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Disruption Event Characterization and Forecasting (DECAF) in Tokamaks

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COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

27th IAEA Fusion Energy Conference

25 October 2018

Gandhinagar, India

MAST-U

KSTAR

NSTX-U

V1.4s

Supported by US DOE grants DE-SC0016614, DE-SC0018623, DE-FG02-99ER54524

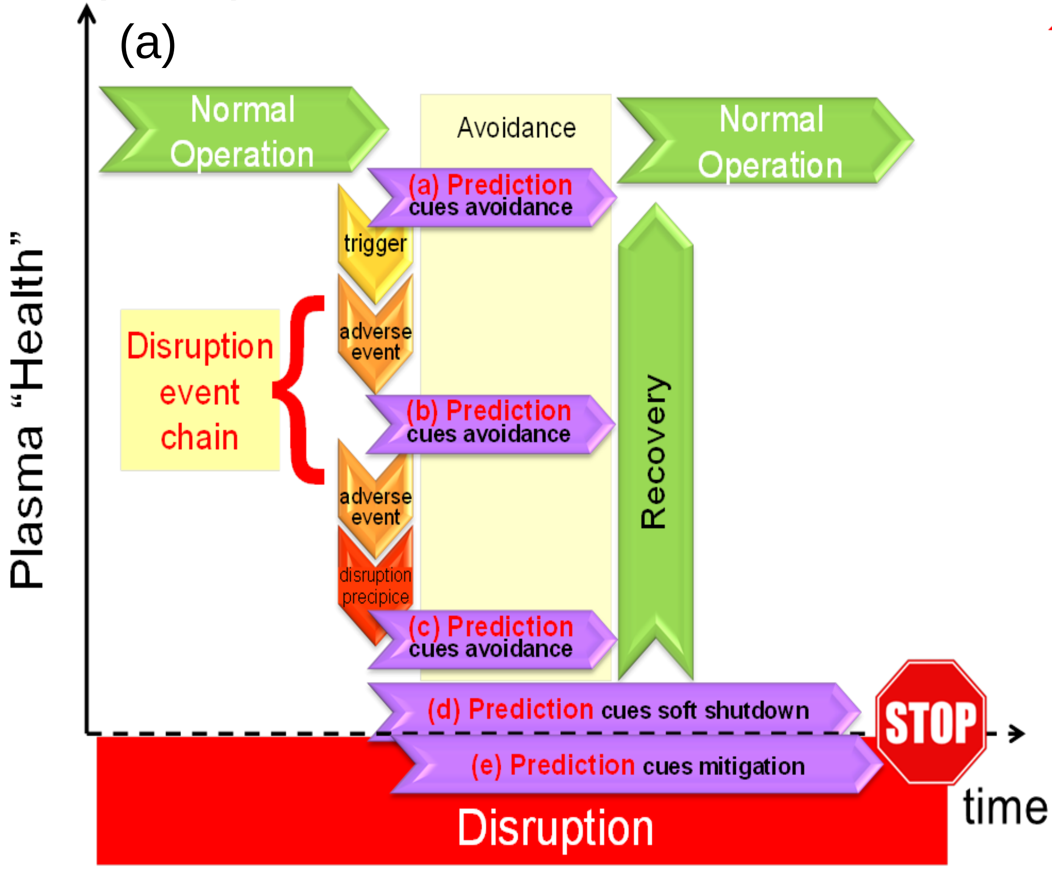
A broadened disruption prediction and avoidance analysis is progressing for ITER and future tokamaks

- Motivation: Disruption prediction/avoidance is a critical need
  - A highest priority DOE FES (Tier 1) initiative - present "grand challenge" in tokamak stability research:
    - Can be done! (JET: < 4% disruptions w/C wall, < 10% w/ITER-like wall)
    - ITER disruption allowance: < 1 - 2% (energy + E&M loads); << 1% (runaways)

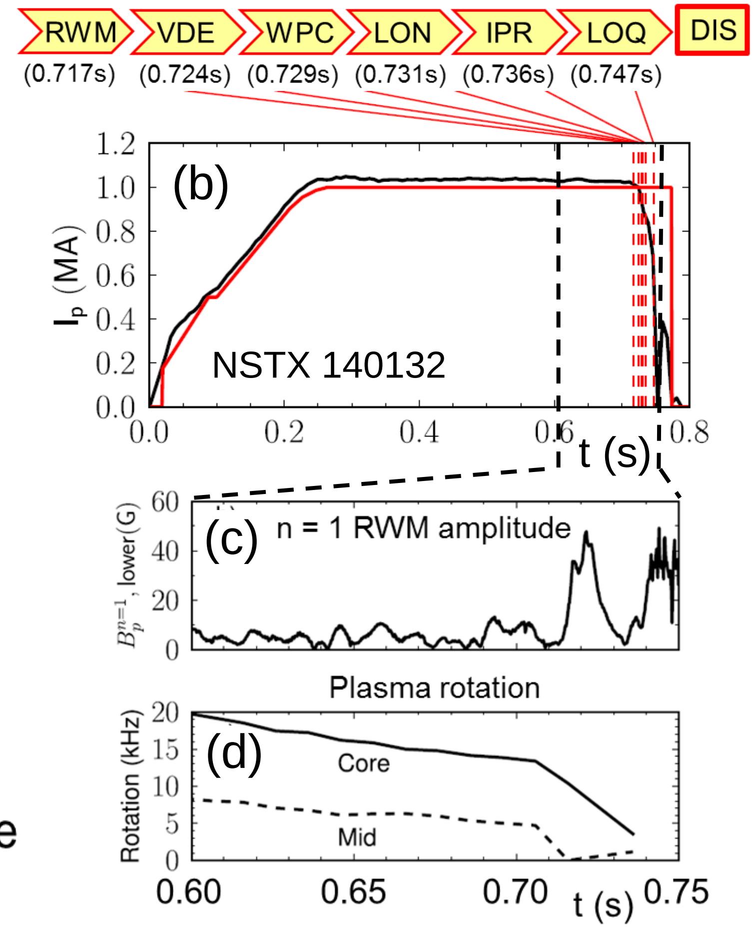
- Talk Outline
  - Disruption Event Characterization and Forecasting (DECAF) introduction
  - Present DECAF progress and initial multi-device examination (now including MAST)
    - Density limits, disruption forecasting w/ rotating MHD, global MHD forecasting
    - Disruption event chain analysis for arbitrary discharges
  - Key supporting analysis
    - KSTAR ideal/resistive stability analysis, high normalized beta, high non-inductive plasmas with 100% NICF "predict-first" projections

Disruption event characterization is a critical and logical step in a disruption avoidance plan

Disruption prediction/avoidance framework



Disruption event chain



- 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)

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

DECAF brief highlights of prior results

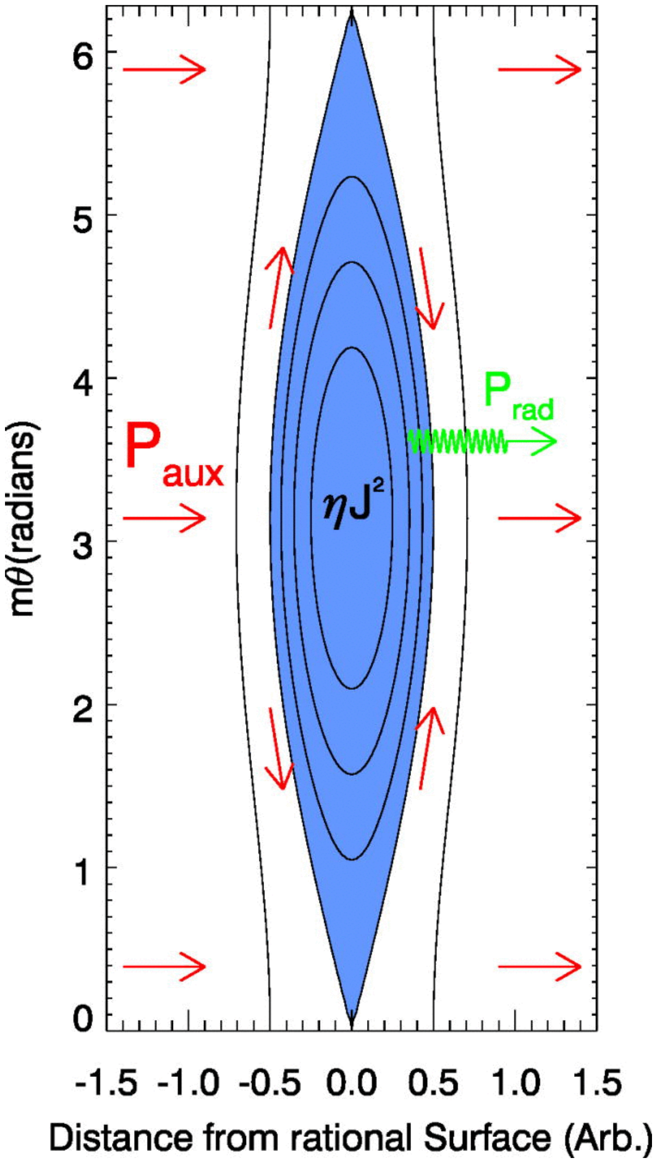
- First automated event chain analysis (followed deVries' manual work)
- Excellent performance on smaller, targeted databases (NSTX)
  - Ex.: DIS, WPC, IPR, LOQ, RWM events found 100%, VDE event 91%
  - Computed events accurately represented experiment (~ 10 events)
  - Physics model forecasted global 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
- Multi-machine database processing with small number of verified events
- Analysis of disruption chains from general databases

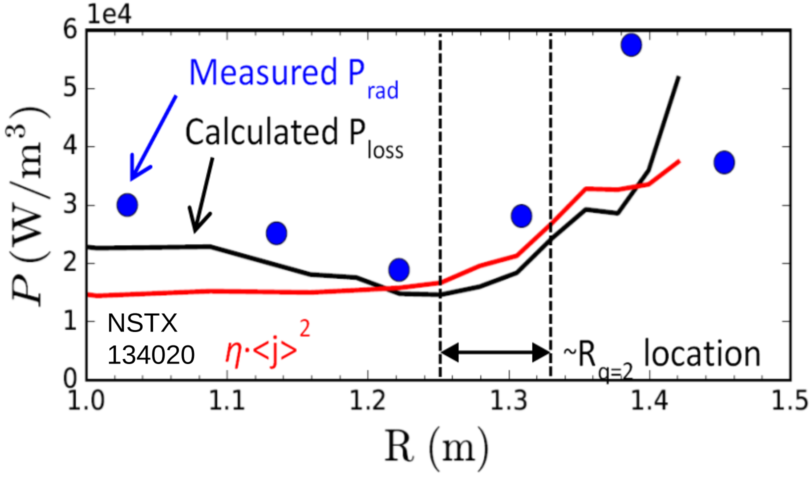
Recently a density limit model has been examined in DECAF based on power balance in an island



- 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

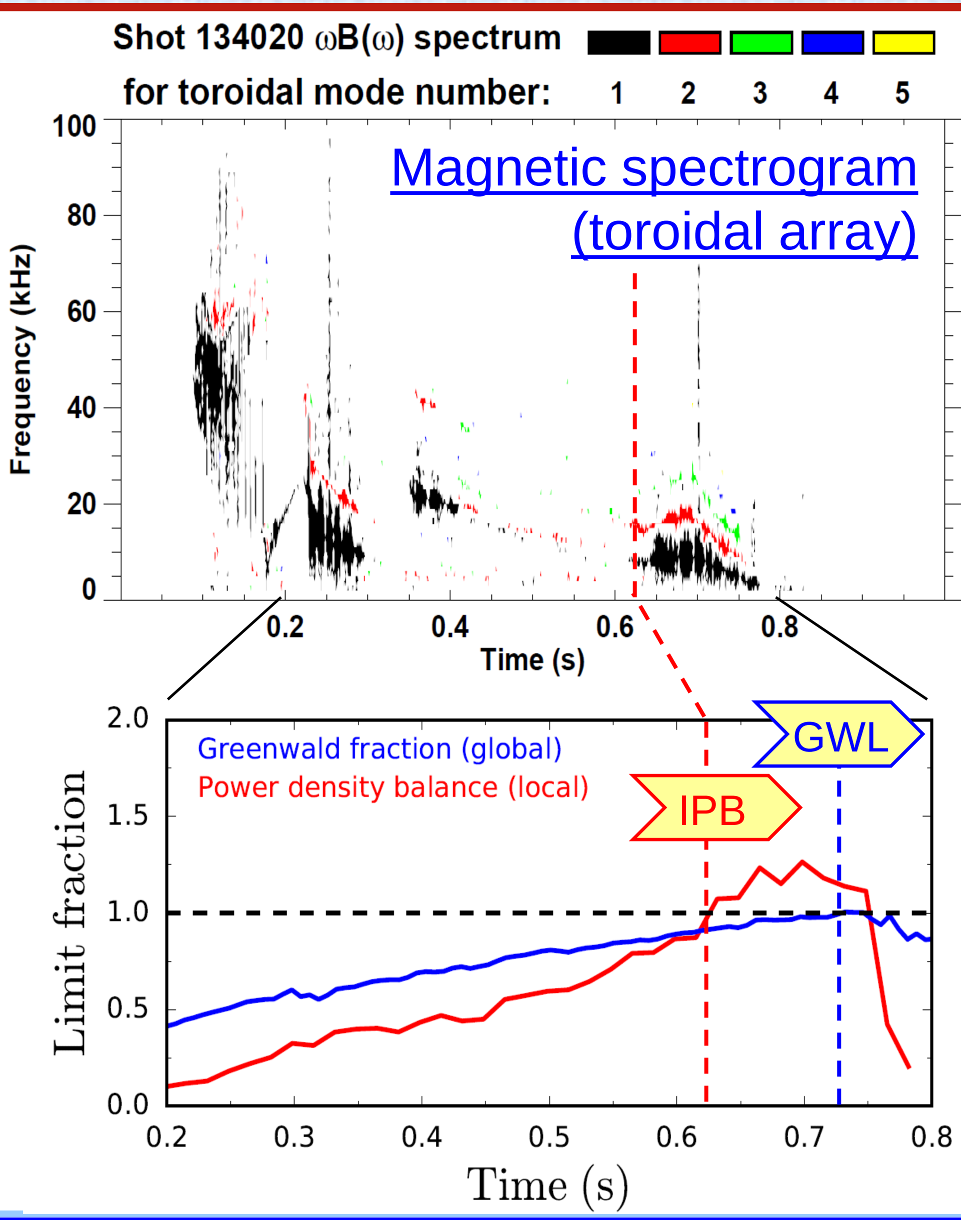
Power density balance: $P_{\text{loss}} < P_{\text{input}}$

$$n_e n_{\text{D}} L_{\text{D}}(T_e) + \sum n_e n_Z L_Z(T_e) < \eta j^2$$

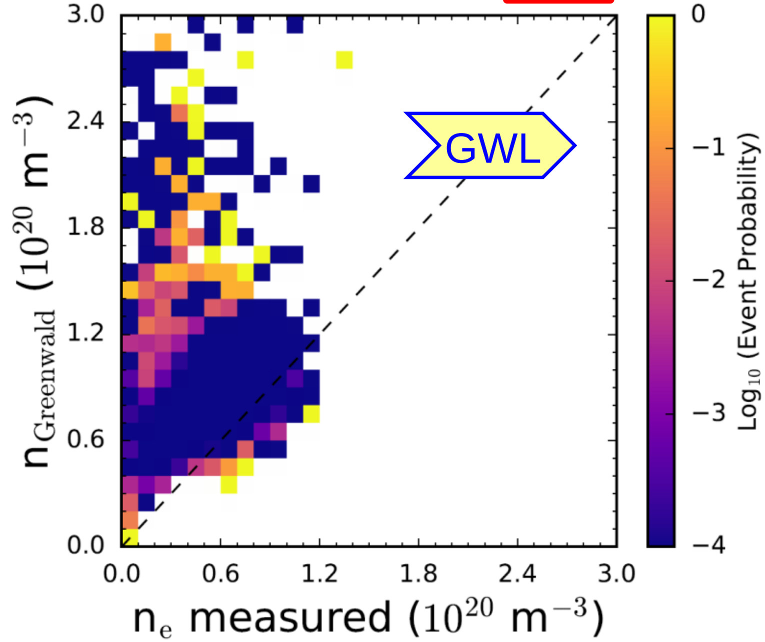


D. Gates et al., Phys. Rev. Lett. **108** 165004 (2012)

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

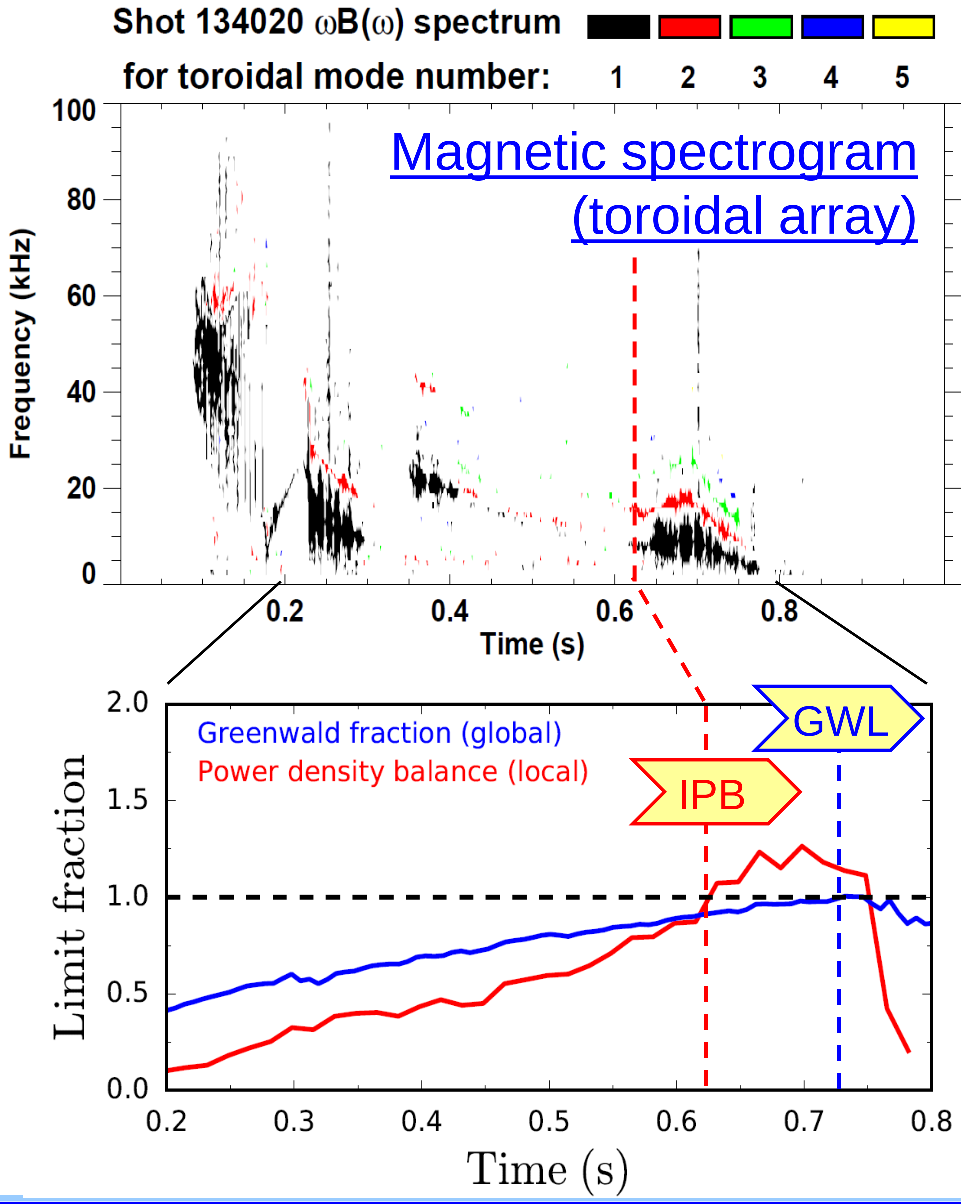


Disruptivity vs. density DIS

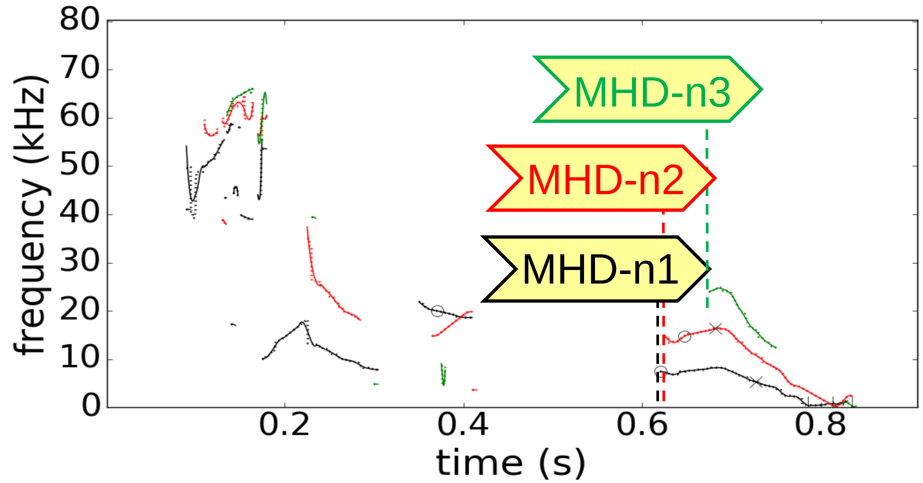


- Greenwald limit GWL
  - Near 0.9 when mode starts (range 0.75 – 1.05)
- Rad. island power balance IPB
  - Near 1.0 when mode starts (range 0.60 – 1.50) ← next step: must reduce range

More powerful automated MHD event objects have been developed for DECAF

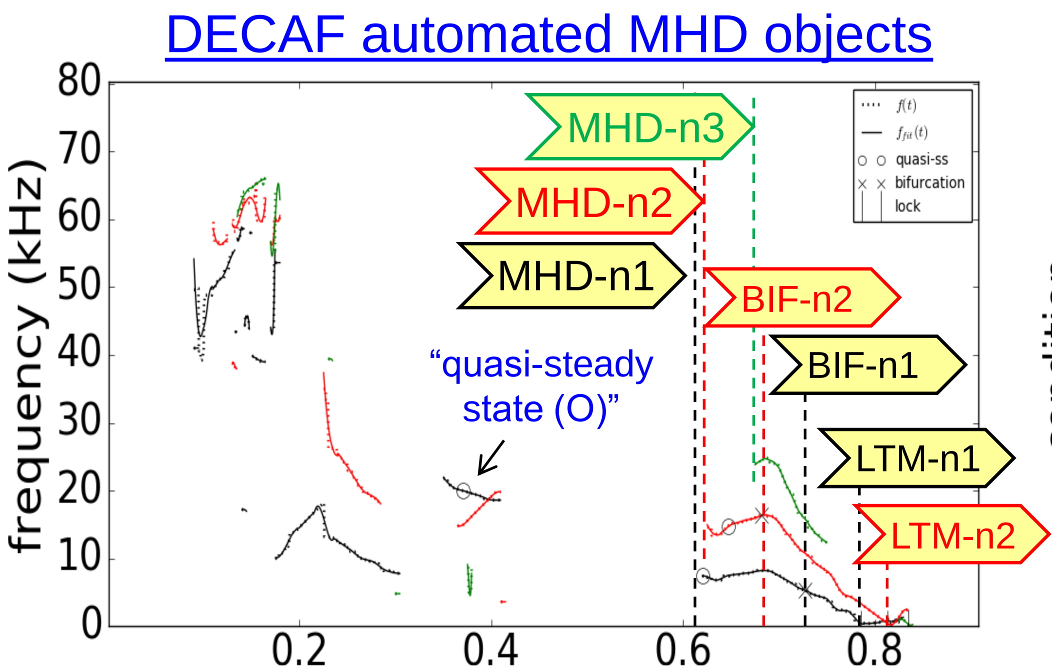


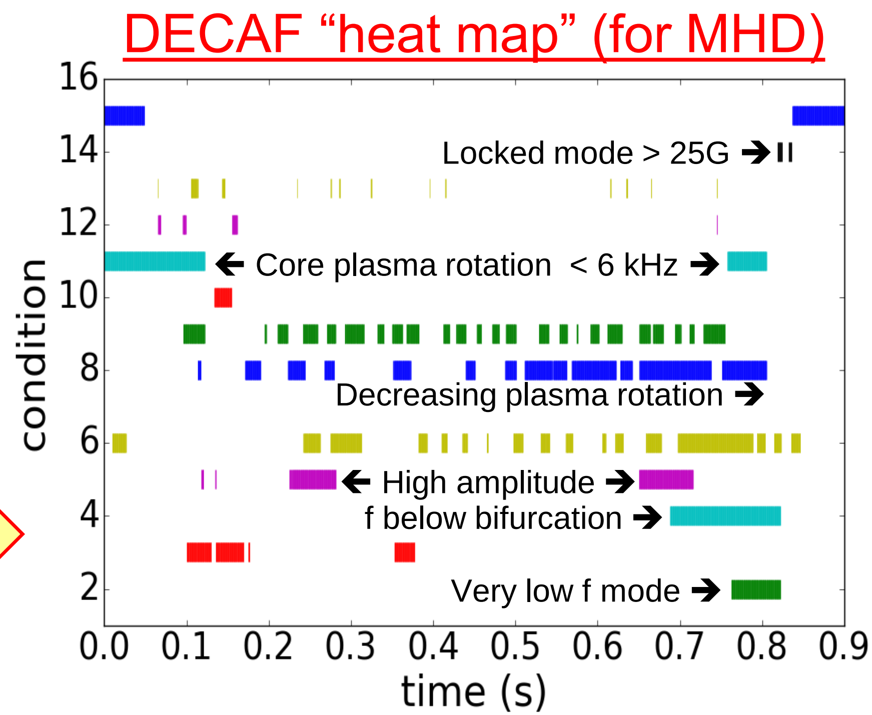
DECAF automated MHD events

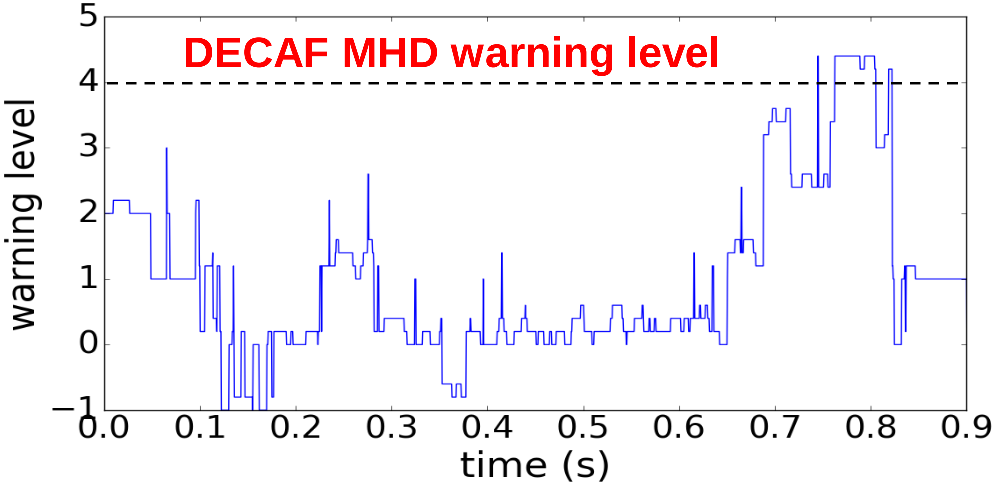


- More capable MHD event objects required for analysis of wider tokamak databases
- DECAF MHD events now include
  - Mode number (n) discrimination
  - Full history of mode evolution, including bifurcation and locking
  - Many disruption warning criteria

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

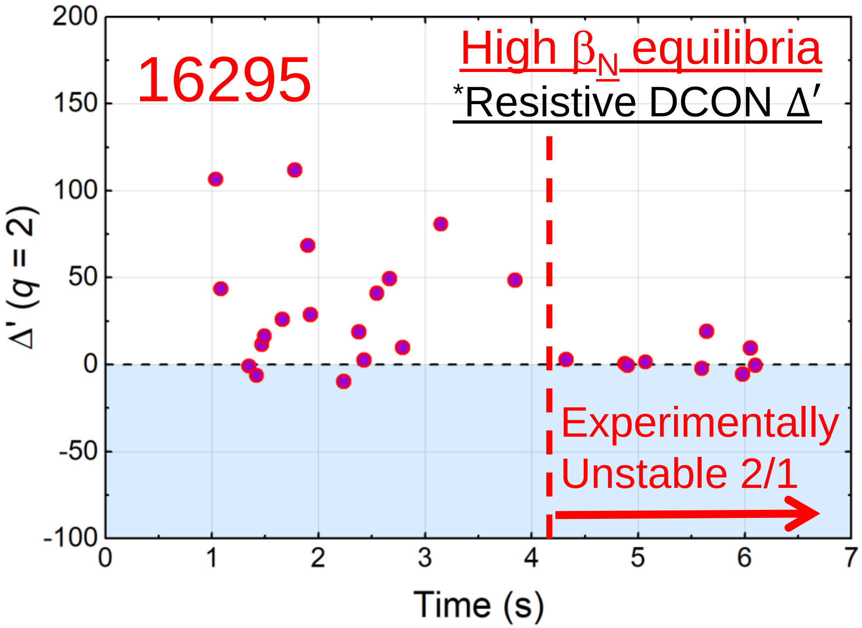


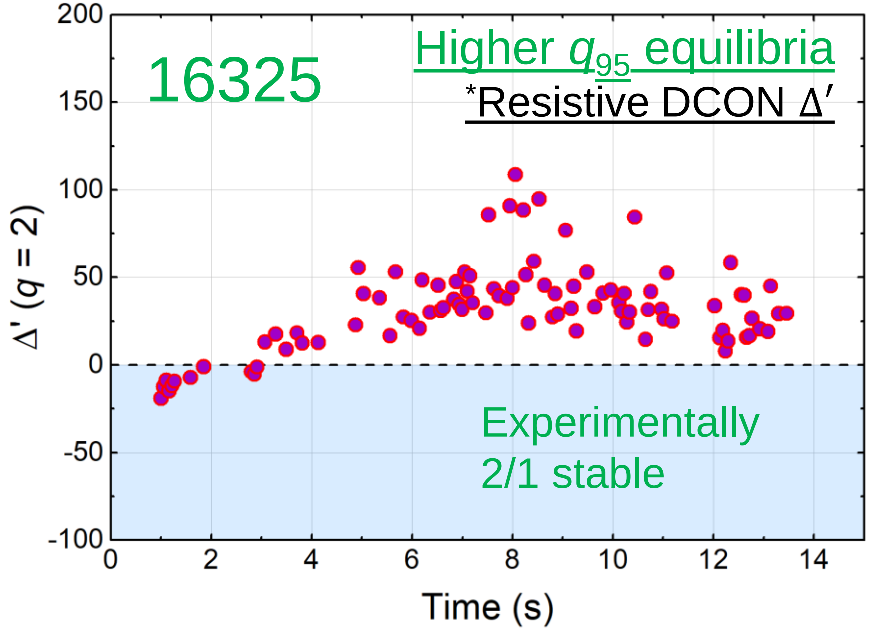




- Key notables of MHD warning
  - "Safe"/"unsafe" MHD periods found
  - Early, slow warning level evolution
    - Locked mode amplitude important, but warning comes in very late
  - Mode frequency below bifurcation, decreasing plasma rotation key

Classical tearing stability examined in KSTAR plasmas varied β_N , q_{95} (for future DECAF models)





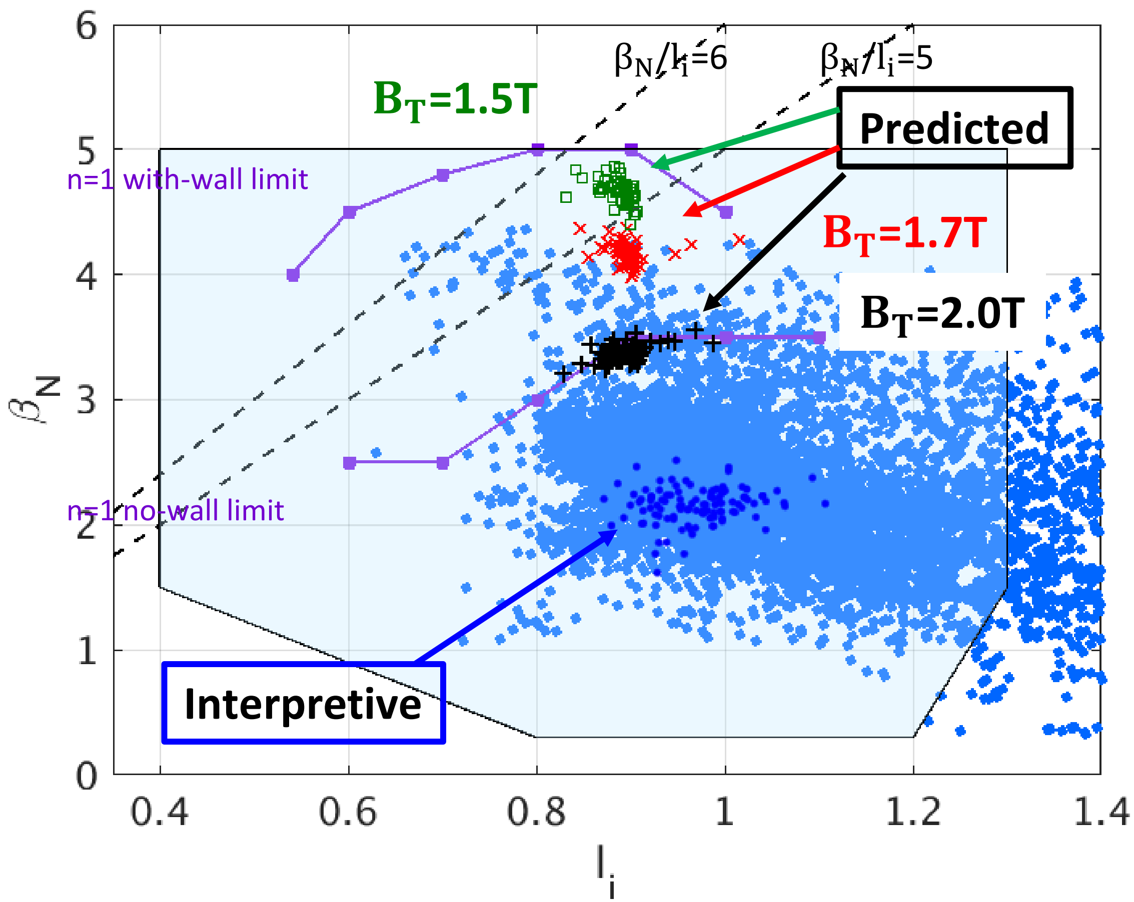
- Classical tearing stability index, Δ', computed at the q = 2 surface using outer layer solutions
- At higher q_{95}, Δ' is mostly positive predicting unstable classical tearing mode
  - Indicates that neoclassical effects or wall effects need to be invoked to produce stability

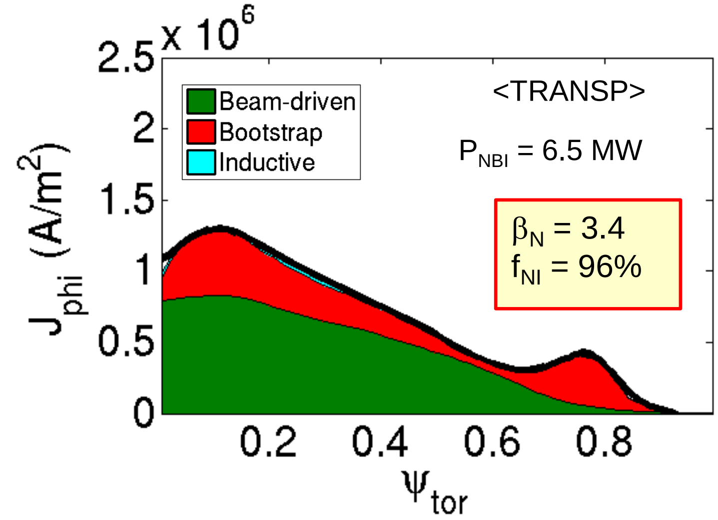
*A.H. Glasser, *et al*., Phys. Plasmas **23** (2016) 112506

See paper EX/P7-16 this conference (Friday) Y.S. Park, S.A. Sabbagh, J.H. Ahn, et al., for further detail

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



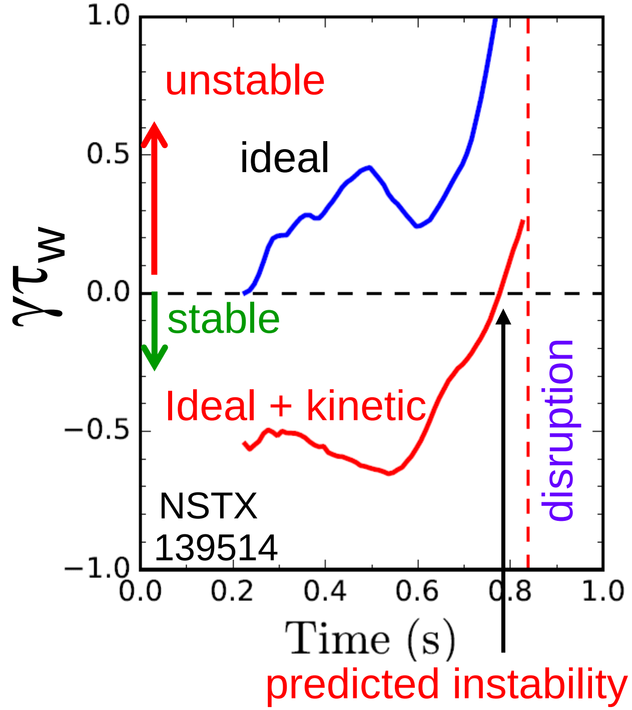


- Up to 75% NICF already reached at high beta
- NBI ➔ 6.5 MW in 2018
- By altering I_P and B_T values, $\beta_N > 4$, up to KSTAR design target 5 can be achieved with 100% NICF

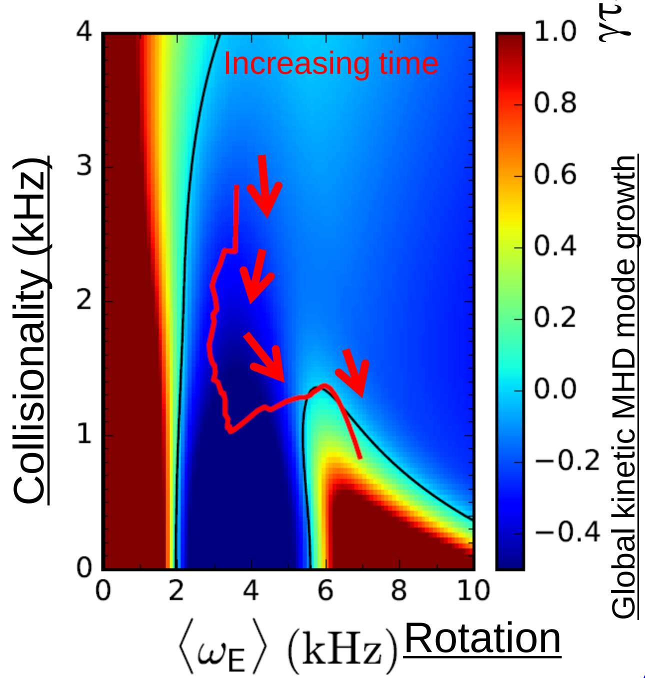
See paper EX/P7-16 this conference (Friday) Y.S. Park, S.A. Sabbagh, J.H. Ahn, et al., for further detail

DECAF reduced kinetic MHD model computations forecast the instability boundary to unstable global MHD modes

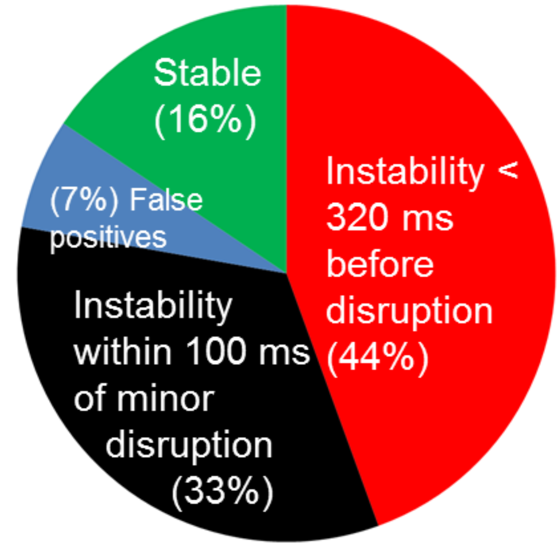
Norm. growth rate vs. time



Disruption forecasting



Predicted instability statistics



- Favorable characteristics
  - Stability contours CHANGE for each time point
  - Possible to compute growth rate prediction in real time

- 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

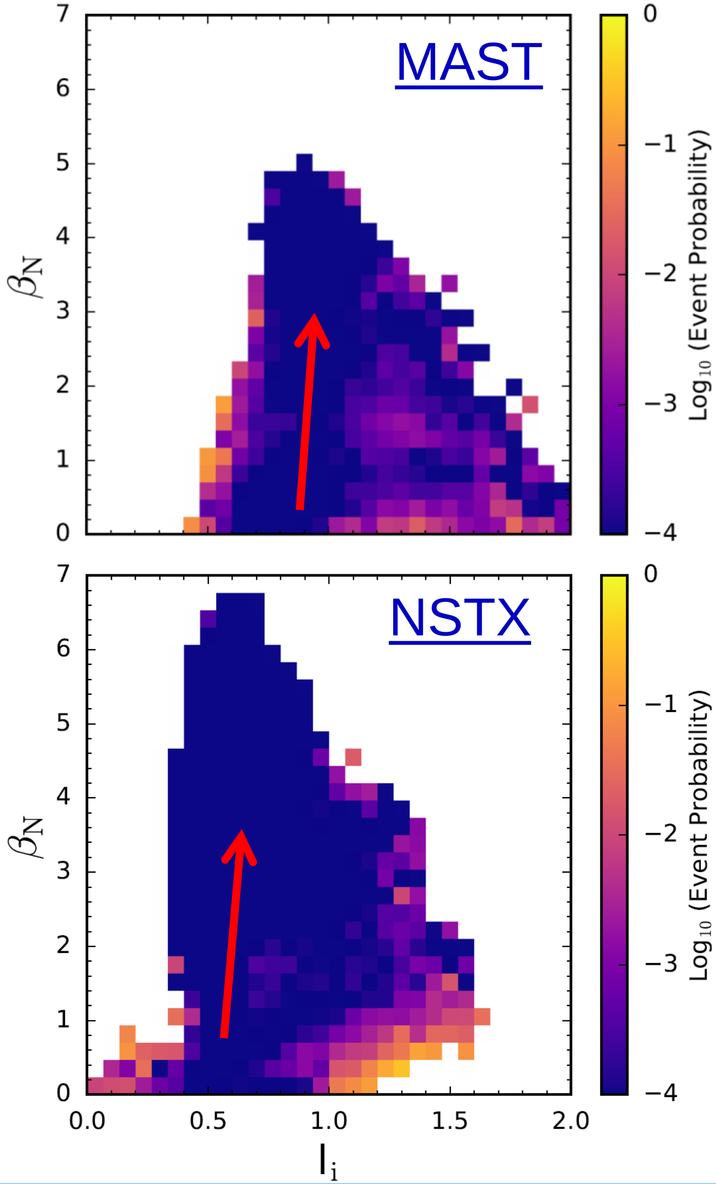
Progress on DECAF now moving to processing of multi-machine databases

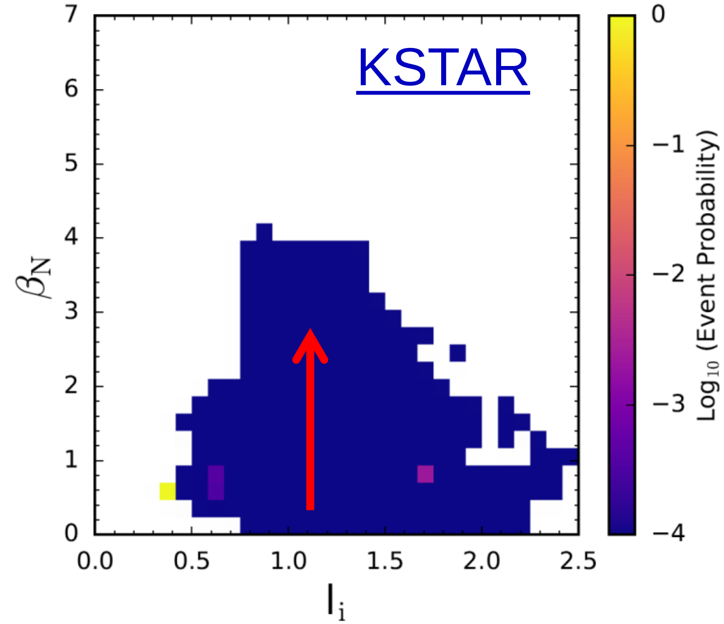
- Analysis
  - Kinetic equilibrium / stability analysis on KSTAR; planned for MAST
- DECAF database started
  - Requires storage of DECAF analysis

Device / Capability	KSTAR	MAST	NSTX	DIII-D	TCV
Full database access (type)	Yes (MDSplus)	Yes (UDA)	Yes (MDSplus)	Yes (MDSplus)	Yes (MDSplus)
Database analysis	started	started	started		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 AUG next, then JET and C-Mod databases

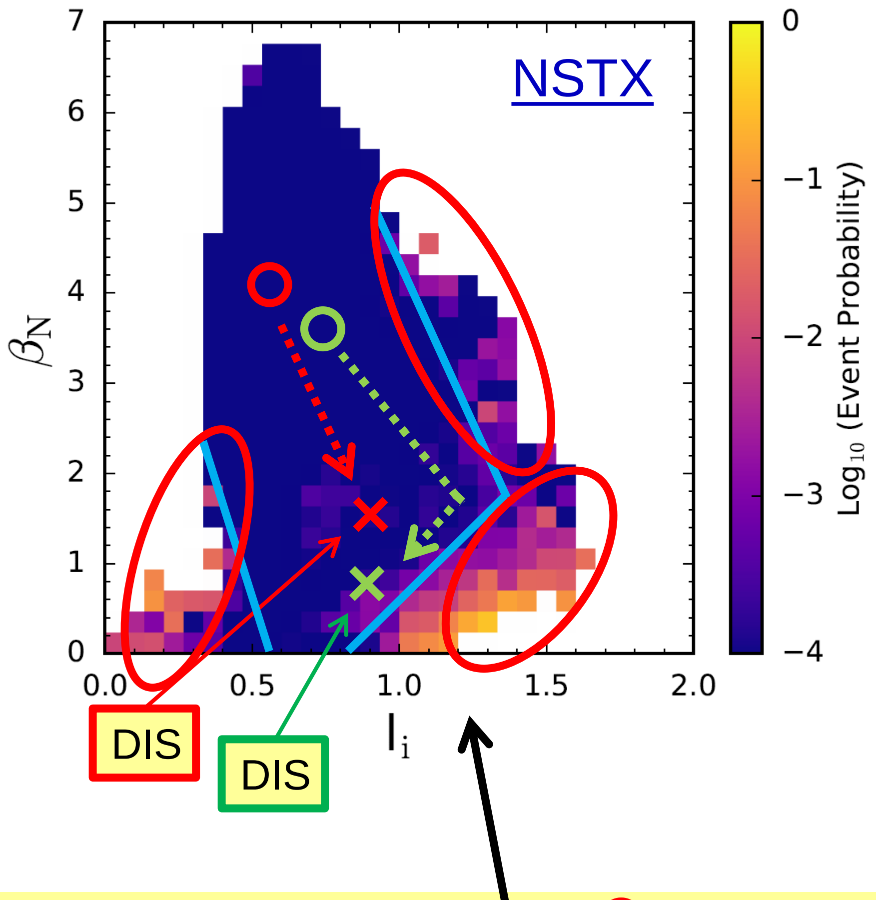
Initial analysis of large databases further supports published result that disruptivity doesn't increase with β_N





- DECAF analysis of DIS event
  - Shots analyzed at 10 ms intervals
  - NEXT STEP: DECAF event chain analysis
- Analysis during I_p flat-top
  - MAST: 8902 plasmas analyzed
  - NSTX: 10,432 plasmas analyzed
  - KSTAR: 1309 plasmas analyzed

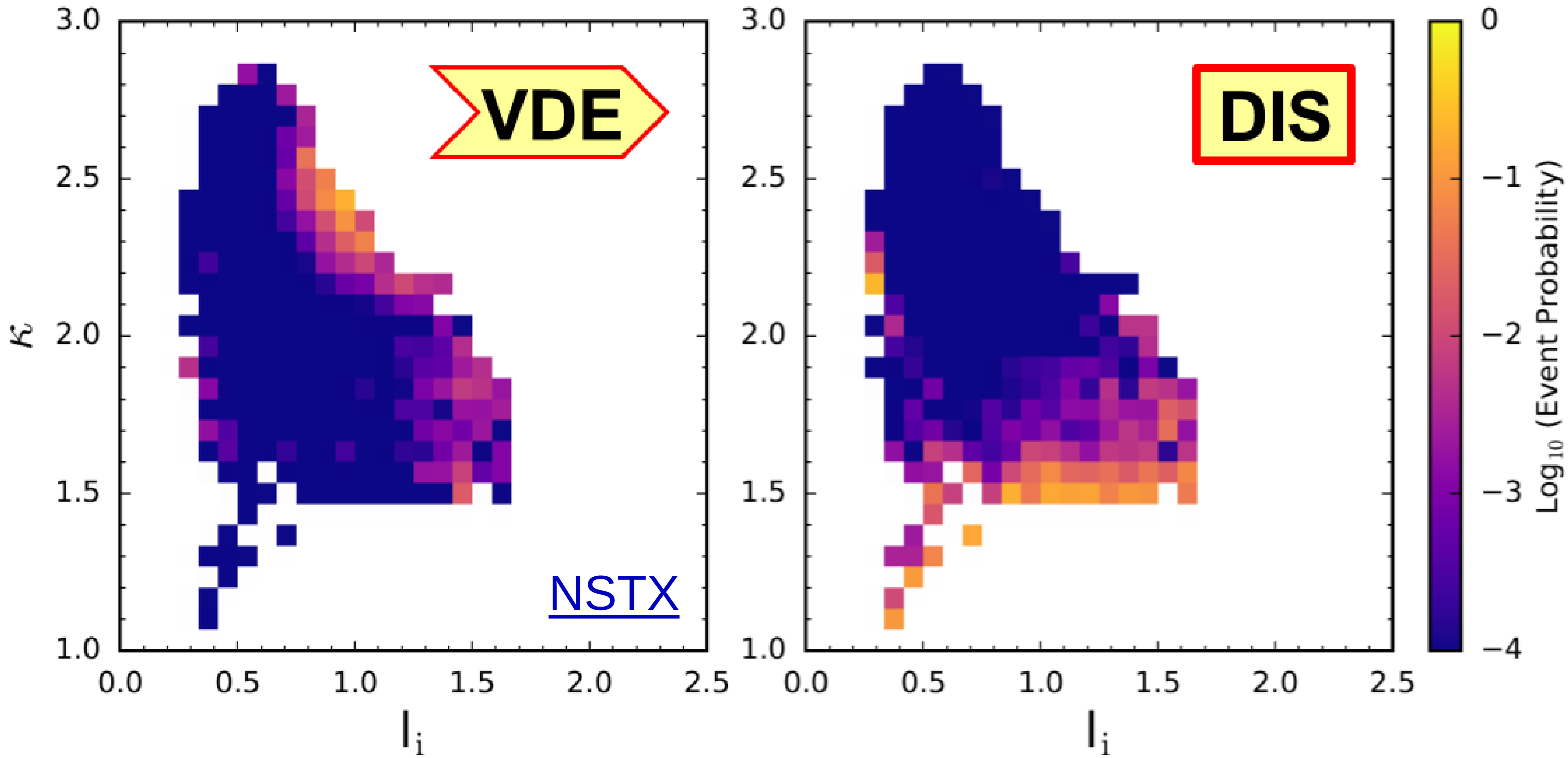
While disruptivity plots provide important information, they can be misleading when used incorrectly



- Example: What are the most important regions to study on this plot?
  - A human might focus on the high event probability regions
  - Machine learning alone might segregate disruptive from non-disruptive regions of the plot and learn from that division
  - Problem ➔plasma conditions can change significantly between first problem detected and when disruption happens

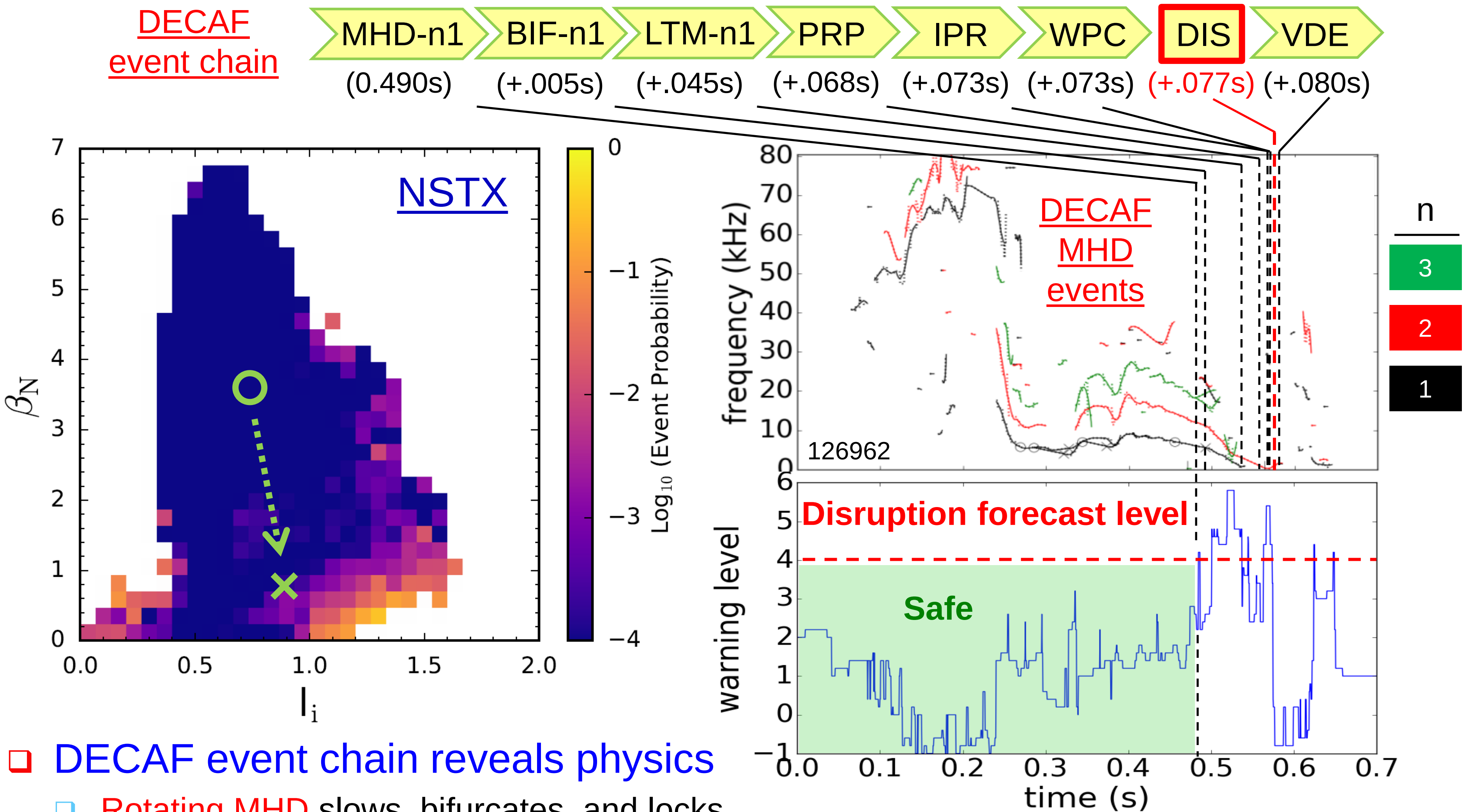
- Answer: the circles mark the key region to study!
  - The shots suffer different "events" that are started in this region, and end up far from that region when they disrupt (at the crosses)

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



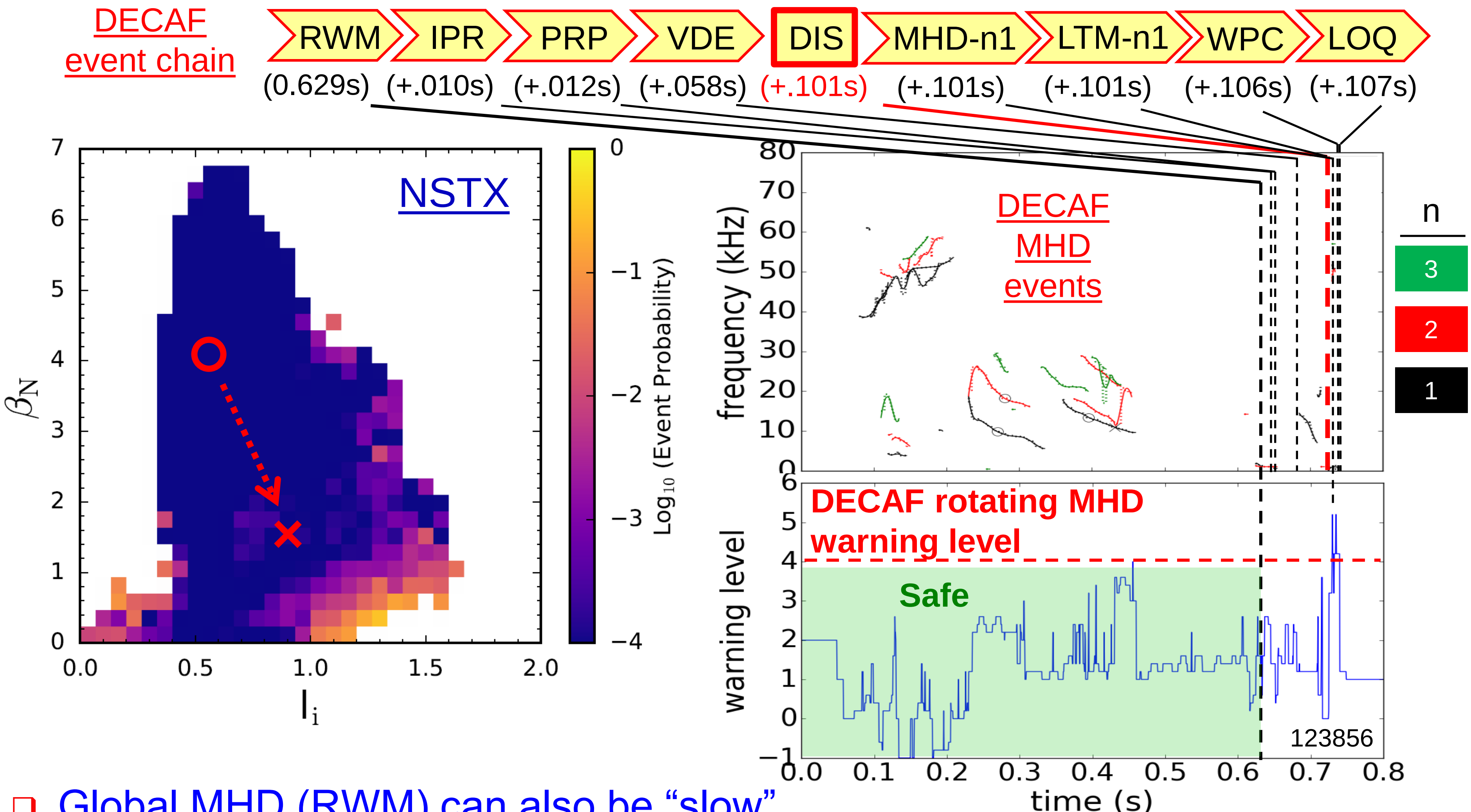
- Largest portion of detected VDE events appear at (l_i, κ) with very small portion of DIS events detected

DECAF provides an early disruption forecast - on transport timescales – 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
  - Early warning gives the potential for disruption avoidance by plasma profile control

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



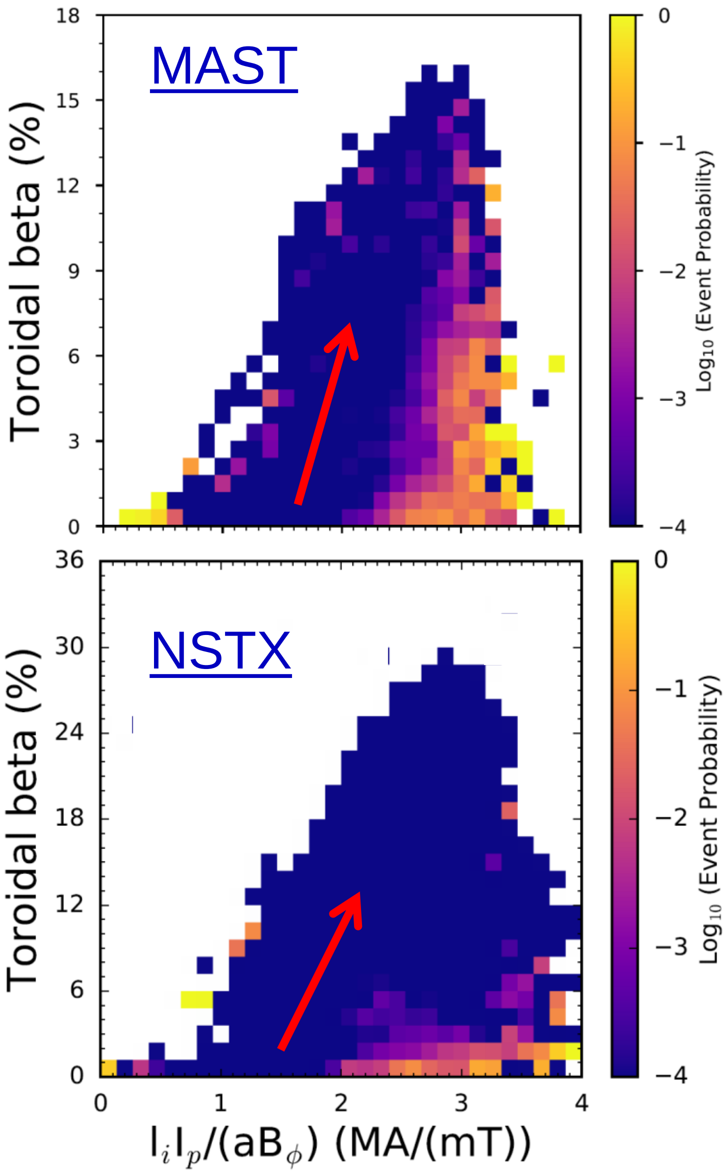
- Global MHD (RWM) can also be “slow”
  - Rotating MHD warning level decreases after 0.46s ➔ DANGEROUS for RWM onset!
  - H – L back transition (PRP) drags out time to disruption (> 100 ms – transport timescale)

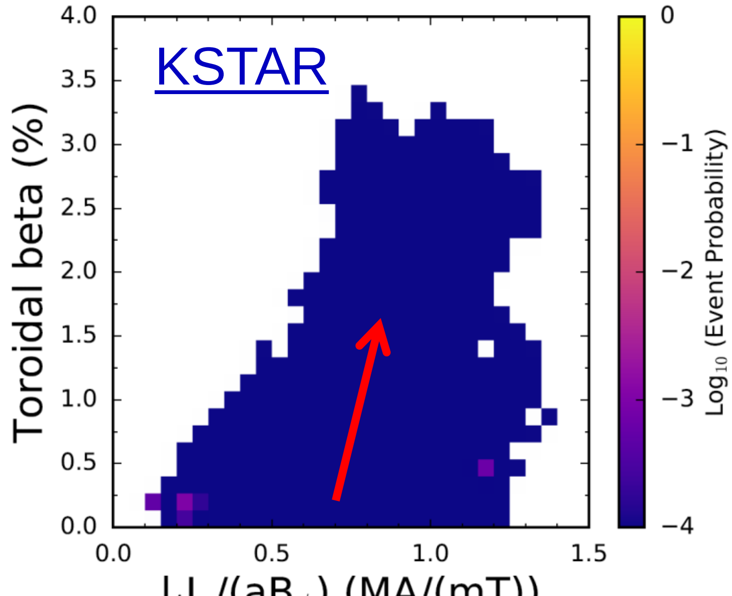
Rapidly-expanding DECAF code provides a new paradigm for disruption prediction research

- Multi-faceted, integrated approach to disruption prediction and avoidance with several key characteristics
  - Physics-based approach yields understanding of evolution toward disruptionss needed for confident extrapolation of forecasting
  - Physics-based DECAF events can guide how to avoid disruption
  - Full multi-machine databases used (full databases needed!)
  - Open to all methods of data analysis (physics, machine learning, etc.)
- DECAF analysis producing early warning disruption forecasts
  - Sufficiently early for potential disruption avoidance by profile control
- Next steps
  - Expand number of DECAF events evaluated in large database analysis
  - Begin evaluation of simple quantitative disruption forecasting figures of merit on expanded databases ➔ first results are imminent

Sign-up Sheet for Reprints (include email address)

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

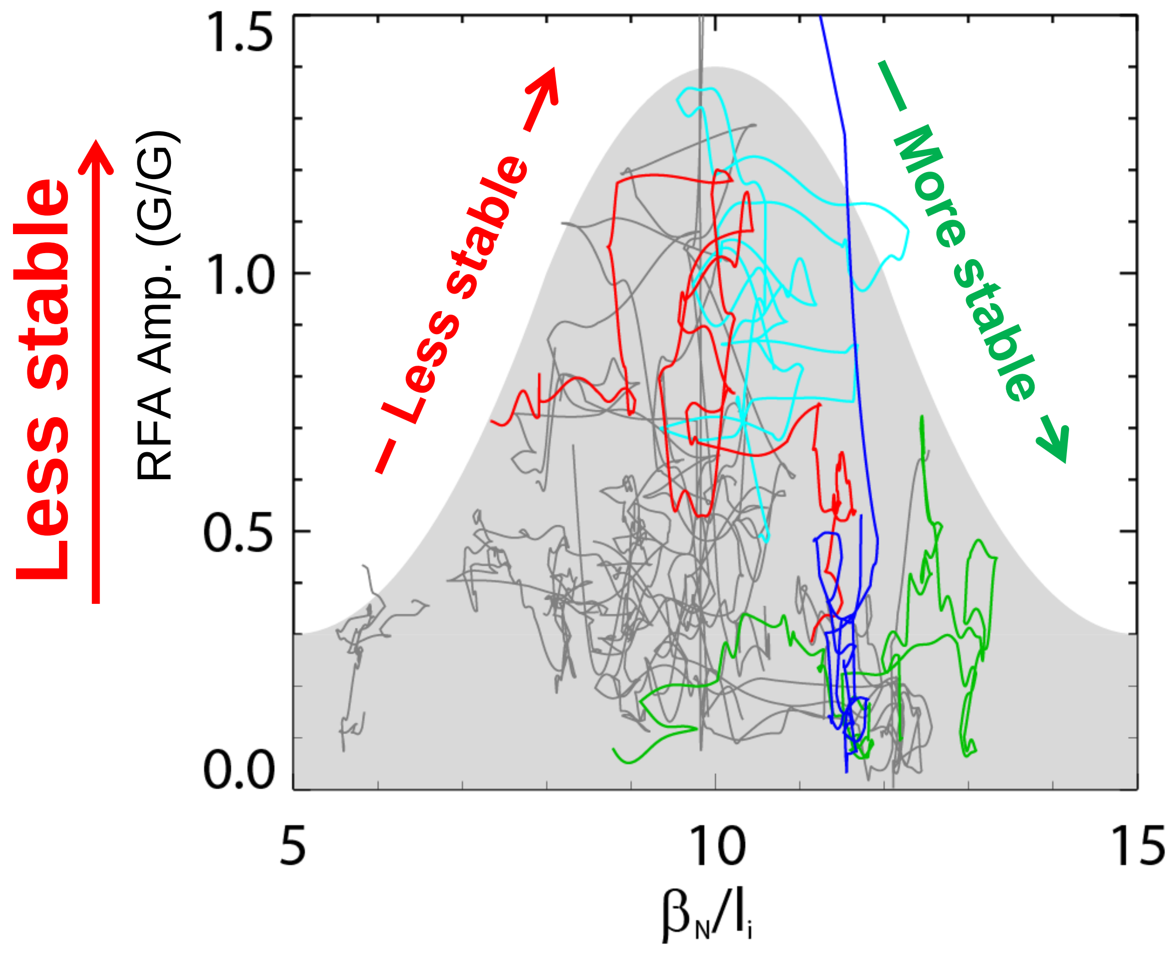




- DECAF analysis of **DIS** event
  - Similar to a "standard" disruptivity analysis
  - Shots analyzed at 10 ms intervals
- Analysis during I_p flat-top
  - MAST: 8902 plasmas analyzed
  - NSTX: 10,432 plasmas analyzed
  - KSTAR: 1309 plasmas analyzed

Experiments directly measuring global MHD stability verify that highest β_N/l_i is ***not*** the least stable scenario (NSTX)

Resonant Field Amplification (RFA) measurement of stability



- *Non-intuitive* stability increase at high β_N/l_i
  - decreases up to β_N/l_i = 10, ***increases*** at higher β_N/l_i

- Understanding: Results consistent with kinetic stabilization theory invoking physical resonances

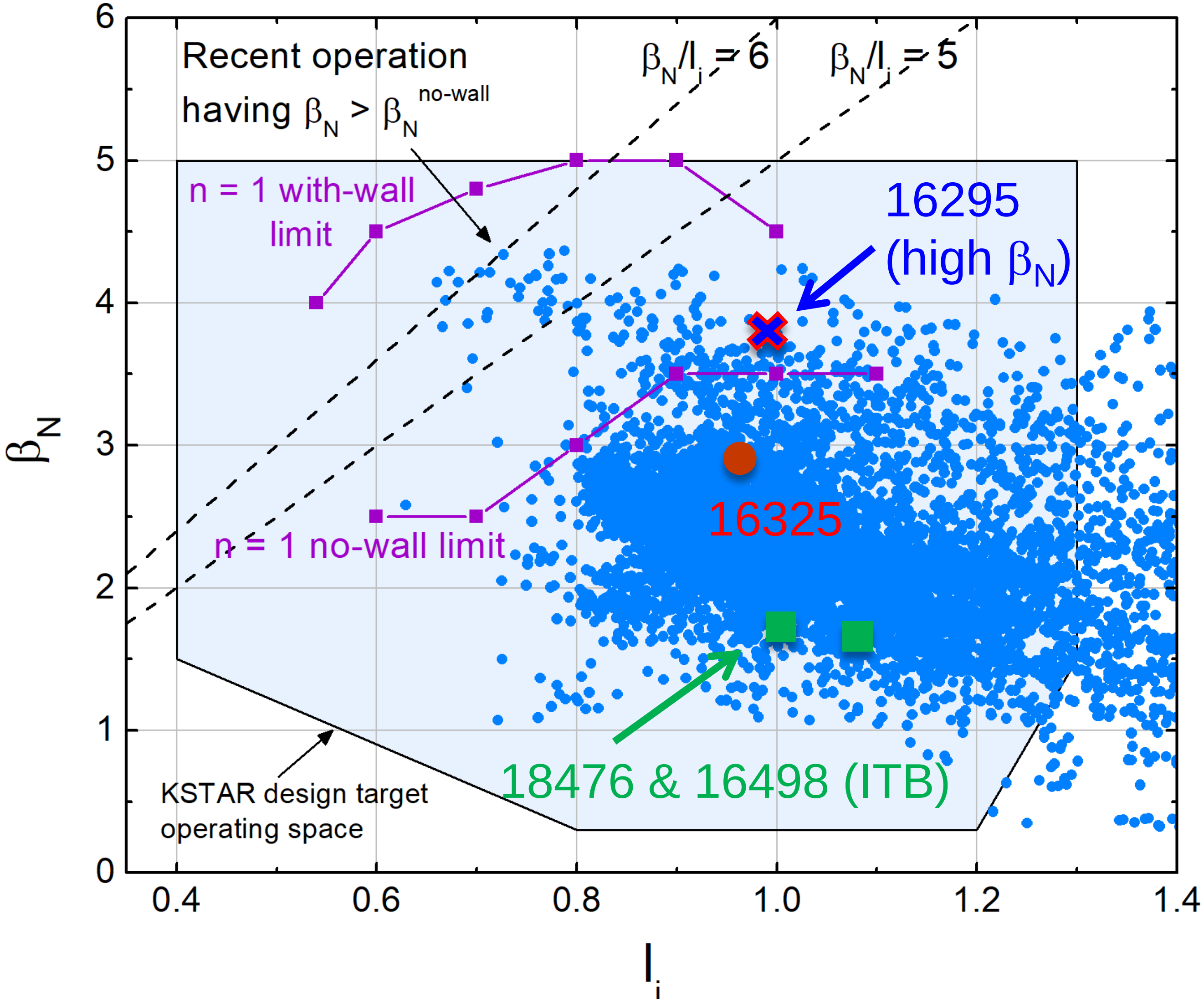
J. Berkery, et al., PoP **21** (2014) 156112

S. Sabbagh,et al., **2016 EPS Landau-Spitzer Award lecture**

DECAF is fueled by coordinated research that continues to validate/develop physics models

- Global MHD
  - Detection: available magnetic diagnostics, plasma rotation, equilibrium
  - Forecasting: Kinetic MHD model has high success in NSTX, DIII-D
- 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
- Physics analysis / experiments to build DECAF models
  - Interpretive and "predict-first" analysis of KSTAR long-pulse, high beta plasmas with high non-inductive fraction

KSTAR kinetic equilibria w/ MSE are examined in the context of past published database

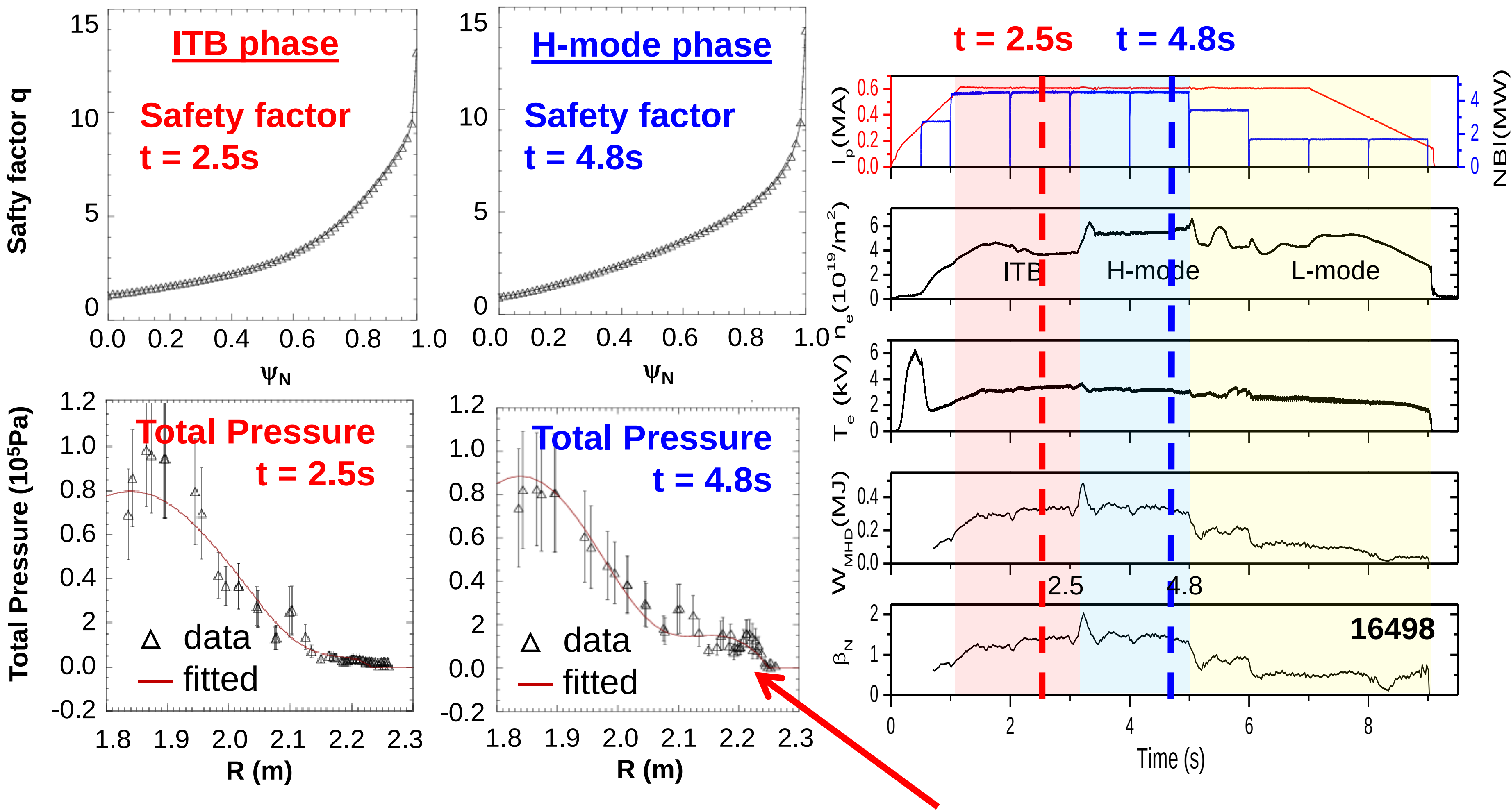


Examples in talk

- 16295
  - High β_N plasma
- 16325
  - Higher B_T (q_{95})
  - Higher edge bootstrap current
- 18476 & 16498
  - Internal Transport Barrier **(ITB)**
- Many thousands of kinetic equilibria run during testing

Y.S. Park, S.A. Sabbagh, *et al*., Nucl. Fusion **53** (2013) 083029 (magnetics-only)

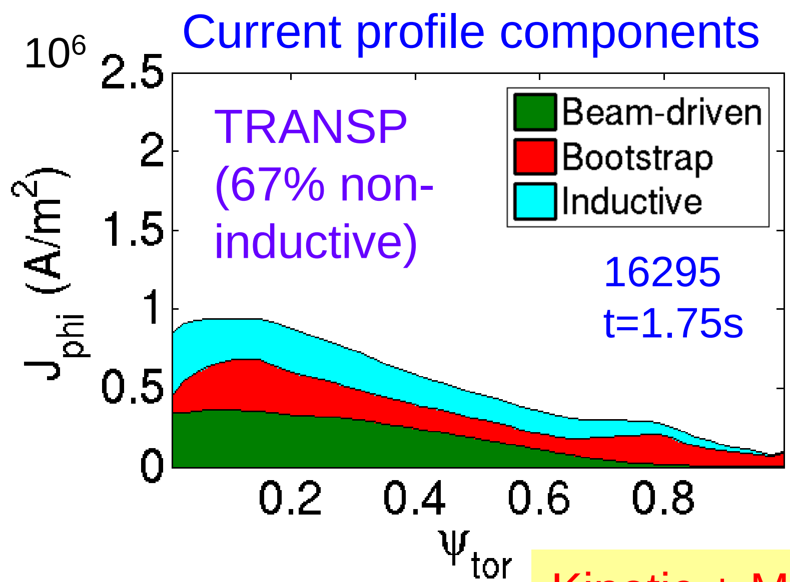
Clear pressure profile distinction between Internal Transport Barrier and H-mode phases

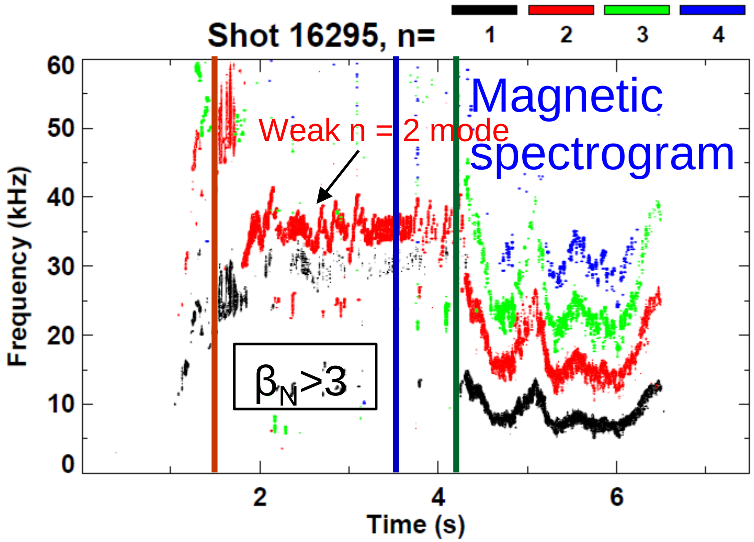


- Broad pedestal pressure reconstructed in H-mode is not observed in earlier ITB phase

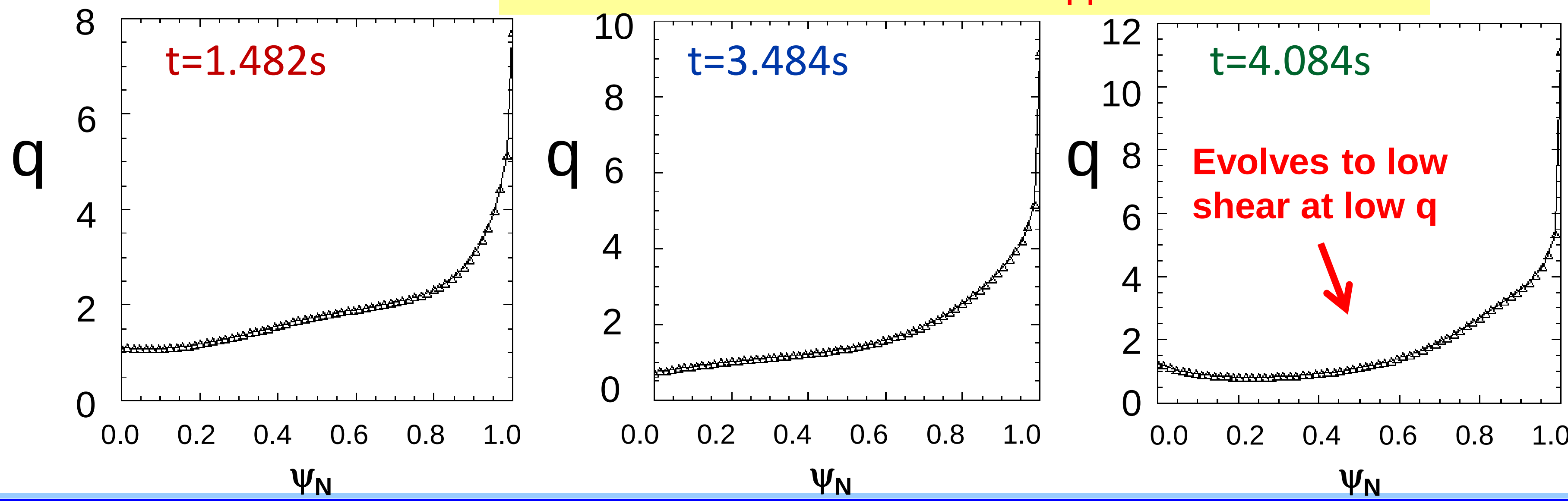
Xp by Jinil Chung

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

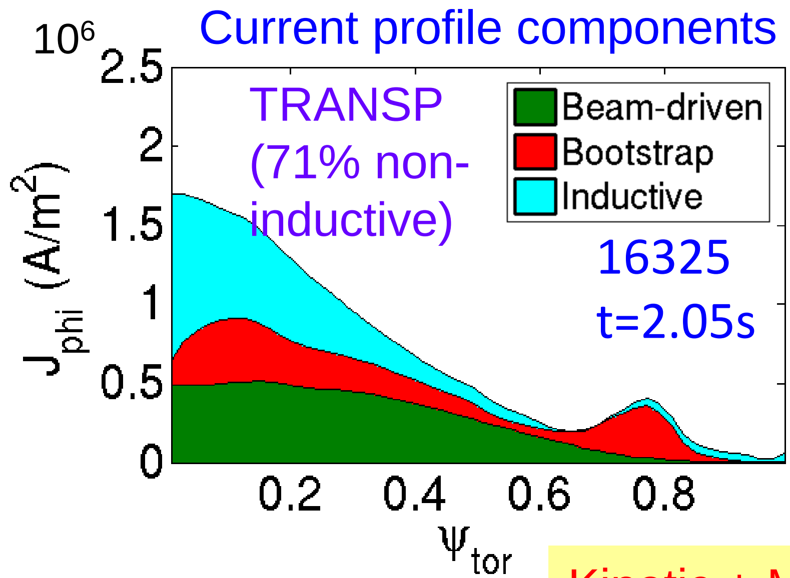


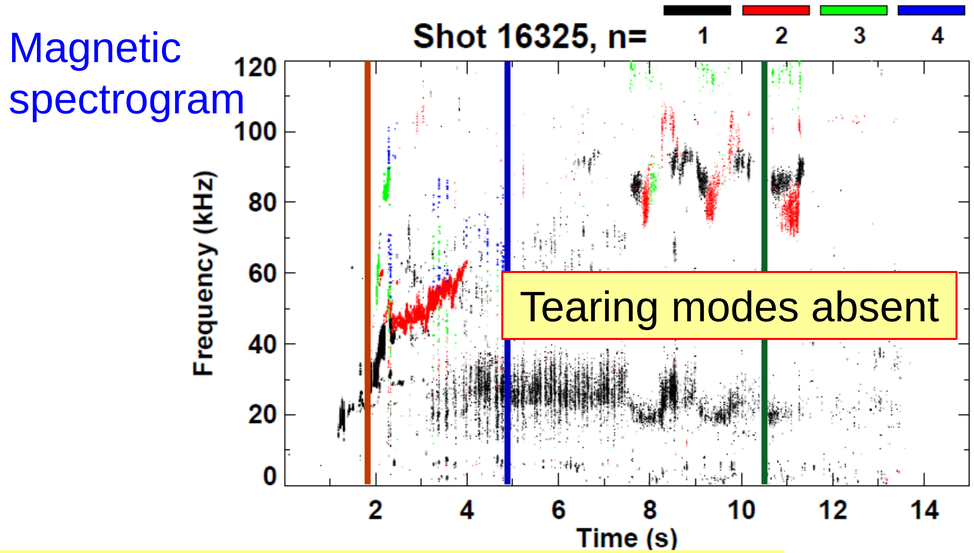


Kinetic + MSE reconstructed q profile evolution



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





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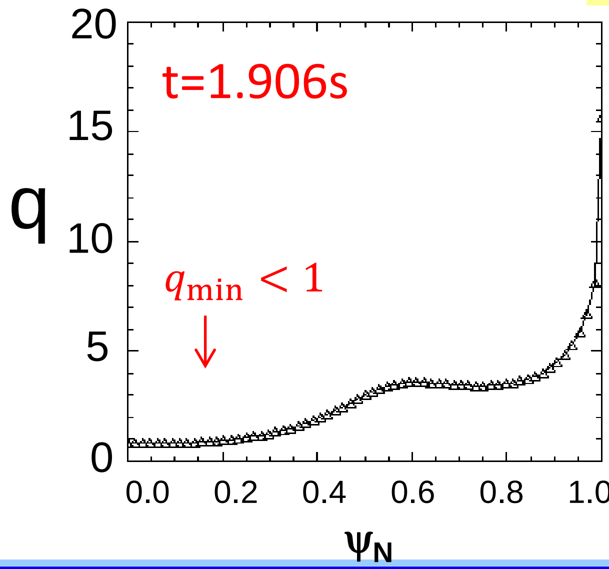
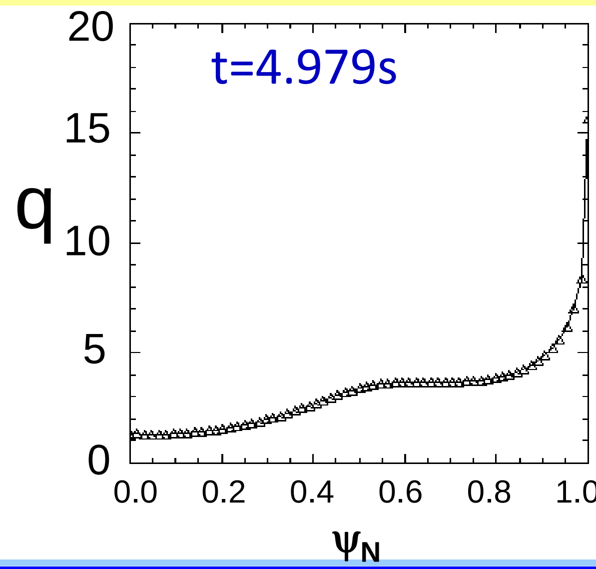
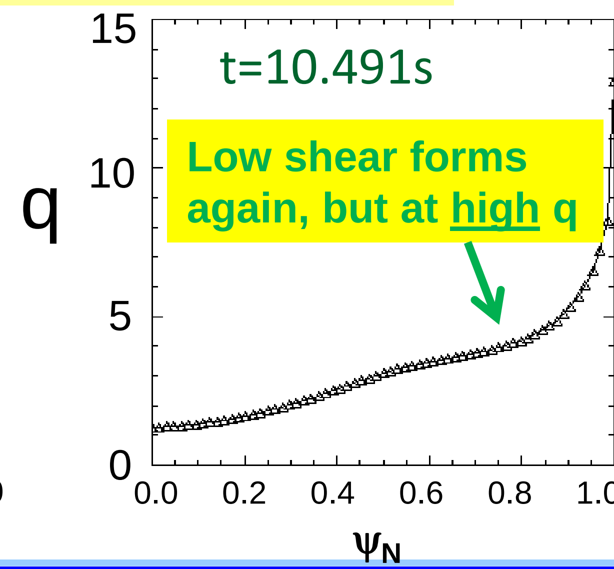
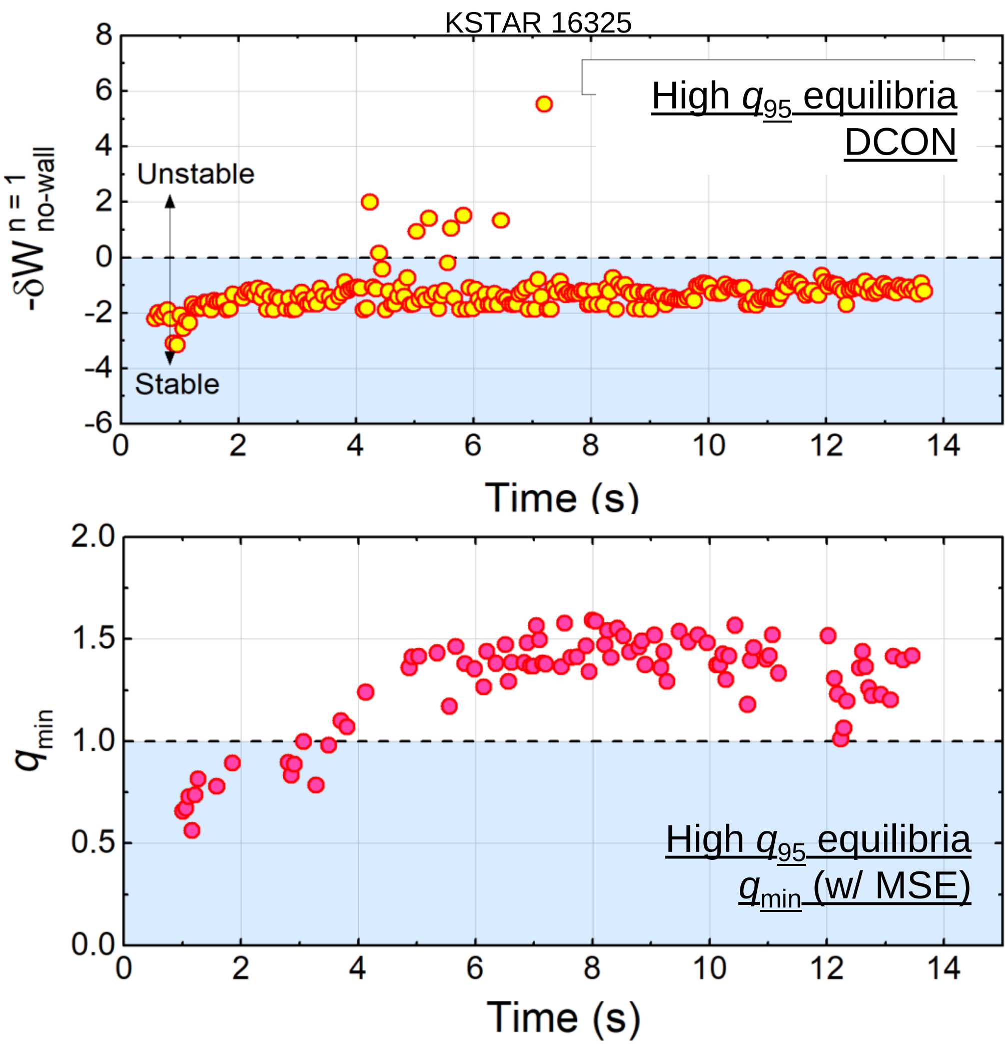






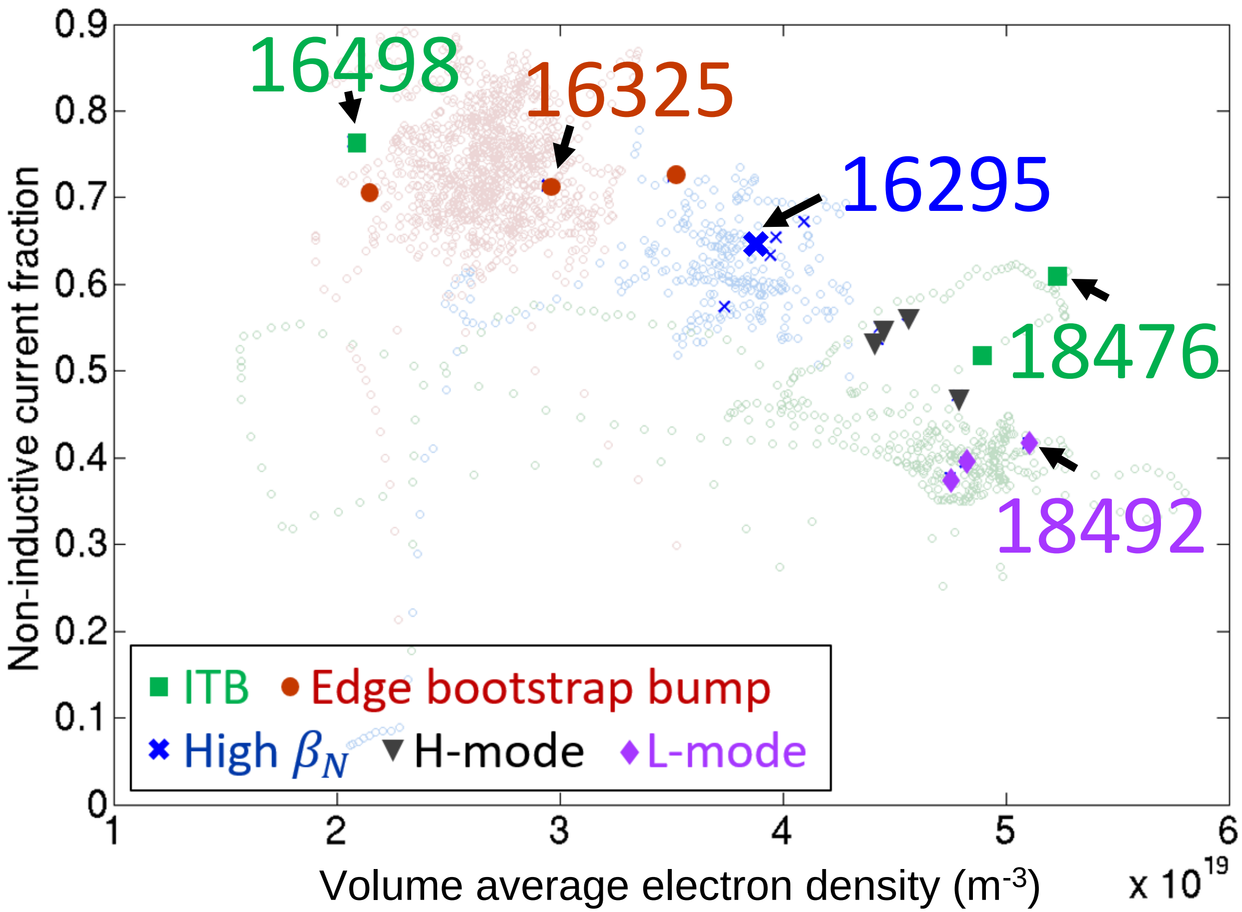
Higher q_{95} plasma has greater ideal n = 1 no-wall stability in DCON, closer to marginal stability



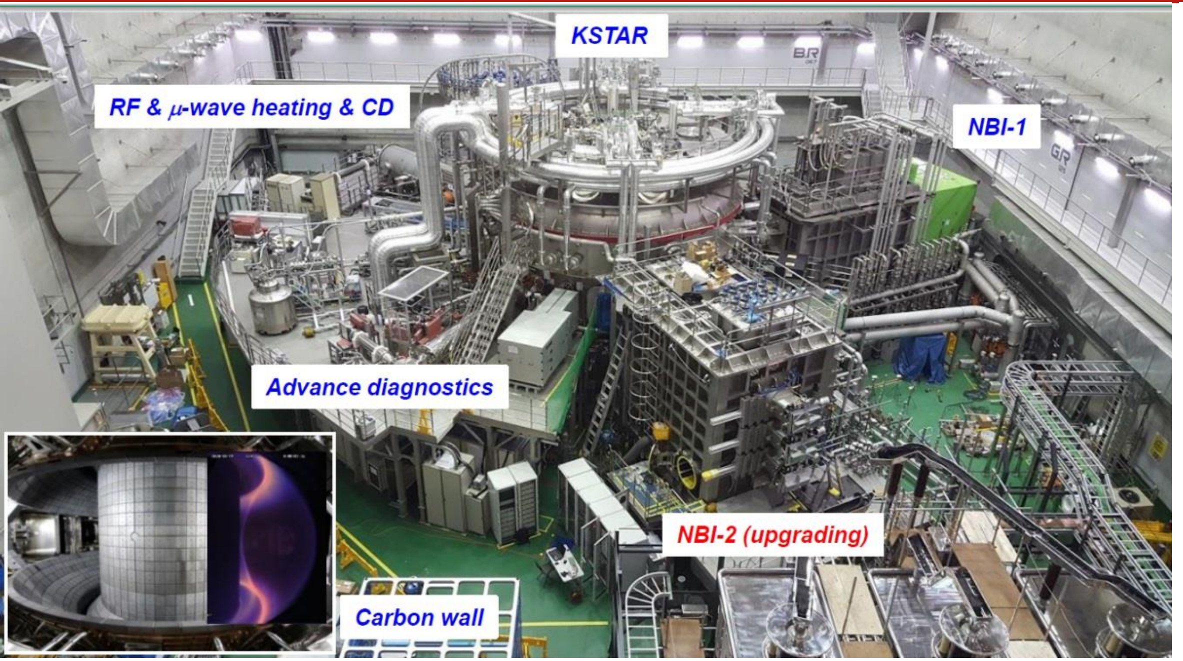
- Unlike higher β_N plasma, equilibria is mostly stable to n = 1 ideal modes in DCON
  - Note generally smooth evolution of stability criterion – reached with improved kinetic equilibria
- The *q*-profile at higher B_T evolves higher q_{min} above 1
  - Sawteeth disappear
- Reconstructed lower q shear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

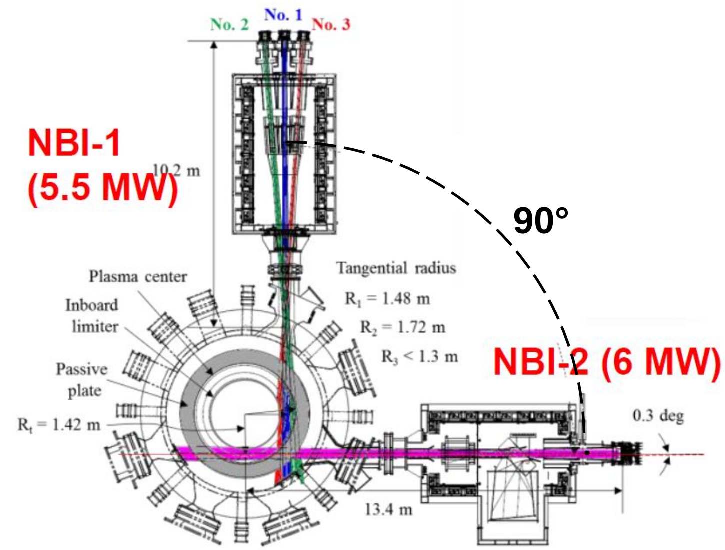
Kinetic reconstructions focused first on KSTAR plasmas with high-non-inductive fraction; NICF exceeds 75%

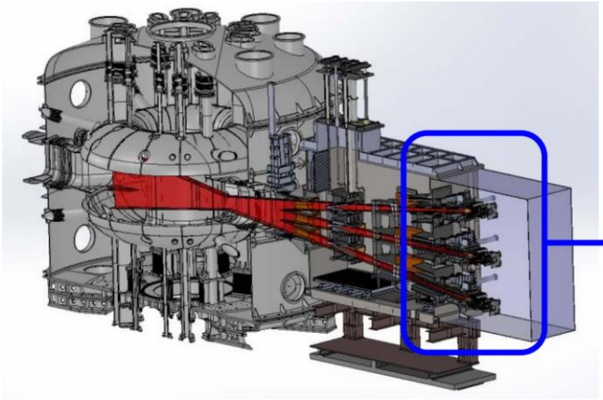
- TRANSP analysis of experimental plasmas
- Non-inductive fraction
  - Beam-driven
  - Bootstrap
- Non-inductive fraction is key for stable high beta steady state operation

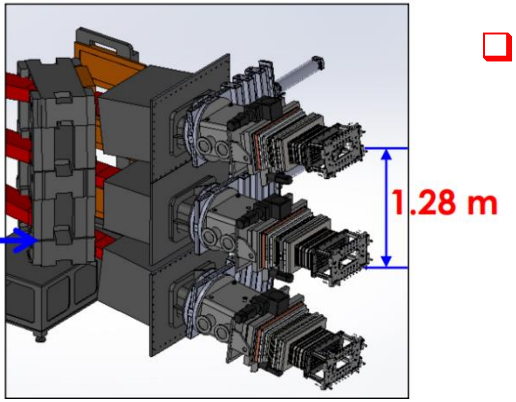


New 2nd NBI system is installed in KSTAR and will be available for 2018 run campaign





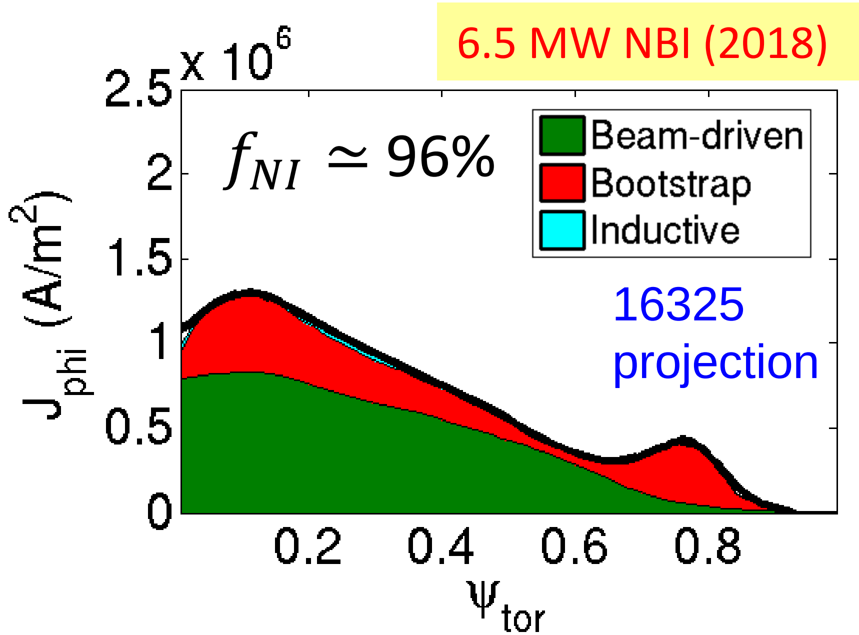




- Geometry of 2nd NBI system is included in TRANSP model
  - 2018 : upward-slanted source
  - 2019+ : all 3 sources available

  ⟶ P_{NBI} ≃1.5MW/source

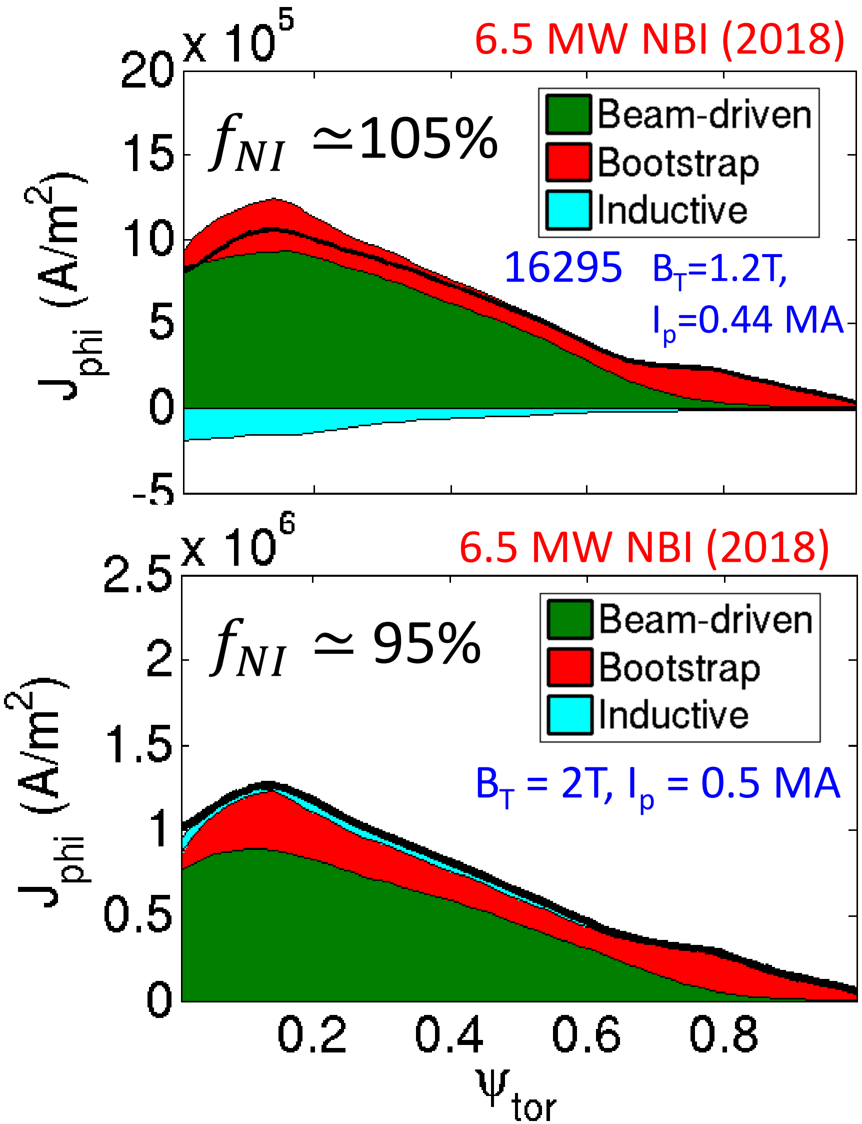
Predictive transport capability (TRANSP) allows "predict-first" projections for upcoming runs



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.

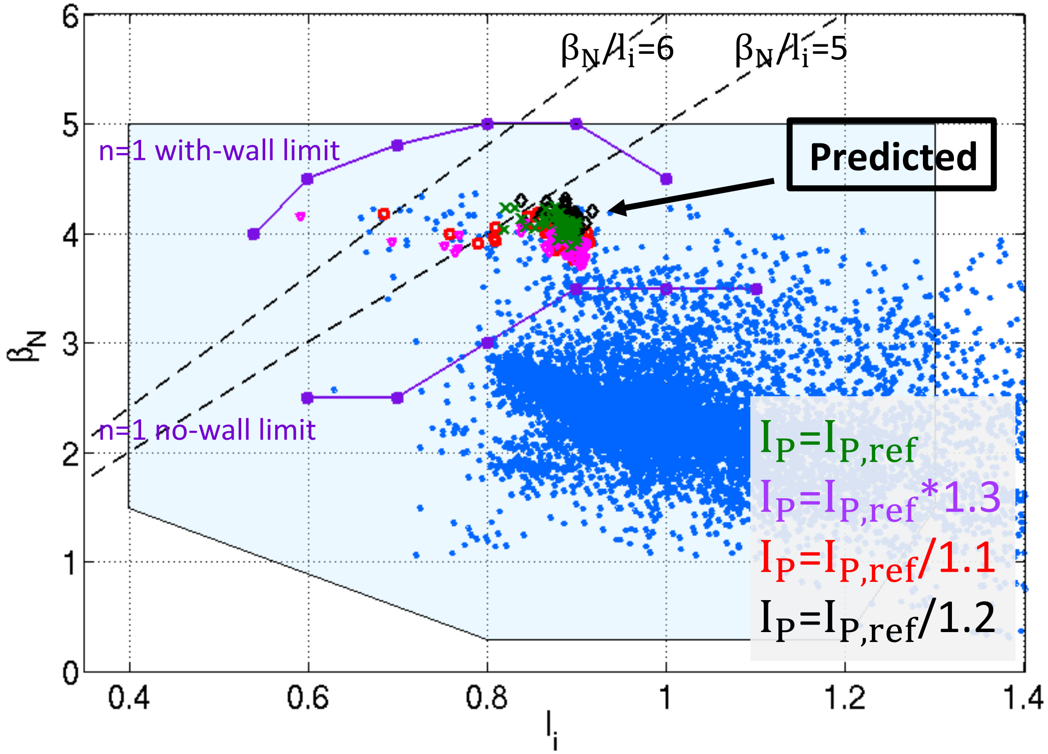
Transport analysis projections allow for variations of plasma parameters to meet targets



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

"Predict-first" analysis being used to design 2018 high-β experiments

- THREE CU group experiments scheduled for 2018 (3 days)
- Predictive TRANSP is being used to develop scenarios for 2018 high-β experimental runs in KSTAR – aiming to obtain :
  - long-pulse, MHD stable high beta plasmas

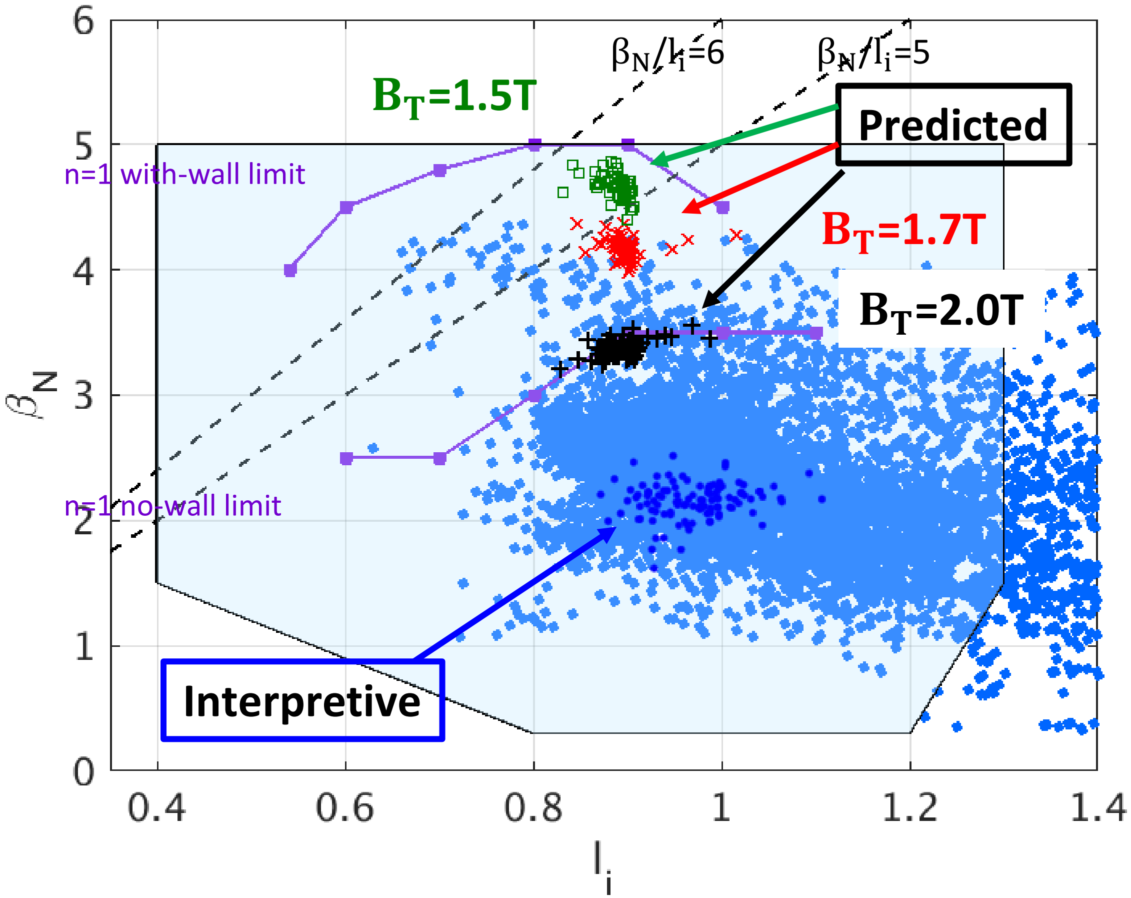


TRANSP calculations with I_P value set lower predict β_N higher than experiments

→ Projection using KSTAR #16325 $\boldsymbol{\beta_N \sim 4.4}$

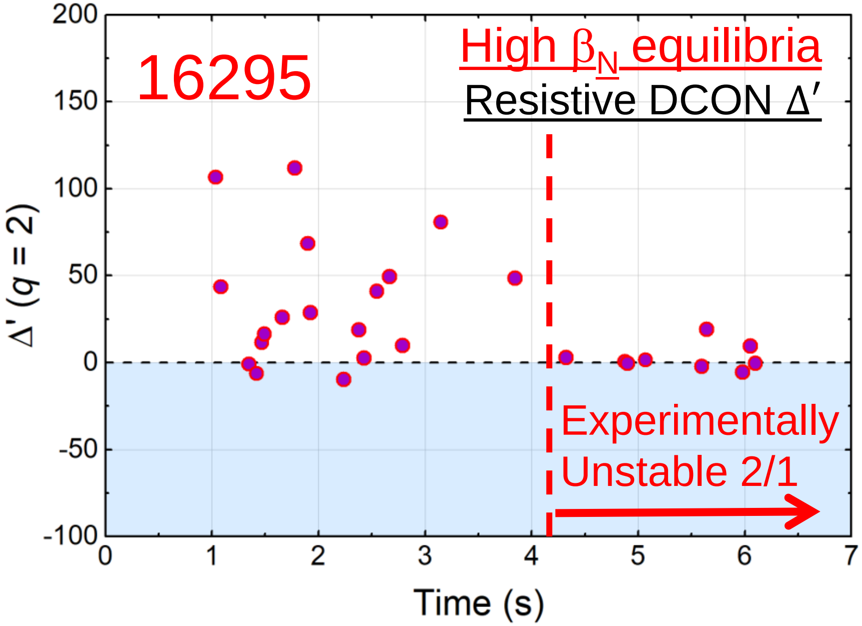
"**Predict-first**" before running sets of experiments

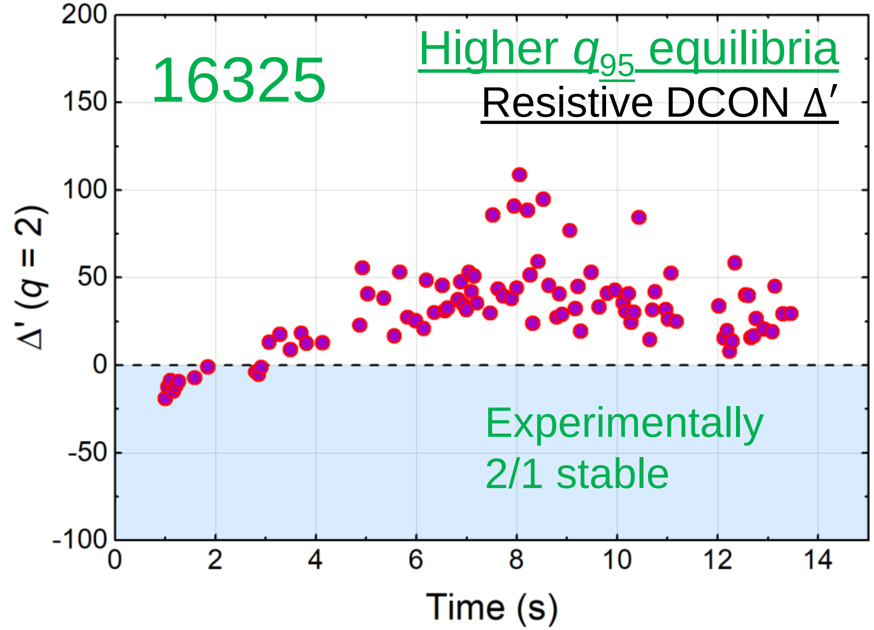
Predictive TRANSP analysis shows KSTAR design target β_N~5 can be approached with f_{NI}~100%



- NBI increased
  - existing shot: 4.5 MW
  - 2018 NBI taken as 6.5 MW
- By altering I_P and B_T values, $\beta_N > 4$, up to KSTAR design target 5 can be achieved with 100% non-inductive current fraction

Classical tearing stability examined using resistive DCON code for high β_N and higher q_{95} plasmas





- Classical tearing stability index, Δ′, computed at the q = 2 surface using outer layer solutions
- At higher q_{95}, Δ′ is mostly positive predicting unstable classical tearing mode
  - Indicates that neoclassical effects or wall effects need to be invoked to produce stability

A.H. Glasser, *et al*., Phys. Plasmas **23** (2016) 112506