Supported by the
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Tokamak Disruption Event Characterization and Forecasting Research and First Real-time Application on KSTAR

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KFE KOREA INSTITUTE OF FUSION ENERGY

KSTAR

PPPL

NOVA PHOTONICS

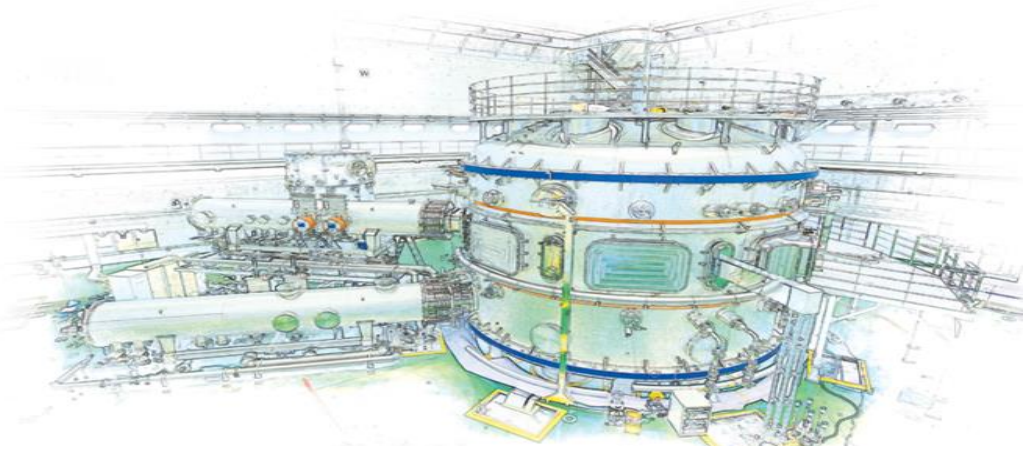
COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

Presented at the

NSTX-U Physics Meeting

PPPL + virtual

5-July-2022



V1.1

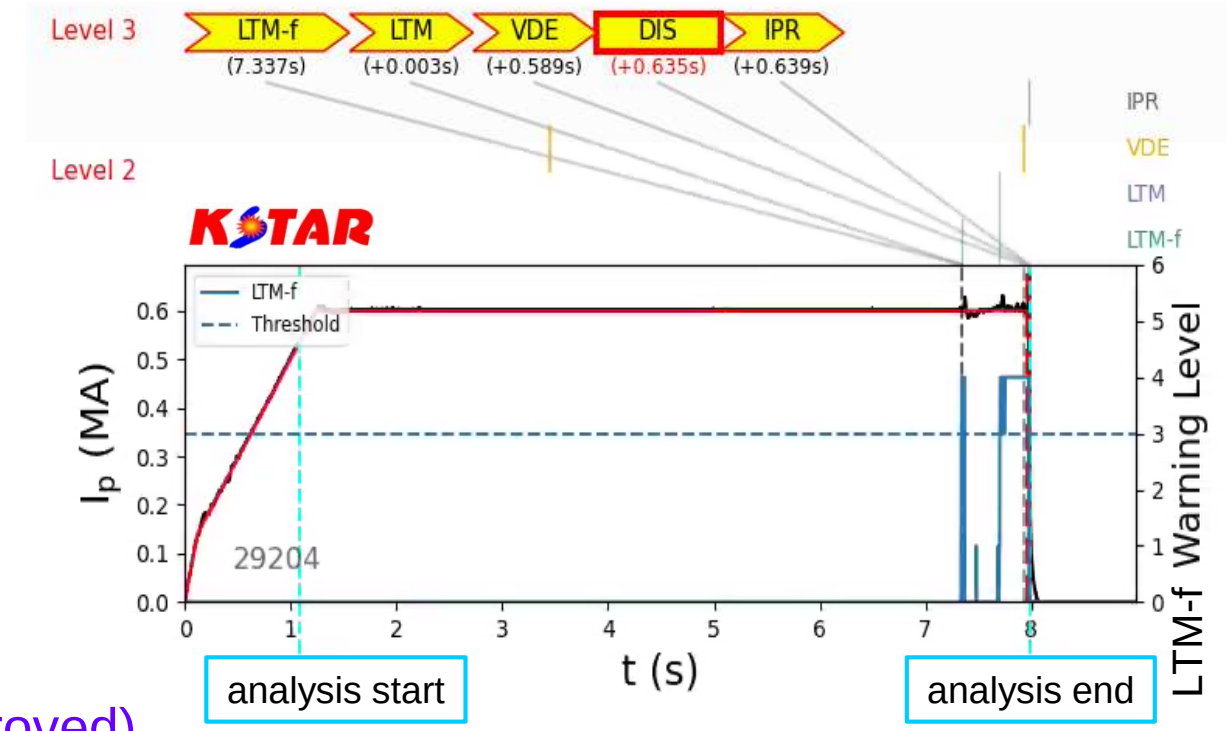
Supported by US DOE grant DE-SC0016614

Disruption Event Characterization and Forecasting Research (DECAF) continues to expand, including first real-time application on KSTAR

- DECAF (very brief) overview ← see Jan 24, 2022 talk for more detail
- Recent automated large database analysis capability
- Real-time DECAF implementation
- Real-time DECAF hardware update

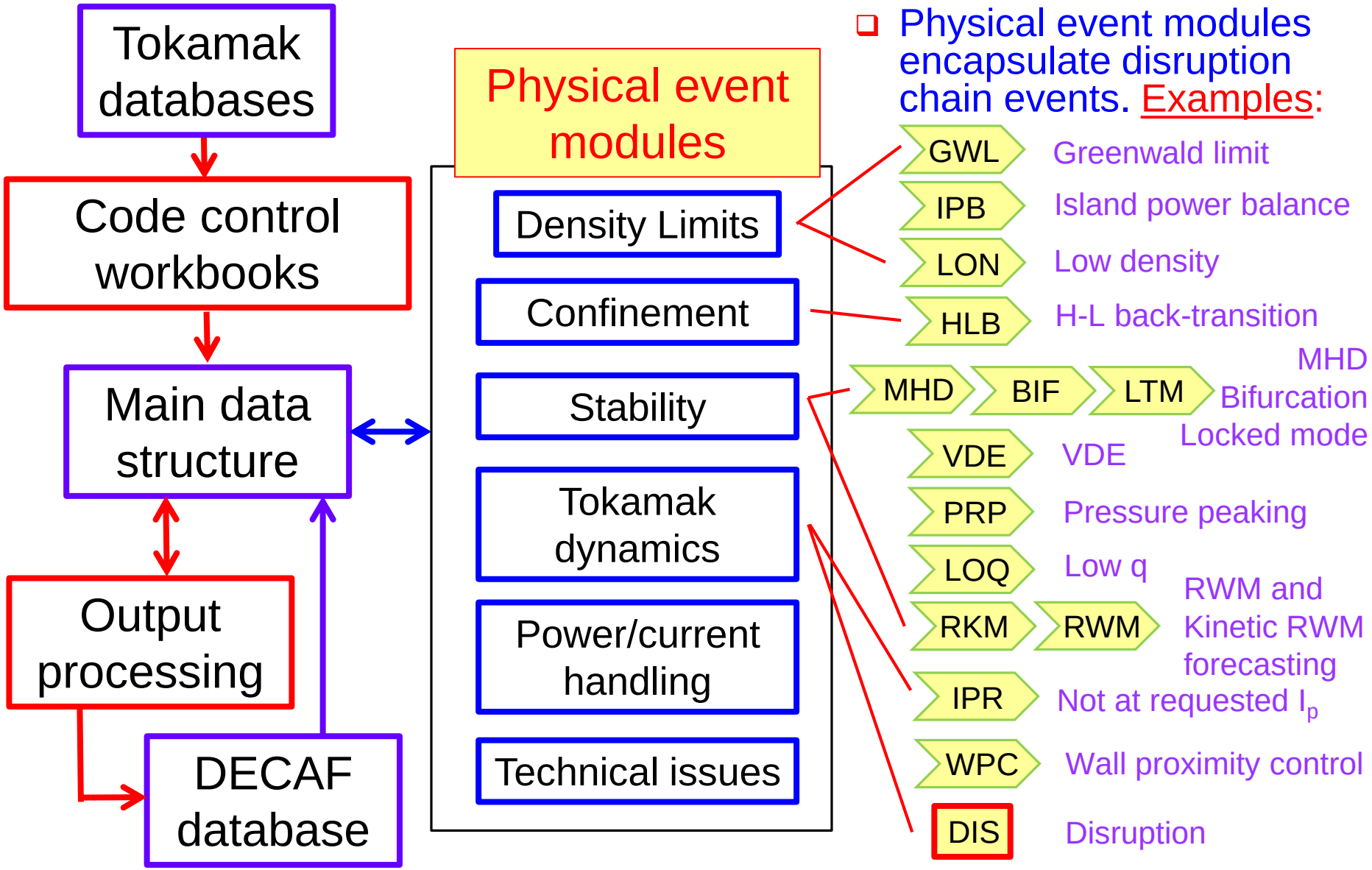
Continued DECAF development builds from an extrapolable approach with strong initial success – now expanded to real-time in KSTAR

- Fully automated, physics-based analysis of existing tokamak databases from multiple devices (e.g. KSTAR, NSTX, MAST/-U, AUG)
- Analyzing all plasma states, continuous and asynchronous events
  - "Critical": (Level 3) event chains leading to disruption if no action taken
  - "Proximity": (Level 2) paths to "critical" events
  - "Safe": (Level 1) events indicate steady operation (e.g. L-mode / H-mode determination, steady ELMing, benign confinement transitions)
- "Forecaster events": give earliest warnings
- High quantitative success found (recently improved)
  - > 91% true positive, ~ 8% false positive (~1e4 shots, ~1e6 samples)
- Research continues focused on improving forecasting to needed accuracy (98%+ goal for ITER, w/low false positives)



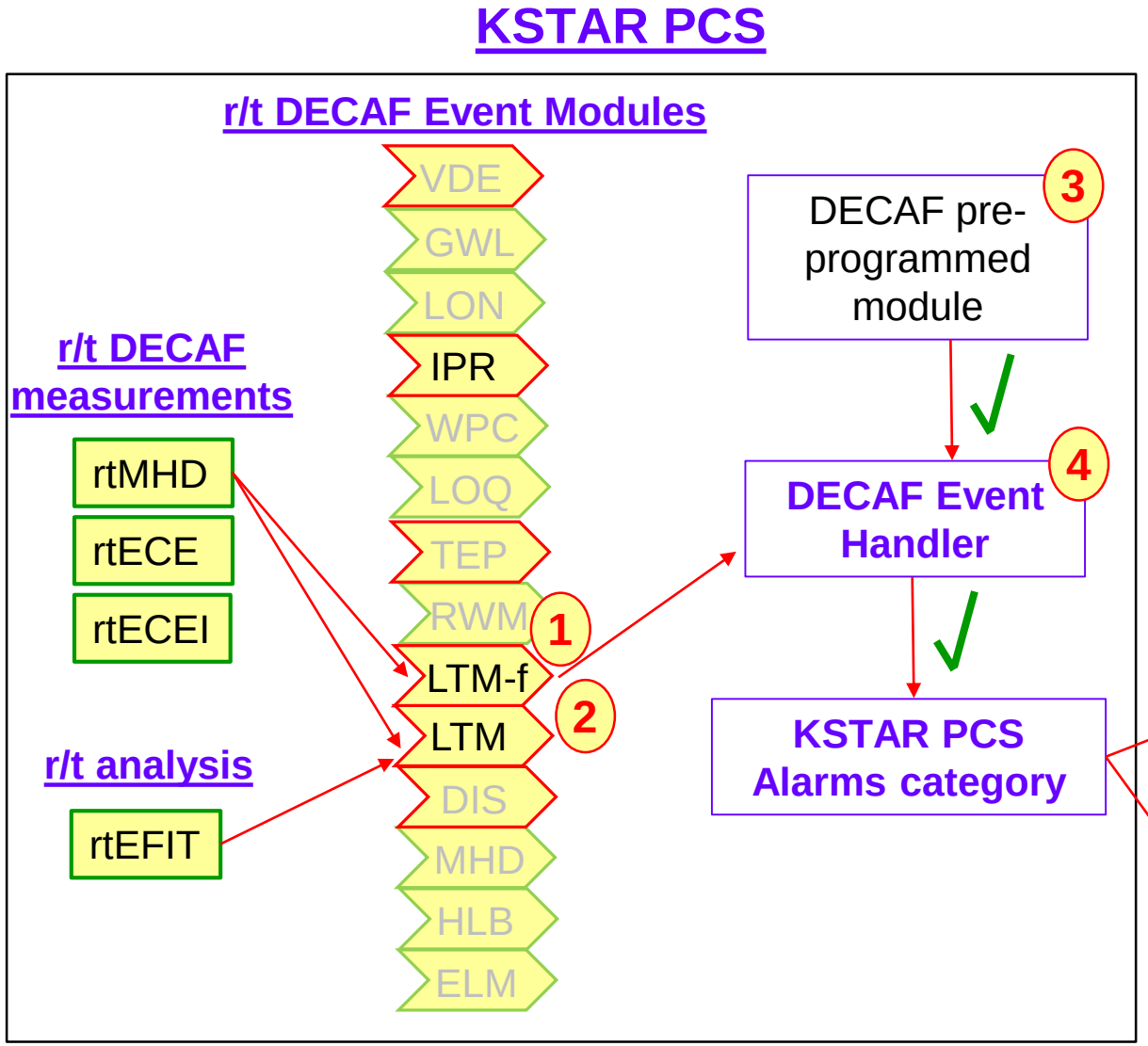
Data / analysis is desired in real time to reproduce offline analysis

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

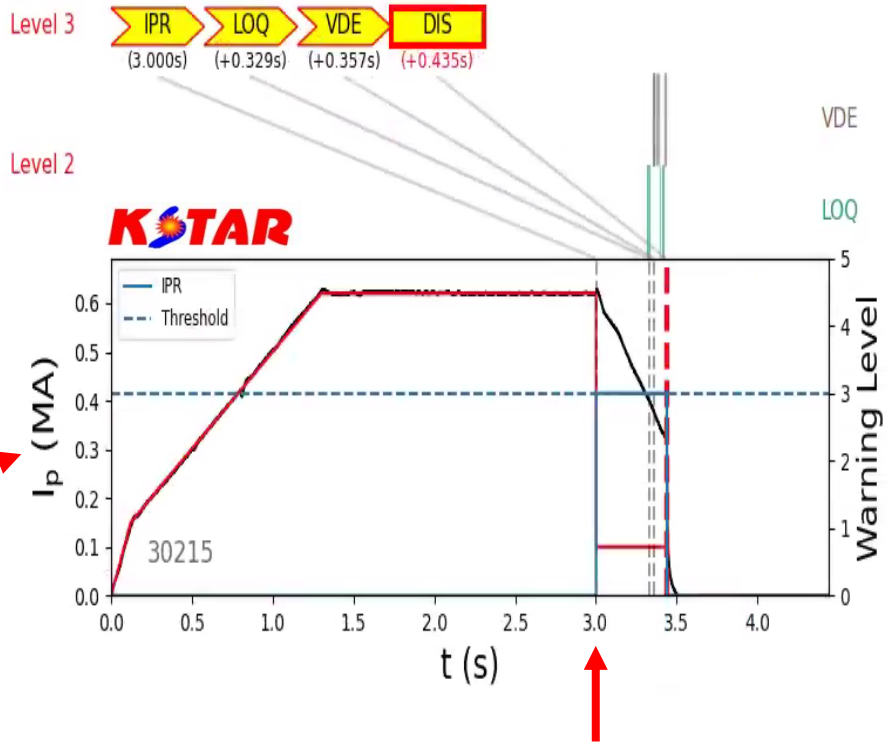


- Physical event modules encapsulate disruption chain events. Examples:
  - GWL — Greenwald limit
  - IPB — Island power balance
  - LON — Low density
  - HLB — H-L back-transition
  - MHD — MHD
  - BIF — Bifurcation
  - LTM — Locked mode
  - VDE — VDE
  - PRP — Pressure peaking
  - LOQ — Low q
  - RKM, RWM — RWM and Kinetic RWM forecasting
  - IPR — Not at requested I_p
  - WPC — Wall proximity control
  - DIS — Disruption

r/t DECAF initial deployment: four real-time software elements were installed, some tested in 2021, running in 2022 + more being added



- Offline and real-time DECAF codes follow similar design; DECAF events added as modules
- Demonstrated plasma shutdown through rtDECAF message



Controlled shutdown triggered
(recent result: MGI triggered)

Island rotation dynamics model is used to compute the critical frequency to forecast disruption

- Cylindrical, rigid body model
- Possible model of drag for both a "slip" and a "no slip" condition:

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

LTM-f

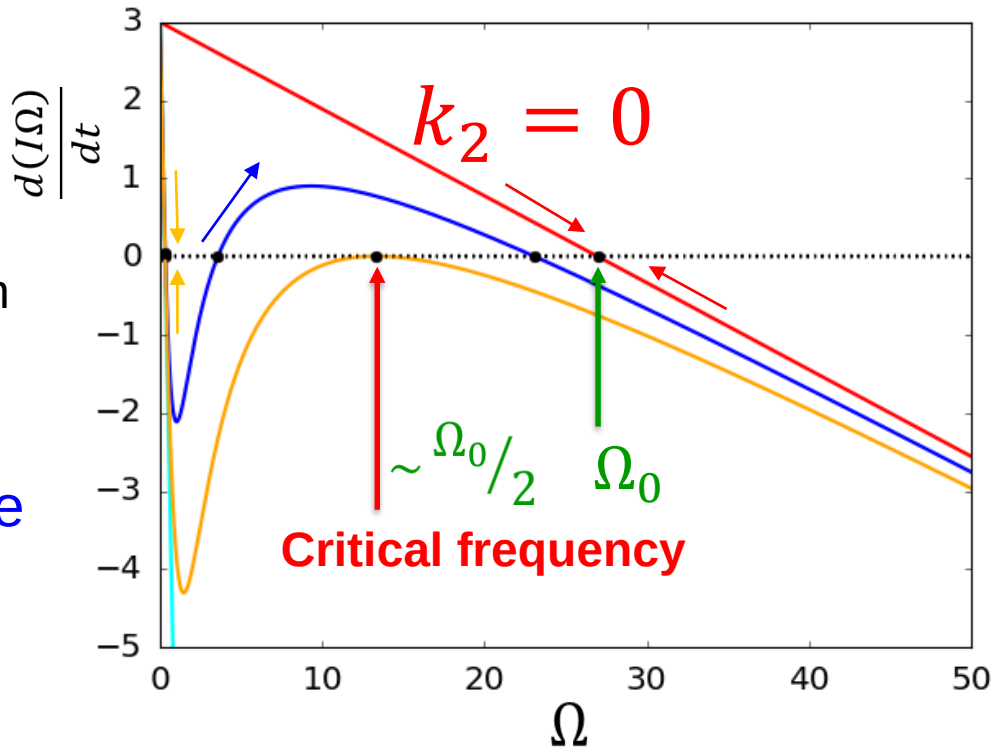
$$T_{mode} = \frac{k_2\Omega}{1 + k_3\Omega^2}$$

R. Fitzpatrick et al., Nucl. Fusion 33 (1993) 1049

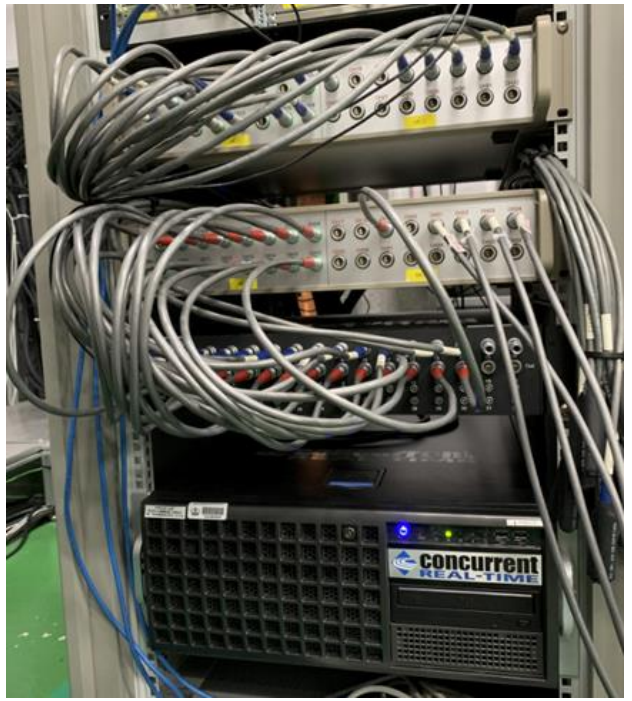
- At very low angular speed, mode can reach a stable steady state,
  - ➔ observed in KSTAR

- First real-time model, assume "no slip" condition

$$T_{mode} = \frac{k_1}{\Omega}$$



- Utilize DECAF real-time MHD system to determine mode, critical frequency

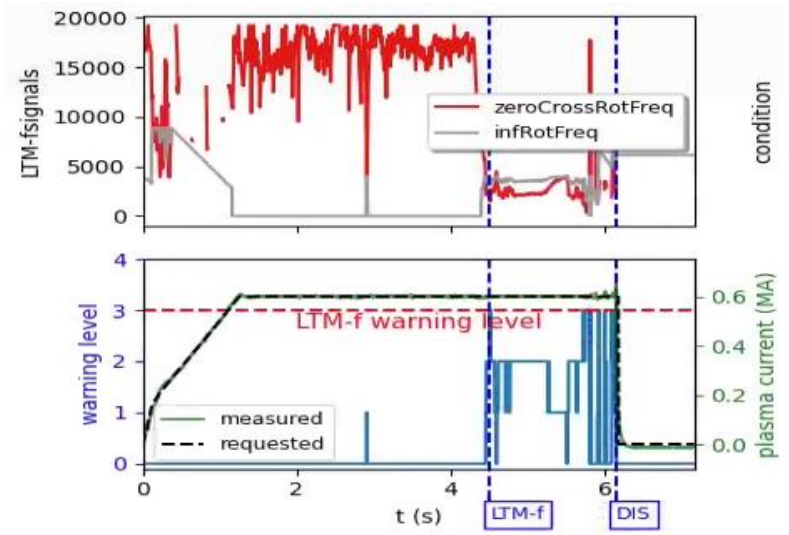


J. Riquezes

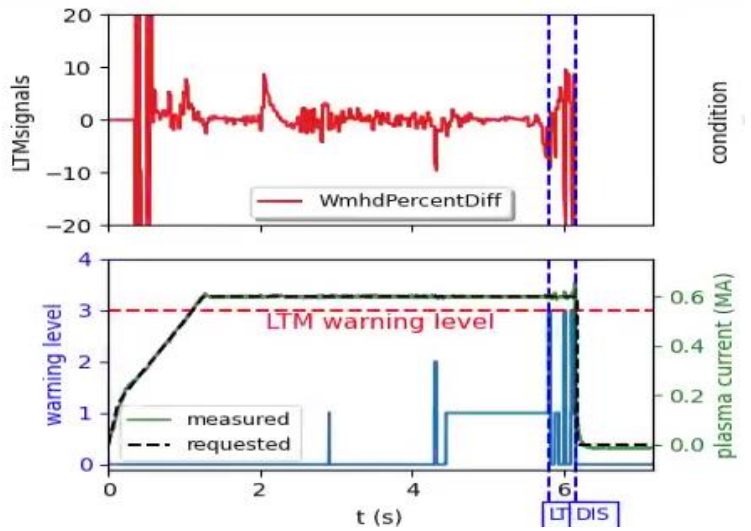
LTM forecaster on KSTAR leaves ample time for potential NTM control before disruption

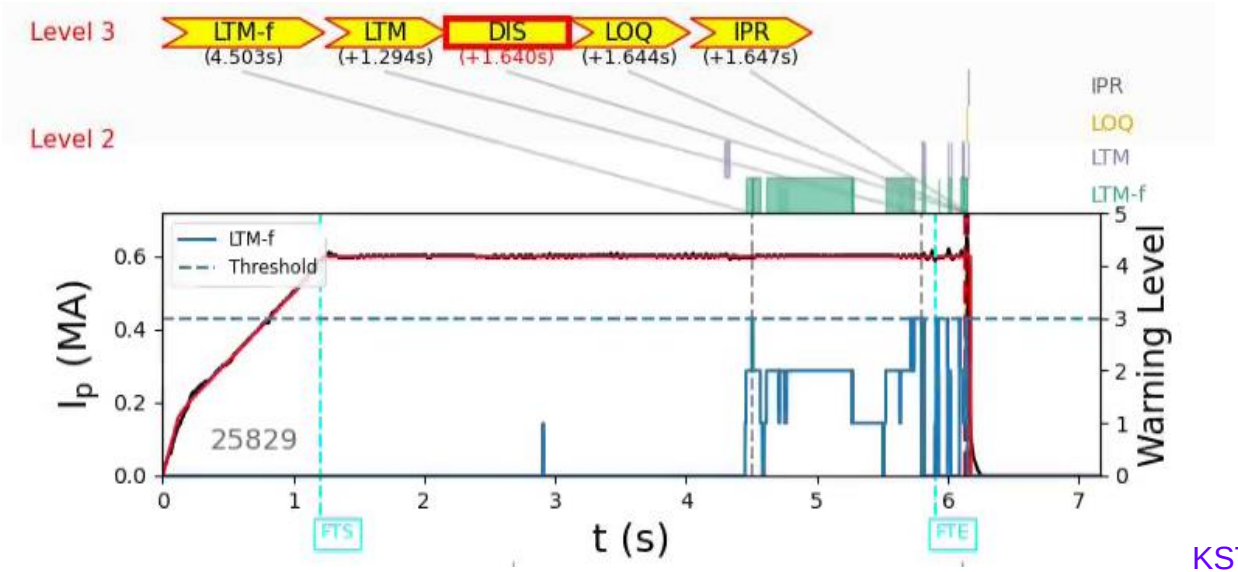
- Plots show summary of DECAF results for characterization and forecaster in a disrupting KSTAR shot
- Bifurcation frequency is crossed at ~4.5 s
  - Locking occurs at ~ 5.8 s
  - Disruption happens at ~ 6.1 s
- Significant time period of 1.6 s between forecasting and disruption

LTM Forecaster



LTM Characterization





DECAF

KSTAR shot 25829

DECAF development attention to real-time system design and implementation on KSTAR, DECAF code analysis processing

- Real-time DECAF on KSTAR
  - several key diagnostics now acquired in real-time as part of the KSTAR PCS
  - initial implementation real-time DECAF software as part of KSTAR PCS

Following slides

- DECAF analysis capability (several development goals recently achieved)
  - Parallel processing over high performance clusters
    - PPPL private (~30 CPUs) and open SLURM queues (~1,000 CPUs)
    - Next step to utilize Princeton Stellar cluster (over 50,000 CPUs)
  - Analysis persistence
    - Automated interaction with the DECAF database
    - 200 TB dedicated storage, funded for further expansion
  - Analysis chunking
    - Standard DECAF analyses are now “one-button” capable to process an *entire run year of data*, or the *entire database of a device(!)* for iterated analysis of DECAF forecasting models, etc.

NSTX DECAF run: 30 CPU SLURM
- **20 shots, 16 DECAF events**
- **30 seconds computation time**

NSTX run year ~ 3,000 shots
- extrapolation: 0.8 hours computation

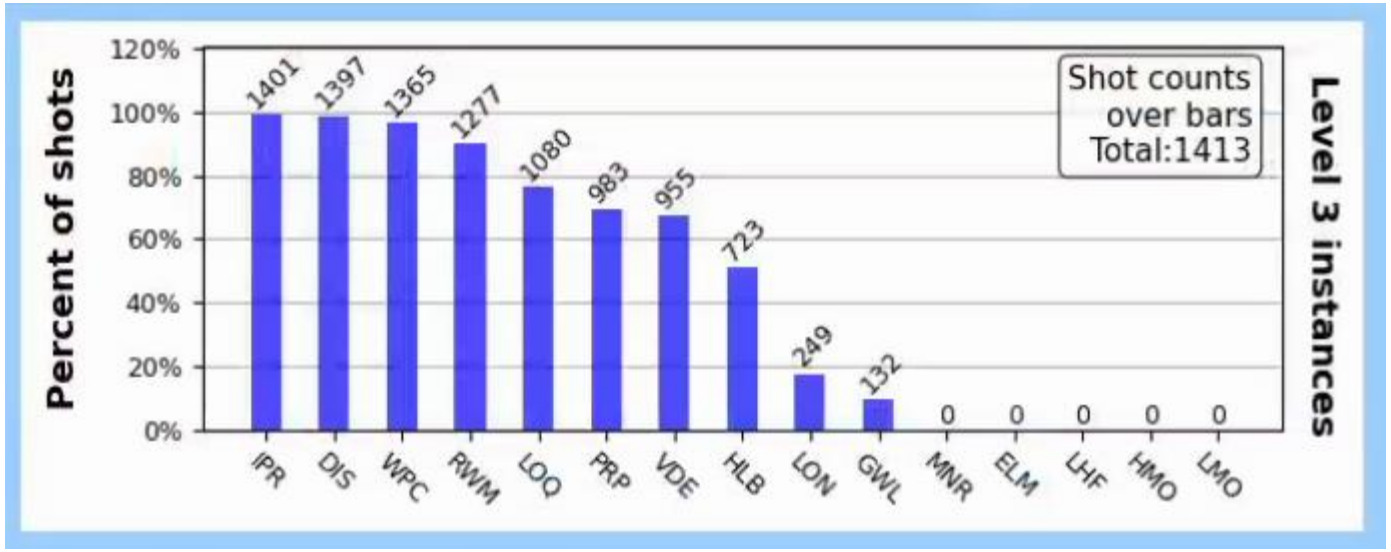
NSTX database ~ 25,000 shots (40 TB)
- extrapolation: 7 hours computation

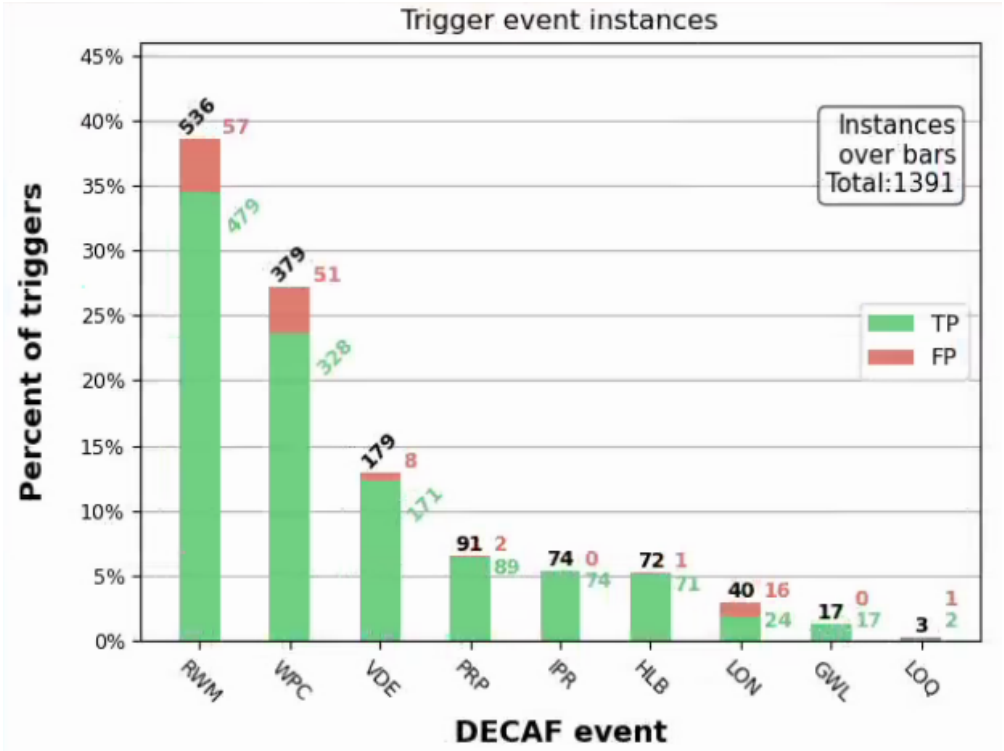
True positive rate for disruption forecasting found to be very high in large database analysis (ex: NSTX 2009 run campaign)

Confusion matrix

	----- Predicted condition -----	
Total population P+N 1401	Positive (PP)	Negative (PN)
Positive (P) 1265	True Positive (TP) 1255	False Negative (FN) 10
Negative (N) 136	False Positive (FP) 136	True Negative (TN) 0

99.2% true positive rate





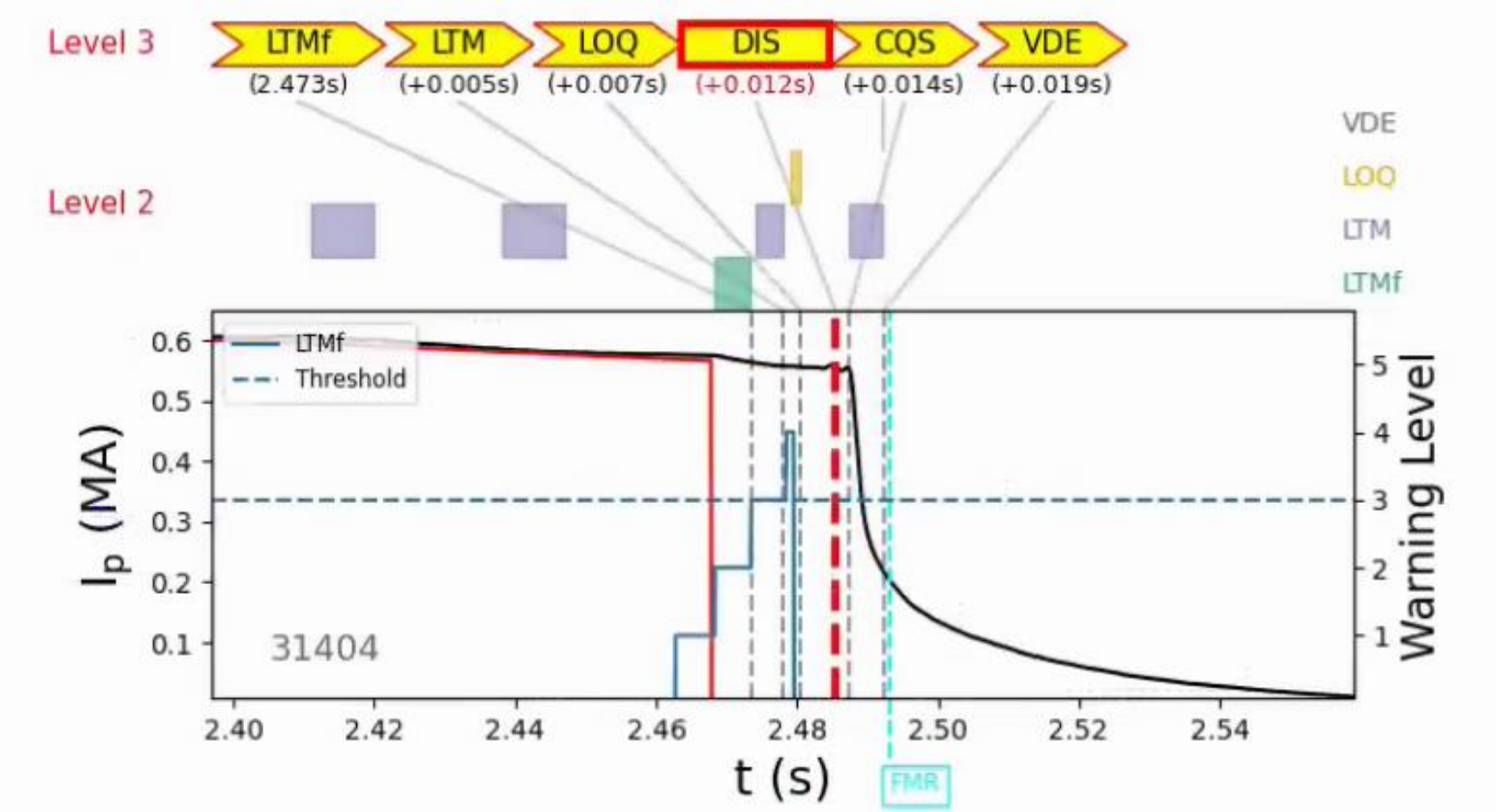
- Key analysis step: Determining causality vs. correlation between warnings and the disruption
  - critical for all disruption prediction algorithms!
  - significant analysis focus now

MP2022-03-01-015: Real-time DECAF event validation at high non-inductive current, control development, and disruption mitigation actuation – MAIN GOALS

- Shot plan includes run time during plasma commissioning

	Number of shots (estimate)
Goal 1: Test 8 CPU PCS, real-time DECAF events during plasma commissioning • rtMHD, rtFFTs during magnetic test shots; rtECE, LTM-f, LTM during plasma shots	16 (commissioning)
Goal 2: Apply rtDECAF event(s) to test warning levels in a controlled disruption prediction experiment to trigger the MGI disruption mitigation (MGI) system • Complete testing of LTM-f, LTM and use them to trigger MGI, varying plasma conditions	14
Goal 3: Test / analyze real-time DECAF event calculations producing disruption prediction warnings in target plasmas now including high non-inductive current • Attempt pre-programmed TM lock prevention; add/test other rtDECAF events (IPR)	14
Goal 4: Test auxiliary system actuation by rtDECAF events for several target plasmas as an initial demonstration of disruption avoidance	12

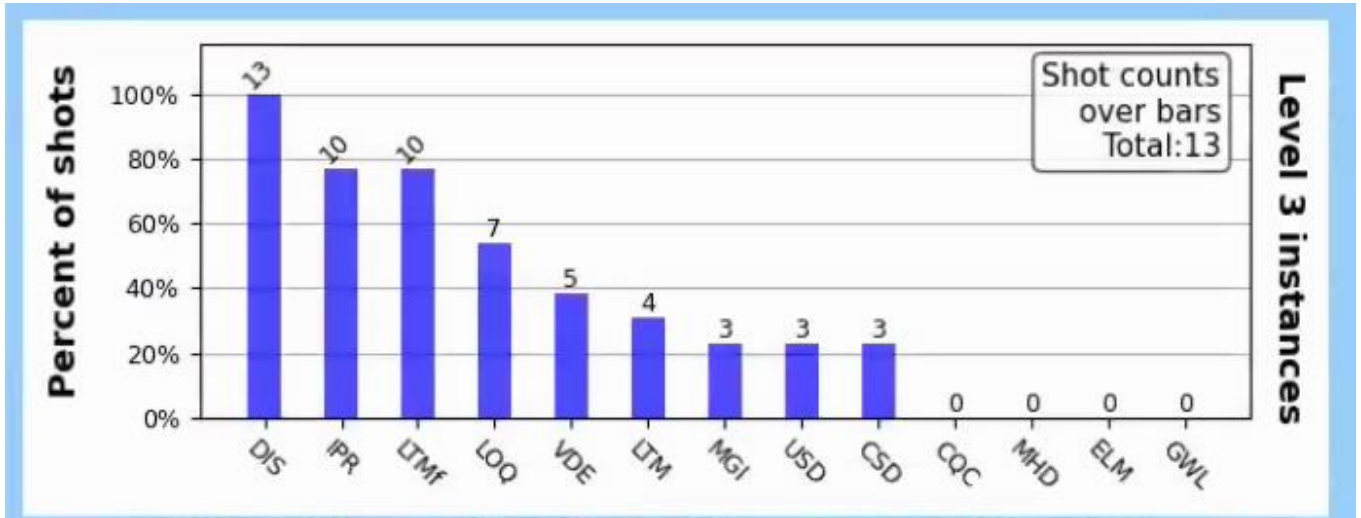
31404: MGI fired – offline DECAF shows LTM-F, LTM events reach Level 3 – 100% accuracy in r/t prediction on dedicated run days

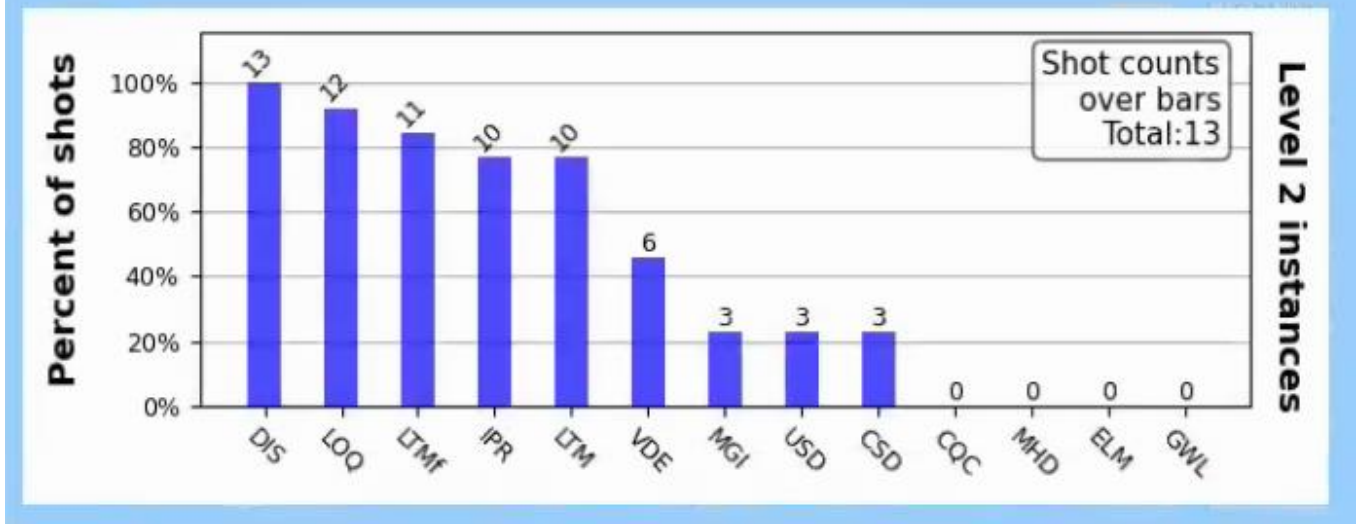


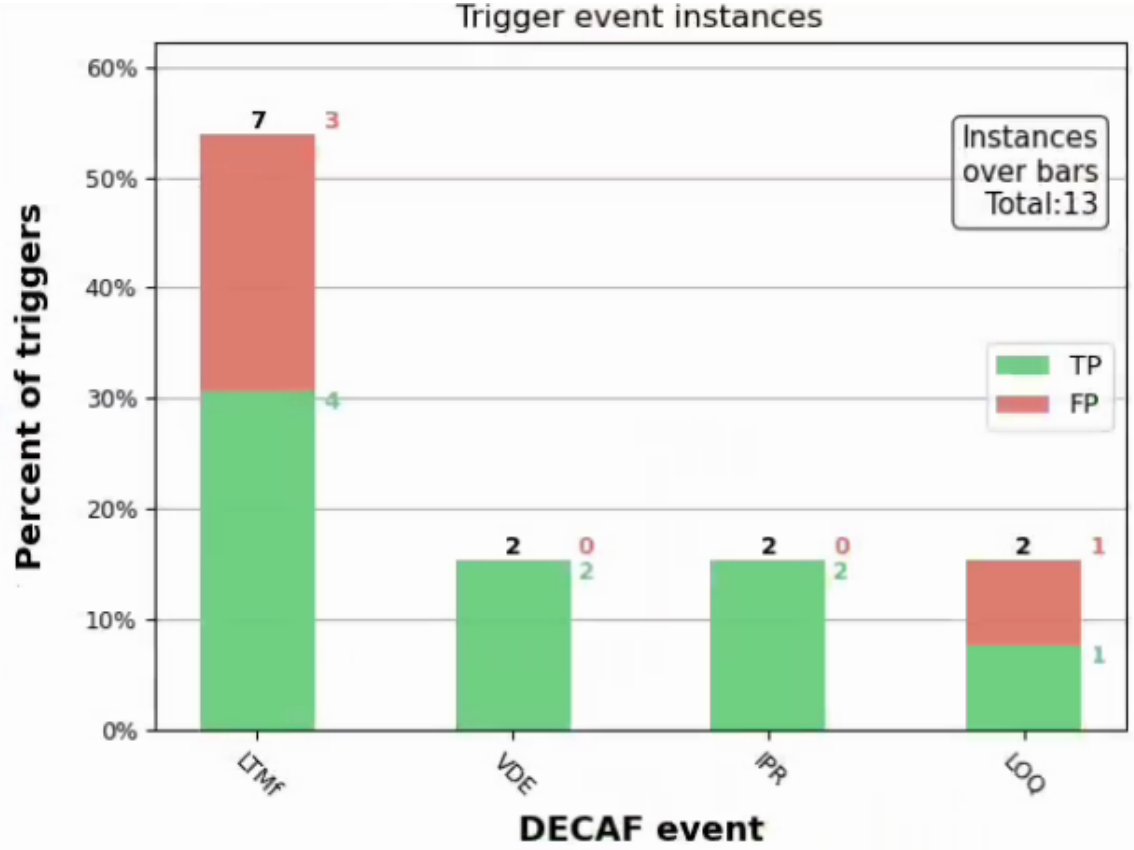
- 100% accuracy in real-time DECAF Level 3 events (6/9/22)
  - 18 shots; 3 MGI
  - 7 true positives
  - 11 true negatives
- 100% accuracy in real-time DECAF Level 3 events (6/15/22 + 6/22/22)
  - 22 shots
  - 12 true positives
  - 10 true negatives
- Excellent distinction between true positives and negatives

DECAF Model: KSTAR-MDL061222sas2 (version: Vv1)

MP2022-03-01-015 1st day: Offline DECAF analysis for shots taken





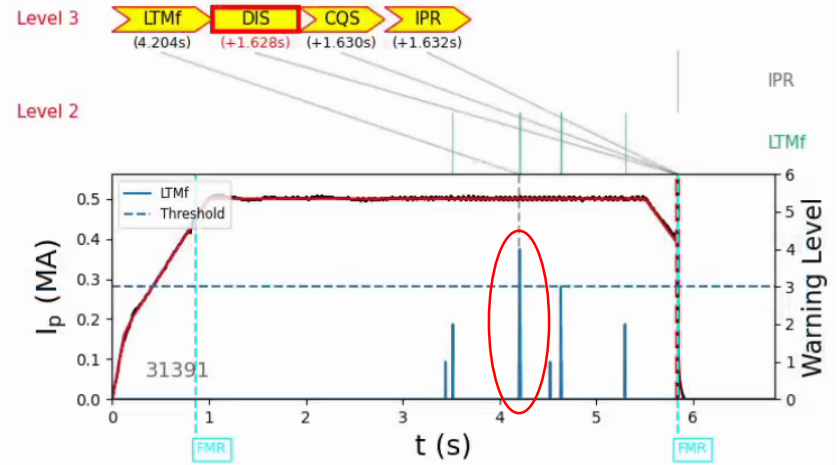


- False positive evaluation too stringent for KSTAR (see next slide)
  - There are less false positives – update offline model

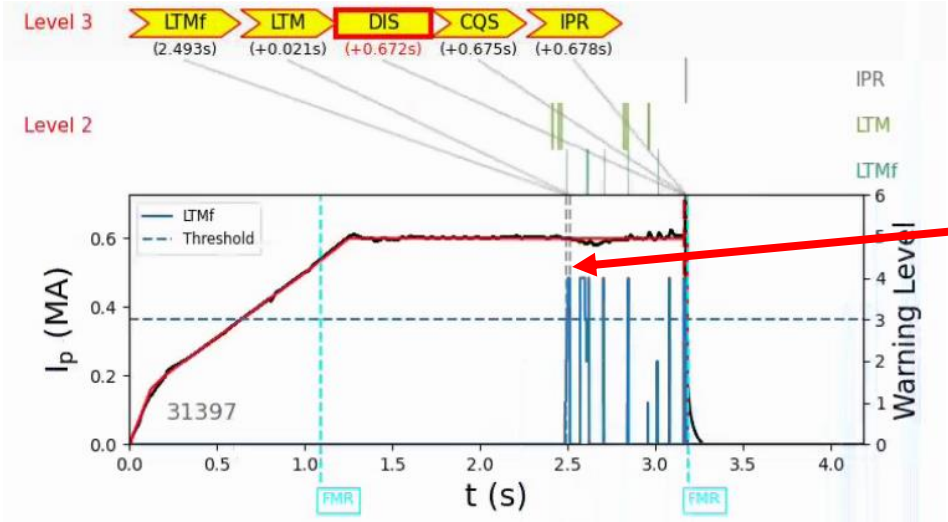
Model: KSTAR-MDL061222sas2 (version: Vv1)

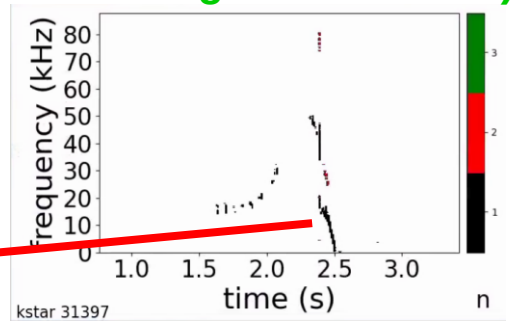
Examination of DECAF False positives (31391, 31392, ~~31397~~, ~~31400~~)

LTM-F Level 3 spike causes false positive (large frequency variation) – fix w/smoothing

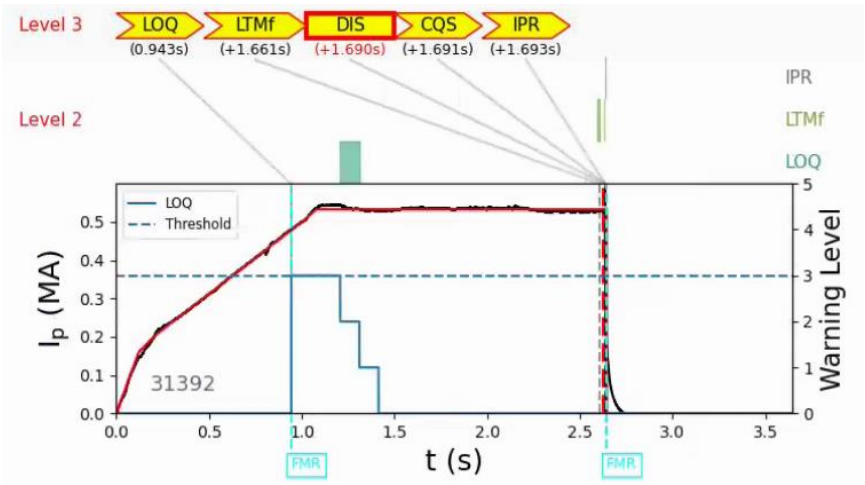


LTM-F is not a false positive in this shot (- 0.5s FP time margin insufficient)

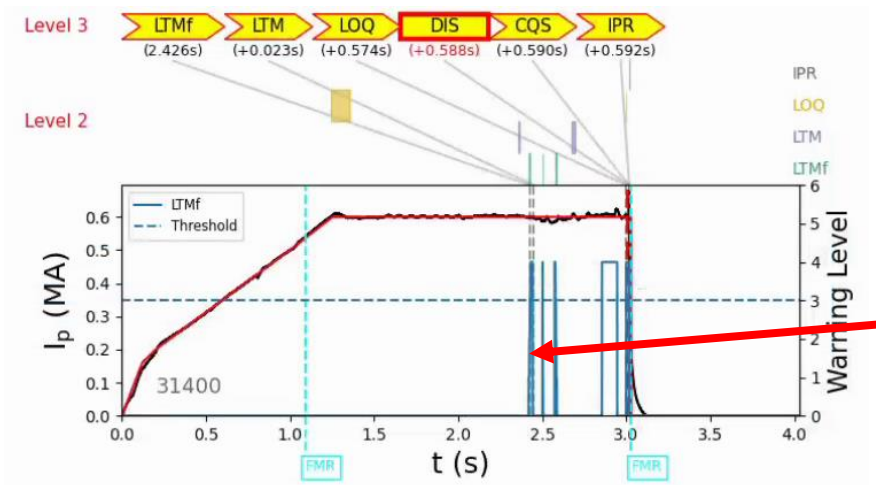


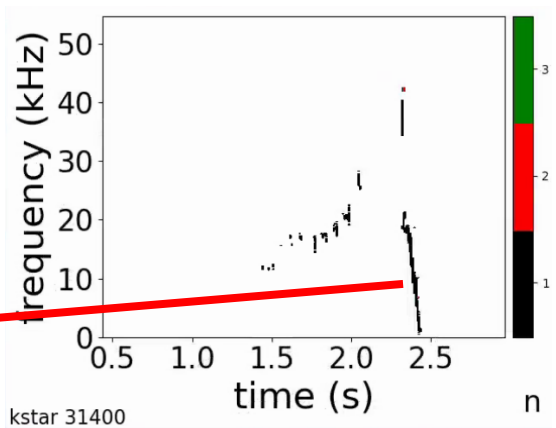


LOQ Level 3 approaching Ip flat-top – check q95 calculation; increase threshold



LTM-F is not a false positive in this shot (- 0.5s FP time margin insufficient)

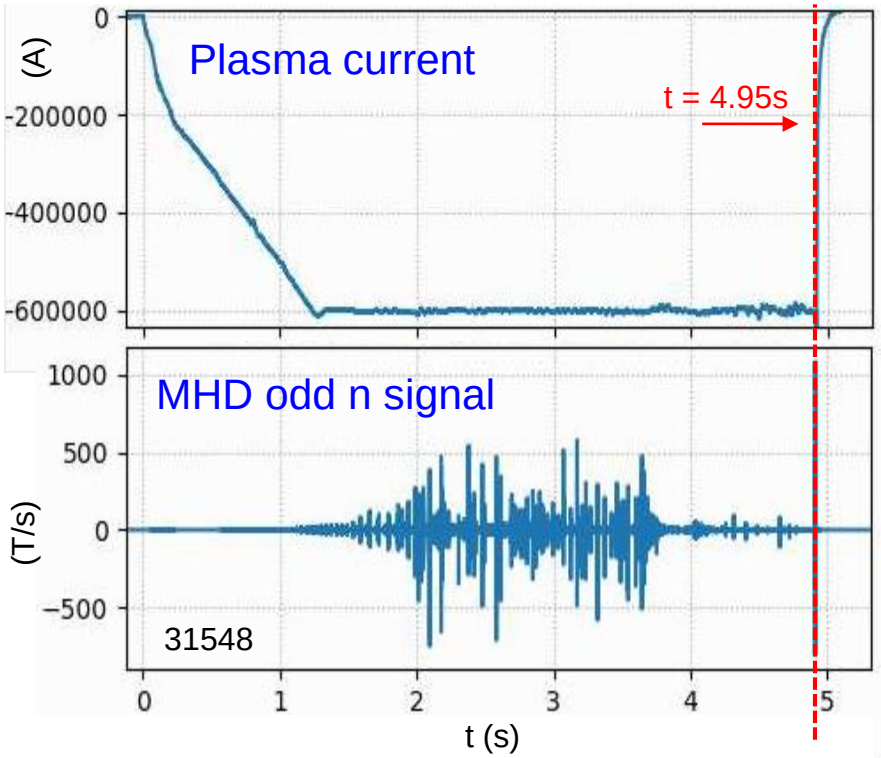




BRIEF review of real-time DECAF results from 6/15/22

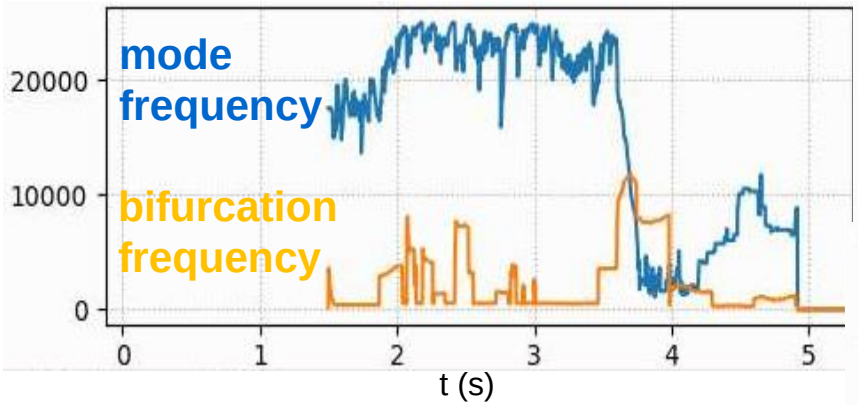
- DECAF warning levels examined for LTM-F and LTM event warnings
  - LTM-F forecasted TM accurately (Level 3)
  - LTM frequency warning reached Level 3 after the LTM-F warning (correct)
  - LTM stored energy warning reached Level 3 after LTM frequency warning (correct)
  - Repeated 100% accuracy in forecasting
- New IPR software was enabled and ran, not yet completed
  - The real-time Ip current target waveform was correct, but the Ip waveform comes up with 0 right now
- The timing demonstration of the disruption avoidance worked, but actuator didn't stop the mode lock yesterday (request more run time to complete this ➔ happening 7/6/22 KST)
  - Just need to add software that connects real-time DECAF warning with disruption avoidance actuator
  - With some more shots (requested) can add toroidal rotation to n = 1 disruption avoidance actuator, also can attempt ECCD as disruption avoidance actuator

Real-time DECAF warnings show early LTM forecast of disruption, and additional LTM warnings for mode locking

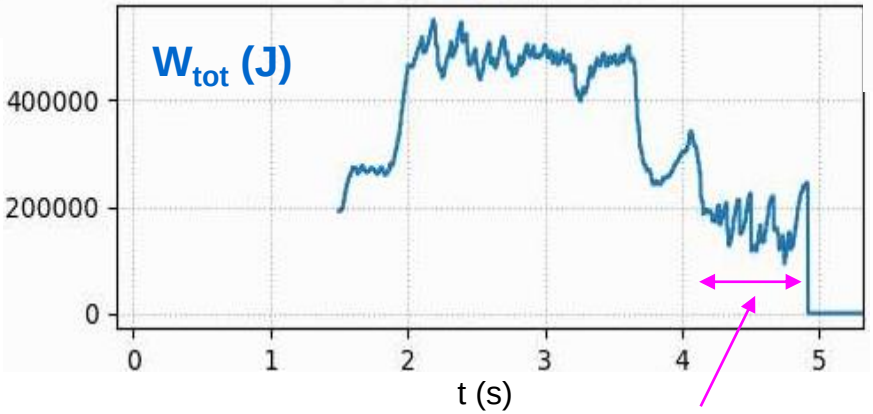


- Real-time LTM forecaster significantly precedes key events:
  - LTM warnings preceded by 0.470 s
  - Plasma current quench preceded by 1.28 s

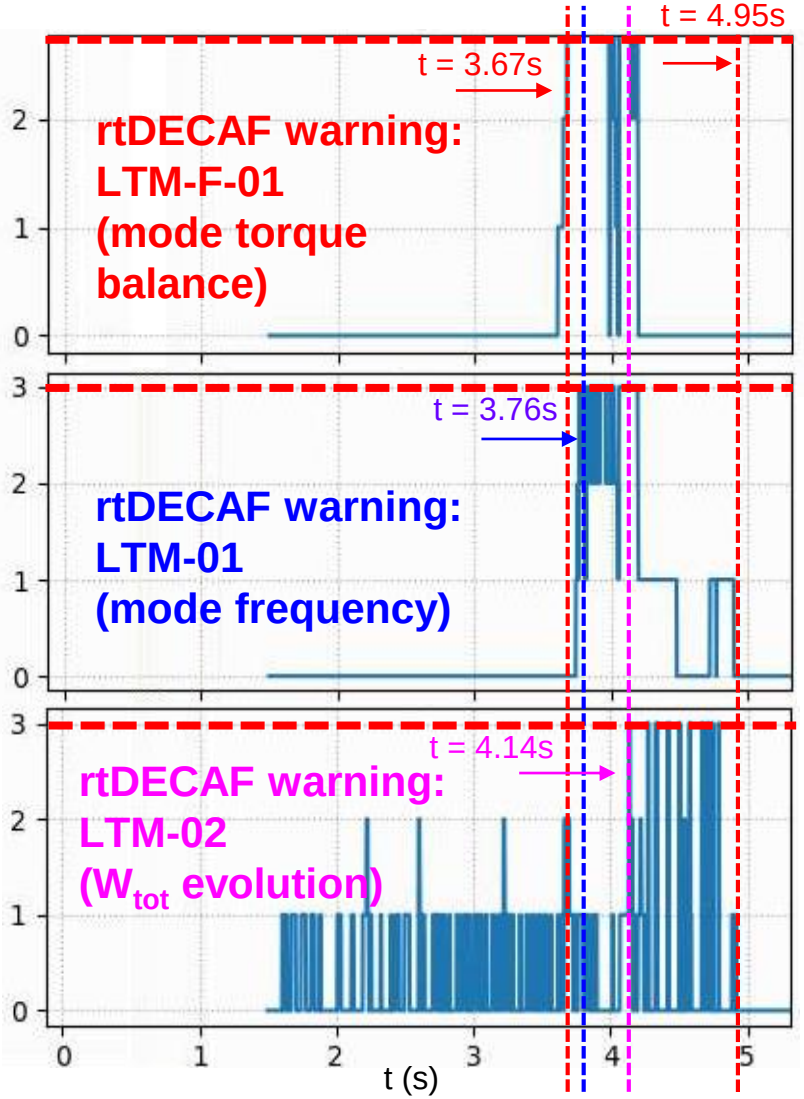
rtDECAF mode torque balance



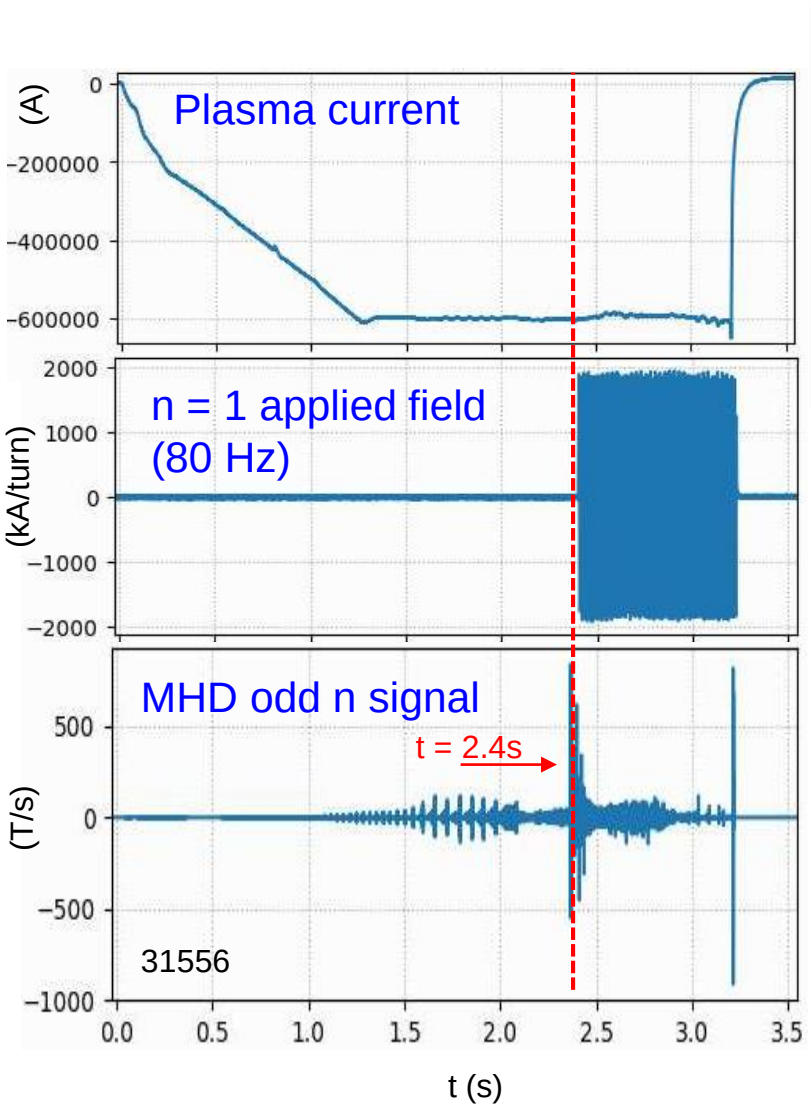
Stored energy evolution

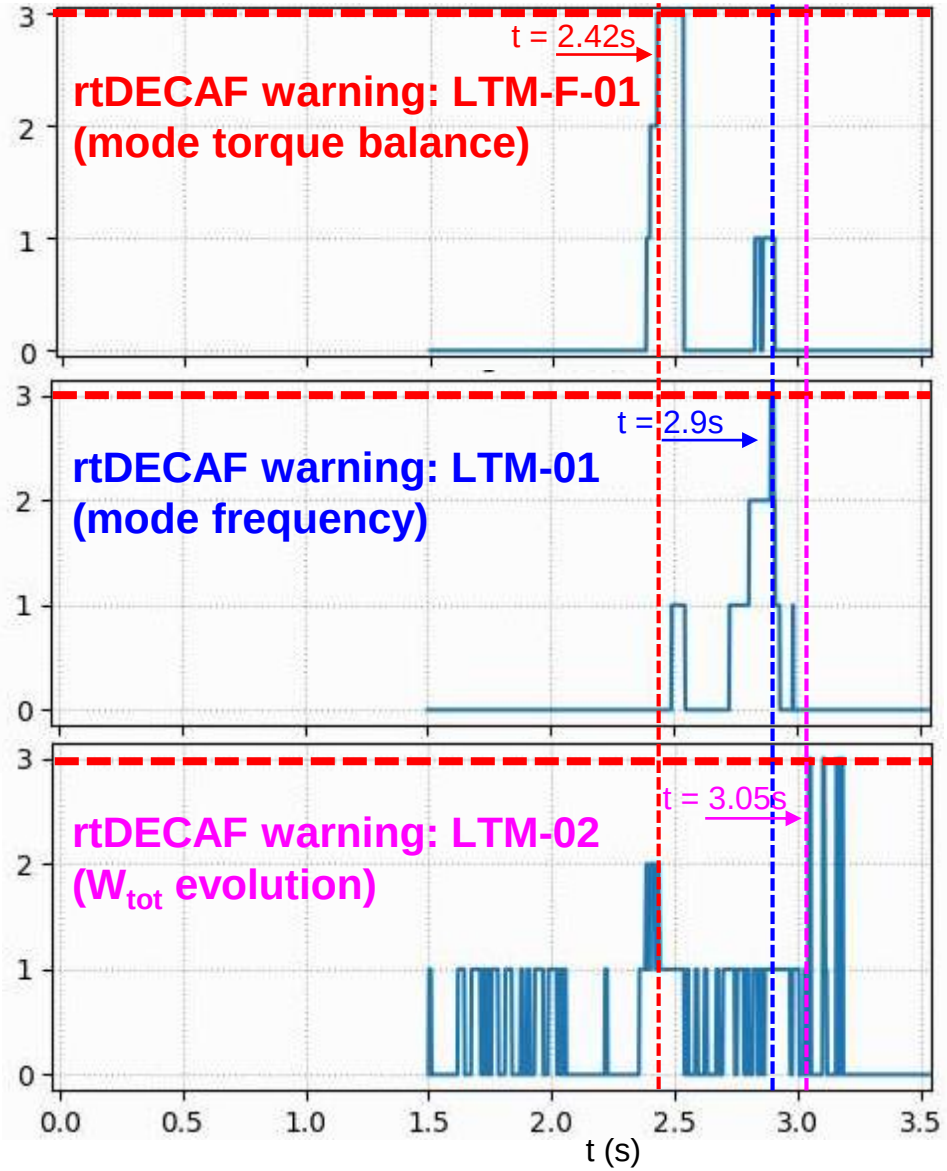


W_{tot} dynamic during mode lock



Pre-programmed n = 1 field applied at same time as critical rtDECAF LTM-F forecast was made to “simulate” disruption avoidance

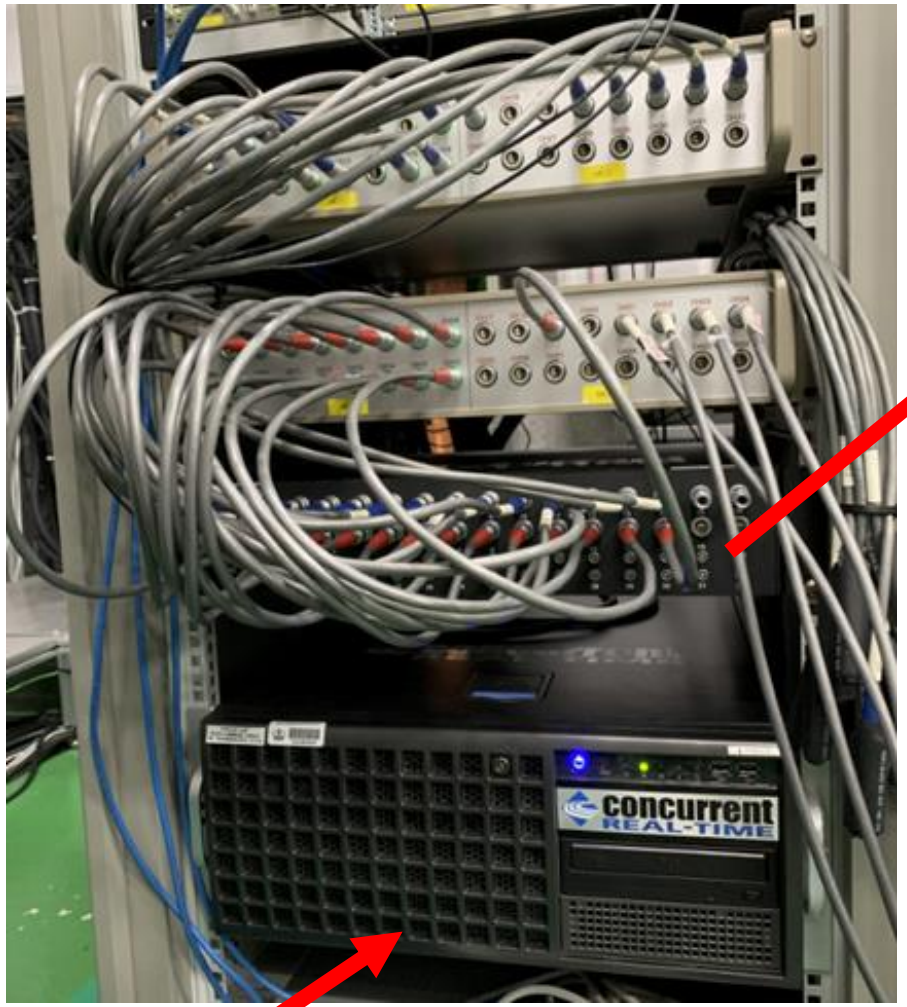




- Forecast worked, but n=1 AC field did not prevent TM mode lock
  - Such an activation was successful in 2021 “NTM entrainment” experiment
- Two differences this year regarding TM lock prevention attempt
  - n = 1 applied AC field did not rotate toroidally (patch panel setting different)
  - target plasma different
- rtDECAF disruption avoidance attempt possible in 2022 run
  - alter rtDECAF software to trigger key actuator
    - n = 1 field, ECCD, etc.

NSTX-U real-time MHD system implementation, part of our present grant research, will enable similar capability for NSTX-U

KSTAR rtMHD system



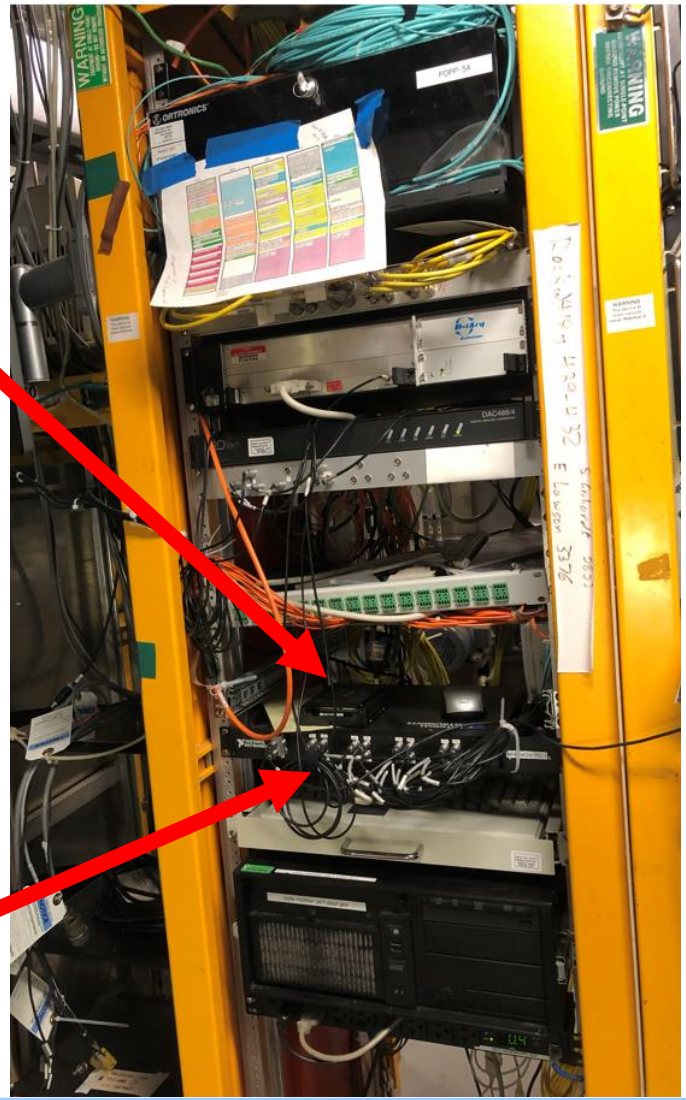
KSTAR real-time MHD computer, DAQ

KSTAR buffer chassis (diagnostic interface box)

- Started discussions on NSTX-U system design
  - Diagnostic discussion with Eric F. and Stefano M.
  - Initial implementation / PCS interfacing discussion with Greg. T. and Frank H.
  - Discussion with Dan B. of in-common interfacing

LEMO cables from high-n array mag probes

NSTX-U High-n system



MP2022-03-01-015: Real-time DECAF event validation at high non-inductive current, control development, and disruption mitigation actuation – address GOAL 4 tonight

- Shot plan includes run time during plasma commissioning

	Number of shots (estimate)
Goal 1: Test 8 CPU PCS, real-time DECAF events during plasma commissioning • rtMHD, rtFFTs during magnetic test shots; rtECE, LTM-f, LTM during plasma shots	16 (commissioning)
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Goal 4: Test auxiliary system actuation by rtDECAF events for several target plasmas as an initial demonstration of disruption avoidance	12

NOTE: Detailed shot plan provided next, target plasmas from 2021, 2022

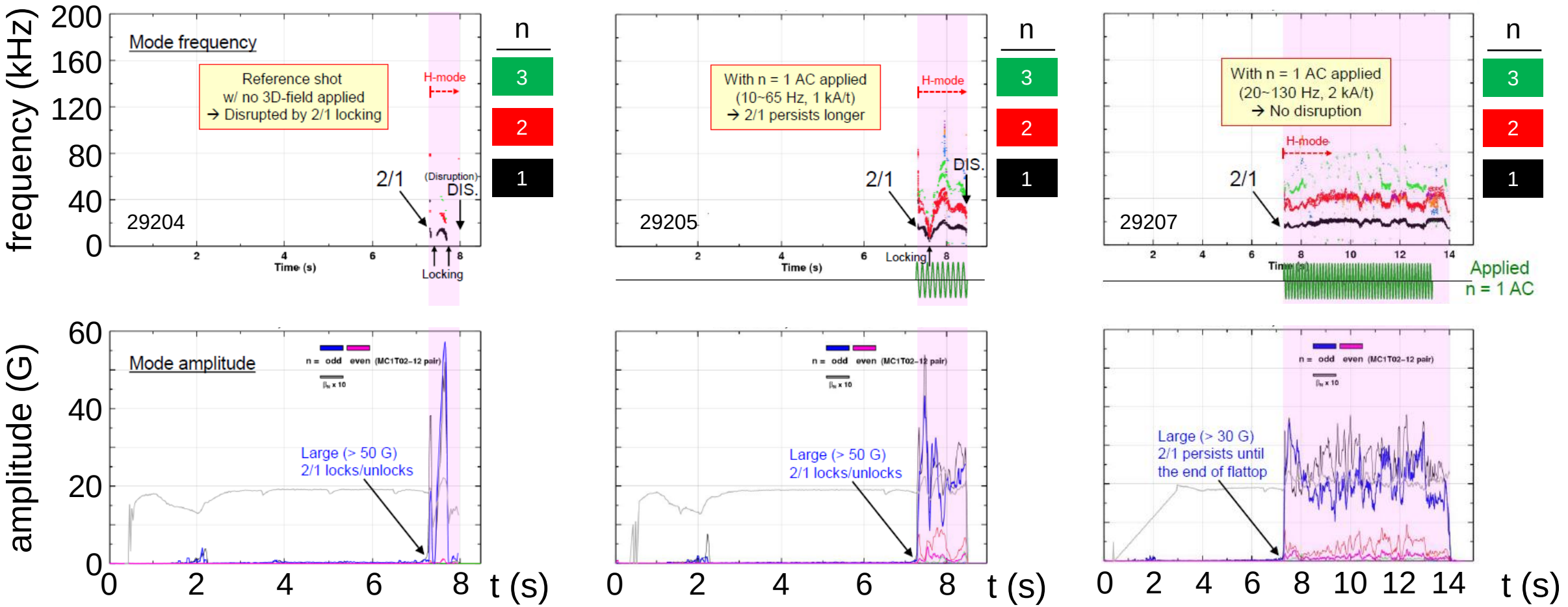
New disruption avoidance actuator: applied entrainment field successful in preventing naturally-occurring 2/1 NTM locking (2021 KSTAR experiment)

Magnetic spectrograms

Natural locked NTM disruption

AC field lengthens shot duration

Disruption avoided with applied AC field



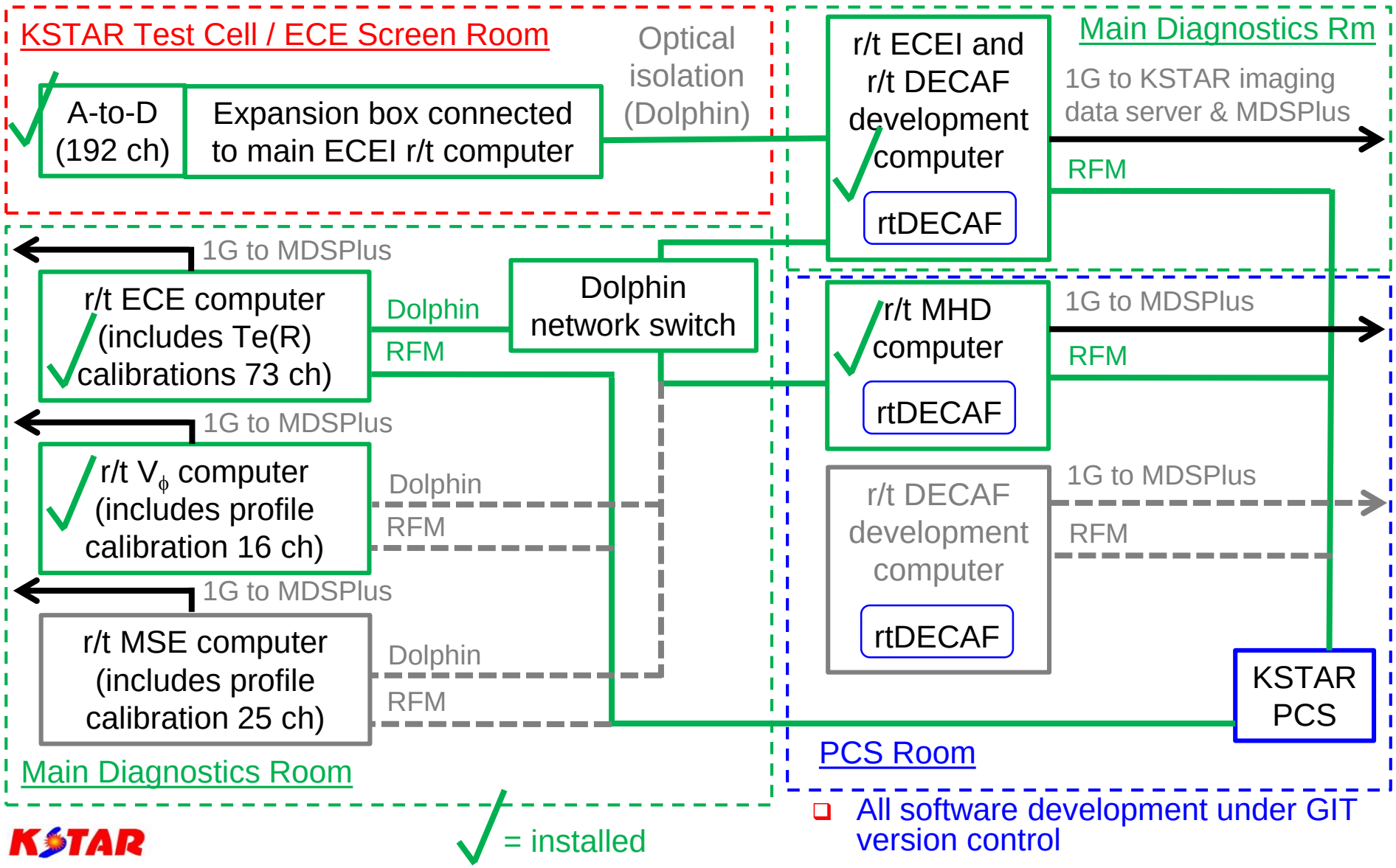
- NOTE: applied AC field frequency is << mode rotation (due to boundary value field alteration? analysis continues)

MP2022-03-01-015: Real-time DECAF event validation at high non-inductive current, control development, and disruption mitigation actuation – 7/6/22

Goal 4): Test auxiliary system actuation by rtDECAF events for several target plasmas as an initial demonstration of disruption avoidance

Task	Number of Shots
(0) SET-UP: IVCC Patch panel: STD-N1A; MGI available: YES; rtDECAF analysis ON at t = 1.5s	
(1) n = 1 toroidally rotating field actuator: Target plasma: "I-mode ➔ H-mode": (NO n = 1 field) 29204; (WITH n = 1 field) 29207	
(1a) Run target plasma to get mode; rtDECAF disruption avoidance turned ON to actuate n = 1 field	2
(1b) If (1a) is successful, turn OFF AC field, turn OFF DECAF disruption avoidance actuation (leave rtDECAF analysis ON)	1
(2) NBI actuator: Target plasma: "delayed H-mode": 25331 (B_T = 1.8T better reproducibility); 31747 B_T = 1.6T	
(2a) Run target plasma 25331 to get mode; rtDECAF disruption avoidance turns ON extra NBI sources (from NBI-2)	2
(2b) If (2a) is successful, turn OFF extra NBI, turn OFF DECAF disruption avoidance actuation (leave rtDECAF analysis ON)	1
(3) ECCD actuator: (both pre-programmed and rtDECAF actuated ECCD) Target plasma: "ECCD TM": 31445; 31444	
(3a) Run target plasma to get mode; when rtDECAF disruption avoidance triggers turn EC5 on, extra ECCD power add EC3	2
(3b) If (3a) is successful, turn OFF ECCD, DECAF disruption avoidance actuation OFF (leave rtDECAF analysis ON)	1
(4) Disruption mitigation, low delay: targets 31399, 31403: produce rtDECAF-induced MGI disruption mitigation with least delay	1
(5) Produce high poloidal beta ~ 3, high non-inductive plasma (Target: 29033 high β_p = 3), rtDECAF disruption avoidance ON	1
(6) Produce high poloidal beta ~ 3, high non-inductive plasma (Target: 29033 high β_p = 3), rtDECAF disruption avoidance OFF, but rtDECAF analysis ON	1
Total number of shots:	**shots: 12**

New real-time diagnostic acquisition in the KSTAR PCS enabling an integrated, world-class r/t DECAF analysis



- All software development under GIT version control

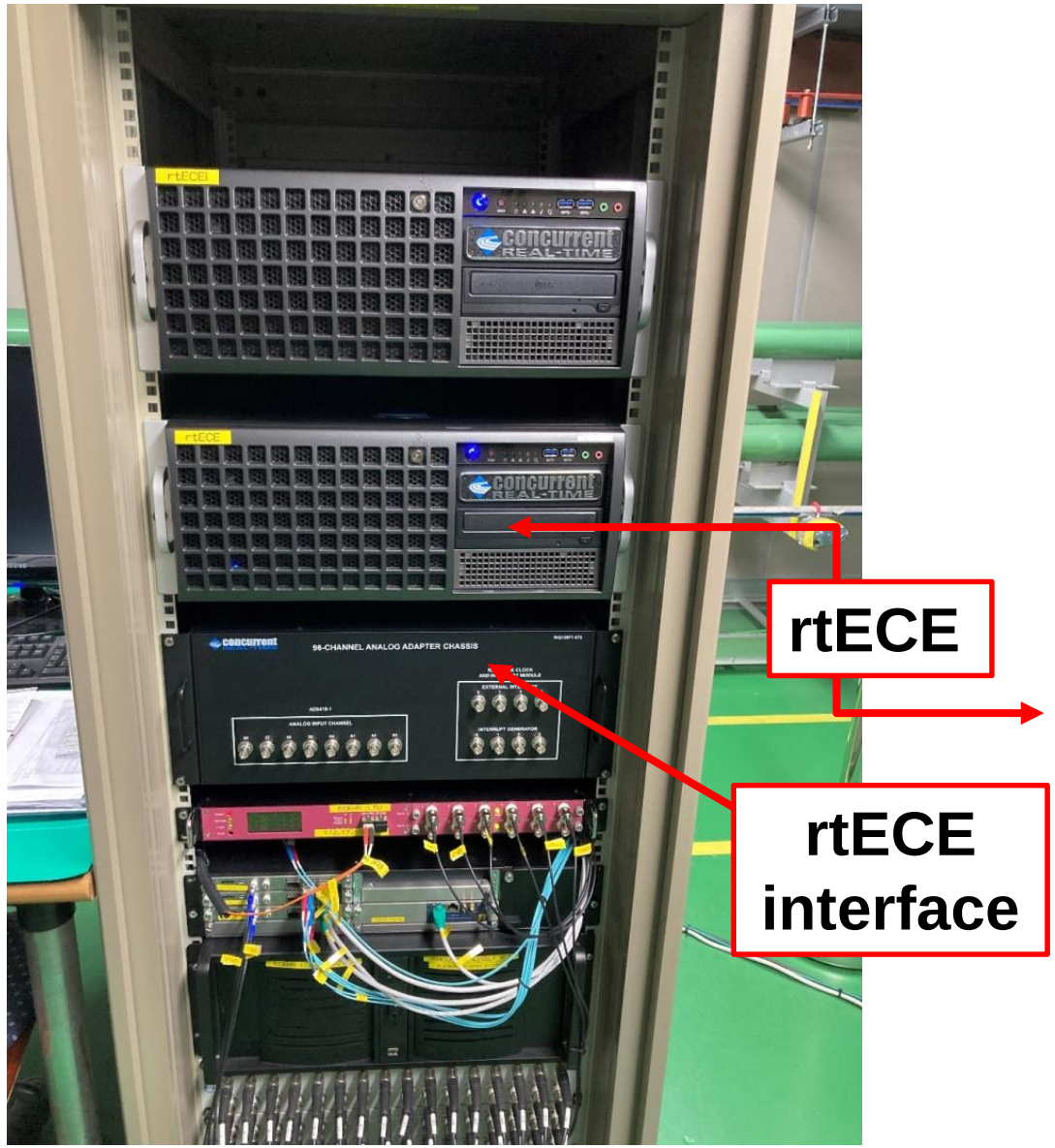
Installed

- Real-time MHD
- Real-time V_ϕ, T_i
  - New system for 2022
- Real-time ECE, (T_e(R), mode ID)
- Real-time ECEI (2D δT_e)

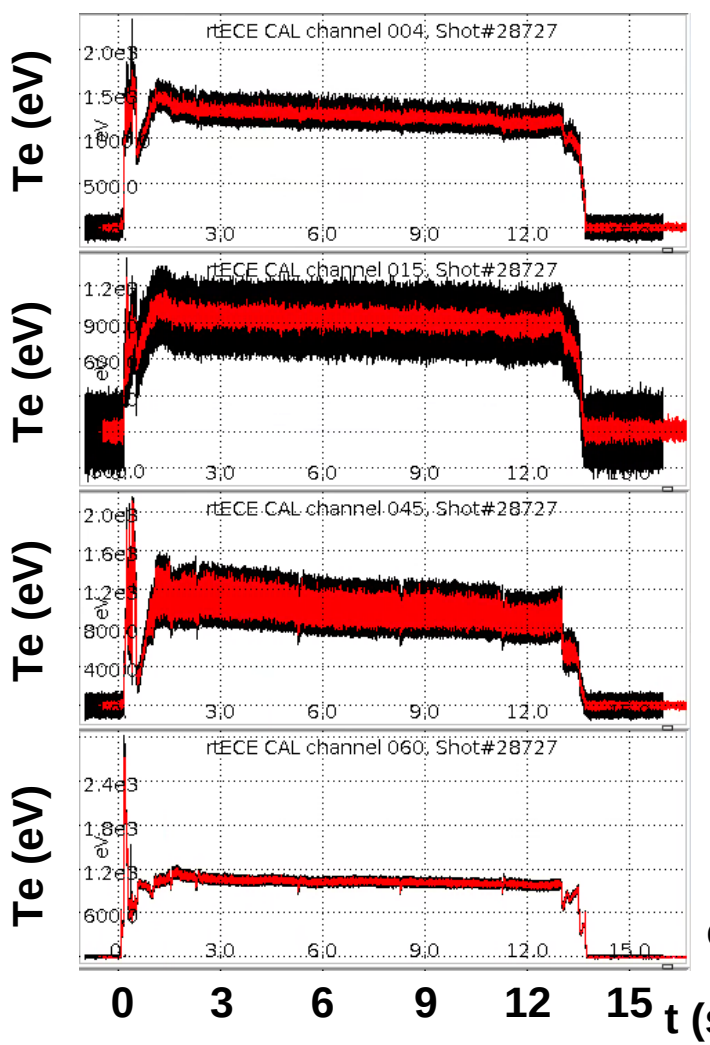
Designed

- Real-time MSE
  - B pitch angle, δB

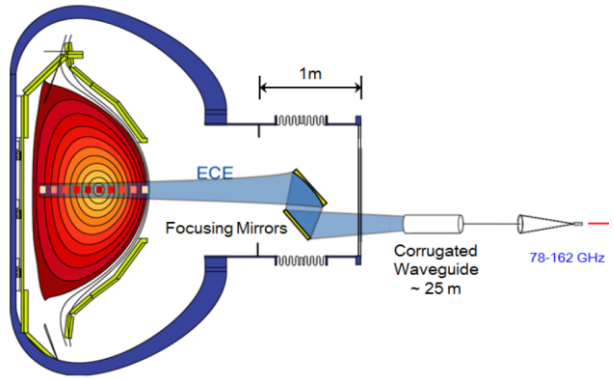
The first real-time DECAF module in KSTAR PCS measuring T_e profile (started during 2021 run campaign)



First real-time ECE data ($T_e(R)$)
(red: real-time; black: off-line)



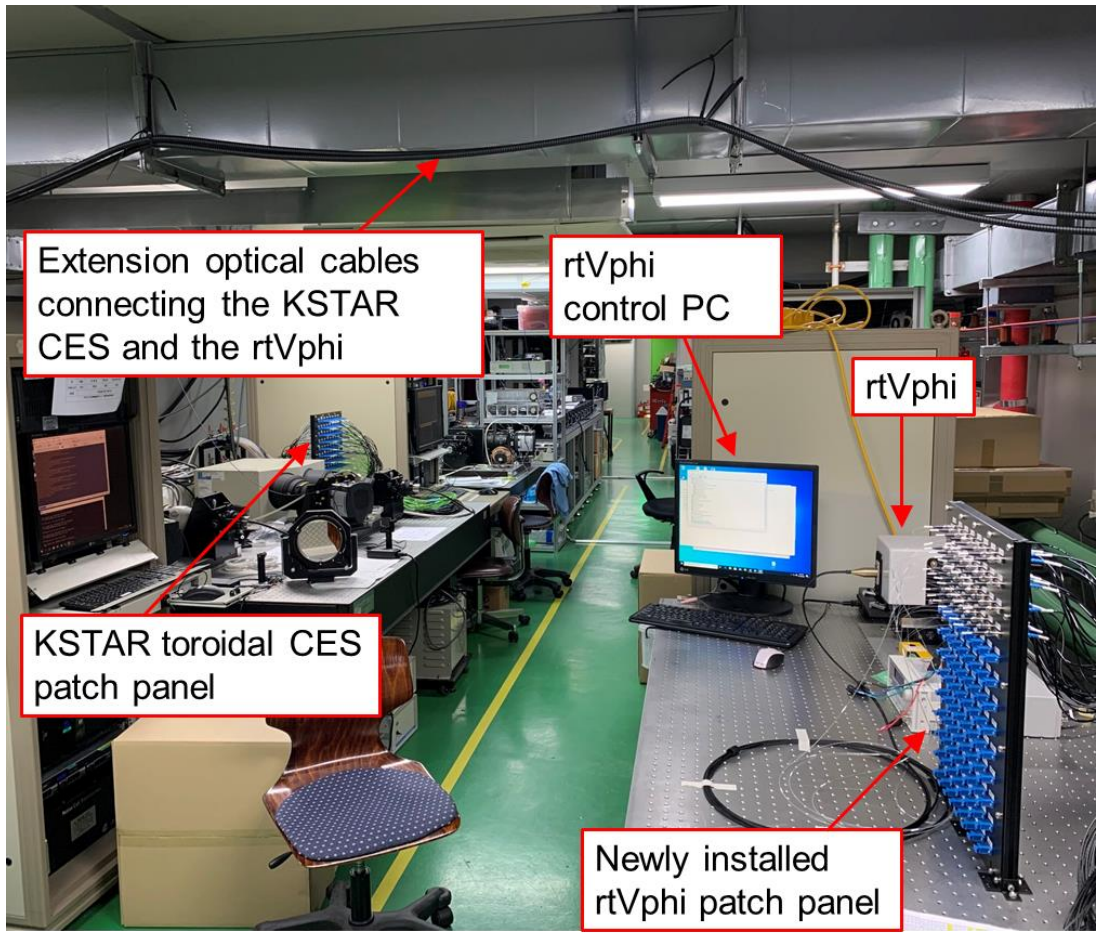
- R/t acquisition of heterodyne radiometer system
  - 4 of 76 channels shown
- Real-time signal compensated and calibrated



S.H. Jeong, K.D. Lee, et al., RSI **81** (2010) 10D922

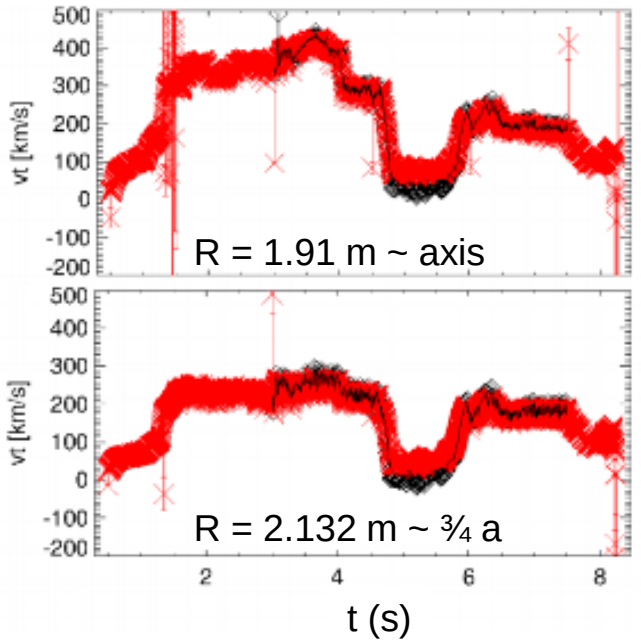
Initial real-time toroidal velocity (rtV_ϕ) diagnostic shows very good agreement with KSTAR CES system

KSTAR real-time V_ϕ , T_i diagnostic



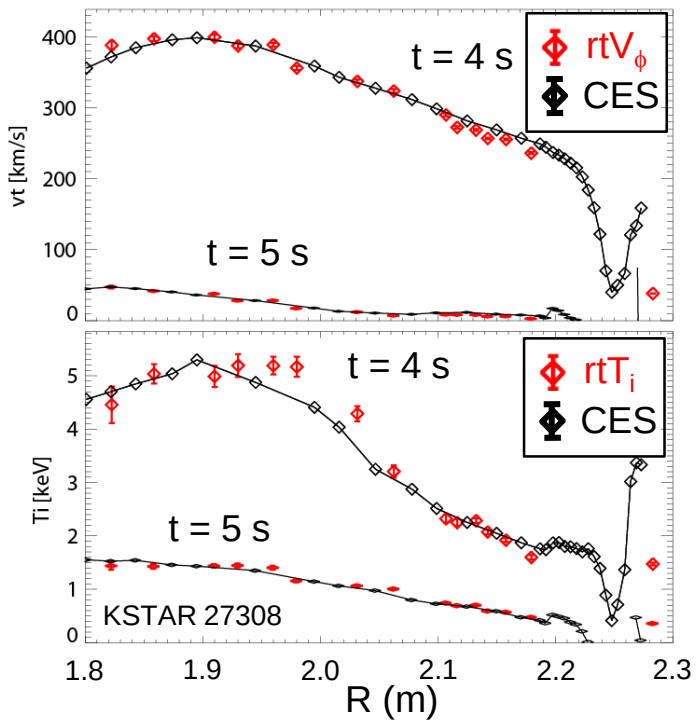
- rtV_ϕ and offline CES system share sightlines

rtV_ϕ time evolution (2 channels)



- rtV_ϕ data
  - First light taken for 32 radial channels
  - Reduced to 16 radial channels at 1 kHz
  - Offline CES analysis at 100 Hz

rtV_ϕ rtT_i radial profiles



- Newly-designed, final system to be installed for operation in 2022

M. Podesta, J. Yoo (PPPL),
Y.S. Park (CU), W.H. Ko (KFE)

NEW real-time toroidal velocity diagnostic (rtV$_\phi$) delivered to KSTAR, now being installed (this week!)

Spectrometer

Fiber bundle

Real-time computer and DAQ

- Switch from Windows 10 to Linux system, more compatible with other r/t systems

Camera

M. Podesta, K. Erickson, J. Yoo (PPPL), Y.S. Park (CU), W.H. Ko (KFE)

DECAF disruption prediction and avoidance research continues and has expanded to real-time operation on KSTAR

- Multi-device, integrated approach to disruption prediction and avoidance that meets disruption predictor requirement metrics (D. Humphreys, et al., PoP **22** (2015) 021806)
  - Physics-based "event chain" yields key understanding of evolution toward disruptions needed for confident extrapolation of forecasting, control
  - Full multi-machine databases. Recent performance for NSTX: > 99% true positive rate
  - Supporting physics analysis, experiments run to create, validate models, expand operating space
- DECAF producing early warning disruption forecasts
  - On transport timescales: ➔ guide disruption avoidance by profile control
- DECAF expanded to real-time operation on KSTAR
  - LTM and LTM forecaster used as critical warnings LTM-f
  - Controlled shutdown, disruption mitigation by MGI triggered in real-time by DECAF warnings
  - 100% success rate in controlled experiments (40 shots)
  - Moving ahead to test initial disruption avoidance for the first time (tonight EDT!)

We are hiring researchers+ ➔ Email: sabbagh@pppl.gov