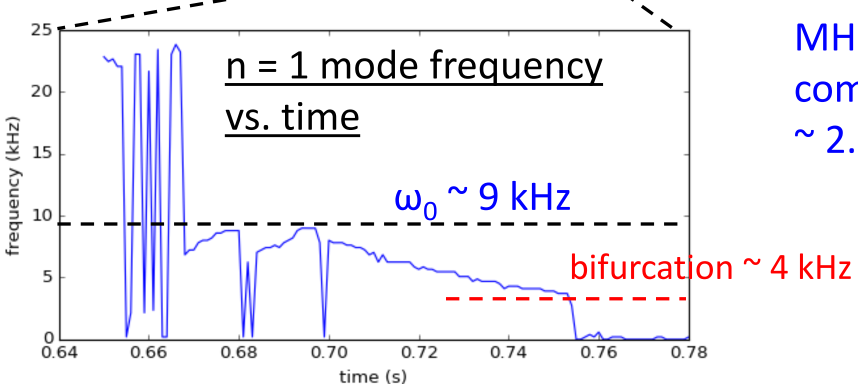
Essential new step for DECAF analysis of general tokamak data: Identification of rotating MHD (e.g. NTMs)

- 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

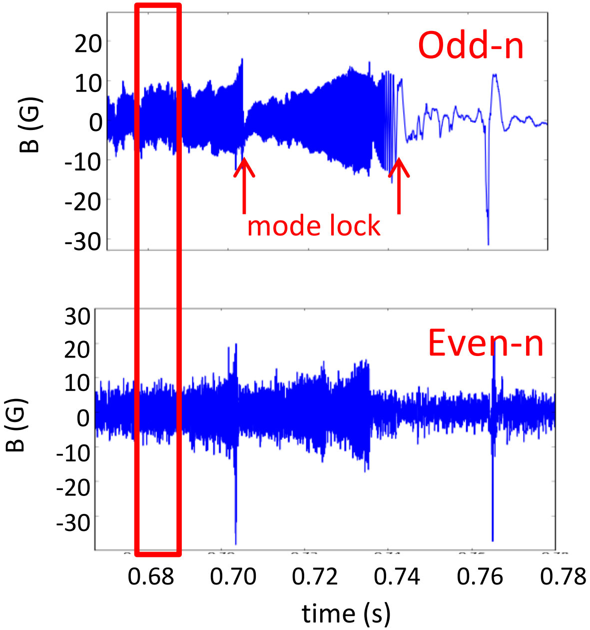




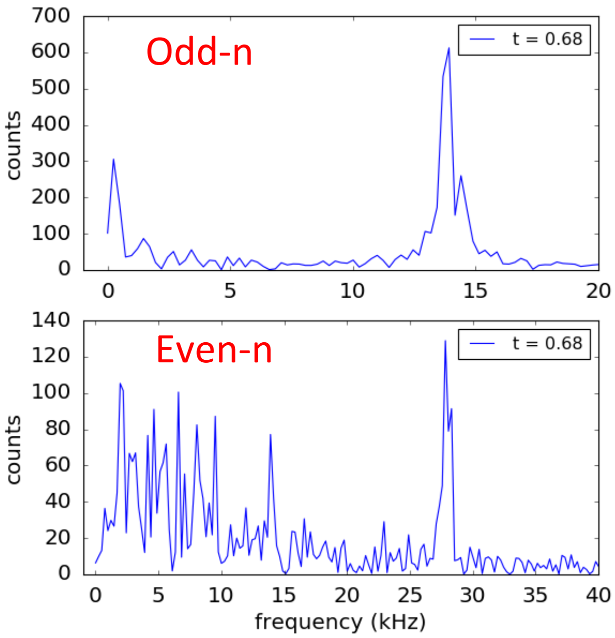
- ❑ NSTX “stable periods” – enhanced by high elongation (κ ~ 2.7), lithium wall conditioning
- ❑ NSTX-U: rotating MHD more common (lower κ ~ 2.3, no lithium)

DECAF rotating MHD analysis identifies the state of the modes found

Signals



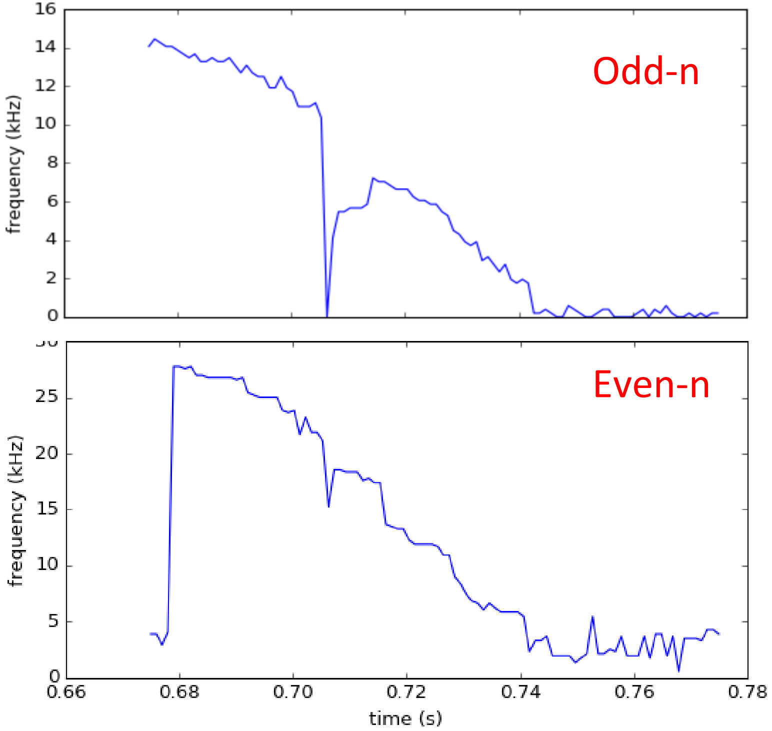
FFTs



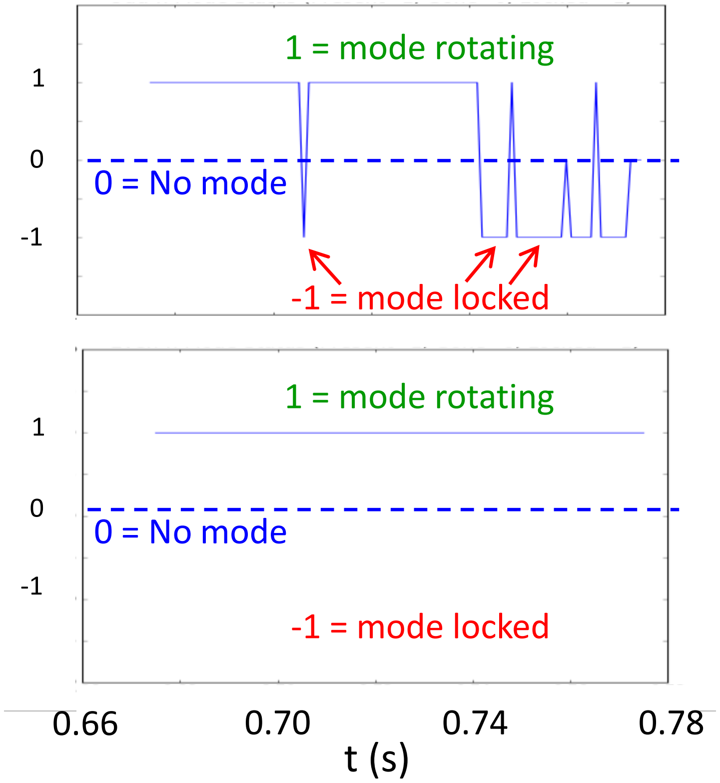
Fast Fourier transforms used to find mode peak frequency within a time interval

DECAF rotating MHD analysis identifies the state of the modes found

Frequency vs. time

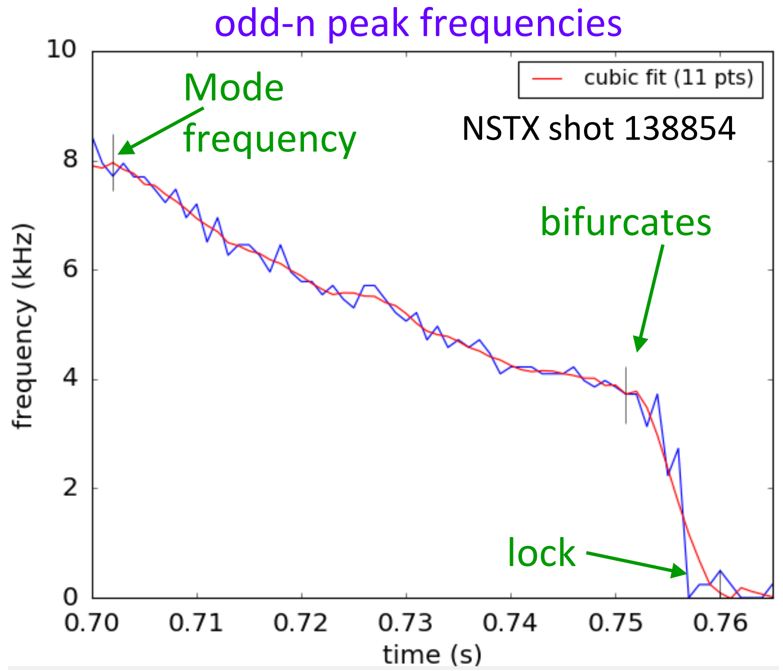


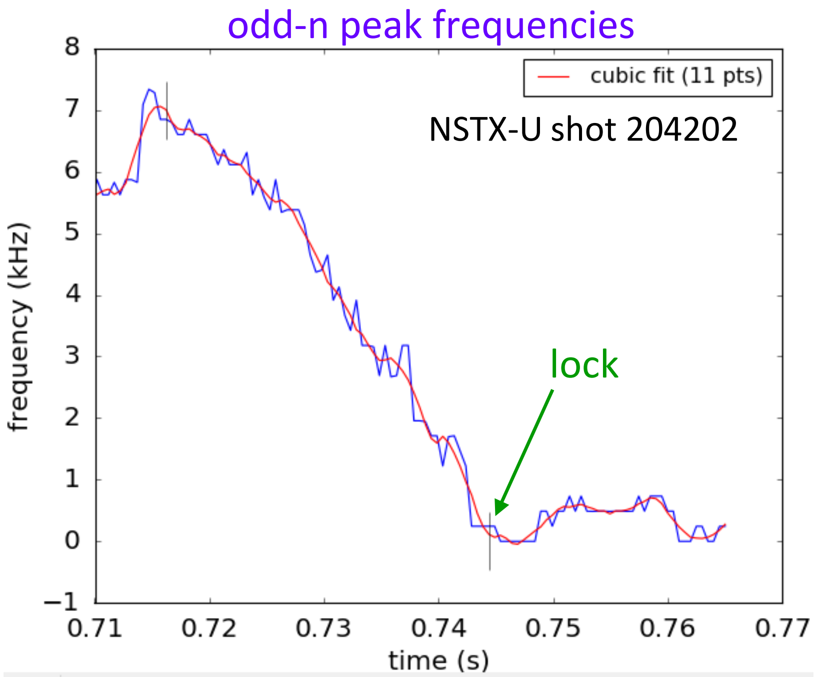
DECAF mode status



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





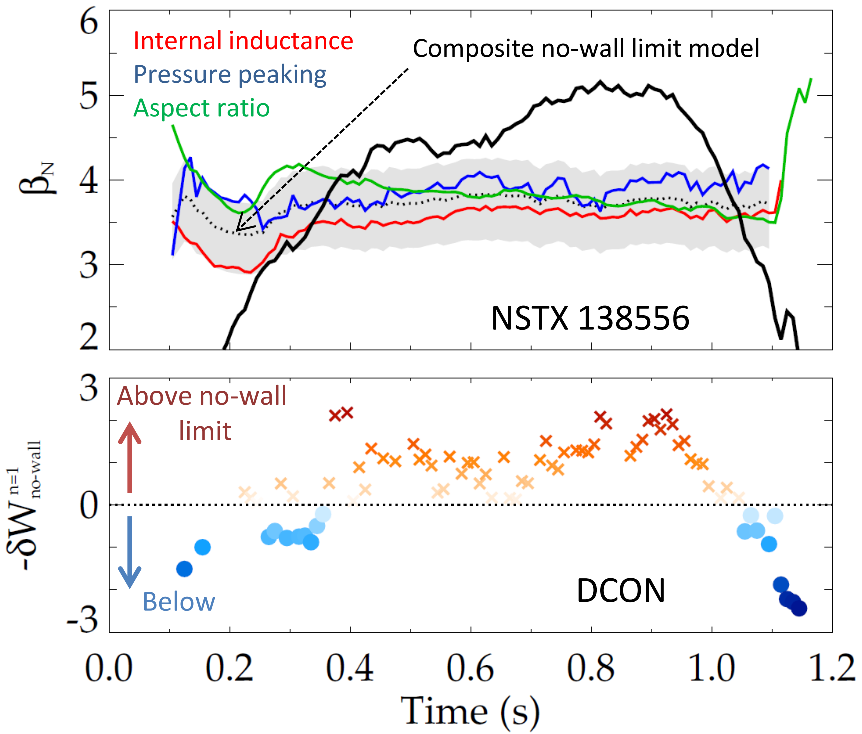
Conclusions

- **The DECAF code can characterize chains of events leading to disruption**
  - Expanding set of modules and warnings used to analyze data sets
- **A reduced kinetic model for resistive wall mode stability**
  - Complex calculation reduced for speed, performs well
- **Algorithm for identifying rotating MHD can find frequency, bifurcation points, locking times**

Backup

DECAF contains modeled quantities for stability estimation

Modeled estimates for NSTX no-wall limit

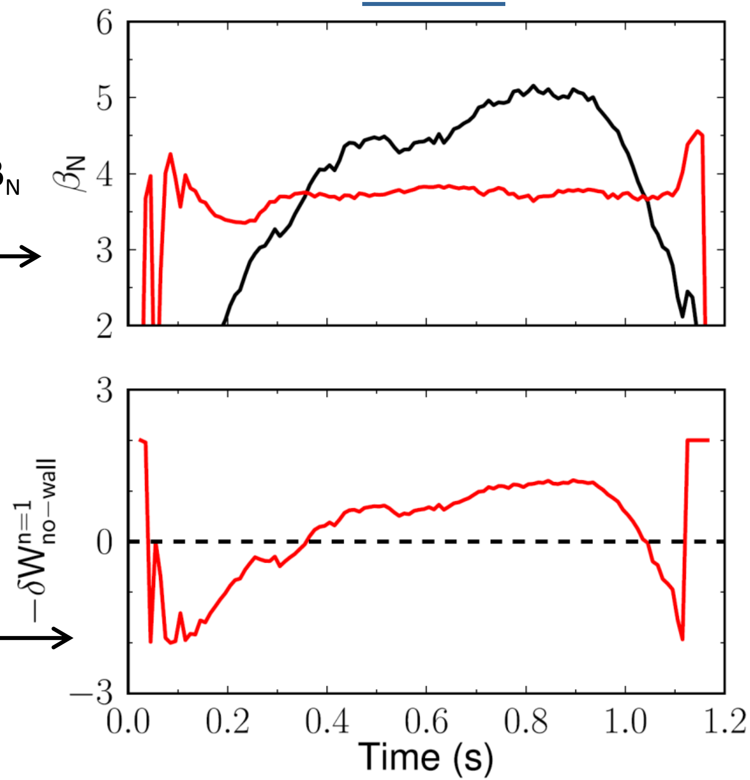


[J.W. Berkery et al., Nucl. Fusion 55, 123007 (2015)]

DECAF

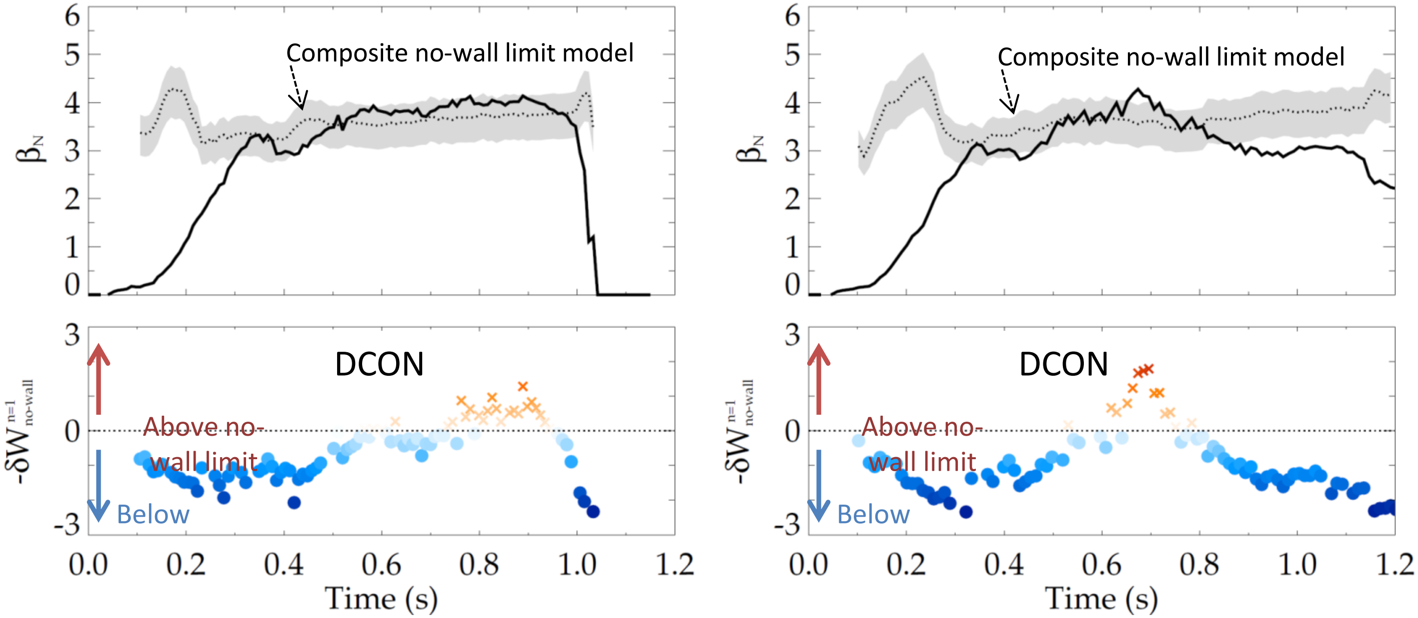
DECAF replicates published NSTX β_N no-wall model

DECAF δW no-wall model similar to DCON results



DCON confirms NSTX-U above the no-wall limit; NSTX-based model gives good estimate

NSTX-U H-mode discharges: 204112 204118 (April 2016)



- NSTX no-wall limit model ([J.W. Berkery et al., Nucl. Fusion 55, 123007 (2015)]) includes internal inductance, pressure peaking, and aspect ratio, predicts NSTX-U DCON no-wall limit