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First Real-Time Application of Disruption Event Characterization and Forecasting and Associated Research

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KFE KOREA INSTITUTE OF FUSION ENERGY KSTAR

PPPL CCFE CULHAM CENTRE FOR FUSION ENERGY

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

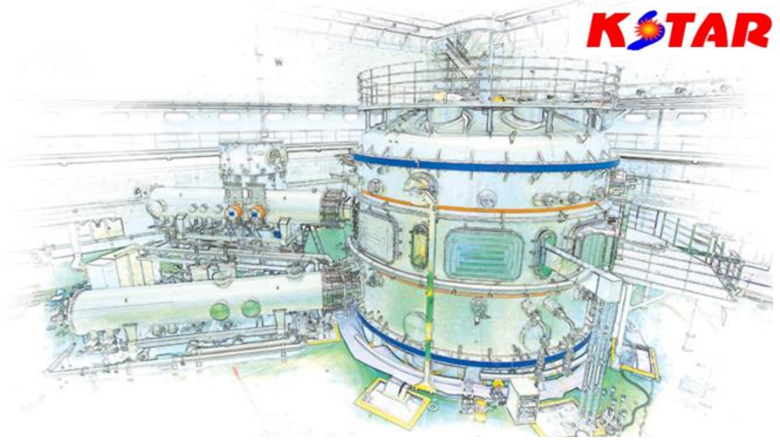
IPP Max Planck Institute for Plasma Physics

Presented at the

PPPL Workshop on Theory and Simulation of Disruptions

PPPL, Princeton, NJ

20 July 2023



V3.0

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

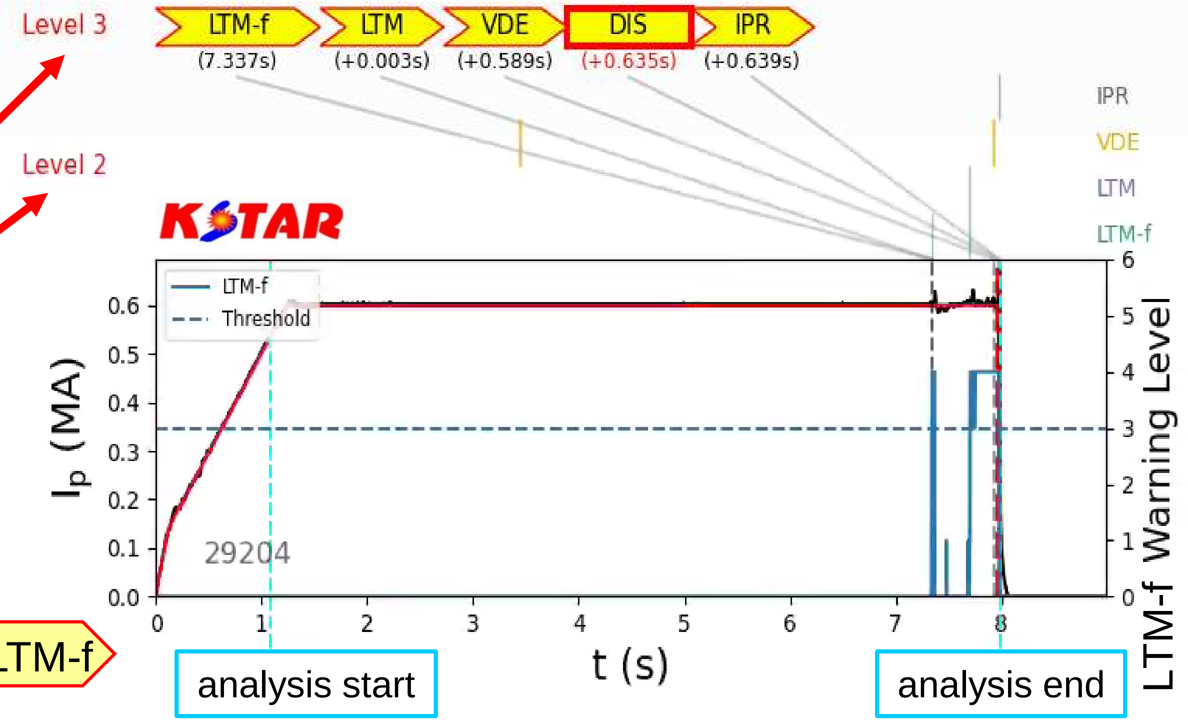
Disruption Event Characterization and Forecasting Research (DECAF*) expanded, including first real-time application with high accuracy forecasting

- DECAF (very brief!) overview
- First real-time DECAF implementation and operation (high accuracy!)
- High accuracy offline DECAF analysis
- State evolution formalism (ex: high beta experiment on MAST-U)
- Example supporting analyses: density limit; counterfactual AI analysis

*DECAF™ patent pending (visit: https://attractorsolutions.com)

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

- Fully automated, physics-based analysis of multiple tokamak device databases (KSTAR, NSTX/-U, MAST/-U, AUG, DIII-D, TCV, ST-40)
- Analyzing all plasma states (continuous and asynchronous events)
  - "Critical": (Level 3) disruption if no action taken
  - "Proximity": (Level 2) potential for "critical" events
  - "Ordered": (Level 1) events indicate steady operation (e.g. L-mode / H-mode, steady ELMing)

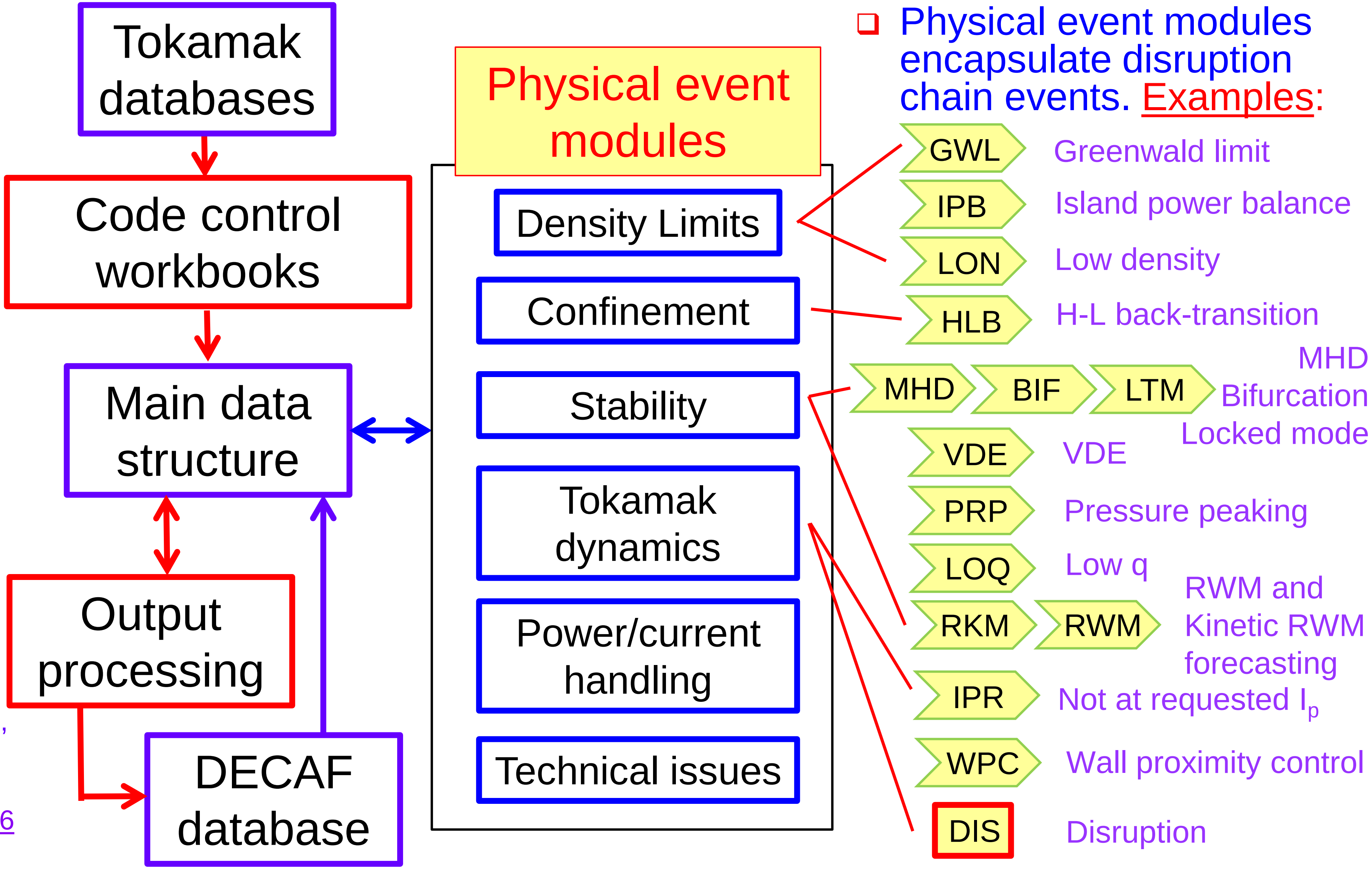


- "Forecaster events": give earliest warnings LTM-f
- High quantitative success reported (improved to > 99%!)
  - > 91% true positive, ~ 9% false positive (~1e4 shots, ~1e6 samples)
- Research continues focused on improving forecasting to needed accuracy (98%+ goal for ITER, w/low false positives)

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

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

- Physical event modules encapsulate disruption chain events. Examples:

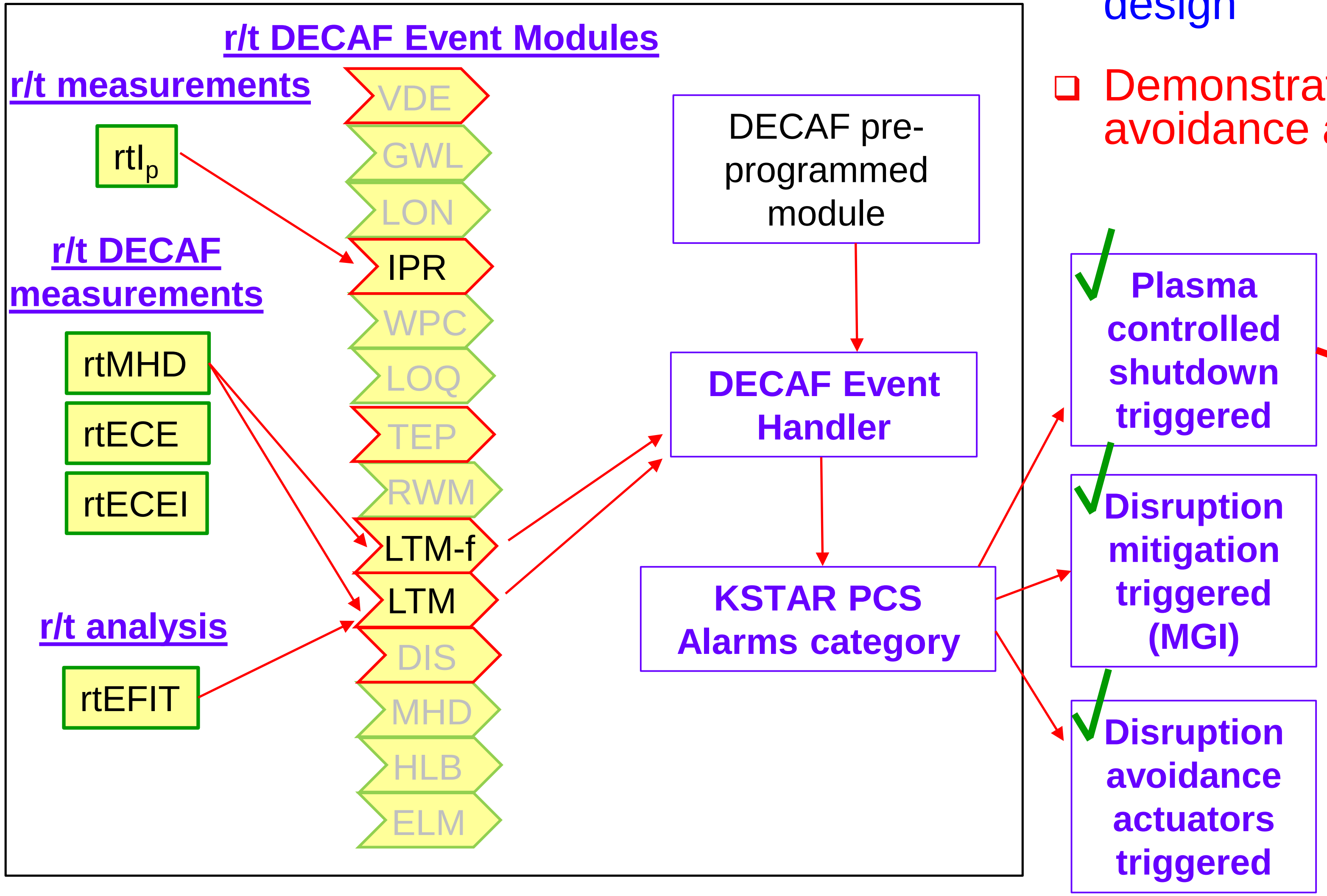


*patent pending

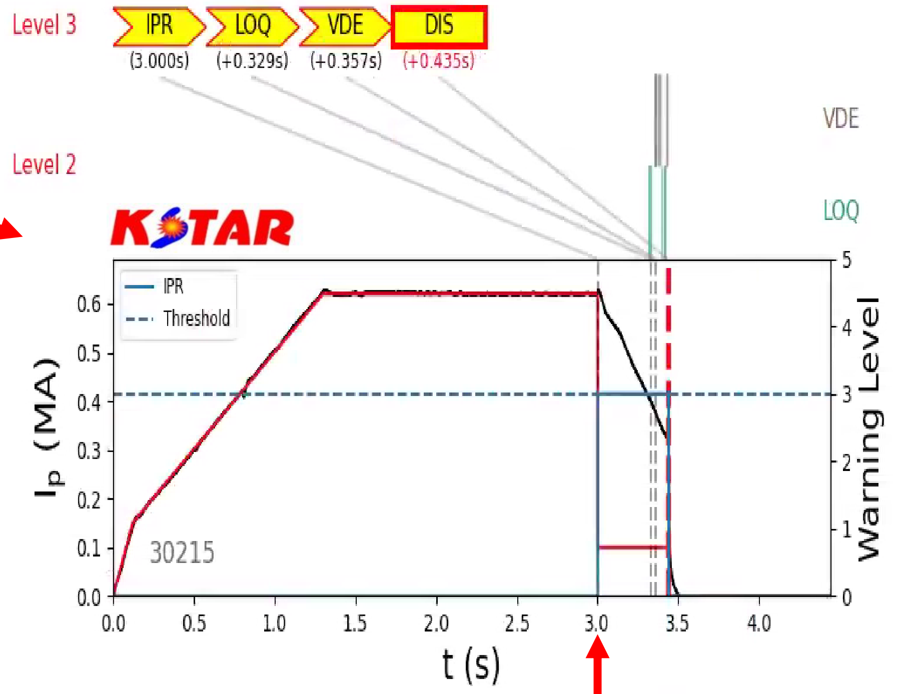
S.A. Sabbagh, et al., Phys. Plasmas **30** (2023) 032506; https://doi.org/10.1063/5.0133825

Real-time (r/t) DECAF deployment in KSTAR: initial real-time software modules installed, ran in 2022 + more being added

KSTAR PCS



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



Controlled shutdown triggered

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

- Possible model of drag for both a "slip" and a "no slip" condition:

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

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

- Present real-time model, assumes "no slip" condition

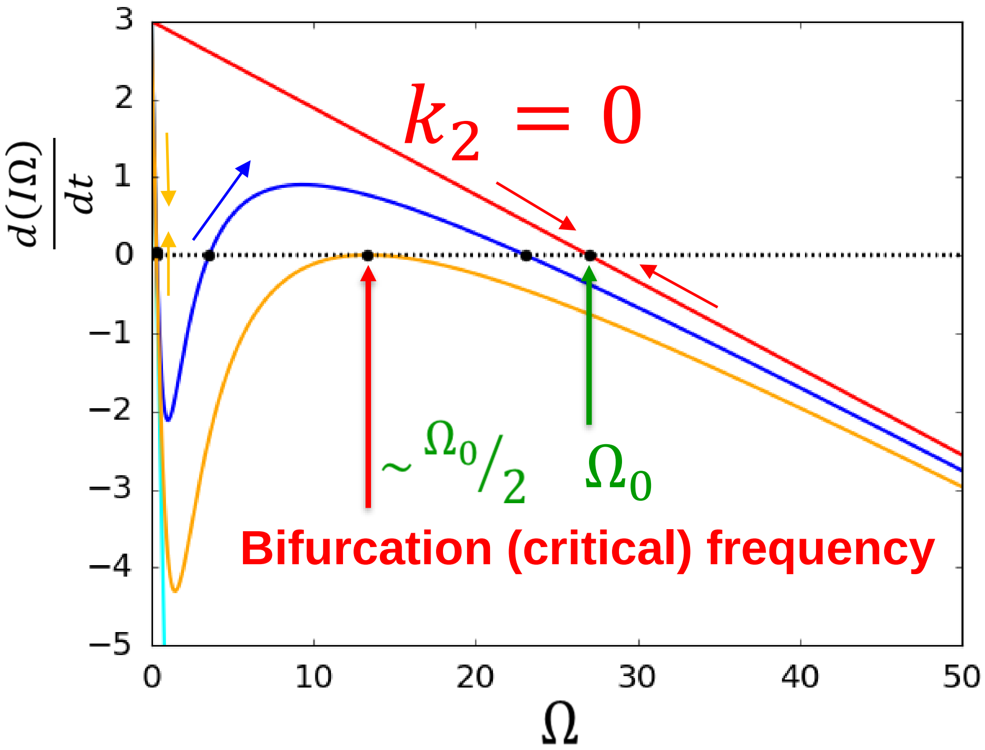
$$T_{mode} = \frac{k_1}{\Omega}$$

- Established model, but accurate forecasting solution requires innovative solution approach

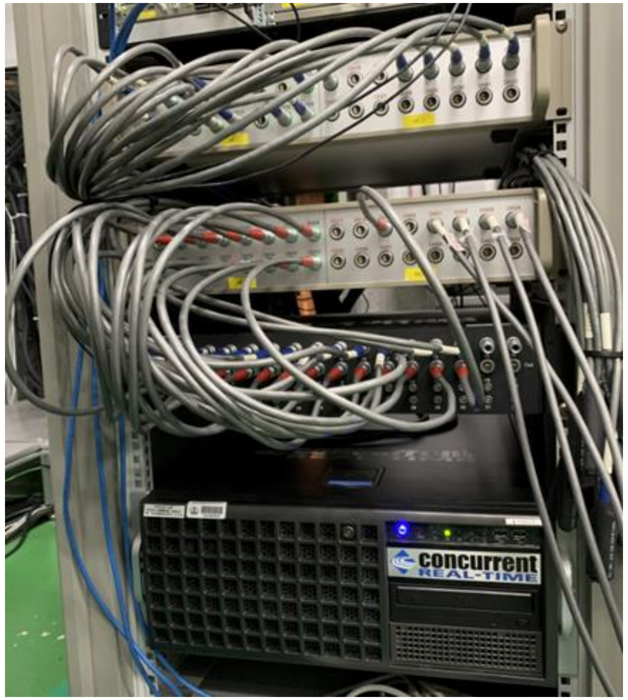
See J. Riquezes (poster) this workshop

LTM-f

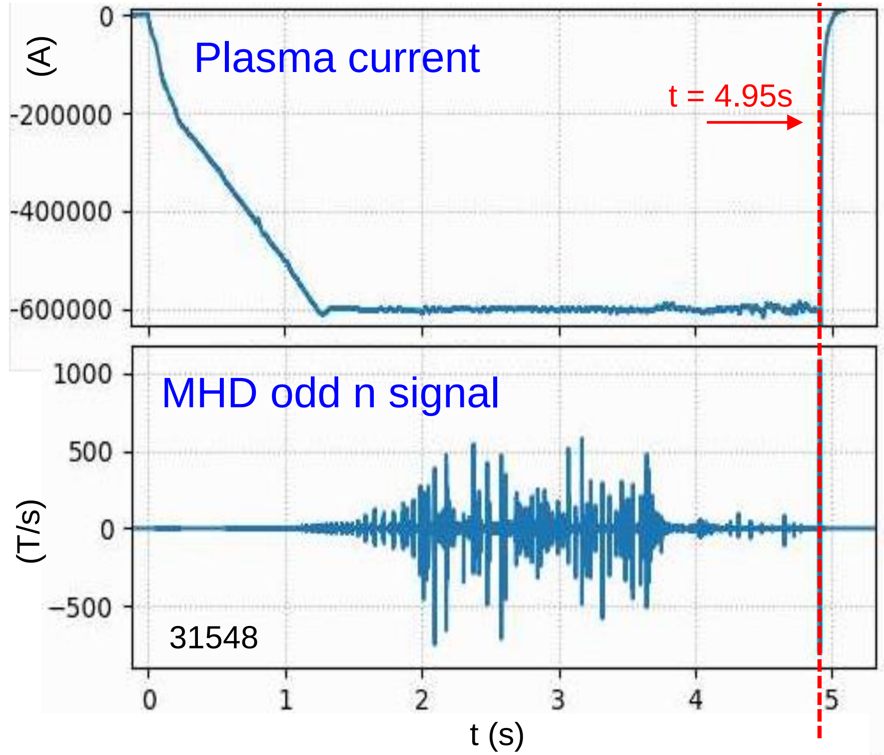
$$\frac{d(I\Omega)}{dt} = T_{aux} - T_{mode} - \frac{(I\Omega)}{\tau_{2D}}$$

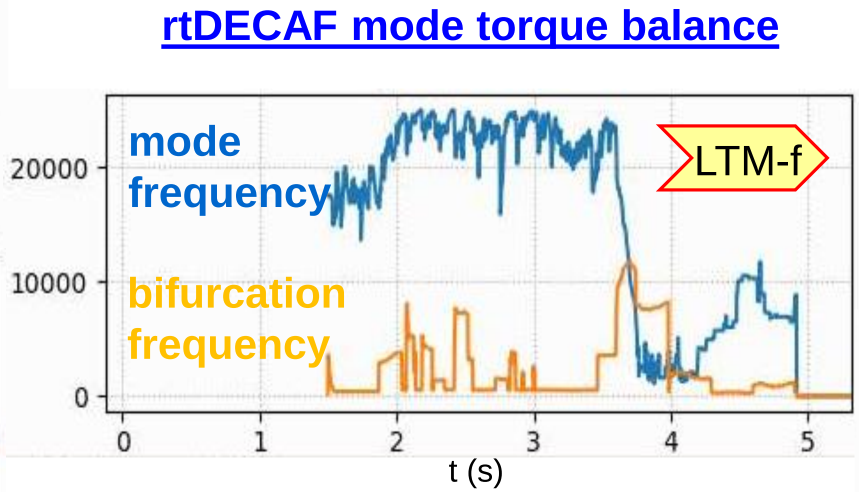


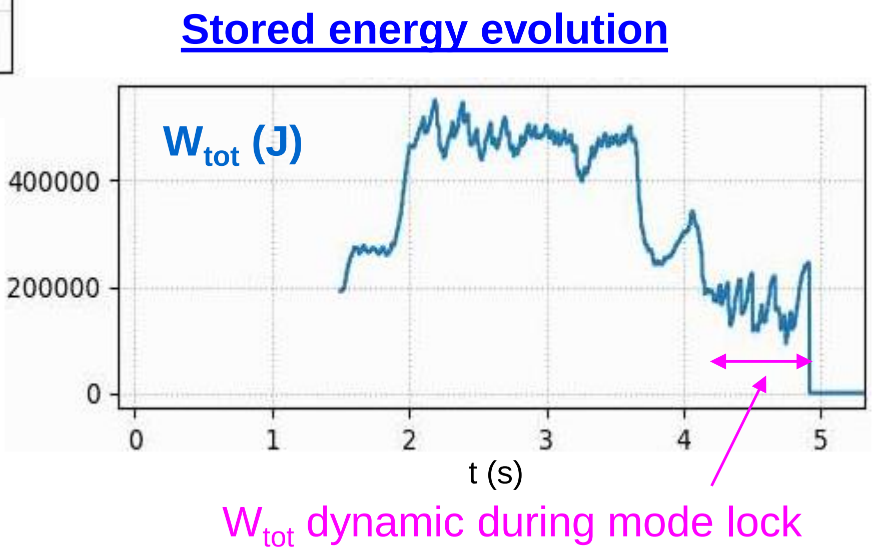
- Utilize DECAF real-time MHD system to determine mode, critical frequency

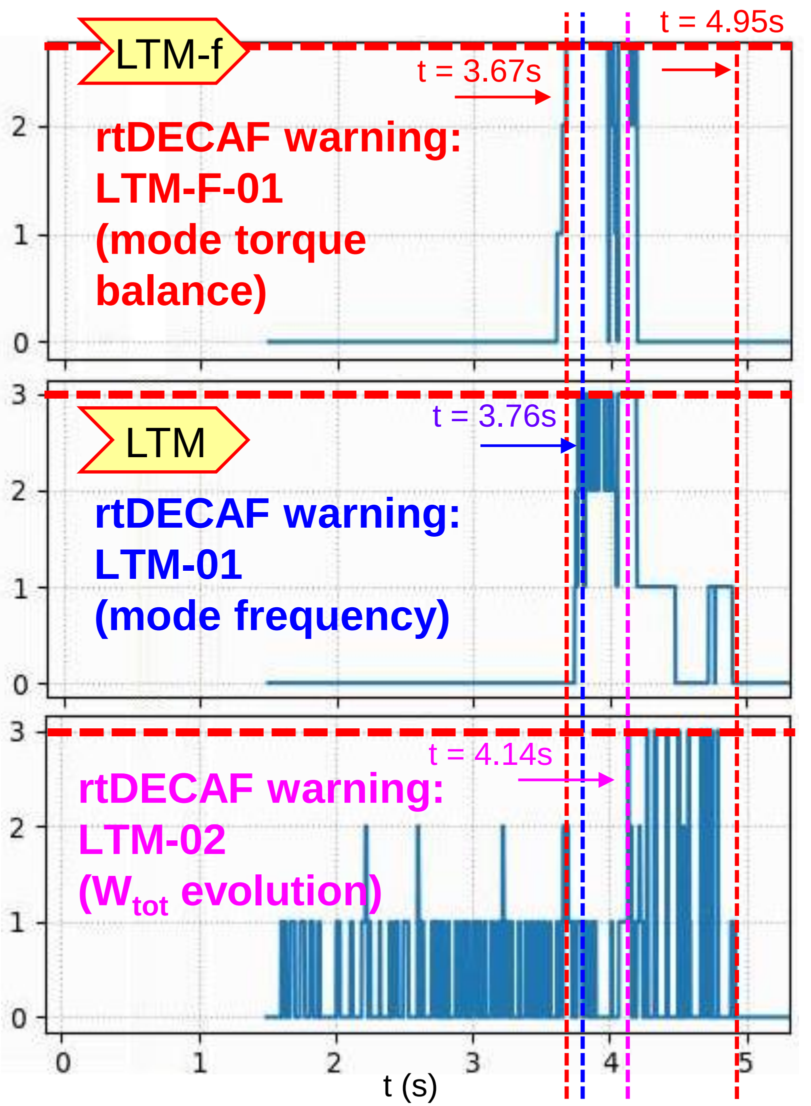


Real-time DECAF warnings show early LTM forecast of disruption, and additional LTM warnings for mode locking >> ITER needs





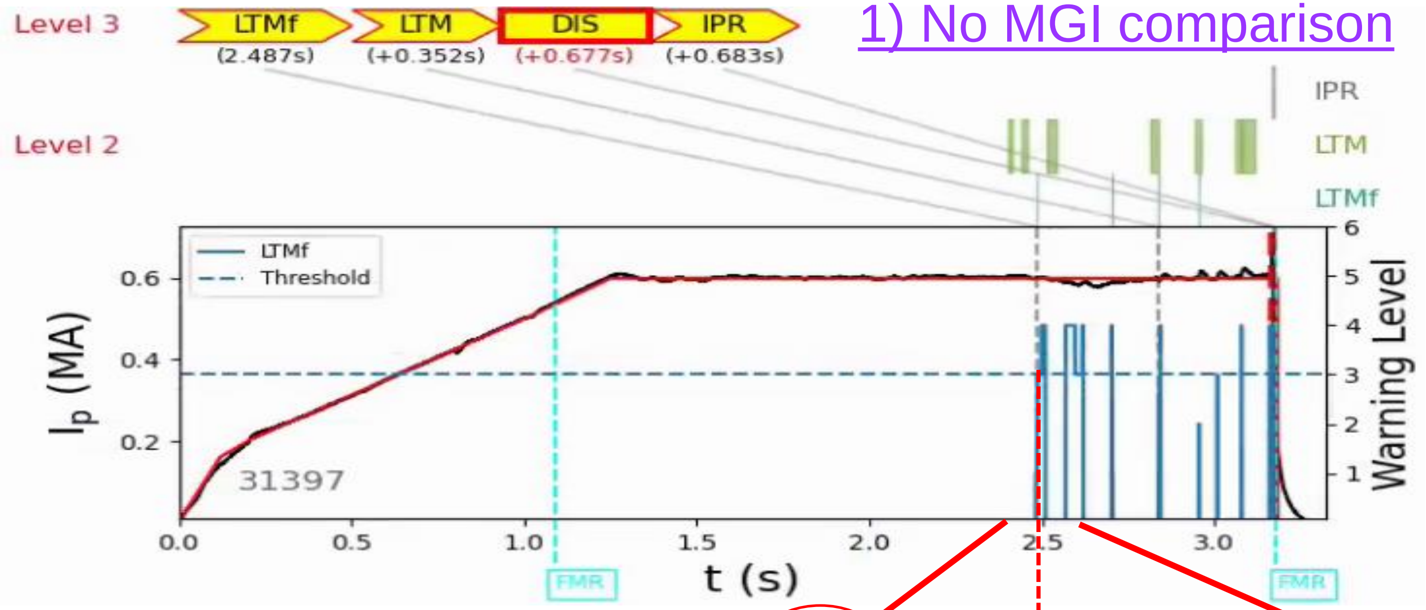




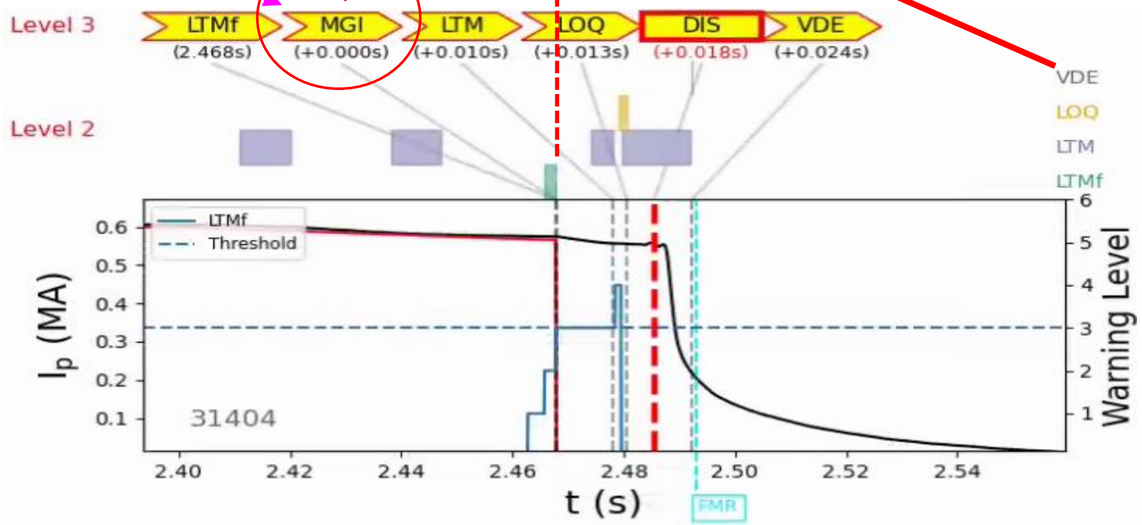
- Real-time LTM forecaster significantly precedes key events:
  - LTM warning preceded by 0.470 s
  - Plasma current quench preceded by 1.28 s >> ITER needs ~ 50 ms

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

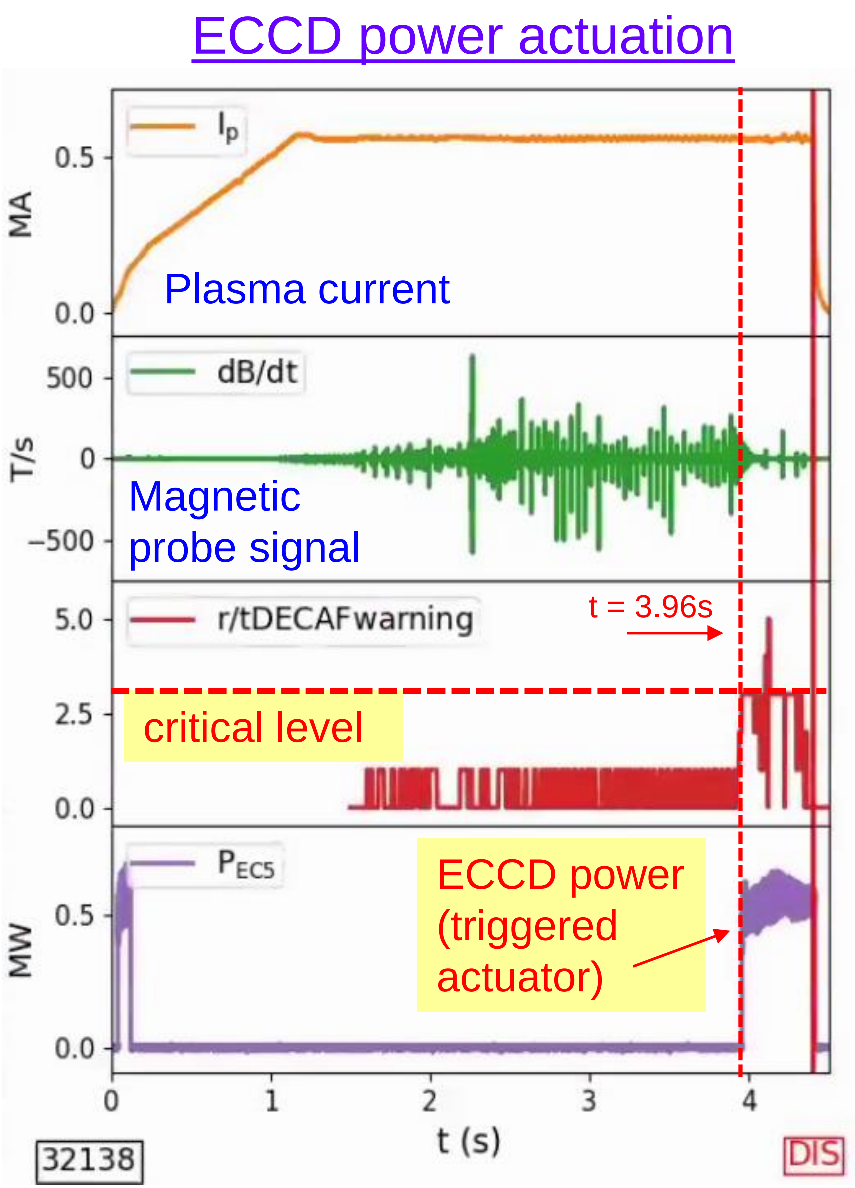


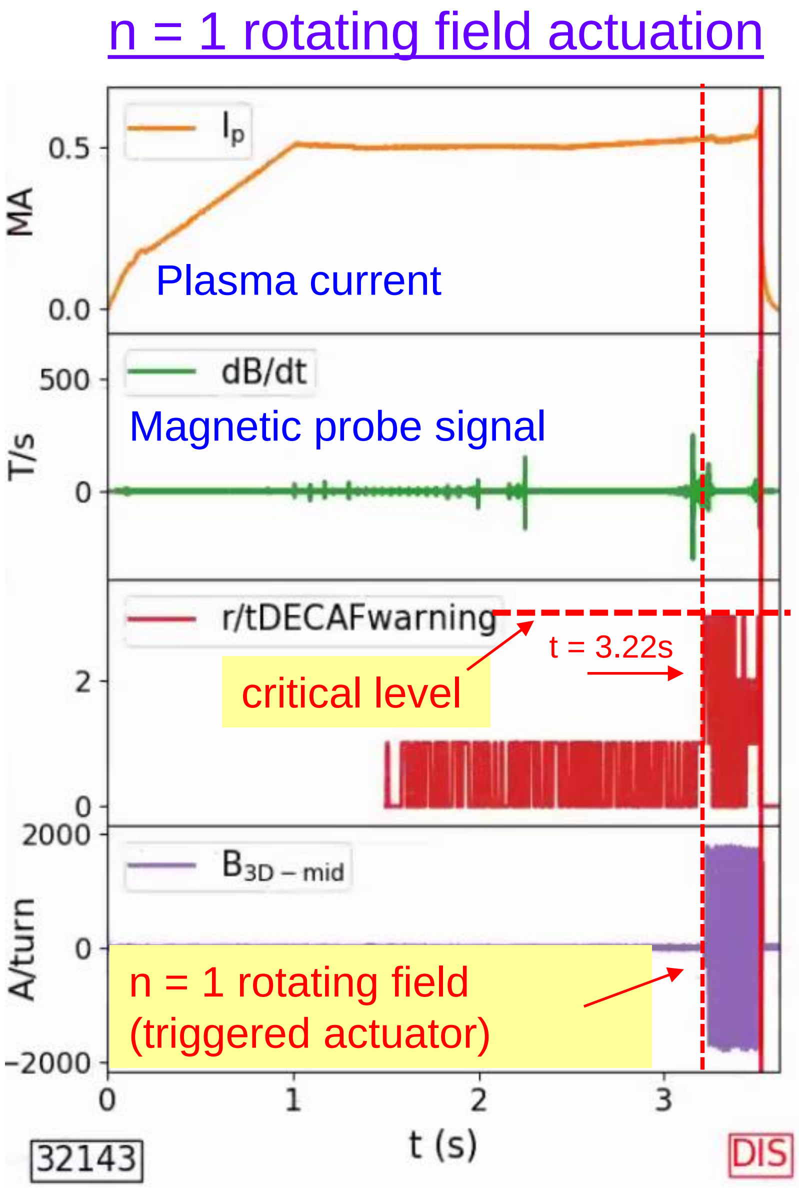
EARLY trigger: occurs ~ 0.677s before disruption in comparison shot (shown above)

- Much time to trigger mitigation
  - far more than ITER minimum
- 100% accuracy of real-time DECAF Level 3 events (first run period)
  - 18 shots; 3 MGI
  - 7 true positives
  - 11 true negatives
- 100% accuracy of real-time DECAF Level 3 events (3 subsequent run periods)
  - 35 shots
  - 20 true positives
  - 15 true negatives
- Excellent distinction between true positives and negatives

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

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

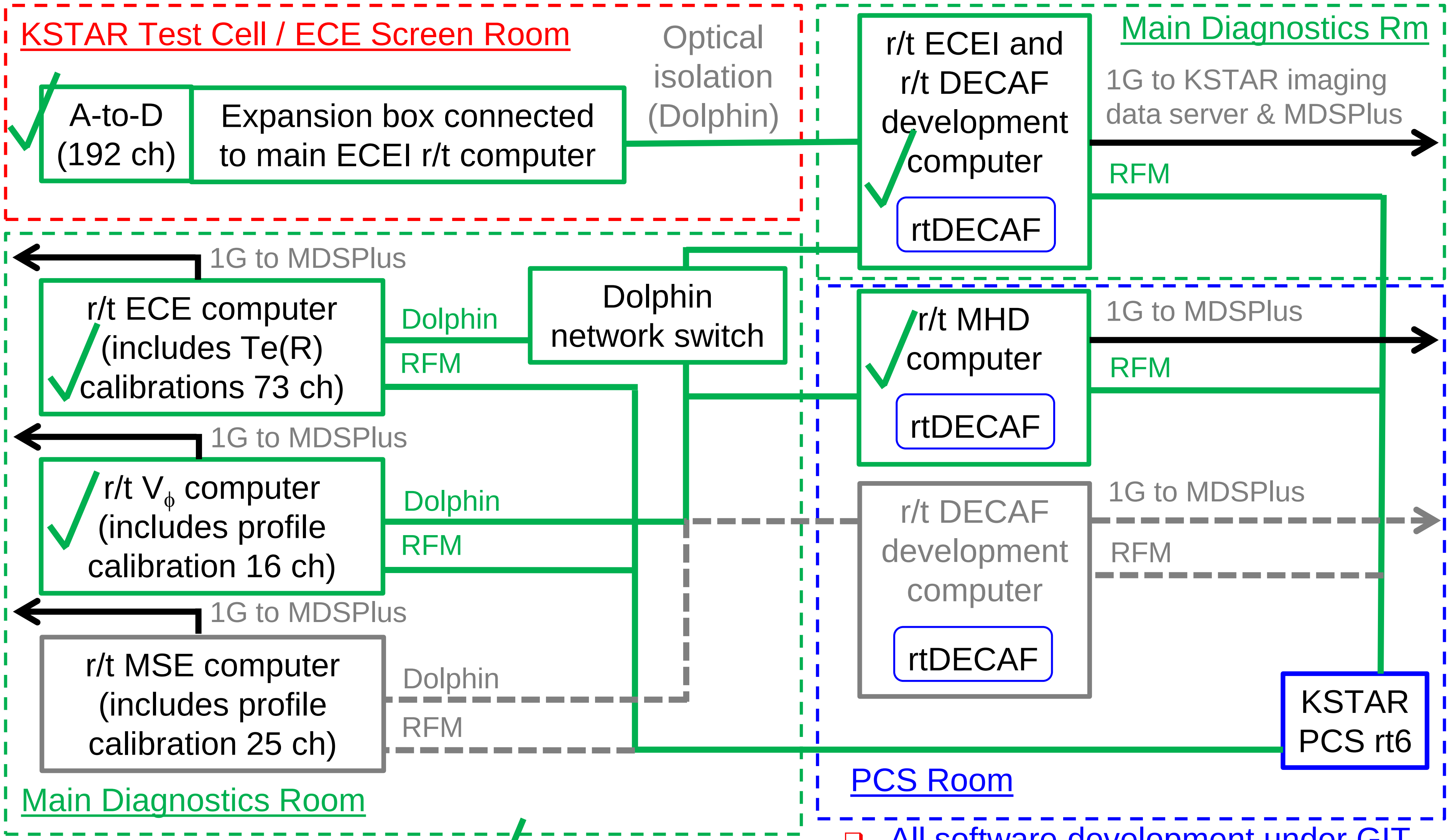




- Real-time LTM forecaster significantly precedes disruption
  - typically hundreds of ms to ~ 1s early warning
  - See backup slides for more detail
- NEXT STEP: demonstrate disruption avoidance!
  - Dedicated research program proposed for KSTAR

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

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



✓ = installed

- All software development under GIT version control

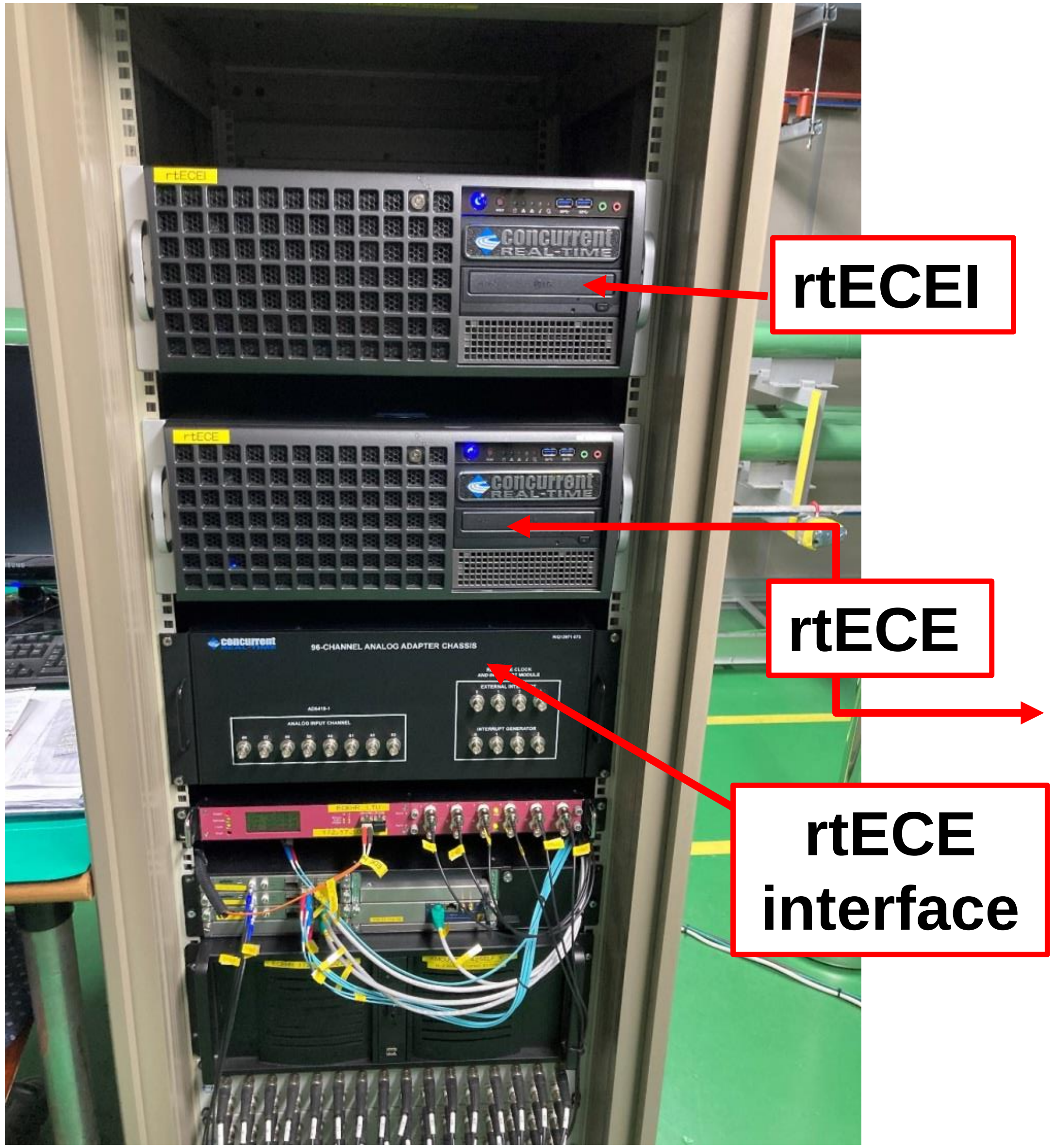
Installed

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

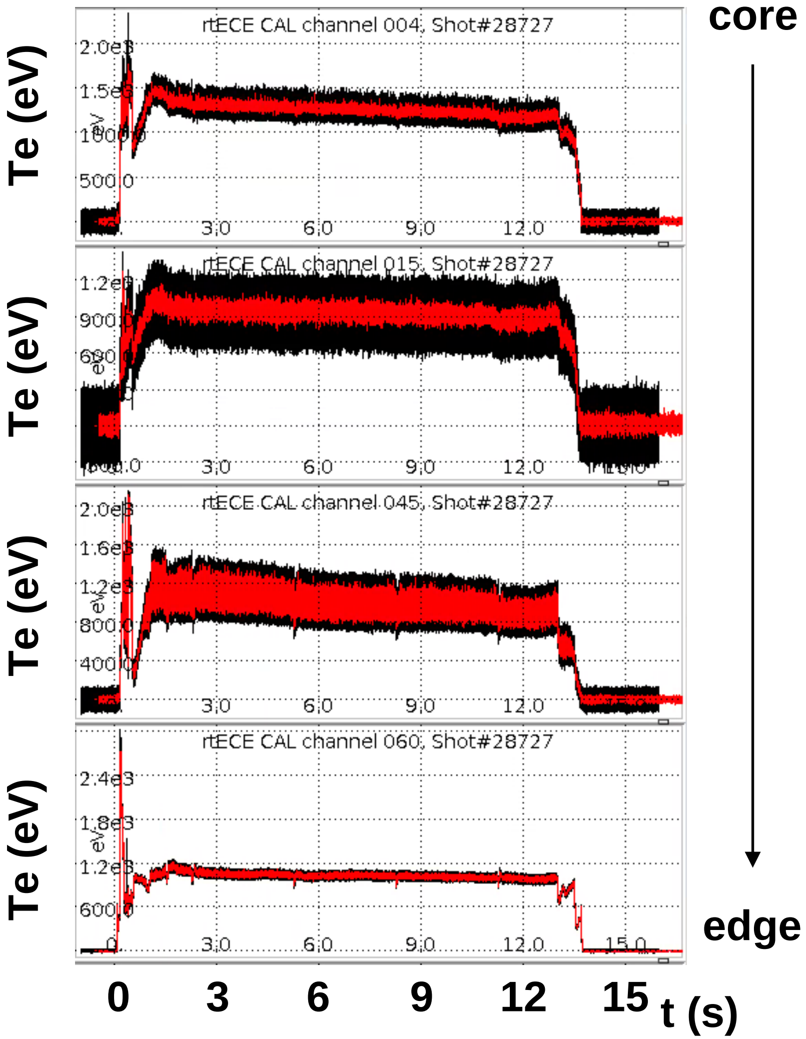
Built

- Real-time MSE
  - B pitch angle, δB

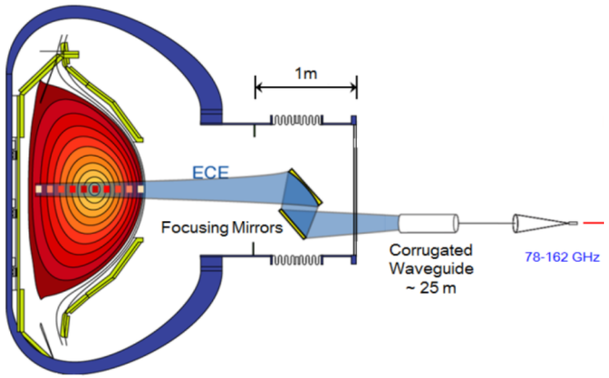
The first real-time DECAF module in KSTAR PCS measured T_e profile, ran routinely in 2022 run campaign



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

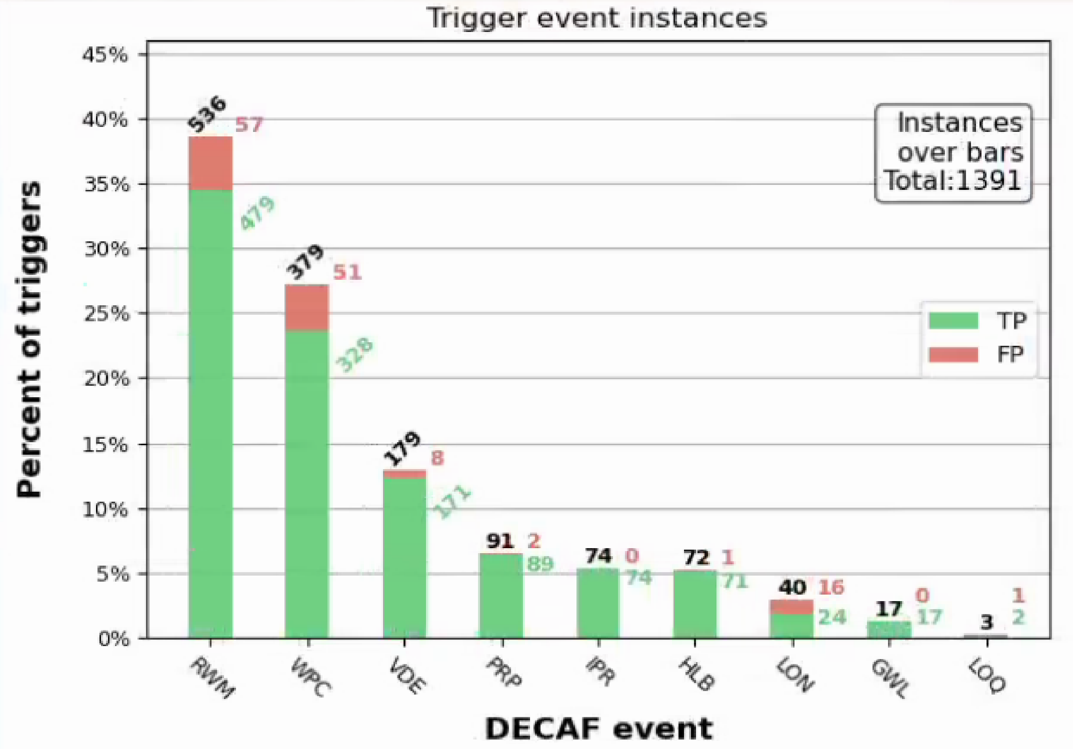
True positive rate for disruption forecasting recently found to be very high in large database analysis (example: NSTX 2009 run campaign)

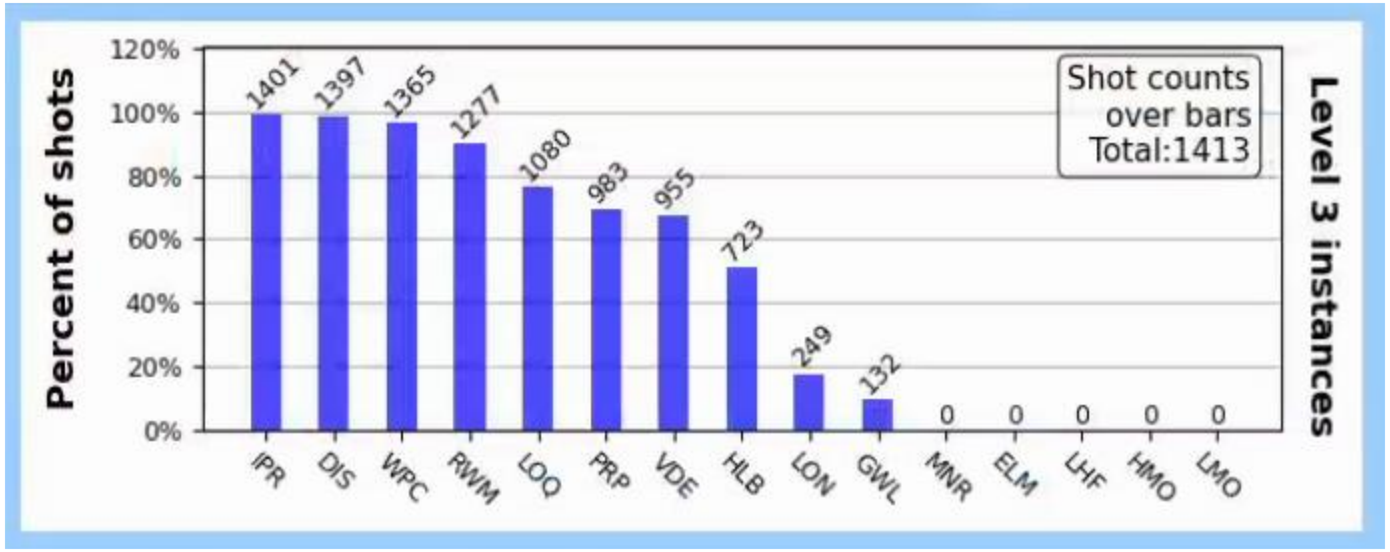
Confusion matrix

	----- 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

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





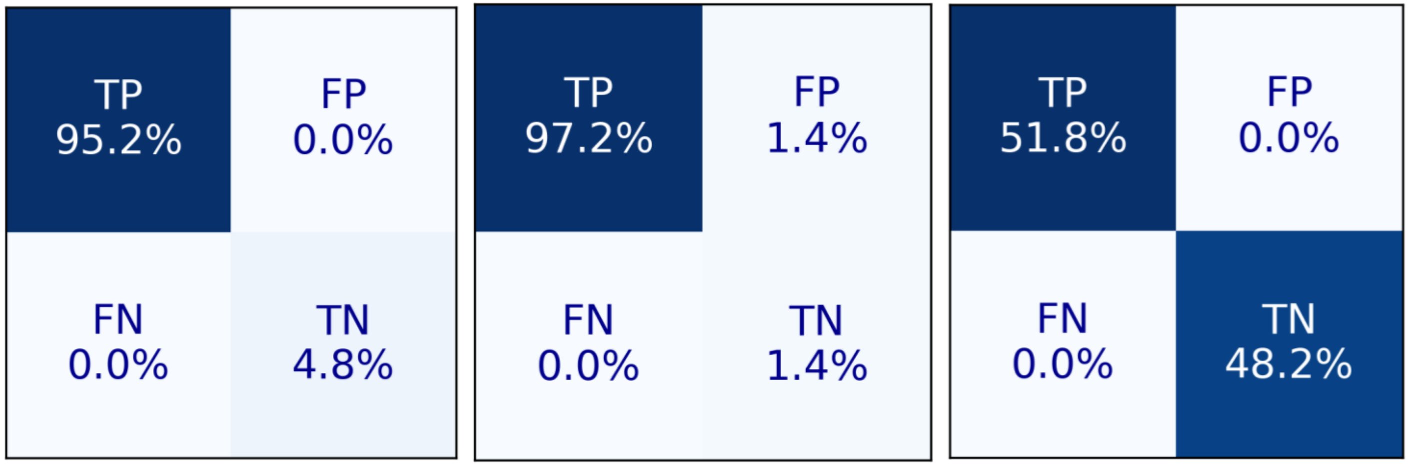
decaf file: NSTX-MDL022522sas2-Vv2

- Present key analysis step: Determining causality vs. correlation between warnings and the disruption
  - critical for all disruption prediction approaches!

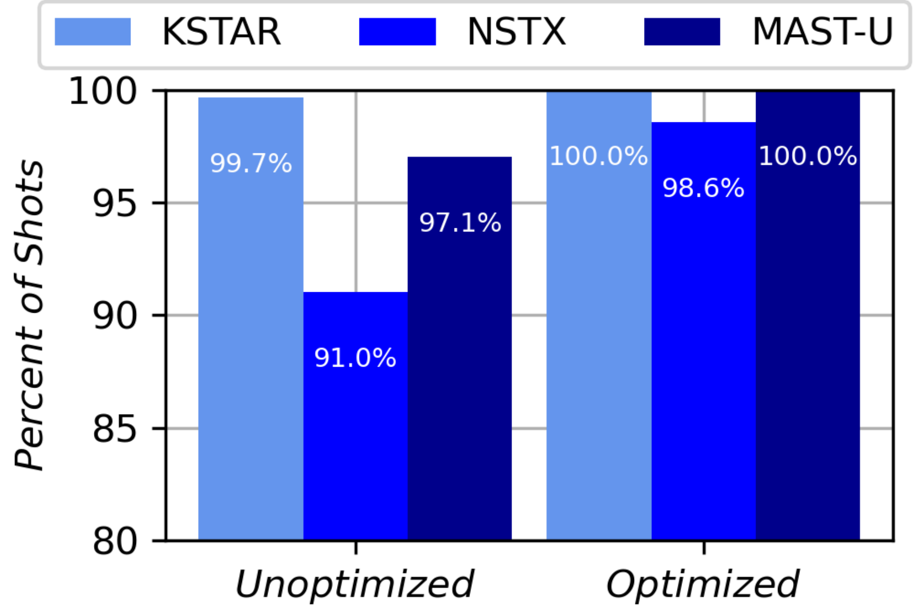
Model improvements are producing very high accuracy of DECAF predictions of VDE (KSTAR, MAST-U, NSTX at / near 100%)

Confusion Matrix Results (optimized)

KSTAR NSTX MAST-U



VDE True positive rates (T / (T + F))

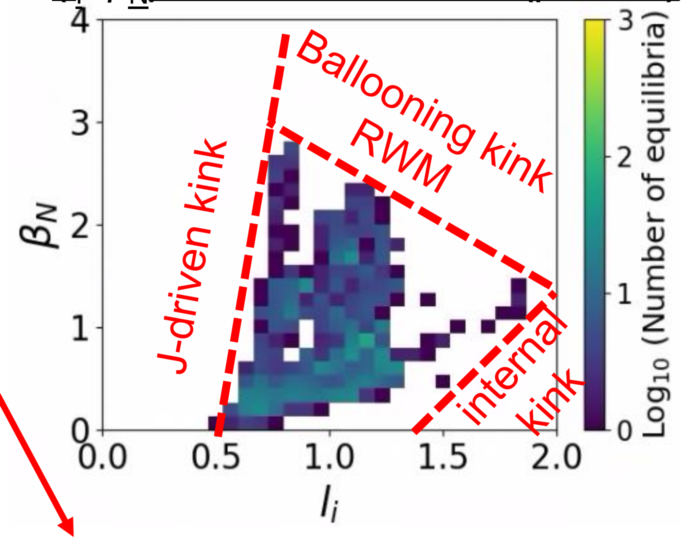


- Logical model improvement technique based on physics / diagnostics can produce 100% prediction accuracy
  - Plasmas: KSTAR: 953 (CY2022 run subset); NSTX: 3875 (CY2010 full run); MAST-U: 559 (MU02 full run)
- Next-step analysis: improve prediction and forecasting accuracy of all DECAF events to ITER desired levels (98%+)

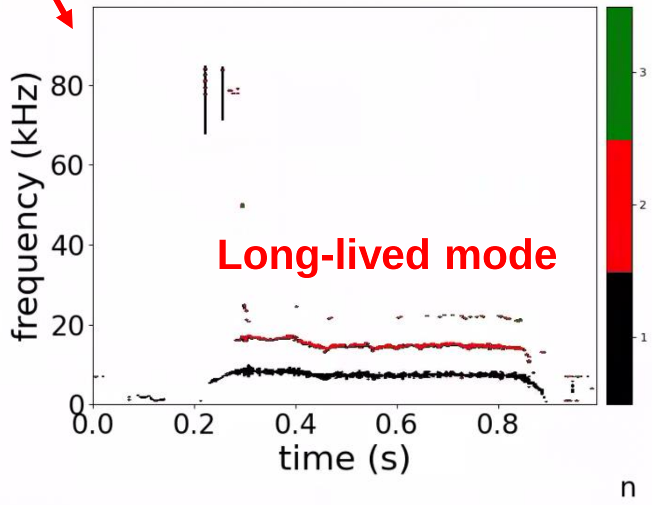
See M. Tobin (poster) this workshop

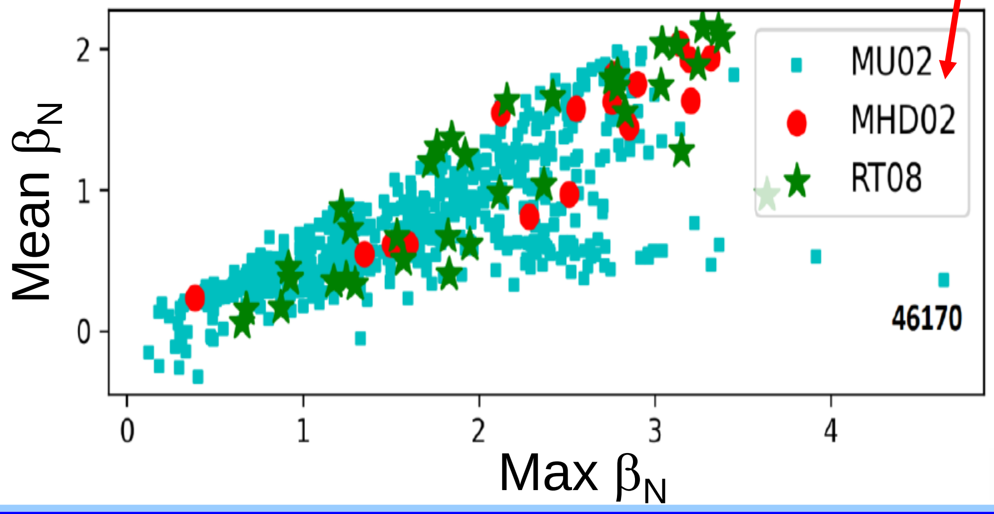
MAST High β_N MU02-MHD-02 broadly examining the conditions for stability of key modes that create beta-limiting operational limits

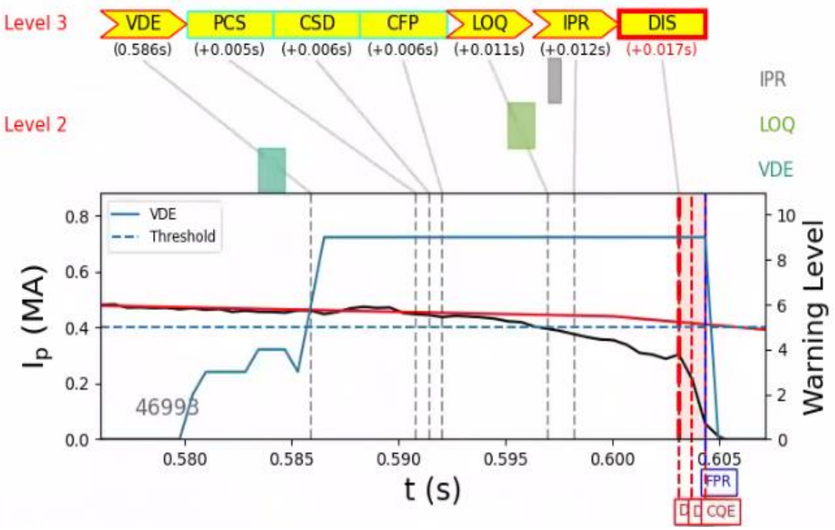
- **Overall goal**
  - Investigate key beta-limiting MHD to determine β_N and other limits, and curtail or eliminate such modes to reach maximum β_N, β_p, β
- **Approaches follow techniques used in NSTX**
  - Very good progress, yet only 2 of 6 steps completed; VDE limits found
  - IREs (leading to uncertain J profile) eliminated during I_p ramp, flat top
  - No tearing "dominant" mode locking; long-lived mode (LLM) dominant
  - Some information for low, constant I_p target (step 4) from XP RT08



DECAF analysis (physics & tech events)

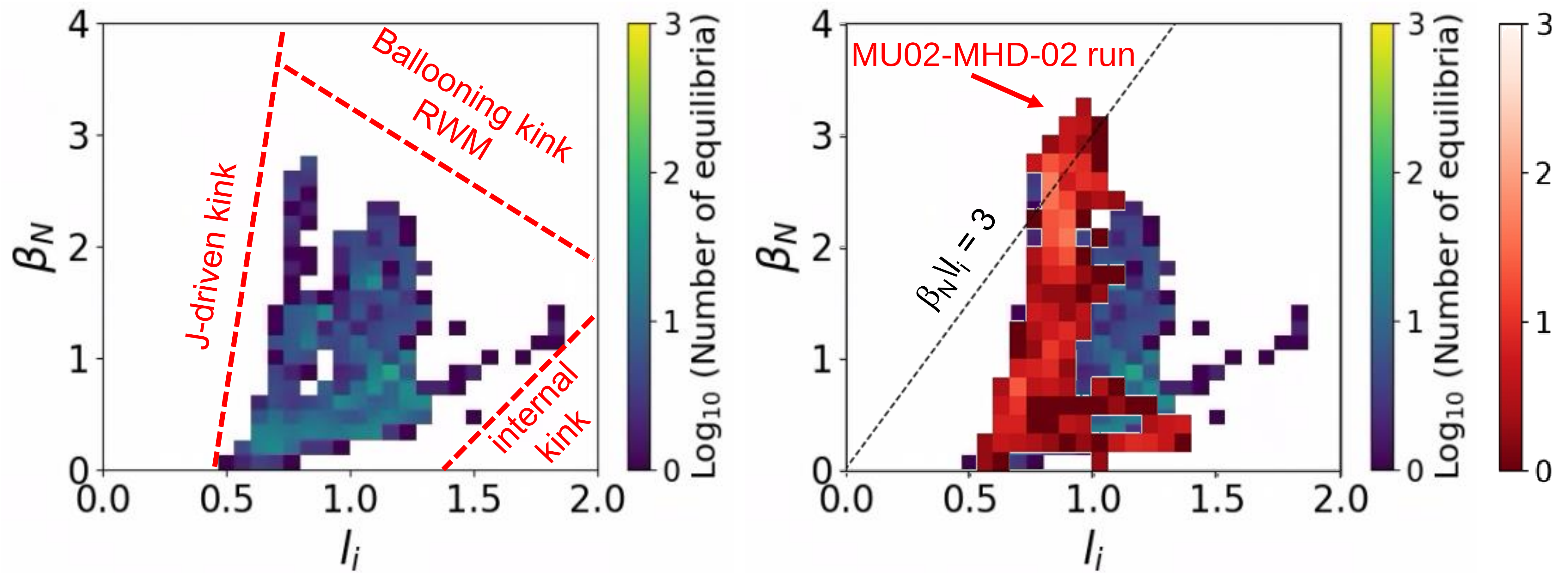






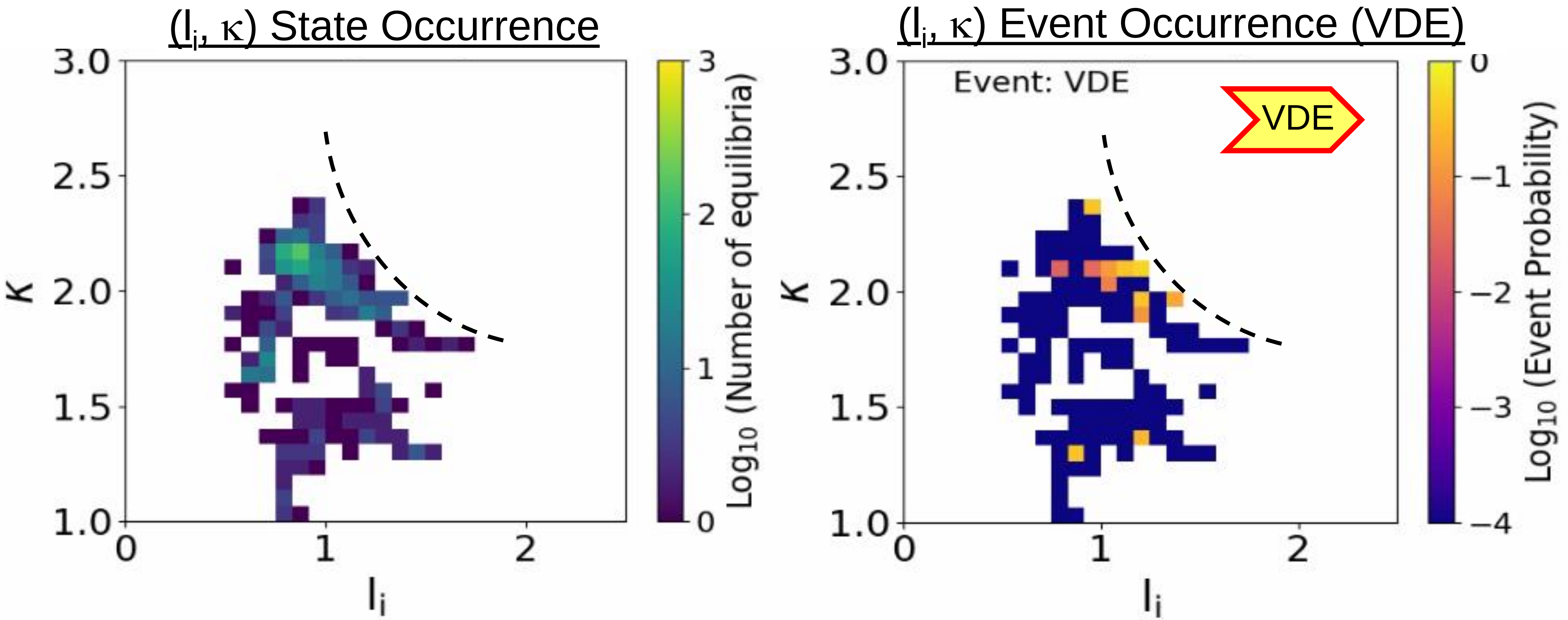
β_N limit: As planned, MU02-MHD-02 expanded MAST-U operation in (l_i, β_N) space

(l_i, β_N) State Occurrence (pre-XP) | (l_i, β_N) State Occurrence (MHD-02 in red)



- Lower l_i than general database somewhat surprising, a positive aspect
- Steps 1,2 of experiment successful in raising β_N, move to next planned steps

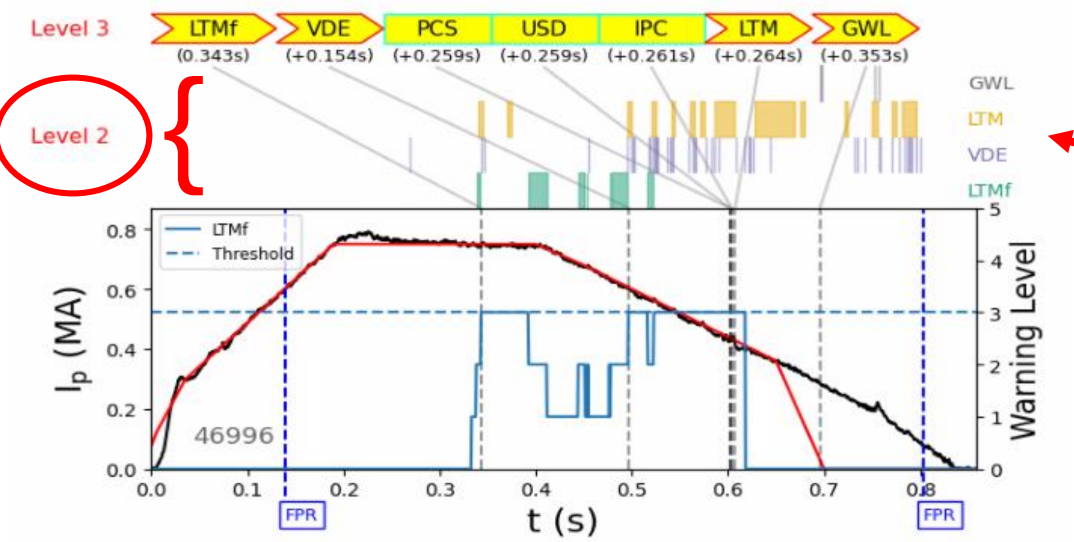
VDE limit investigation: MU02-MHD-02 showed expected behavior of VDE event occurrence in (l_i,κ) space



- Apparent limit to elongation inversely proportional to l_i
- VDE critical warning occurs at high elongation, shows inverse l_i relation

State space analysis formalism in DECAF being used as a generalization of critical (Level 3) warning analysis

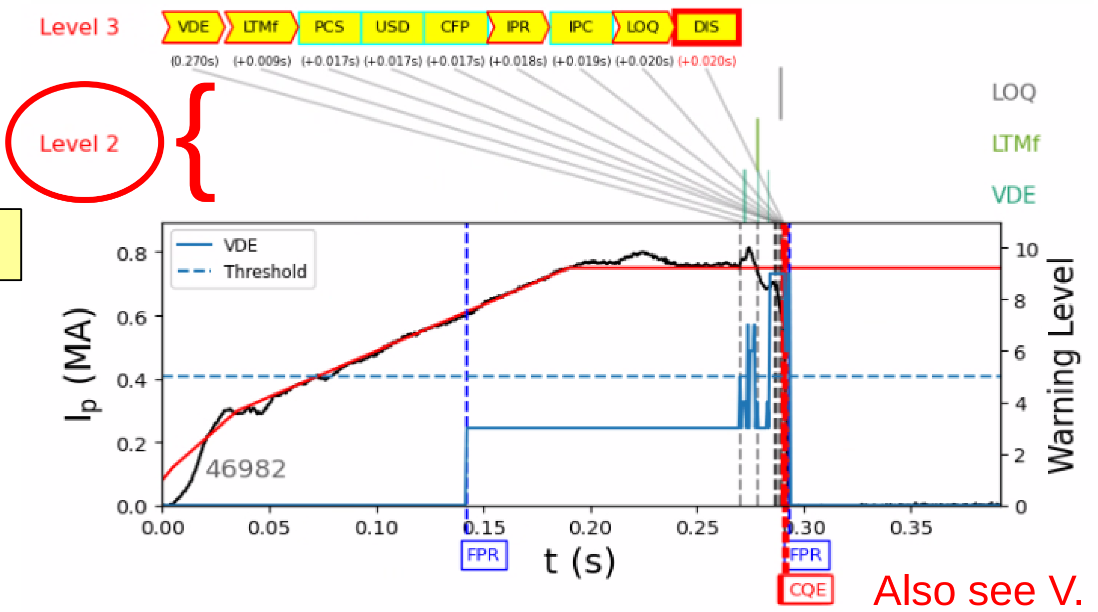
1.



MAST-U High β experiment (Jan 2023) states

1. Non-disruptive plasma conclusion
   - more Level 2 states; richer assembly of events ("QR code")
2. Disruptive conclusion – insufficient trigger states
   - Level 3 a clear attractor state; less Events in Level 2 states
3. Disruptive conclusion – sufficient trigger states
   - more specific states (less spectrum)

2.



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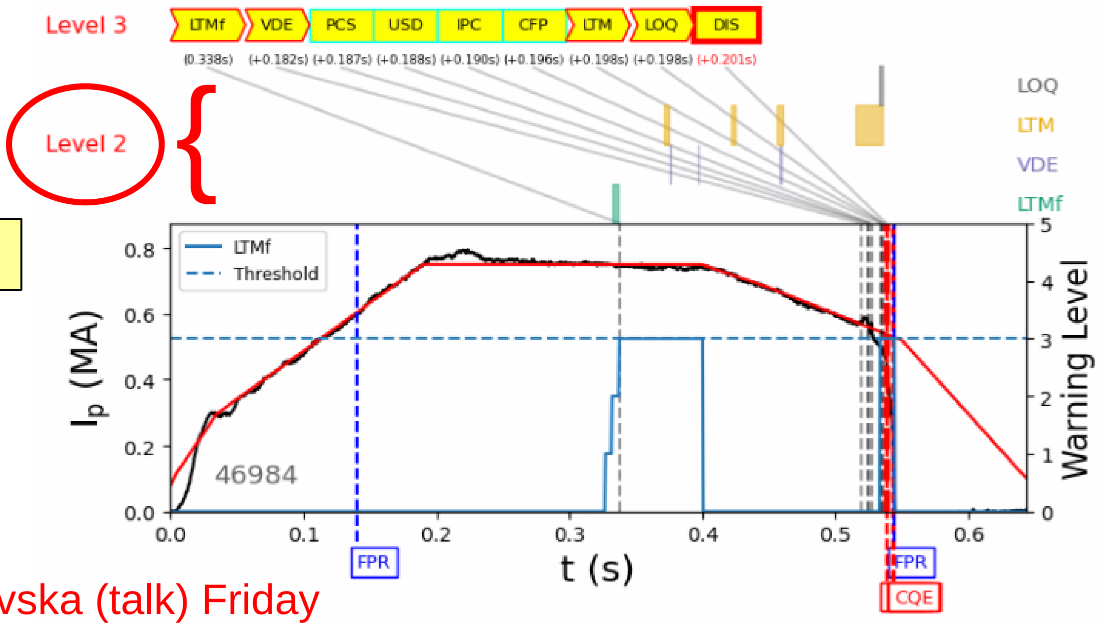
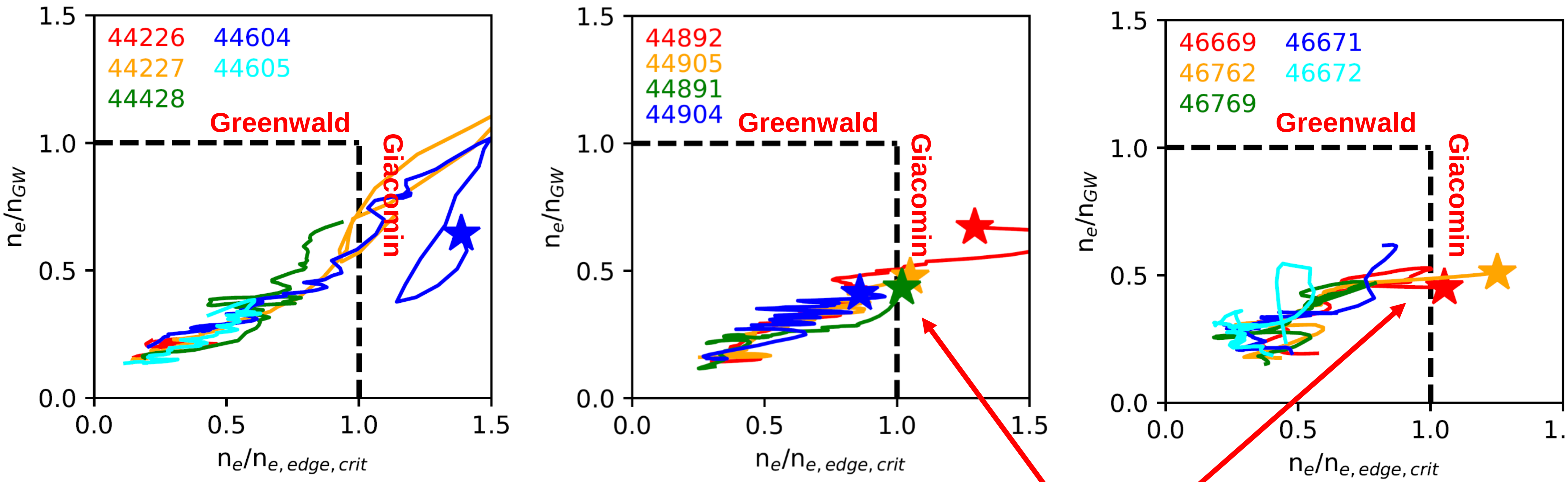


Also see V. Zamkovska (talk) Friday

Density limit: recent analysis shows plasmas disrupt after crossing Giacomin edge limit before reaching global Greenwald limit (MAST-U)



Crosses edge limit, but not Greenwald limit

- Need equilibrium quantities, P_{heat}, P_{rad}
  - Currently using TRANSP for P_{heat}
  - Next steps: Validation; Use proxies for wider database analysis, real-time

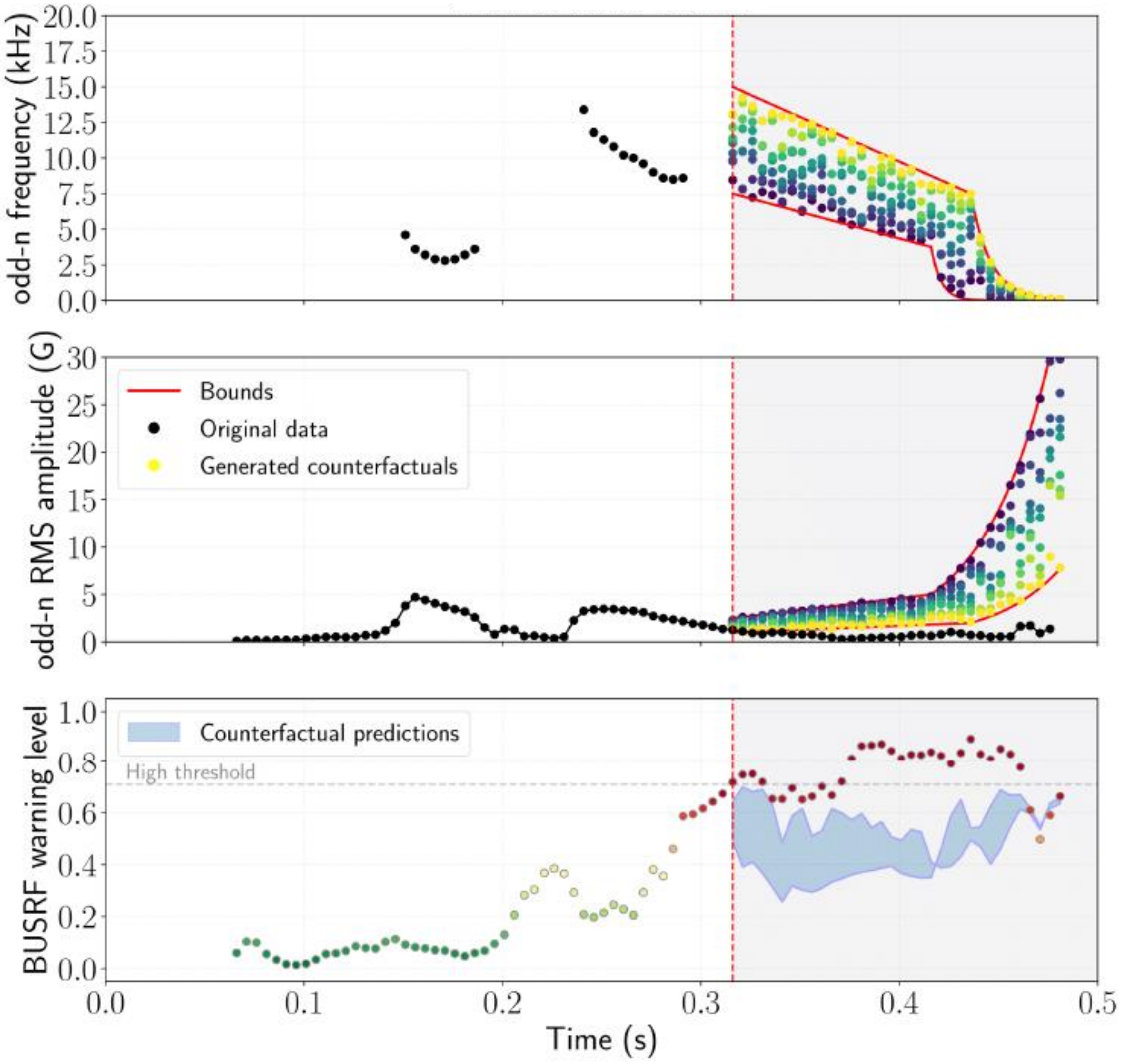
J. Berkery, et al., just accepted PPCF (July 2023)

M. Giacomin, et al., PRL 128 (2022) 185003

$$n_{\lim} = \alpha A^{1/6} a^{3/14} P_{\rm SOL}^{10/21} R_0^{-43/42} q^{-22/21} (1+\kappa^2)^{-1/3} B_T^{2/3}$$

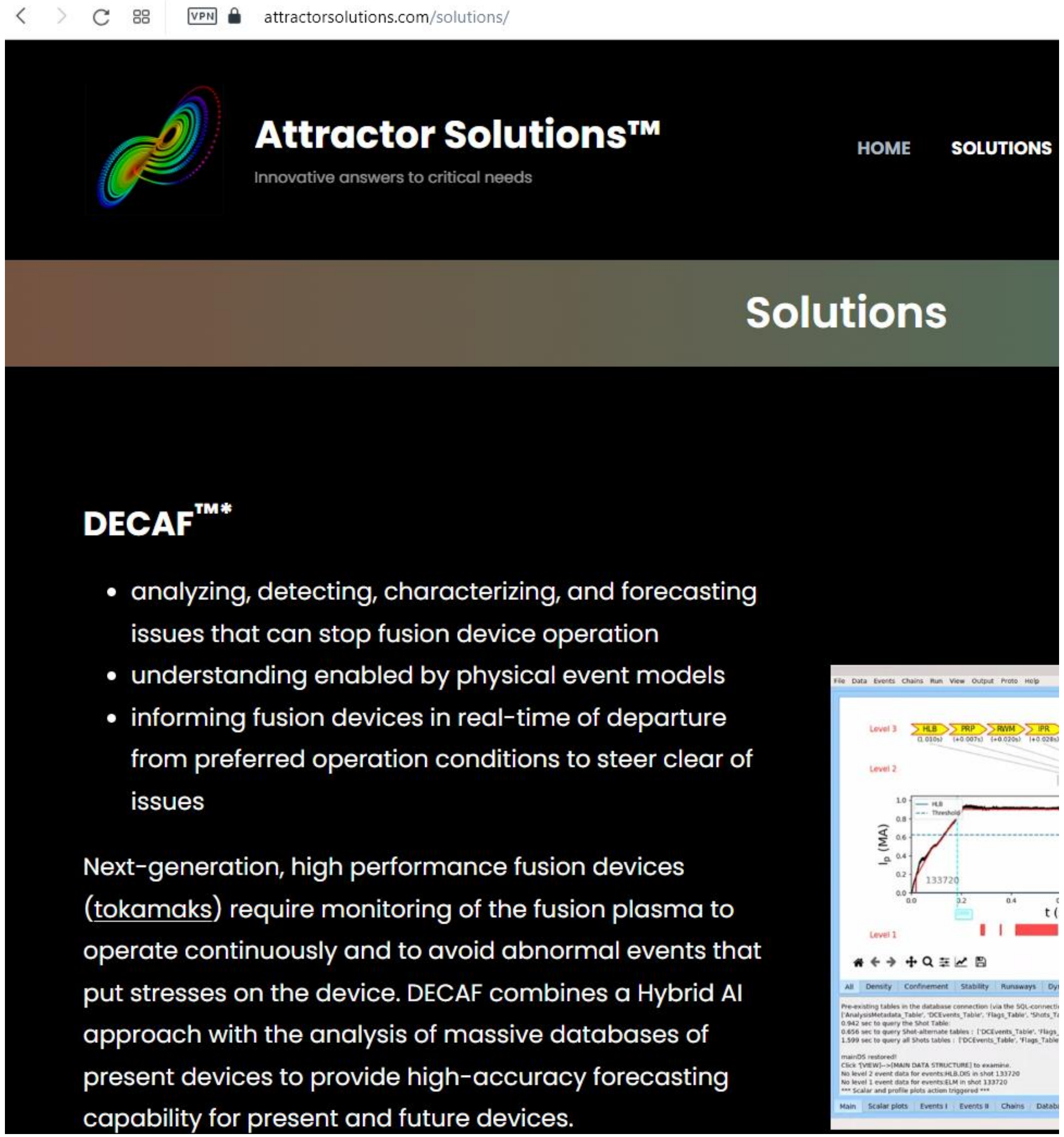
Innovative counterfactual machine learning introduced for the first time to generate hypothetical activity contradicting observations

- Global MHD (kink / RWM) typically do not grow if strong rotating MHD is present (e.g. NSTX)
- 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



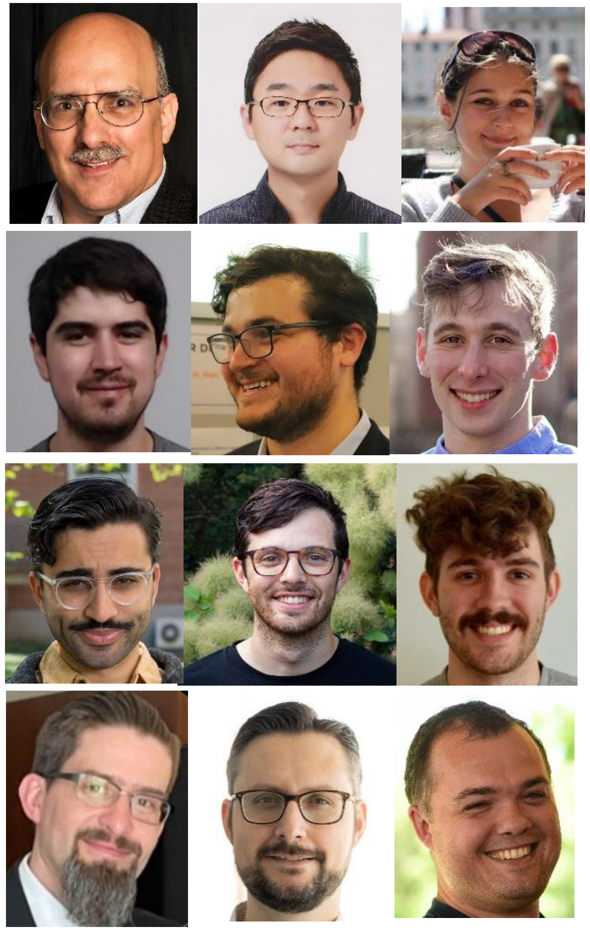
A. Piccione, J.W. Berkery, S.A. Sabbagh, Y. Andreopoulos, Nucl. Fusion **62** (2022) 036002

DECAF Goal: Enable disruption avoidance in tokamaks for the new, growing fusion industry



Research Team

16 researchers across
4 U.S. institutions



- $6.2 billion private investment funding for the fusion industry
  - 56 companies!
- Attractor Solutions, LLC was started to prepare to meet requests from major tokamak facilities
  - http://attractorsolutions.com
- DECAF Team significantly expanded
  - come join us!
  - **Please contact: sabbagh@pppl.gov**

…

DECAF disruption prediction and avoidance research continues and has expanded to real-time operation for the first time

- 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 (9) databases. Recent performance (NSTX example): > 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 LTM
  - 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 (all levels, especially control) ➔ Please contact: sabbagh@pppl.gov ⬅

Supporting slides follow

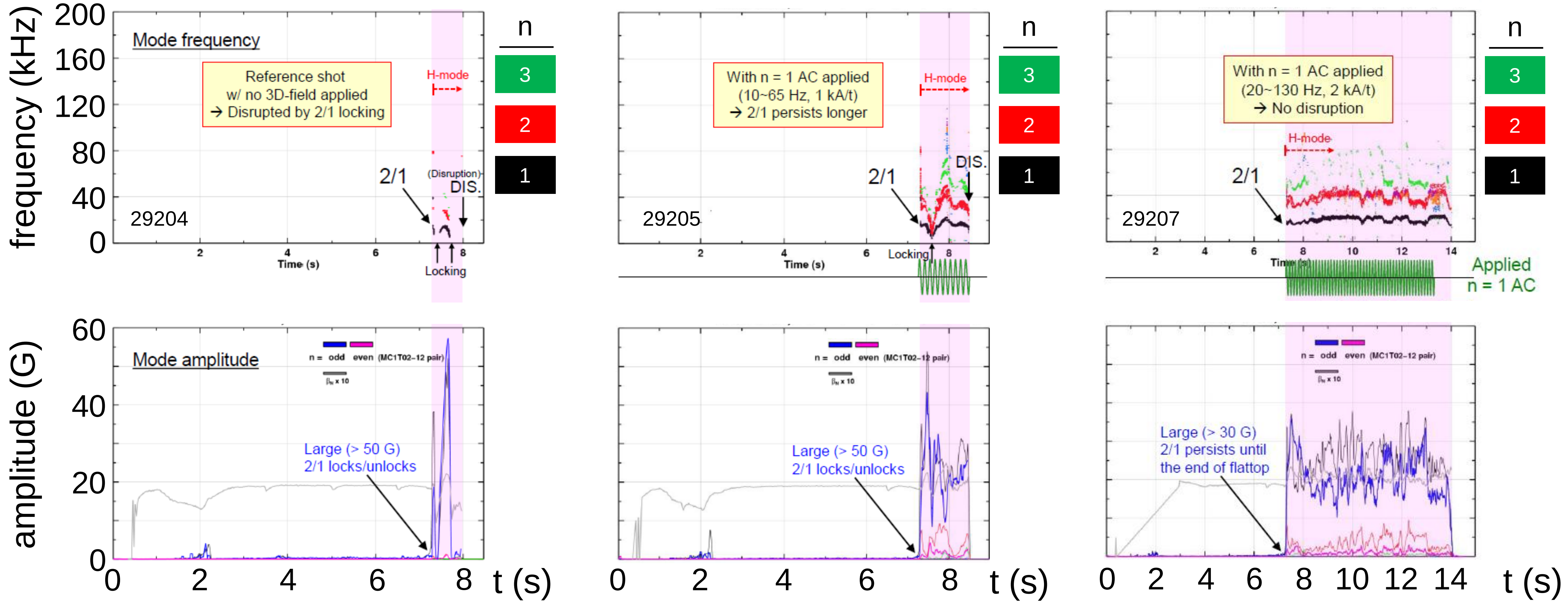
New disruption avoidance actuator: applied rotating 3D field successful in preventing naturally-occurring 2/1 NTM locking in KSTAR

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 (mode rotation sustained due to field alteration at boundary)

Model improvements are producing very high accuracy of DECAF predictions of VDE (MAST-U, KSTAR near 100%)

KSTAR Confusion Matrix Results

VDE

EFIT Model

TP 36.2%	FP 18.3%
FN 0.8%	TN 44.8%

Flux loop Model

TP 57.3%	FP 11.0%
FN 0.5%	TN 31.3%

Mag. probe Model

TP 61.7%	FP 0.2%
FN 0.2%	TN 38.0%

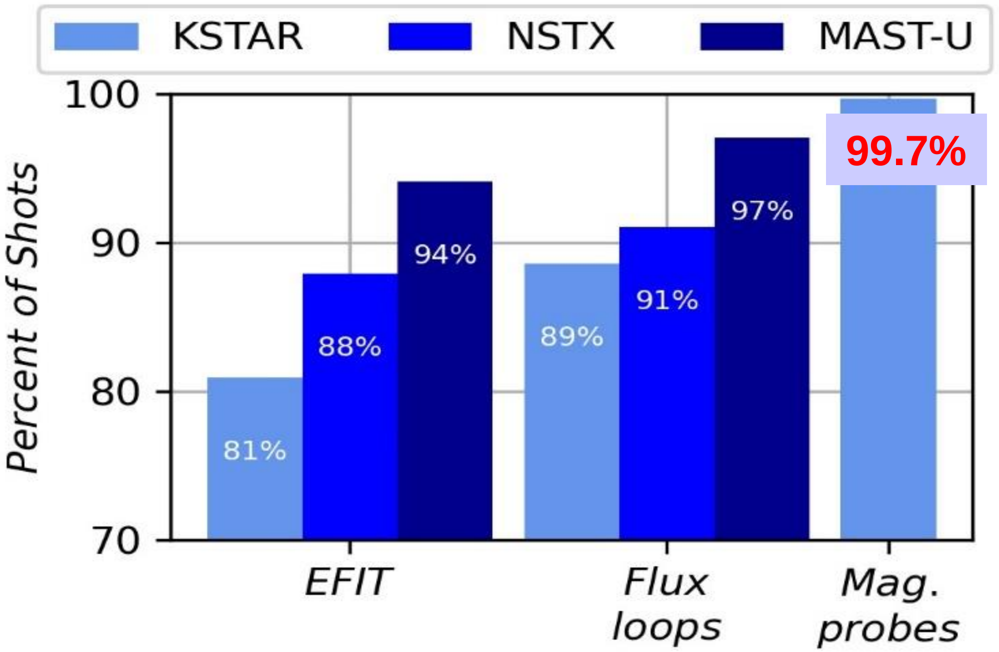
NSTX EFIT Model

TP 59.9%	FP 11.2%
FN 0.9%	TN 28.0%

NSTX Flux loop Model

TP 85.0%	FP 8.5%
FN 0.4%	TN 6.1%

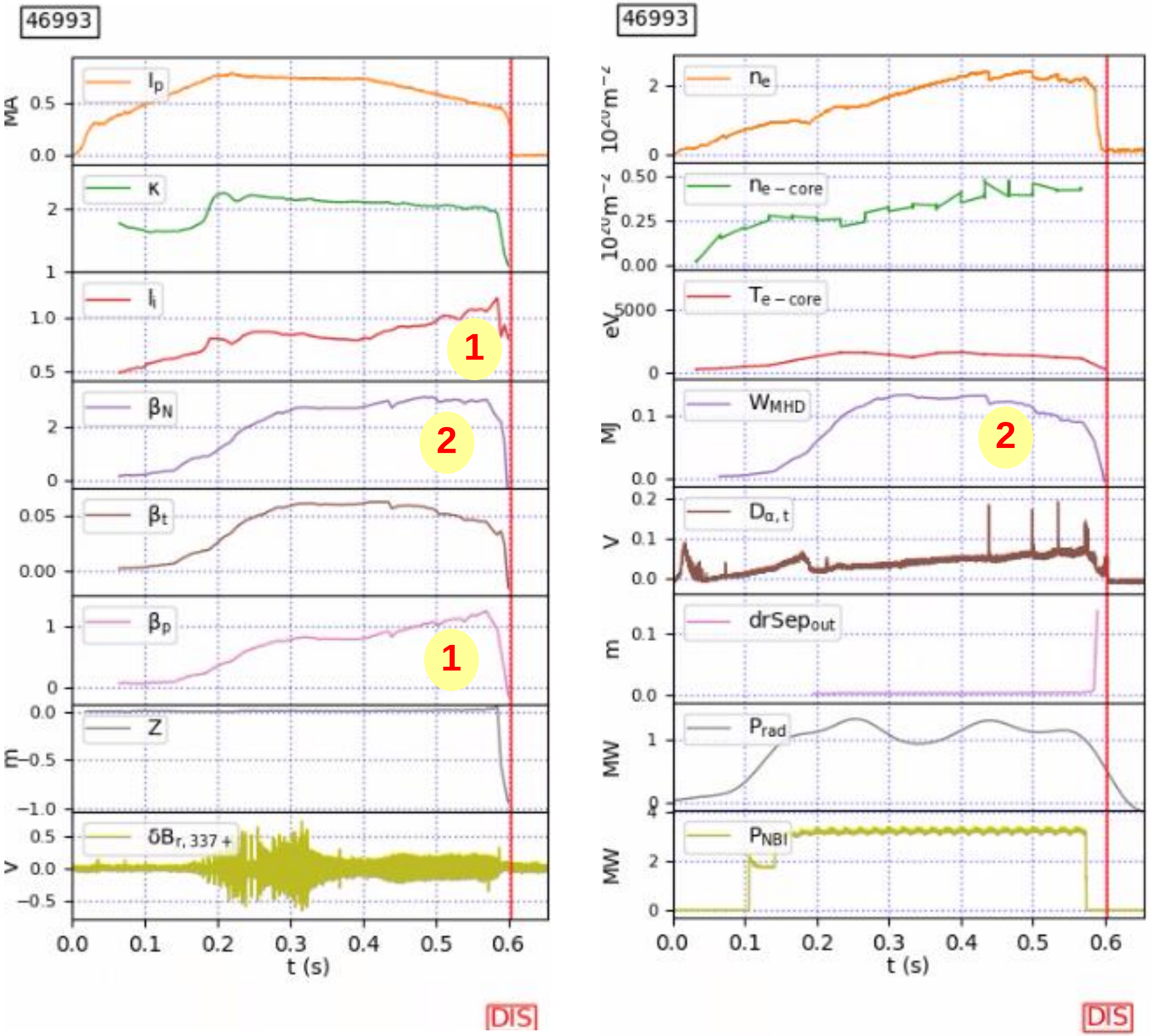
True positive rates (T / (T + F))



- Database of ~ 650 KSTAR plasmas, full MAST-U and NSTX run campaigns
- Next-step of analysis: continue to improve prediction and forecasting accuracy of all DECAF events to ITER levels

See M. Tobin (poster) this workshop

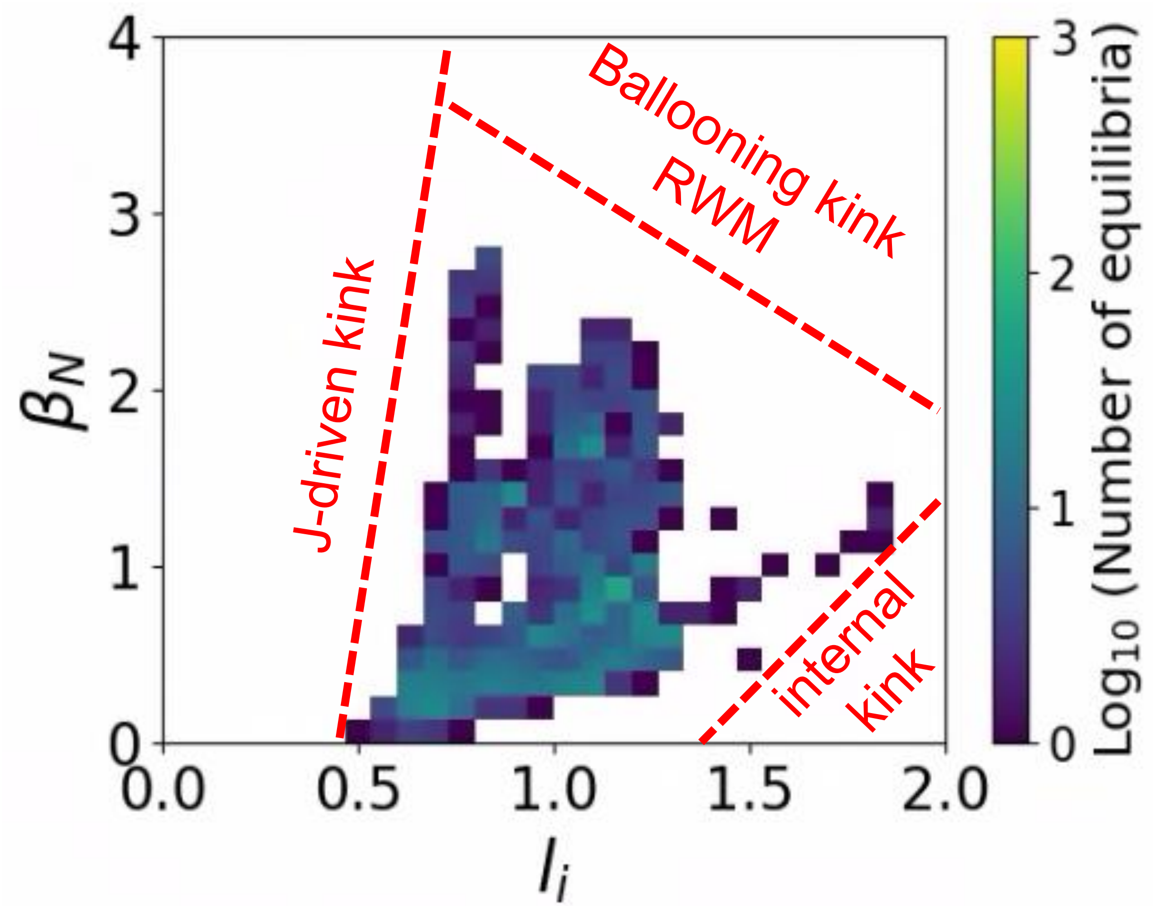
MU02-MHD-02 proceeding as planned – quite successful, with good understanding of the results attained so far with great diagnostics



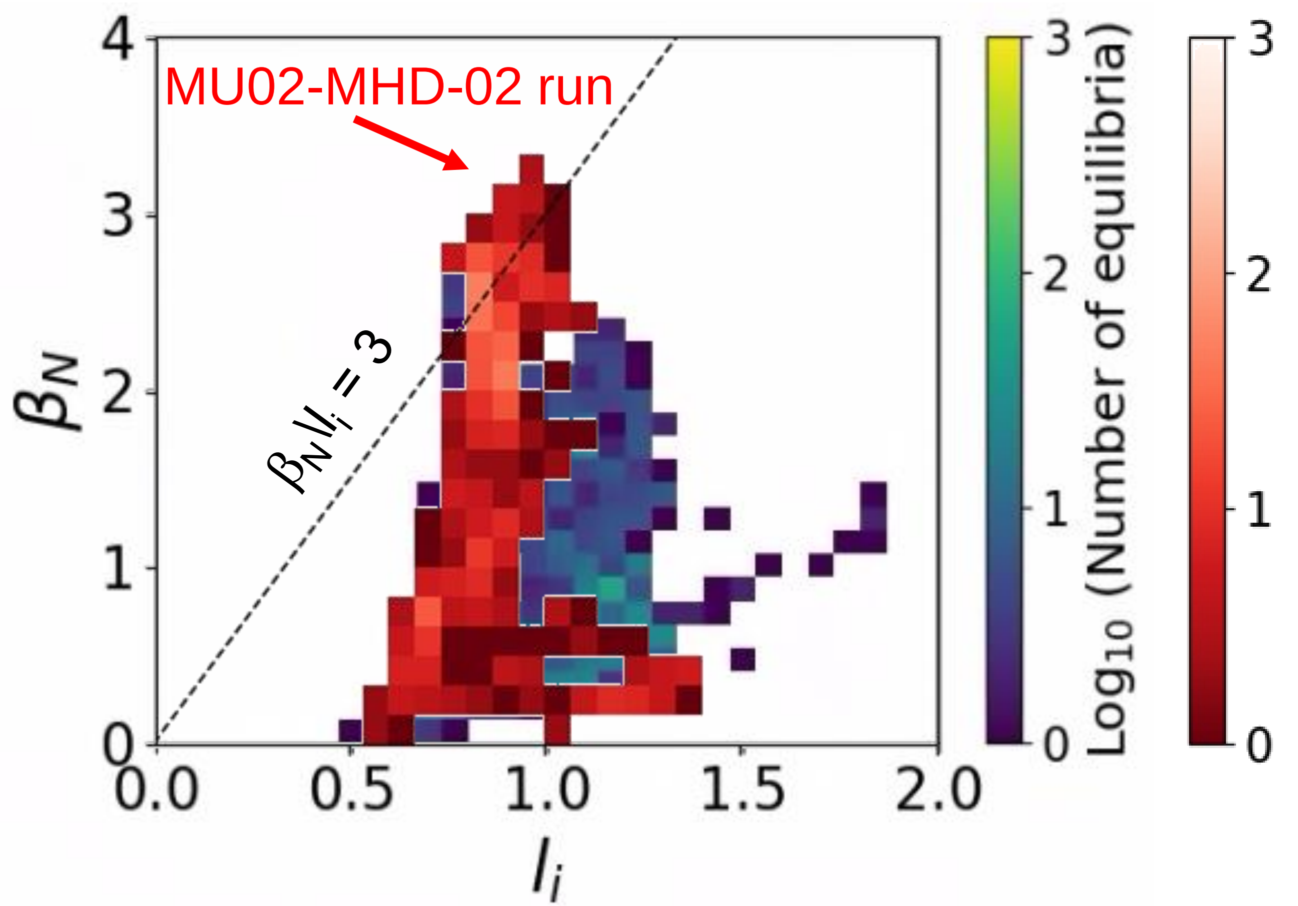
- More to do! Only reached Step 2 (of 6)
  - 18 shots, BUT constraint of 50 ms steps of the NBI during I_p ramp-down development
  - More approaches next 4 steps to affect MHD
  - Burst Thomson shows flat T_e spots (islands)
- Parameter variations as expected
  - 1 The l_i and β_p = 1.3 are still increasing
  - 2 The β_N saturating at ~ 3.3, W_{tot} decreasing
  - The β_p is more than double the base scenario ➔ higher $I_{bootstrap}$
- MU03-THR-02 campaign thrust XP!
  - Expand stability limit tests (more variations) shaping, higher NBI, MHD spectroscopy, etc
    - Expand stability space, inform DECAF analysis

β_N limit: As planned, MU02-MHD-02 expanded MAST-U operation in (l_i, β_N) space

(l_i, β_N) State Occurrence (pre-XP)

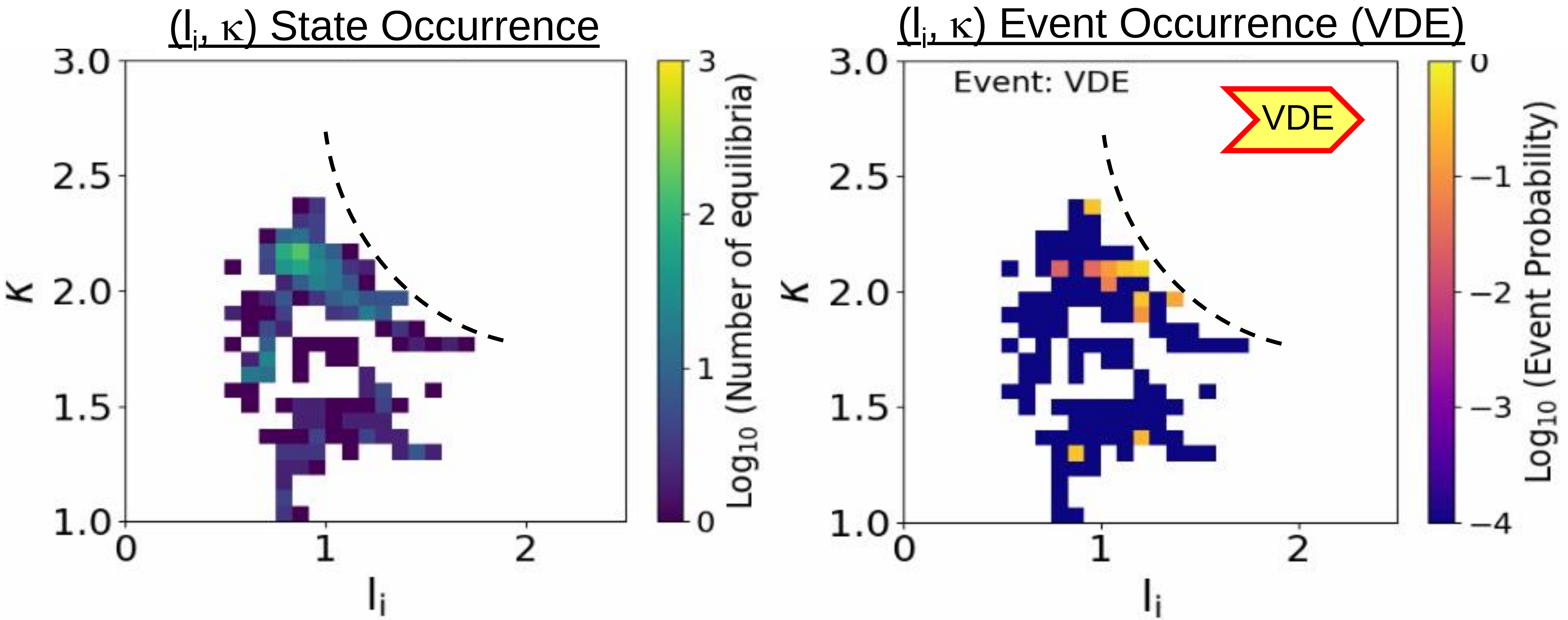


(l_i, β_N) State Occurrence (MHD-02 in red)



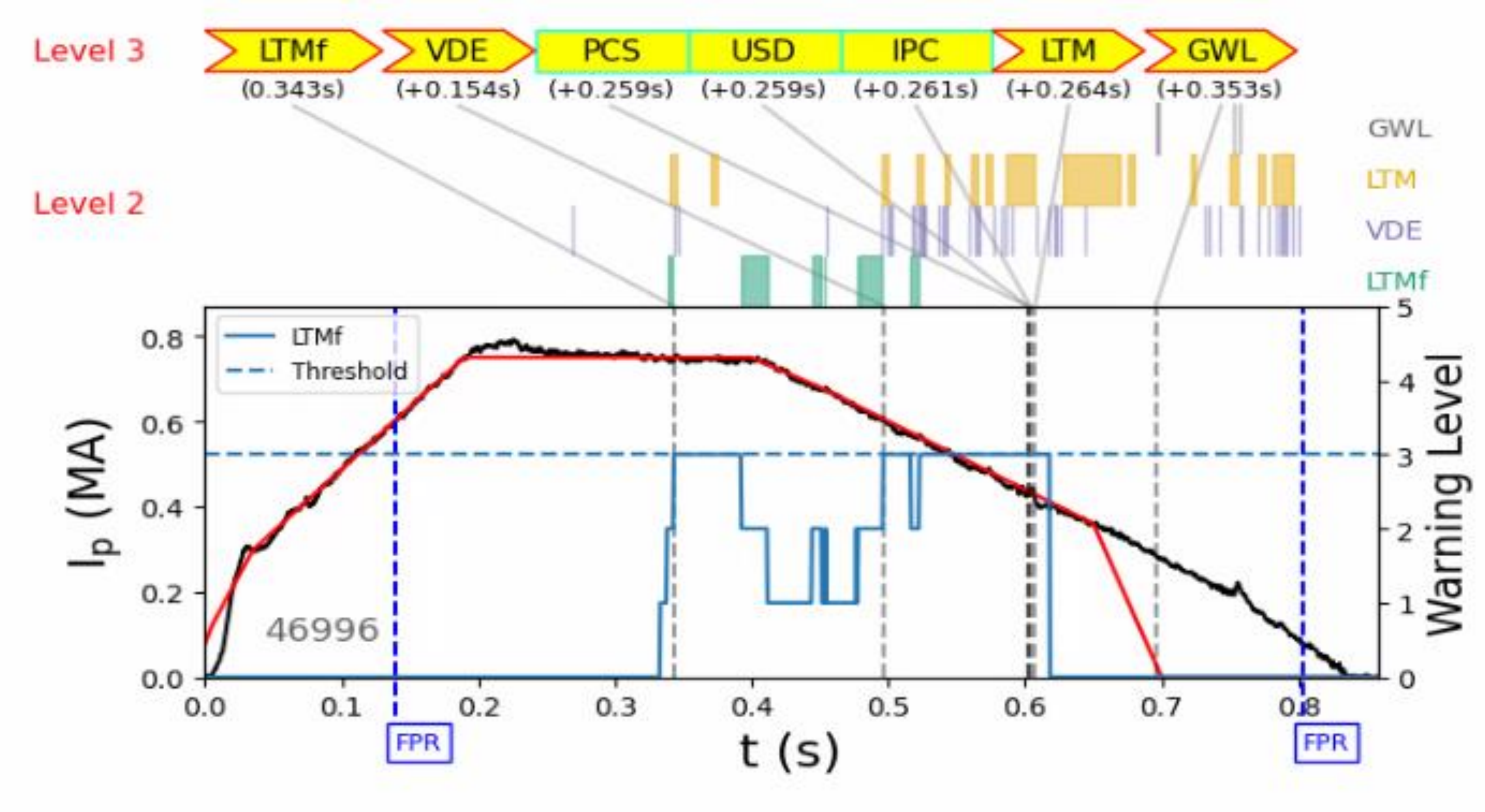
- Lower l_i than general database somewhat surprising, a positive aspect
- Steps 1,2 of experiment successful in raising β_N, move to steps 3 – 6 to go further

VDE limit: MU02-MHD-02 showed expected behavior of VDE event occurrence in (l_i,κ) space



- Apparent limit to elongation inversely proportional to l_i
- VDE occurs at high elongation and also shows inverse l_i relation

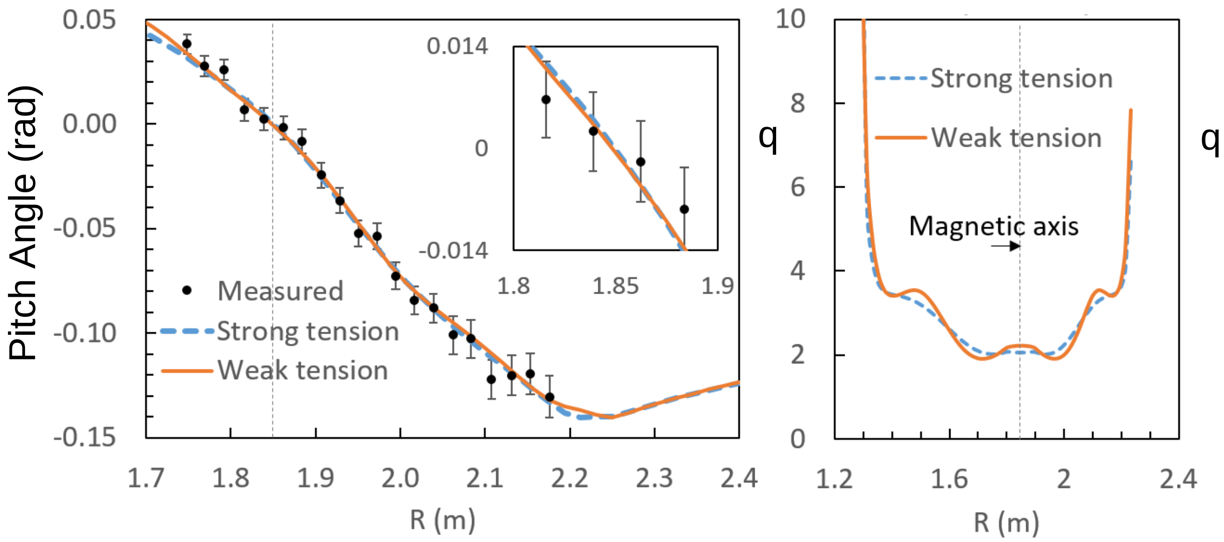
DECAF contains the state evolution



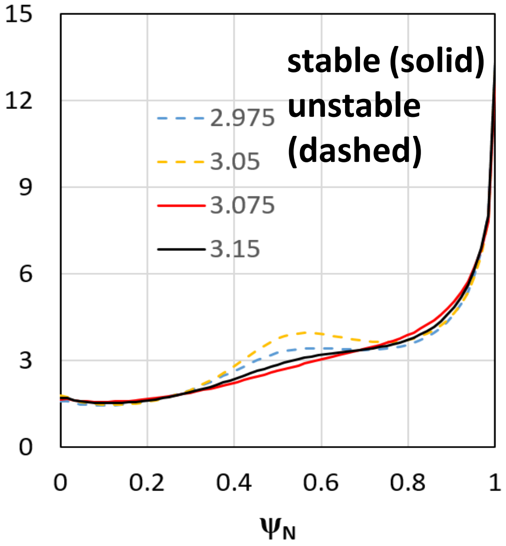
- DECAF example Level 3 chain and Level 2 events
- Level 1 events are also already identified in DECAF
- DECAF states can be similarly identified
  - Events comprise states
  - The highest event level in a state defines the state level

Experimental advanced tokamak equilibrium and transport analysis manifests localized reversed shear ➔ sensitive stability at high NICD

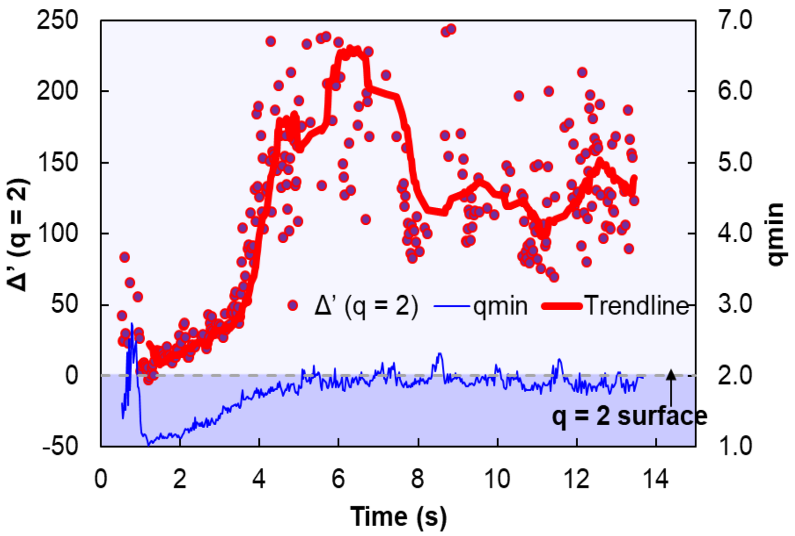
Kinetic equilibrium reconstruction (B pitch angle and q)



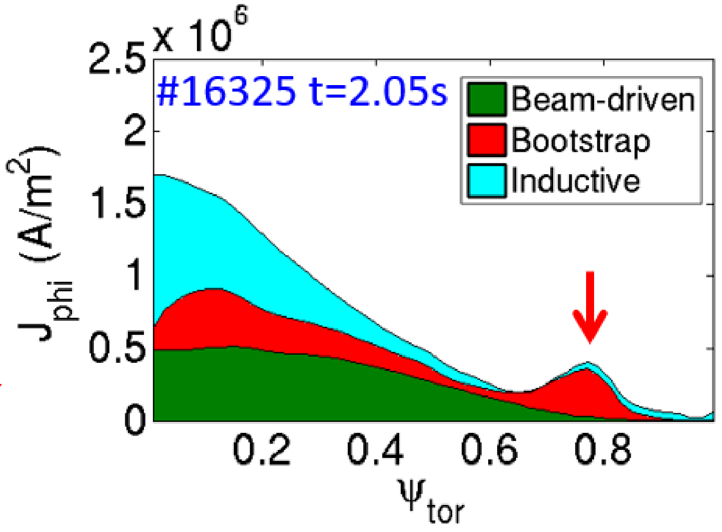
Ideal stability of profiles



Resistive stability



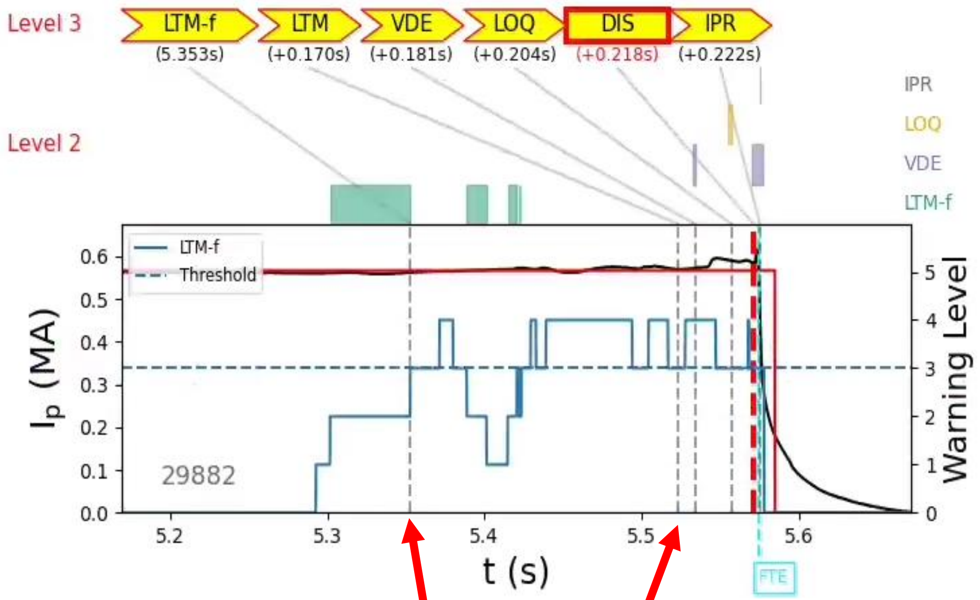
- Spline and polynomial basis function models both reproduce MSE measured data
- Local flat spots form in q profile
  - challenging for ideal and resistive stability evaluation
- KSTAR TRANSP shows high non-inductive current evaluation (~ 75% total non-inductive current)

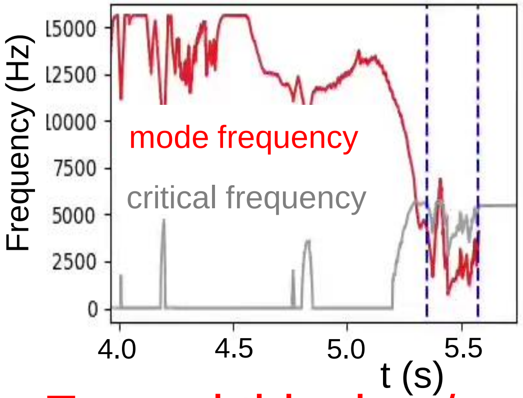


Y. Jiang, S.A. Sabbagh, *et al.*, Nucl. Fusion **61** (2021) 116033

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

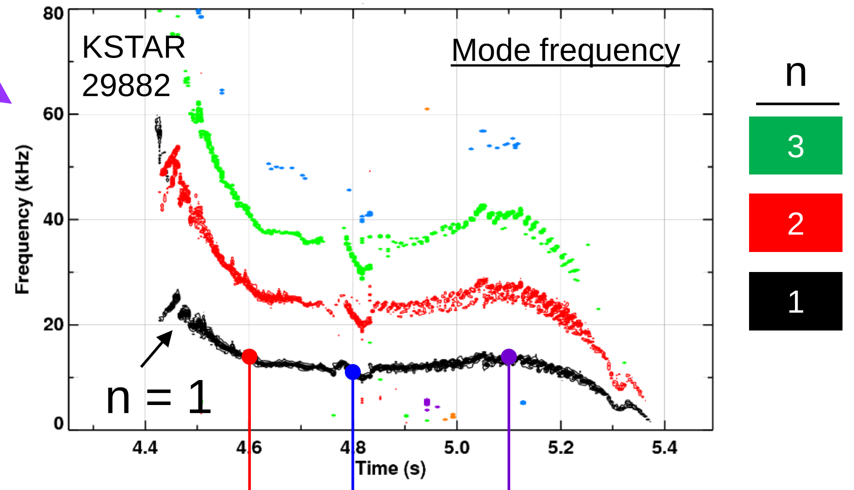
DECAF locked mode (LTM), forecaster (LTM-F) events (rtMHD system)





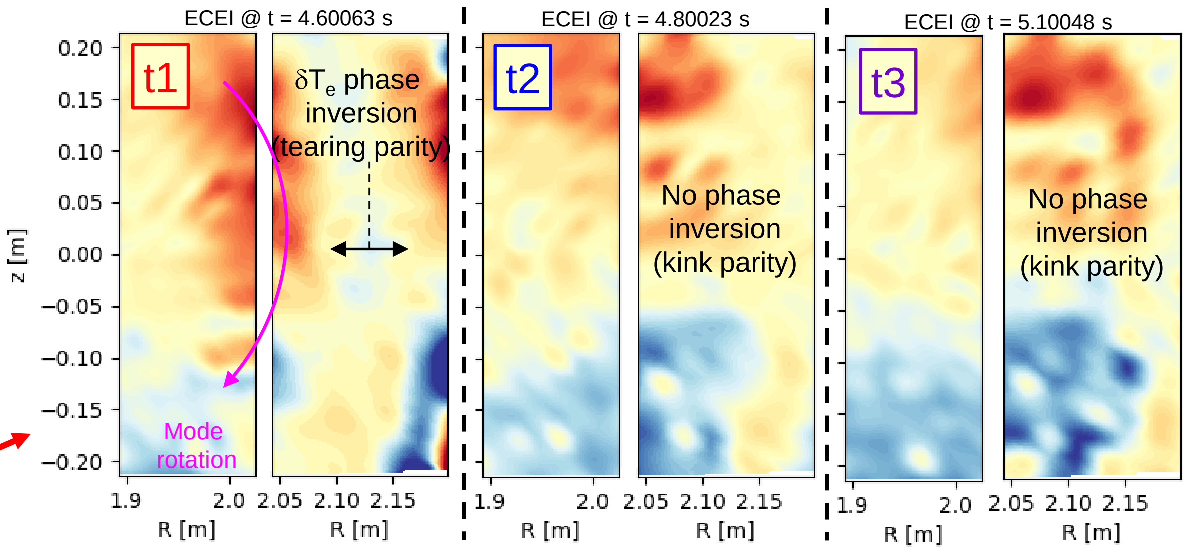
- LTM-f forecaster triggered 218 ms before disruption
- LTM event 170 ms after it was forecast

Magnetic spectrogram (toroidal array)



2D ECE imaging (ECEI)

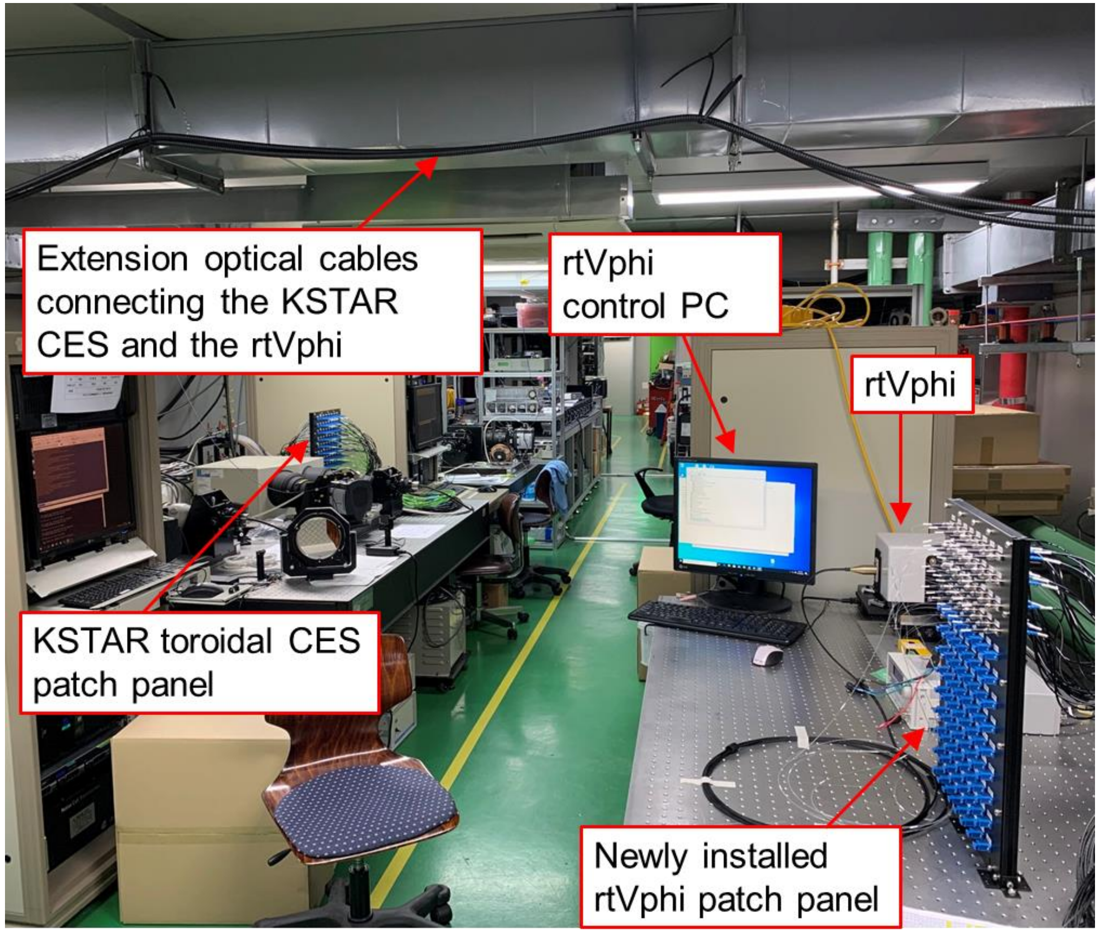
Tearing (outer) with core kink → Kink dominant



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

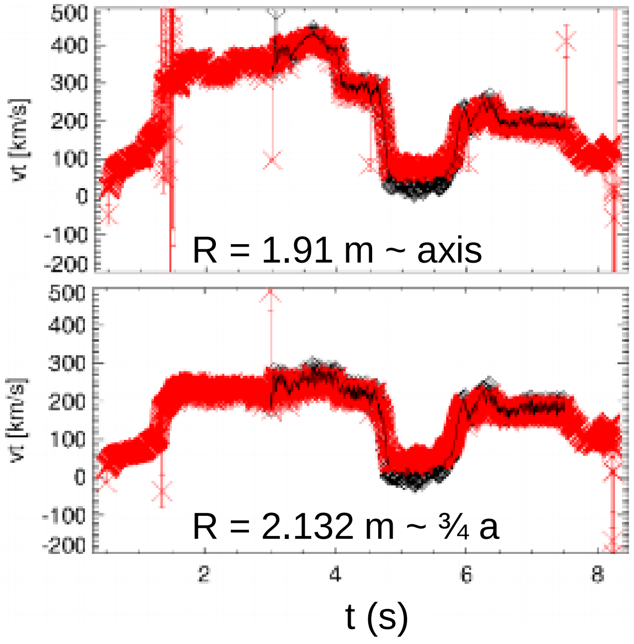
Initial real-time toroidal velocity, (possible) ion temperature diagnostic (rtV_ϕ) shows very good agreement with KSTAR CES

KSTAR real-time V_ϕ , T_i diagnostic



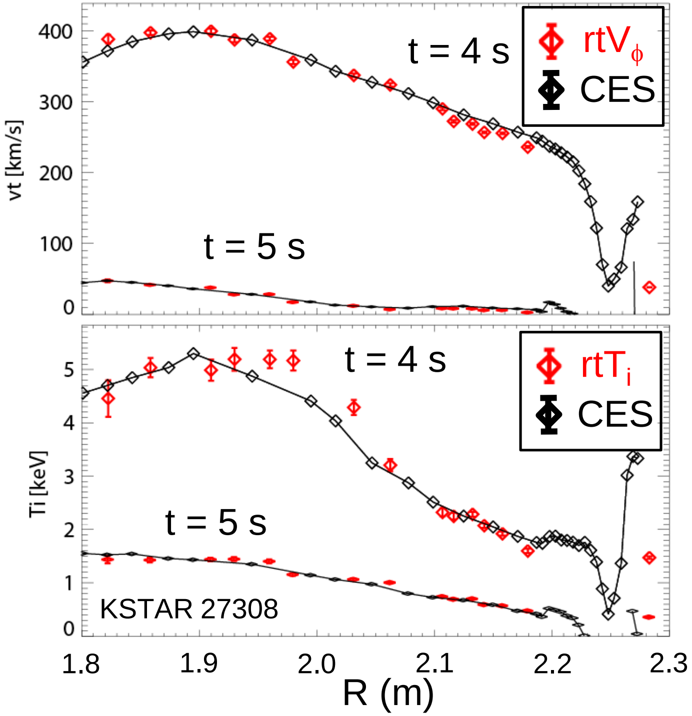
- ❑ rtV_ϕ and offline CES system share sightlines

rtV_ϕ time evolution (2 channels)



- ❑ rtV_ϕ data
  - ❑ 16 radial channels at 1 kHz
  - ❑ Offline CES analysis at 100 Hz

rtV_ϕ 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_ϕ) delivered to KSTAR, installed, undergoing tests

Spectrometer

Camera

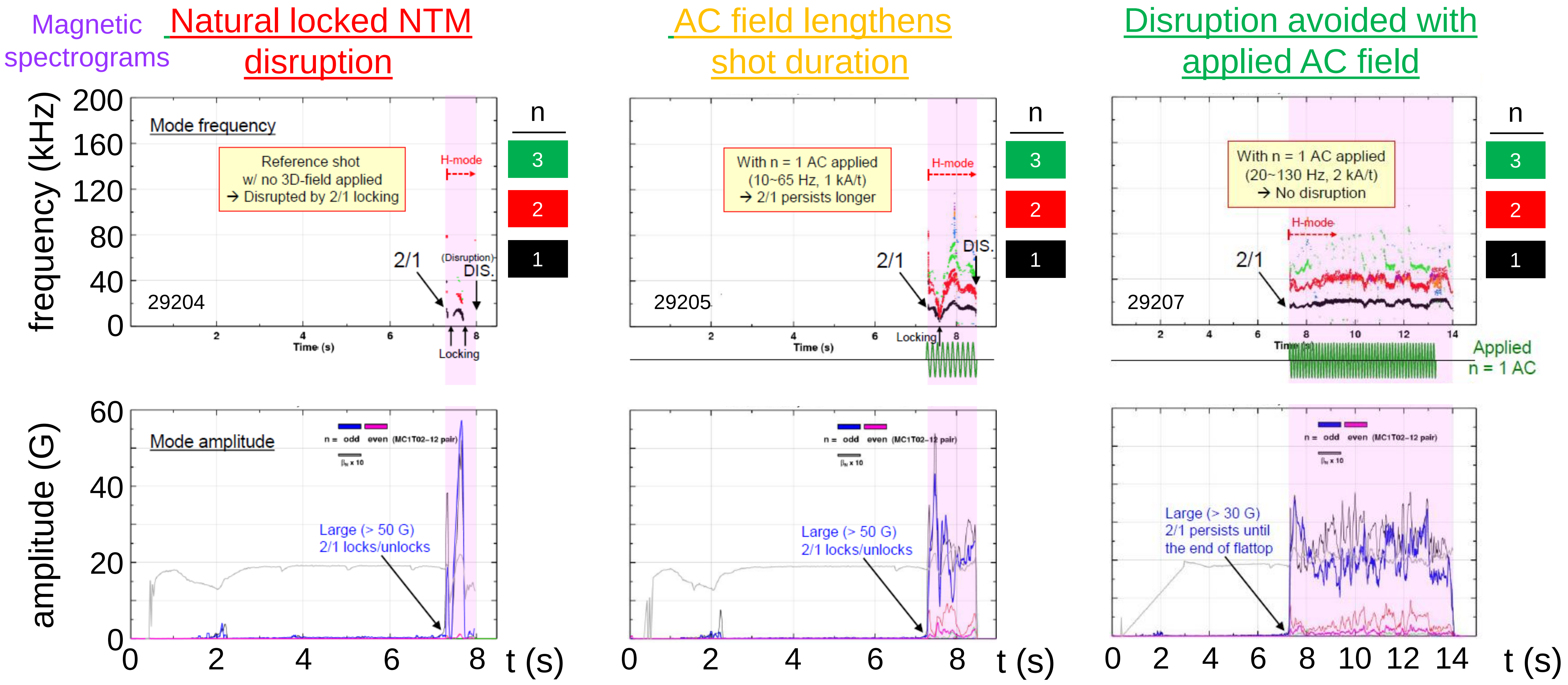
Real-time computer and DAQ

- switch to Linux from Windows system
- first light on last day of 2022 run (7/29/22)

New diagnostic – completed installation

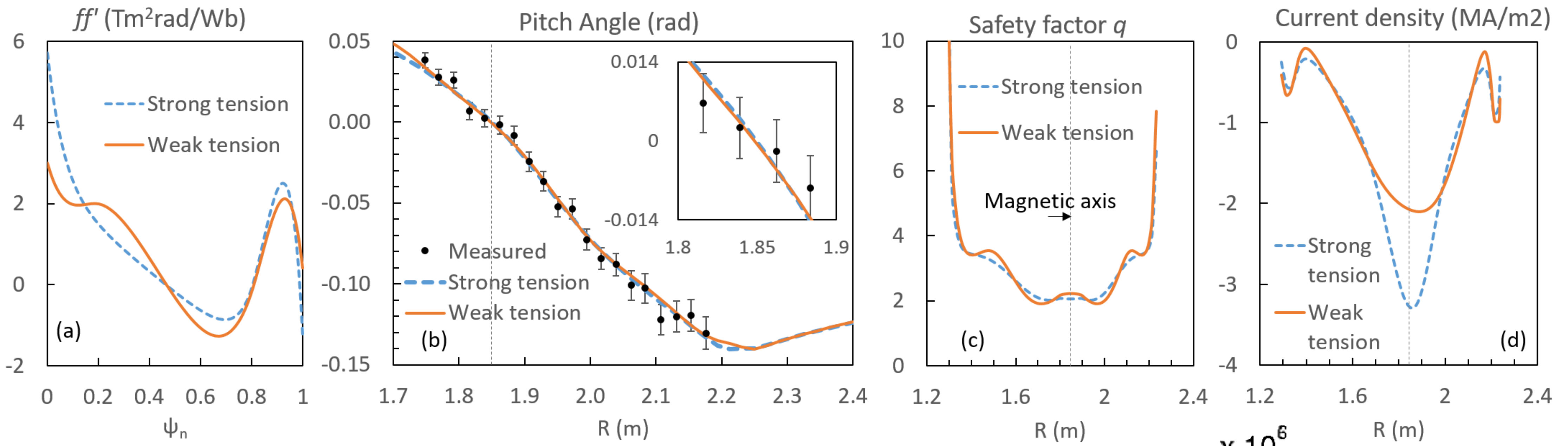
M. Podesta, K. Erickson, J. Yoo (PPPL), Y.S. Park (CU), W.H. Ko (KFE)

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

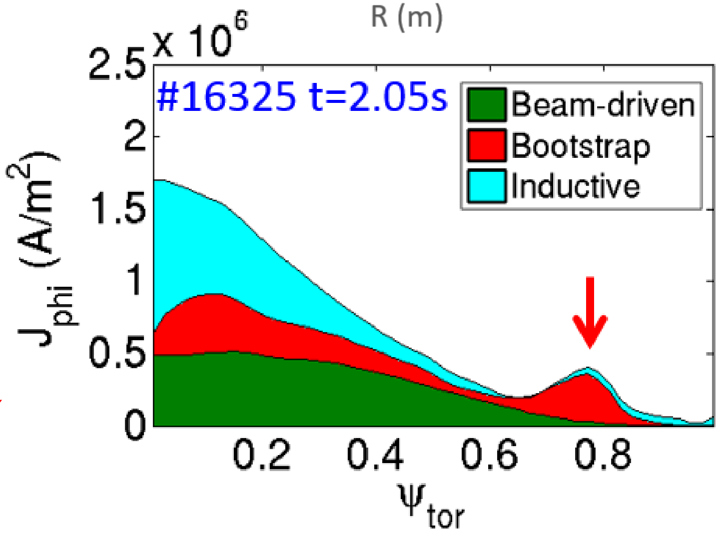


❑ NOTE: applied AC field frequency is << mode rotation (due to boundary value field alteration? analysis continues)

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)



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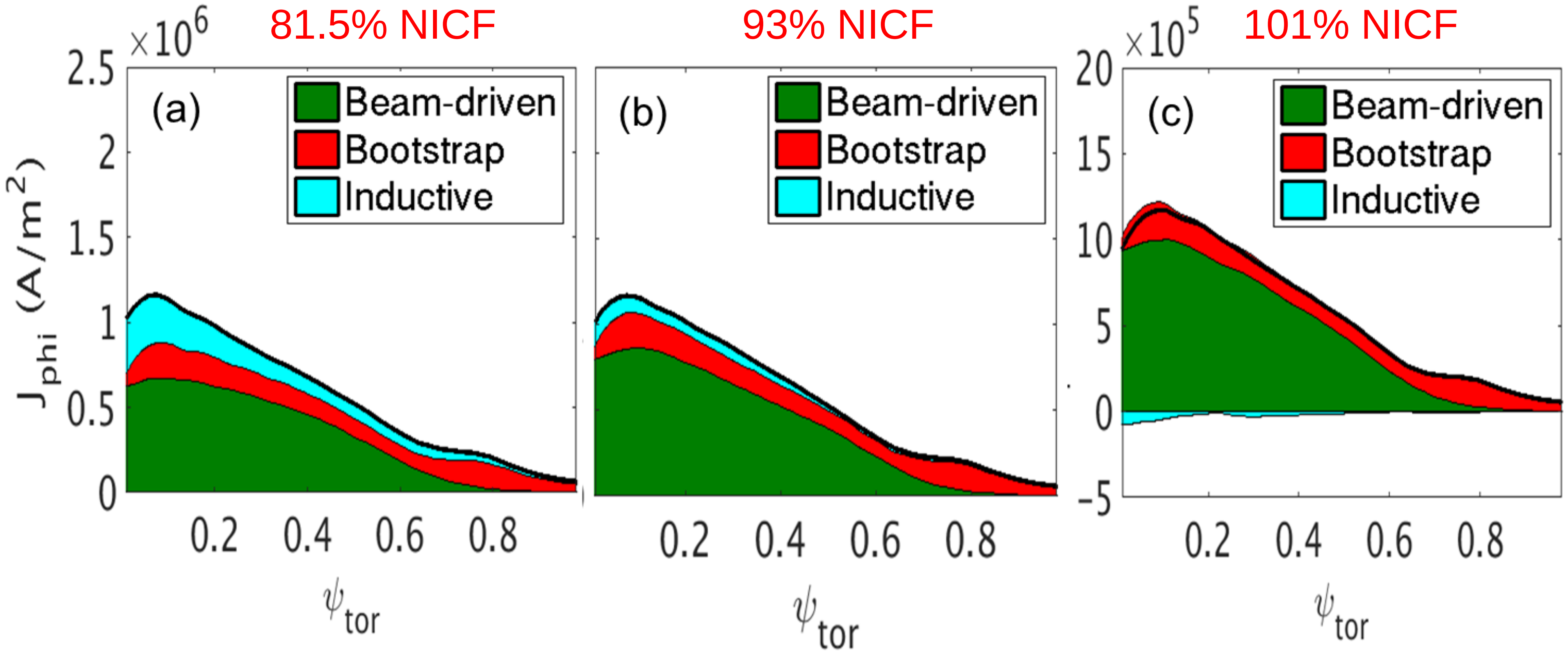
"Predict-first" KSTAR TRANSP analysis shows expected high performance plasmas at > 80% NICF

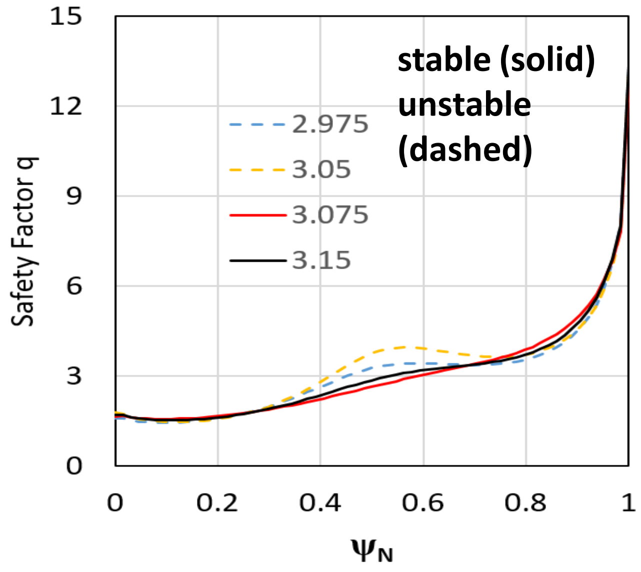
Predicted high non-inductive current fraction (NICF) current profiles

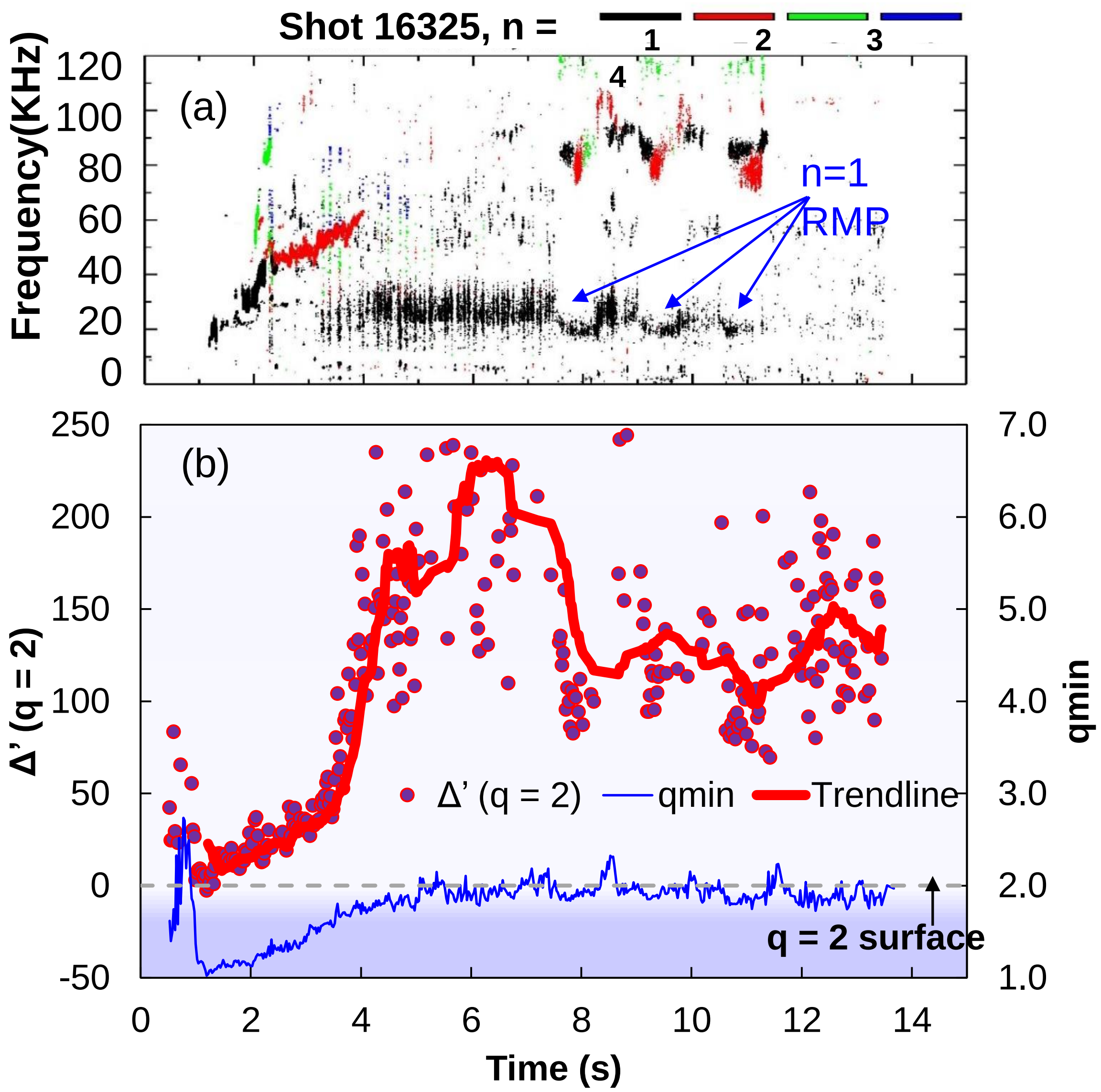


- High non-inductive current fraction predicted for 6.5, 7.5, 8.5 MW NBI
  - The β_N ranges from 3.0 – 3.5; based on KSTAR plasmas with NICF ~70%
- Produced high NICF plasmas (2021 run) with ~record β_p = 3 in KSTAR (analysis pending)

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



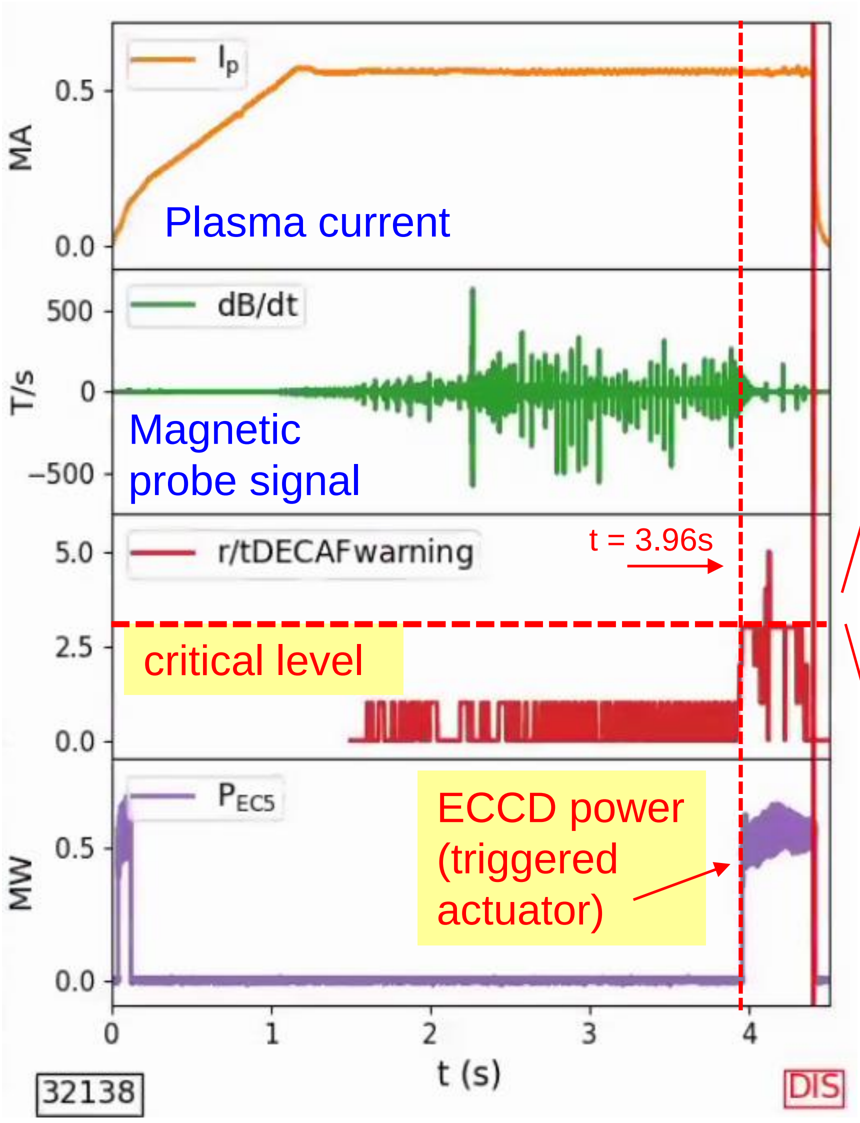


- Δ' analysis supporting evaluation of modified Rutherford equation as resistive stability indicator

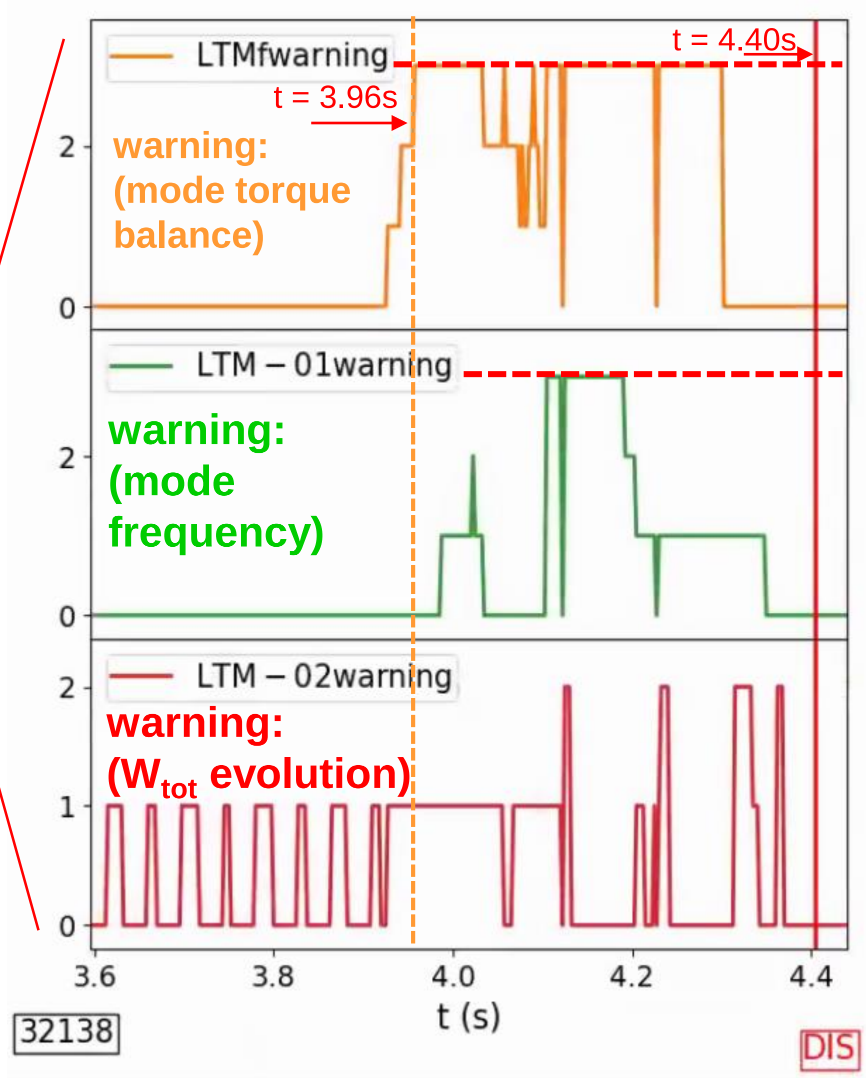
- Less freedom in equilibrium basis functions produces less computed stability variation

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

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

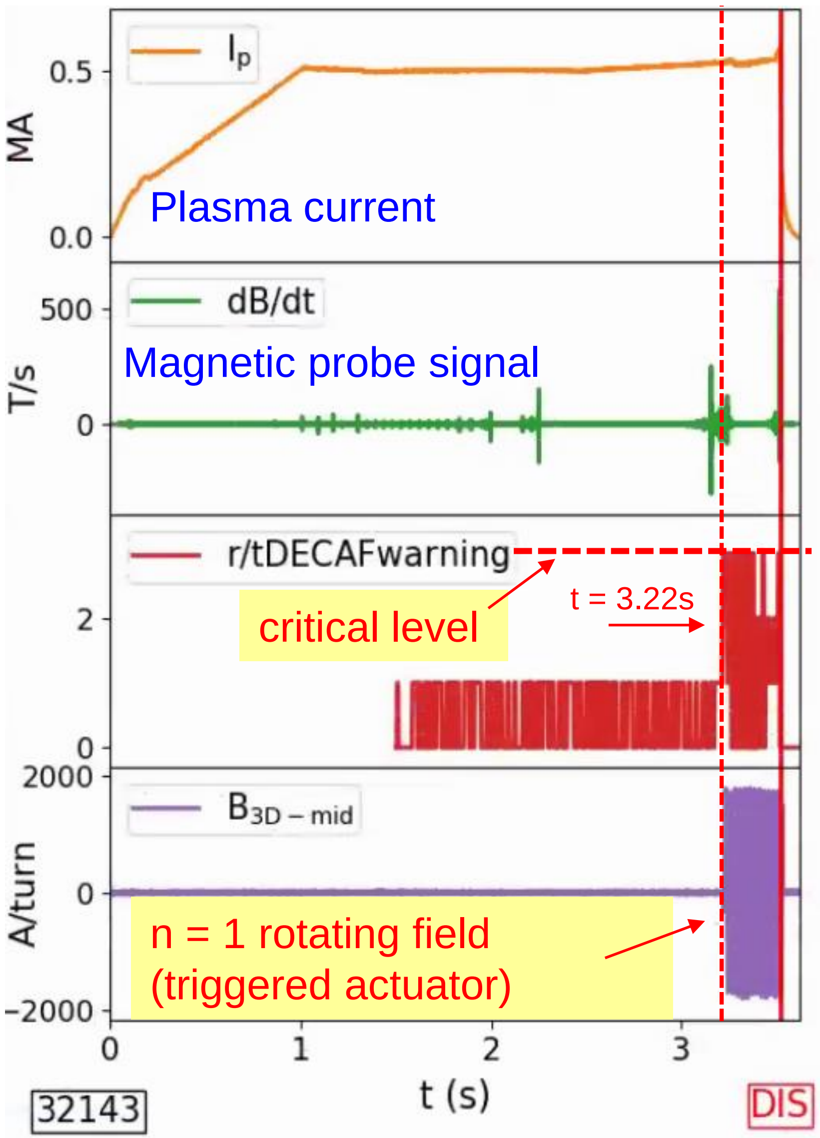


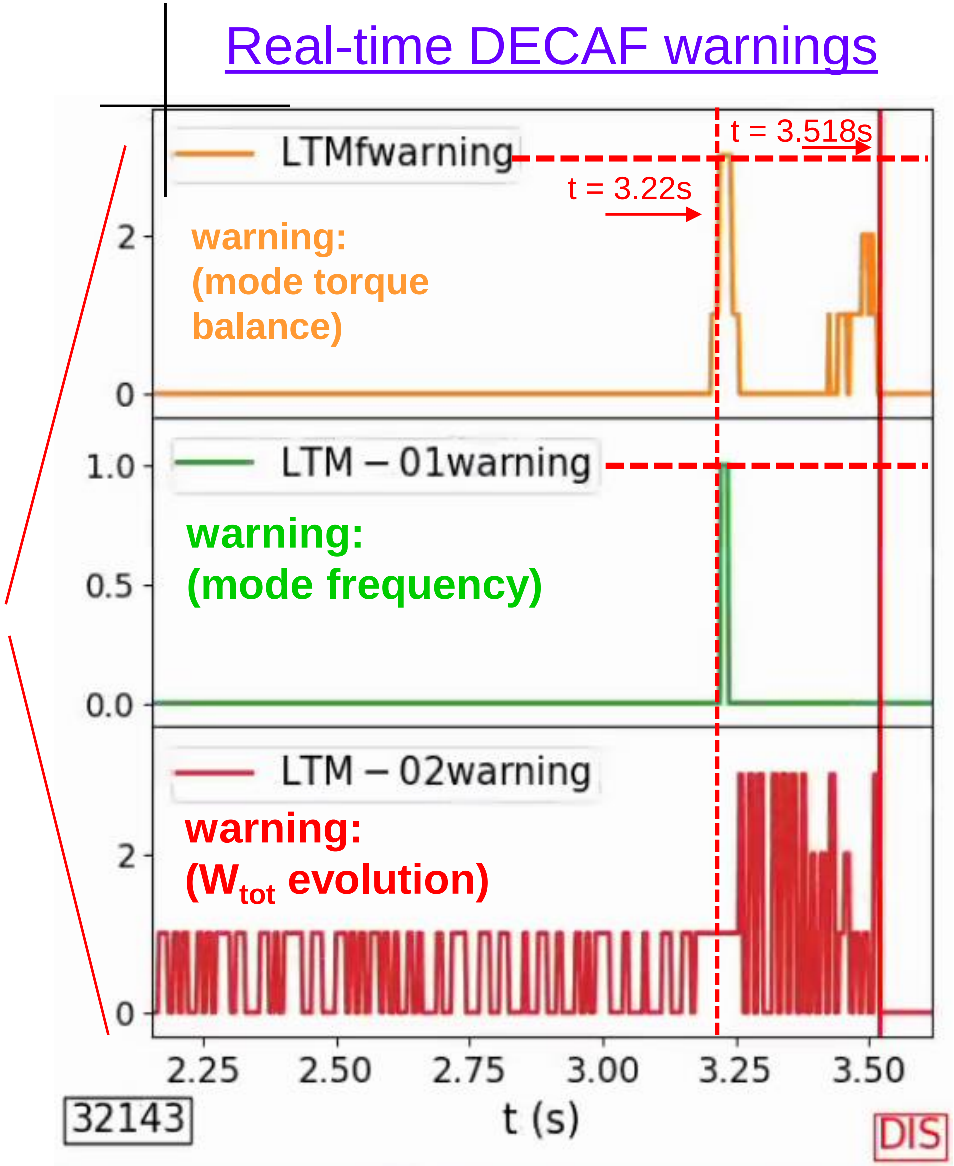
Real-time DECAF warnings



- 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

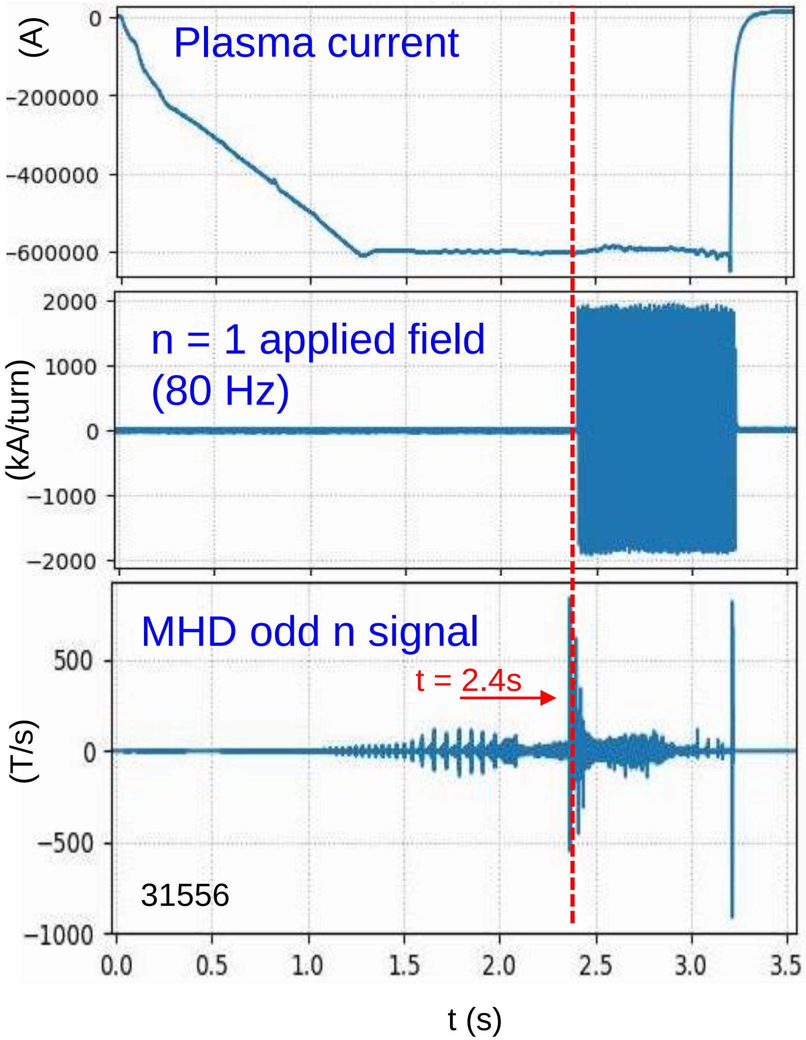
Critical real-time DECAF warning also triggered an n = 1 rotating field actuator

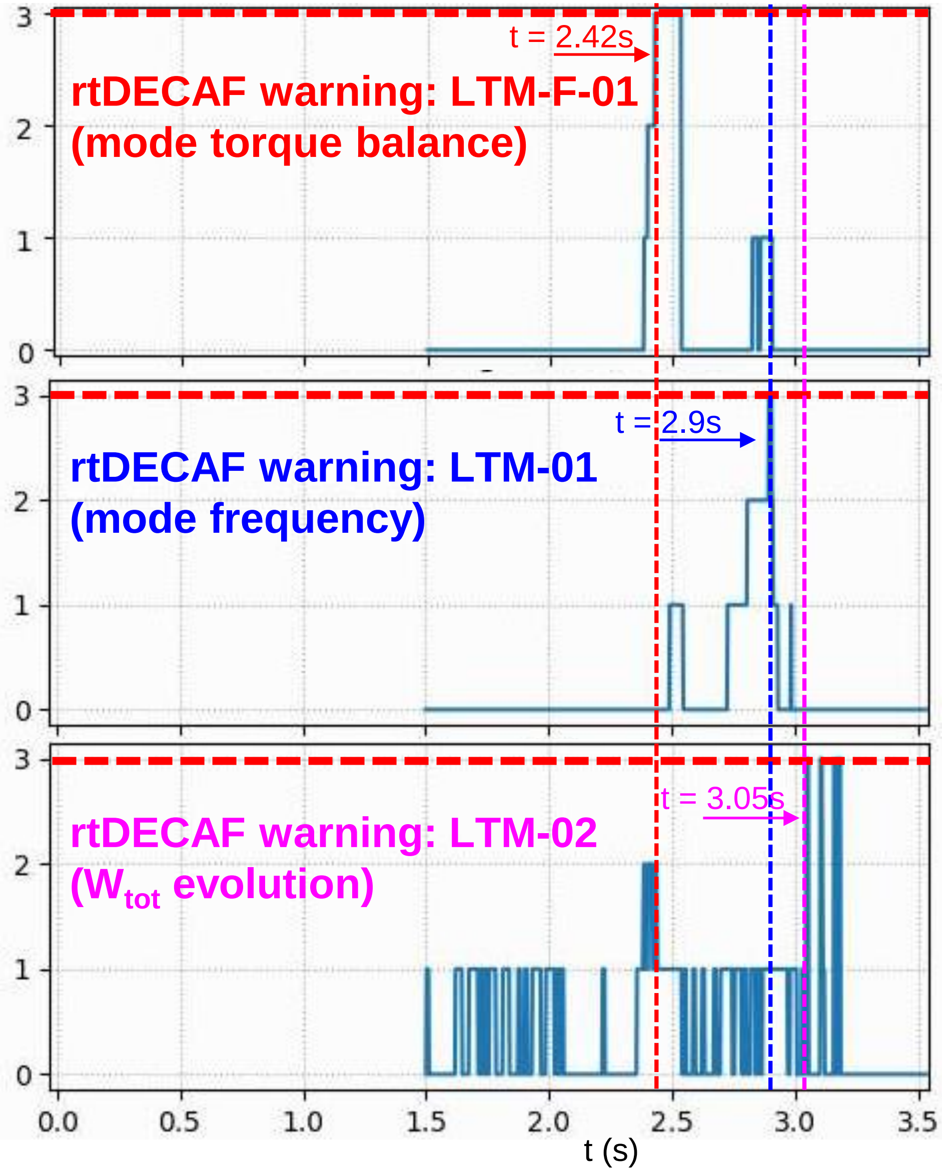




- n = 1 rotating field from IVCC triggered by real-time DECAF
  - LTM forecaster reaches critical level at t = 3.22s
- DECAF warnings successfully tracked varying mode onset times in different shots
- NEXT STEP: demonstrate disruption avoidance!
  - Complete the XP: Use EITHER NBI actuation or n = 1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

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

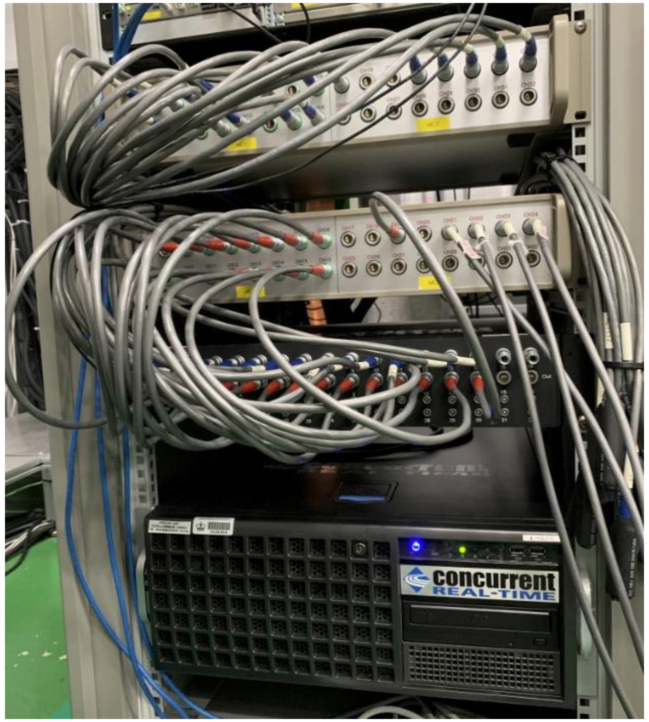




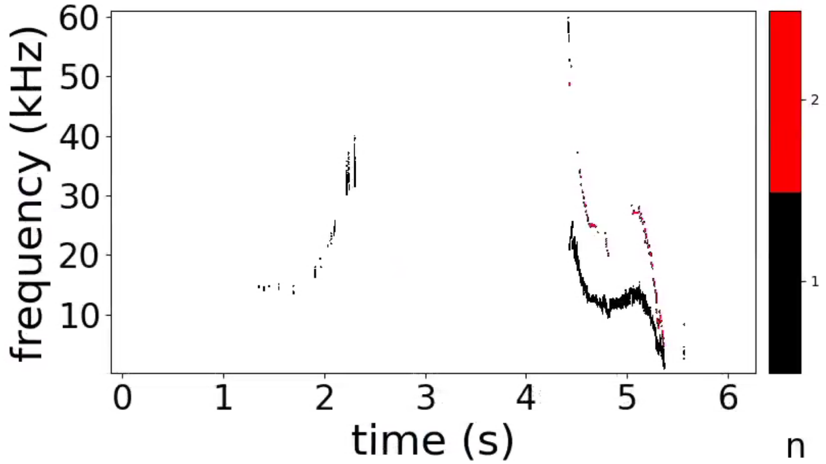
- Forecast worked, but n=1 AC field did not prevent TM mode lock
  - Such an activation was successful in 2021 "NTM entrainment" experiment
- Two differences this year regarding TM lock prevention attempt
  - n = 1 applied AC field did not rotate toroidally (patch panel setting different)
  - target 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

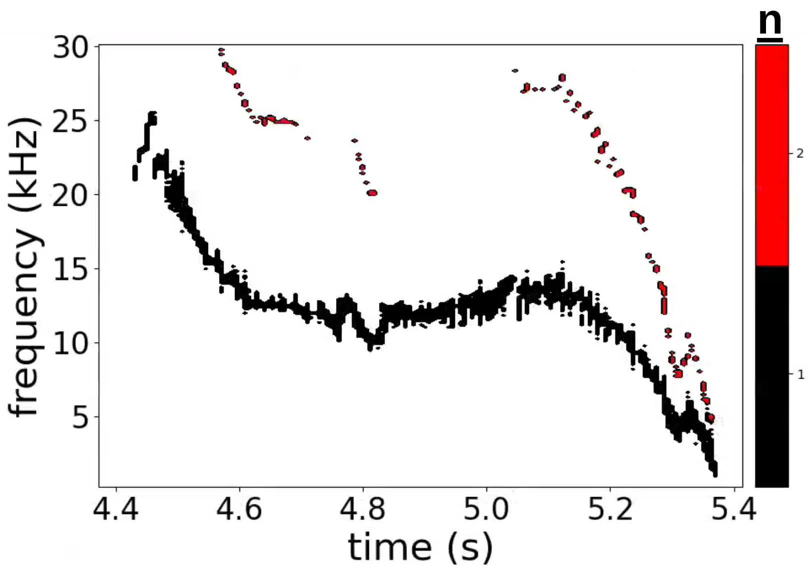


Magnetic probe array toroidal mode spectrogram (offline)

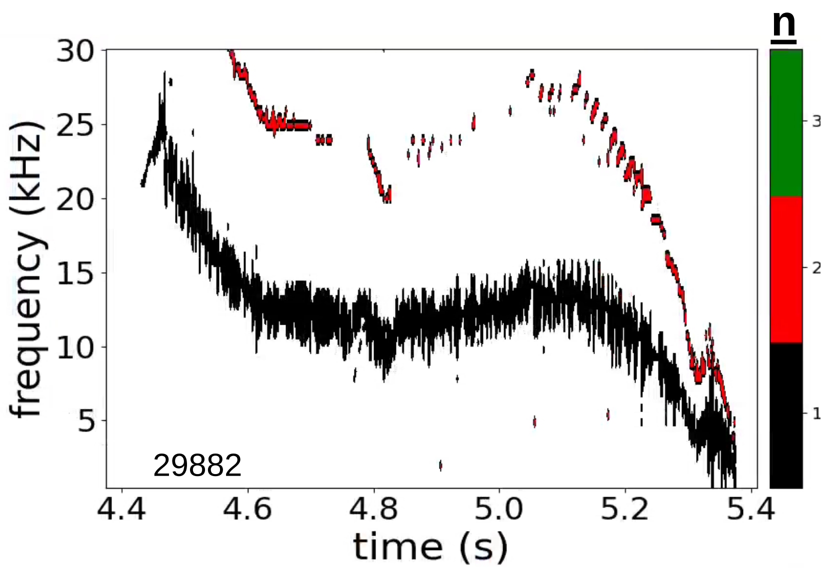


J. Riquezes (CU)

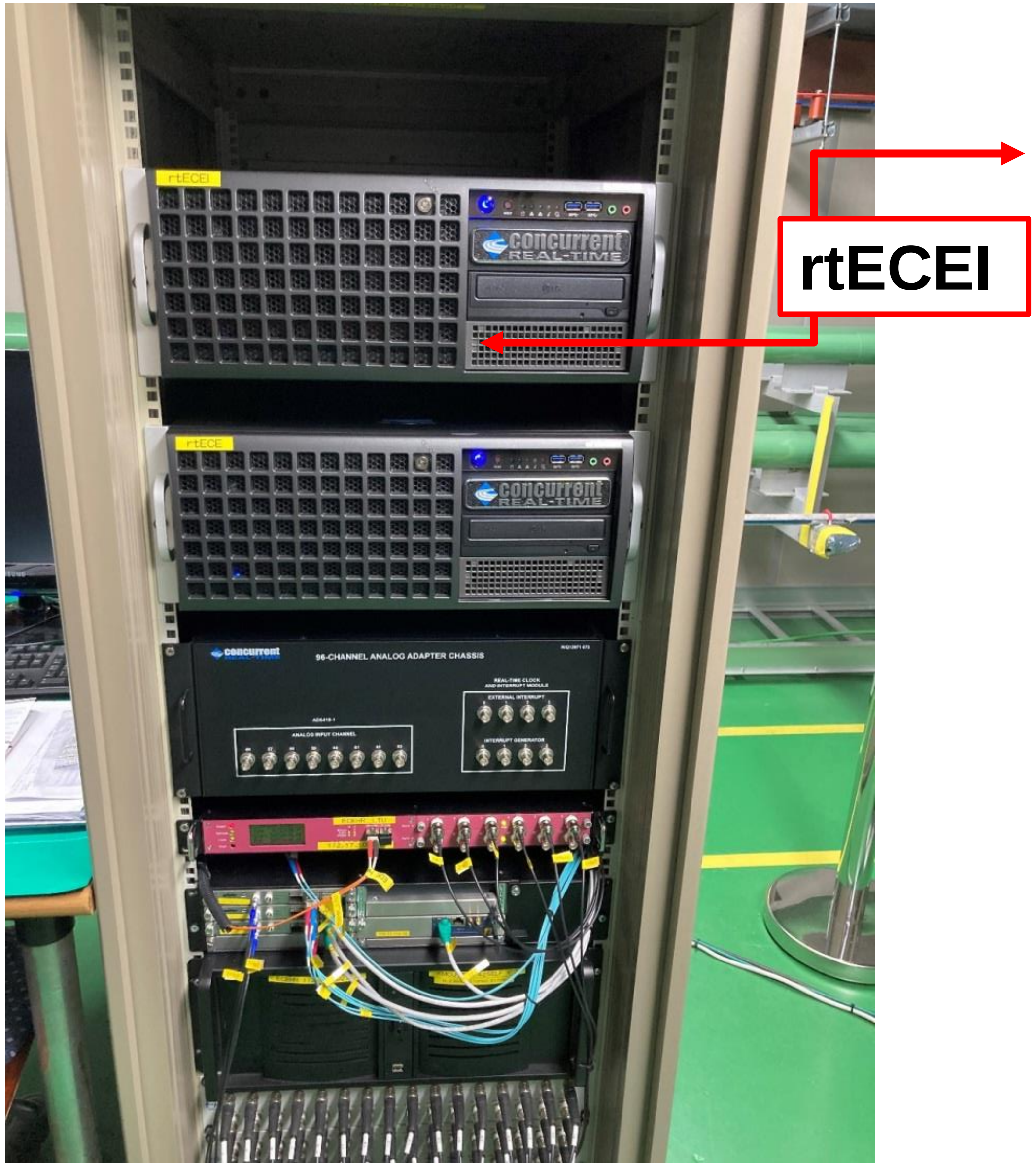
DECAF spectrogram (offline FFTs)

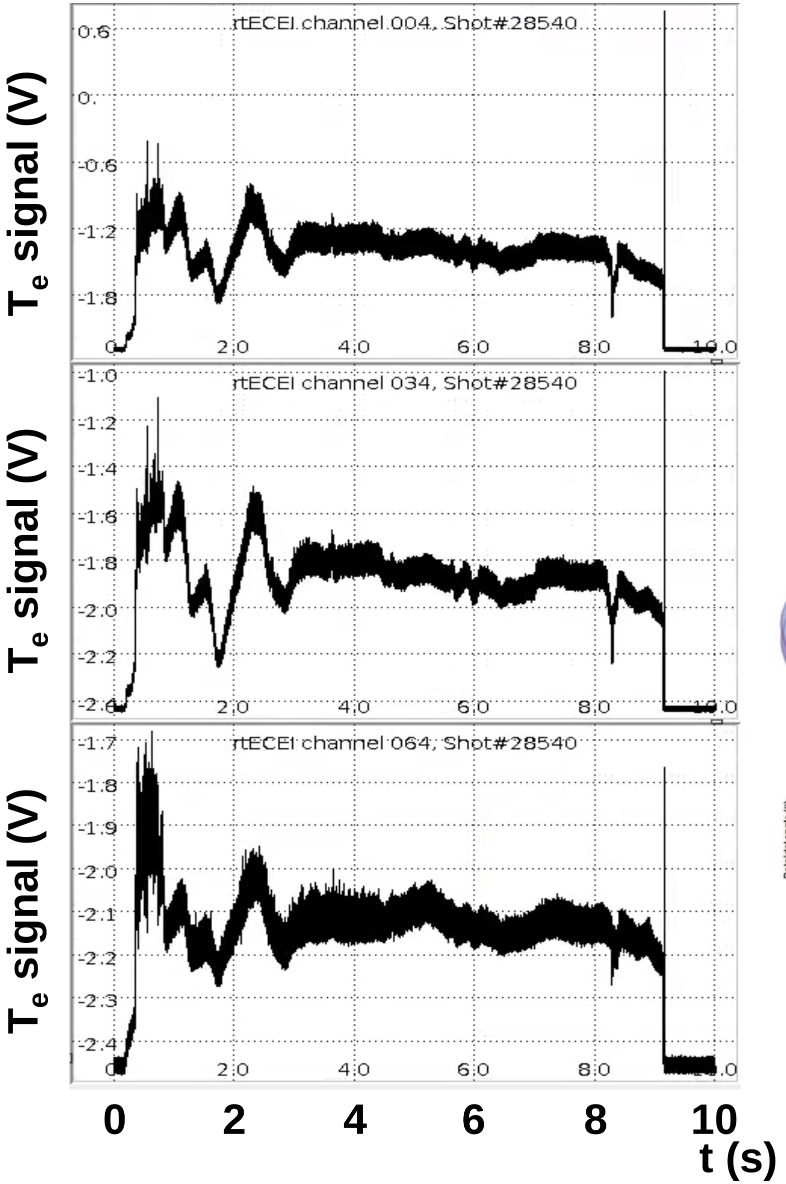


DECAF spectrogram (real-time FFTs)

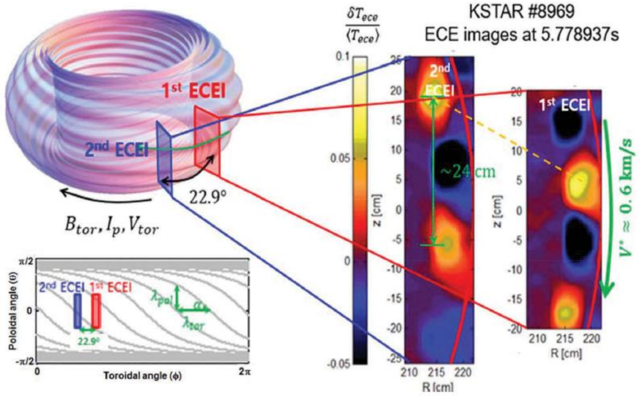


The first real-time ECEI data on KSTAR was taken as well in 2021 run campaign



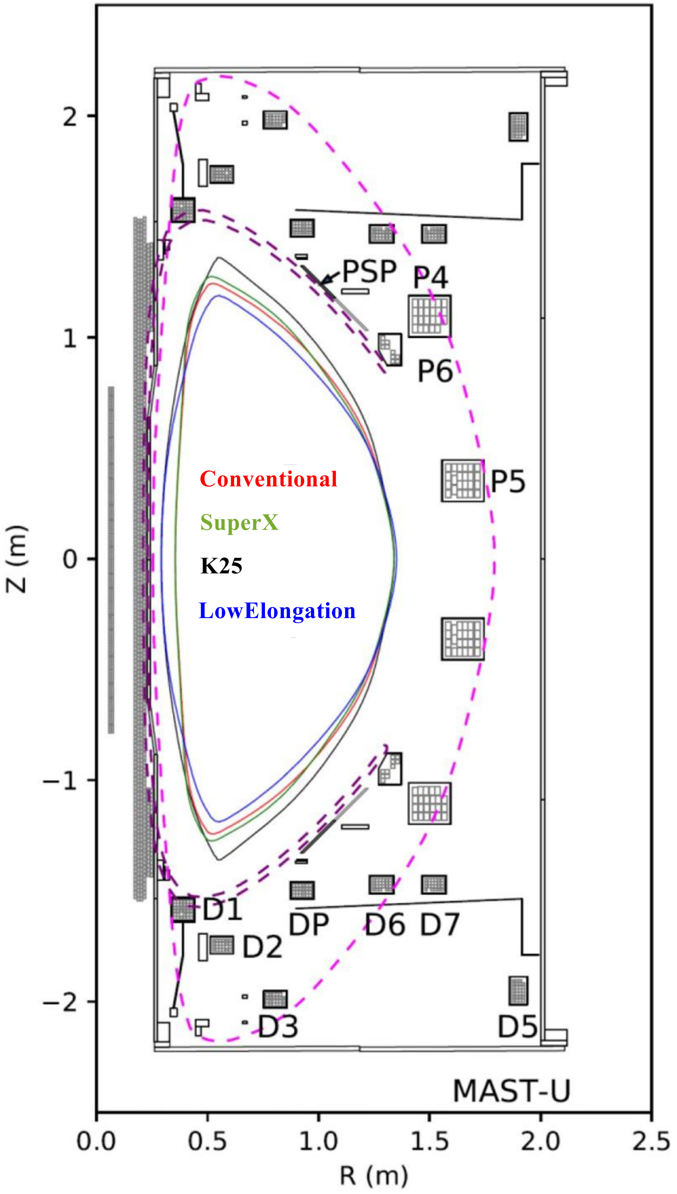


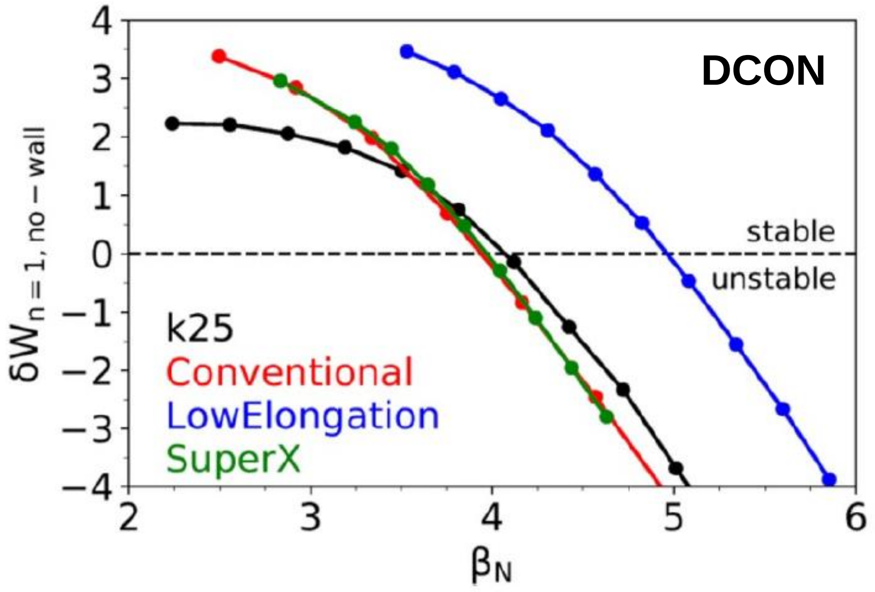
- Full 2D poloidal cross-section acquired in r/t - 192 channels!
- 3 of 192 channels shown



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

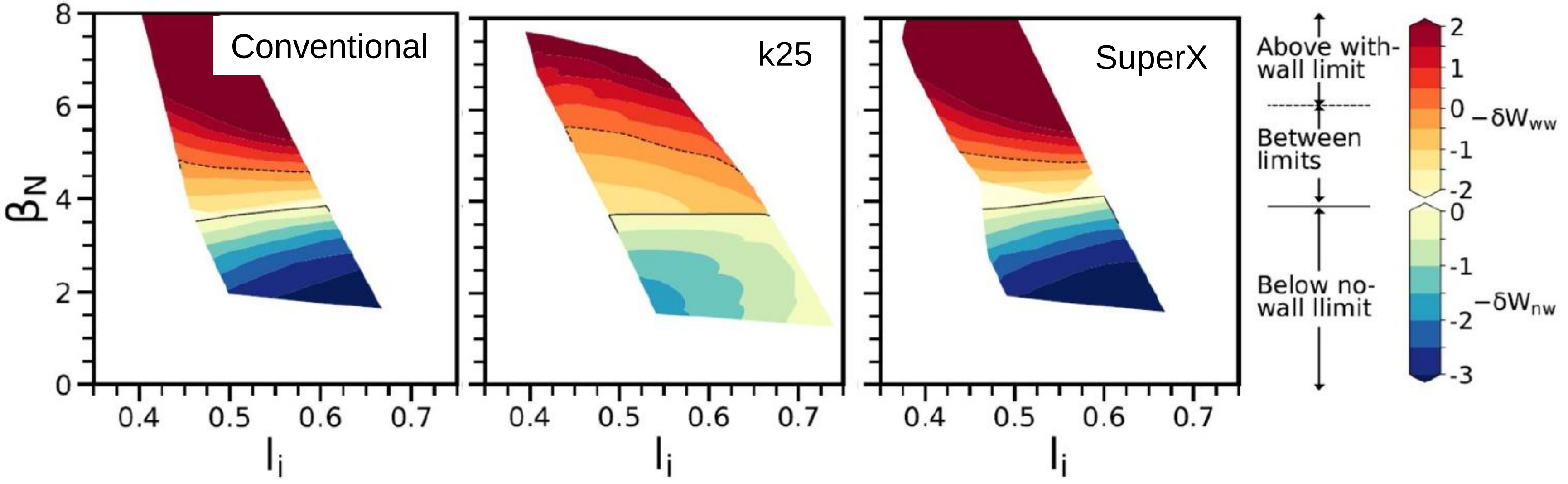
Ideal stability of four MAST-U projected equilibria shapes were evaluated for stability by scaling pressure, etc.





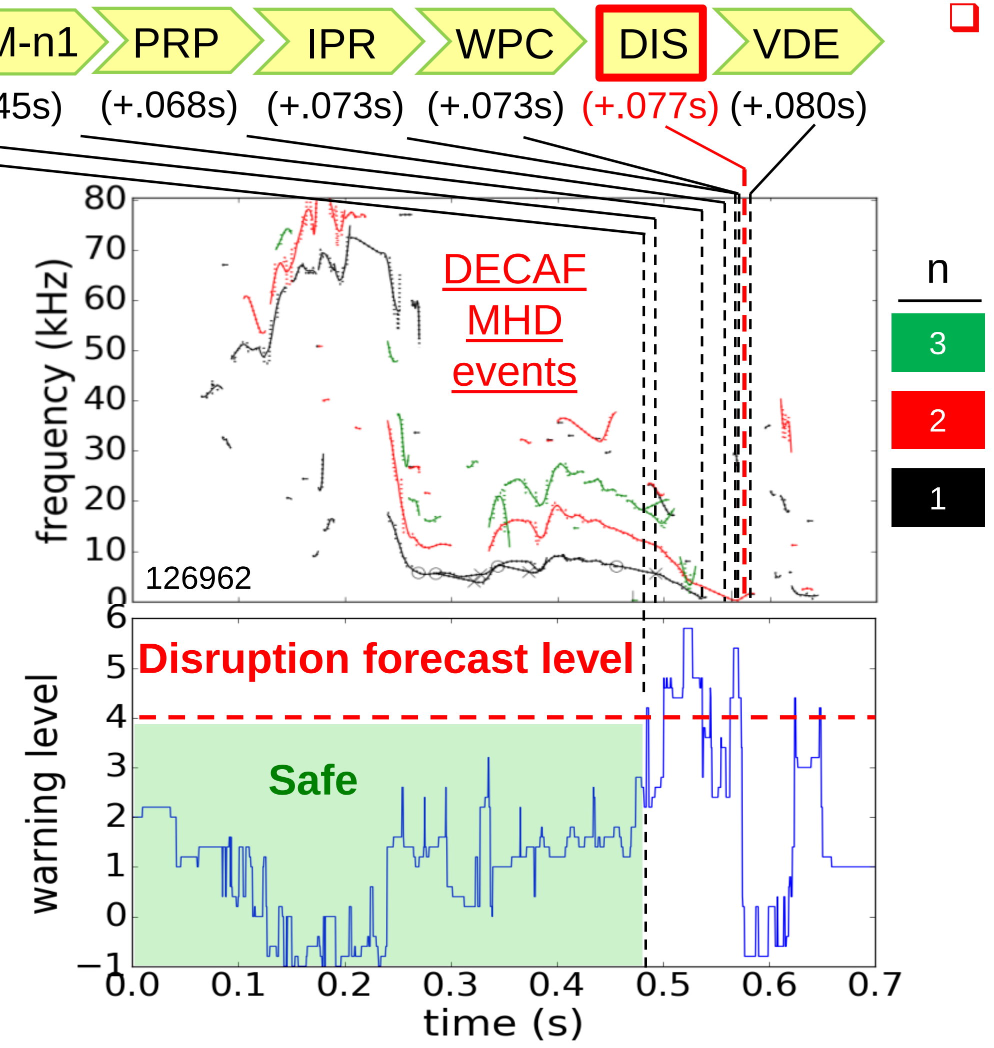
- Ideal stability evaluation
  - pressure profile scans
  - q(0) scans
  - Projected no-wall limit: β_N ~ 4 and β_N/l_i ~ 7

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

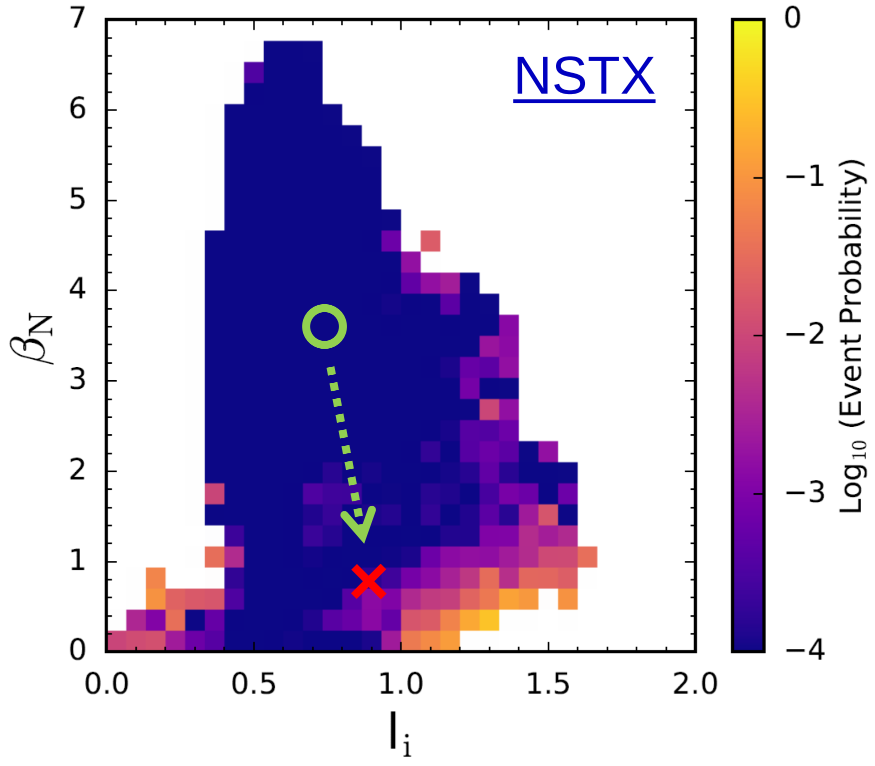


Review: DECAF provides an early disruption forecast - on transport timescales – giving potential for disruption avoidance

DECAF Level 3 event chain



NSTX stability operational space



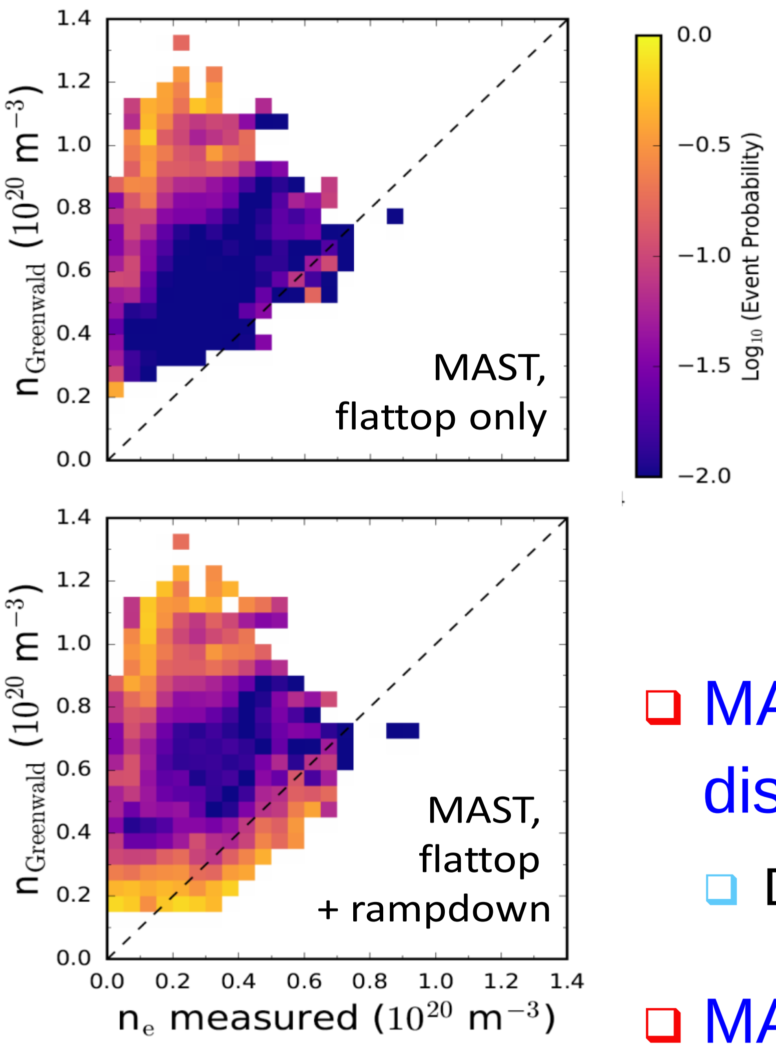
- DECAF event chain reveals physics
  - Rotating MHD slows, bifurcates, locks
  - Plasma has an H-L back-transition (pressure peaking warning PRP) before DIS
  - Early warning occurs in apparently SAFE region of operating space!

- NOTE: 15 conditions used including plasma velocity profile

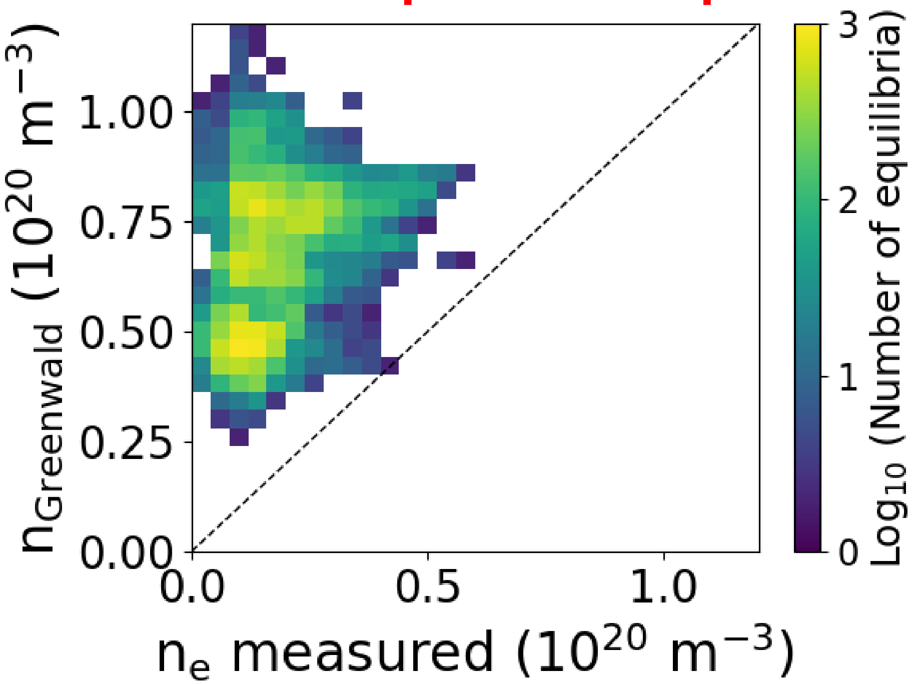
S.A. Sabbagh, et al., 2020 IAEA Fusion Energy Conference, Paper IAEA-CN-286/1025

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

MAST disruptivity



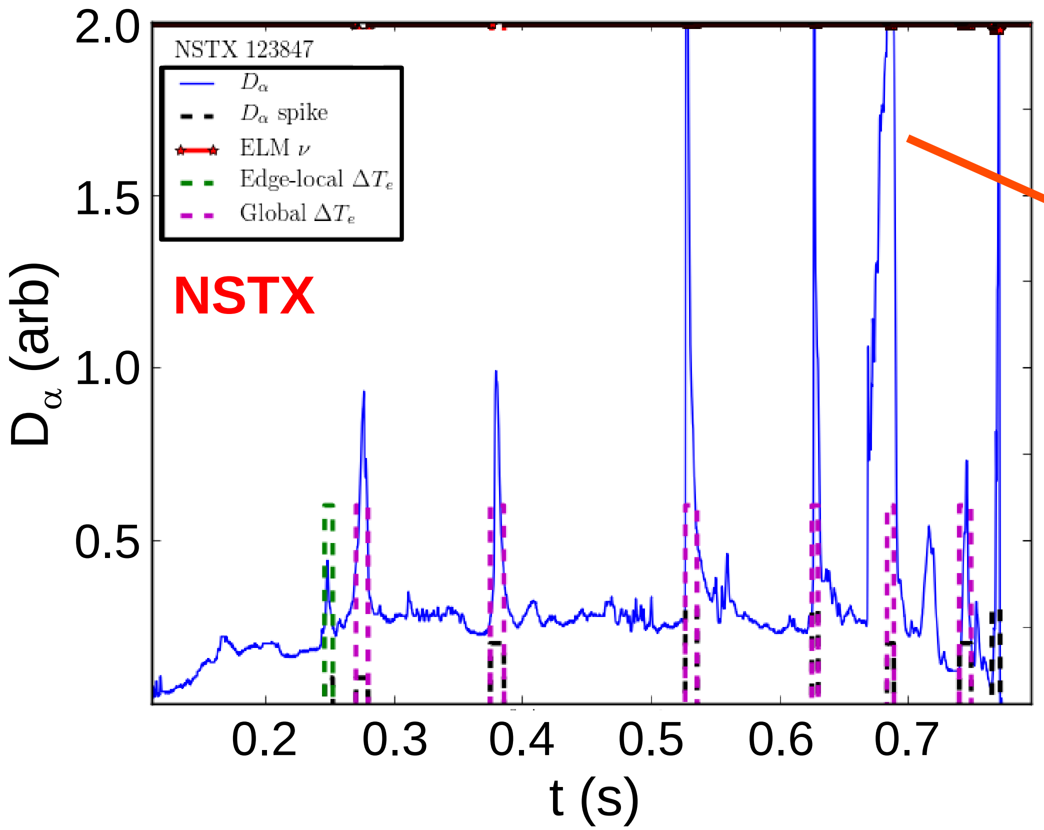
MAST-U operational space



- 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

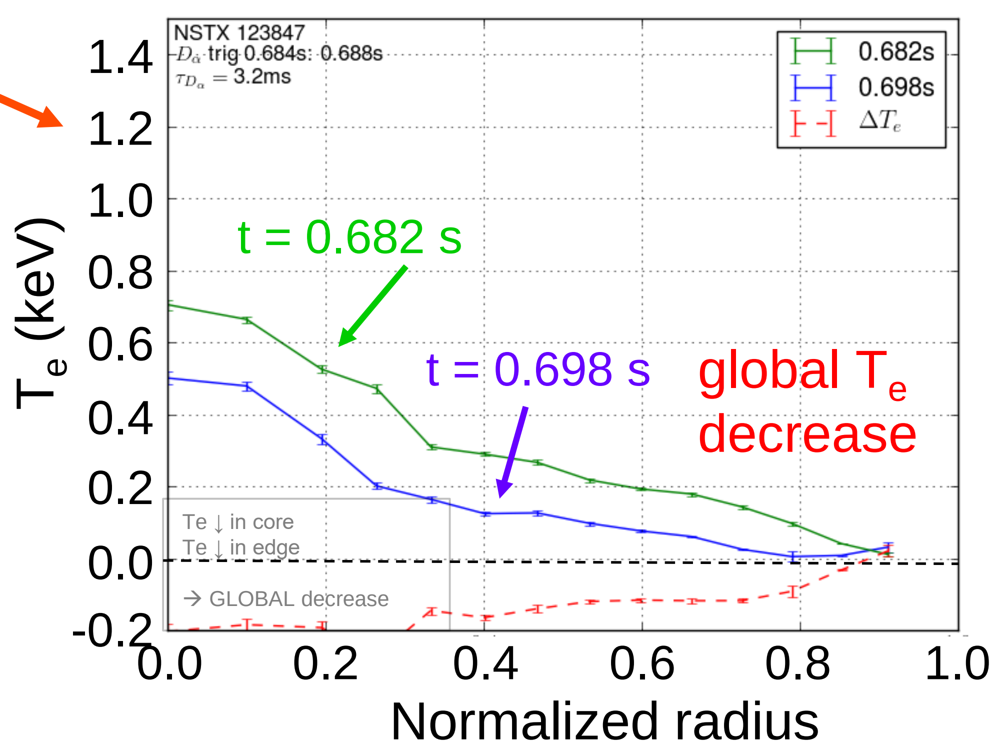
J. Berkery, et al., APS DPP BP11.00016

T_e profile provides critical addition to D_α ELM detection by determining the radial extent of perturbation – needed to distinguish disruptive MHD



D_α 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)

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