NSTX-U

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

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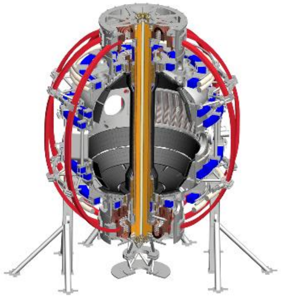
Princeton, NJ
July 19, 2017

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

PPPL

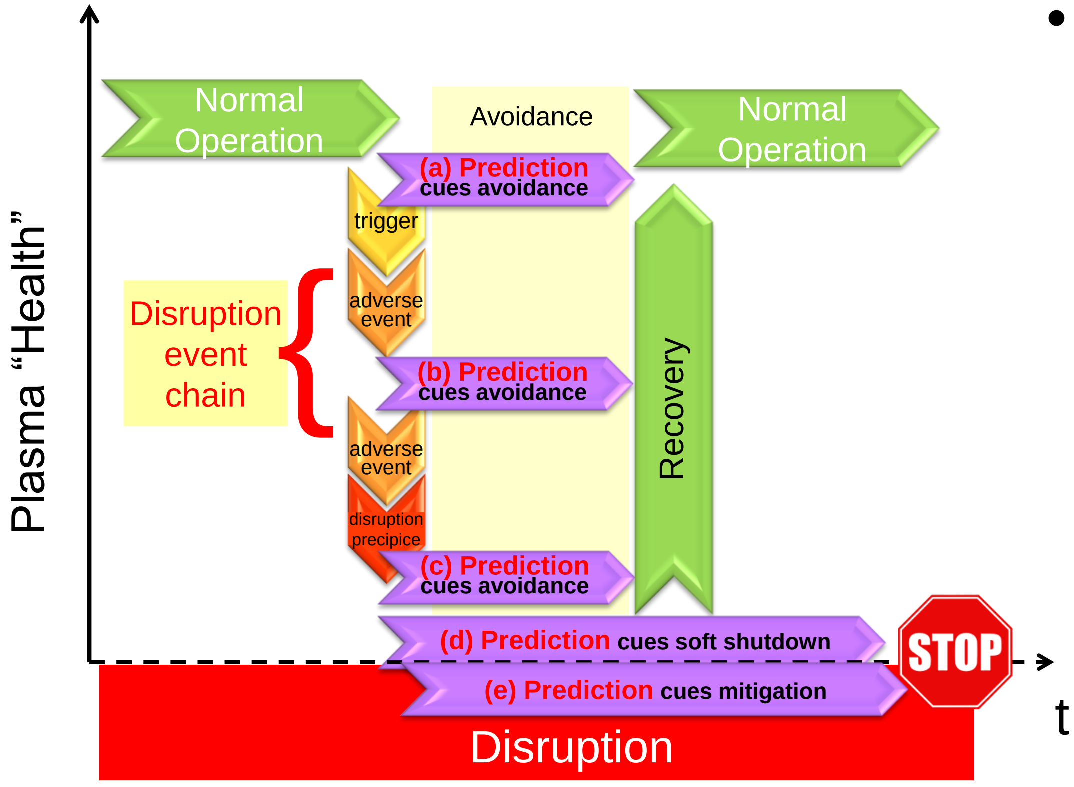


**This work is supported by the US DOE contracts DE-AC02-09CH11466 and DE-FG02-99ER54524*

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

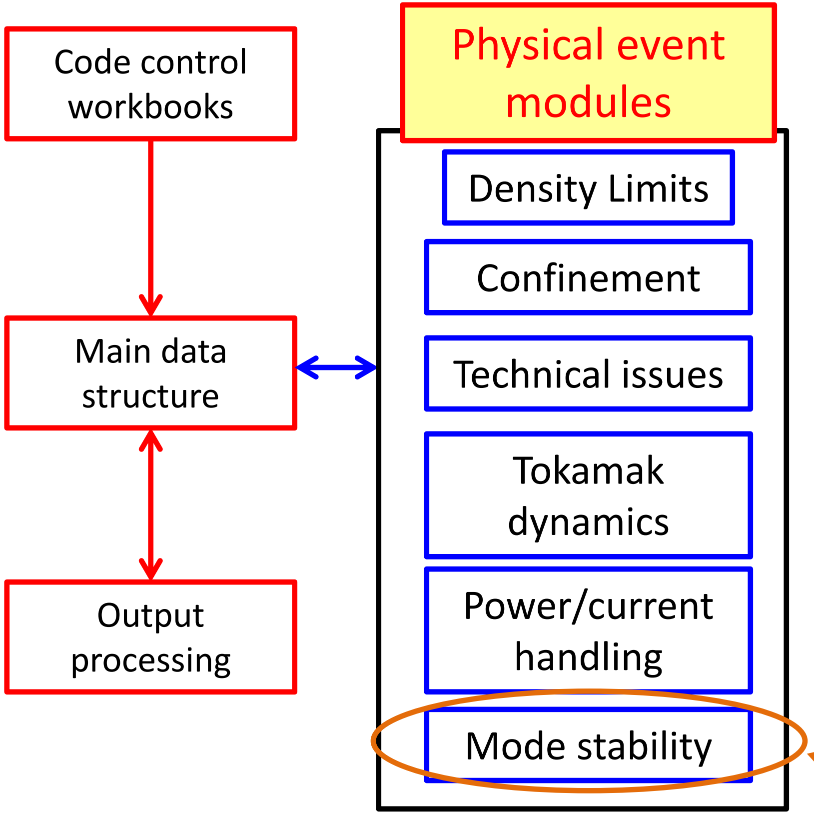
Disruption event chain characterization capability continues as next step in disruption avoidance plan



From DOE Report on Transients in Tokamak Plasmas (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 to prevent disruption
  - Builds upon both physics and control successes of NSTX
    - Presently expanding analysis on data from other tokamaks (DIII-D, KSTAR, TCV)

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

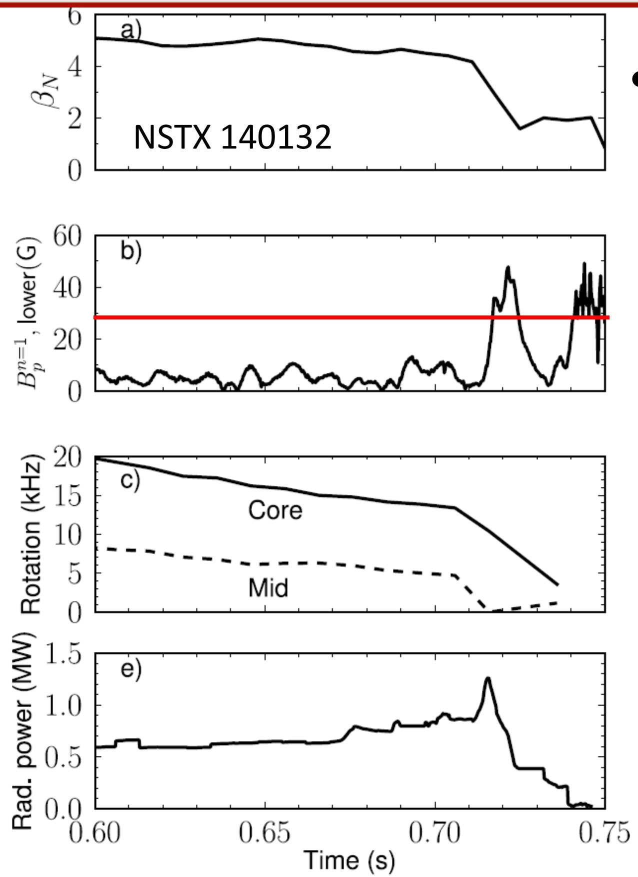
RWM and tearing mode stability

Several of the more than 50 planned disruption chain events are currently implemented in DECAF

Disruption chain event		Points	Test Criteria	Test Thresholds	Points
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]
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]
Plasma current request	IPR	3	$\lvert I_p^{req} - I_p\rvert / I_p^{req} >$	[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]

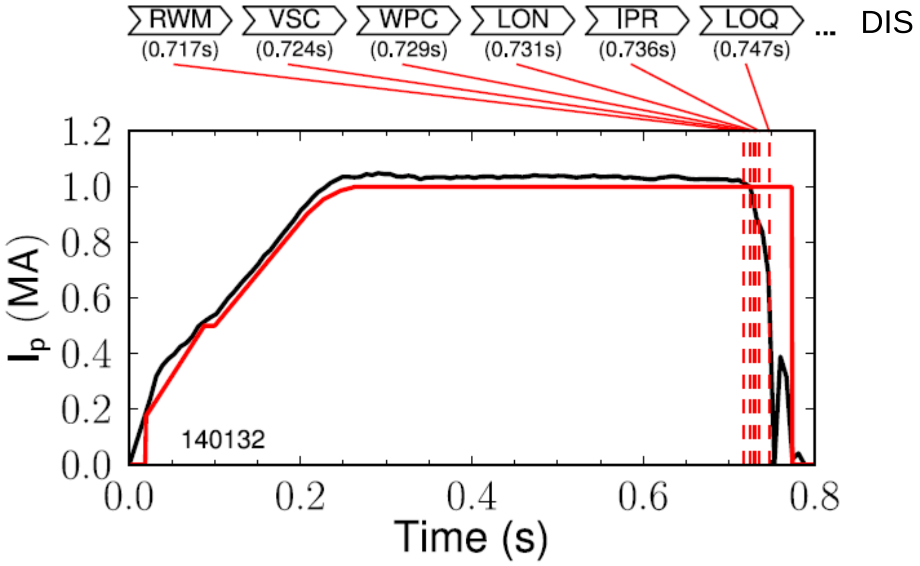
- Accomplished by reading in >50 scalar and profile measurements plus derived and modelled quantities; continued development to improve results

DECAF uses a range of analyses, from multiple signal comparisons to more sophisticated physics models to declare events



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

Disruption event chain



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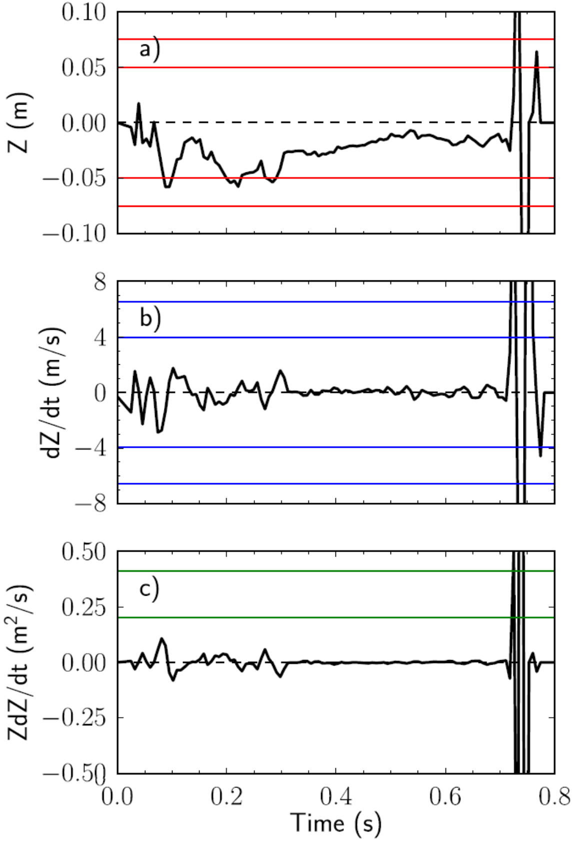

- Ex. DECAF analysis on single NSTX discharge
  - Example: RWM $B_p^{n=1}$ threshold 30G ($\delta B/B0 \sim 0.67\%$)
- Tests can be combined with "warning points"
  - Ex: VSC uses Z, dZ/dt, and ZdZ/dt

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]
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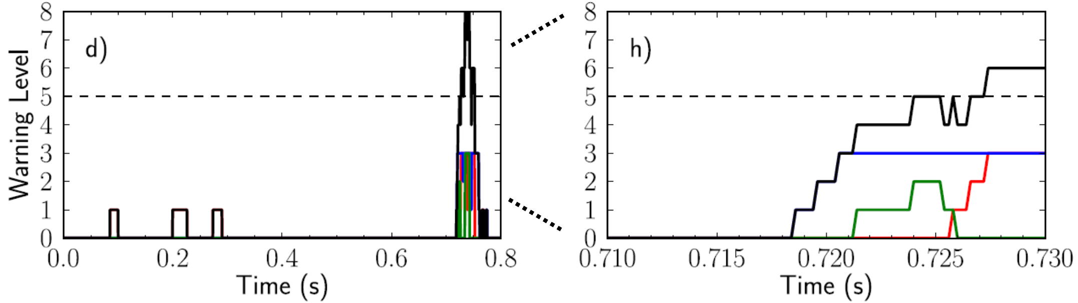
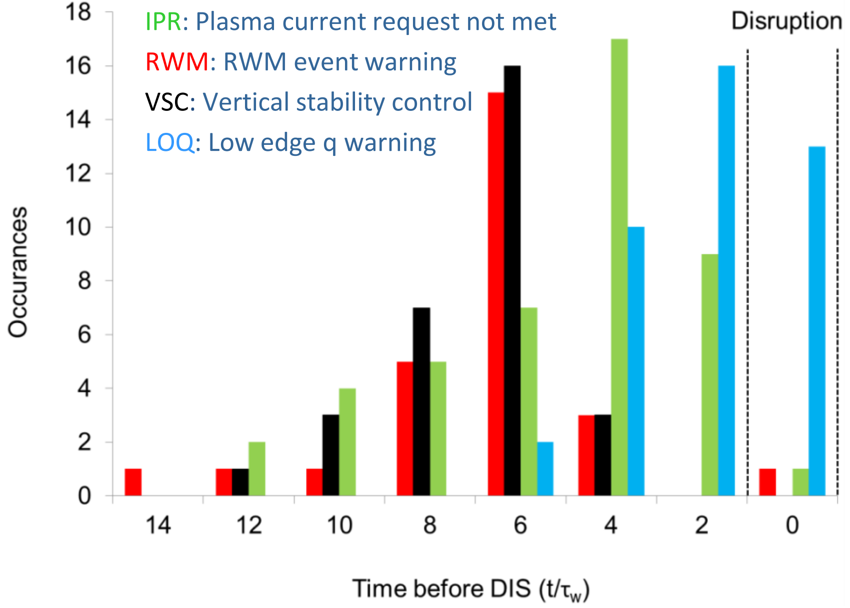
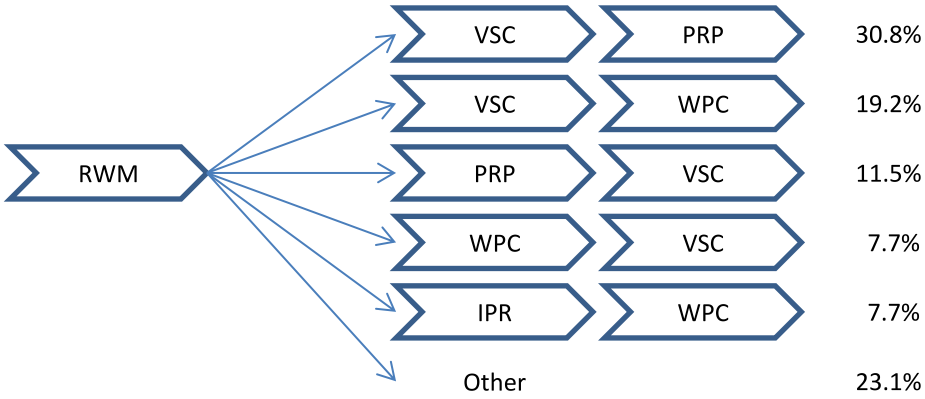


DECAF detects disruption chain events when applied to dedicated 45 shot NSTX RWM disruption database

- 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)



- 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 14τ_w of DIS)



(WPC: Wall proximity control, PRP: Pressure peaking)

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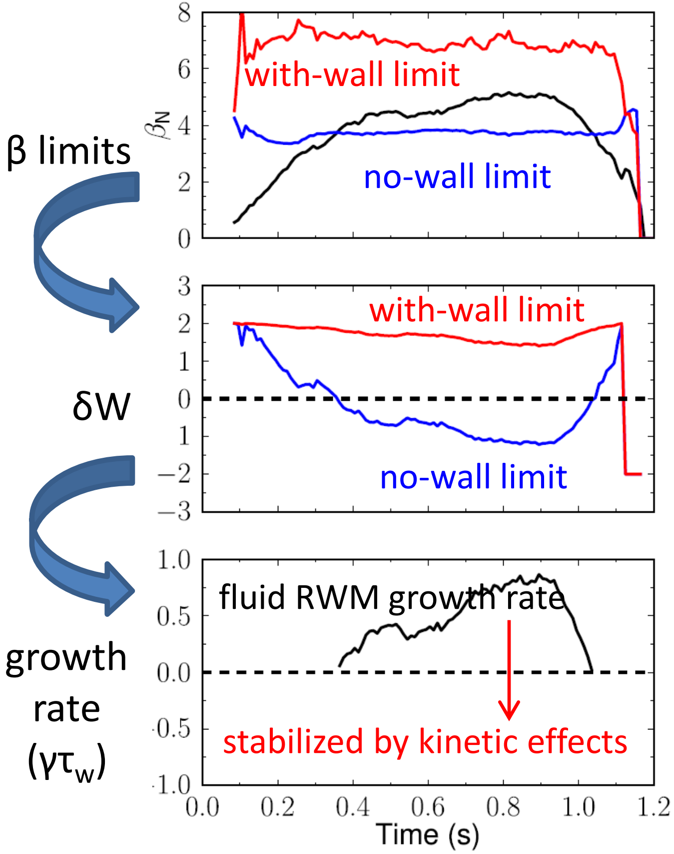
Goal is to forecast mode growth rate in real-time using reduced models of the full kinetic MHD stability calculation



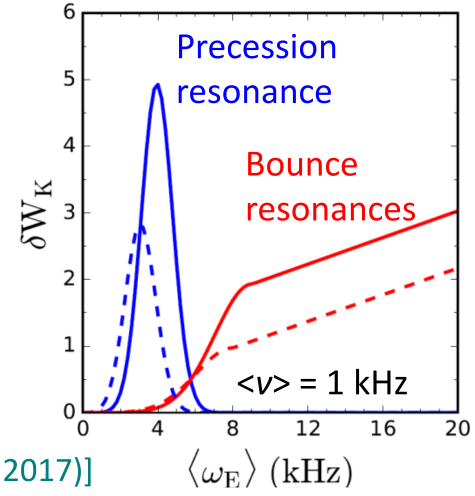
RWM dispersion relation

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

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

Fluid terms   Kinetic effects: Collisionality   Rotation

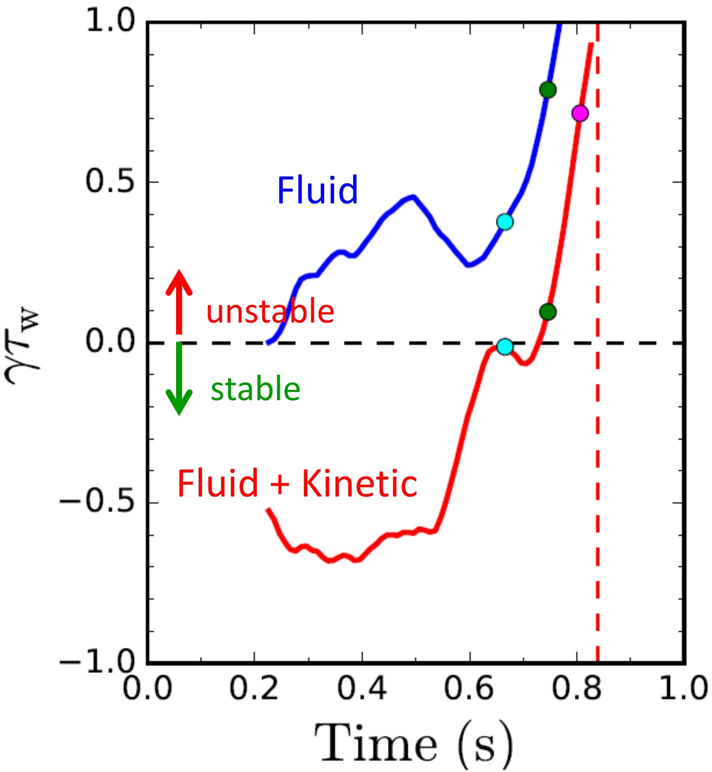
- Gaussian functions used for resonances
  - Coefficients selected to reflect NSTX experience



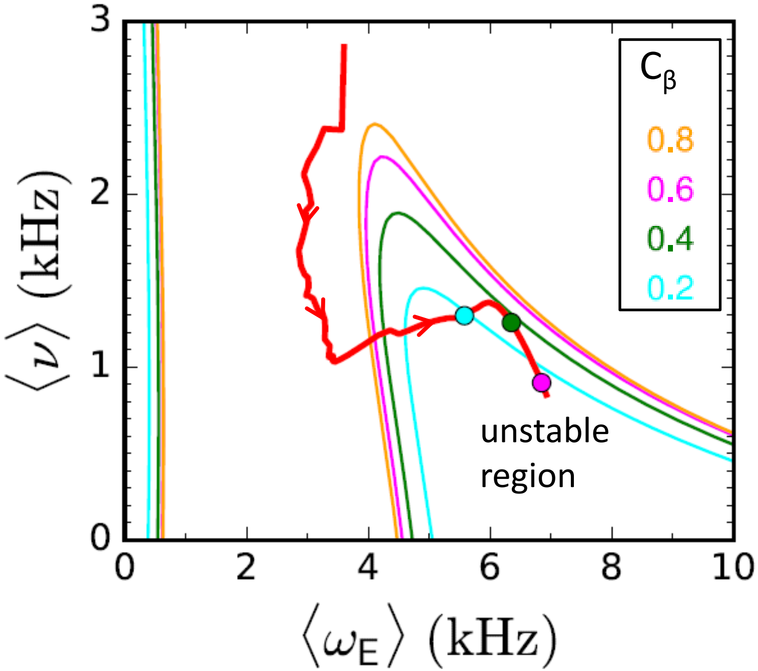
[J.W. Berkery et al., Phys. Plasmas 24, 056103 (2017)]

DECAF contains modeled kinetic quantities for generation of time-evolving stability boundaries

Normalized growth rate vs. time



- Stability diagram shows trajectory of a discharge towards unstable regions

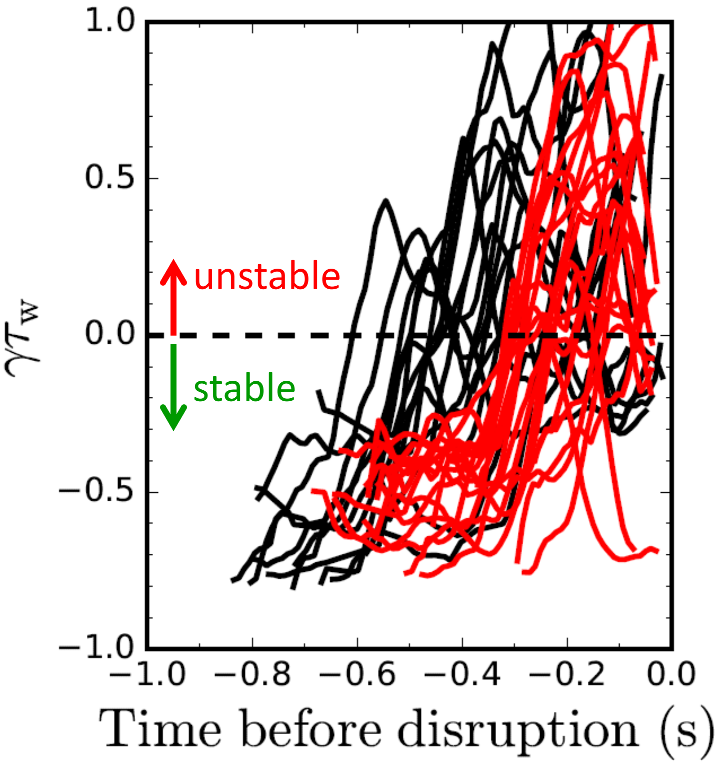


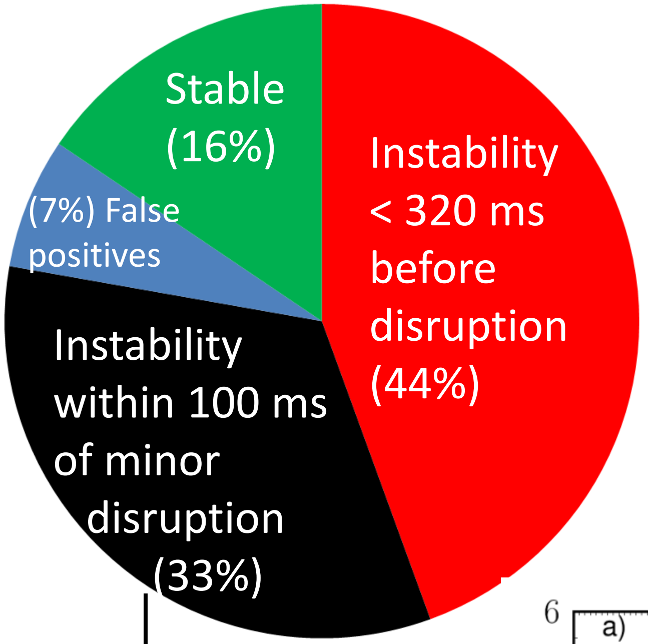
$C_\beta = (\beta_N - \beta_N^{no\text{-}wall}) / (\beta_N^{with\text{-}wall} - \beta_N^{no\text{-}wall})$

[J.W. Berkery et al., Phys. Plasmas 24, 056103 (2017)]

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

Normalized growth rate vs. time

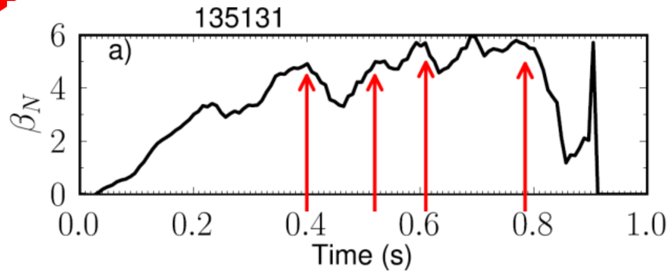




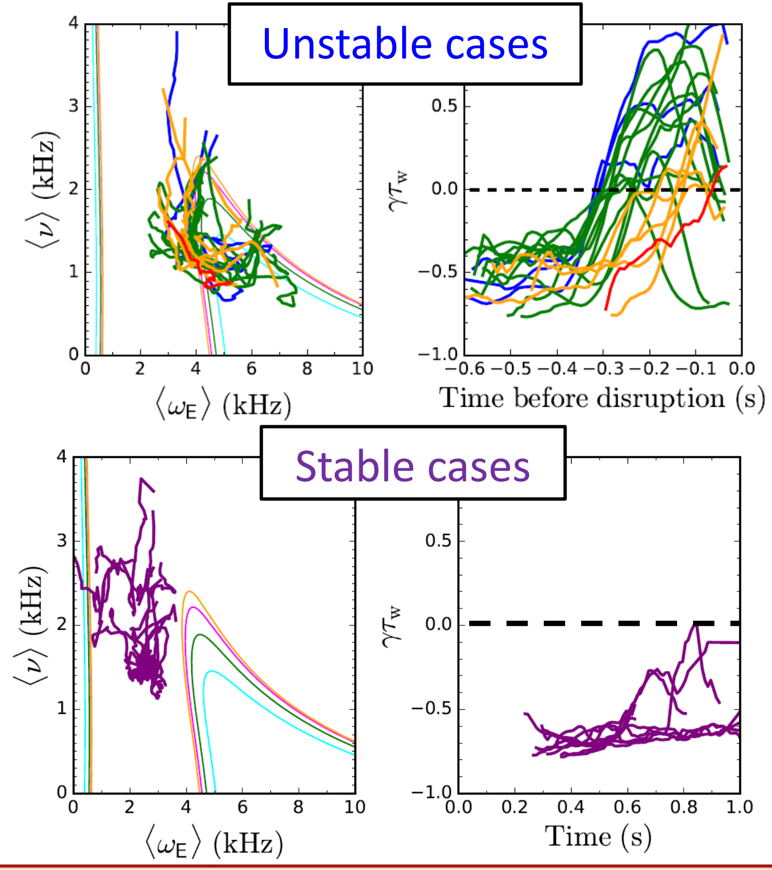
Predicted instability statistics (45 shots)

[J.W. Berkery et al., Phys. Plasmas 24, 056103 (2017)]

Minor disruptions are not false positives!



Reduced kinetic model distinguishes between stable and unstable NSTX discharges



- 84% unstable discharges are predicted unstable
- 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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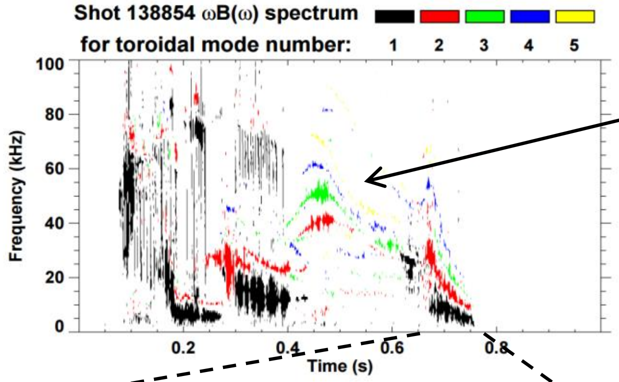
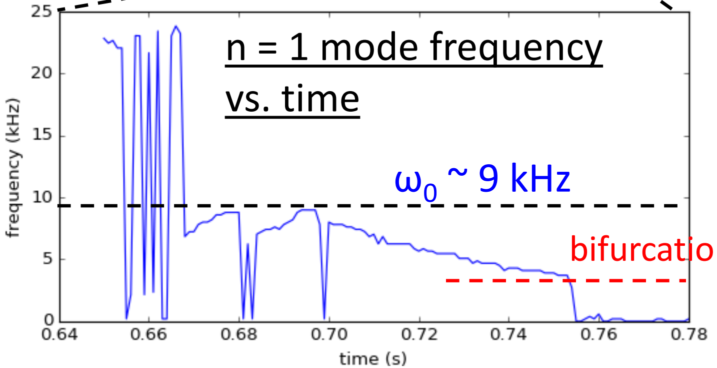
Essential new step for DECAF analysis of general tokamak data: Identification of rotating MHD (e.g. NTMs)

- 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

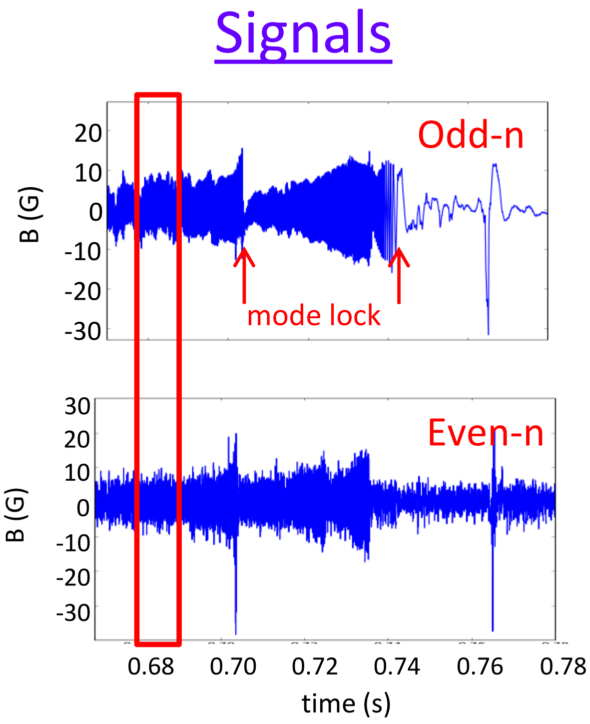
Magnetic spectrogram of rotating MHD in NSTX

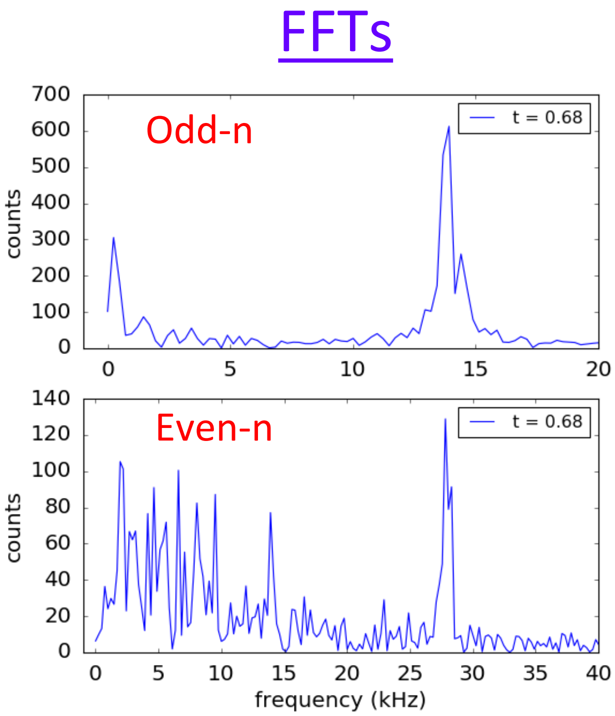




- NSTX "stable periods" – enhanced by high elongation (κ ~ 2.7), lithium wall conditioning
- NSTX-U: rotating MHD more common (lower κ ~ 2.3, no lithium)

DECAF rotating MHD analysis identifies the state of the modes found

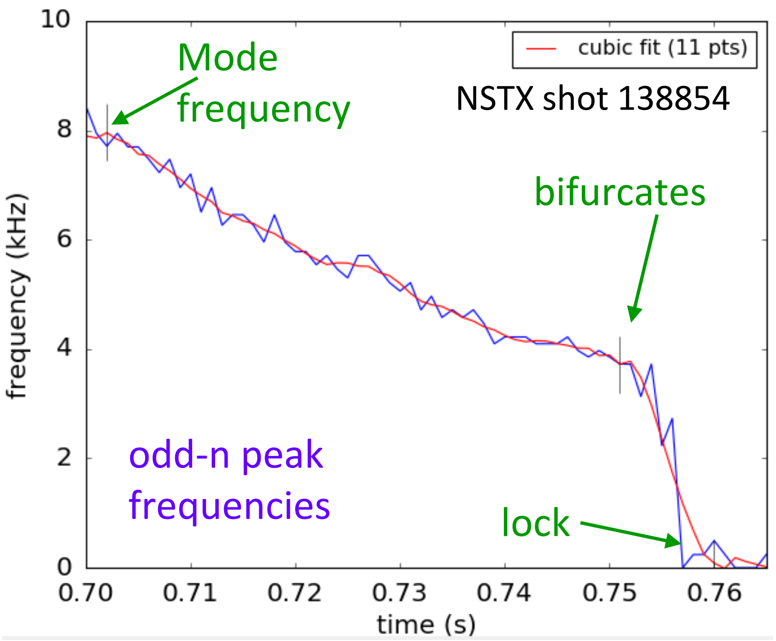


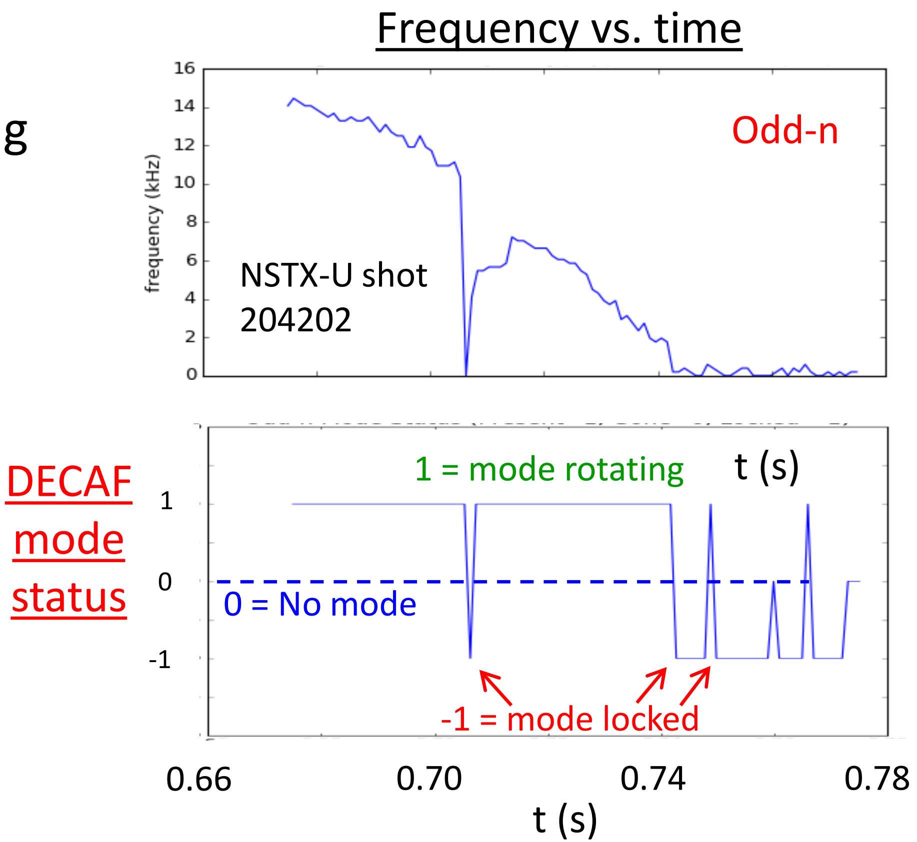


- Fast Fourier transforms used to find mode peak frequency within a time interval
- Presently adding phase matching and SVD algorithms to DECAF to determine mode numbers, track strongest modes
- General algorithm with ability to process multi-machine data

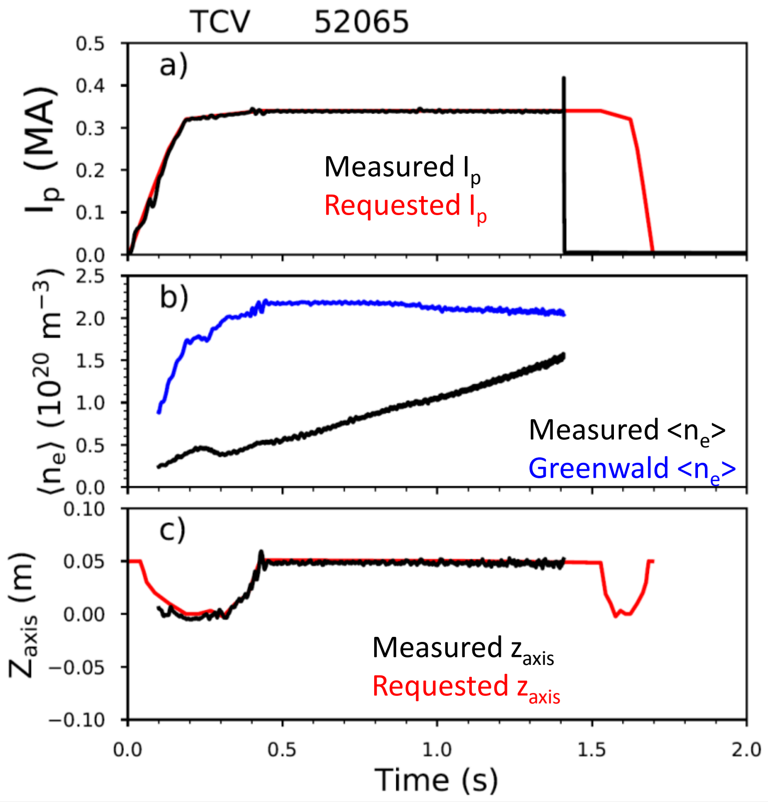
The characterization algorithm shows that the expected bifurcation and locking events can be automatically found

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





Example of expansion to multiple machines: DECAF now being tested on TCV tokamak data



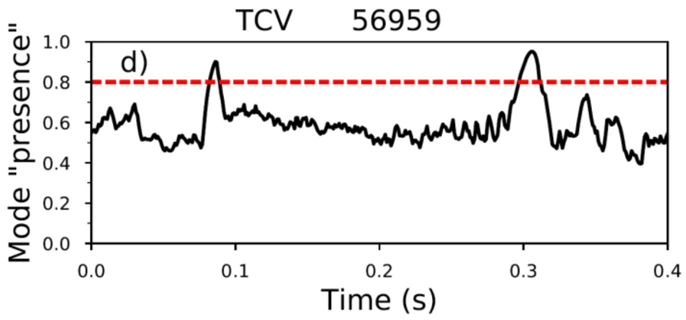
DECAF events implemented:

- IPR (I_p not meeting request)
- GWL (Greenwald density limit)
- VSC (Vertical stability control)

TCV advantage:

Excellent real-time measurement and control capabilities

- MHD (presence of an MHD mode)



[C. Galperti et al., IEEE TNS 64, 1446 (2017)]

Next: radiated power, more real-time MHD signals…

Conclusions and next steps

- **The DECAF code characterizes 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**
- **Next steps**
  - Significant expansion of events and continued improvement of accuracy
  - Starting DECAF analysis on other tokamaks (DIII-D, KSTAR, TCV available)

Backup