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Tokamak Disruption Event Characterization and Forecasting (DECAF) and Progress on Real-Time Implementation

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KFE KOREA INSTITUTE OF FUSION ENERGY

KSTAR

PPPL

NOVA PHOTONICS

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

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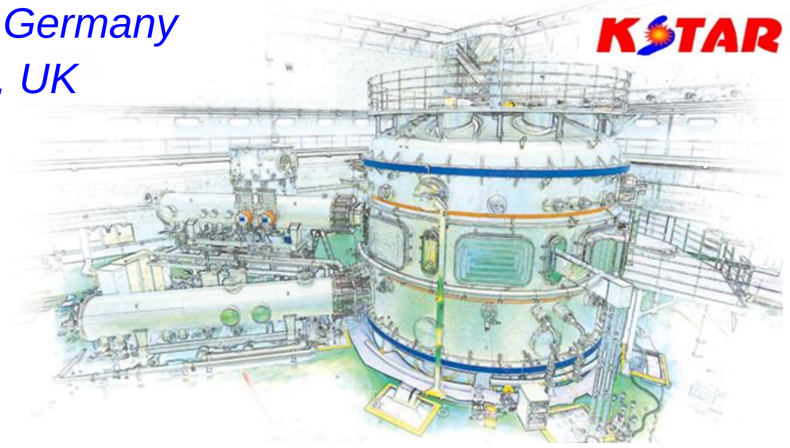
APAM Physics Colloquium

(Virtual)

18-Feb-2022



V1.0

Supported by US DOE grant DE-SC0016614

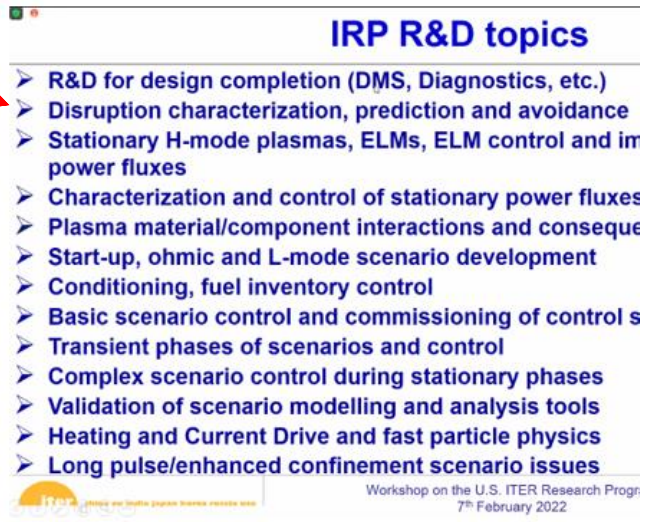
DECAF is a broad-based physics research program aimed at a "grand-challenge" goal of disruption elimination in tokamaks

- Disruption Event Characterization and Forecasting (DECAF) quick review
- MAST-U stability projections, initial stability space investigation
- DECAF ELM detection with global MHD discrimination
- Initial DECAF locked mode proximity determination in ASDEX-U
- DECAF locked mode forecasting model and application to KSTAR
- Stability sensitivity study on KSTAR examining potential use in MRE
- Predict-first analysis of 100% non-inductive current KSTAR plasmas
- Counterfactual machine learning analysis examination for DECAF
- DECAF computational and database capability expansion
- Real-time DECAF implementation on KSTAR

Disruption Prediction and Avoidance is a Highest Priority International Topic for ITER and Beyond – KSTAR is a key leader

- Present DOE U.S.-ITER ReNeW Workshop
  - Disruption prediction and avoidance remains a highest priority topic
  - Alberto Loarte (ITER) showed this topic as a highest priority ITER need

From Alberto's Talk



- The ITPA MHD and IOS Topical Groups
  - ITPA MHD Spring meeting will emphasize this topic
  - MDC-22 (G. Pautasso) is holding special meetings to prepare
  - We are keeping the MDC-22 group informed regarding DECAF capability, integrated real-time diagnostics / real-time DECAF implementation and research on KSTAR
- The ITER Control Team
  - Starting participation in design meetings of the ITER PFP01 control system for implementation of real-time DECAF in the ITER control system

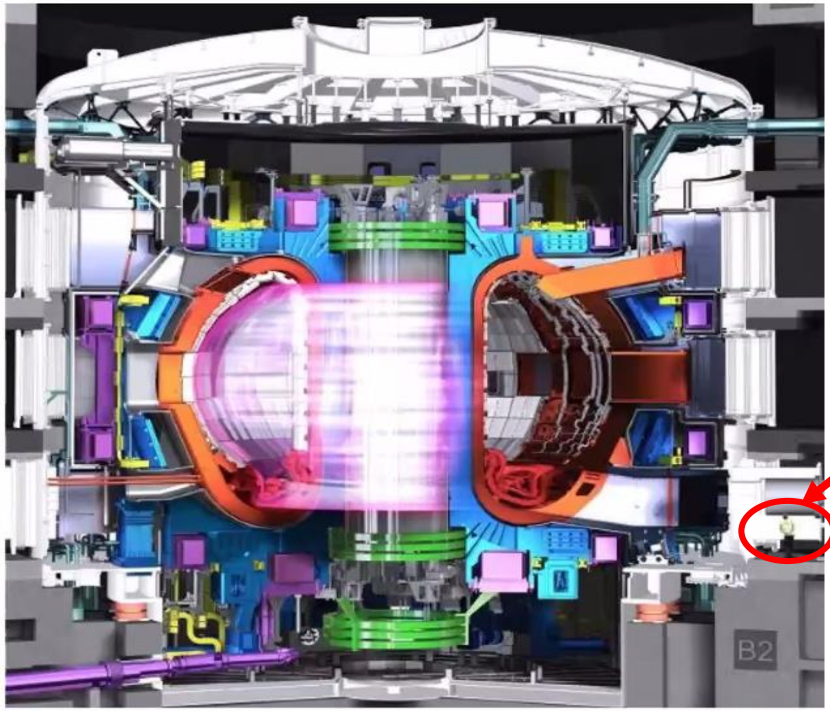
ITER is the largest tokamak in the world (construction 80% completed) that will produce a burning fusion plasma for the first time

A. Loarte, et al., U.S.-ITER Research Program talk 2/7/22

ITER Mission and Goals

To demonstrate the scientific and technological feasibility of fusion power as energy source for humankind

- Pulsed operation:
  Q ≥ 10 for burn lengths of 300-500 s inductively driven current
  → Baseline scenario 15 MA / 5.3 T
  $P_\alpha \geq 2\ P_{external\text{-}heat}$
- Long pulse operation:
  Q ~ 5 for long pulses up to 1000 s
  → Hybrid scenario ~ 12.5 MA / 5.3 T
- Steady-state operation:
  Q ~ 5 for long pulses up to 3000 s, with fully non-inductive current drive
  → Steady-state scenario ~ 10 MA / 5.3 T



person (!)

iter china eu india japan korea russia usa

Workshop on the U.S. ITER Research Program
7th February 2022

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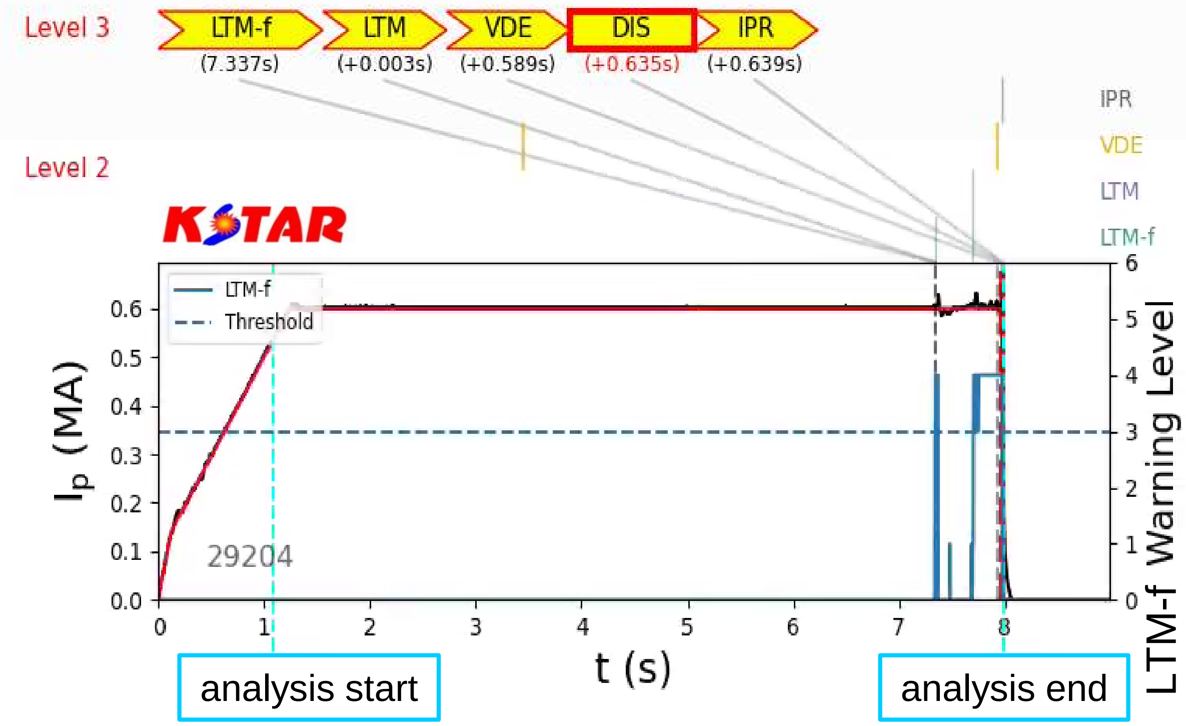
- Please visit https://www.iter.org for full information including GREAT photos!

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

- Fully automated, physics-based analysis of existing tokamak databases from multiple devices (e.g. KSTAR, NSTX, MAST/-U, AUG)

(J. Berkery BP11.00016 ➔ MAST/-U)
(V. Klevarova JP11.00059 ➔ AUG)

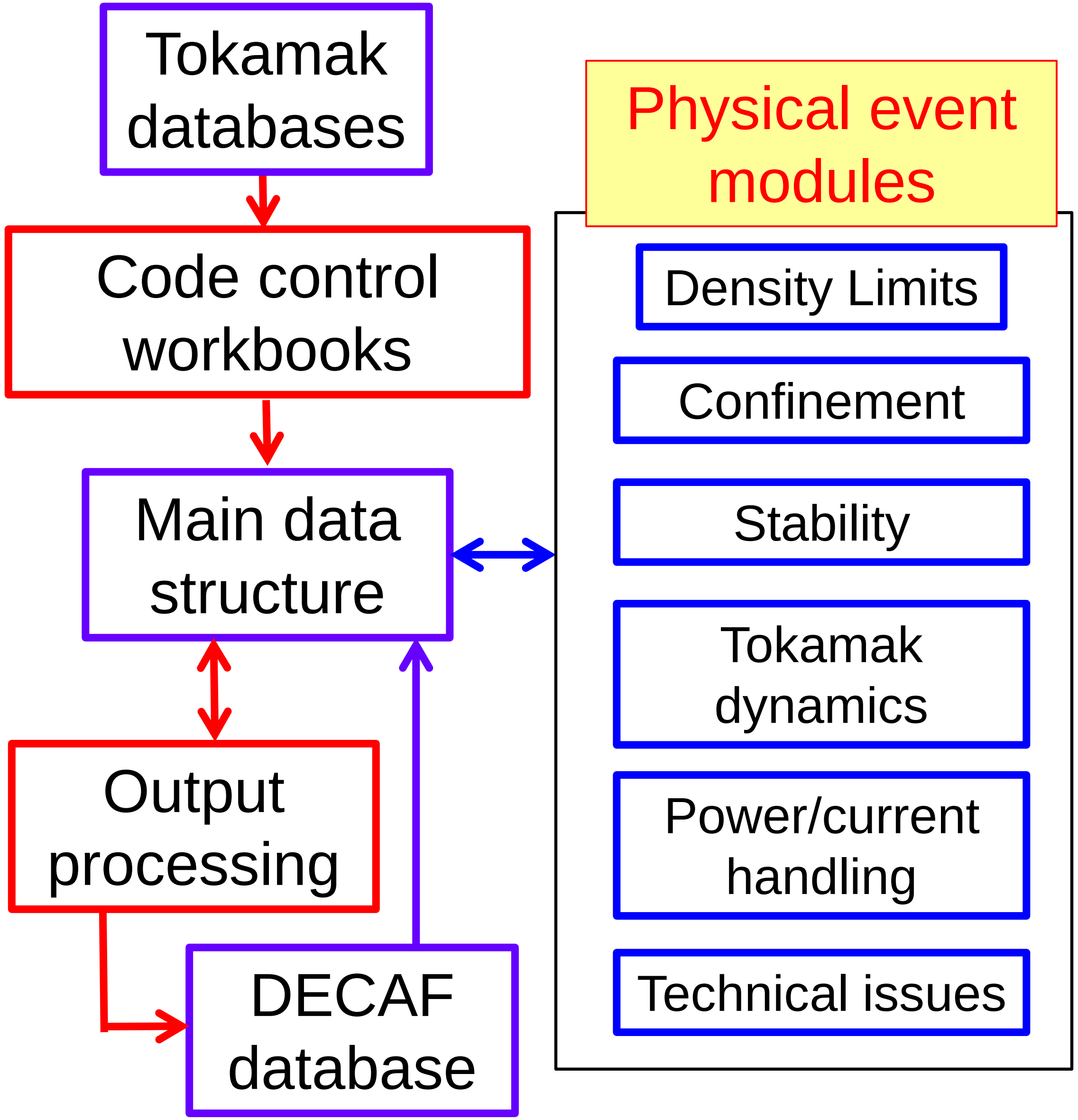
- Analyzing all plasma states, continuous and asynchronous events
  - "Critical": (Level 3) event chains leading to disruption if no action taken
  - "Proximity": (Level 2) paths to "critical" events
  - "Safe": (Level 1) events indicate steady operation (e.g. L-mode / H-mode determination, steady ELMing, benign confinement transitions)



- "Forecaster events": give earliest warnings
- High quantitative success found to date
  - > 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

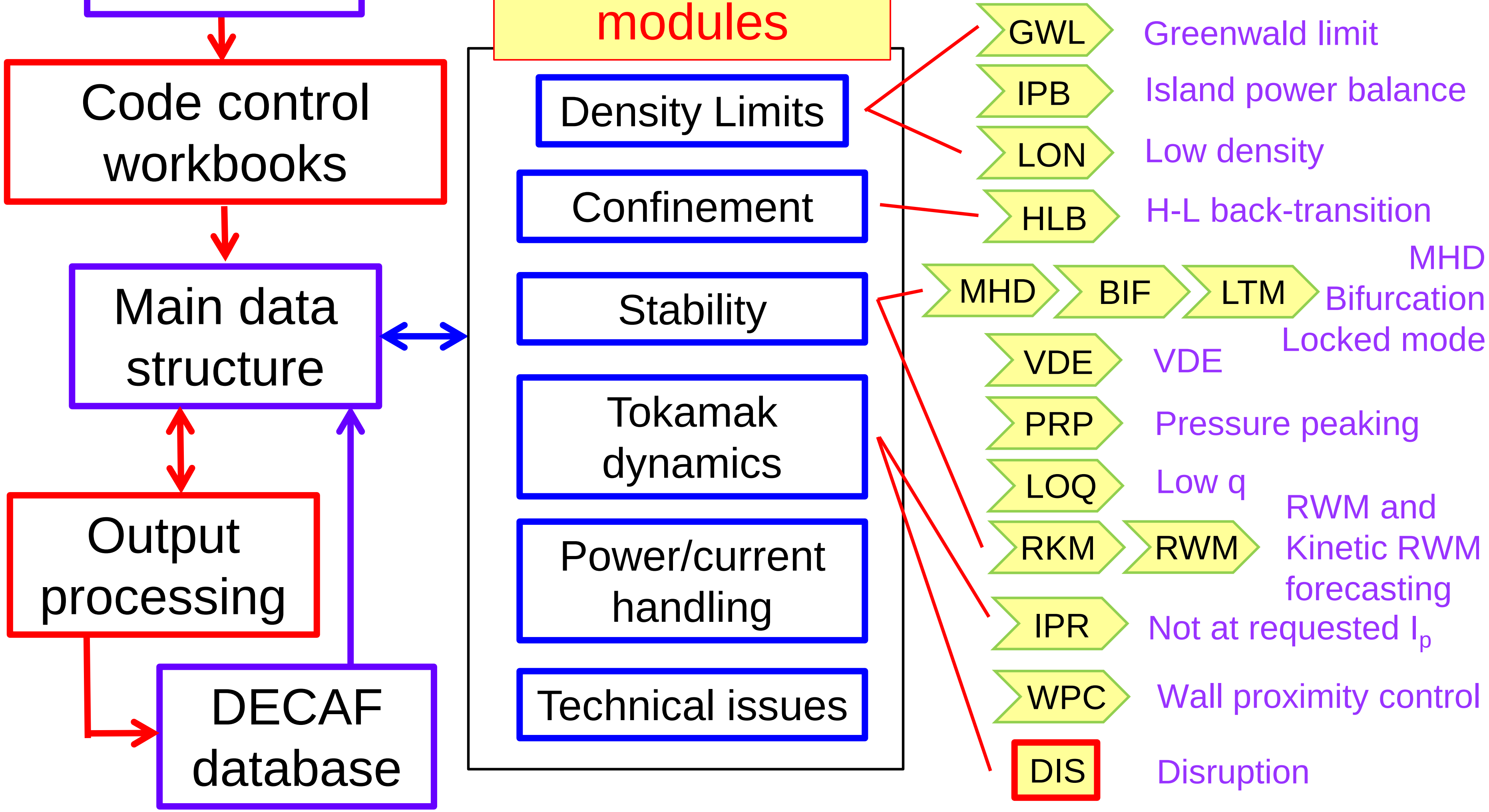
DECAF is a physics-based approach to disruption event understanding / forecasting to enable disruption avoidance



- Physical event modules encapsulate disruption chain events
  - Continued development focuses on improving these modules
  - Structure eases parallel development incl. real-time
- KEY: Offline and real-time analysis INTEGRATED
  - The SAME researchers that oversee the offline code/analysis are responsible for real-time code specifications

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

- Physical event modules encapsulate disruption chain events. Examples:

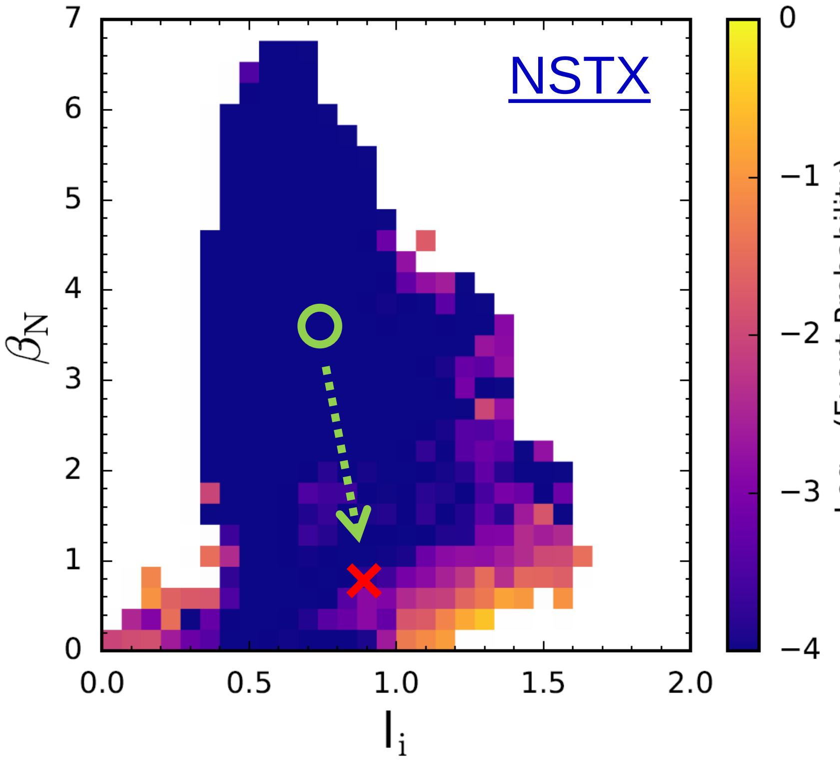


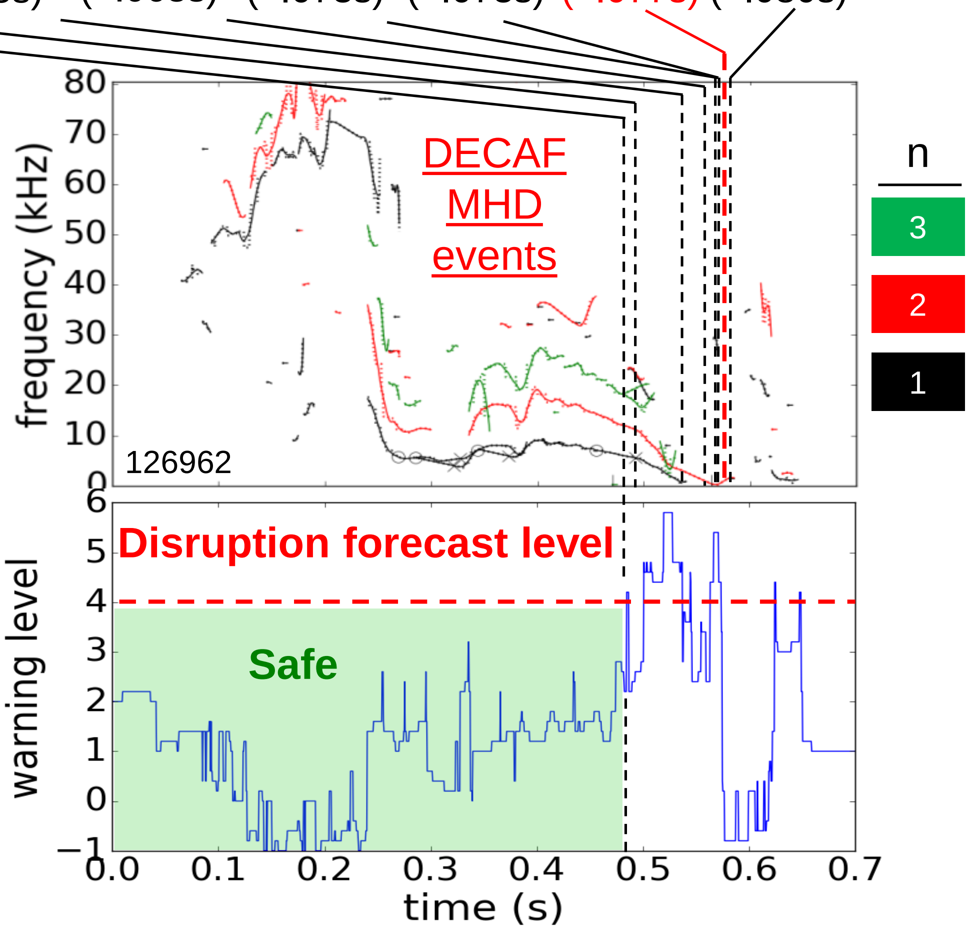
Review: DECAF provides an early disruption forecast - on transport timescales – giving potential for disruption avoidance

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





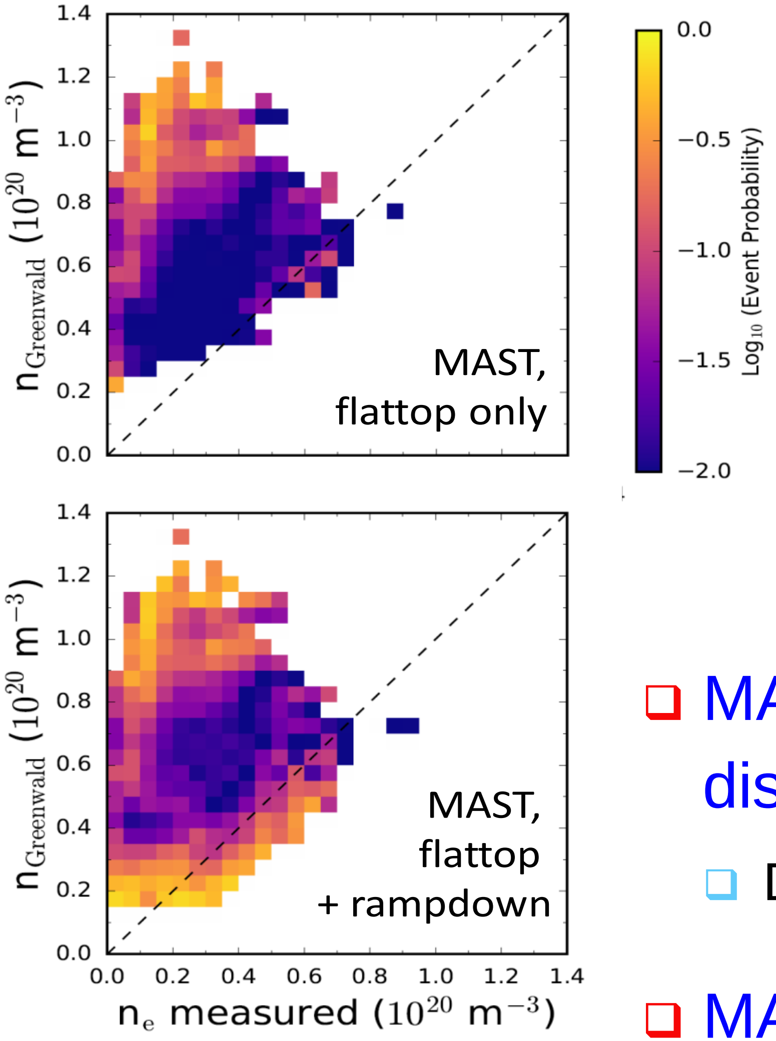
- DECAF event chain reveals physics
  - Rotating MHD slows, bifurcates, locks
  - Plasma has an H-L back-transition (pressure peaking warning PRP) before DIS
  - Early warning occurs in apparently SAFE region of operating space!

- NOTE: 15 conditions used including plasma velocity profile

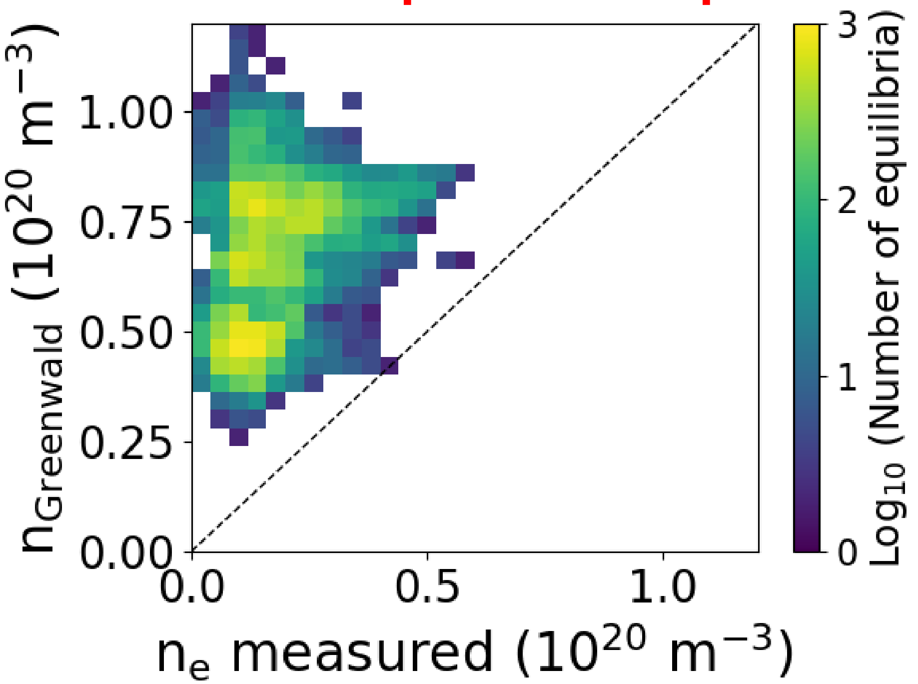
S.A. Sabbagh, et al., 2020 IAEA Fusion Energy Conference, Paper IAEA-CN-286/1025

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

MAST disruptivity



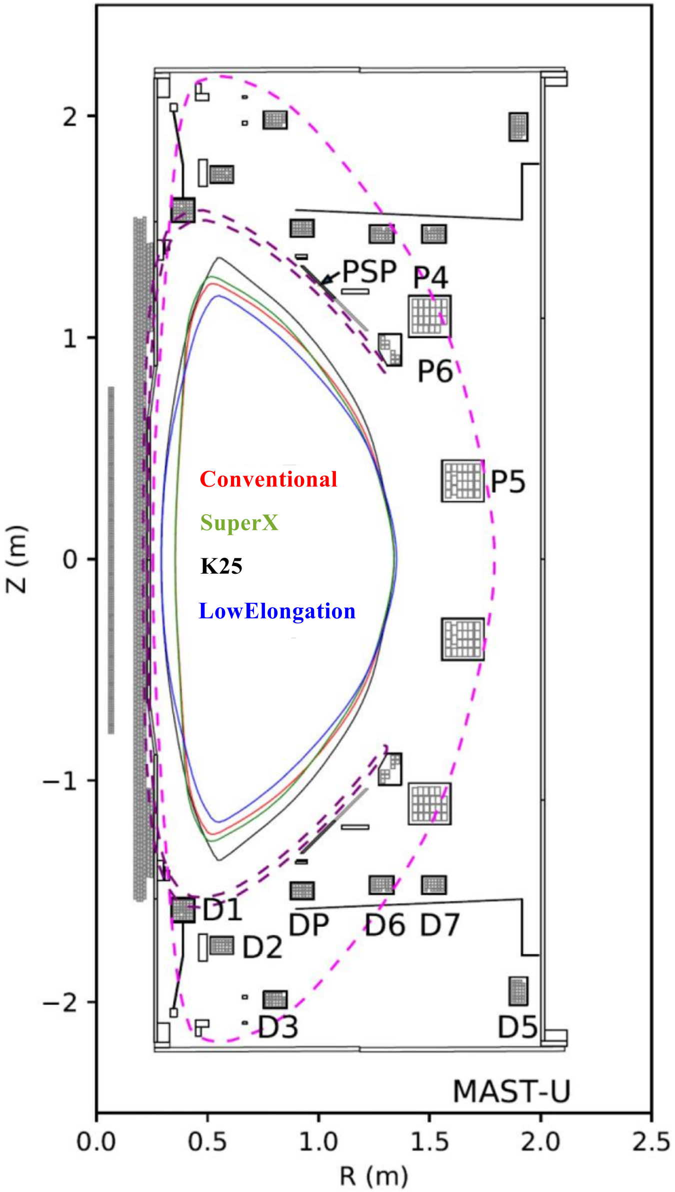
MAST-U operational space

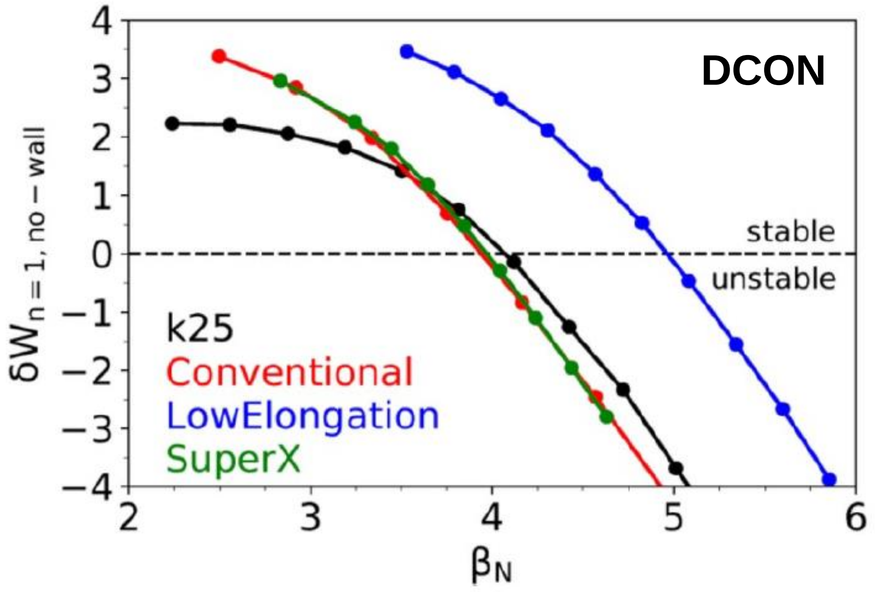


- MAST flattops reached the Greenwald limit, but disruptions over the limit were relatively rare
  - Decreasing I_p in ramp down reduces the limit
- MAST-U flattops usually well below limit

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

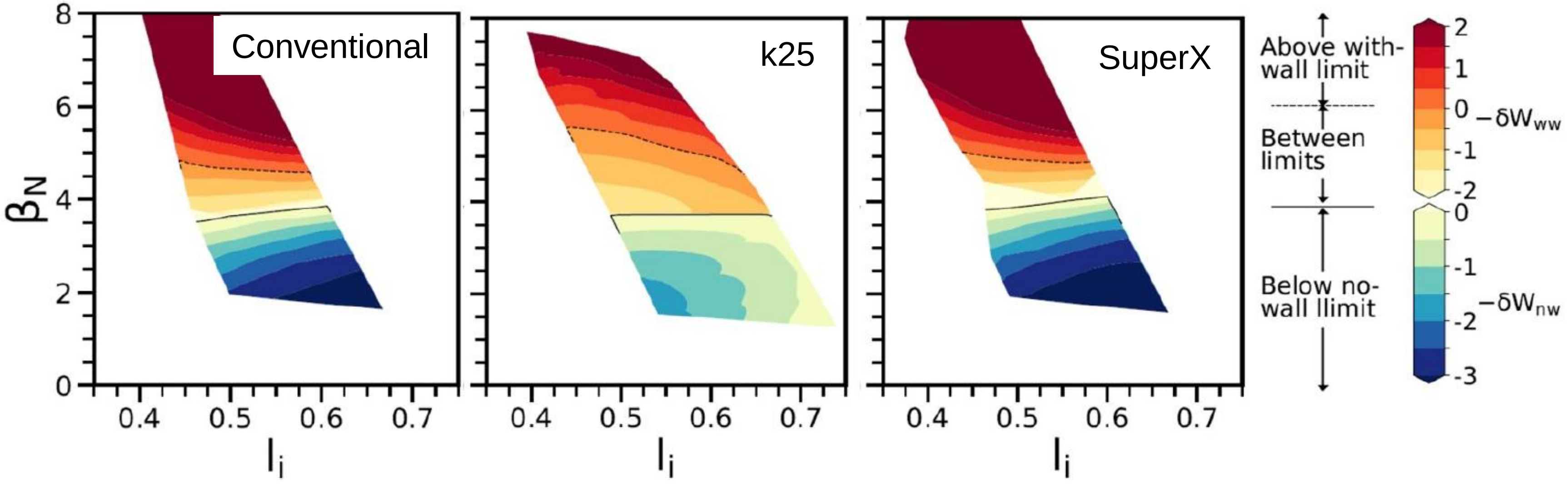
Ideal stability of four MAST-U projected equilibria shapes were evaluated for stability by scaling pressure, etc.



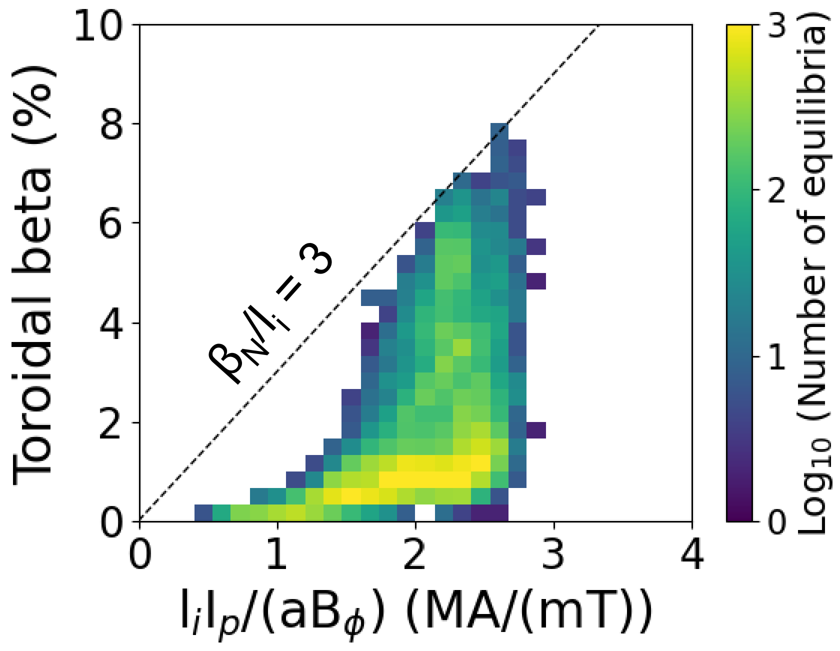


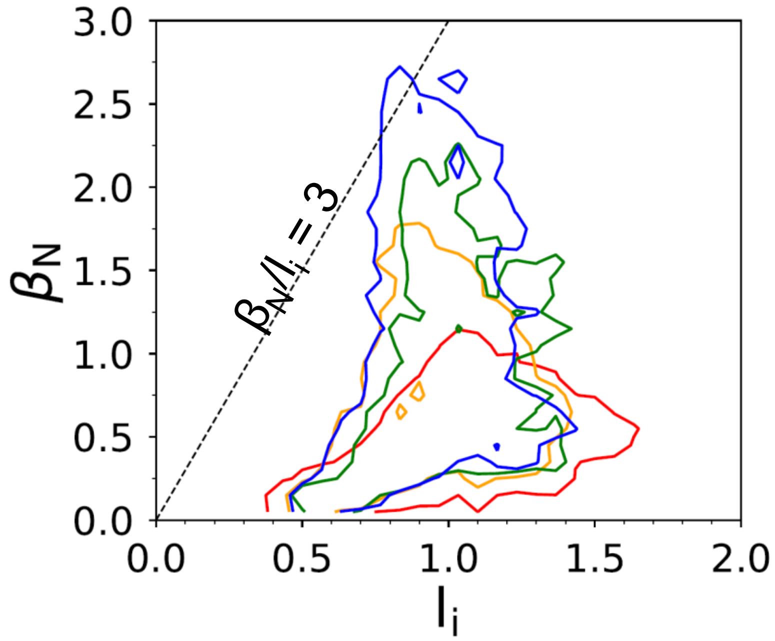
- Ideal stability evaluation
  - pressure profile scans
  - q(0) scans
  - Projected no-wall limit: β_N ~ 4 and β_N/l_i ~ 7

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



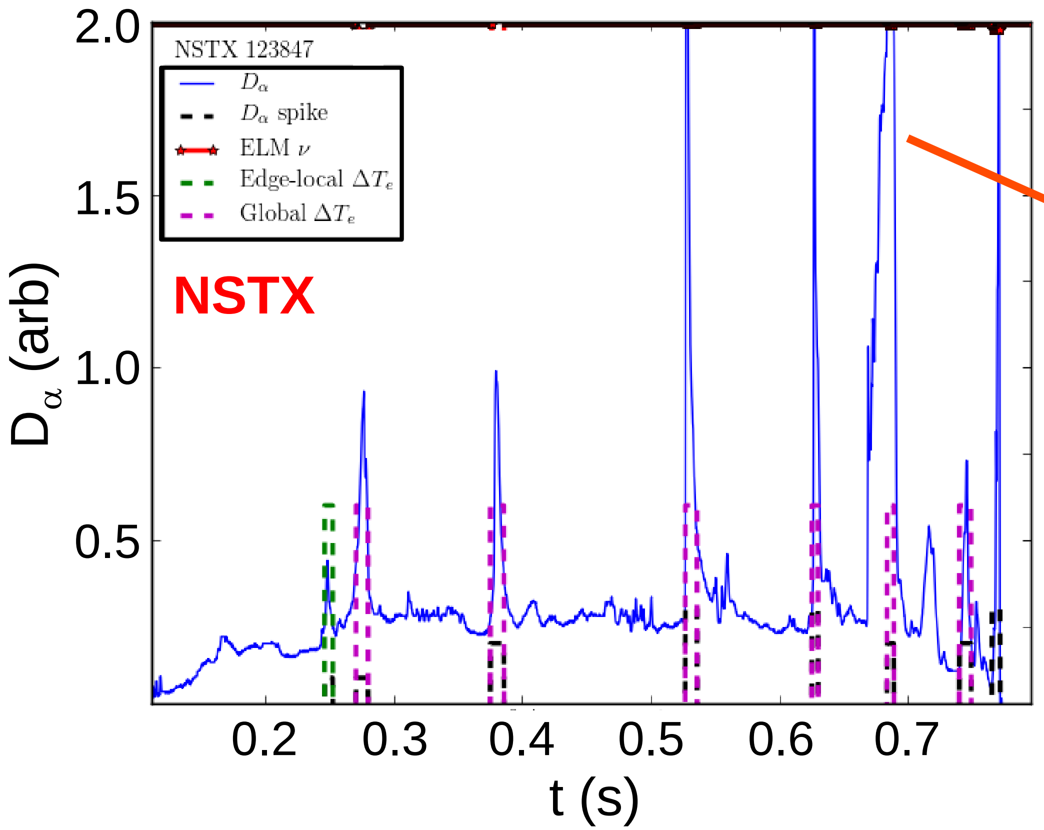
DECAF examination of MAST-U operation has reached max β_N of 3.18 and β_N/l_i of ~3.3, still below computed global stability limits





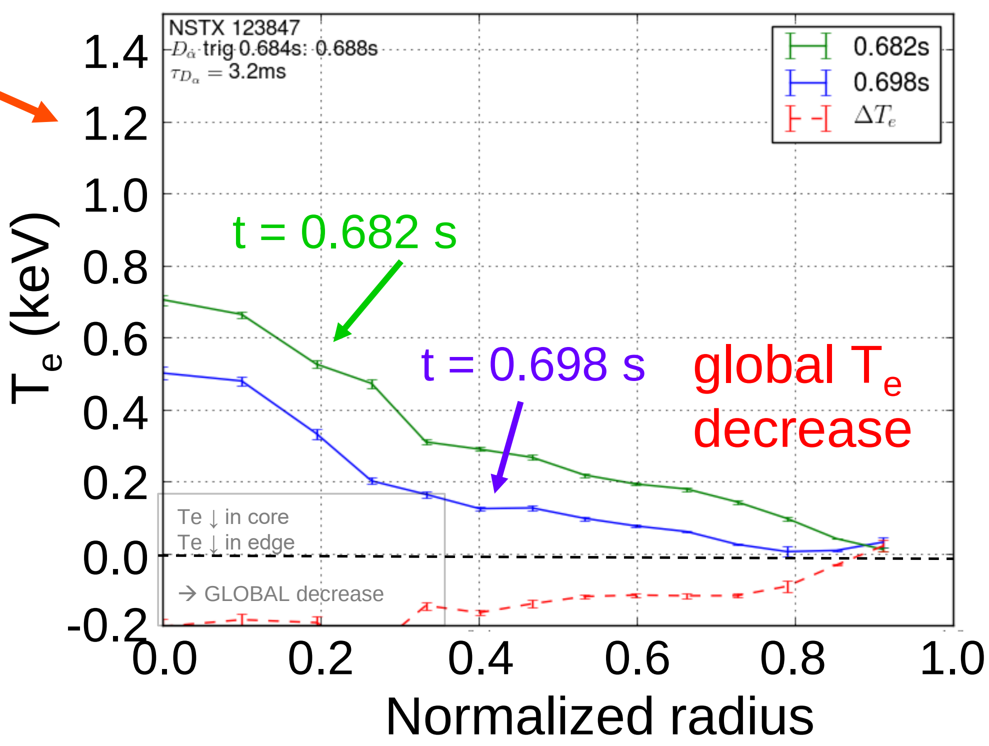
- Normalized beta diagrams show macroscopic stability limits
  - The colored lines are contours containing at least 10 equilibria for:
  - Ohmic (red), SW off axis beam (orange), SS on axis beam (green), and two beam (blue)
- Projected MAST-U no-wall limit: β_N ~ 4 and β_N/l_i ~ 7

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)

Locked mode dependence on plasma parameters being studied for "proximity" disruption prevention approach

(V. Klevarova JP11.00059 ➔ AUG)

- In large devices, static ('locked') modes (LM) are frequently detected close to the end of chain of events that lead to disruption [1, P.C. de Vries et al., *Nucl. Fusion* **51** (2011) 053018]
- Semi-empirical scaling relations for mode locking based on mode amplitude have been derived and (routinely) applied

  -> Some normalize LM amplitude to plasma current, e.g. in JET

  'Mode lock/Ip: 400–520 pT/A' [2, C. Reux et al. *Fusion Engin. and Design* 88 (2013) 1101-1104, Table 1]

- Multi-device study of disruptive LM amplitude $B_{LM,disr}$ shown in [3, P.C. de Vries et al., *Nucl. Fusion* **56** (2016) 026007] resulted in a scaling containing more physics ingredients:

$$\hat{B}_{LM,\,disr}(r_c) \propto I_p \cdot a^{-1.1} \cdot (li/q_{95})^{1.2} \cdot \rho_c^{-2.8} \qquad (1)$$

$\rho_c = r_c/a$, $r_c = |R_{mag} - R_{coils}|$
a .. plasma size, ρ_c .. mode structure
q_{95} .. mode-plasma edge distance
li/q_{95} .. proxy for energy driving mode growth

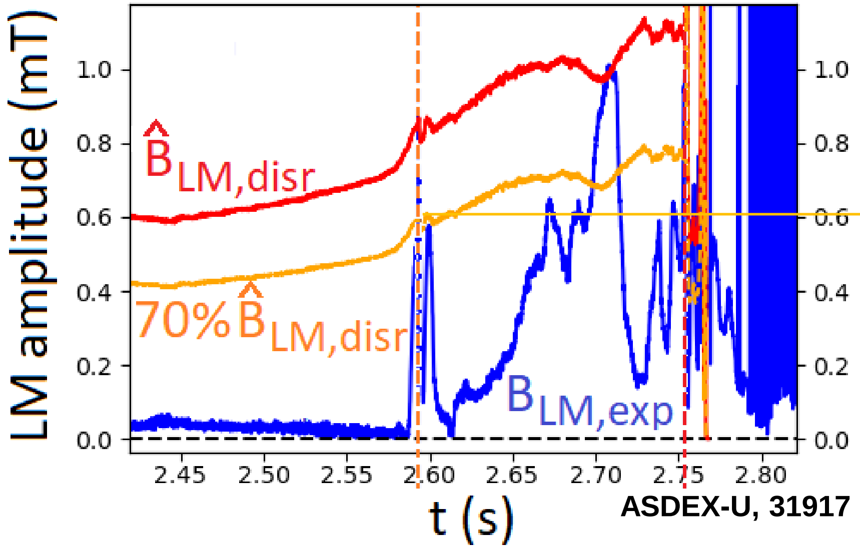
- Scaling (1) was further validated on large database (JET, ASDEX-U, DIII-D, COMPASS) in [4, V. Klevarova et al., *Fusion Engin. and Design* 160 (2020) 111945]
  - For example in ASDEX-U $B_{LM,disr}$ ~ (0.95 ± 0.42) $\hat{B}_{LM,disr}$ at the disruption time

Proximity of experimental and scaled disruptive mode amplitudes a measure of disruption onset (ASDEX-U)

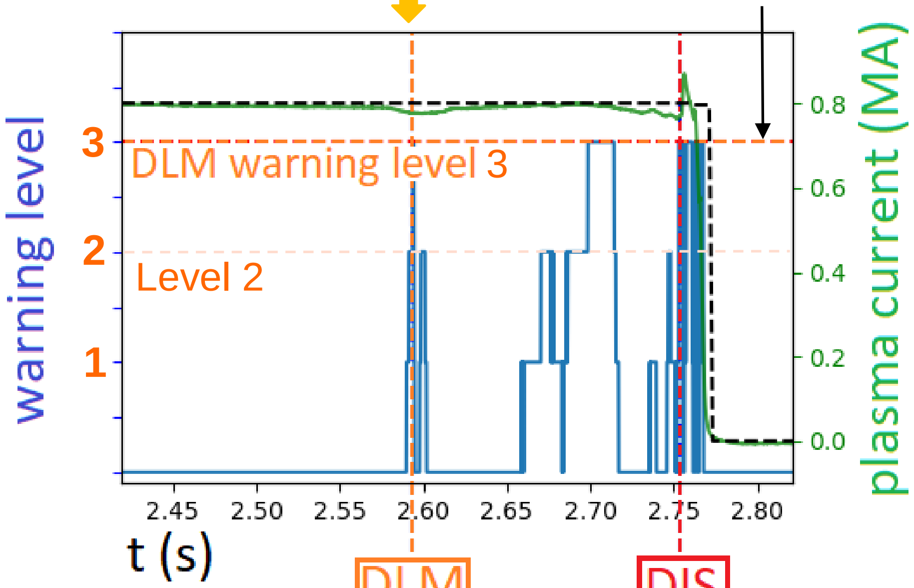
(V. Klevarova APS DPP JP11.00059)

- When compared to experimental data, scaling (1) can estimate how '*close*' the mode, in terms of amplitude, is to disrupt the plasma
  - **Here, (1) added to DECAF, warning is generated once experimental mode amplitude $B_{LM,exp}$ reaches a certain level of $\widehat{B}_{LM,disr}$ -> this will become one of DECAF events, the DLM event ('disruptive locked mode')**

here 70%



Level 3 = *event will disrupt plasma, take action!*
Level 2 = *disruptive level is approached, pay attention!*



- **Level of $\widehat{B}_{LM,disr}$ can be varied, allowing study of DLM performance in pre-disruptive warning generation**

Upper figure: Comparison of scaled $\hat{B}_{LM,disr}$ and experimental $B_{LM,exp}$ mode amplitudes for an ASDEX-U discharge
Right figure: Generation of DLM warning in DECAF once $B_{LM,exp}$ reaches certain level (70%) of $\hat{B}_{LM,disr}$ (DIS: disruption time)

Initial confusion matrix evaluation of DLM capability for ASDEX-U shows promise for use as a proximity

(V. Klevarova APS DPP JP11.00059)

Confusion Matrix Result

TP: 17.7 %	FP: 15.7%
FN: 22.3 %	TN: 44.3%

STUDY INTERVAL [FTE-0.5 s, FTE+0.1s]

DLM

- **Level 3 warning generated (33.4%)**
  - **Had DIS (26.5%, 79.2%)**
    - Median(DIS-DLM) $\pm$ MAD: 5.6 $\pm$ 7.7 ms
    - **DLM <= DIS (17.7%, 66.8%)**
      - TRUE POSITIVE
      - DIS-DLM: 24.0 $\pm$ 21.4 ms
    - **DLM > DIS (8.8%, 33.2%)**
      - FALSE POSITIVE
      - DIS-DLM: -1.3 $\pm$ 0.5 ms
  - **No DIS (6.9%, 20.8%)**
    - FALSE POSITIVE
- **No Level 3 warning (66.6%)**
  - **Had DIS (22.3%, 33.5%)**
    - FALSE NEGATIVE
  - **No DIS (44.3%, 66.5%)**
    - TRUE NEGATIVE

- First % in parentheses refer to full set of 2694 shots (Slide 13), second % to number of shots in the upper category

MAD: Median absolute deviation

Island rotation dynamics model 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:

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

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

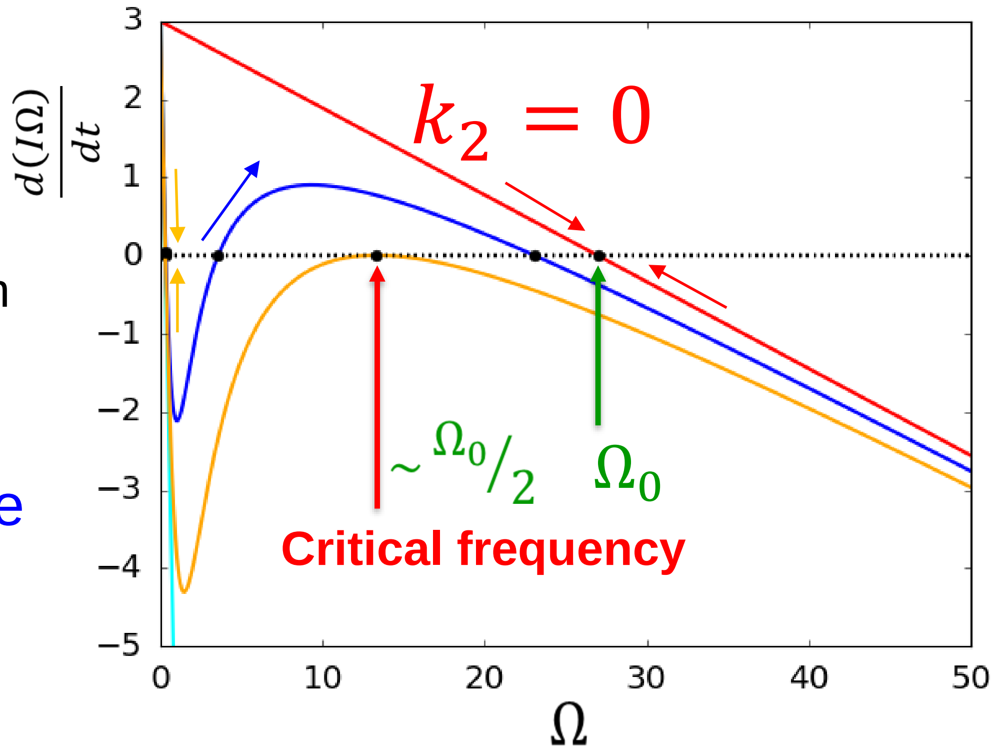
- At very low angular speed, mode can reach a stable steady state,
  ➔ observed in KSTAR

- First real-time model, assume “no slip” condition

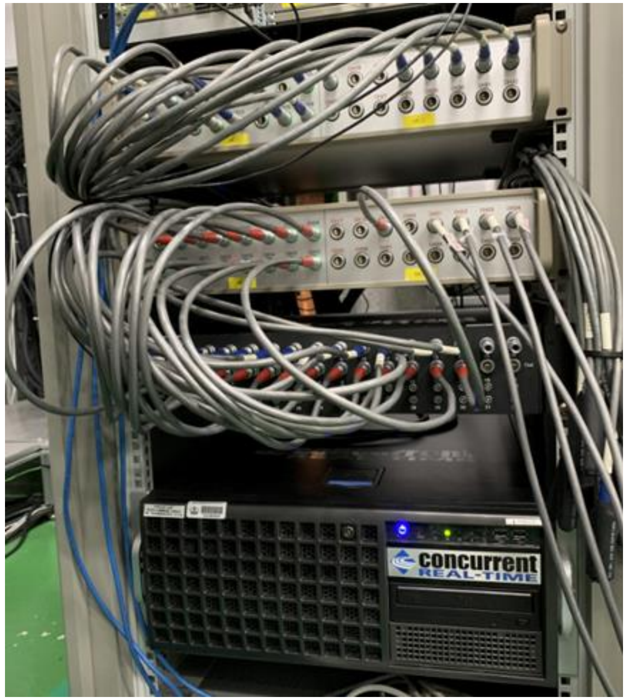
$$T_{mode} = \frac{k_1}{\Omega}$$

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

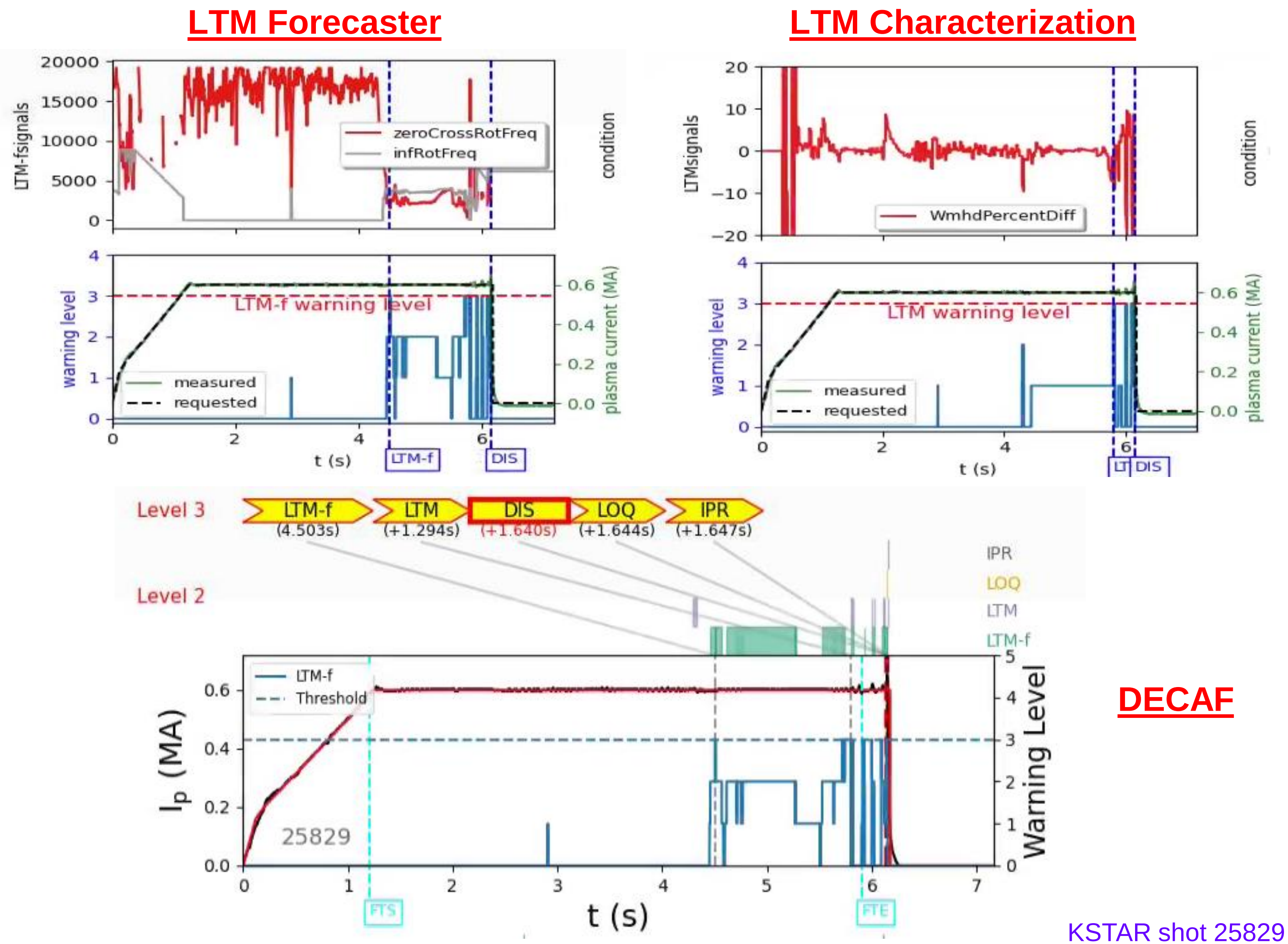


J. Riquezes, et al. APS DPP PO09.00007

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

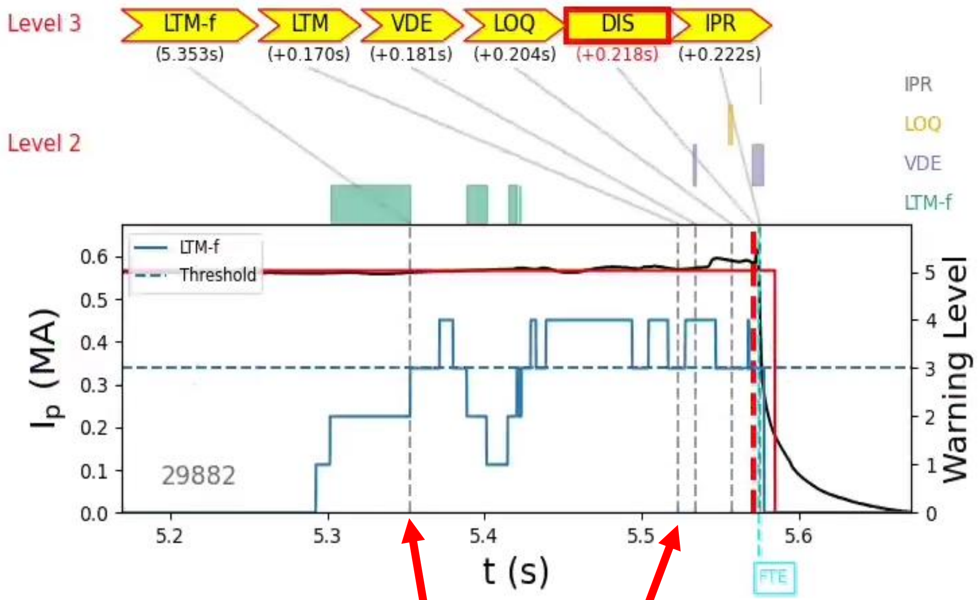
J. Riquezes, et al. APS DPP PO09.00007

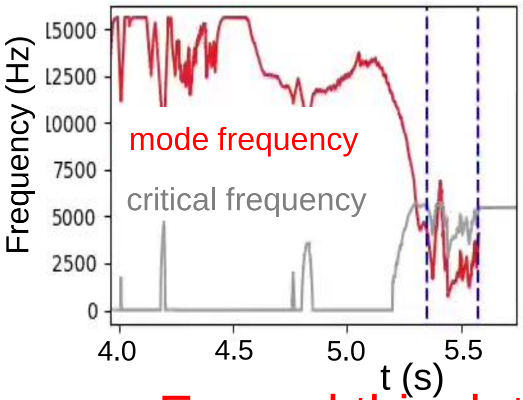


KSTAR shot 25829

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

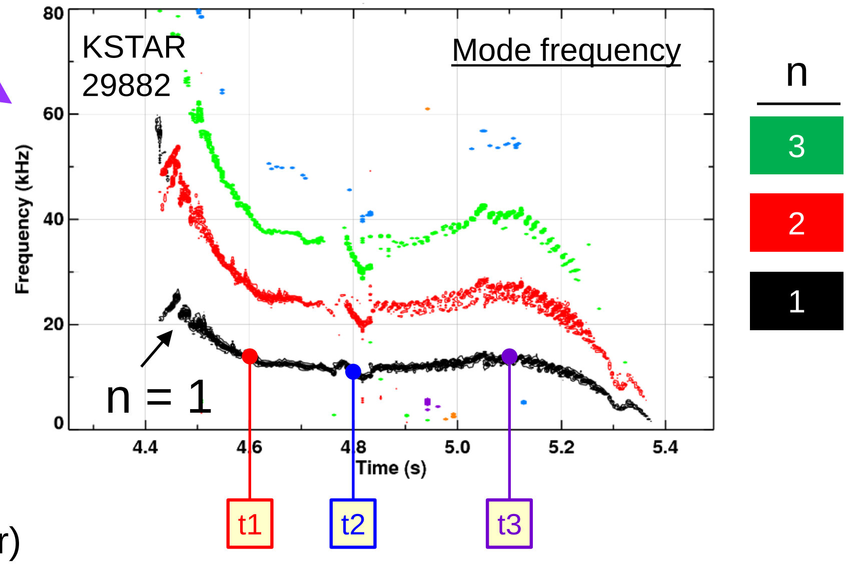
DECAF locked mode (LTM), forecaster (LTM-F) events (rtMHD system)



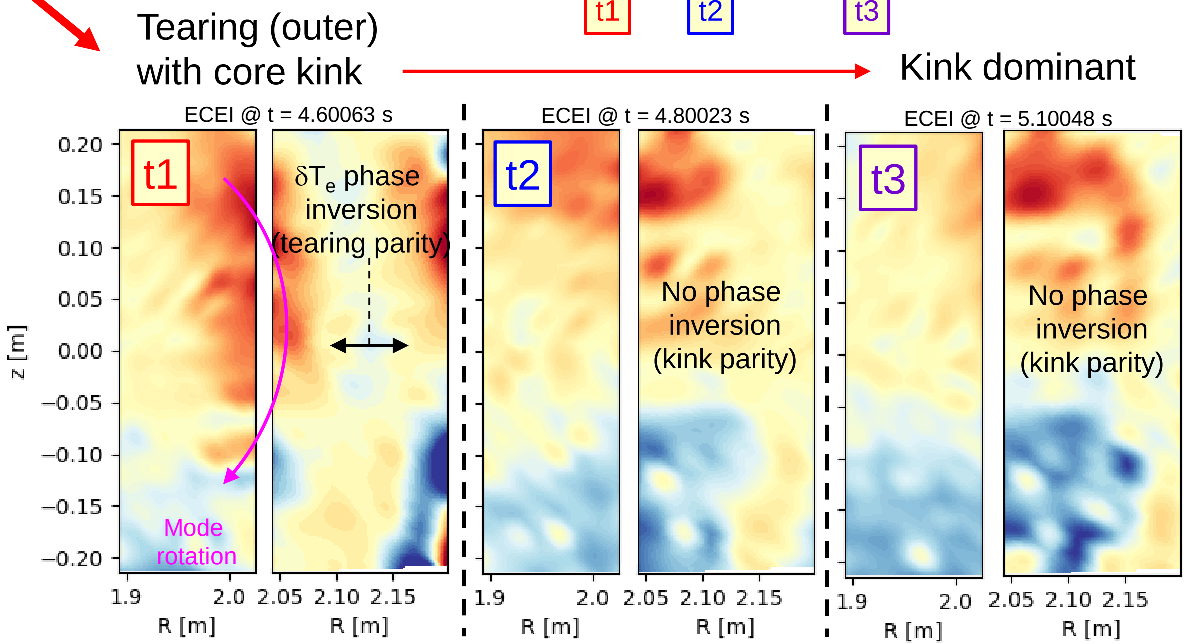


- LTM-f forecaster triggered 218 ms before disruption
- LTM event 170 ms after it was forecast

Magnetic spectrogram (toroidal array)



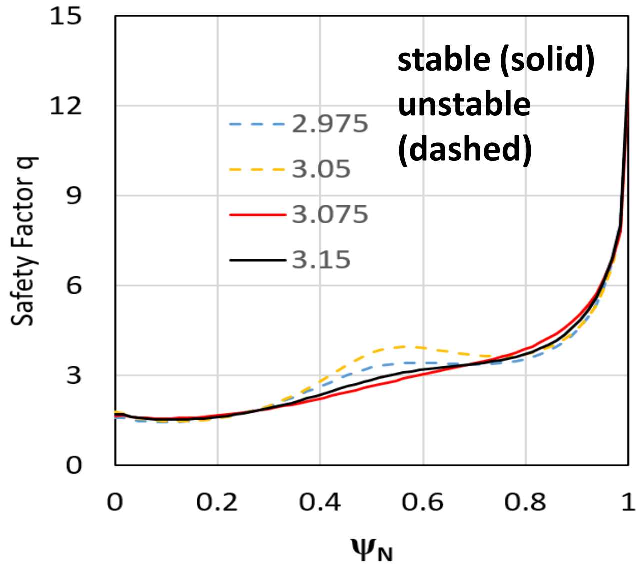
2D ECE imaging (ECEI)

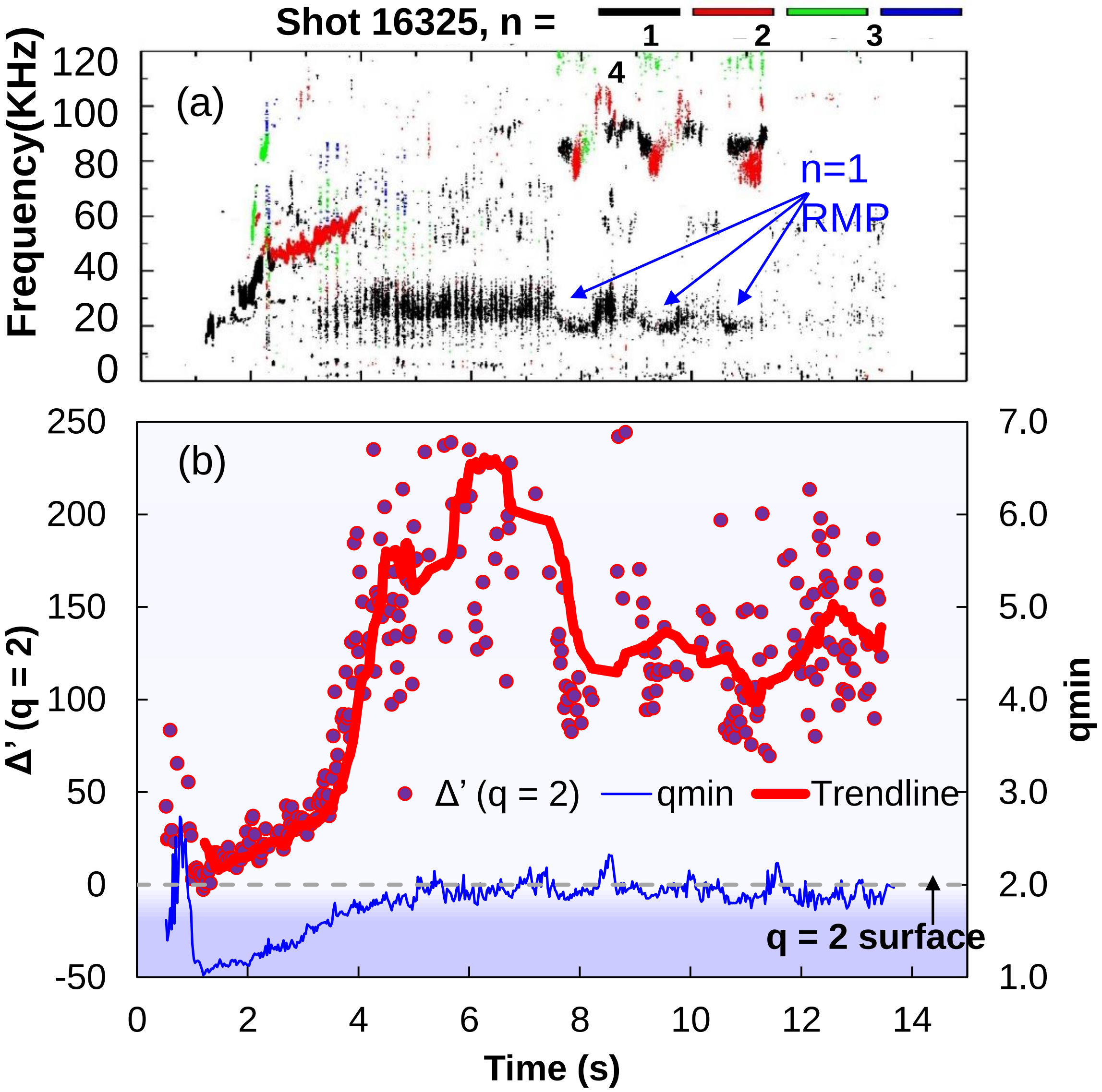


- Expand this data/analysis, including real-time!

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

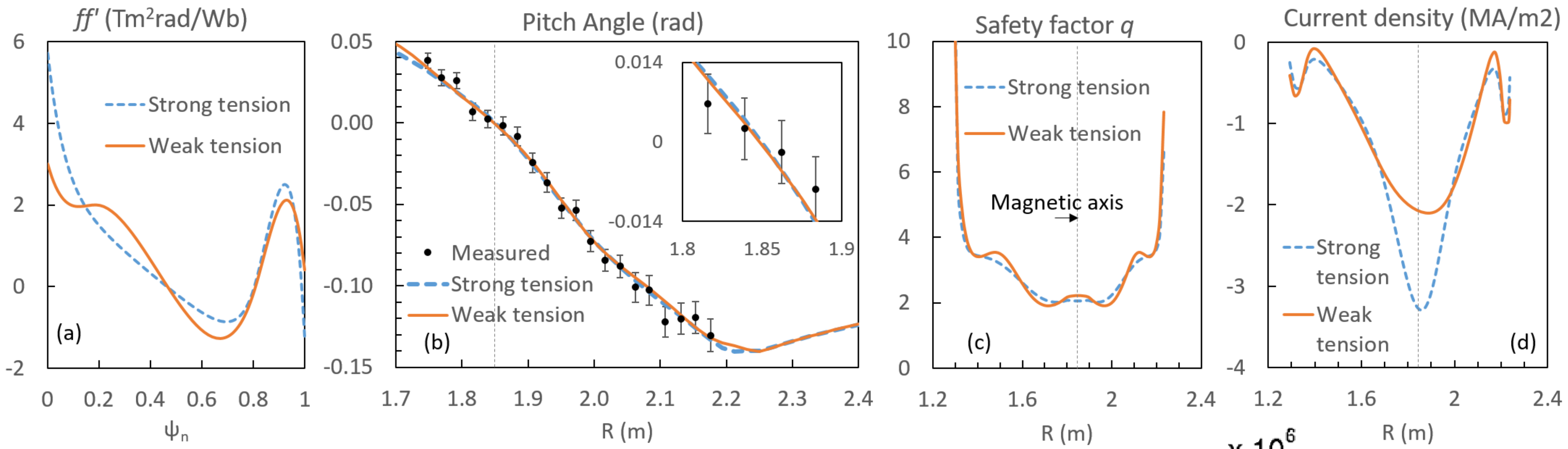




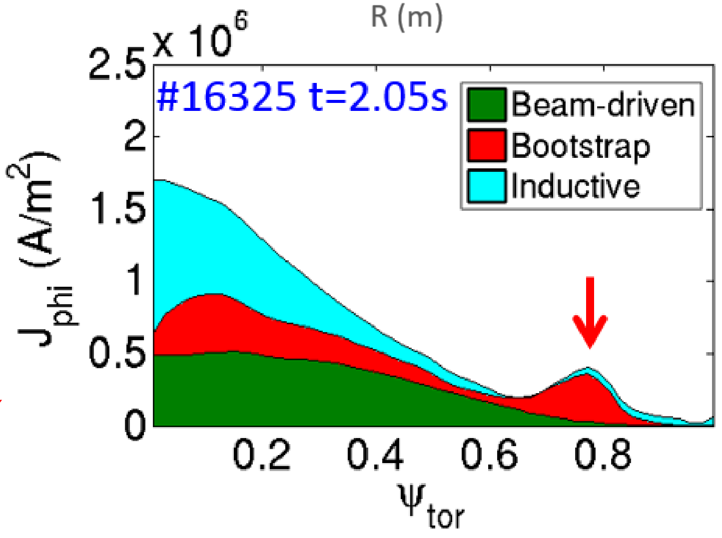
- Δ' analysis supporting evaluation of modified Rutherford equation as resistive stability indicator
- Less freedom in equilibrium basis functions produces less computed stabilty variation

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

Weak splined tension basis function model manifests greater localized reversed shear and off-axis current profile



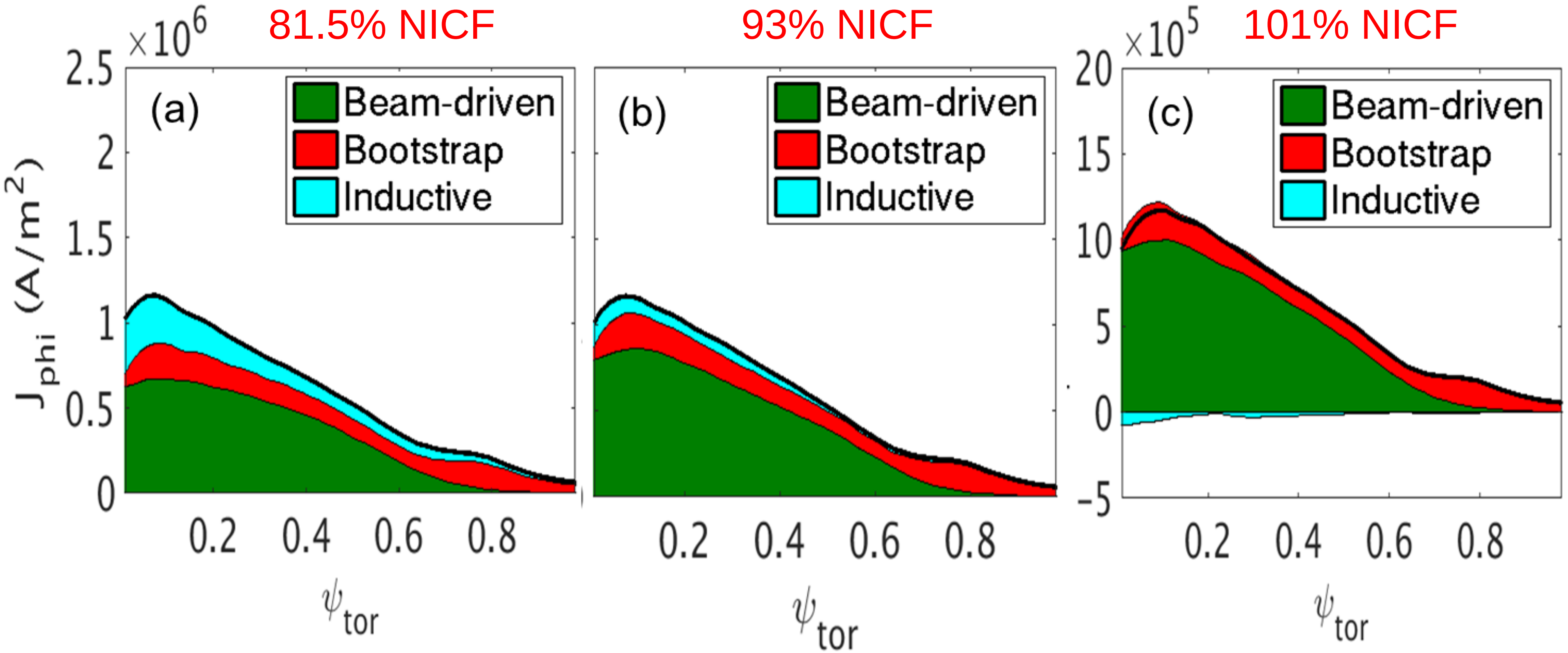
- Polynomial basis function models also produce MSE measured data
- Local flat spots form in q profile
  - challenging for ideal and resistive stability evaluation
- Consistent with KSTAR TRANSP high non-inductive current evaluation (~ 75% total non-inductive current)



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

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

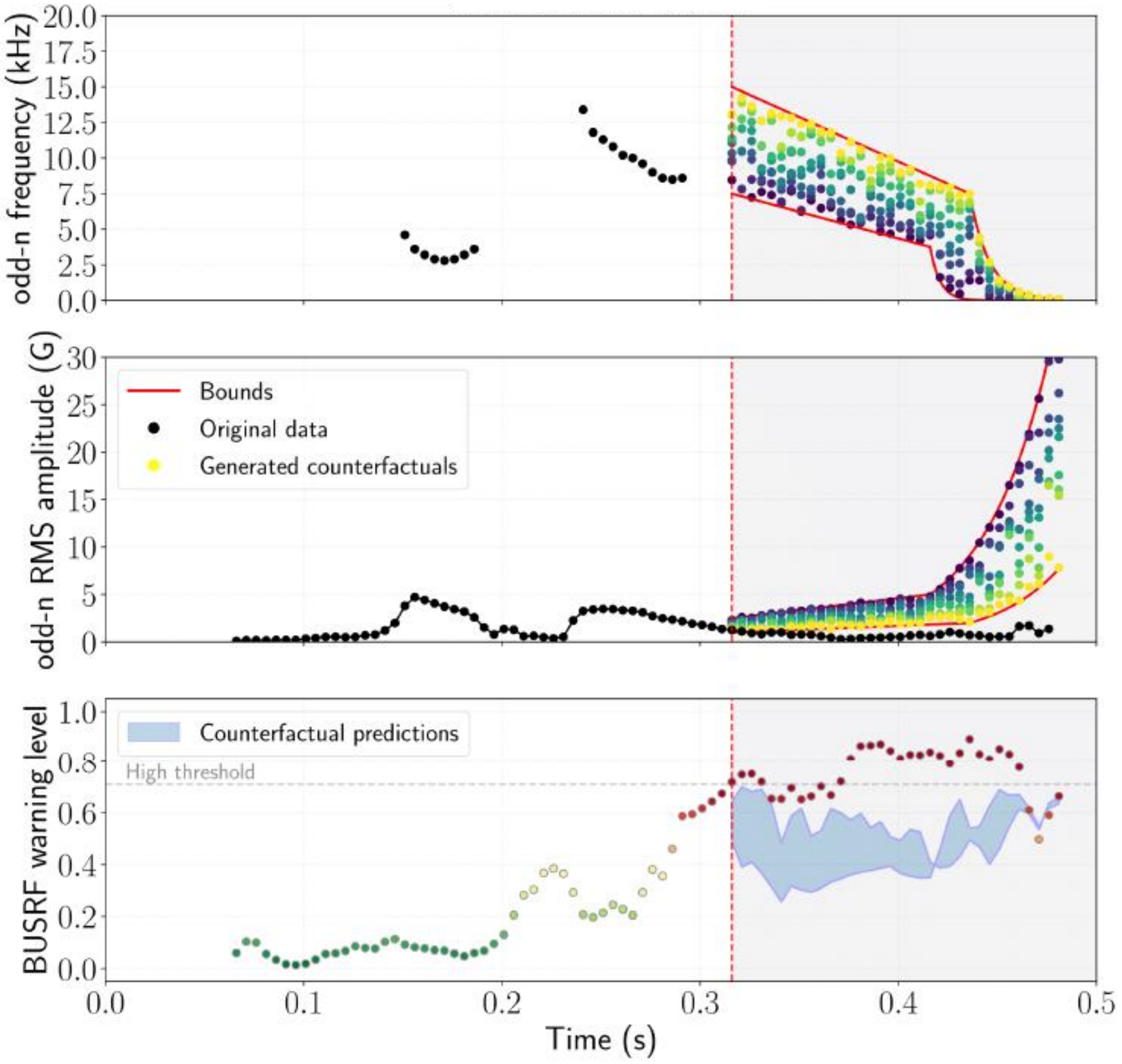
Predicted high non-inductive current fraction (NICF) current profiles



- 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)

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

- RWMs typical do not grow in NSTX if strong rotating MHD is present
- Consideration of 10 different MHD activity evolutions that would have kept the RWM stable on NSTX
- Counterfactual generation 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 development attention 2020 – 2021 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

See NEXT slides!

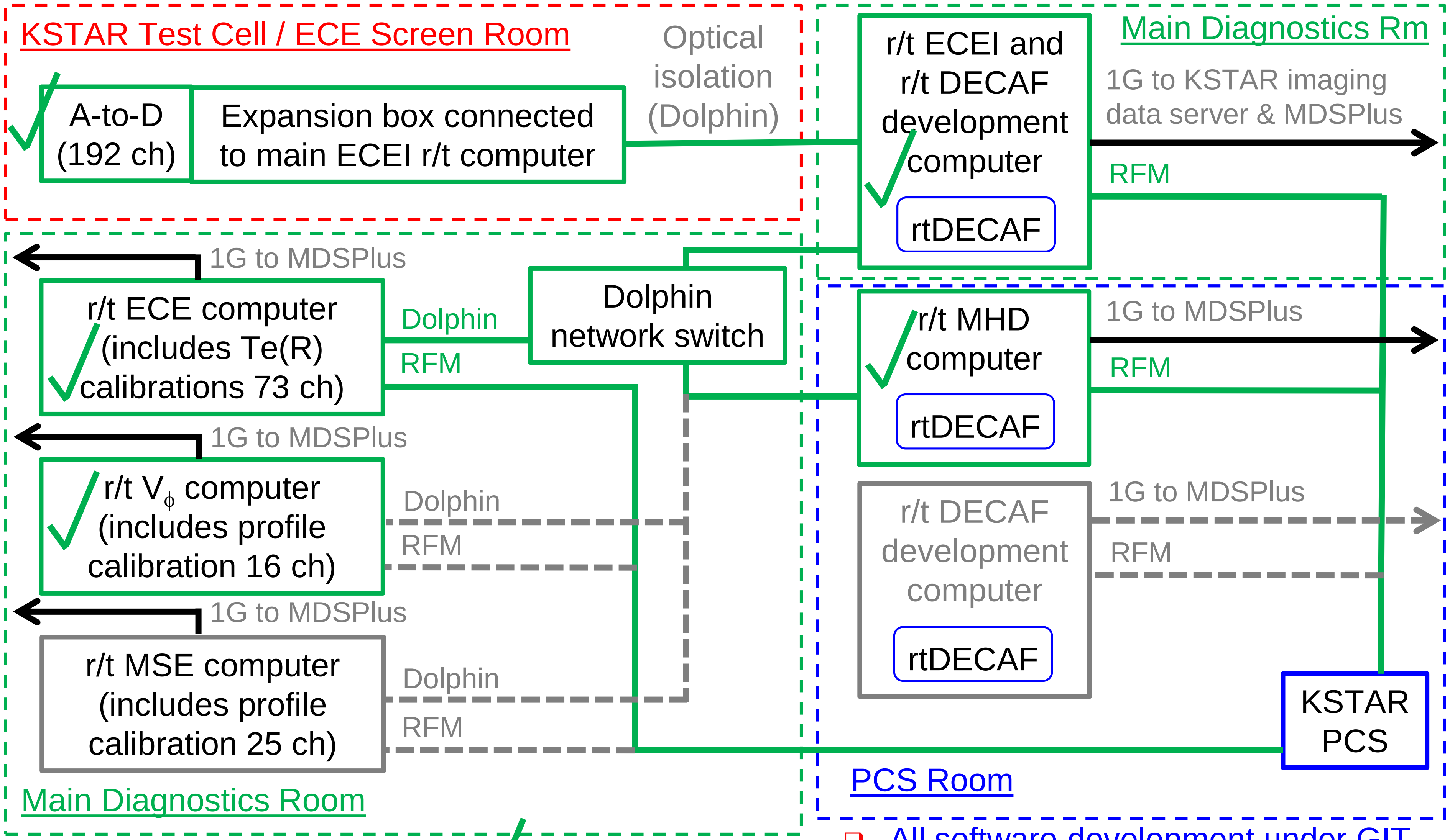
- DECAF analysis capability (several development goals recently achieved)
  - Parallel processing over high performance clusters
    - PPPL private (~30 CPUs) and open SLURM queues (~1,000 CPUs)
    - Next step to utilize Princeton Stellar cluster (over 28,000 CPUs)
  - Analysis persistence
    - Automated 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: 1.2 hours computation

NSTX database ~ 25,000 shots (40 TB)
- extrapolation: 10.4 hours computation

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



✓ = installed

- All software development under GIT version control

Installed

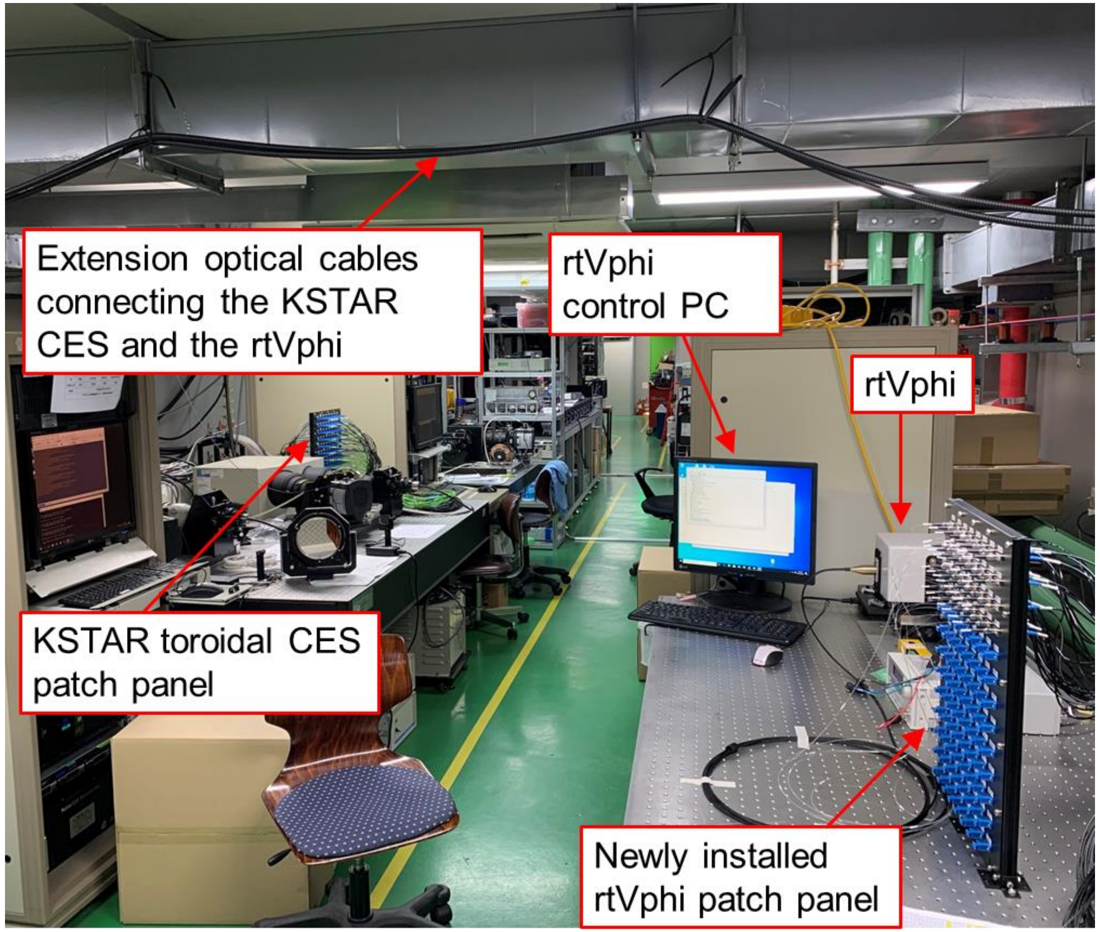
- Real-time MHD
- Real-time V_ϕ, T_i
  - New system for 2022
- Real-time ECE, (T_e(R), mode ID)
- Real-time ECEI (2D δT_e)

Designed

- Real-time MSE
  - B pitch angle, δB

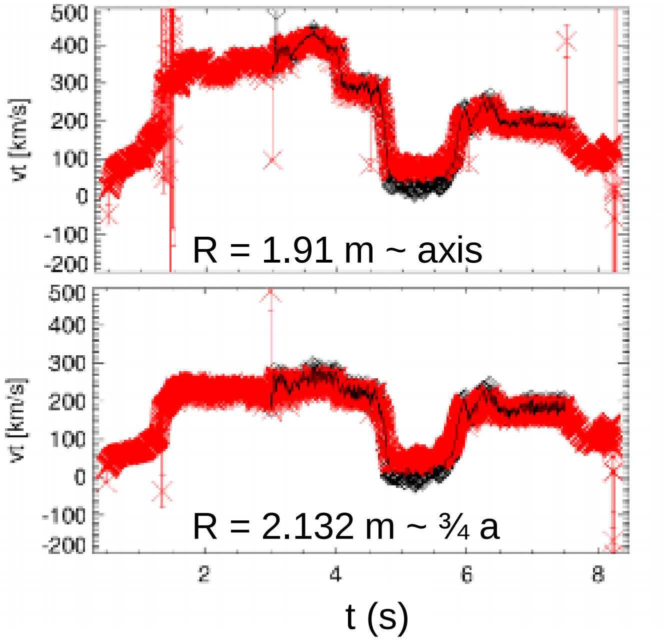
Initial real-time toroidal velocity, ion temperature diagnostic (rtV$_\phi$) shows very good agreement with KSTAR CES system

KSTAR real-time V_ϕ , T_i diagnostic



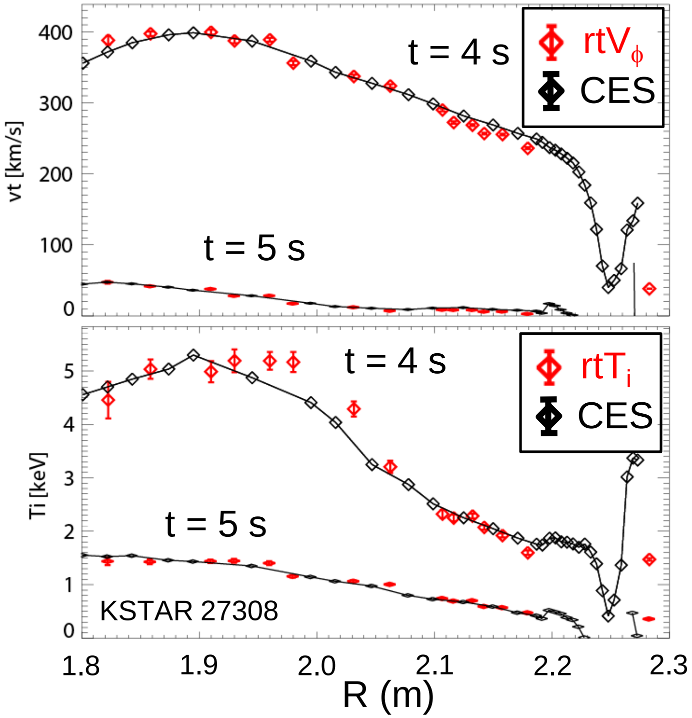
- rtV$_\phi$ and offline CES system share sightlines

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



- rtV$_\phi$ data
  - First light taken for 32 radial channels
  - Reduced to 16 radial channels at 1 kHz
  - Offline CES analysis at 100 Hz

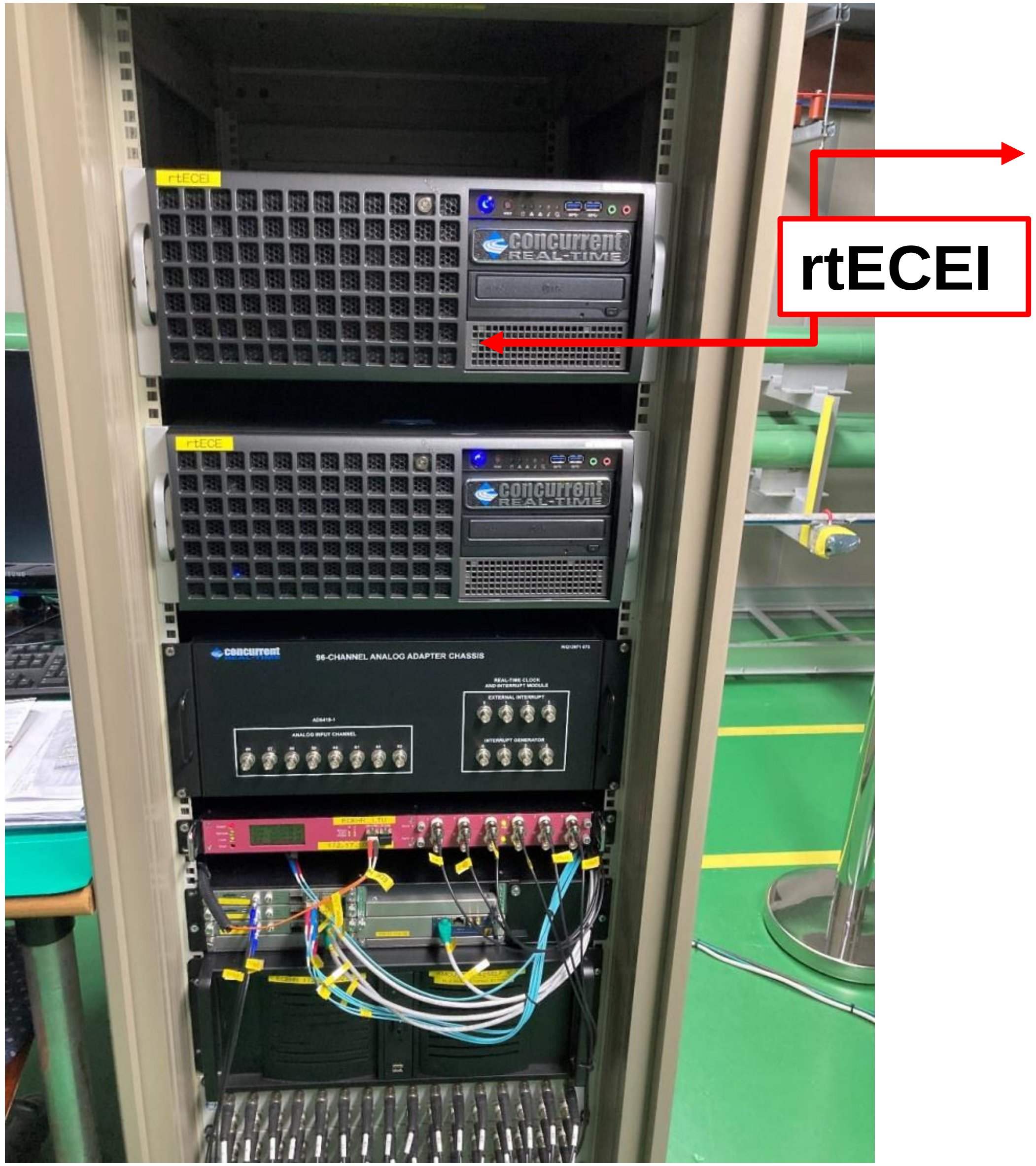
rtV$_\phi$ rtT$_i$ radial profiles

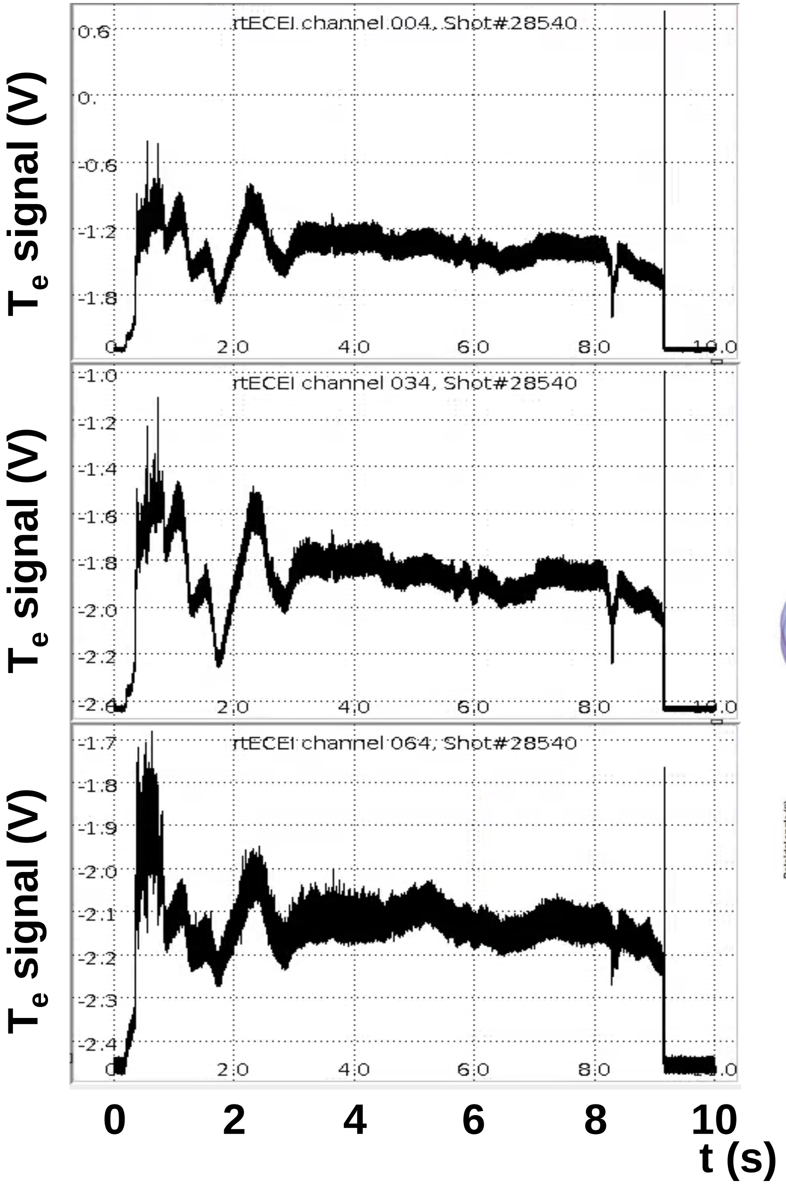


- Newly-designed, final system to be installed for operation in 2022

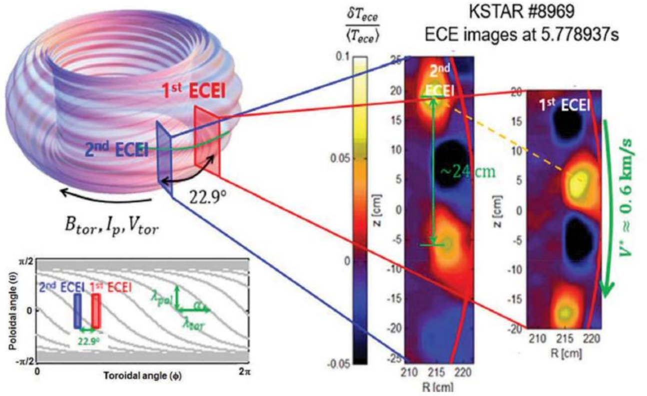
M. Podesta, J. Yoo (PPPL),
Y.S. Park (CU), W.H. Ko (KFE)

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



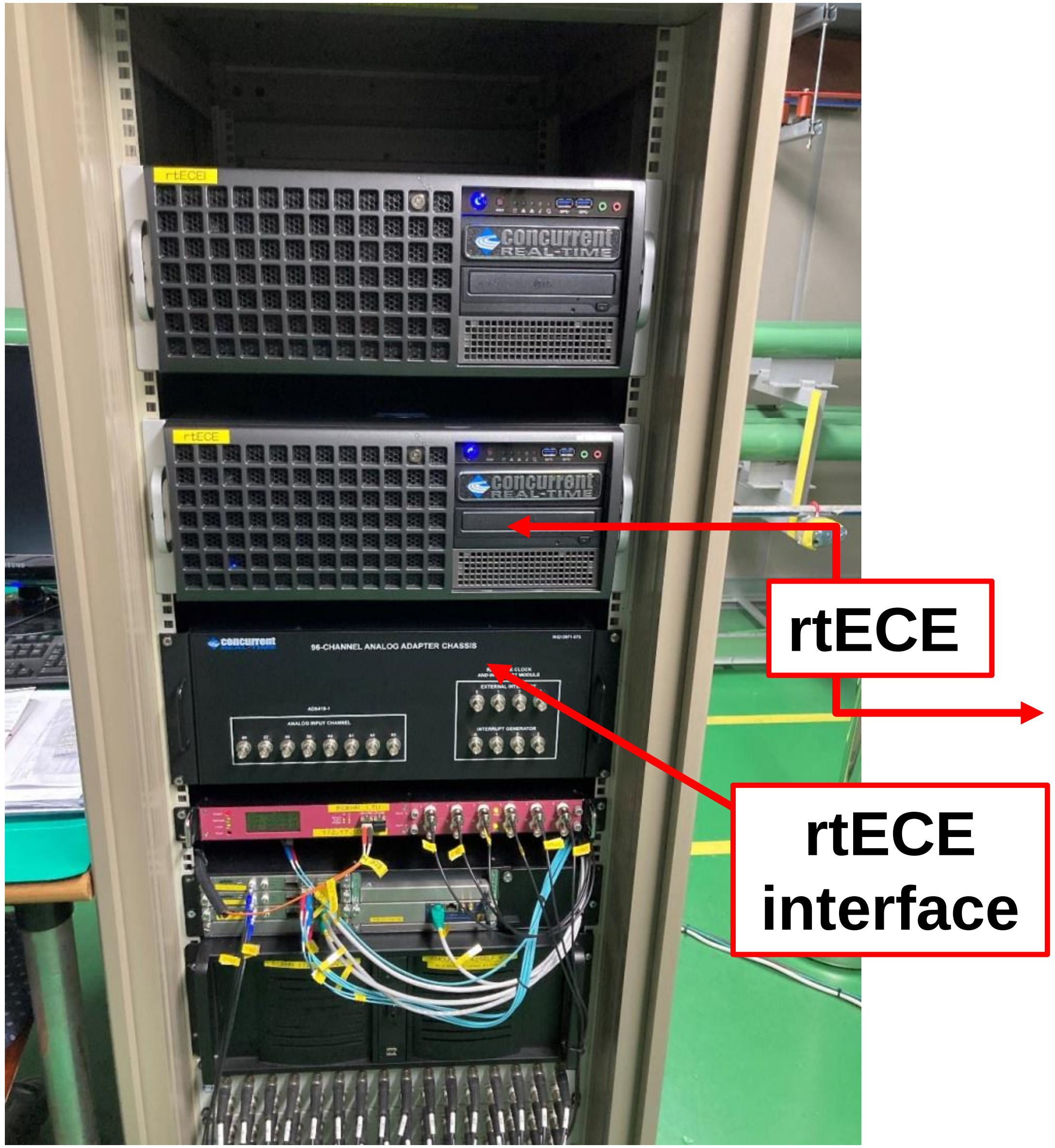


- Full 2D poloidal cross-section acquired in r/t - 192 channels!
- 3 of 192 channels shown

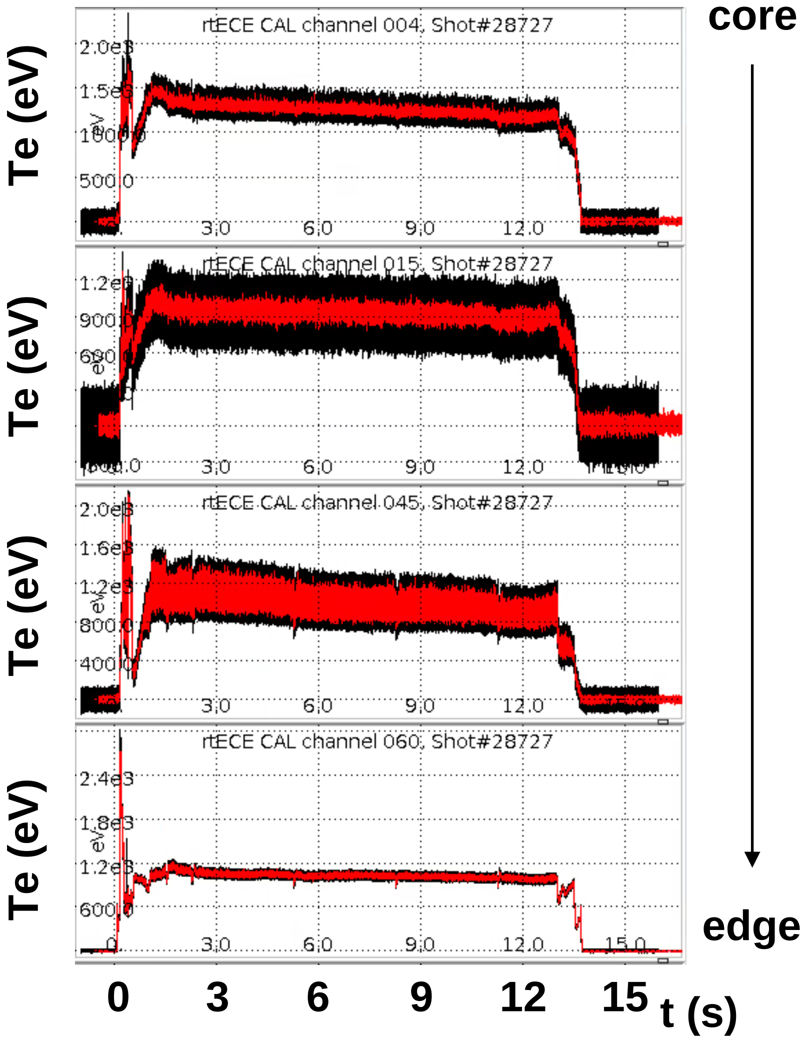


H.K. Park, Adv. in Physics: X, 4:1, 1633956 (2019)

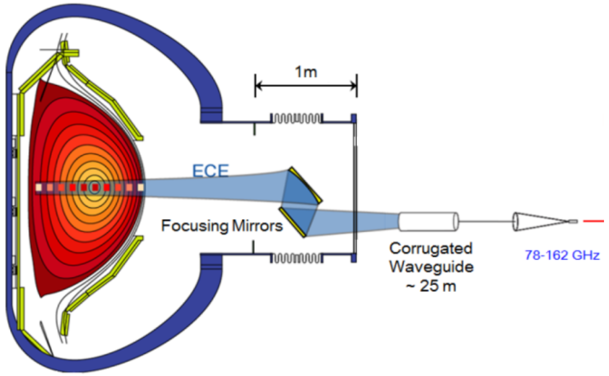
The first real-time DECAF module in KSTAR PCS recently measured T_e profile (in 2021 run campaign)



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



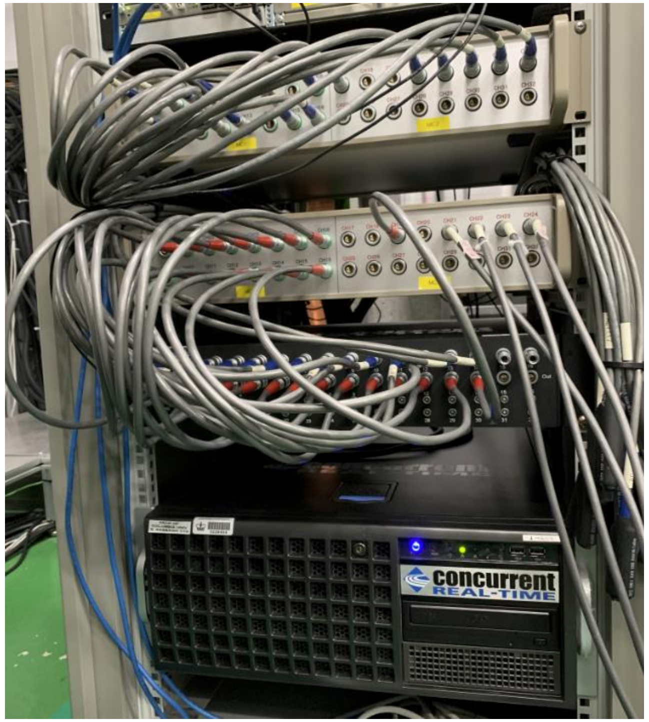
- R/t acquisition of heterodyne radiometer system
  - 4 of 76 channels shown
- Real-time signal compensated and calibrated



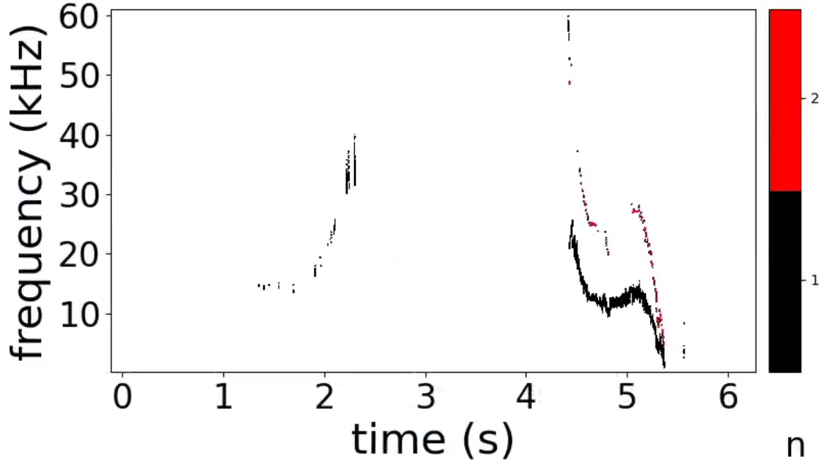
S.H. Jeong, K.D. Lee, et al., RSI **81** (2010) 10D922

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

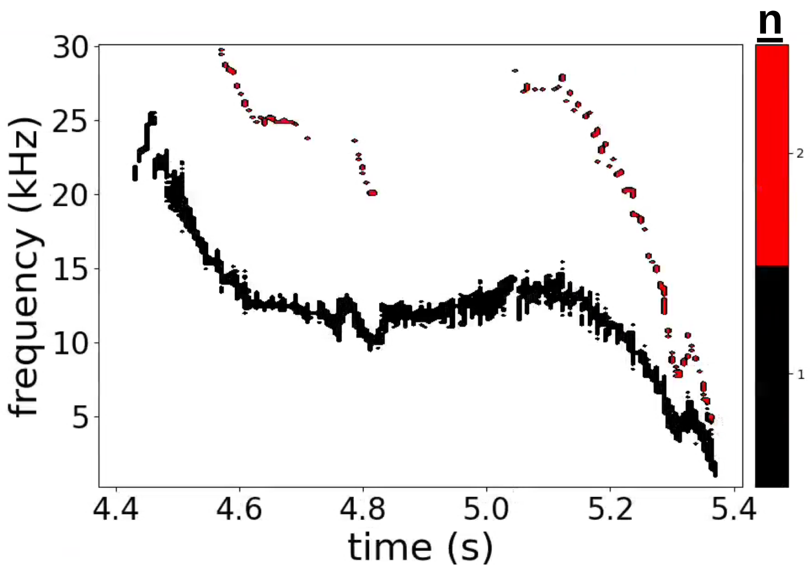


Magnetic probe array toroidal mode spectrogram (offline)

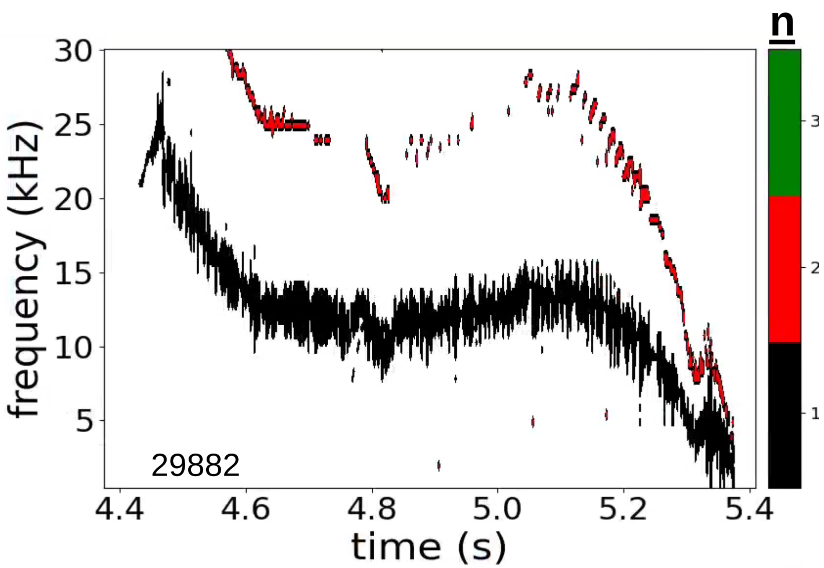


J. Riquezes (CU)

DECAF spectrogram (offline FFTs)

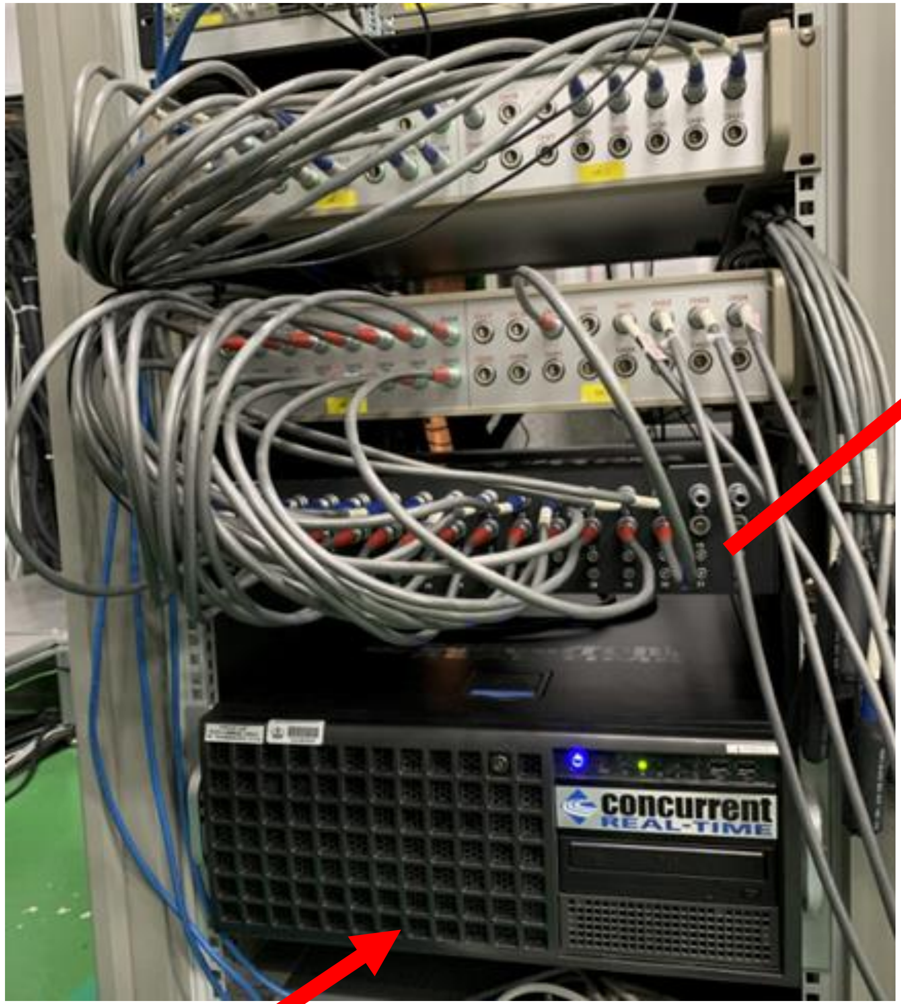


DECAF spectrogram (real-time FFTs)



NSTX-U real-time MHD system implementation is part of our present grant research

KSTAR rtMHD system



KSTAR real-time MHD computer, DAQ

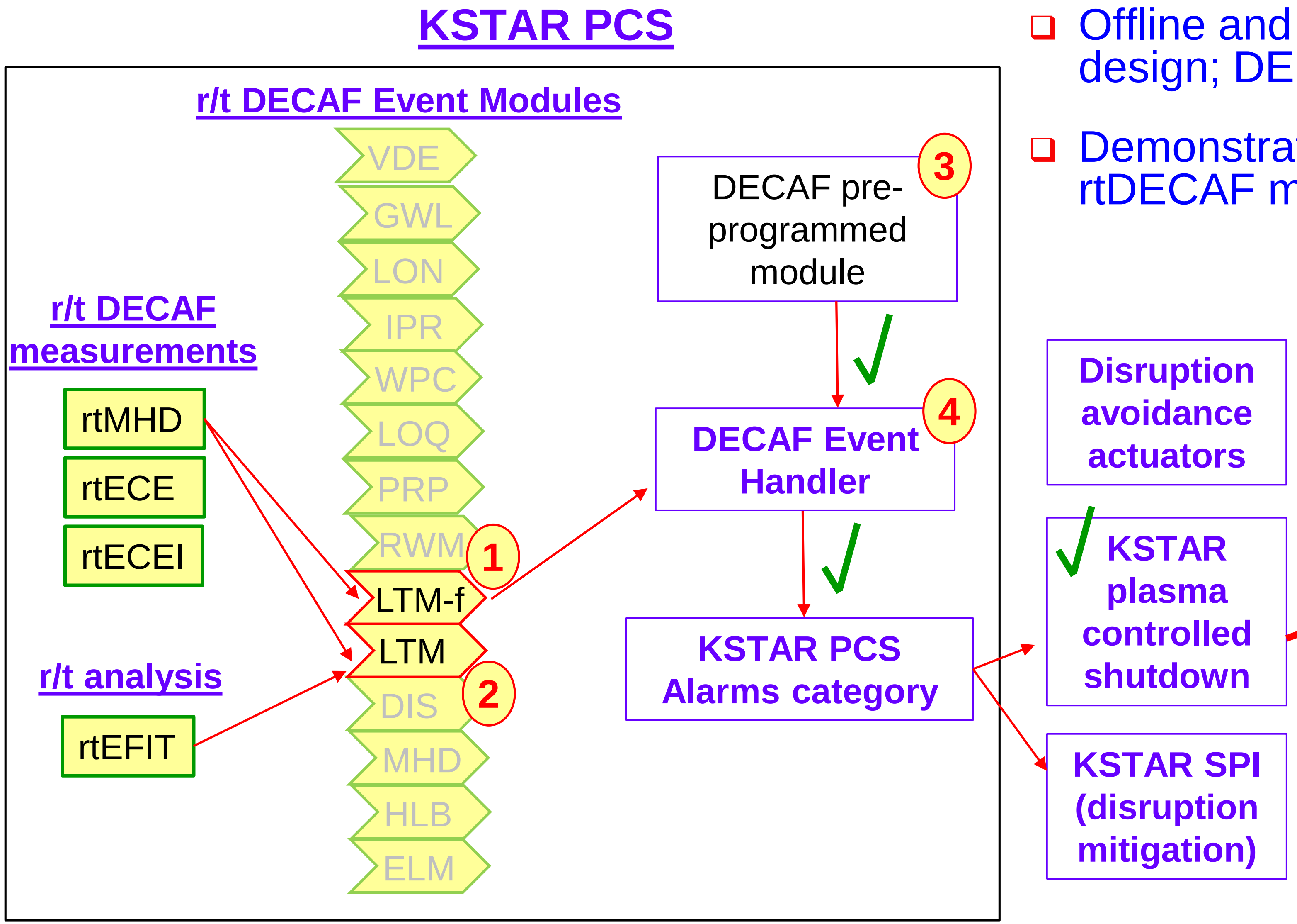
KSTAR buffer chassis (diagnostic interface box)

- 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

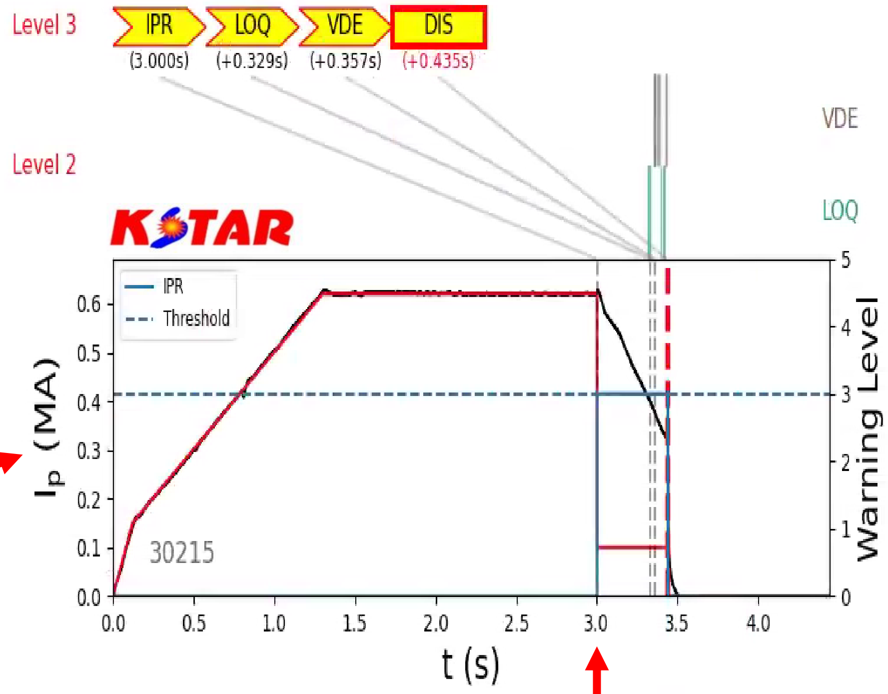
NSTX-U High-n system

LEMO cables from high-n array mag probes

r/t DECAF initial deployment: four real-time software elements were ①–④ installed and tested in 2021 experiment



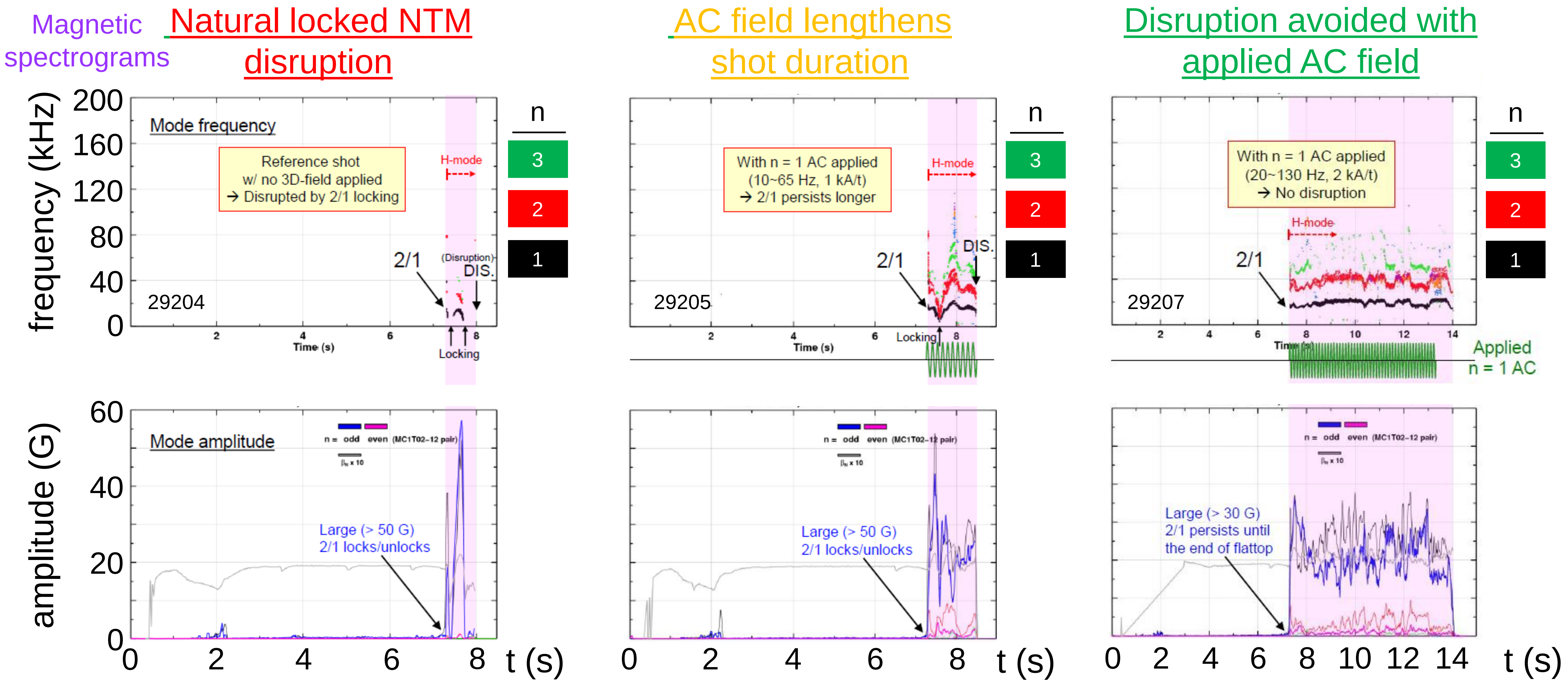
- Offline and real-time DECAF codes follow similar design; DECAF events added as modules
- Demonstrated plasma shutdown through rtDECAF message



Controlled shutdown triggered

See M. Boyer, this meeting (related plasma control collaboration)

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



❑ NOTE: applied AC field frequency is << mode rotation (analysis continues)

Expanding Columbia U. Team at PPPL is conducting an international effort on disruption prediction / avoidance

- Eight CU scientists and students based at PPPL
  - Including 2 students
  - New full-time post-doc/student for NSTX-U grant
- Innovative high beta, long-pulse, non-inductive superconducting tokamak plasma research on KSTAR
- Compact, high beta spherical tokamak plasma research on MAST-U and NSTX-U

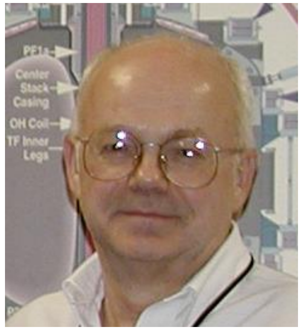
Full access to databases of 6 world-leading tokamaks
(and expanding to more devices…)

We are hiring post-doctoral researchers and presently offering one student GRA! ➔ Email: sabbagh@pppl.gov


S.A. Sabbagh


J.W. Berkery


Y.S. Park


J.M Bialek


V. Klevarova


J. Butt

STUDENTS


J. Riquezes


M. Tobin

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

- Multi-device, integrated approach to disruption prediction and avoidance that meets disruption predictor requirement metrics
  - Physics-based "event chain" yields key understanding of evolution toward disruptions needed for confident extrapolation of forecasting, control
  - Full multi-machine databases. Performance ~10^4 shots : 91.2% true positive rate ➔ keep improving!
  - 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
  - Research continues / expands disruption forecasting performance analysis (➔ ITER ~ 98%+ level)
- DECAF expansion to real-time implementation (KSTAR)
  - Real-time acquisition of magnetics (MHD) r/t FFT analysis, V_ϕ, T_i, T_e, δT_e, (B pitch angle, δB coming)
  - Implemented, tested initial DECAF disruption events, forecasting models in real-time (e.g. LTM-f)
- New disruption avoidance actuator demonstrated on KSTAR using 3D applied field

We are hiring post-doctoral researchers and offering a student GRA! ➔ Email: sabbagh@pppl.gov

Supporting Slides Follow

DECAF related presentations at the APS DPP 2021 Meeting

- Mon AM: J.W. Berkery et al. (BP11.00016): Equilibrium Reconstructions, Stability Calculations, and Disruption Event Characterization of Plasmas in the MAST and MAST Upgrade Spherical Tokamaks
- Tue PM: V. Klevarova et al. (JP11.00059): Implementation of MHD-mode Induced Disruption Forecaster into the DECAF Code
- Wed 3 PM: S. A. Sabbagh et al. (PO09.00006): Tokamak Disruption Event Characterization and Forecasting Research and Expansion to Real-Time Application in KSTAR
- Wed 3:12 PM: J. D. Riquezes et al. (PO09.00007): Torque balance analysis of rotating MHD for disruption prediction and avoidance in KSTAR
- Wed PM: A. Piccione, et al. (PP11.00142): "Resistive Wall Mode Stability Forecasting in NSTX through Balanced Random Forests and Counterfactual Explanations
- Thu AM: J. Butt et al. (TP11.00109): Edge-Localized Mode Detection and Correlation with Rotating MHD modes for Disruption Event Characterization and Forecasting
- Thu AM: Y. Jiang et al. (TP11.00111): Kinetic Equilibrium Reconstruction of KSTAR and the Impact on Stability Analysis of High Performance Plasmas