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Tokamak Disruption Event Characterization and Forecasting Research and Progress on Expansion to Real-Time Application

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2021 IAEA-PPPL Workshop: Theory/Sim of Disruptions

23 July 2021

Virtual Meeting

ASDEX-U
KSTAR
MAST-U
NSTX-U

V4

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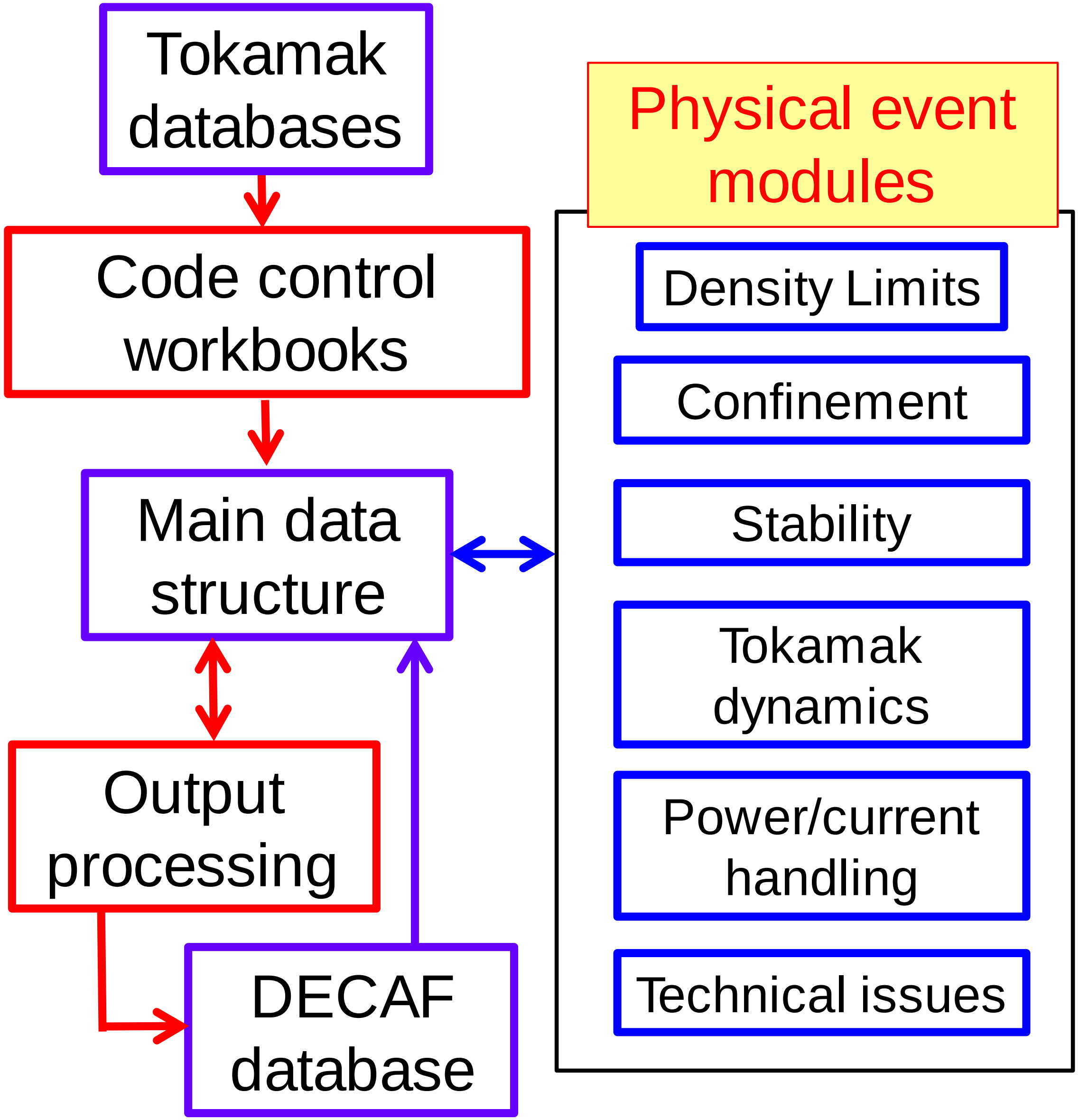
Disruption prediction and avoidance research progressing for ITER and future tokamaks – expanding to real-time

- Motivation: Disruption prediction/avoidance is a critical need
  - Why? A disruption stops plasma operation, might cause device damage
  - A highest priority DOE FES (Tier 1) initiative - present "grand challenge" in tokamak stability research:
    - Can be done! (JET: < 4% disruptions with carbon wall)
    - ITER disruption allowance: < 1 - 2% (energy + E&M loads); << 1% (runaways)

- Outline
  - Disruption Event Characterization and Forecasting (DECAF) analysis
    - Disruption event chains, early forecasting, brief results, continued development
  - Recent focus on real-time DECAF design and implementation on KSTAR
  - Expanded physics analysis supporting DECAF
    - e.g. KSTAR high β_N, Δ' analysis, high to ~100% non-inductive CD transport analysis

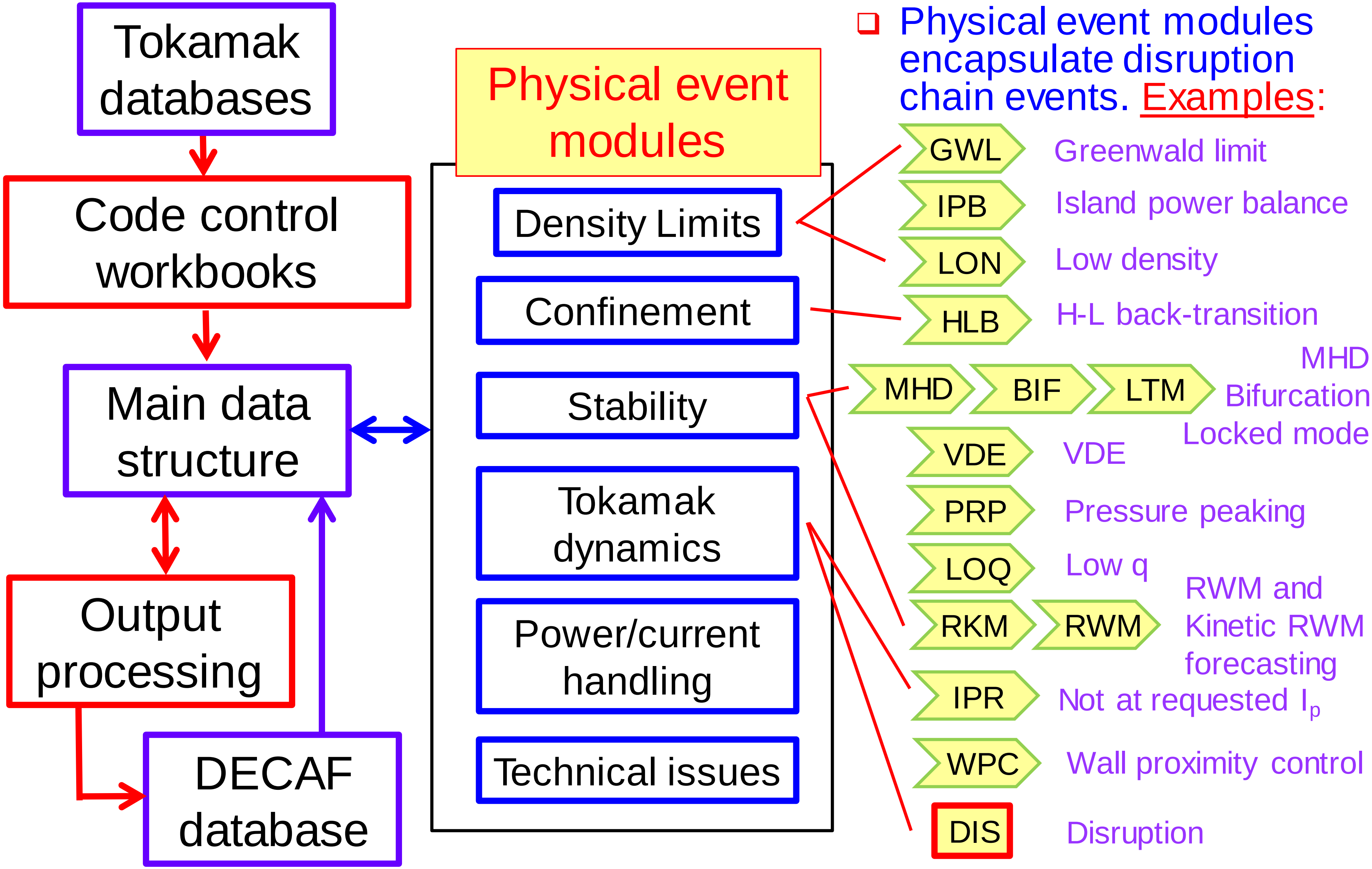
DECAF is a physics-based approach to disruption event understanding / forecasting to enable disruption avoidance



- 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

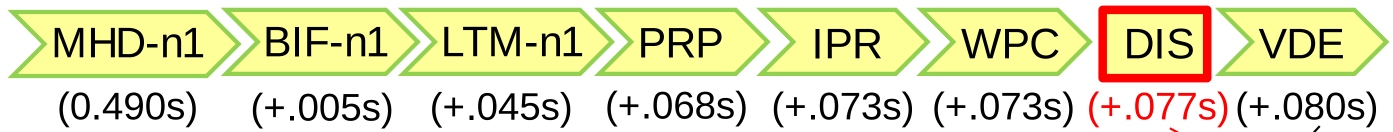
DECAF is structured to ease parallel development of disruption characterization, event criteria, and forecasting

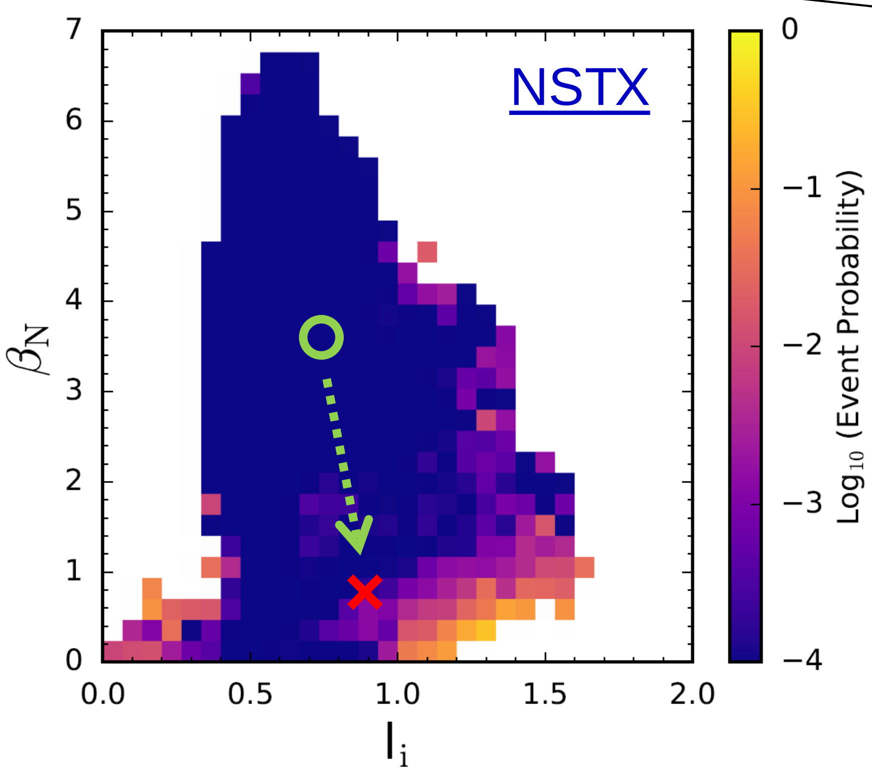
- Physical event modules encapsulate disruption chain events. Examples:

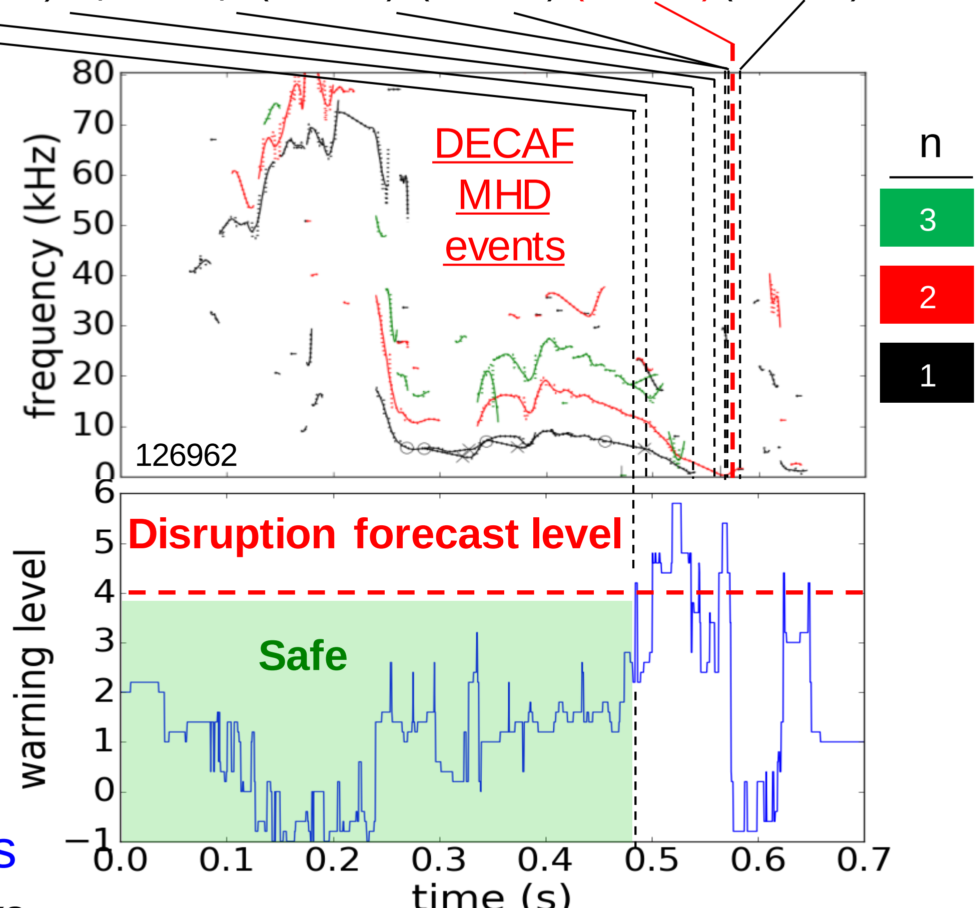


DECAF provides an early disruption forecast - on transport timescales – giving potential for disruption avoidance

DECAF event chain



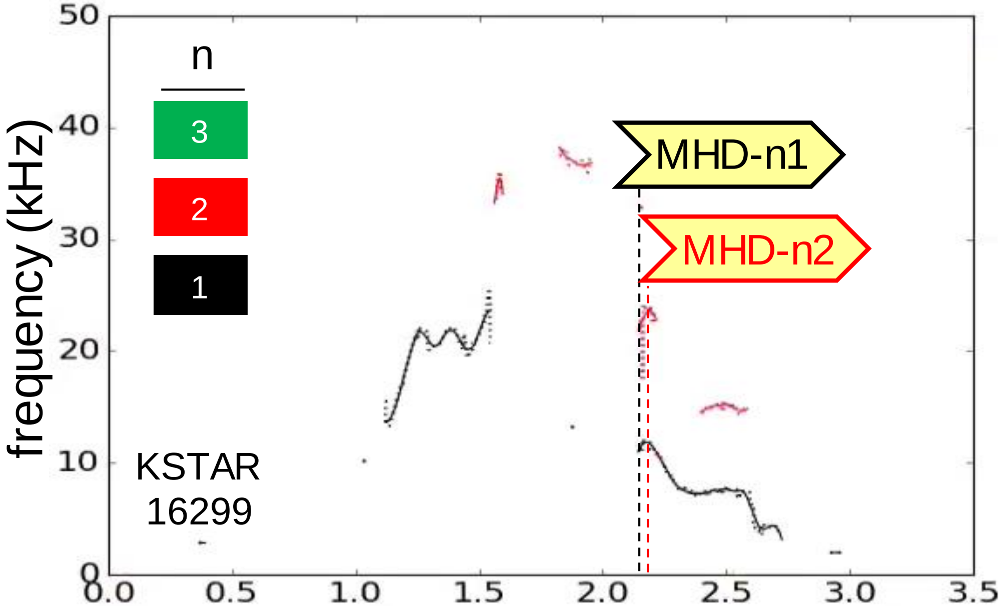


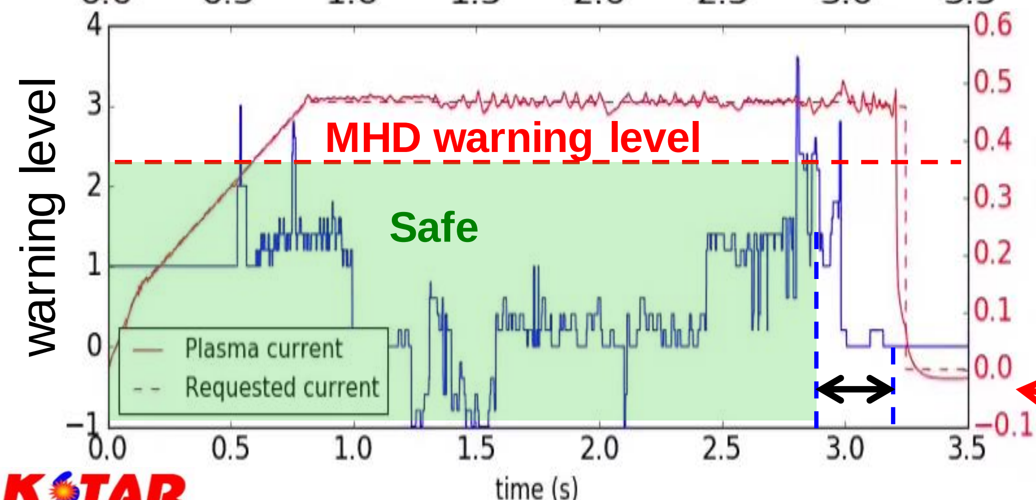


- DECAF event chain reveals physics
  - Rotating MHD slows, bifurcates, and locks
  - Then, plasma has an H-L back-transition (pressure peaking warning PRP) before DIS
  - Important: Early warning occurs in apparently SAFE region of operating space!

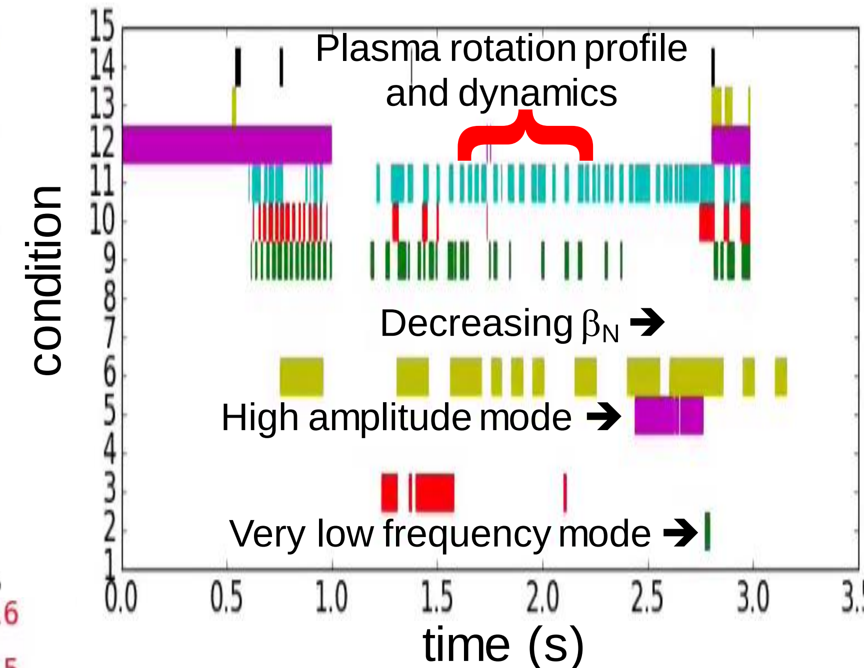
DECAF MHD events also produce early disruption warnings for KSTAR; aim to compute in real-time

DECAF automated MHD objects





DECAF "heat map" (for MHD)

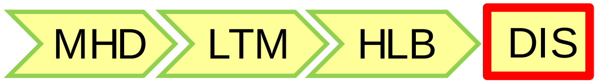


- Mode locking at reduced plasma rotation
- Key notables of MHD warning
  - "Safe"/"unsafe" MHD periods
  - <u>Early</u> disruption warning (300 ms) ➔ on transport timescale

Continued development of DECAF builds from an extrapolable approach with strong initial success

- Fully automated, physics-based analysis of existing tokamak databases from multiple devices

- Analysis of all plasma states, continuous and asynchronous events, continuous "warning level" determination
  - "<u>Safe</u>": events indicating steady operation (e.g. determination of L-mode, H-mode, steady ELMing, etc.)
  - "<u>Proximity</u>": expected paths to "critical" events



  - "<u>Critical</u>": event chains leading to disruption if no action taken

- "Forecaster events" using models to provide the earliest possible indication of issues

- High success found to date, determined quantitatively
  - > 91% true positive, ~ 8% false positive rate (~1e4 shots, ~1e6 samples)

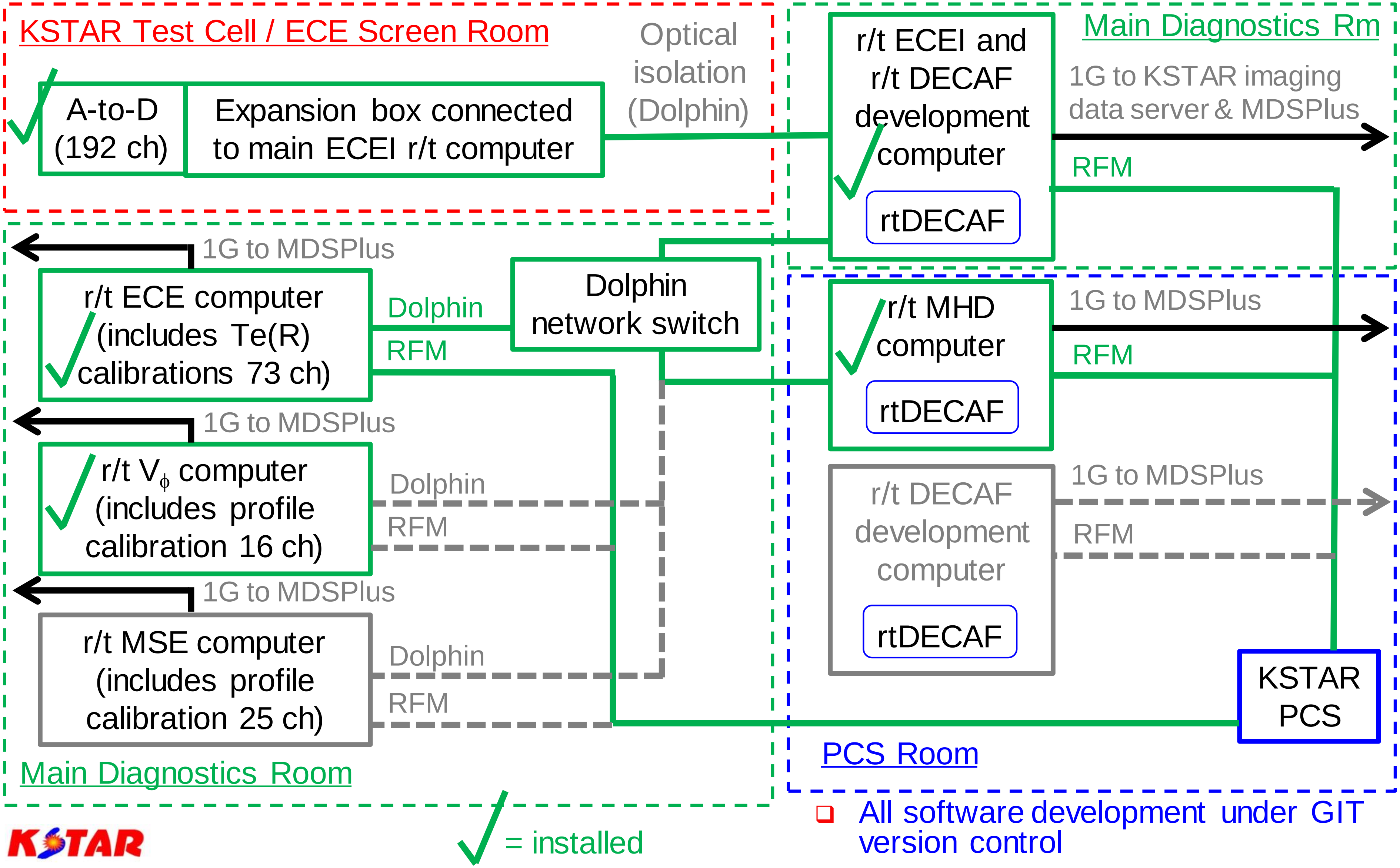
- Research <u>continues</u> focused on improving forecasting to needed accuracy (98%+ goal, w/low false positives),

Recent focus: implementation of real-time (r/t) diagnostic hardware at KSTAR enabling DECAF

- Implementation of real-time diagnostic capabilities
  - ✓ rtMHD system taking data; FPGA card real-time processing of FFTs with programming for all 16 channels channels completed (W. Que)
  - ✓ rtV_ϕ system installed, data taken in 2020, $V_\phi(R)$ profile measured with temporary calibration; new system designed, to install 2021 (M. Podesta)
  - ✓ rtECE system ($T_e(R)$) installed at KSTAR, accessible, on new Dolphin r/t network (10x bandwidth of present RFM network)
  - ✓ rtECEI system (2D δT_e) installed at KSTAR, accessible, on new Dolphin network
  - rtMSE computer and interface in design (B pitch angle, δB) (F. Levinton)

- DOE "Reach: Milestone (for KSTAR 2021 run campaign)
  - DEPARTE-2021-4R: Utilize first real-time DECAF events to actuate the KSTAR shattered pellet injectors (SPI) for disruption mitigation
  - DECAF "LTM event forecaster" planned to be used for this demonstration

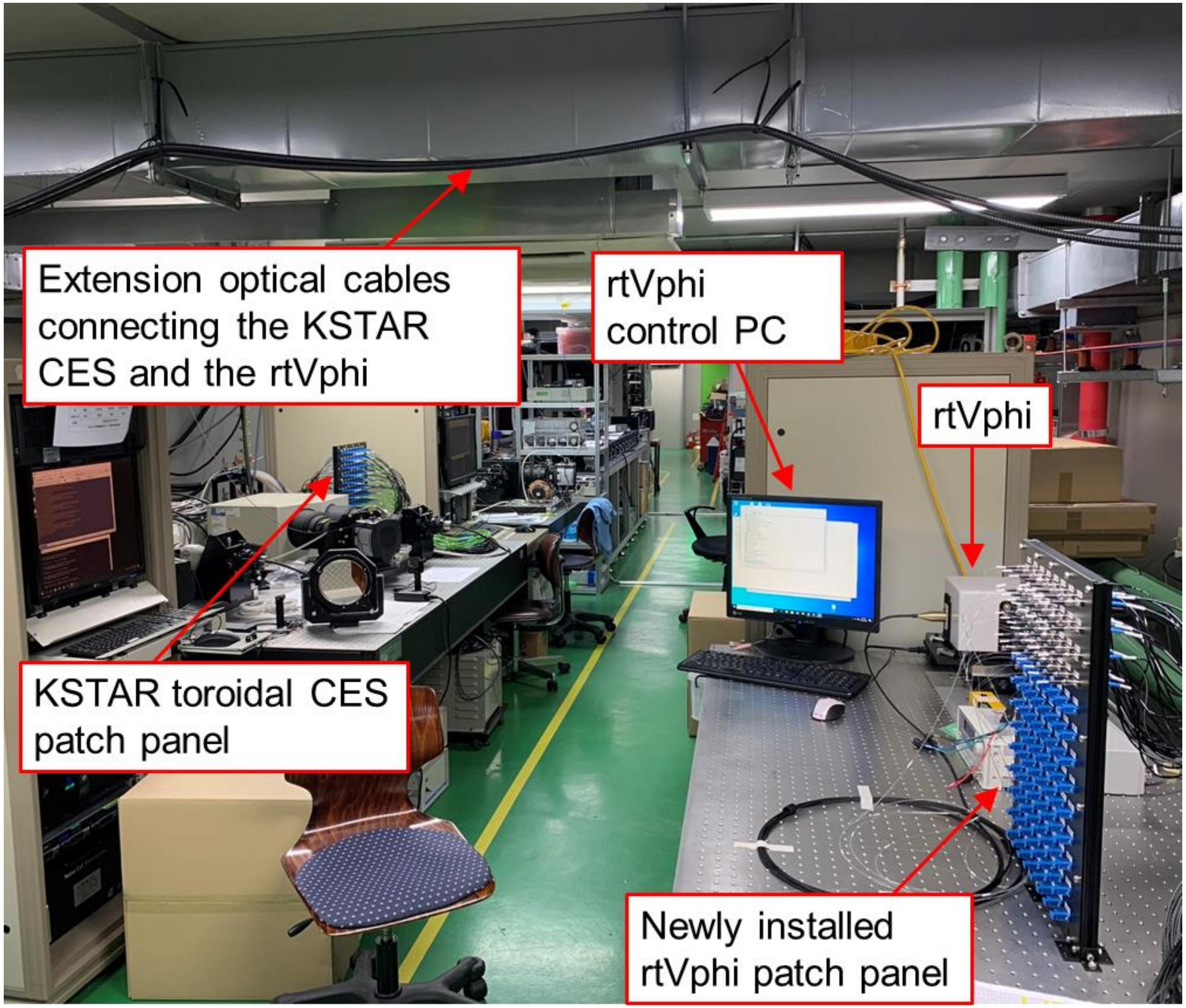
Overall setup for KSTAR real-time diagnostic integration and DECAF analysis for the PCS



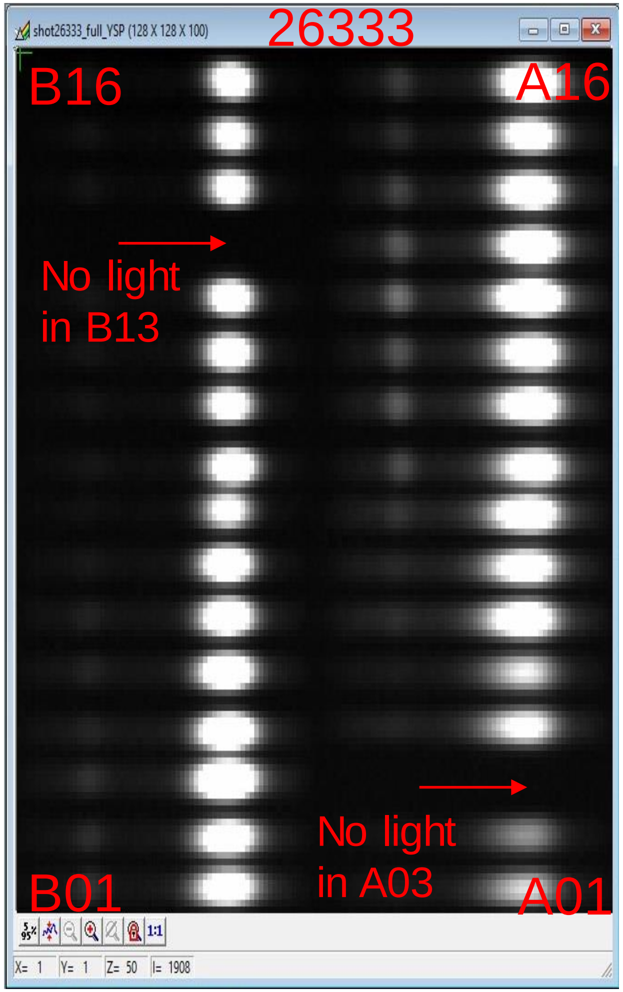
- All software development under GIT version control

KSTAR

Real-time toroidal velocity diagnostic (rtV$_\phi$) installation completed on KSTAR (Oct. 29th), first light the next day!



First Light! 32 channels



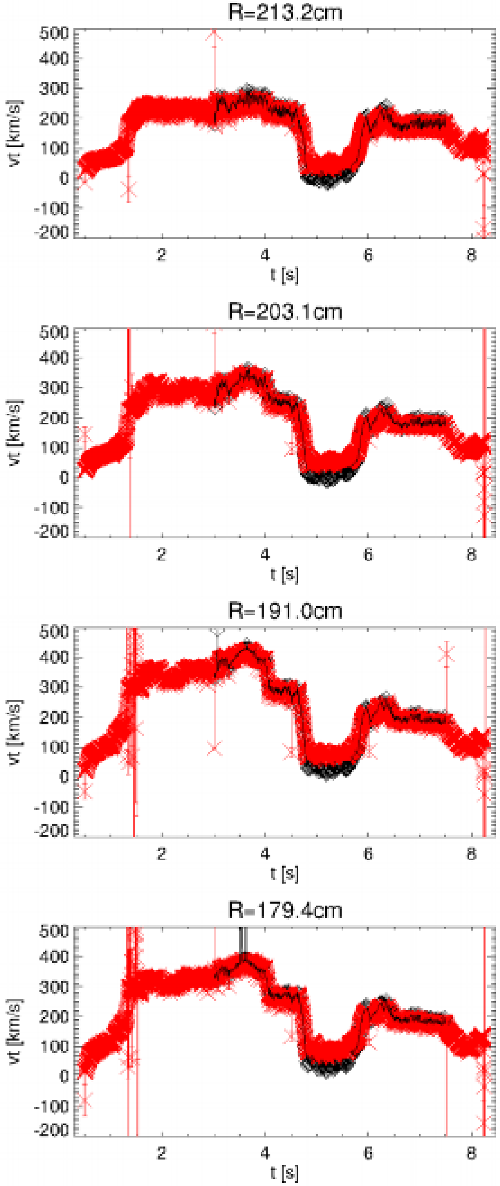
- ❑ Initial real-time KSTAR V$_\phi$ profile data taken 2020

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

Real-time V_ϕ profile shows very good agreement with KSTAR CER system

- No Ne glow wavelength calibration performed
- Raw calibration based on passive spectra
- Refined through comparison with CER

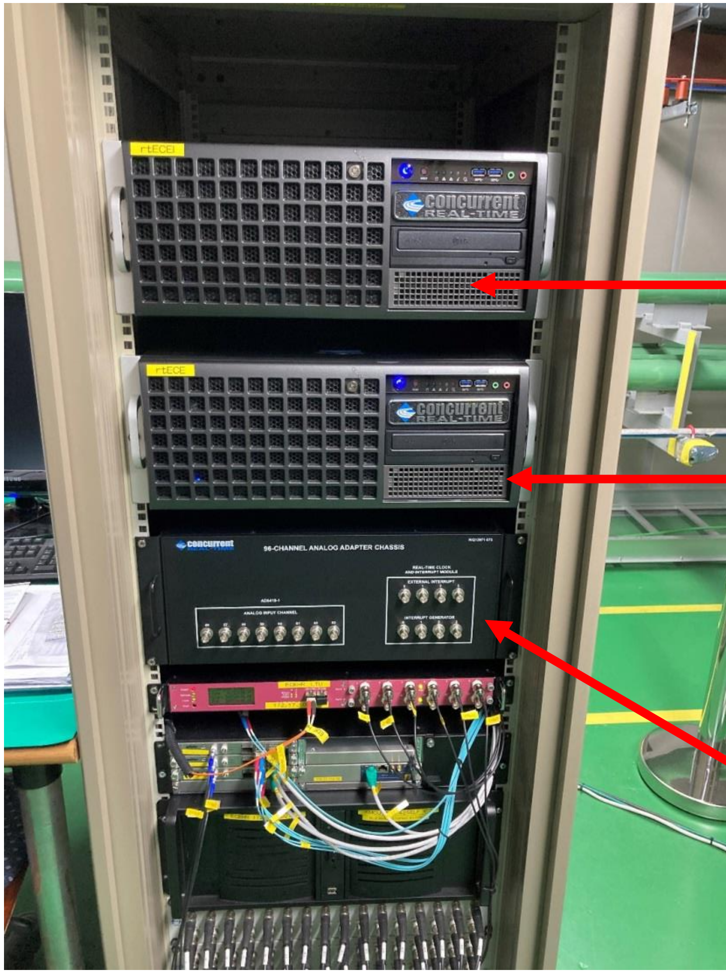
- Overall, good agreement between the two systems
- Shown: RTV @1kHz vs CER @100Hz
  - Other shots show “blips” in rotation over ~1-5ms time-scale
- Tested for 16 channels at 1Khz
  - May have to reduce to 8 channels for final system



KSTAR

Status and plans for RTV system on KSTAR (Podestà)

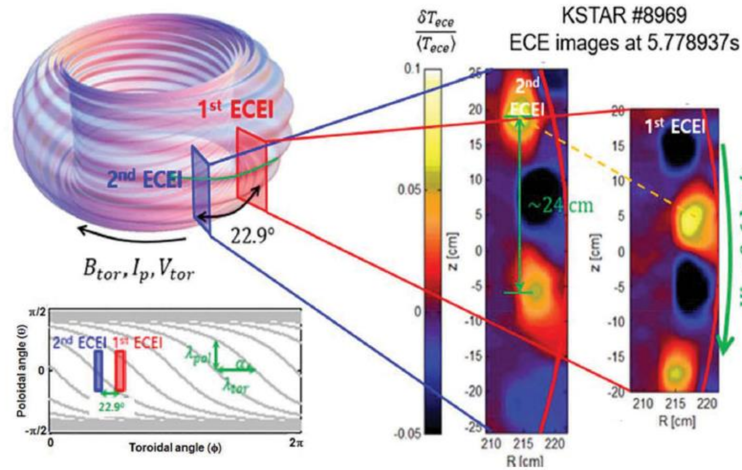
KSTAR real-time ECE and ECEI data acquisition hardware installed earlier this year (2021)



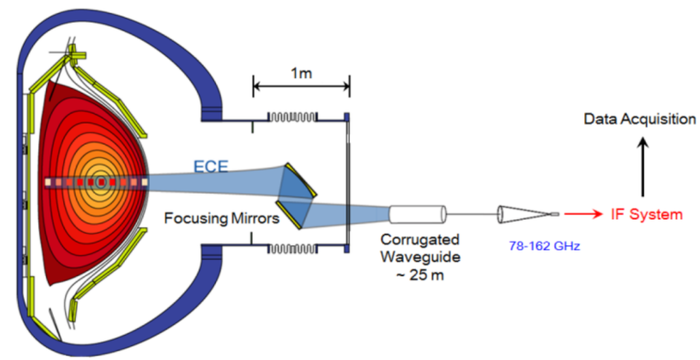
rtECEI

rtECE

rtECE interface



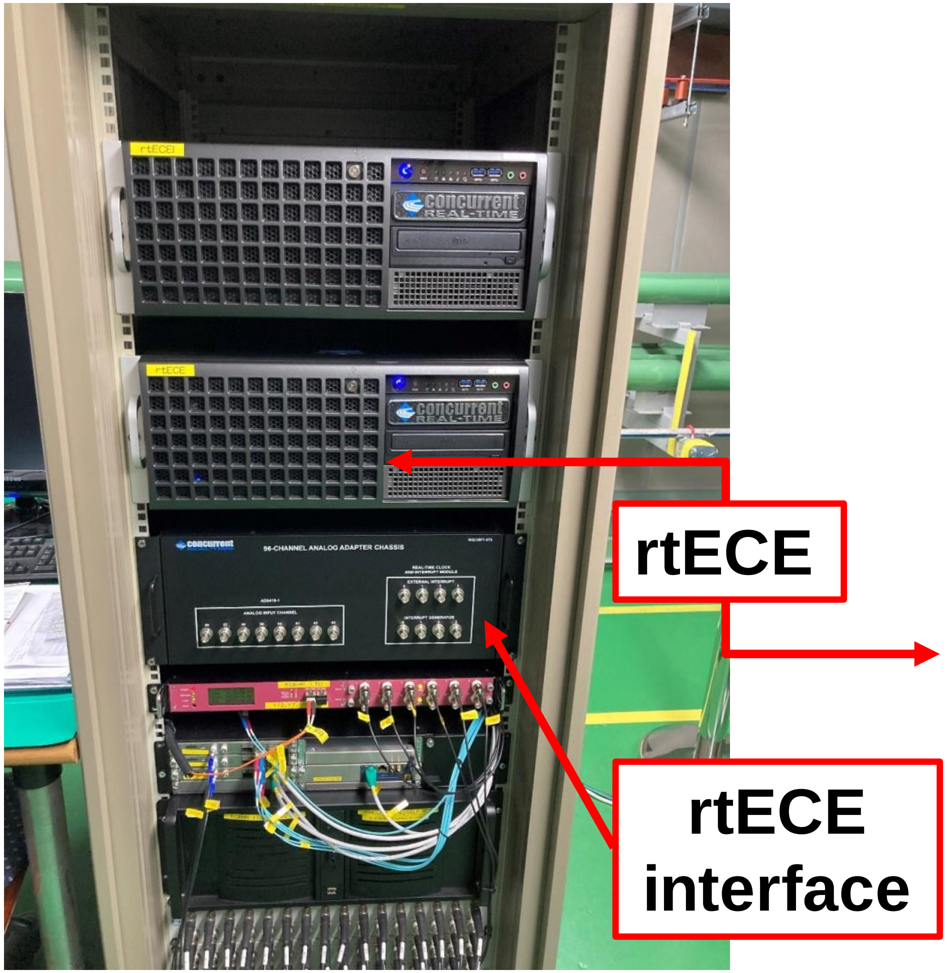
H.K. Park, Adv. in Physics: X, 4:1, 1633956 (2019)



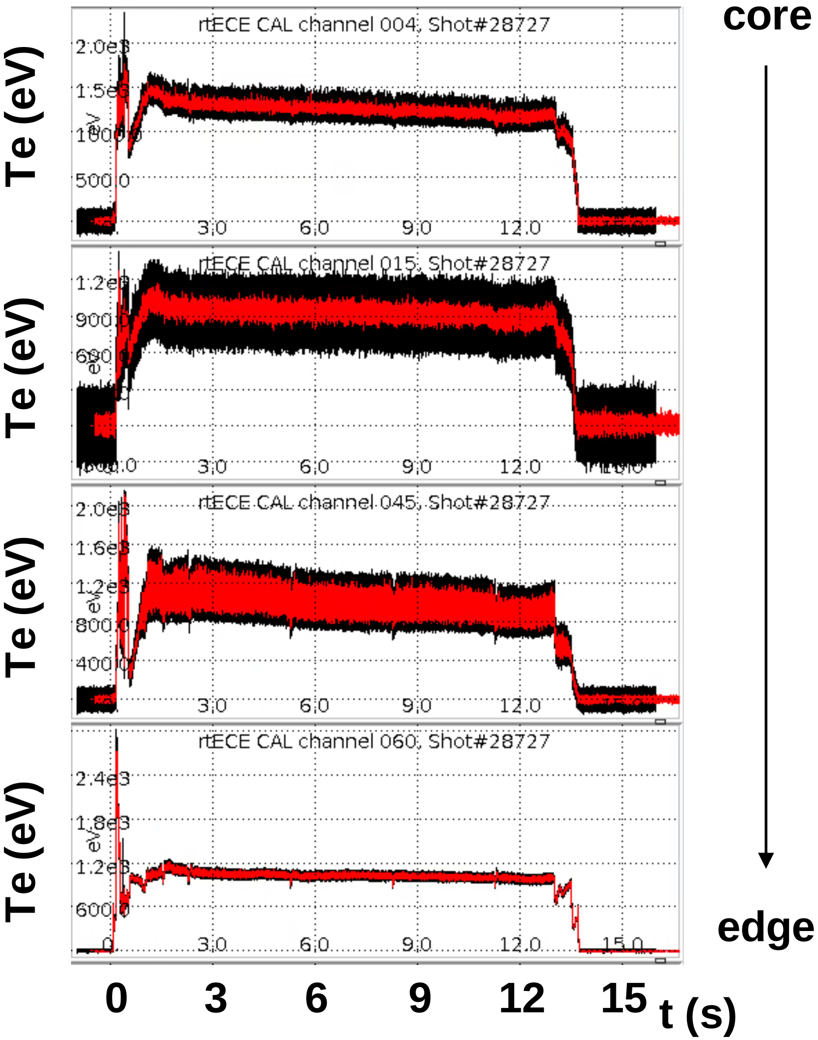
K.D. Lee, KFE

- rtECE computer near heterodyne radiometer (76 channels)
- rtECEI computer connected to diagnostic by PCIe expansion box and custom interface in test cell (2D: 192 channels!)

The first real-time DECAF module in KSTAR PCS recently measured T_e profile (1st time last week)



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

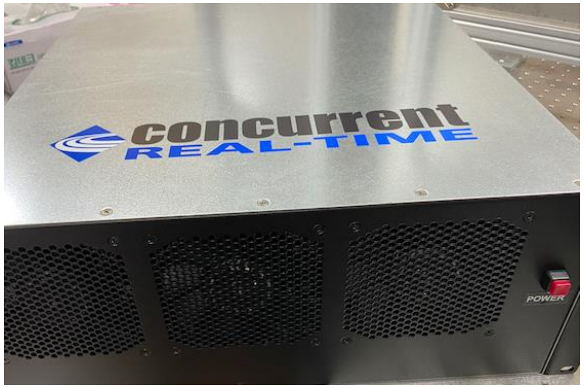


- ❑ Calibrated system, agrees with offline data acquisition

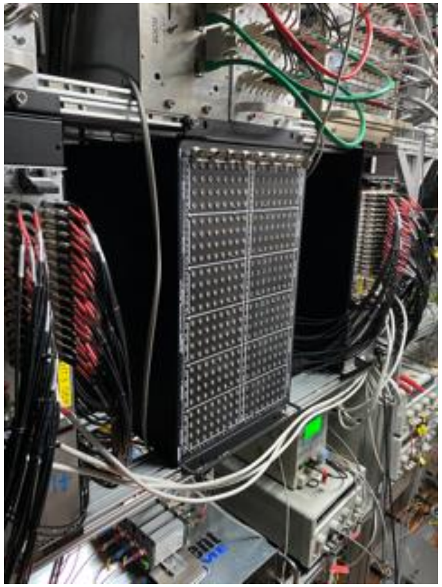
rtECEI DAQ system installed in the KSTAR test cell

Buffer chassis (192 channels)

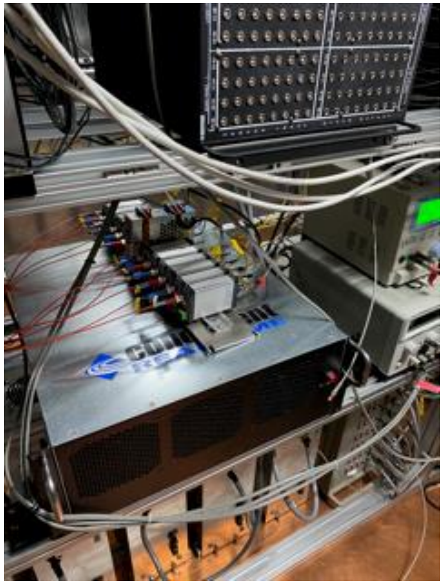
PCIe expansion chassis



In ECEI DAQ room (test cell)

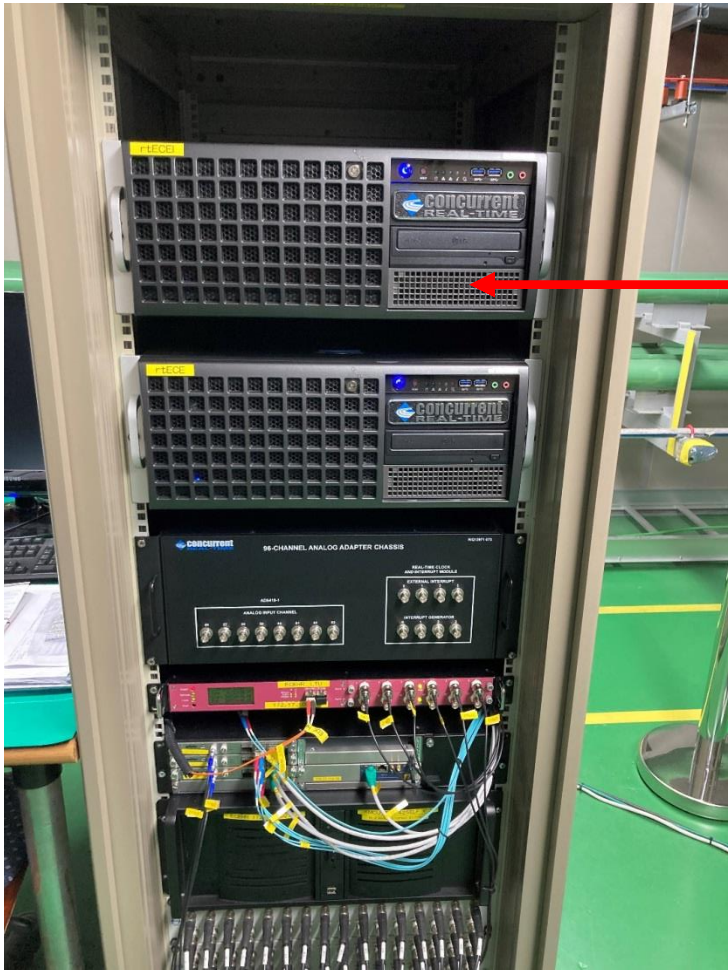


In ECEI DAQ room (test cell)

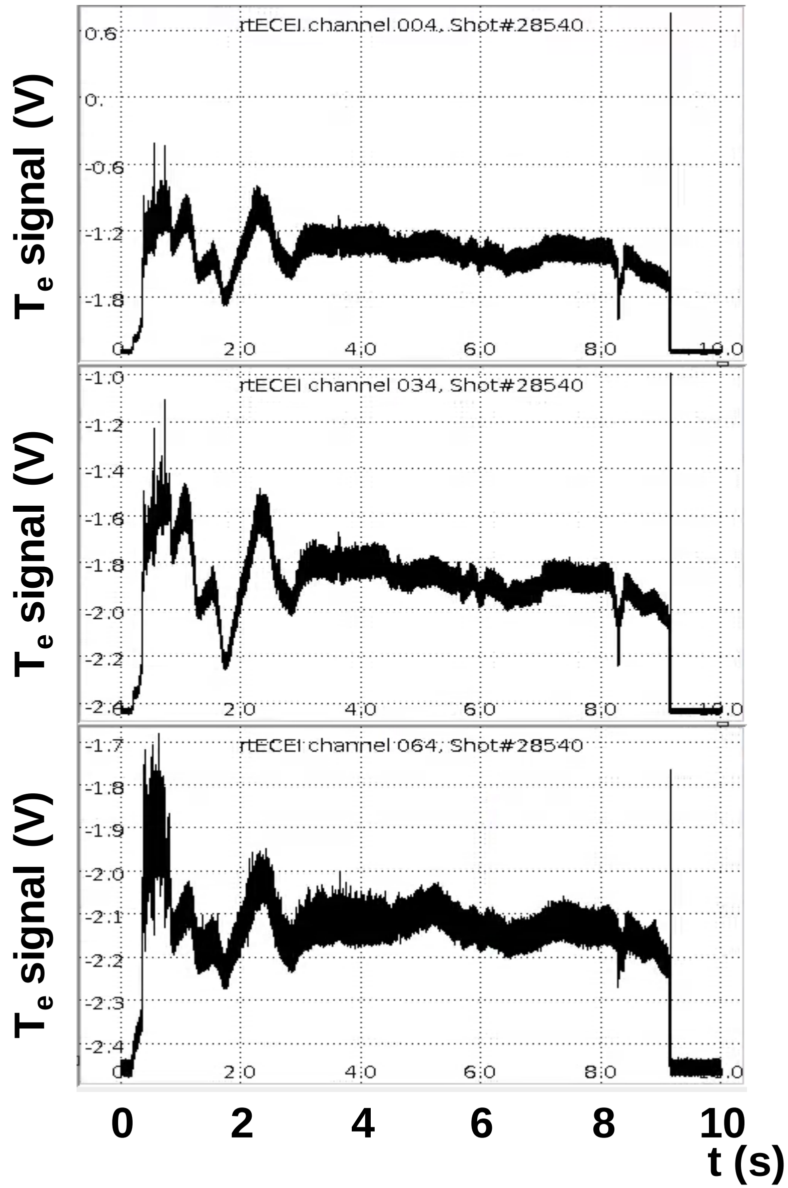


- rtECEI computer located in the ECE rack (diagnostics room)
- LEMO cables installed for buffer chassis hook-up
- Dolphin cable run from ECEI DAQ in test cell to rtECEI computer

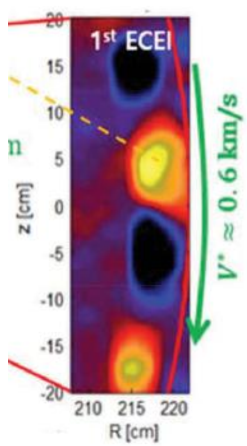
The first real-time ECEI data on KSTAR was recently taken as well (1st time last week)



rtECEI



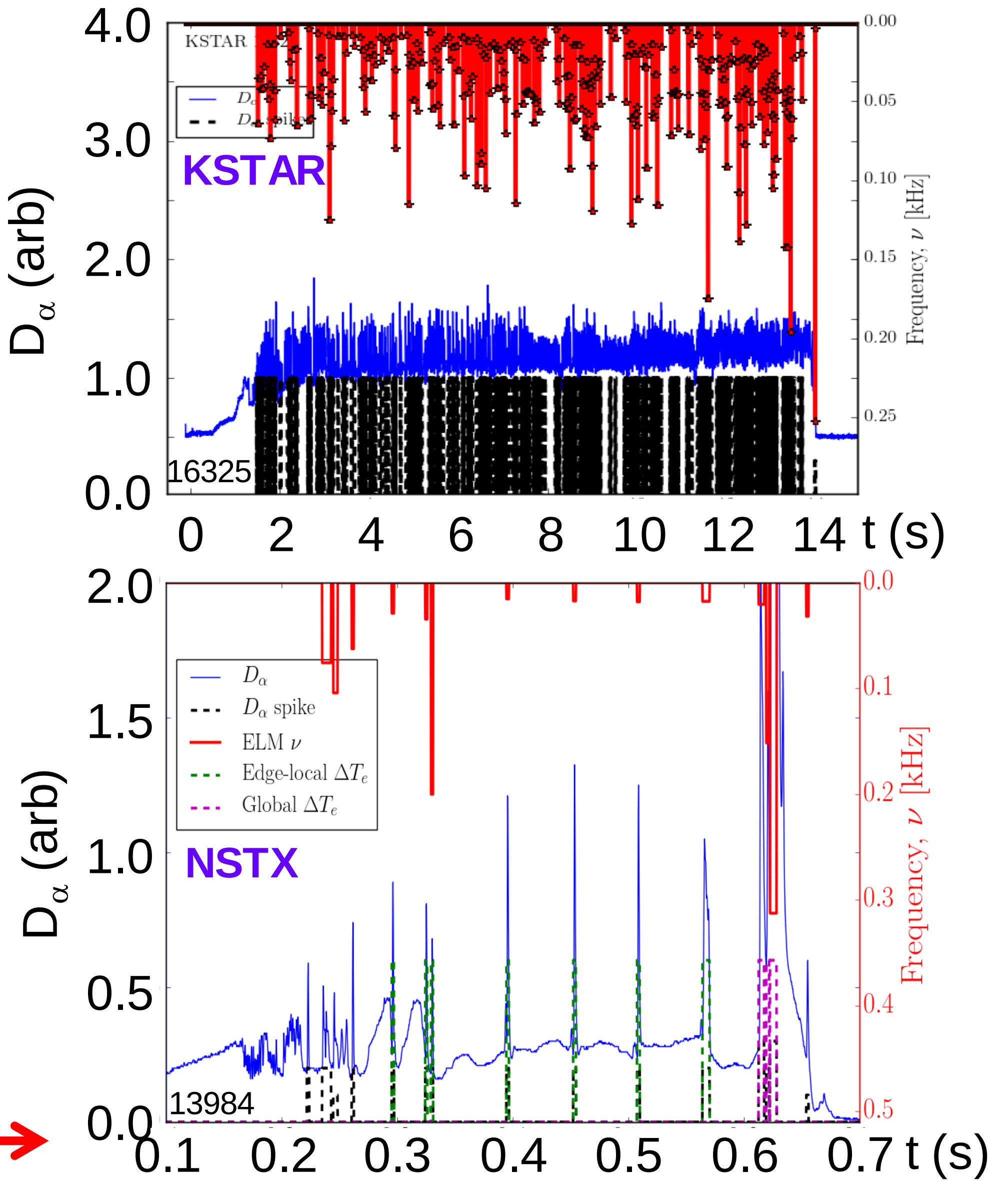
- ❑ 3 of 192 channels shown



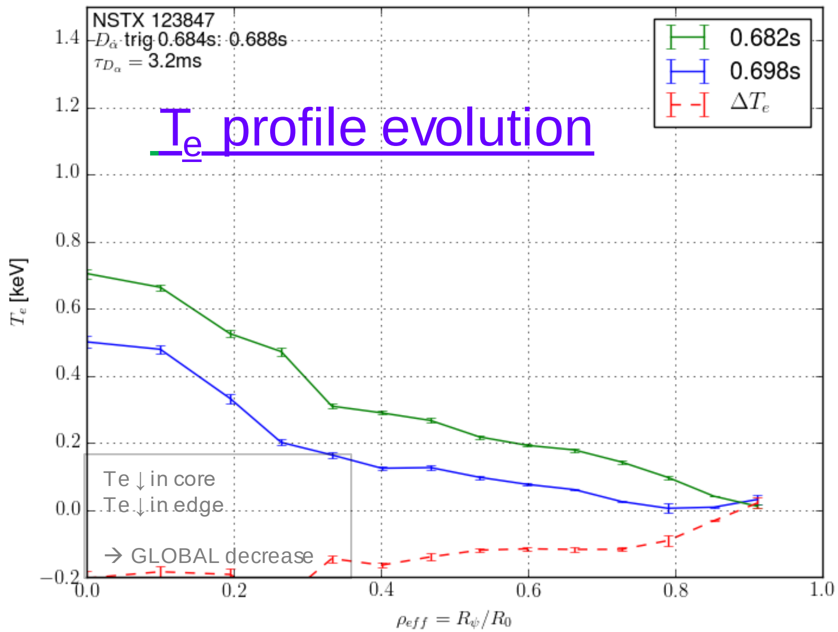
New DECAF edge localized mode event created to start examining correlations to other MHD

ELM

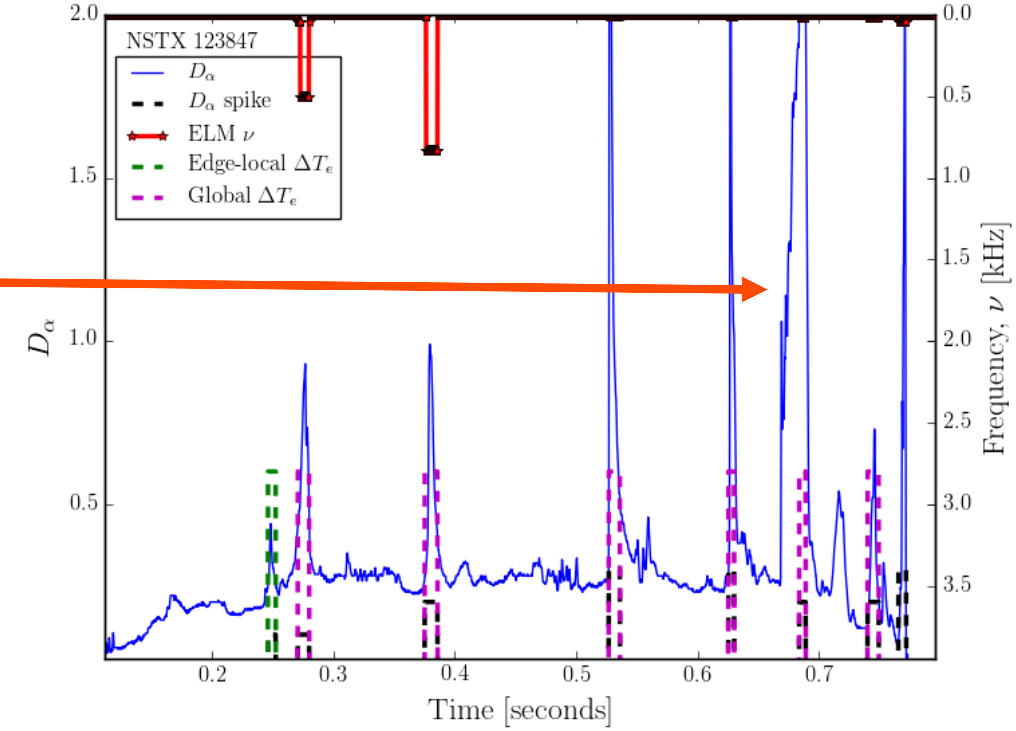
- DECAF ELM event
  - Presently determines ELM triggering times, along with frequency and relative amplitude
- Algorithm compatible with real-time use
- Distinguishes true “ELMs” from other events (global MHD, etc.) that generate D_α light
  - Magenta dashed lines at t = 0.6s is a global mode

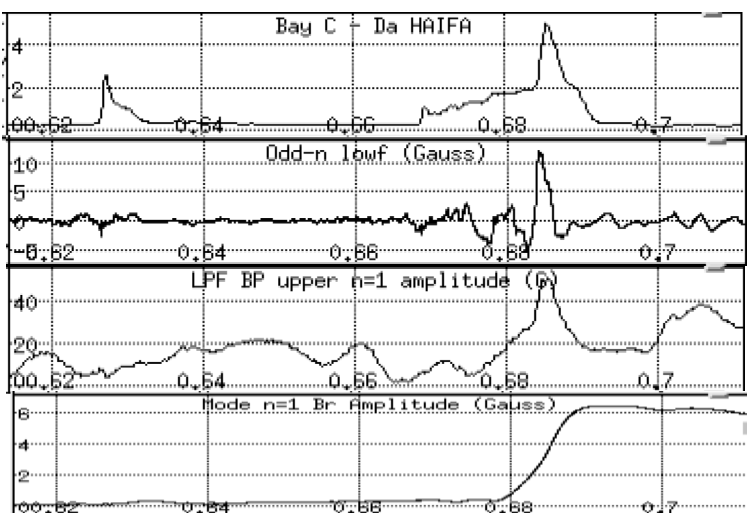


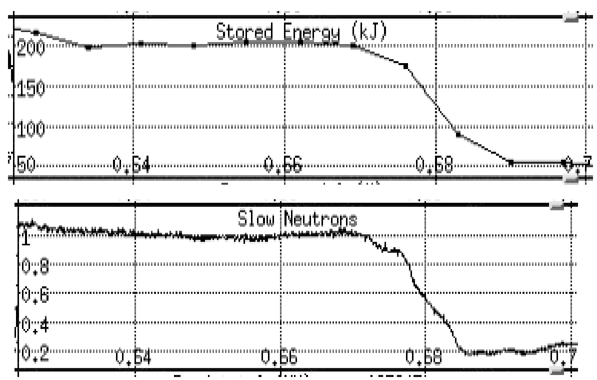
T_e profile provides critical addition to D_α ELM detection by determining radial extent of perturbation – useful for real-time



NSTX





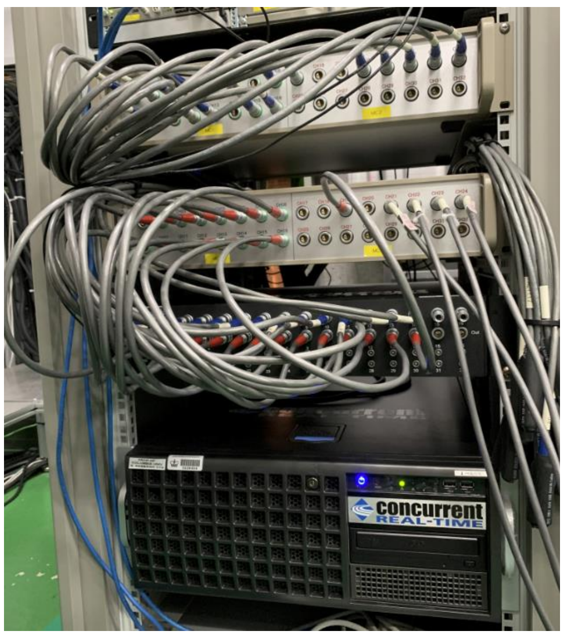


- Global T_e drop, Slow Neutrons (& W_{tot}) exhibit catastrophic drop
  - *→ D_α info now to be passed to other DECAF events*
- Low frequency, large-amplitude *low-f* mode
- Strong RWM sensor (B_R, B_p) signal increase
- → Apparent RWM, not ELM

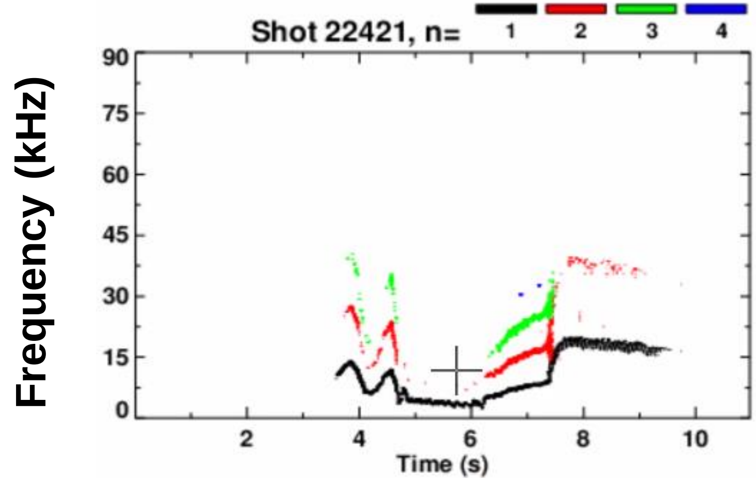
J. Butt (this meeting)

Real-time MHD system taking data on KSTAR to be used for real-time DECAF application in 2021

- Real-time MHD analysis computer installed at KFE
  - Part of plasma control system
  - System FGPA chip now computing FFTs in real-time

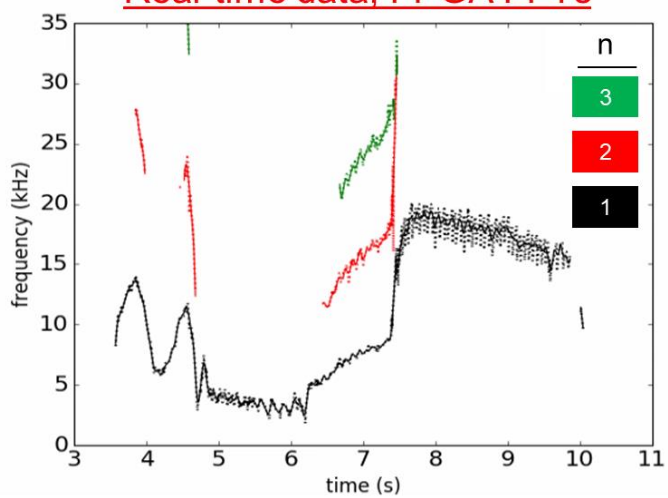


Offline Magnetic probe spectrogram analysis

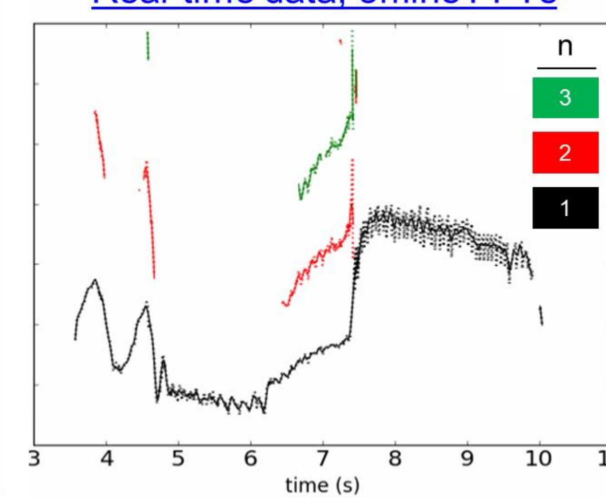


DECAF analysis of real-time signals

Real-time data, FPGA FFTs



Real-time data, offline FFTs



KSTAR

Simple island rotation dynamics model used to forecast the bifurcation point to signal disruption

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

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

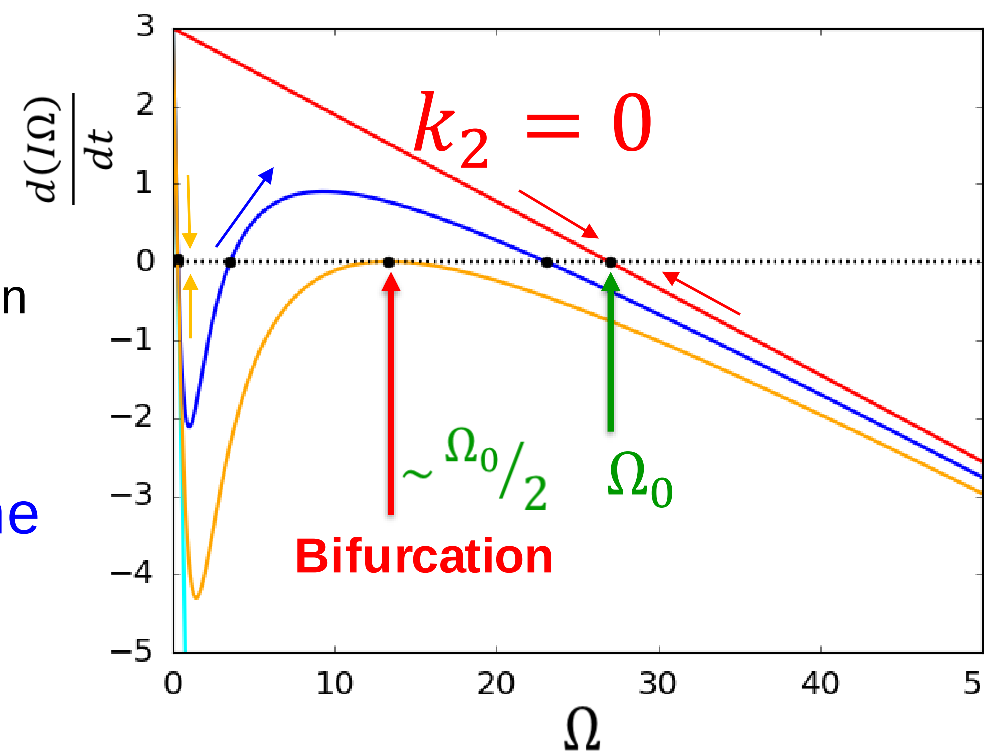
$$T_{mode} = \frac{k_2\Omega}{1+k_3\Omega^2}$$

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

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

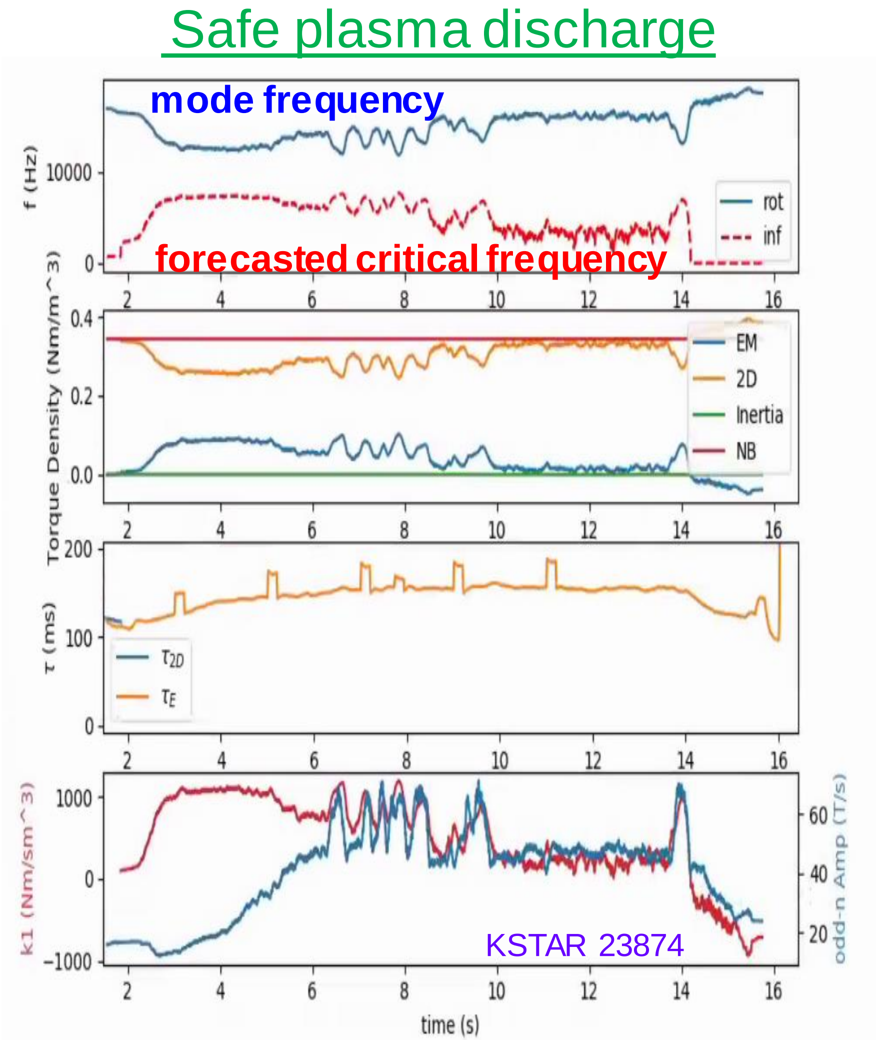
- First real-time model, assume "no slip" condition

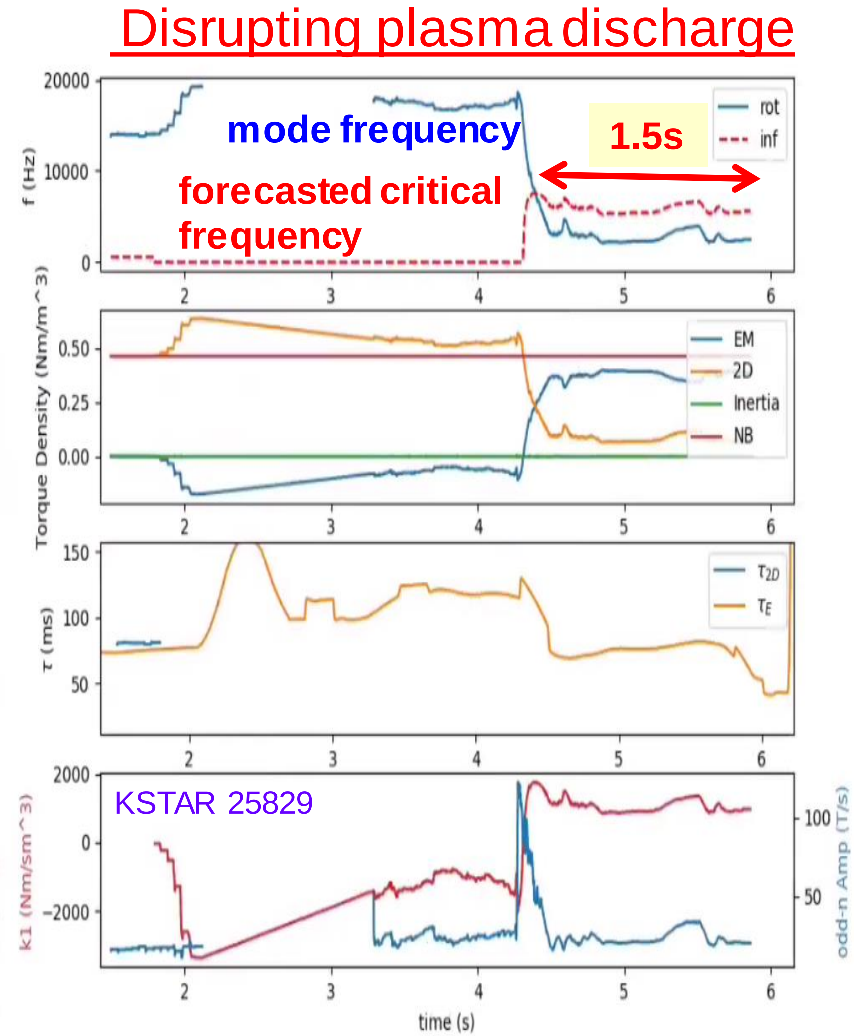
$$T_{mode} = \frac{k_1}{\Omega}$$



J. Riquezes (this meeting)

New locked mode (LTM) forecaster "measures" key parameters, provides early warning, high success



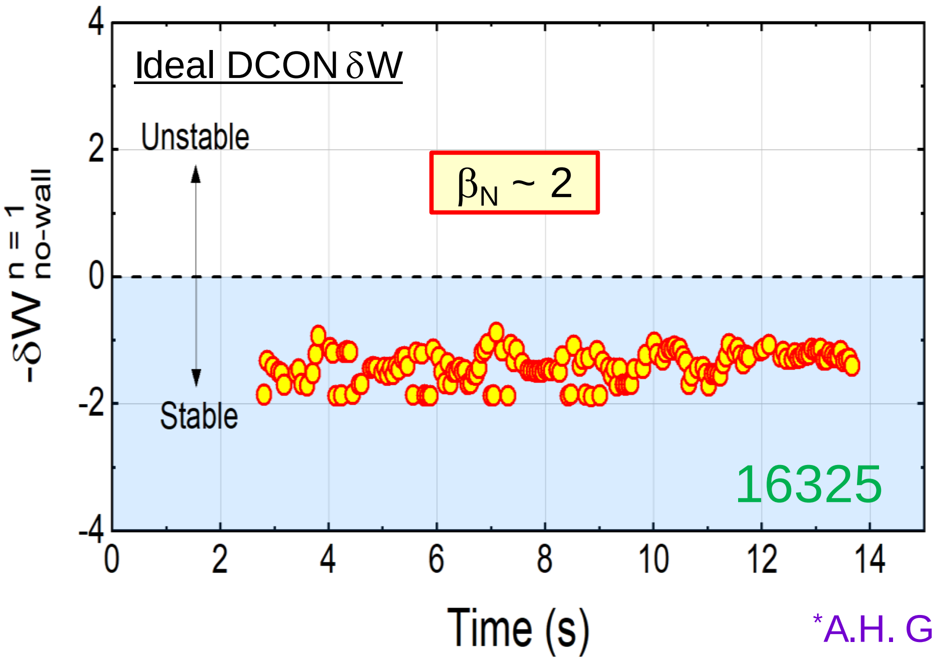


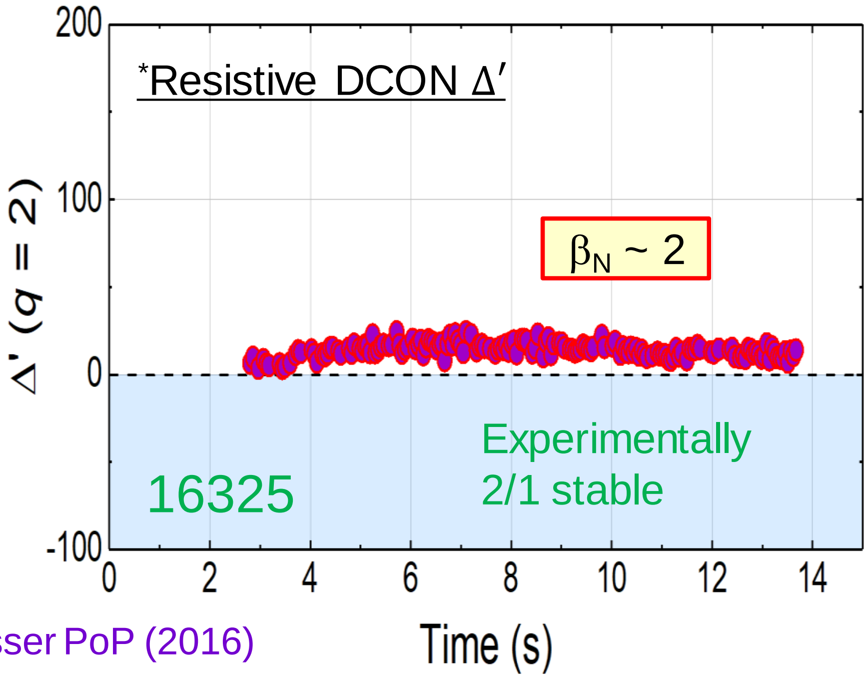
- Disruption forecasted when mode freq. < 0.5x computed inflection freq.
- 13 KSTAR shots from 2020 analysed, 100% success rate; 1.5s warning!

DECAF is fueled by coordinated research that continues to validate/develop physics models, e.g.:

- Resistive MHD
  - Detection / forecasting: available magnetic diagnostics, plasma rotation
  - Forecasting: examination of MRE ➔ start with Δ' evaluation
- Density limits
  - Detection: rad. power, global empirical limit
  - Forecasting: examination of rad. island power balance model
- Global MHD
  - Detection: available magnetic diagnostics, plasma rotation, equilibrium
  - Forecasting: Kinetic MHD model has high success in NSTX, DIII-D
- Physics analysis / experiments to build DECAF models
  - Interpretive and "predict-first" TRANSP analysis of KSTAR long-pulse, high beta plasmas with high non-inductive fraction

Tearing mode classical Δ’ stability examined in KSTAR plasmas (supports future DECAF models)

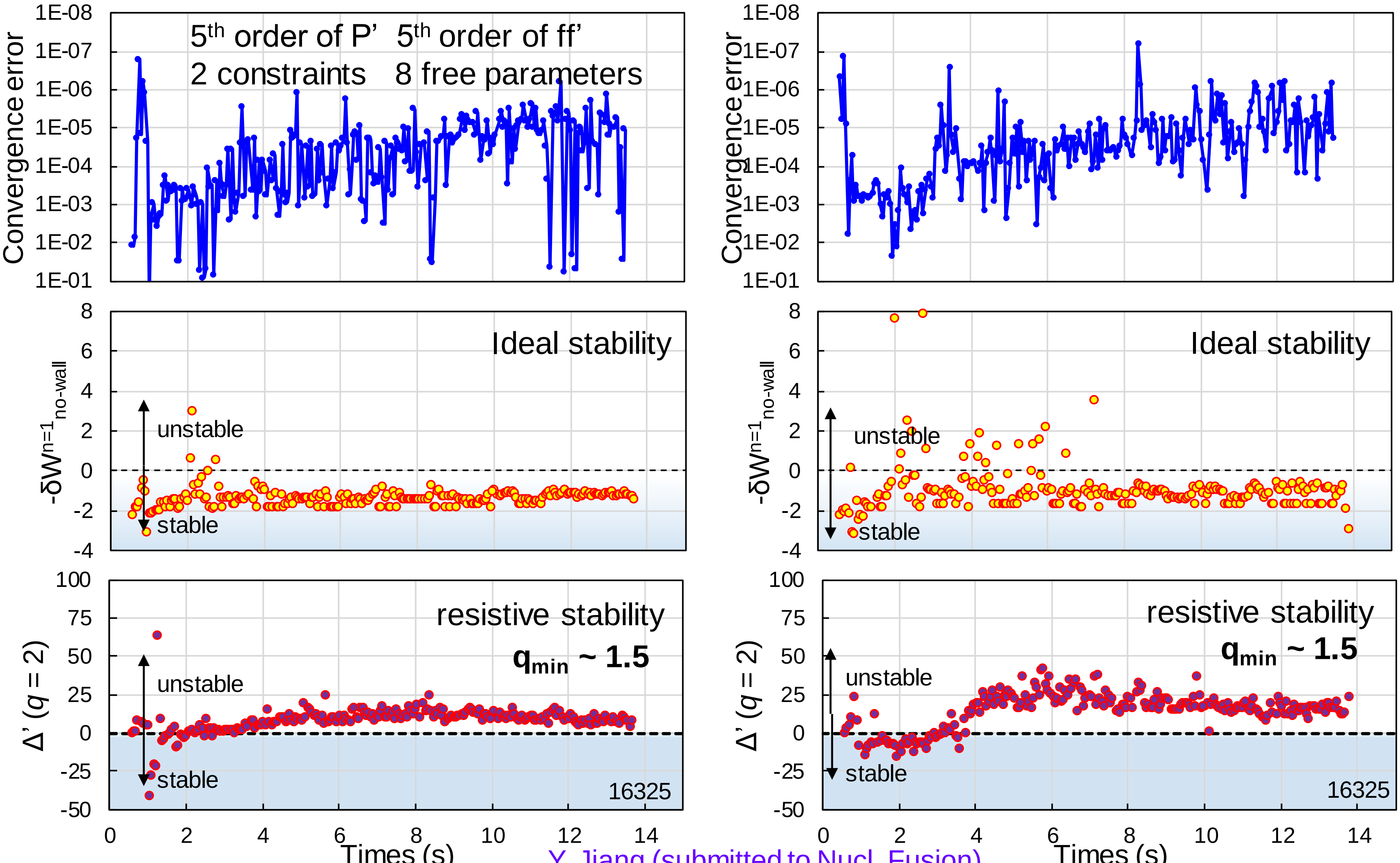




*A.H. Glasser PoP (2016)

- Classical tearing stability index, Δ′, computed at $q = 2$ surface using outer layer solutions
- At higher q_{95}, Δ′ is mostly positive predicting unstable classical tearing mode
  - Indicates neoclassical effects, additional physics needed to reproduce XP
  - KEY POINT: Conclusions regarding Δ’ evolution can be made!
    - Recent paper with MRE evaluation ➔ Y.S. Park, et al., NF **60** (2020) 056007

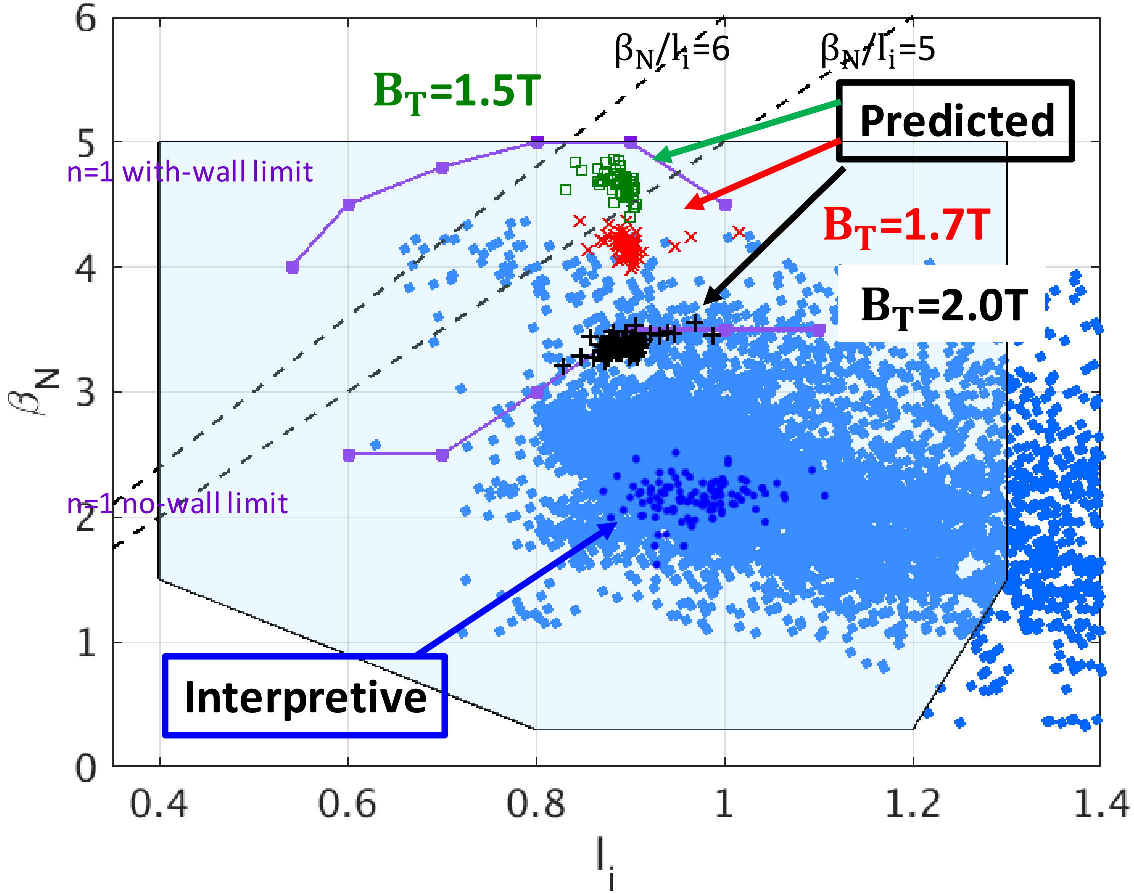
Tearing mode classical Δ' and ideal stability sensitivity to models also studied in KSTAR

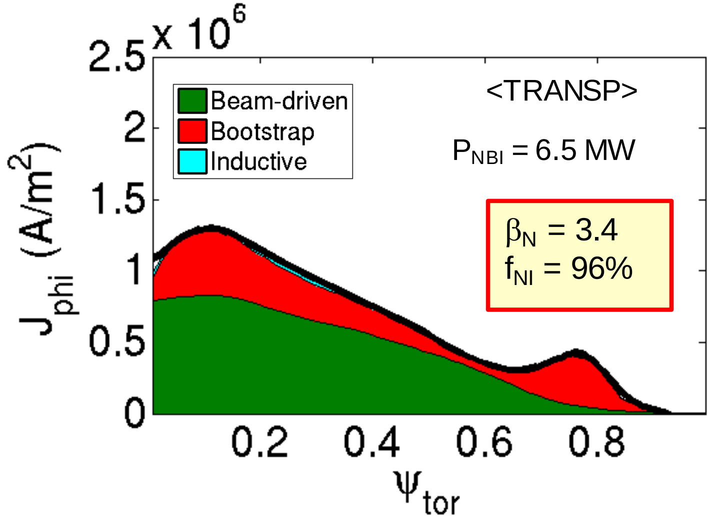


Y. Jiang (submitted to Nucl. Fusion)

Predictive TRANSP analysis shows KSTAR design target β_N~5 can be approached with f_{NI}~100%

- "Predict-first" analysis used to design high-β , 100% non-inductive current fraction (NICF) experiments for present KSTAR run campaign





- Up to 75% NICF already reached in similar plasmas
- By altering I_P and B_T values, $\beta_N > 4$, up to KSTAR design target 5 can be achieved with 100% NICF

KSTAR

DECAF application and research for disruption prediction and avoidance expanding to real-time

- Multi-faceted, integrated approach to disruption prediction and avoidance with several key characteristics
  - Physics-based approach yields key understanding of evolution toward disruptions: confident extrapolation of forecasting, avoidance by control
  - Full multi-machine databases used (full databases needed!)
  - Open to all methods of data analysis (physics, machine learning, etc.)

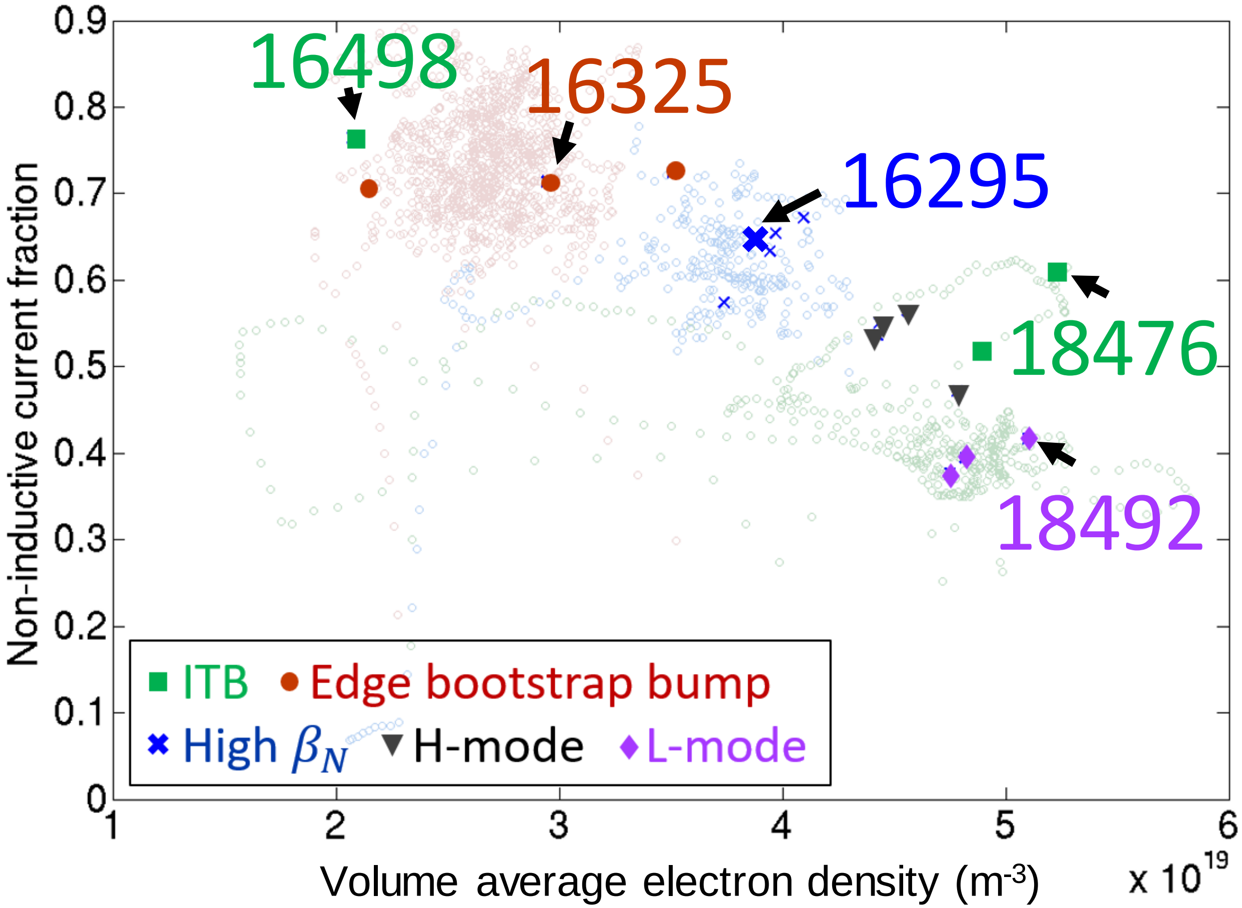
See A. Piccione poster (this meeting)

- DECAF analysis produces early warning disruption forecasts
  - Sufficiently early for potential disruption avoidance by profile control
- Significant physics support efforts from multiple devices
  - KSTAR Δ' analysis, high to ~100% non-inductive CD transport analysis
- Implementing real-time DECAF analysis in KSTAR (4 out of 5 new real-time diagnostic data acquisition systems installed)

Supporting slides

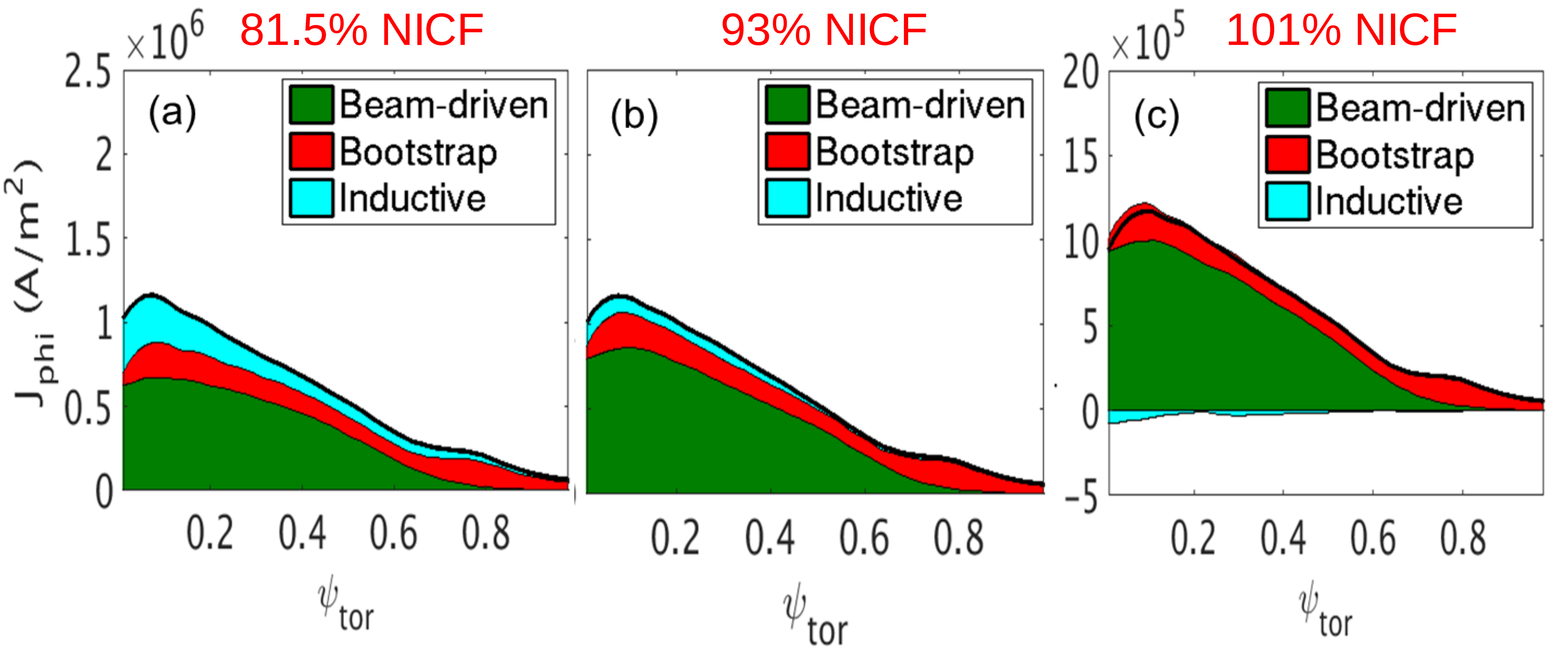
A database of high-non-inductive fraction plasmas is important for disruption forecasting ; NICF ~ 75% in KSTAR

- TRANSP analysis of experimental plasmas
- Non-inductive fraction
  - Beam-driven
  - Bootstrap
- Non-inductive fraction is key for stable high beta steady state operation



"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%
- Aim to generate a significant database of long pulse, high NICF plasmas in 2021 KSTAR run for disruption prediction studies