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Disruption Event Characterization and Forecasting (DECAF) in Tokamaks

S.A. Sabbagh[1], J.W. Berkery[1], Y.S. Park[1], J.H. Ahn[1], Y. Jiang[1], J.D. Riquezes[1], R.E. Bell[2], M.D. Boyer[2], A.H. Glasser[3], J. Hollocombe[4], J. Kim[5], A. Kirk[4], J. Ko[5], W. Ko[5], L. Kogan[4], B. LeBlanc[2], J.H. Lee[5], Y.K. Oh[5], F. Poli[2], S.D. Scott[2], A. Thornton[4], L. Terzolo[5], S.W. Yoon[5], S.J. Wang[5], Z.R. Wang[2]

[1]Department of Applied Physics, Columbia University, New York, NY
[2]Princeton Plasma Physics Laboratory, Princeton, NJ
[3]Fusion Theory and Computation, Inc., Kingston, WA
[4]Culham Centre for Fusion Energy, UKAEA, Abingdon, UK
[5]National Fusion Research Institute, Daejeon, Republic of Korea

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Portland, OR

MAST-U

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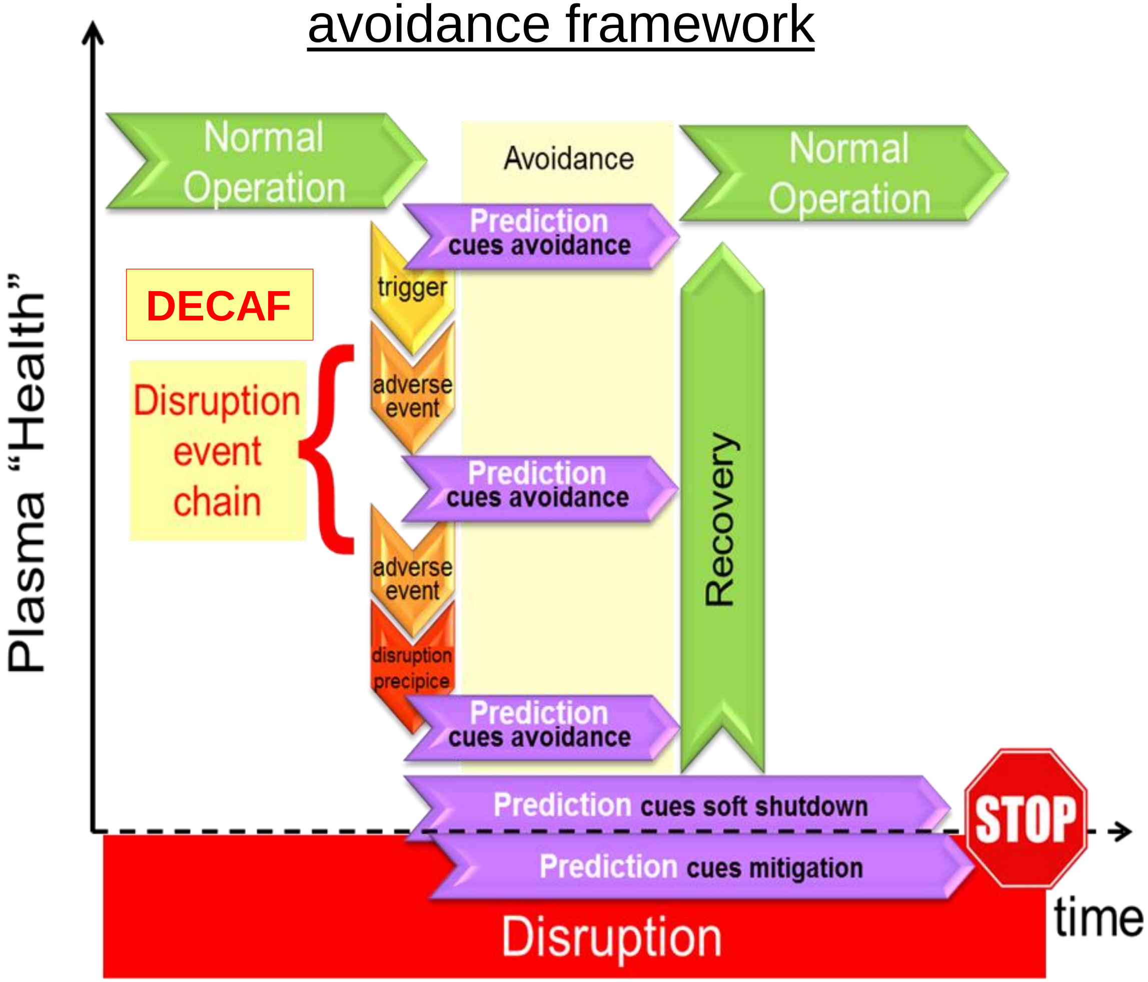
A broadened disruption prediction and avoidance approach is progressing for ITER and future tokamaks

- 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 tokamak: < 4% disruptions with carbon wall)
    - ITER disruption allowance: < 1 - 2% (energy + E&M loads); << 1% (runaways)

- Talk Outline
  - Disruption predictor requirement metrics
  - Disruption Event Characterization and Forecasting (DECAF) approach
  - Physical models in DECAF, continued progress toward early prediction
  - Initial multiple-device, large database analysis
  - Present evolution of disruption forecasting performance

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

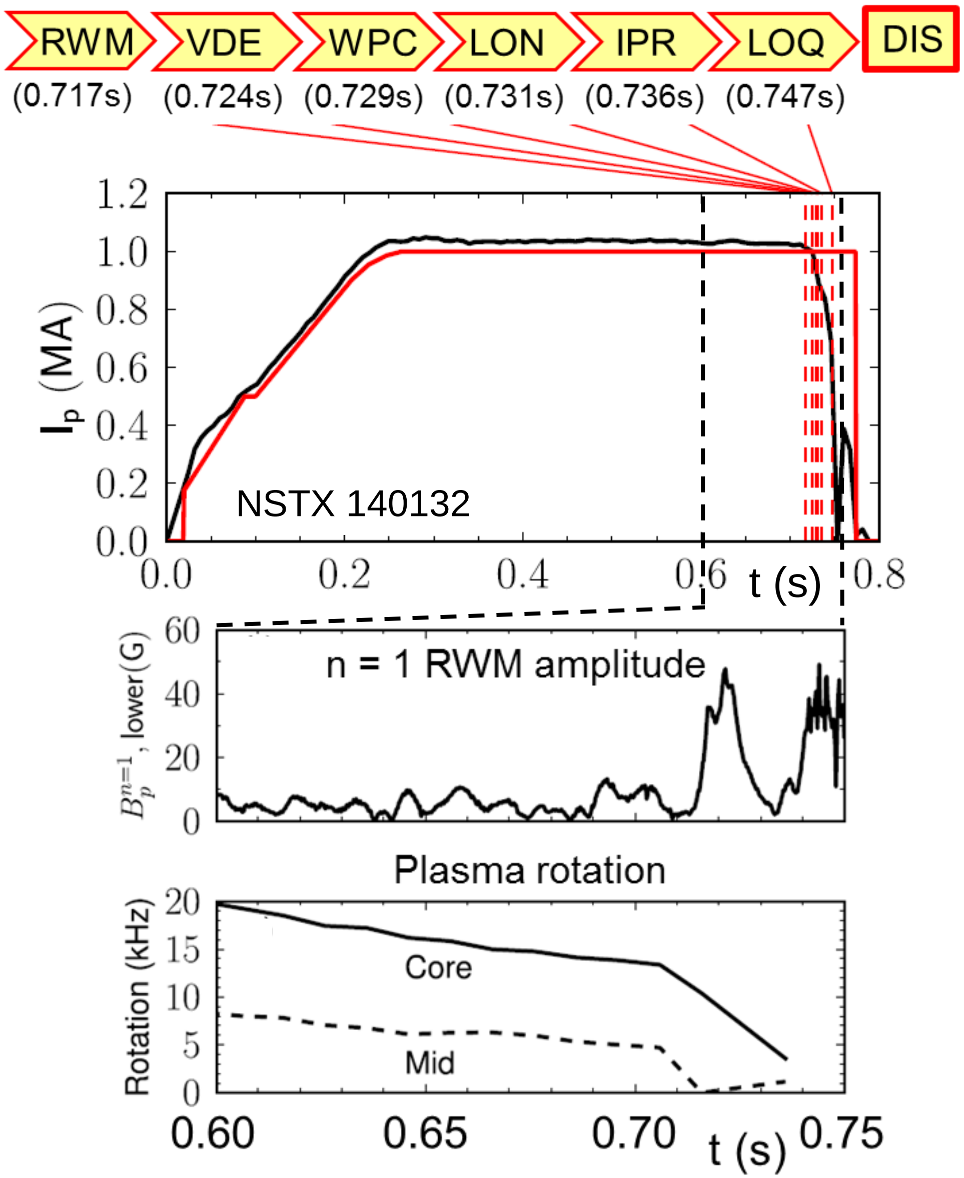
DECAF in disruption prediction / avoidance framework



- 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

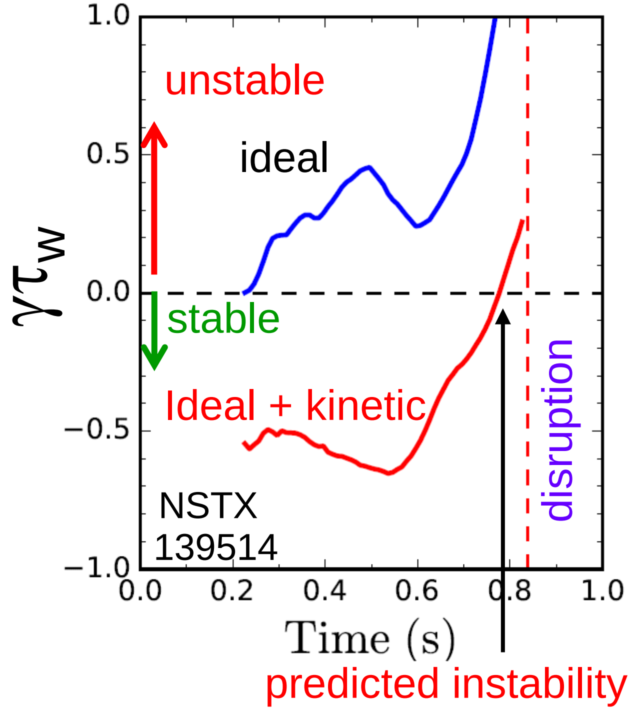
DECAF determines disruption triggers and automatically generates event chains



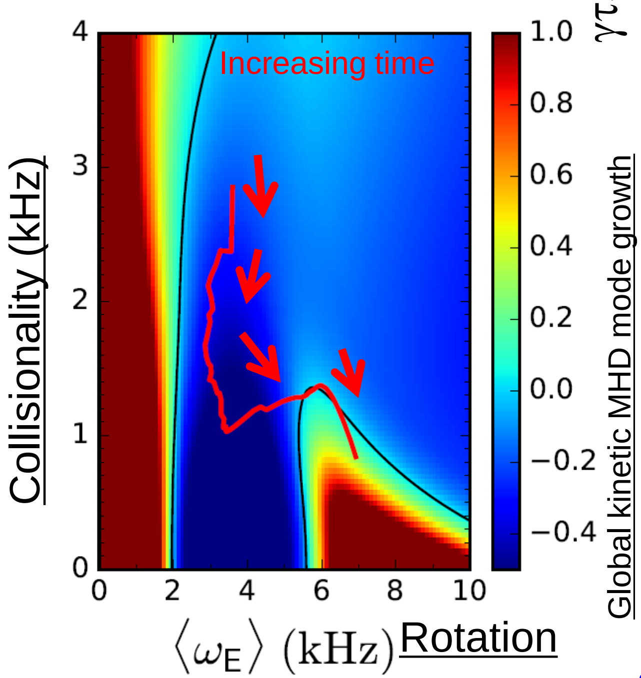
- Global MHD mode trigger
- Warning time: 30 ms
  - Absolute: Just sufficient time for disruption mitigation in ITER
  - Normalized: ~ 6 RWM growth times in NSTX – far longer time (~ s) in ITER
- Events (in this chain)
  - RWM resistive wall mode
  - VDE vertical instability
  - WPC wall proximity control
  - LON low density warning
  - IPR not meeting I_p request
  - LOQ low q warning
  - DIS disruption (current quench)

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

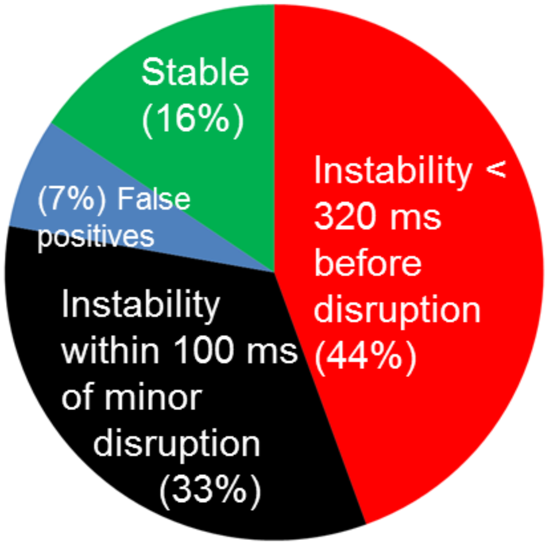
Norm. growth rate vs. time



Disruption forecasting



Predicted instability statistics

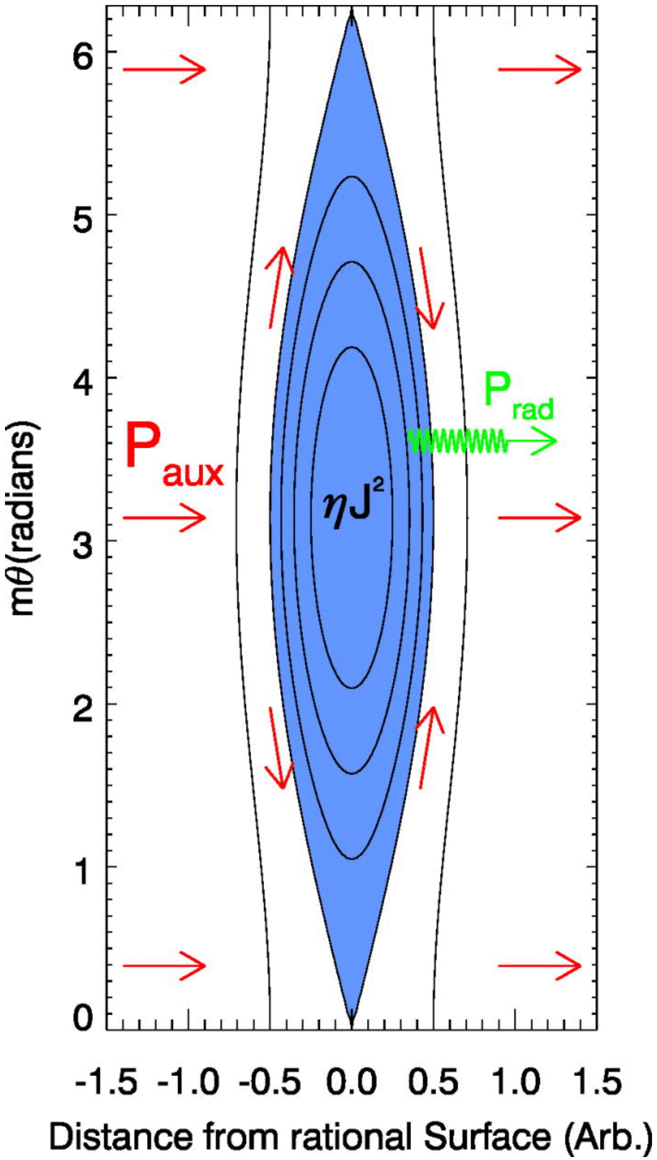


- Full physics model (years of effort) reduced
  - Stability contours CHANGE for each time point
  - Allows real-time stability and mode growth rate prediction

- 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

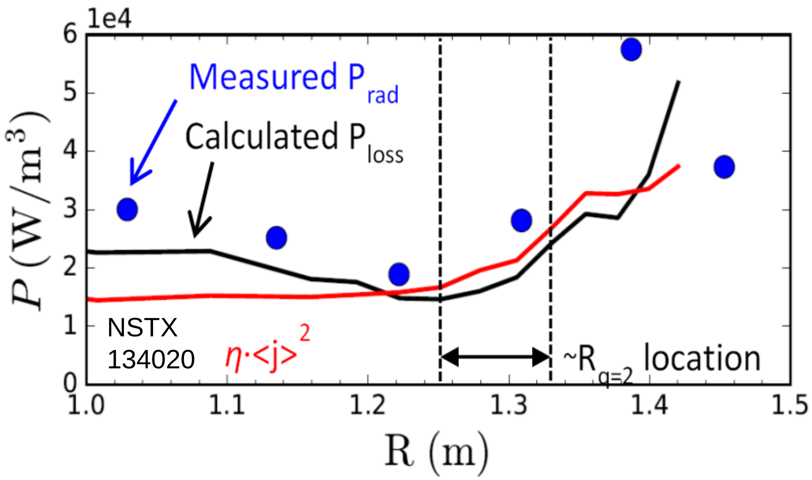
Recently a density limit model has been examined in DECAF based on power balance in an island



- 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

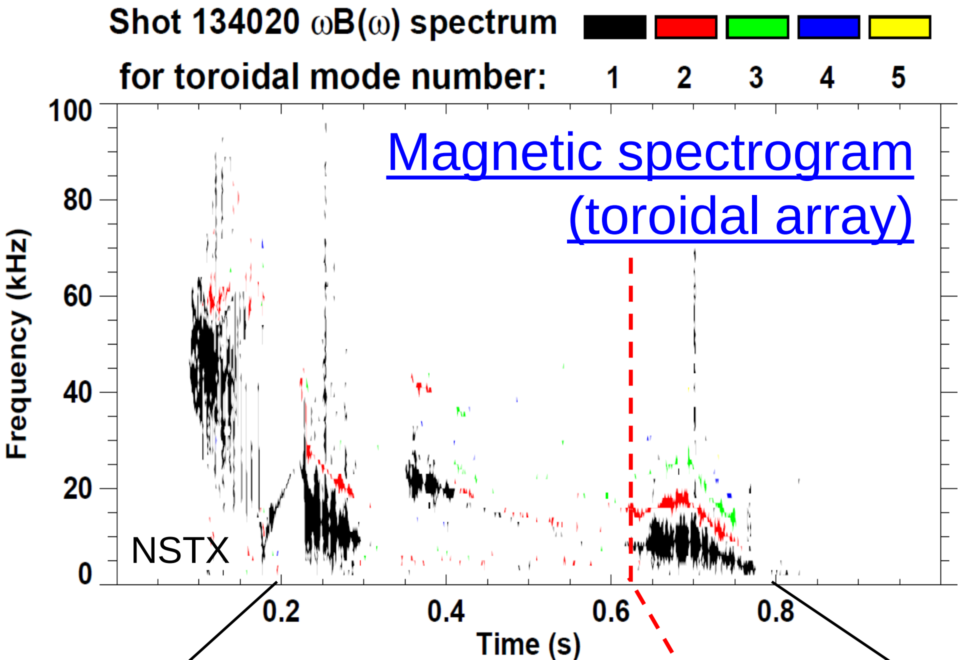
Power density balance: $P_{\mathrm{loss}} < P_{\mathrm{input}}$

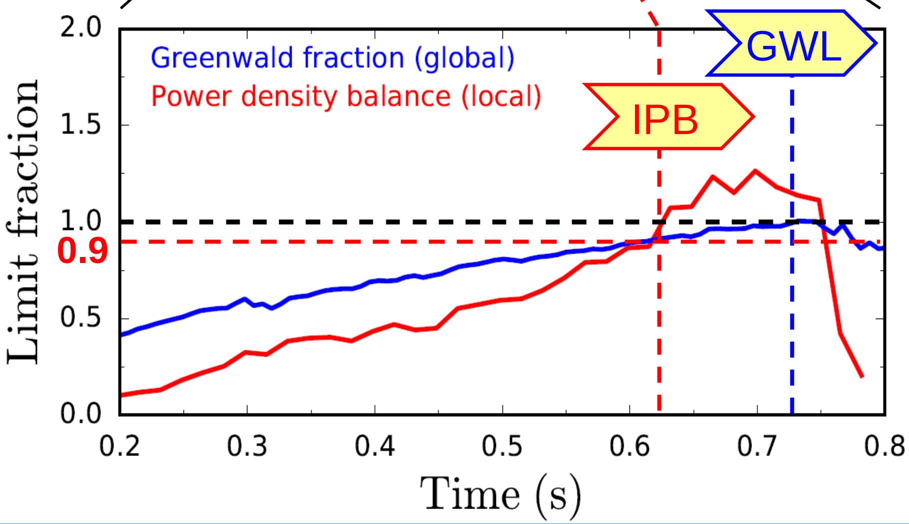
$$n_e n_D L_D(T_e) + \sum n_e n_Z L_Z(T_e) < \eta j^2$$



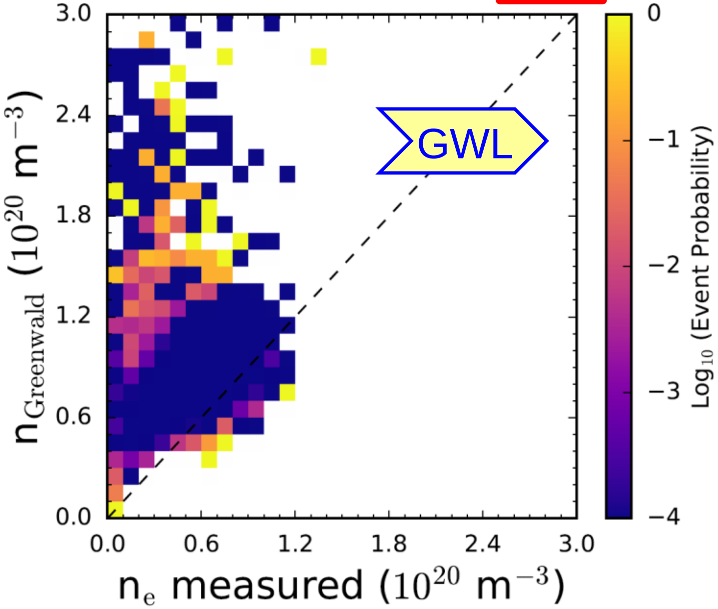
D. Gates et al., Phys. Rev. Lett. **108** 165004 (2012)

DECAF density limit analysis started: global, local density limits examined, correlation of MHD onset near limits





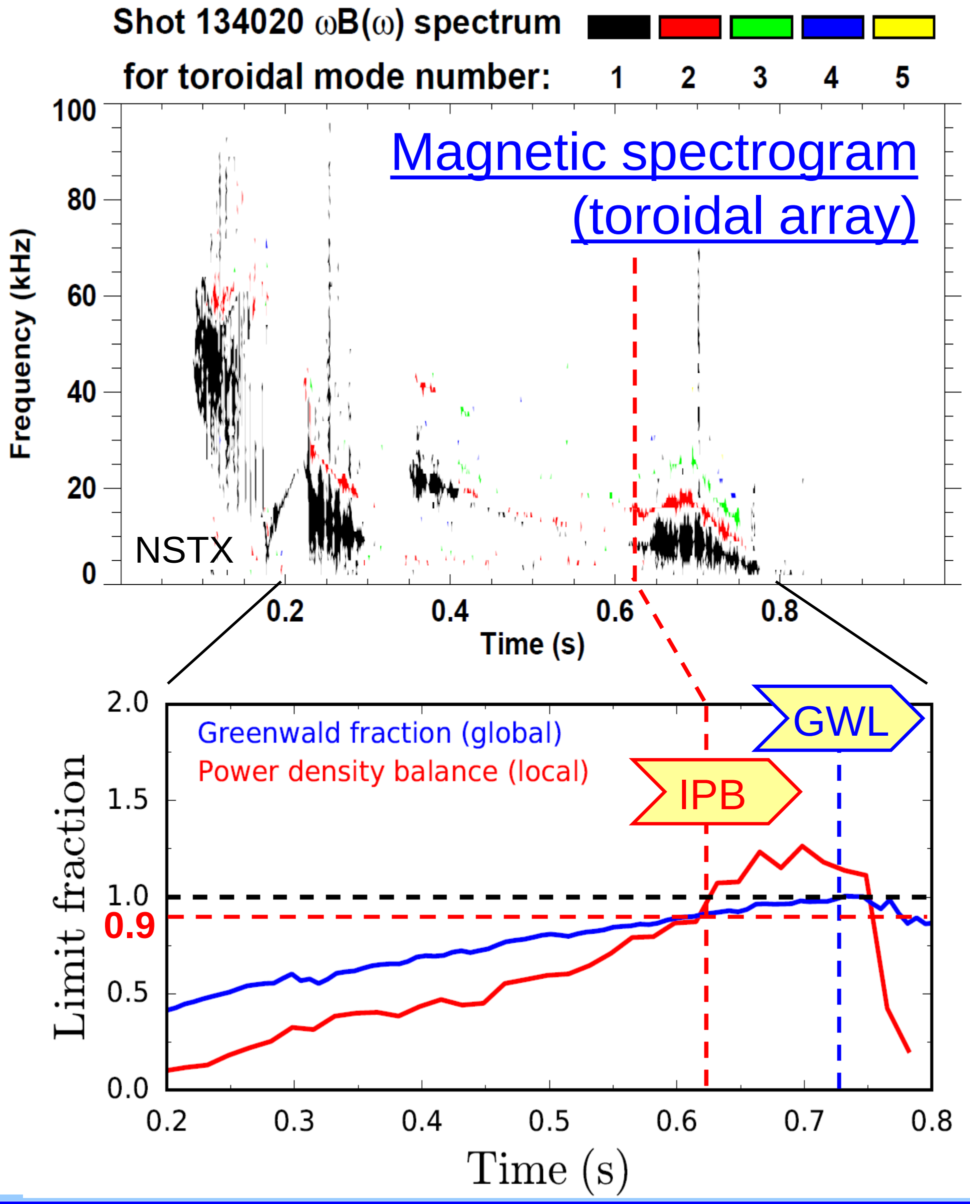
Disruptivity vs. density DIS



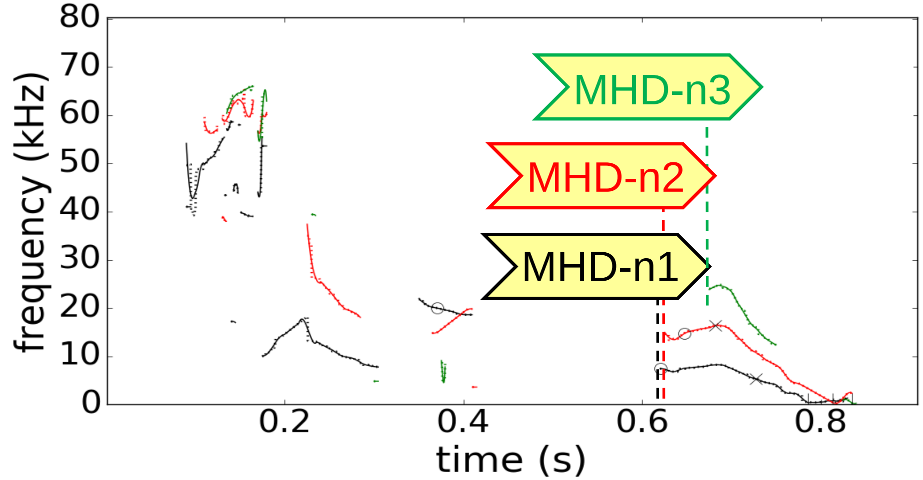
- Greenwald limit GWL
  - Near 0.9 when mode starts (range 0.75 – 1.05)
- Rad. island power balance IPB
  - Near 1.0 when mode starts (range 0.60 – 1.50) ← next step: reduce range

See CP11.00095: J.W. Berkery

More powerful automated MHD event objects have been developed for DECAF



DECAF automated MHD events

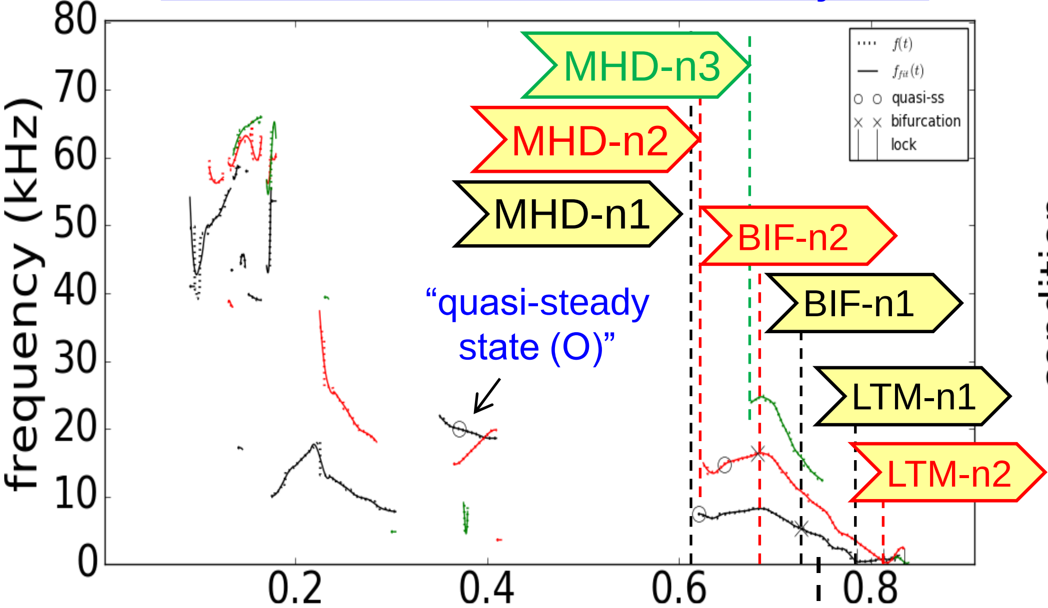


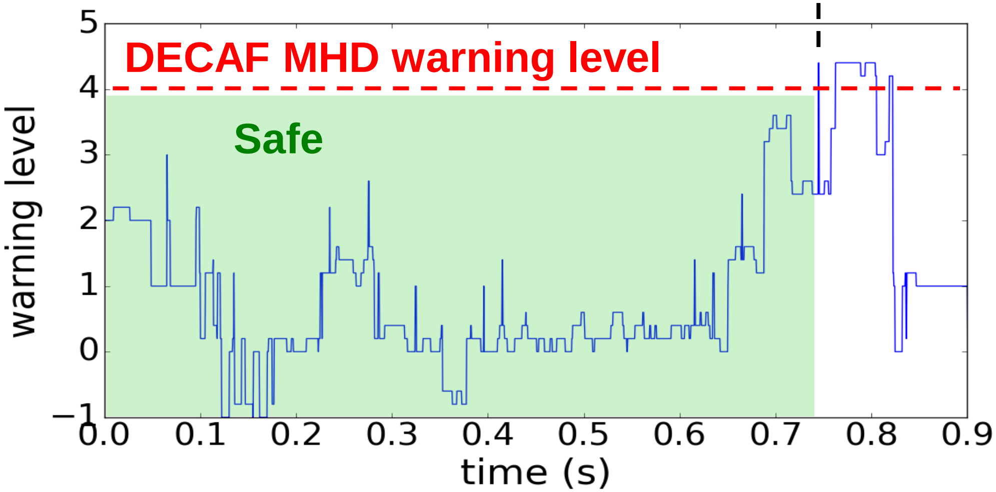
- More capable MHD event objects required for analysis of wider tokamak databases
- DECAF MHD events now include
  - Mode number (n) discrimination
  - Full history of mode evolution, including bifurcation and locking
  - Many disruption warning criteria

See CP11.00110: J.D. Riquezes

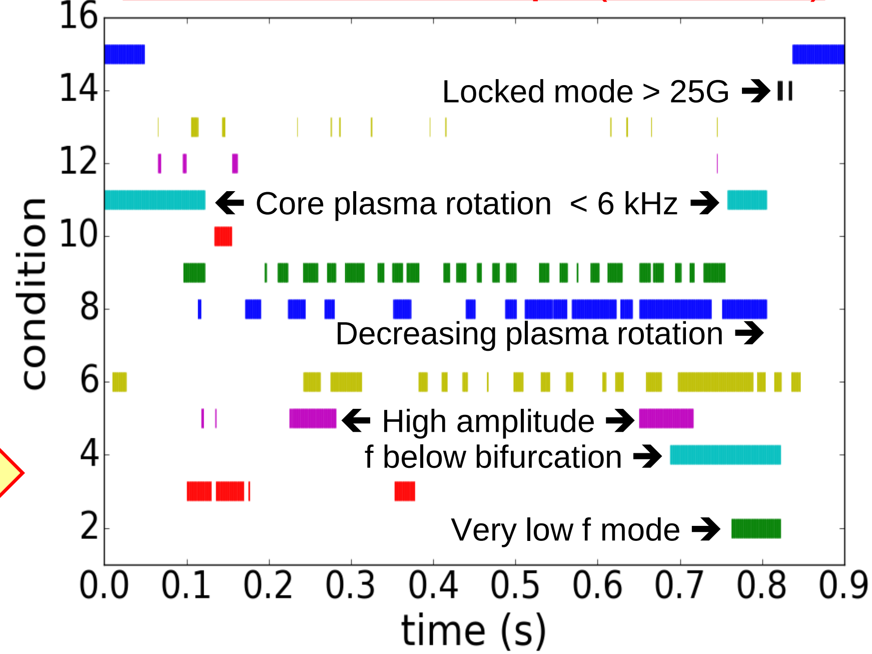
New DECAF MHD events utilize history of 15 criteria to define time evolving disruption warning level

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

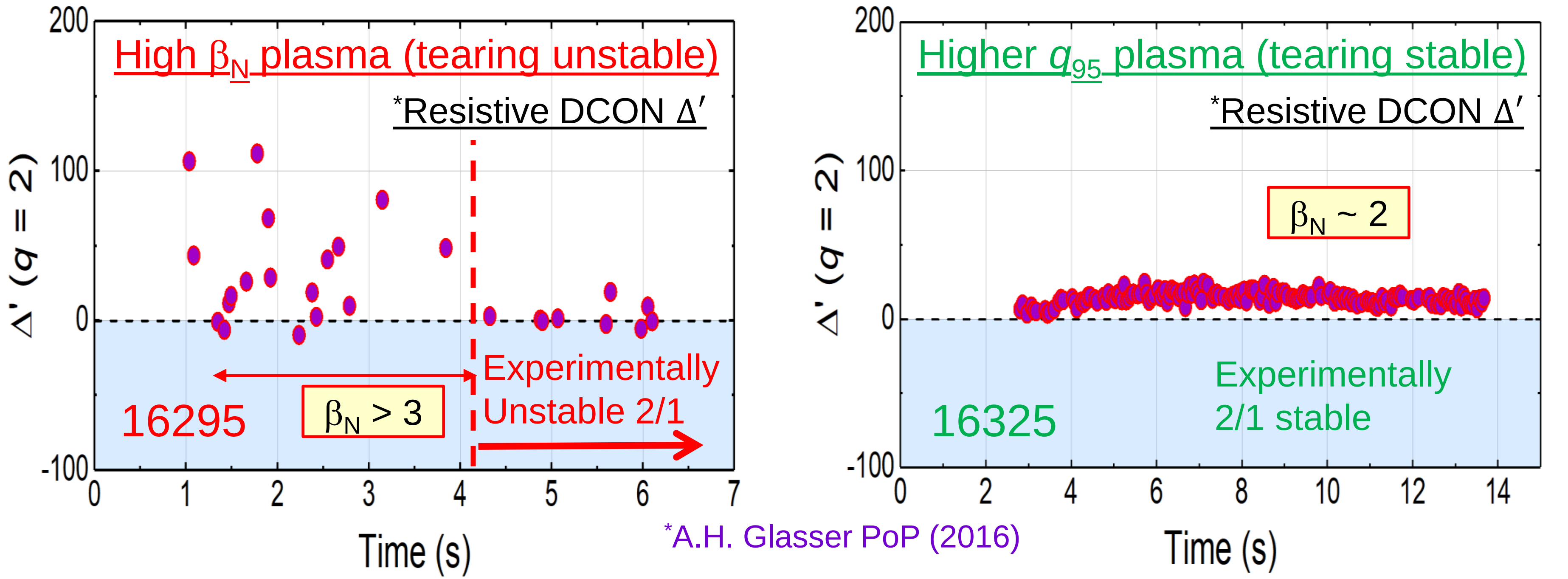
Progress on DECAF now moving to processing of multi-machine databases

- Analysis
  - Kinetic equilibrium / stability analysis on KSTAR; planned for MAST
- DECAF database started
  - Requires storage of DECAF analysis

Device / Capability	KSTAR	MAST	NSTX	DIII-D	TCV
Full database access (type)	Yes (MDSplus)	Yes (UDA)	Yes (MDSplus)	Yes (MDSplus)	Yes (MDSplus)
Database analysis	continuing	continuing	continuing		started
Equilibrium analysis	Kinetic + MSE	scheduled	Kinetic + MSE	available	
Stability	Ideal, Resistive Kinetic MHD	scheduled	Ideal, kinetic MHD (resistive)	Ideal, kinetic MHD	
shot*seconds (for kinetic analysis)	1,886 (2016+2017)	2,667 (est) (M5 - M9 runs)	2,000 / year (est)		

- Aim to add ASDEX-U next, then JET and C-Mod databases

Tearing mode stability examined in KSTAR plasmas varied β_N, q_{95} (supports future DECAF models)

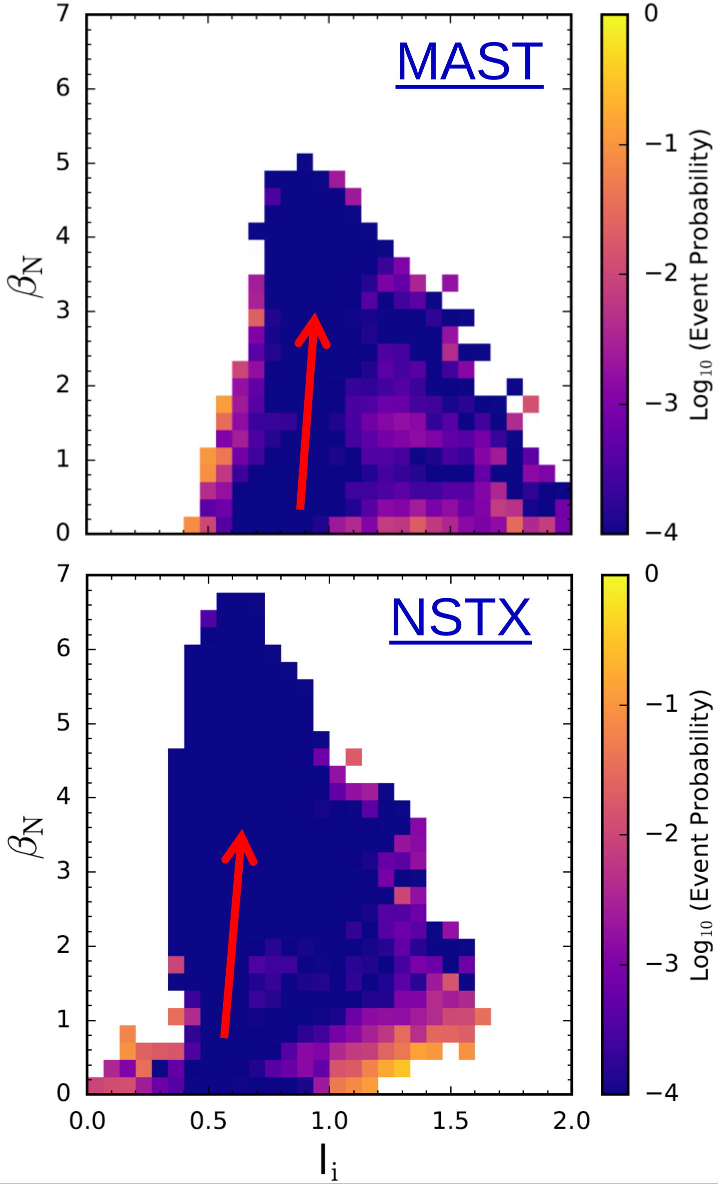


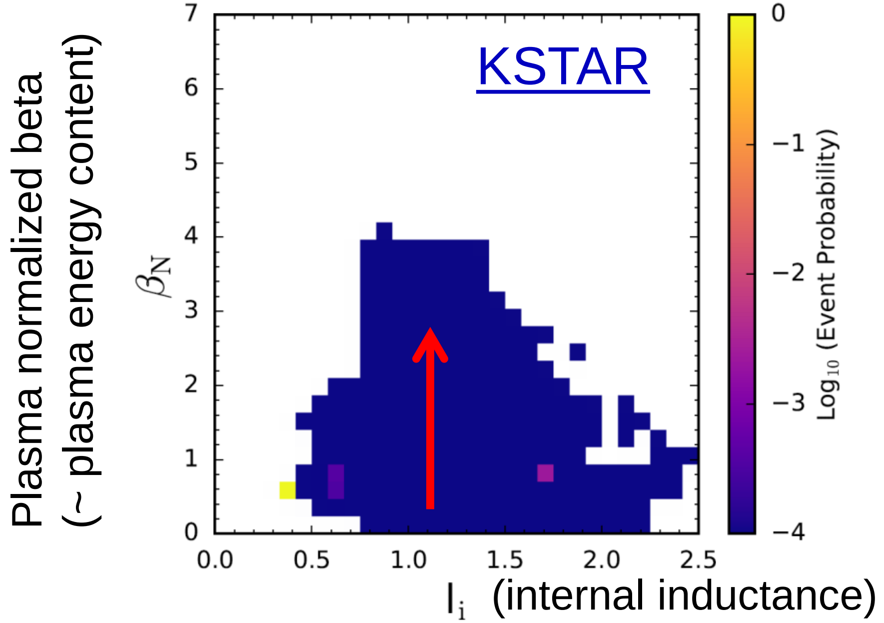
*A.H. Glasser PoP (2016)

- 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 are needed to produce stability
- Time evolution of ideal MHD stability <u>also</u> computed with DCON to support DECAF

See POSTER version of talk (next session) for more | See CP11.00100: Y.S. Park | See CP11.00099: Y. Jiang

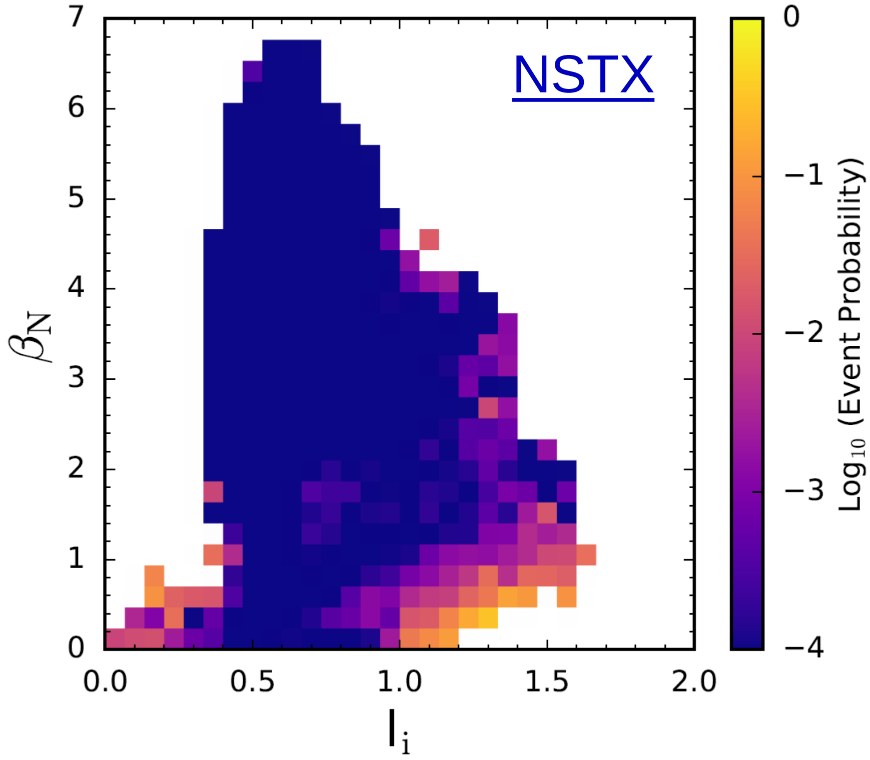
Initial DECAF analysis of large databases further supports result that disruptivity doesn't increase with β_N





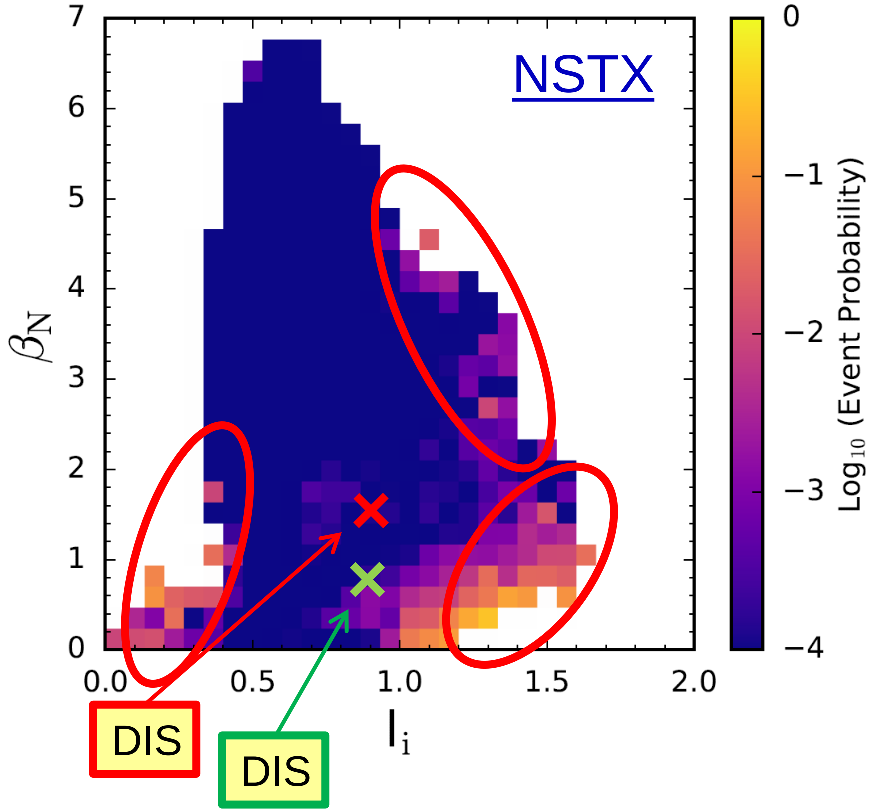
- DECAF analysis of DIS event alone
  - Similar to a "standard" disruptivity analysis
  - Analyzed at 10 ms intervals (> million tests)
- Analysis during steady plasma current
  - MAST: 8,902 plasmas analyzed
  - NSTX: 10,432 plasmas analyzed
  - KSTAR: 1,309 plasmas analyzed

DECAF provides early disruption warning and understanding of disruption event chain beyond disruptivity plots



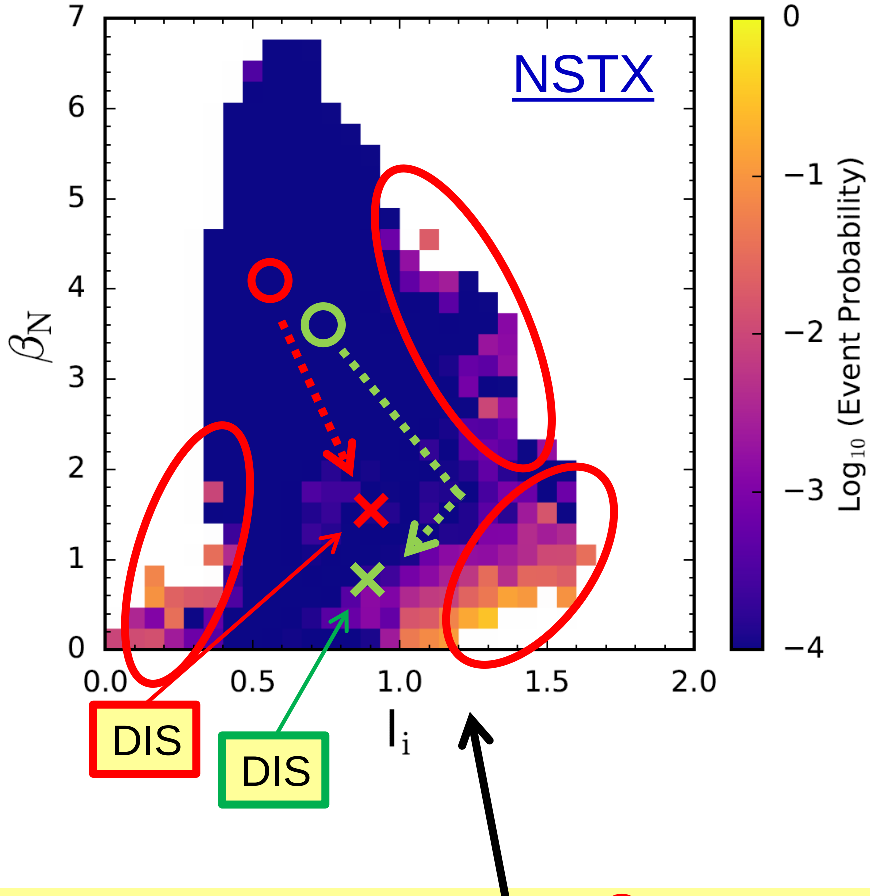
- Example: What are the most important regions to study on this plot?

DECAF provides early disruption warning and understanding of disruption event chain beyond disruptivity plots



- <u>Example</u>: What are the most important regions to study on this plot?
  - Studies usually focus on the high disruption probability regions
  - What causes the disruptions? (low β_N, mid-l_i ???)
  - <u>Problem</u> ➔plasma conditions can change significantly between first problem detected and when disruption happens

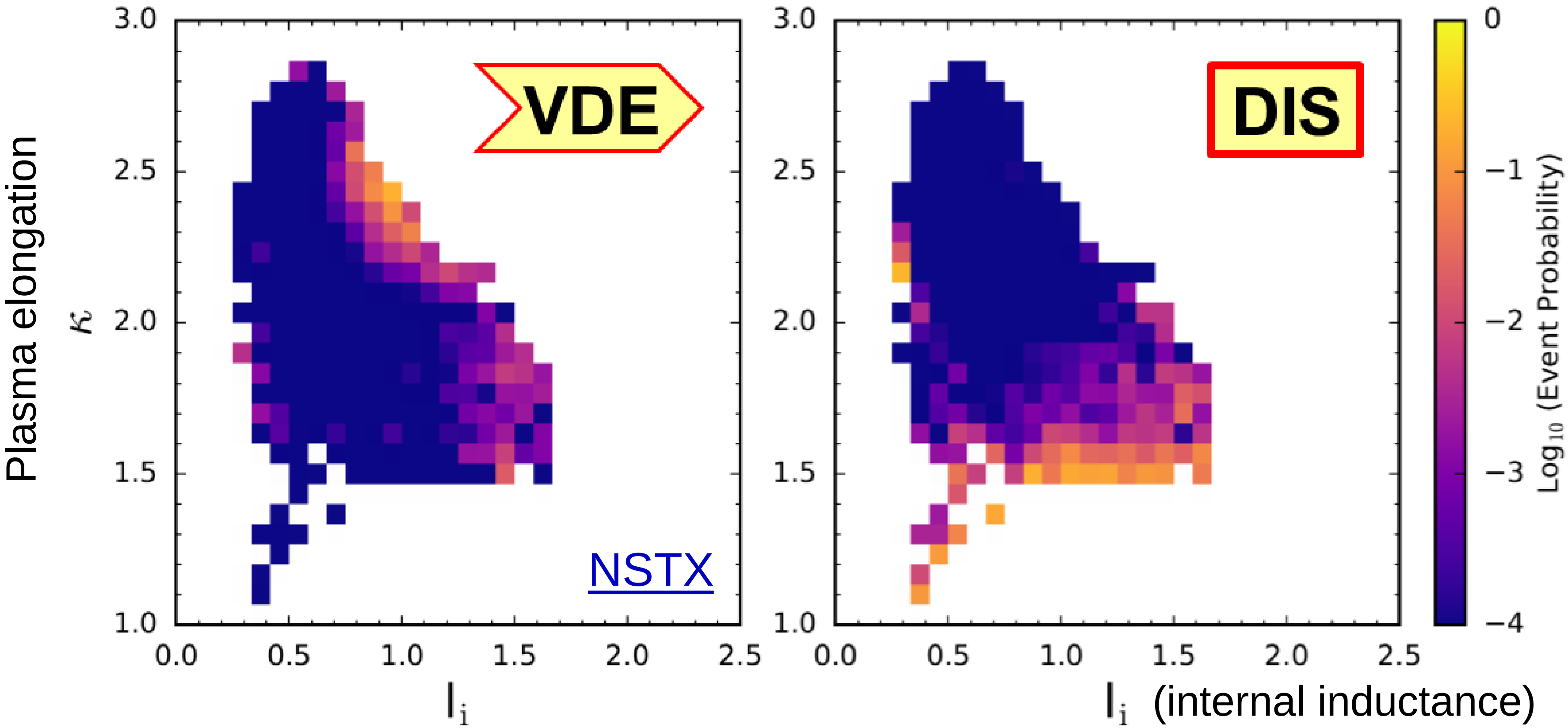
DECAF provides early disruption warning and understanding of disruption event chain beyond disruptivity plots



- <u>Example</u>: What are the most important regions to study on this plot?
  - Studies usually focus on the high event probability regions
  - What causes the disruptions? (low β_N, mid-l_i ???)
  - <u>Problem</u> ➔plasma conditions can change significantly between first problem detected and when disruption happens

- <u>Answer</u>: the <u>circles</u> ○ ○ mark the key region to study!
  - DECAF shows the plasmas suffer several "events" that are started in this region, and end up far from that region when they disrupt (at the crosses ✕ ✕)

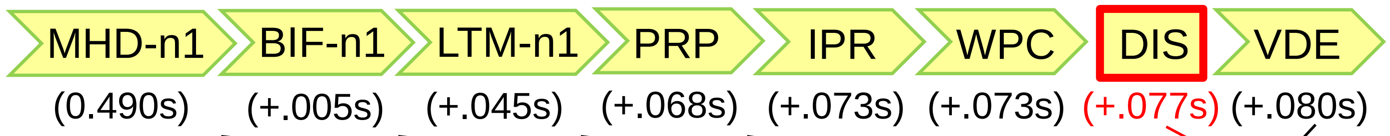
Example: DECAF shows plasma parameters of VDE event can occur far from those of DIS event

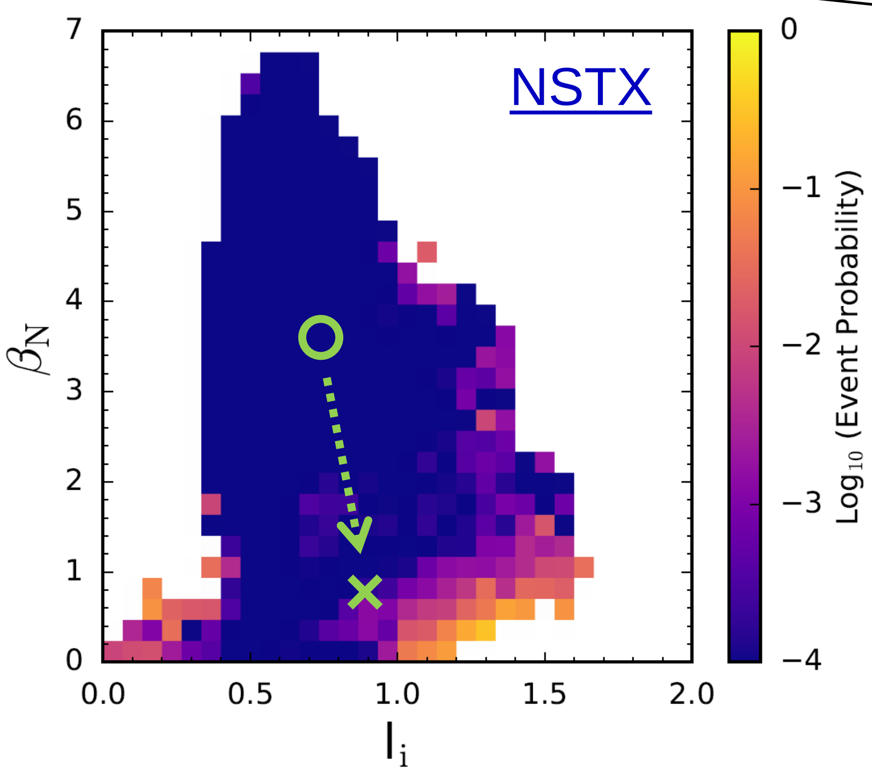


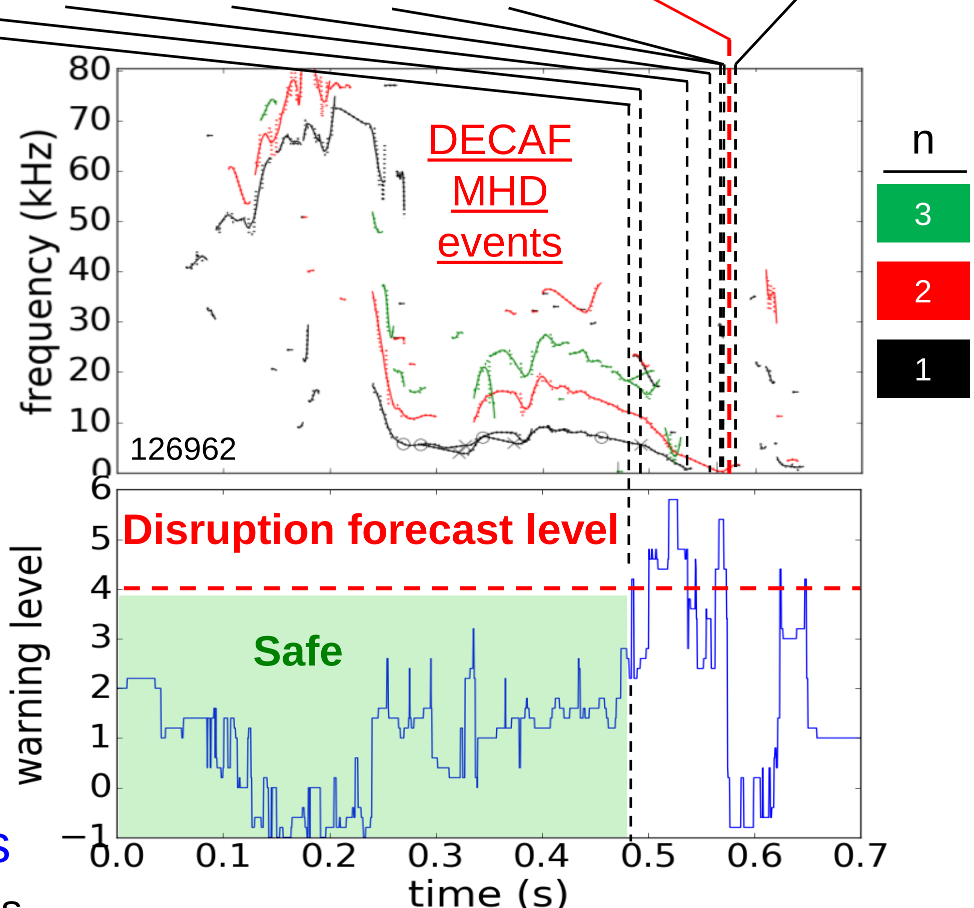
- Largest portion of detected VDE events appear at (l_i, κ) with very small portion of DIS events detected

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

DECAF event chain

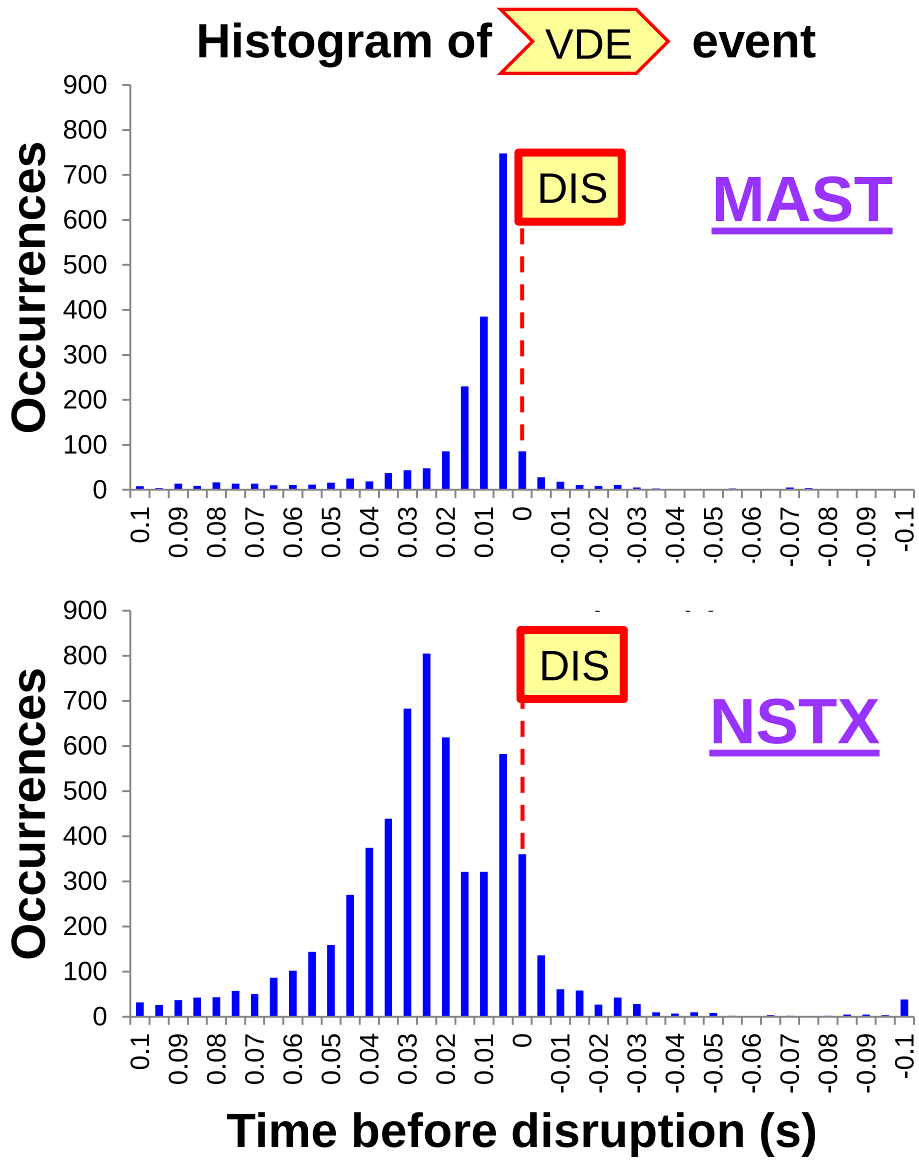






- DECAF event chain reveals physics
  - Rotating MHD slows, bifurcates, and locks
  - Then, plasma has an H-L back-transition (pressure peaking warning PRP) before DIS
  - Early warning gives the potential for disruption avoidance by plasma profile control

DECAF event analysis of large databases of different devices shows physical distinctions

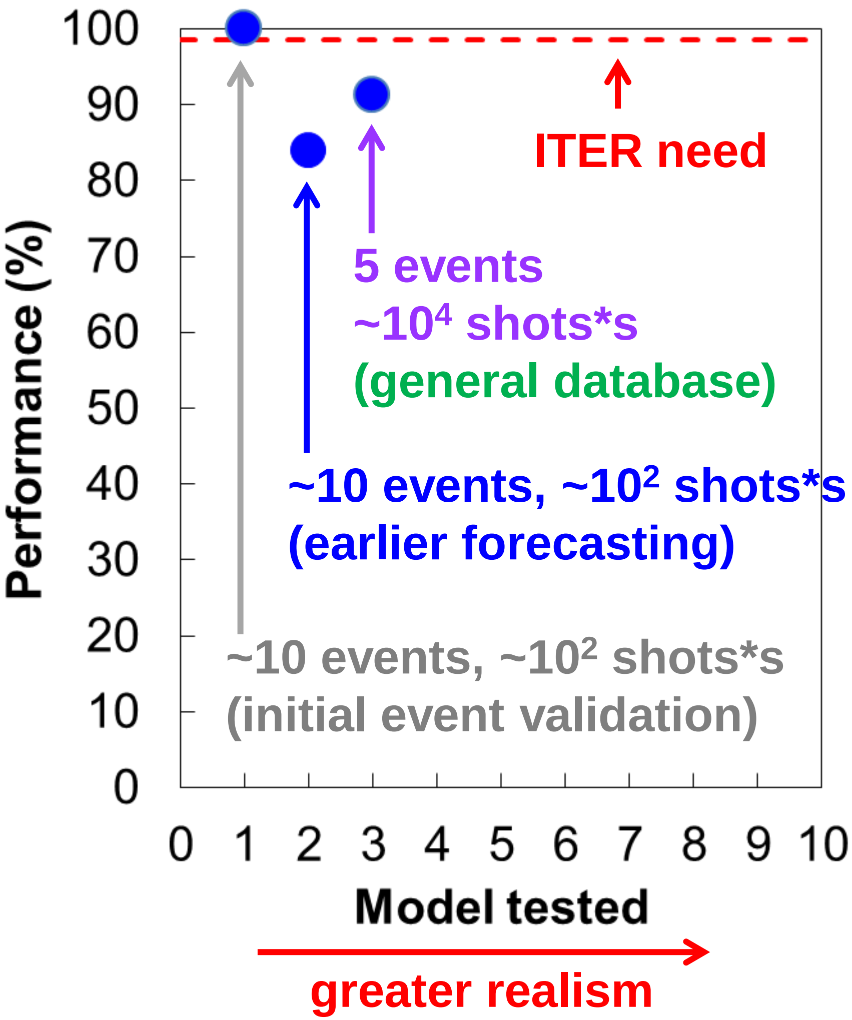


- Databases
  - MAST: 8,789 shots (3,360 shots*seconds)
  - NSTX: 10,094 shots (6,400 shot*seconds)
- Loss of vertical stability control occurs closer in time to disruption in MAST compared to NSTX
  - May be due to presence of copper stabilizing plates in NSTX
- Understanding aids in DECAF extrapolation to new devices

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 was part of the disruption chain

DECAF Disruption Forecasting Performance Evolution



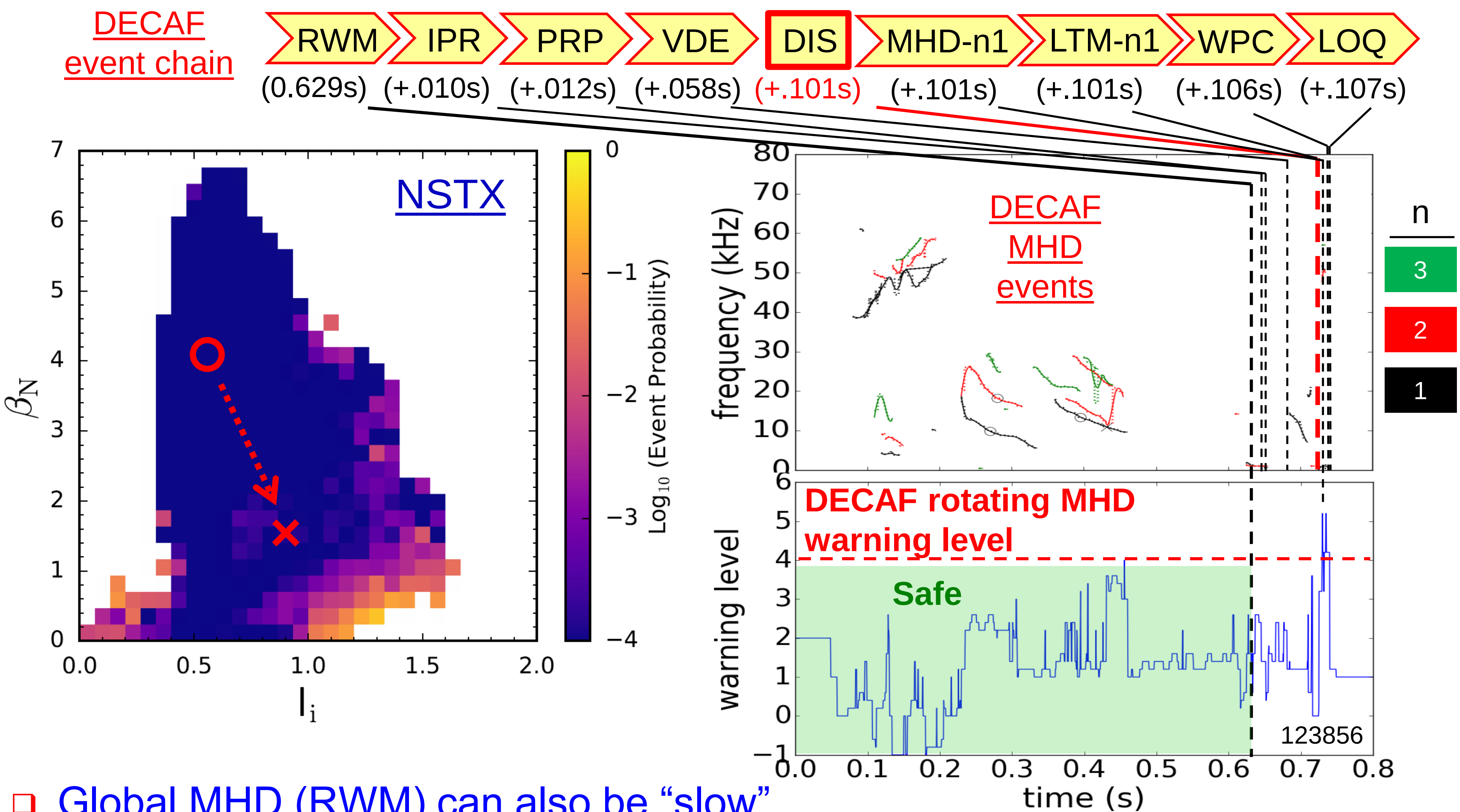
Rapidly-expanding DECAF code provides a new paradigm for disruption prediction research

- Multi-faceted, integrated approach to disruption prediction and avoidance that meets disruption predictor requirement metrics
  - Physics-based approach yields key understanding of evolution toward disruptions needed for confident extrapolation of forecasting
  - Physics-based DECAF events can guide disruption avoidance by control
  - Full multi-machine databases used (full databases needed!)
  - Open to all methods of data analysis (physics, machine learning, etc.)
- DECAF is now producing early warning disruption forecasts
  - On transport timescales: potential disruption avoidance by profile control
- Next steps
  - Expand number of DECAF events evaluated in large database analysis
  - Continue / expand disruption prediction performance analysis (➔ ITER)
  - Implement DECAF disruption prediction models in real-time (➔ KSTAR)

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

Supporting Slides Follow

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)

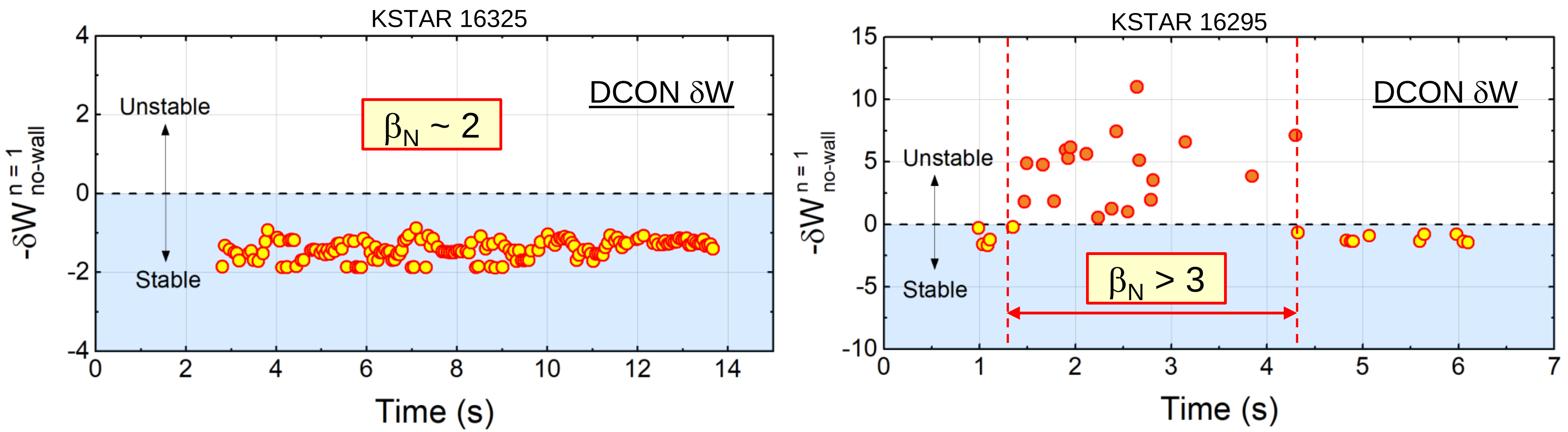
DECAF code based on initial successful research/results is now advancing to a new level

- DECAF brief highlights of prior results
  - First automated event chain analysis (followed deVries' manual work)
  - Excellent performance on smaller, targeted databases (NSTX)
    - Ex.: DIS, WPC, IPR, LOQ, RWM events found 100%, VDE event 91%
    - Computed events accurately represented experiment (~ 10 events)
    - Physics model forecasted global MHD disruptions with ~ 85% reliability
  - Disruption chains often repeated, e.g.: RWM > VDE > WPC > IPR > DIS

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

- Recent progress
  - Density limit model based on radiating island power balance being tested
  - New MHD events in DECAF allow forecasting on transport timescales
  - Linear resistive MHD analysis as first step to theory-based forecasting
  - Analysis of disruption chains from general databases
  - Multi-machine database analysis and disruption prediction with small number of verified events

DCON stability calculation shows high β_N equilibria are subject to n = 1 ideal instability



DCON computed ideal MHD n = 1 δW with no-wall

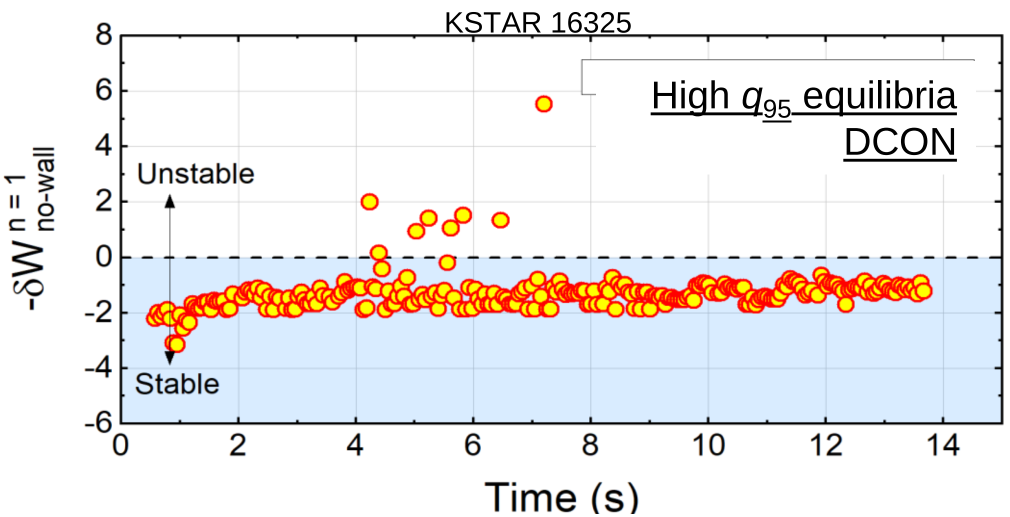
- Equilibria at lower β_N ~ 2 is consistently stable to n = 1 ideal modes in DCON
- Unlike the lower β_N case, DCON calculates unstable n = 1 mode with no-wall ($\beta_N > \beta_N^{\text{no-wall}}$) at the achieved high $\beta_N > 3$
- The small deviations in the reconstructed profiles in the high β_N phase is responsible for reduced equilibrium convergence and the scatter in δW

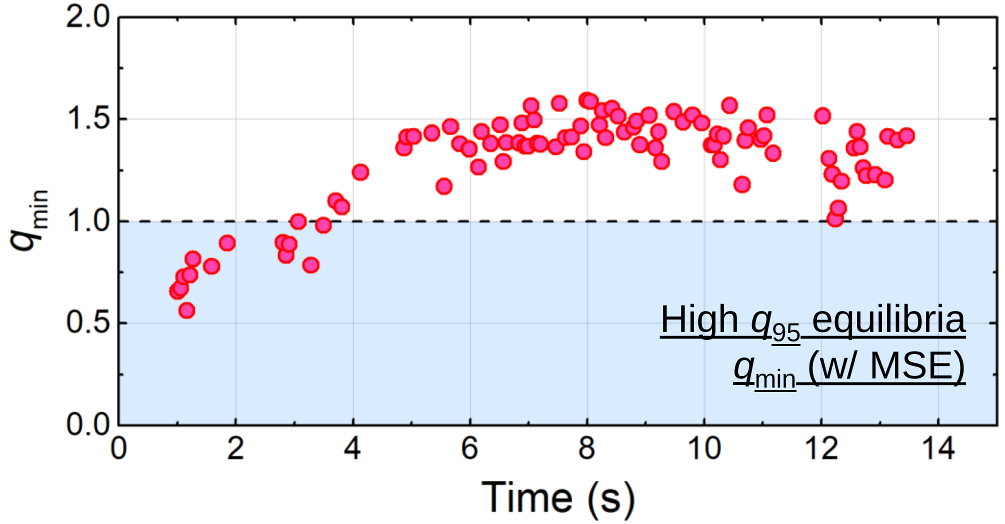
See CP11.00100: Y.S. Park

See CP11.00099: Y. Jiang

A.H. Glasser, Phys. Plasmas **23** (2016) 072505

Higher q_{95} plasma has greater ideal n = 1 no-wall stability computed in DCON



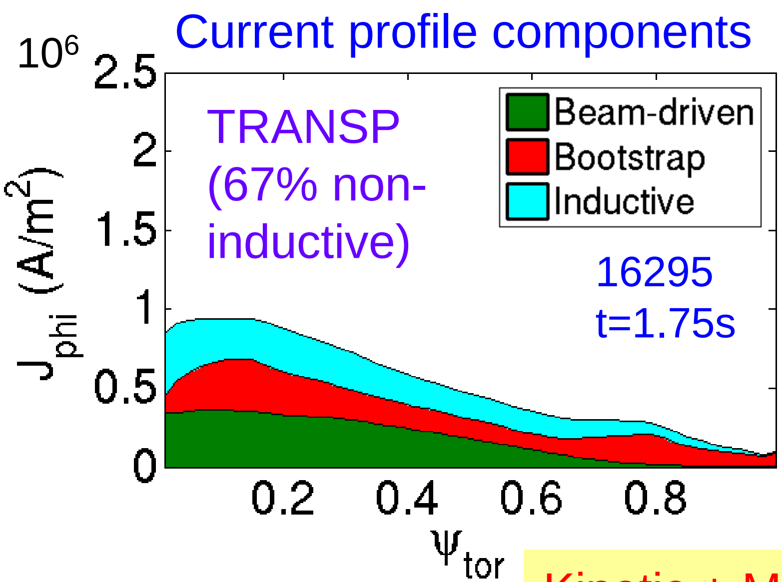


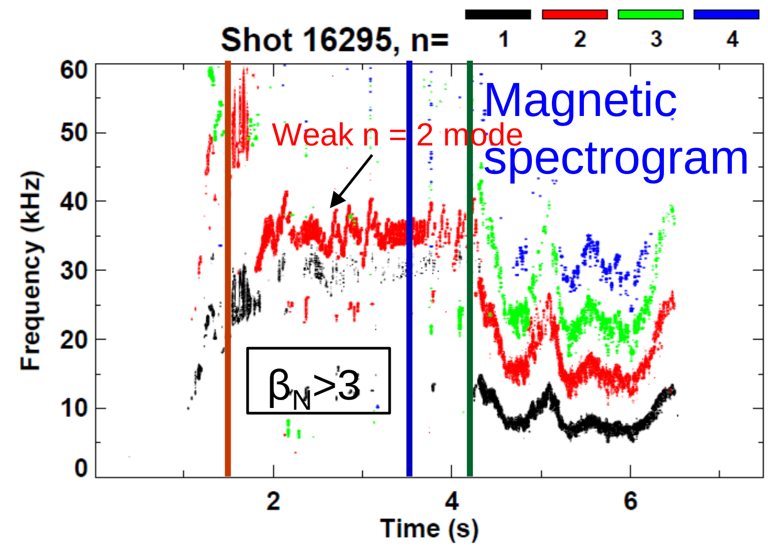
See CP11.00100: Y.S. Park

See CP11.00099: Y. Jiang

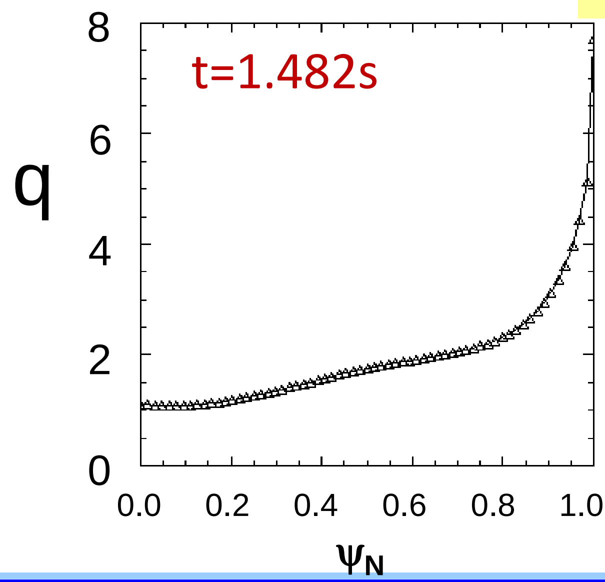
- Unlike higher β_N plasma, equilibria is mostly stable to n = 1 ideal modes in DCON
  - Note generally smooth evolution of stability criterion – reached with improved kinetic equilibria
- The *q*-profile at higher B_T evolves higher q_{min} above 1
  - Sawteeth disappear
- Reconstructed lower q shear at higher values of q does not lead to n = 1 instability in DCON

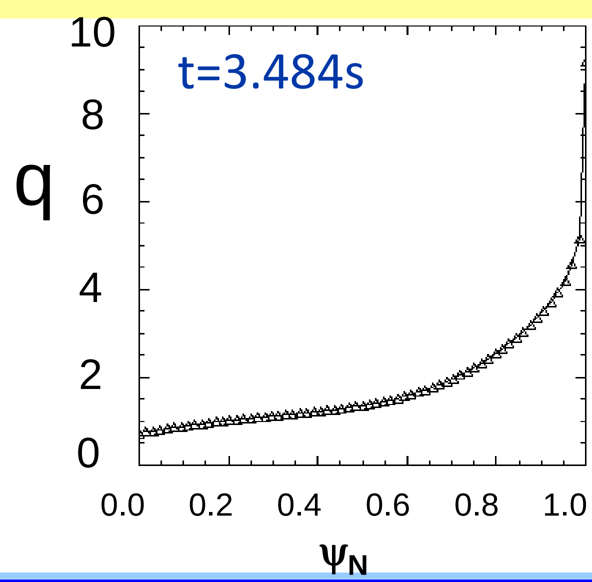
A broad non-inductive current fraction profile leads to low shear at low q in high β_N plasma

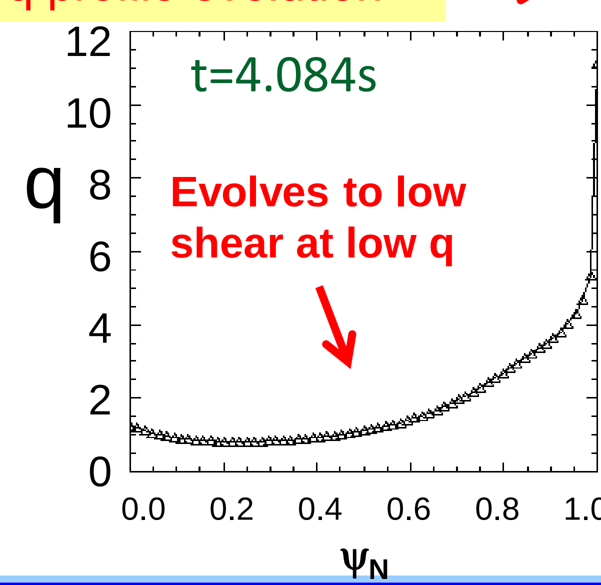




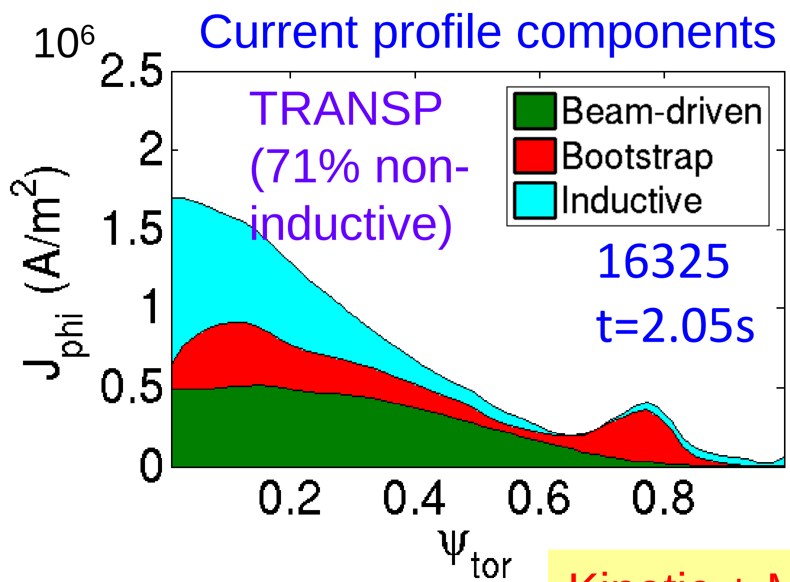
Kinetic + MSE reconstructed q profile evolution

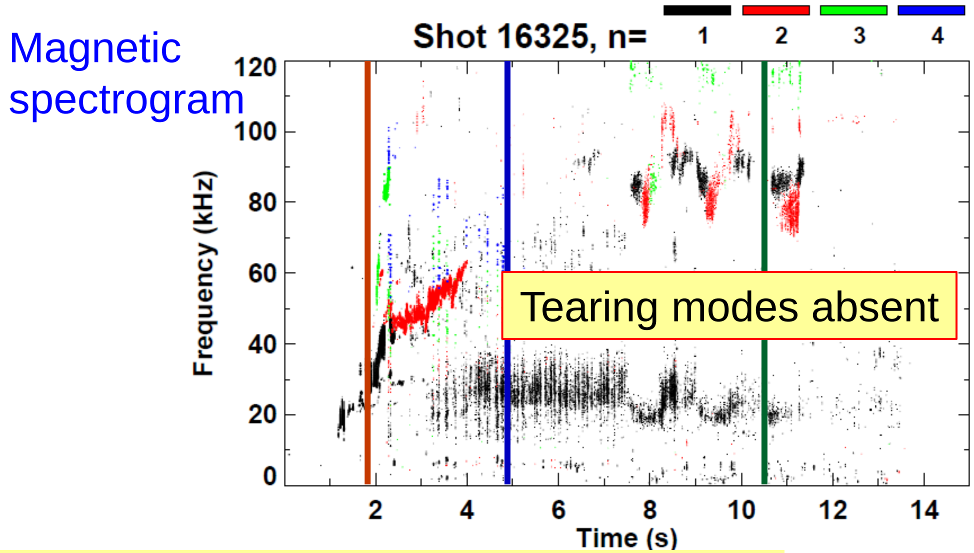






Kinetic EFIT reconstructed again shows evolution to low-sheared q-profiles but now at high q





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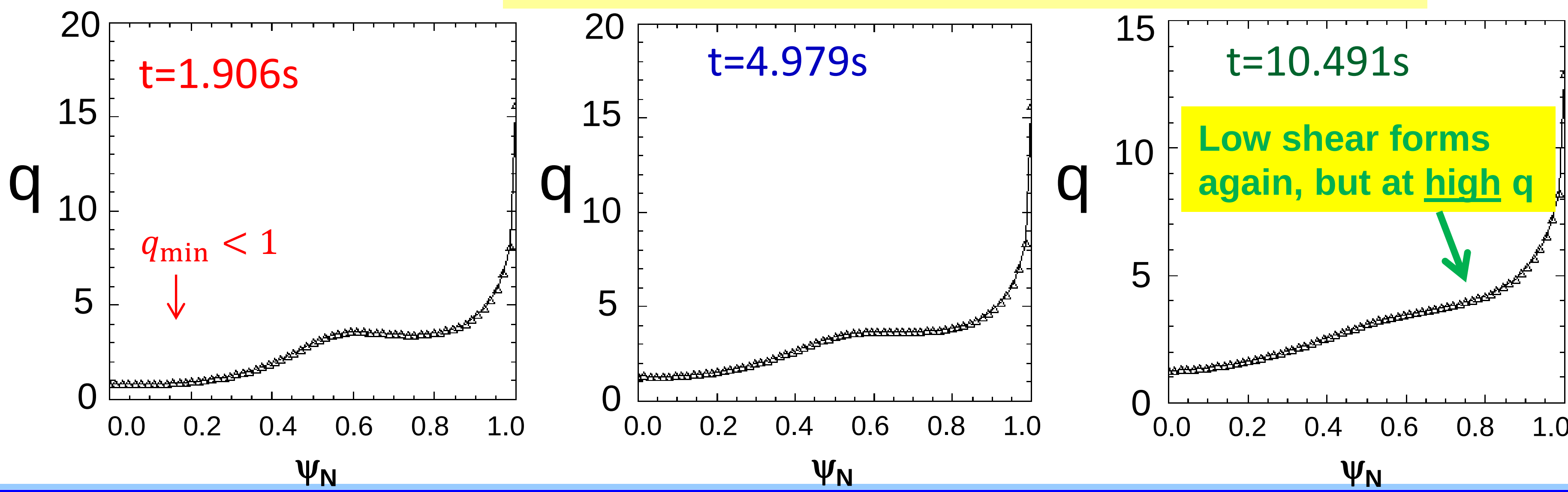
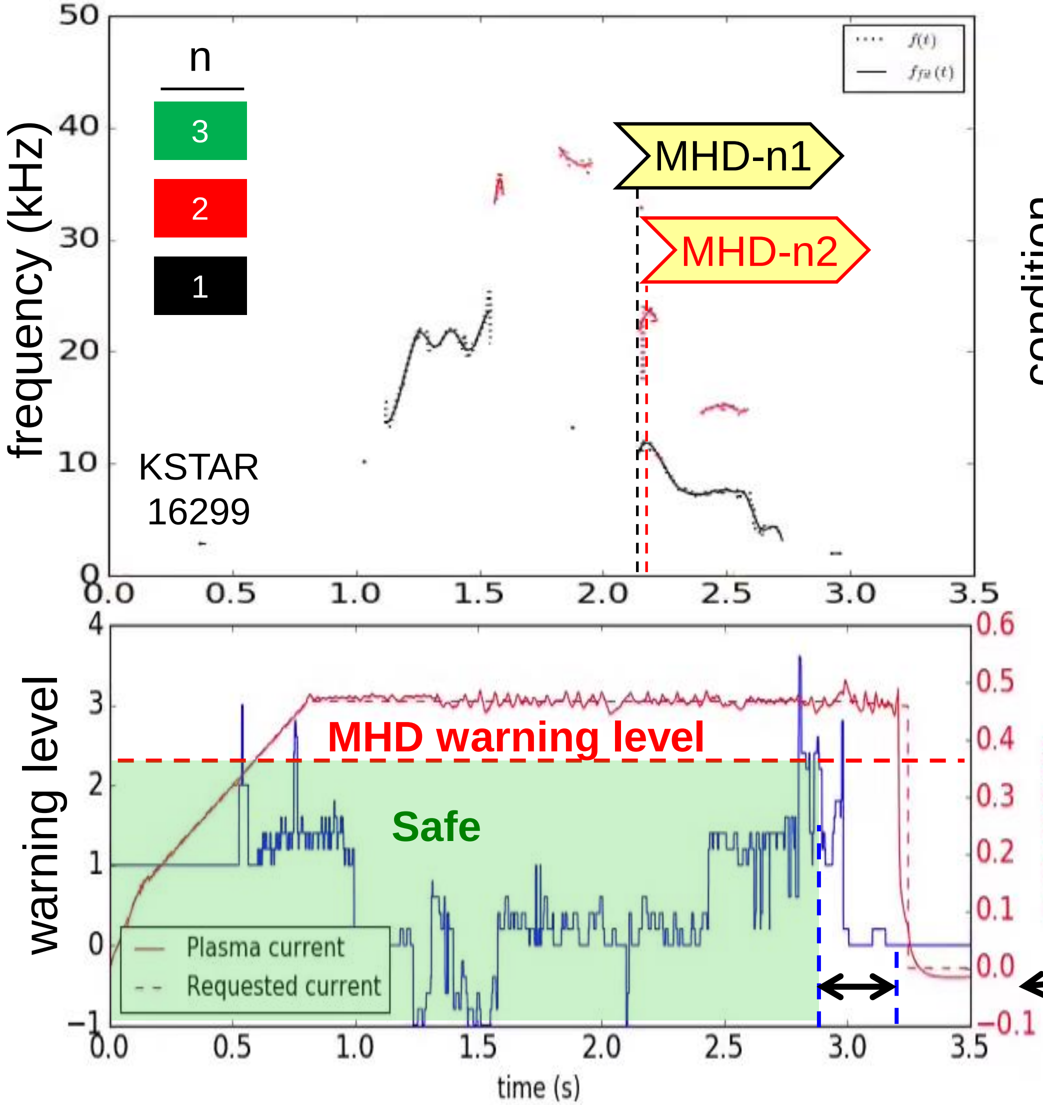
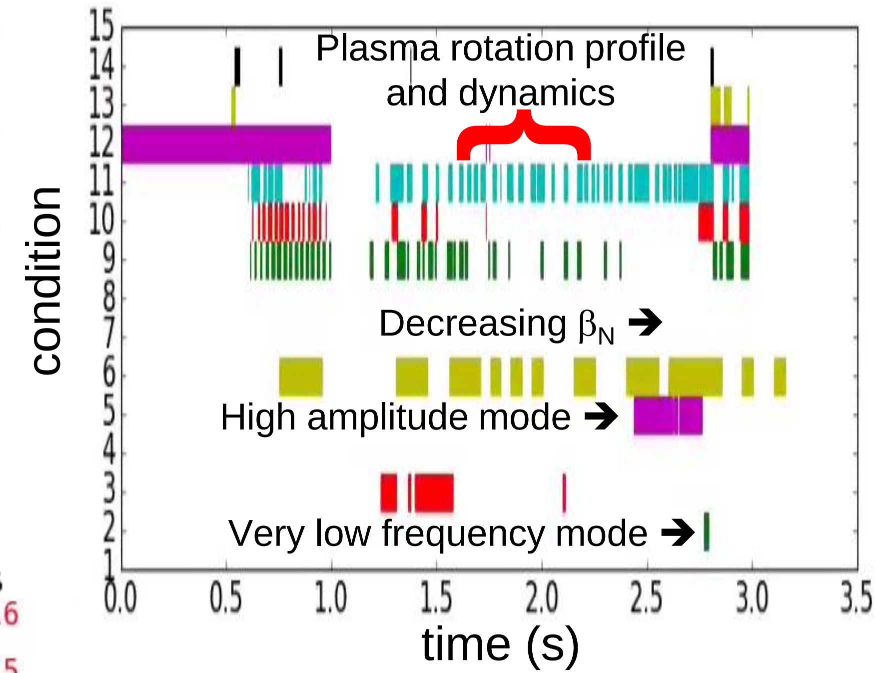


New DECAF MHD events are now being tested on KSTAR to define evolving disruption warning level

DECAF automated MHD objects



DECAF "heat map" (for MHD)

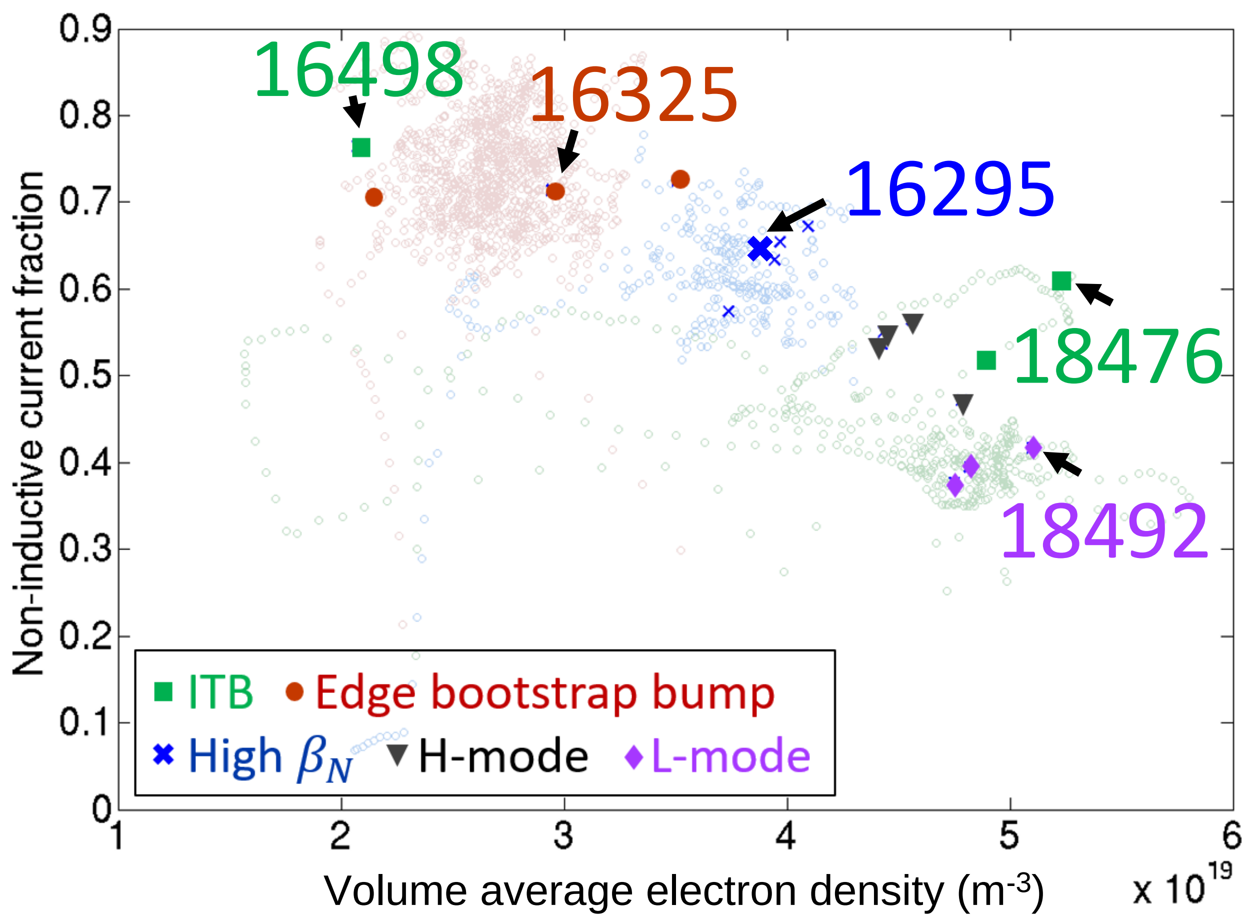


- Mode locking at reduced plasma rotation
- Key notables of MHD warning
  - "Safe"/"unsafe" MHD periods
  - Early disruption warning (300 ms) ➔ on transport timescale

See CP11.00110: J.D. Riquezes

Kinetic reconstructions focused first on KSTAR plasmas with high-non-inductive fraction; NICF exceeds 75%

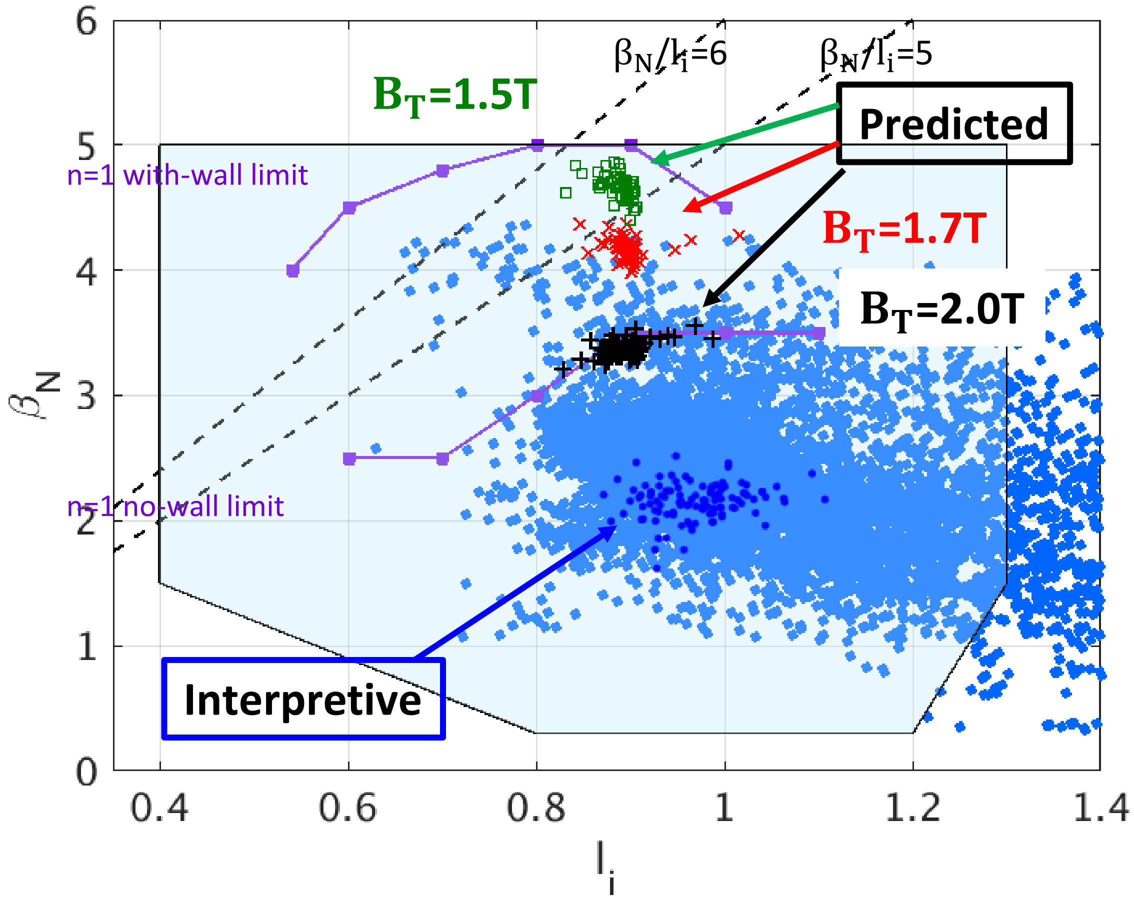
- TRANSP analysis of experimental plasmas
- Non-inductive fraction
  - Beam-driven
  - Bootstrap
- Non-inductive fraction is key for stable high beta steady state operation

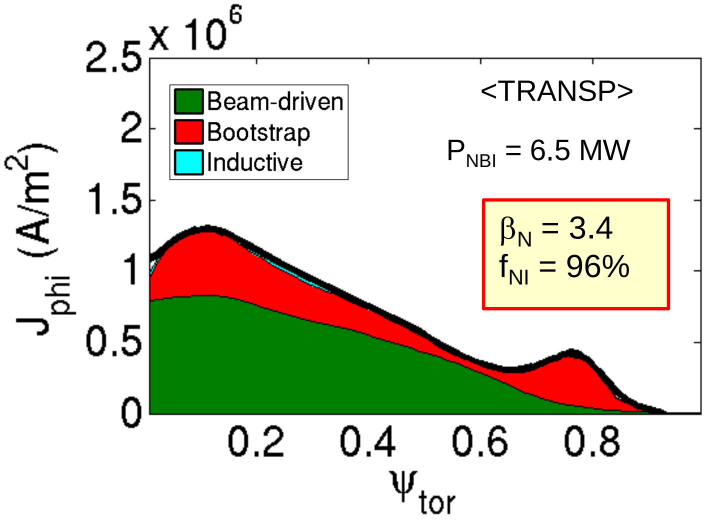


See CP11.00102: J.H. Ahn

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

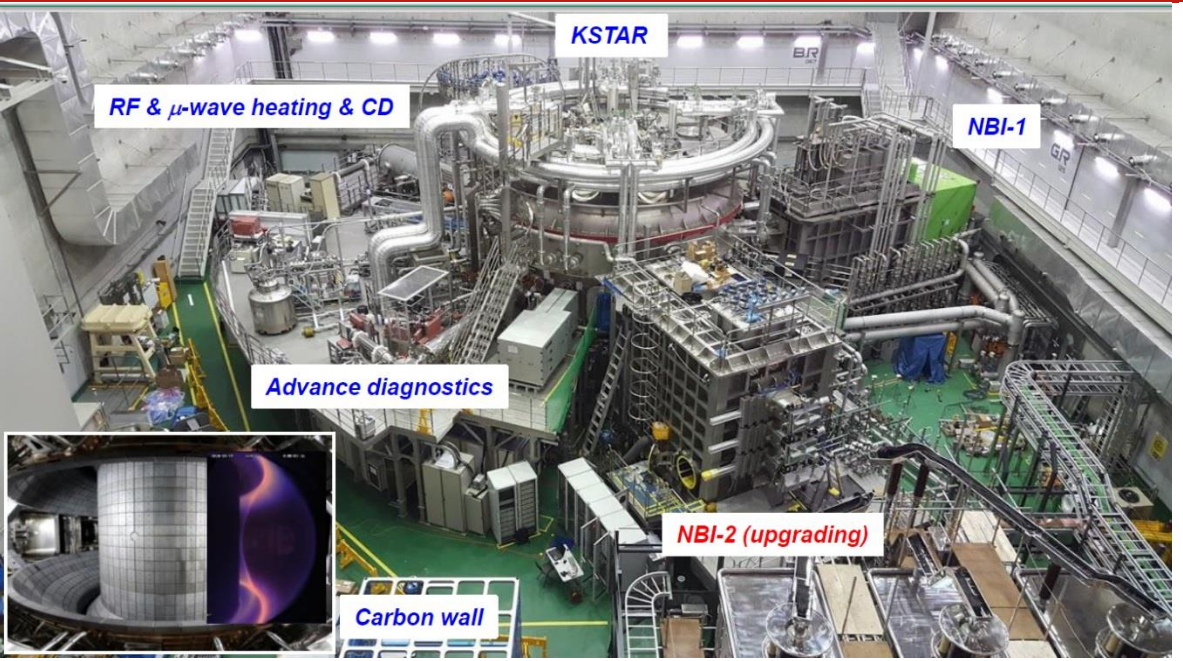


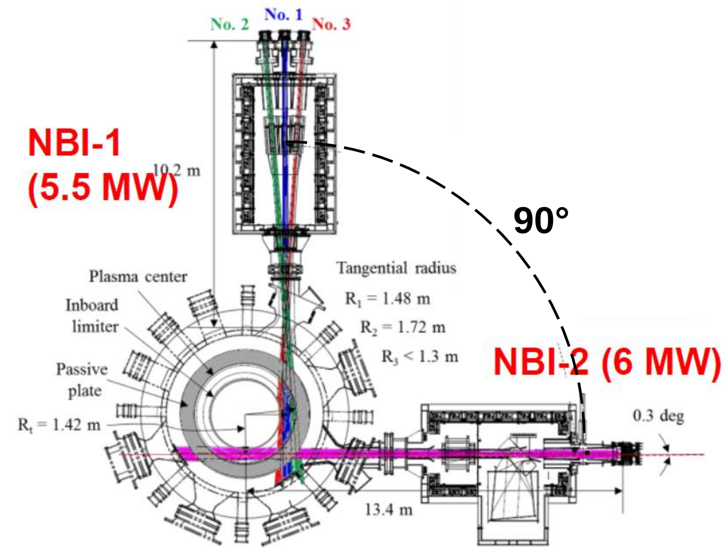


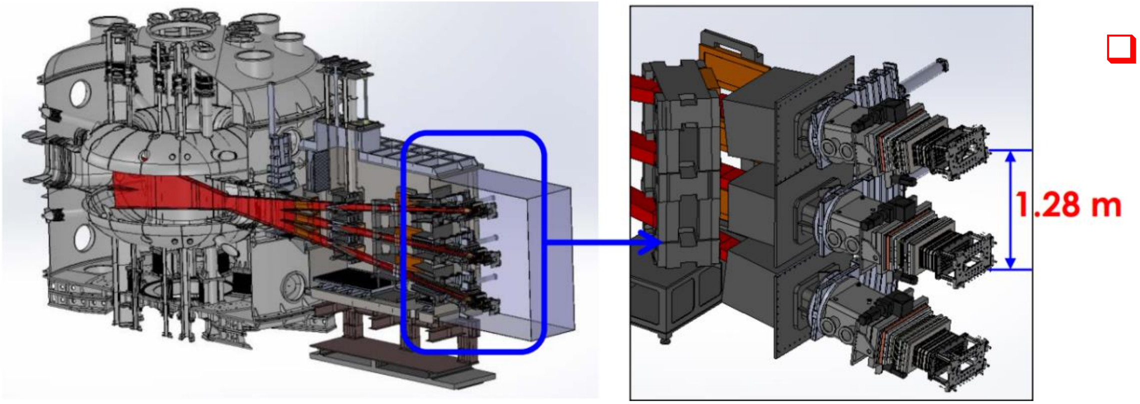
- Up to 75% NICF already reached in similar plasmas
- NBI ➔ 6.5 MW (4 sources)
- By altering I_P and B_T values, $\beta_N > 4$, up to KSTAR design target 5 can be achieved with 100% NICF

See CP11.00102: J.H. Ahn

New 2nd NBI system is installed in KSTAR aims to be available for 2018 run campaign



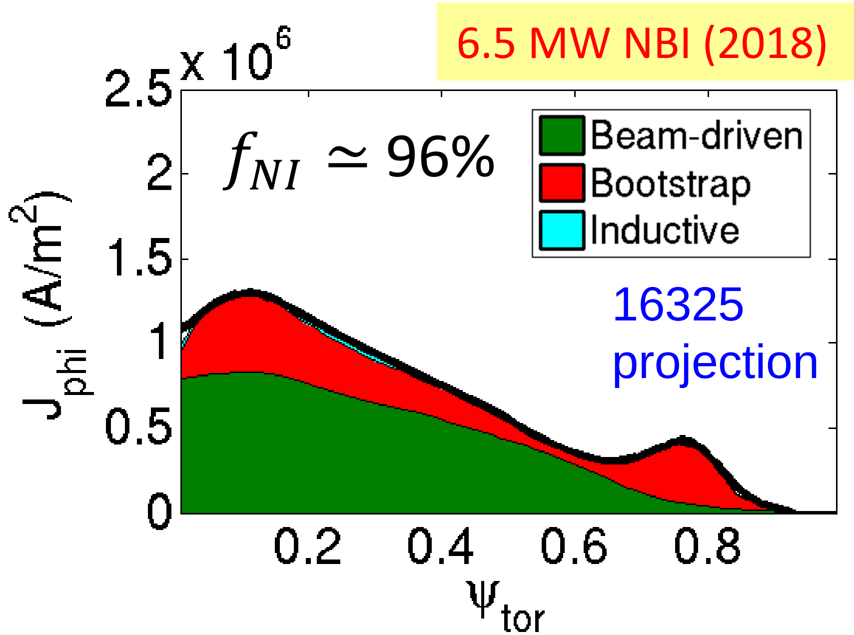




- Geometry of 2nd NBI system is included in TRANSP model
  - 2018 : upward-slanted source
  - 2019+ : all 3 sources available

→ $P_{NBI} \simeq 1.5$MW/source

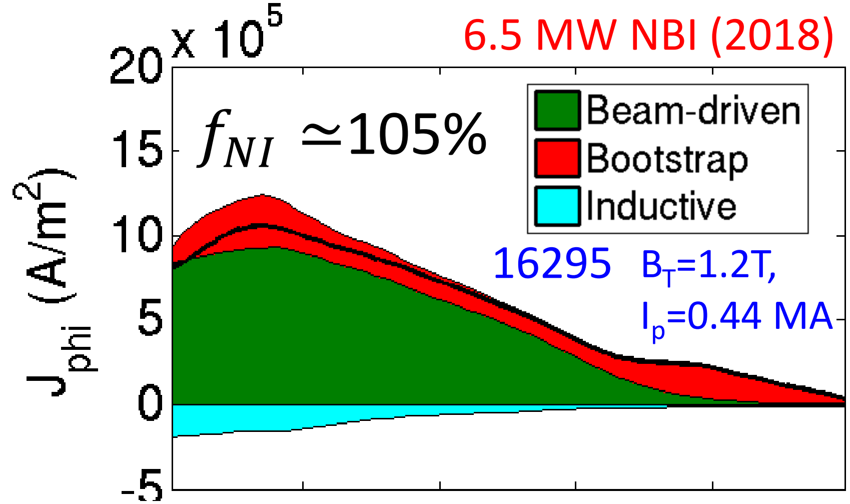
Predictive transport capability (TRANSP) allows "predict-first" projections for upcoming runs

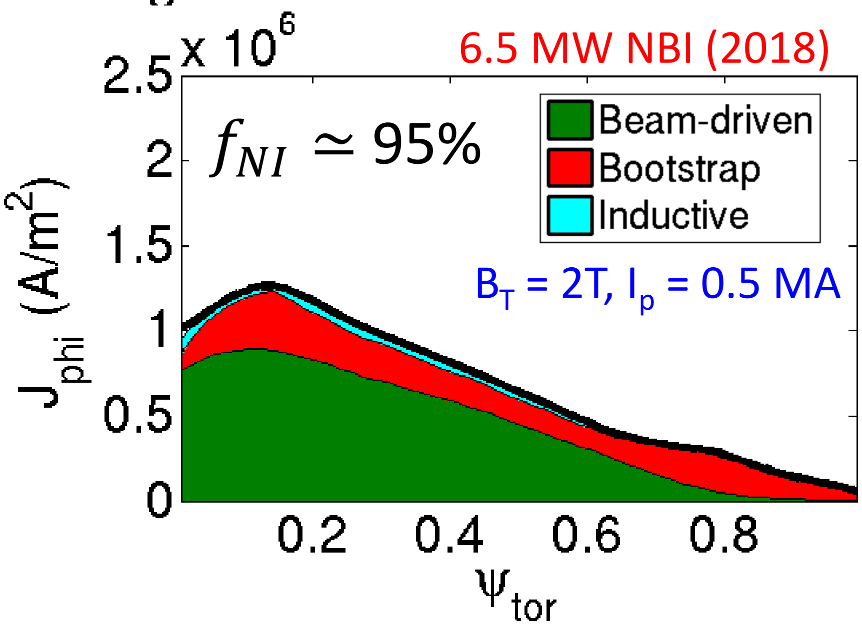


TRANSP 16325	2016 actual	2018 NBI	2019 NBI
NIC fract. (%)	71%	96%	130%
β_N	2.7	3.4	4.4
l_i	0.9	0.91	0.95
$T_i(0)$ (keV)	4.5	5.5	7.2
$T_e(0)$ (keV)	4.6	3.3	3.3
$n_e(0)$ ($10^{20}m^{-3}$)	5.2	5.6	5.5
$f_{Greenwald}$	0.5	0.5	0.5
H_{98y2}	1.25	1.25	1.25

- Project from existing KSTAR plasmas
  - Set fraction of Greenwald density and confinement factor ITER H_{98y2}
    - Neoclassical ion transport, electron transport set to match H_{98y2}
  - KSTAR 1st and 2nd NBI systems are modeled (incl. aiming angles); power levels set realistically based on MSE needs, etc.

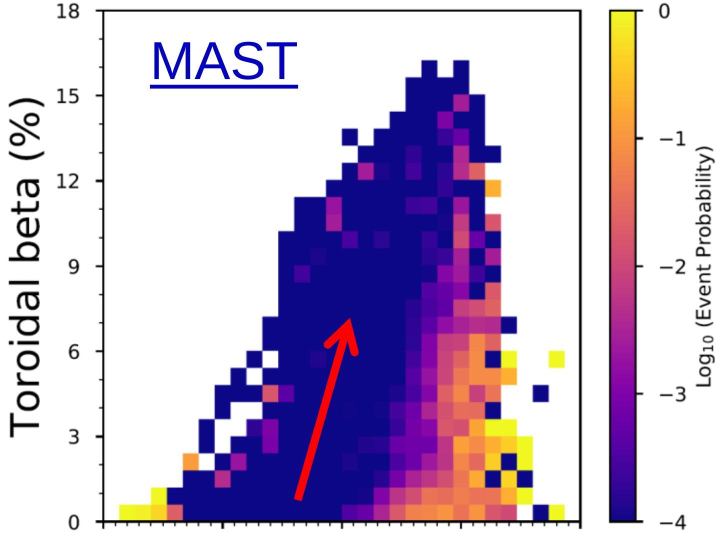
Transport analysis projections allow for variations of plasma parameters to meet targets

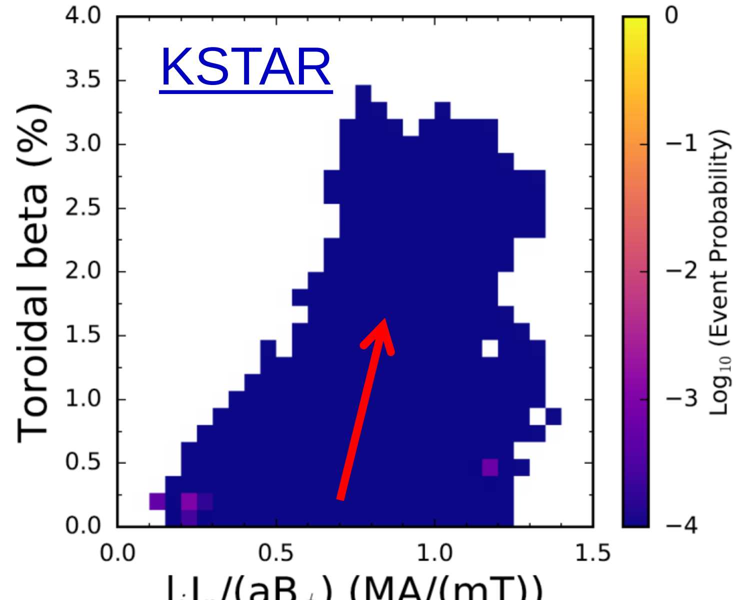


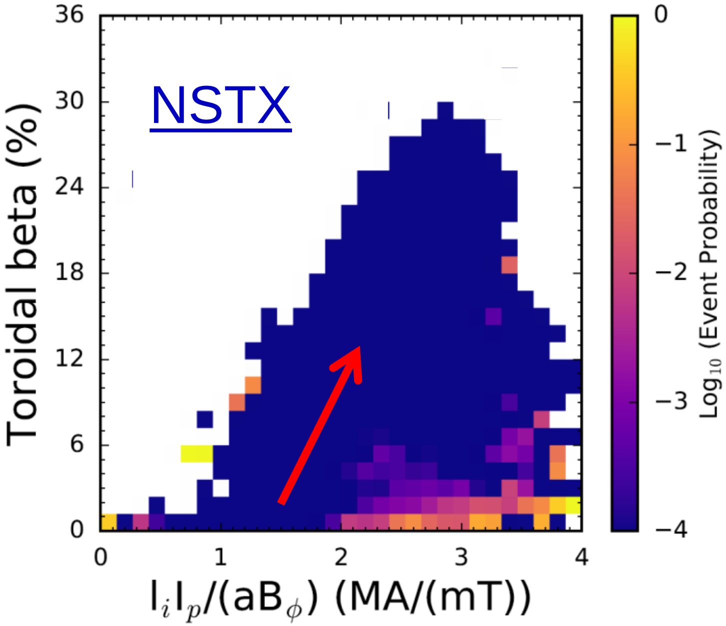


TRANSP 16295 (B_T; I_p)	2016 actual (1.2T)	2018 NBI (1.2T)	2018 NBI (2T, 0.5 MA)	2019 NBI
NIC fract. (%)	67%	105%	95%	126%
β_N	3.5	5.4	3.5	4.4
l_i	0.9	0.83	0.95	0.84
$T_i(0)$ (keV)	3.6	4.8	5.4	7.3
$T_e(0)$ (keV)	2.3	2.8	3.2	3.3
$n_e(0)$ ($10^{19}m^{-3}$)	6.0	4.8	5.6	5.6
$f_{Greenwald}$	0.6	0.5	0.5	0.5
H_{98y2}	1.25	1.25	1.25	1.25

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: 8902 plasmas analyzed
  - NSTX: 10,432 plasmas analyzed
  - KSTAR: 1309 plasmas analyzed