*Supported by the*
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*Fusion Energy Sciences*

# Disruption Event Characterization and Forecasting Results and Initial Real-Time Application

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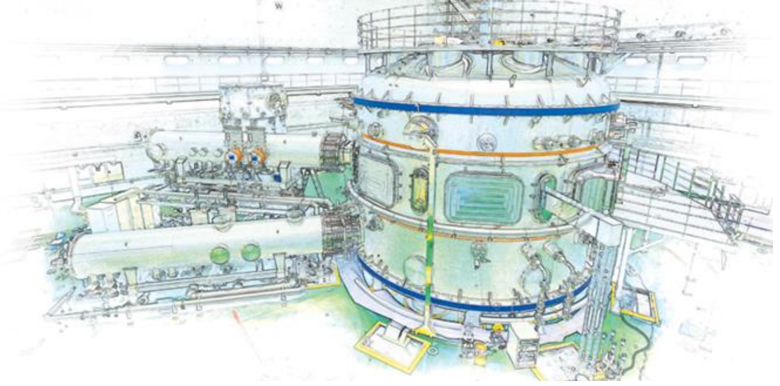
Presented at the

**2nd IAEA Technical Meeting on Plasma Disruptions and their Mitigation**

20-July-2022



V1.5

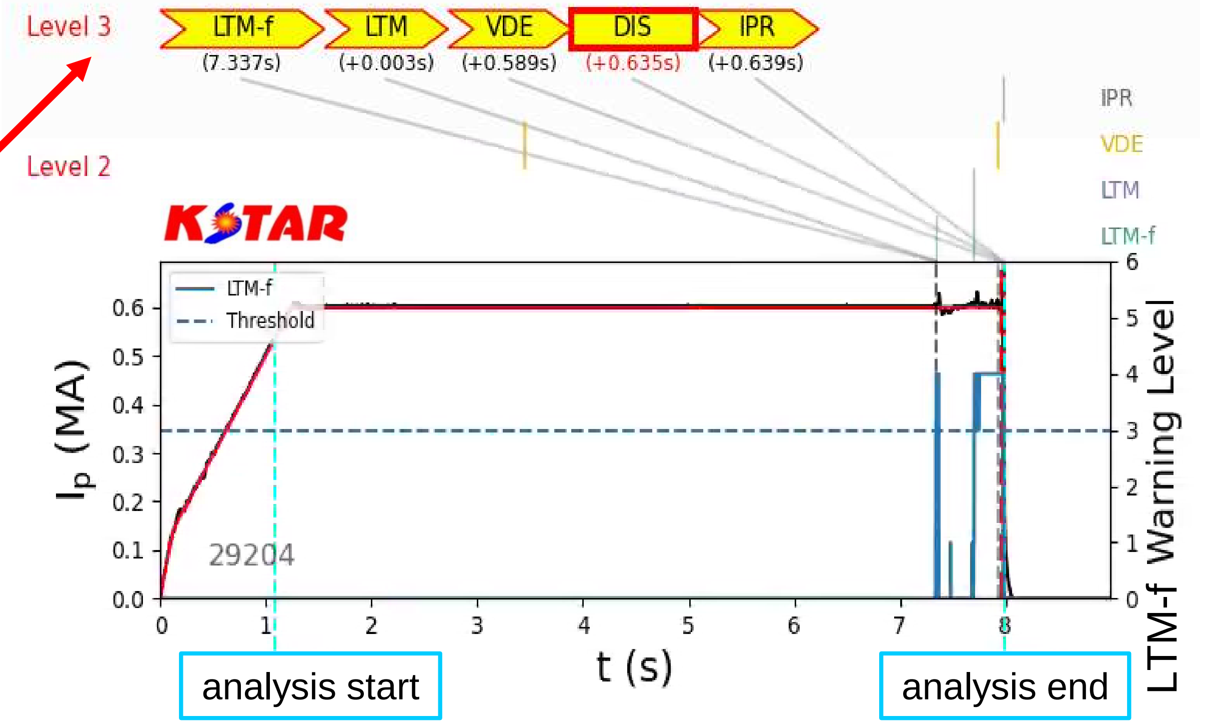
***Supported by US DOE grants DE-SC0018623, DE-SC0020415, and DE-SC0021311***

# Disruption Event Characterization and Forecasting Research (DECAF) expanded, including first real-time application on KSTAR with high accuracy forecasting

- DECAF (very brief) overview
- Automated large database analysis capability (new)
- Initial real-time DECAF operation on KSTAR
- Real-time DECAF hardware update
- Some supporting physics and AI analysis

# 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 multiple tokamak device databases (e.g. KSTAR, NSTX/-U, MAST/-U, AUG, DIII-D)
- Analyzing all plasma states (continuous and asynchronous events)
  - "Critical": (Level 3) event chains lead 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, steady ELMing, etc.)
- "Forecaster events": give earliest warnings

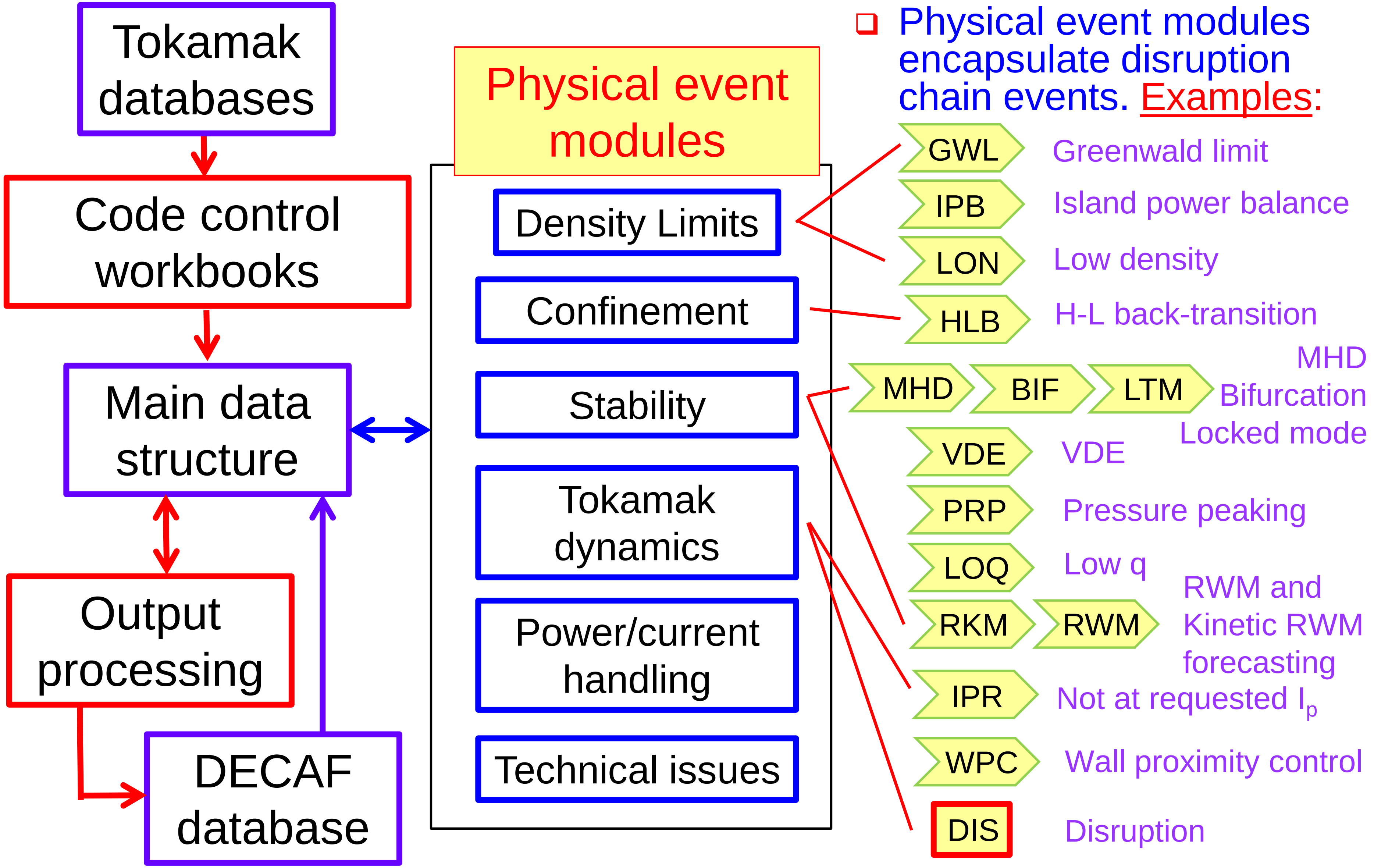



- High quantitative success reported (recently improved!)
  - > 91% true positive, ~ 8% false positive (~1e4 shots, ~1e6 samples)
- Research continues focused on improving forecasting to needed accuracy (98%+ goal for ITER, w/low false positives)

Initial real-time DECAF experiments have produced 100% forecasting accuracy

# DECAF is a physics-based approach providing understanding of event characterization and forecasting; modular design and workflow

- Physical event modules encapsulate disruption chain events. Examples:



# Recent DECAF development: attention to real-time system implementation and use on KSTAR; DECAF code analysis processing

- Real-time DECAF on KSTAR
  - several key diagnostics now acquired in real-time - part of KSTAR PCS
  - initial implementation real-time DECAF software - 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
    - Hundreds of TB dedicated storage
  - Analysis chunking
    - Standard DECAF analyses are now "one-button" capable to process, e.g. 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**
- **0.5 hours (~ 1,000 CPUs shared queue)**

**NSTX database ~ 25,000 shots (40 TB)**
- **extrapolation: 4.2 hours computation**

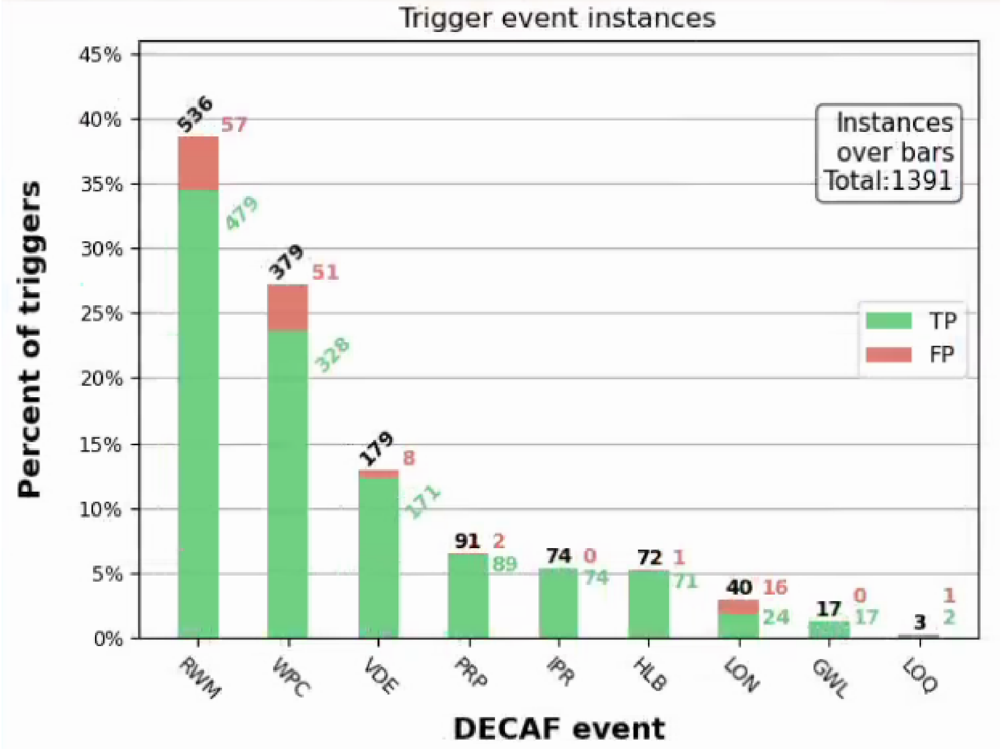
# True positive rate for disruption forecasting found to be very high in large database analysis (example: NSTX 2009 run campaign)

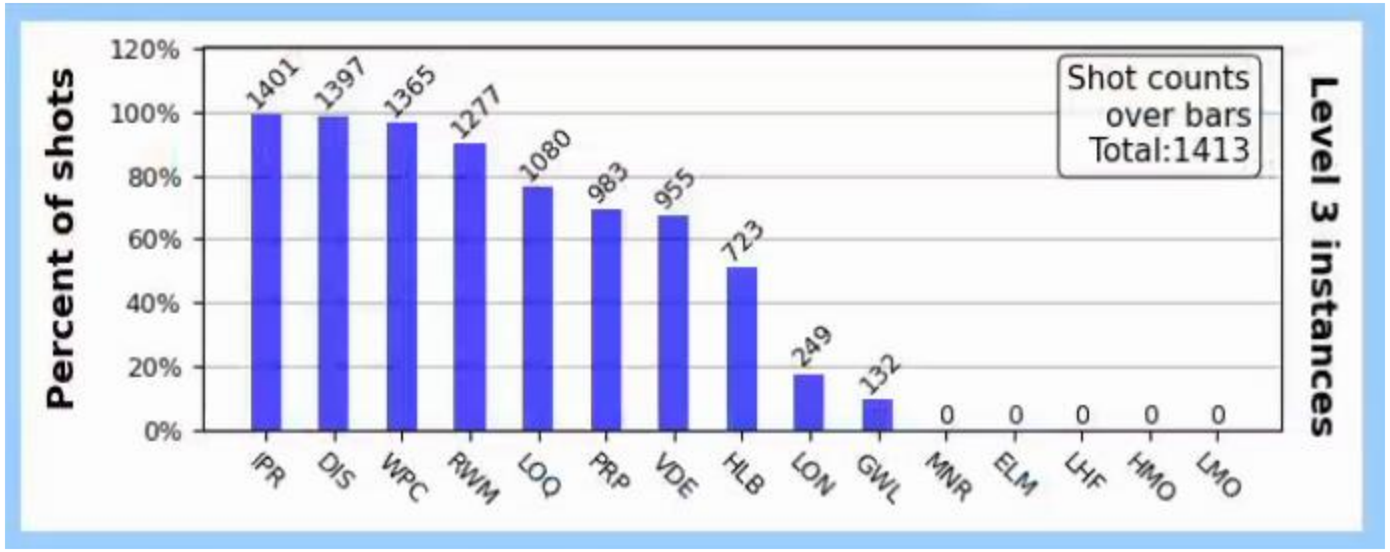
**Confusion matrix**

| Total population P+N 1401 | ----- Predicted condition ----- 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

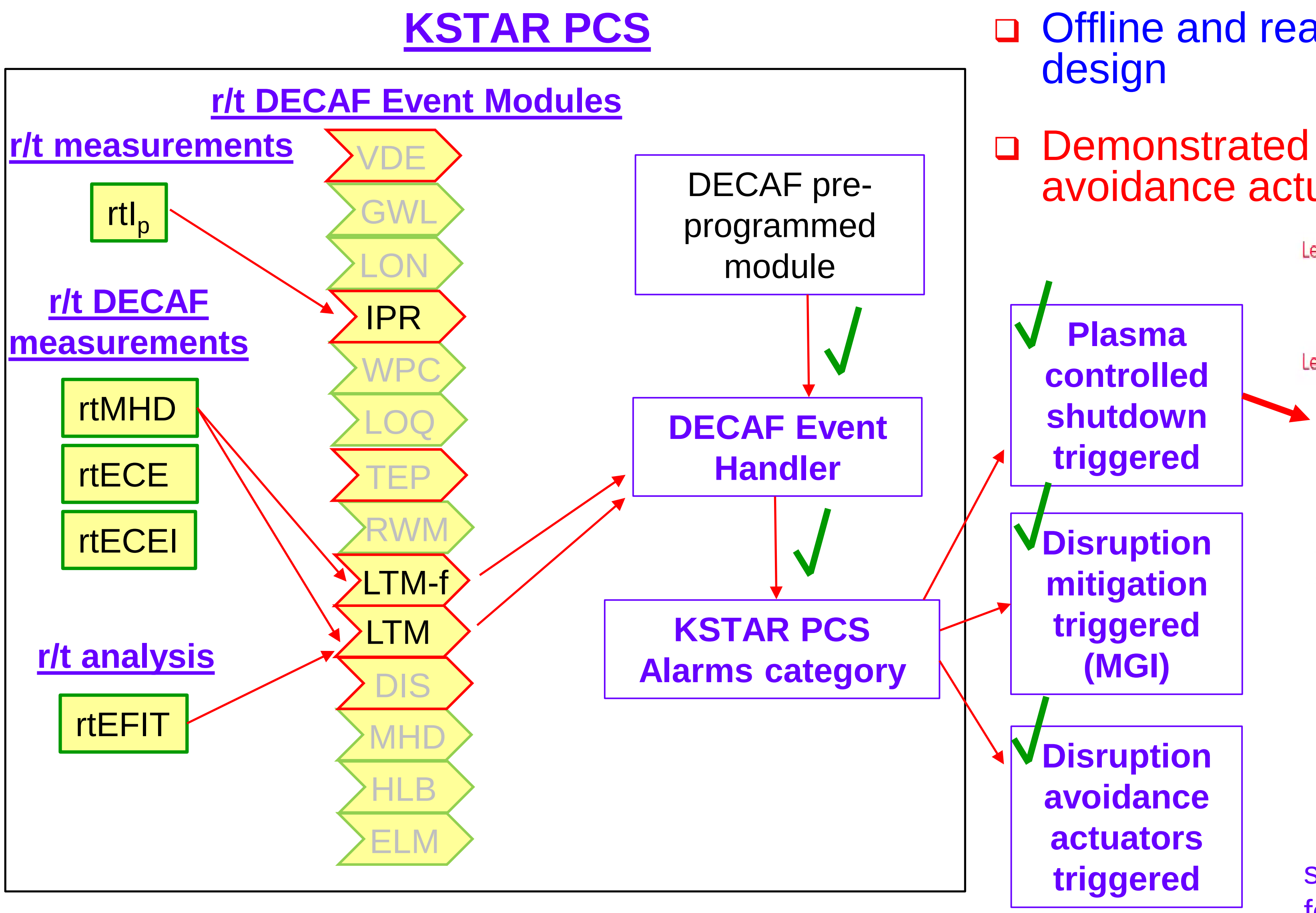
$$TPR = \frac{TP}{(TP + FN)}$$



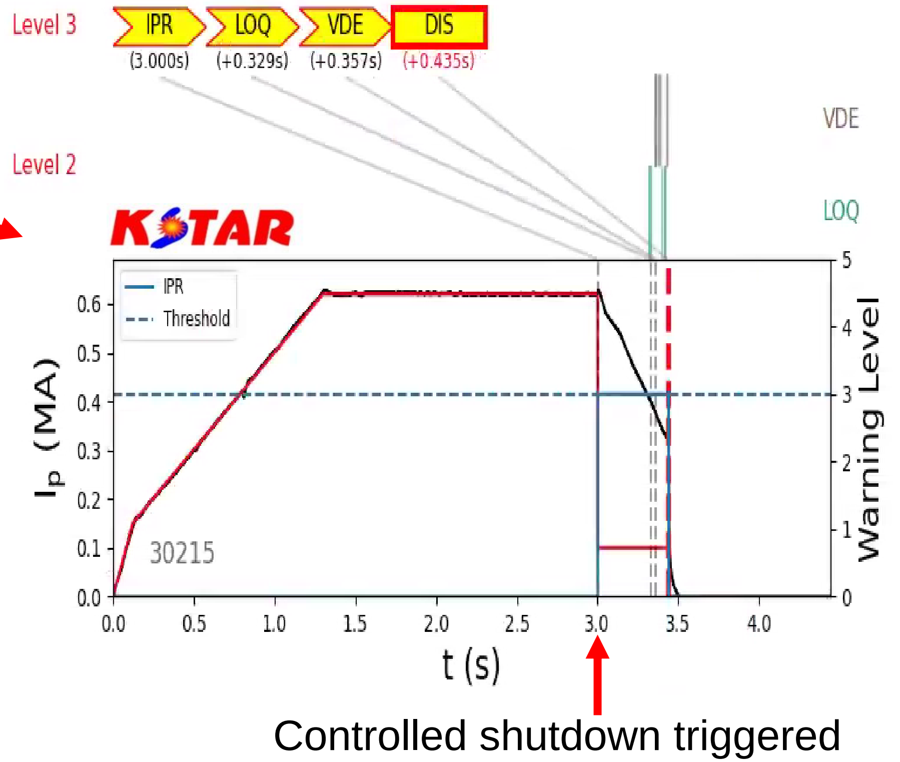




- Key analysis next step: Determining causality vs. correlation between warnings and the disruption
  - critical for all disruption prediction approaches!
  - significant analysis focus now

# r/t DECAF deployment in KSTAR: initial real-time software elements installed in 2021, running in 2022 + more being added




- Offline and real-time DECAF codes follow similar design
- Demonstrated plasma shutdown, mitigation, and avoidance actuators triggered by rtDECAF (2022)




see V. Zamkovska, et al. this meeting - poster 45 for disruption timing analysis

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

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

LTM-f

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

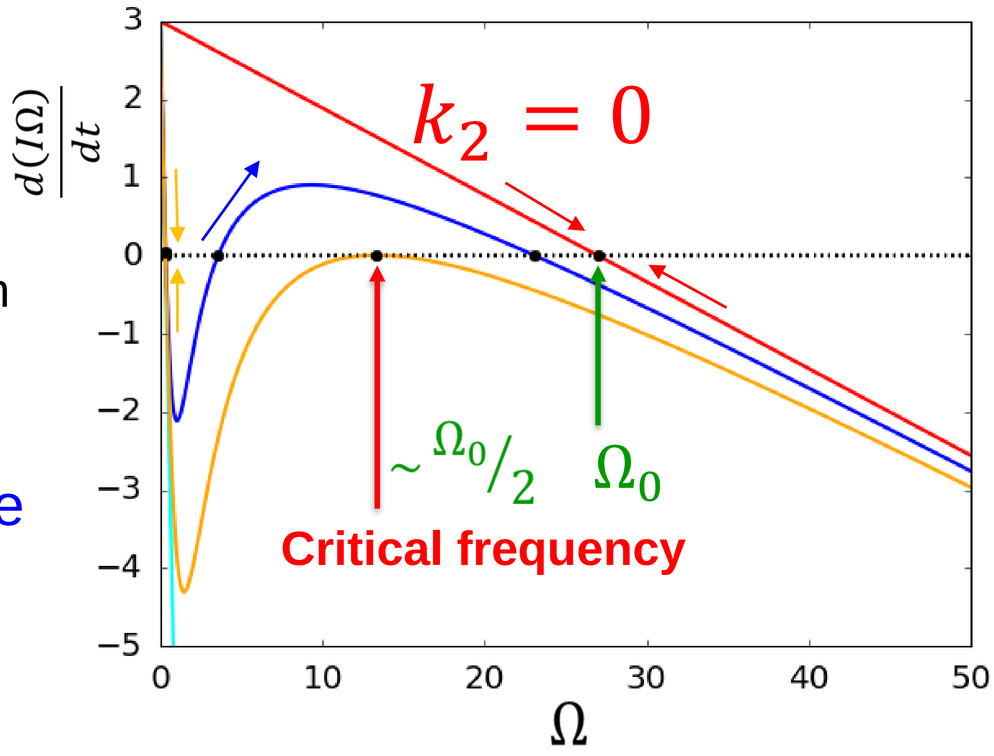
$$T_{mode} = \frac{k_2\Omega}{1 + k_3\Omega^2}$$

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

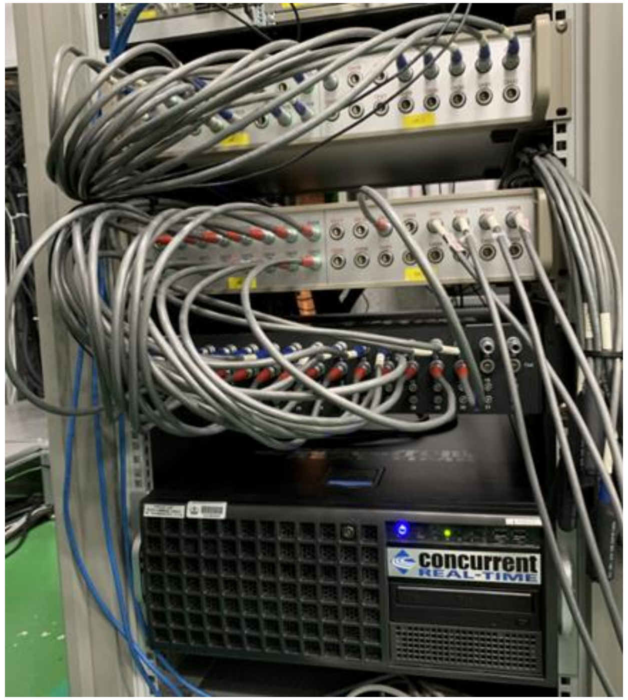
- At very low angular speed, mode can reach a stable steady state,
  ➔ observed in KSTAR

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

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

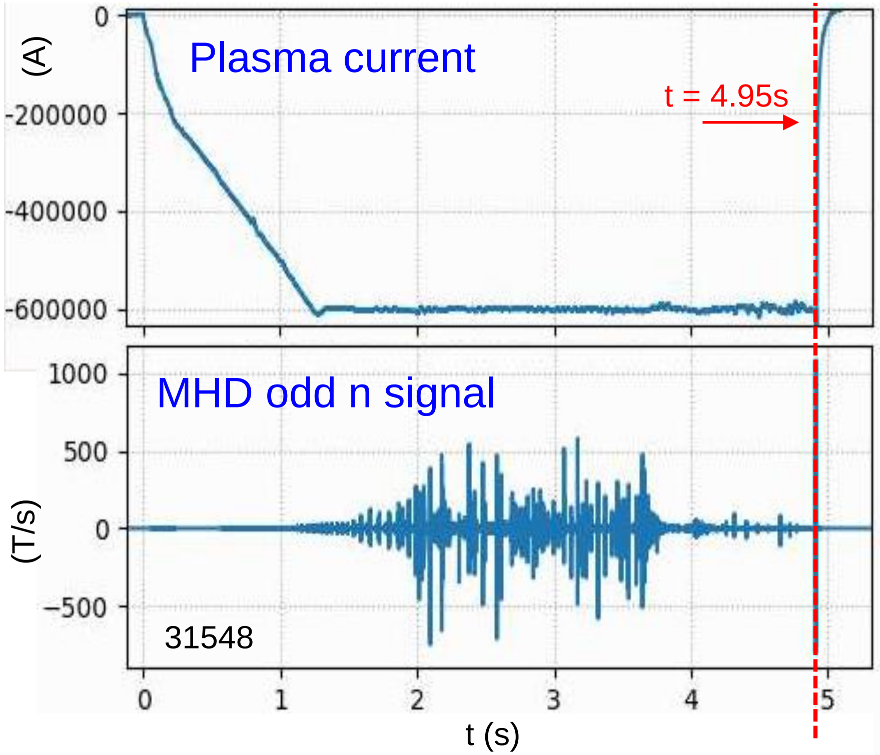



- Utilize DECAF real-time MHD system to determine mode, critical frequency

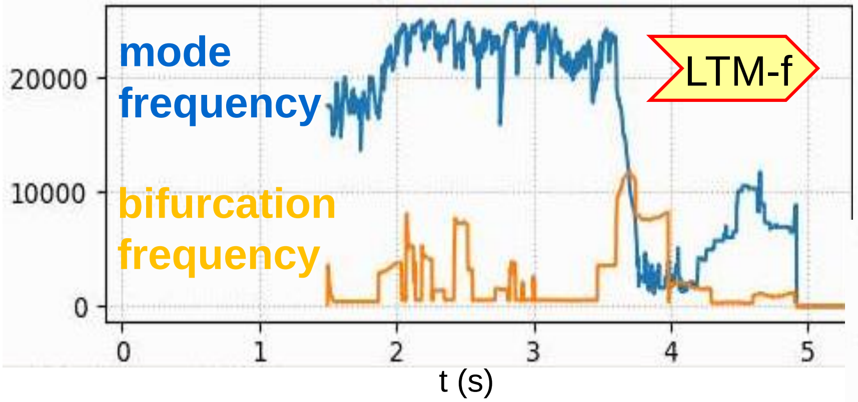



see J. Riquezes, et al. this meeting – poster 48

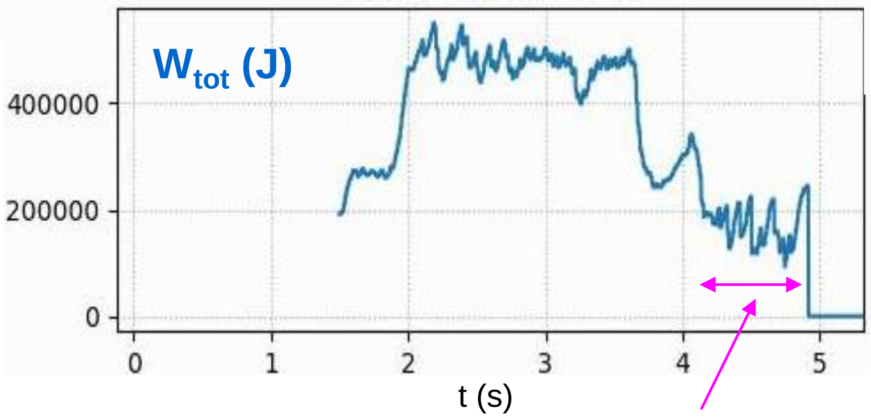
# Real-time DECAF warnings show early LTM forecast of disruption, and additional LTM warnings for mode locking



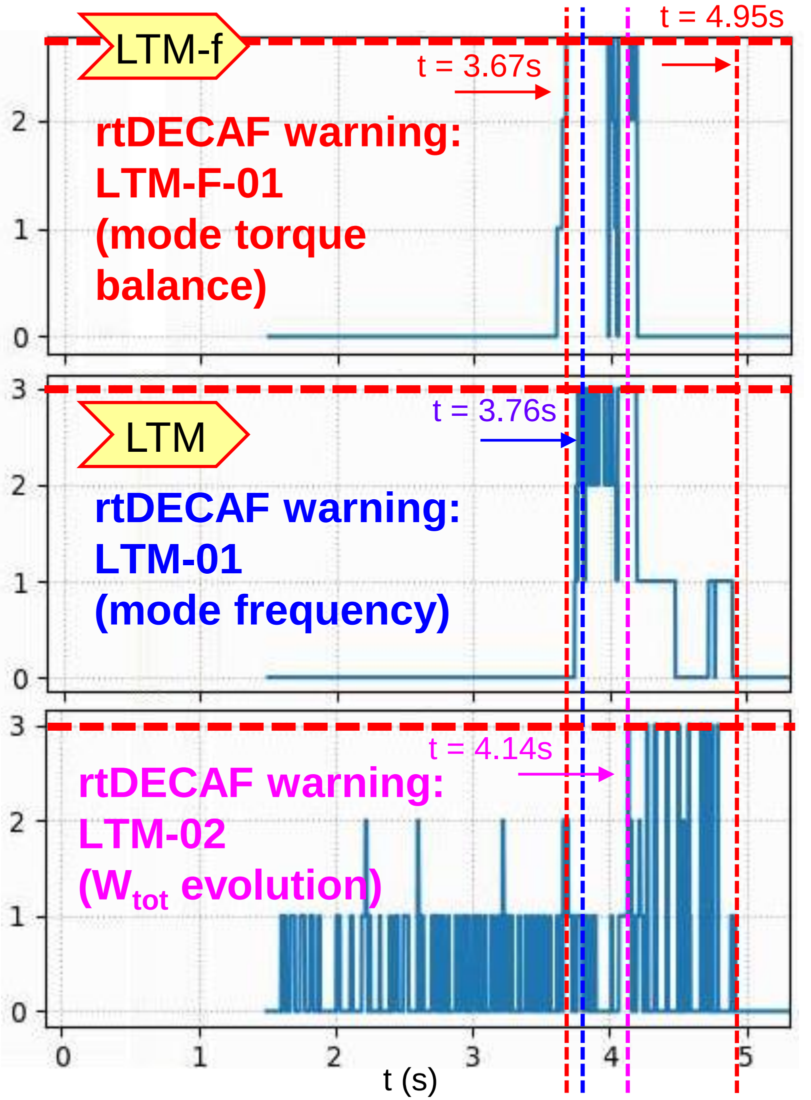

**rtDECAF mode torque balance**




**Stored energy evolution**



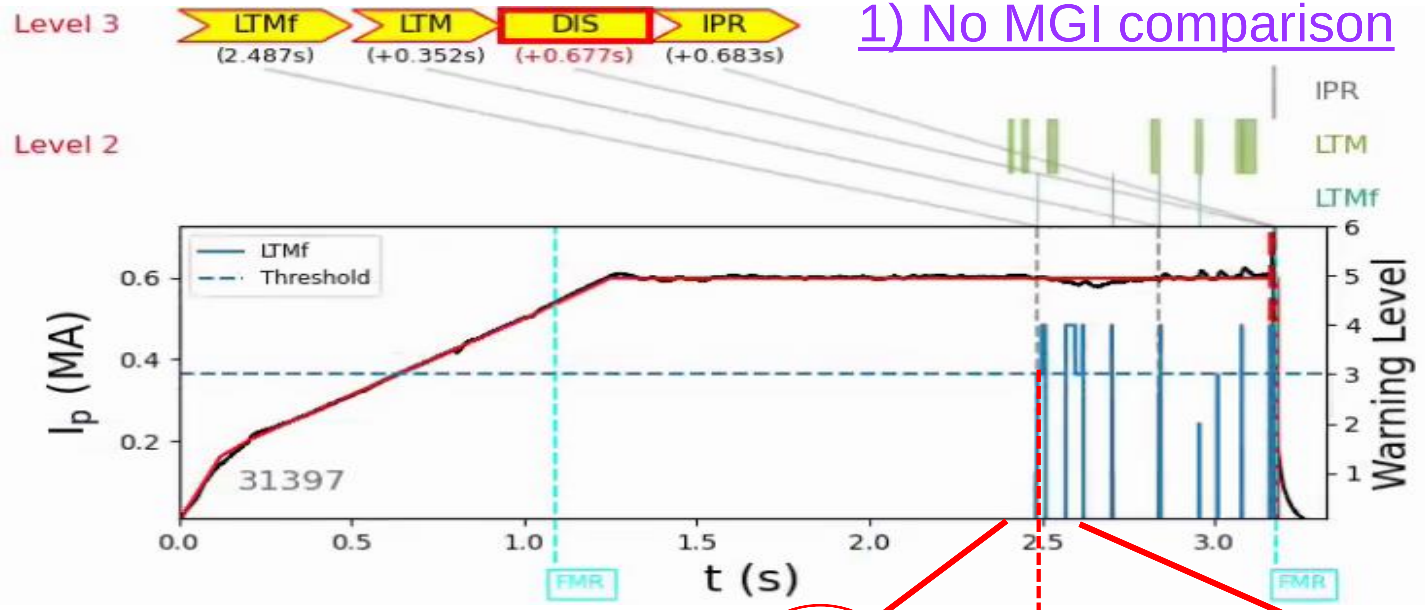

$W_{tot}$ dynamic during mode lock




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

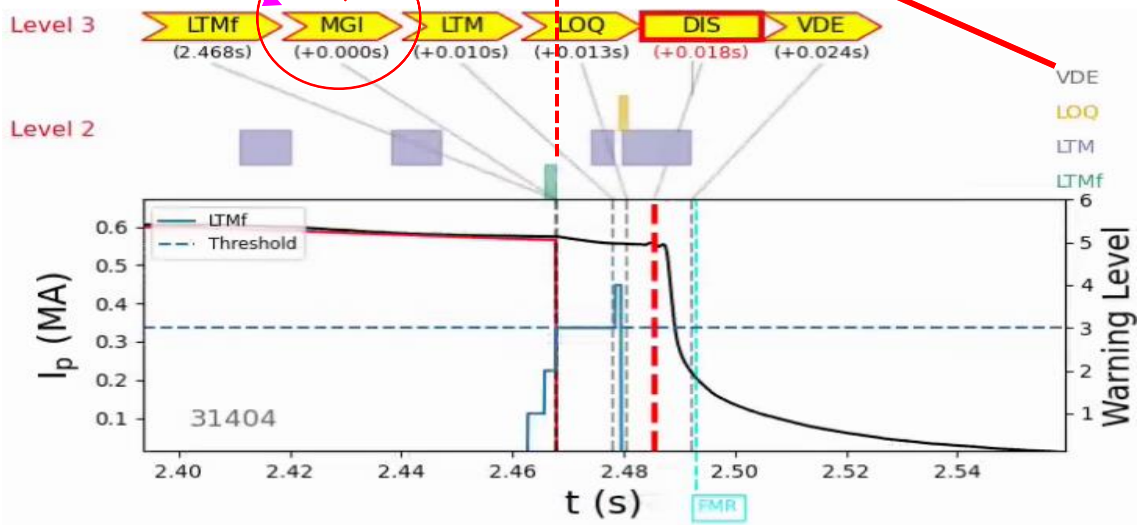
# DECAF triggered MGI – offline analysis shows LTM-F, LTM events produce early warning; 100% accuracy of real-time forecasts

1) No MGI comparison




2) MGI triggered by LTMf

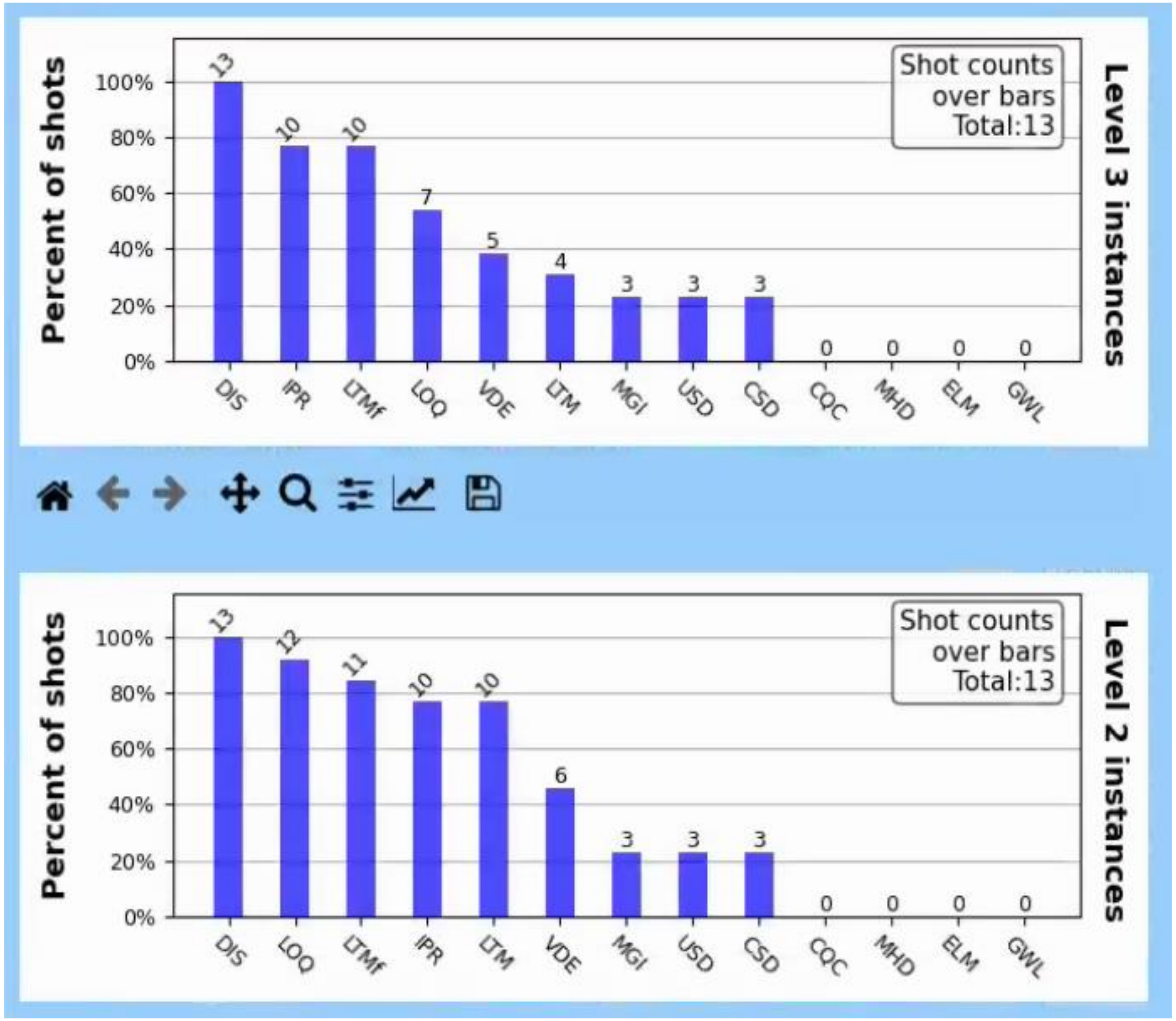
EARLY trigger: occurs ~ 0.677s before disruption in comparison shot (shown above)

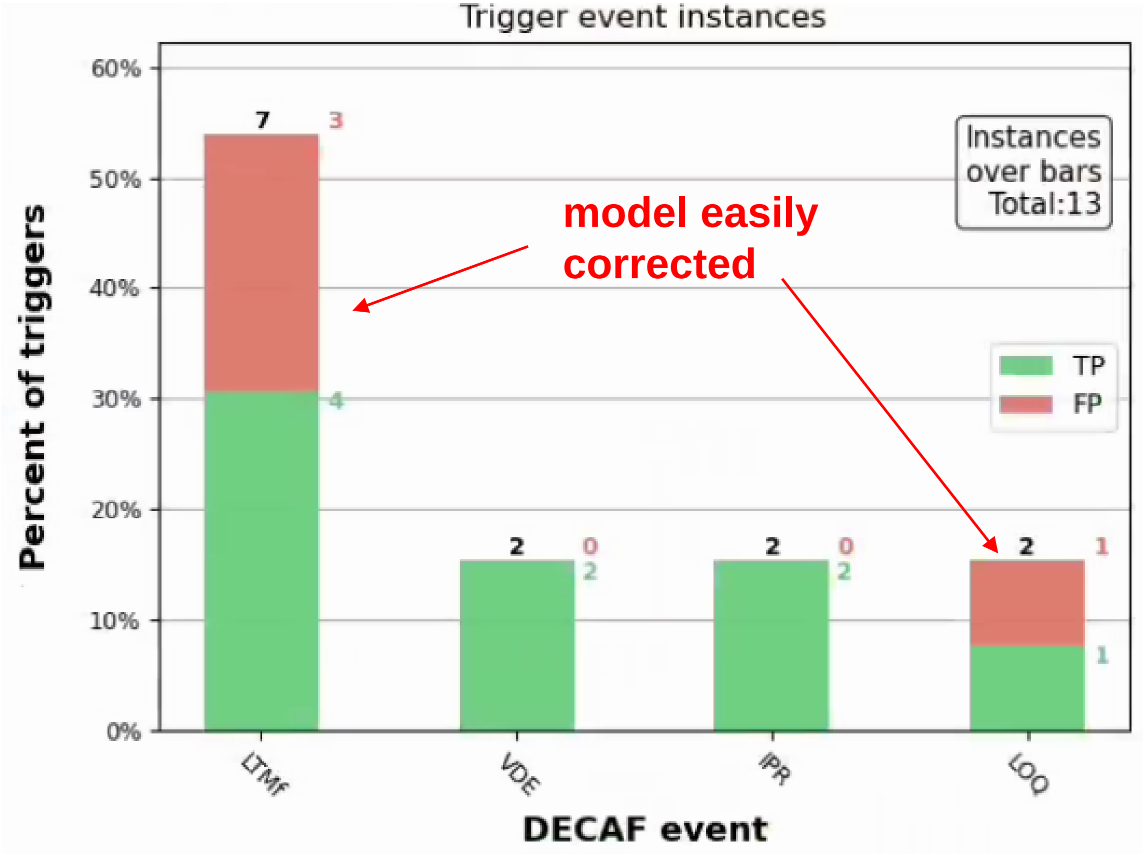



- Much time to trigger mitigation
  - far more than ITER minimum
- 100% accuracy of real-time DECAF Level 3 events (6/9/22 shots)
  - 18 shots; 3 MGI
  - 7 true positives
  - 11 true negatives
- 100% accuracy of real-time DECAF Level 3 events (6/15, 6/23, 7/6/22 shots)
  - 35 shots
  - 20 true positives
  - 15 true negatives
- Excellent distinction between true positives and negatives

Model: KSTAR-MDL070622sas2 (version: XP-V1b)

# Analysis workflow: Offline DECAF analysis shows how analysis model is constantly improved; physics-based approach is key



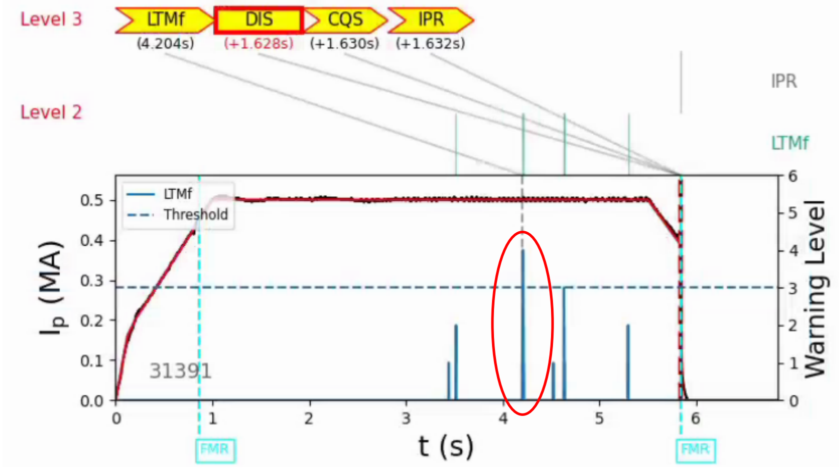




- False positive evaluation too stringent for KSTAR (easily fixed here)
- Initial inclusion of technical events
  - MGI, (un)controlled shutdown USD, CSD

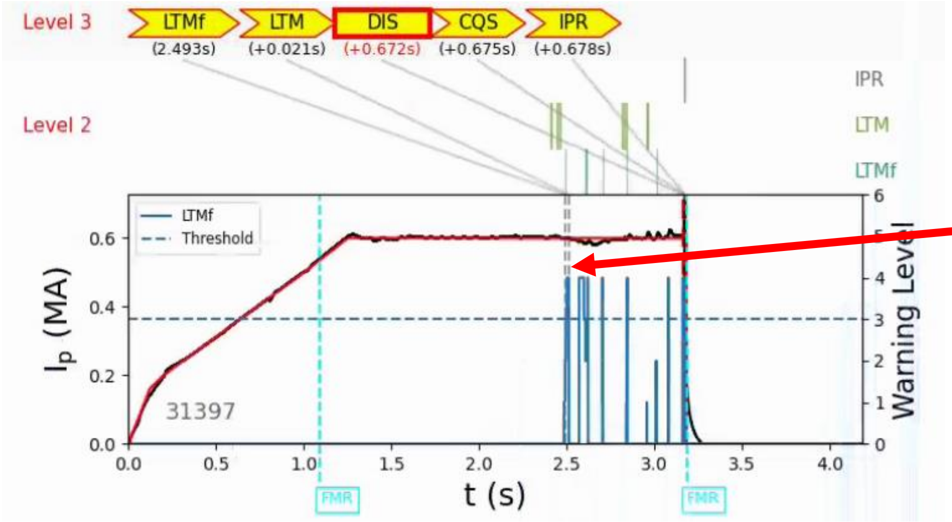
Model: KSTAR-MDL061222sas2 (version: Vv1)

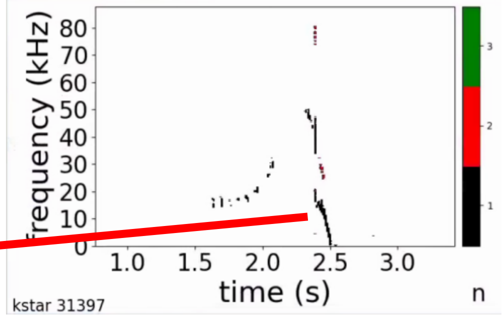
# Physics-based DECAF analysis aids false positive repair, causality vs. correlation determination between warnings and disruption

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

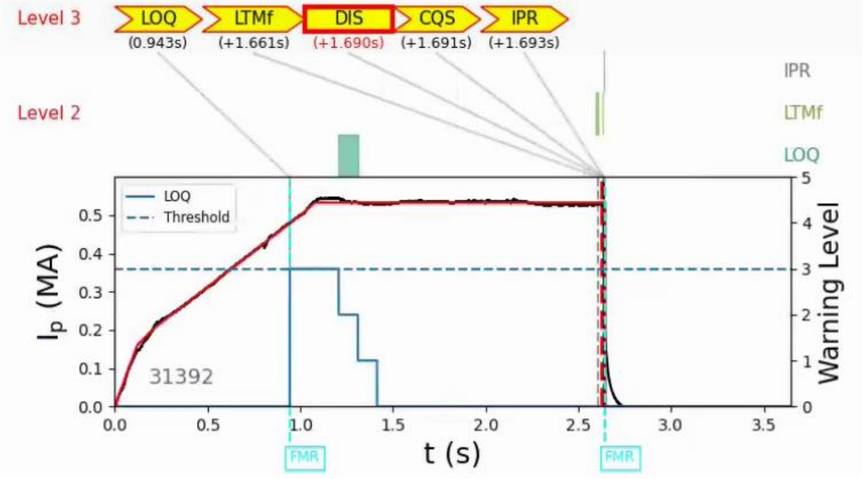



**LTM-F is not a false positive in this shot (- 0.5s FP time margin insufficient)**

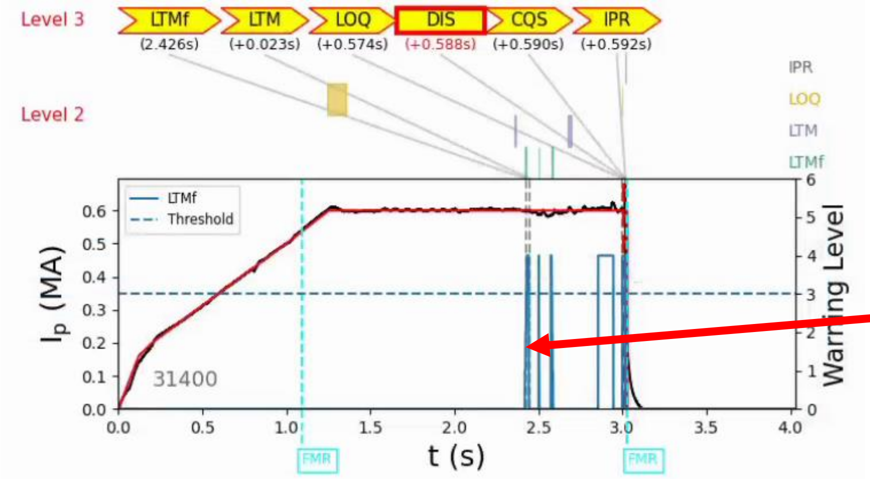


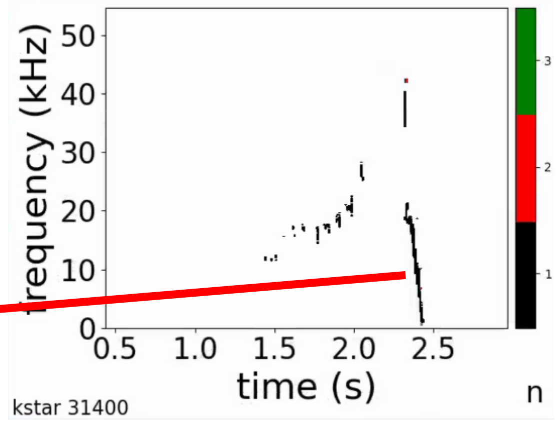




**LOQ Level 3 approaching Ip flat-top – check q95 calculation; increase threshold**

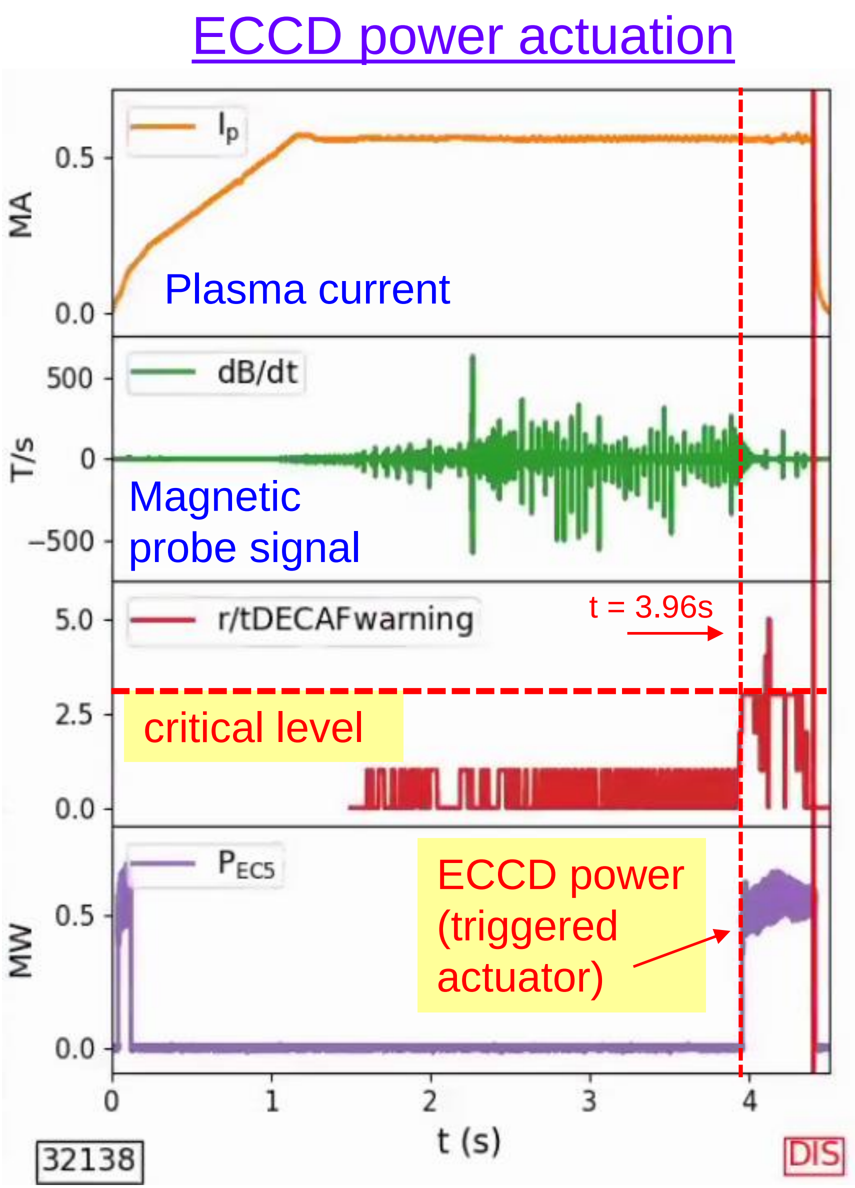


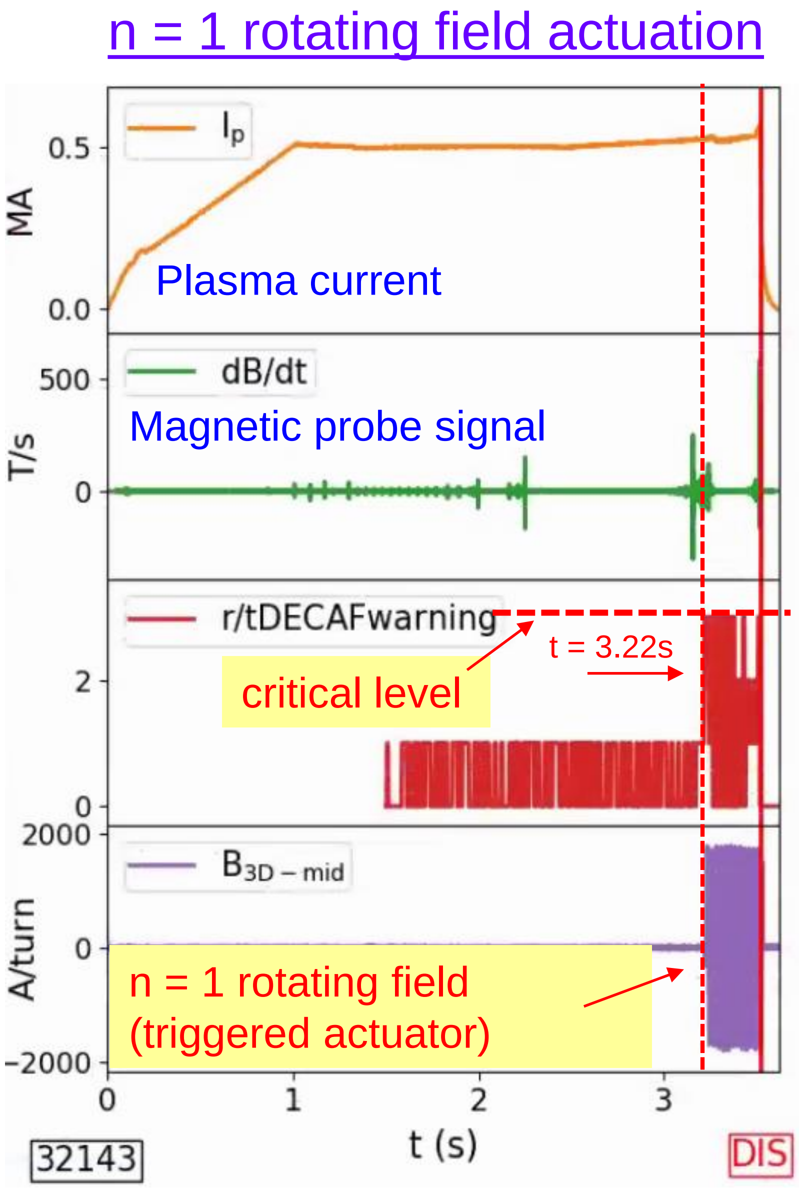

**LTM-F is not a false positive in this shot (- 0.5s FP time margin insufficient)**



# Critical real-time DECAF warning successfully triggered ECCD power, and n = 1 rotating field actuator for the first time in KSTAR



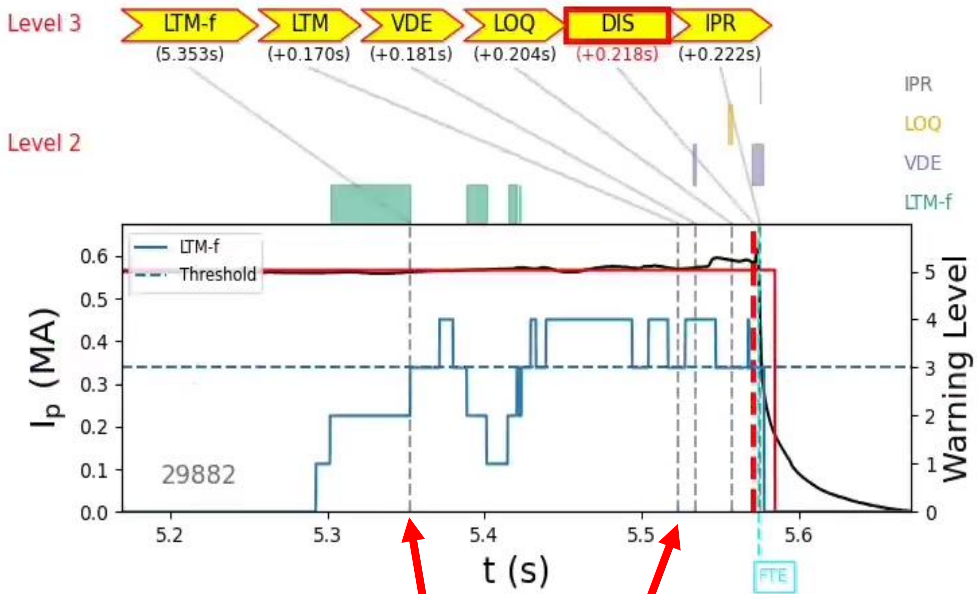



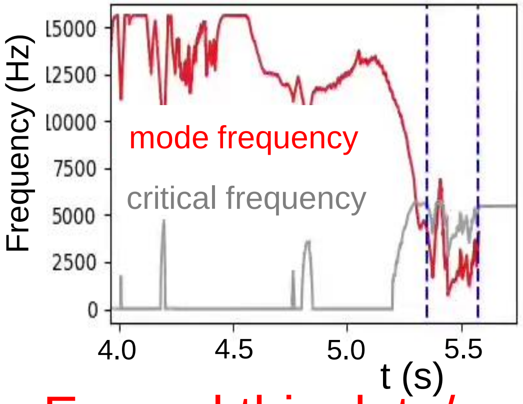

- Real-time LTM forecaster significantly precedes disruption
  - typically hundreds of ms to ~ 1s early warning
  - See backup slides for more detail
- NEXT STEP: demonstrate disruption avoidance!
  - Dedicated research program proposed for KSTAR

Model: KSTAR-MDL070622sas1 (version: XP-V1a)

# DECAF MHD mode lock event forecaster provides early warning; MHD shows tearing and kink-like characteristics in ECEI

## DECAF locked mode (LTM), forecaster (LTM-F) events (rtMHD system)

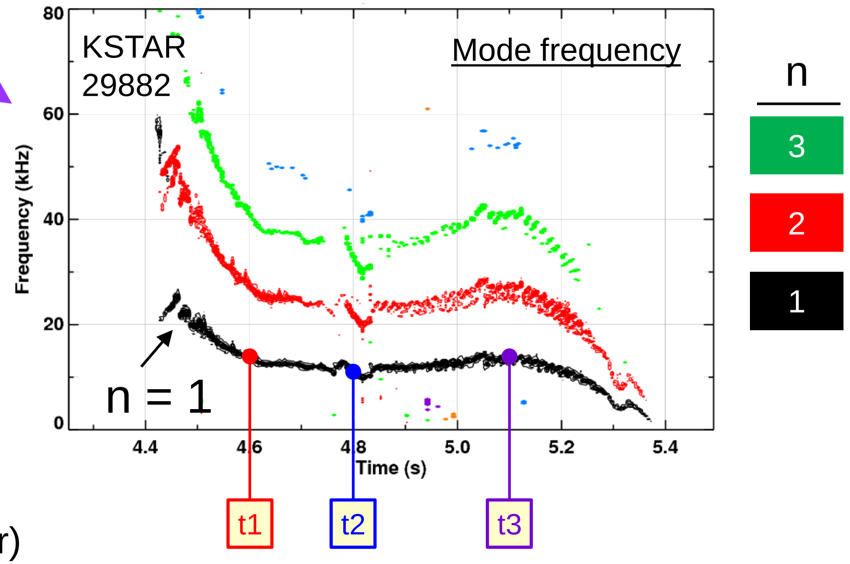



- LTM-f forecaster triggered 218 ms before disruption
- LTM event 170 ms after it was forecast

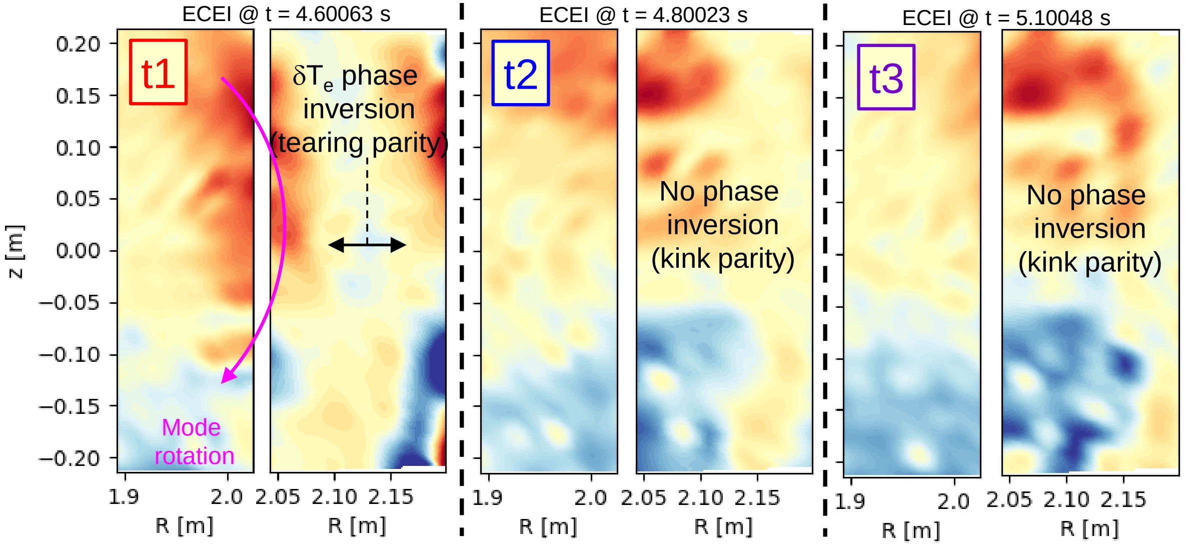
- Expand this data/analysis, including real-time!

Magnetic spectrogram (toroidal array)

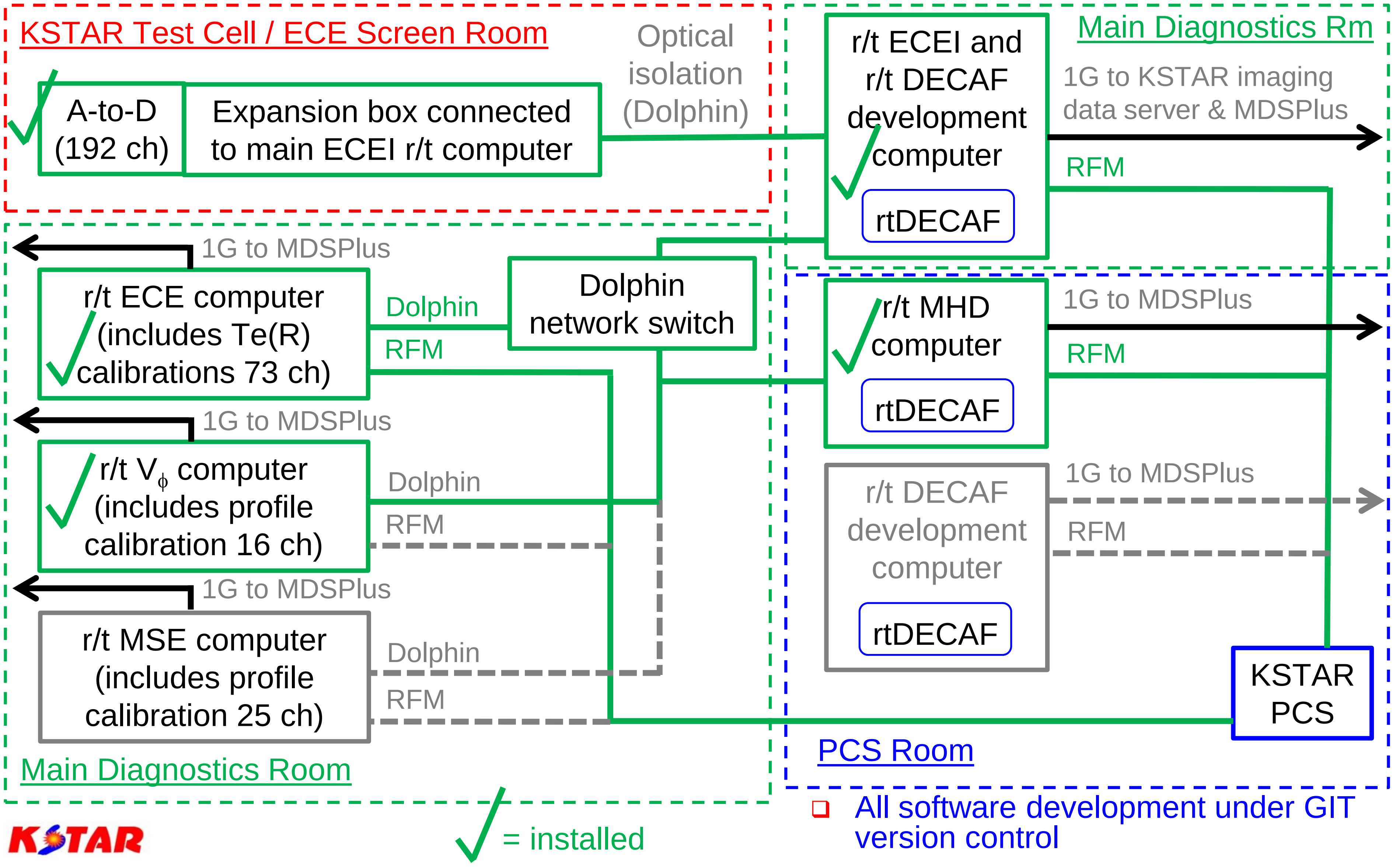



2D ECE imaging (ECEI)

Tearing (outer) with core kink → Kink dominant



# New real-time (r/t) diagnostic acquisition in the KSTAR PCS enabling an integrated, broadly-scoped r/t DECAF analysis




- All software development under GIT version control

## Installed

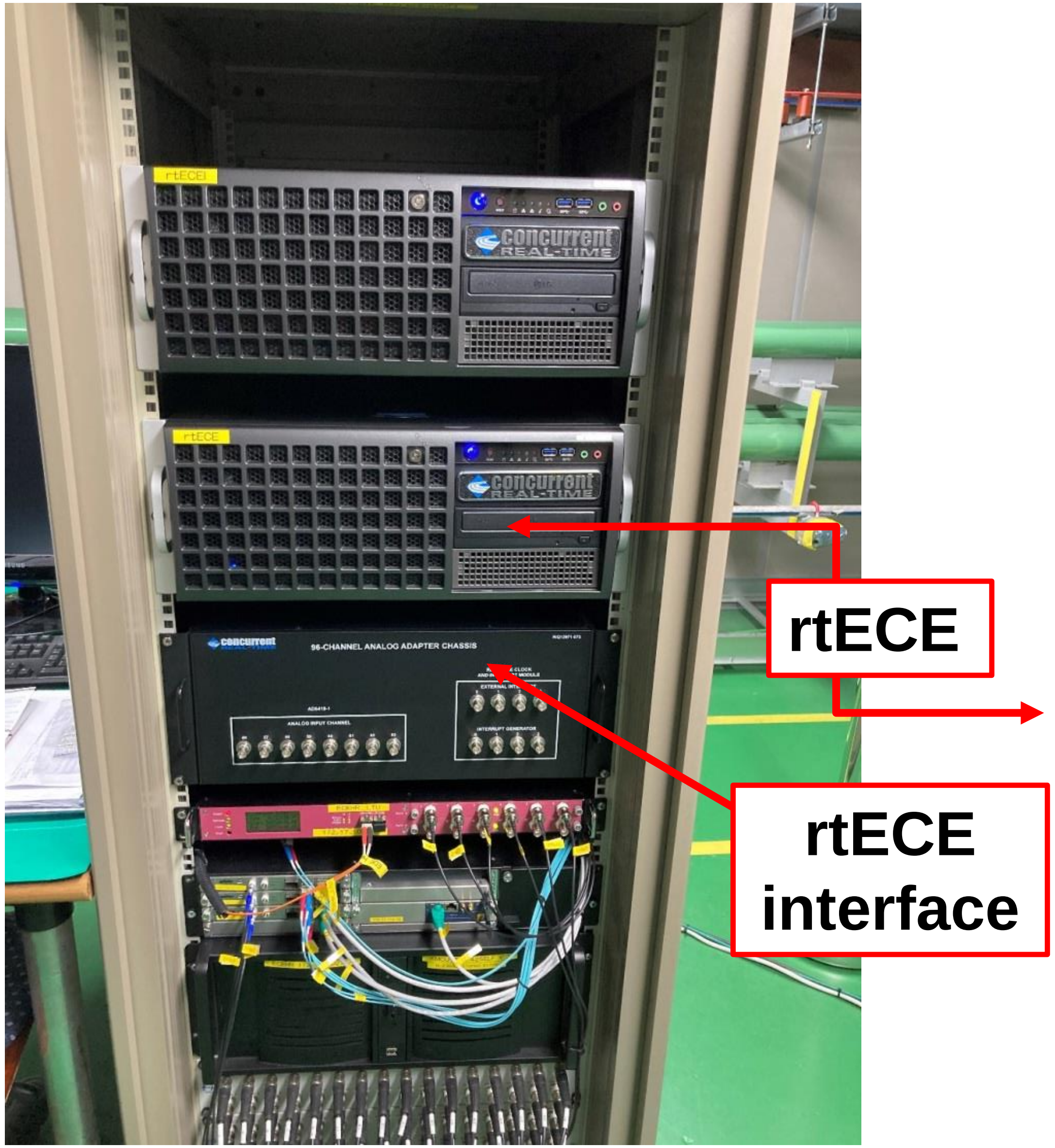
- Real-time MHD
- Real-time $V_\phi$, $T_i$
  - New system for installed (2022)
- Real-time ECE, ($T_e$(R), mode ID)
- Real-time ECEI (2D $\delta T_e$)

## Designed

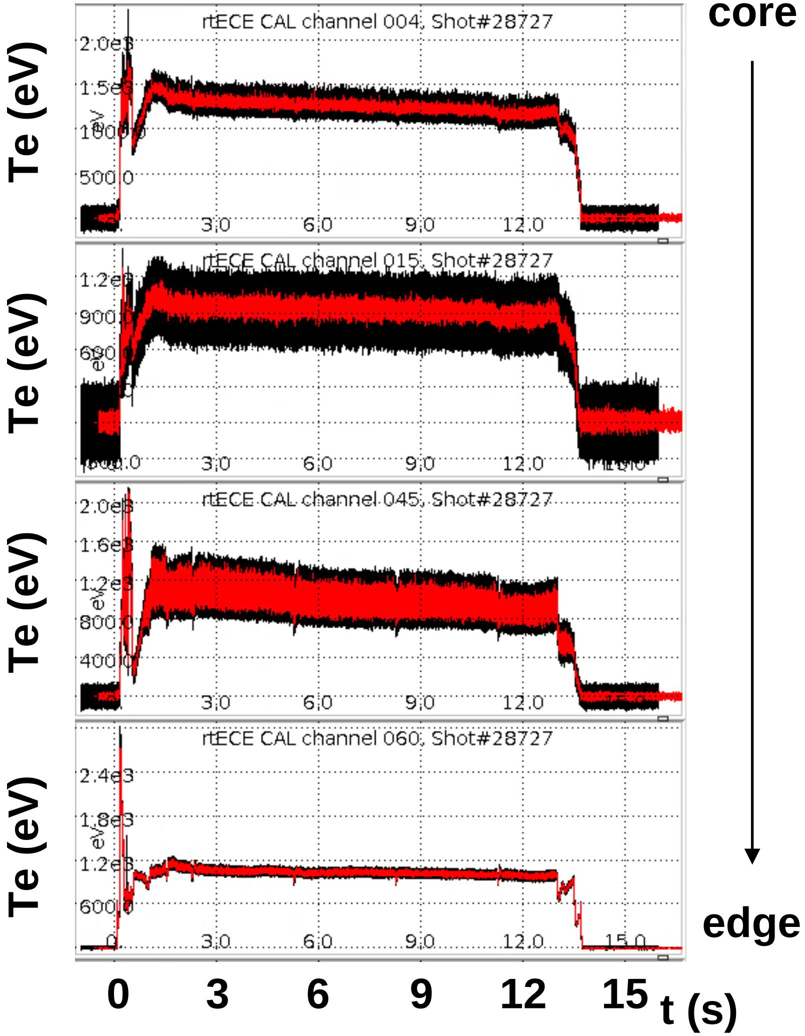
- Real-time MSE
  - B pitch angle, $\delta$B

KSTAR

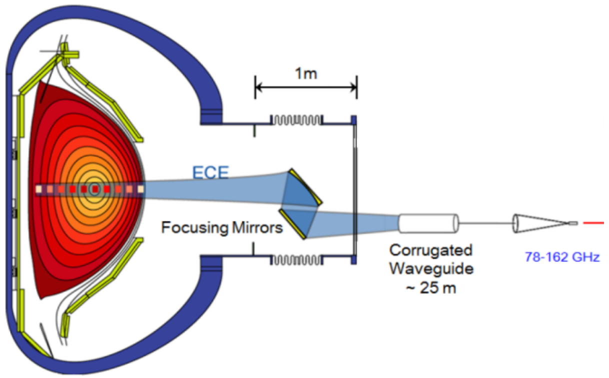
# The first real-time DECAF module in KSTAR PCS measured $T_e$ profile, now run routinely in 2022 run campaign)




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



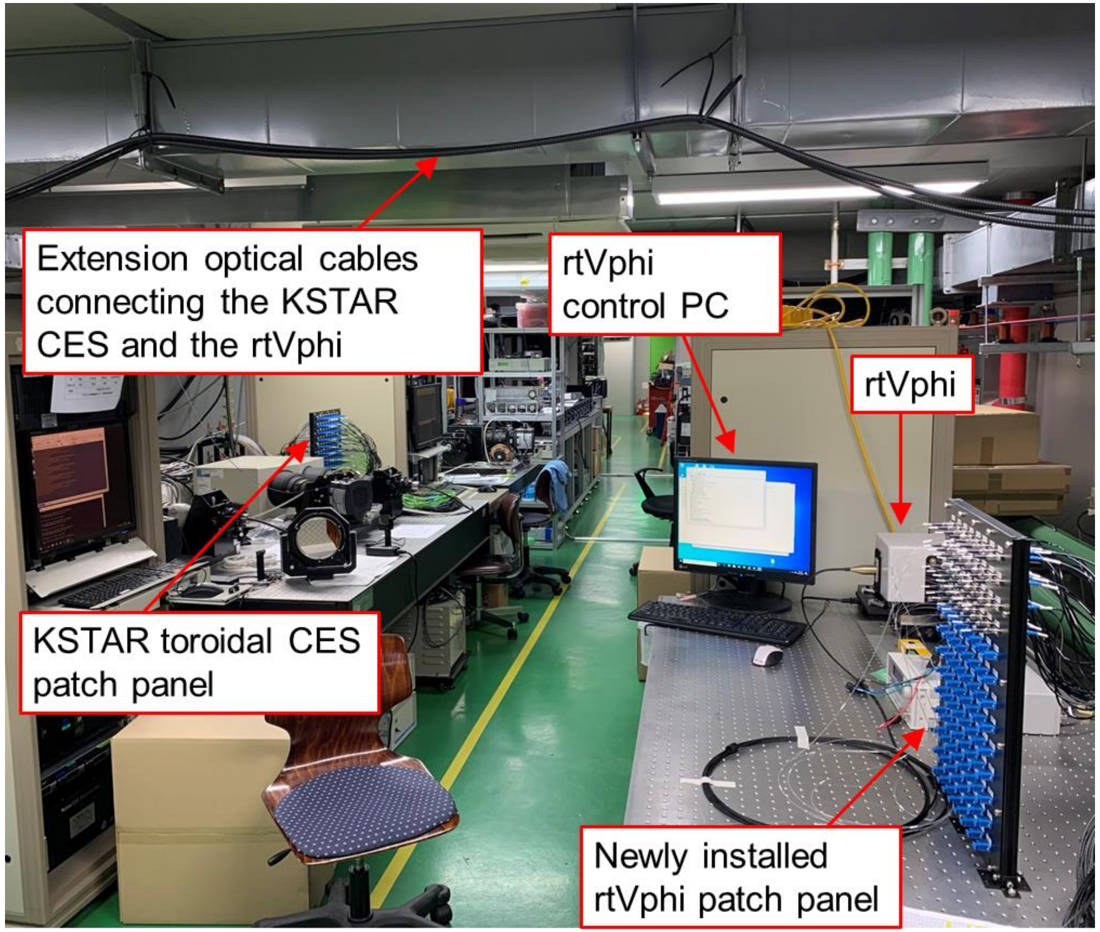

- R/t acquisition of heterodyne radiometer system
  - 4 of 76 channels shown
- Real-time signal compensated and calibrated




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

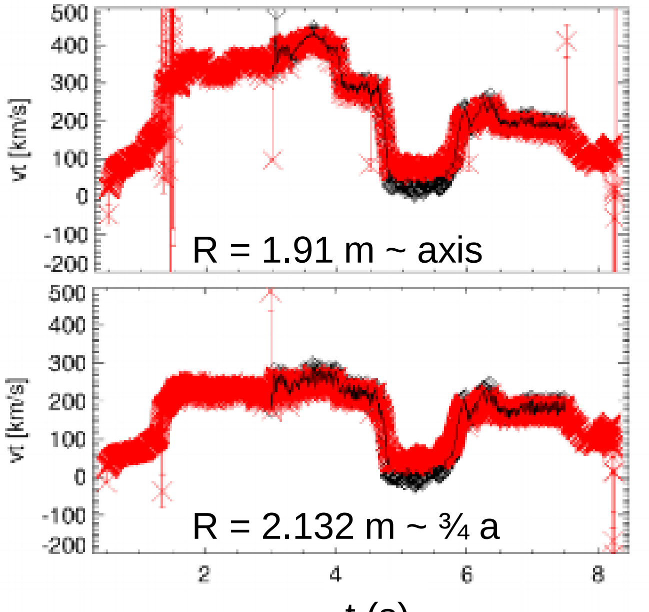
# Initial real-time toroidal velocity, (possible) ion temperature diagnostic (rtV$_\phi$) shows very good agreement with KSTAR CES

## KSTAR real-time $V_\phi$ , $T_i$ diagnostic



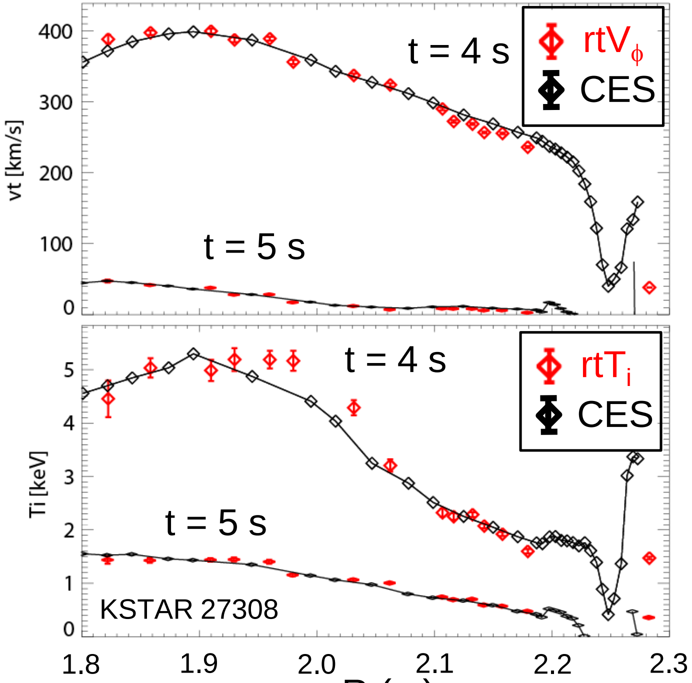

- rtV$_\phi$ and offline CES system share sightlines

## rtV$_\phi$ time evolution (2 channels)




- rtV$_\phi$ data
  - 16 radial channels at 1 kHz
  - Offline CES analysis at 100 Hz

## rtV$_\phi$ rtT$_i$ radial profiles




- Newly-designed, final system (very) recently installed

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

# NEW real-time toroidal velocity diagnostic (rtV$_\phi$) delivered to KSTAR, installed (two weeks ago)

Spectrometer


Camera


Real-time computer and DAQ


- Switch to Linux from Windows system
- aiming for first light this week (7/18/22)

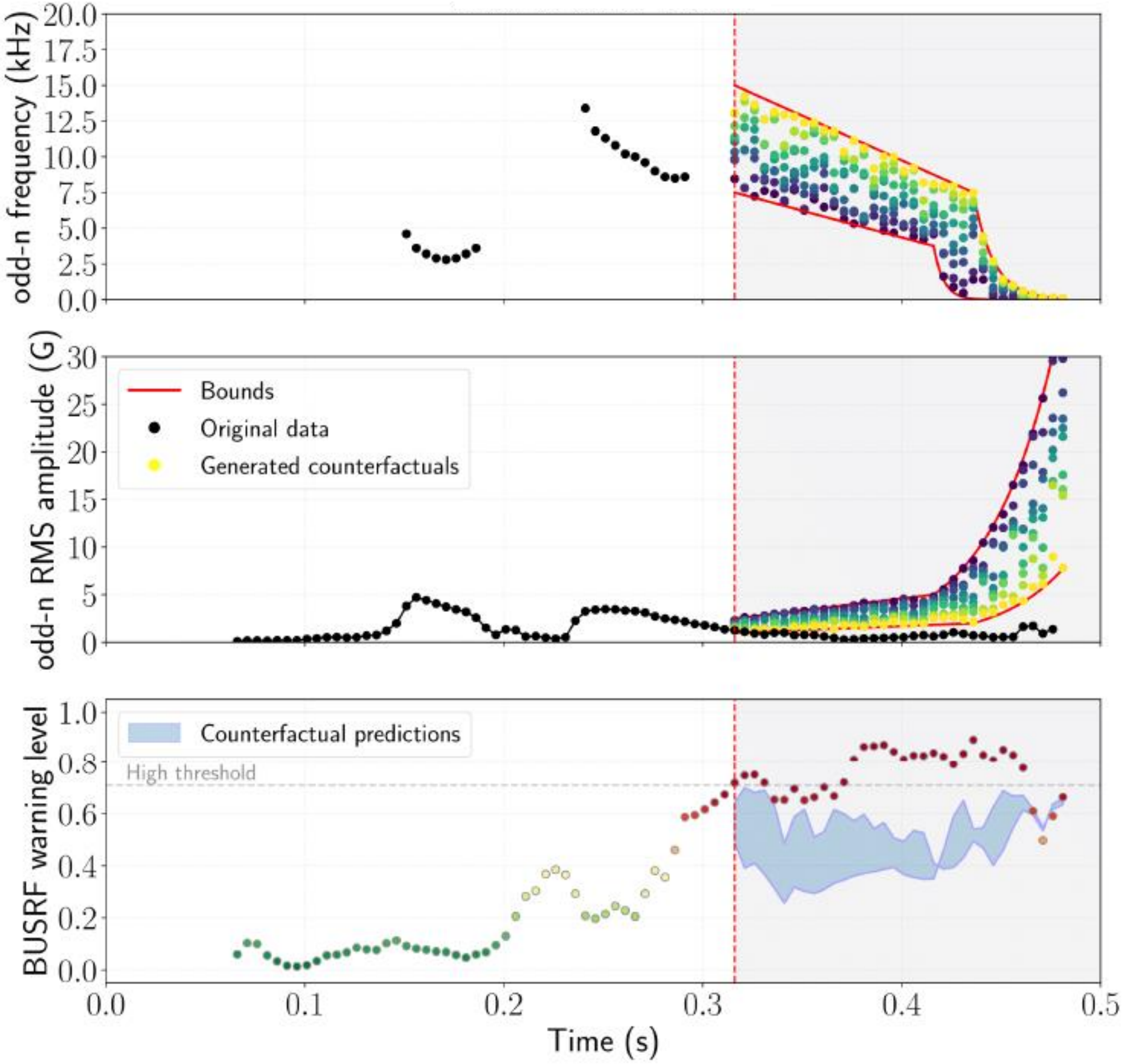
New diagnostic – completed installation


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

# Innovative counterfactual machine learning introduced for the first time to generate hypothetical activity contradicting observations

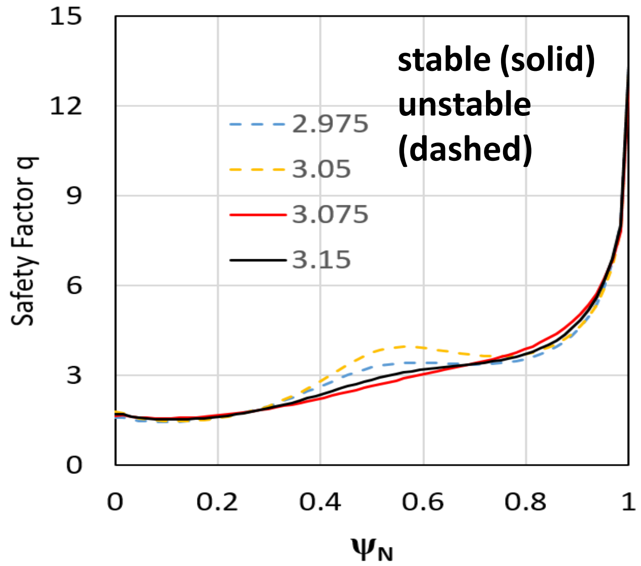
- Global MHD (kink / RWM) typically do not grow in NSTX if strong rotating MHD is present
- Consider 10 different MHD activity evolutions that would have kept global MHD stable
- Counterfactual generation is constrained within bounds based on NSTX rotating MHD operational experience
- Examining for use in DECAF for disruption proximity avoidance

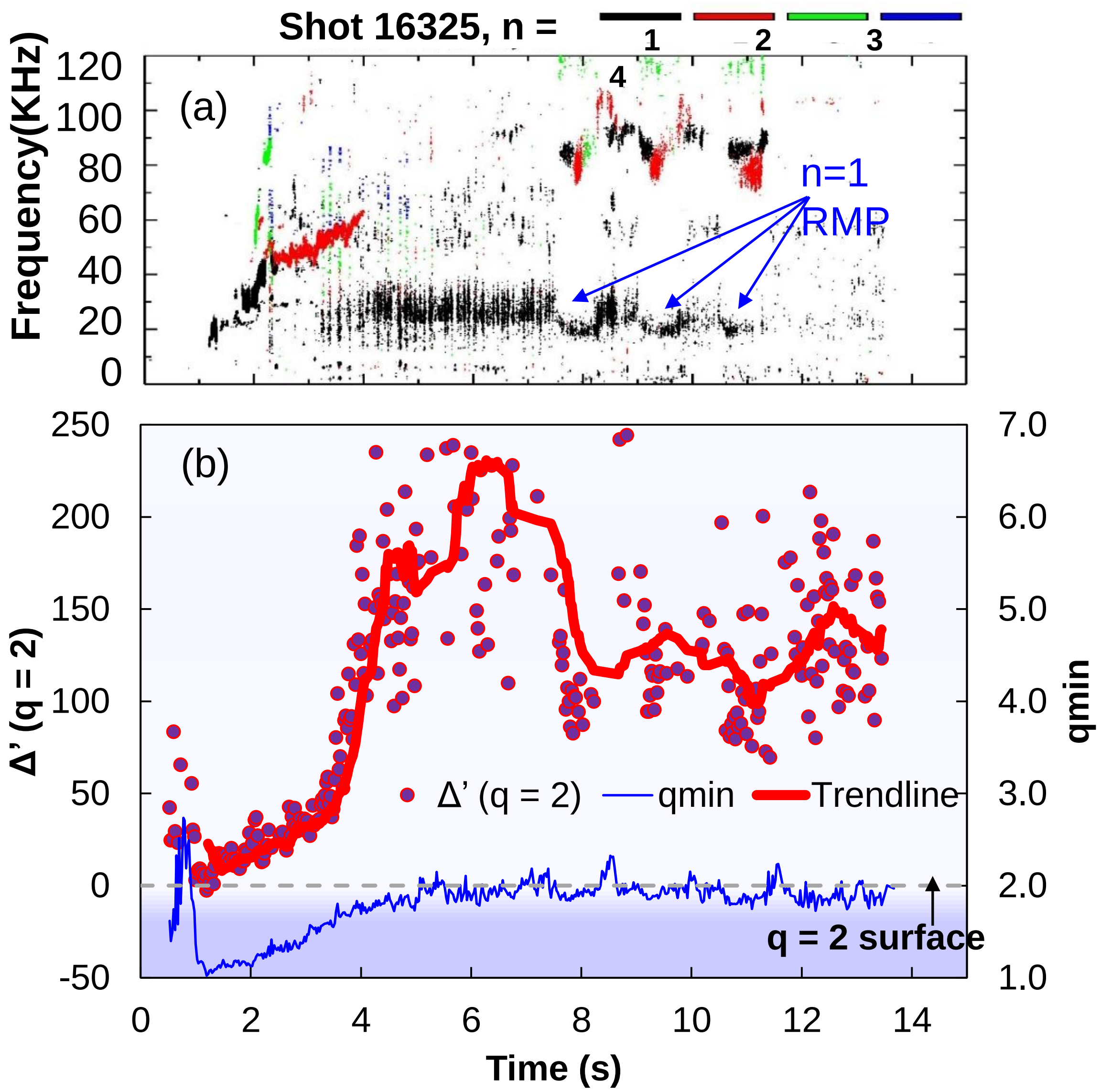
A. Piccione, J.W. Berkery, S.A. Sabbagh, Y. Andreopoulos, Nucl. Fusion **62** (2022) 036002



# Sensitivity of resistive, ideal DCON stability on KSTAR examined for high non-inductive plasmas – potential use of Δ' as stability indicator

Ideal stability of profiles: q shear reversal

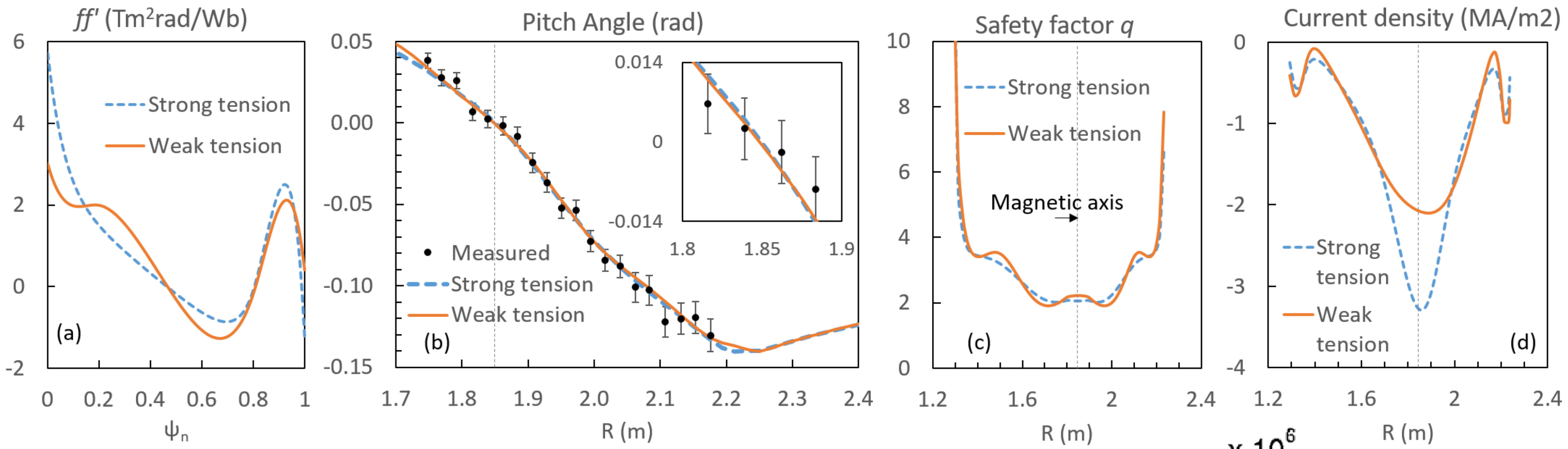


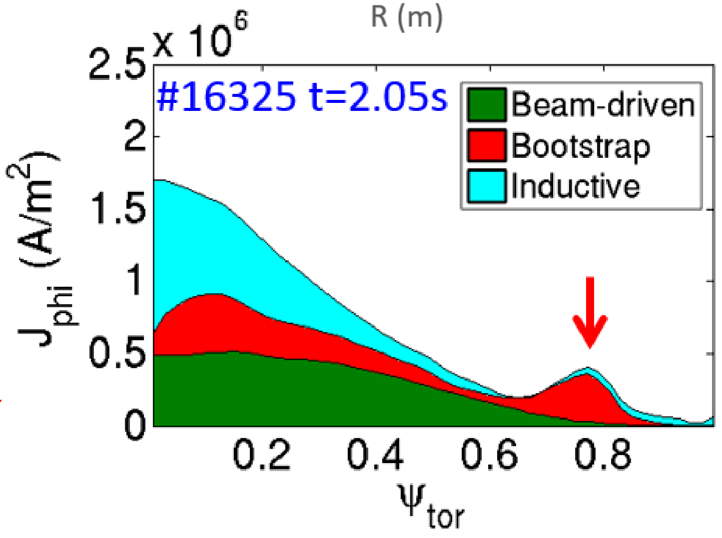

- Δ' analysis supporting evaluation of modified Rutherford equation as resistive stability indicator
- Less freedom in equilibrium basis functions produces less computed stability variation

Y. Jiang, S.A. Sabbagh, *et al*., Nucl. Fusion **61** (2021) 116033

# Kinetic equilibrium reconstruction and transport analysis manifests localized reversed shear and off-axis current profile




- Spline and polynomial basis function models both reproduce MSE measured data
- Local flat spots form in q profile
  - challenging for ideal and resistive stability evaluation
- KSTAR TRANSP shows high non-inductive current evaluation (~ 75% total non-inductive current)




Y. Jiang, *et al.*, Nucl. Fusion **61** (2021) 116033

# 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: sufficient for disruption mitigation ➔ focus moving to disruption avoidance
- DECAF expanded to real-time operation on KSTAR
  - LTM and LTM forecaster used as critical warnings LTM-f
  - Controlled shutdown, MGI, disruption avoidance actuators triggered in real-time by DECAF warnings
  - 100% success rate of real-time system in controlled experiments (greater than 50 shots)

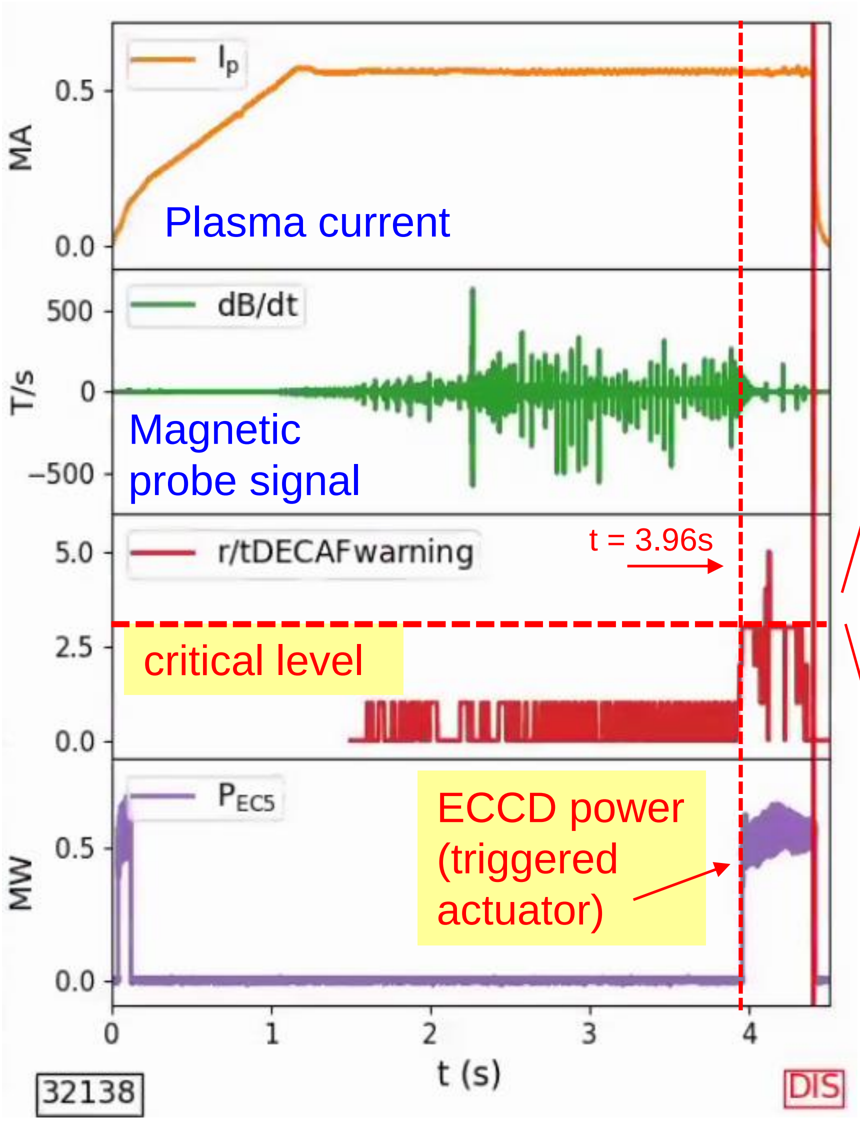
**We are hiring researchers+ ➔ Please contact by Email: sabbagh@pppl.gov**

# Discussion: Given present successes in disruption prediction and avoidance, what are ITER needs for next steps in analysis?

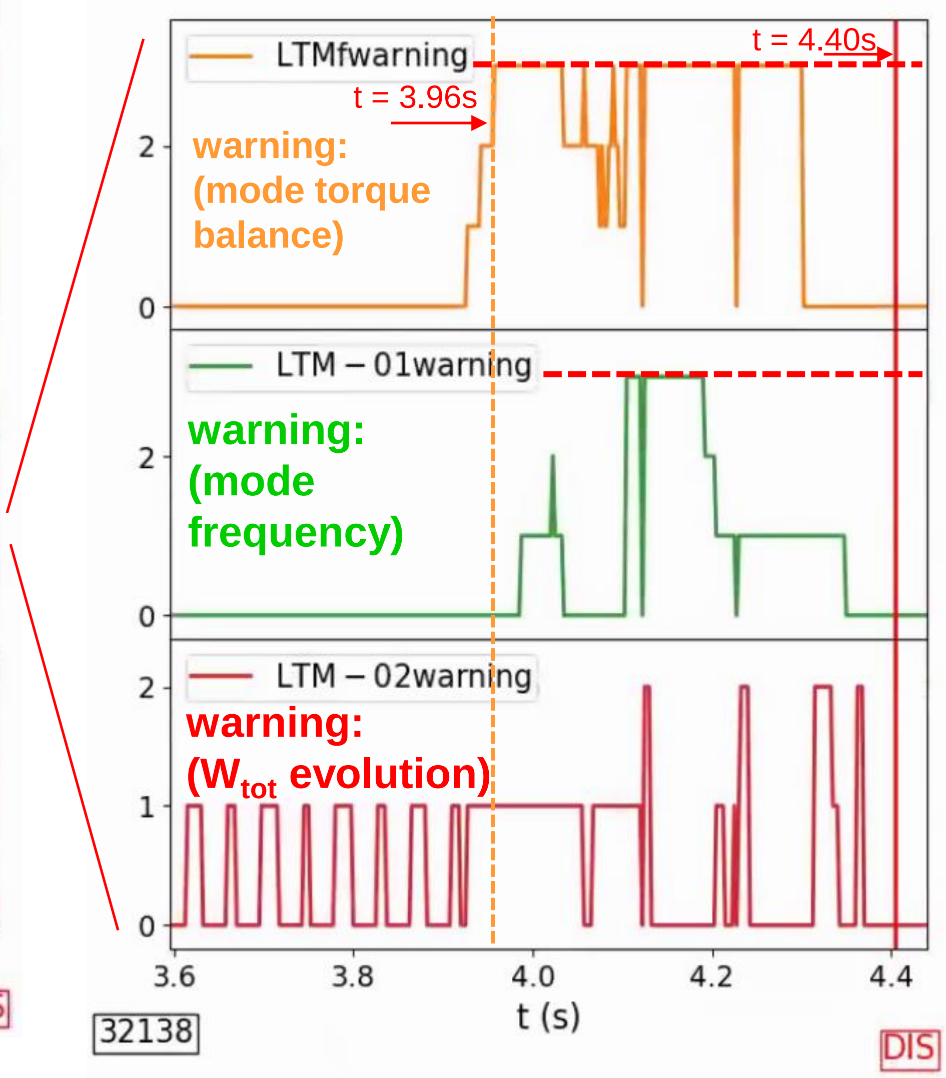
- Especially important for ITER Team to provide specific guidance now
- Relevance to ITER and next step devices
  - sufficiency of early warning for (i) mitigation, (ii) avoidance. What timing is needed?
  - relevance of a disruption regarding analysis for ITER / next devices (e.g. $I_p$ threshold)
    - what specific criteria can ITER Team give in this regard?
  - extrapolation of present analysis, models, etc. to ITER / next devices
  - sufficiency of ITER diagnostics for real-time analysis
  - ability to perform analysis in real time
- Confidence in analysis
  - event analysis correlation vs. causality to disruption ← VERY important !!
    - what certainty do we have in any analysis that events really cause the disruption?
  - deterministic vs. probabilistic approaches
  - physics-based vs. "black-box" AI approaches

# Supporting Slides Follow

# Critical real-time DECAF warning successfully triggered ECCD power actuator for the first time

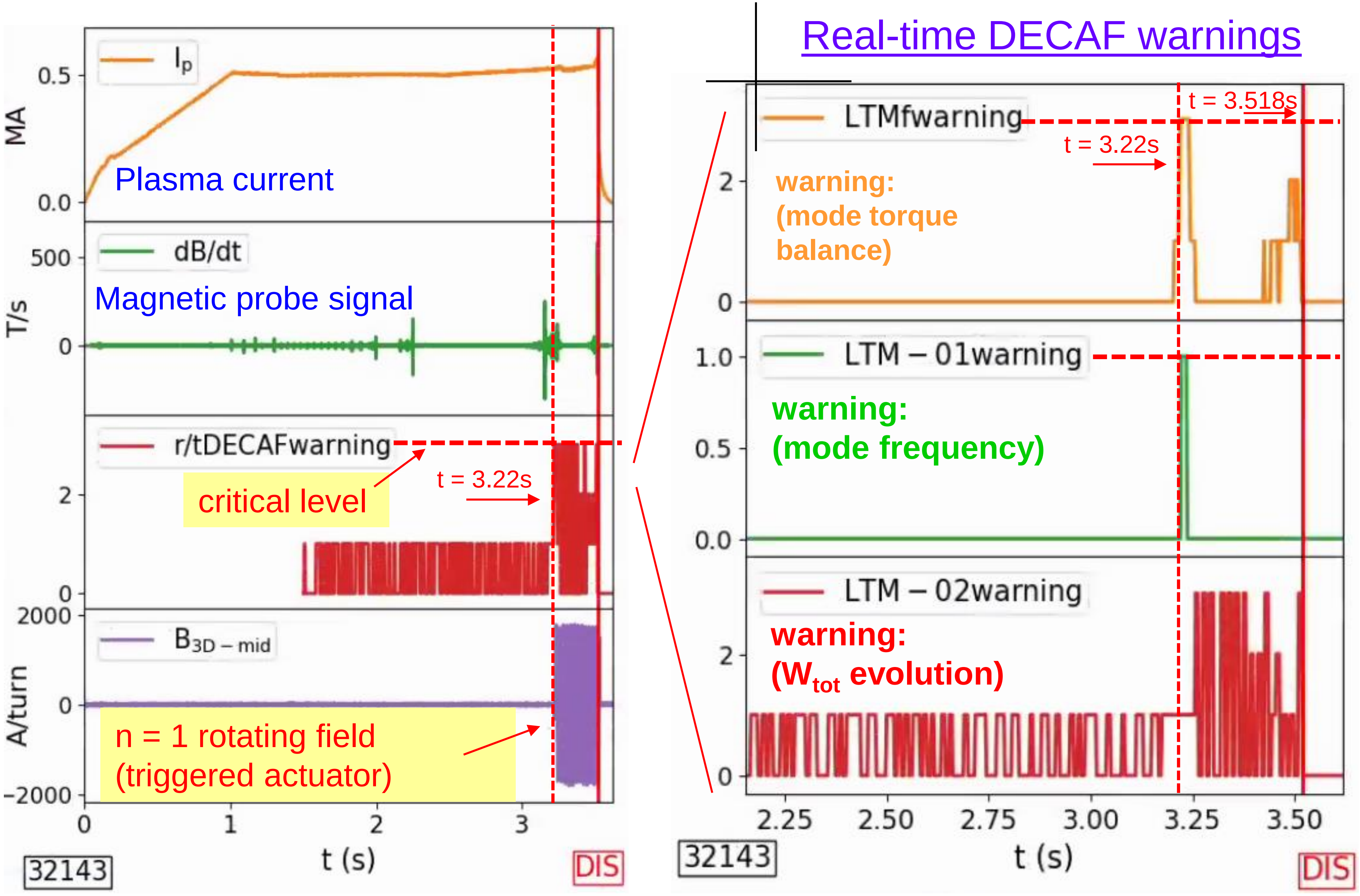



## Real-time DECAF warnings




- ECCD power from EC5 triggered by DECAF
  - LTM forecaster reaches critical level at t = 3.96s
- Real-time LTM forecaster significantly precedes disruption
  - Plasma current quench preceded by 0.440 s

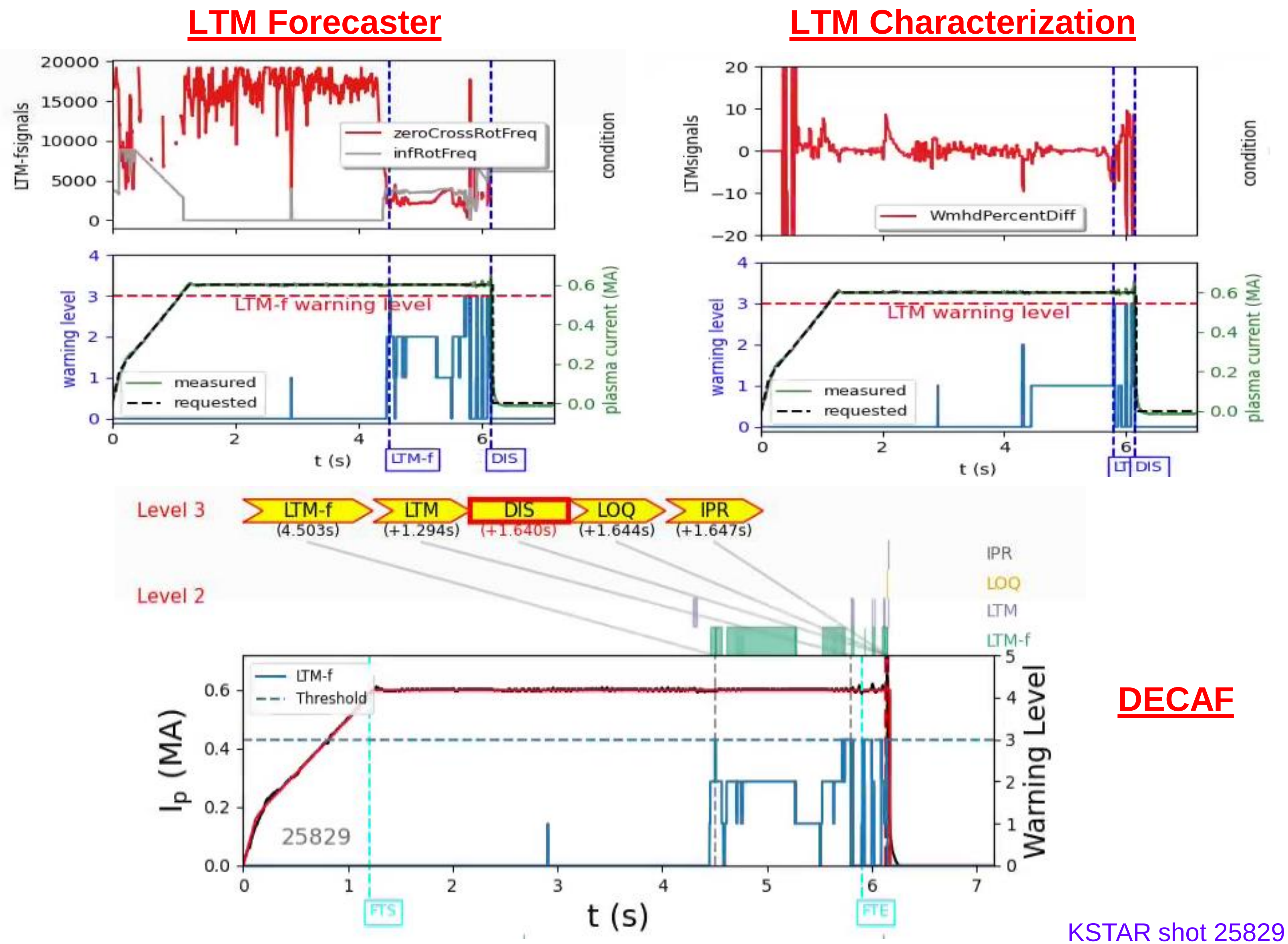
# Critical real-time DECAF warning also triggered an n = 1 rotating field actuator




- n = 1 rotating field from IVCC triggered by real-time DECAF
  - LTM forecaster reaches critical level at t = 3.22s
- DECAF warnings successfully tracked varying mode onset times in different shots
- NEXT STEP: demonstrate disruption avoidance!
  - Complete the XP: Use EITHER NBI actuation or n = 1 field actuation

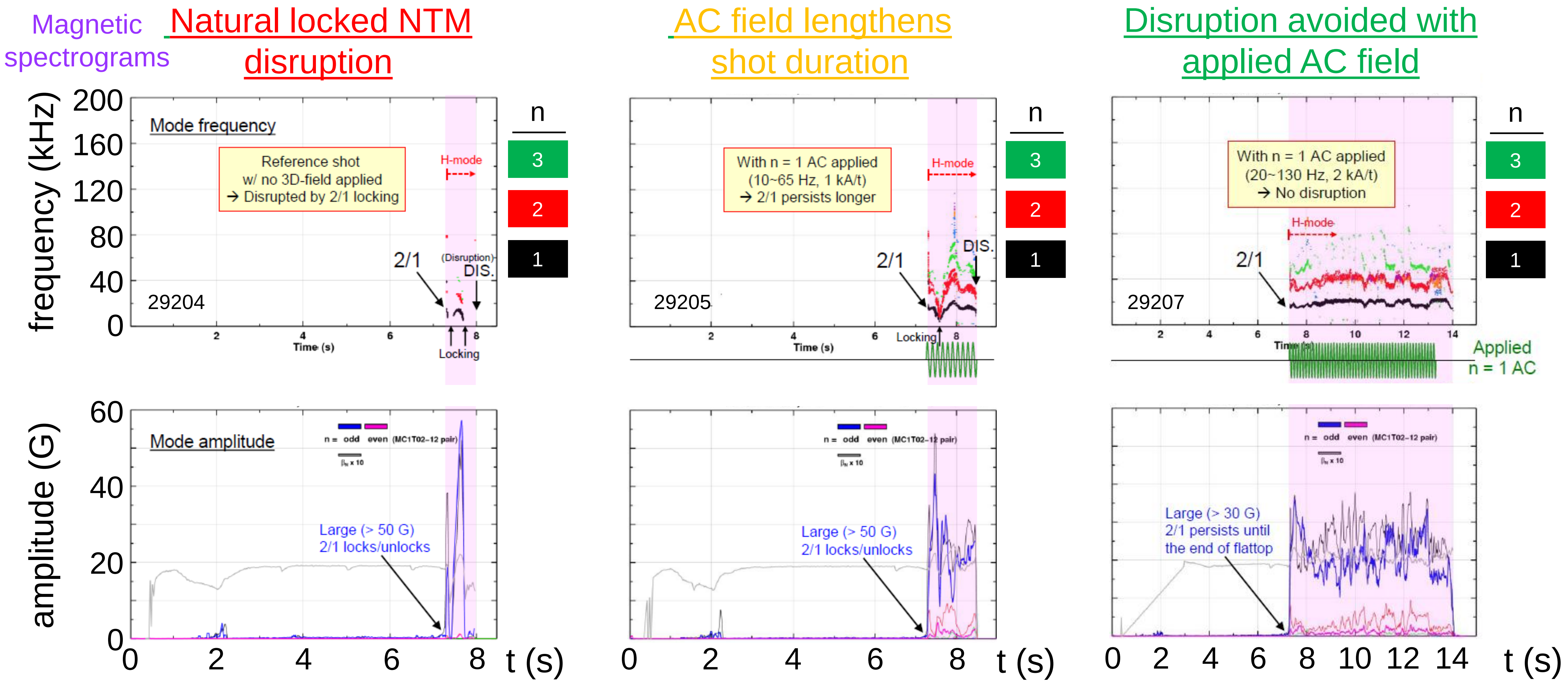
# LTM forecaster on KSTAR leaves ample time for potential NTM control before disruption

- 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



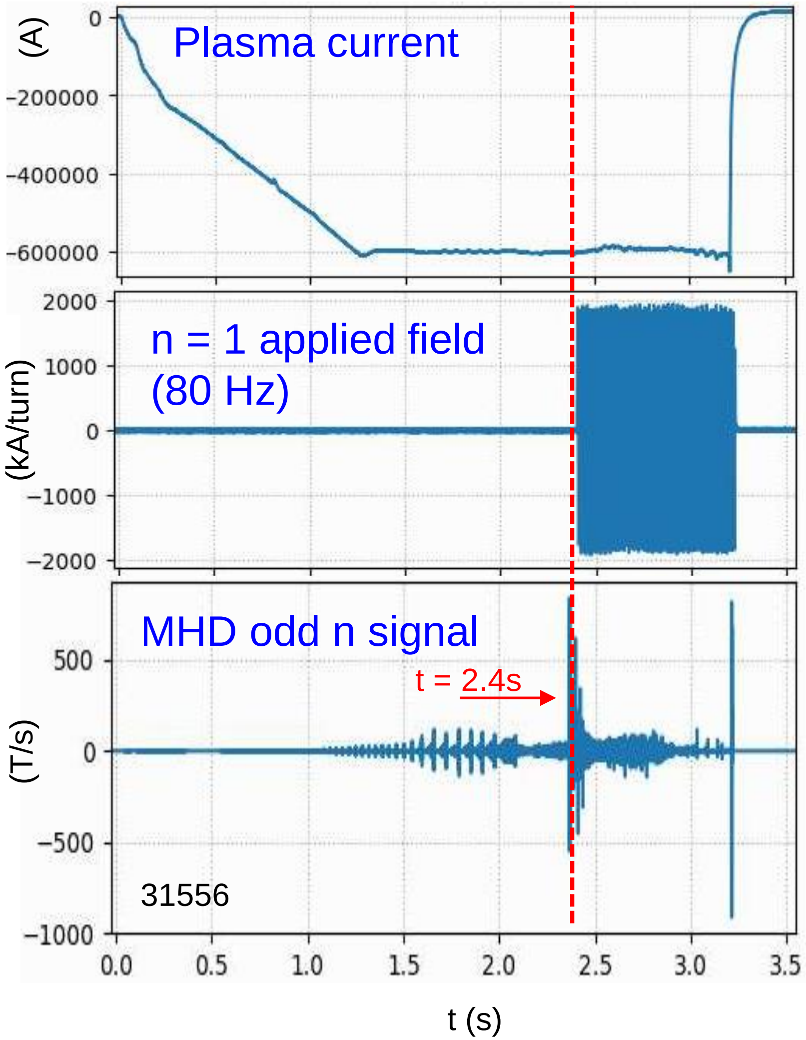

KSTAR shot 25829

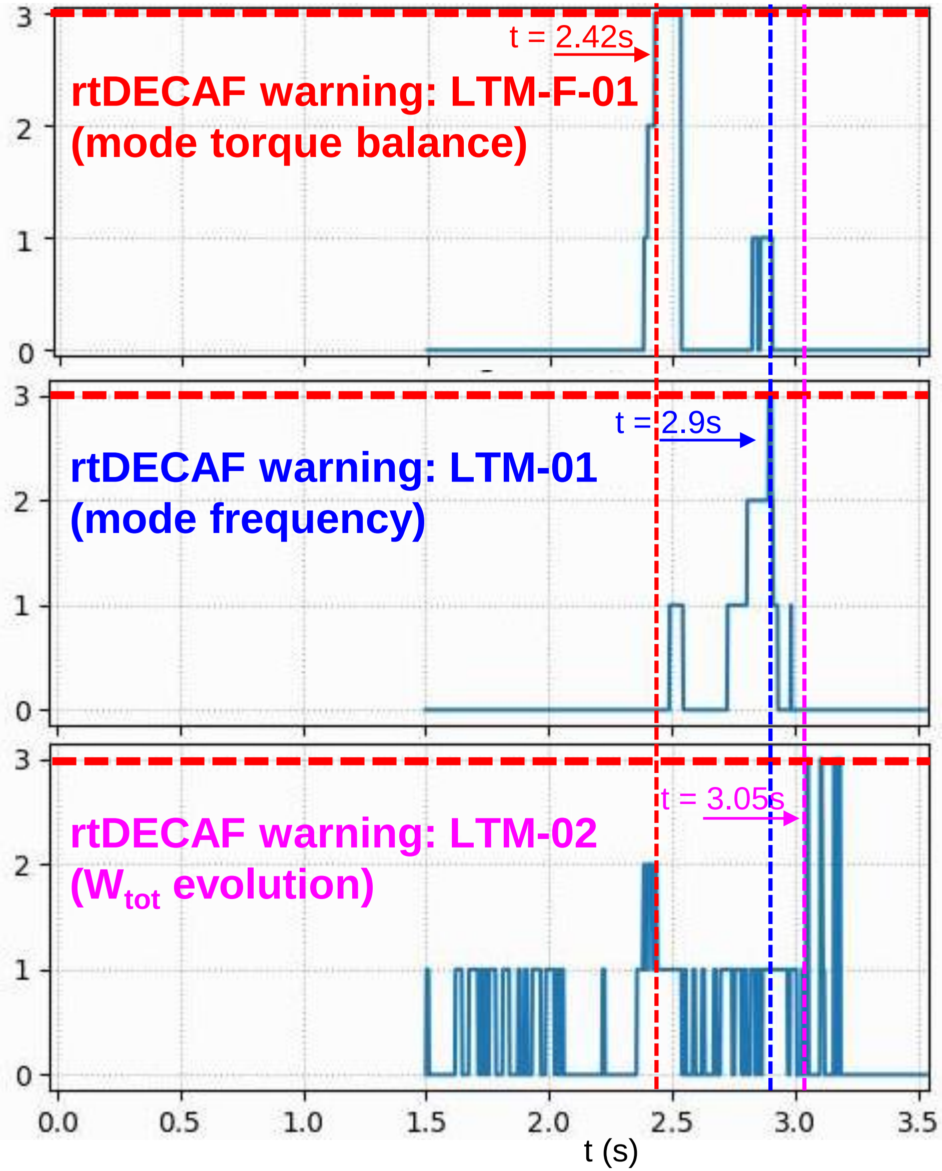
# New disruption avoidance actuator: applied entrainment field successful in preventing naturally-occurring 2/1 NTM locking (2021 KSTAR experiment)




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

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

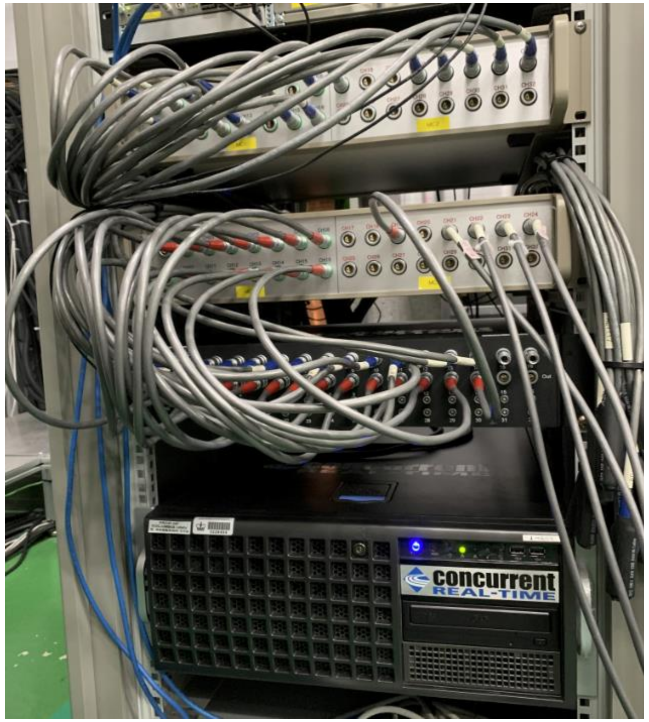


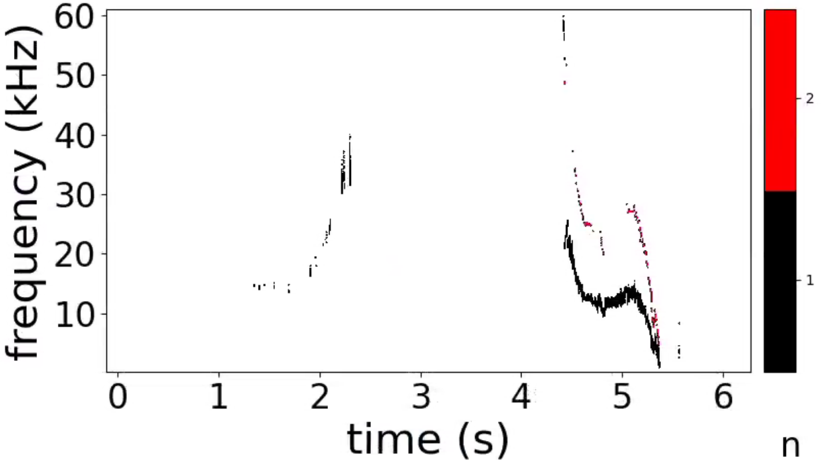

- Forecast worked, but n=1 AC field did not prevent TM mode lock
  - Such an activation was successful in 2021 "NTM entrainment" experiment
- Two differences this year regarding TM lock prevention attempt
  - n = 1 applied AC field did not rotate toroidally (patch panel setting different)
  - target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

# Real-time MHD system on KSTAR computed real-time FFTs for first time in 2021 for real-time DECAF application

- Real-time MHD analysis computer installed on KSTAR
  - Connected to plasma control system (PCS)
  - Real-time FFT analysis taken in 2021 – comparison to offline

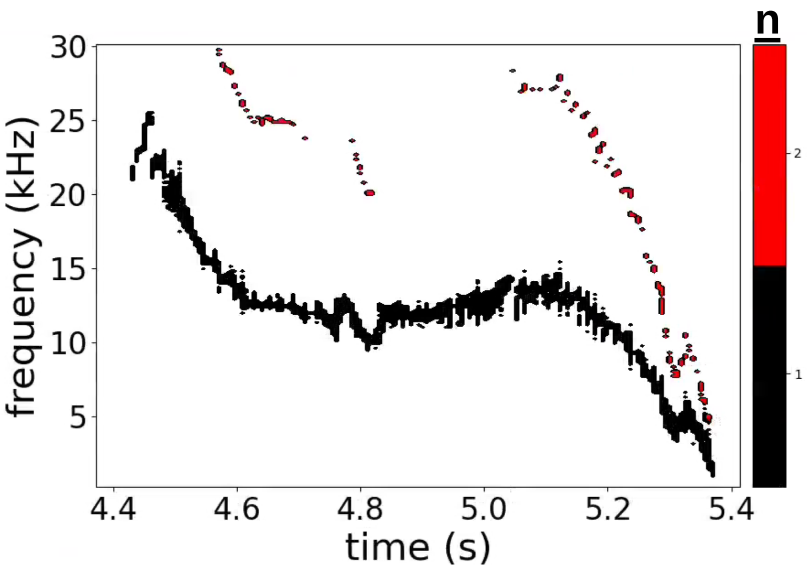



Magnetic probe array toroidal mode spectrogram (offline)

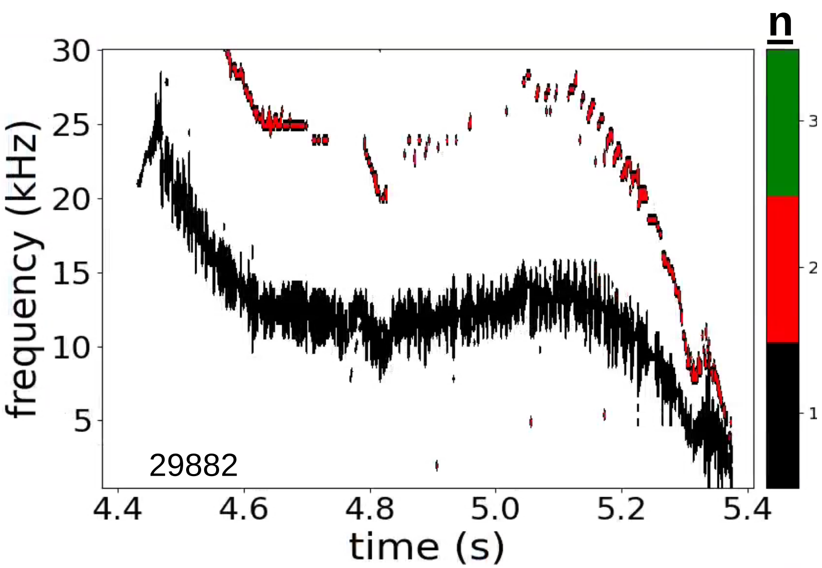



J. Riquezes (CU)

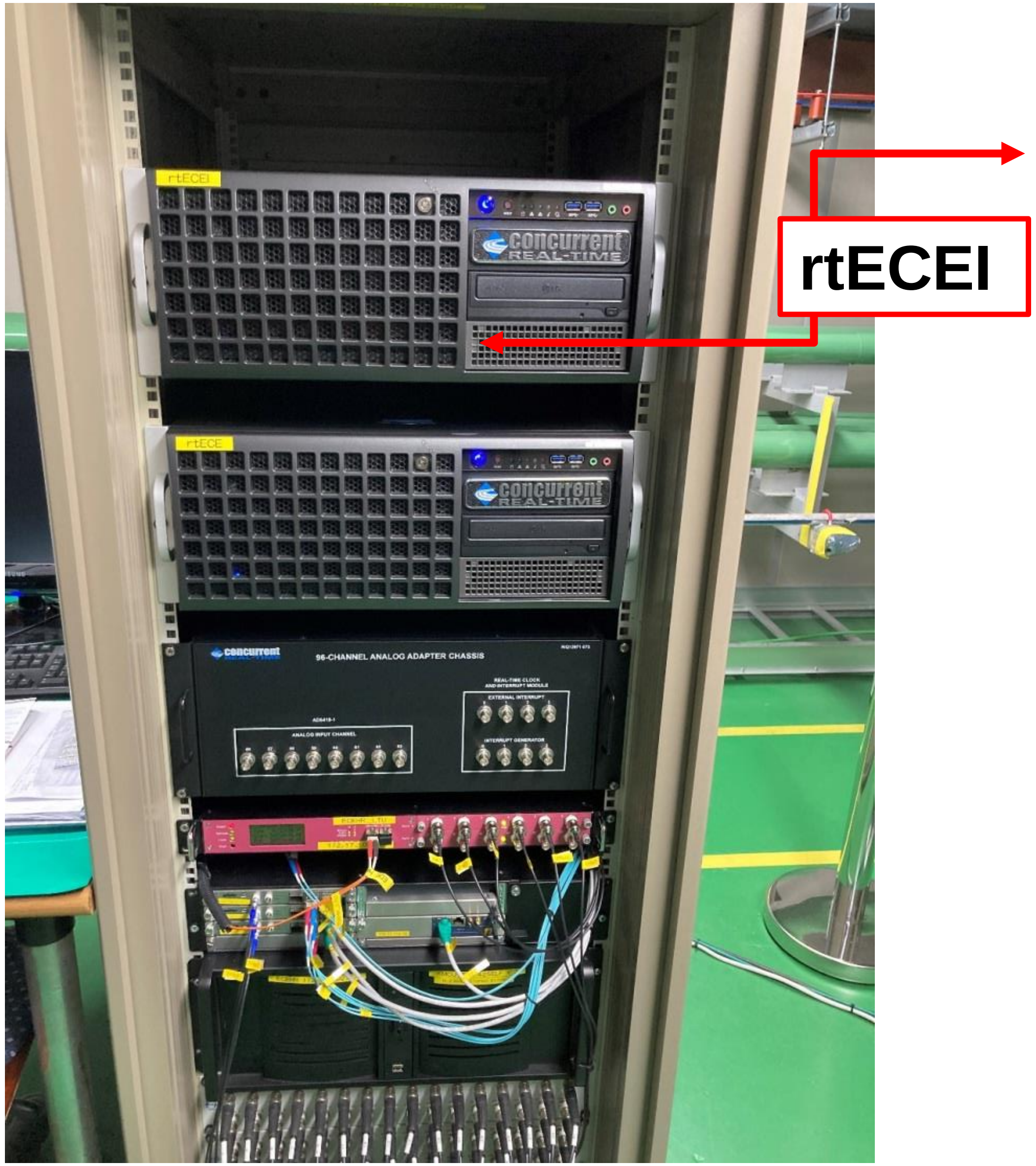
DECAF spectrogram (offline FFTs)

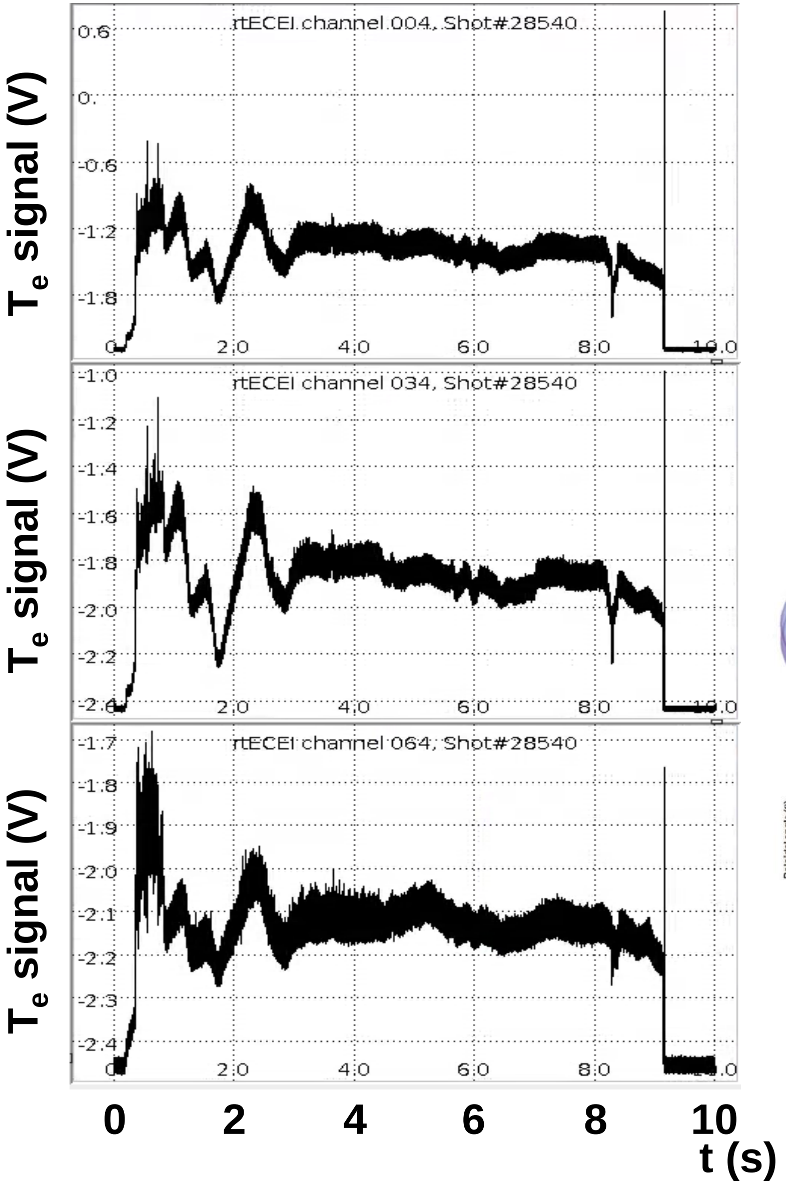



DECAF spectrogram (real-time FFTs)

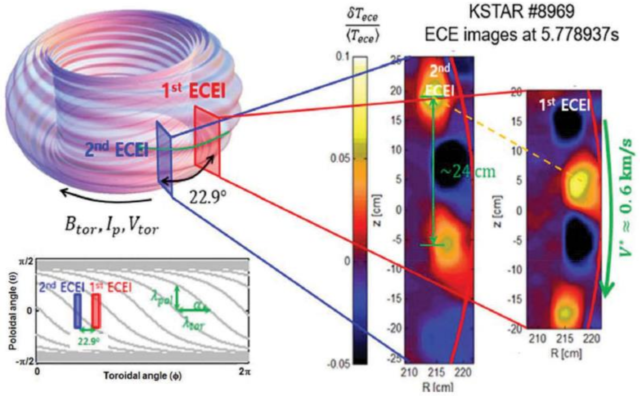


# The first real-time ECEI data on KSTAR was taken as well in 2021 run campaign




- Full 2D poloidal cross-section acquired in r/t - 192 channels!
- 3 of 192 channels shown



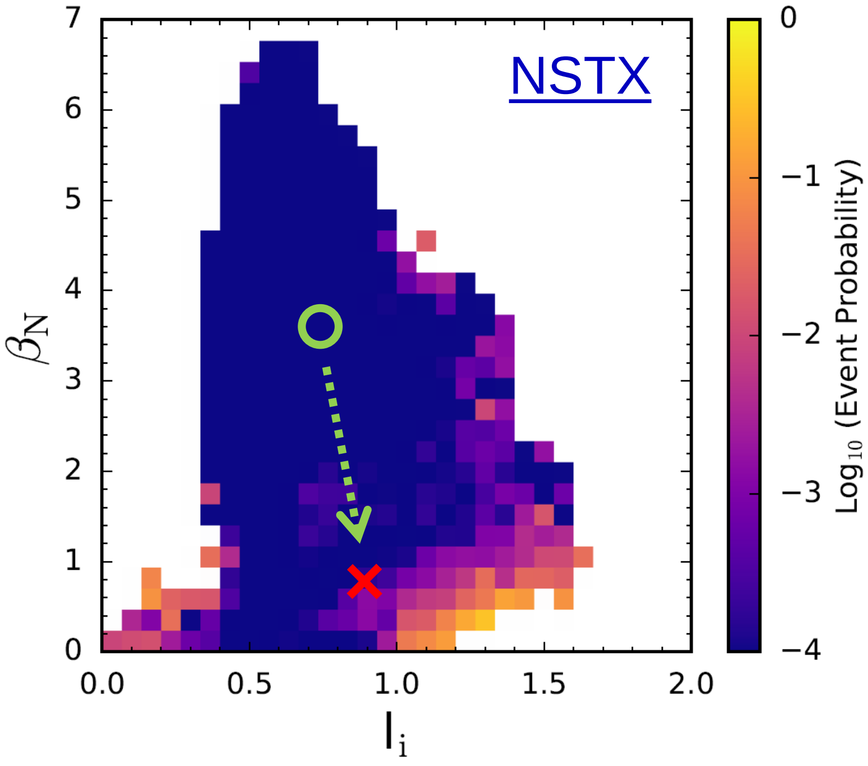

H.K. Park, Adv. in Physics: X, 4:1, 1633956 (2019)

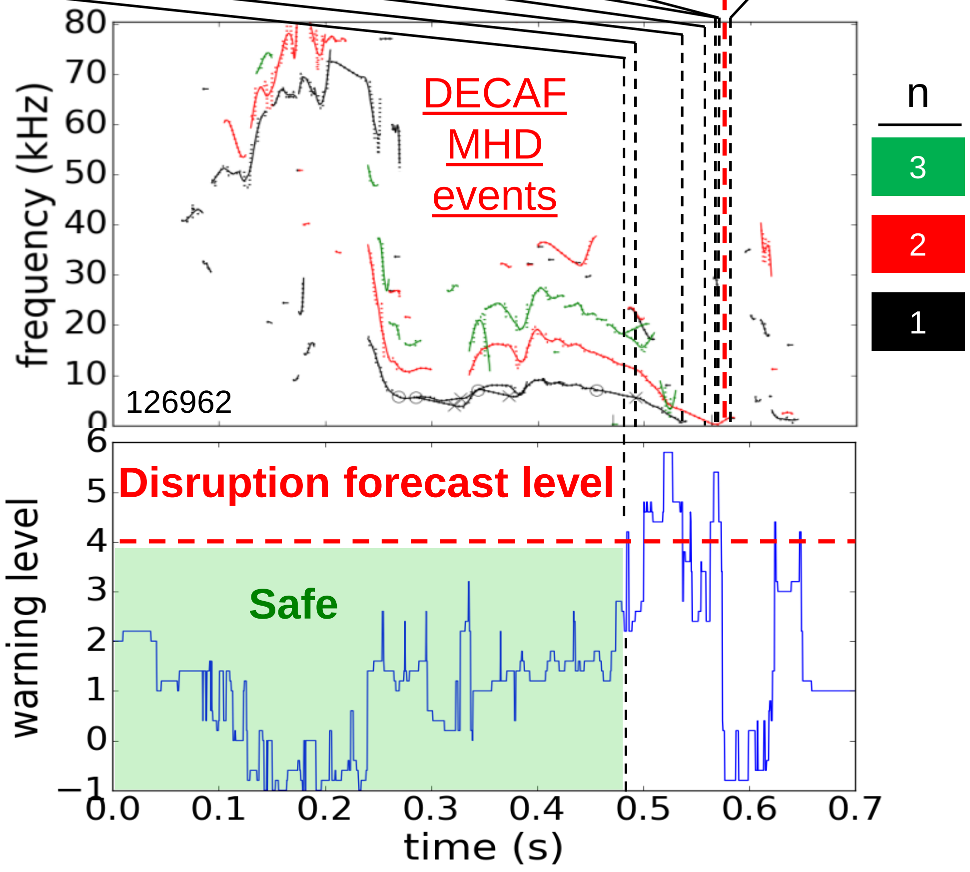
# Review: DECAF provides an early disruption forecast - on transport timescales – giving potential for disruption avoidance

DECAF Level 3 event chain

MHD-n1 (0.490s) → BIF-n1 (+.005s) → LTM-n1 (+.045s) → PRP (+.068s) → IPR (+.073s) → WPC (+.073s) → DIS (+.077s) → VDE (+.080s)

NSTX stability operational space



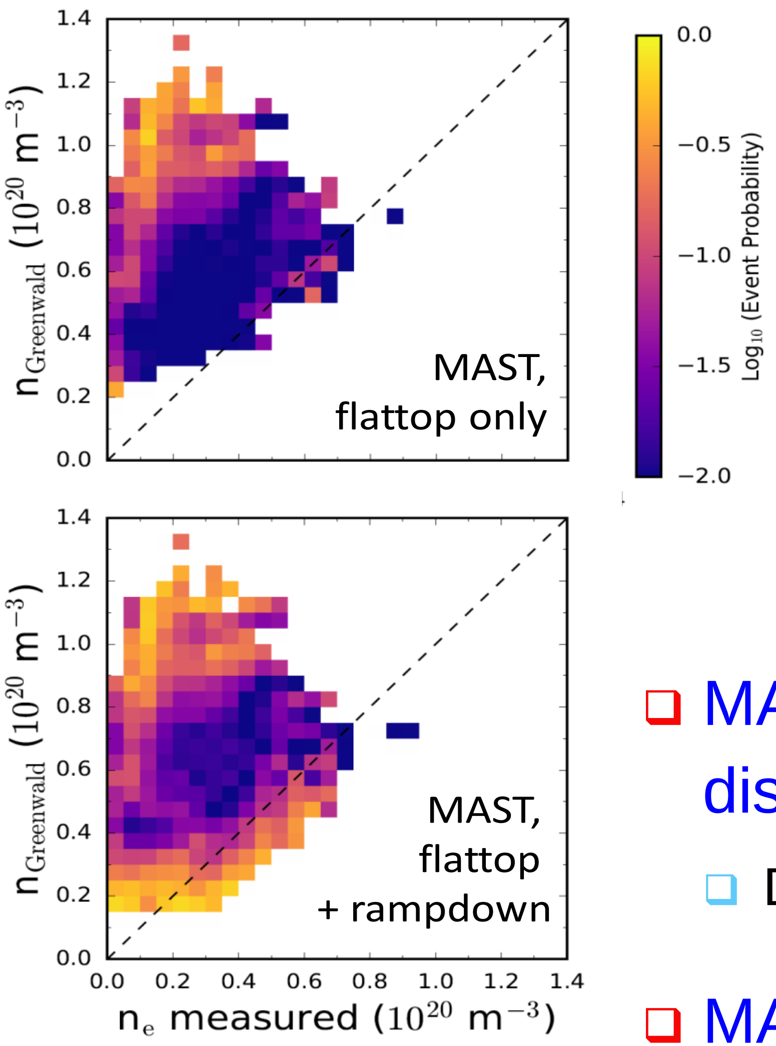

- DECAF event chain reveals physics
  - Rotating MHD slows, bifurcates, locks
  - Plasma has an H-L back-transition (pressure peaking warning PRP) before DIS
  - Early warning occurs in apparently SAFE region of operating space!

• NOTE: 15 conditions used including plasma velocity profile

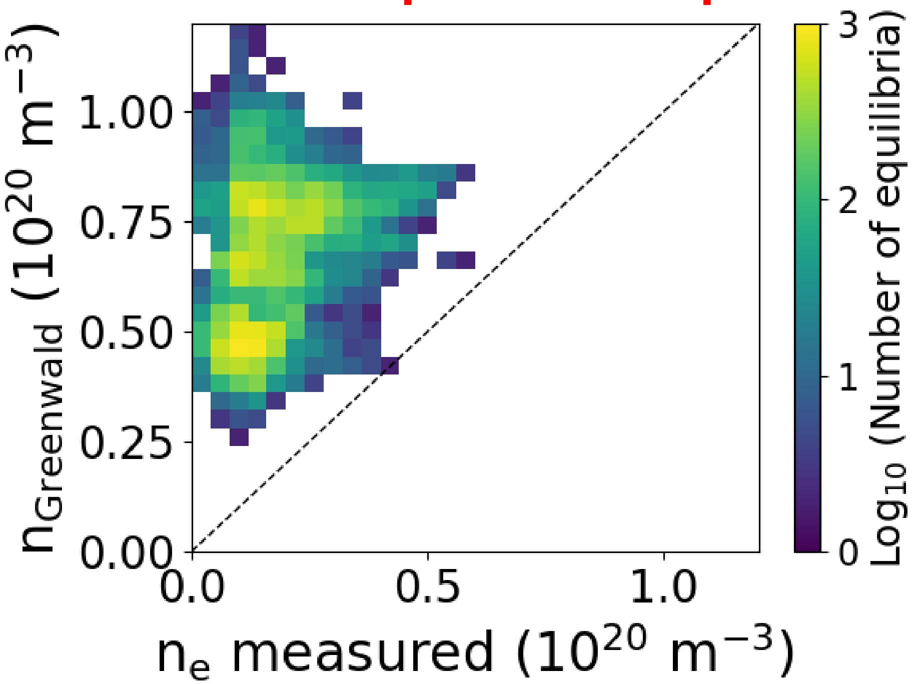
S.A. Sabbagh, et al., 2020 IAEA Fusion Energy Conference, Paper IAEA-CN-286/1025

# DECAF analysis of MAST showed disruptions with Greenwald limit violation common in ramp down; MAST-U flattops mostly below limit

**MAST disruptivity**



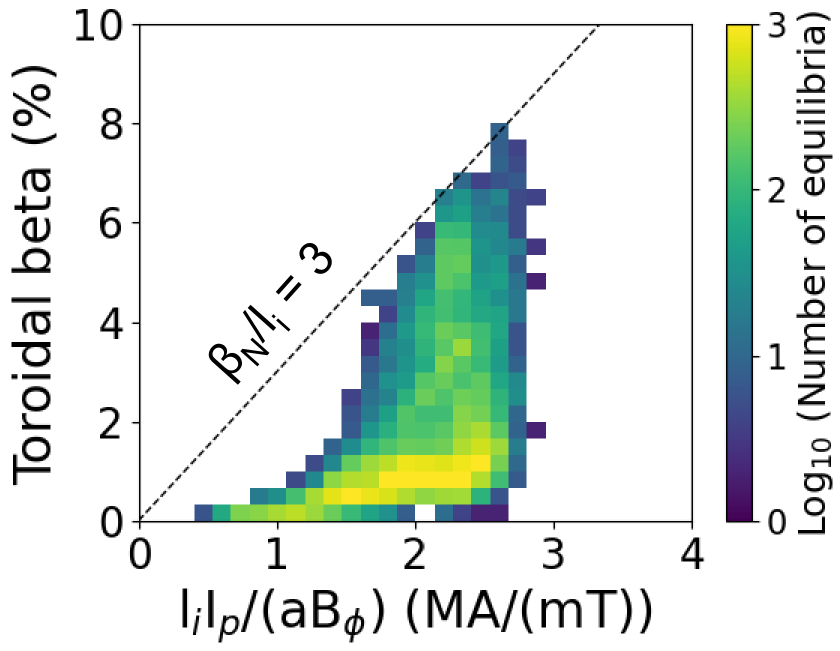

**MAST-U operational space**

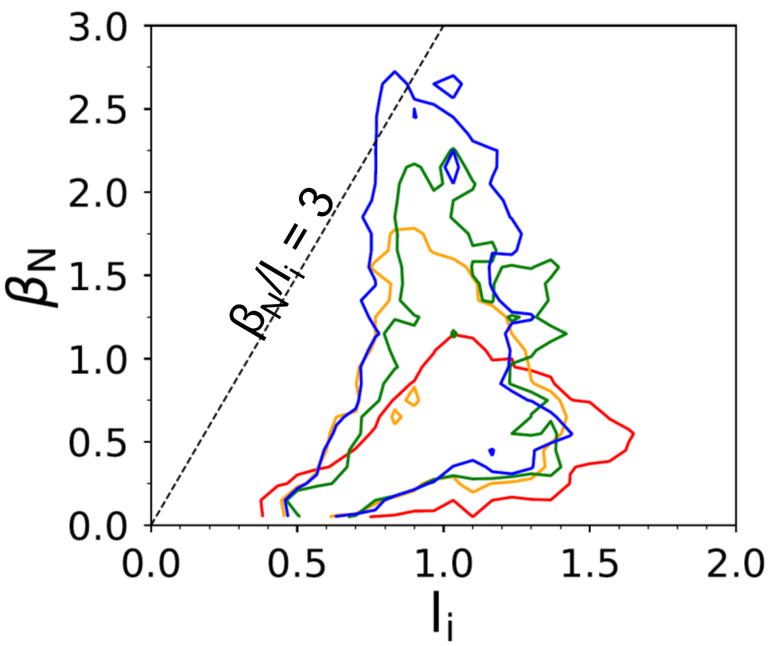



- MAST flattops reached the Greenwald limit, but disruptions over the limit were relatively rare
  - Decreasing $I_p$ in ramp down reduces the limit
- MAST-U flattops usually well below limit

J. Berkery, et al., APS DPP BP11.00016

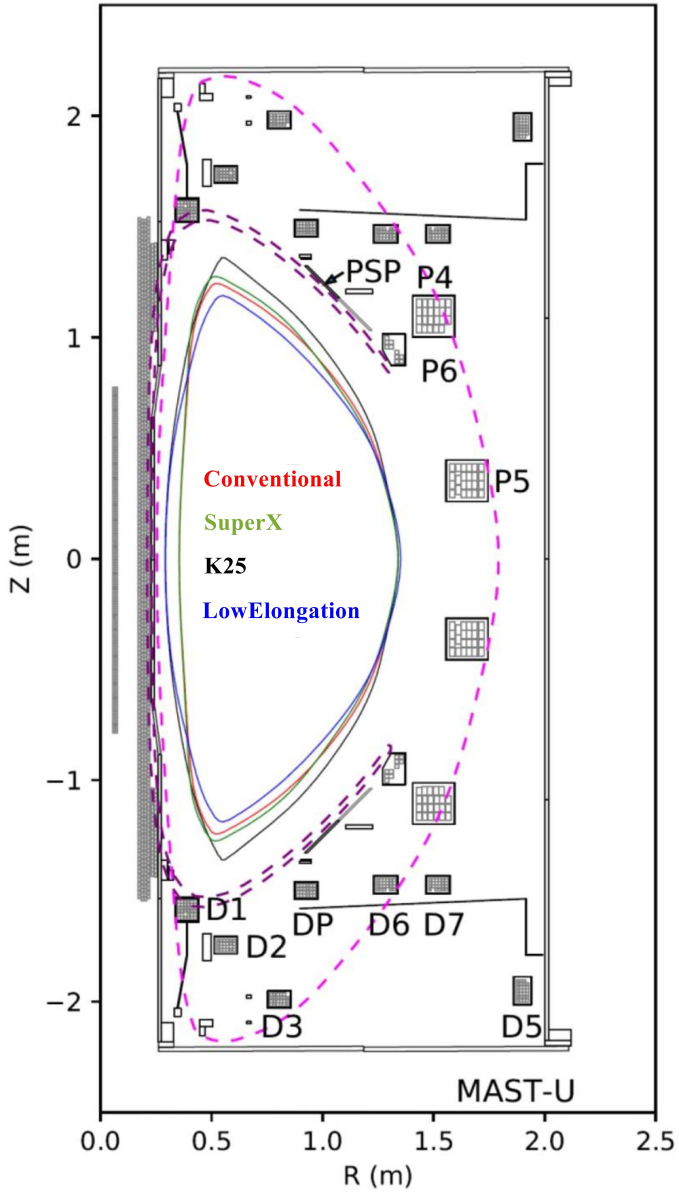
# DECAF examination of MAST-U operation has reached max $\beta_N$ of 3.18 and $\beta_N/l_i$ of ~3.3, still below computed global stability limits

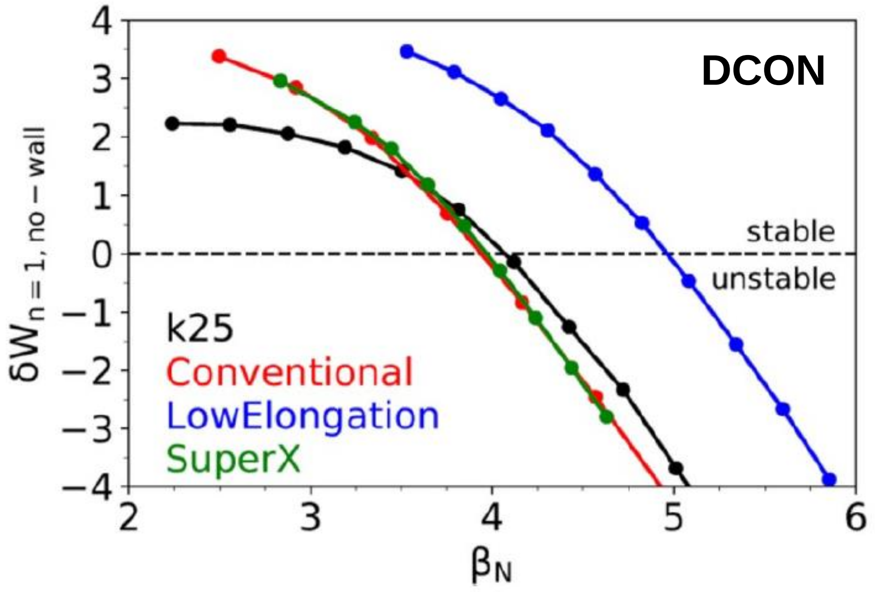



- Normalized beta diagrams show macroscopic stability limits
  - The colored lines are contours containing at least 10 equilibria for:
  - Ohmic (red), SW off axis beam (orange), SS on axis beam (green), and two beam (blue)
- Projected MAST-U no-wall limit: $\beta_N$ ~ 4 and $\beta_N/l_i$ ~ 7

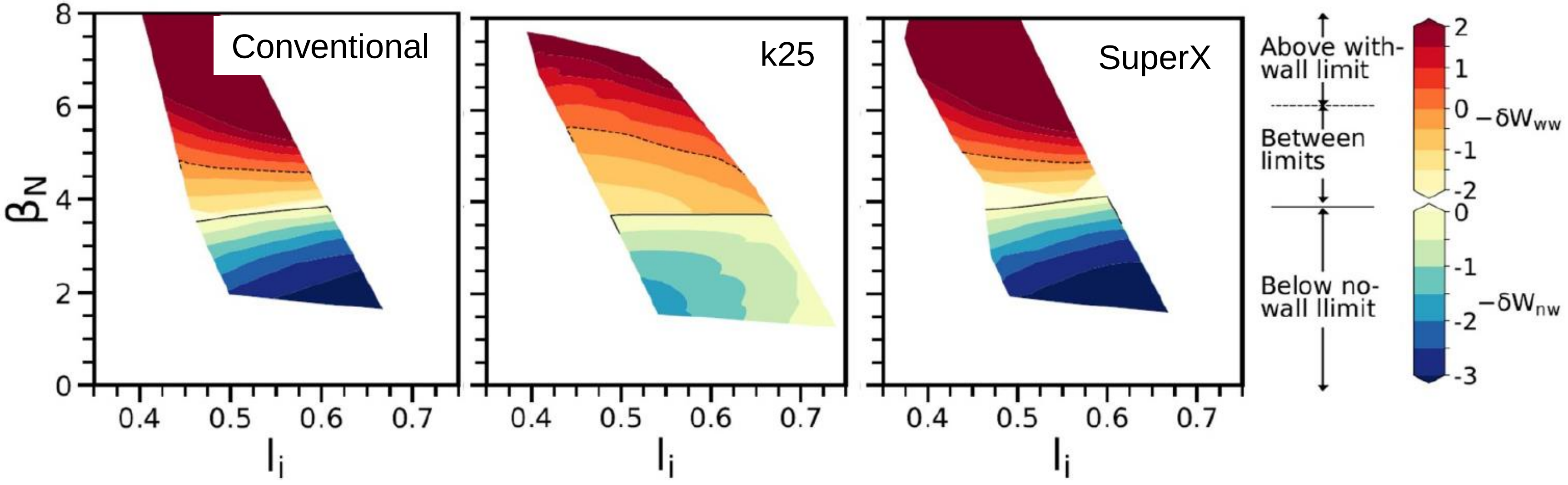
# Ideal stability of four MAST-U projected equilibria shapes were evaluated for stability by scaling pressure, etc.



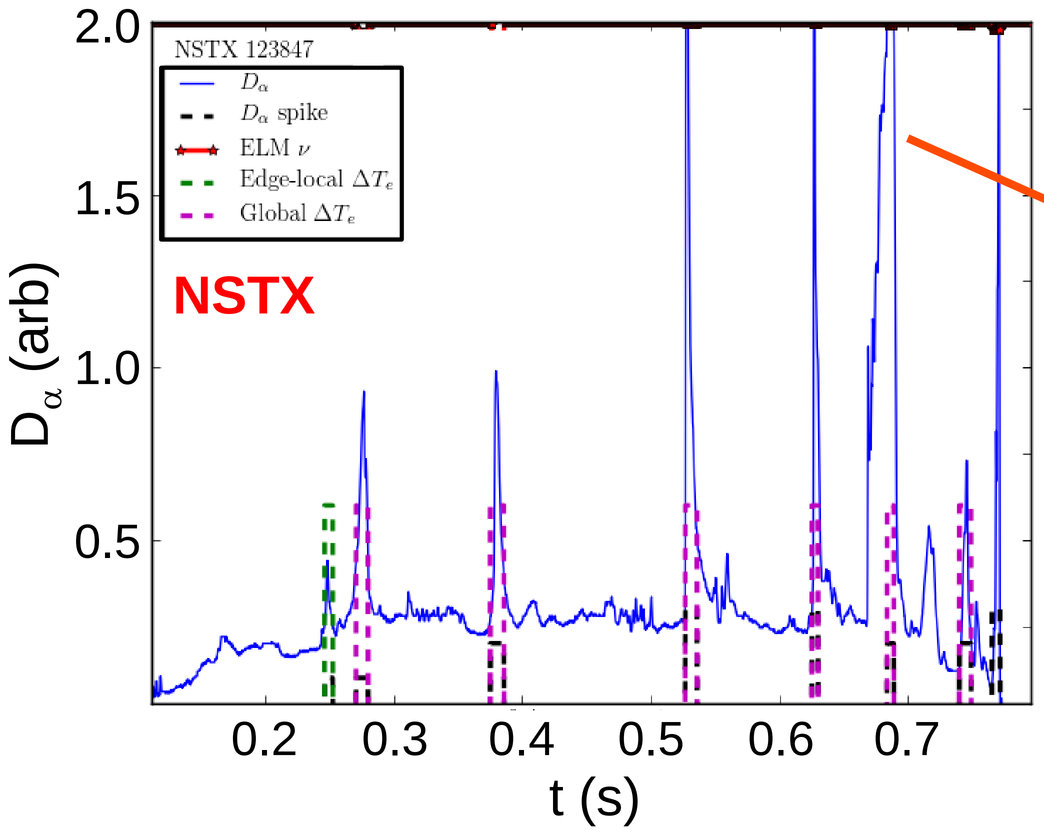




- Ideal stability evaluation
  - pressure profile scans
  - q(0) scans
  - Projected no-wall limit: $\beta_N$ ~ 4 and $\beta_N/l_i$ ~ 7

J.W. Berkery, *et al.*, PPCF **62** (2020) 085007

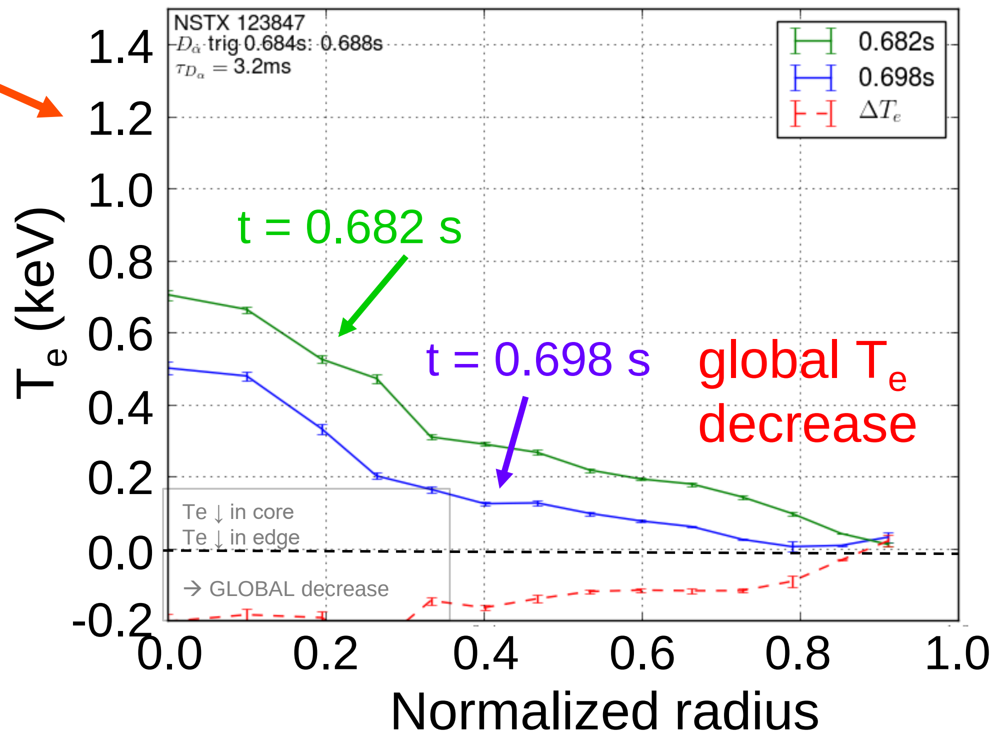


# $T_e$ profile provides critical addition to $D_\alpha$ ELM detection by determining the radial extent of perturbation – needed to distinguish disruptive MHD




$D_\alpha$ spikes normally considered "edge localized"….

## $T_e$ profile evolution



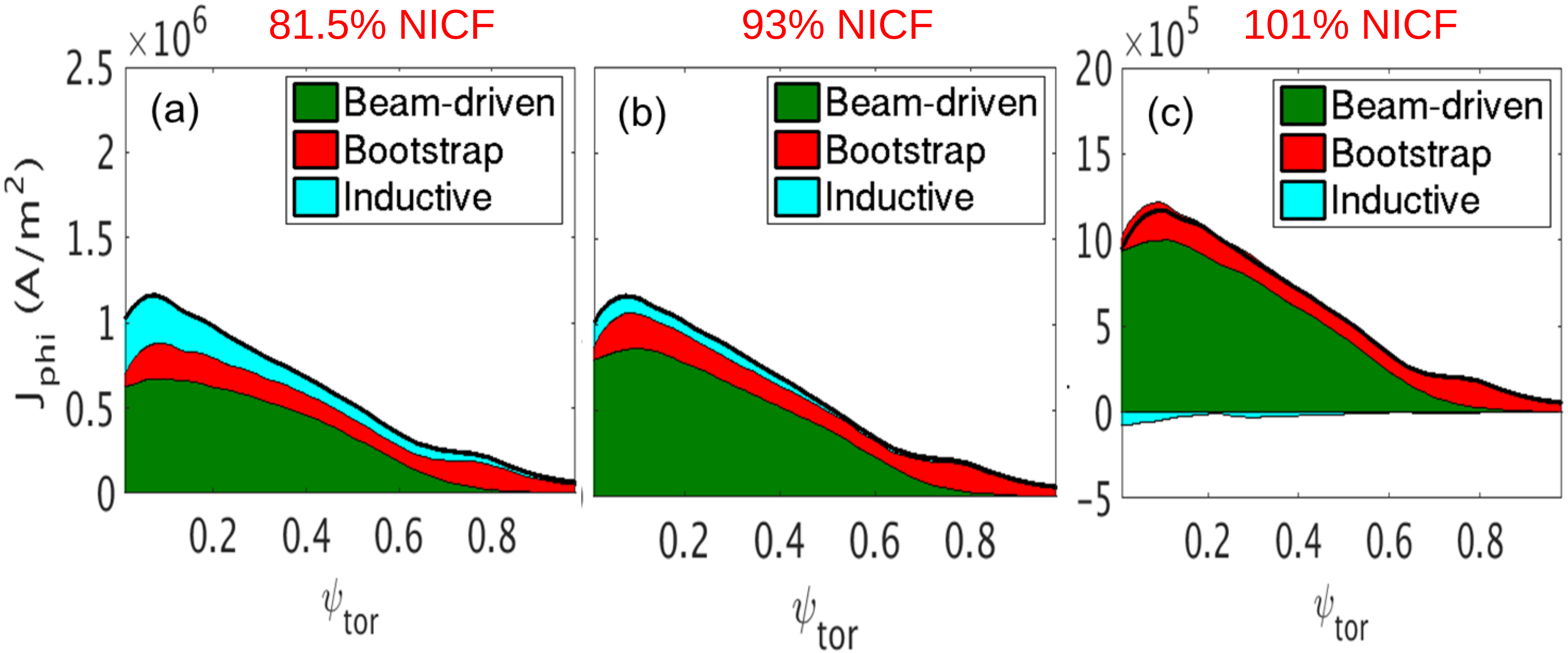

… can in fact be global
- In this case, a global kink / RWM

- Need a real-time system that measures $T_e(R)$
- ELMs can also trigger tearing modes, locking
  - For KSTAR, a real-time ECE system can also examine mode position, geometry

J. Butt, et al. (APS DPP 2021 TP11.00109)

# “Predict-first” KSTAR TRANSP analysis shows expected high performance plasmas at > 80% NICF

Predicted high non-inductive current fraction (NICF) current profiles




- High non-inductive current fraction predicted for 6.5, 7.5, 8.5 MW NBI
  - The $\beta_N$ ranges from 3.0 – 3.5; based on KSTAR plasmas with NICF ~70%
- Produced high NICF plasmas (2021 run) with ~record $\beta_p$ = 3 in KSTAR (analysis pending)

# Continue to engage plasma theory to reach disruption forecasting and avoidance goals and produce essential understanding

- Workflow: use human intelligence, *then* artificial intelligence
  - Understanding needed for confident extrapolation across devices
  - Enhance computational efficiency
- Many important topical areas (just some examples…)
  - Density limits: both high and low (stringent evaluations)
  - Power balance: impurity accumulation, radiative collapse characteristics
  - Tearing stability: refinement of approaches (e.g. Modified Rutherford Equation)
  - Tearing characteristics: triggering mechanisms, mode coupling relation to disruption
  - Confinement transitions: profile dynamics – effect on plasma stability
  - Scenario resilience / plasma control: plasma state evolution and proximity to disruption

**We are hiring post-doctoral researchers+ ➔ Email: sabbagh@pppl.gov**