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

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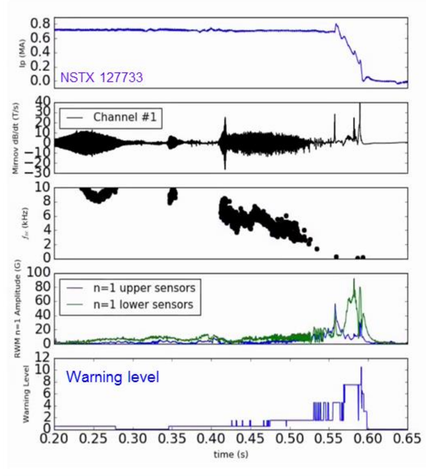
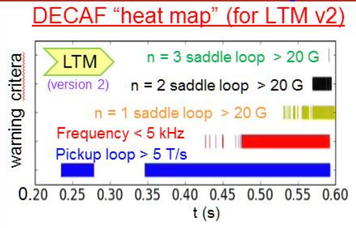
Disruption prediction and avoidance research progressing for ITER and future tokamaks – expanding to real-time

- 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, prediction performance, development
  - Expanded physics analysis supporting DECAF
    - KSTAR high β_N, Δ' analysis, high to ~100% non-inductive CD transport analysis
    - Resistive wall mode physics investigation in MAST, analysis for MAST-U
  - Recent focus on real-time DECAF design and implementation on KSTAR

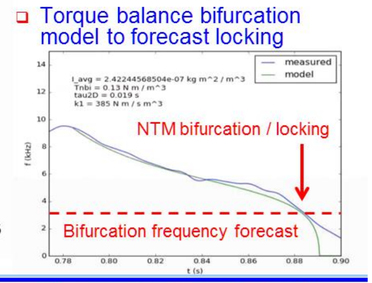
New "reduced" locked tearing mode event aimed for real-time use; bifurcation forecaster developed



DECAF "heat map" (for LTM v2)

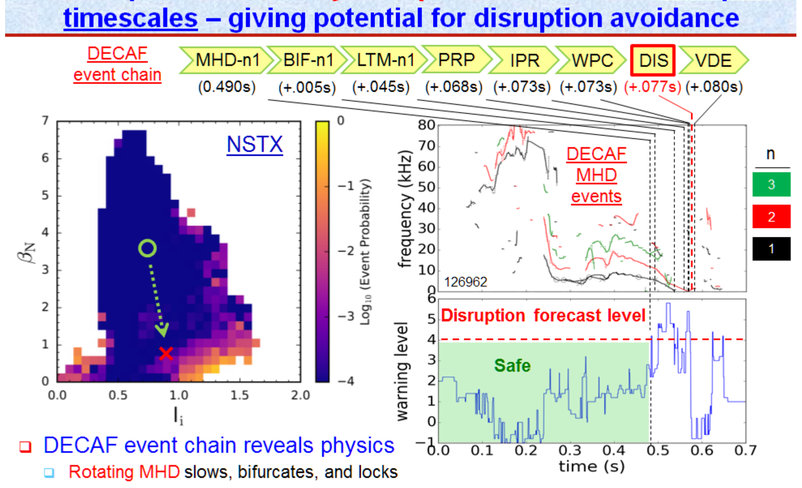


- Torque balance bifurcation model to forecast locking



DECAF Analysis

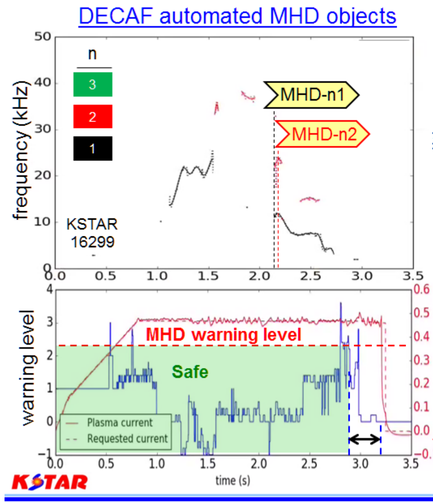
DECAF provides an early disruption forecast - on transport timescales – giving potential for disruption avoidance



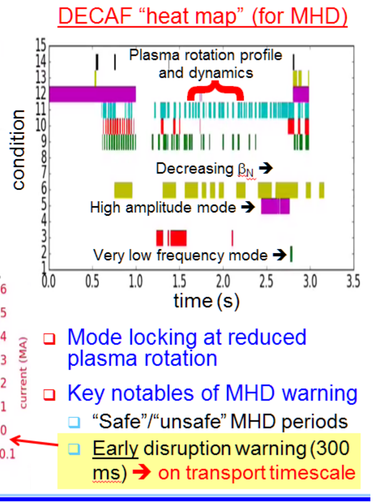
- DECAF event chain reveals physics
  - Rotating MHD slows, bifurcates, and locks
  - Then, plasma has an H-L back-transition (pressure peaking warning PRP) before DIS
  - Important: Early warning occurs in apparently SAFE region of operating space!

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)

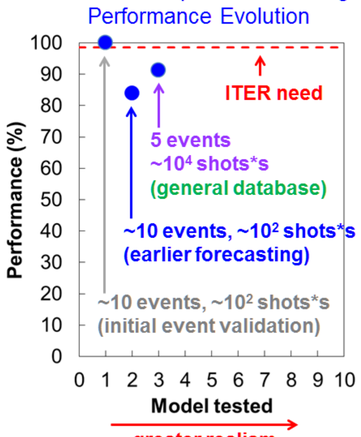


- Mode locking at reduced plasma rotation
- Key notables of MHD warning
  - "Safe"/"unsafe" MHD periods
  - Early disruption warning (300 ms) → on transport timescale

Limited event chain analysis of large databases evolves initial performance of disruption prediction

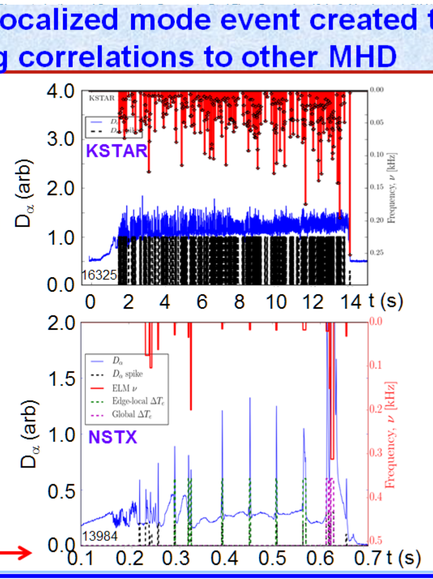
- First test on large, general database
- Analysis with only 5 DECAF events tested for 10,094 discharges with disruptions (NSTX)
  - Events used: VDE, GWL, LOQ, IPR, DIS
- Performance (Model 3)
  - 91.2% true positives (warning occurs)
  - 8.7% false negatives (no warning)
    - Somewhat high number of false negatives expected: only 5 DECAF events are used in this large database analysis
- In 5,909 shots, vertical instability > VDE is part of the disruption chain
- VDE not a large factor in MAST
  - See J. Berkery, this conference (P7/645)

DECAF Disruption Forecasting Performance Evolution



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

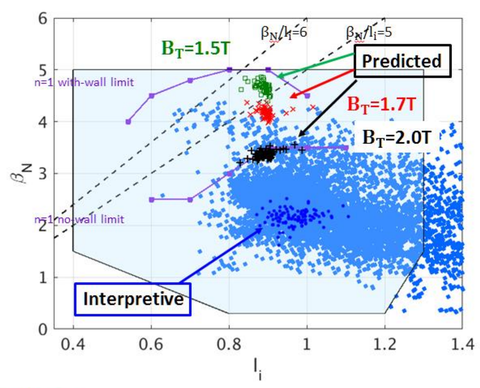
- DECAF ELM event
  - Presently determines ELM triggering times, along with frequency and relative amplitude
- Algorithm compatible with real-time use
- Distinguishes true "ELMs" from other events (global MHD, etc.) that generate D_α light
  - Magenta dashed lines at t = 0.6s is a global mode

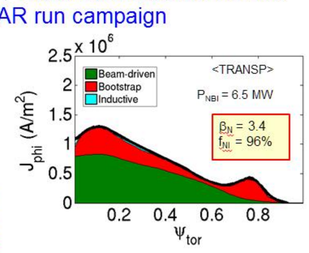


Physics research supporting DECAF

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

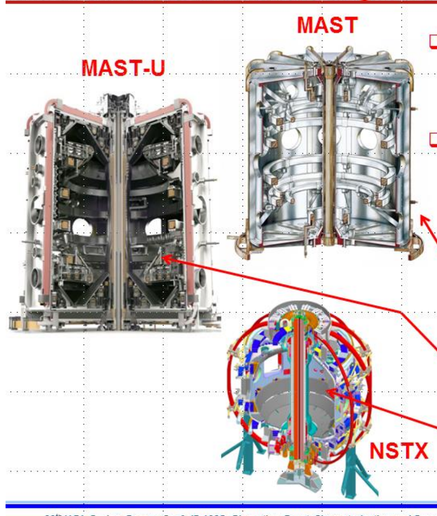
- "Predict-first" analysis used to design high-β , 100% non-inductive current fraction (NICF) experiments for present KSTAR run campaign





- 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

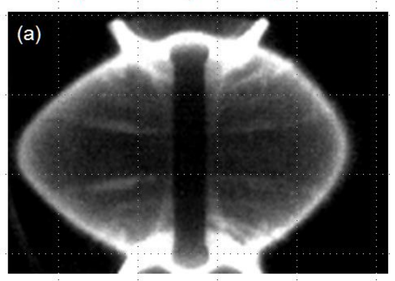
Continued results on key proposed DOE study to determine effect of conducting structure on ST stability



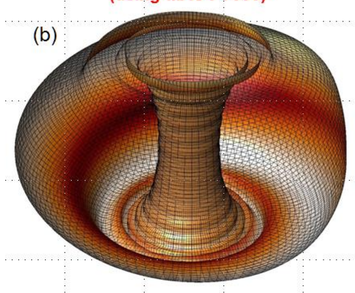
- Effect of wall is "theoretical"
  - High power ST devices can't easily remove conducting wall
- MAST and MAST-U provide unique global mode boundary conditions allowing joint device (experimental) study
  - MAST: Least amount of mode stabilizing conducting structure; PF coil jackets provide stability?
  - MAST-U: Divertor plates add substantial stabilizing structure
  - NSTX: 4 toroidal rows of ¾" copper stabilizing plates

Initial VALEN code analysis models similar distortion to RWM in MAST

Fast camera image (MAST 21436, t ~ 0.280s)

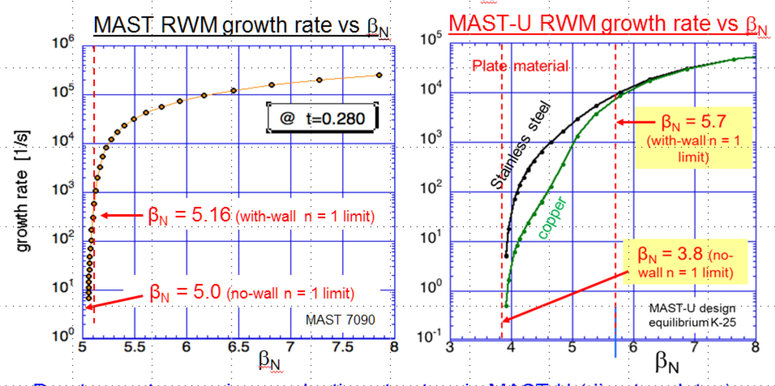


VALEN analysis (n = 1 RWM) (using MAST 7090)



- Analysis of RWM eigenfunction in VALEN resembles MAST fast camera image, some subtle differences
  - More flattened appearance in analysis may be due to present assumption of pure n = 1 mode in model
  - Magnetics-only equilibrium used, and from a different plasma (7090)

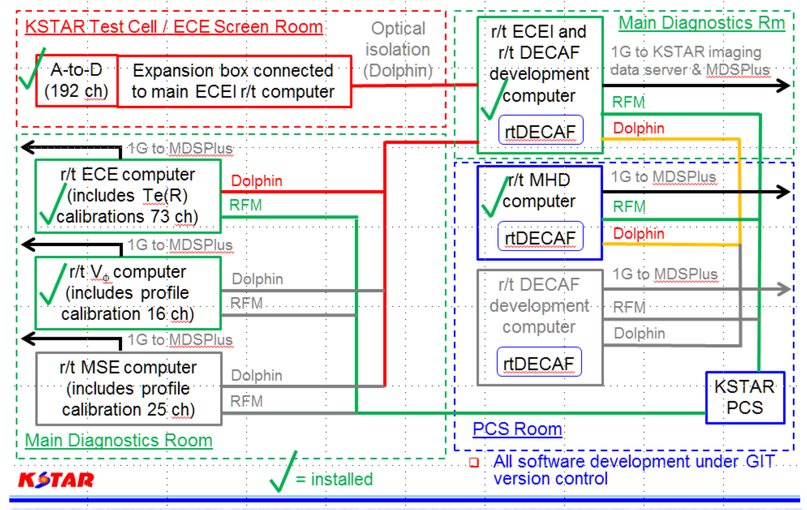
VALEN analysis shows a significantly larger window between the no-wall/with-wall β_N limits for MAST-U



- Due to greater passive conducting structure in MAST-U (divertor plates)
  - Computed wall stabilized $\Delta\beta_N$ window only for MAST 0.15 (→ 3% of β_N operational space)
  - Computed $\Delta\beta_N$ window is 1.9 for MAST-u (for K-25 case) →33% of β_N operation space (result not optimized – greater stabilization with plasma in closer proximity to the wall)

Expansion to Real-Time DECAF

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

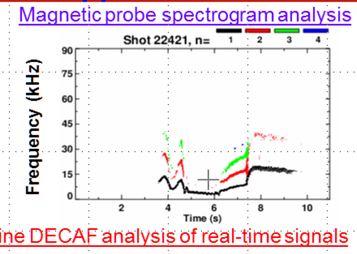


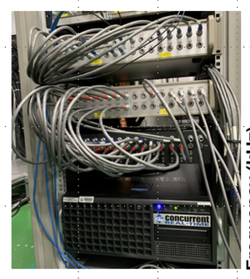
- All software development under GIT version control

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 NFRI
  - Designed for connection to plasma control system (PCS)
  - Interface to MHD probes built

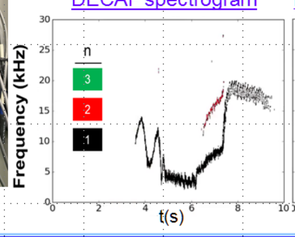
Magnetic probe spectrogram analysis



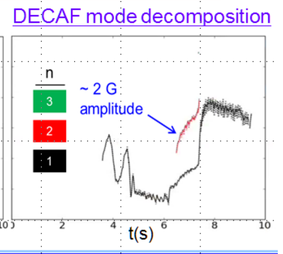


Offline DECAF analysis of real-time signals

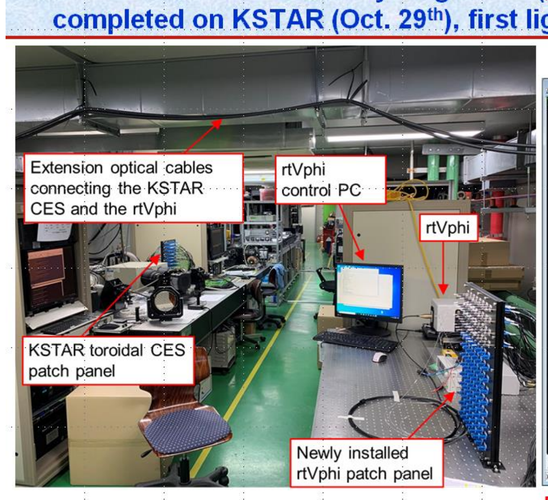
DECAF spectrogram



DECAF mode decomposition



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



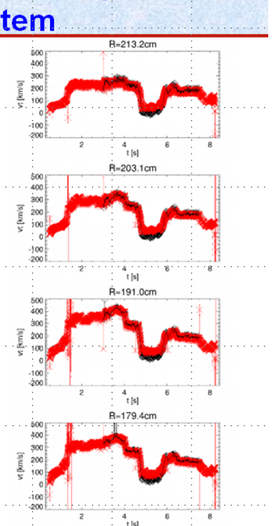
First Light! 32 channels

- Initial real-time KSTAR V_ϕ profile data taken 2020

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

Real-time V_ϕ profile shows reasonable 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



Status and plans for RTV system on KSTAR (Podestà)

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 (5 now) used (full databases needed!)
  - Open to all methods of data analysis (physics, machine learning, etc.)
- DECAF analysis producing 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
  - RWM observed in MAST: mode eigenfunction shape and growth rate are significantly altered by location of conducting structure vs. NSTX
- Implementing real-time DECAF analysis in KSTAR (4 out of 5 new real-time diagnostic DAQ installed)