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

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PPPL

NFRI 국가핵융합연구소 National Fusion Research Institute

CCFE CULHAM CENTRE FOR FUSION ENERGY

IPP Max-Planck-Institut für Plasmaphysik

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK

IAEA Technical Meeting on Plasma Disruptions and their Mitigation

20-23 July 2020

St. Paul-lez-Durance, France

ASDEX-U

KSTAR

MAST-U

NSTX-U

V1.5

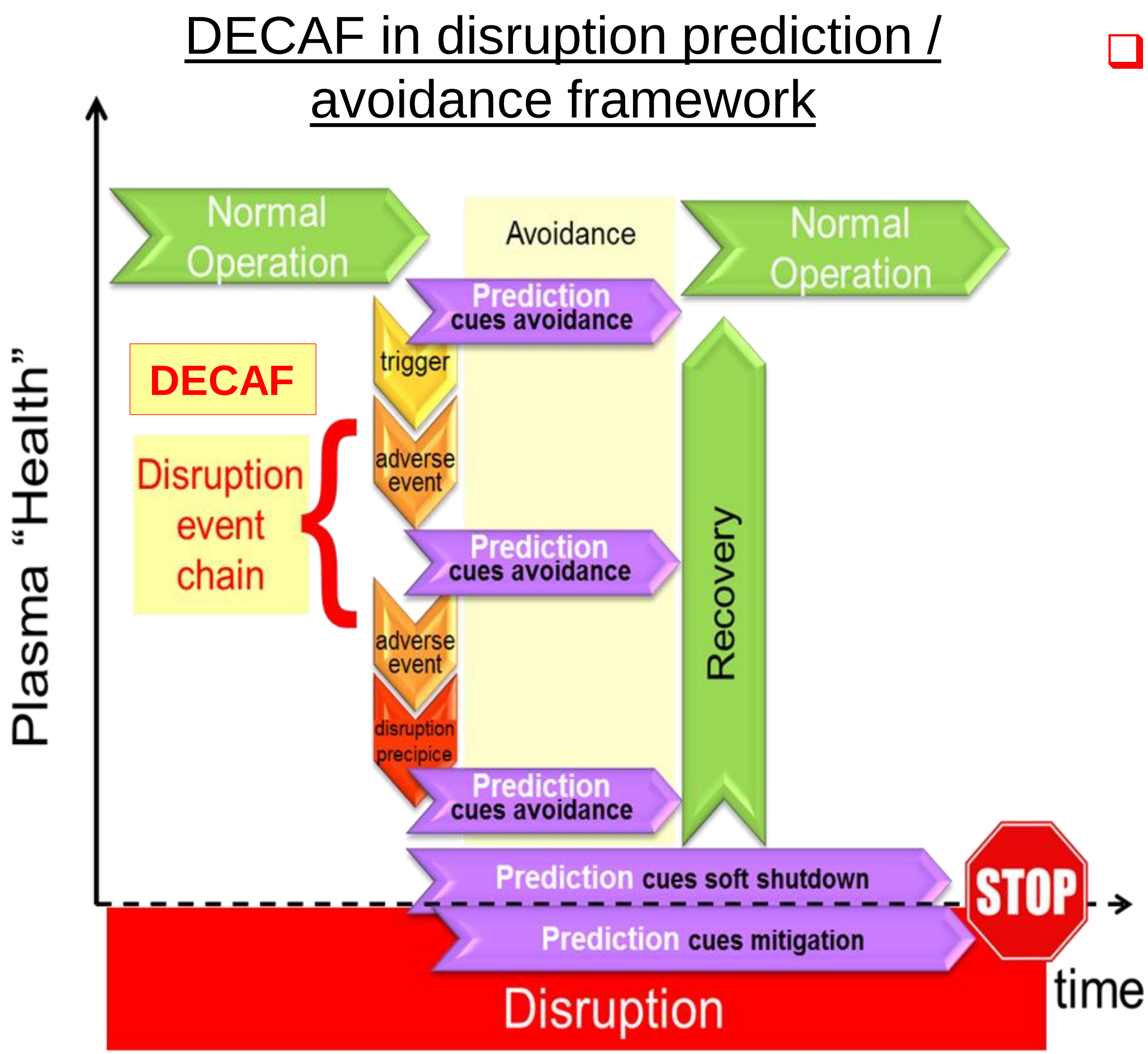
Supported by US DOE grants DE-SC0016614, DE-SC0018623, DE-FG02-99ER54524 and contract DE-AC02-09CH11466

A broadened disruption prediction and avoidance analysis is progressing for ITER and future tokamaks

- 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) approach
  - Overview of DECAF results, disruption event chains, early forecasting
  - Initial multiple-device, large database analysis, forecasting performance
  - Physics support research: i.e. KSTAR high β_N, Δ', ~100% non-inductive CD
  - Recent focus on real-time design and implementation on KSTAR

DECAF is a logical, physics-based paradigm that meets all disruption predictor requirement metrics

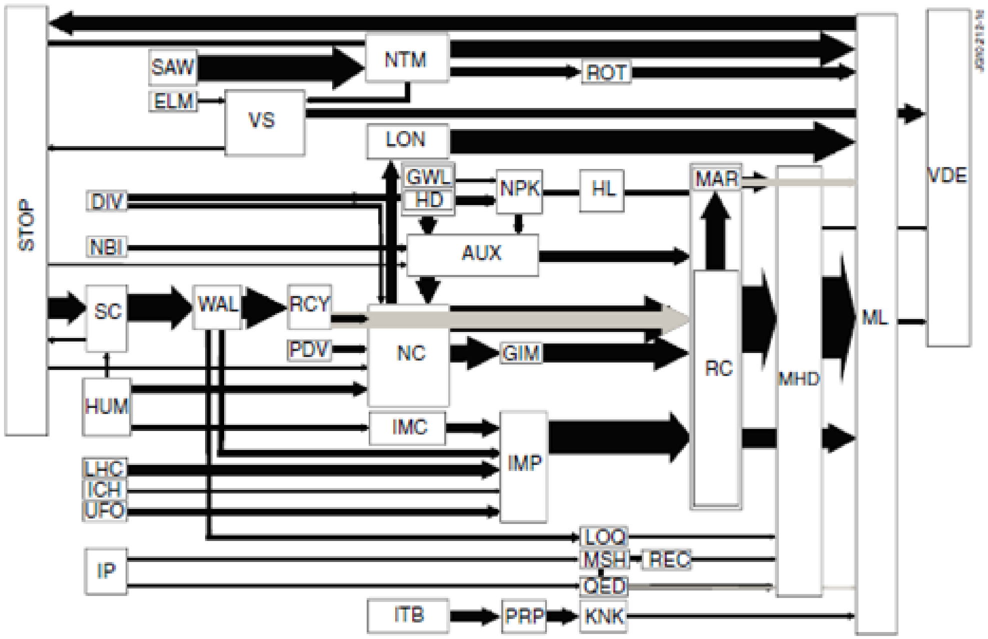


- Disruption predictor must
  - ✓ Predict SPECIFIC pre-disruptive phenomena ➔ link to control
  - ✓ Provide CONTINUOUS variable quantifying proximity (& can GENERATE triggers)
  - ✓ Provide SUFFICIENT LEAD TIME for mitigation or avoidance
  - ✓ Be EXTRAPOLABLE to new device (e.g. ITER) prior to operation
  - ✓ Be REAL-TIME calculable

D. Humphreys, et al., PoP **22** (2015) 021806

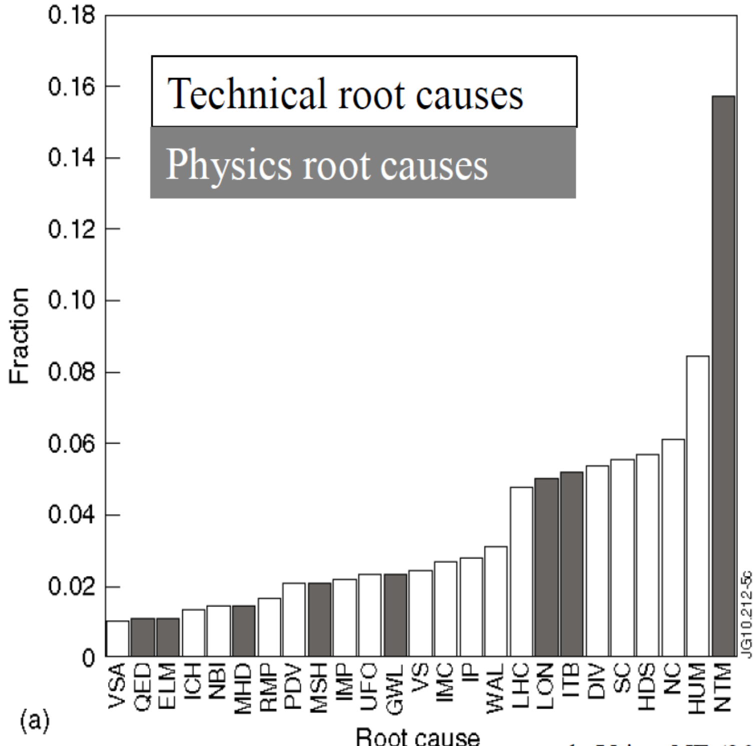
DECAF follows disruption event framework (de Vries) to provide understanding of disruption chains → automates it

JET disruption event chains



P.C. de Vries *et al*., Nucl. Fusion **51** (2011) 053018

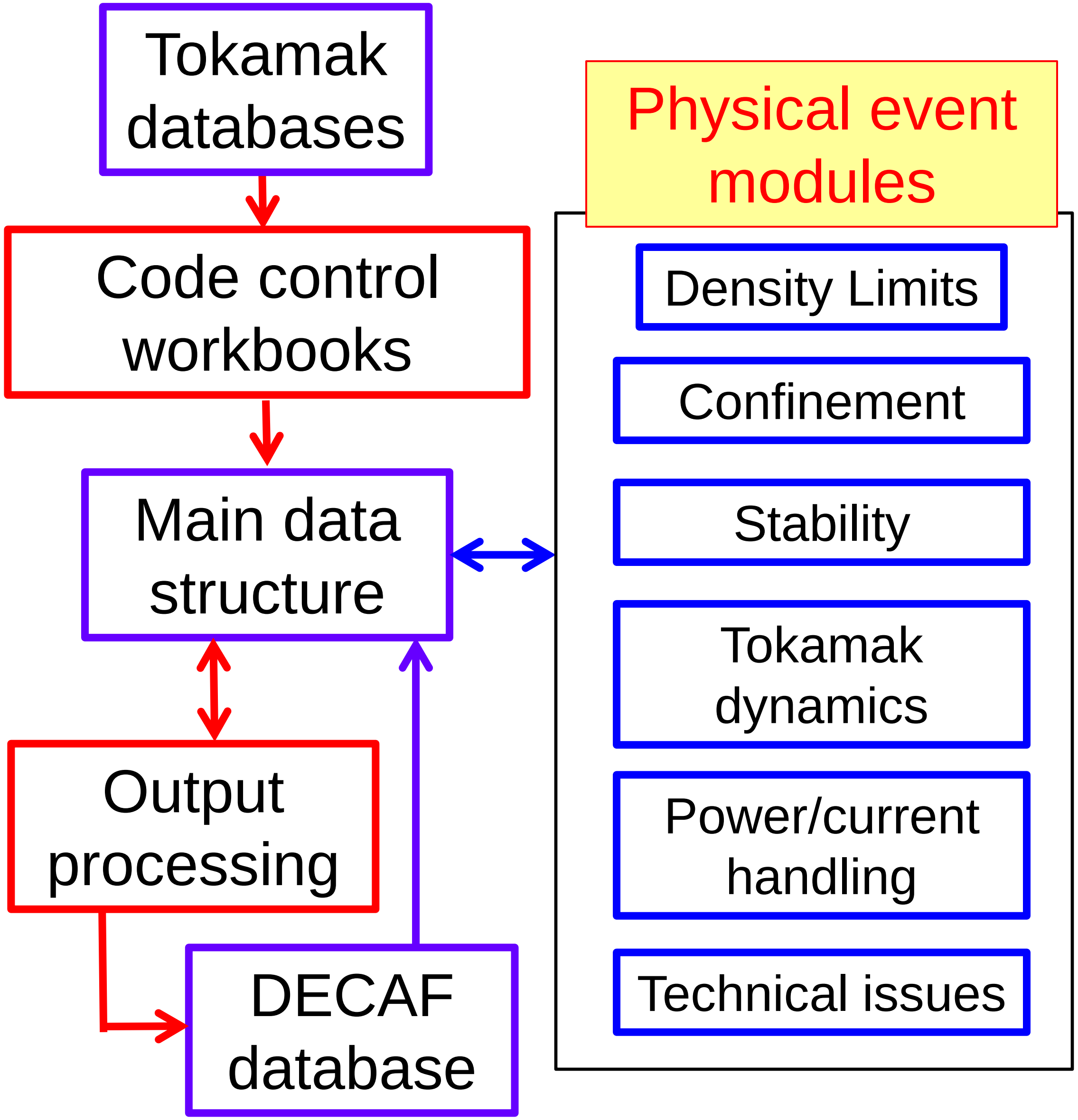
Related disruption event statistics



de Vries, NF (2011)

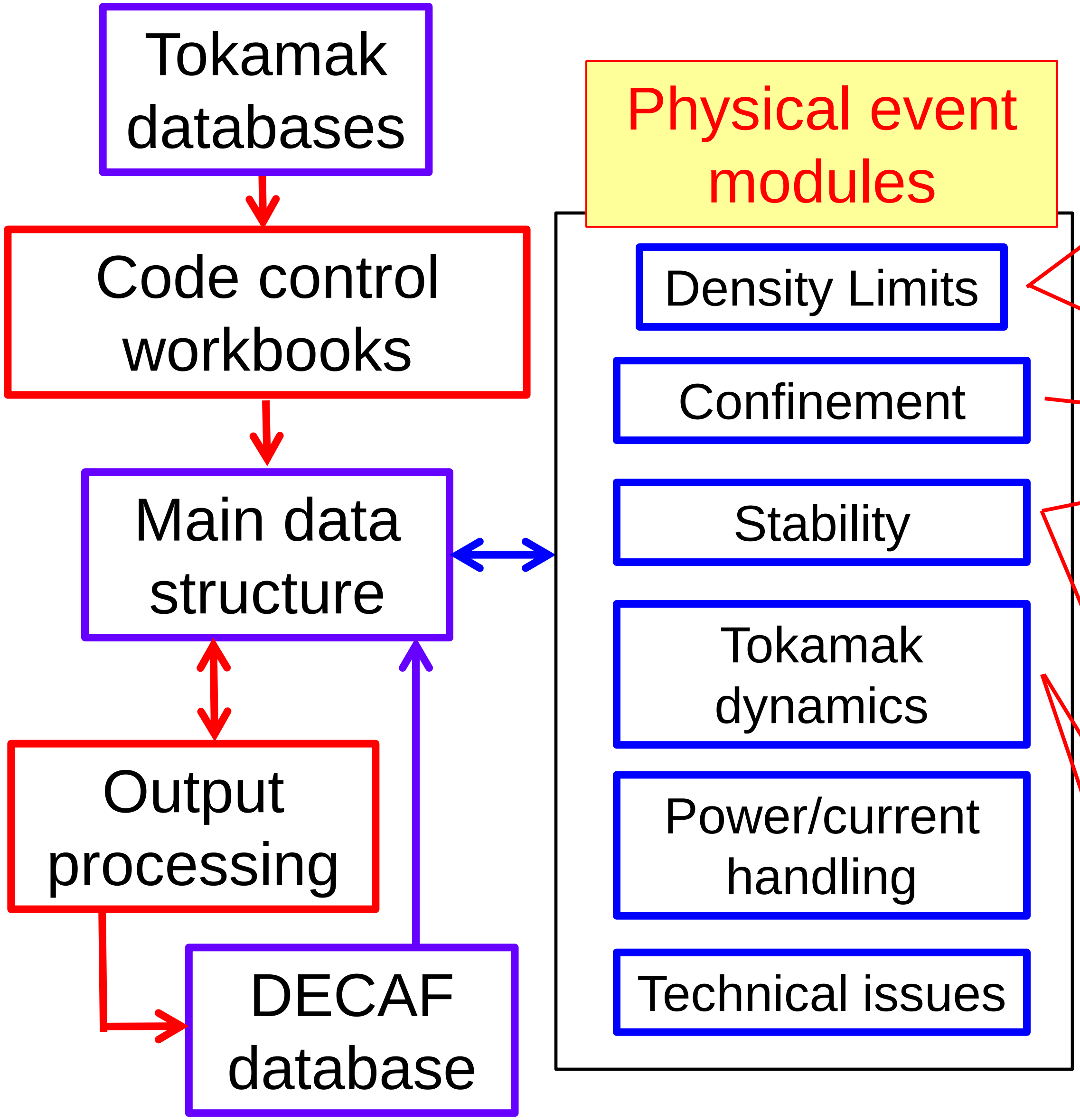
- JET disruption event chain analysis performed by hand, desire to automate
- General code DECAF: automates event chain process, provides disruption warning signals, being validated against databases from multiple devices

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

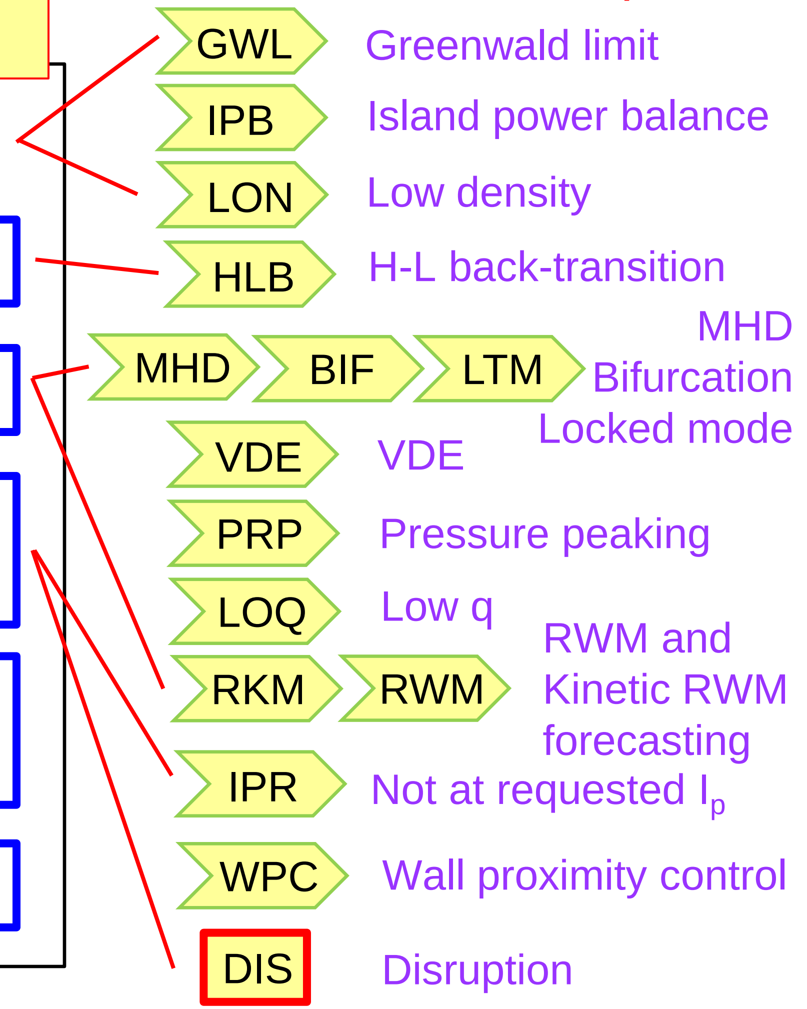


- Physical event modules encapsulate disruption chain events
  - Development focused on improving these modules
  - Structure eases parallel development incl. real-time
- Physical events are objects in physics modules
  - e.g. VDE, LOQ, RWM are objects in “Stability”
  - Python “objects” having attributes and methods
  - Carry metadata, event forecasting criteria, event linkages, etc.

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



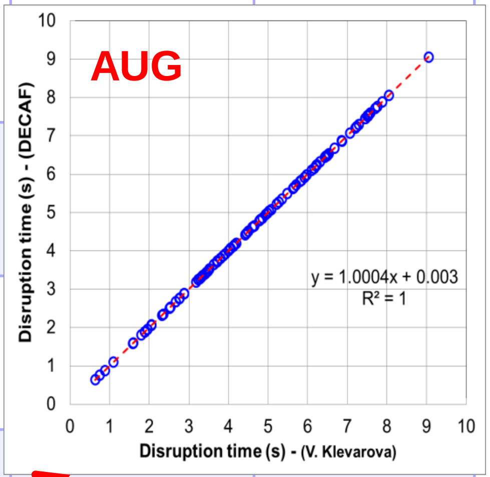
- Physical event modules encapsulate disruption chain events. Examples:



DECAF connected to databases from multiple machines, expanding analysis

- Analysis
  - Density limits
  - Ideal, kinetic, resistive MHD stability
  - Rotating MHD, etc.
- DECAF database started
  - Presently ~50 TB stored

Device / Capability	KSTAR	MAST	NSTX	DIII-D	AUG, TCV
Full database access (required!)	Yes (MDSplus)	Yes (UDA)	Yes (MDSplus)	Yes (MDSplus)	Yes (MDSplus)
Database analysis	continuing	continuing	continuing		
Equilibrium analysis	Magnetic, Kinetic + MSE	Magnetic, Kinetic + MSE	Magnetic, Kinetic + MSE		
Stability	Ideal, Resistive Kinetic MHD	Ideal (so far)	Ideal, kinetic MHD (resistive)		
shot*seconds (for kinetic analysis)	~ 3,880 (2016-2018)	2,667 (est) (M5 - M9 runs)	2,000 / year (est)		



- Now, full access interface to AUG database; expanding to others
  - 100 shot LTM disruption database by V. Klevarova analyzed for DIS

DECAF now connected to databases from multiple machines, expanding analysis

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  - Density limits
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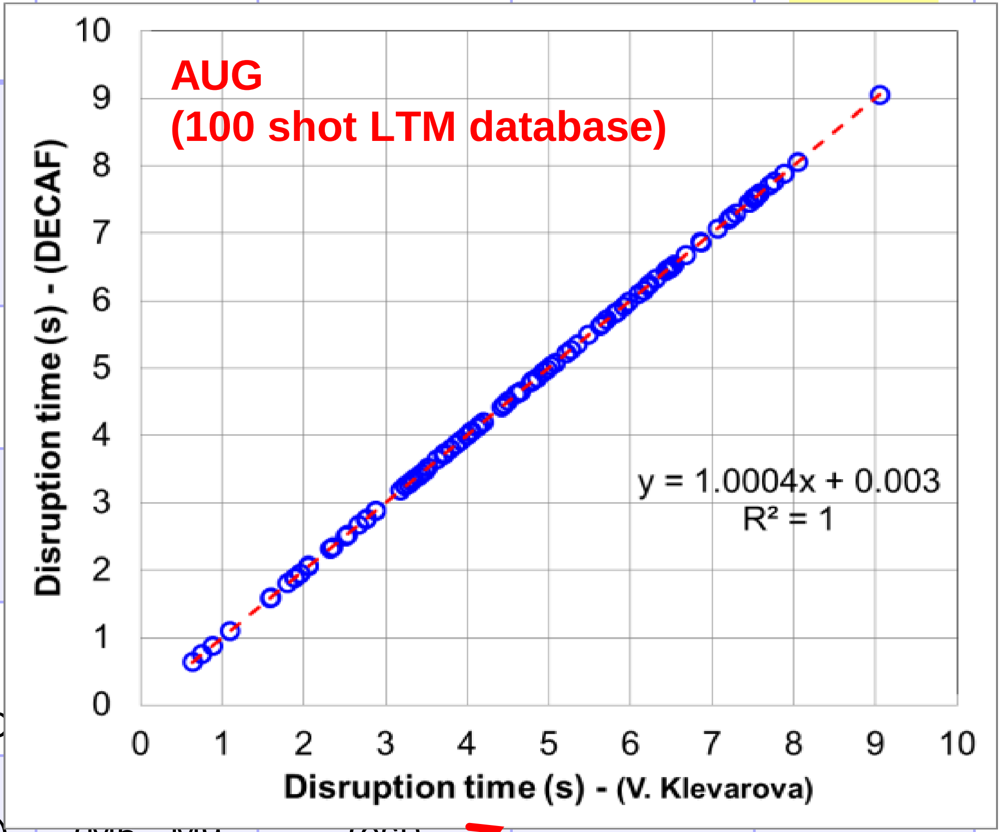
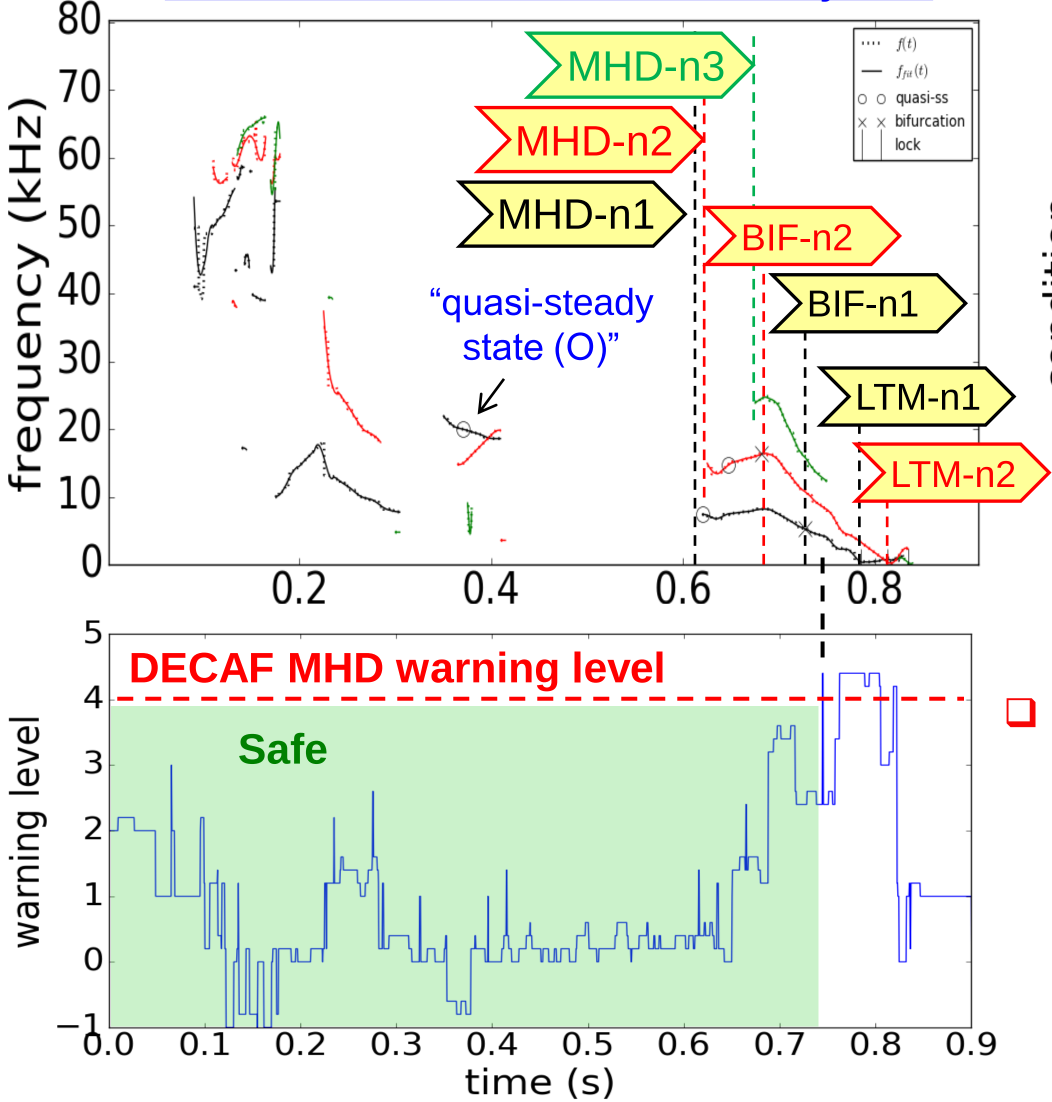


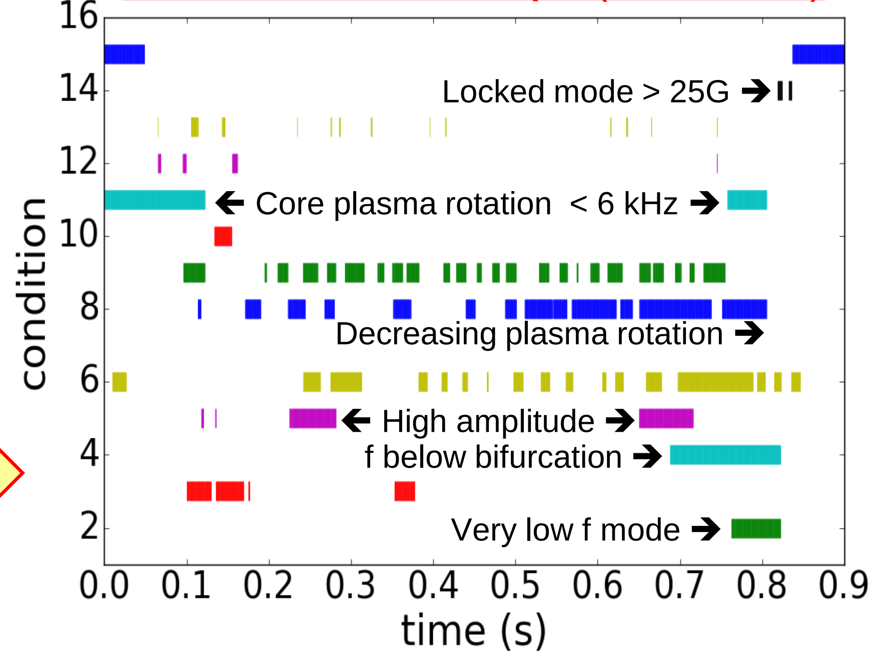
- Now, full access interface to AUG database; expanding to others
  - 100 shot LTM disruption database by V. Klevarova analyzed for DIS

DECAF MHD events utilize history of 15 criteria to define time evolving disruption warning level

DECAF automated MHD objects

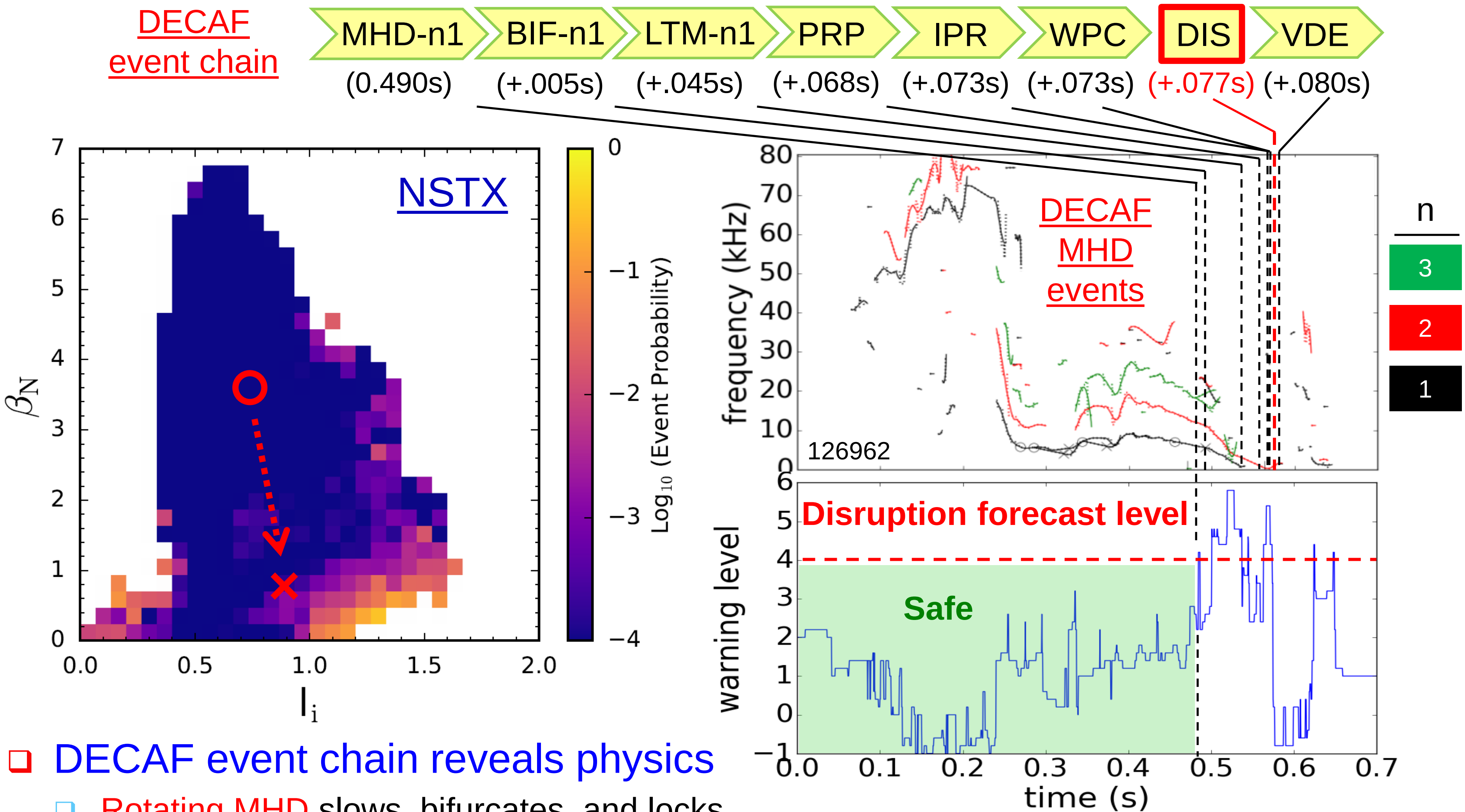


DECAF "heat map" (for MHD)



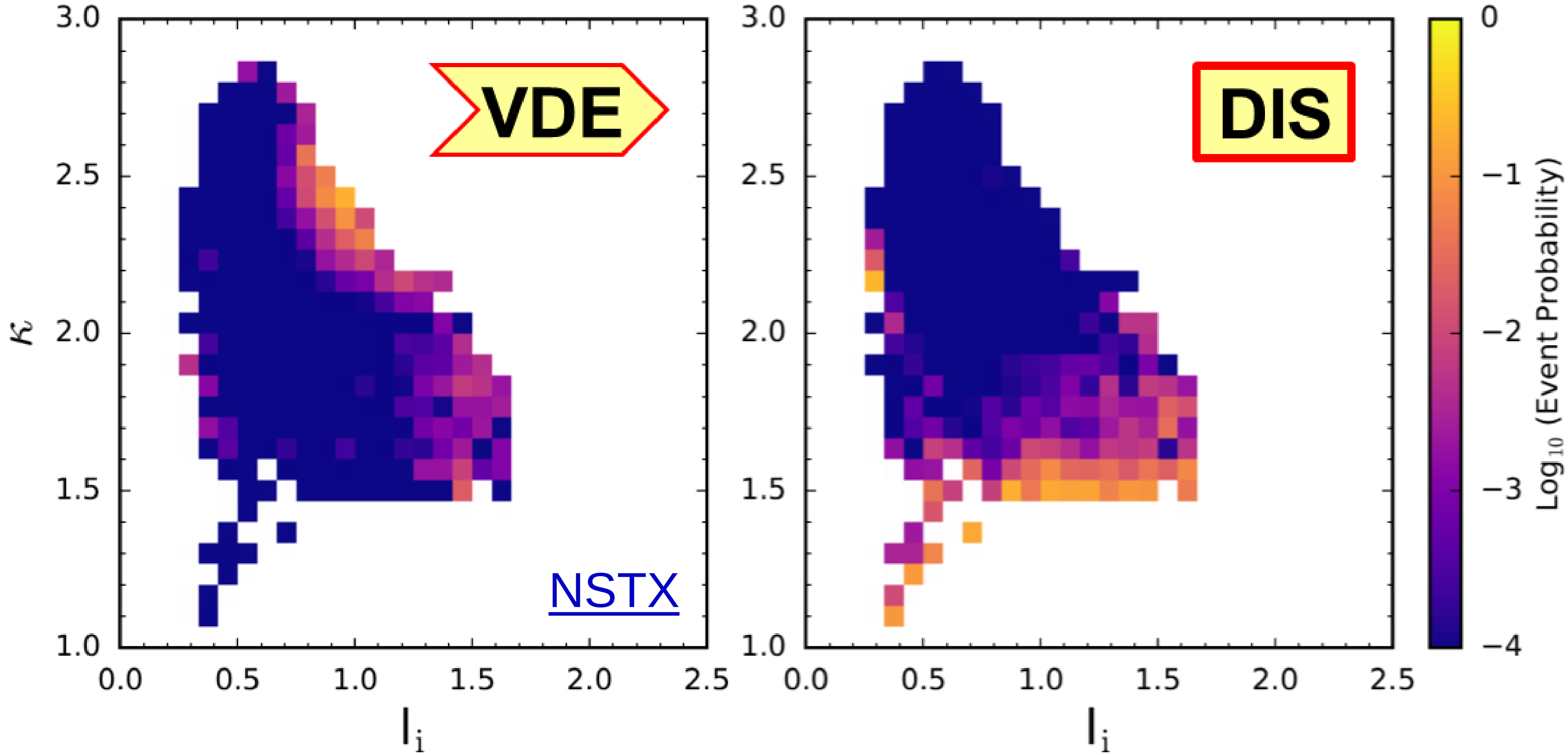
- Key notables of MHD warning
  - "Safe"/"unsafe" MHD periods found
  - Early, slow warning level evolution
    - Locked mode amplitude important, but warning comes in very late
  - Mode frequency below bifurcation, decreasing plasma rotation key

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!

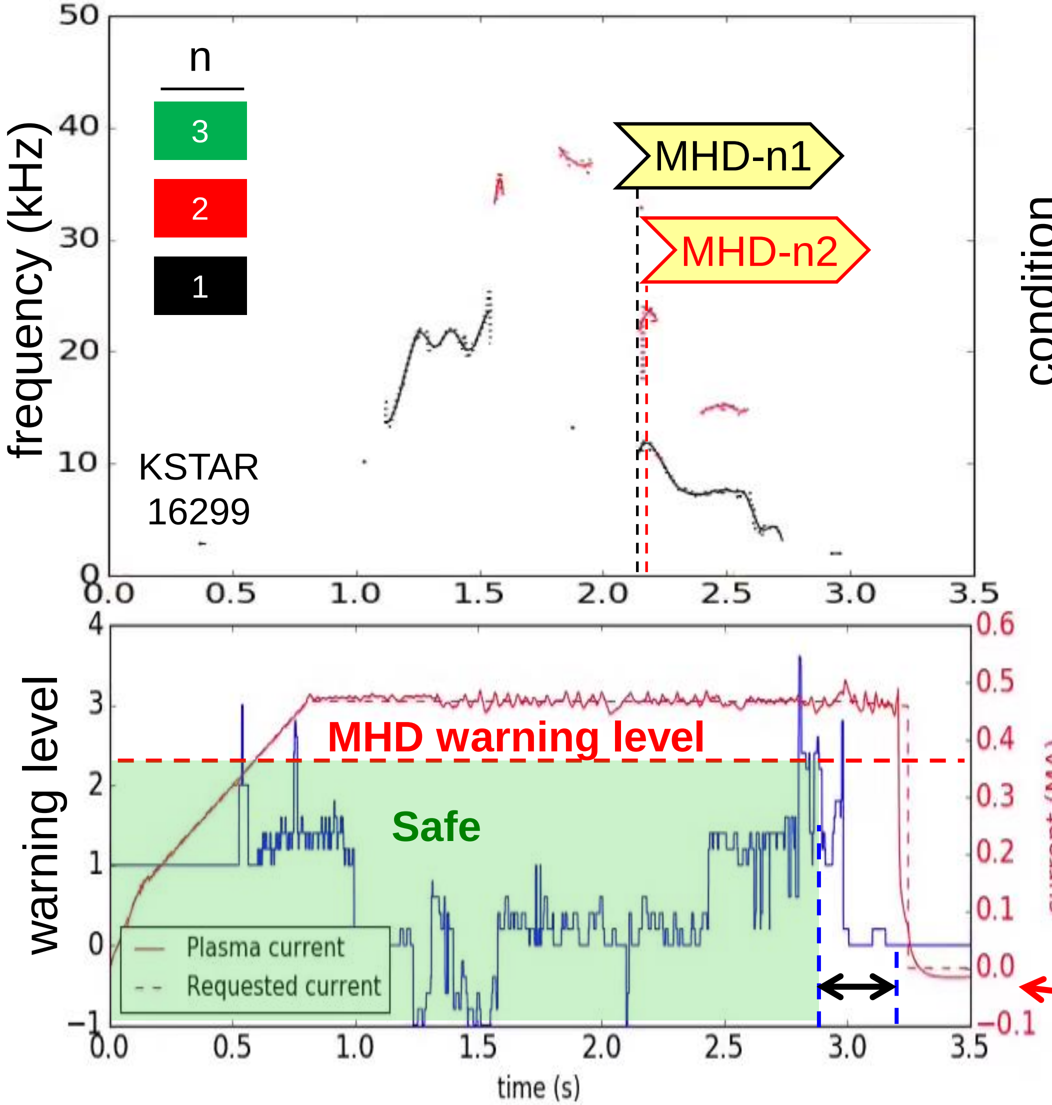
Example: DECAF shows plasma parameters of VDE event can occur far from those of DIS event



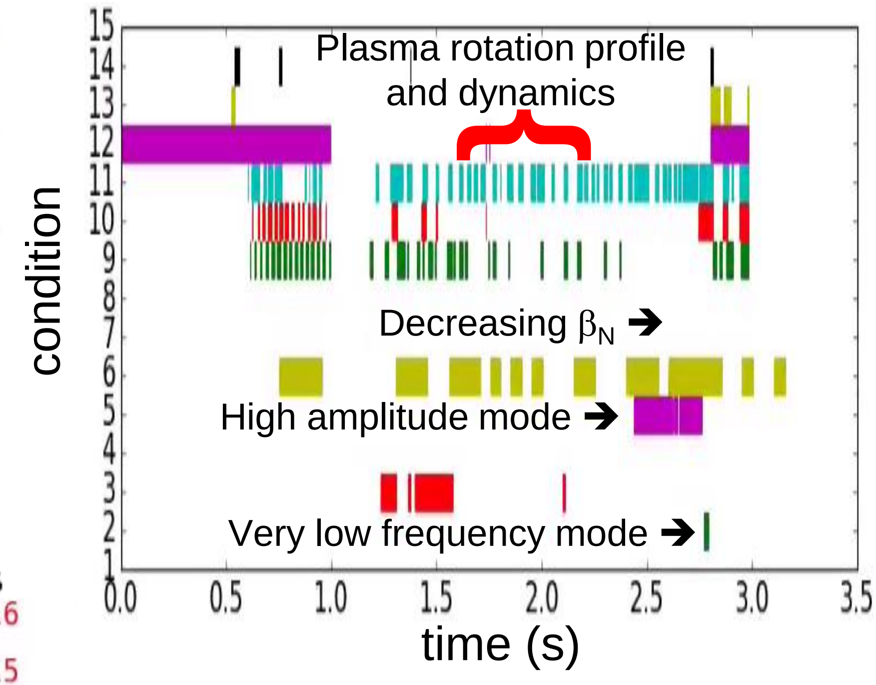
- Largest portion of detected VDE events appear at (l_i, κ) with very small portion of DIS events detected

DECAF MHD events also produce early disruption warnings for KSTAR

DECAF automated MHD objects

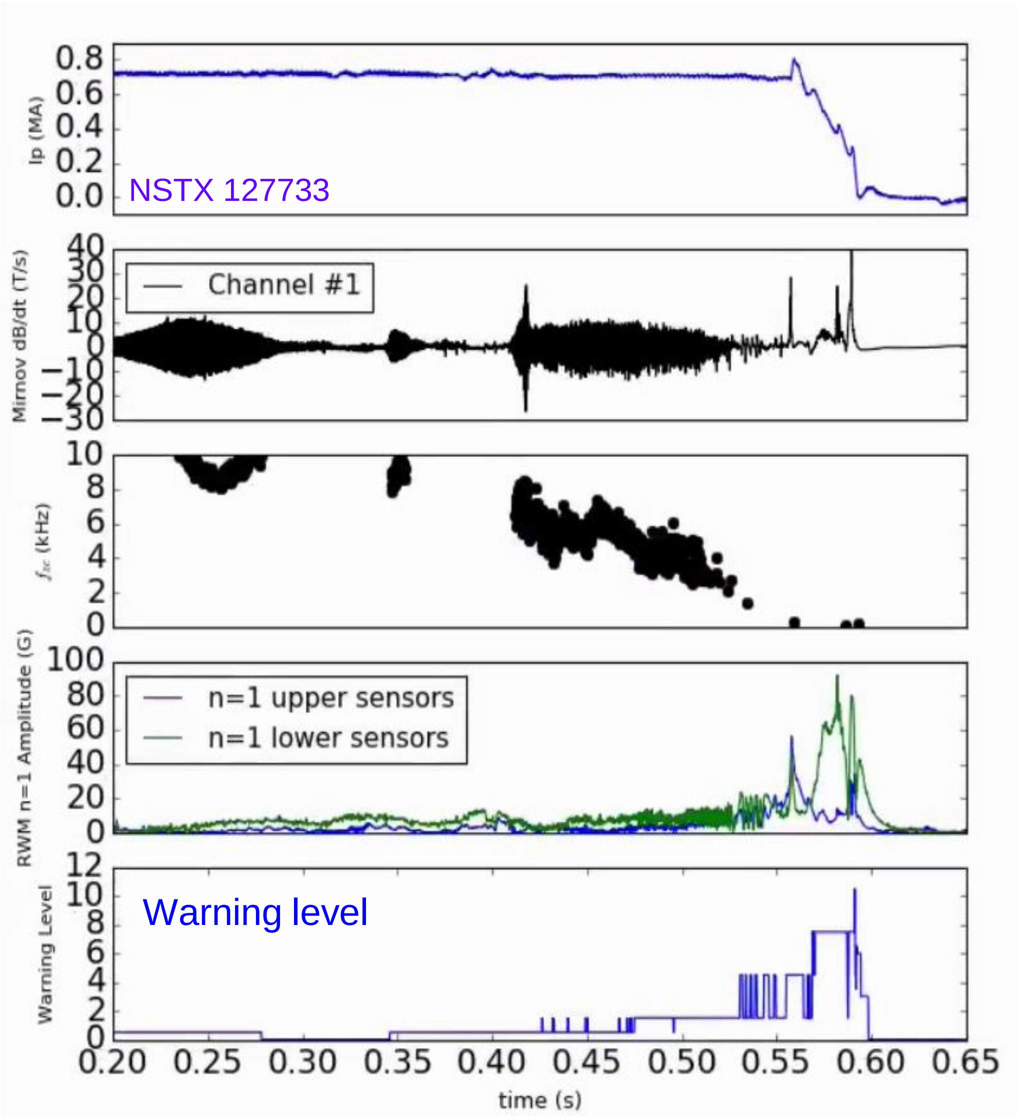


DECAF "heat map" (for MHD)

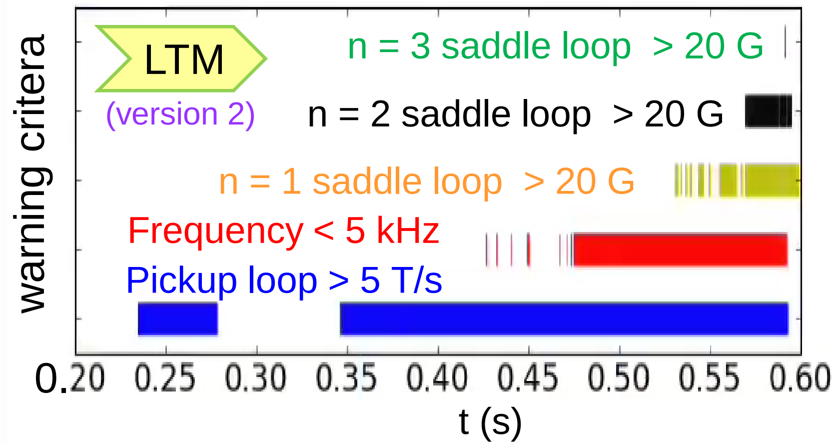


- Mode locking at reduced plasma rotation
- Key notables of MHD warning
  - "Safe"/"unsafe" MHD periods
  - Early disruption warning (300 ms) ➔ on transport timescale

New "reduced" locked tearing mode event being created, aimed for real-time use / comparison



DECAF "heat map" (for LTM v2)



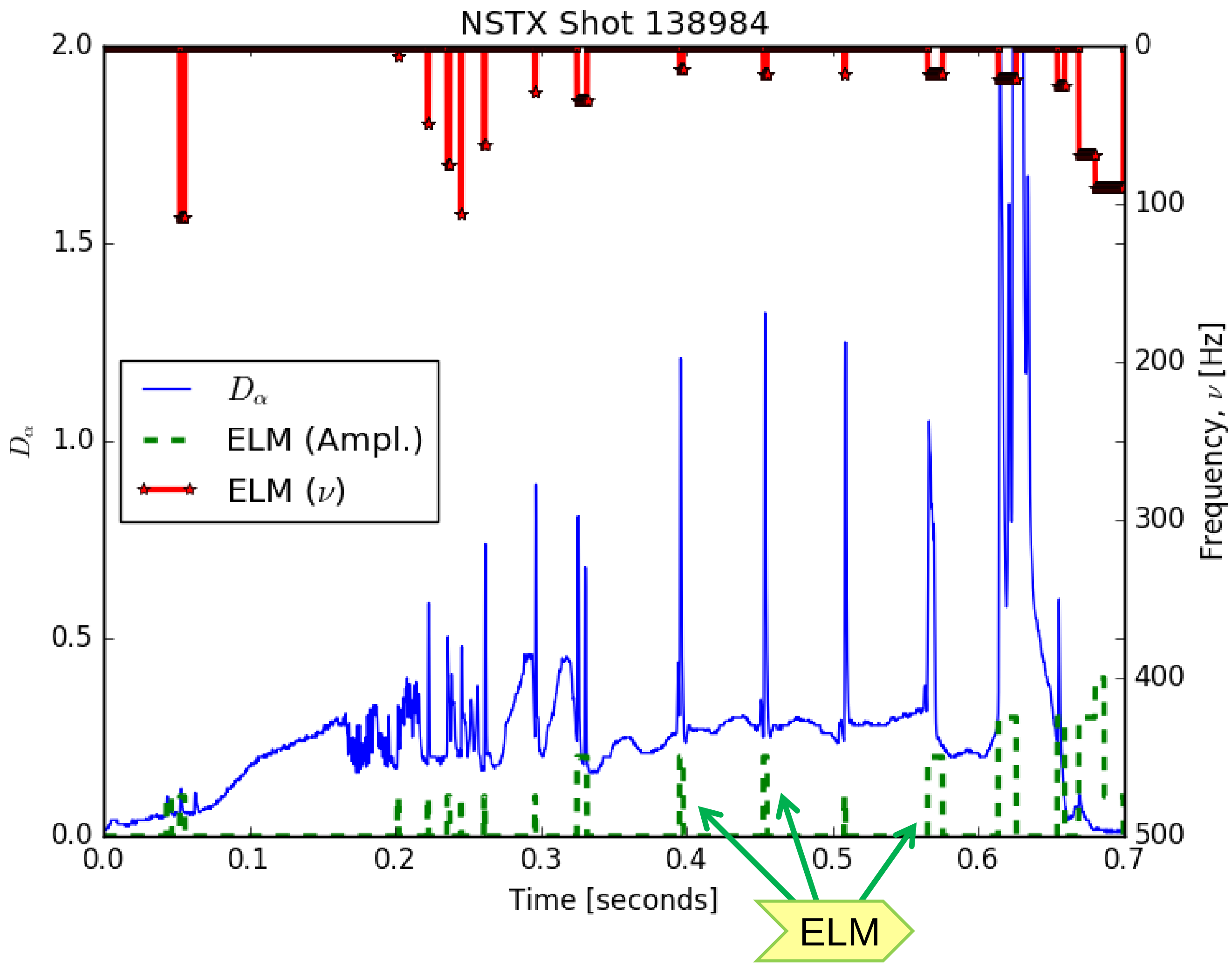
- Using pickup coils and partial saddle loops
- Compare to full FFT approach
- Warning level criteria
  - Pickup coil amplitude > 5 T/s
  - Low zero-crossing measured frequency < 5 kHz
  - High mode identified saddle loops amplitude > 20 G

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

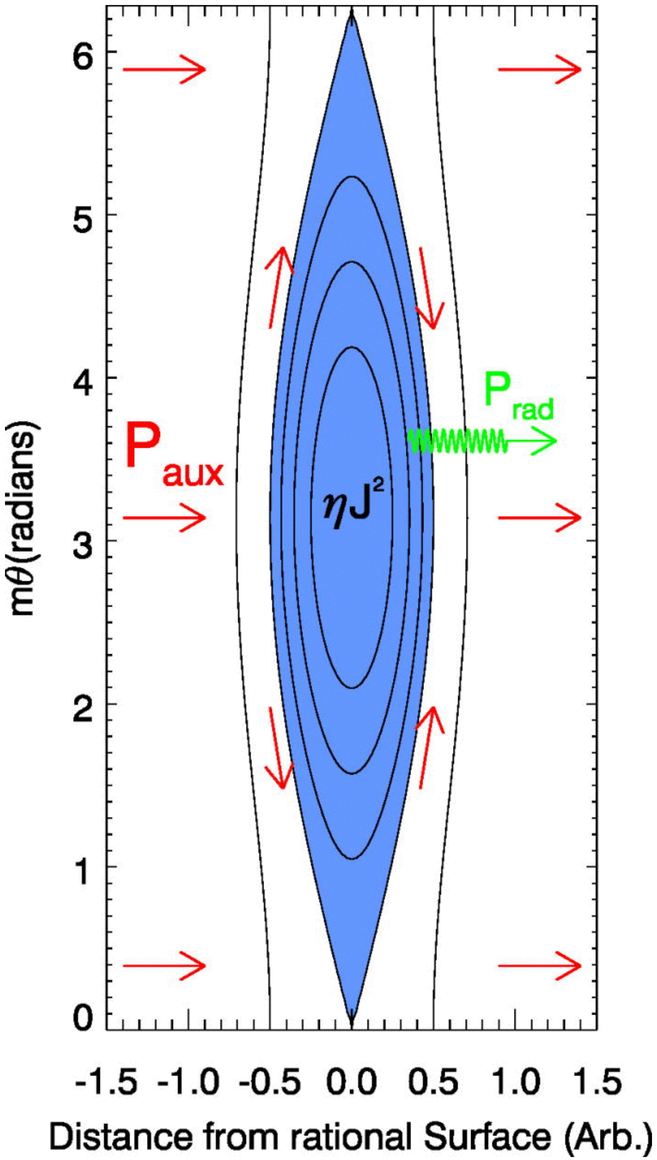
- DECAF ELM event
  - Presently determines ELM triggering times, along with frequency and relative amplitude

- Near-term-goals
  - Determine greater understanding between ELM triggering and more deleterious MHD excitation

- Compatible with real-time use



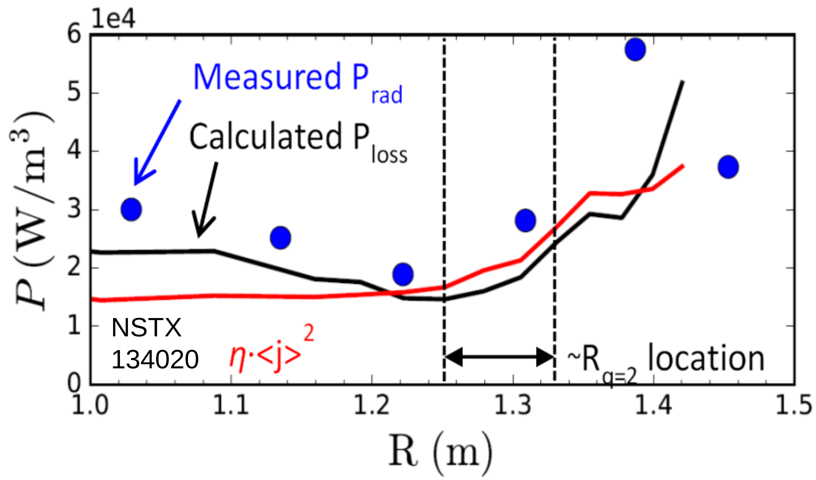
A density limit model has been examined in DECAF based on power balance in an island



- Local island power balance limit
  - Power balance in island between Ohmic heating and radiated power loss
  - If radiated power at the island exceeds the input power (P_{loss} > P_{input}), island grows

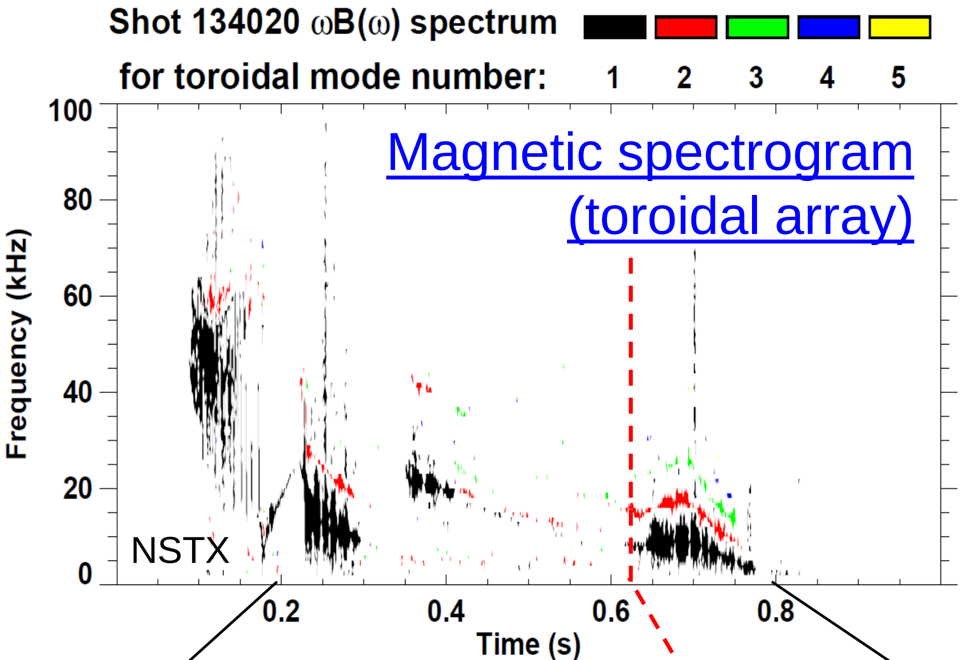
Power density balance: $P_{loss} < P_{input}$

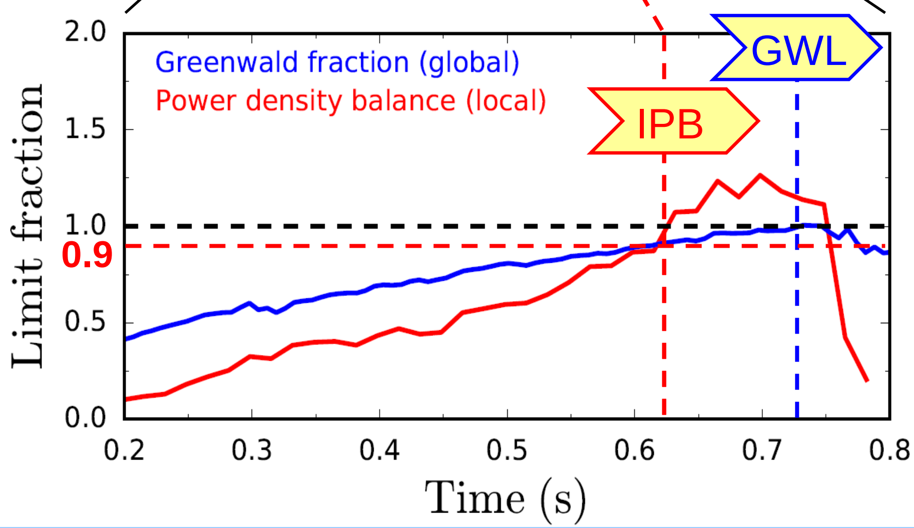
$$n_e n_D L_D(T_e) + \sum n_e n_Z L_Z(T_e) < \eta j^2$$



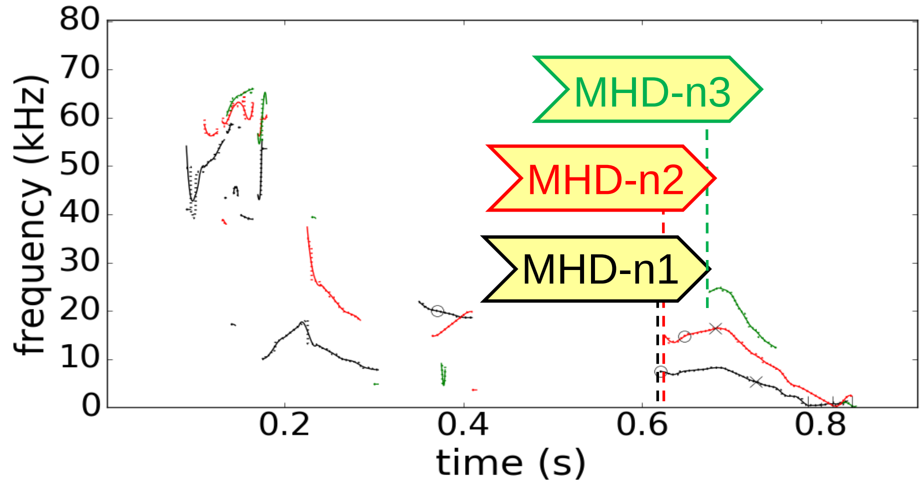
D. Gates et al., Phys. Rev. Lett. **108** 165004 (2012)

Initial assessment of density limit model shows correlation with MHD events





DECAF automated MHD events

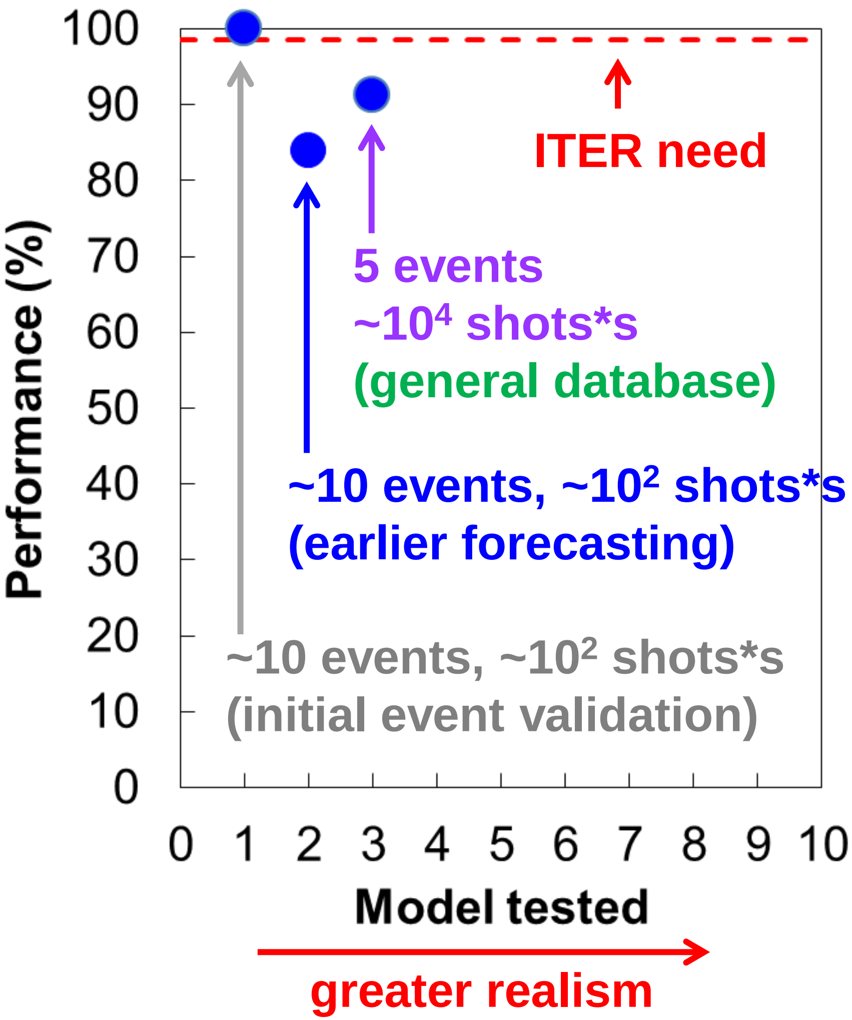


- Greenwald limit
  - Near 0.9 when mode starts (range 0.75 – 1.05)
- Rad. island power balance
  - Near 1.0 when mode starts (range 0.60 – 1.50) ← next step: reduce range

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
- <u>Performance (Model 3)</u>
  - 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

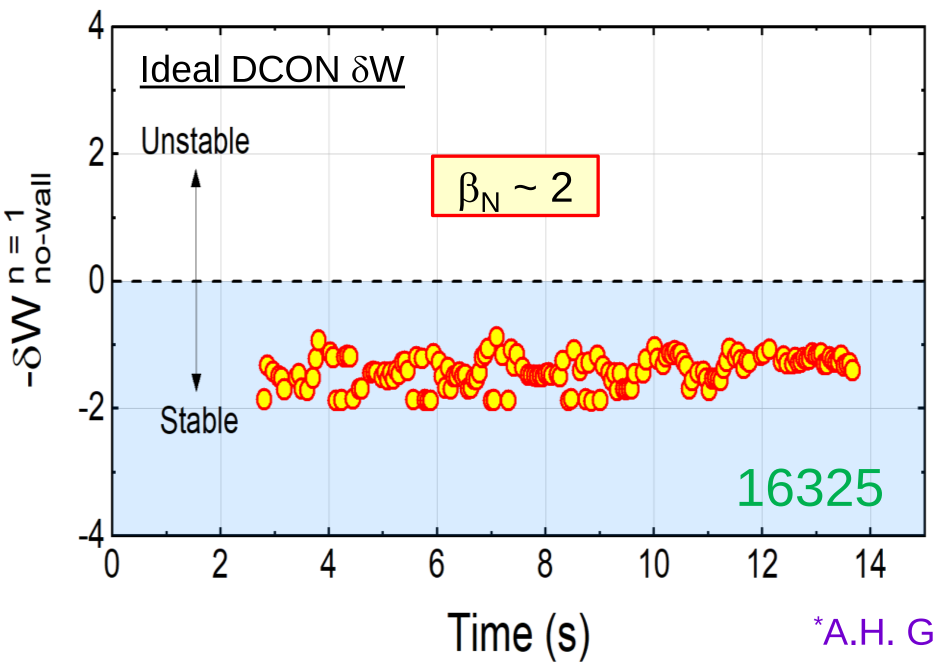
DECAF Disruption Forecasting Performance Evolution

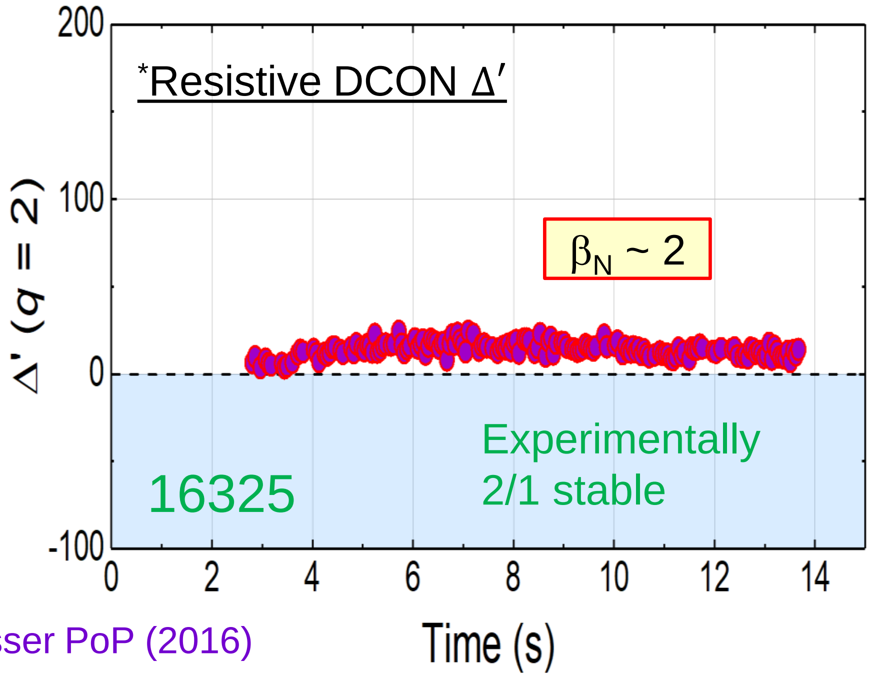


DECAF is fueled by coordinated research that continues to validate/develop physics models, e.g.:

- Resistive MHD
  - Detection / forecasting: available magnetic diagnostics, plasma rotation
  - Forecasting: starting examination of MRE ➔ start with Δ' evaluation
- Density limits
  - Detection: rad. power, global empirical limit
  - Forecasting: starting 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)



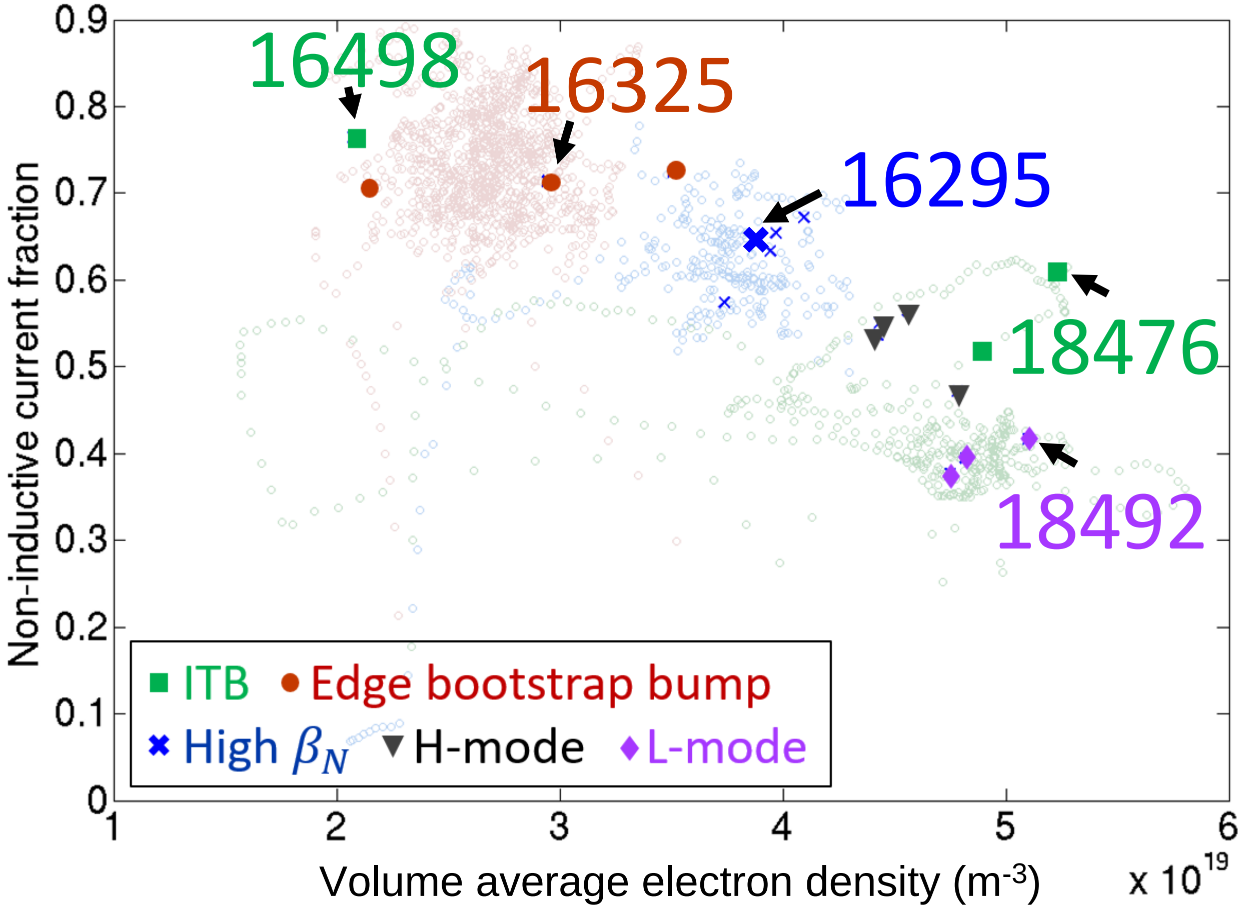


*A.H. Glasser PoP (2016)

- 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

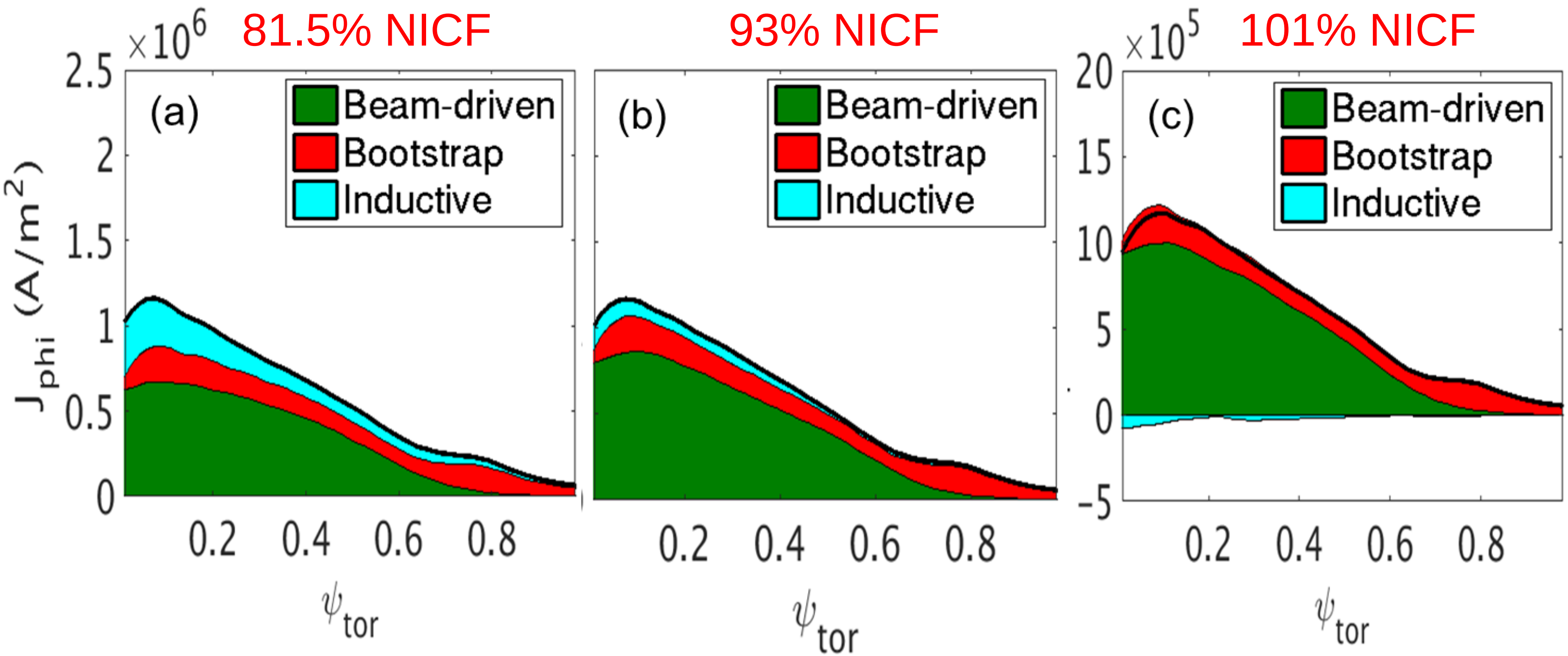
A database of high-non-inductive fraction plasmas is important for disruption forecasting ; NICF ~ 75% in KSTAR

- 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 2020-2021 KSTAR runs for disruption prediction studies

Machine learning approaches are now coupling to DECAF to compute sub-elements of computations

Determination of ideal MHD no-wall stability limit by DL NN

(2019 Marseille conference)

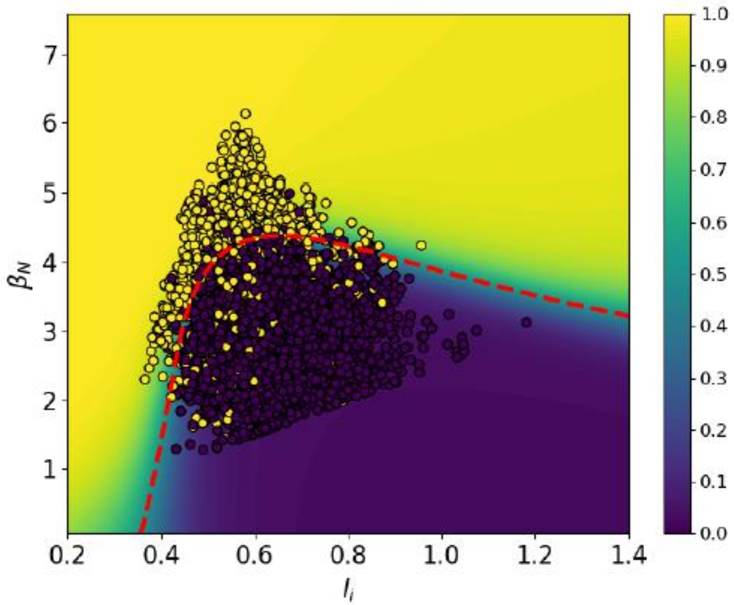


Figure 1: β_n vs l_i decision boundary. The contour plot shows the probability distribution predicted by the neural network.

Determination of ideal MHD stability function by non-linear random forest regression

(2019 IAEA ML conference)

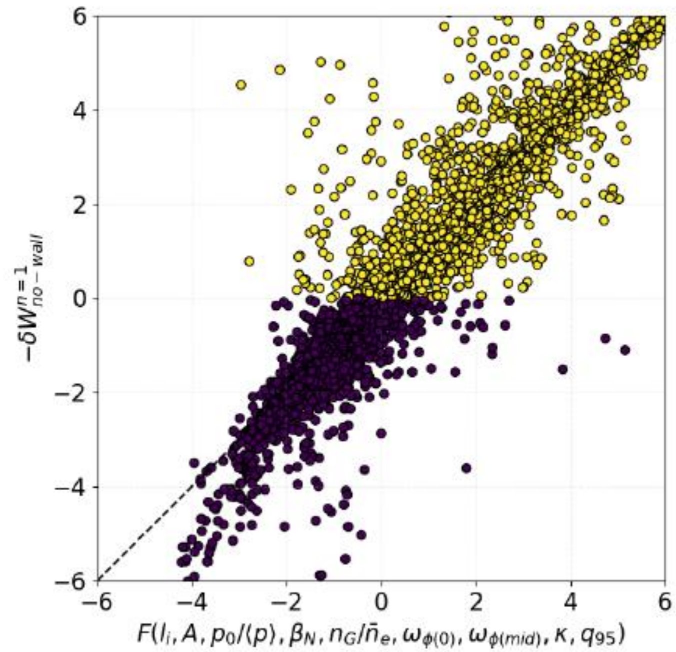


Figure 1: -δW vs F for the NSTX database, showing linear correspondence with some spread ($R^2 = 0.878$).

Collaboration with CCFE / UCL (A. Piccone (UCL)); ➔ A. Piccone, et al, Nucl. Fusion **60** (2020) 046033

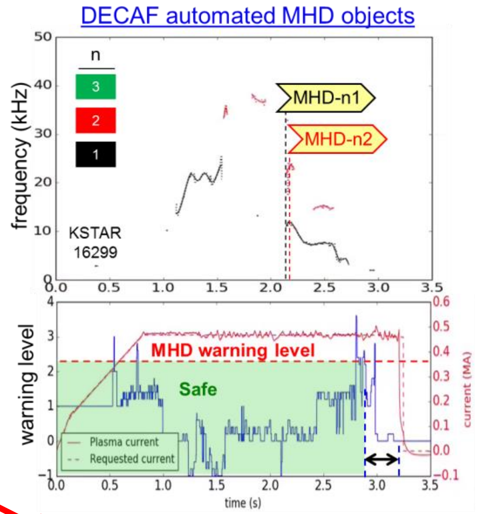
FES/ACSR Advancing Fusion with Machine Learning - Research Needs Workshop (May 2019)

Disruption prediction and avoidance research on KSTAR moving to real-time application

1. Disruption forecasting physics analysis expansion

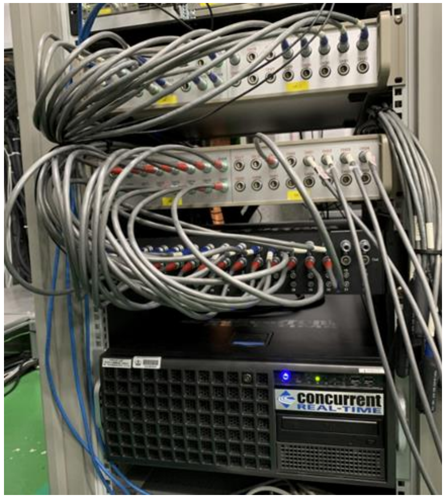
2. Implementation of real-time diagnostic capabilities

Next slides



3. Real-time implementation of DECAF analysis and sensor input
   - Plasma control system (PCS) code specifications written for 10 DECAF events – process continues

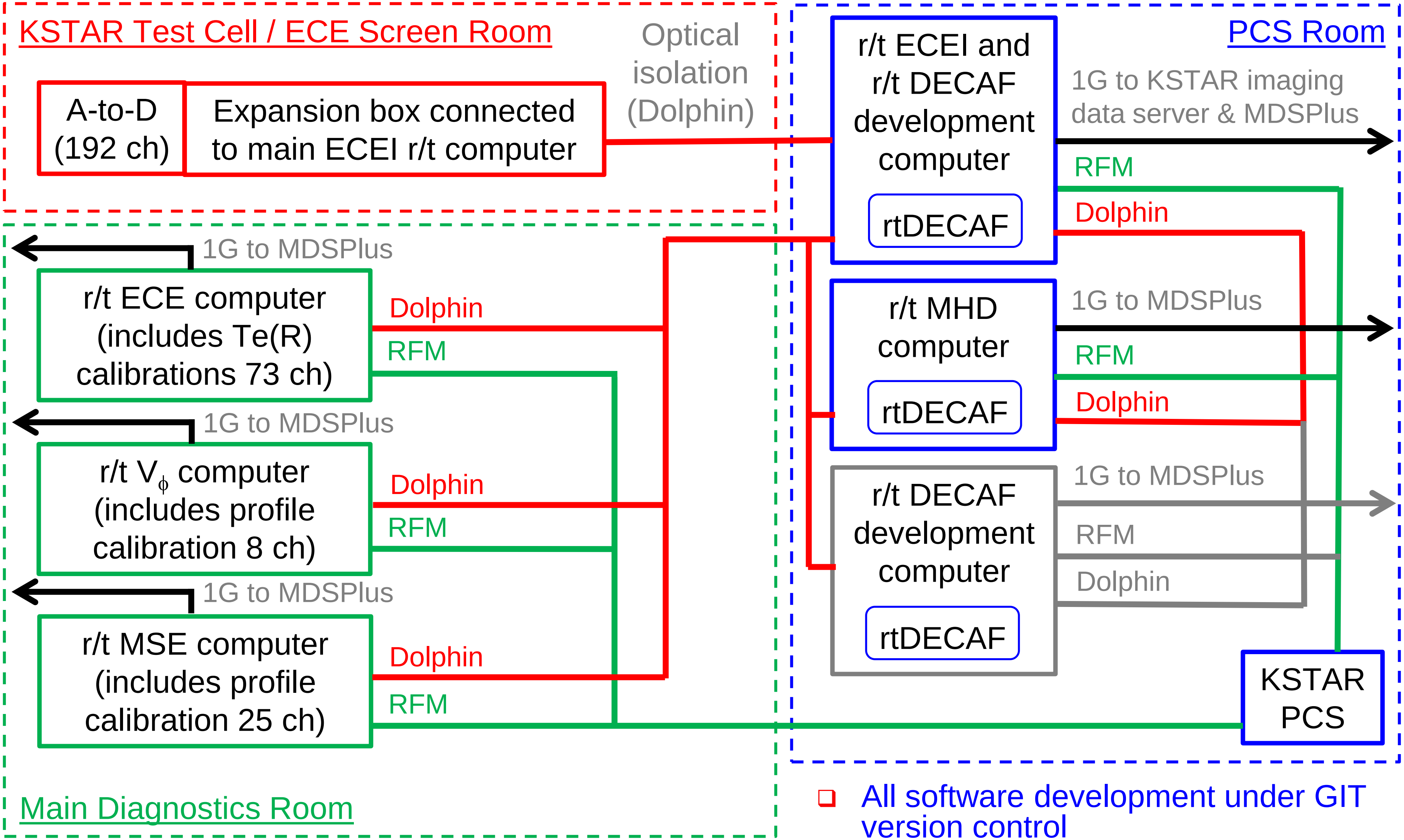
4. Real-time control leveraging real-time DECAF analysis and sensors
   - Initial specification for model-based control in the PCS is written; interfaces to DECAF events being made



KSTAR DPA grant research "fills in" the desired real-time (r/t) diagnostic capability for r/t DECAF

- ✓ Real-time measurement of rotating / locking MHD
  - < 300 kHz; Data collected during Jan/Feb 2020 run
- Real-time and offline Motional Stark Effect - IN FINAL DESIGN
  - "offline" MSE background polychrometer system, Z_{eff} profile
  - Real-time implementation of MSE; includes δB profile measurement
- Real-time plasma rotation profile – 1^{st} system shipped to NFRI
  - Completely new for KSTAR: 8 channels; 1 – 2 kHz time resolution
- Real-time electron temperature profile – IN PROCUREMENT
  - Implement real-time acquisition of heterodyne radiometer system
- Real-time T_e fluctuation profile – IN PROCUREMENT
  - Implement real-time acquisition to 2-D ECE imaging system

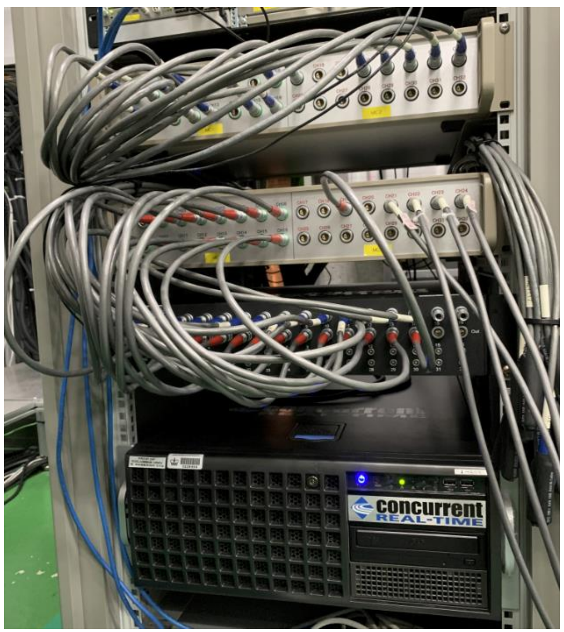
Overall setup for KSTAR real-time diagnostic integration and DECAF analysis for the PCS



- All software development under GIT version control

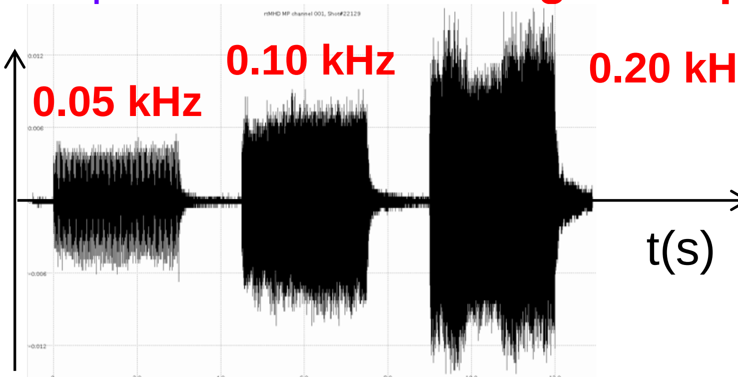
Disruption prediction and avoidance research on KSTAR moving to real-time application

- Real-time MHD analysis computer installed at NFRI
  - Designed for connection to plasma control system (PCS)
  - Interface to MHD probes built



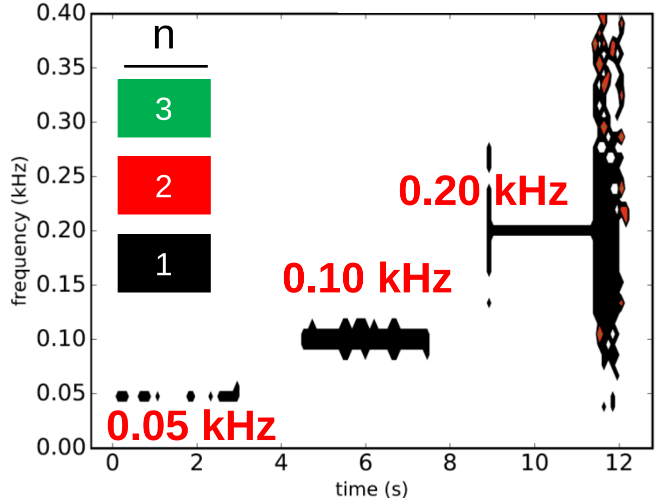
Real-time magnetic probe data acquired

(14 toroidal probes: **n = 1 rotating field applied)**

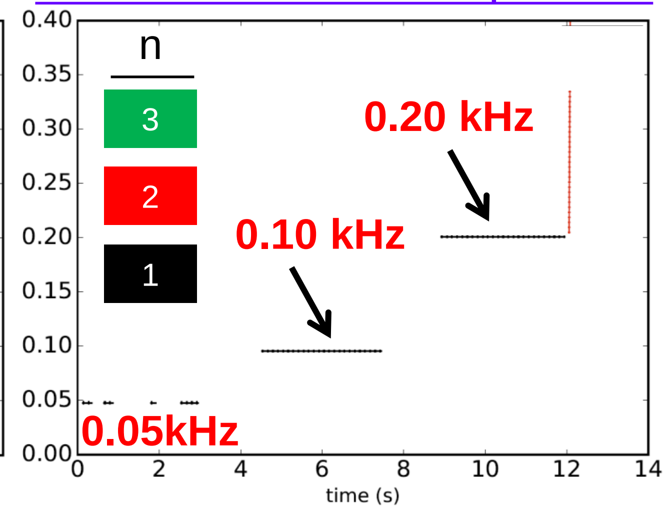


Offline DECAF analysis of real-time signals

DECAF spectrogram

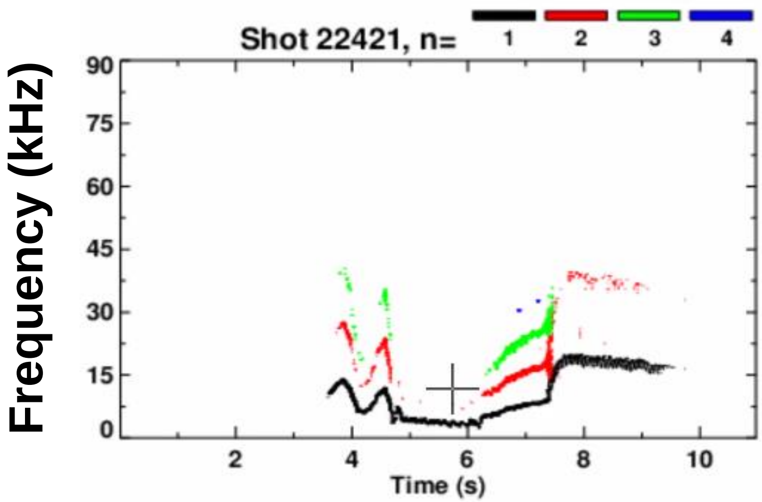


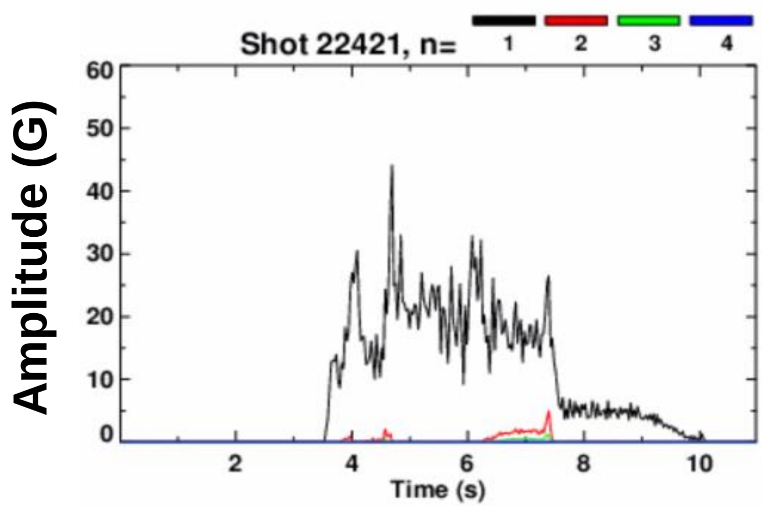
DECAF mode decomposition



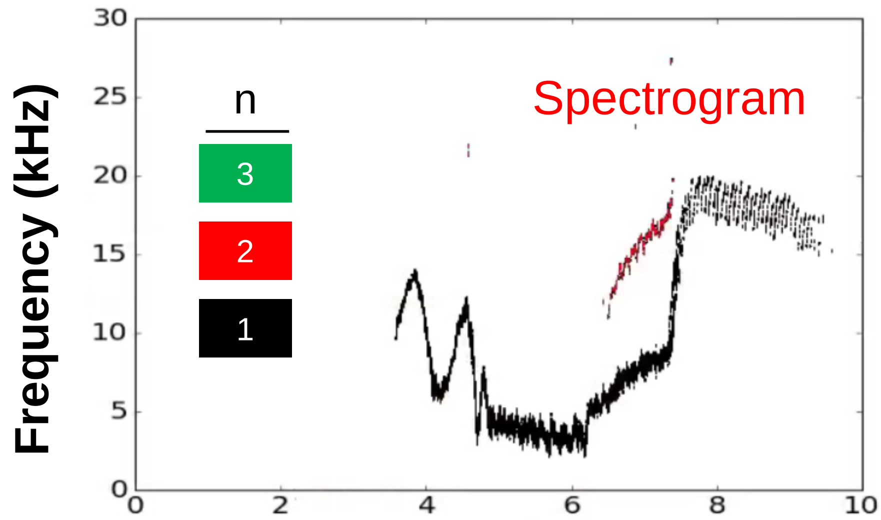
KSTAR real-time MHD computer acquired data for 2019 campaign – data quality as good as offline

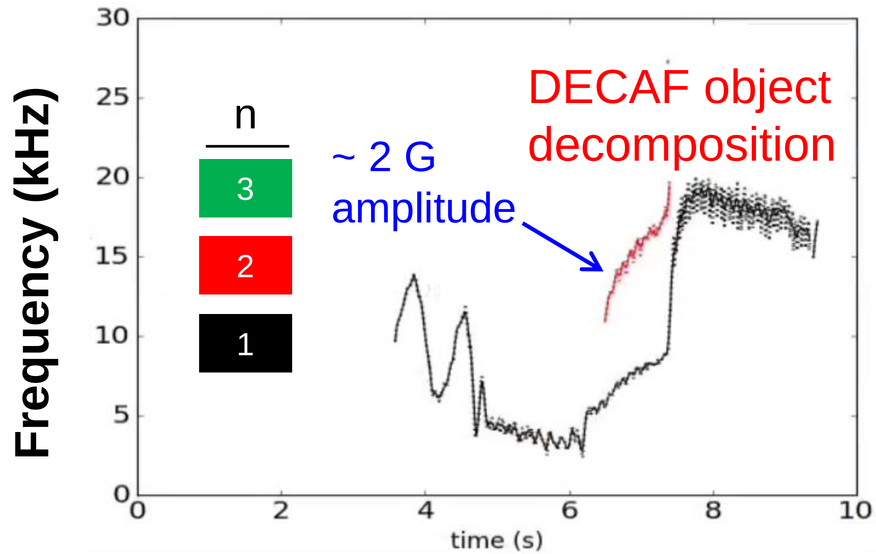
Offline data, native code analysis





Real-time data, DECAF analysis (offline)

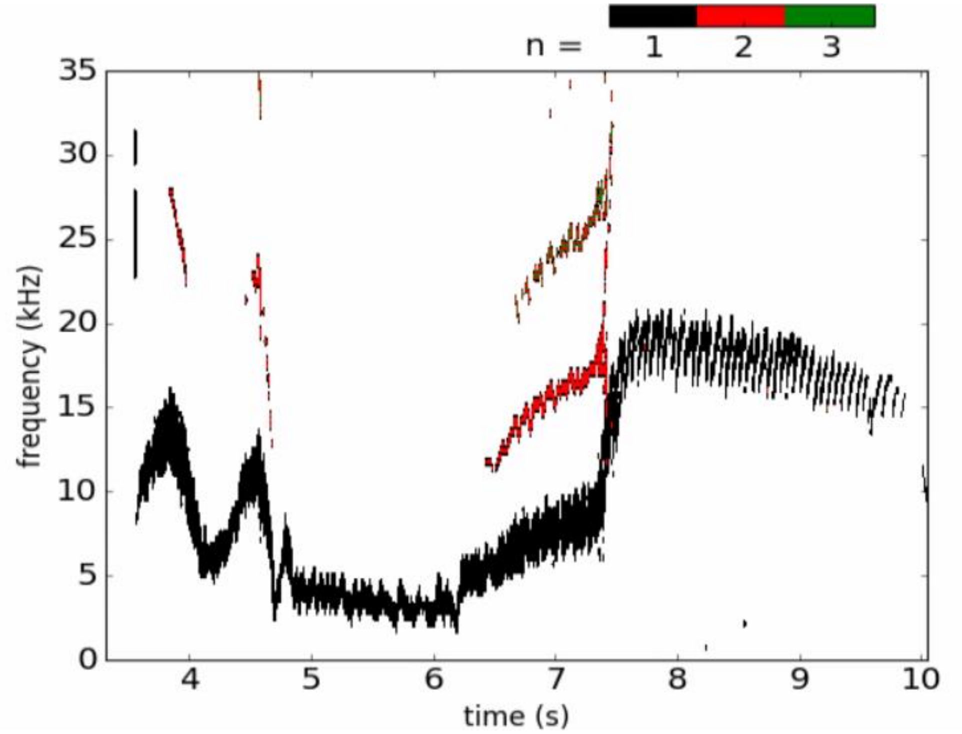




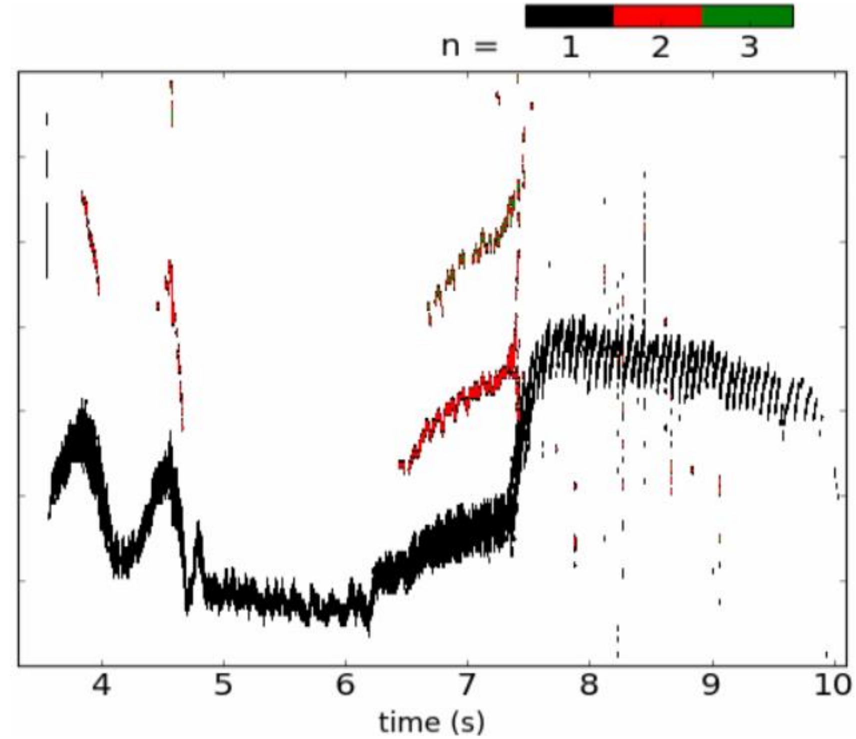
Analysis of KSTAR real-time MHD computer data compared to simulated FPGA* r/t analysis (I)

DECAF analysis using various inputs

From simulated FPGA FFTs



From offline FFTs



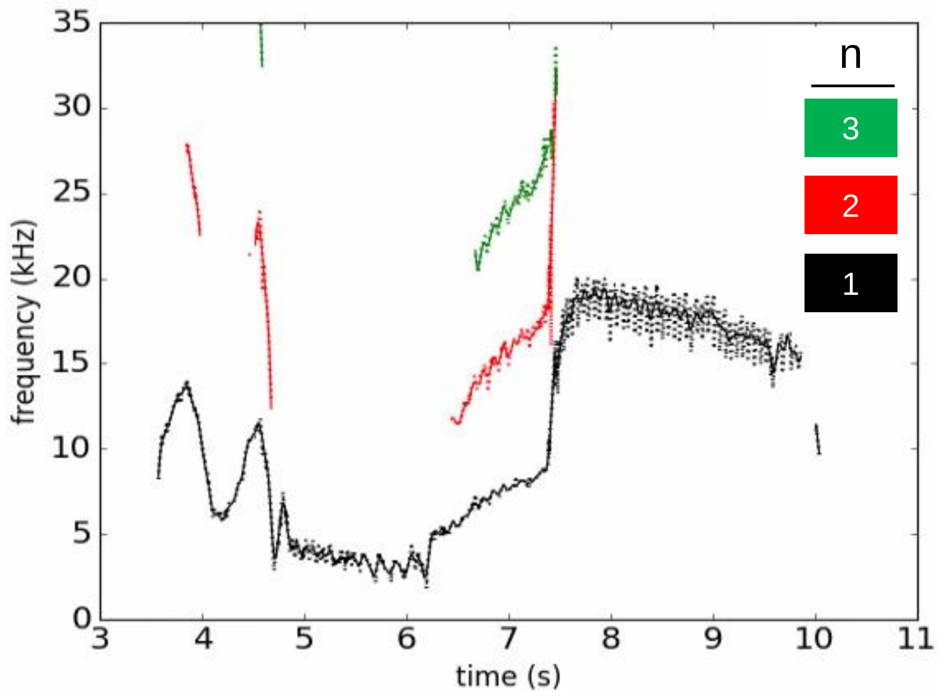
- Δt = 3.06 ms , Δf = 0.31 kHz (offline analysis set to match FPGA)

*FPGA: field-programmable gate array

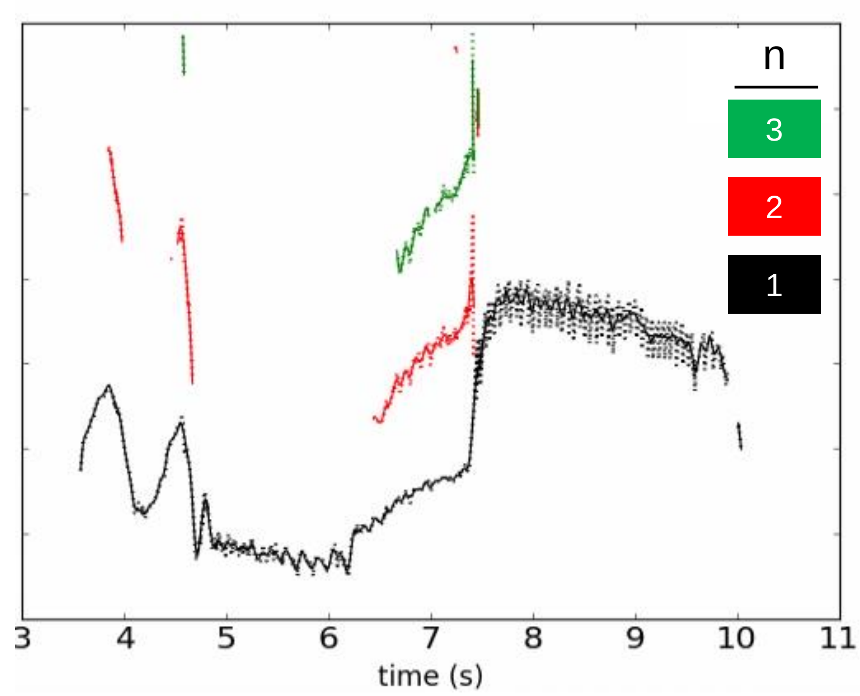
DECAF object decompoition of r/t MHD computer data works well on simulated FPGA analysis

DECAF object decomposition

From simulated FPGA FFTs

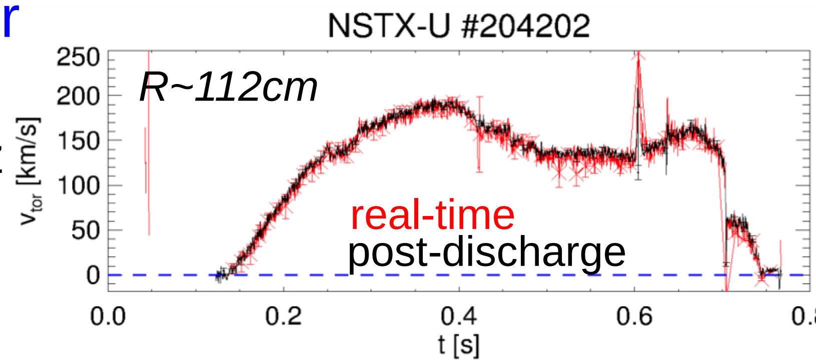


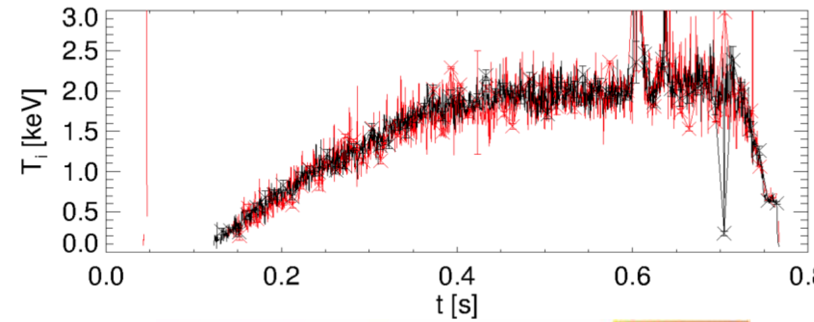
From offline FFTs

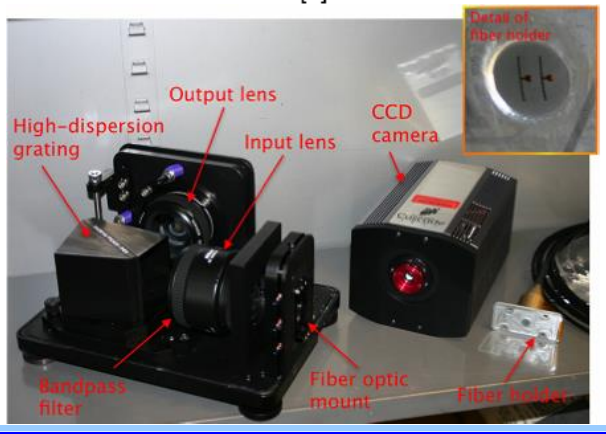


New real-time velocity diagnostic for KSTAR expands design of NSTX-U system (operated in 2016)

- NSTX-U: demonstrated RT analysis for v_ϕ, T_i (for T_i>150eV)
  - 4 radial channels, active + backgrd, 5 kHz
- KSTAR: plan for 8 radial channels, ~1kHz sampling rate
  - Assess requirements in FY20 to optimize design & analysis software
  - Re-locate NSTX-U system, interface w/ KSTAR
- Status / plan
  - NSTX-U system shipped to KSTAR (arrival this Wed July 22nd evening)
  - Use data from initial system for final design of new KSTAR system
  - Install new KSTAR system 2021







M. Podesta (PPPL)

Expanding DECAF approach provides a new paradigm for disruption avoidance research

- 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
  - Present performance on large (10^4) databases: 91.2% w/ only 5 Events
  - Full multi-machine databases used (full databases needed!)
  - Innovative use of machine learning started (event analysis, pred. models)
  - Physics analysis, experiments run to understand, create, validate models

- DECAF producing early warning disruption forecasts
  - On transport timescales: ➔ guide disruption avoidance by profile control

- Continuing development
  - Improve DECAF forecasting performance run on large database analysis
  - Continue / expand disruption forecasting performance analysis (➔ ITER)
  - Implement DECAF disruption forecasting models in real-time (➔ KSTAR)

Supporting slides follow

Simple island rotation dynamics model presently being constructed to forecast the bifurcation point

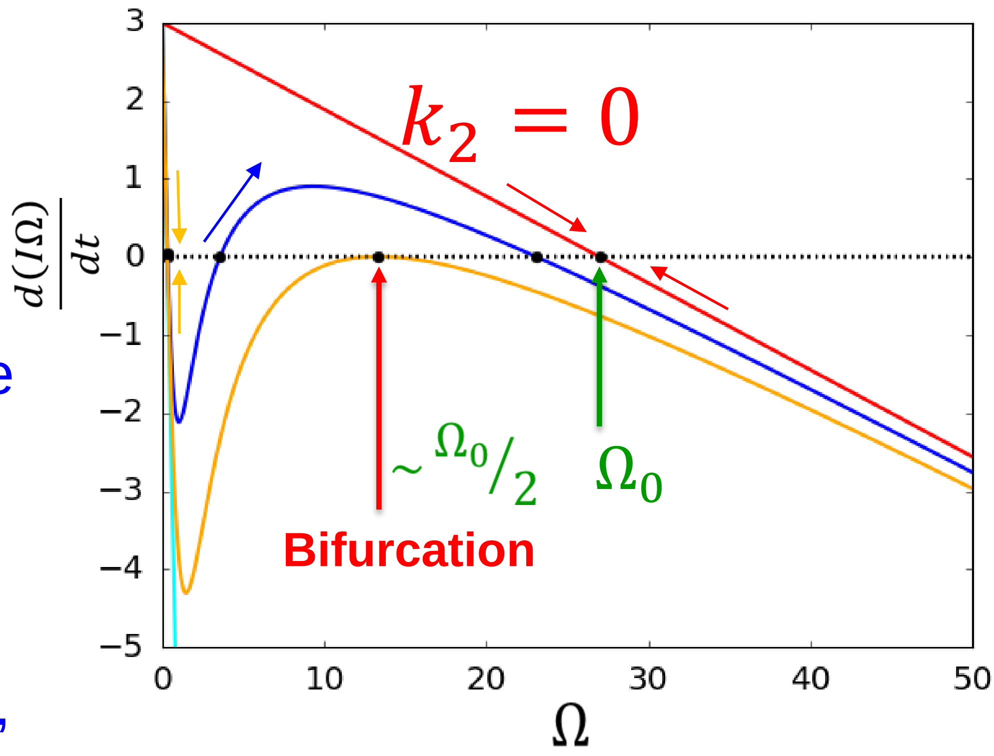
- Start with cylindrical, rigid body model

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

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

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

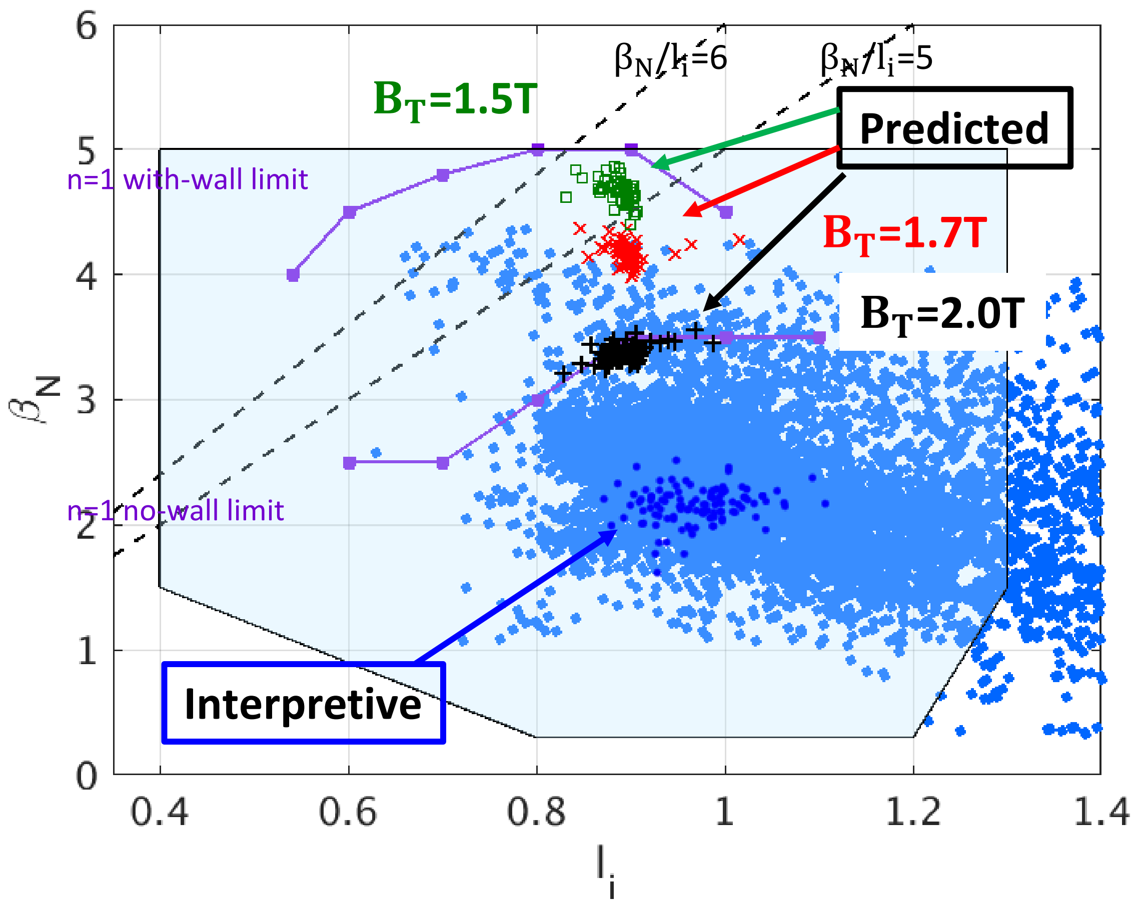
R. Fitzpatrick et al., Nucl. Fusion 33 (1993) 1049

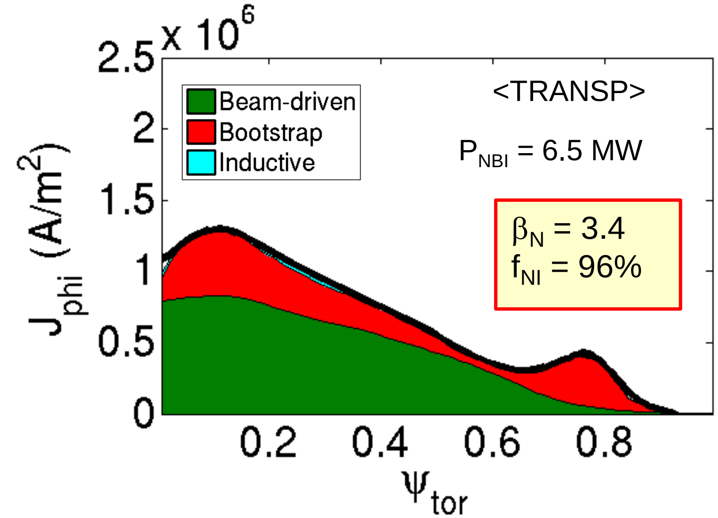


- At very low angular speed mode reaches a stable steady state, ➔ investigating this in KSTAR
- Collaborating with UW Madison theoreticians to add explicit effect of island size on viscosity, toroidal effects, etc.

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



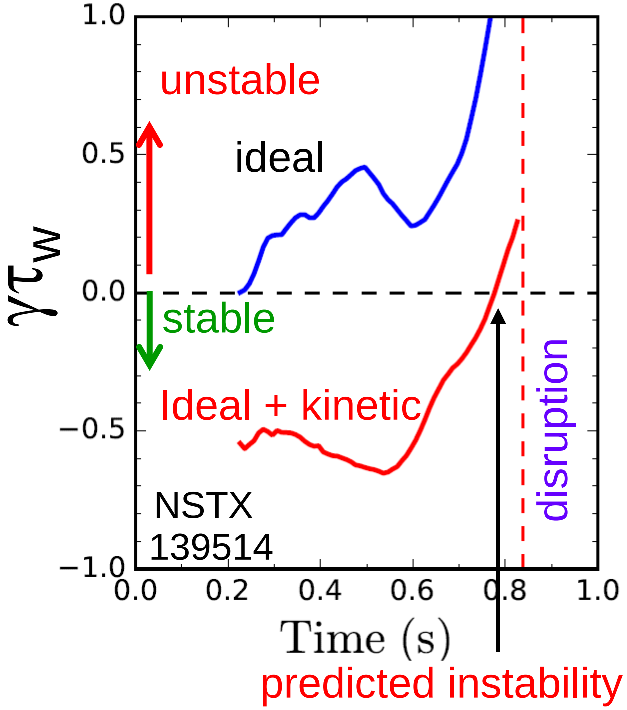


- Up to 75% NICF already reached in similar plasmas
- NBI ➔ 6.5 MW in 2018
- By altering I_P and B_T values, $\beta_N > 4$, up to KSTAR design target 5 can be achieved with 100% NICF

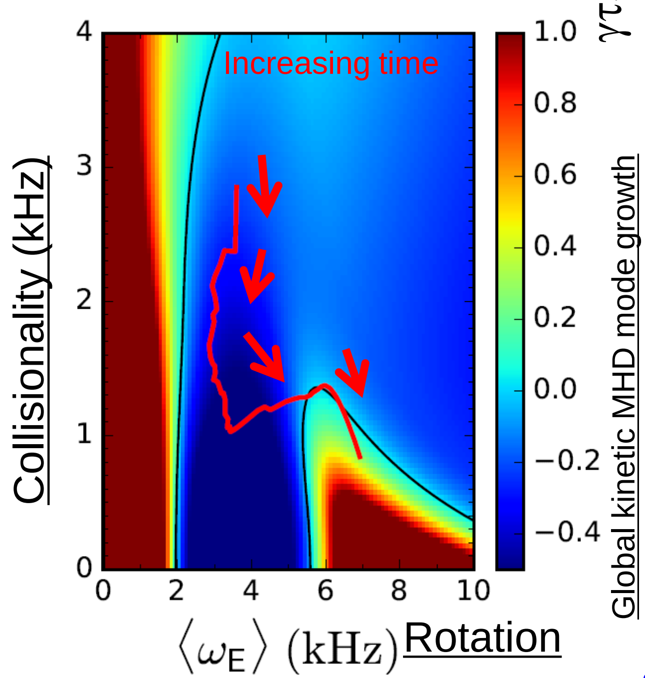
See J-H Ahn CO6.00005

DECAF reduced kinetic MHD model provides early forecast of instability boundary to global MHD modes

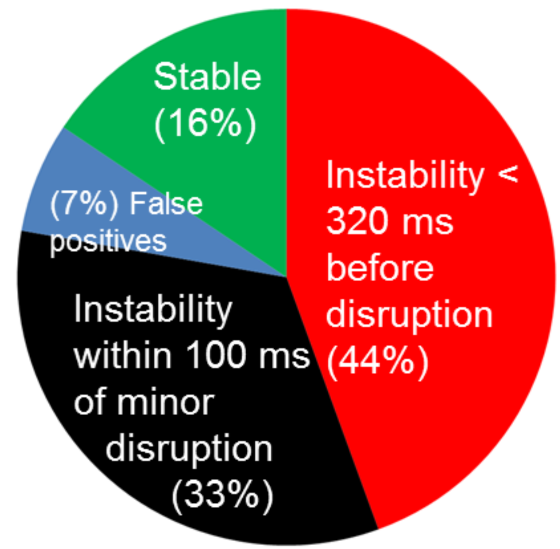
Norm. growth rate vs. time



Disruption forecasting



Predicted instability statistics

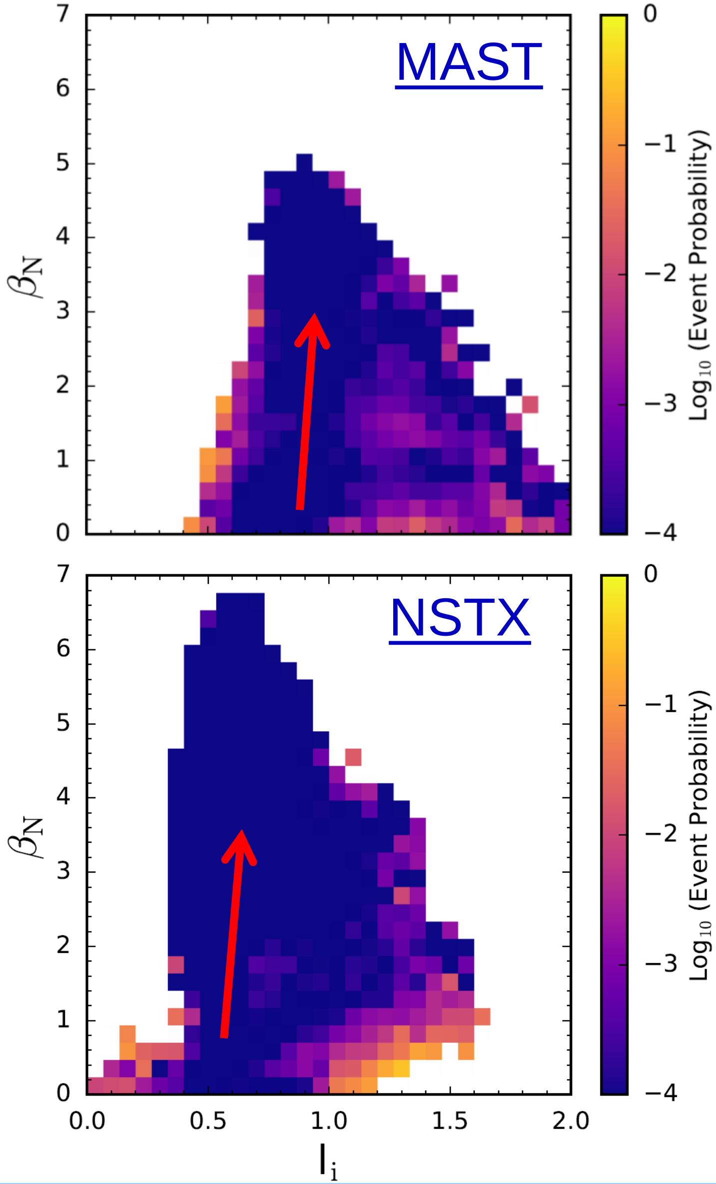


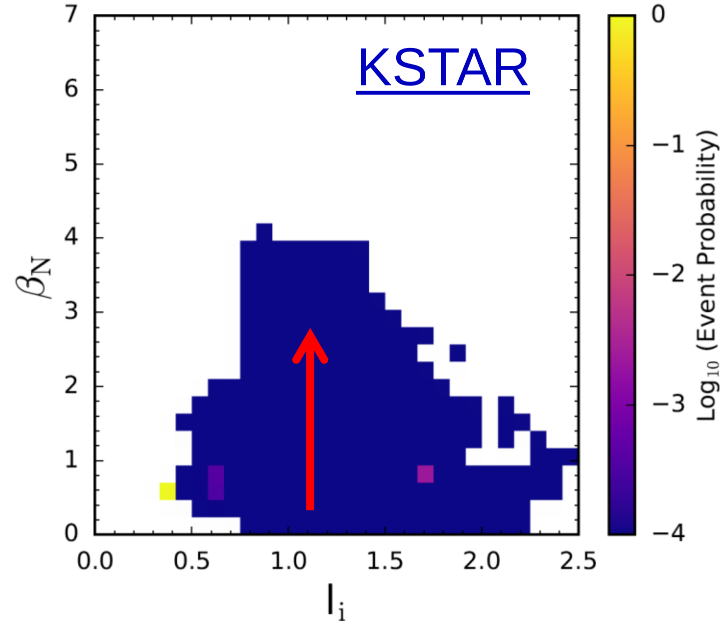
- Favorable characteristics
  - Stability contours CHANGE for each time point
  - Model allows real-time stability and mode growth rate prediction

J.W. Berkery, S.A. Sabbagh, R. Bell, *et al.*, Phys. Plasmas **24** (2017) 056103

- 84% of shots are predicted unstable (stringent evaluation)
- 44% predicted unstable < 320 ms (approx. 60τ_w) before current quench
- 33% predicted unstable within 100ms of a minor disruption

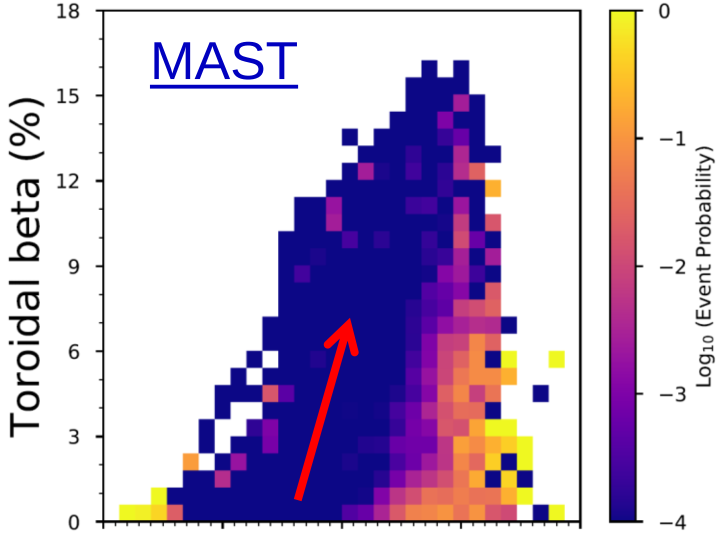
DECAF analysis of large databases further supports published results that disruptivity doesn't increase with β_N

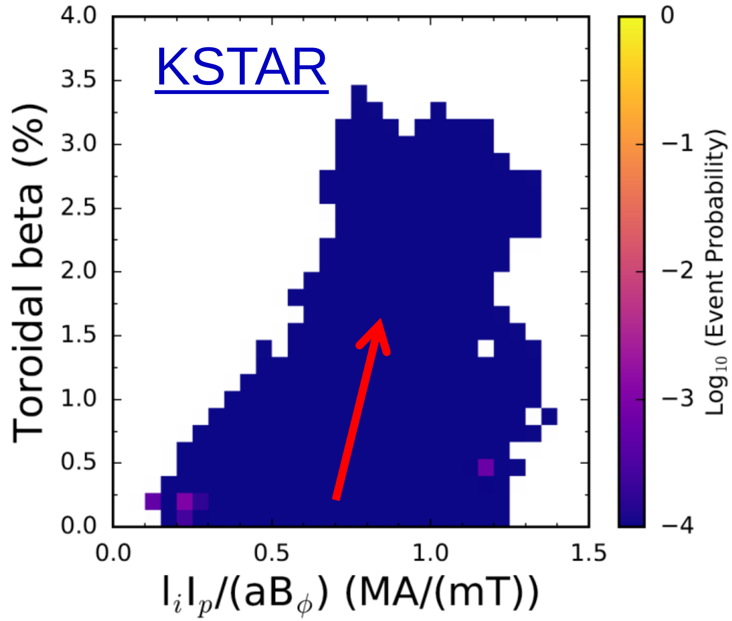


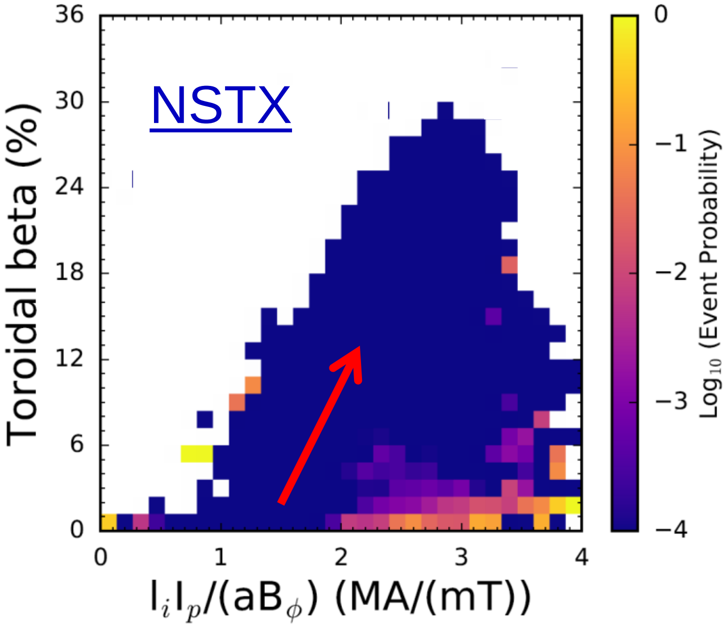


- DECAF analysis of DIS event
  - Shots analyzed at 10 ms intervals
- Analysis during I_p flat-top
  - MAST: 8,902 plasmas analyzed
  - NSTX: 10,432 plasmas analyzed
  - KSTAR: 1,309 plasmas analyzed

Initial analysis of large databases further supports published result that disruptivity doesn't increase with plasma β



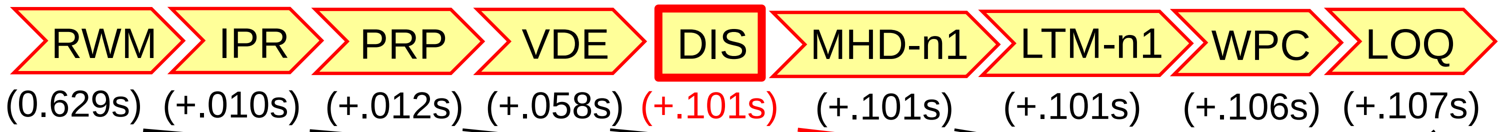


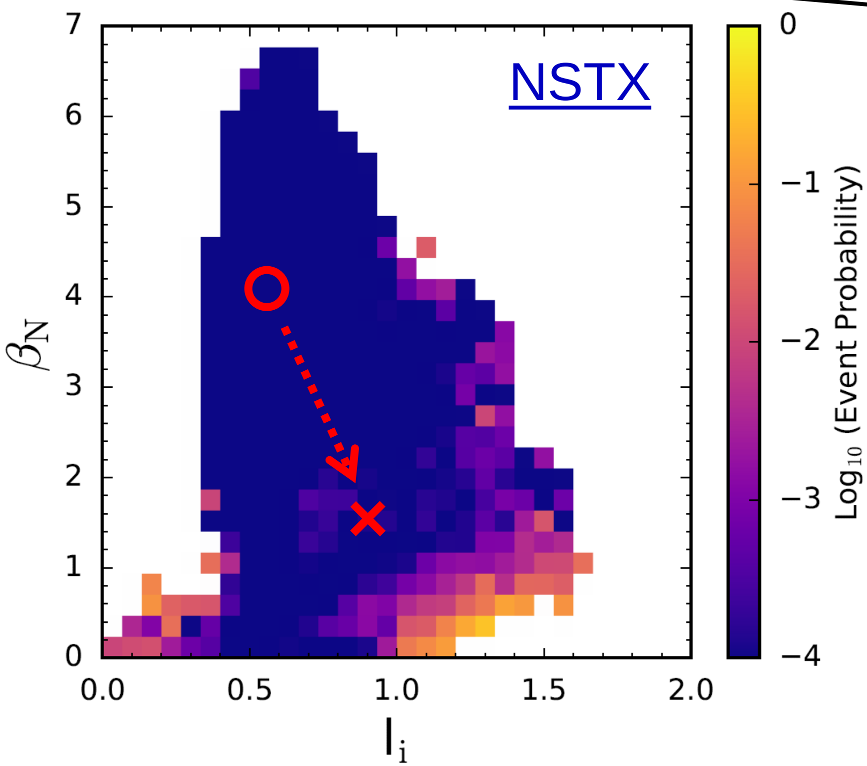


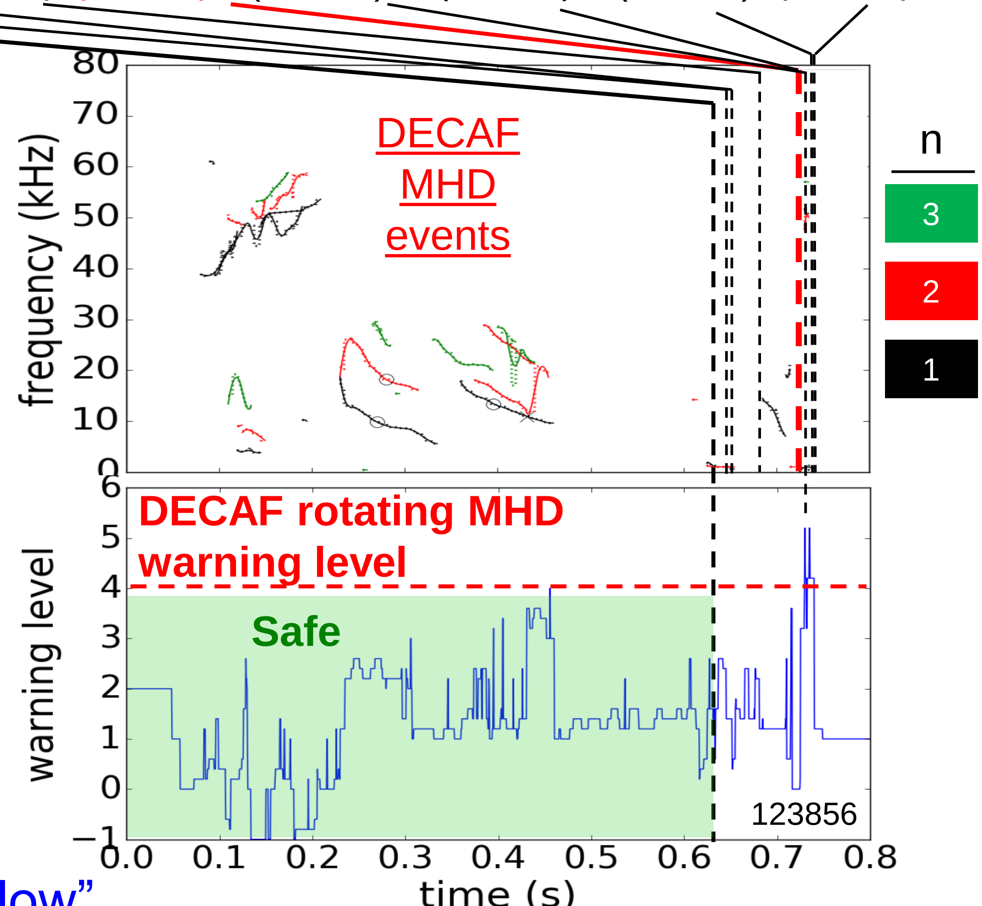
- DECAF analysis of DIS event
  - Similar to a "standard" disruptivity analysis
  - Shots analyzed at 10 ms intervals
- Analysis during I_p flat-top
  - MAST: 8,902 plasmas analyzed
  - NSTX: 10,432 plasmas analyzed
  - KSTAR: 1,309 plasmas analyzed

Global MHD modes can also be "slow" and allow early warnings for disruptions, potentially allowing avoidance

DECAF event chain

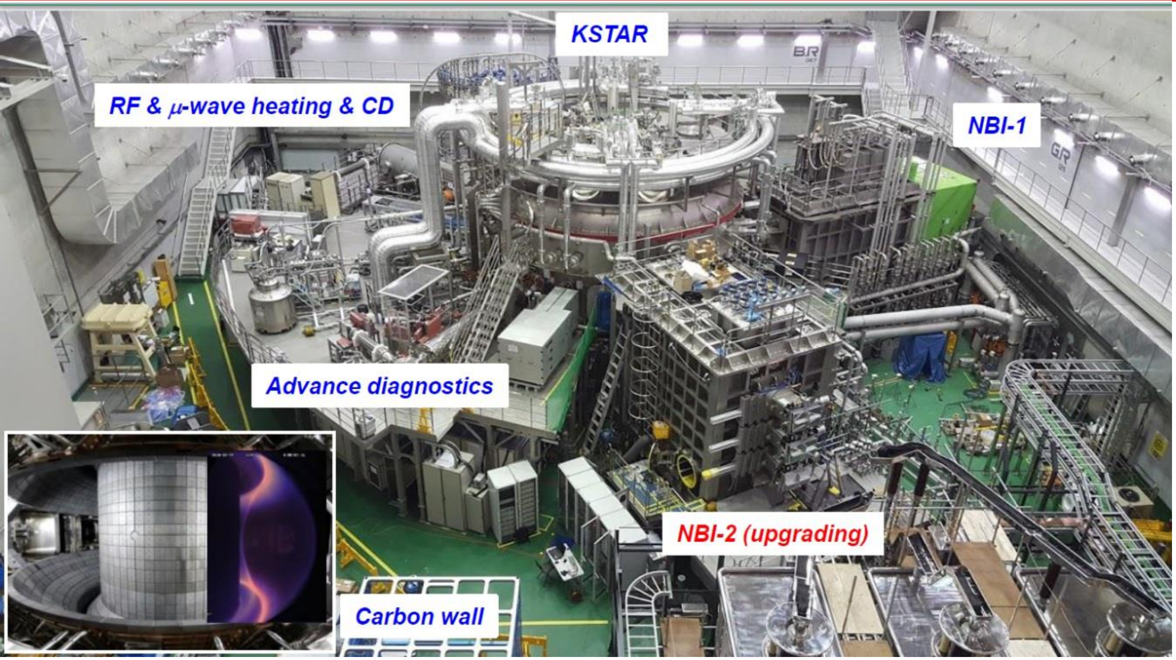


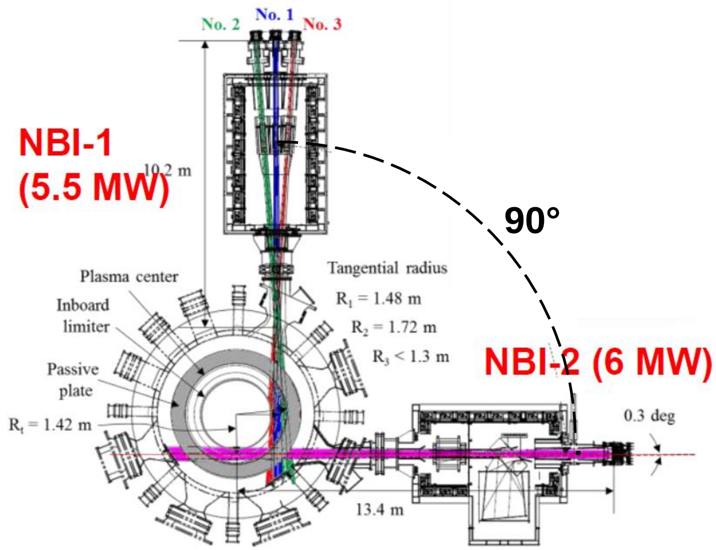


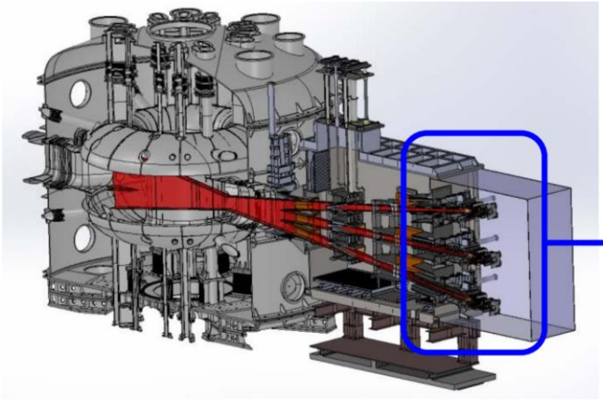


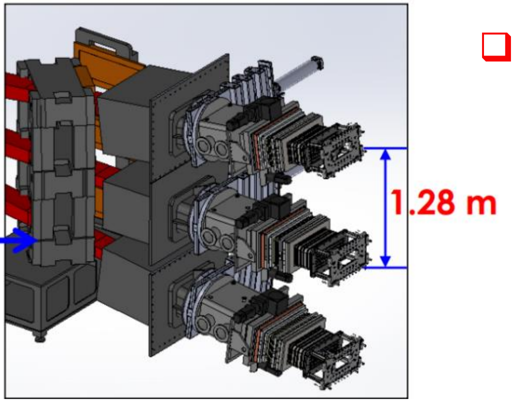
- Global MHD (RWM) can also be "slow"
  - Rotating MHD warning level decreases after 0.46s ➔ DANGEROUS for RWM onset!
  - H – L back transition (PRP) drags out time to disruption (> 100 ms – transport timescale)

New 2nd NBI system installed in KSTAR, may be available for 2020 run campaign



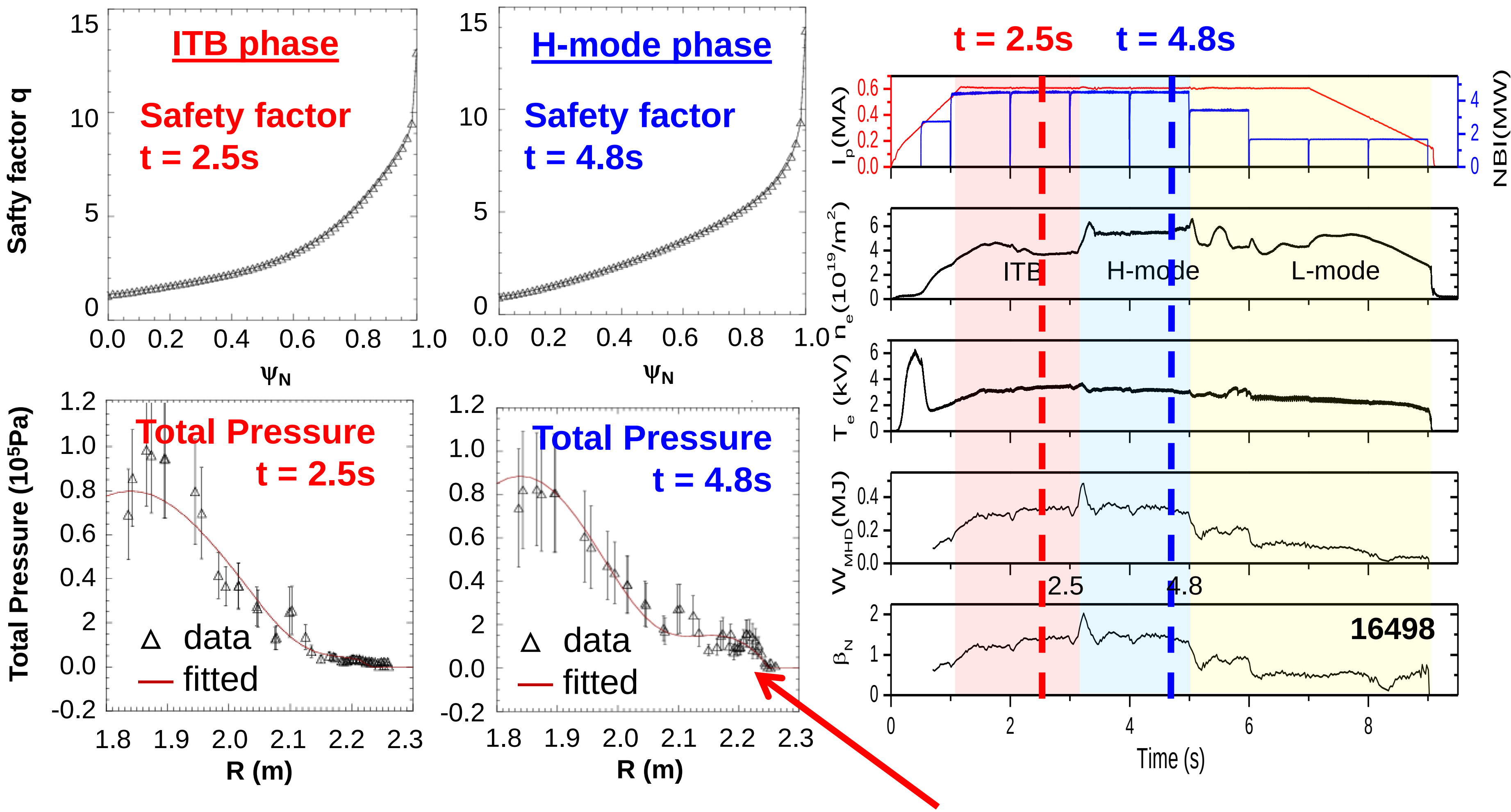






- Geometry of 2nd NBI system is included in TRANSP model
  - Available power
    → $P_{NBI} \simeq 1.5$MW/source (conservative)

Clear pressure profile distinction between Internal Transport Barrier and H-mode phases



- Broad pedestal pressure reconstructed in H-mode is not observed in earlier ITB phase

Xp by Jinil Chung