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Disruption Prediction and Avoidance at High Beta in NSTX-U – Spherical Tokamak Science and Real-Time Application

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NSTX-U Physics Meeting

15 February 2021

Virtual Meeting

ASDEX-U
KSTAR
MAST-U
NSTX-U

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

V1.1

Disruption prediction and avoidance research on NSTX-U funded to address critical need for ITER, 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
  - Abbreviated outline of funded proposal research
  - Disruption Event Characterization and Forecasting (DECAF) research
  - Initial multiple-device, large database analysis, forecasting performance
  - Supporting science research, including equilibrium reconstruction, ideal / resistive stability, non-inductive CD scenarios
    - i.e. KSTAR high β_N, Δ', ~100% non-inductive CD
  - Recent focus on real-time design and implementation on KSTAR

NSTX-U disruption forecasting and avoidance began on NSTX, expanded to multiple devices

- Evolution of research (Began on NSTX, large group meetings > 40 people)
  - Expansion of KSTAR research (including real-time systems); added MAST-U research during NSTX-U recovery; other device databases

- Newly funded NSTX-U Elements synergize with this research – ST science elements and real-time – 3 Elements:
  - Element 1: Fundamental physics analysis with support for disruption prediction
    - Kinetic equilibrium reconstruction w/V_ϕ (expanding our decade-long work on NSTX)
    - Ideal, resistive, and kinetic MHD stability analyses; ELM transient suppression (w/ IFS)
    - Neoclassical toroidal viscosity (NTV) at low collisonality
    - Kinetic RWM stability at low collisionality
  - Element 2: Physics-based disruption prediction validation, expanded development
    - Forecast / characterize physics based disruption events (DECAF analysis)
    - Generate high β, high NICD, low disruptivity plasmas to validate disruption forecasting
    - Use real-time plasma response (RFA), RWM state space controller observer for disruption forecasting
  - Element 3: Real-time disruption avoidance analysis and control
    - Real-time DECAF implementation on NSTX-U including r/t MHD system implementation
    - Plasma rotation profile control for mode control / disruption avoidance; use of rtMSE
    - RWM active control – update/use implemented state space controller on NSTX-U

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

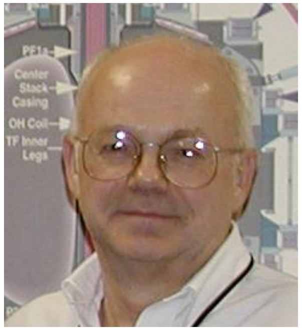
- Eight CU scientists and students based at PPPL
  - Including 2 students
  - New full-time post-doc/student for NSTX-U grant
- Innovative high beta, long-pulse, non-inductive superconducting tokamak plasma research on KSTAR
- Compact, high beta spherical tokamak plasma research on MAST-U and NSTX-U

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


S.A. Sabbagh


J.W. Berkery


Y.S. Park


J.M Bialek


Y. Jiang


V. Klevarova

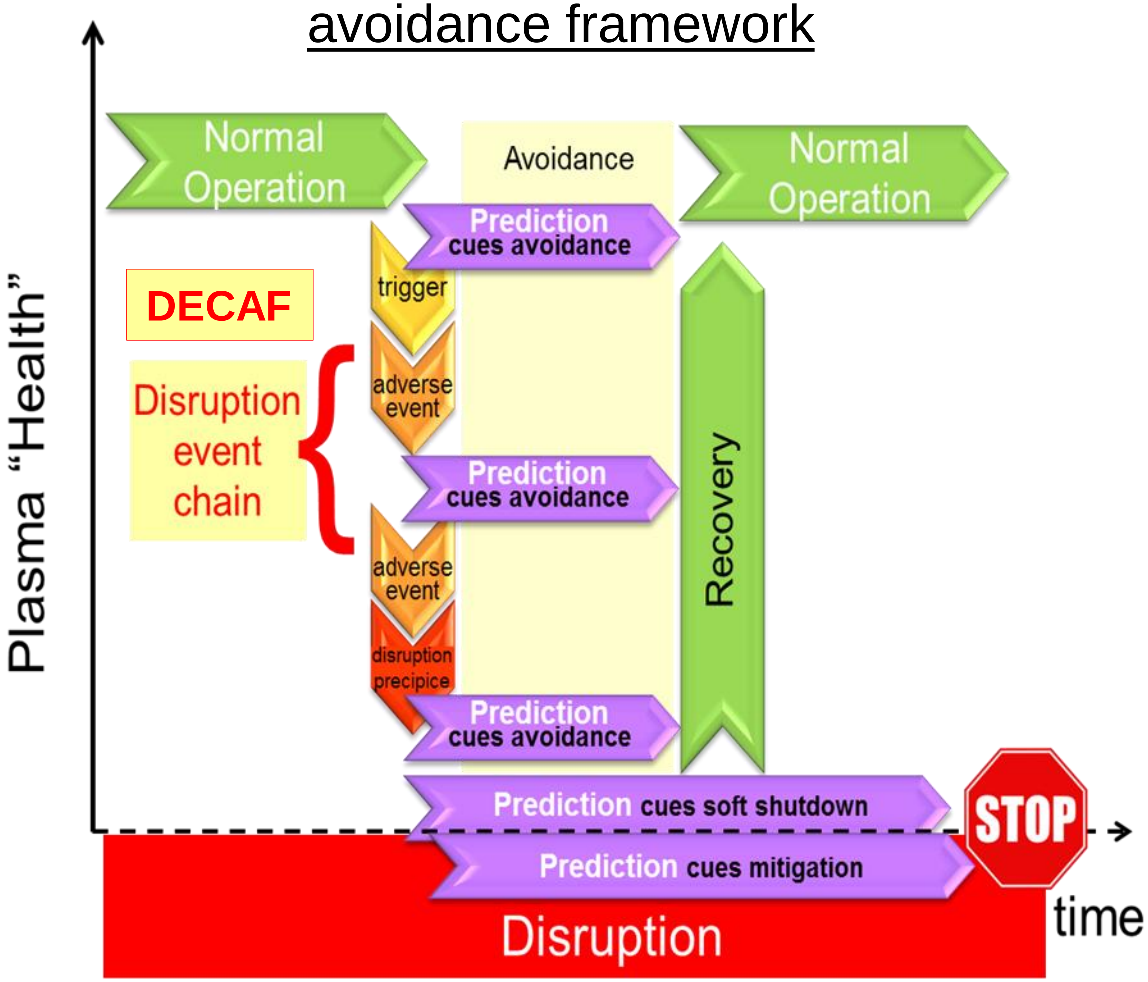
STUDENTS


J. Riquezes


J. Butt

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

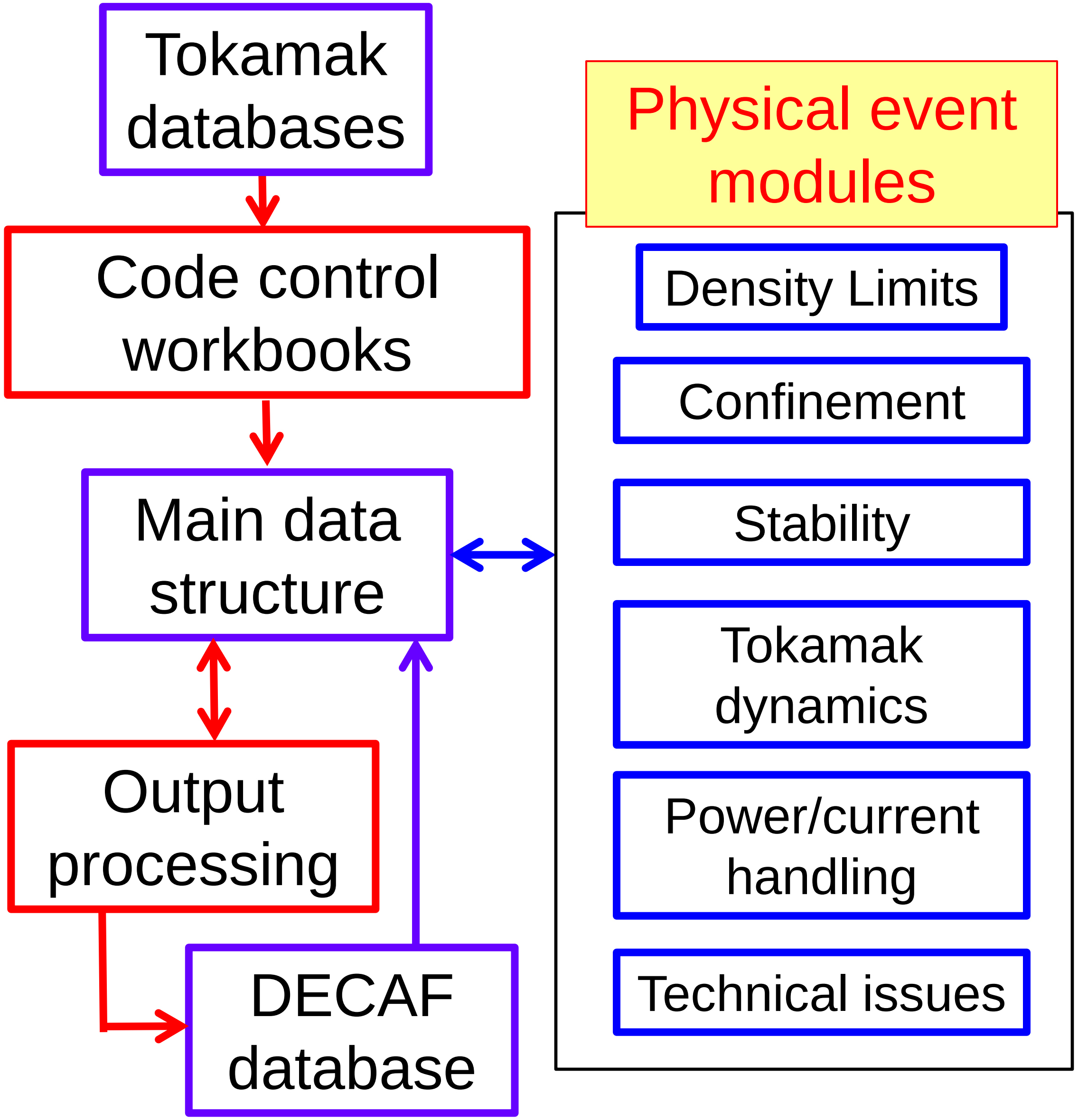
DECAF in disruption prediction / avoidance framework



- 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

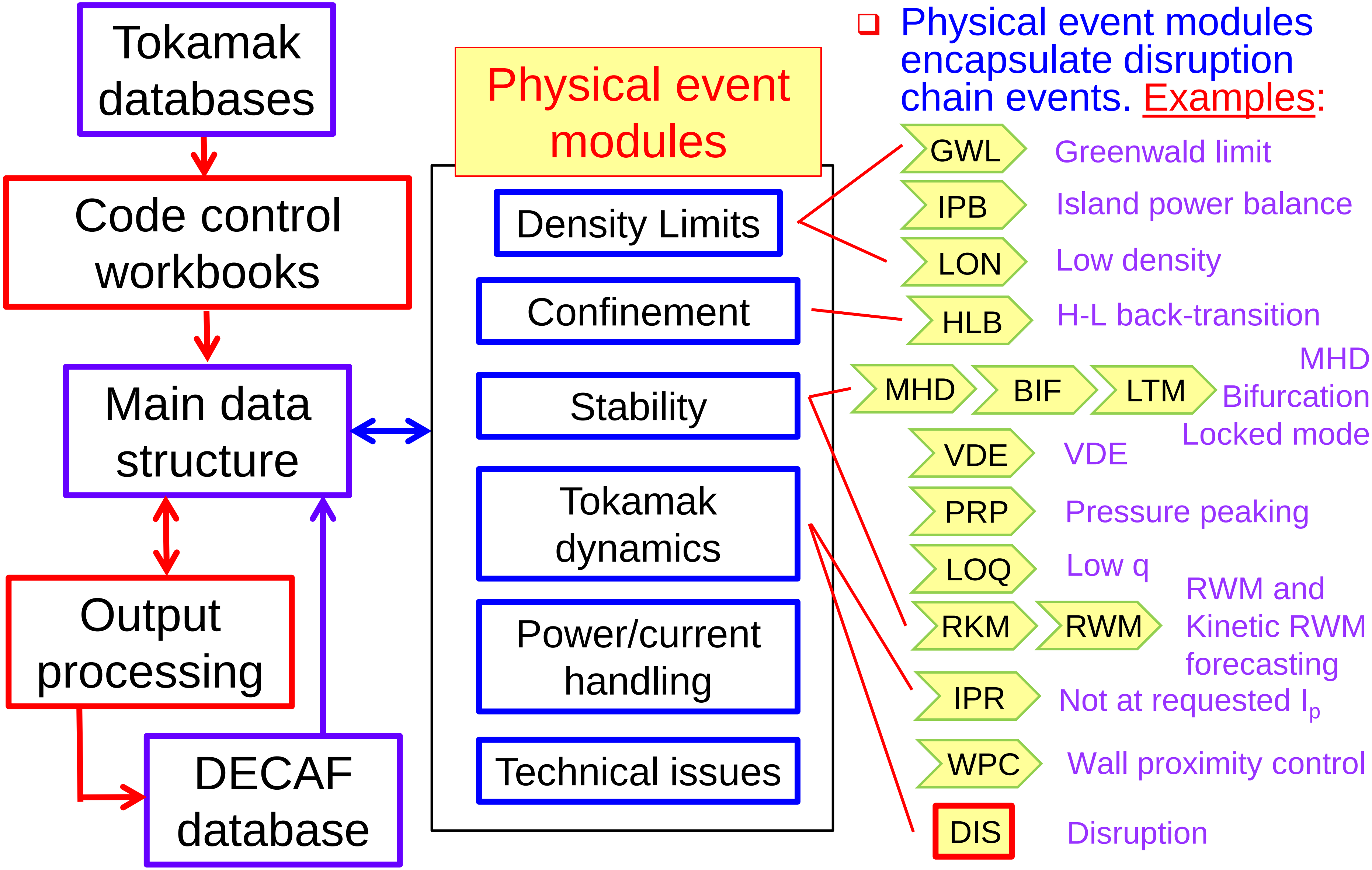
DECAF is structured to ease parallel development of disruption characterization, event criteria, and forecasting



- 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

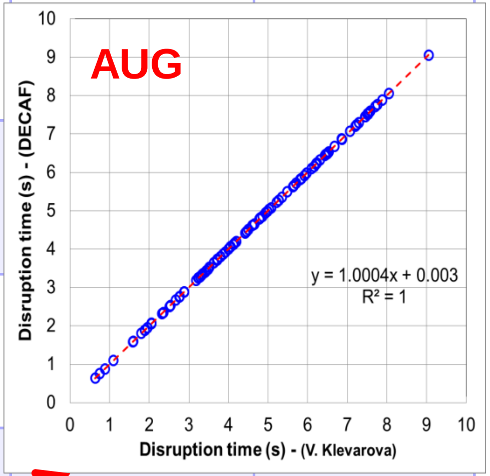
- Physical event modules encapsulate disruption chain events. Examples:



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 connected to databases from multiple machines, expanding analysis

- Analysis
  - Density limits
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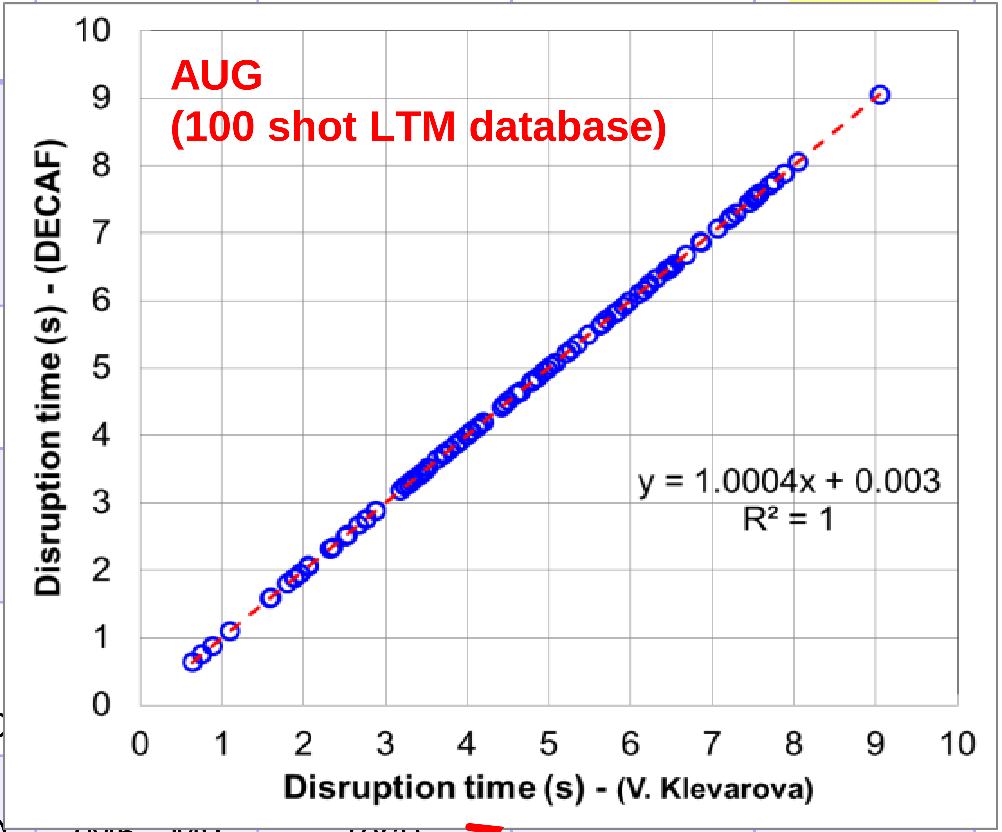

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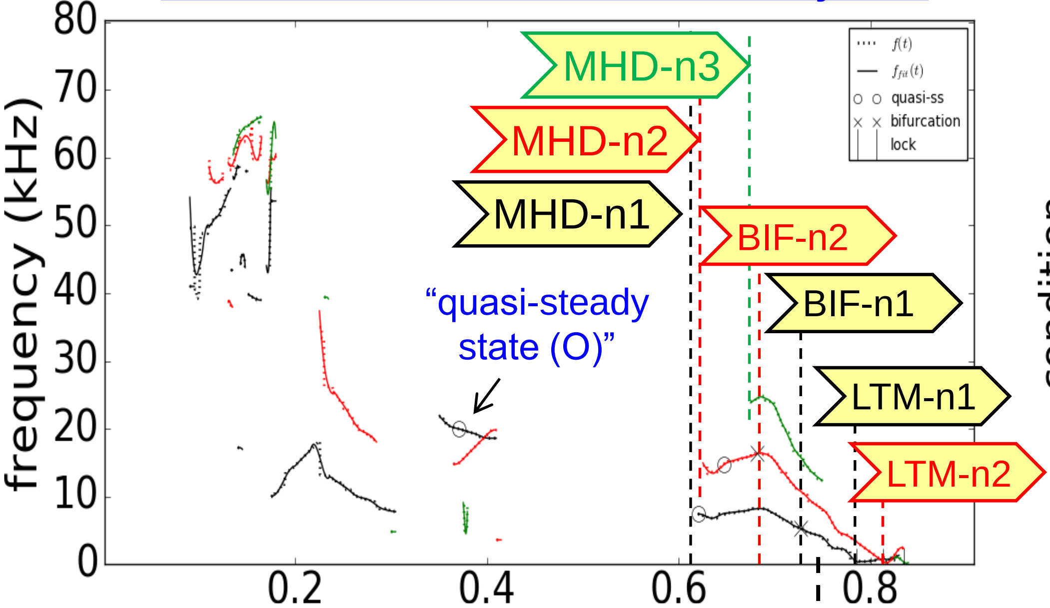
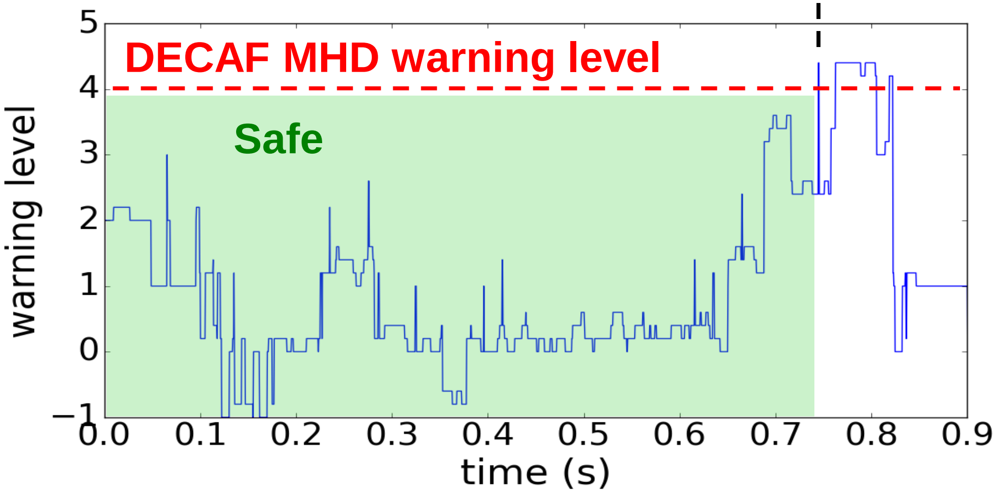
  - 100 shot LTM disruption database by V. Klevarova analyzed for DIS

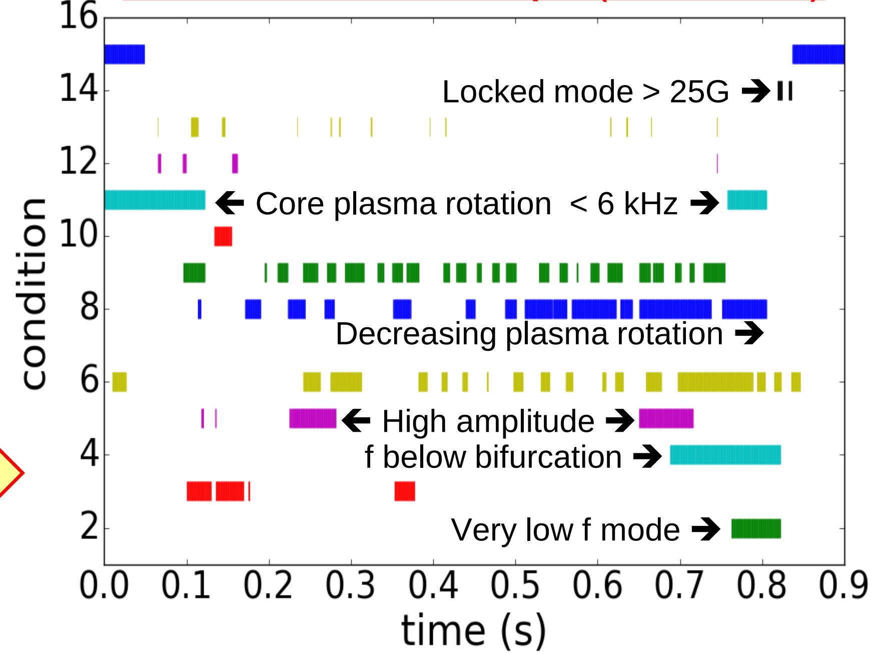
DECAF MHD events utilize history of 15 criteria to define time evolving disruption warning level

DECAF automated MHD objects



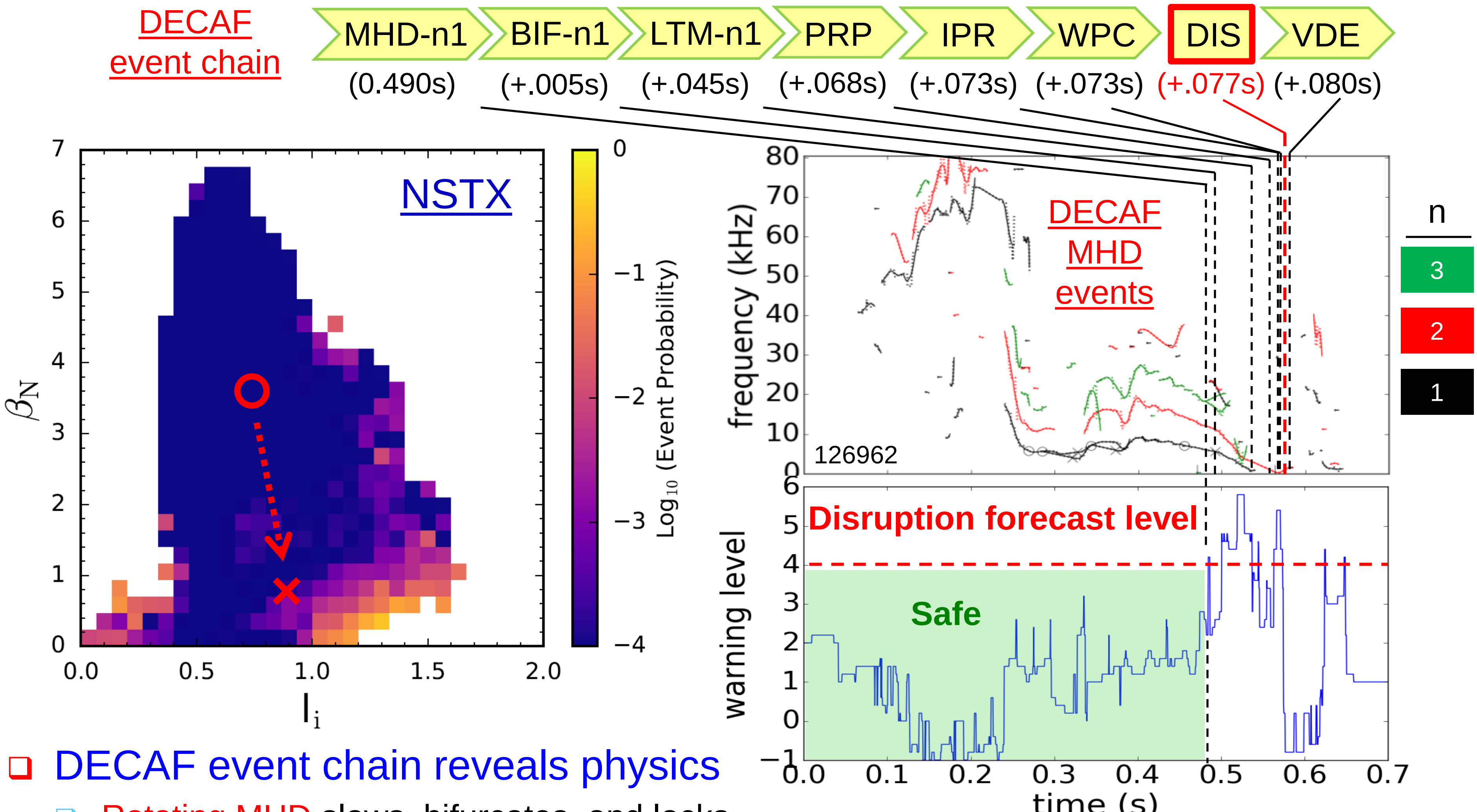


DECAF "heat map" (for MHD)



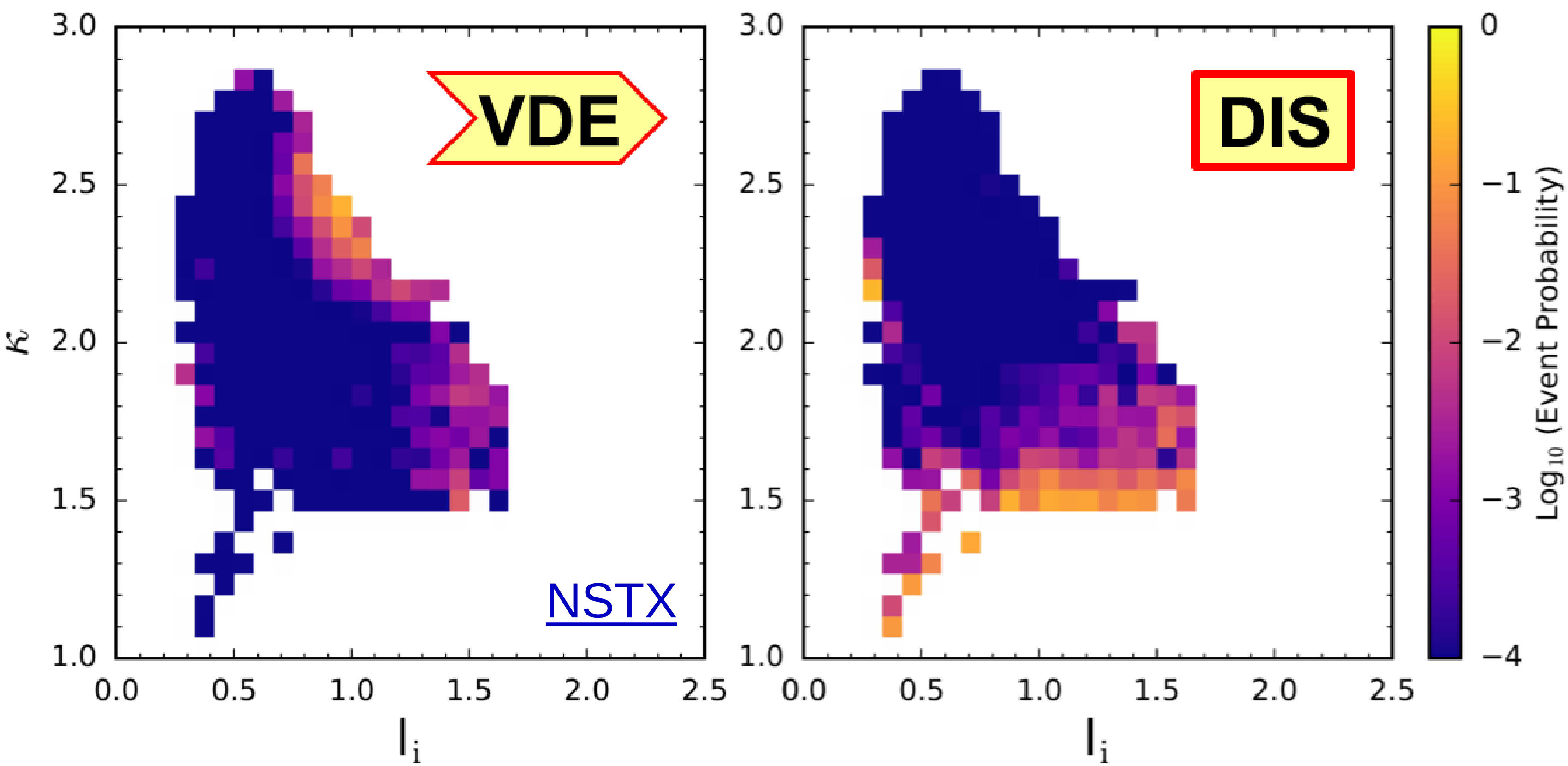
- Key notables of MHD warning
  - "Safe"/"unsafe" MHD periods found
  - Early, slow warning level evolution
    - Locked mode amplitude important, but warning comes in very late
  - Mode frequency below bifurcation, decreasing plasma rotation key

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

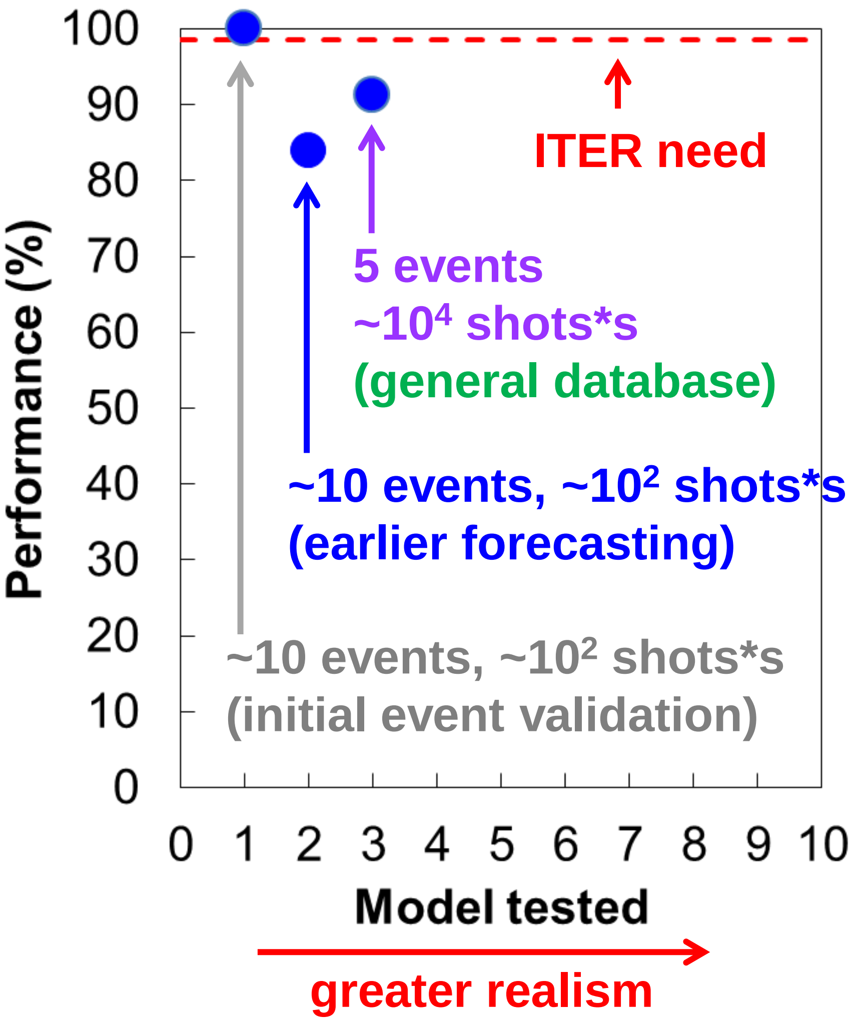


- Largest portion of detected VDE events appear at (l_i, κ) with very small portion of DIS events detected

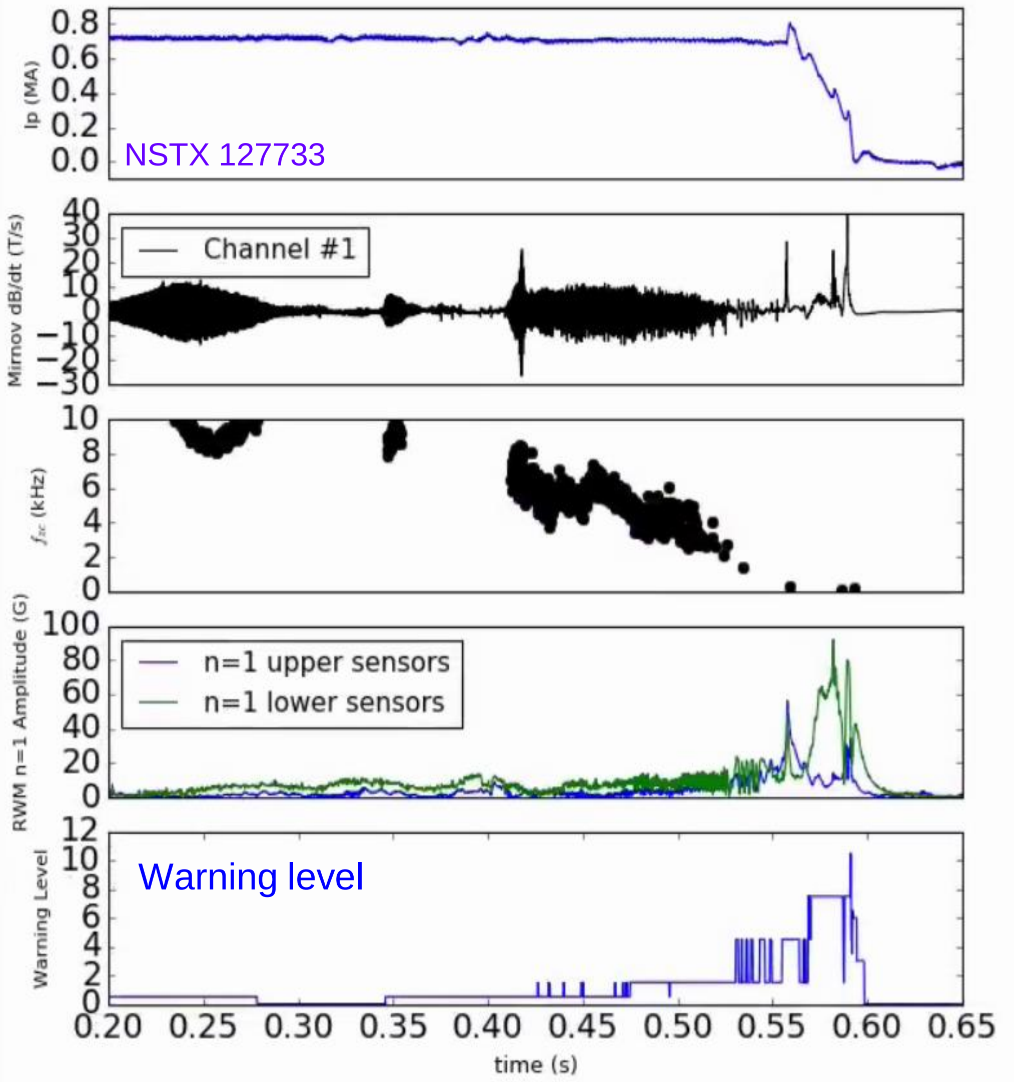
Limited event chain analysis of large databases evolves initial performance of disruption prediction

- 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

DECAF Disruption Forecasting Performance Evolution

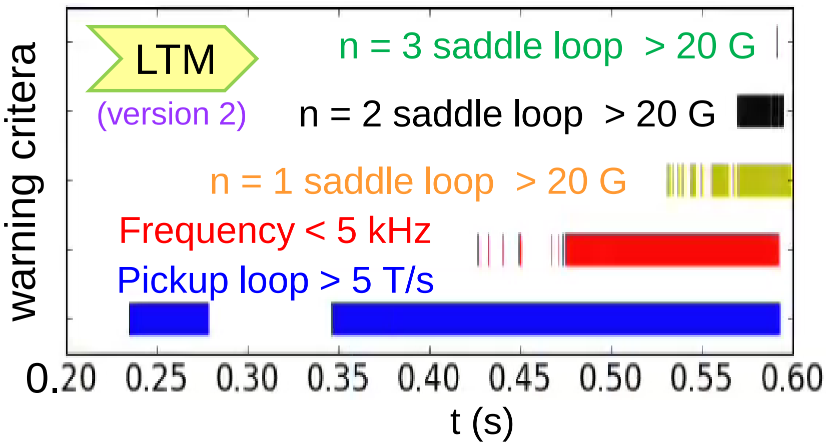


New "reduced" locked tearing mode (LTM) event being created, aimed for real-time use / comparison



J.D. Riquezes, APS DPP 2020, NP17.07

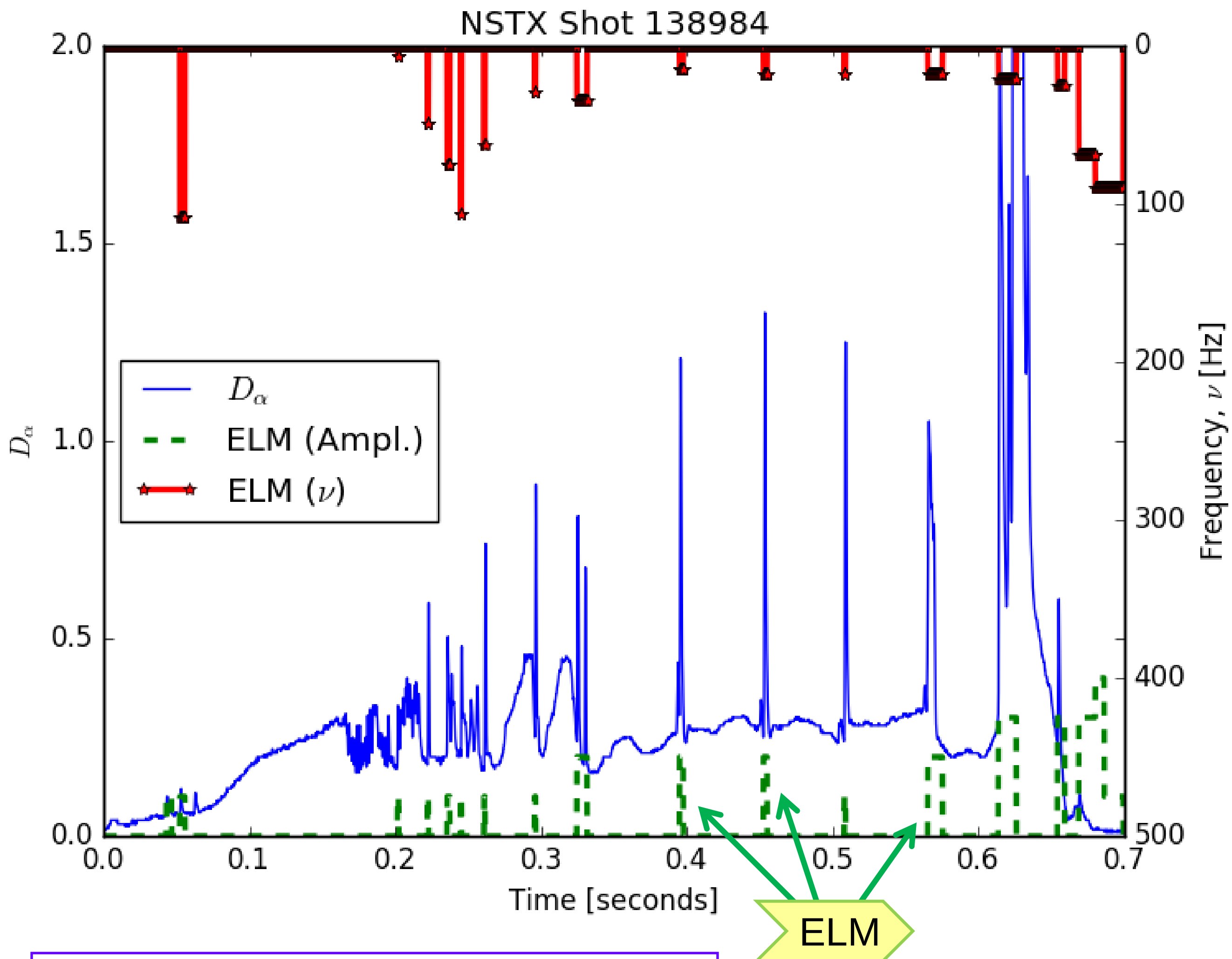
DECAF "heat map" (for LTM v2)



- Using pickup coils and partial saddle loops
- Compare to full FFT approach
- LTM forecaster now being developed
  - Based on Fitzpatrick-style island torque balance model
  - Determines critical NBI torque needed to avoid lock, critical mode frequency

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
- Compatible with real-time use
- Distinguishes true "ELMs" from others events (MHD, etc.) that generate D_α light
- L-H determination/ transition event underway



J. Butt, APS DPP 2020 NP17.06

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

- Resistive MHD

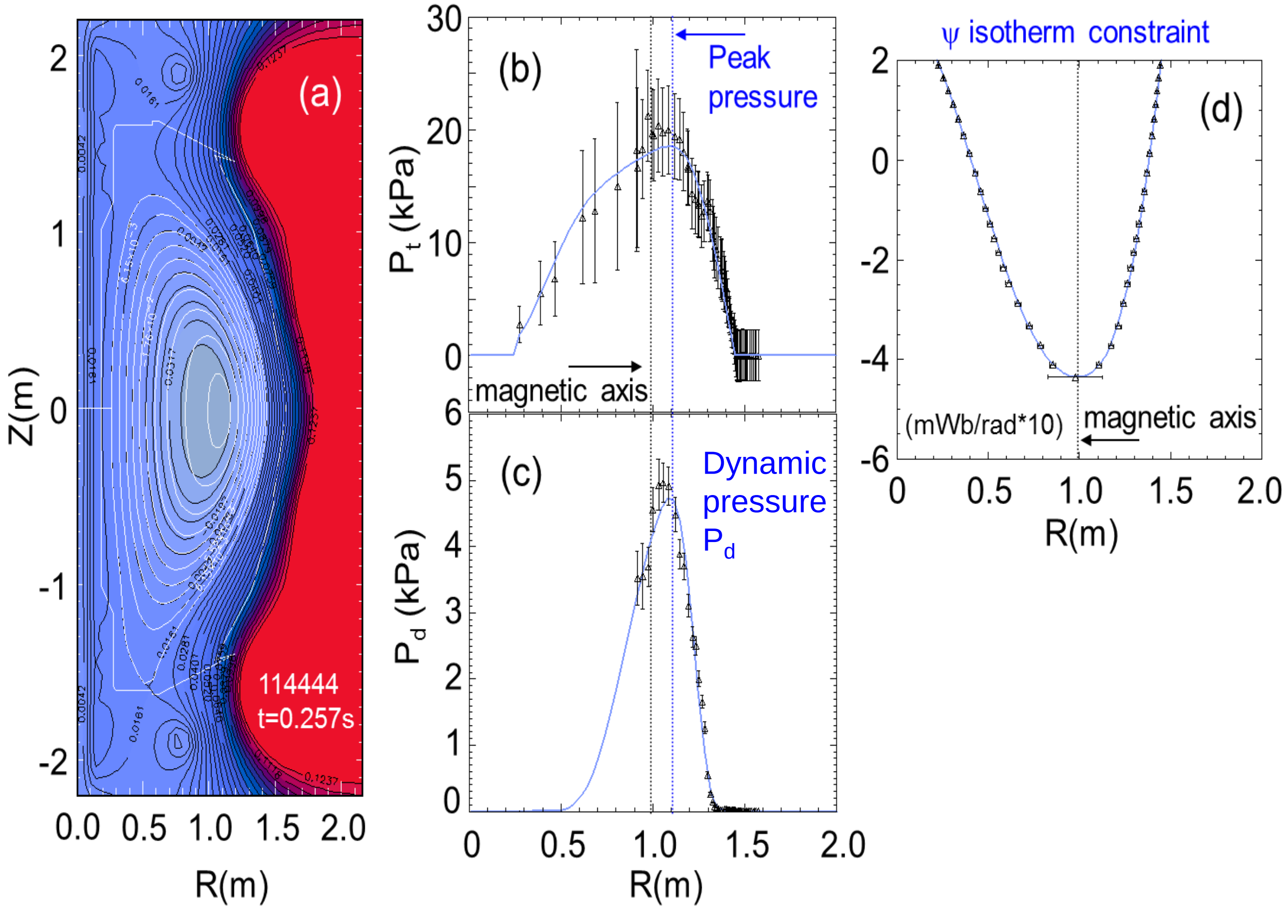
See Y. Jiang, NP17.05 Wed AM

  - Detection / forecasting: available magnetic diagnostics, plasma rotation
  - Forecasting: starting examination of MRE ➔ start with Δ' evaluation

See Y.S. Park, NP17.08 Wed AM

- 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

Kinetic equilibrium reconstruction will continue and expand for NSTX-U

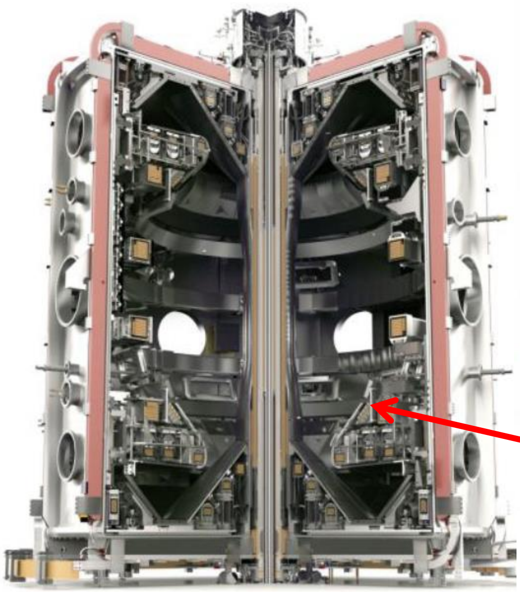


NSTX EFIT equilibrium reconstruction including toroidal rotation and flux isotherm constraints [S.A. Sabbagh, et al., Nucl. Fusion 46 (2006) 635].

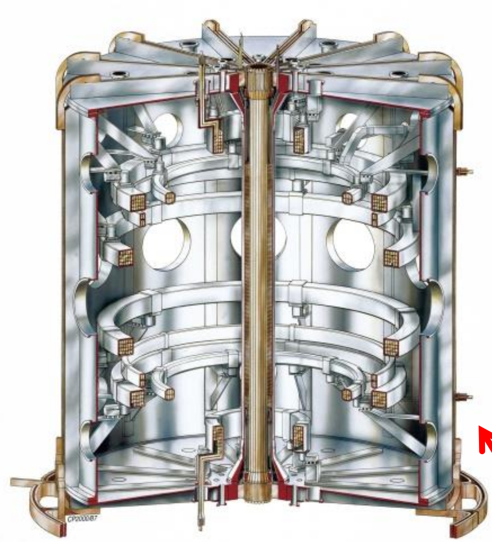
- Equilibrium reconstruction essential stability analysis, etc.
- Expands our more than decade-long effort on NSTX / NSTX-U
- Results distributed to entire NSTX-U Team
  - Kinetic reconstructions between shots
  - Analysis with MSE
  - Higher time / space resolution as requested
  - Ability to reconstruct with plasma rotation implemented

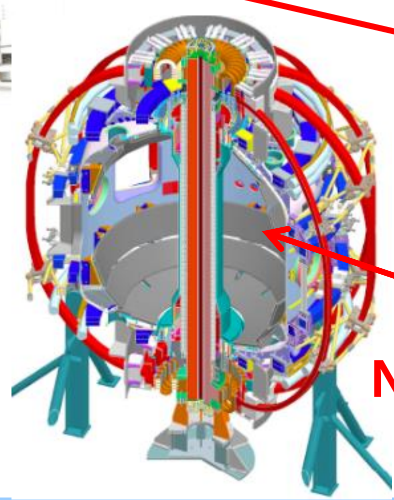
Recent DECAF supporting effort: key proposed DOE study to determine effect of conducting structure on ST stability

MAST-U



MAST





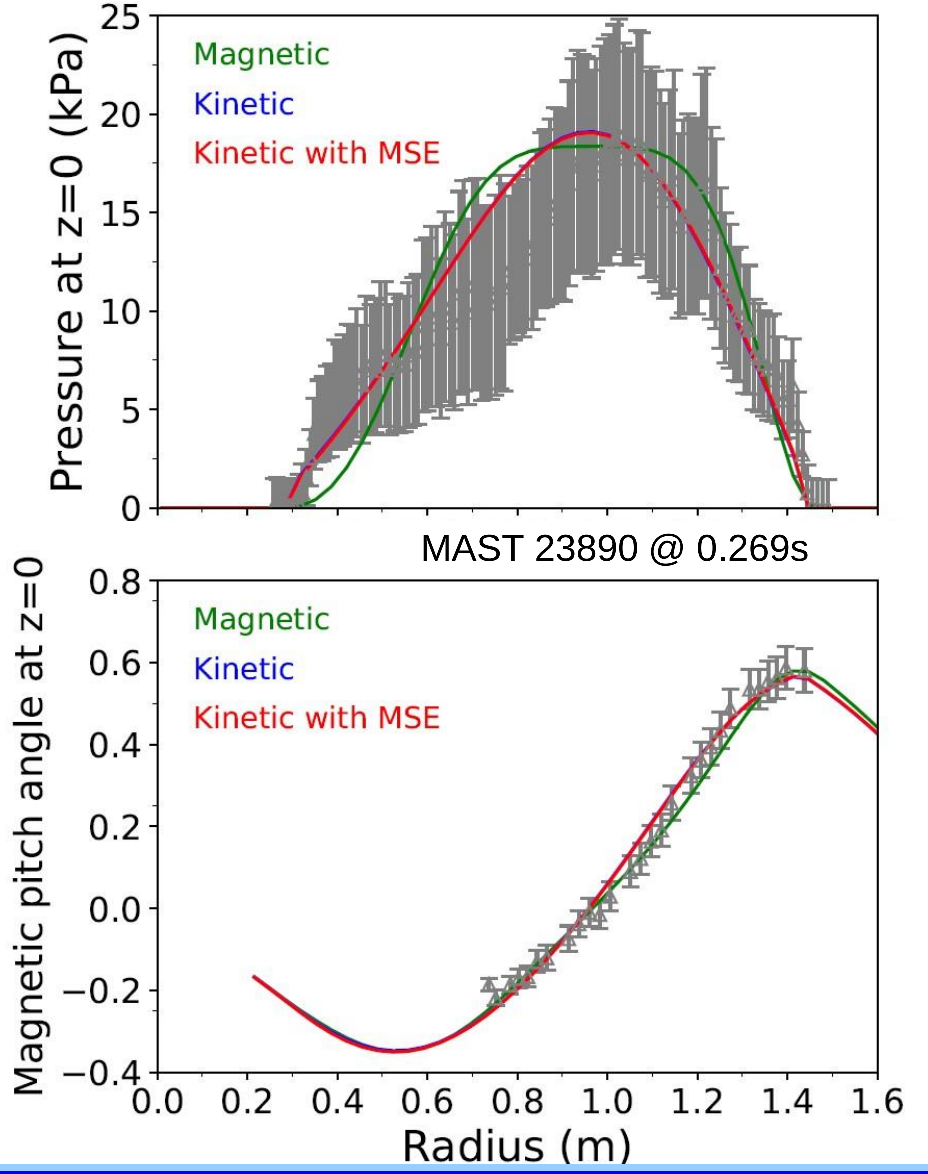
NSTX

- 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

CU group MAST research can reliably reconstruct plasmas with various levels of diagnostic inclusion

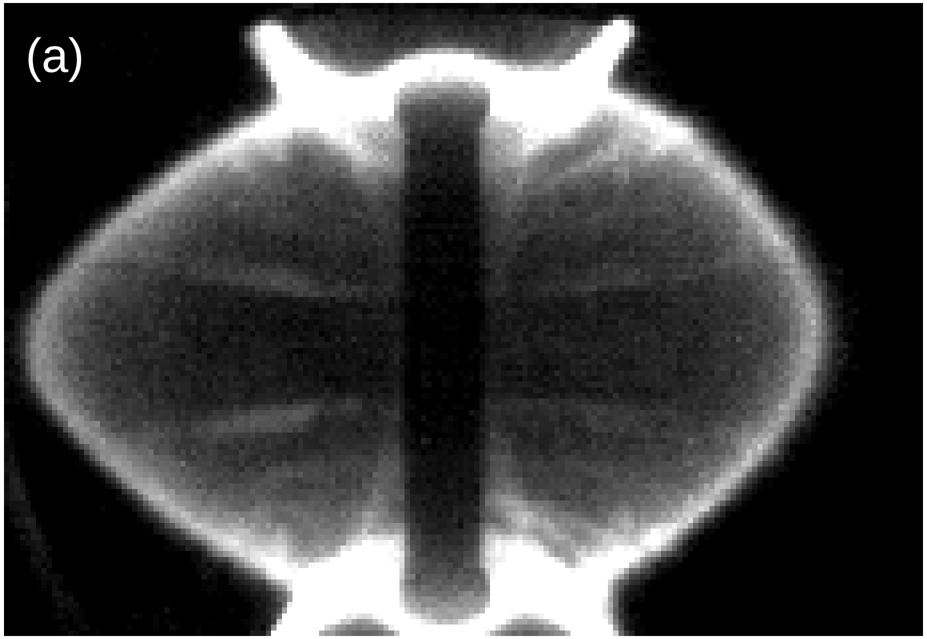
- Magnetics only
  - Vessel structure currents are modelled with the VALEN code
- Partial kinetic
  - Includes magnetics plus available pieces of the pressure profile: n_e, T_e, n_i… with models for the other pieces
- Kinetic with MSE
  - Includes magnetic pitch angle
- KEY for direct analysis comparison to NSTX/NSTX-U!

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

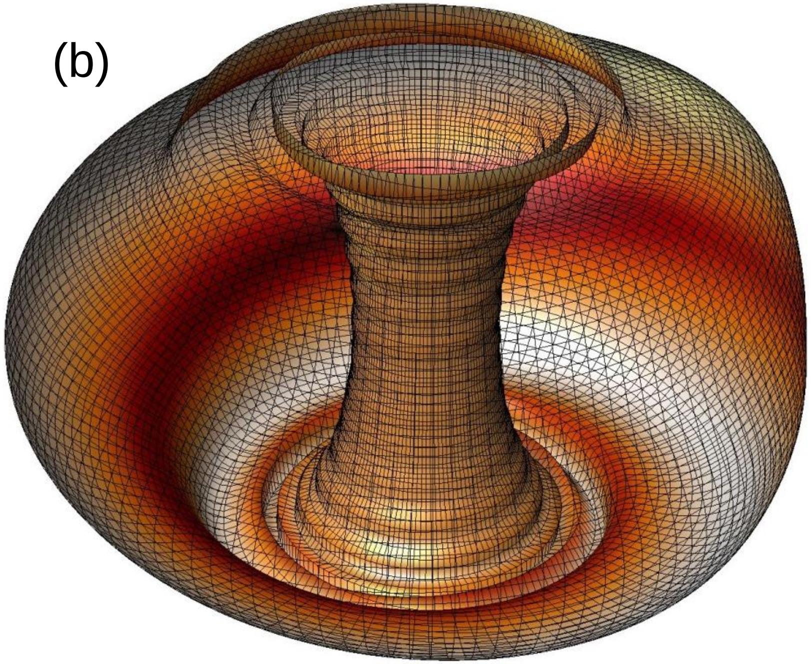


VALEN code analysis models similar distortion to egg shape mode in MAST

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

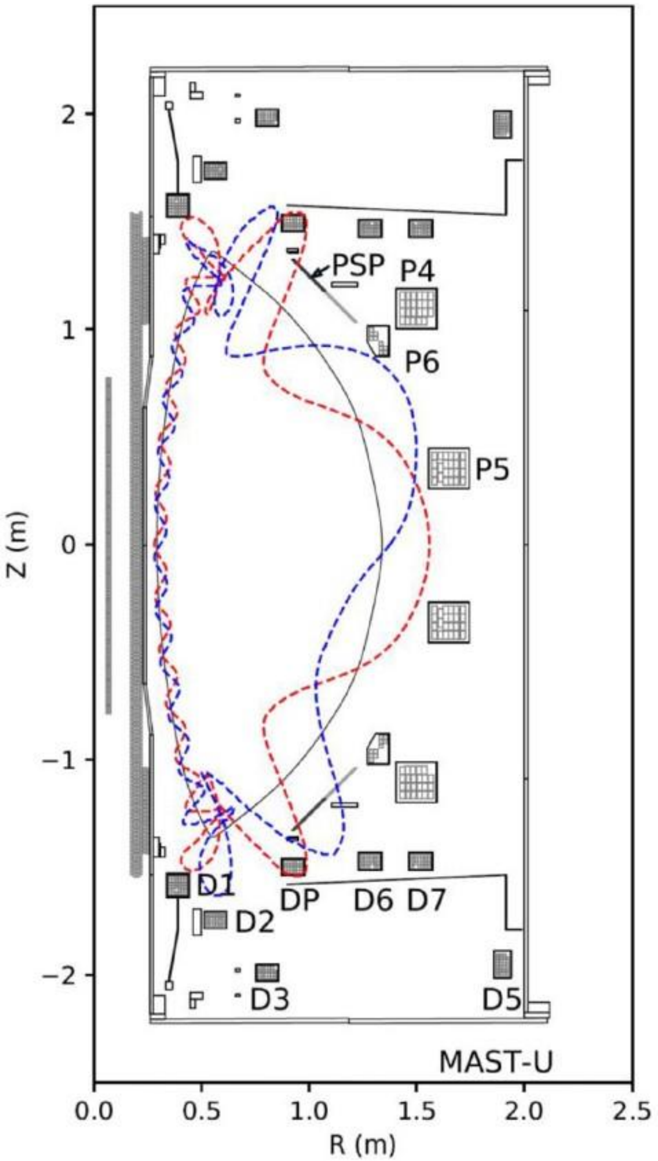


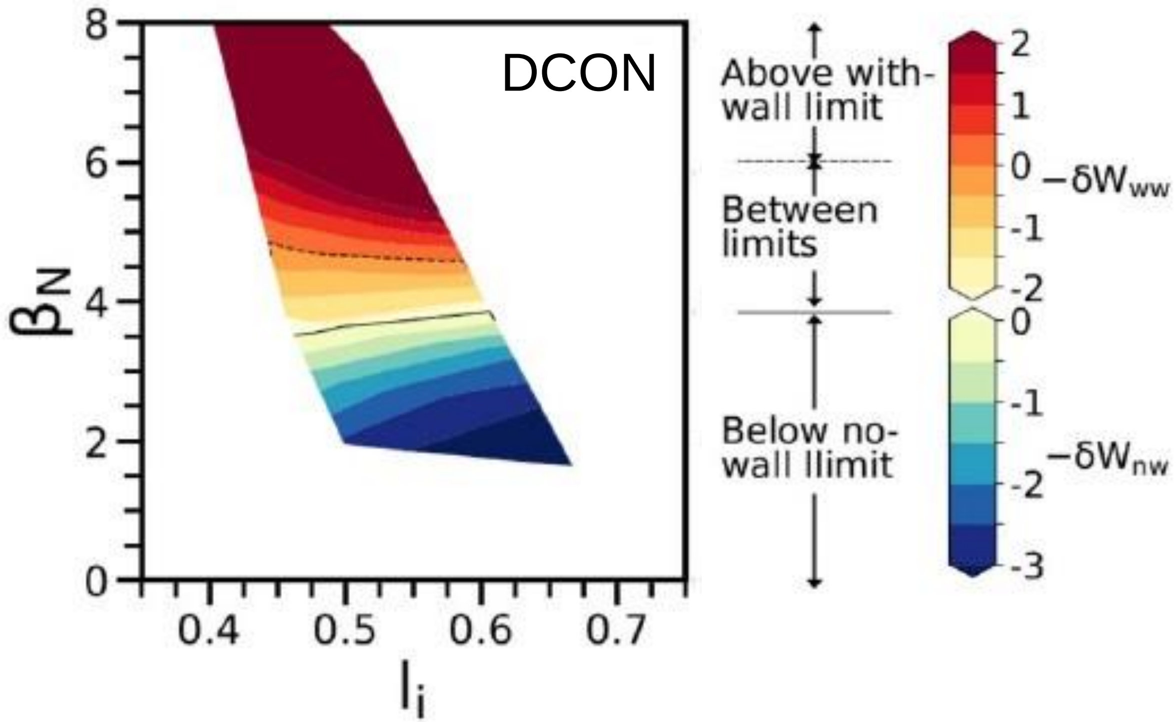
VALEN analysis (n = 1 RWM) (using MAST 7090)



- 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)

Projected MAST-U equilibria were used to evaluate the ideal MHD stability space



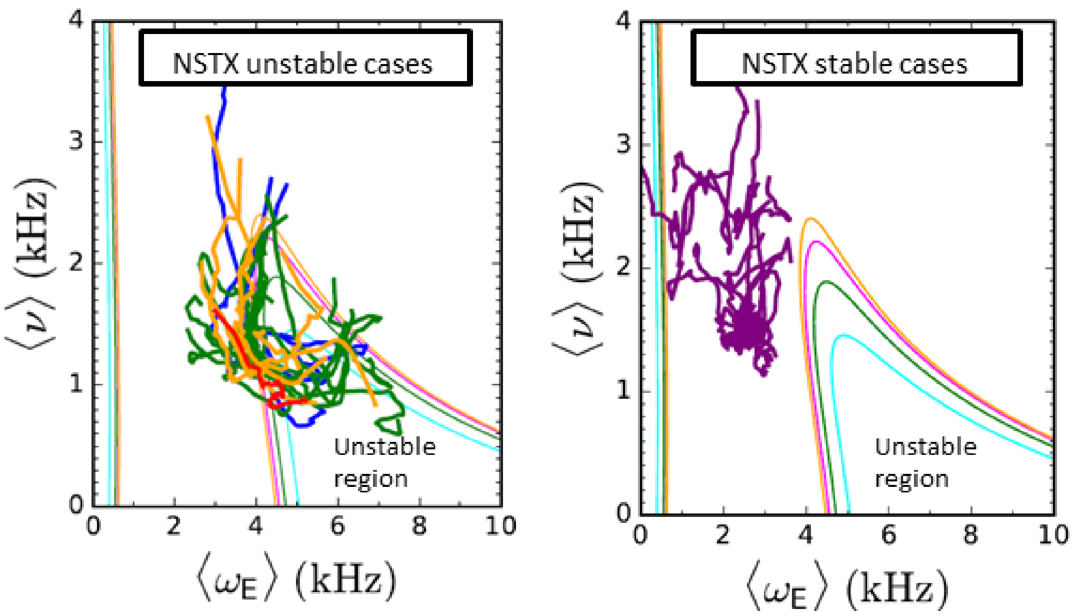


- Exaggerated view of perturbation shows importance of PSP for wall stabilization
- Scans of pressure and q profiles map stable and wall-stabilized MAST-U regimes

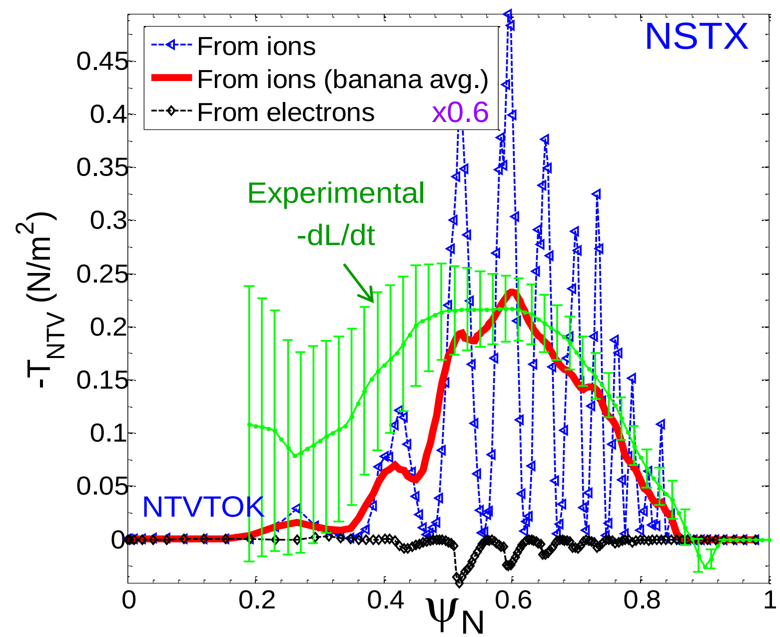
J.W. Berkery, *et al*., PPCF **62** (2020) 085007

Kinetic MHD global mode (RWM) stability and NTV dependence on collisionality to be studied (as originally planned)

Kinetic resistive wall mode (RWM) stability on NSTX

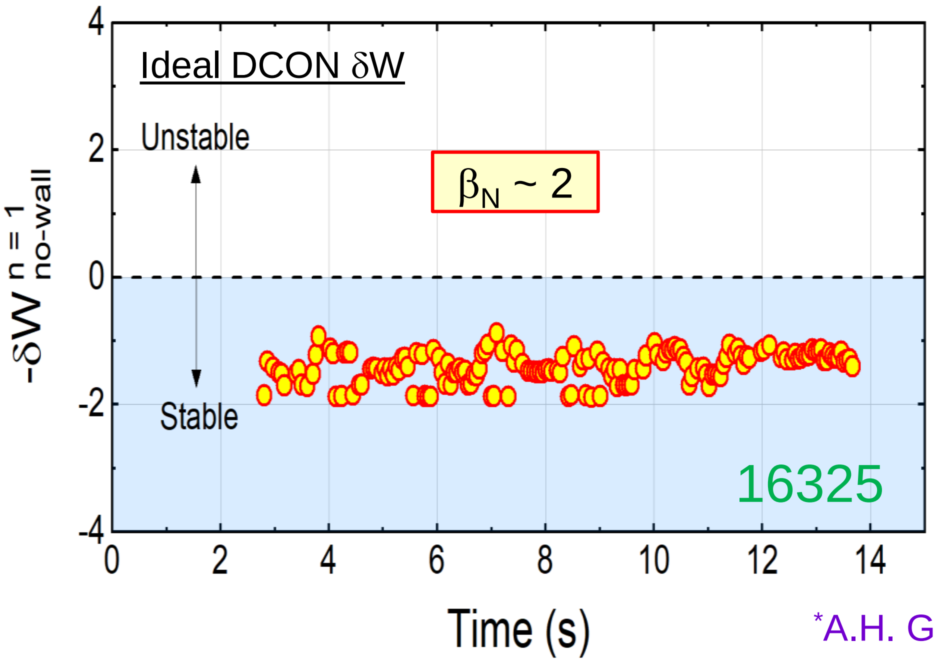


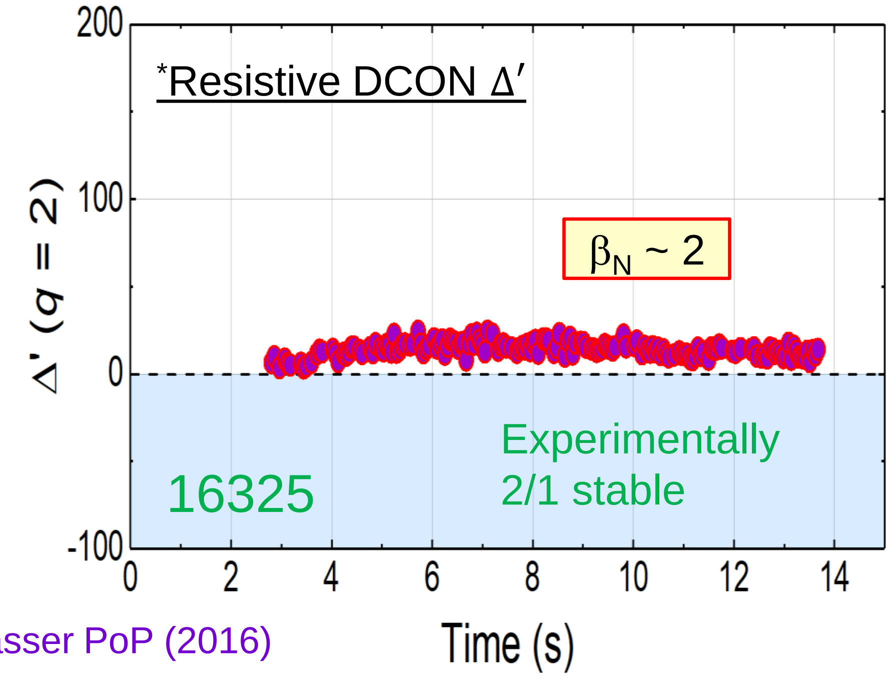
Neoclassical toroidal viscosity (NTV) profile validated on NSTX



- Both kinetic RWM stability and NTV depend on plasma collisionality and velocity
- Theory to validate: RWM stability can improve but only for “favorable” plasma rotation profiles; NTV should increase at lower collisionality

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



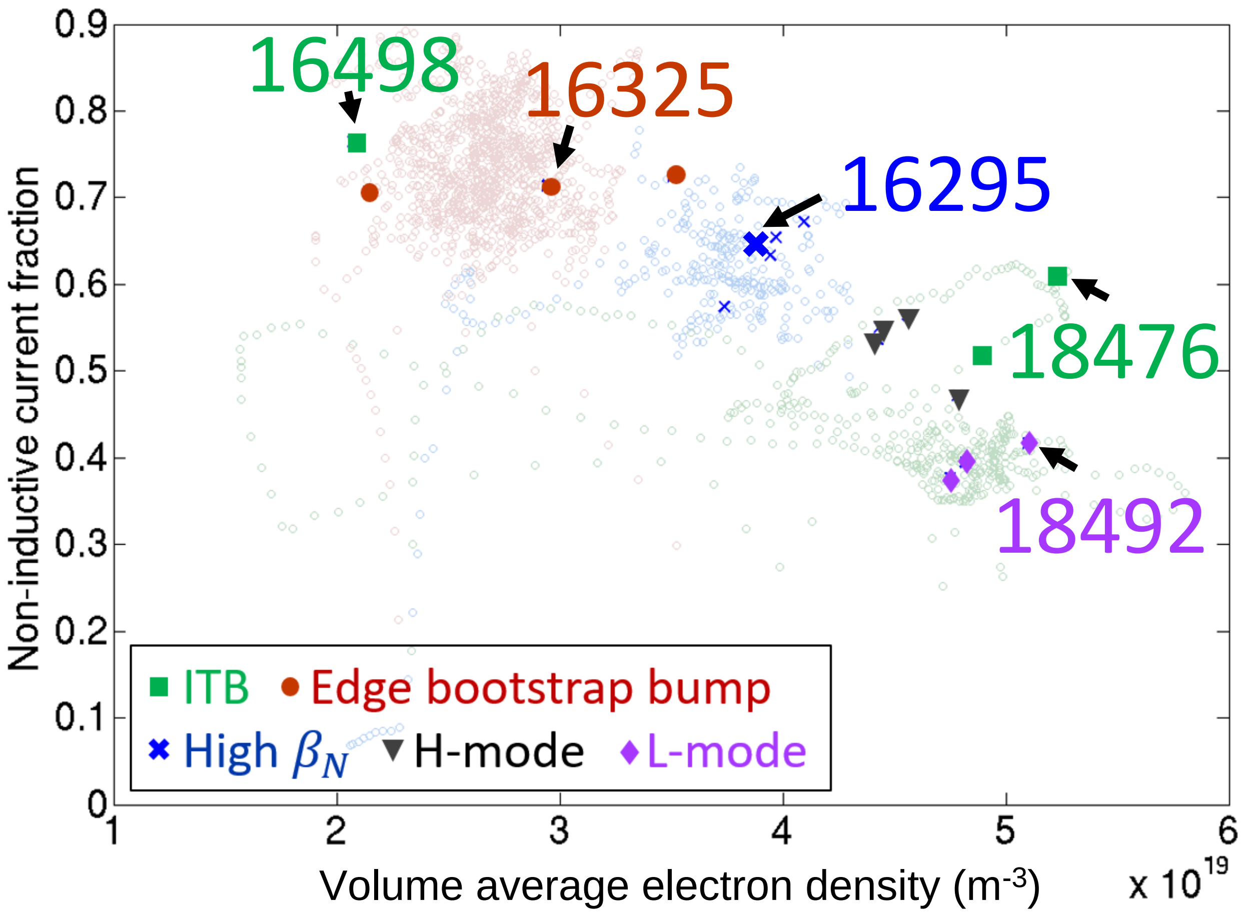


*A.H. Glasser PoP (2016)

- 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

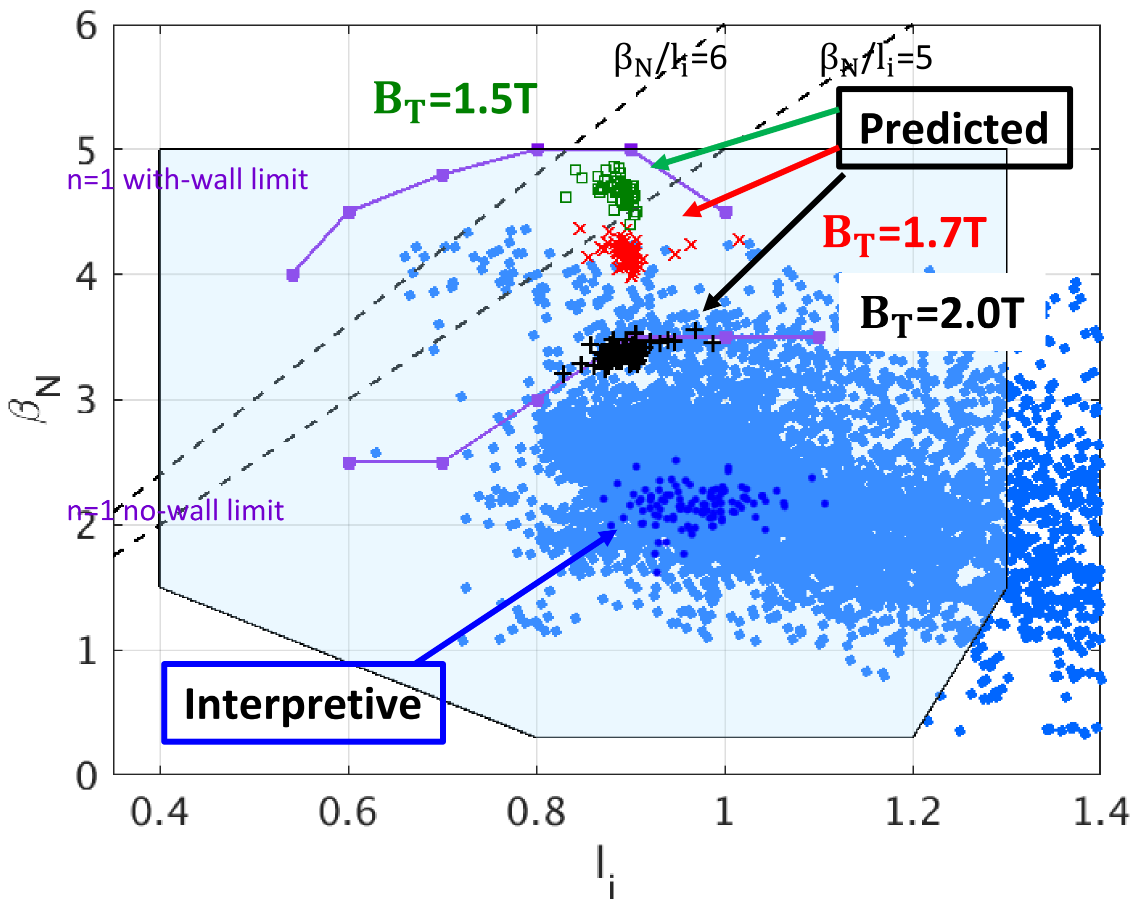
A database of high-non-inductive fraction plasmas is important for disruption forecasting ; NICF ~ 75% in KSTAR

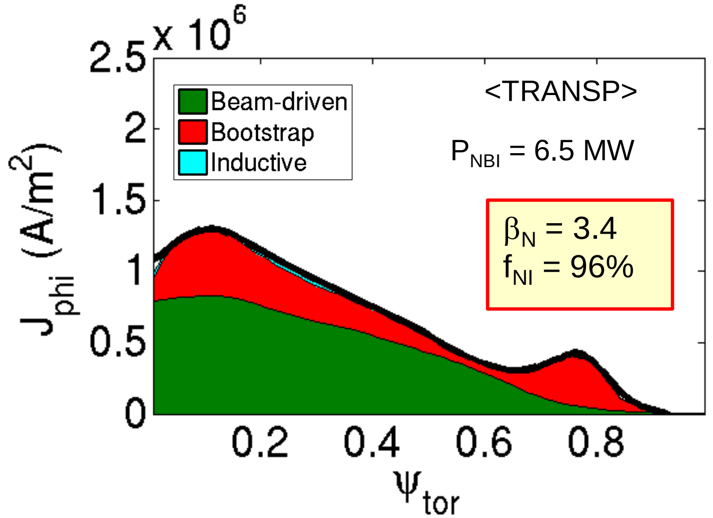
- TRANSP analysis of experimental plasmas
- Non-inductive fraction
  - Beam-driven
  - Bootstrap
- Non-inductive fraction is key for stable high beta steady state operation



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

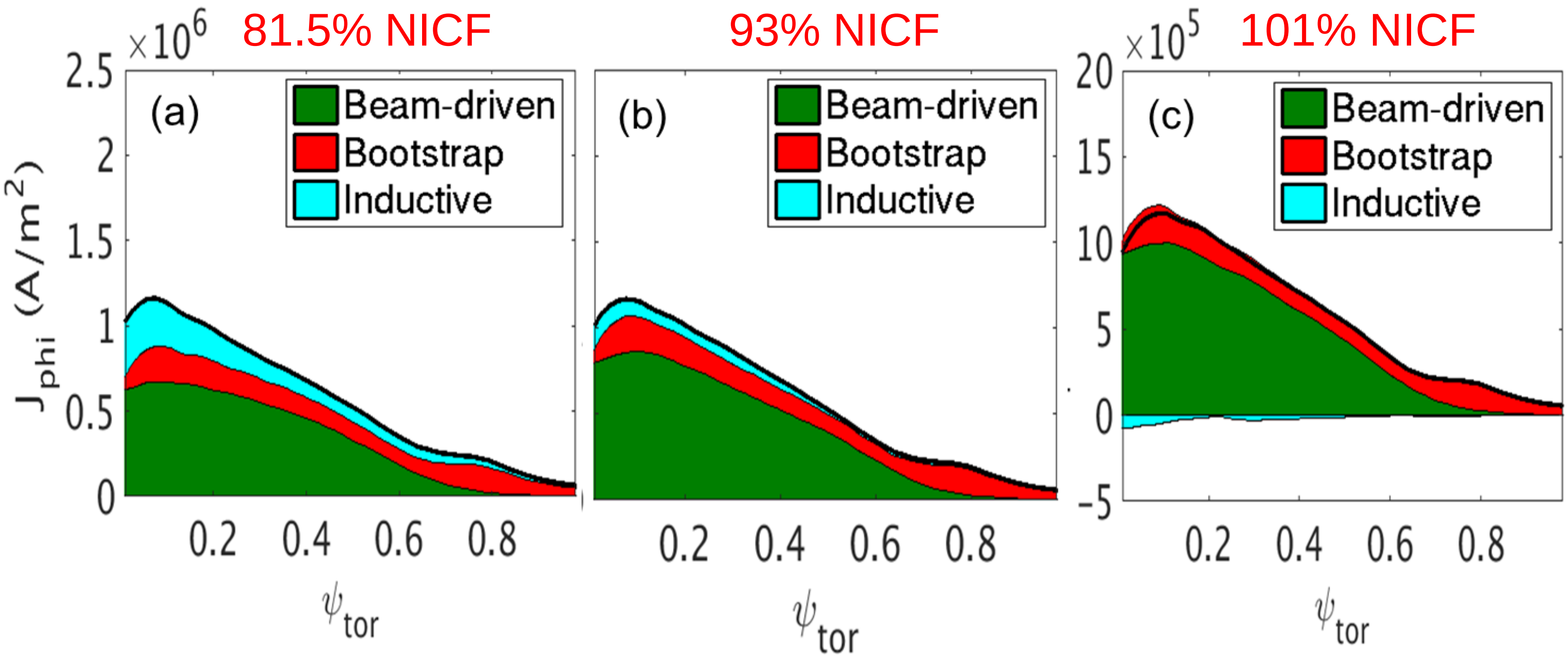




- Up to 75% NICF already reached in similar plasmas
- NBI ➔ 6.5 MW in 2021
- By altering I_P and B_T values, $\beta_N > 4$, up to KSTAR design target 5 can be achieved with 100% NICF

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

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



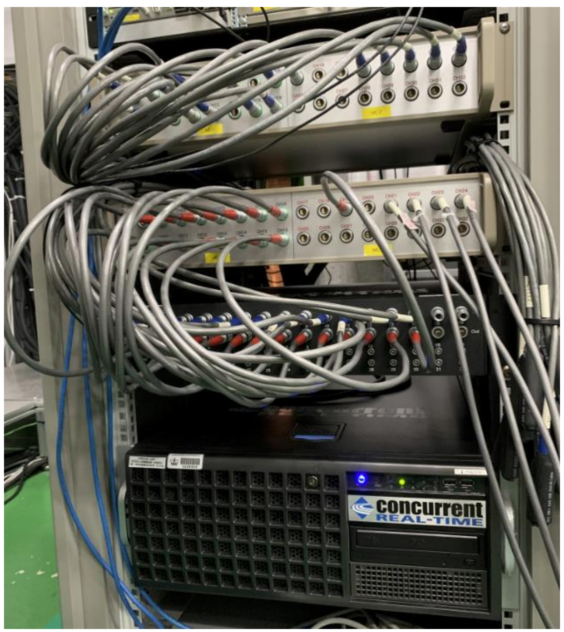
- High non-inductive current fraction predicted for 6.5, 7.5, 8.5 MW NBI
  - The β_N ranges from 3.0 – 3.5; based on KSTAR plasmas with NICF ~70%
- Aim to generate a significant database of long pulse, high NICF plasmas in 2021 KSTAR run for disruption prediction studies

KSTAR disruption avoidance research "fills in desired real-time (r/t) diagnostic capability for r/t DECAF

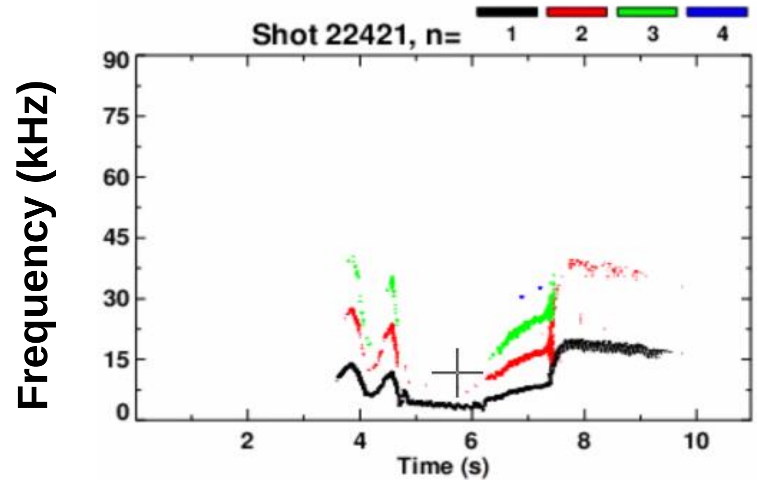
- ✓ Real-time measurement of rotating / locking MHD
  - < 300 kHz; Data collected during 2019 - 2020 runs
- ✓ Real-time plasma rotation profile – installed at KSTAR
  - Completely new for KSTAR: < 32 channels; 1 – 2 kHz time resolution
- Real-time and offline Motional Stark Effect - IN FINAL DESIGN
  - "offline" MSE background polychrometer system, Z_{eff} profile
  - Real-time implementation of MSE; includes δB profile measurement
- ✓ Real-time electron temperature profile – installed at KSTAR
  - Real-time acquisition of heterodyne radiometer system – use in 2021
- ✓ Real-time T_e fluctuation profile – installed at KSTAR
  - Real-time acquisition to 2-D ECE imaging system – use in 2021

Real-time MHD analysis computer installed on KSTAR for disruption prediction and avoidance

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

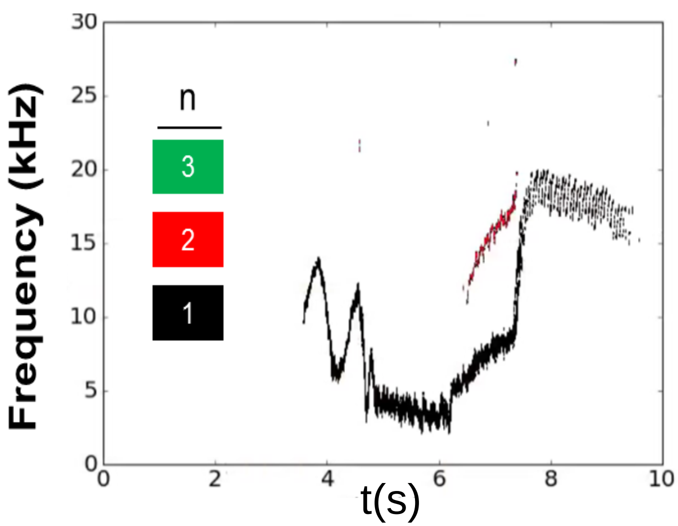


Magnetic probe spectrogram analysis

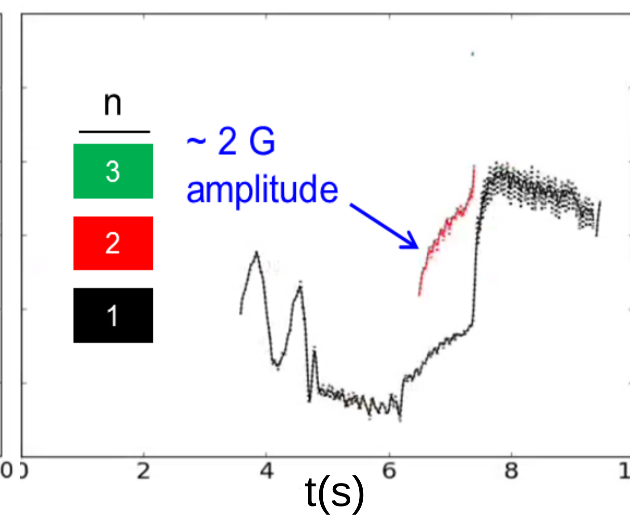


Offline DECAF analysis of real-time signals

DECAF spectrogram

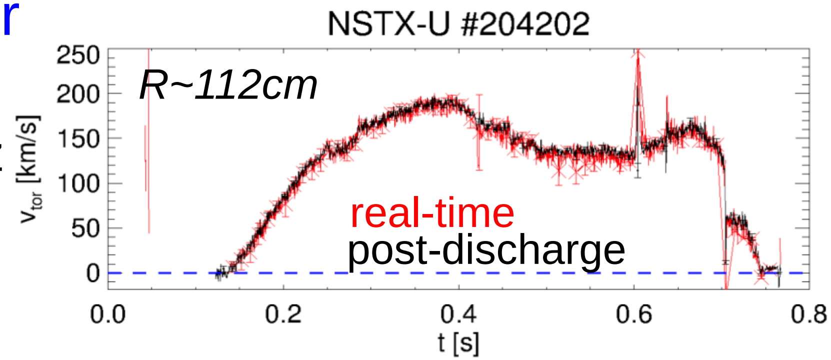


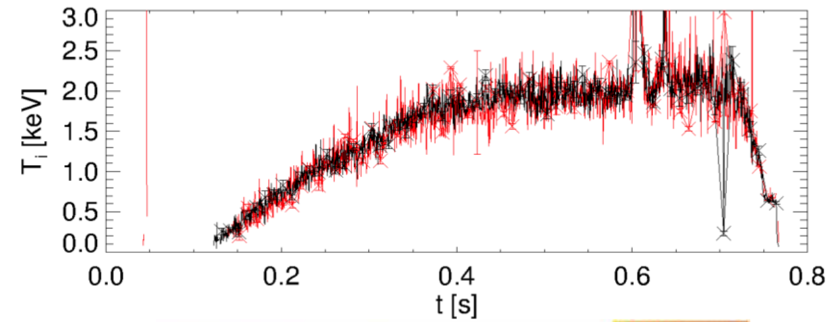
DECAF mode decomposition

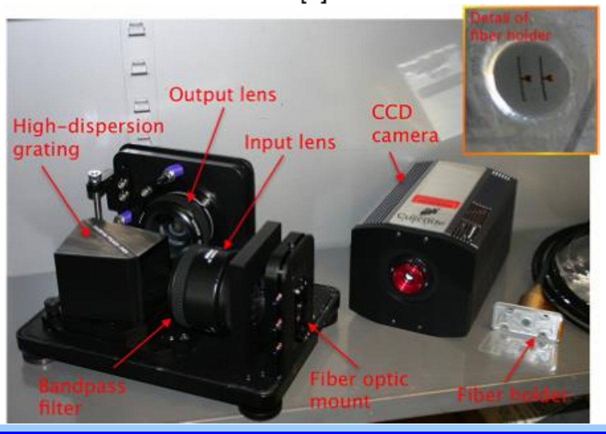


New real-time velocity diagnostic for KSTAR expands design of system used on NSTX-U

- NSTX-U: demonstrated RT analysis for v_ϕ, T_i (for T_i>150eV)
  - 4 radial channels, active + backgrd, 5 kHz
- KSTAR: plan for up to 32 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 (arrived Wed July 22nd evening)
  - Use data from initial system for final design of new KSTAR system
  - Install new KSTAR system 2021

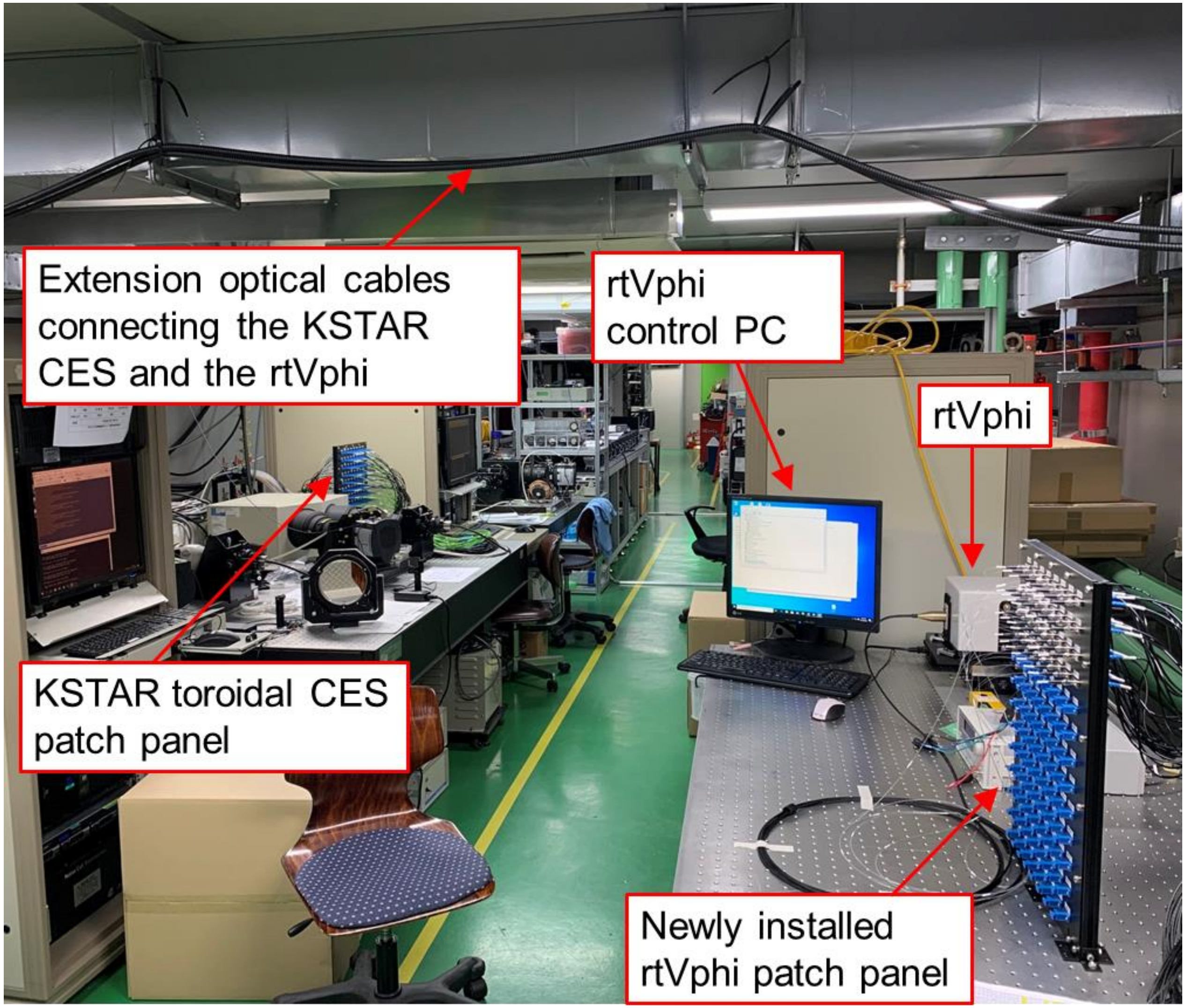




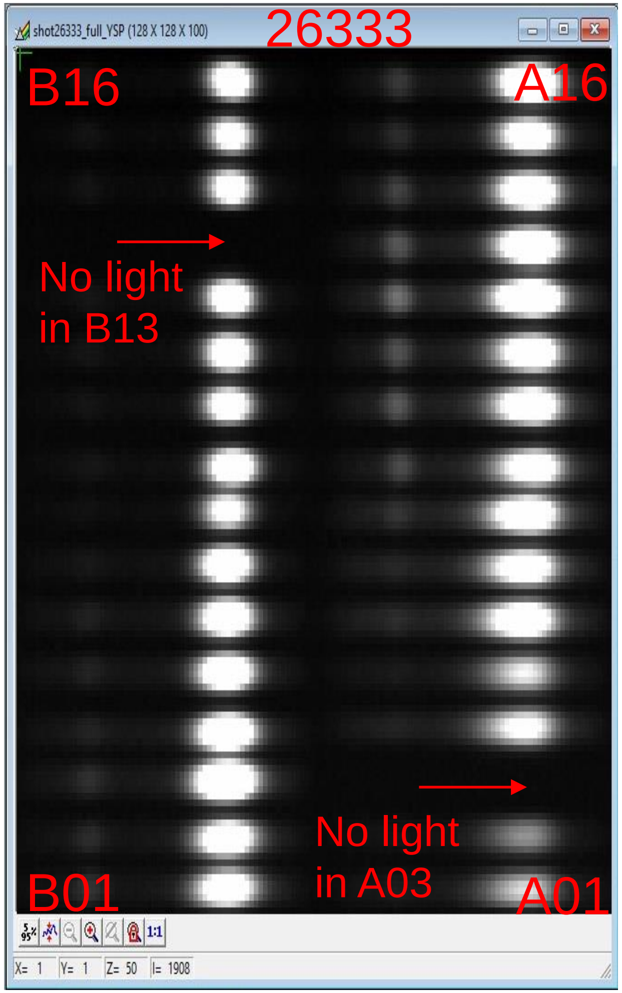


M. Podesta (PPPL)

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



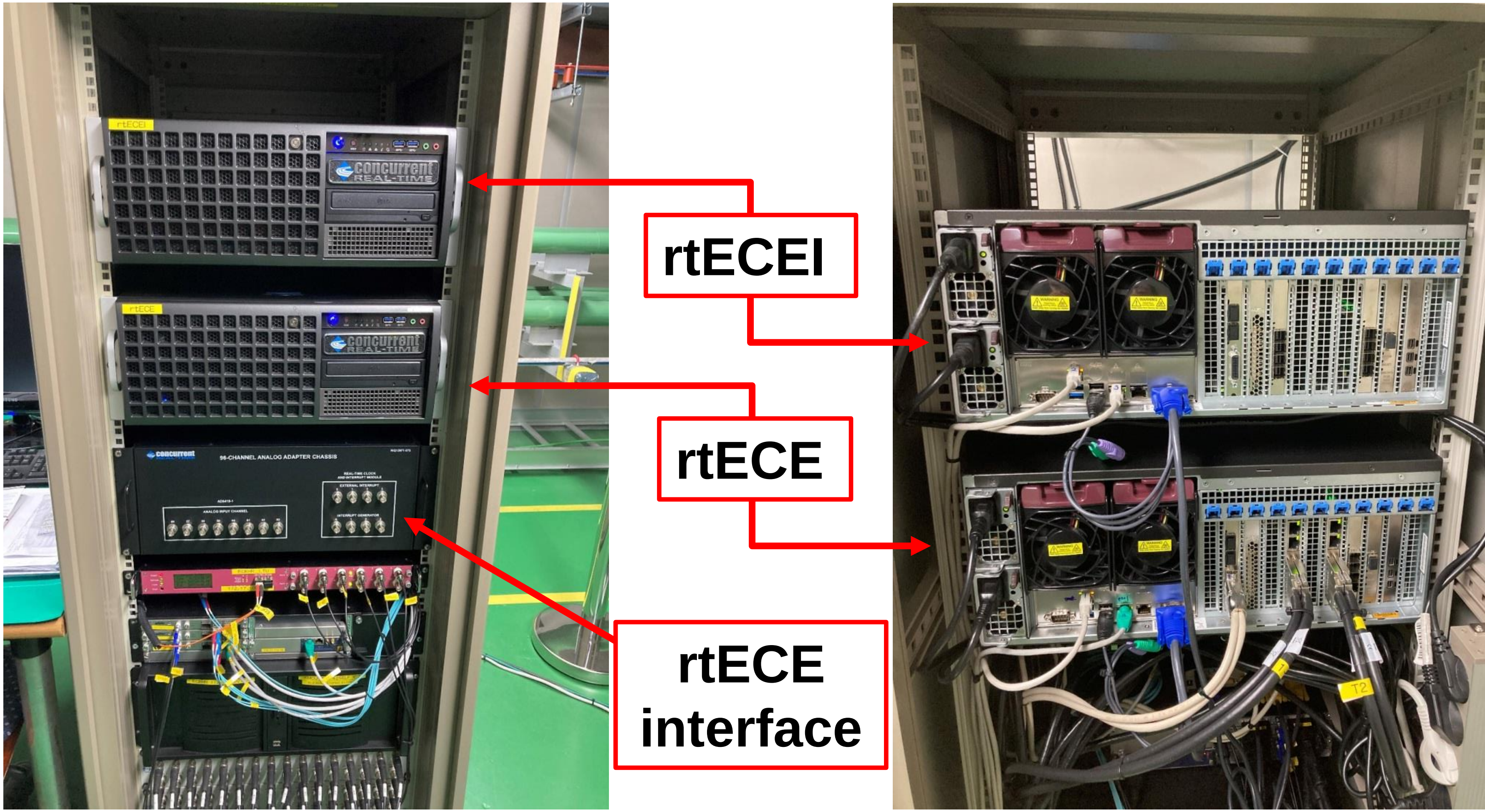
First Light!



- Initial real-time KSTAR V_ϕ profile data taken 2020

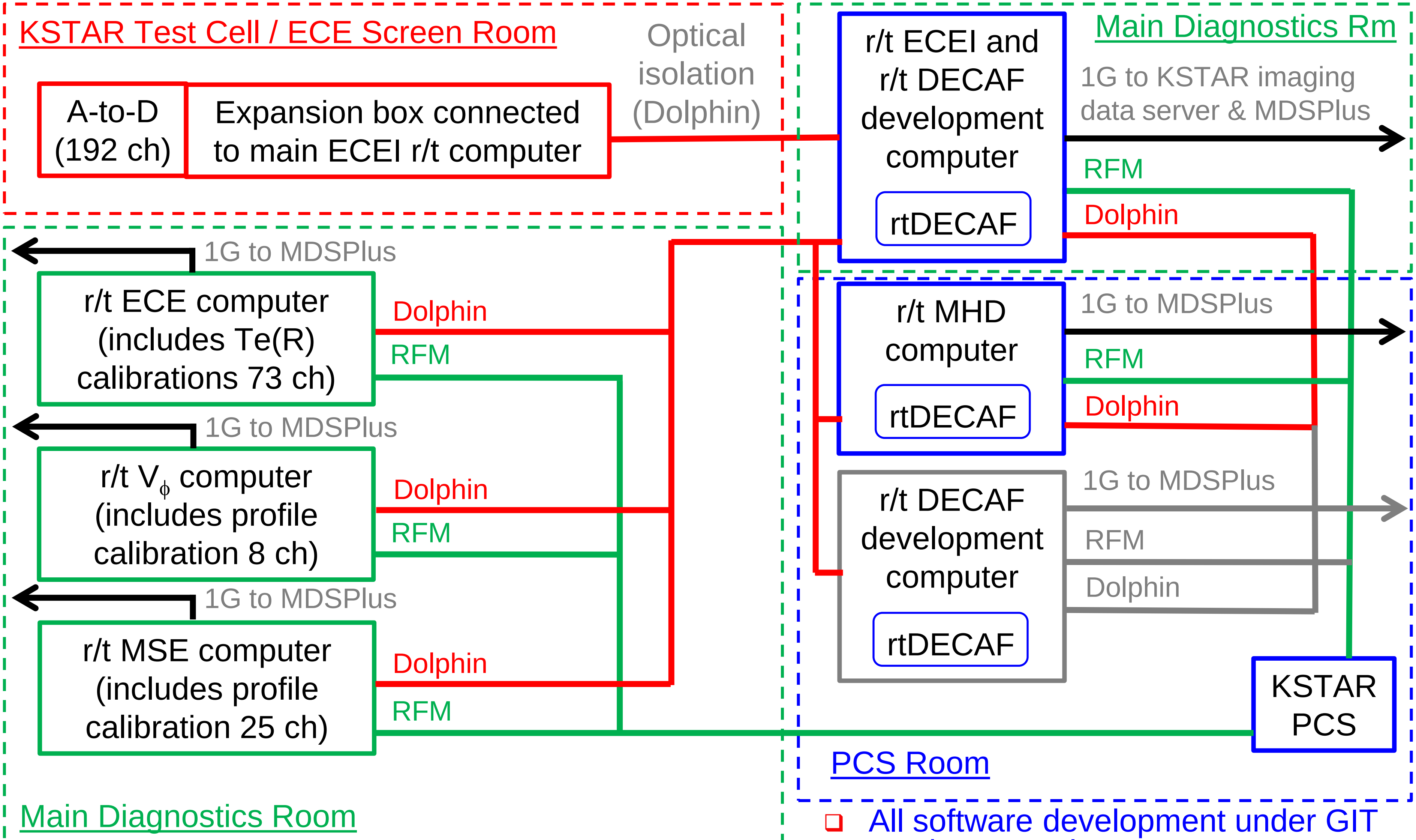
M. Podesta, J. Yoo (PPPL), Y.S. Park (Columbia)

KSTAR real-time ECE and ECEI data acquisition hardware recently installed (Feb 2021)



- rtECE computer in proximity to heterodyne radiometer system
- rtECEI computer connected to diagnostic by PCIe expansion box and custom interface in test cell (192 channels!)

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



- All software development under GIT version control

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

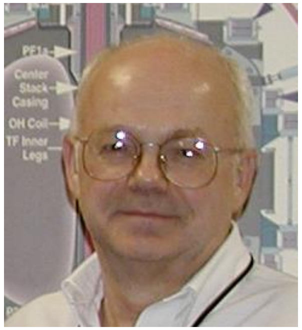
- Eight CU scientists and students based at PPPL
  - Including 2 students
  - New full-time post-doc/student for NSTX-U grant
- Innovative high beta, long-pulse, non-inductive superconducting tokamak plasma research on KSTAR
- Compact, high beta spherical tokamak plasma research on MAST-U and NSTX-U

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


S.A. Sabbagh


J.W. Berkery


Y.S. Park



J.M Bialek


Y. Jiang


V. Klevarova

STUDENTS

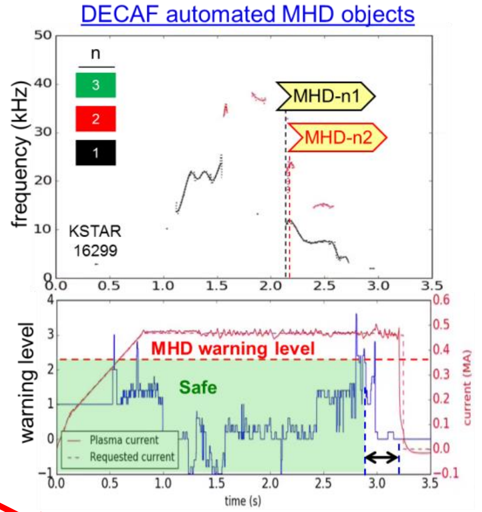

J. Riquezes


J. Butt

Supporting slides follow

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

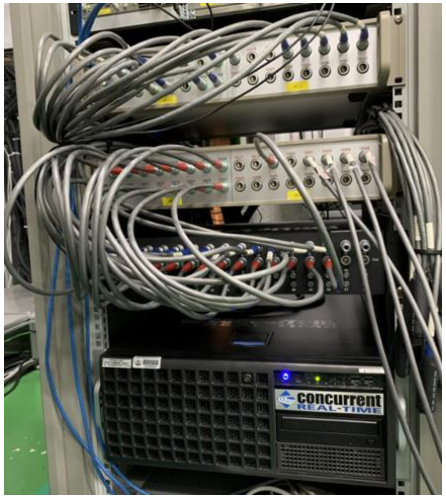
1. Disruption forecasting physics analysis expansion



2. Implementation of real-time diagnostic capabilities

Next slides

3. Real-time implementation of DECAF analysis and sensor input
   - 10+ DECAF event specs now written for the PCS implementation, including r/t sensors (e.g. ECE)

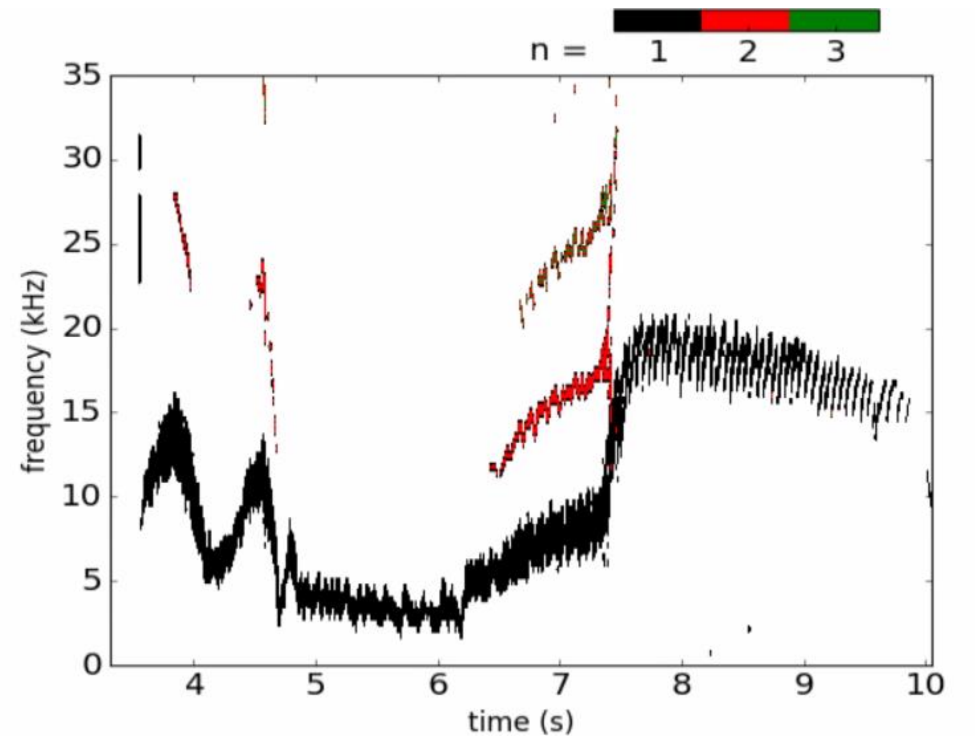


4. Real-time control leveraging real-time DECAF analysis and sensors
   - Initial specification for model-based control in the PCS is written; interfaces to DECAF events being made

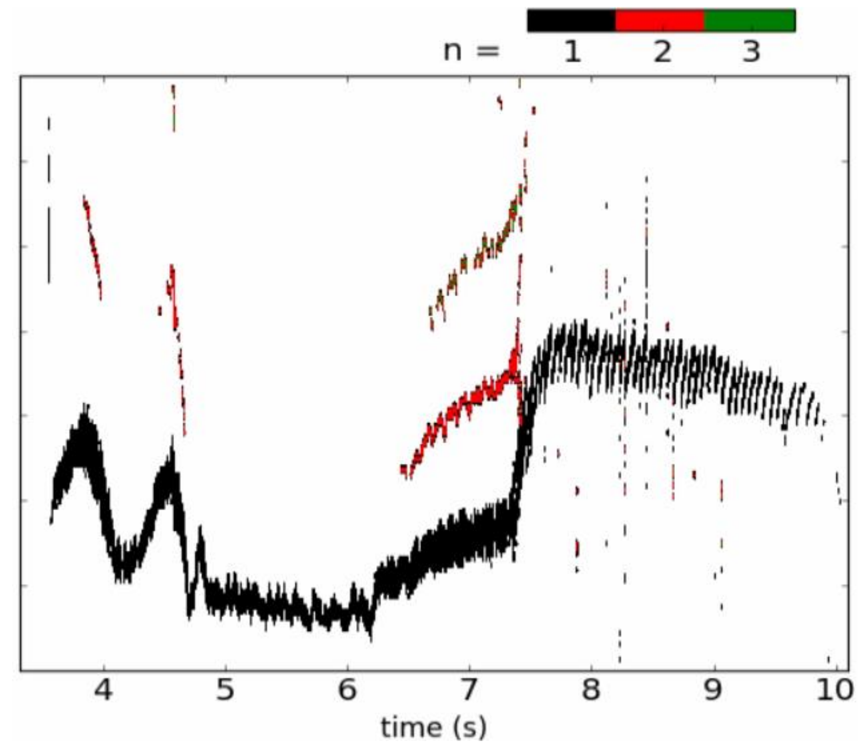
Analysis of KSTAR real-time MHD computer data compared to simulated FPGA* r/t analysis

DECAF analysis using various inputs

From simulated FPGA FFTs



From offline FFTs



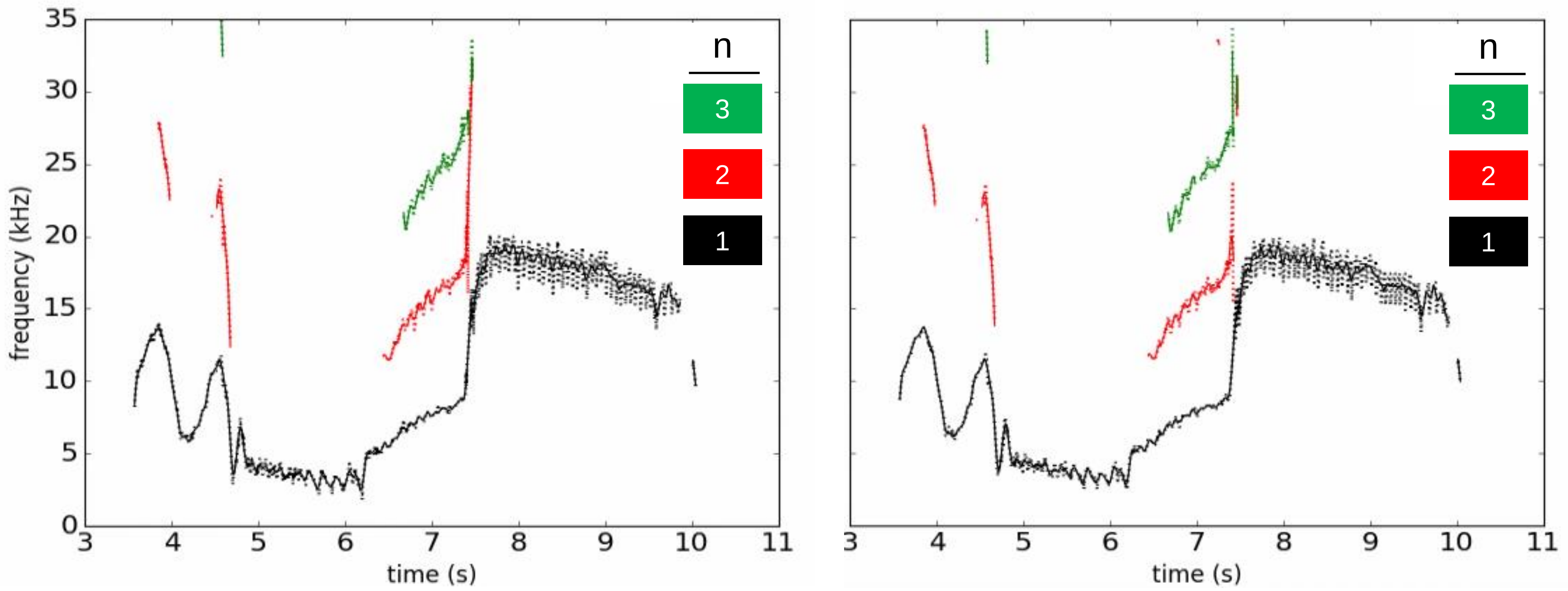
- Δt = 3.06 ms , Δf = 0.31 kHz

*FPGA: field-programmable gate array

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

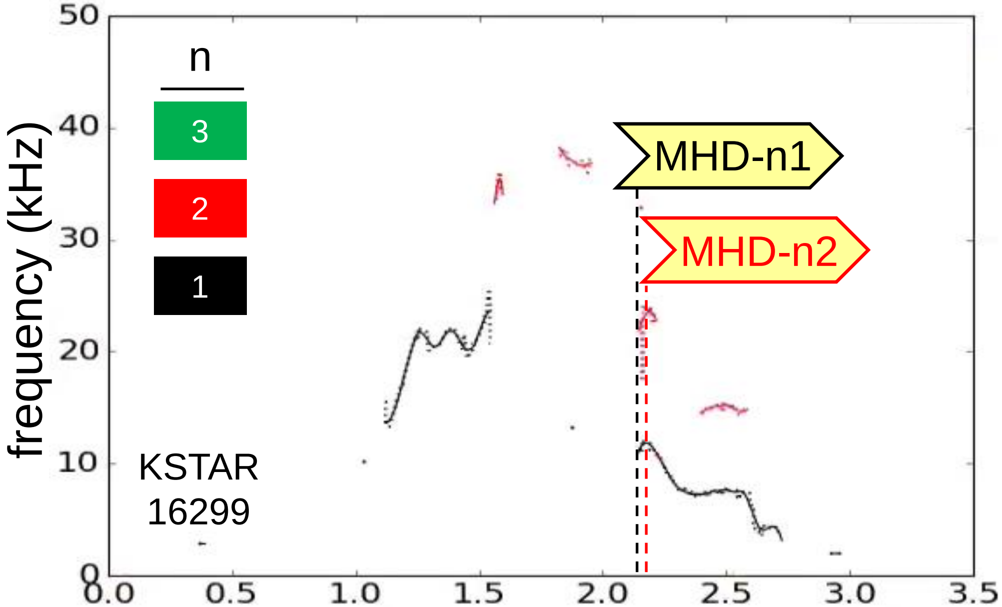
DECAF object decomposition

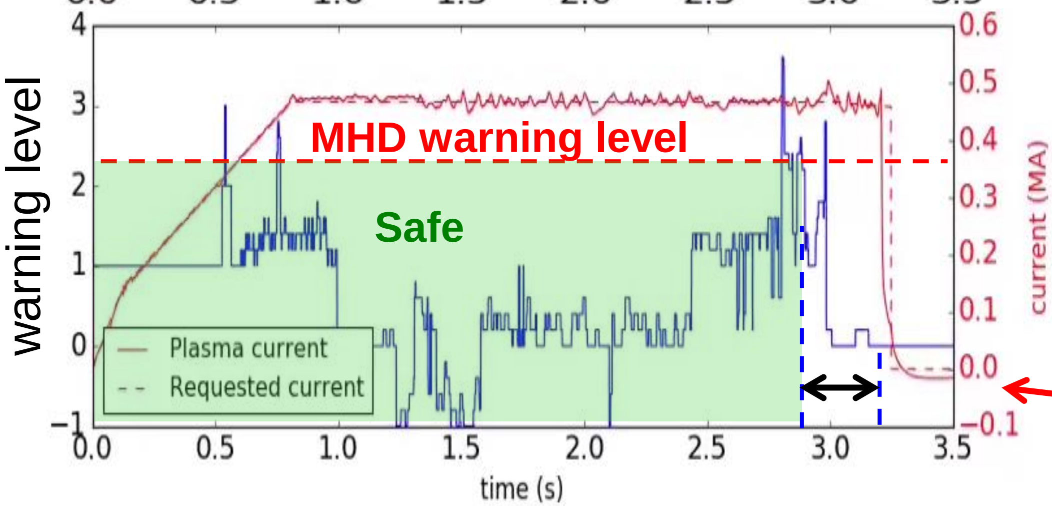
From simulated FPGA FFTs | From offline FFTs



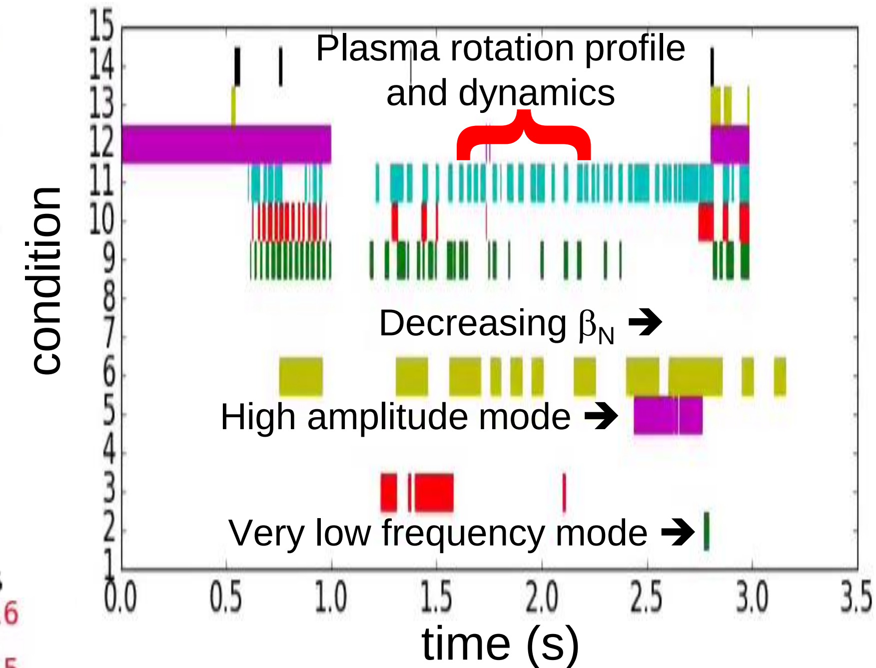
DECAF MHD events also produce early disruption warnings for KSTAR; aim to compute in real-time

DECAF automated MHD objects





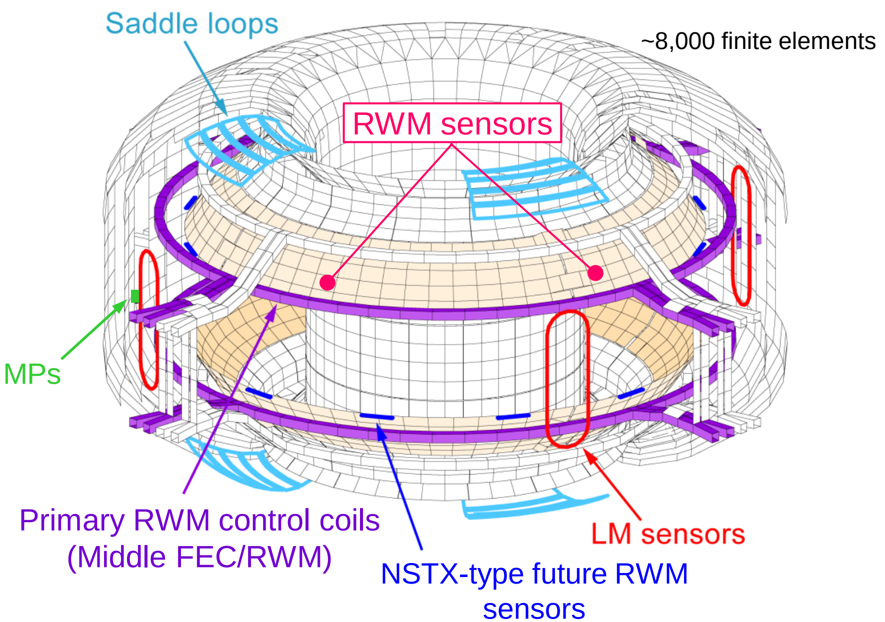
DECAF "heat map" (for MHD)



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

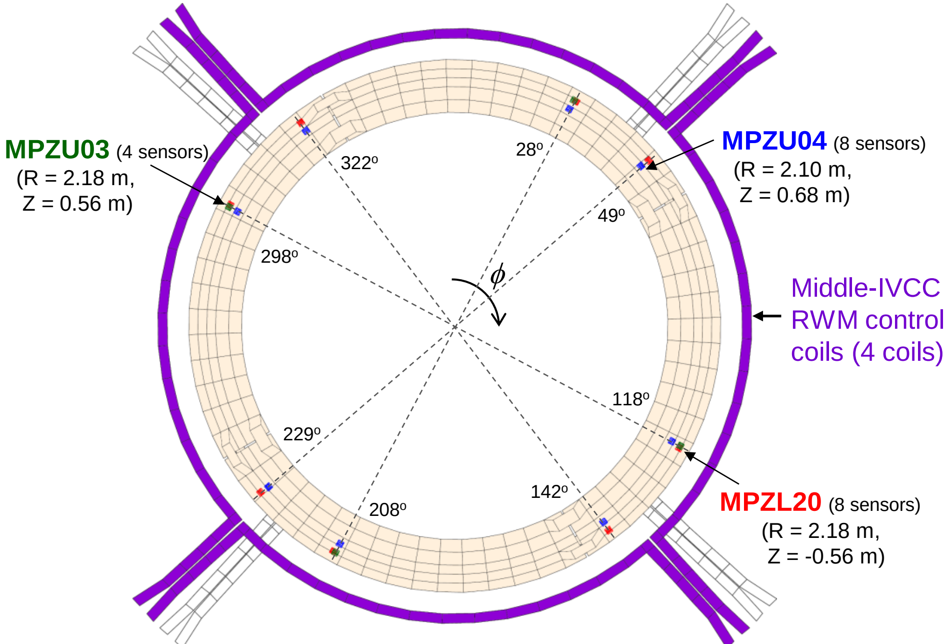
Active RWM control system components now fully installed in KSTAR PCS (CU group collaboration)

KSTAR RWM feedback model in VALEN-3D



Y.S. Park, *et al*., Phys. Plasmas **21** (2014) 012513

RWM feedback sensors on passive plates

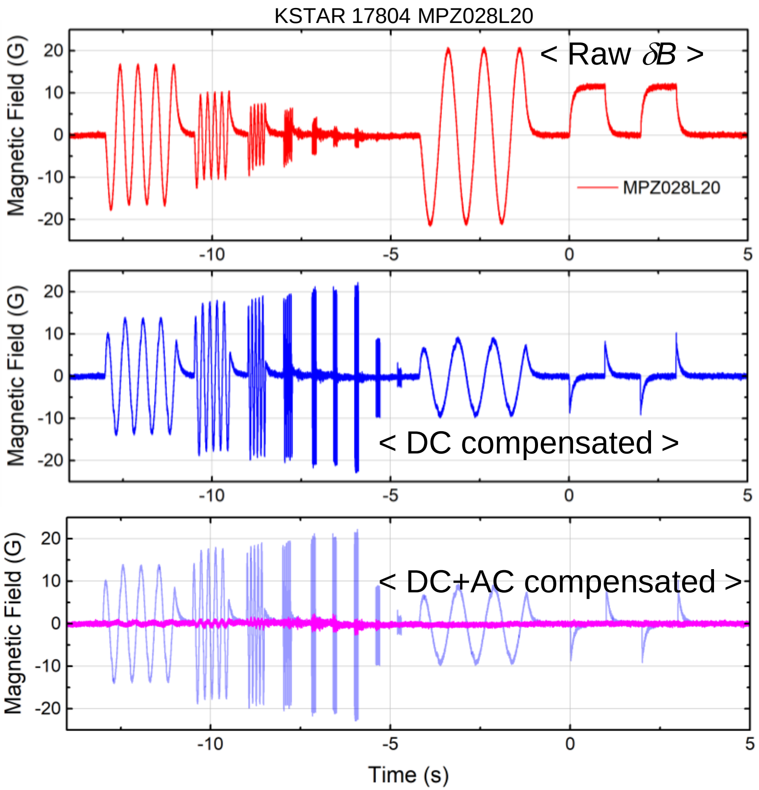


<lower passive plate - top view>

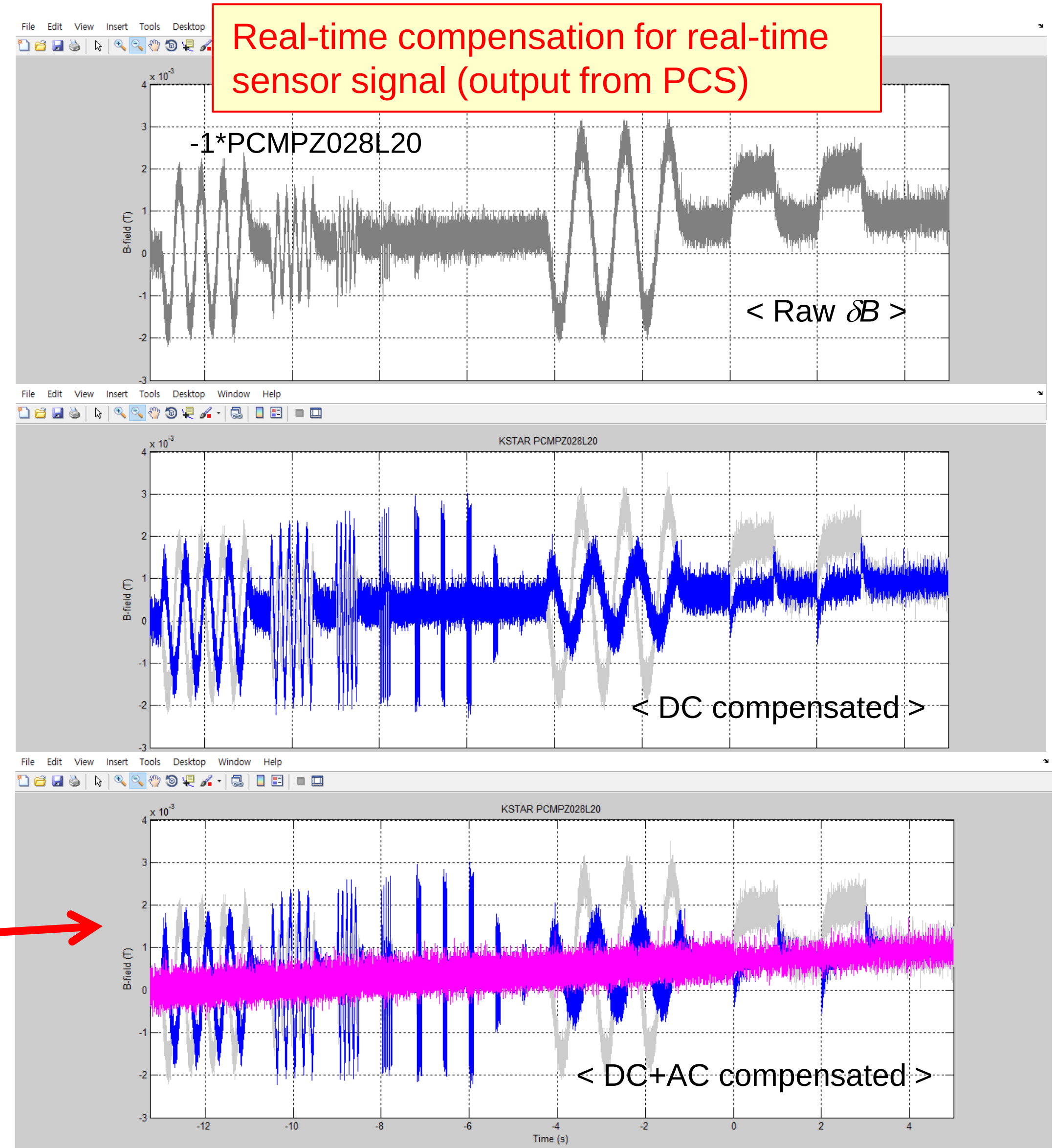
- For plasma operation at $\beta_N > \beta_N^{no\text{-}wall}$, RWM control system is prepared in KSTAR
  - The middle in-vessel control coils (IVCCs) minimizes the inductive shielding by the copper passive stabilizing plates during RWM feedback
  - Three sets of RWM B_p sensors with max. 8 toroidal locations (Upper – MPZU03 & MPZU04, and Lower – MPZL20) have been installed on the inner surface of the passive plates ⇒ total 20 independent B_p measurements for RWM identification (f_{sample} = 20 kHz)

Real-time DC and AC compensation of RWM feedback sensor signals now installed and tested in the KSTAR PCS

Off-line compensation for off-line sensor signal

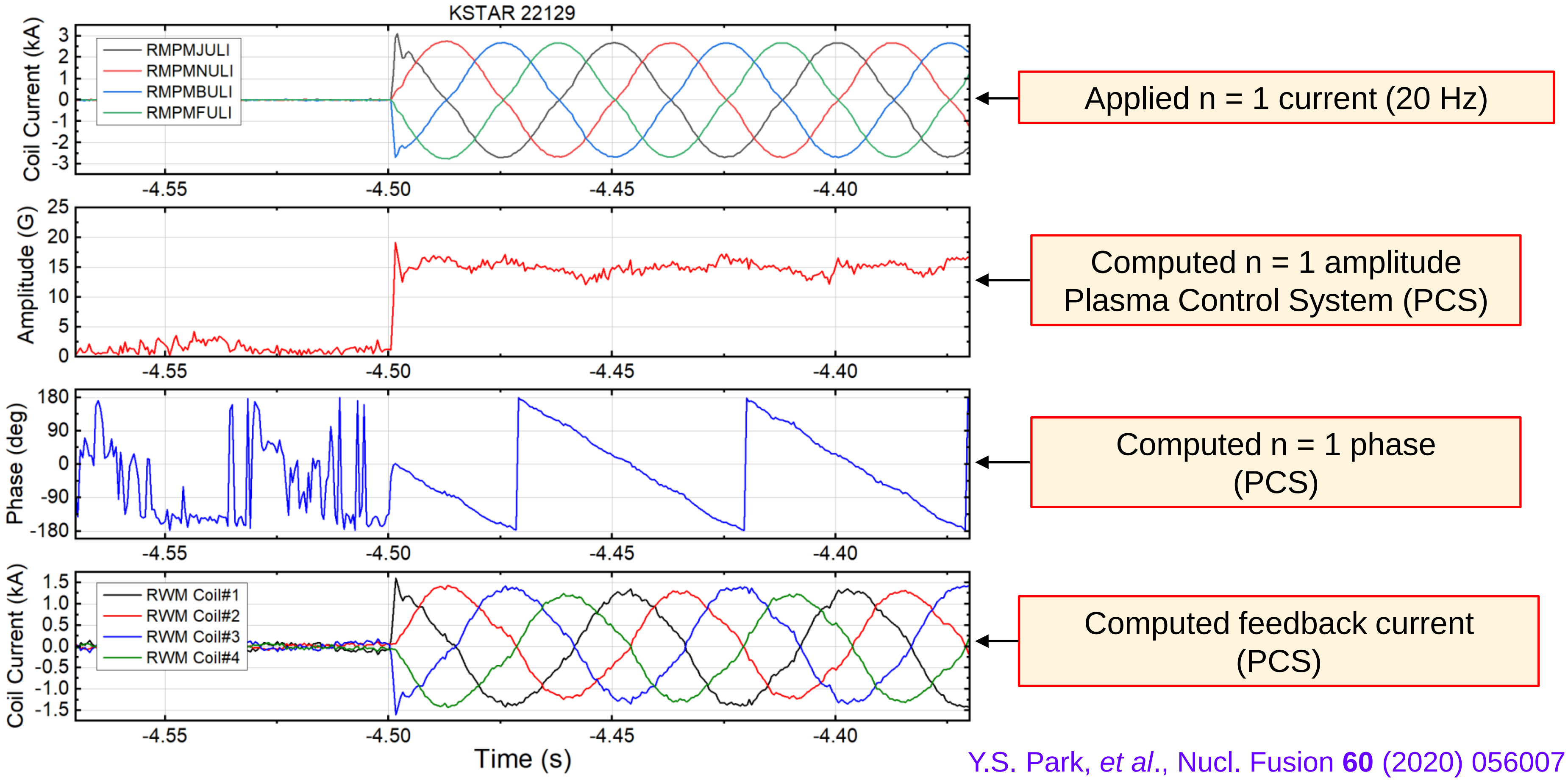


Real-time compensation for real-time sensor signal (output from PCS)



- Real-time signal shows DC and DC expected compensation
- Signal drift over long timescales
  - Working with KSTAR magnetics diagnosticians to reduce drift

Developed RWM control algorithm with fully compensated sensor signals was first validated in late 2019 KSTAR operation; recent 2020 XPs



Y.S. Park, *et al*., Nucl. Fusion **60** (2020) 056007

- PCS algorithm reliably computes the n = 1 component of the toroidally rotating n = 1 applied fields, and feedback current to the RWM coils
- Sep.29th, 2020 experiment: RWM active control system used in plasma

DECAF disruption prediction and avoidance research expanding to r/t implementation (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
  - Present performance on large (10^4) databases: 91.2% w/ only 5 Events
  - Full multi-machine databases used (full databases needed!)
  - Physics analysis, experiments run to understand, create, validate models

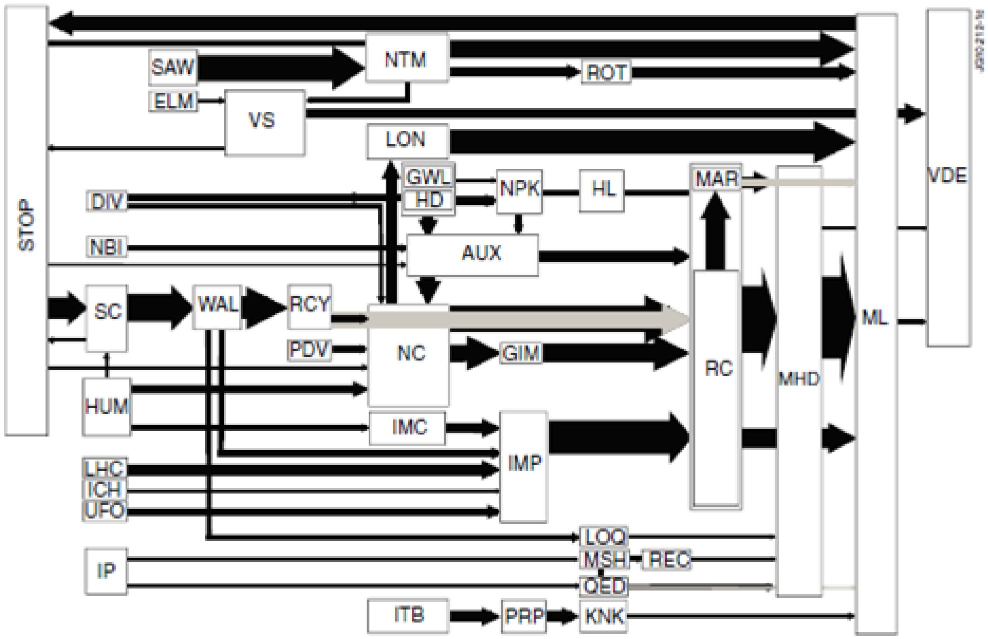
- DECAF producing early warning disruption forecasts
  - On transport timescales: ➔ guide disruption avoidance by profile control
  - Continue / expand disruption forecasting performance analysis (➔ ITER)

- Expansion to real-time implementation (KSTAR)
  - Real-time acquisition of magnetics (MHD), V_ϕ, T_e, δT_e, B pitch angle, δB
  - Implementing DECAF disruption forecasting models in real-time

We are hiring post-doctoral researchers! ➔ Email: sabbagh@pppl.gov

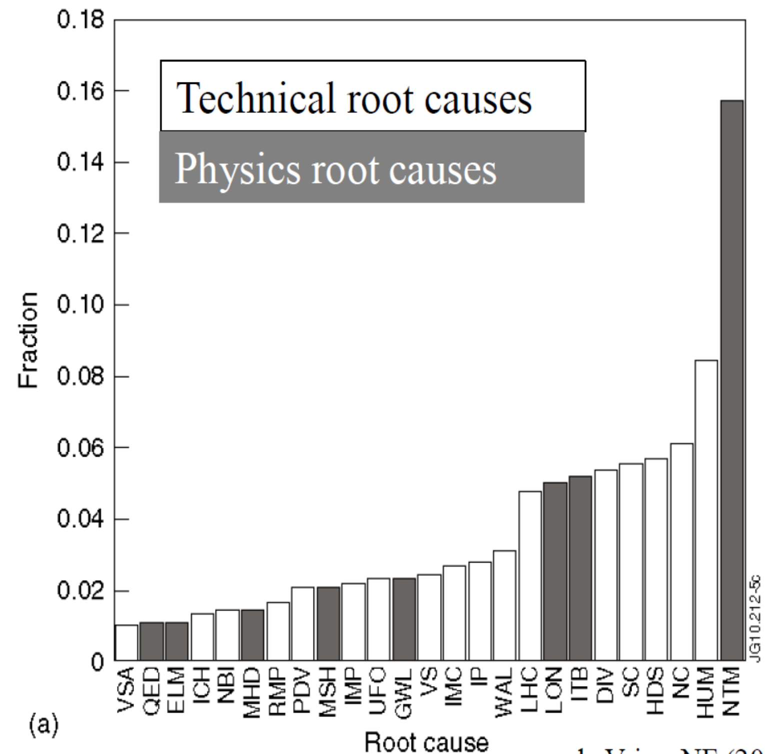
DECAF follows disruption event framework (de Vries) to provide understanding of disruption chains ➔ automates it

JET disruption event chains



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

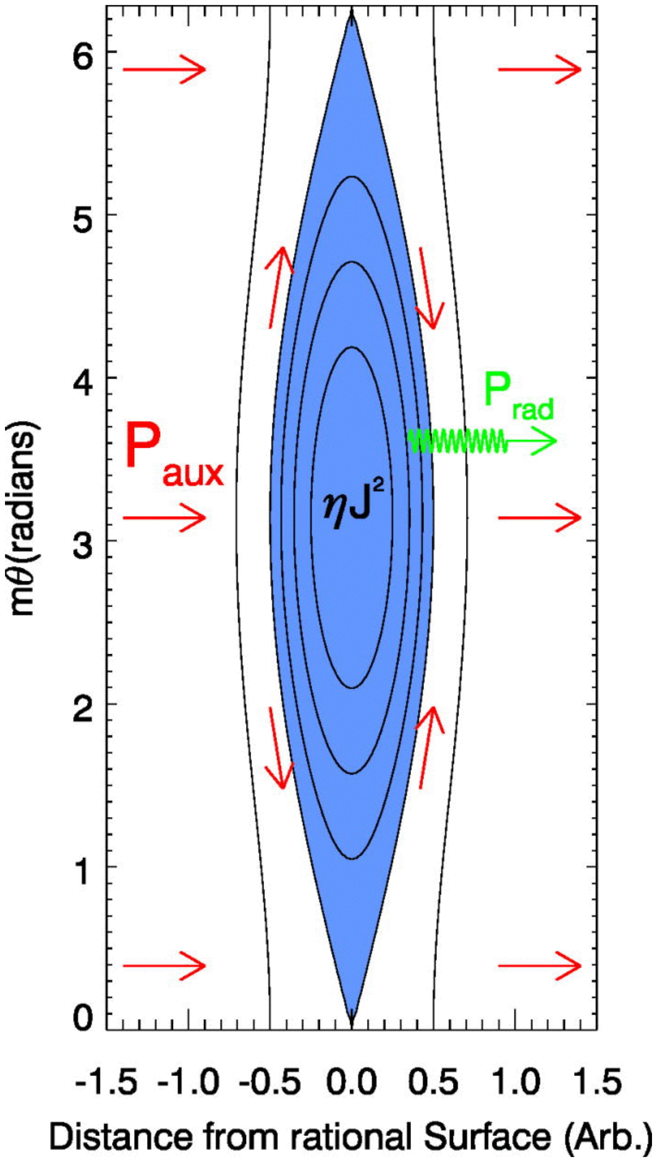
Related disruption event statistics



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

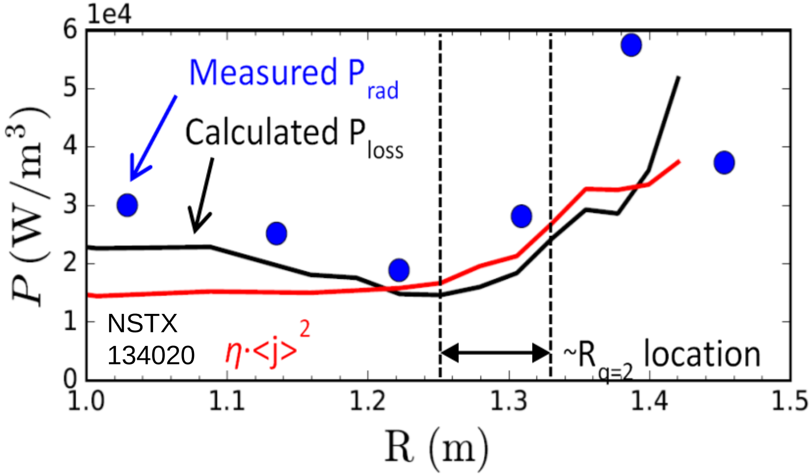
A density limit model has been examined in DECAF based on power balance in an island



- 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

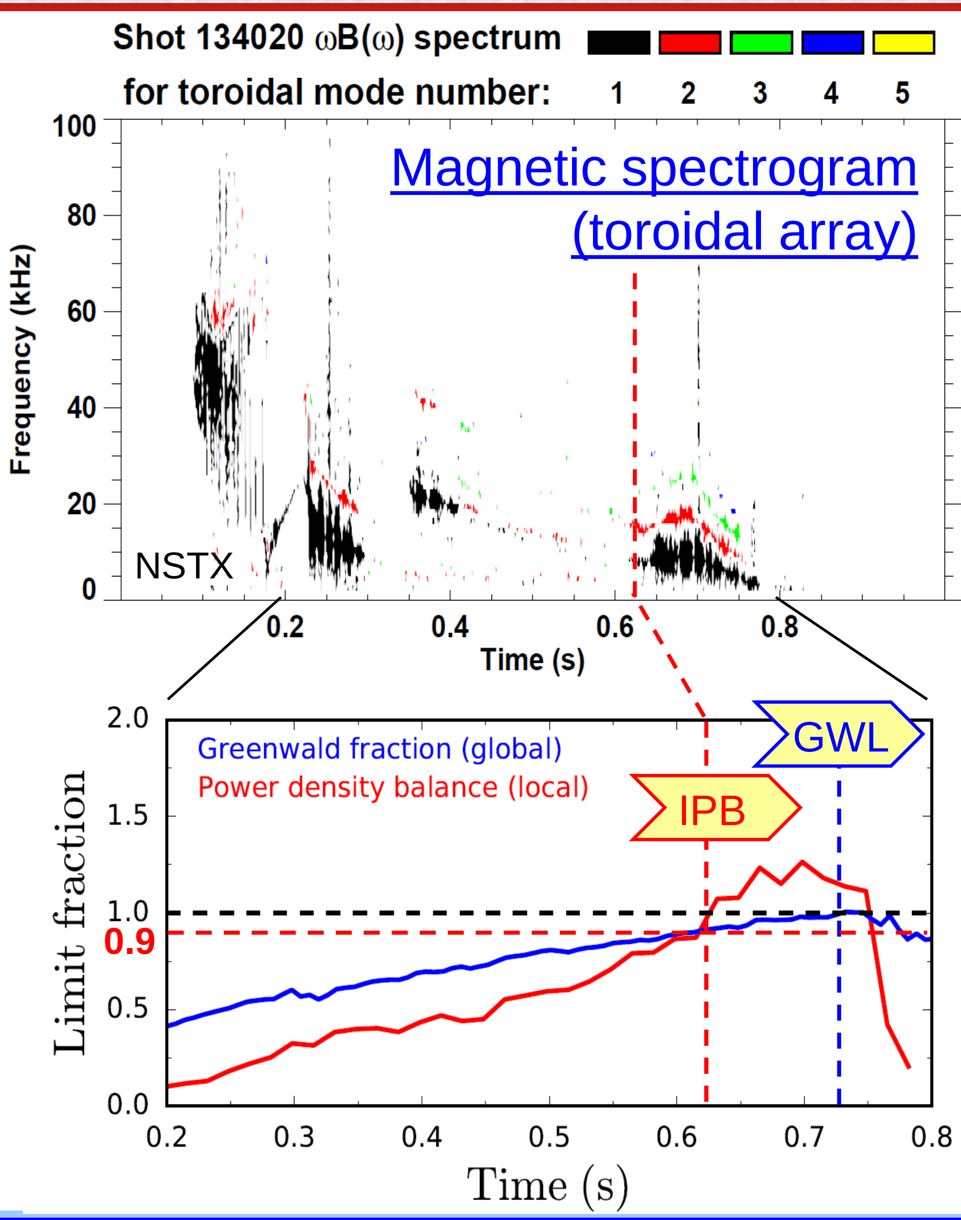
Power density balance: $P_{loss} < P_{input}$

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

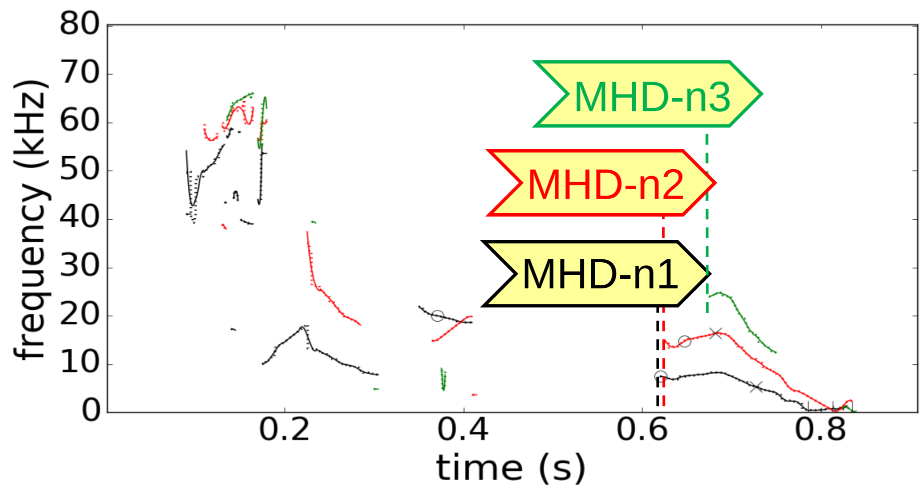


D. Gates et al., Phys. Rev. Lett. **108** 165004 (2012)

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

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

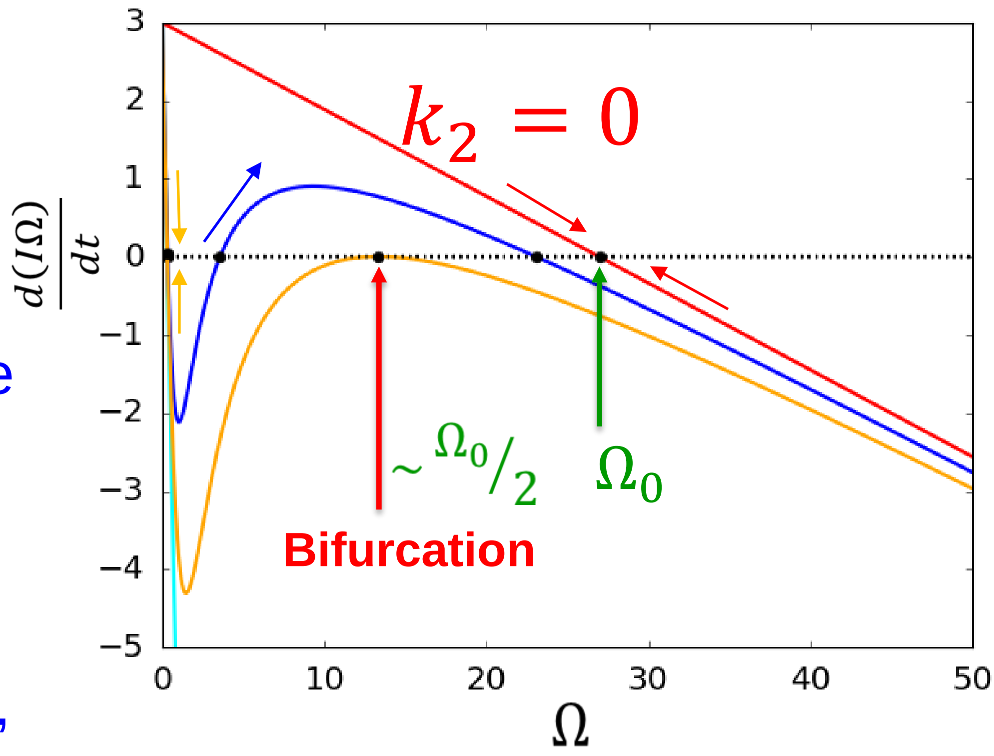
- Start with cylindrical, rigid body model
- Possible model of drag for both a "slip" and a "no slip" condition:

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

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

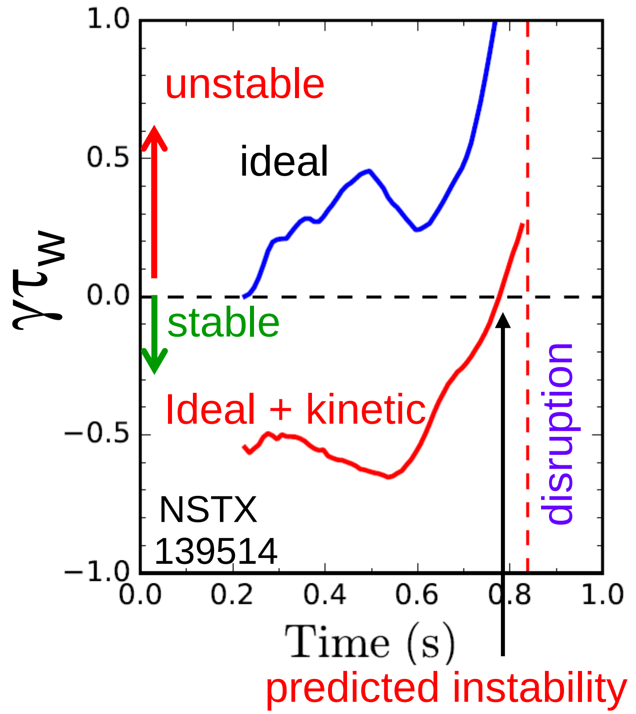
- At very low angular speed mode reaches a stable steady state, ➔ investigating this in KSTAR
- Collaborating with UW Madison theoreticians to add explicit effect of island size on viscosity, toroidal effects, etc.

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

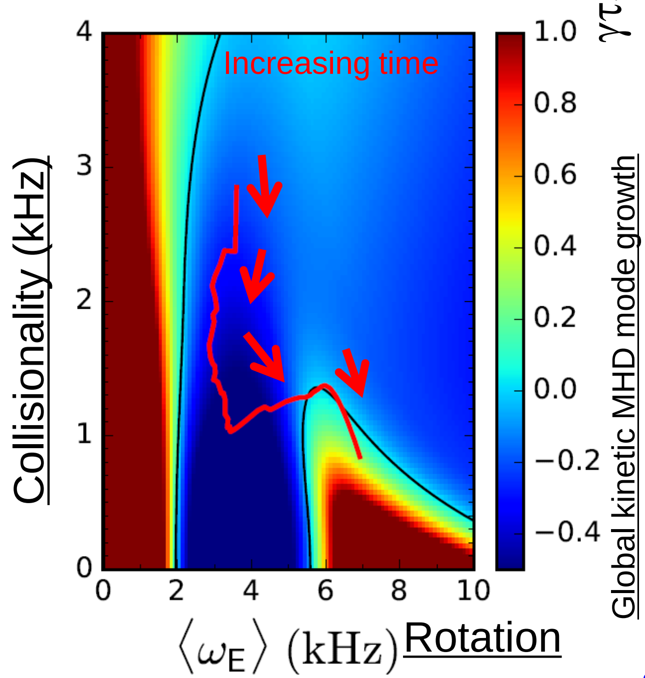


DECAF reduced kinetic MHD model provides early forecast of instability boundary to global MHD modes

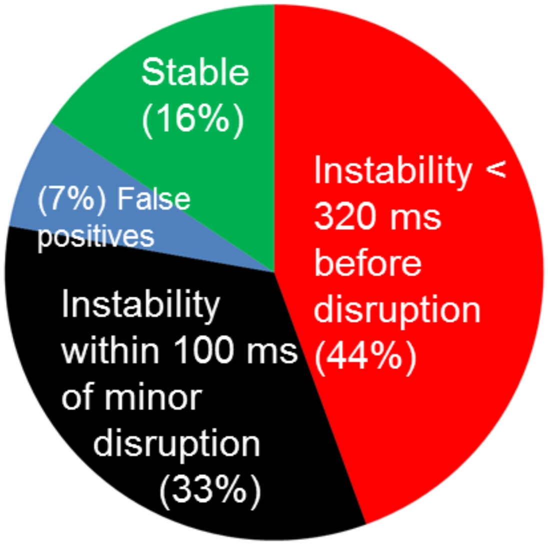
Norm. growth rate vs. time



Disruption forecasting



Predicted instability statistics

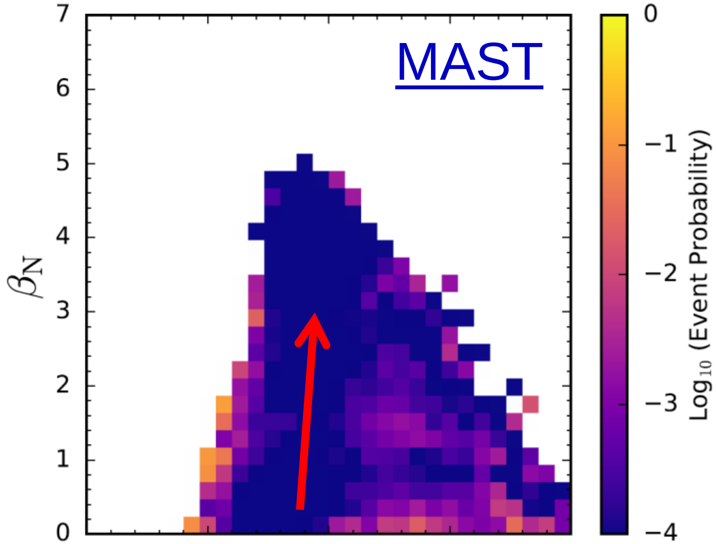


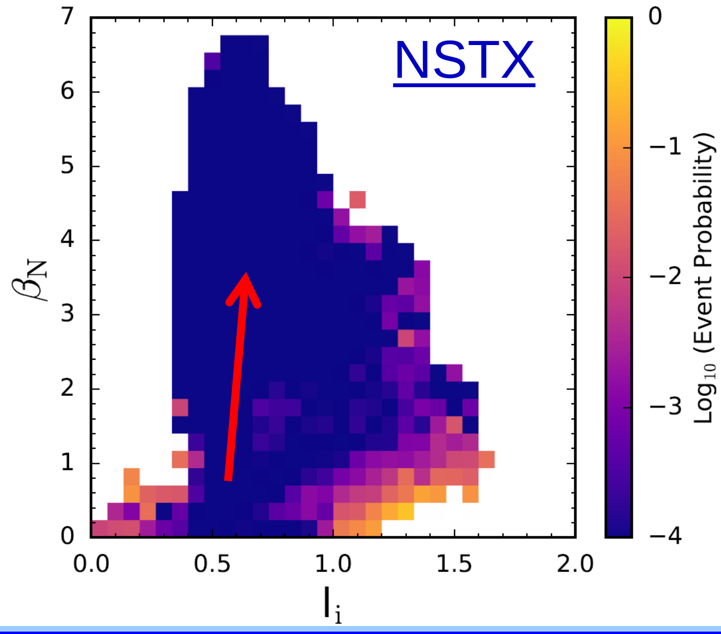
- Favorable characteristics
  - Stability contours CHANGE for each time point
  - Model allows real-time stability and mode growth rate prediction

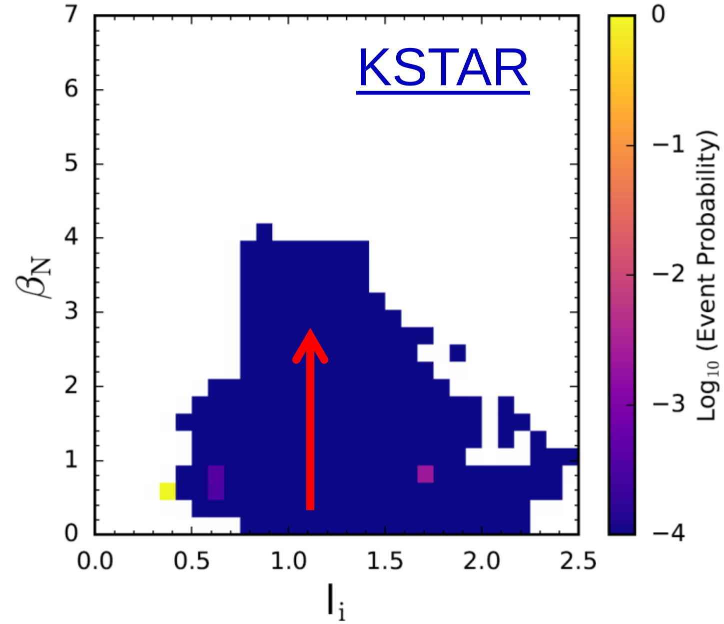
- 84% of shots are predicted unstable (stringent evaluation)
- 44% predicted unstable < 320 ms (approx. $60\tau_w$) before current quench
- 33% predicted unstable within 100ms of a minor disruption

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

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

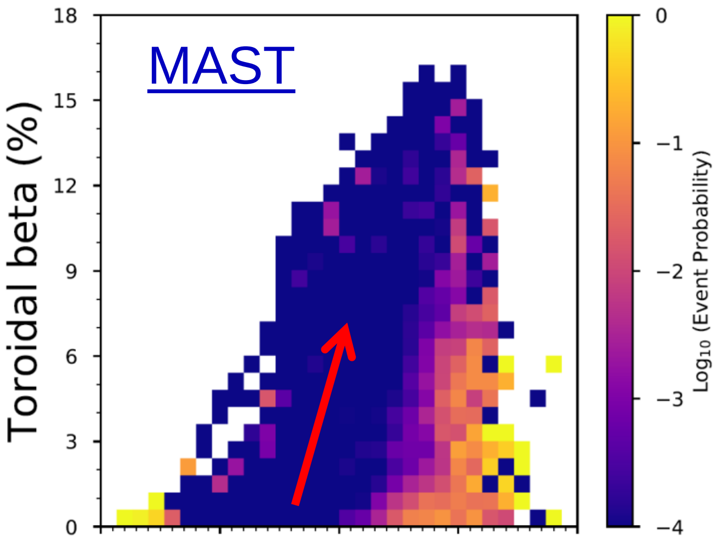


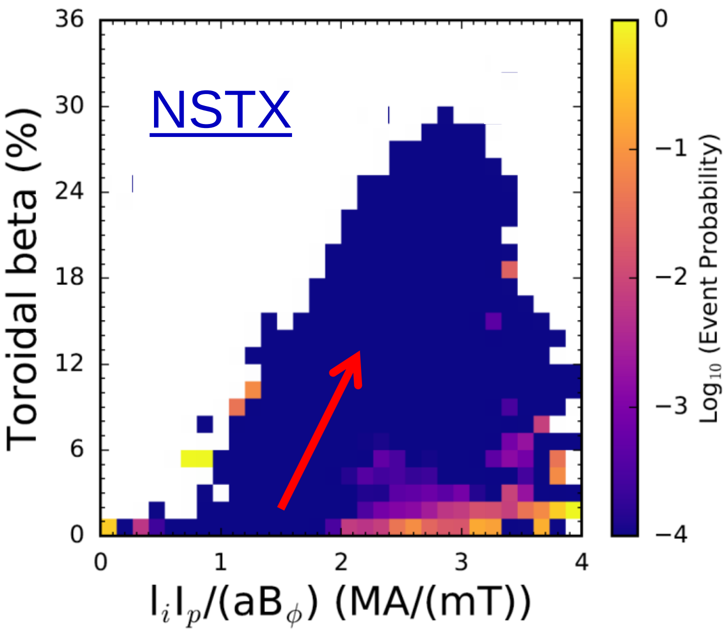


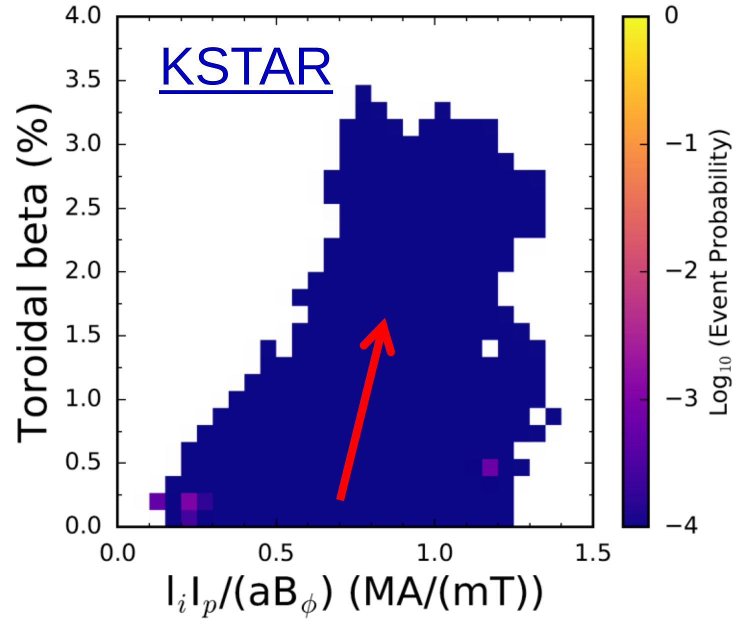


- DECAF analysis of DIS event
  - Shots analyzed at 10 ms intervals
- Analysis during I_p flat-top
  - MAST: 8,902 plasmas analyzed
  - NSTX: 10,432 plasmas analyzed
  - KSTAR: 1,309 plasmas analyzed

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

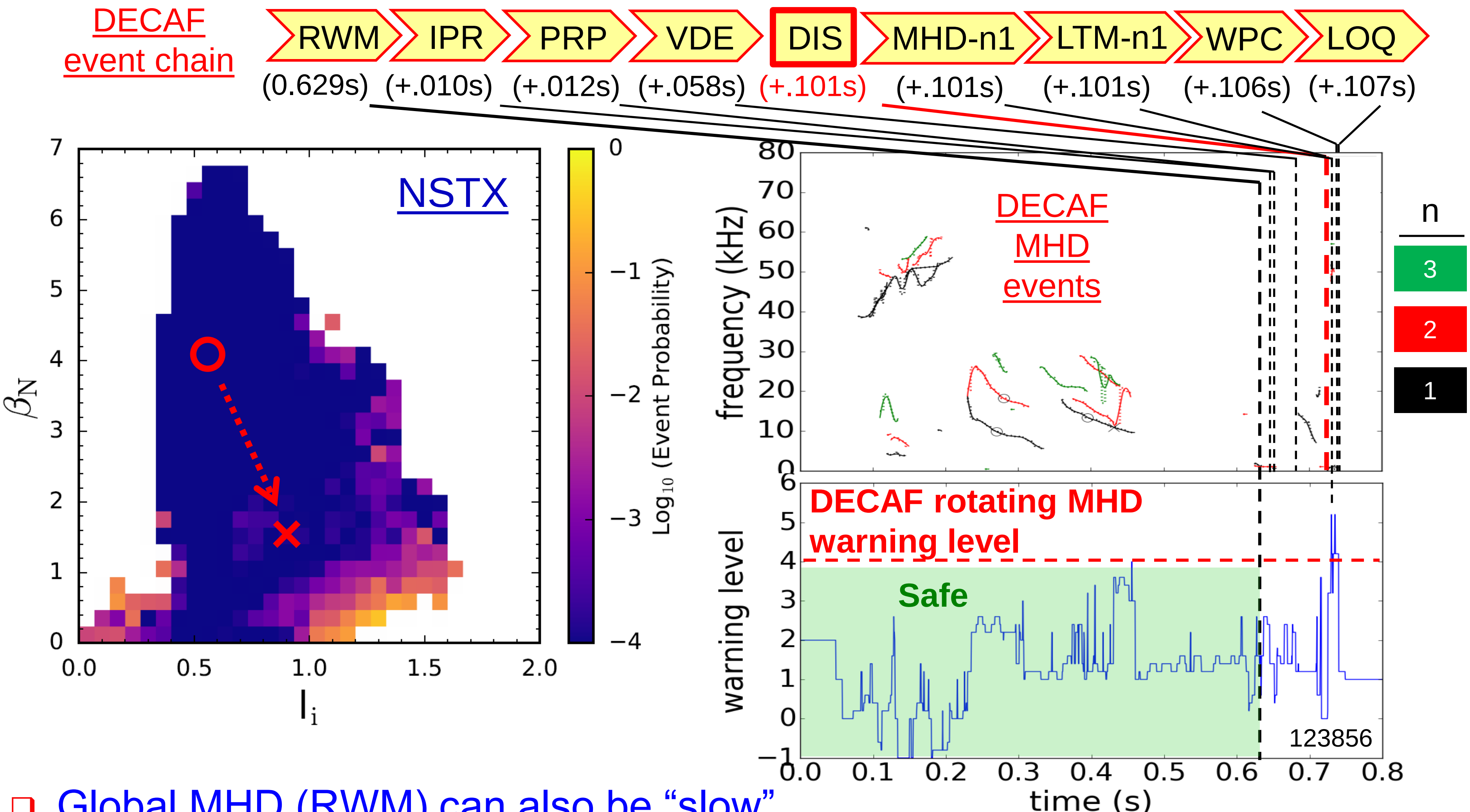






- DECAF analysis of DIS event
  - Similar to a "standard" disruptivity analysis
  - Shots analyzed at 10 ms intervals
- Analysis during I_p flat-top
  - MAST: 8,902 plasmas analyzed
  - NSTX: 10,432 plasmas analyzed
  - KSTAR: 1,309 plasmas analyzed

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



- 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)

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)

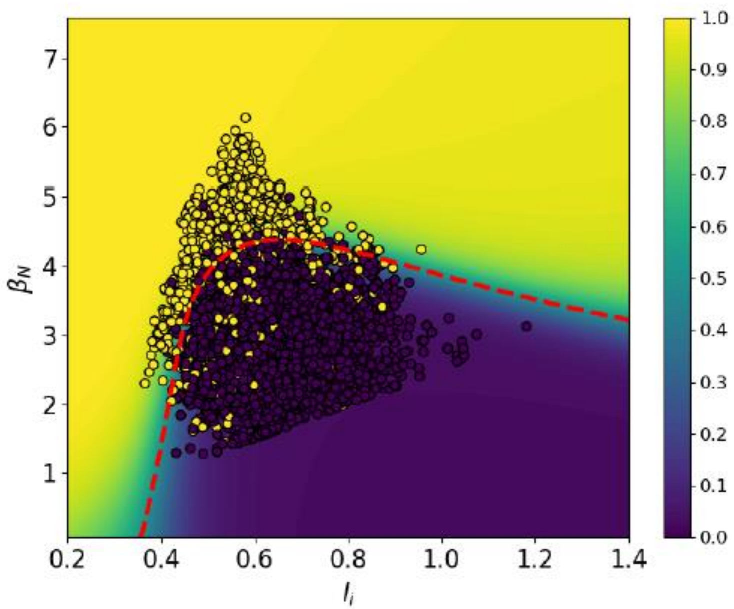


Figure 1: β_n vs l_i decision boundary. The contour plot shows the probability distribution predicted by the neural network.

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

(2019 IAEA ML conference)

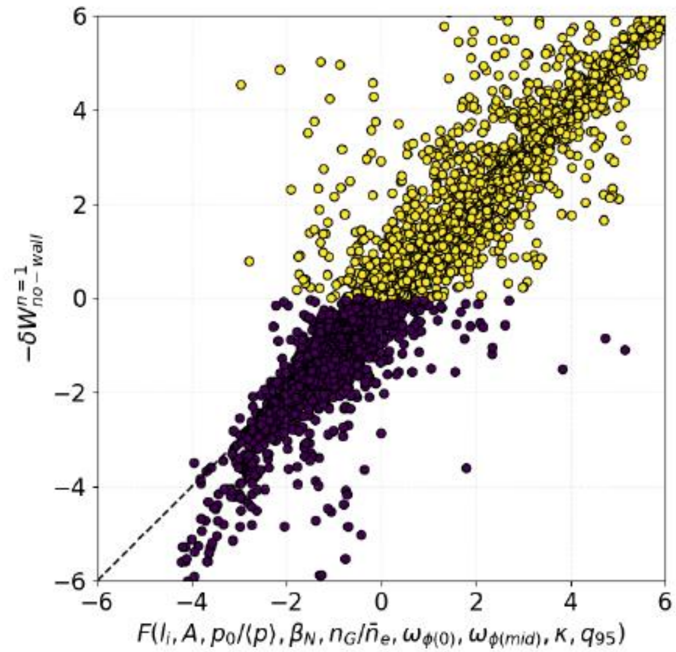
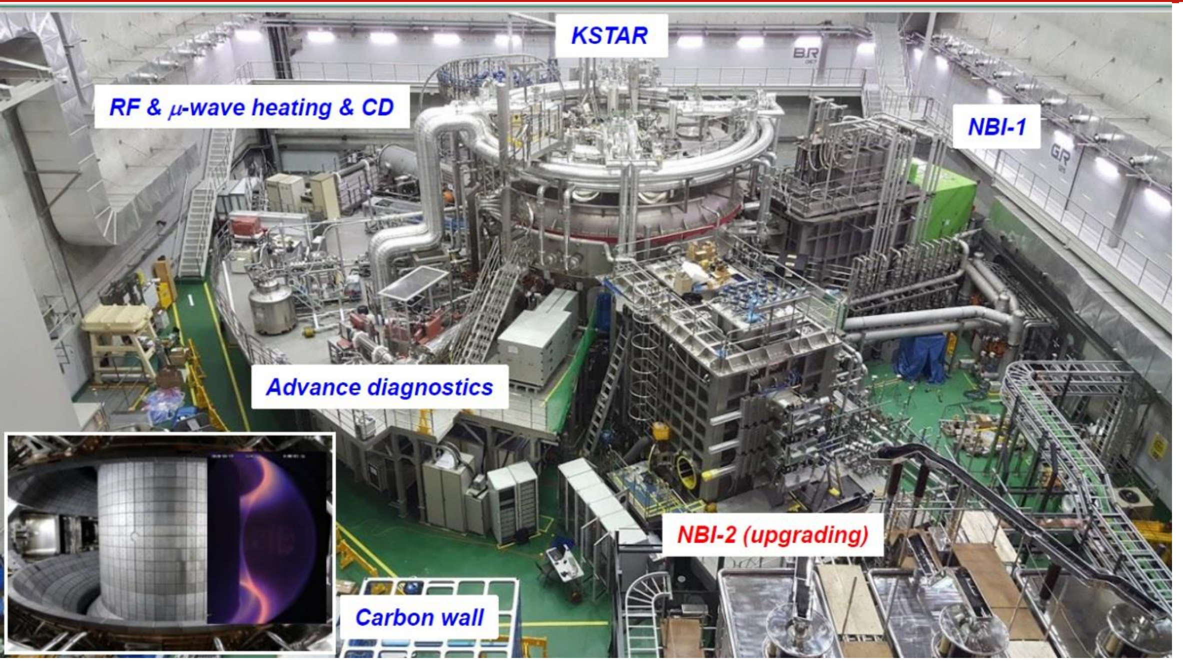


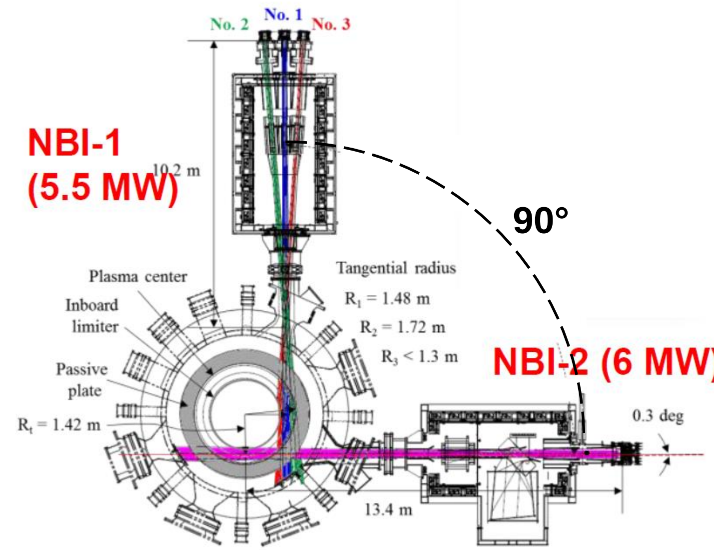
Figure 1: -δW vs F for the NSTX database, showing linear correspondence with some spread ($R^2 = 0.878$).

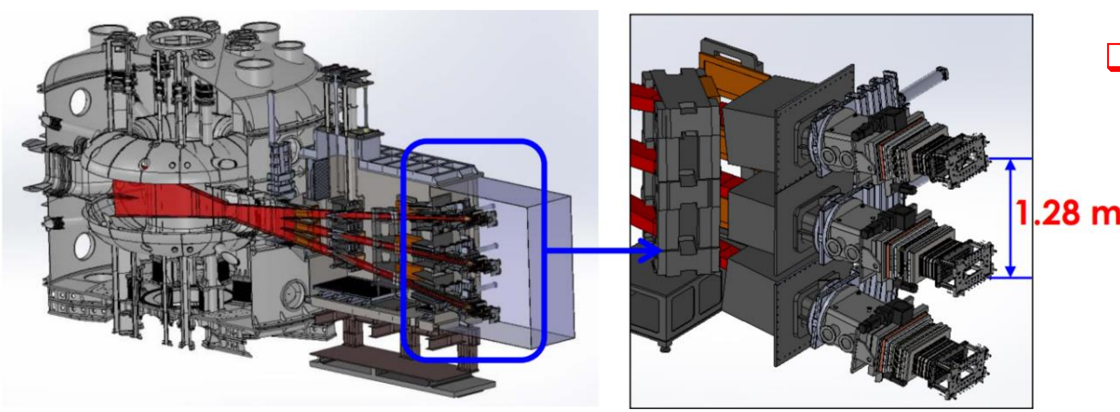
Collaboration with CCFE / UCL (A. Piccone (UCL)); ➔ A. Piccone, et al, Nucl. Fusion **60** (2020) 046033

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

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



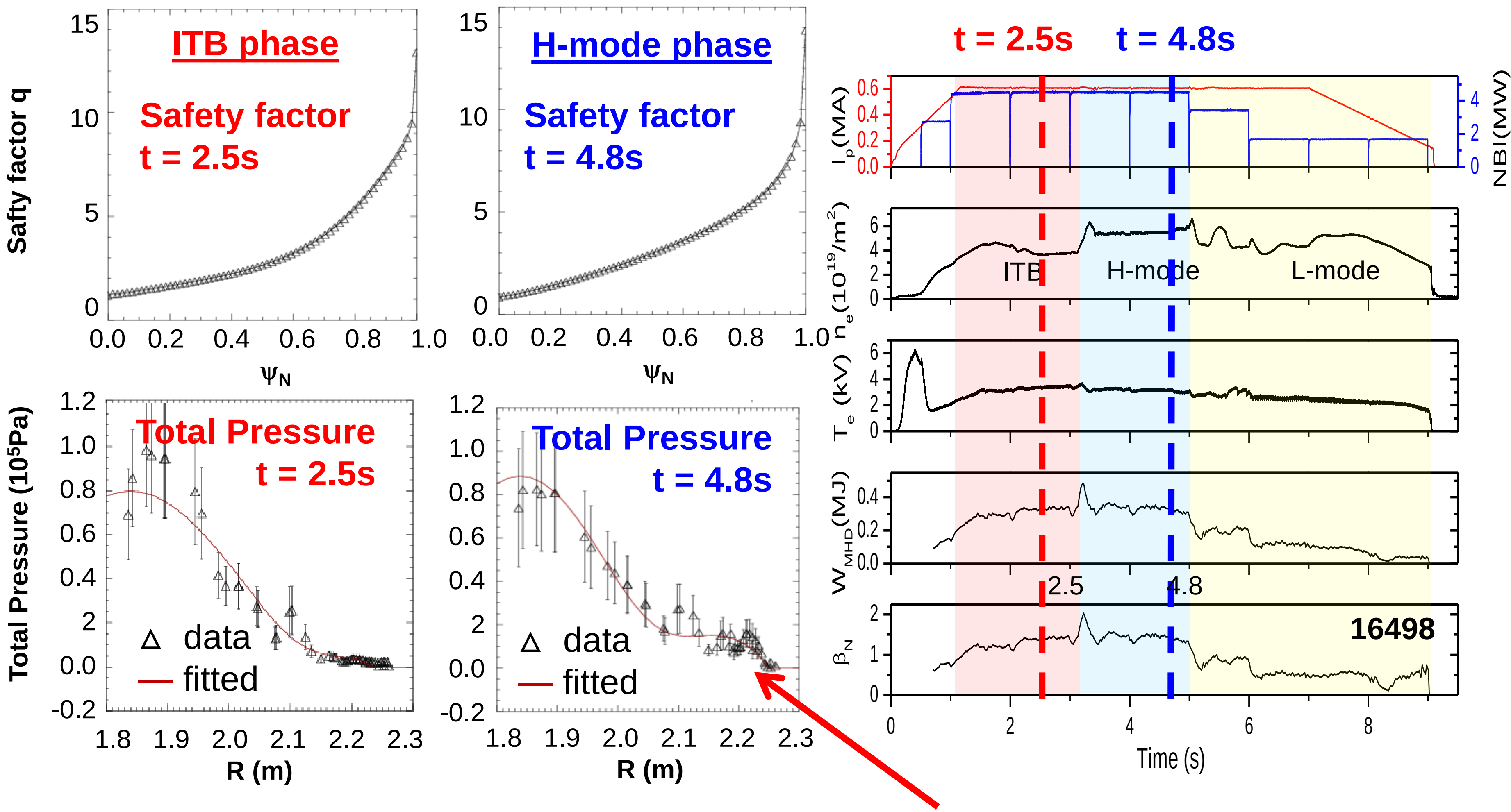




- Geometry of 2nd NBI system is included in TRANSP model
  - Available power

    → $P_{NBI} \simeq 1.5$MW/source (conservative)

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

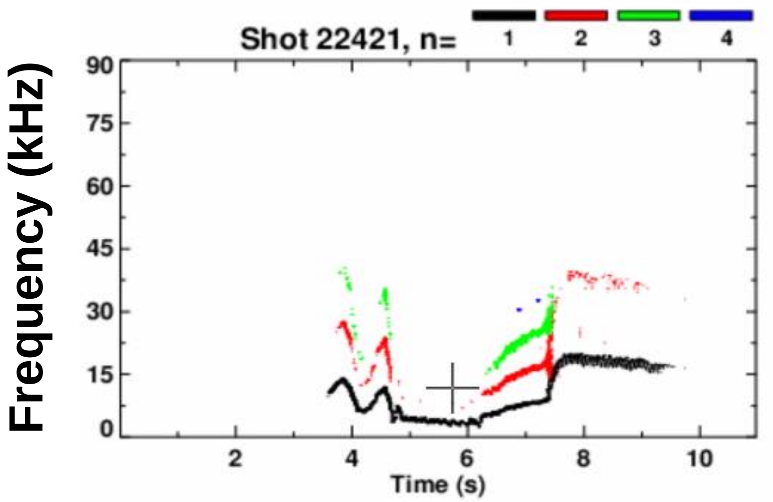


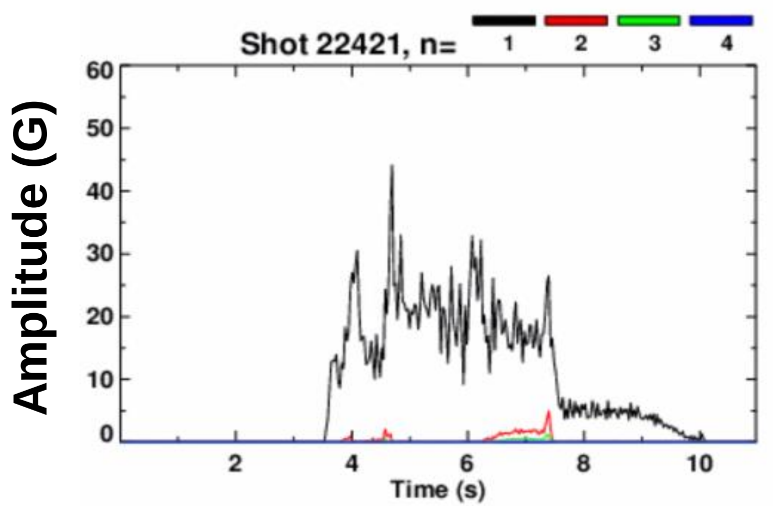
- Broad pedestal pressure reconstructed in H-mode is not observed in earlier ITB phase

Xp by Jinil Chung

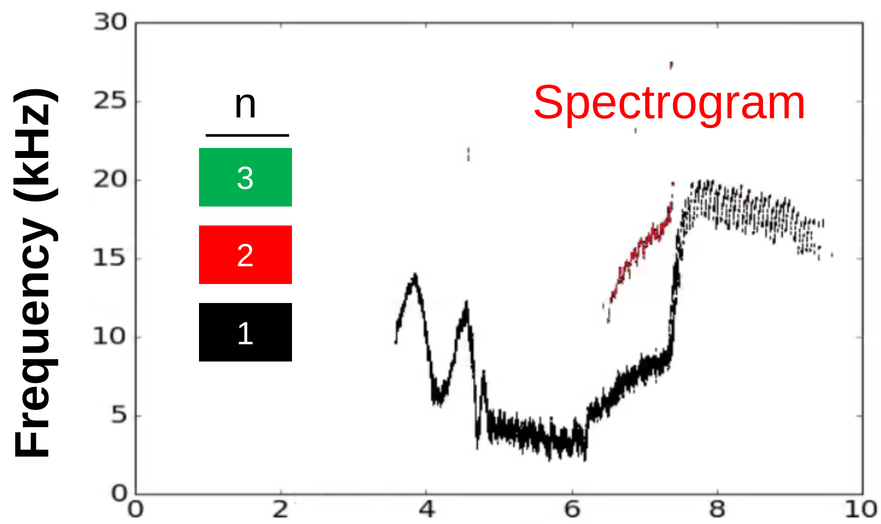
KSTAR real-time MHD computer acquired data for 2019 campaign – data quality as good as offline

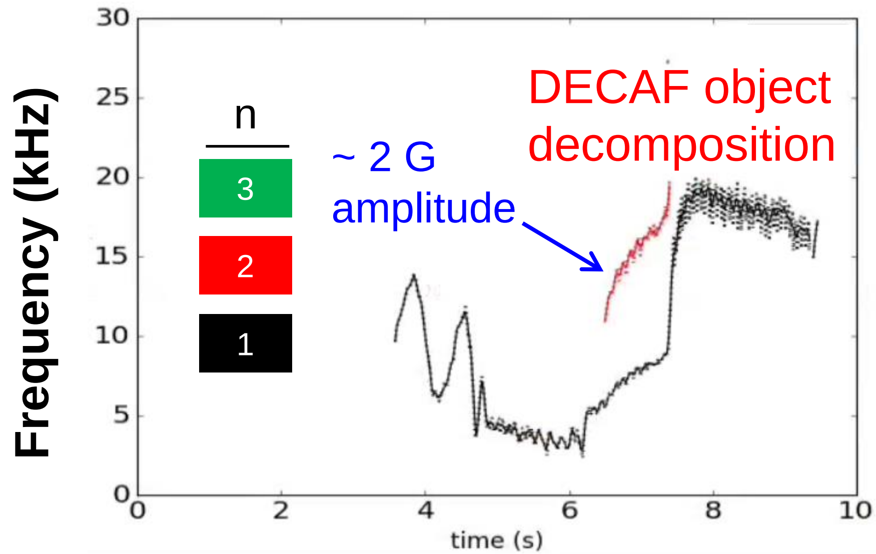
Offline data, native code analysis



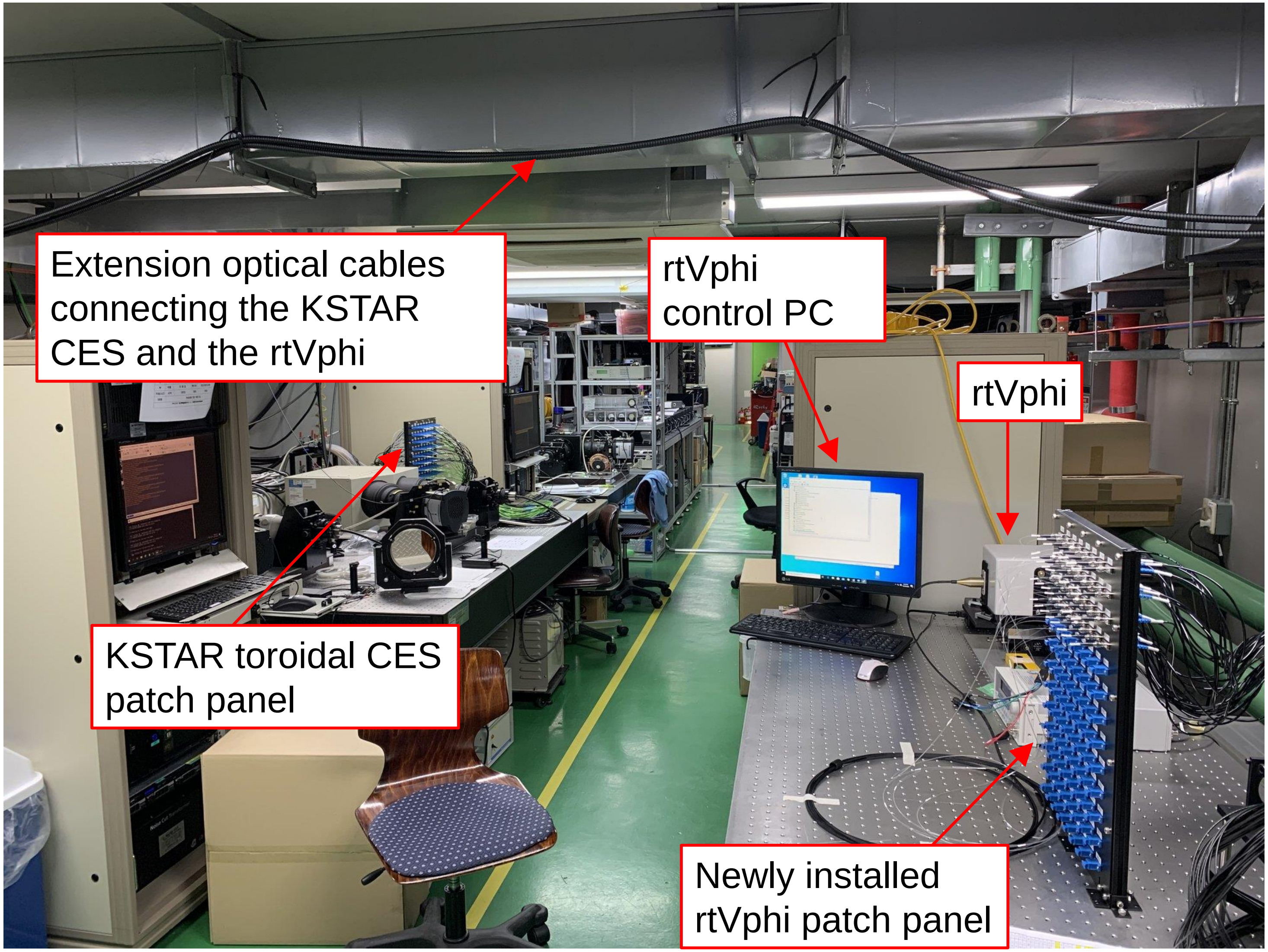


Real-time data, DECAF analysis (offline)

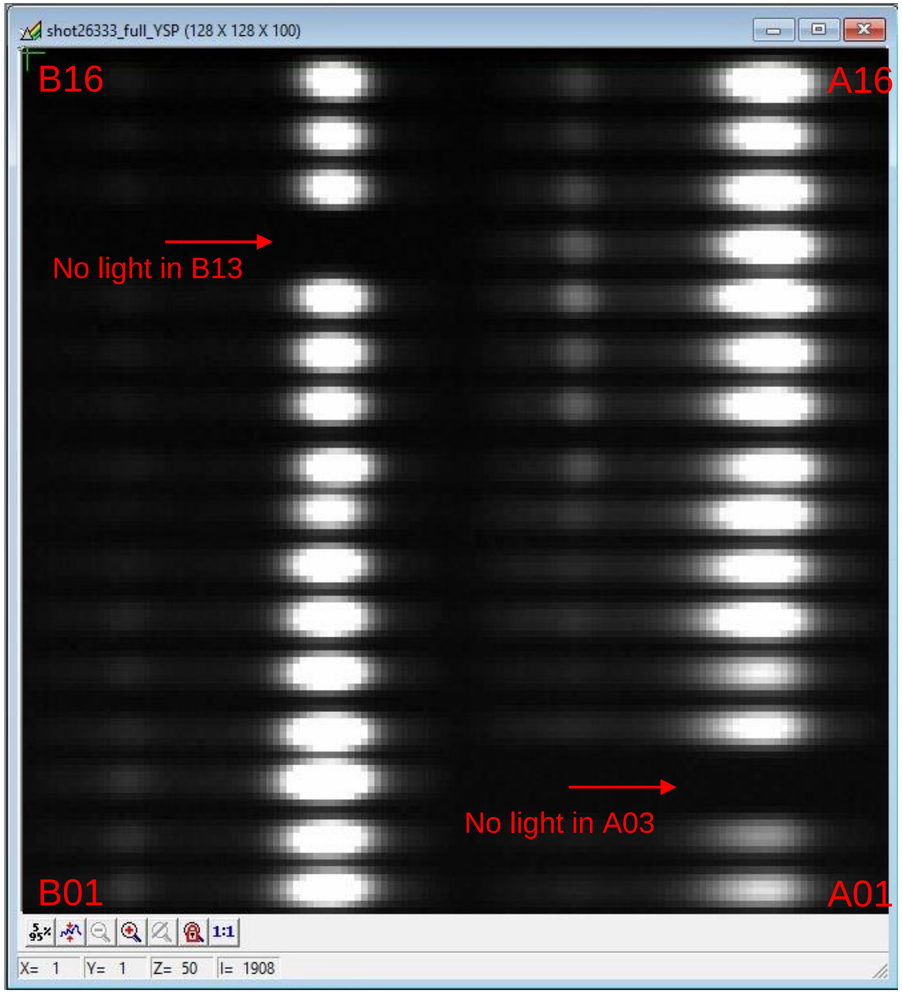


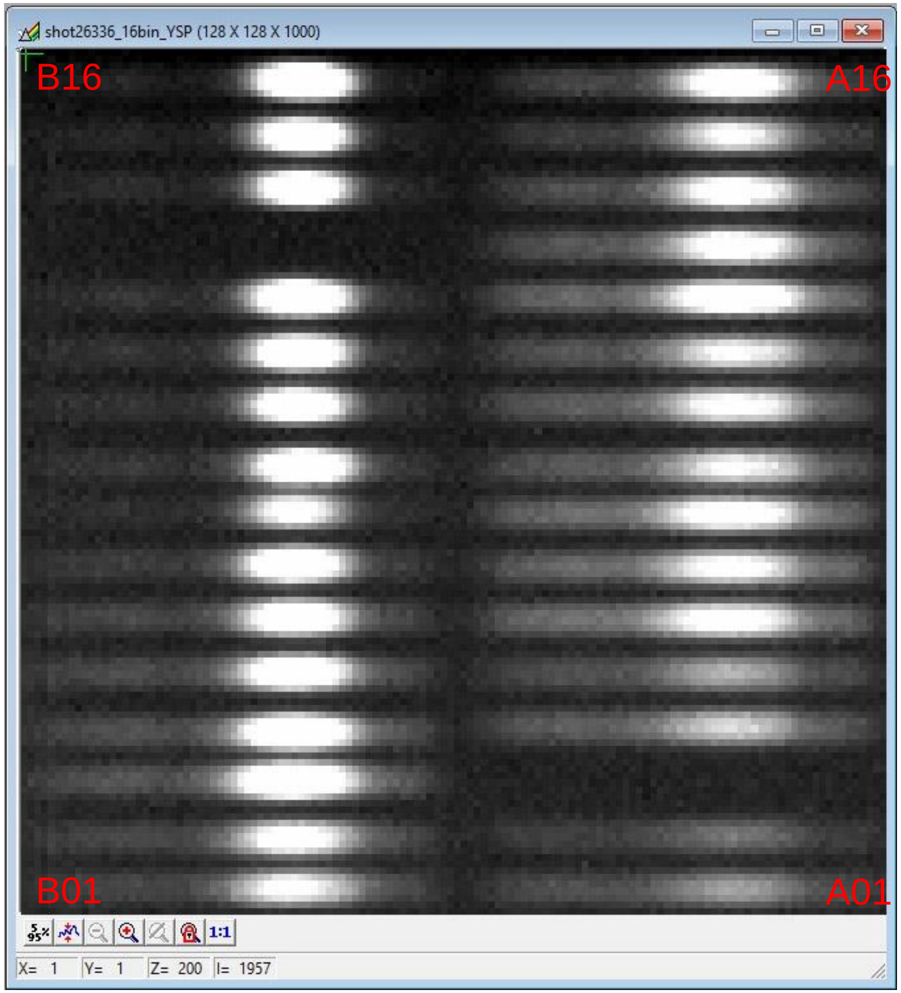


Real-time toroidal velocity diagnostic (rtVphi) in KSTAR (Oct. 29th)



First measurements from rtVphi for shot 26333, 26336 on Oct. 30th 2020





Shot 26333 (w/ NBI-1A/B):
Used the *full frame* setup by M. Podesta
Result saved as file *shot26333_full_YSP.spe*

Shot 26336 (w/ NBI-1A/B):
Used the *16 binning* setup
Result save as file *shot26336_16bin_YSP.spe*