Abstract

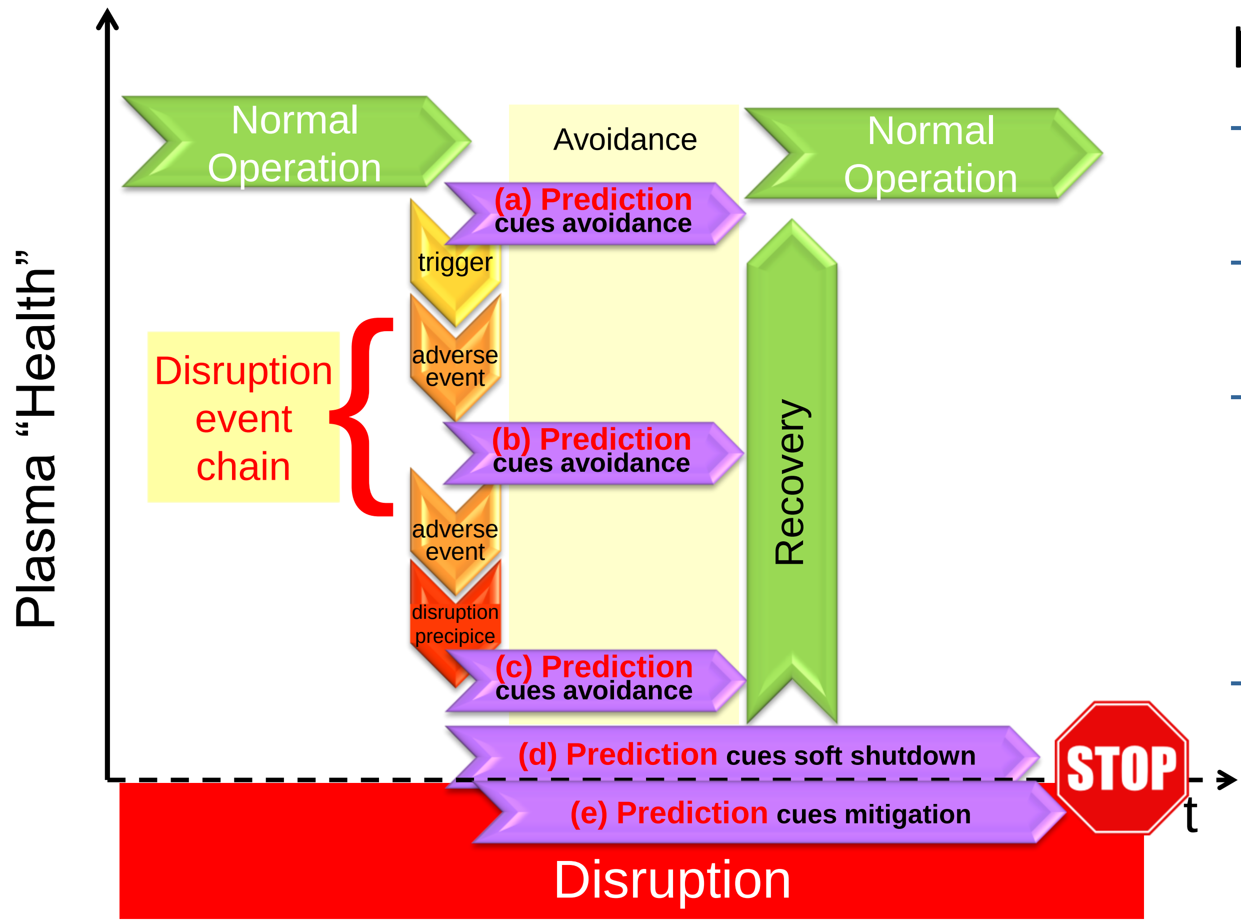
The Disruption Event Characterization and Forecasting (DECAF) code, being developed to meet the challenging goal of high reliability disruption prediction in tokamaks, automates data analysis to determine chains of events that lead to disruptions and to forecast their evolution. The relative timing of magnetohydrodynamic modes and other events including plasma vertical displacement, loss of boundary control, proximity to density limits, reduction of safety factor, and mismatch of the measured and desired plasma current are considered. NSTX/-U databases are examined with analysis expanding to DIII-D, KSTAR, and TCV. Characterization of tearing modes has determined mode bifurcation frequency and locking points. In an NSTX database exhibiting unstable resistive wall modes (RWM), the RWM event and loss of boundary control event were found in 100%, and the vertical displacement event in over 90% of cases. A reduced kinetic RWM stability physics model [1] is evaluated to determine the proximity of discharges to marginal stability. The model shows high success as a disruption predictor (greater than 85%) with relatively low false positive rate.

[1] J.W. Berkery, et al., Phys. Plasmas 24 (2017) 506103

*Supported by US DOE Contracts DE-FG02-99ER54524, DE-AC02-09CH11466, and DE-SC0016614.

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

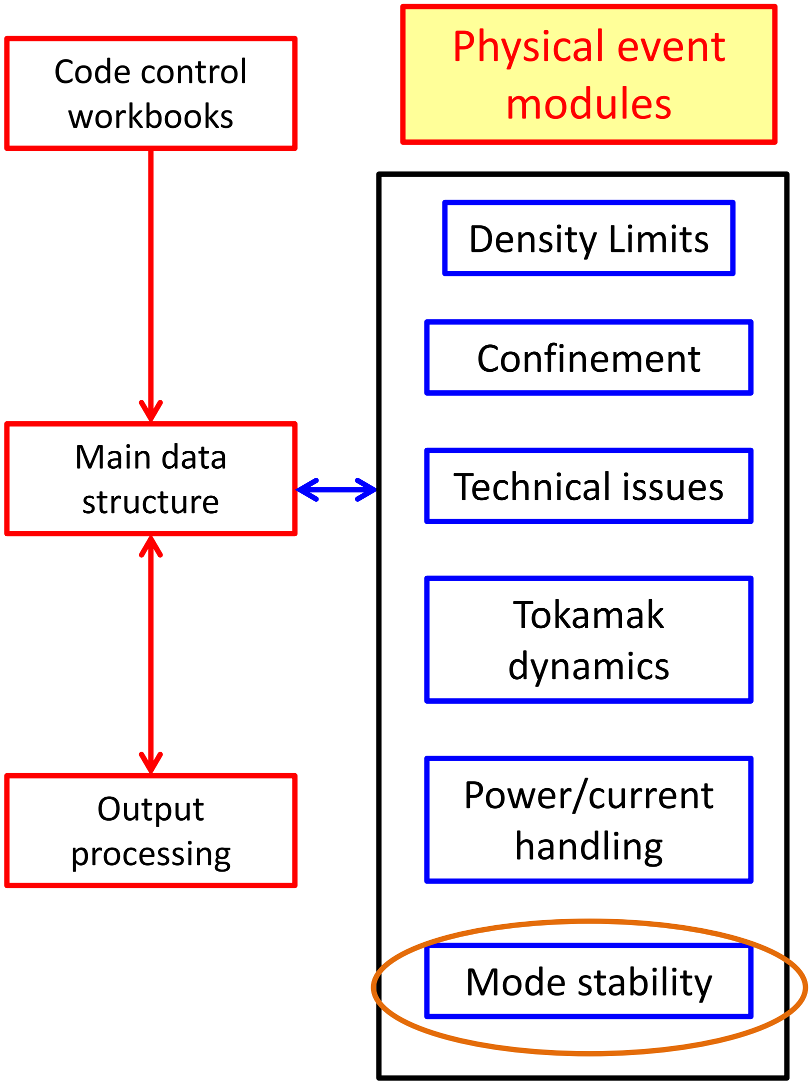
Disruption prediction/avoidance framework



[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



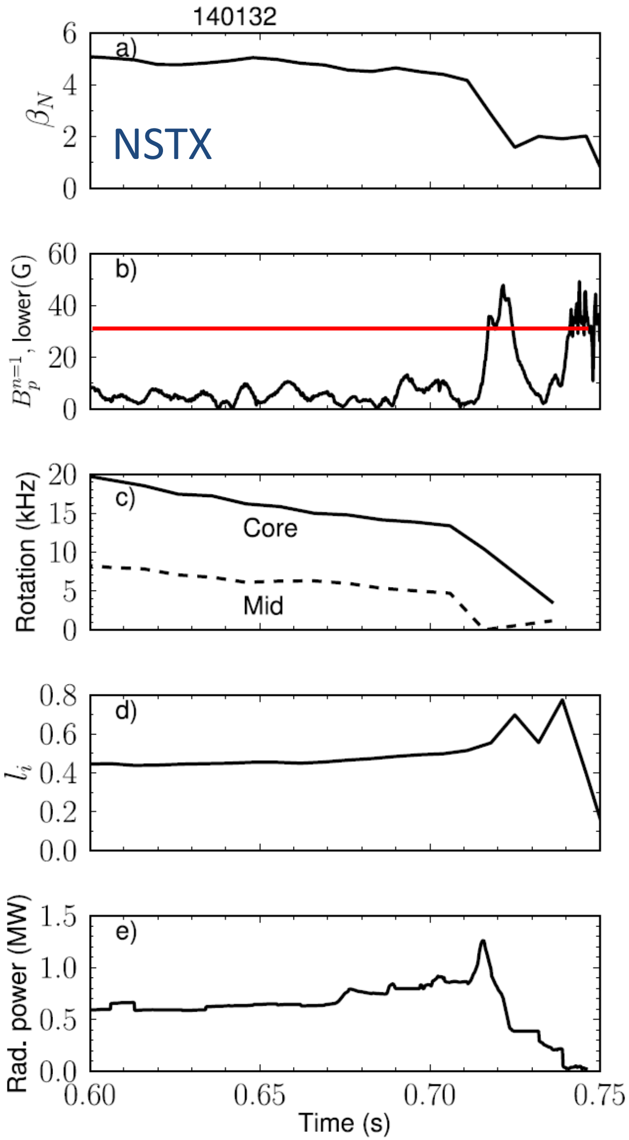
- Physical event modules
  - Present grouping follows work of deVries [P.C. de Vries et al., Nucl. Fusion 51, 053018 (2011)]
  - BUT, easily appended or altered
- Warning algorithms
  - Present approach follows [S.P. Gerhardt et al., Nucl. Fusion 53, 063021 (2013)]
  - More flexible: arbitrary number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

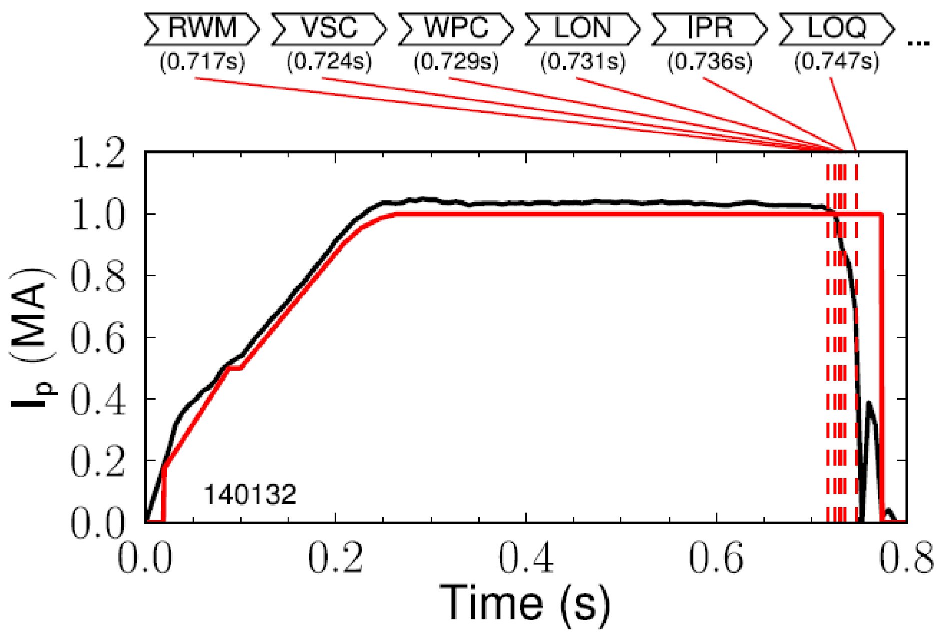
Group	Disruption chain event		Points	Test Criteria	Test Thresholds	Points
NL	Greenwald limit	GWL	3	Greenwald density limit	[0.90,0.95,0.99]	[1,2,3]
	Low density (error field)	LON	3	Decrease in line density (10^{14} cm^3/s) too large	[-10.0,-20.0,-30.0]	[1,2,3]
				Line density (10^{14} cm^3) too low	[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	$\lvert I_p^{req} - I_p \rvert / I_p^{req} >$	[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]
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

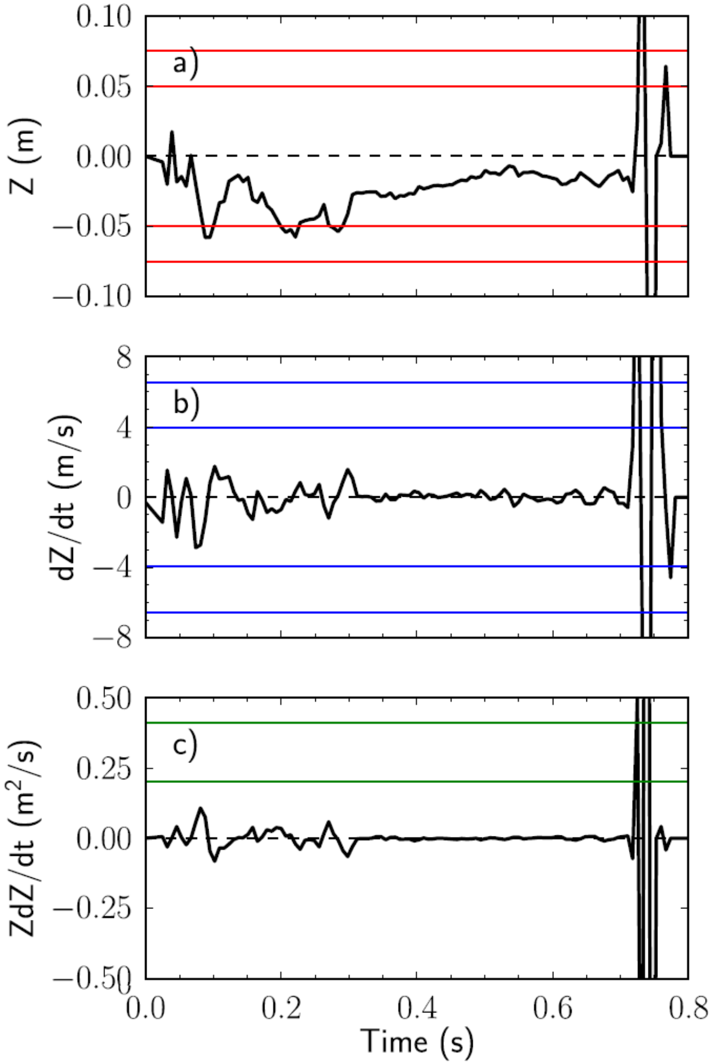


- Example DECAF analysis on single NSTX discharge
  - Ex: RWM $B_p^{n=1}$ threshold 30G ($\delta B/B0 \sim 0.67\%$)

<u>Disruption Events and Chain</u>

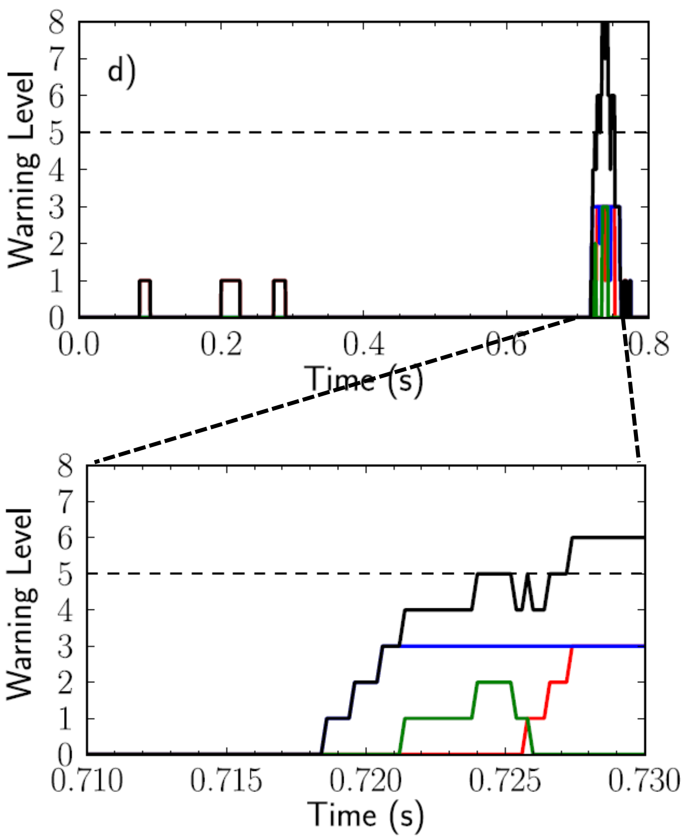


Tests can be combined with “warning points”



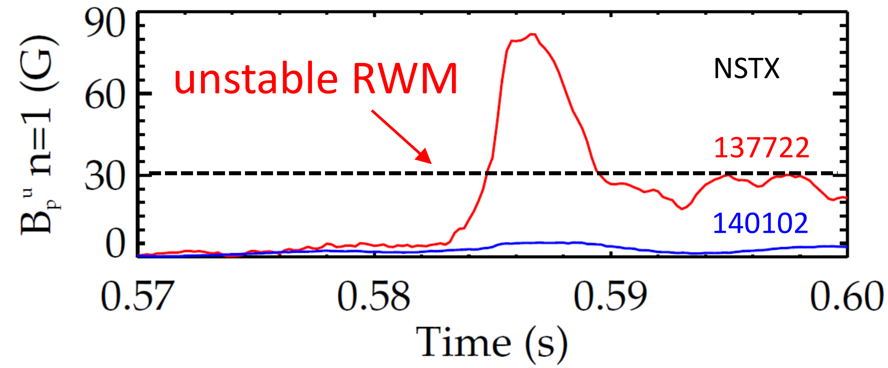
Example DECAF analysis on single NSTX discharge

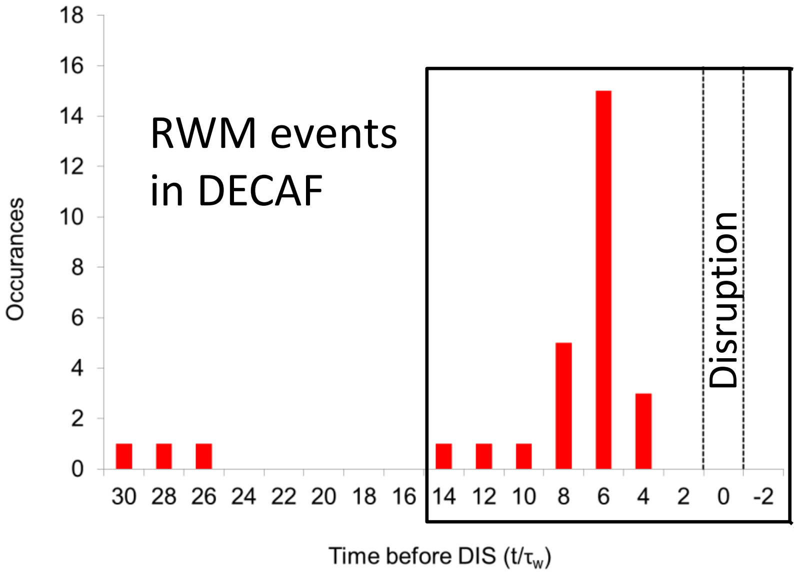
– Ex: VSC uses Z, dZ/dt, and ZdZ/dt

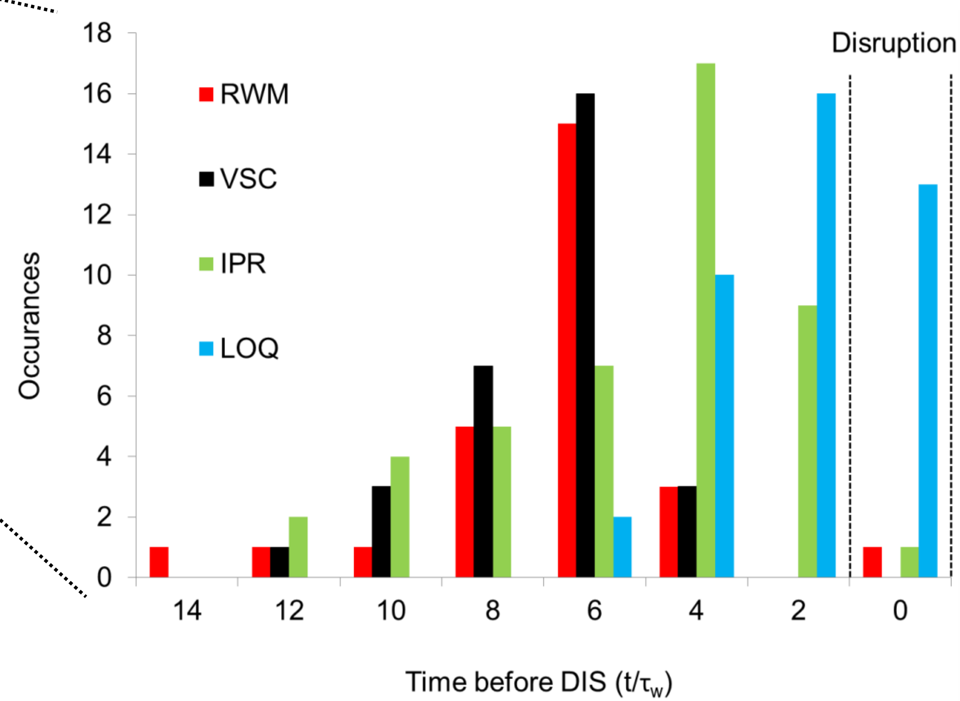


Initial DECAF results detects disruption chain events when applied to dedicated 45 shot NSTX RWM disruption database

- 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

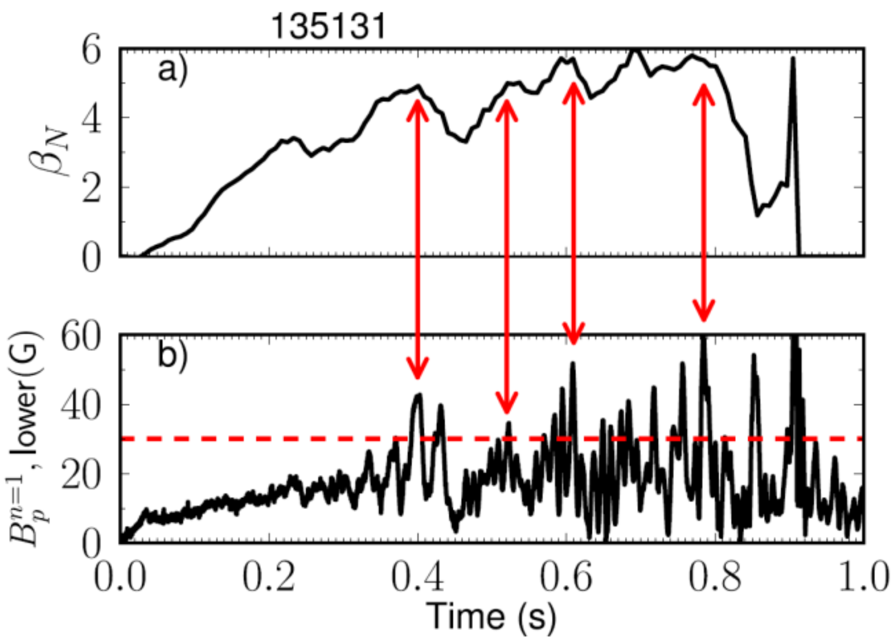
IPR: Plasma current request not met

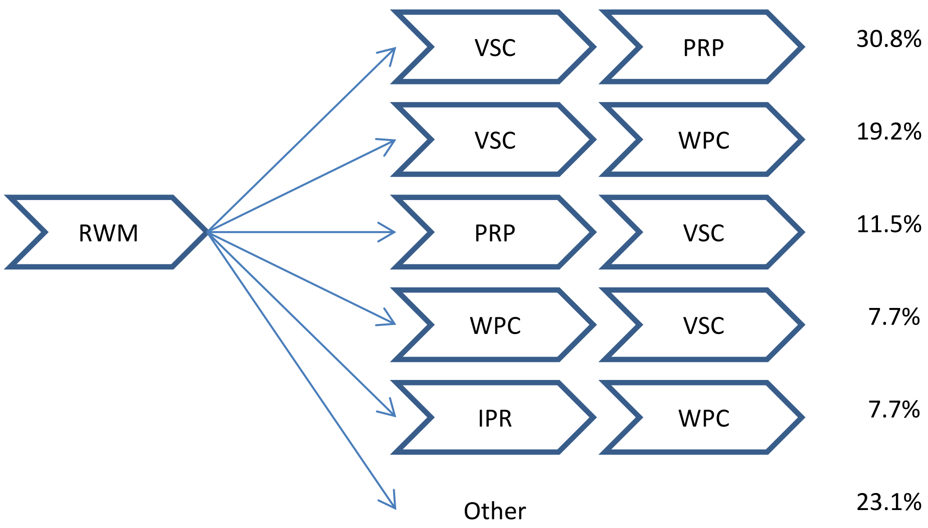
LOQ: Low edge q warning

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

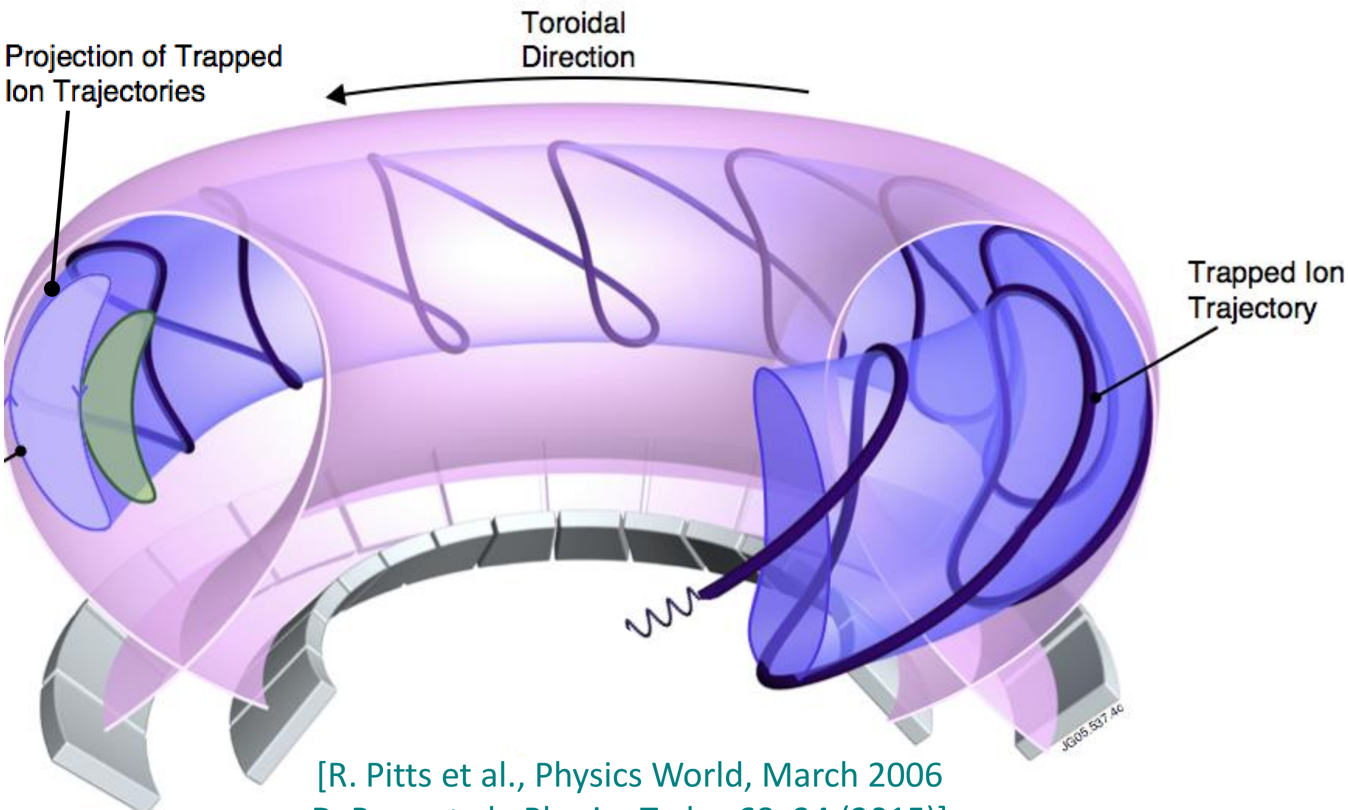
- Earlier RWM events *not* false positives
  - cause large decreases in β_N and stored energy with subsequent recovery (minor disruptions)

- 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

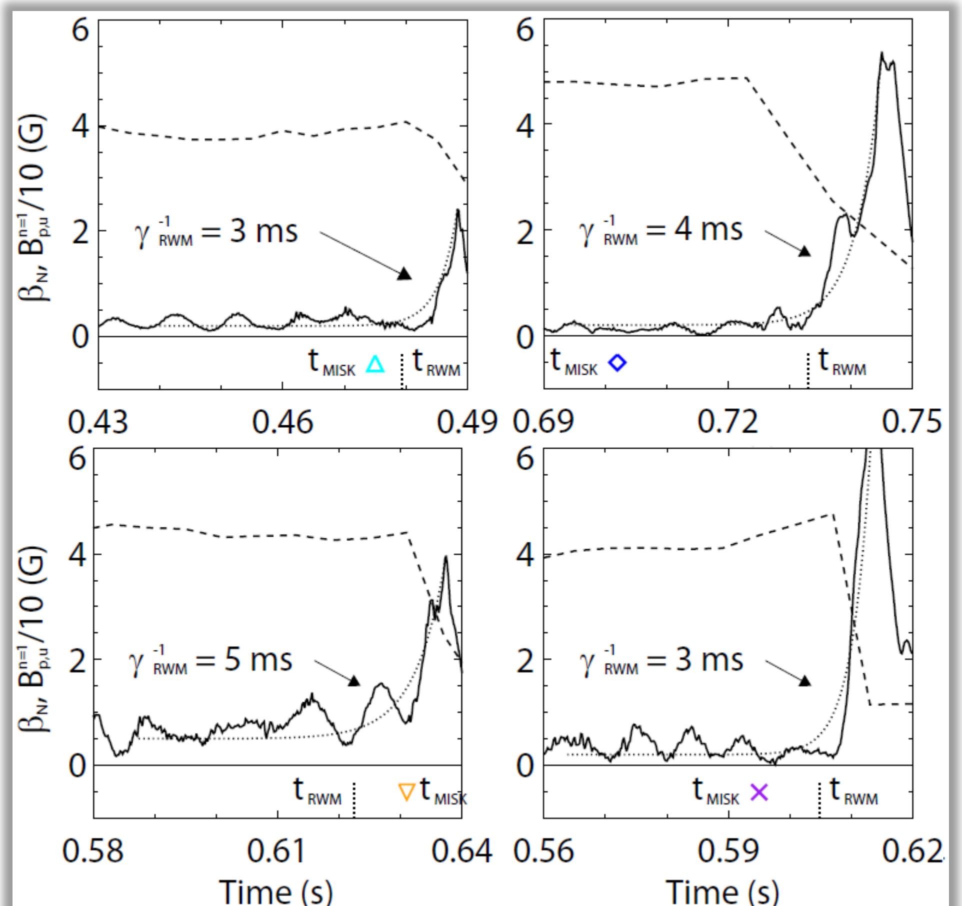
Precession Drift ~ Plasma Rotation

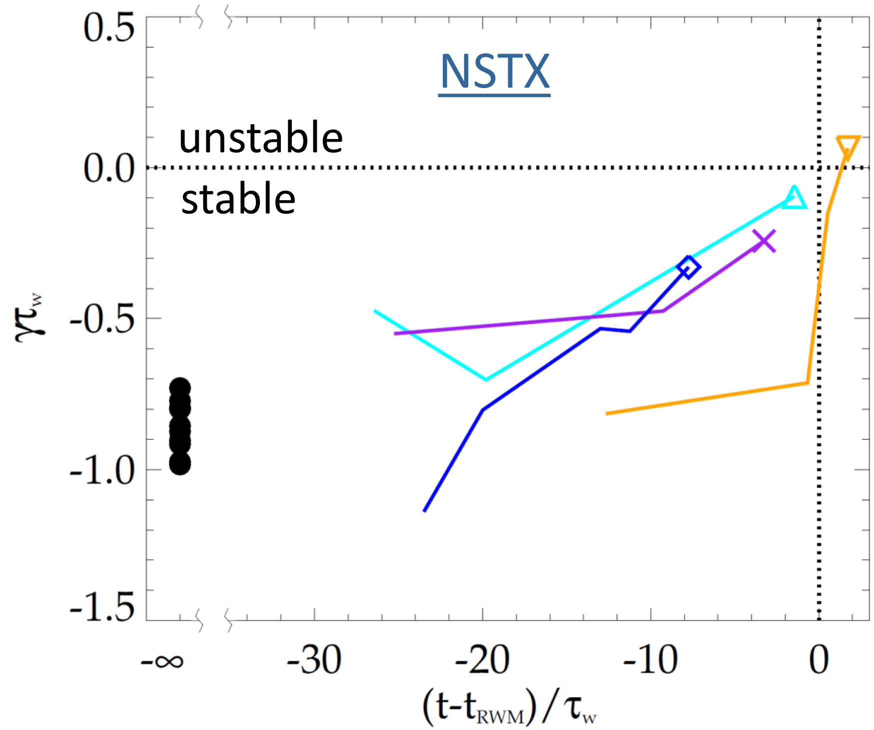
Rotational resonance effect

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

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

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

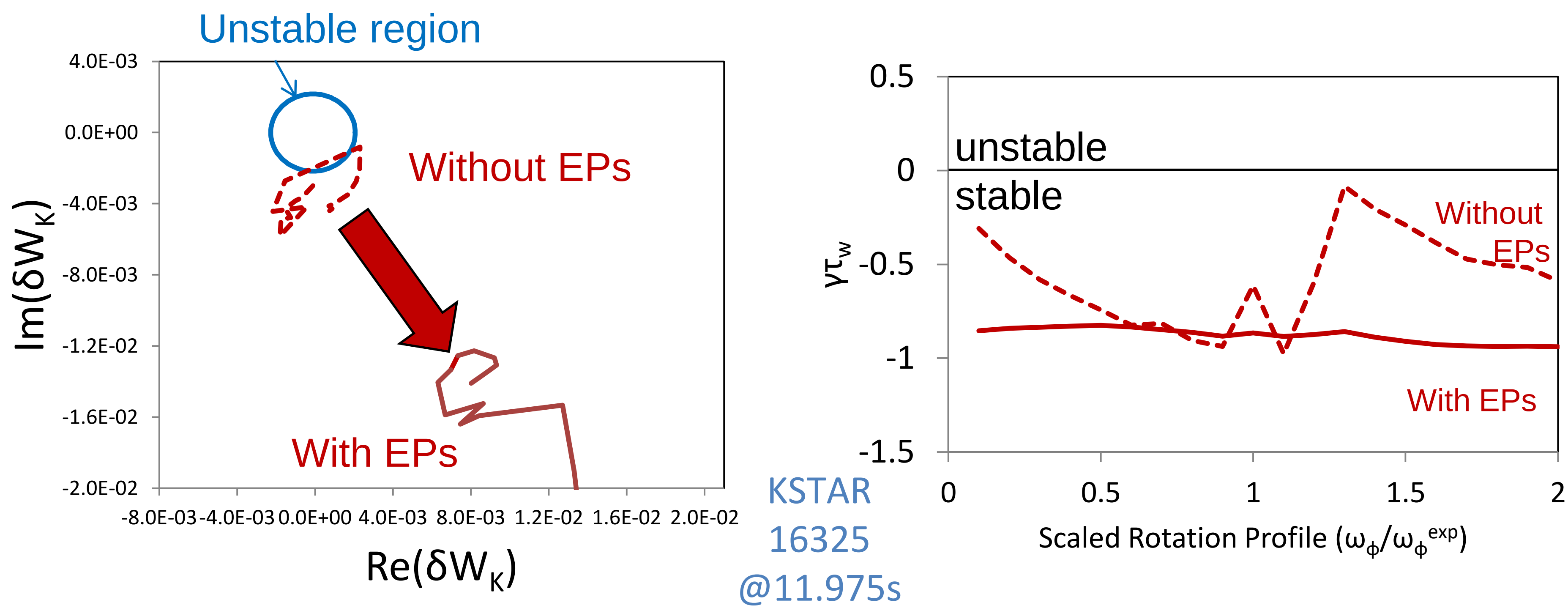




[J. Berkery et al., Nucl. Fusion 55, 123007 (2015)]

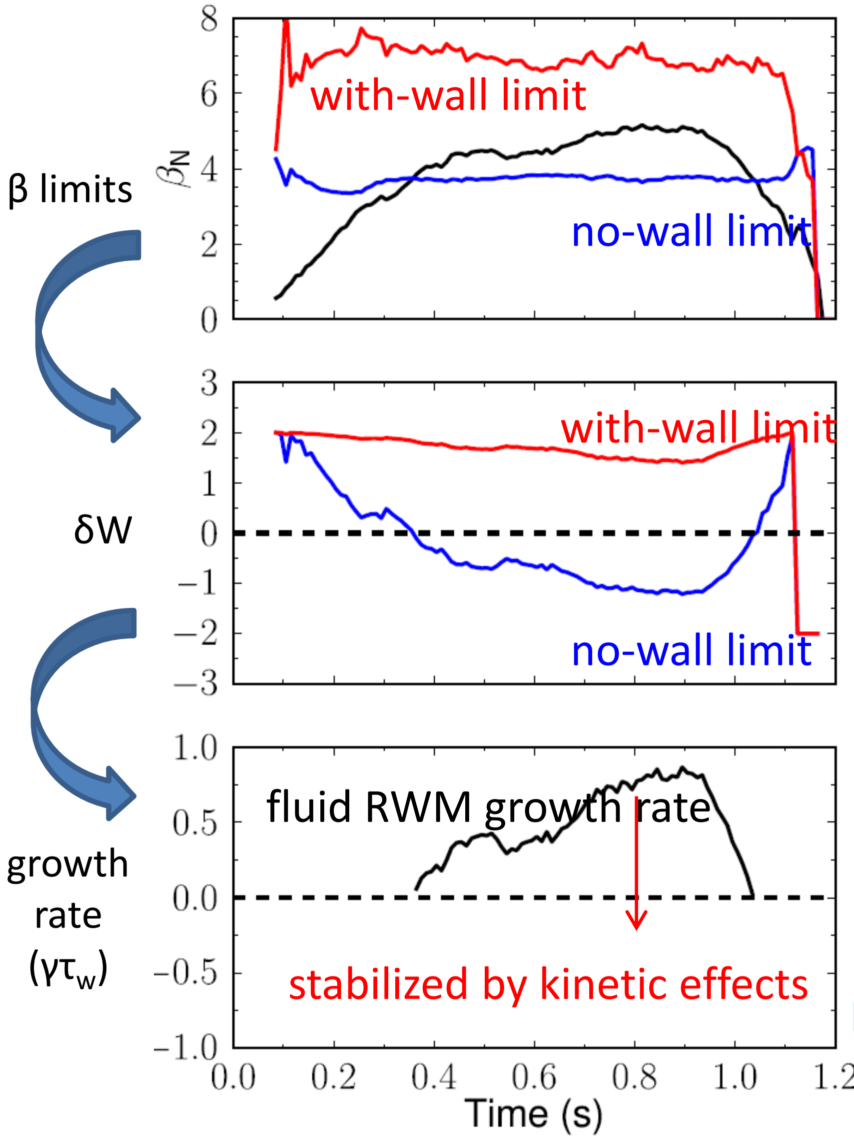
- MISK calculations including kinetic effects have been tested against many marginally stable NSTX experimental cases
- MISK also validated in dedicated DIII-D experiment, analogous to NSTX expts

MISK kinetic stability analysis of KSTAR indicates large stabilizing effect of energetic particles



- MISK calculations find the equilibrium is stable to resistive wall modes (consistent with experiment)
  - Close to marginal stability with variation of the experimental rotation profile and without considering energetic particles
  - Energetic particles contribute large stabilizing effect (due to large EP fraction)

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



NSTX 138556

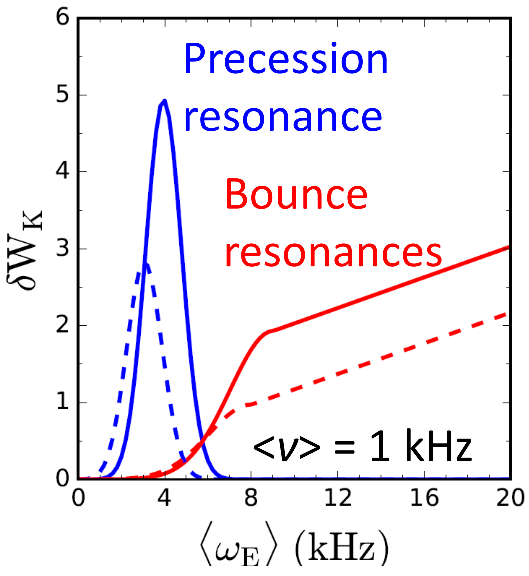
RWM dispersion relation

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



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

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

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

MISK[2] Calculations

Fluid terms[10]

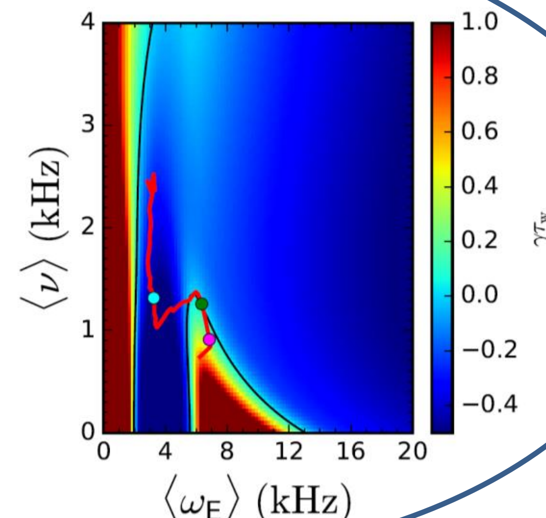
Kinetic effects[1]: Collisionality[5] Rotation[3]

+ 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)
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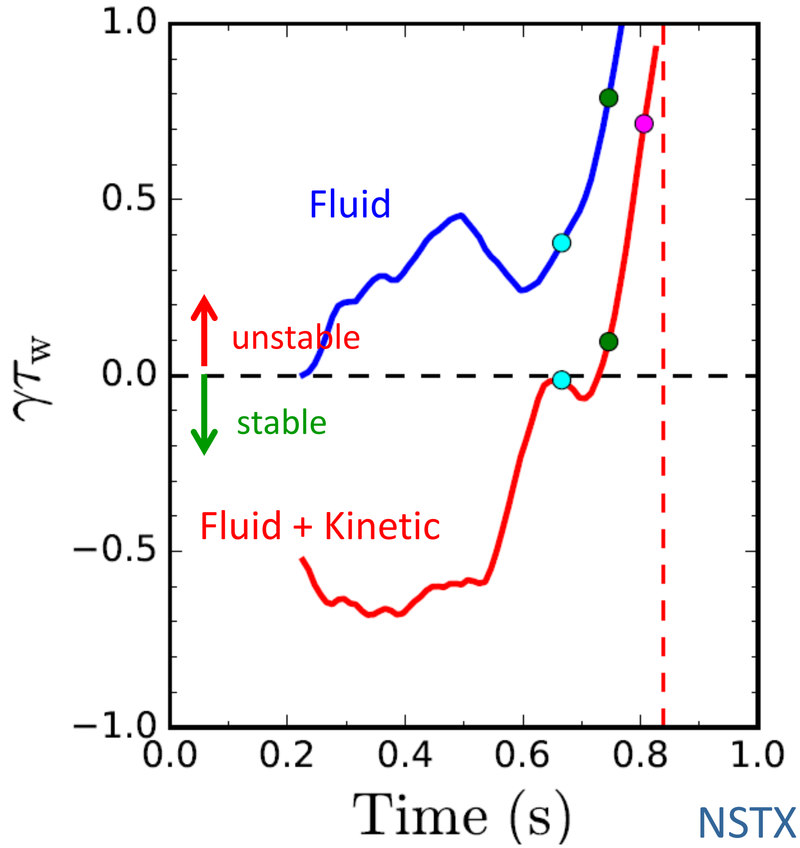
DECAF contains modeled kinetic quantities for generation of stability maps

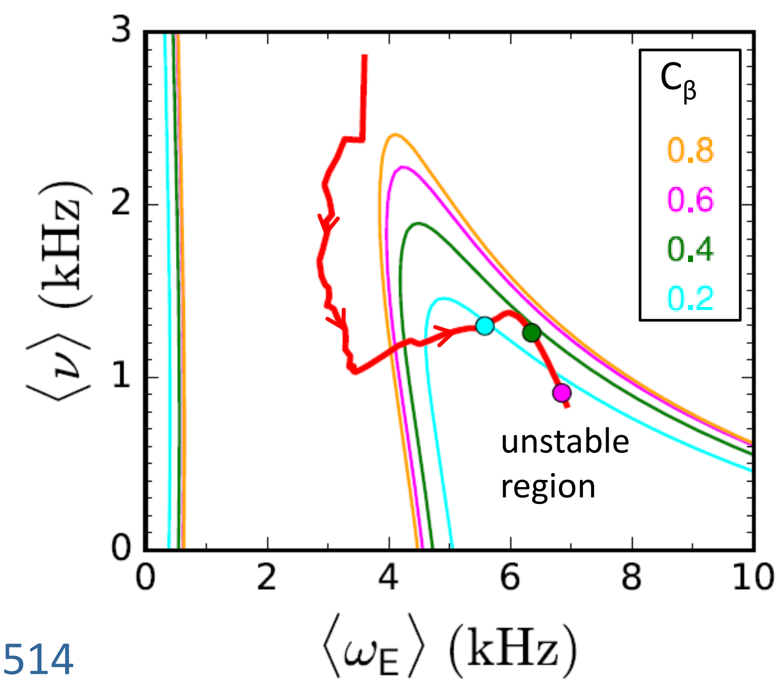
Normalized growth rate vs. time



NSTX 139514

- Stability diagram shows trajectory of a discharge towards unstable regions

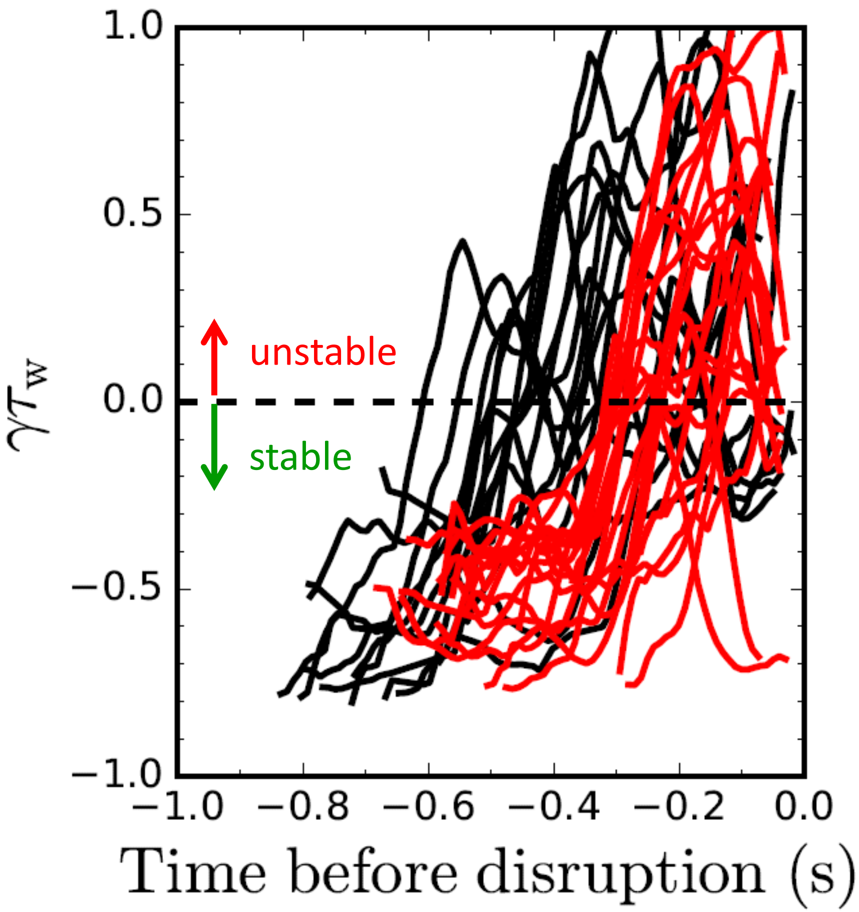
$C_\beta = (\beta_N - \beta_N^{no\text{-}wall}) / (\beta_N^{with\text{-}wall} - \beta_N^{no\text{-}wall})$



[J. Berkery et al., Physics of Plasmas 24, 056103 (2017)]

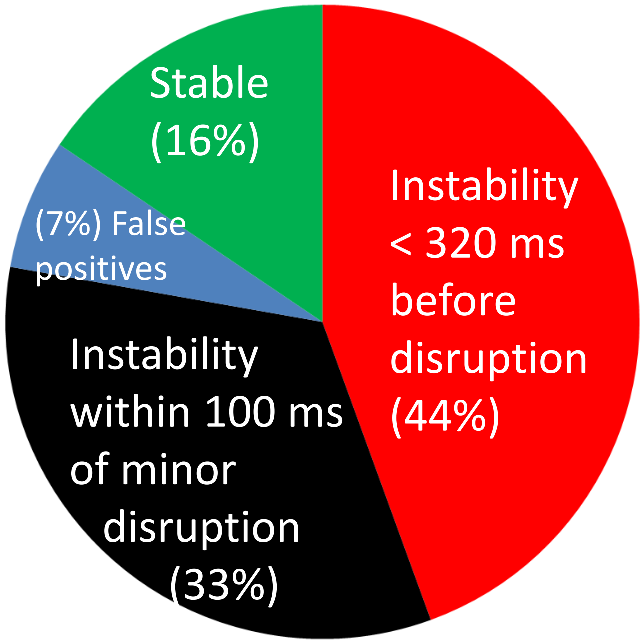
DECAF reduced kinetic model results initially tested on a database of NSTX discharges with unstable RWMs

Normalized growth rate vs. time



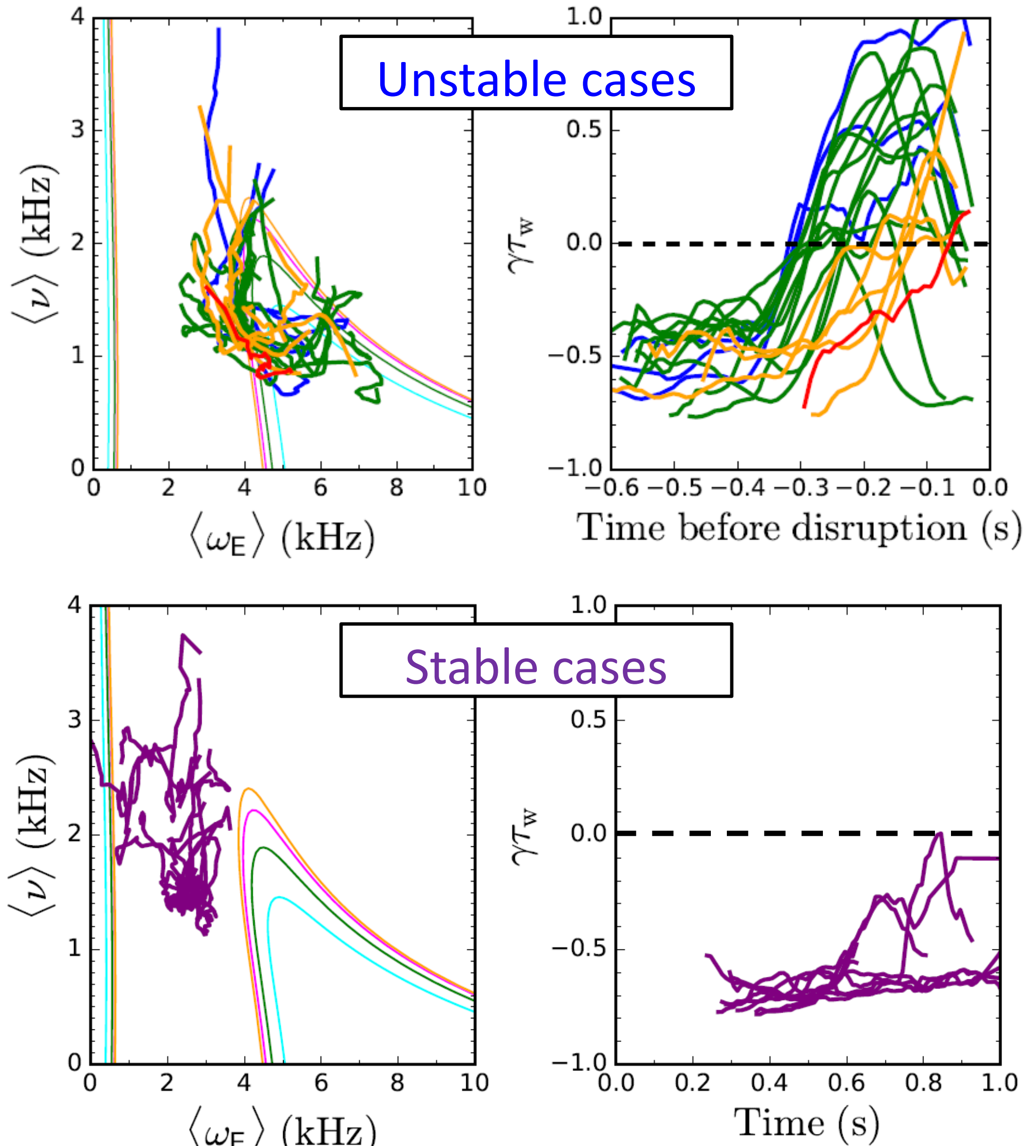
[J. Berkery et al., Physics of Plasmas 24, 056103 (2017)]

Predicted instability statistics (45 shots)



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

Reduced kinetic model distinguishes between stable and unstable NSTX discharges



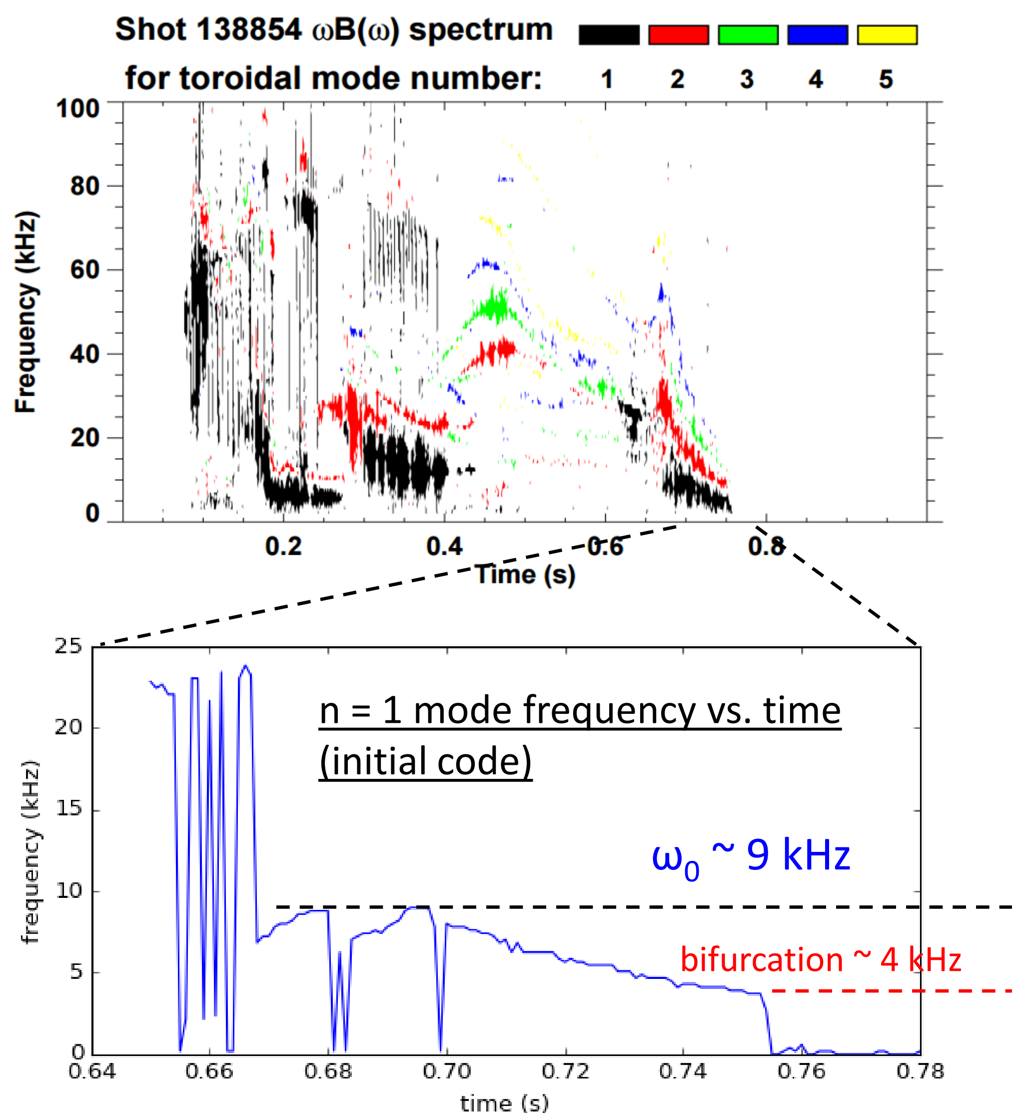
- If $\langle\omega_E\rangle \sim 0$ warnings are eliminated, 10/13, or 77%, of stable cases are stable in the model
- Model is successful in first incarnation - development continues to improve forecasting performance

[J. Berkery et al., Physics of Plasmas 24, 056103 (2017)]

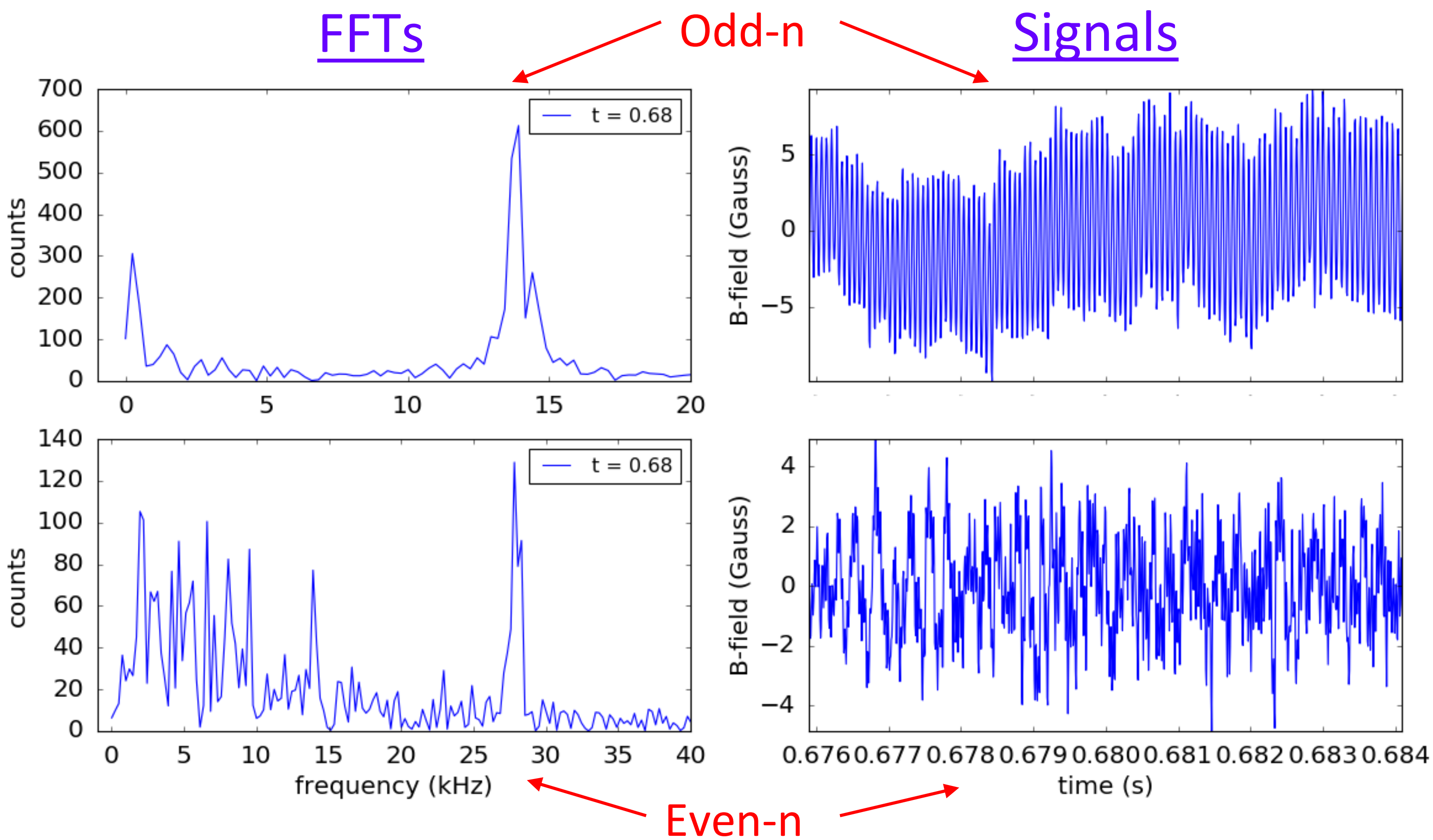
Essential new step for DECAF analysis of general tokamak data: Identification of rotating MHD (e.g. NTMs)

- 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



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

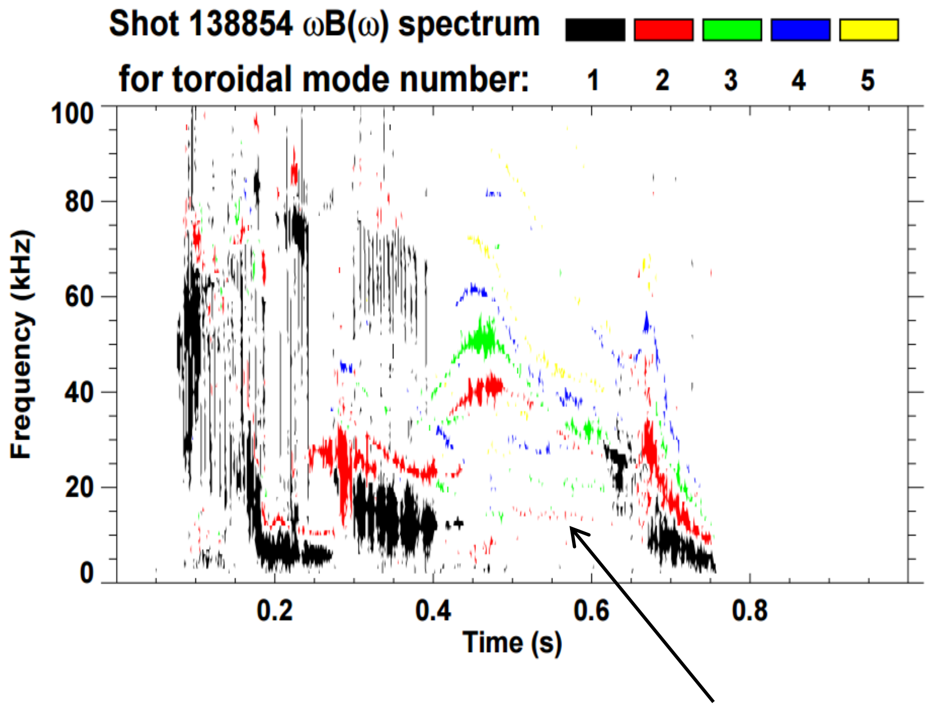


- Reveals potential issues handling multiple frequency peaks
- Now adding processing of toroidal array / *n* number discrimination

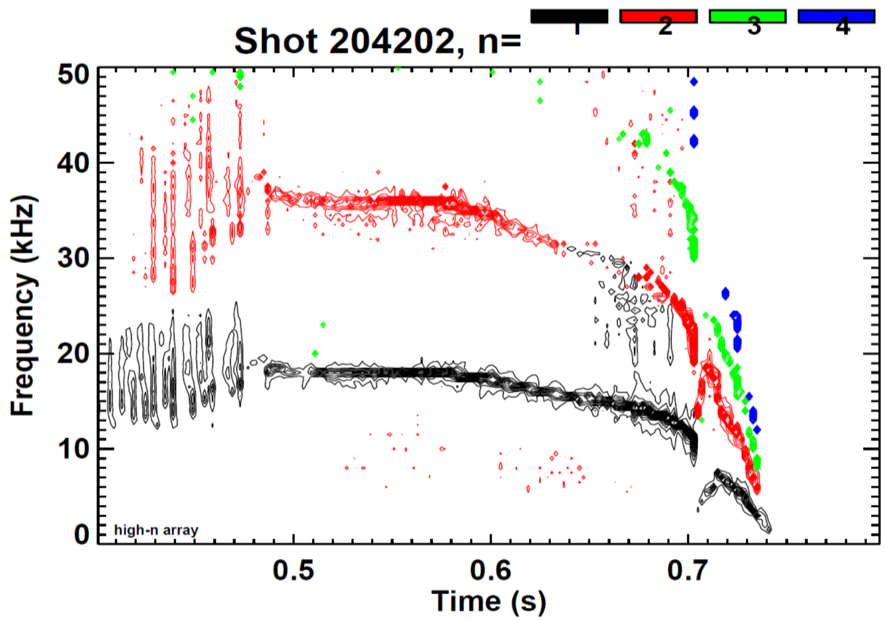
Many shots with rotating MHD (e.g. NTMs) examined for NSTX and NSTX-U – two illustrated here

Magnetic spectrogram of rotating MHD mode locking termination

NSTX 138854



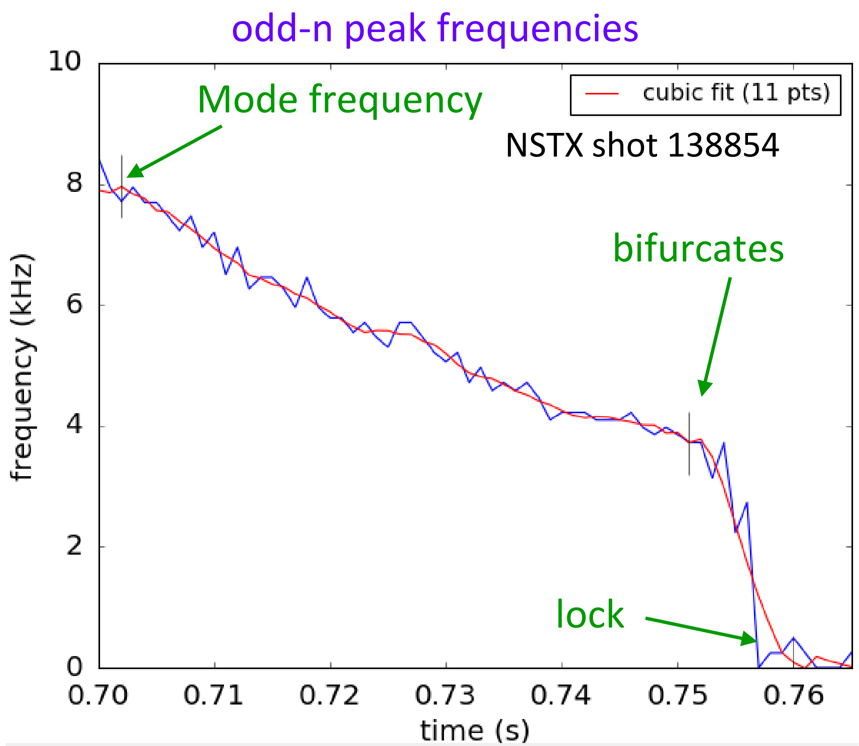
NSTX-U 204202

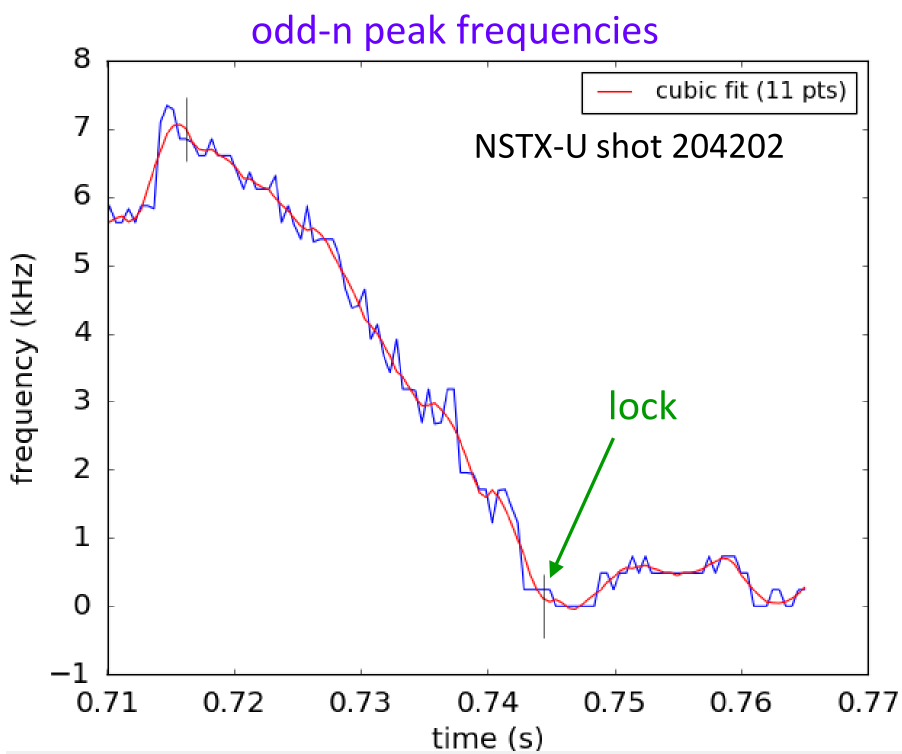


- NSTX "stable periods" – enhanced by high elongation (κ ~ 2.7), lithium wall conditioning
- NSTX-U: rotating MHD at lower κ ~ 2.3 , no Li wall conditioning

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

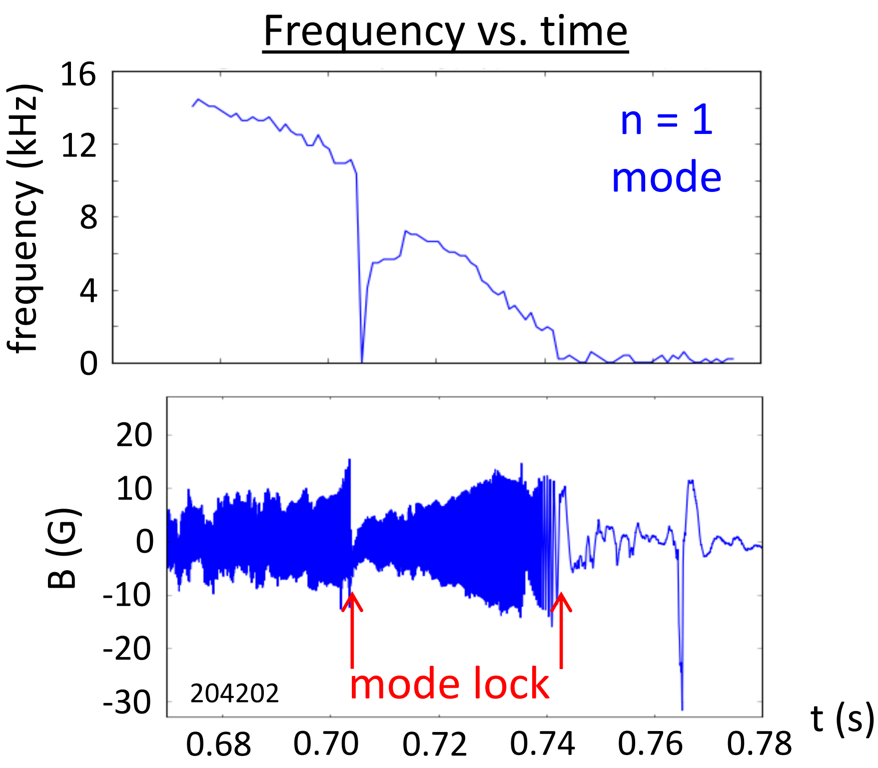
- Algorithm written looks for a "quasi-steady state" period, a potential bifurcation, and possible mode locking

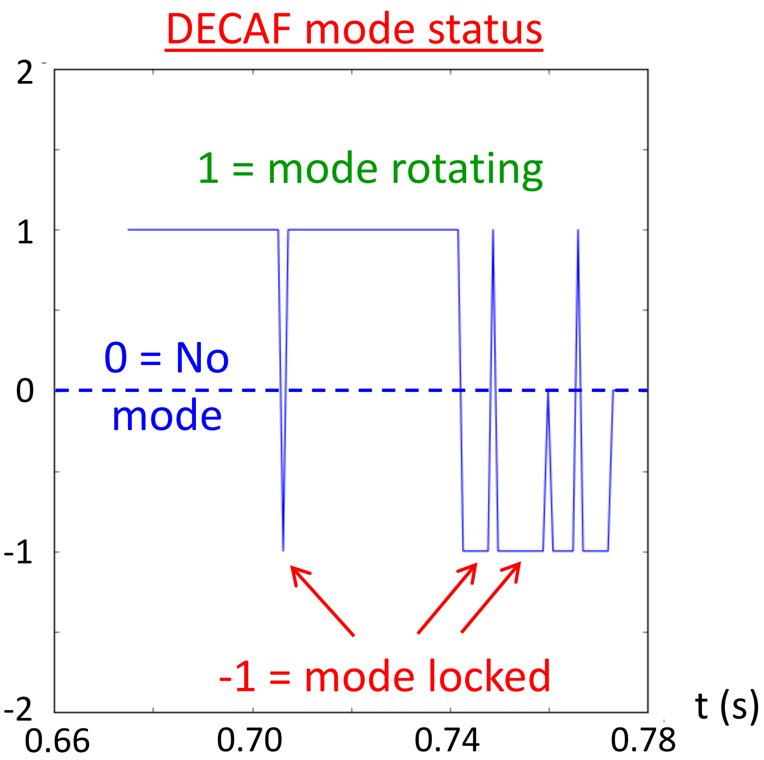




DECAF rotating MHD analysis identifies the state of the modes found (n = 1)

Magnetic signal / analysis (mode locking / unlocking)

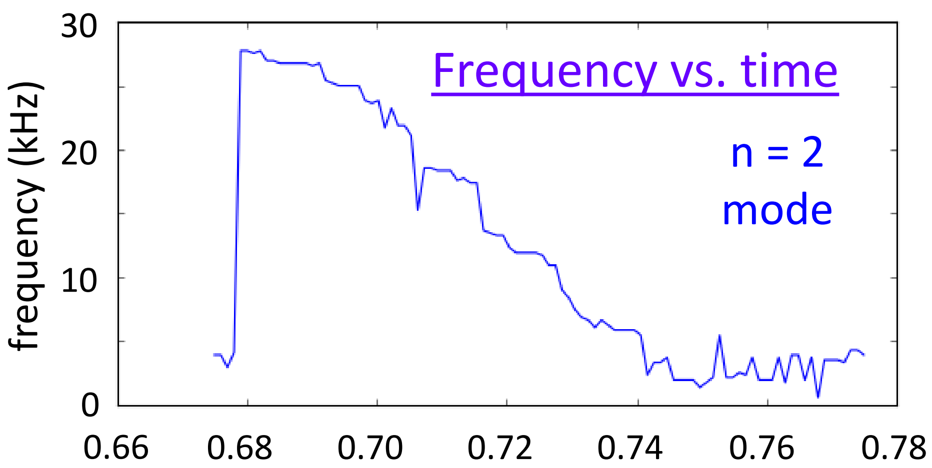


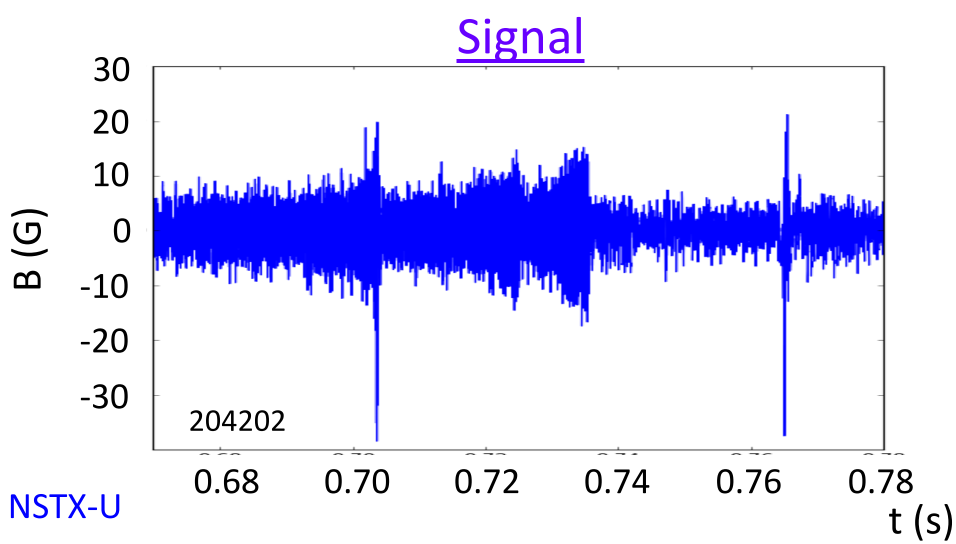


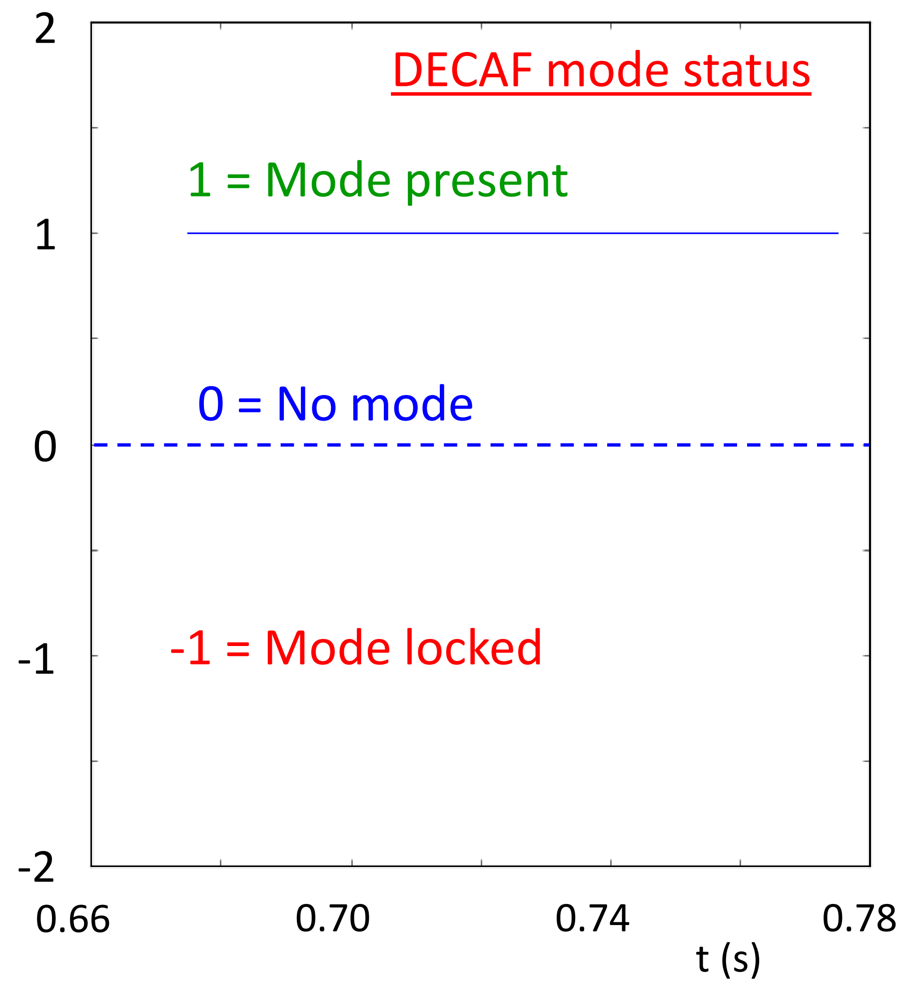
NSTX-U

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

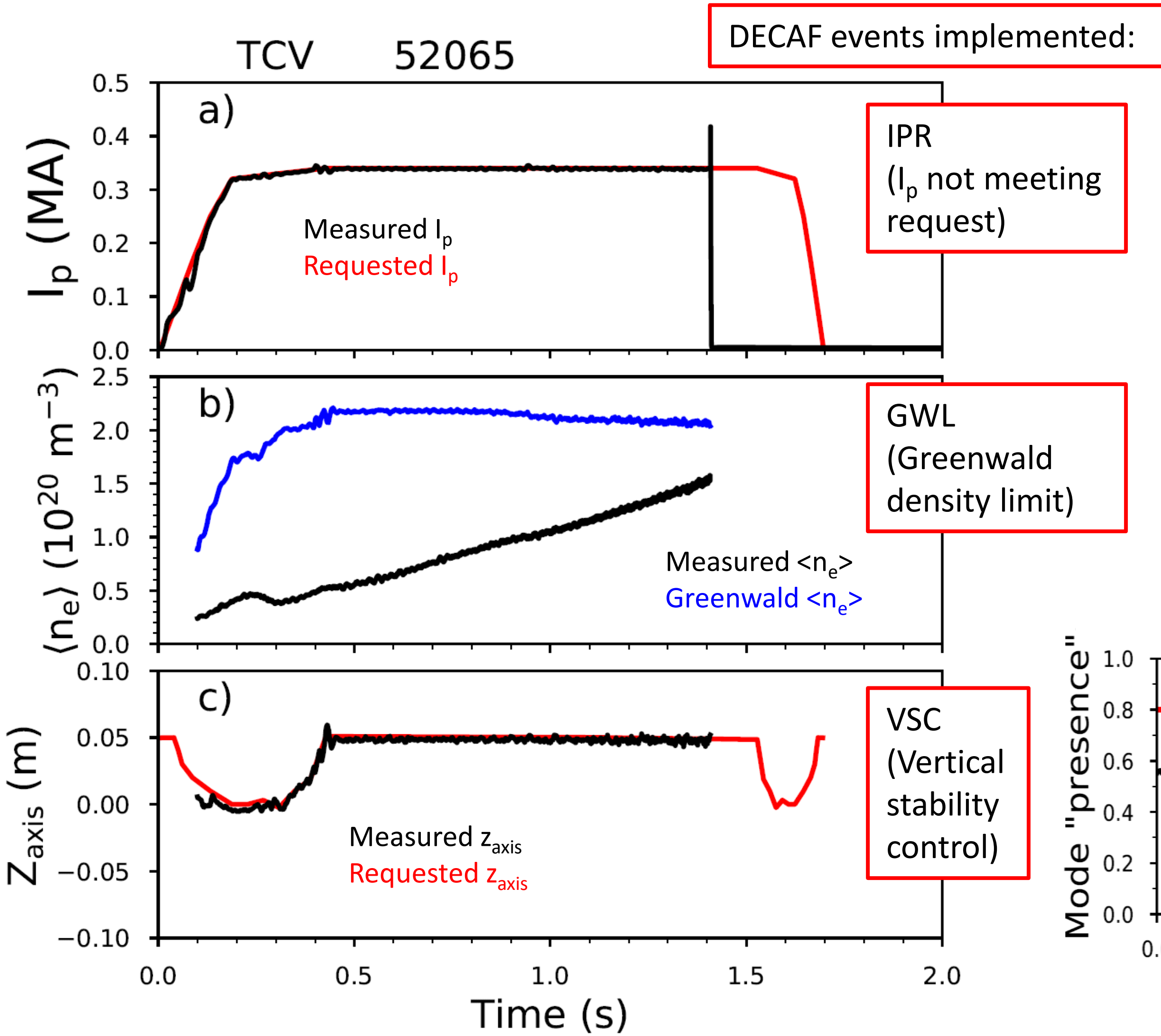
Magnetic signal / analysis (mode present, not locked)



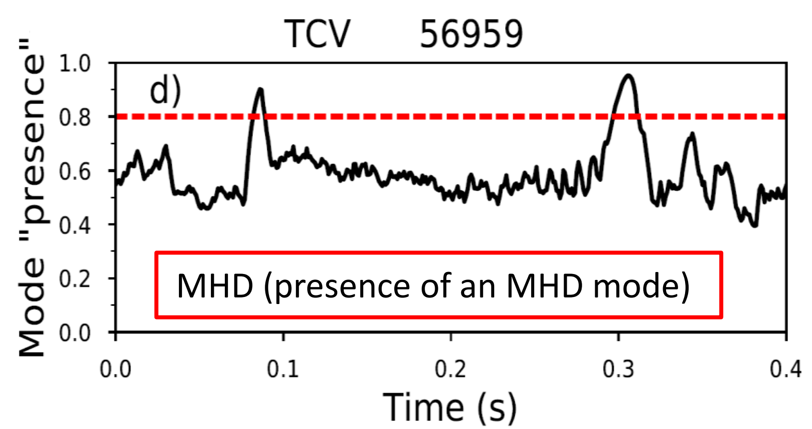




DECAF now being tested on TCV tokamak data, including detection of MHD



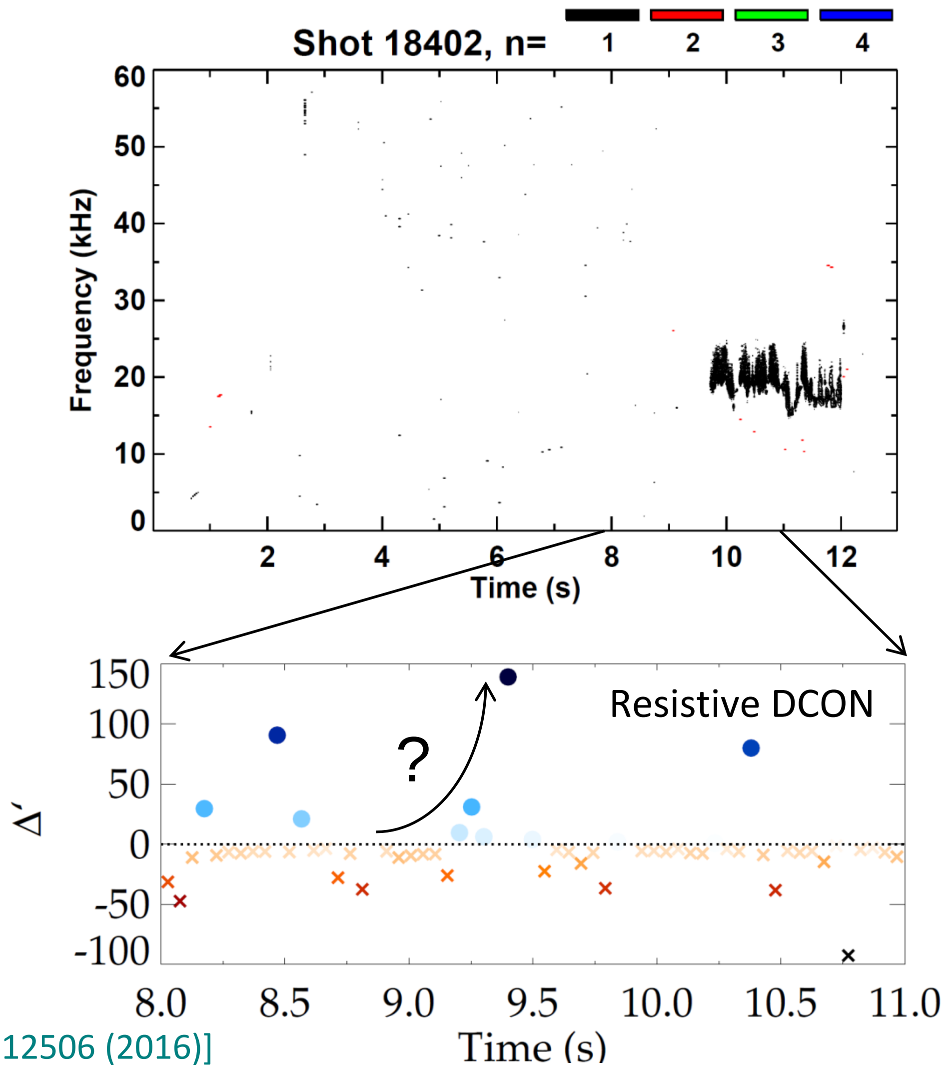
- TCV advantages:
  - Excellent real time measurement and control capabilities
  - Capability to detect modes (also in real time)



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

New tool for MHD stability analysis, resistive DCON, used on KSTAR for the first time

- New resistive DCON code used to calculate the q=2 Δ’ for a KSTAR case with sudden appearance of n=1 mode
  - Positive Δ’ would indicate classical instability at q=2
- Calculation shows a near marginal Δ’ around time of mode onset
  - Requires further analysis
- Resistive DCON capability could be used for future DECAF mode onset warning



Resistive DCON: [A. H. Glasser et al., Physics of Plasmas 23, 112506 (2016)]

Summary and next steps

- The Disruption Event Characterization and Forecasting code (DECAF)
  - Focuses on quantitative characterization, based on physics models, of the chains of events which most often lead to disruption of plasmas
  - The goal is to provide forecasts which integrate with a disruption avoidance system and are ultimately utilized in real-time during a device's operation
- Reduced kinetic model for disruption avoidance is implemented
  - Success rate is surprisingly high for the initial analysis
- Rotating MHD is common, causes disruptions; Identification 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, TCV, KSTAR)

**This work supported by the US DOE contracts DE-AC02-09CH11466, DE-FG02-99ER54524, and DE-SC0016614*

Related talk/posters

- Observation of the Generalized Neoclassical Toroidal Viscosity Offset Rotation Profile in KSTAR – S.A. Sabbagh, 10:54am Wednesday

Thursday afternoon posters

- Automated Identification of MHD Mode Bifurcation and Locking in Tokamaks – J.D. Riquezes
- Kinetic equilibrium reconstruction of KSTAR plasmas including internal pitch angle profile measurement – Y. Jiang
- Transport and stability analyses supporting disruption prediction in high beta KSTAR plasmas – J.H. Ahn
- MHD stability analysis and global mode identification preparing for high beta operation in KSTAR – Y.S. Park

Sign up for a copy

Disruption Event Characterization and Forecasting in Tokamaks

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Milwaukee, Wisconsin, October 23-27, 2017

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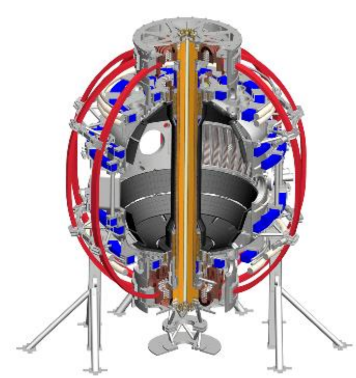

This work supported by the US DOE contracts DE-AC02-09CH11466 and DE-FG02-99ER54524

Another TCV slide?