U.S. DEPARTMENT OF ENERGY | Office of Science

NSTX-U

Disruption Event Characterization and Forecasting in NSTX-U

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11/1/16

Columbia University in the City of New York

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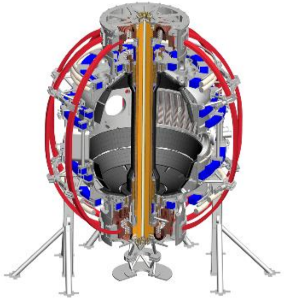
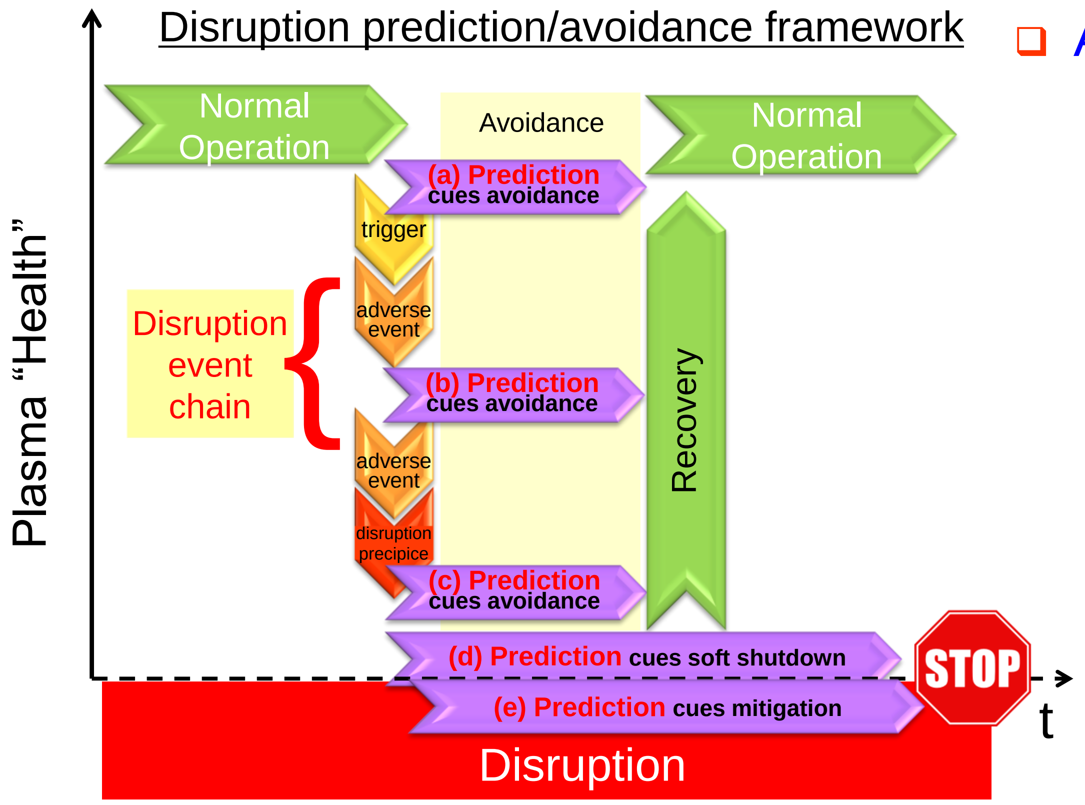
V1.6



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

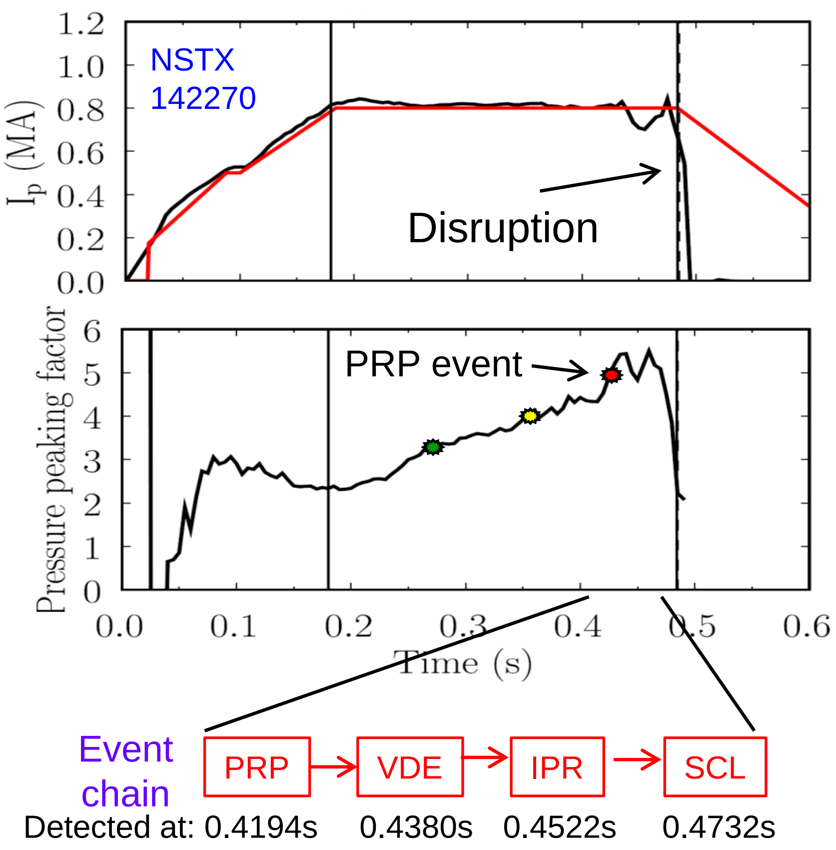
Disruption event chain characterization capability started for NSTX-U as next step in disruption avoidance plan



(from DOE Report on Transients in Tokamak Plasmas (2015))

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

Disruption Event Characterization And Forecasting Code (DECAF) yielding initial results

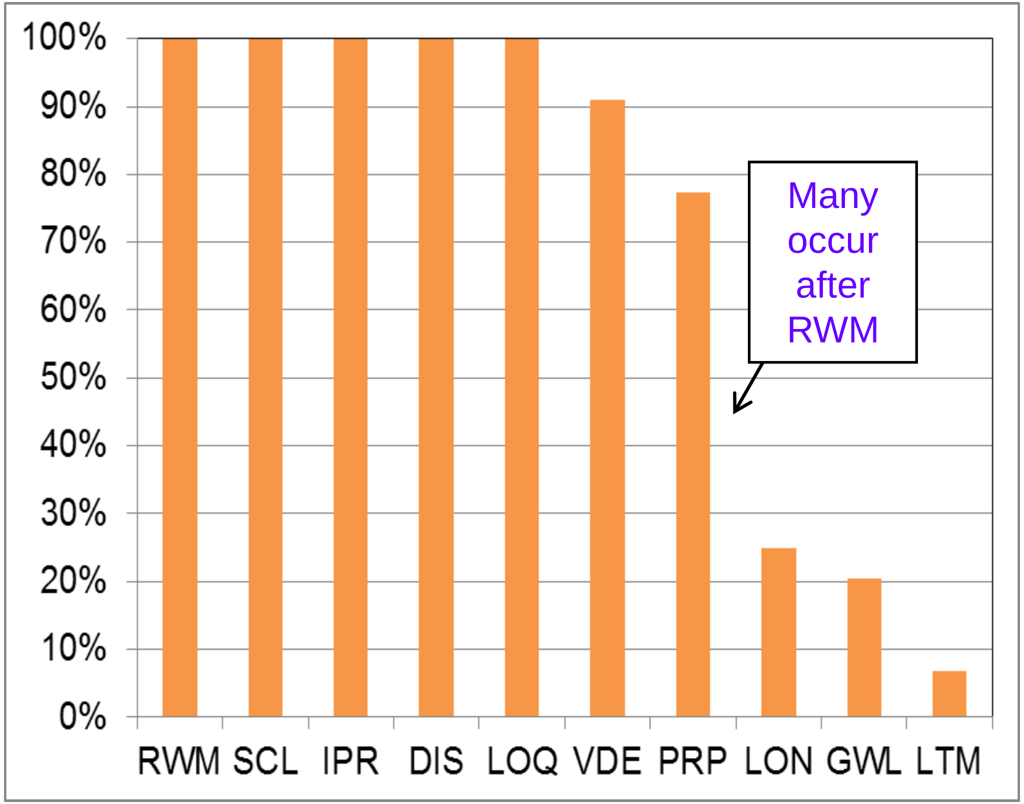


- 10 physical events presently defined in code with quantitative warning points
  - Builds on characterization work of de Vries
    P.C. de Vries *et al*., Nucl. Fusion **51** (2011) 053018
  - Builds on warning algorithm of Gerhardt
    S.P. Gerhardt *et al*., Nucl. Fusion **53** (2013) 063021
  - New code written (in Python) to be easily expandable, portable to other tokamaks (reads NSTX, NSTX-U, DIII-D data)

- Example: Pressure peaking (PRP) disruption event chain identified by code
  1. (PRP) Pressure peaking warnings identified first
  2. (VDE) VDE condition subsequently found 19 ms after last PRP warning
  3. (IPR) Plasma current request not met
  4. (SCL) Shape control warning issued

DECAF results detect disruption chain events when applied to dedicated 44 shot NSTX RWM disruption database

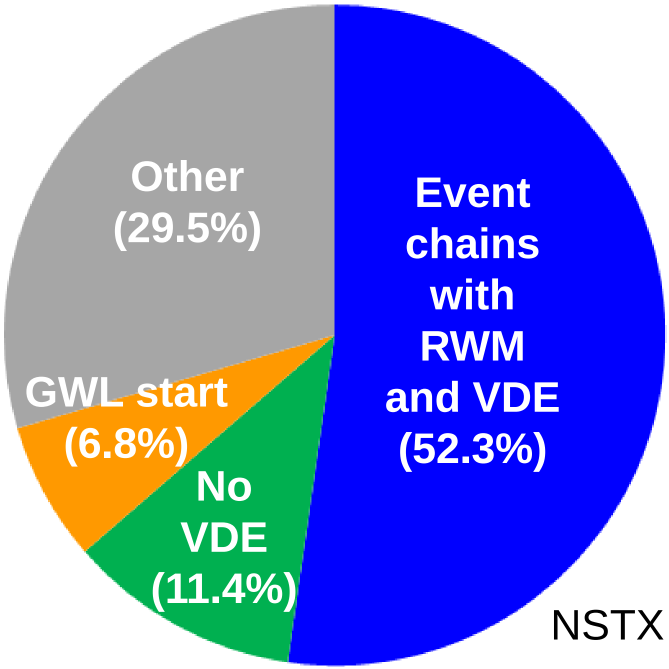
- Several events detected for all shots
  - RWM: Resistive wall mode
  - SCL: Loss of shape control
  - IPR: Plasma current request not met
  - DIS: Disruption occurred
  - LOQ: Low edge q warning
  - VDE: VDE warning (40 shots)
- Other Events
  - PRP: Pressure peaking warning
  - LON: Low density warning
  - GWL: Greenwald limit
  - LTM: Locked tearing mode



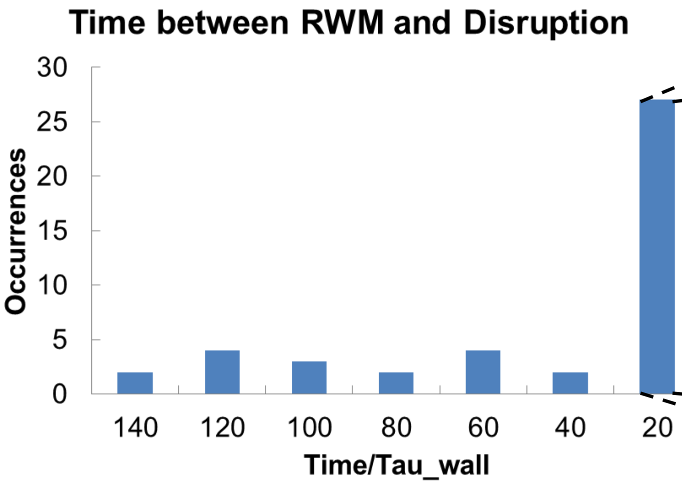
DECAF analysis is finding common disruption event chains

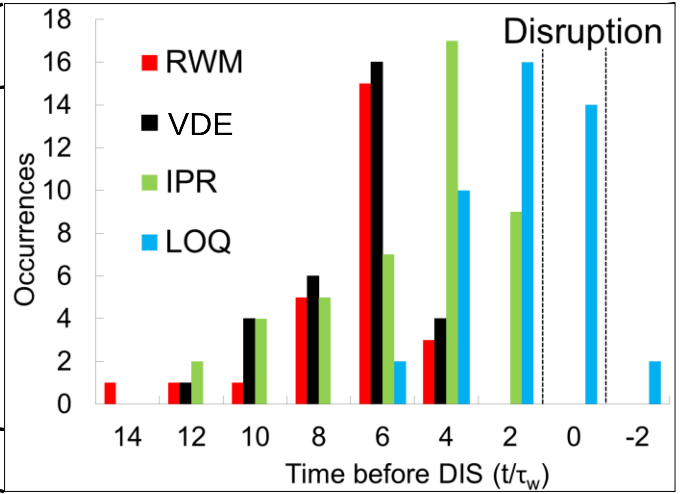
- Event chains with RWM and VDE (52.3%)
  - Related chains
    - RWM ➔ VDE ➔ SCL ➔ IPR ➔ DIS
    - RWM ➔ SCL ➔ VDE ➔ IPR ➔ DIS
    - VDE ➔ RWM ➔ SCL ➔ IPR ➔ DIS
    - VDE ➔ RWM ➔ IPR ➔ DIS ➔ SCL
    - RWM ➔ SCL ➔ VDE ➔ GWL ➔ IPR ➔ DIS
- Disruption event chains w/o VDE (11.4%)
- New insights being gained
  - Chains starting with GWL are found that show rotation and β_N rollover before RWM (6.8%)
    - GWL ➔ VDE ➔ RWM ➔ SCL ➔ IPR ➔ DIS
    - GWL ➔ SCL ➔ RWM ➔ IPR ➔ DIS

Disruption event chains with RWM (44 shot database)

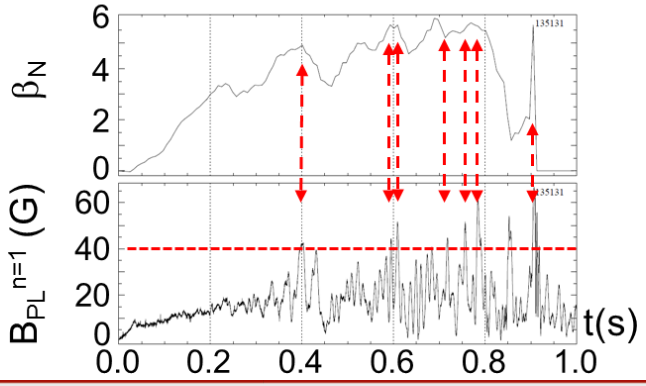


DECAF analysis yields time relation of chain events when applied to NSTX RWM disruption database



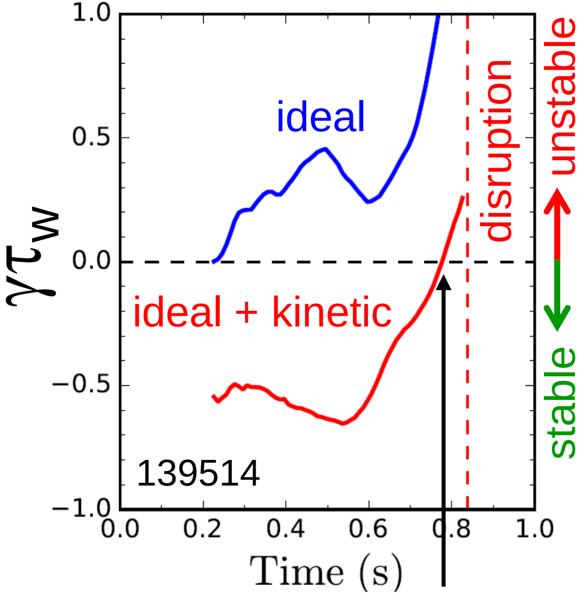


- Most RWM events near major disruption
  - 61% of RWM occur within 20 τ_w of disruption time (τ_w = 5 ms)
  - Earlier RWM events NOT false positives – cause large decreases in β_N with recovery (minor disruptions)



Global mode stability forecasting: DECAF initial reduced kinetic MHD model tests well on unstable RWM database

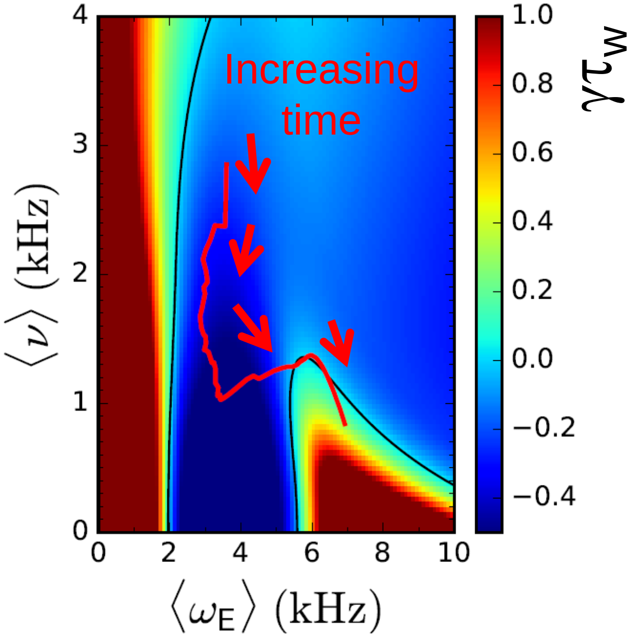
Norm. growth rate vs. time



predicted instability

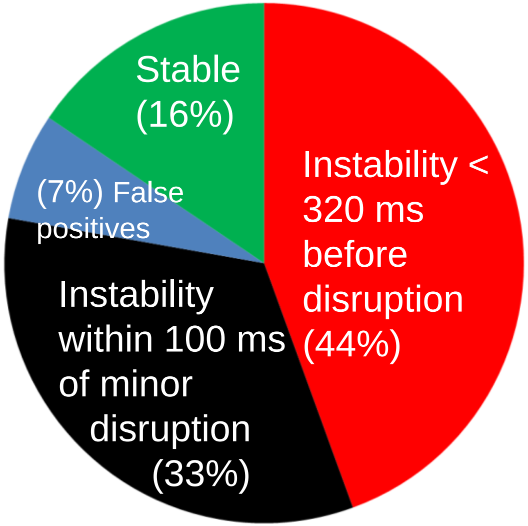
- Reduced model guided by full kinetic RWM stability model

$\gamma\tau_w$ contours vs. ν and ω_E



See J. Berkery invited talk **YI2.00005** (Fri 11:30 AM)

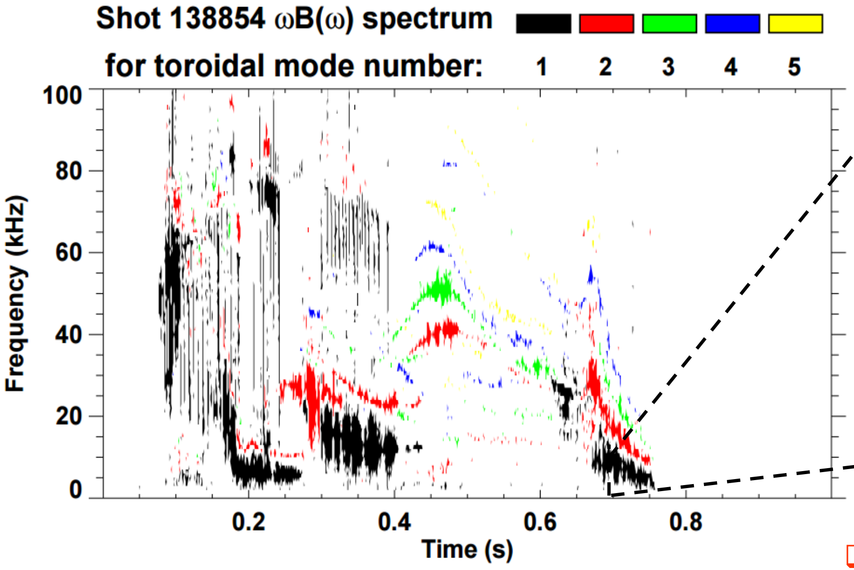
Predicted instability statistics



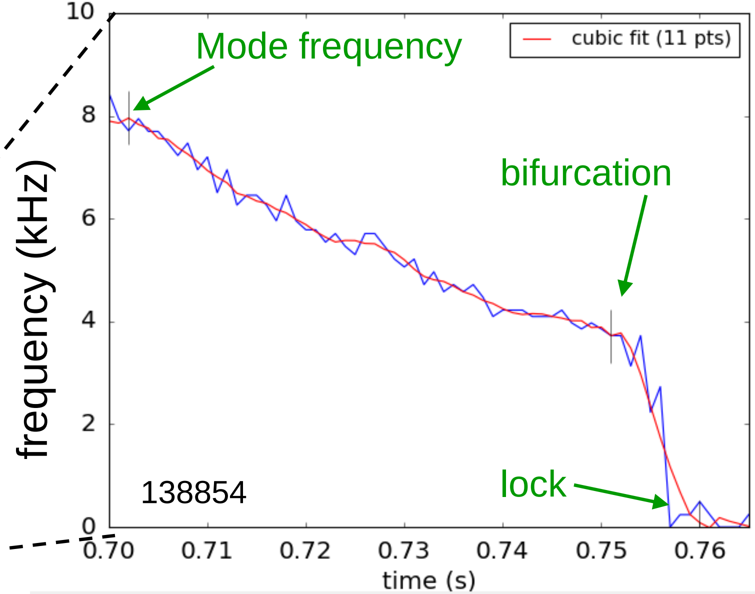
- 84% predicted unstable (unoptimized)
- 7% false positives

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

Magnetic spectrogram of rotating MHD



Mode frequency vs. time (zoomed in)



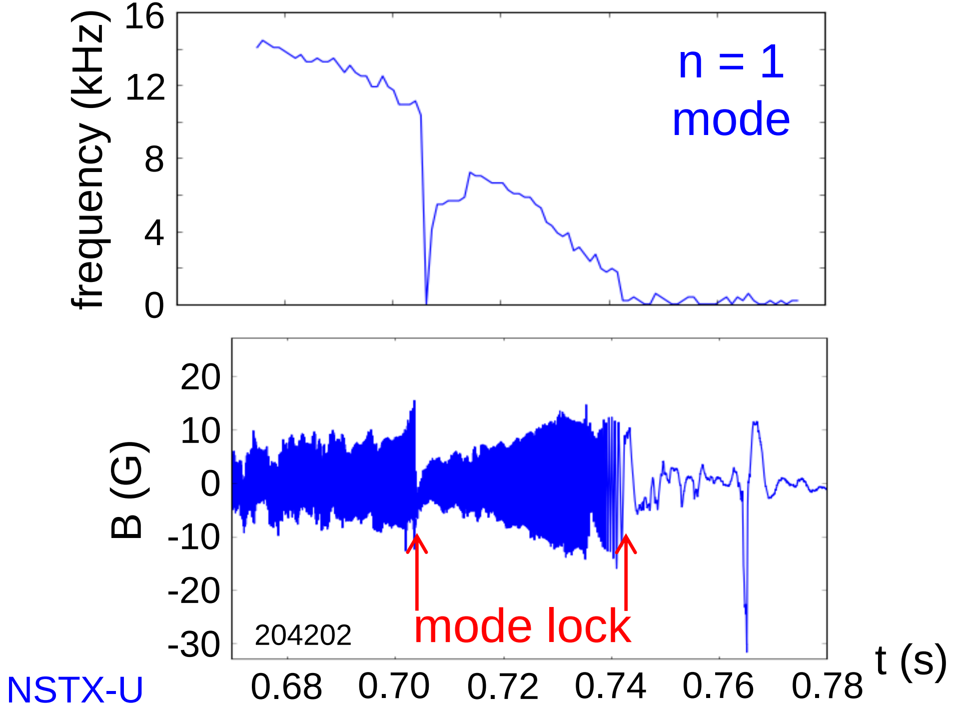
See **JP10.00057** J. Riquezes (Tue PM)

- DECAF FFT analysis determines mode frequency, bifurcation, and mode locking
- Initial mode locking prediction model developed

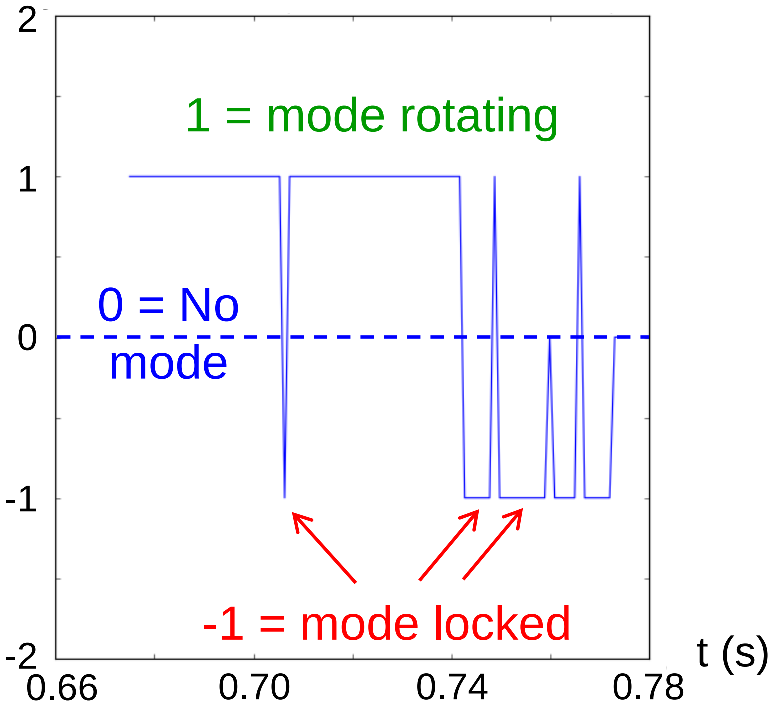
DECAF rotating MHD analysis identifies the state of the modes found

Magnetic signal / analysis (mode locking / unlocking)

Frequency vs. time



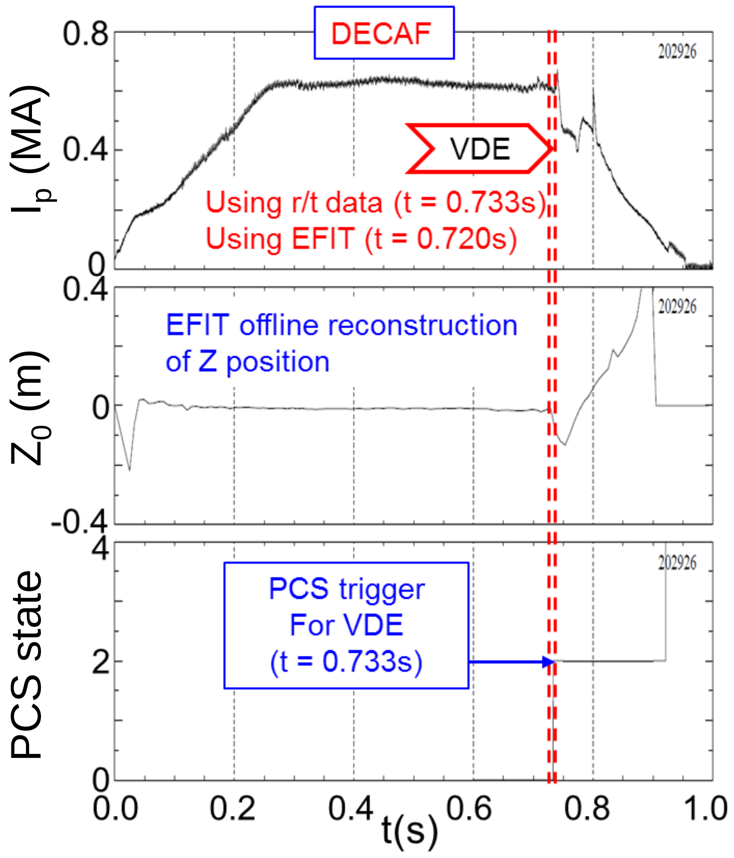
DECAF mode status



DECAF replicates the triggers found in new real-time plasma shutdown capability of NSTX-U

- Important capability of DECAF: compare analysis using offline vs. real-time data
- Plasma Shutdown Handler conditions are analogous to DECAF events
  - Control system loss of vertical control
    ➔ DECAF VDE
- DECAF comparison: VDE event
  - Matches Plasma Control System when r/t signal is used (1 criterion)
  - VDE event 13 ms earlier using offline EFIT signals (3 criteria: Z_0, dZ_0/dt, $Z_0 \times dZ_0/dt$)

(for shutdown handler: see **NP10.00005** S. Gerhardt (Wed AM)



Disruption event characterization, forecasting, and control are synergizing in NSTX-U for disruption avoidance

- **Physics Understanding**
  - Disruption Event Characterization and Forecasting code (DECAF) development continues: defining / forecasting disruption event chains
  - Recent DECAF development includes initial kinetic RWM forecasting, and initial identification of rotating MHD modes, bifurcation, and locking

- **Stability Control**
  - An arsenal of control tools will be available on NSTX-U for disruption avoidance (e.g. rotation, q profile control; RWM state-space controller)

Supporting Slides Follow

Disruption avoidance is a critical need for future tokamaks; NSTX-U is focusing stability research on this

- The present "grand challenge" in tokamak stability research
  - Can be done! (JET: < 4% disruptions w/C wall, < 10% w/ITER-like wall)
    - ITER disruption rate: < 1 - 2% (energy load, halo current); << 1% (runaways)

- Strategic plan: utilize/expand stability/control research success
  - Synergize and build upon past MHD stability/control success (don't just repeat!)
  - Utilize this knowledge / evolve into disruption prediction and avoidance research

- FESAC 2015 DOE Transient Events report: Disruption Predicition, Avoidance, Mitigation a Tier 1 (highest priority) initiative

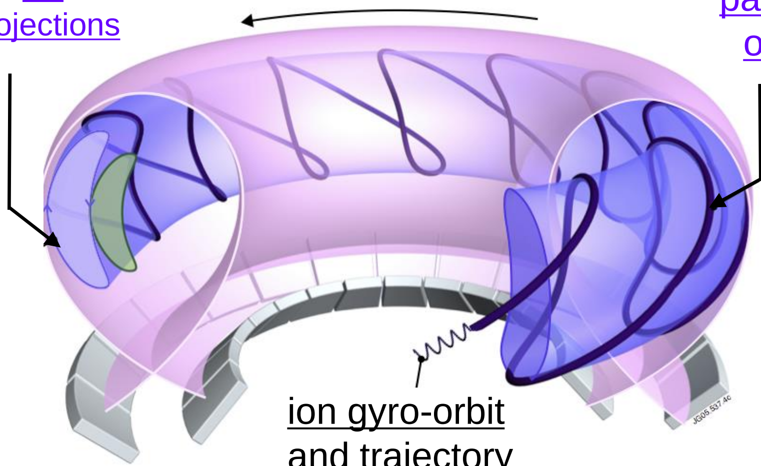
- Research at NSTX-U producing focused approach on disruption prediction and avoidance with quantitative measures of progress

Global mode stability forecasting: build from success of drift kinetic theory modification to MHD as a model

- Kinetic modification to ideal MHD

$$\gamma\tau_w = -\frac{\delta W_\infty + \delta W_K}{\delta W_{wall} + \delta W_K}$$

- Stability depends on
  - Trapped / circulating ions, electrons
  - Collisionality; Energetic particles
  - Integrated ω_ϕ profile matters!!! : broad rotation resonances in δW_K



(Fig. adapted from R. Pitts et al., Physics World (Mar 2006))

plasma integral over particle energy

$$\delta W_K \propto \int \left[\frac{\omega_{*N} + \left(\hat{\varepsilon} - 3/2\right)\omega_{*T} + \omega_E - \omega - i\gamma}{\langle \omega_D \rangle + l\omega_b - i\nu + \omega_E - \omega - i\gamma} \right] \hat{\varepsilon}^{\frac{5}{2}} e^{-\hat{\varepsilon}} d\hat{\varepsilon}$$

precession drift   bounce   collisionality ω_ϕ profile (enters in ω_E)

Just some references:

B. Hu, R. Betti, et al., PoP 12 (2005) 057301

J. Berkery *et al.*, PRL **104** (2010) 035003

S. Sabbagh, et al., NF **50** (2010) 025020

J. Berkery *et al.*, PRL **106** (2011) 075004

J. Berkery *et al.*, NF **55** (2015) 123007