U.S. DEPARTMENT OF ENERGY | Office of Science

NSTX-U

Equilibrium, NTV, and Disruption Event Characterization and Forecasting Results Update for NSTX/NSTX-U

***S.A. Sabbagh*[1]**, *J.W. Berkery*[1], *R.E. Bell*[2], *J.M Bialek*[1], *M.D. Boyer*[2], *D.A. Gates*[2], *S.P. Gerhardt*[2], *I Goumiri*[3], *C. Myers*[2], *Y.S. Park*[1], *J.D. Riquezes*[4], *C. Rowley*[3]

[1]*Department of Applied Physics, Columbia University, New York, NY*
[2]*Princeton Plasma Physics Laboratory, Princeton, NJ*
[3]*Princeton University, Princeton, NJ*
[4]*University of Michigan, Ann Arbor, MI*

NSTX-U Results Review

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PPPL

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Columbia University in the City of New York

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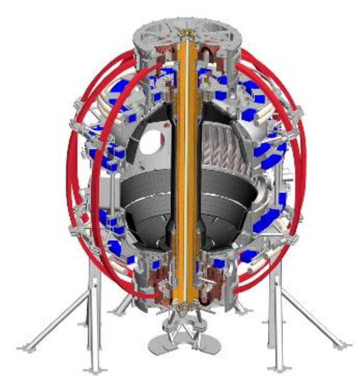
V1.2



OUTLINE – Updates on three subjects

- Impact of PF1aU on equilibrium reconstruction
- Disruption Event Characterization and Forecasting development
- Neoclassical Toroidal Viscosity on NSTX-U
  - One shot identified in Walter's L-mode experiments has sufficient data for NTV profile analysis
  - More to do, not enough time to show – will send by email

Equilibrium reconstruction recent conclusion: PF1aU issue has negligible effect on reconstructions since it appeared

Near maximum difference — Near peak stored energy

Stored energy — Stored energy — DRSEP

		Wtot (kJ)		Pct Diff		Wtot (kJ)		Pct Diff	DRSEP (cm)		Diff
Shot	t (s)	EFIT04	EFIT02	(%)	t (s)	EFIT04	EFIT02	(%)	EFIT04	EFIT02	(mm)
203655	0.266	50.1	46.6	6.986%	0.673	142.79	142.72	0.049%	0.422	0.183	2.39
204112	0.196	36.3	33.6	7.438%	0.772	284.8	282.8	0.702%	-0.298	-0.397	0.99
204118	0.2	34.2	32	6.433%	0.674	335.14	333.2	0.579%	-0.702	-0.838	1.36
204971	0.18	24.4	24.18	0.902%	0.731	73.5	73.6	-0.136%	-0.637	-0.603	-0.34
204980	0.2	31.37	31.37	0.000%	0.5	87.91	88.22	-0.353%	0.107	0.1136	-0.066
205055	0.173	12.06	11.44	5.141%	0.307	118.46	118.25	0.177%	-0.3	-0.38	0.8
205057	0.196	39.33	39.25	0.203%	0.346	146.6	146.48	0.082%	-0.418	-0.444	0.26
205062	0.16	14.74	14.47	1.832%	0.325	44.05	44.18	-0.295%	-0.36	-0.387	0.27
205069	0.163	15.92	15.65	1.696%	0.331	61.58	61.78	-0.325%	-0.59	-0.65	0.6
205084	0.225	29.43	29.36	0.238%	0.289	27.84	27.87	-0.108%	0.046	0.032	0.14
	Average			3.087%				0.037%			0.6404

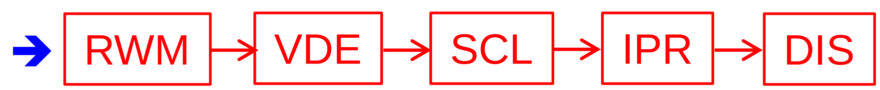
- Reconstructions use PF coil currents, have small error (~ 0.5%), so PF1aU issue might affect result
- However, the balance of the magnetics minimize reconstruction changes
  - The **fitted** PF1aU does deviate from the measured value – becomes worse in time

DECAF is structured to ease parallel development of disruption characterization, event criteria, and forecasting

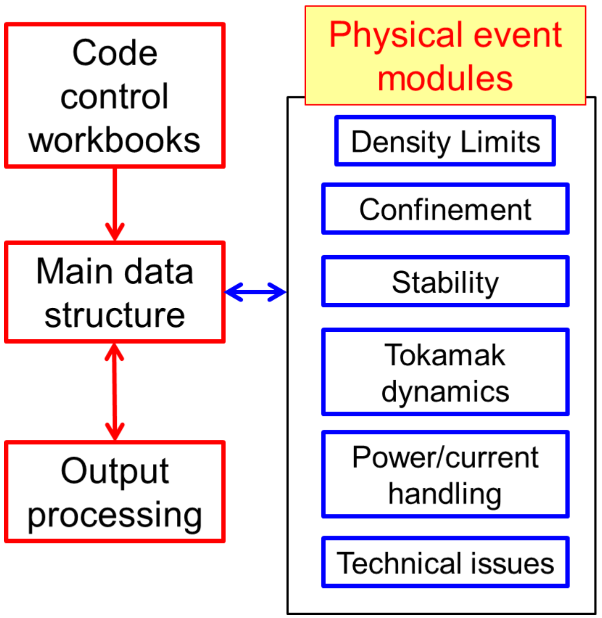
- **Initial DECAF analysis goals**
  - ✓ Define physics criteria that define an initial set of disruption "events"
  - ✓ Characterize time sequences of events in disruptive shots
  - → Produce initial physics models to define marginal points of key events
  - → Enable initial disruption forecasting capability for most well-defined events / sequences

DECAF disruption events and chains

→ e.g. SCL Loss of shape control

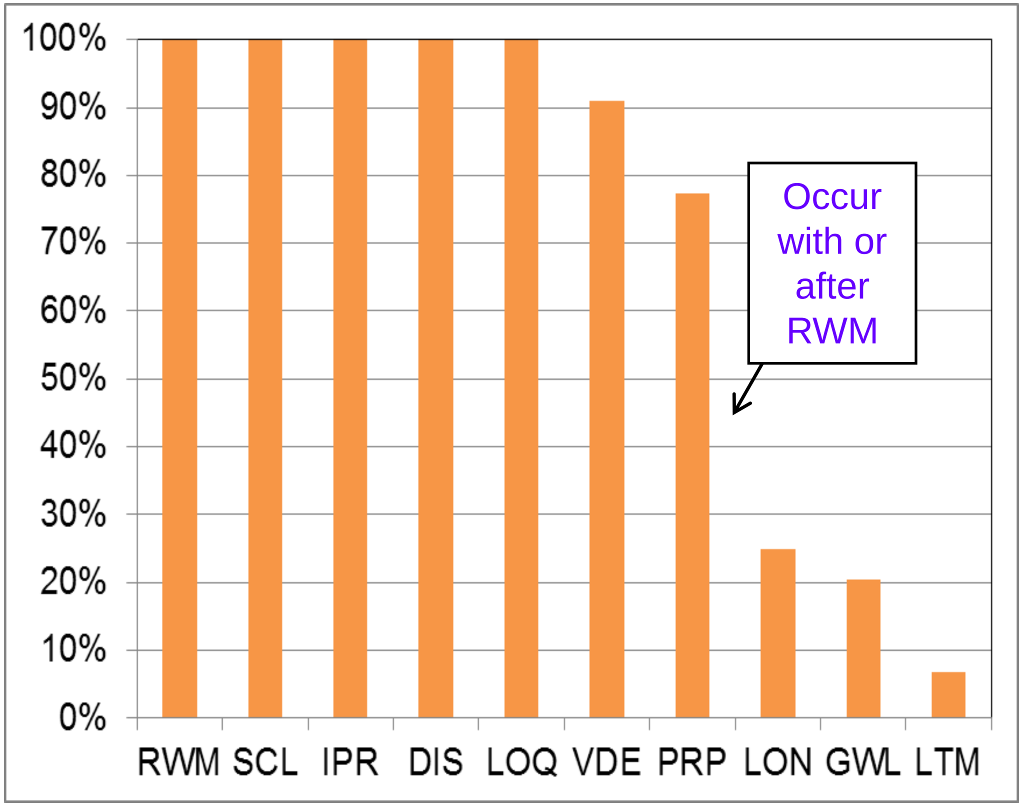


DECAF code schematic

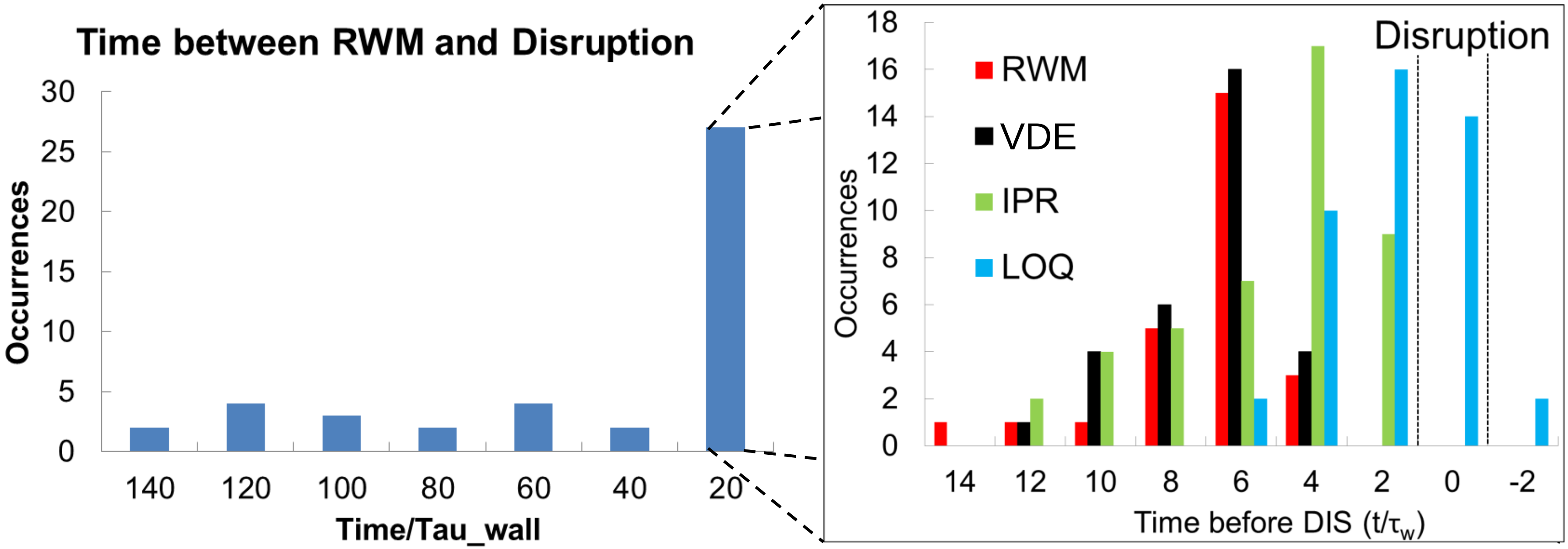


Recap: DECAF results detect disruption chain events when applied to dedicated 44 shot NSTX RWM disruption database

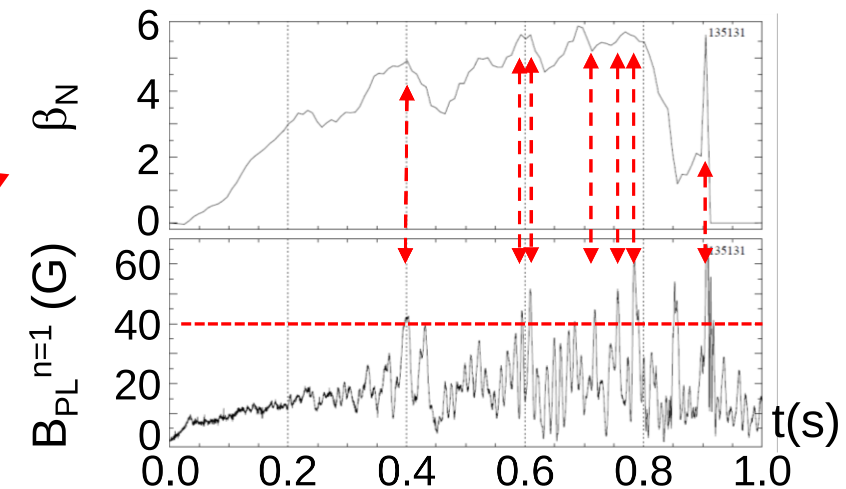
- Several events detected for all shots
  - RWM: RWM event warning
  - SCL: Loss of shape control
  - IPR: Plasma current request not met
  - DIS: Disruption occurred
  - LOQ: Low edge q warning
  - VDE: VDE warning (40 shots)
- Others:
  - PRP: Pressure peaking warning
  - GWL: Greenwald limit
  - LON: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



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



- Most RWM 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)



Initial DECAF analysis finds common disruption event chains (44 shot NSTX disruption database)

- Common disruption event chains (52.3%)

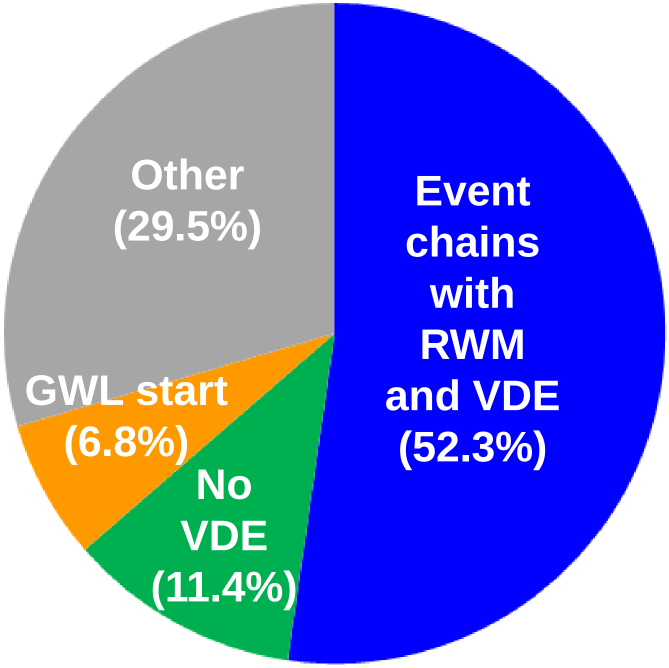
  RWM → VDE → SCL → IPR → DIS

  - Related chains
    - 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%)

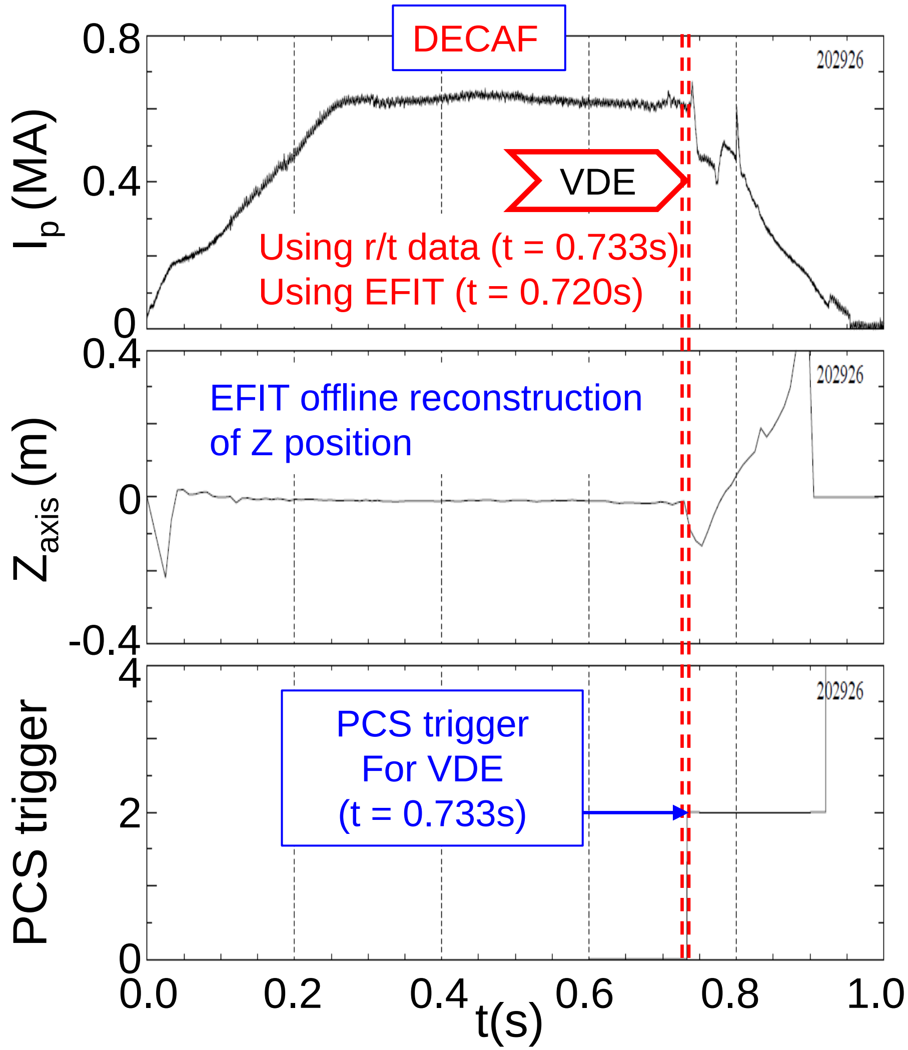
- New insights being gained
  - Chains starting with GWL are found that show rotation and β_N rollover before RWM (6.8%)
  - Related chains
    - GWL ➔ VDE ➔ RWM ➔ SCL ➔ IPR ➔ DIS
    - GWL ➔ SCL ➔ RWM ➔ IPR ➔ DIS

Disruption event chains with RWM



First DECAF results for NSTX-U replicate the triggers found in new real-time state machine shutdown* capability

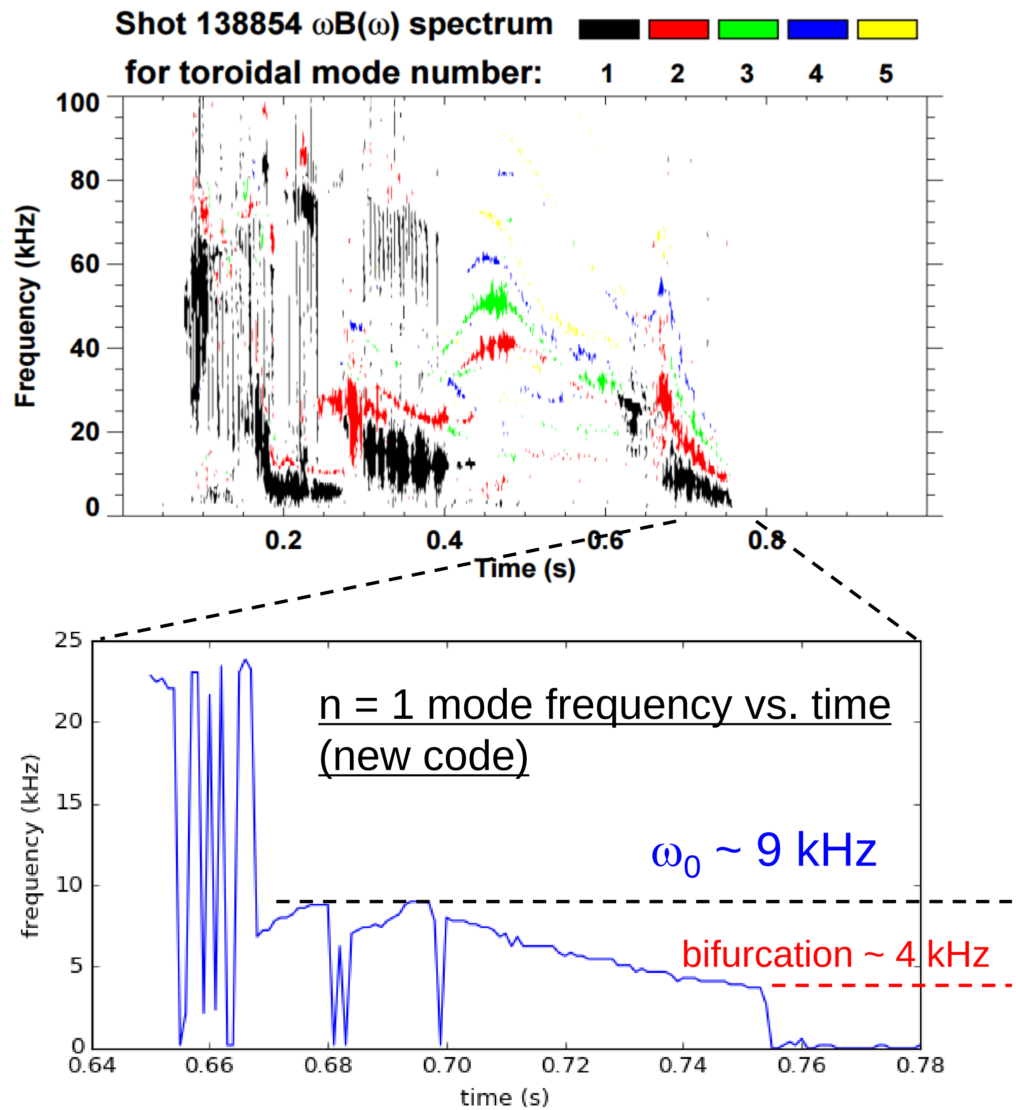
- Important capability of DECAF to compare analysis using offline vs. real-time data
  - Simple, initial test
- PCS Shut-down conditions are analogous to DECAF events
  - PCS loss of vertical control ➔ DECAF VDE
- DECAF comparison:VDE event
  - Matches PCS when r/t signal used (1 criterion)
  - VDE event 13 ms earlier using offline EFIT signals (3 criteria)



*See S.P. Gerhardt, et al., NSTX-U shutdown handler talk

Next essential step for DECAF analysis: 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

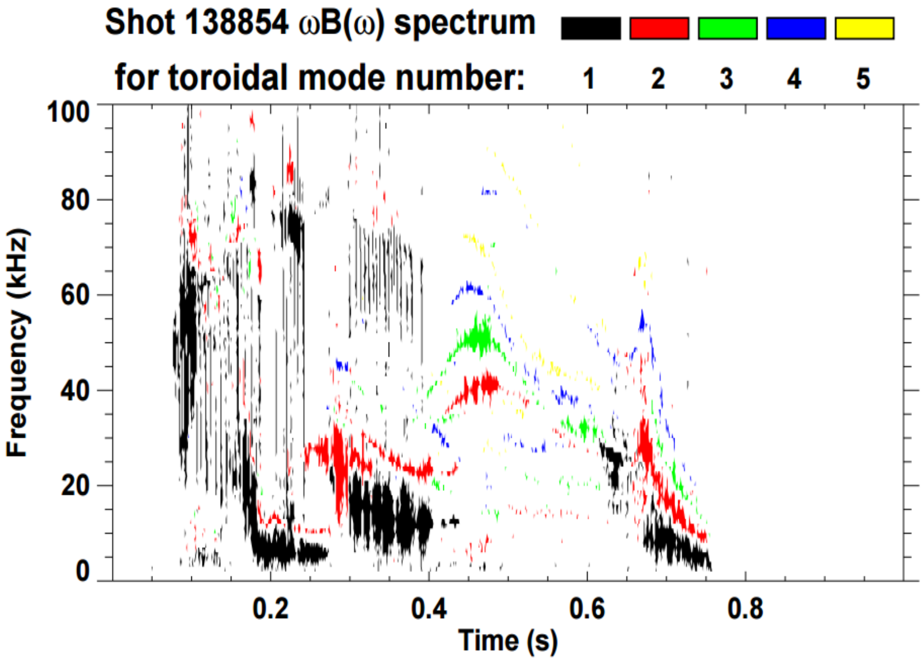


w/ J. Riquezes (U. Michigan – SULI student)

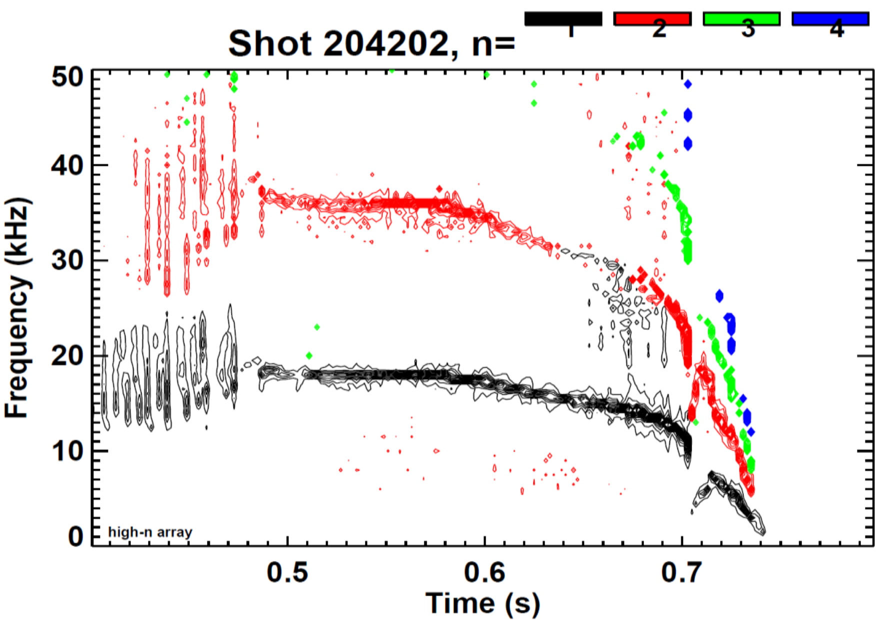
Many shots with rotating MHD (e.g. NTMs) examined for NSTX and NSTX-U – two illustrated here

Magnetic spectrogram of rotating MHD mode locking termination

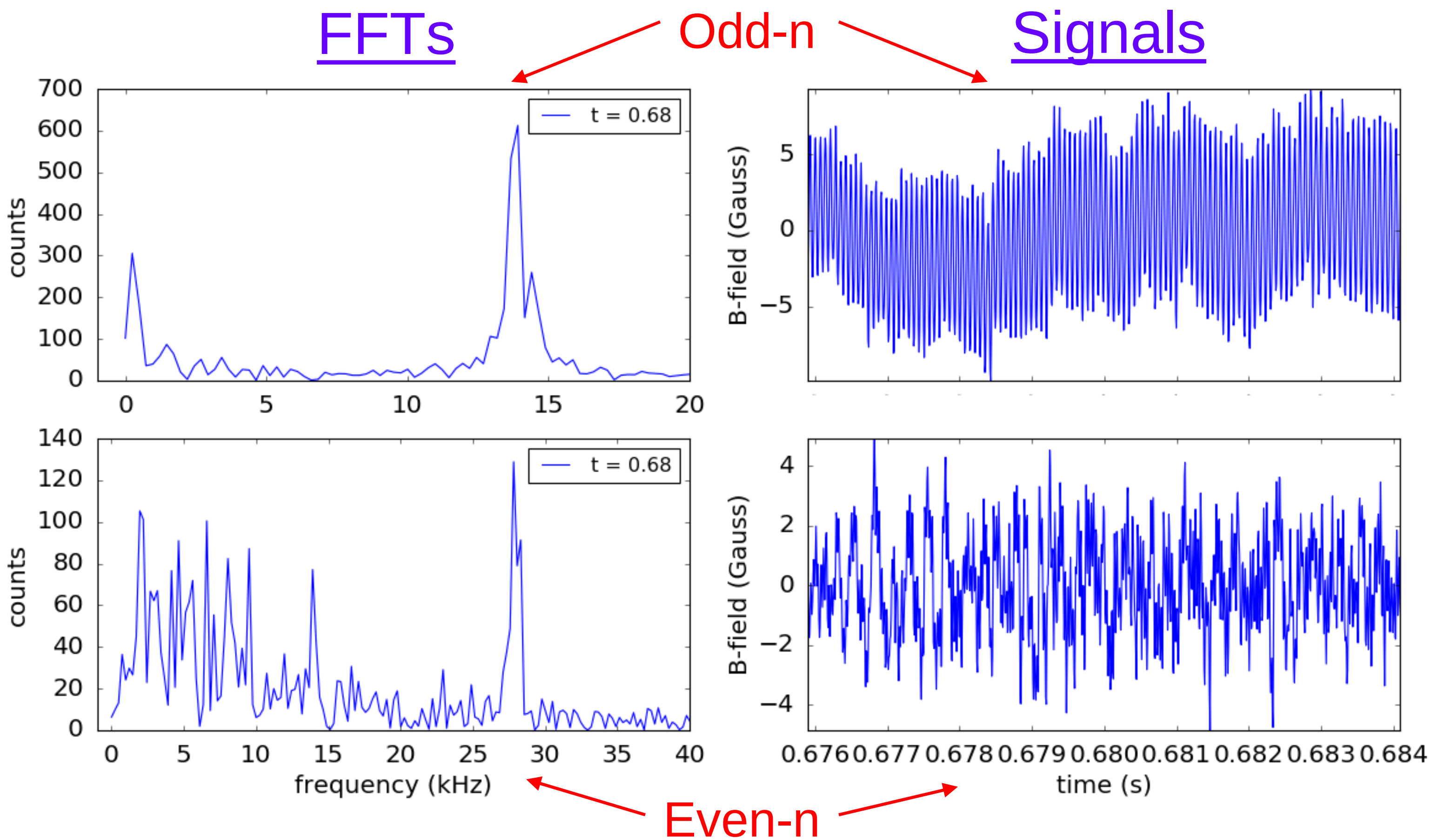
NSTX 138854



NSTX-U 204202



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

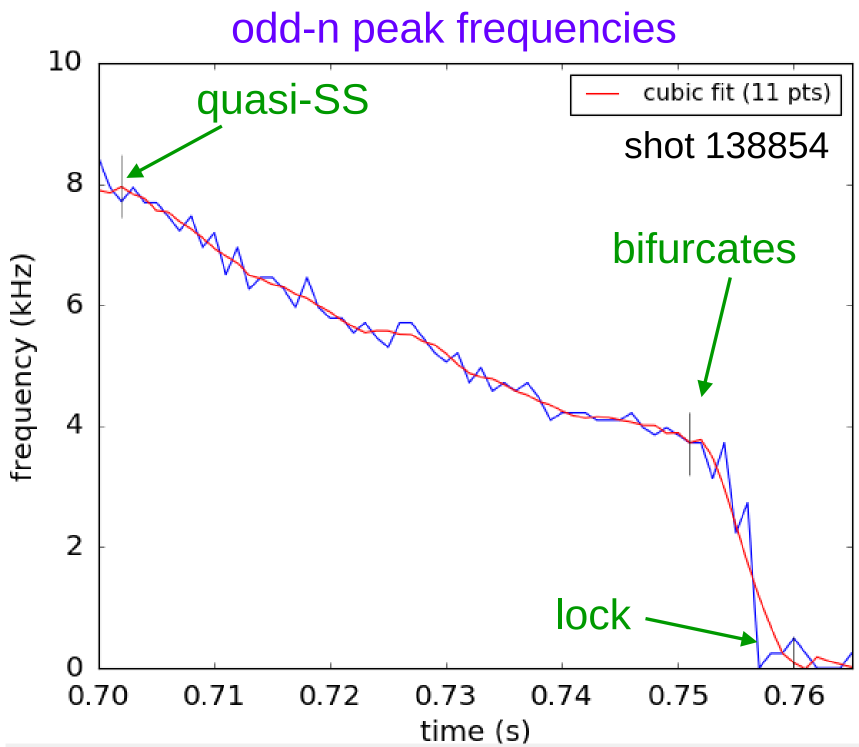


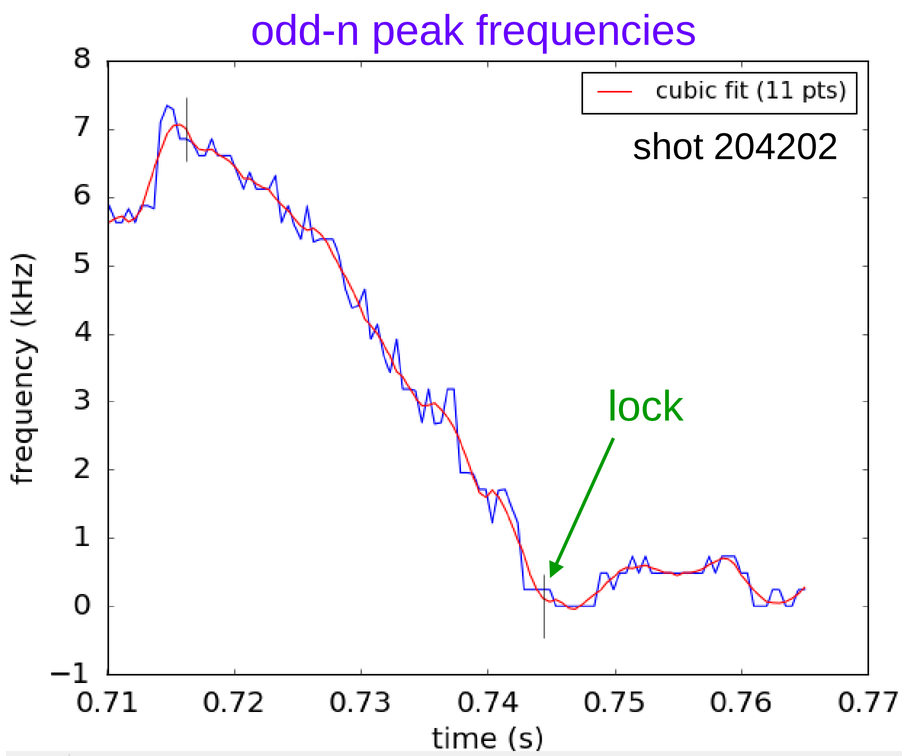
- Reveals potential issues handling multiple frequency peaks
- Next step to include toroidal array / n number discrimination

J. Riquezes (U. Michigan – SULI student)

The characterization algorithm shows that the expected bifurcation event can be found

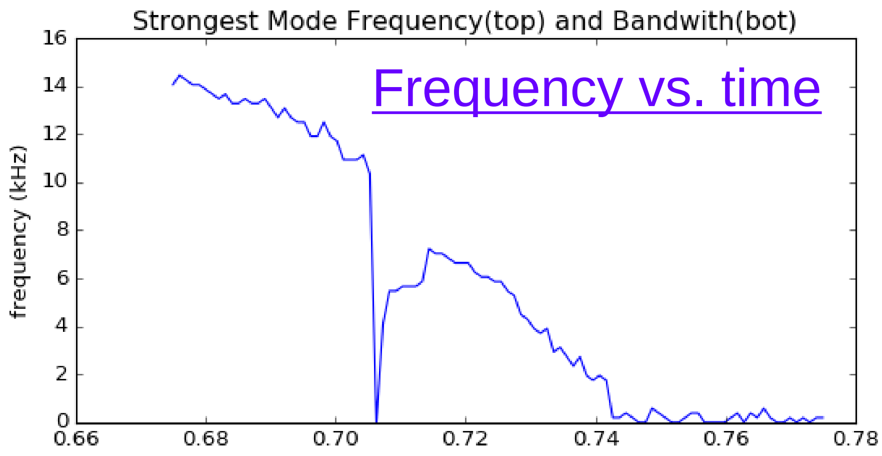
- Algorithm written looks for a "quasi-steady state" period, a potential bifurcation, the possible mode locking

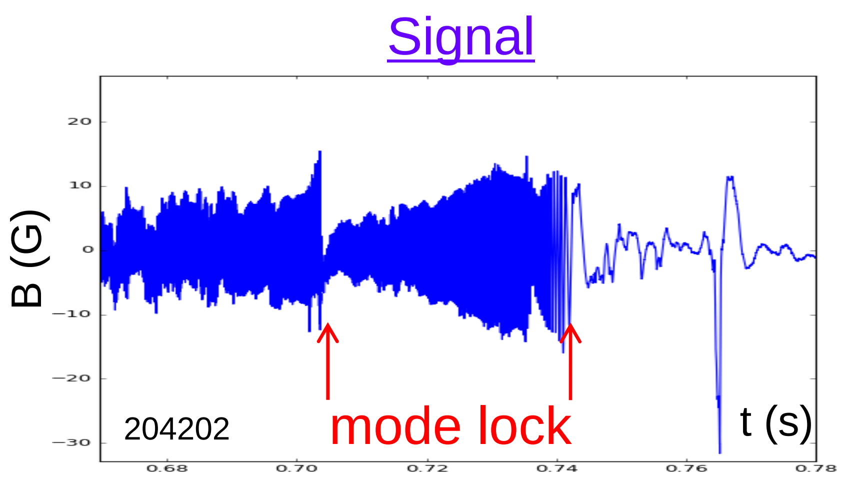


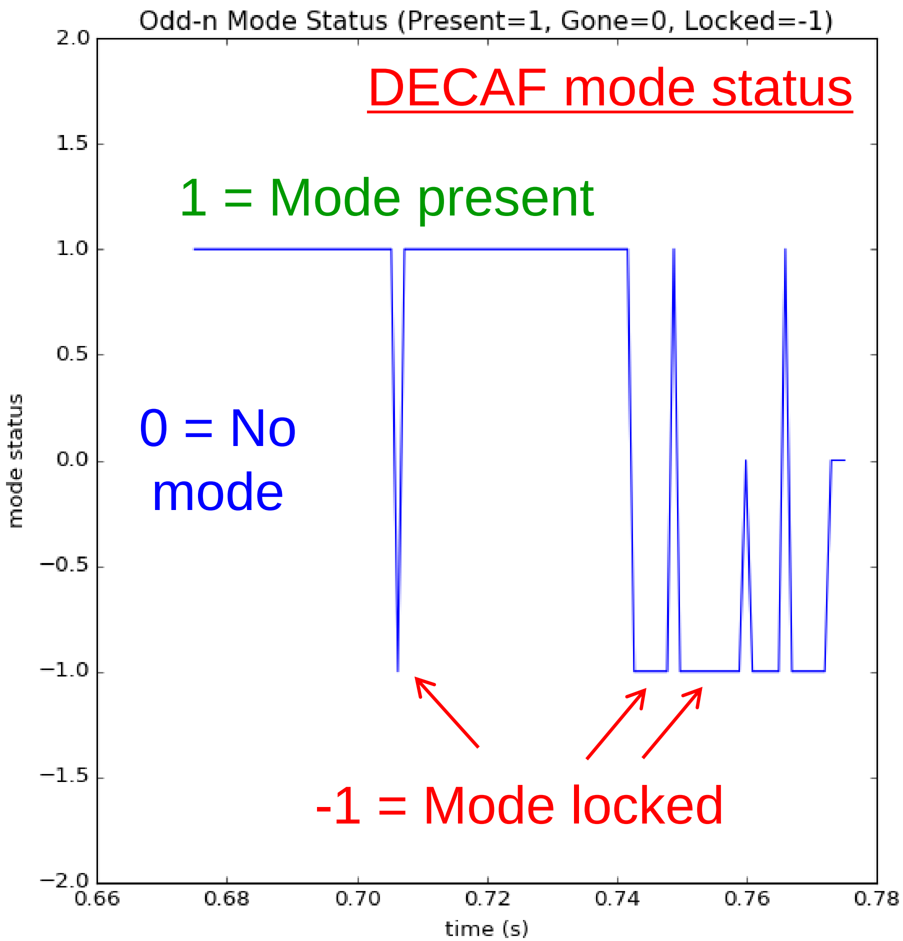


Continuing analysis of rotating MHD for DECAF includes accurate analysis of mode "status" (I)

Odd-n magnetic signal / analysis (mode locking / unlocking)

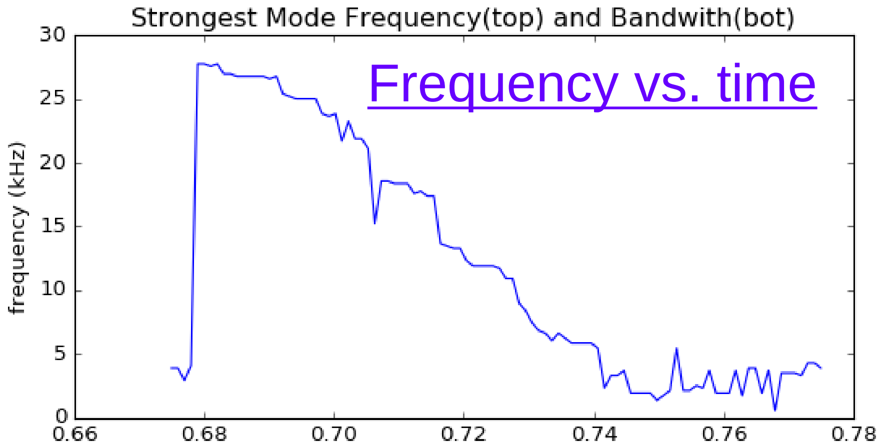




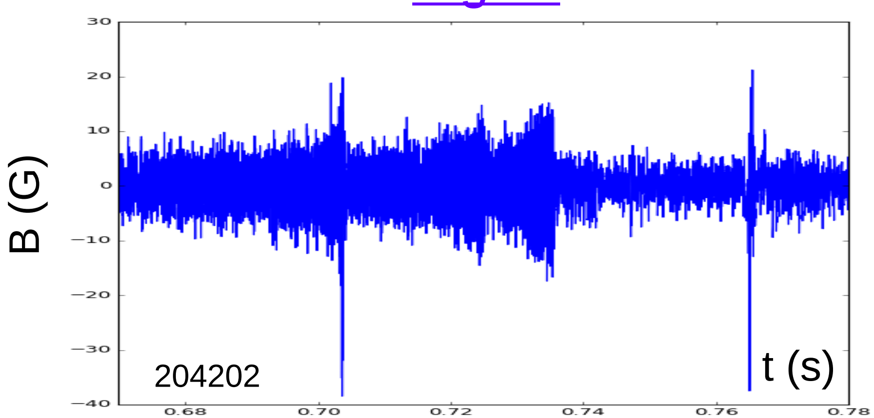


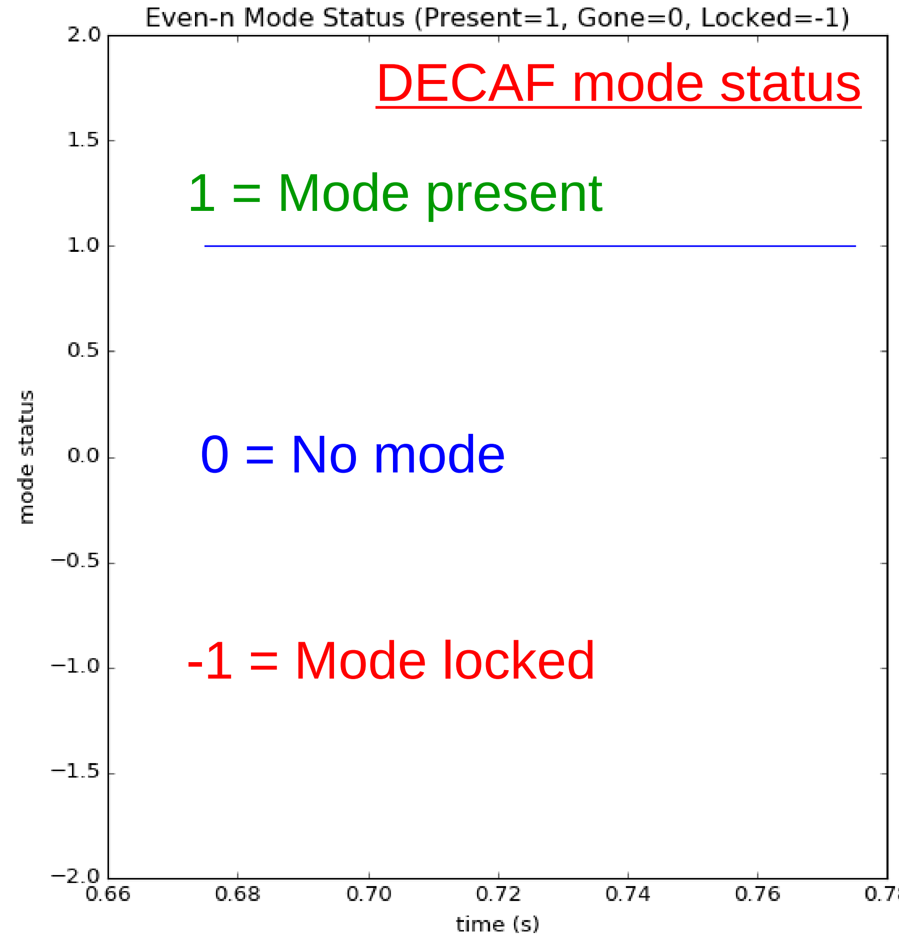
Continuing analysis of rotating MHD for DECAF includes accurate analysis of mode “status” (II)

Even-n magnetic signal / analysis (mode present, not locked)



Signal





Model for mode rotation evolution / mode lock forecasting derived, will be tested in DECAF in next step

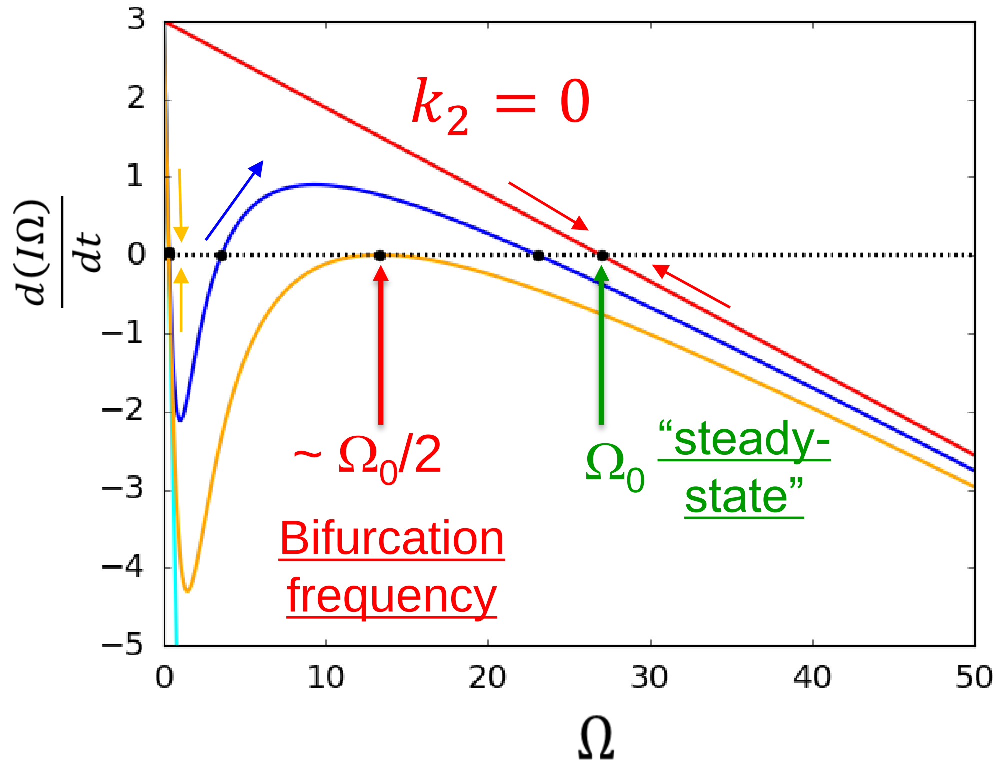
- Model derived to allow island drag for both "slip" and a "no slip" condition

$$T_{mode} = \frac{k_2\Omega}{1 + k_3\Omega^2}$$

Model based on
R. Fitzpatrick et al., Nucl. Fusion **33** (1993) 1049

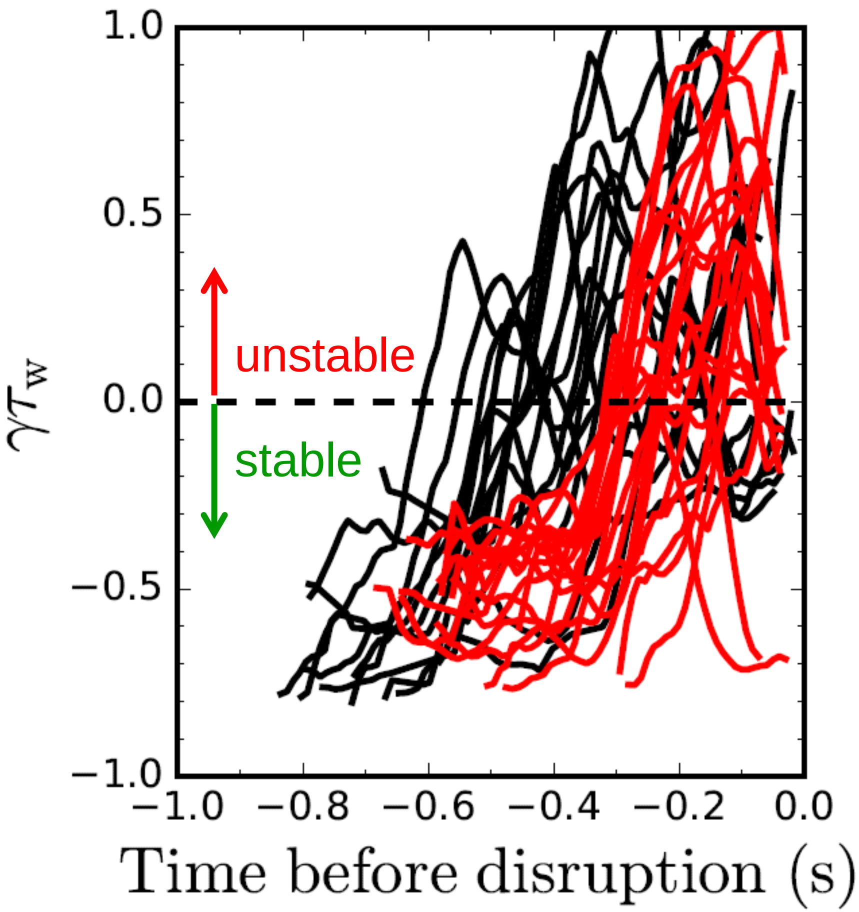
- Simple "Ω_0" defines steady state
  - Best way to define this?
- Simple "$\Omega_0/2$" defines bifurcation point
  - ➔ Next step is to analyze this model using DECAF

$$\frac{d(I\Omega)}{dt} = T_{aux} - \frac{k_2\Omega}{1 + k_3\Omega^2} - \frac{(I\Omega)}{\tau_{2D}}$$



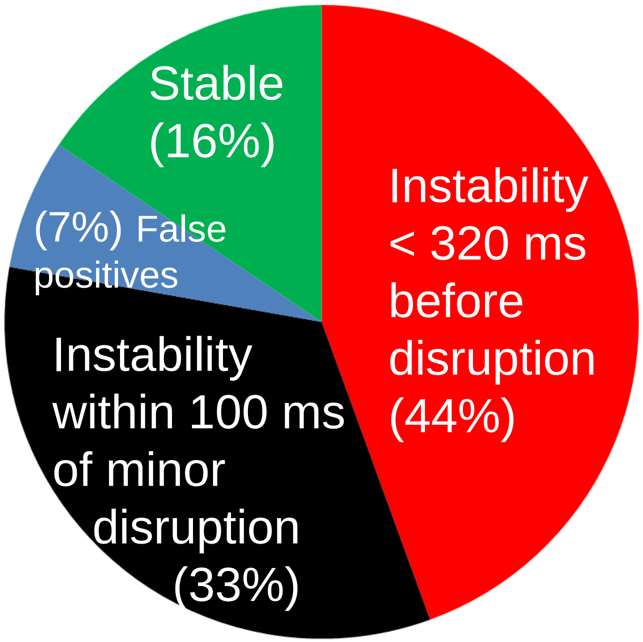
DECAF reduced kinetic MHD model implemented: initially tested on database of NSTX discharges with unstable RWMs

Normalized growth rate vs. time



See Jack Berkery's talk (next) for full detail

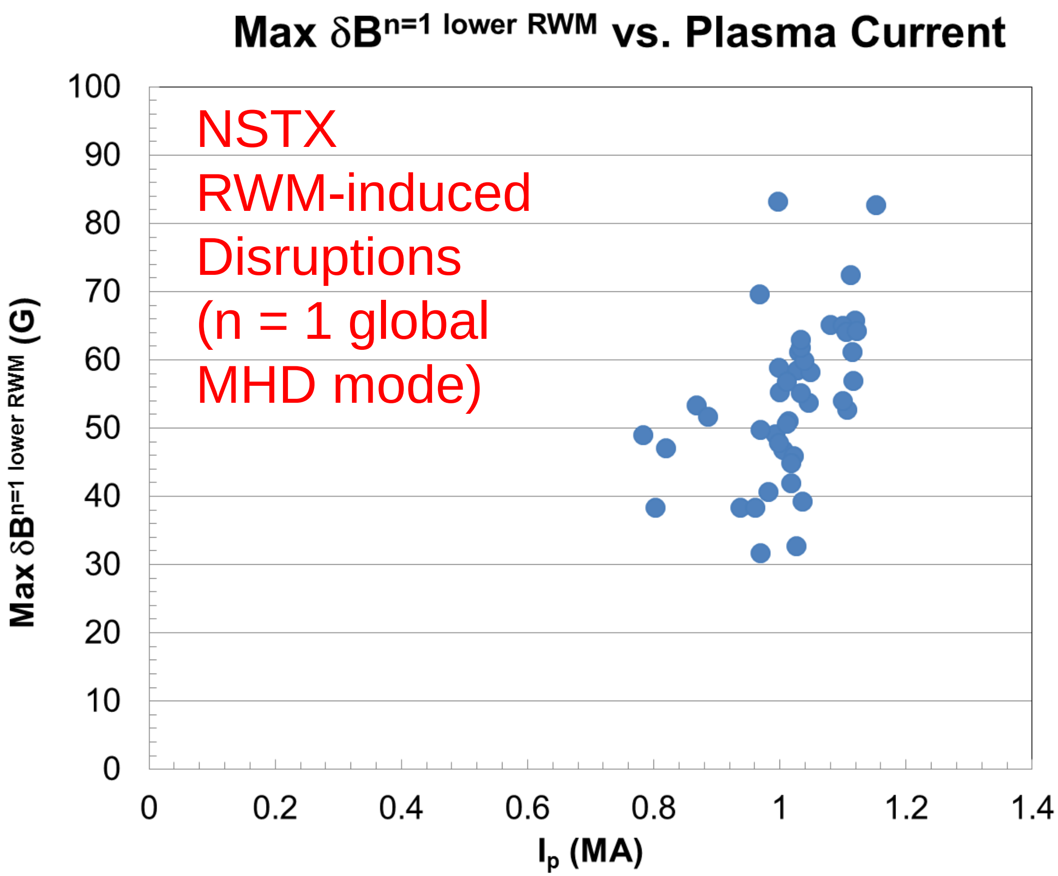
Predicted instability statistics (45 shots)



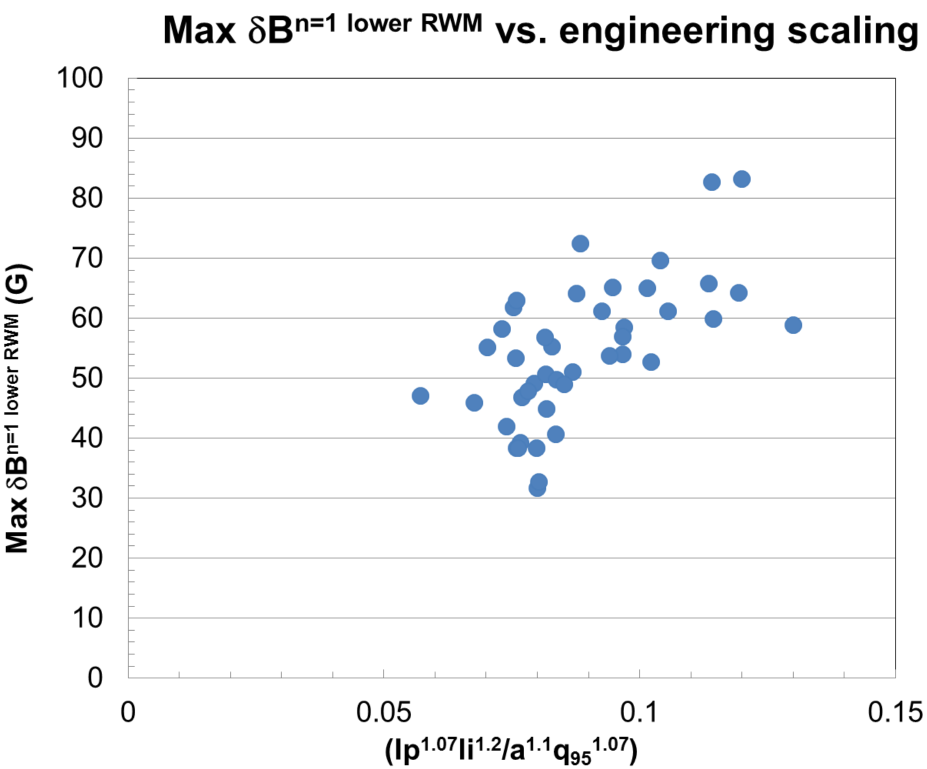
- 84% of shots are predicted unstable
- 44% predicted unstable < 320 ms (approx. 60τ_w) before current quench
- 33% predicted unstable within 100 ms of a minor disruption

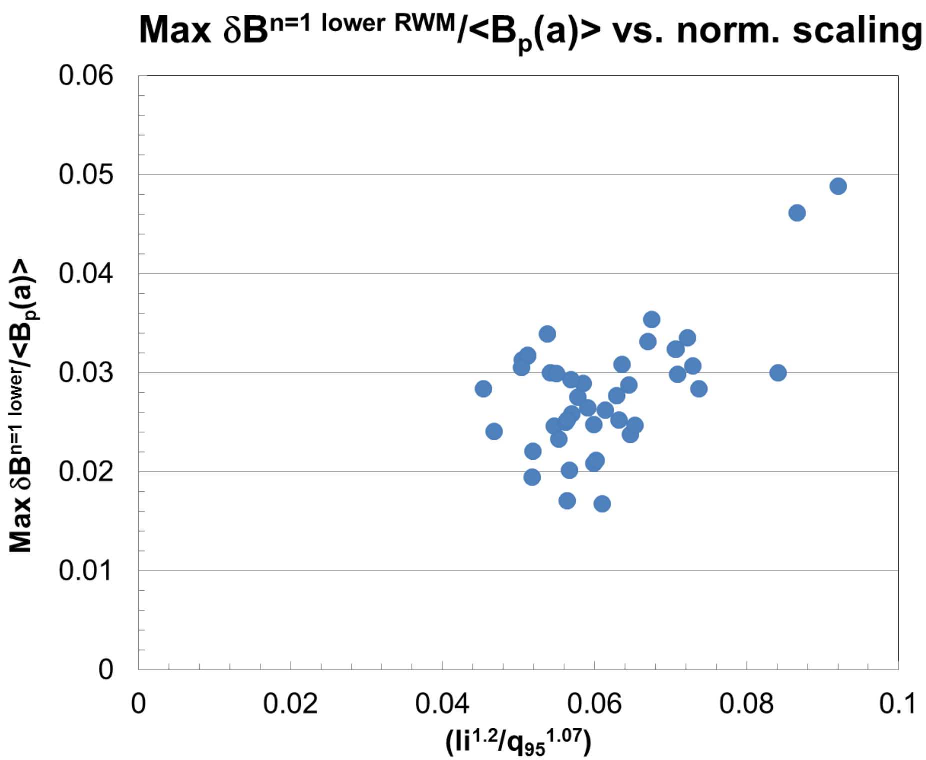
Another criterion: what levels of plasma disturbances (δB_p; $\delta B_p/B_p(a)$) are permissible to avoid disruption MHD modes?

- ITER high priority need
  - Analysis requested by ITER
  - Vetted through ITPA
- Compare maximum δB_p (n = 1 amplitude) causing disruption vs I_p
  - Maximum δB_p increases with I_p
- Further analysis may provide guidance for a disruption predictor in DECAF



Maximum δB_p might follow de Vries-style* empirical scalings

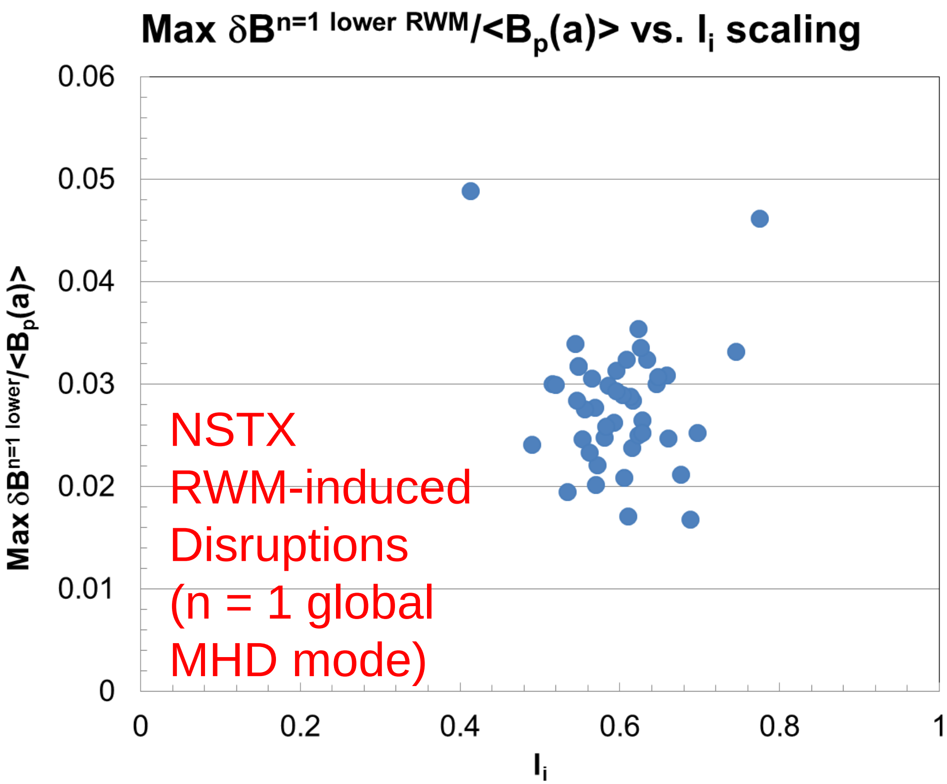




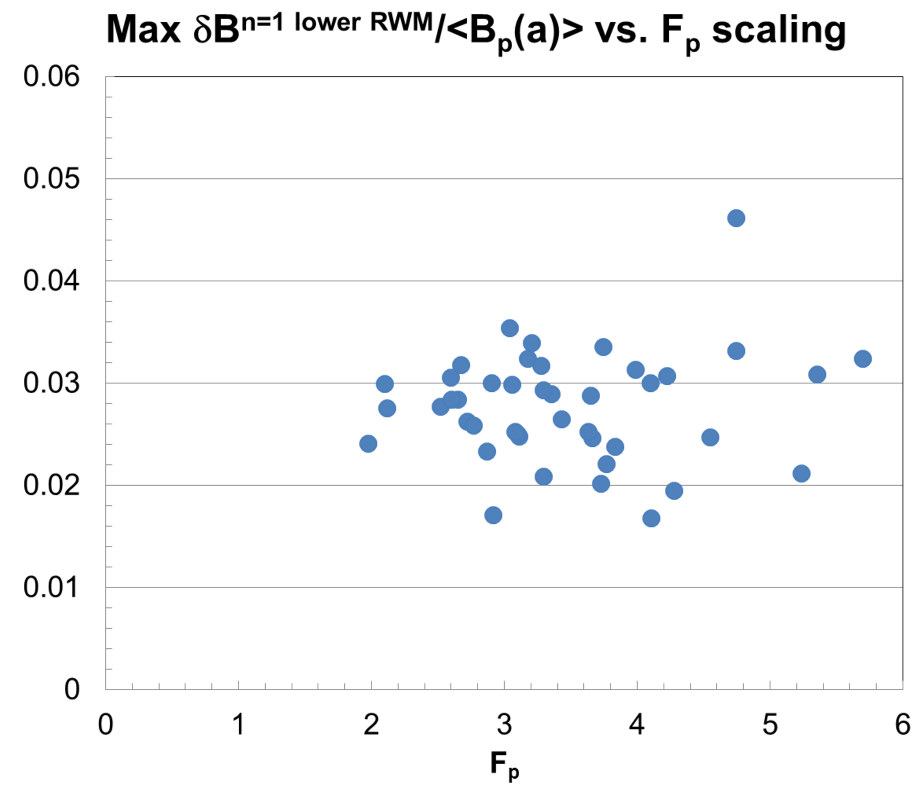
- NSTX RWM-induced disruptions (n = 1 global MHD mode)
- Will be tested in DECAF as a “tolerable limit” to global mode amplitude

*P.C. de Vries, G. Pautasso, E. Nardon, et al., Nucl. Fusion **56** (2016) 026007

In contrast, maximum $\delta B_p/\langle B_p(a)\rangle$ seems independent of scaling on (l_i) or (F_p) (or (F_p/l_i))



internal inductance

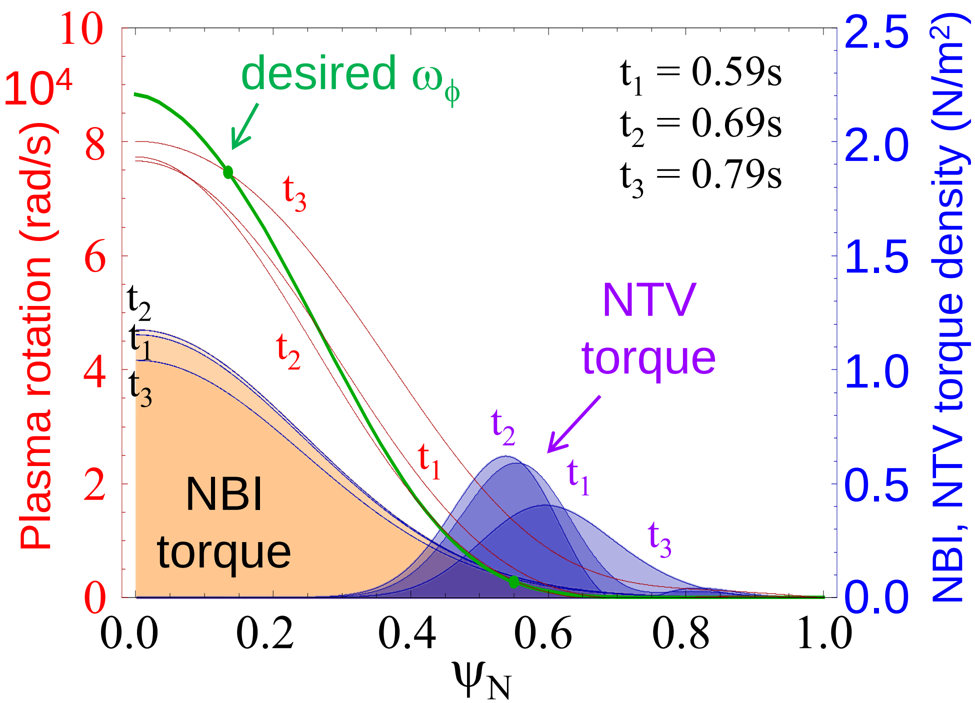


total pressure peaking factor

- $F_p = p_{tot}(0)/\langle p_{tot}\rangle_{vol}$ (from kinetic equilibrium reconstructions)
- Dependence on l_i, F_p expected for RWM marginal stability points

Reminder: NSTX-U rotation controller including NTV and NBI torque profiles can compensate for T_i variations in NTV

Rotation evolution and NBI and NTV torque profiles

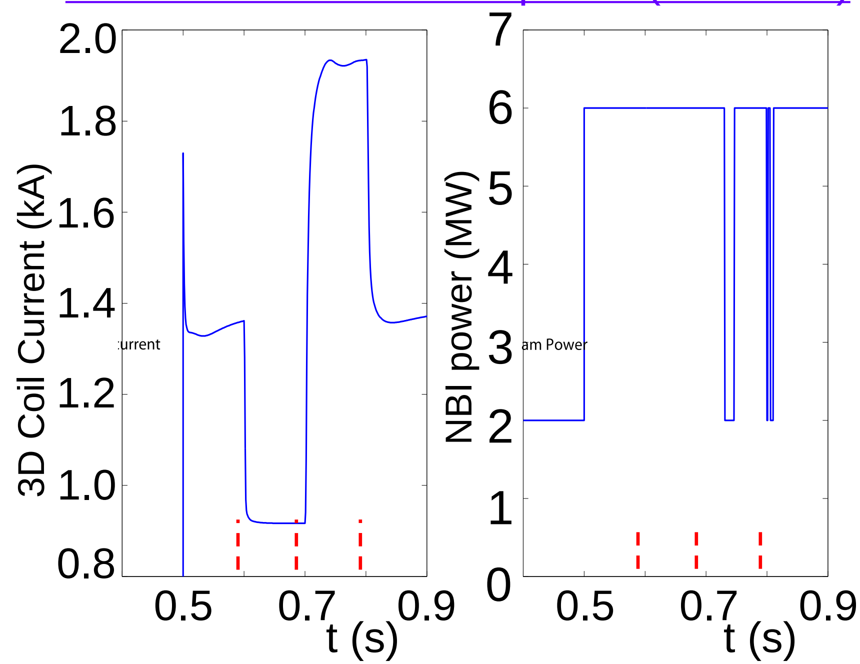


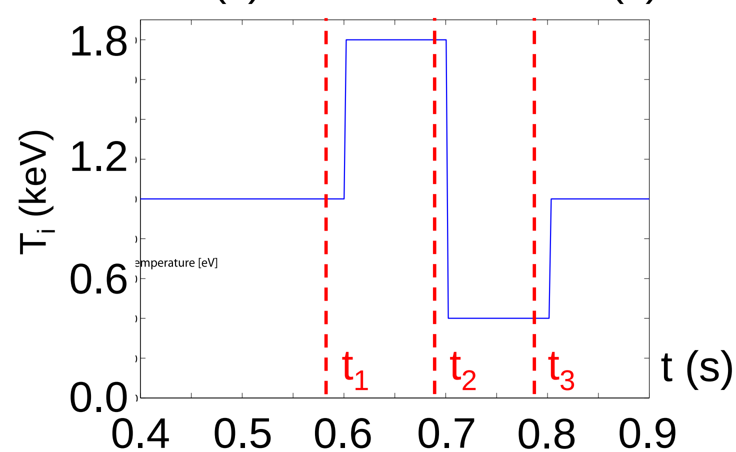
$$T_{NTV} \propto K \times f\left(n_{e,i}{}^{K1} T_i^{K2}\right) g\left(\delta B(\rho)\right)\left[I_{coil}{}^{2}\omega\right]$$

K1 = 0, K2 = 2.5

- NTV torque profile model for feedback dependent on ion temperature

3D coil current and NBI power (actuators)

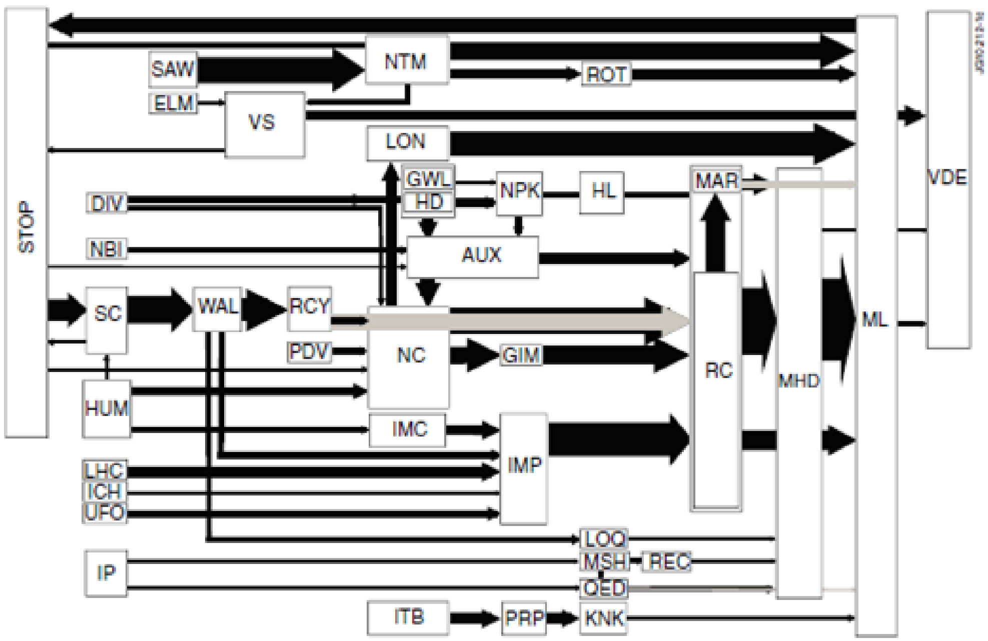




Supporting Slides Follow

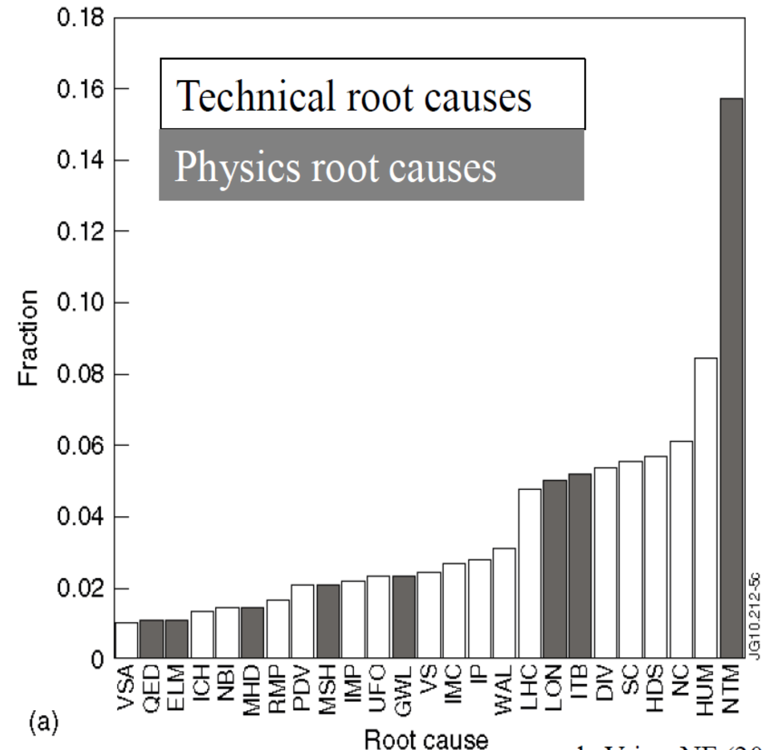
JET disruption event characterization provides framework for understanding / quantifying disruption prediction

JET disruption event chains



P.C. de Vries *et al*., Nucl. Fusion **51** (2011) 053018

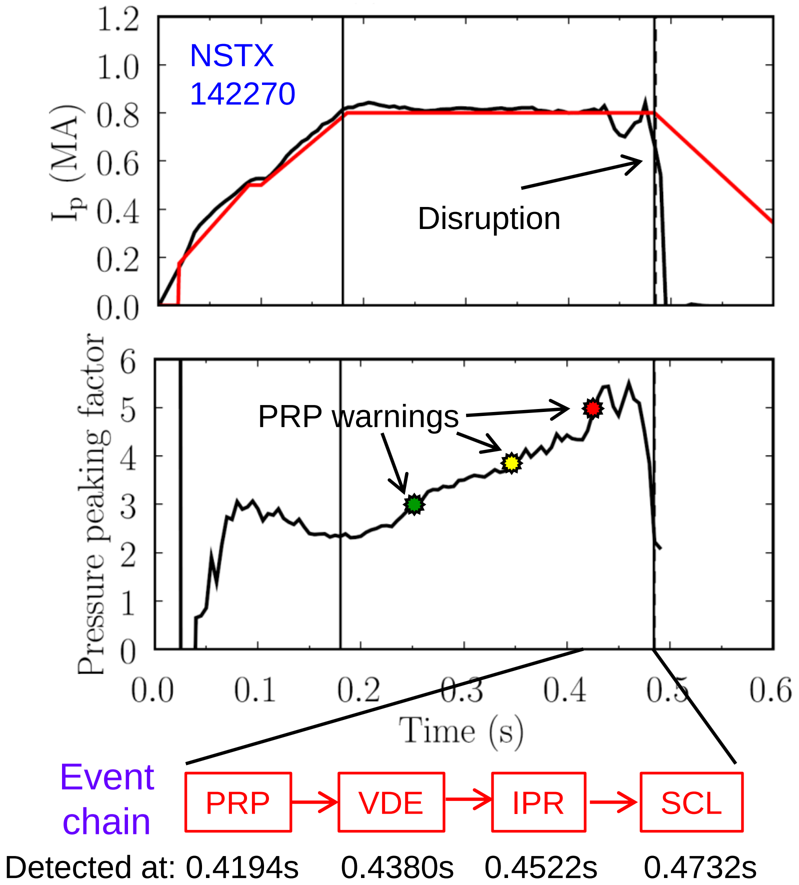
Related disruption event statistics



de Vries, NF (2011)

- ❑ JET disruption event chain analysis performed by hand, desire to automate

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



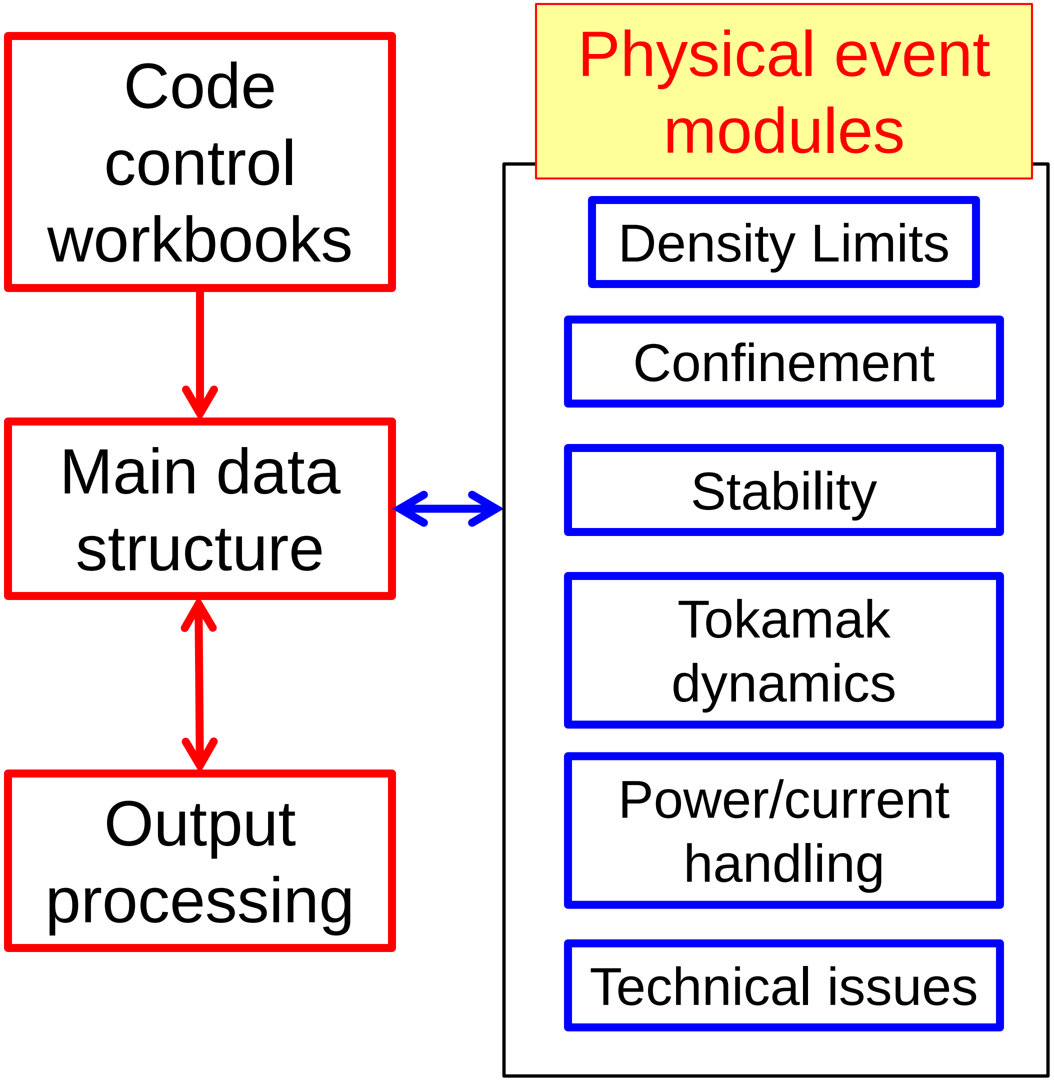
- 10 physical events presently defined in code with quantitative warning points
  - Builds on manual analysis of de Vries

    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), easily expandable, portable to other tokamaks (can now read DIII-D data)
- Example: Pressure peaking (PRP) disruption event chain identified by code before disruption
  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

J.W. Berkery, S.A. Sabbagh, Y.S. Park (Columbia U.)
and the NSTX-U Disruption PAM Working Group

DECAF is structured to ease parallel development of disruption characterization, event criteria, and forecasting



- Physical event modules encapsulate disruption chain events
  - Development focused on improving these modules
  - Structure eases development
    - E.g. separate code by C. Myers that improved disruption timing definition was quickly imported
- Physical events are objects in physics modules
  - e.g. VDE, LOQ, RWM are objects in “Stability”
  - Carry metadata, event forecasting criteria, event linkages, etc.

The model using a "no slip" condition has no steady state solutions at a large enough island width (k_1)

- For steady state solutions: $\left(\frac{d(I\Omega)}{dt} = 0\right)$

- $k_1 = 0$: "red curve"
  - No mode present

- $k_1 < \frac{{T_{aux}}^2 \tau_{2D}}{4I}$: "blue curve"
  - Two steady state solution

- $k_1 = \frac{{T_{aux}}^2 \tau_{2D}}{4I}$" : "orange curve"
  - One steady state solution $(\sim \frac{\Omega_0}{2})$
  - Bifurcation
    - At close to half the steady state natural rotation frequency (Ω_0)

$$\frac{d(I\Omega)}{dt} = T_{aux} - \frac{k_1}{\Omega} - \frac{(I\Omega)}{\tau_{2D}}$$