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Progress on 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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Princeton, NJ USA

MAST-U

V2.0

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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) review
  - Present DECAF development and initial multi-device examination (now including MAST)
  - Key related analysis (e.g. long pulse, high beta KSTAR kinetic equilibrium reconstruction, stability analysis, high non-inductive plasmas)
  - “Predict-first” TRANSP analysis: 2018/2019 KSTAR operation with 2nd NBI system
  - Summary / next steps

International collaborative research on disruption prediction/avoidance expands effort to MAST-U, KSTAR

- US DOE supports our efforts
  - Multi-institutional collaborative grant on KSTAR, new grant on MAST-U
  - Multi-faceted physics research includes equilibrium, stability, transport, control, diagnostic hardware elements
    - Research originated on the NSTX spherical torus

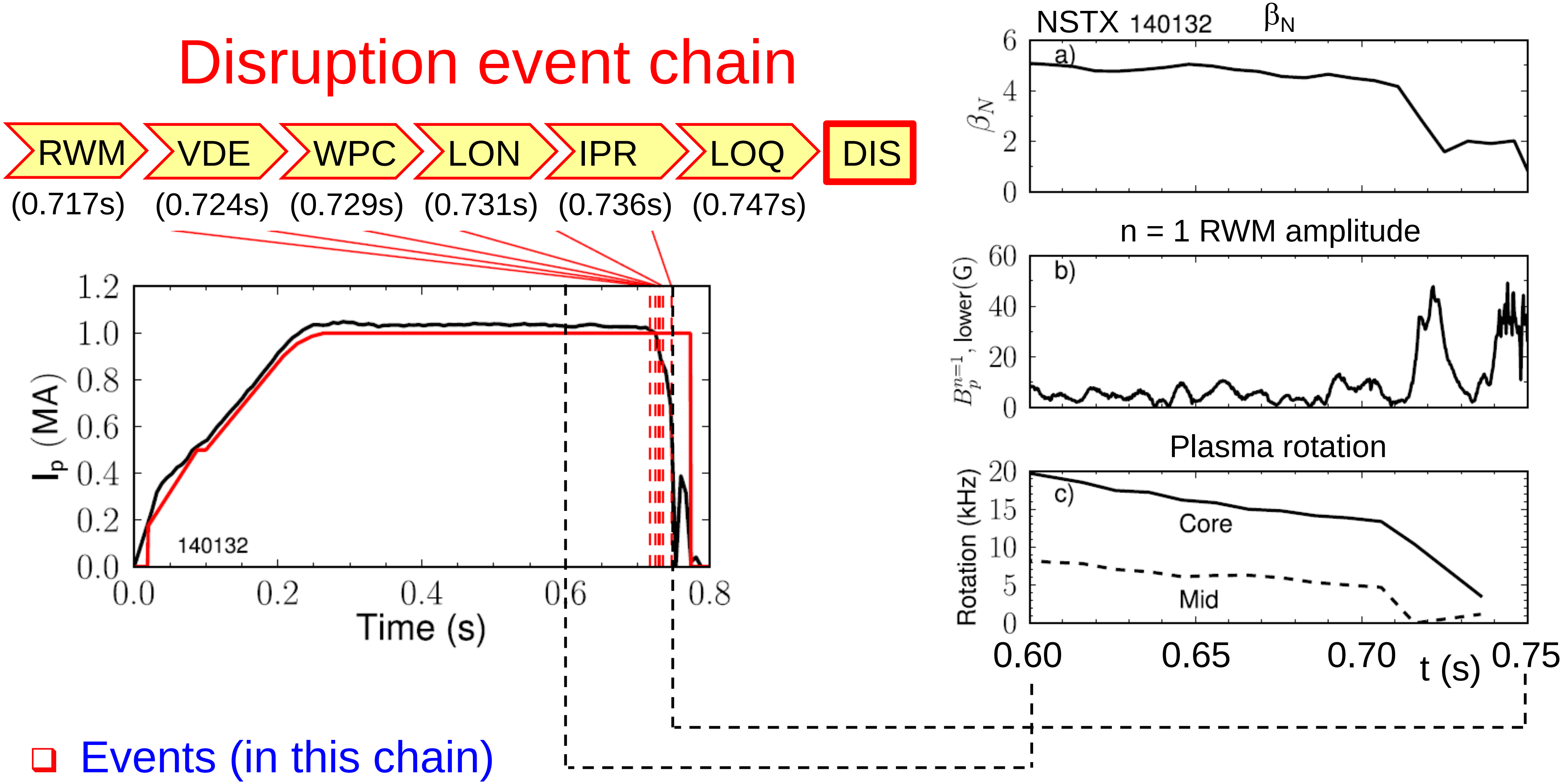
- Personnel
  - Columbia U.:
    - S.A. Sabbagh* (Lead PI), Y.S. Park, J.H. Ahn*, Y. Jiang* (post-doctoral)
    - J.W. Berkery*, J. Bialek (part time); J.D. Riquezes* (Columbia student)
  - PPPL: S. Scott (~full time, inst. PI), M. Boyer, B. LeBlanc (part time)
  - MIT/ORISE: E.S. Marmar (inst. PI), B. Mumgaard

*Speakers presenting at this meeting

Brief review: the DECAF code automatically computes events + disruption event chains leading to disruption

Disruption event chain

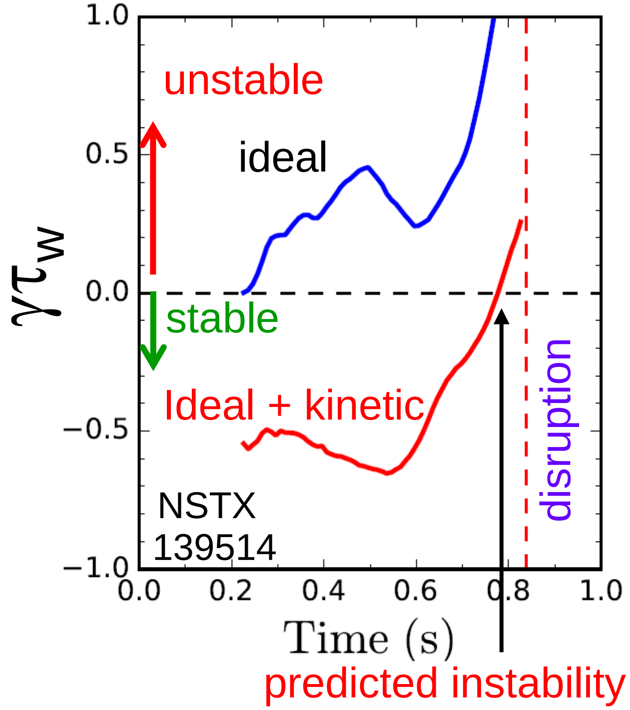
RWM (0.717s) → VDE (0.724s) → WPC (0.729s) → LON (0.731s) → IPR (0.736s) → LOQ (0.747s) → **DIS**



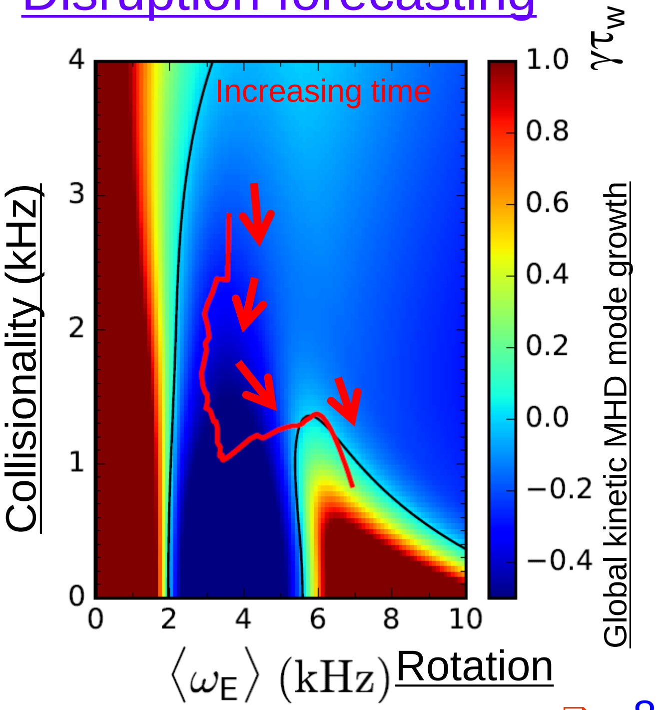
- Events (in this chain)
  - RWM: resistive wall mode
  - VDE: vertical instability
  - WPC: wall proximity control
  - LON: low density warning
  - IPR: not meeting I_p request
  - LOQ: low q warning
  - DIS: disruption

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

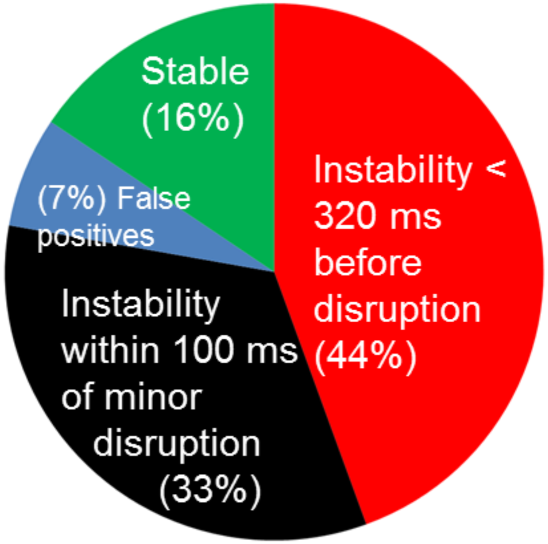
Norm. growth rate vs. time



Disruption forecasting



Predicted instability statistics



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

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

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

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)
    - DIS event always found (100%), VDE event appeared in 90% of cases
    - Computed events accurately represented experiment (~ 10 events)
    - Physics model forecasted global MHD disruptions with ~ 85% reliability
  - Disruption chains often repeated, e.g.:

- Recent progress
  - New DECAF MHD events allow analysis of general databases
  - Coupling of new physics analysis tools and DECAF events
  - Multi-machine databases (analysis now starting)
  - Large database processing with small number of verified events

Very rapid progress on DECAF in these directions occurring day-to-day at the moment

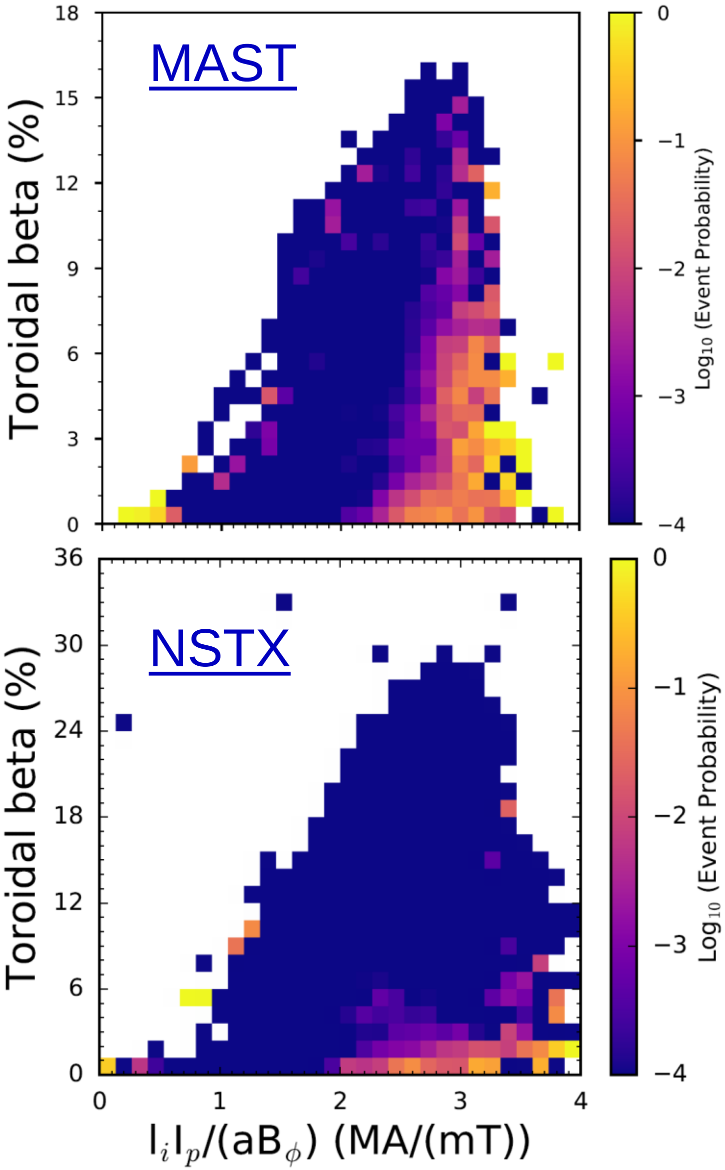
Progress on DECAF now moving to processing of multi-machine databases

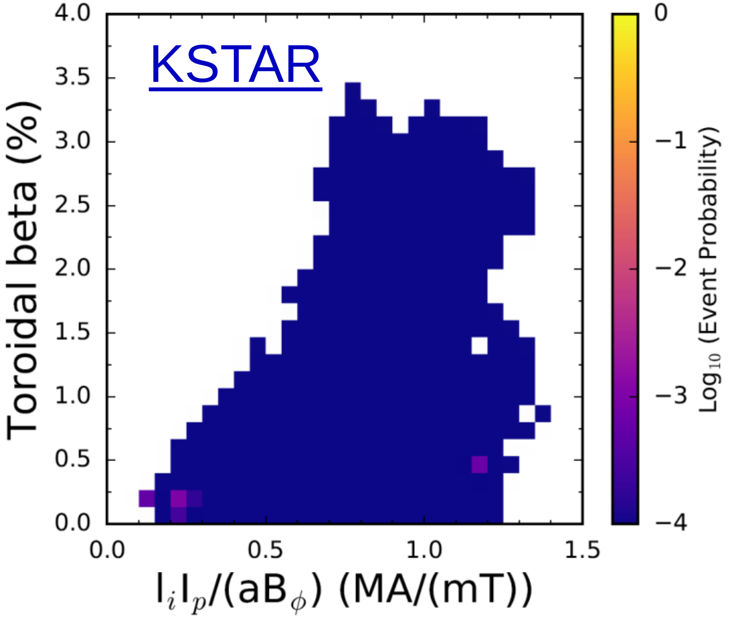
- Analysis
  - Kinetic equilibrium / stability analysis on KSTAR; planned for MAST
- DECAF database started
  - Requires storage of DECAF analysis

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) (M7,M8, M9 runs)	2,000 / year (est)		

- Aim to bring in JET and C-Mod databases

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

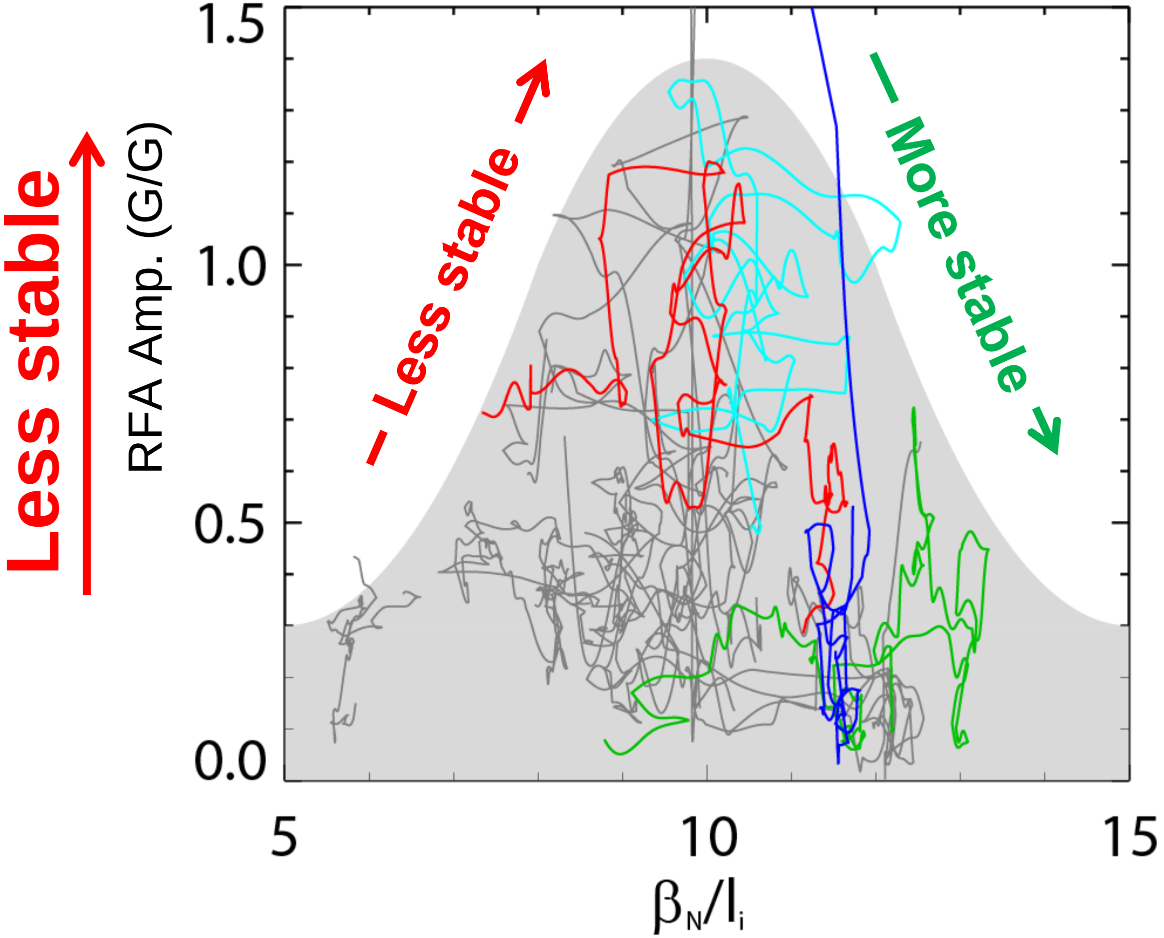




- DECAF analysis of DIS event
  - Similar to a "standard" disruptivity analysis
  - Shots analyzed at 10 ms intervals
- Analysis during I_p flat-top
  - MAST: 8902 plasmas analyzed
  - NSTX: 4706 plasmas analyzed
  - KSTAR: 750 plasmas analyzed (so far)

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



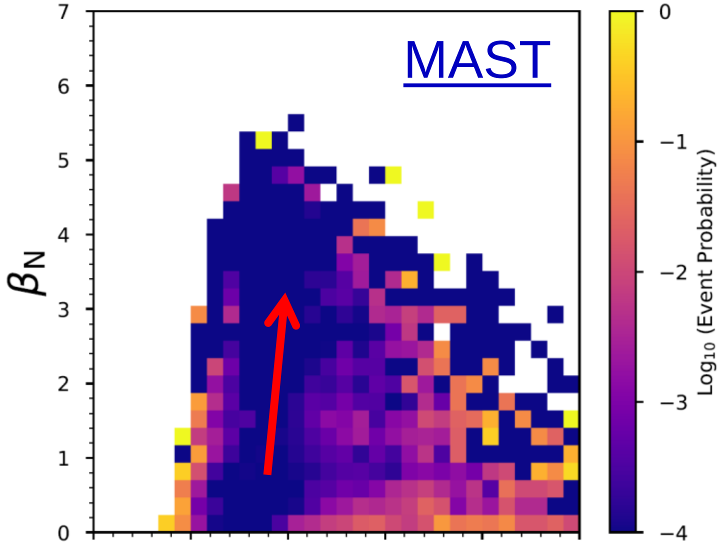
- *Non-intuitive* stability increase at high β_N/l_i
  - decreases up to $\beta_N/l_i = 10$, ***increases*** at higher β_N/l_i

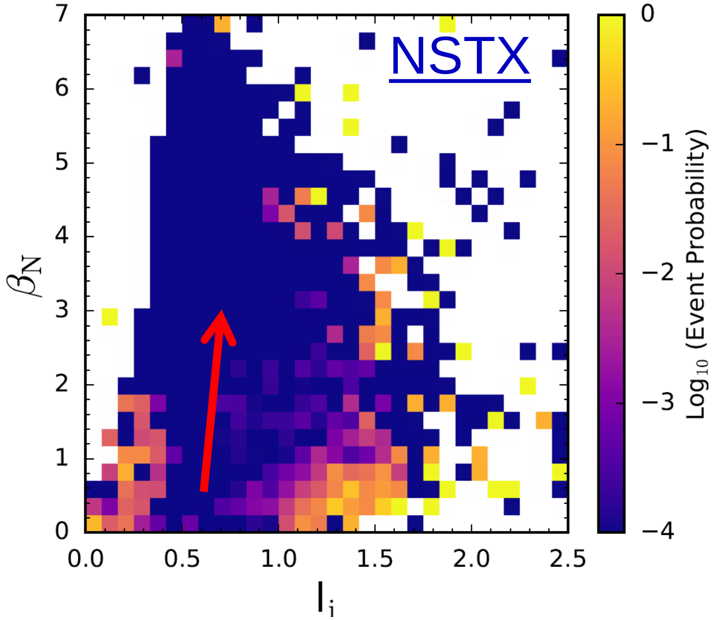
- Understanding: Results consistent with kinetic stabilization theory invoking physical resonances

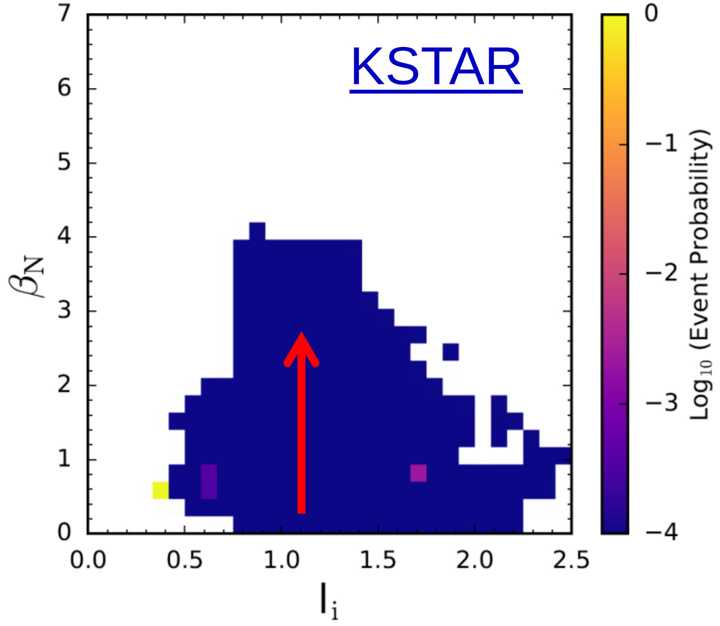
J. Berkery, et al., PoP **21** (2014) 156112

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

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

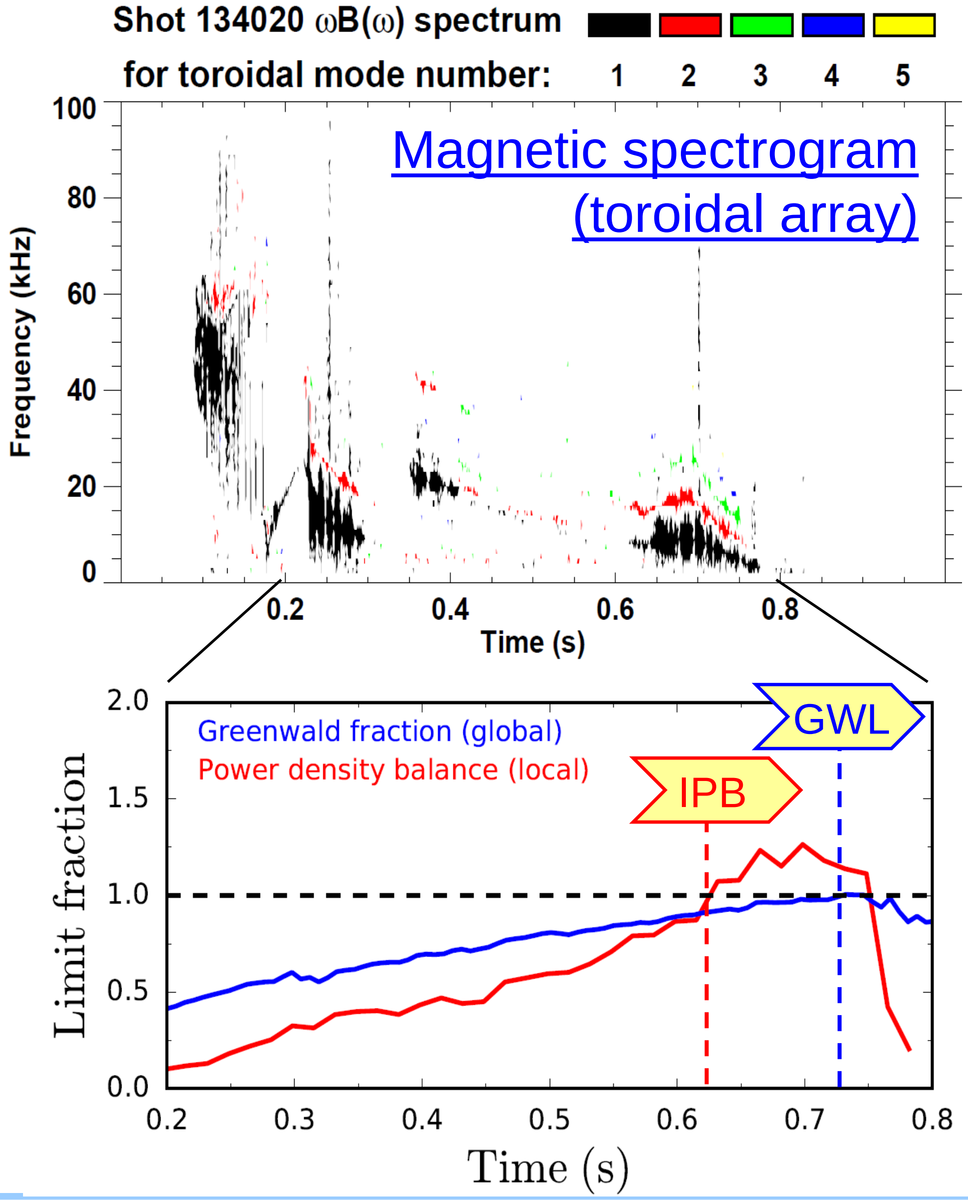




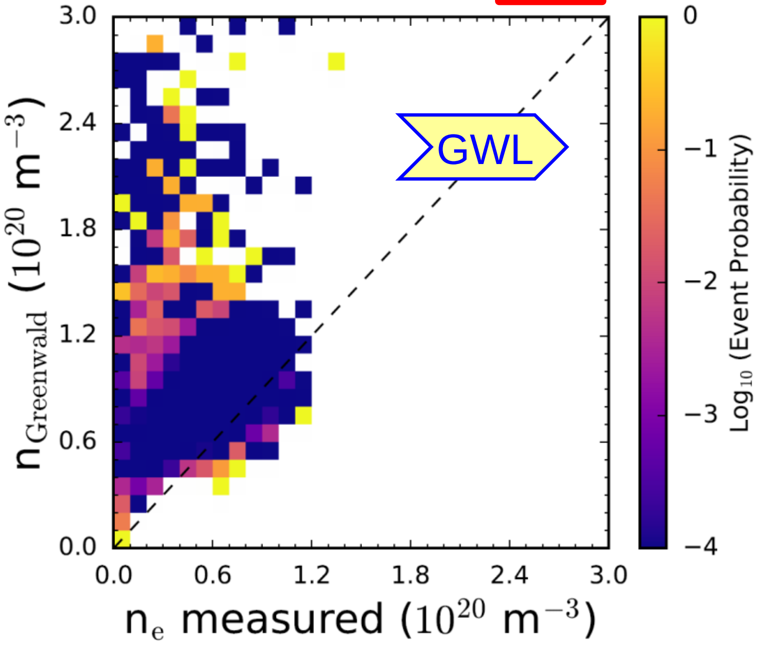


- DECAF analysis of **DIS** event
  - Shots analyzed at 10 ms intervals
  - NEXT STEP: DECAF event chain analysis
- Analysis during I_p flat-top
  - MAST: 8902 plasmas analyzed
  - NSTX: 4706 plasmas analyzed
  - KSTAR: 750 plasmas analyzed (so far)

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



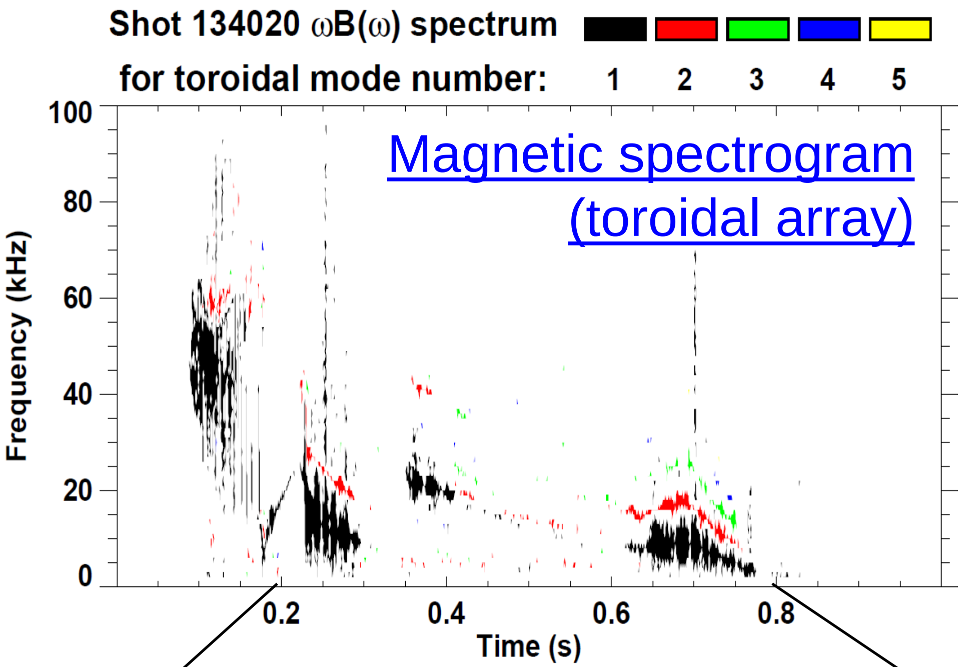
Disruptivity vs. density **DIS**



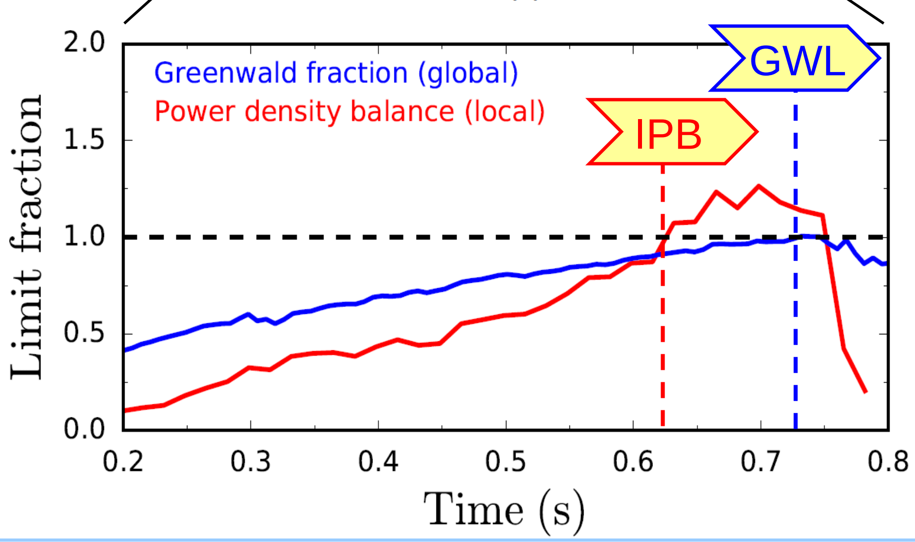
- Greenwald limit
  - Approaches 1 near mode lock
- Rad. island power balance
  - Examining utility of this physics model for disruption warning

See talk by J. Berkery, Wednesday

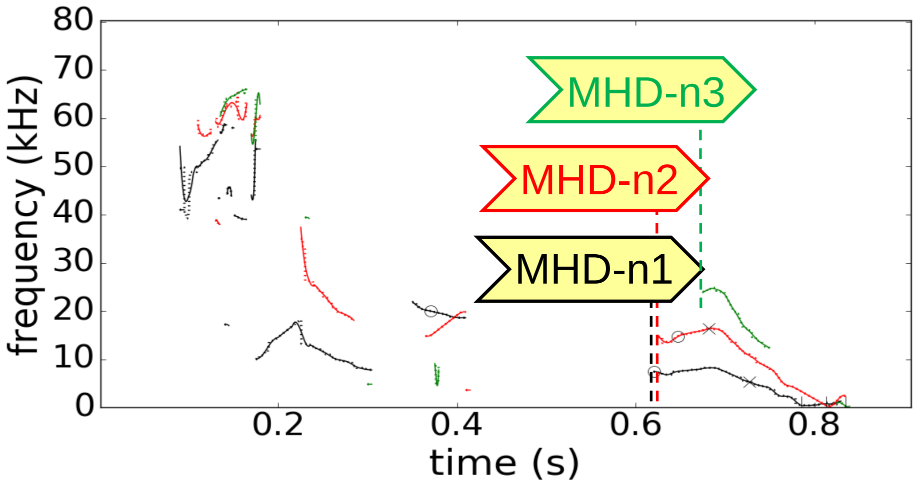
More powerful automated MHD event objects have been developed for DECAF



Magnetic spectrogram (toroidal array)



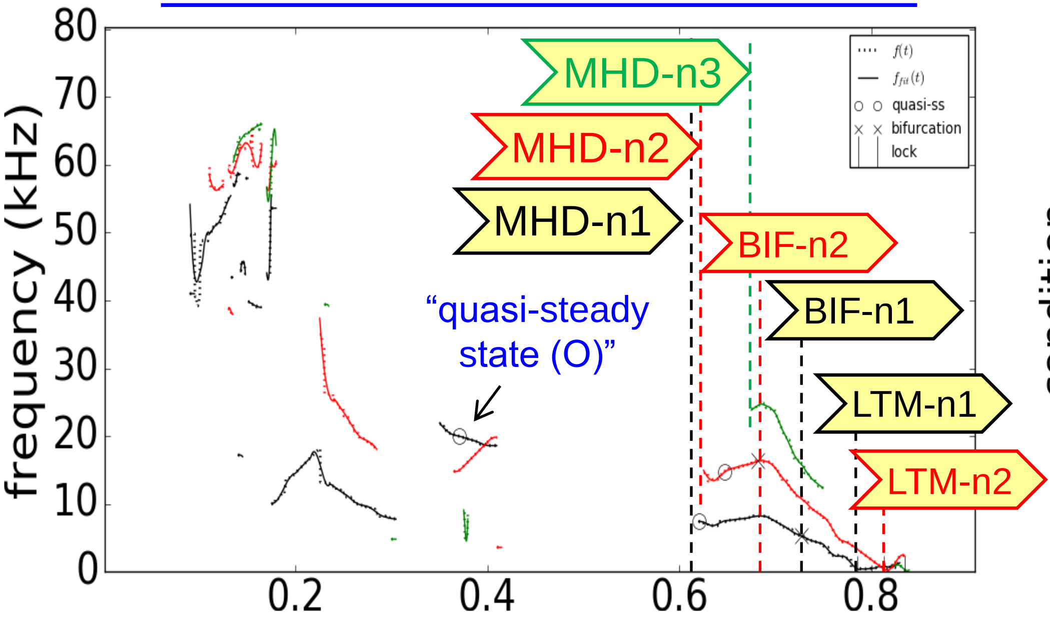
DECAF automated MHD events



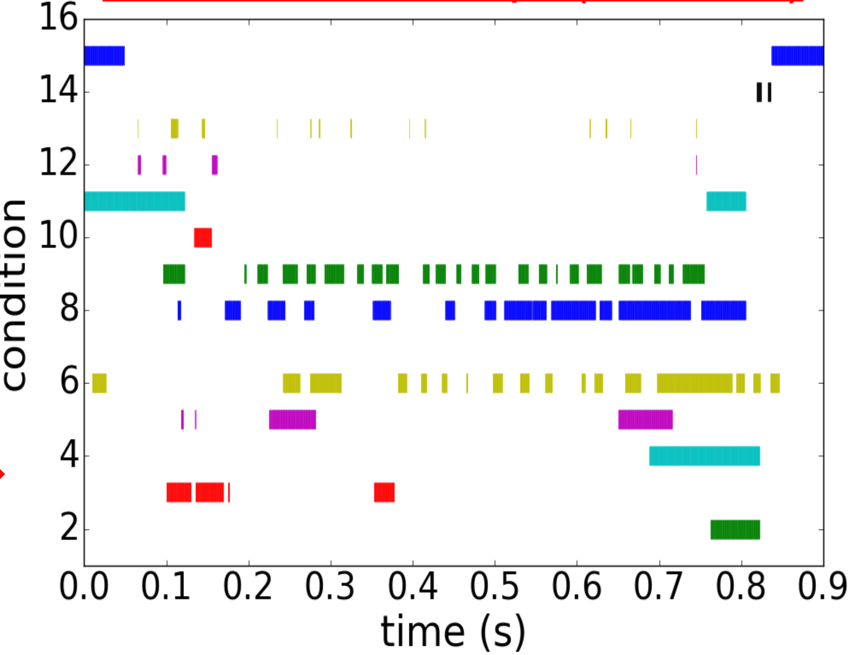
- ❑ More capable MHD event objects required for analysis of wider tokamak databases
- ❑ DECAF MHD events now include
  - ❑ Mode number (n) discrimination
  - ❑ Full history of mode evolution, including bifurcation and locking
  - ❑ Many disruption warning criteria

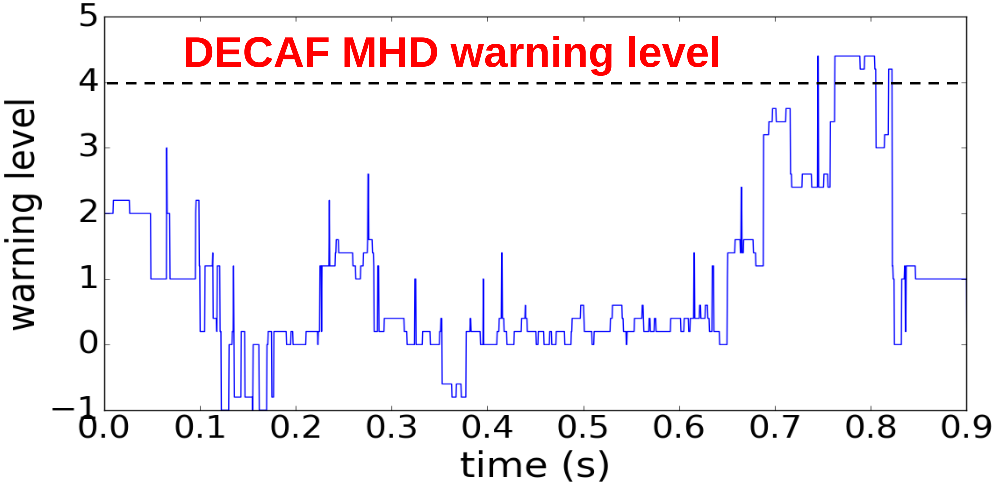
New DECAF MHD events utilize history of 15 criteria to define time evolving disruption warning level

DECAF automated MHD events



DECAF "heat map" (for MHD)

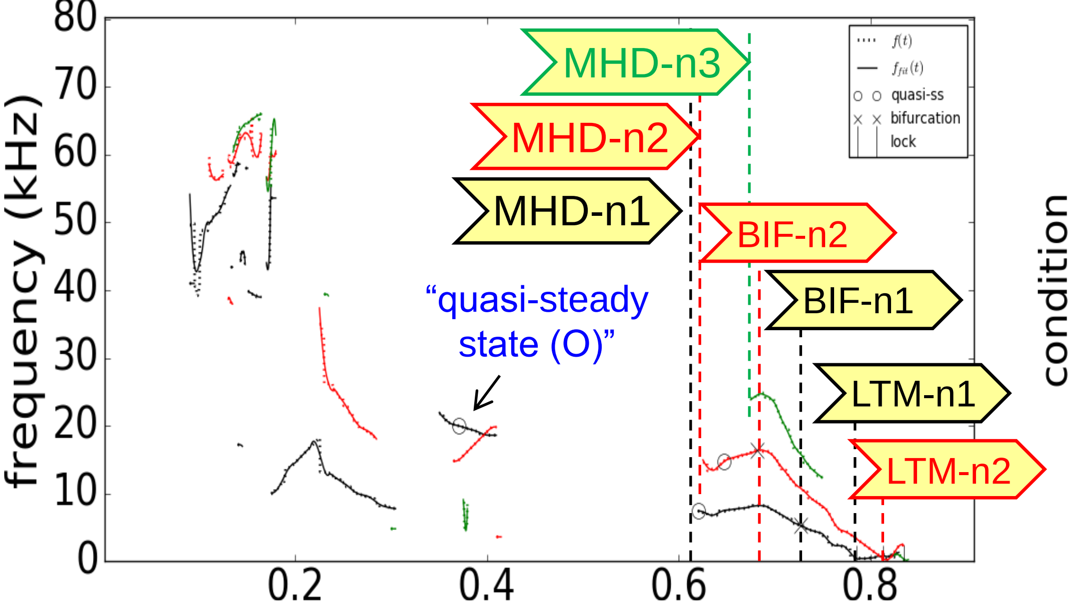




- Initial findings
  - Clear "safe" and "unsafe" periods of MHD appear in warning level
  - Criterion history of wider range of plasma parameters improved the disruption warning reliability ➔ illustrated by "Heat Map"

MHD heat map illustration summarizes understanding of disruption warning level

DECAF automated MHD objects



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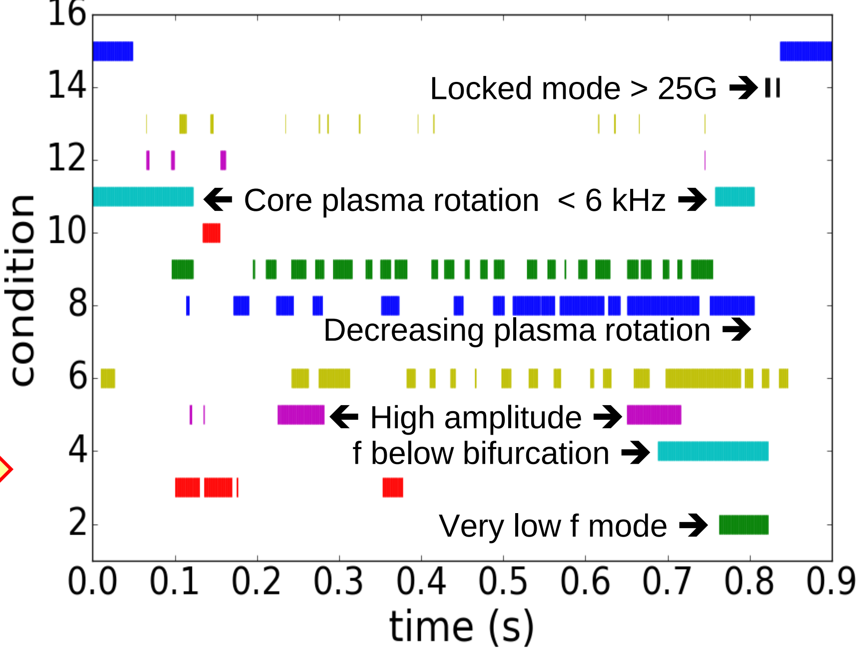
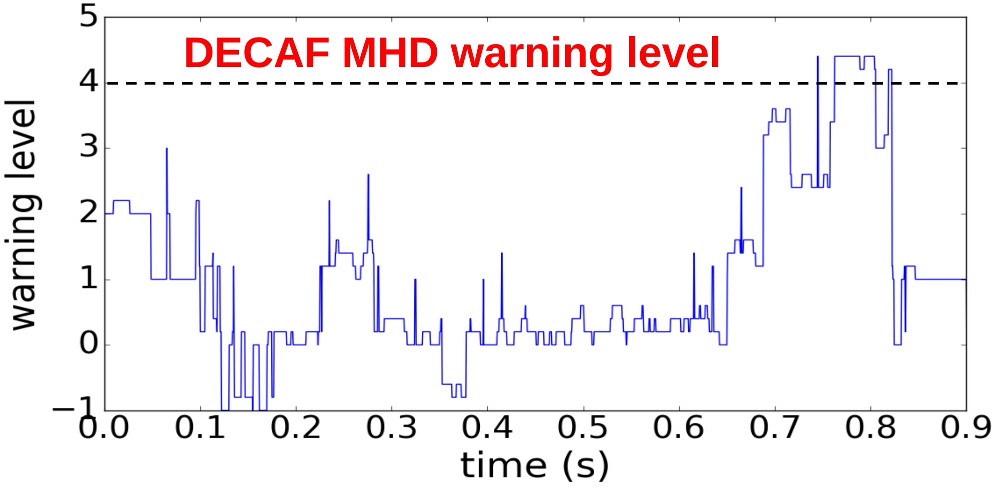
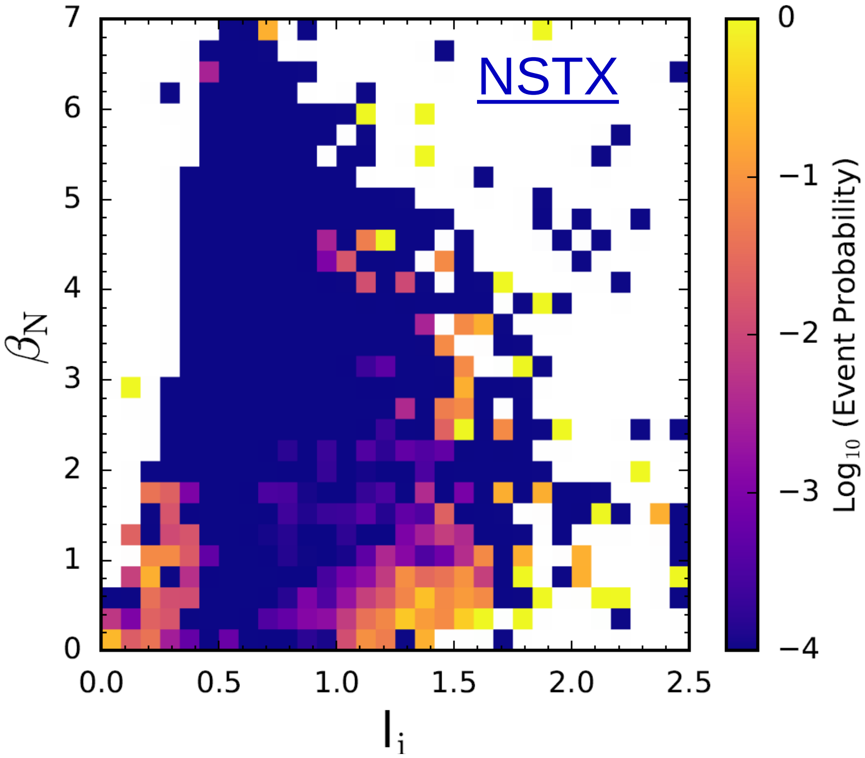




- Some notable for this heat map
  - Mode frequency below bifurcation, decreasing plasma rotation key
  - Early, slow warning level evolution
  - Locked mode amplitude important, but warning comes in late

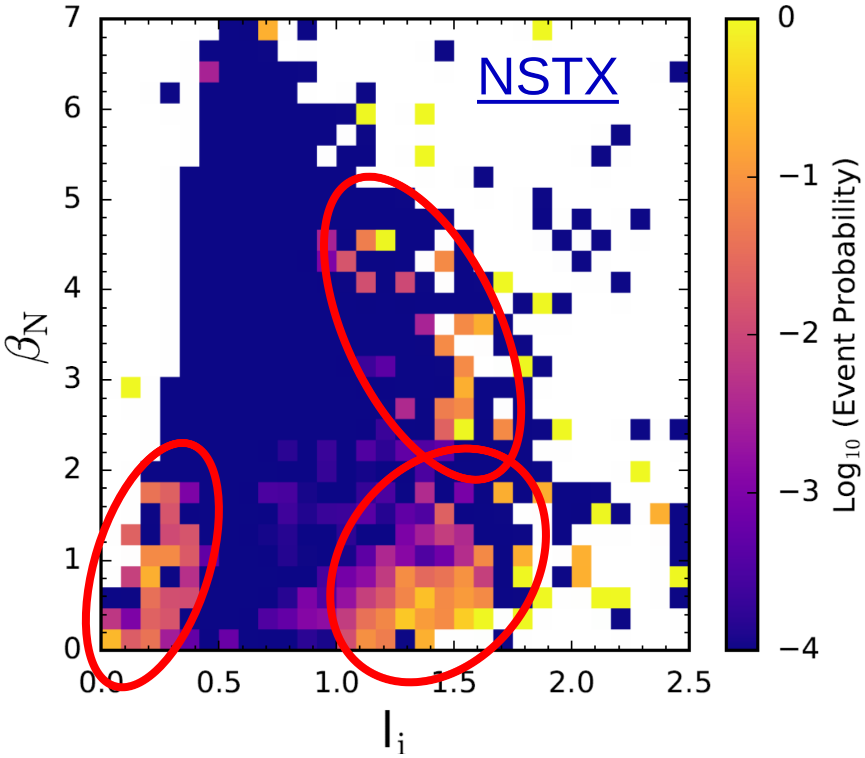
See talk by J. Riquezes, Wednesday

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



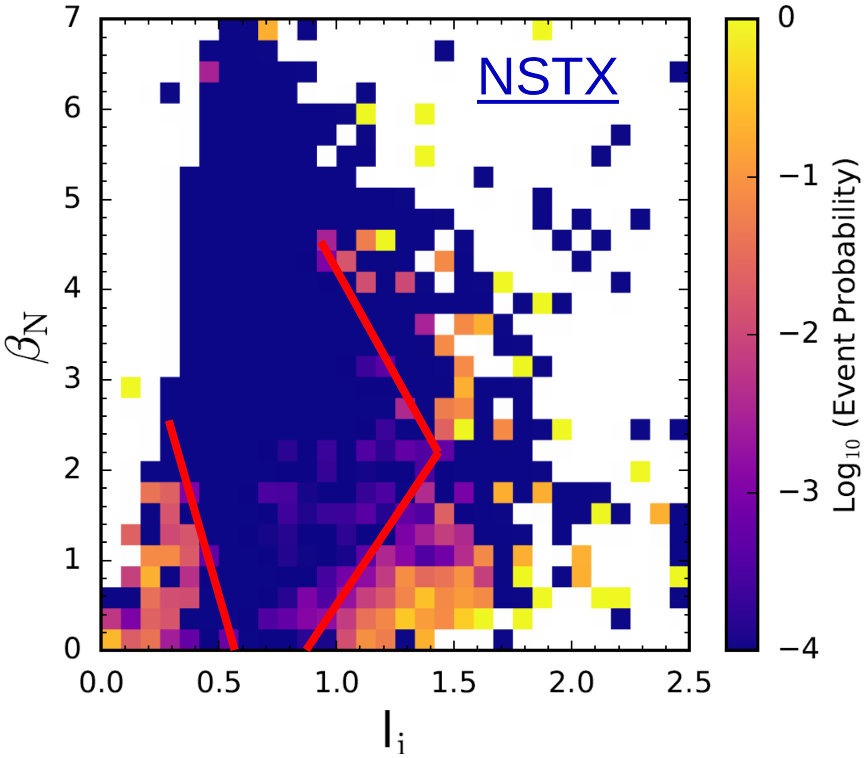
- <u>Example</u>: What are the most important regions to study on this plot?

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



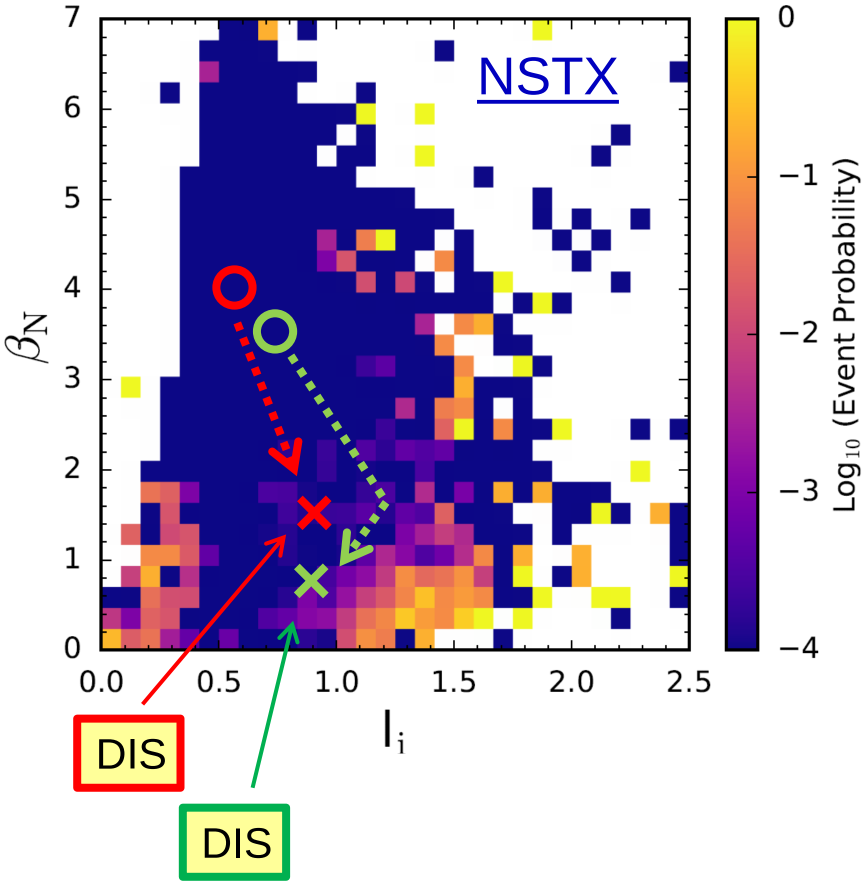
- Example: What are the most important regions to study on this plot?
  - A human might focus on the high disruption probability regions
  - ➔ What causes the disruptions? (low β_N, mid-l_i ???)

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



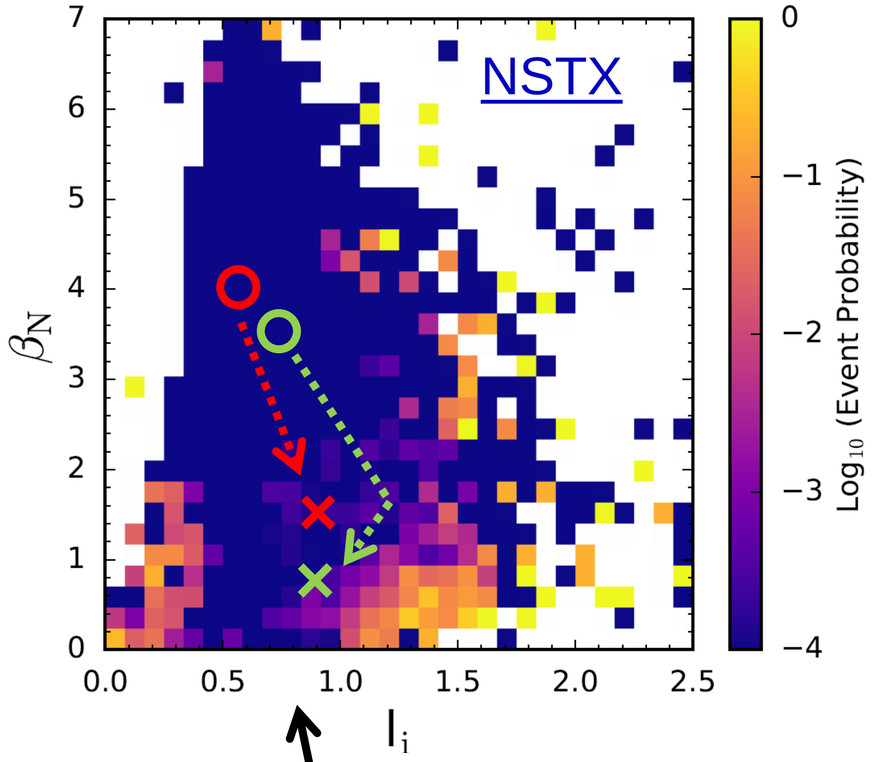
- Example: What are the most important regions to study on this plot?
  - A human might focus on the high disruption probability regions
  - Black-box machine learning might segregate disruptive from non-disruptive regions of the plot and learn from that division

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
  - A machine learning algorithm 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

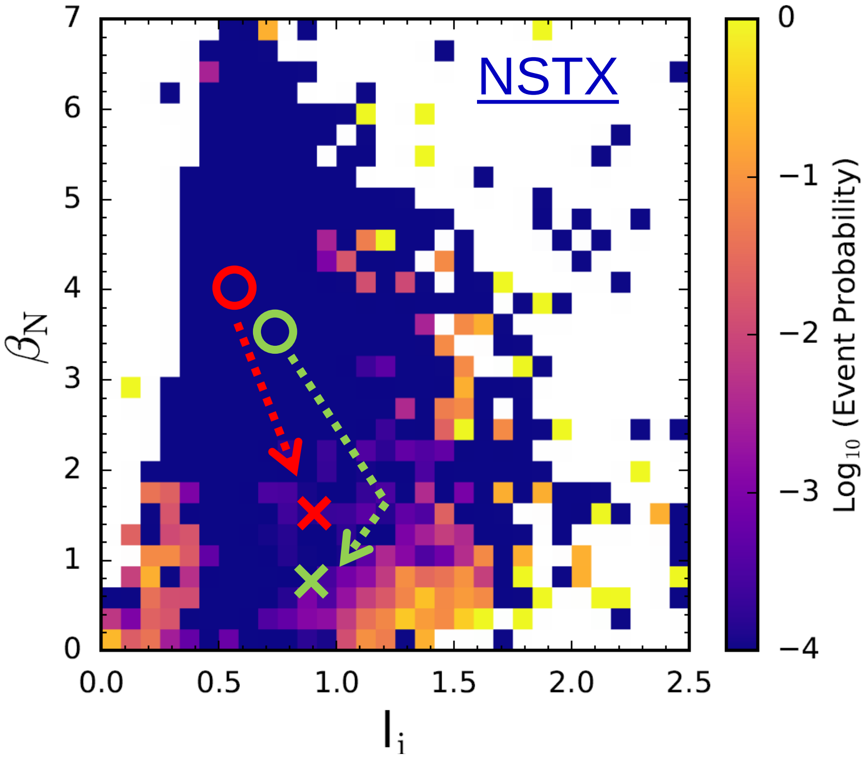
While disruptivity plots provide important information, they can be misleading when used incorrectly



- Example: What are the most important regions to study on this plot?
  - A human might focus on the high event probability regions
  - A machine learning algorithm might segregate disruptive from non-disruptive regions of the plot and learn from that division
  - Problem ➔plasma conditions can change significantly by the time the 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 × ×)

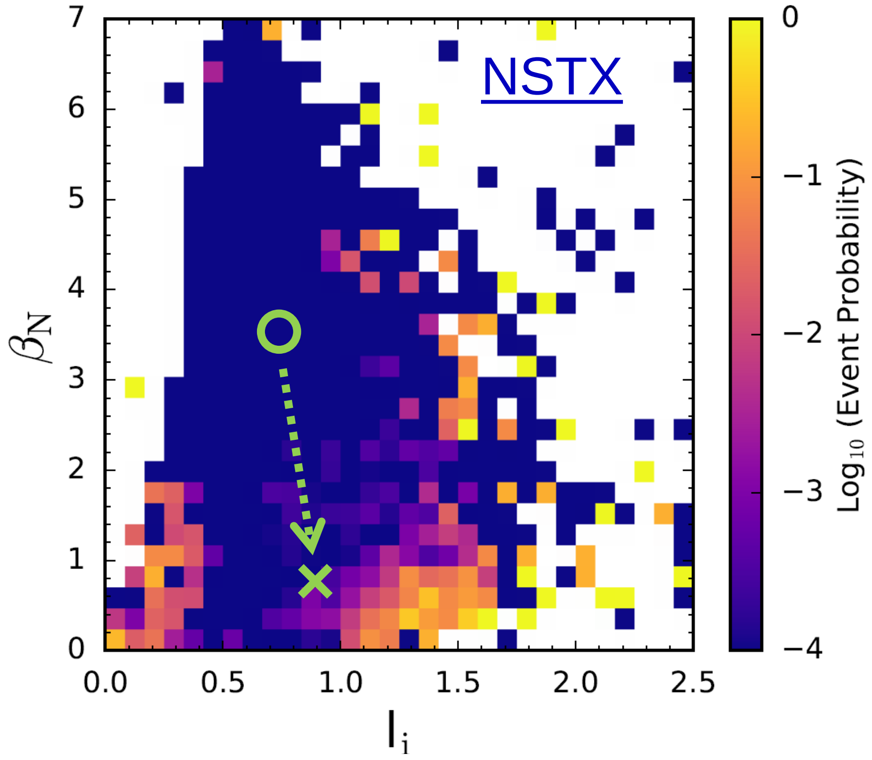
While disruptivity plots can provide information, they can be highly misleading when used incorrectly

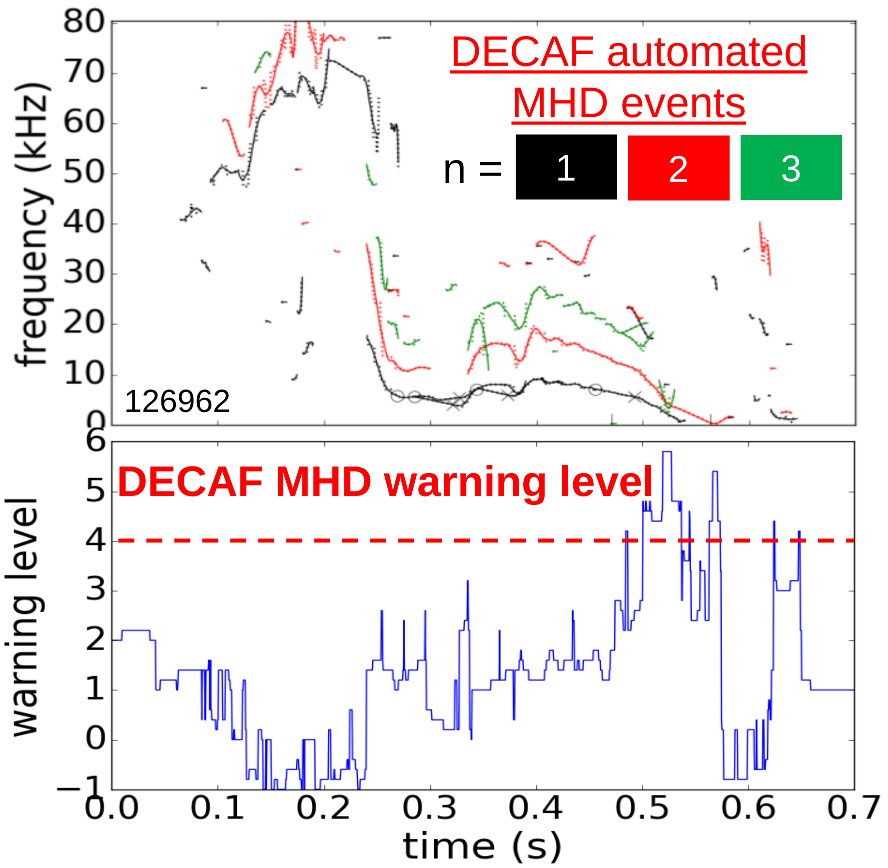


- Example: What are the most important regions to study on this plot?
  - A human might focus on the high event probability regions
  - A machine learning algorithm might segregate disruptive from non-disruptive regions of the plot and learn from that division
  - Problem ➔plasma conditions can change significantly by the time the disruption happens

- Key Lessons:
  1) Using a "disruption database" that only contains data near the disruption time is misleading for disruption forecasting
  2) Only analyzing plasma conditions near the disruption time is not useful in many cases, even if one can figure out a way to forecast 100% accurately

Standard disruptivity plots give no insight into physics; DECAF reveals the physics to provide improved forecasting

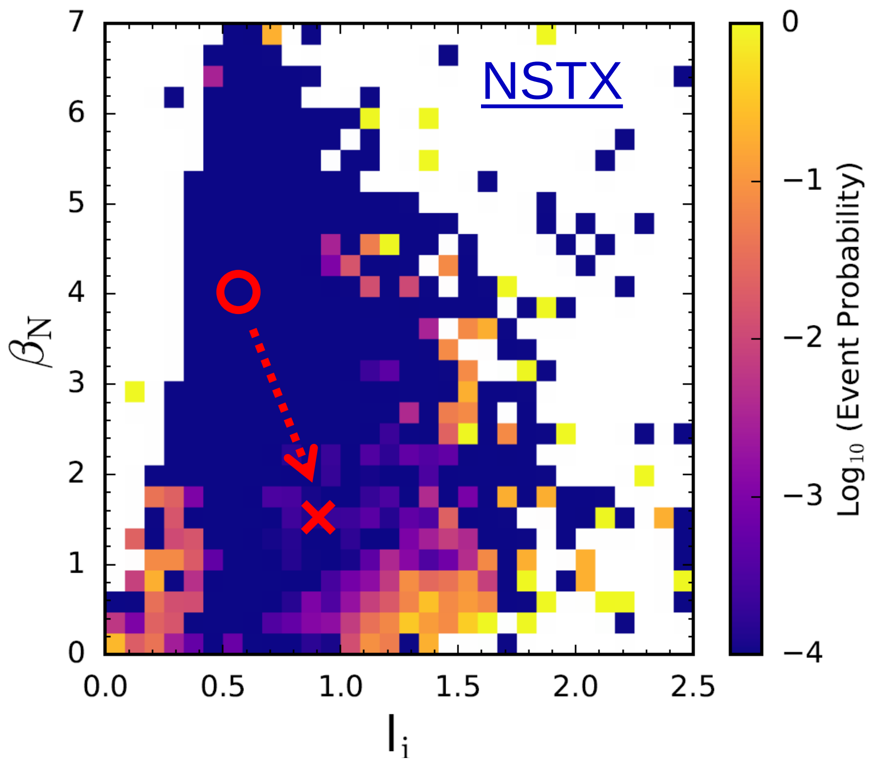


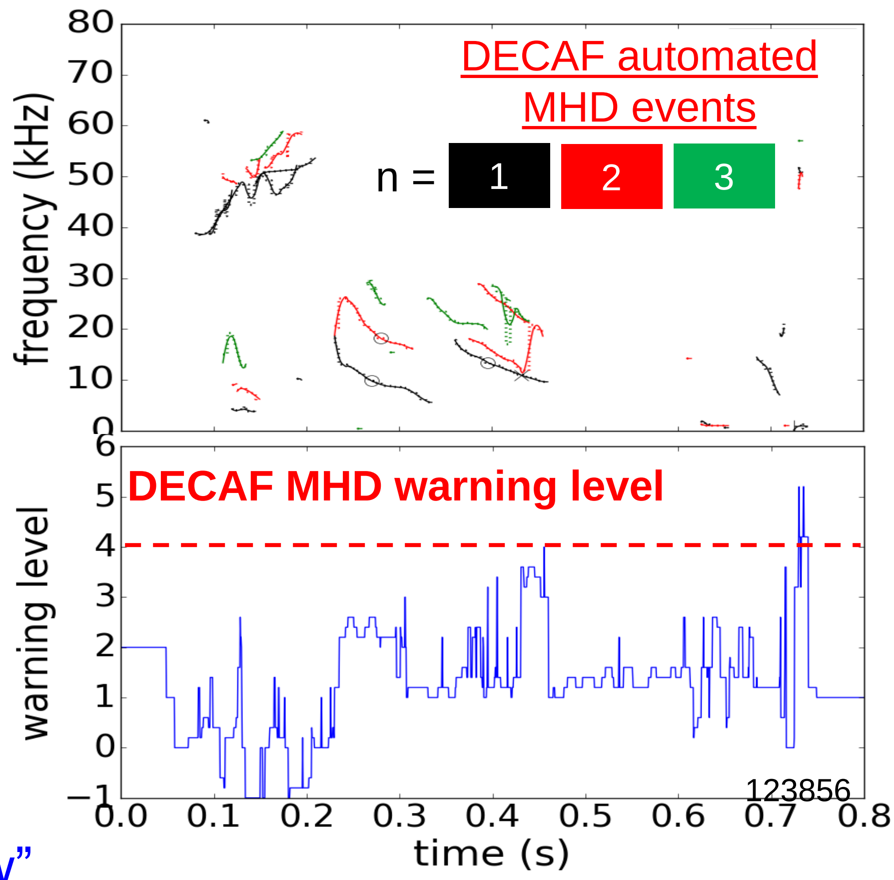


- Long interval leading up to disruption
  - Rotating MHD slows, bifurcates, and locks
  - Then, plasma has an H-L back-transition (pressure peaking warning PRP) before DIS

DECAF event chain

Standard disruptivity plots give no insight into physics; DECAF reveals the physics to provide improved forecasting





- 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)

DECAF event chain

RWM (0.629s) ➔ IPR (+.010s) ➔ PRP (+.012s) ➔ VDE (+.058s) ➔ DIS (+.101s) ➔ MHD-n1 (+.101s) ➔ LTM-n1 (+.101s) ➔ WPC (+.106s) ➔ LOQ (+.107s)

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

See talk by J. Riquezes, Wednesday

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

See poster by Y. Jiang, Tuesday

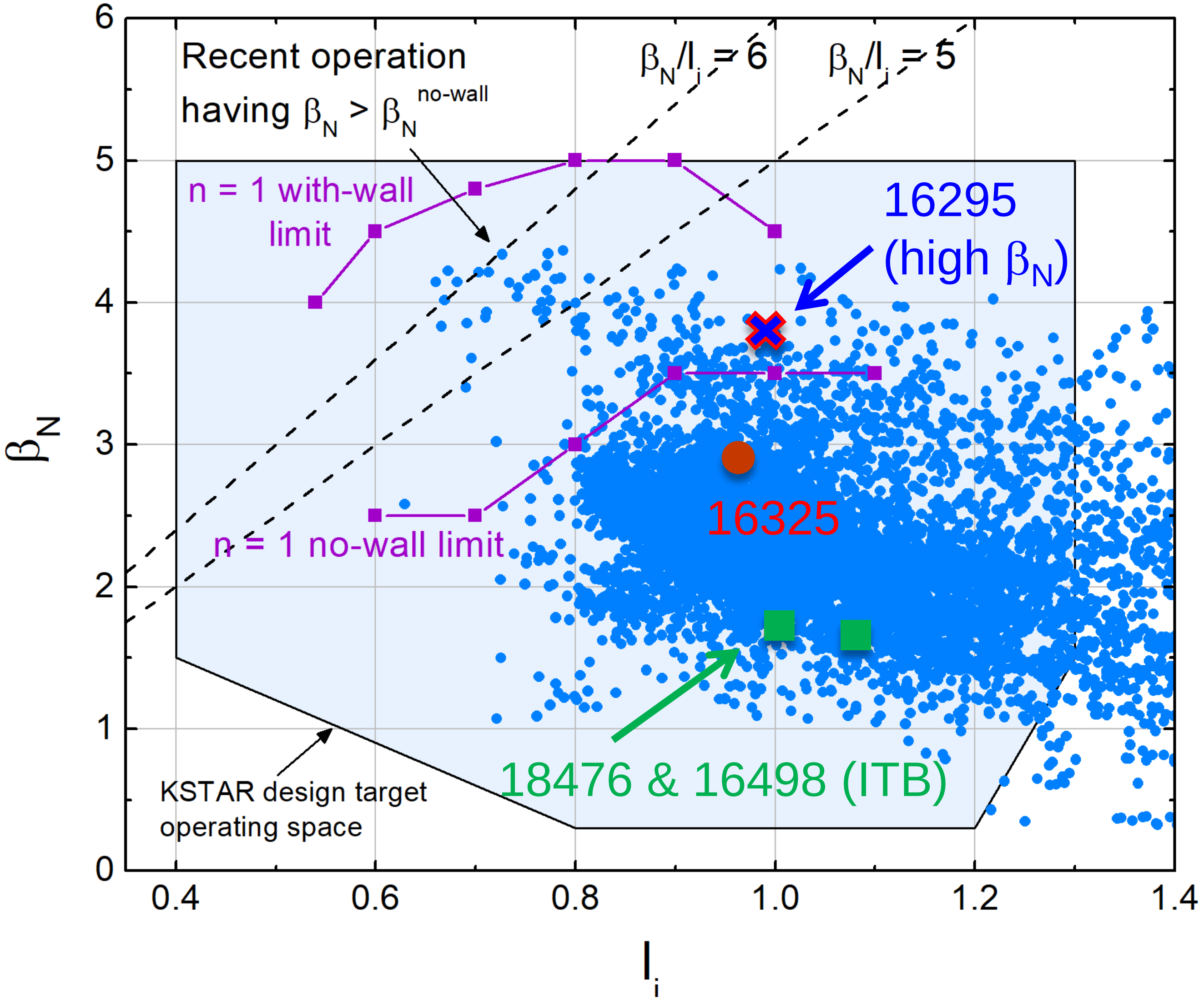
- Density limits
  - Detection: rad. power, global empirical limit
  - Forecasting: starting examination of rad. island power balance model

See talk by J. Berkery, Wednesday

- Physics analysis / experiments to build DECAF models
  - Interpretive and “predict-first” analysis of KSTAR long-pulse, high beta plasmas with high non-inductive fraction

See poster by J.H. Ahn, Tuesday

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



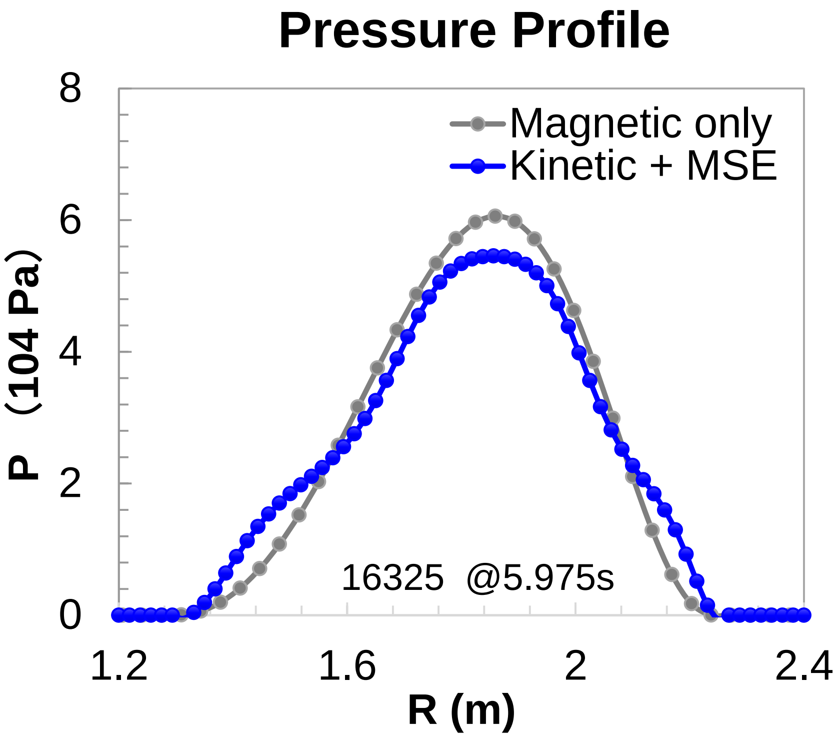
Examples in talk

- ✖ 16295
  - High β_N plasma
- ● 16325
  - Higher B_T (q_{95})
  - Higher edge bootstrap current
- 🟩 18476 & 16498
  - Internal Transport Barrier **(ITB)**

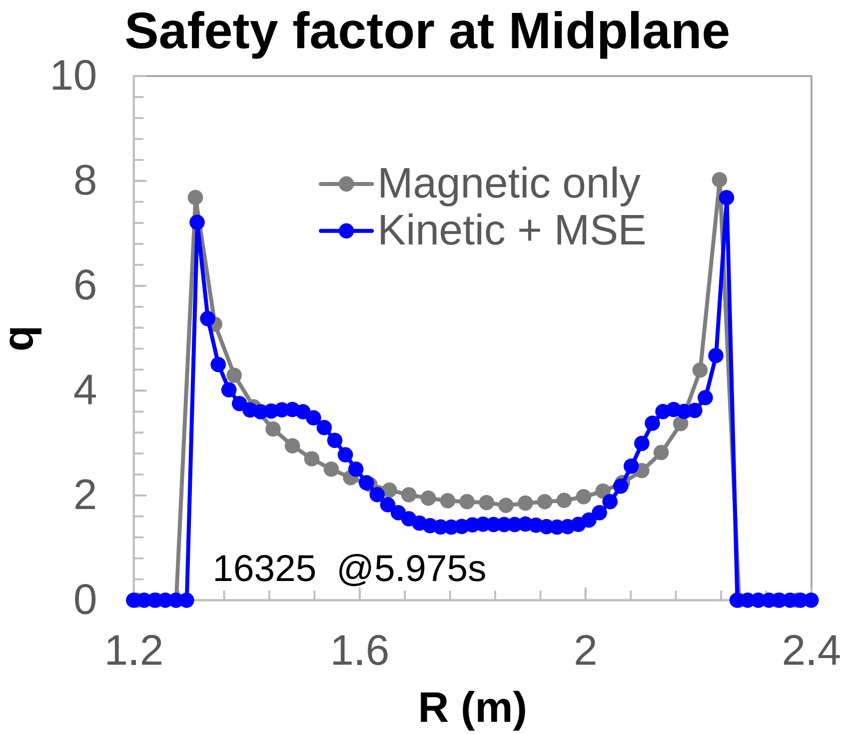
- Many thousands of kinetic equilibria run during testing

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

Kinetic equilibria with MSE produces greater detail in P and q profiles than magnetics-only



Pressure Profile

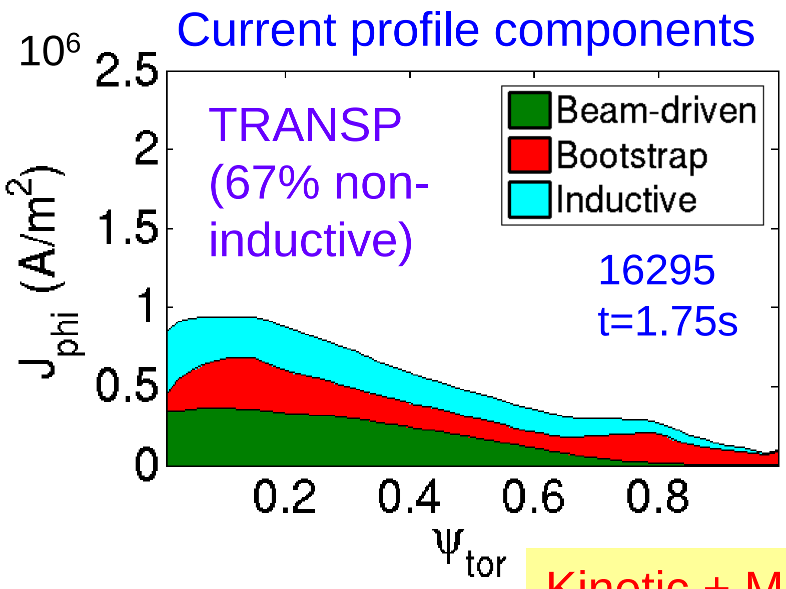


Safety factor at Midplane

Global parameter	χ^2	Error	R_{axis} (cm)	Z_{axis} (cm)	κ	δ_{TOP}	δ_{BOT}	β_T	β_p	β_n	l_i	q_{95}
Magnetic only	202	1.60E-07	186.1	-0.7	1.68	0.54	0.80	0.95	1.86	1.89	1.05	6.39
Kinetic	231	9.70E-05	185.6	-2.4	1.68	0.50	0.80	1.09	1.95	2.10	0.97	5.91

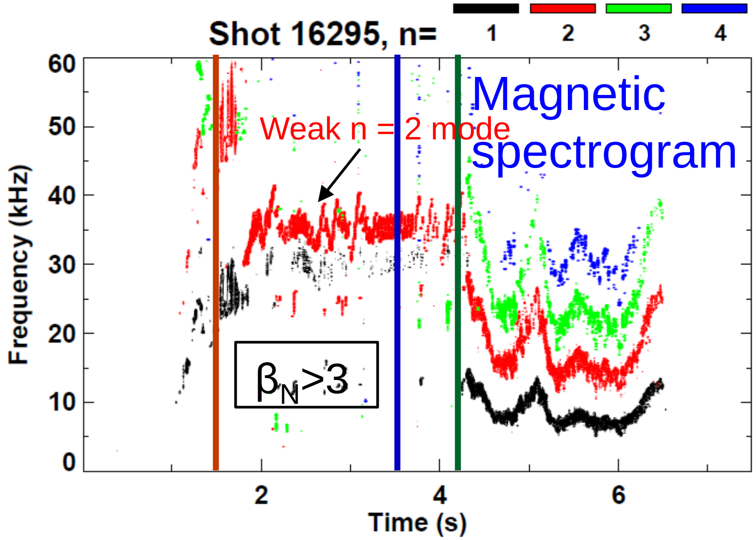
See poster by Y. Jiang, Tuesday

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


Current profile components

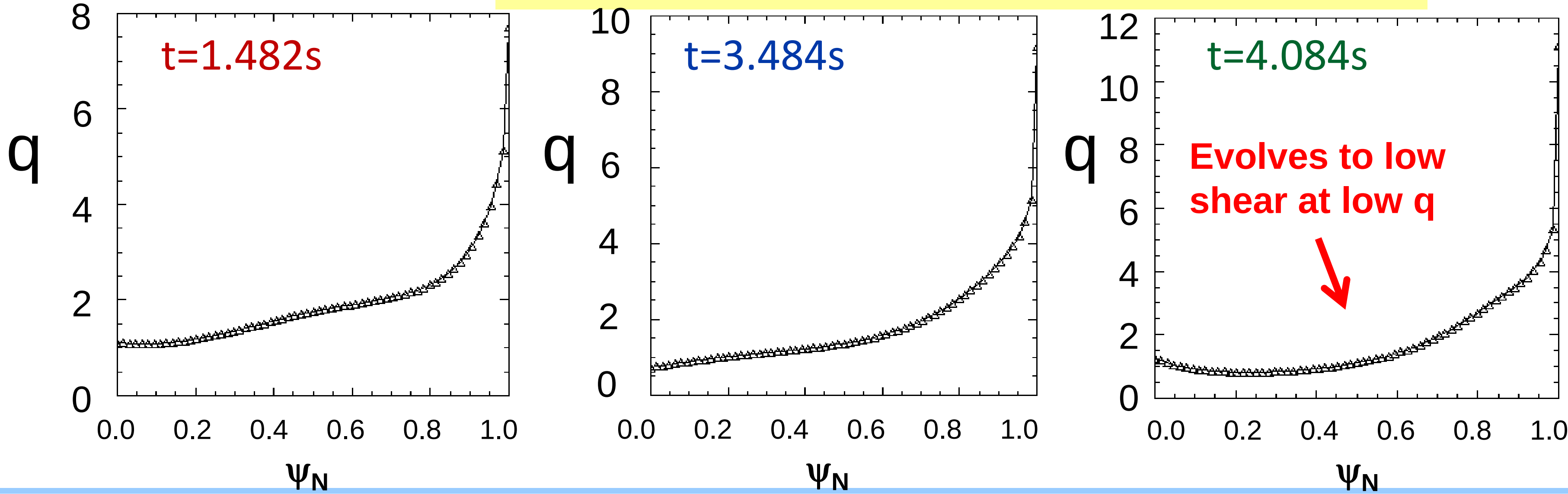
TRANSP (67% non-inductive)

16295 t=1.75s


Magnetic spectrogram

Weak n = 2 mode

Kinetic + MSE reconstructed q profile evolution


t=1.482s

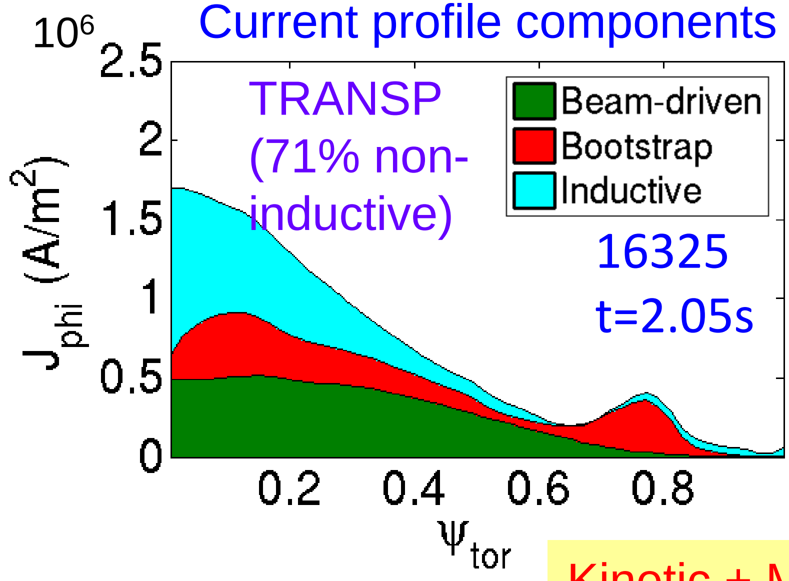
t=3.484s

t=4.084s

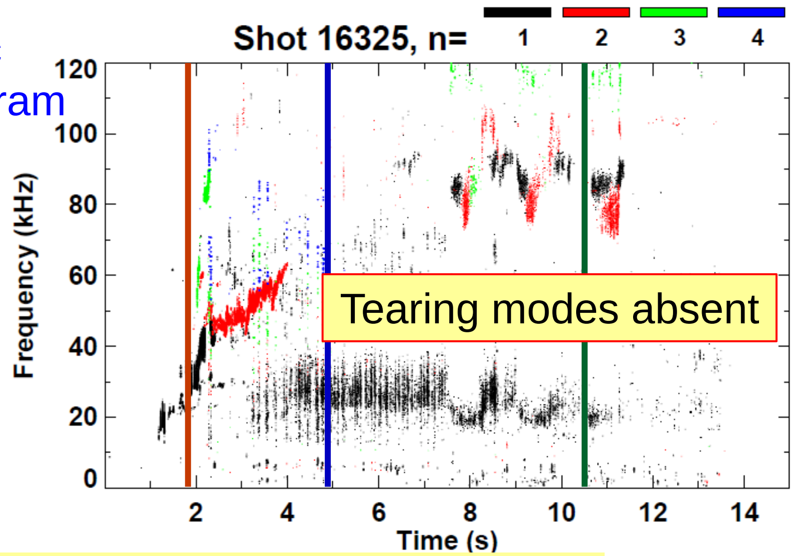
Evolves to low shear at low q

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

Current profile components

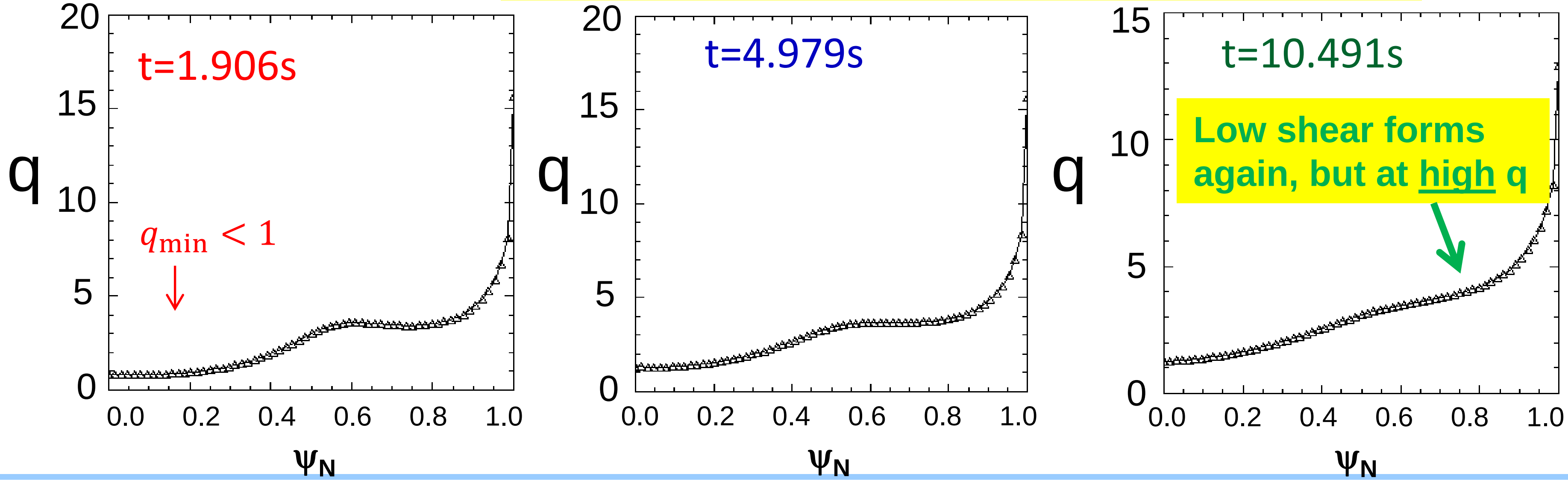


Magnetic spectrogram



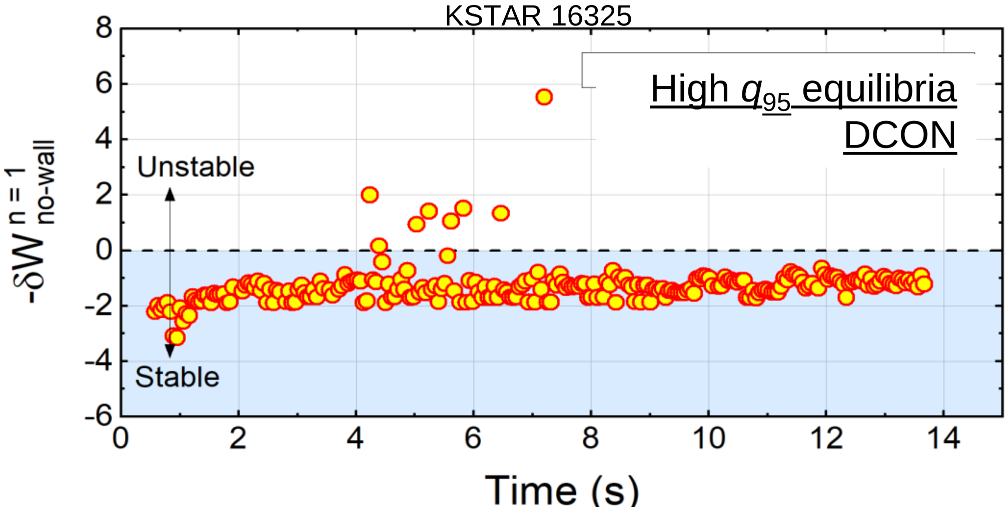
Tearing modes absent

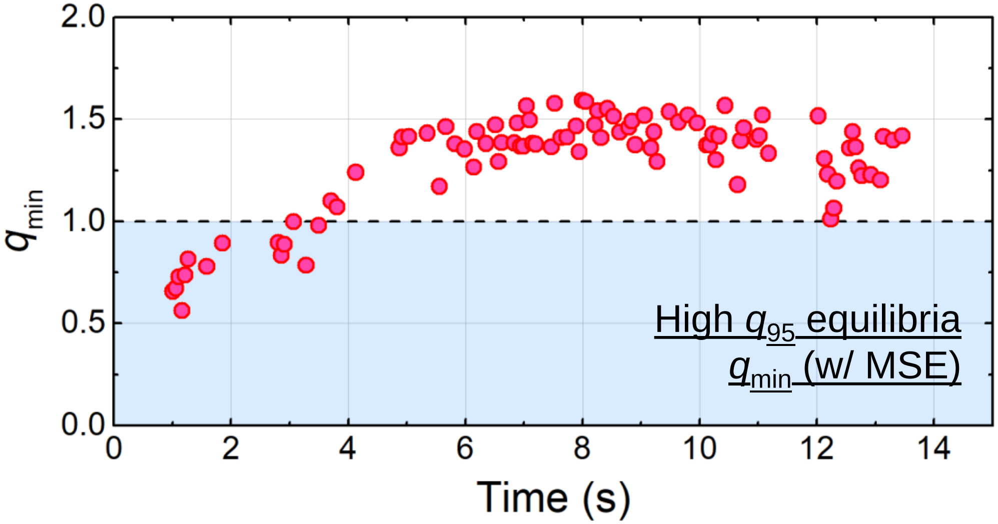
Kinetic + MSE reconstructed q profile evolution →



Low shear forms again, but at high q

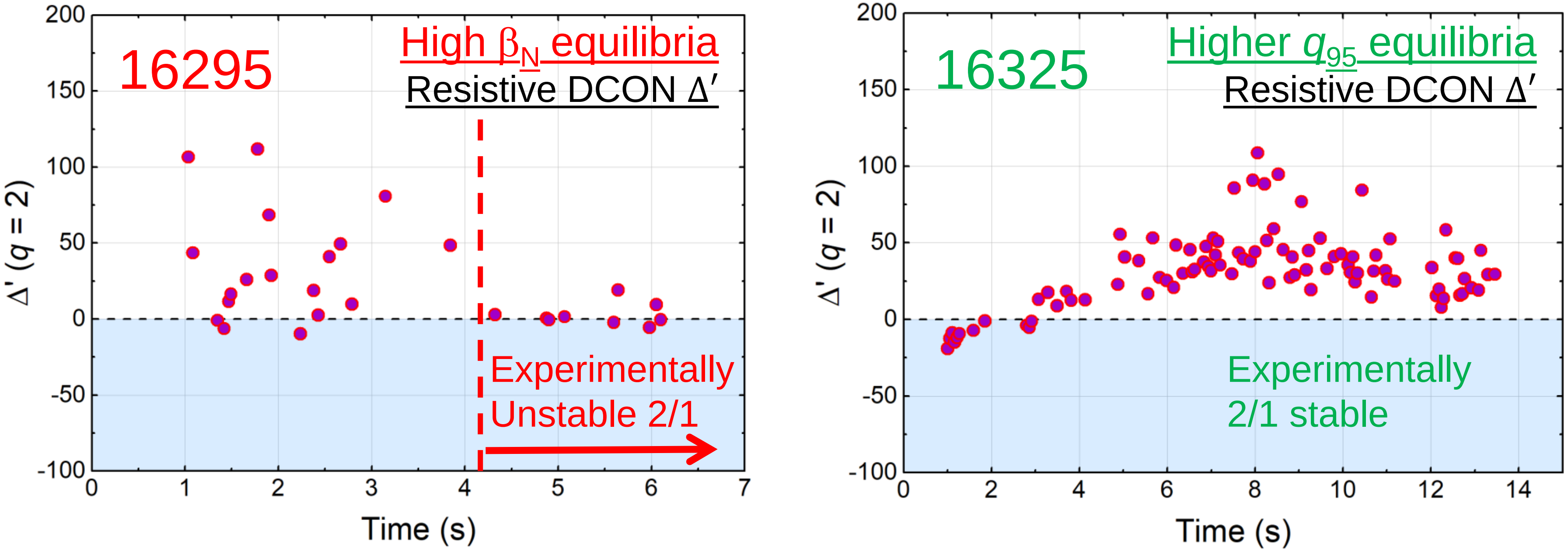
Higher q_{95} plasma has greater ideal n = 1 no-wall stability in DCON, closer to marginal stability





- 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

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

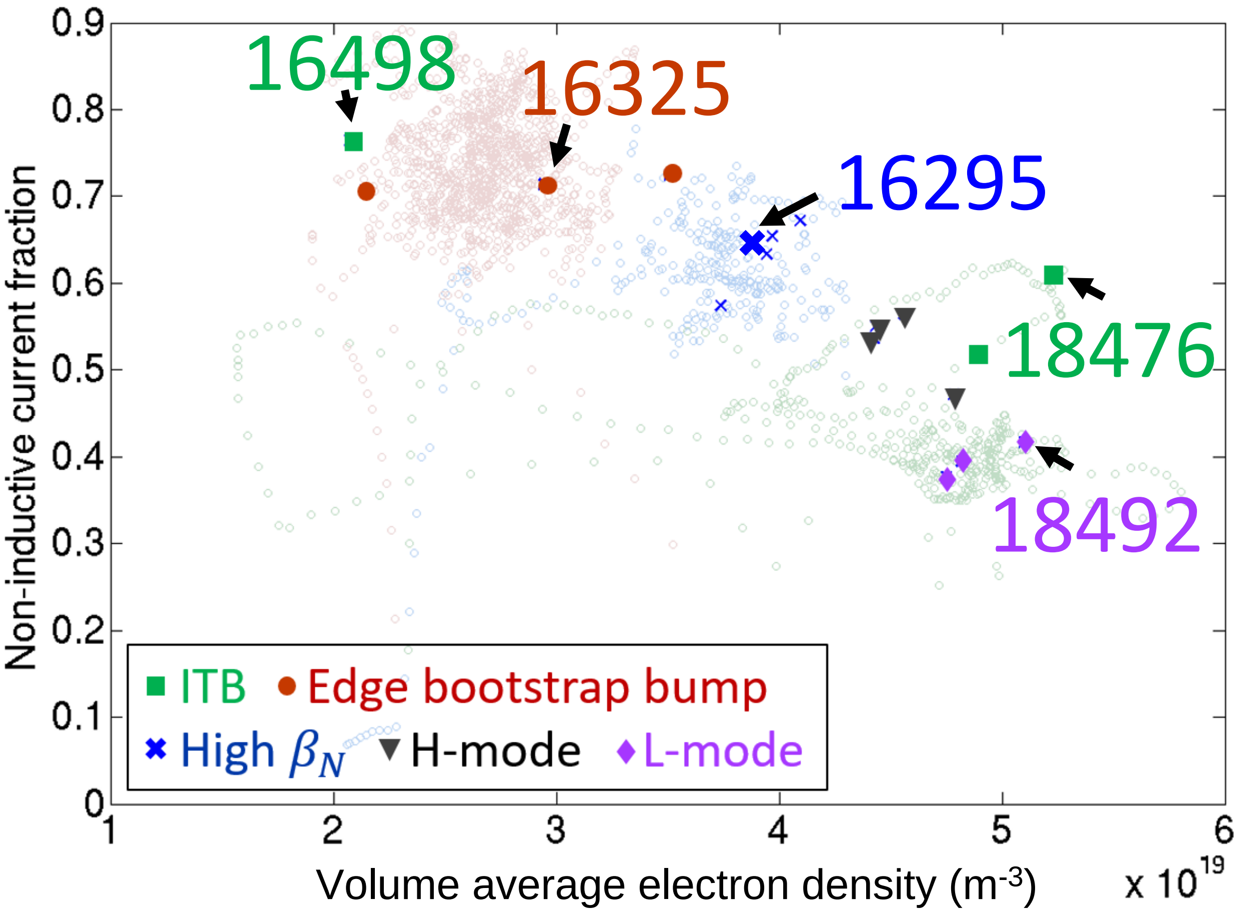


- ❑ Classical tearing stability index, Δ′, computed at the $q = 2$ surface using outer layer solutions
- ❑ At higher q_{95}, Δ′ is mostly positive predicting unstable classical tearing mode
  - Indicates that neoclassical effects or wall effects need to be invoked to produce stability

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

Kinetic reconstructions focused first on KSTAR plasmas with high-non-inductive fraction

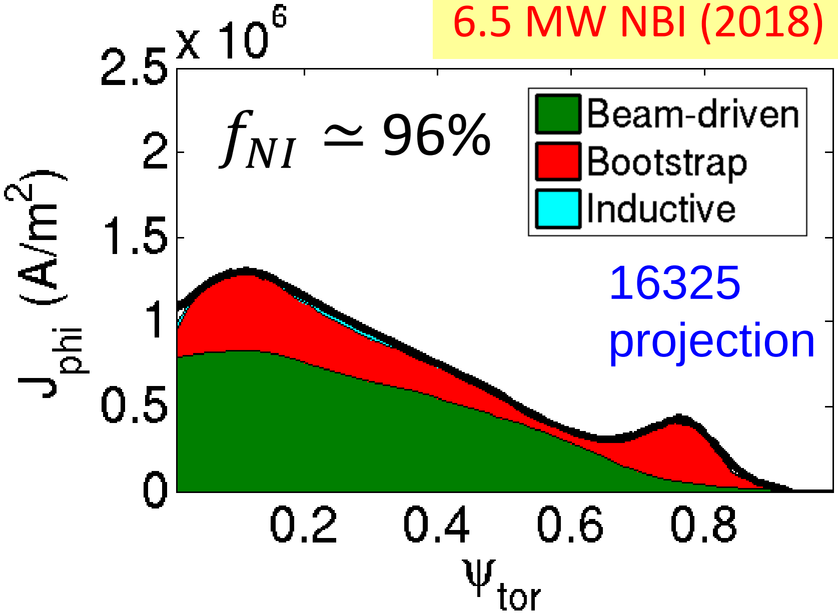
- TRANSP analysis
- Non-inductive fraction
  - Beam-driven
  - Bootstrap
- Non-inductive fraction is key for stable high beta steady state operation



➔ see poster by J.H. Ahn (Columbia U.) on Tuesday

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

6.5 MW NBI (2018)

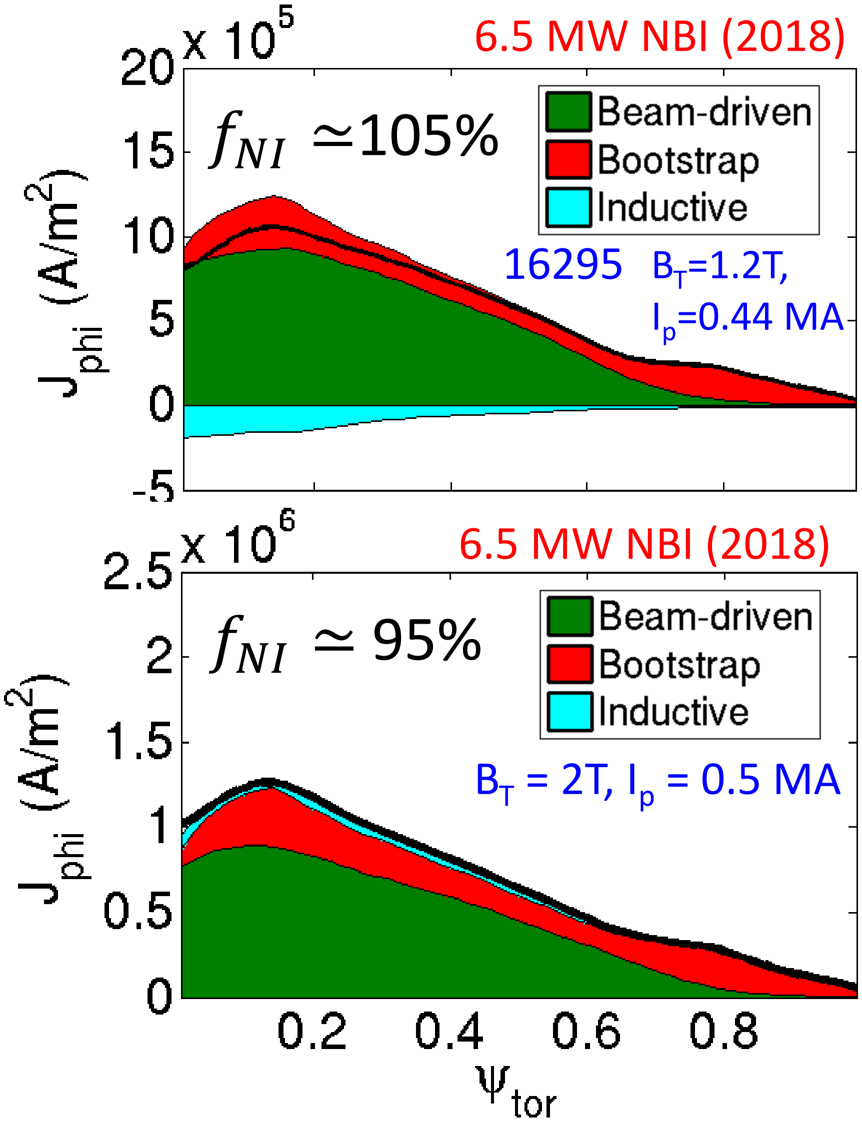


- Project from existing KSTAR plasmas
  - Set fraction of Greenwald density and confinement factor ITER H_{98y2}
    - Neoclassical ion transport, electron transport set to match H_{98y2}
  - KSTAR 1st and 2nd NBI systems are modeled (incl. aiming angles); power levels set realistically based on MSE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

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

➔ see poster by J.H. Ahn (Columbia U.) on Tuesday for further KSTAR TRANSP analysis

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

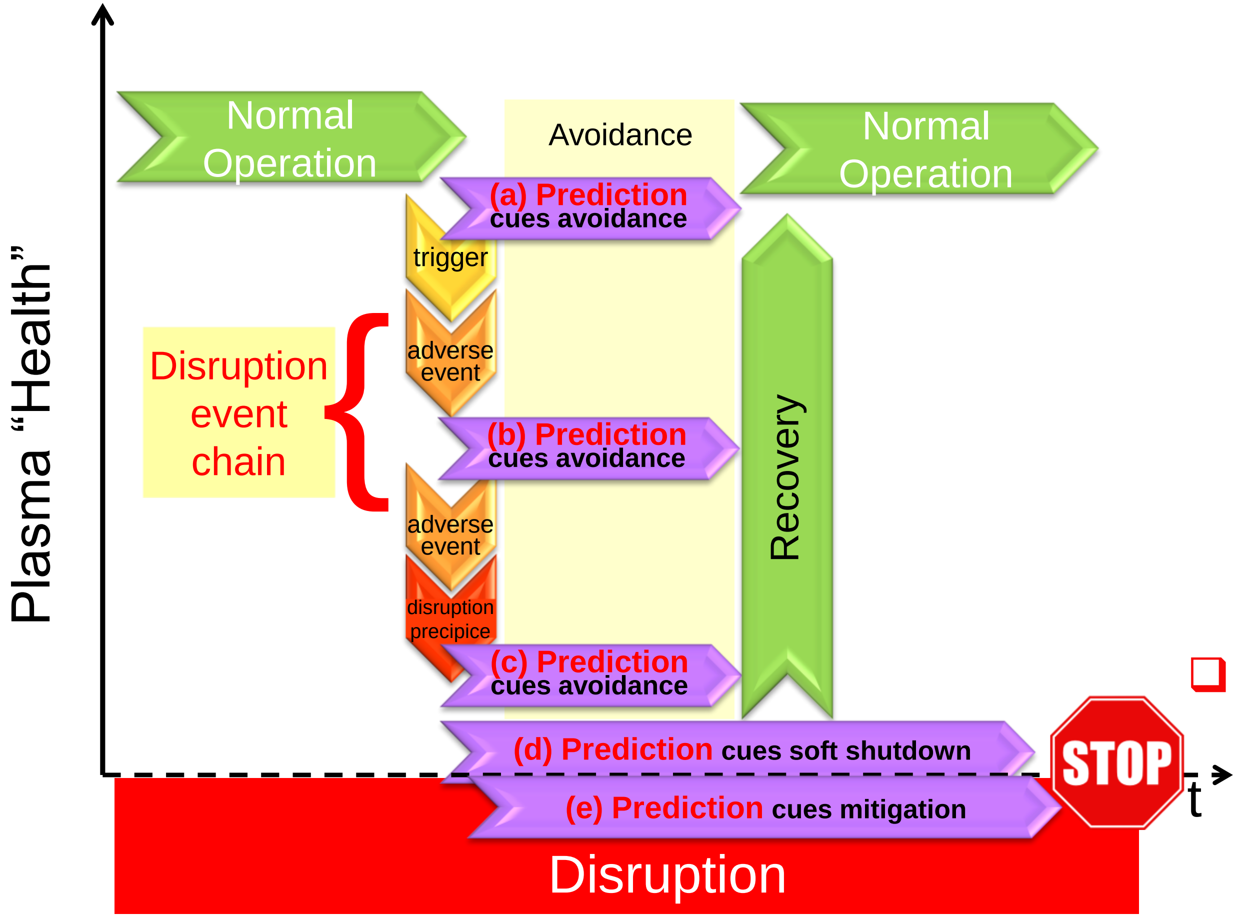
Rapidly-expanding DECAF approach provides a new paradigm for disruption prediction research

- Multi-faceted, integrated approach to disruption prediction and avoidance with several key characteristics
  - Physics-based approach yields understanding that is needed for confident extrapolation of disruption 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.)
- Automated determination of disruption event chains teach us the important regions of operating space to study
  - Disruption DB "boundaries" are often NOT the important regions
- Next steps
  - Couple new MHD events to other events to reduce false positives
  - Expand number of DECAF events evaluated in large database analysis
  - Begin evaluation of simple quantitative figures of merit on large databases ➔ aim for fall 2018 ITPA MHD meeting for these results

Supporting slides follow

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

Disruption prediction/avoidance framework
(from DOE "Transient Events" report (2015))

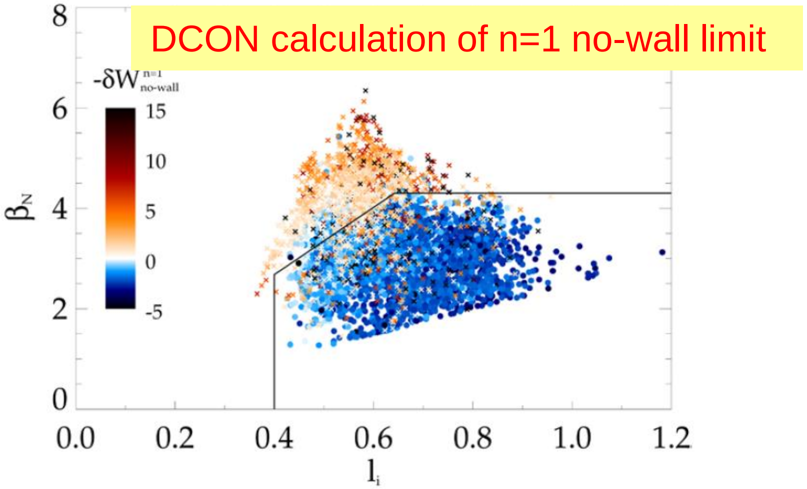


- ❑ Approach to disruption prevention
  - ❑ Identify disruption event chains
  - ❑ Predict events in disruption chains
  - ❑ Cue disruption avoidance systems to break event chains
    - Attack events at several places with active control
- ❑ Expand analysis to more tokamak data
  - ❑ Requires expansion of code analysis tools

A reduced kinetic RWM model was created for DECAF code analysis

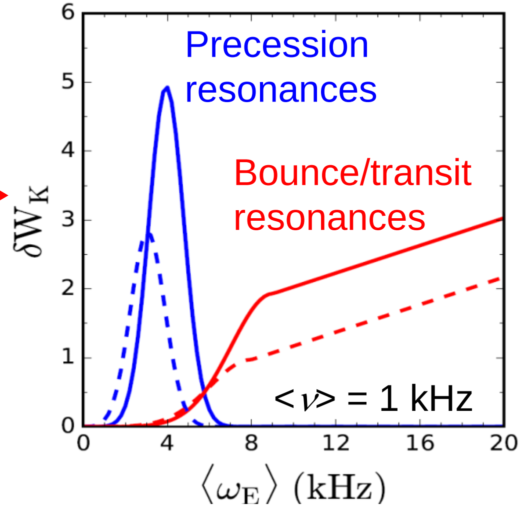
Elements: mode growth rate calculation

- Ideal component δW
  - Equilibrium quantities including l_i, $p_0/\langle p \rangle$, A, used in beta limit models for δW_b, δW_{inf}


DCON calculation of n=1 no-wall limit

J.W. Berkery, S.A. Sabbagh, R.E. Bell, *et al.*, NF **55** (2015) 123007

- Kinetic component δW_k
  - Functional forms (mainly Gaussian) used to reproduce precession and bounce/transit resonances
  - Height, width, position of peak depend on collisionality

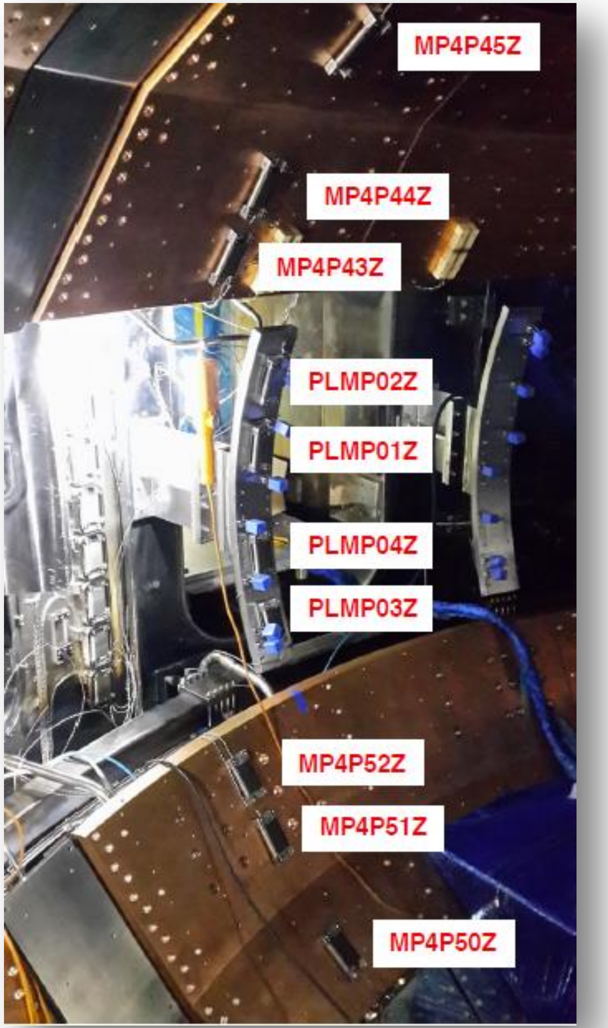


KSTAR magnetic diagnostics provide the basis for "magnetics-only" equilibrium reconstruction

- ❑ KSTAR equilibrium magnetics
  - ❑ Flux loops (45)
  - ❑ Magnetic probes (105)
  - ❑ Plasma currents (1)
  - ❑ Coil currents (18)
  - ❑ Loop voltage monitors (5)
  - ❑ Vessel wall current groups (12)
- ❑ Stabilizing plates / divertor plates included in model
- ❑ PF, IVC, IVCC currents in model

S.A. Sabbagh, et al., Nucl. Fus. **41** (2001) 1601

Y.S. Park, et al., Nucl. Fus. **51** (2011) 053001

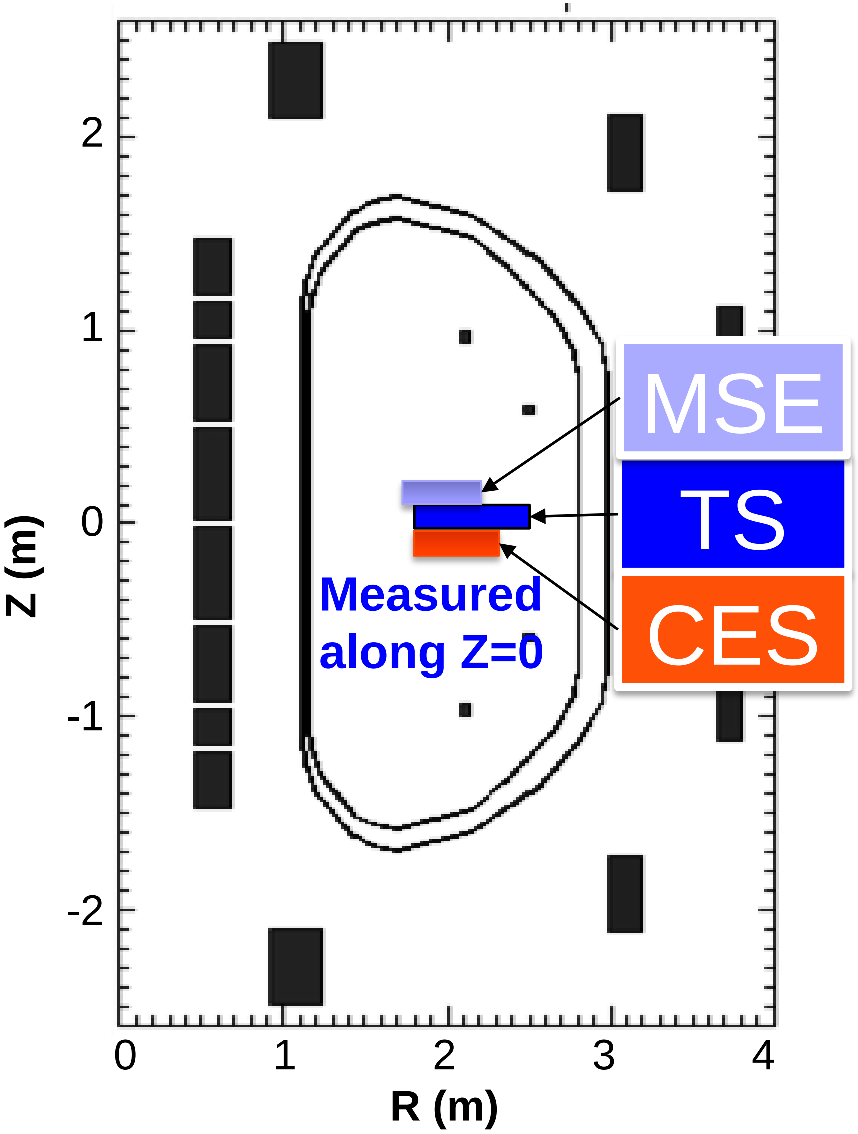


- Magnetic probes on the passive plates and outboard limiter

(Photo courtesy of J.G. Bak and S.H. Hahn)

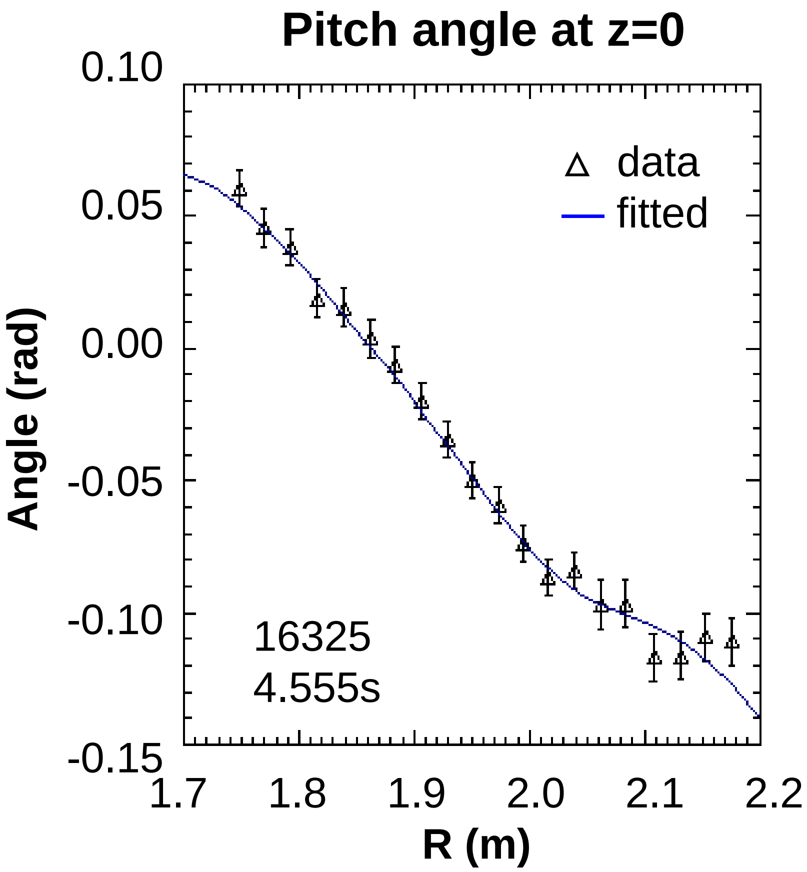
Kinetic data supplements magnetics input for KSTAR kinetic equilibrium reconstructions

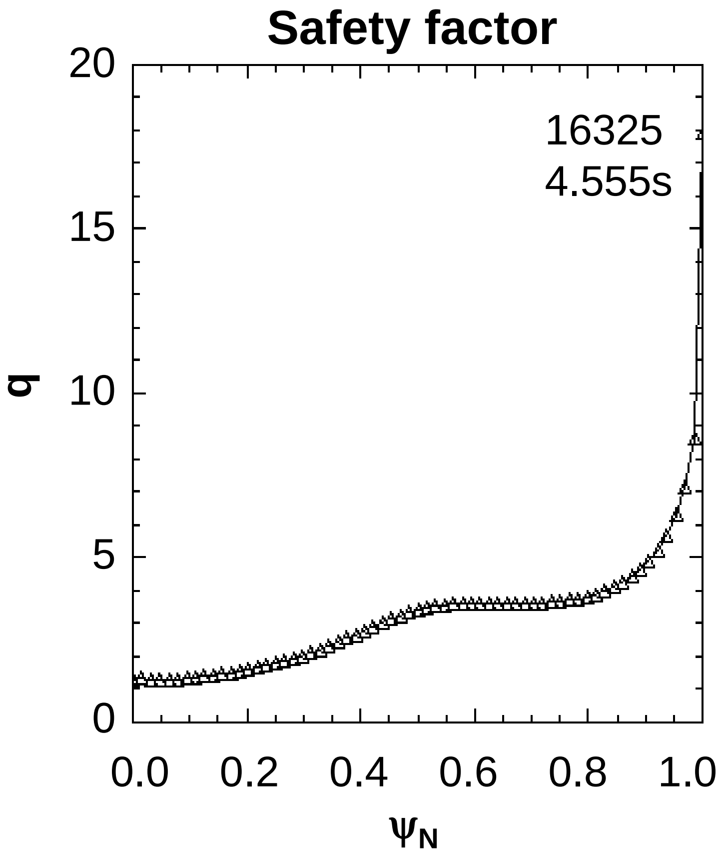
- Motional Stark Effect (MSE)
  - MSE (up to 25 channels) measuring plasma magnetic field pitch angle
- Thomson scattering (TS)
  - TS 27 channels
  - Electron density & temperature (N_e, T_e)
- Charge exchange spectroscopy (CES)
  - CES 32 channels
  - Ion Temperature (T_i)



Measured along Z=0

Motional stark effect data provides magnetic pitch angle, q-profile constraint

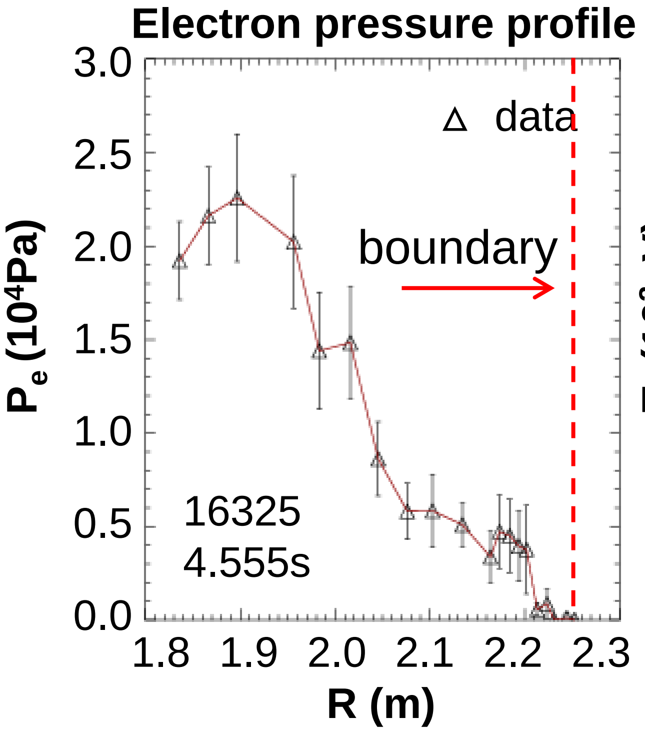


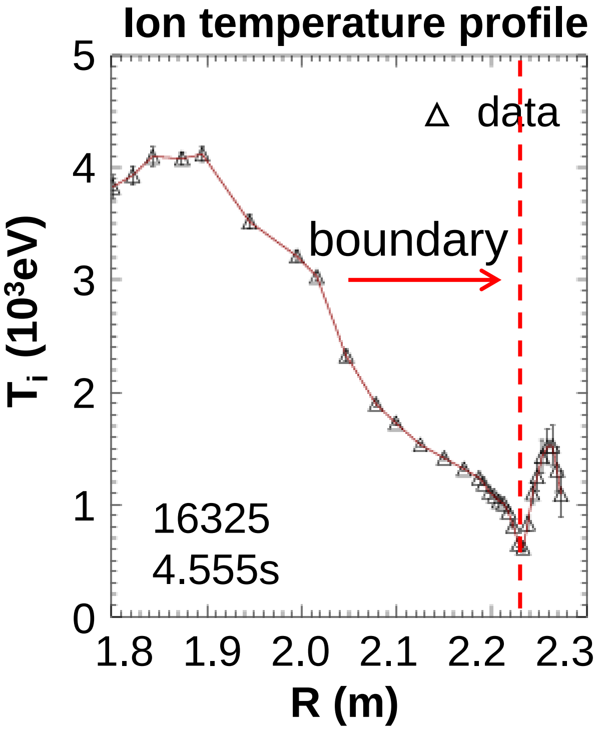


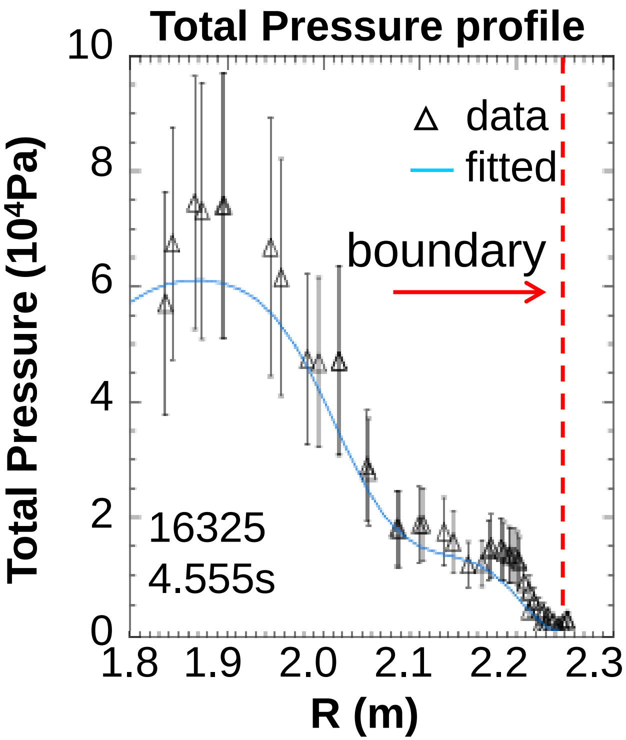
- Systematic and statistical error estimates included in error bars
  - E.g. background light subtraction (w/ Jinseok Ko, S. Scott)

"Partial kinetic" approach for total pressure allows greater flexibility in profile shape

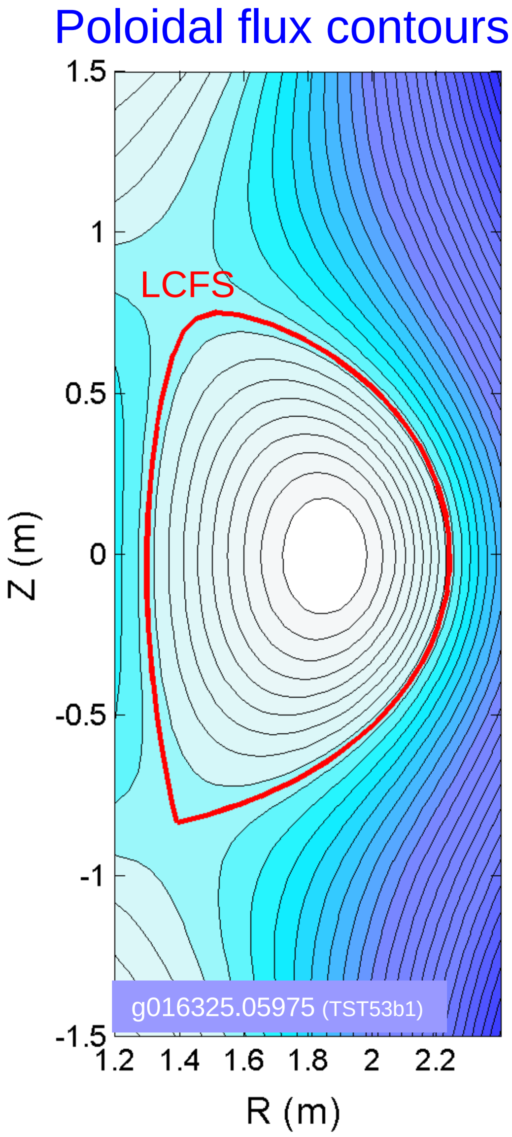
- Electron Pressure $P_e \leftarrow$ 27 Thomson scattering (T_e & N_e), systematic error
- Ion Pressure $P_i \leftarrow$ 32 CES (T_i & N_i estimated from N_e)
- Fast particle pressure P_{fast} "based" on P_e with 100% error bar
- Total pressure $P_{tot} = P_e$ + "P_i" + "P_{fast}" with large total error





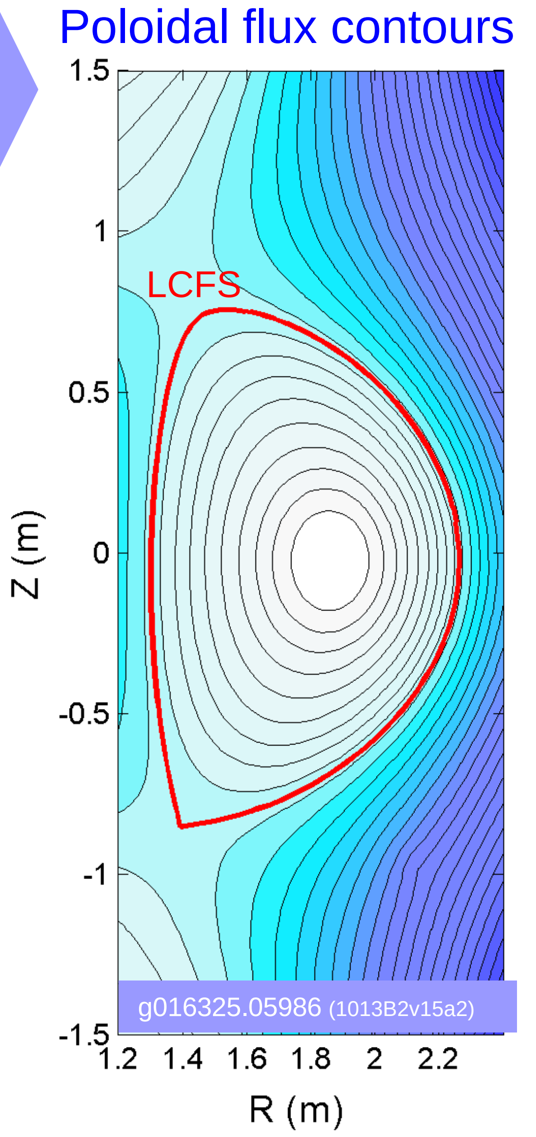


Kinetic equilibrium with MSE has similar global parameters to magnetic-only equilibrium, some differences do occur



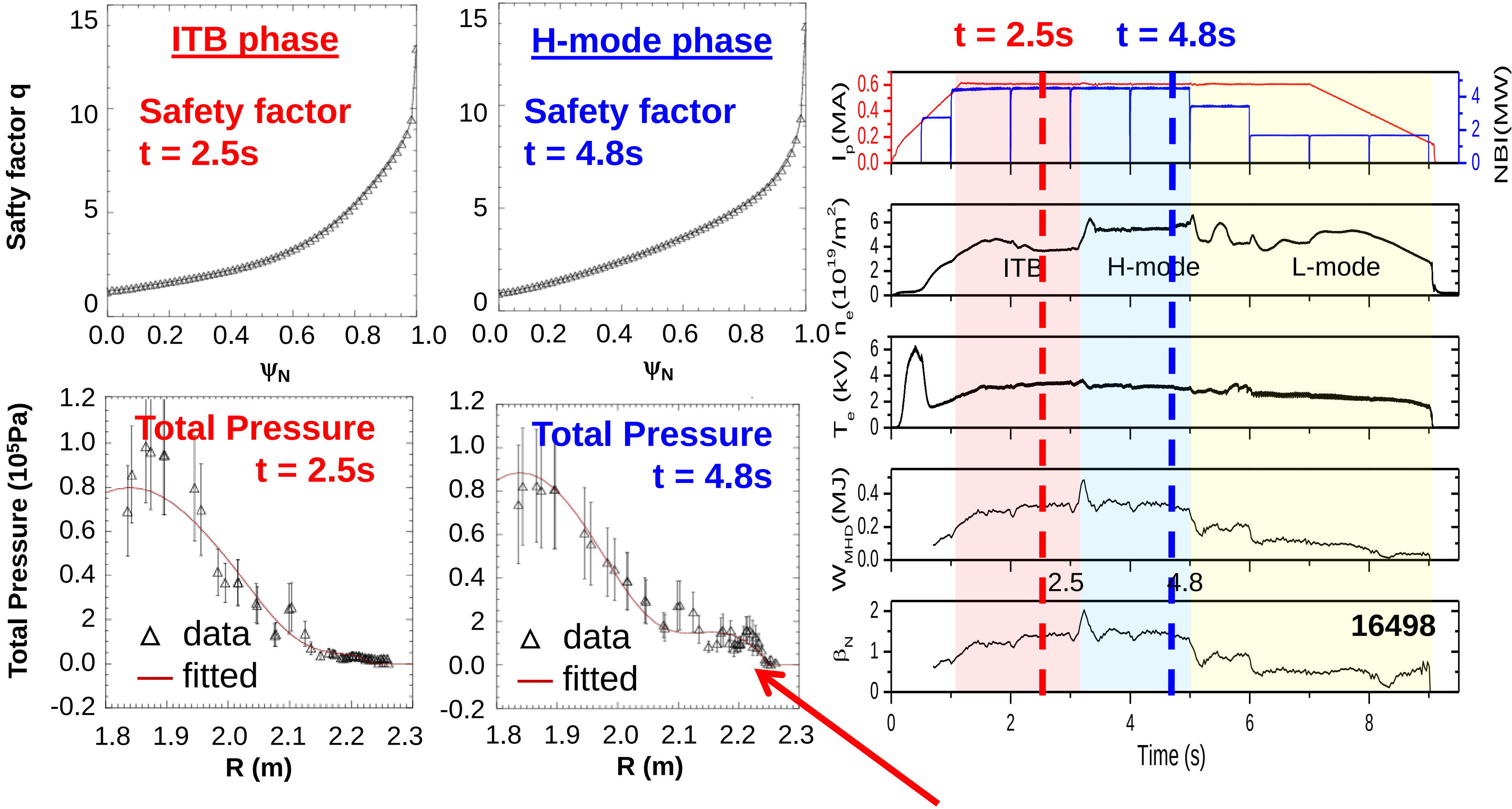
16325 5.975s

Magnetic only	Global parameter	Kinetic
202.4	χ^2	222.6
1.86	R_{axis}(m)	1.86
-0.01	Z_{axis}(m)	-0.02
1.68	κ	1.68
0.54	δ_{TOP}	0.51
0.80	δ_{BOT}	0.81
0.95	β_T	1.04
1.86	β_p	1.86
1.89	β_n	1.99
1.05	l_i	0.96
6.39	q_{95}	5.96



16325 5.986s

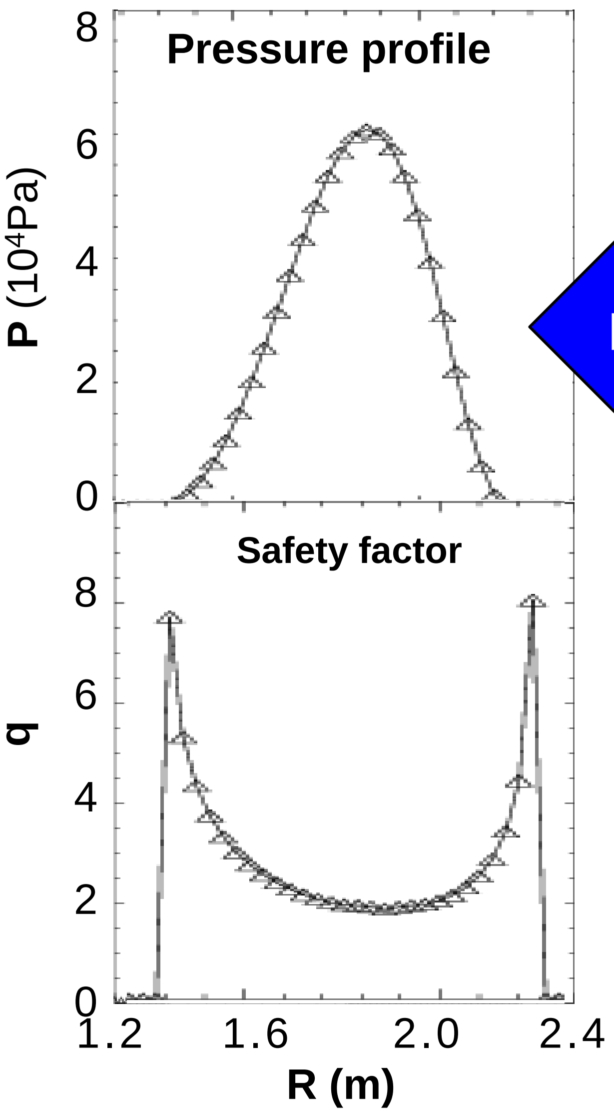
Clear pressure profile distinction between Internal Transport Barrier and H-mode phases



- ❑ Broad pedestal pressure reconstructed in H-mode is not observed in earlier ITB phase ➔ see poster by Y. Jiang (CU) Tuesday

Xp by Jinil Chung

In contrast, kinetic equilibrium reconstruction with MSE produces substantial detail in P and q profiles

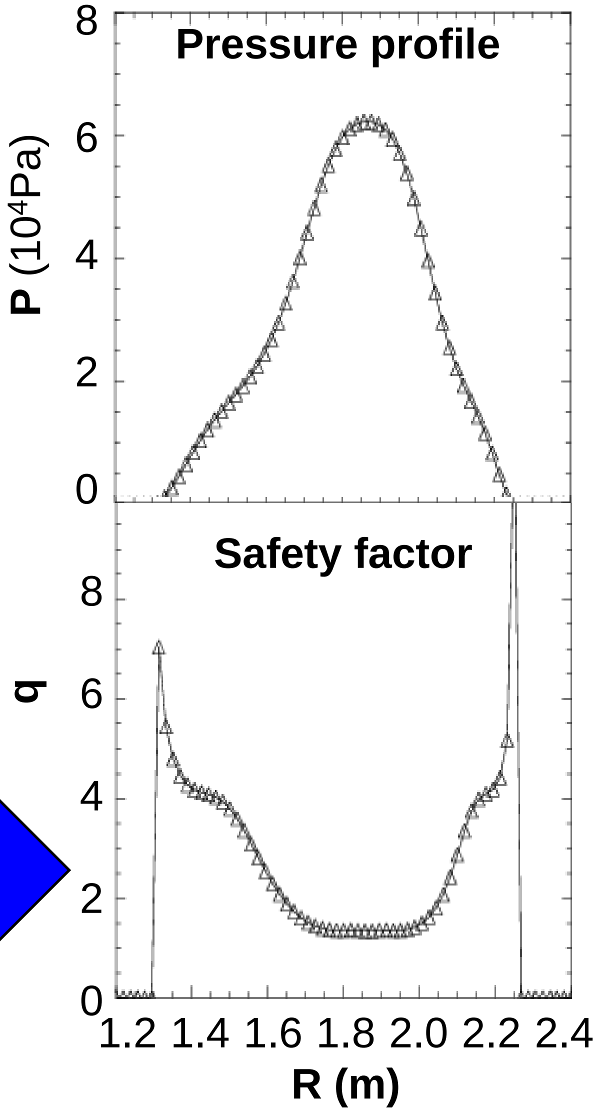


Magnetics only

16325 5.975s

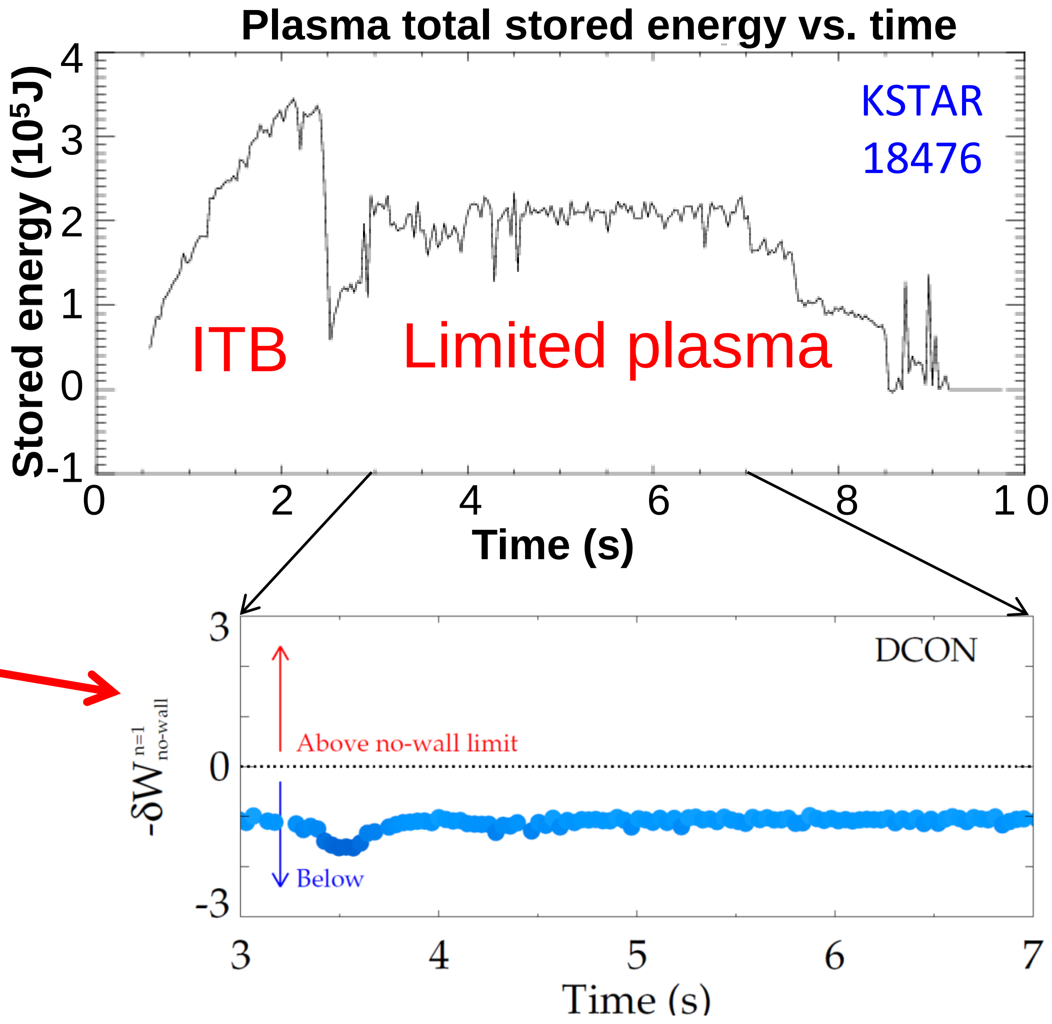
16325 5.986s

Kinetic + MSE



DCON ideal stability of kinetic equilibria with good convergence yield steady analysis evolution

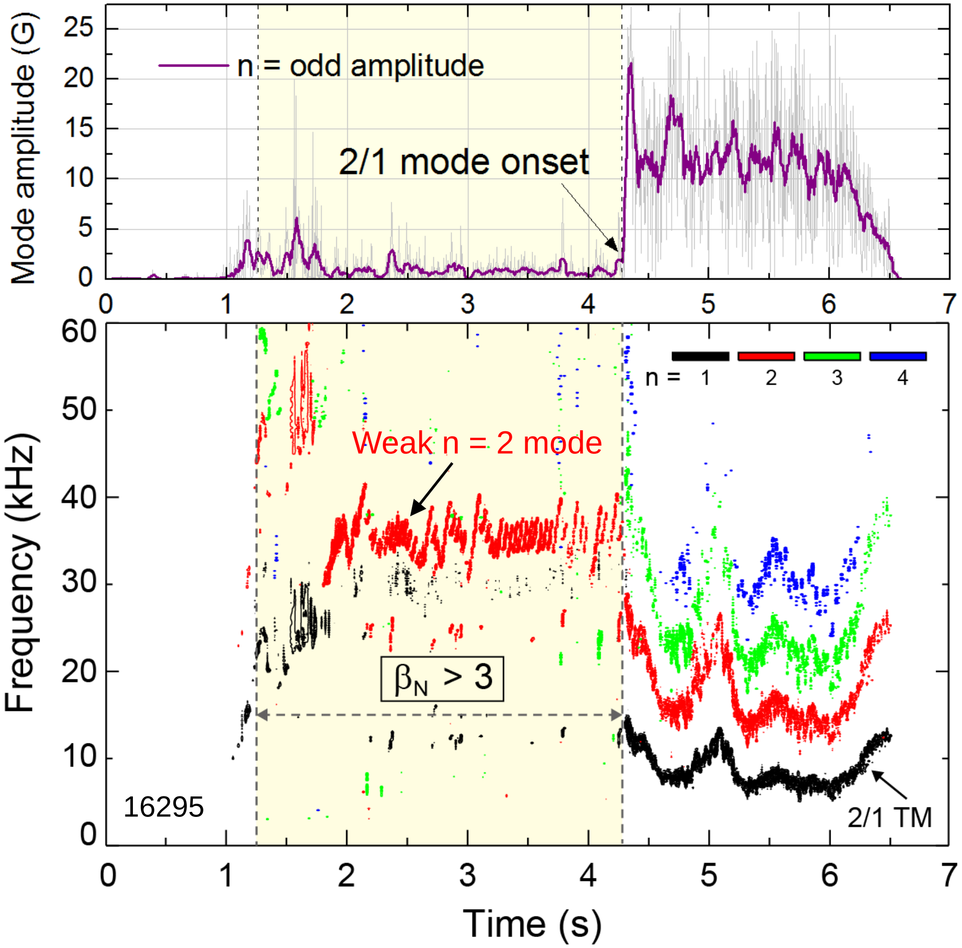
- DCON stability calculations of δW indicate if plasma exceeds the ideal no-wall beta limit
- Analysis of new KSTAR kinetic equilibria indicates ideal stability (below no-wall limit) during period shown (as expected)



DCON: (A. H. Glasser, Physics of Plasmas **23** (2016) 072505

Strong 2/1 tearing mode onset terminated high β_N

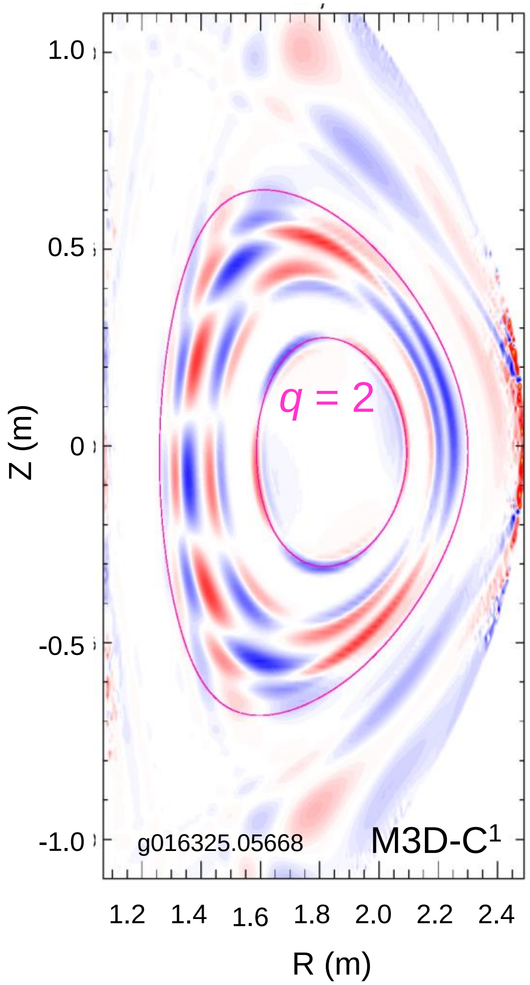
Mode amplitude and toroidal magnetic probe spectrum in high β_N discharge



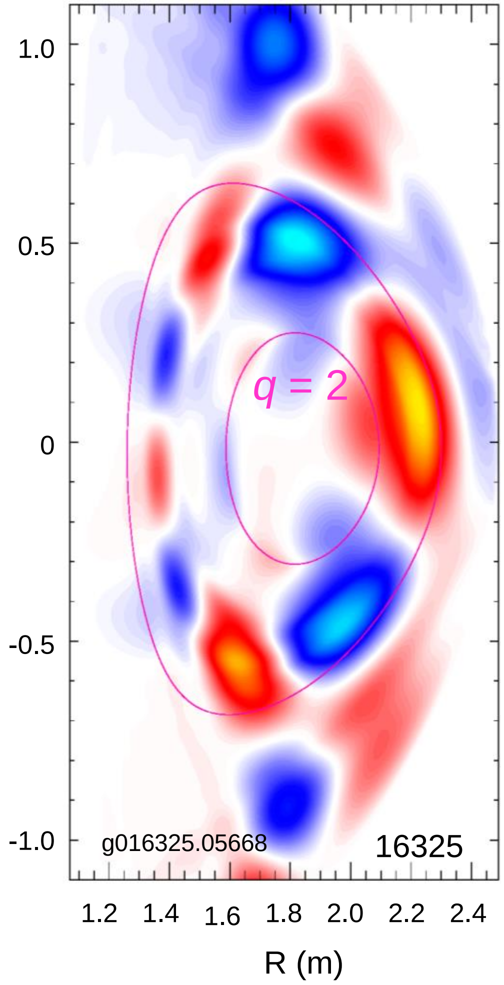
- ❑ Weak n = 2 activity during high β_N phase
    - ❑ $|\delta B_p| \sim 2$ G
- ❑ High β_N operation was limited by strong 2/1 tearing mode onset
    - ❑ Measured mode amplitude > 20 G
    - ❑ Both W_{tot} and β_N were reduced by ~35% but maintained H-mode
- ❑ Plasma rotation profile significantly reduced by > 20% due to the 2/1 mode onset

Resistive tearing mode stability of higher q_{95} plasma examined using M3D-C[1]

Perturbed toroidal current



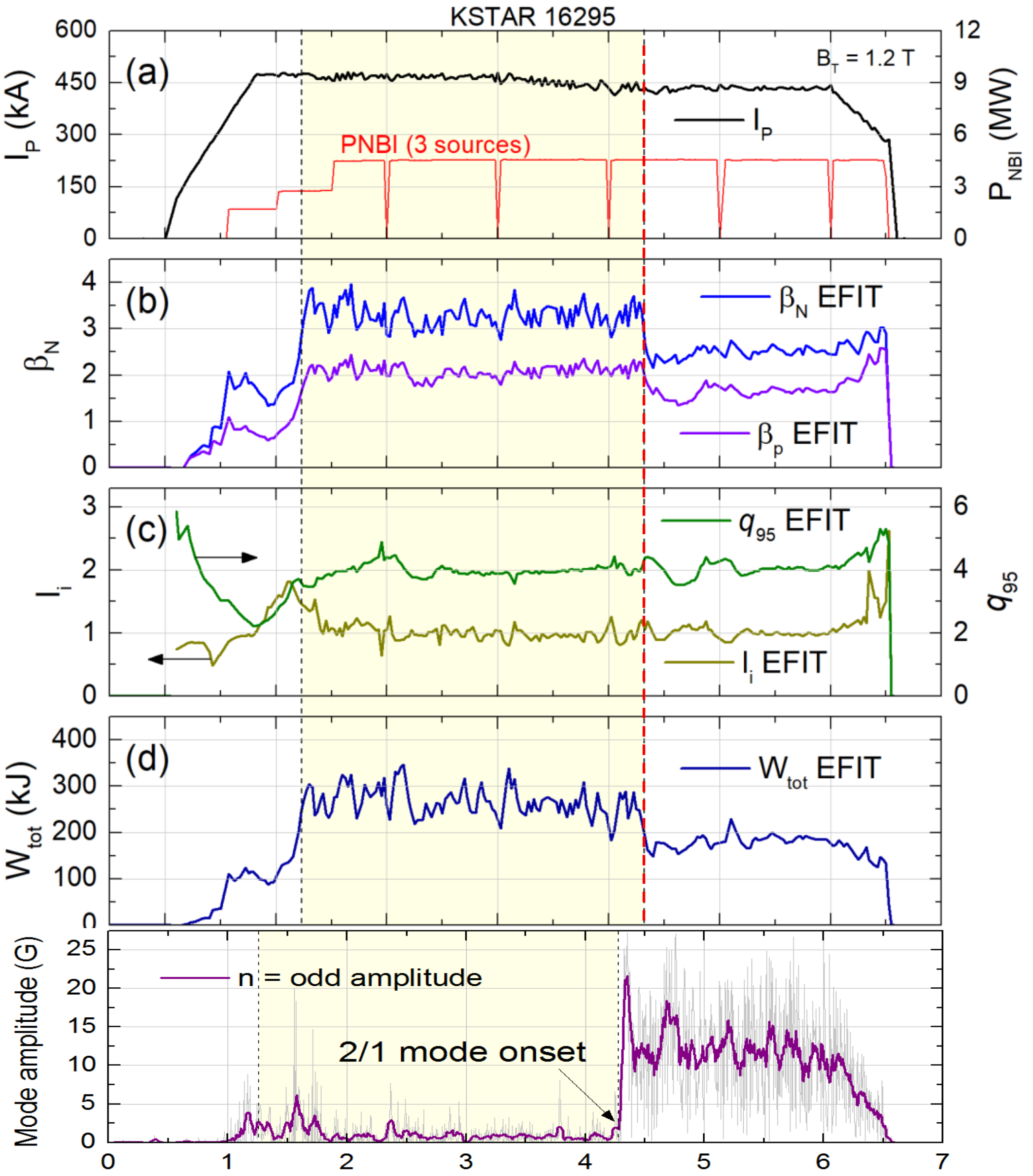
Perturbed poloidal flux



- Kinetic equilibrium 16325 at t = 5.668s
  - $\beta_N = 2.0$, $\beta_p = 1.9$, $q_{min} = 1.4$
  - DCON ➔ ideal stable)
- Resistive MHD computed to be stable by M3D-C[1]
  - Consistent with experiment
  - Initial analysis showing capability – will be continued

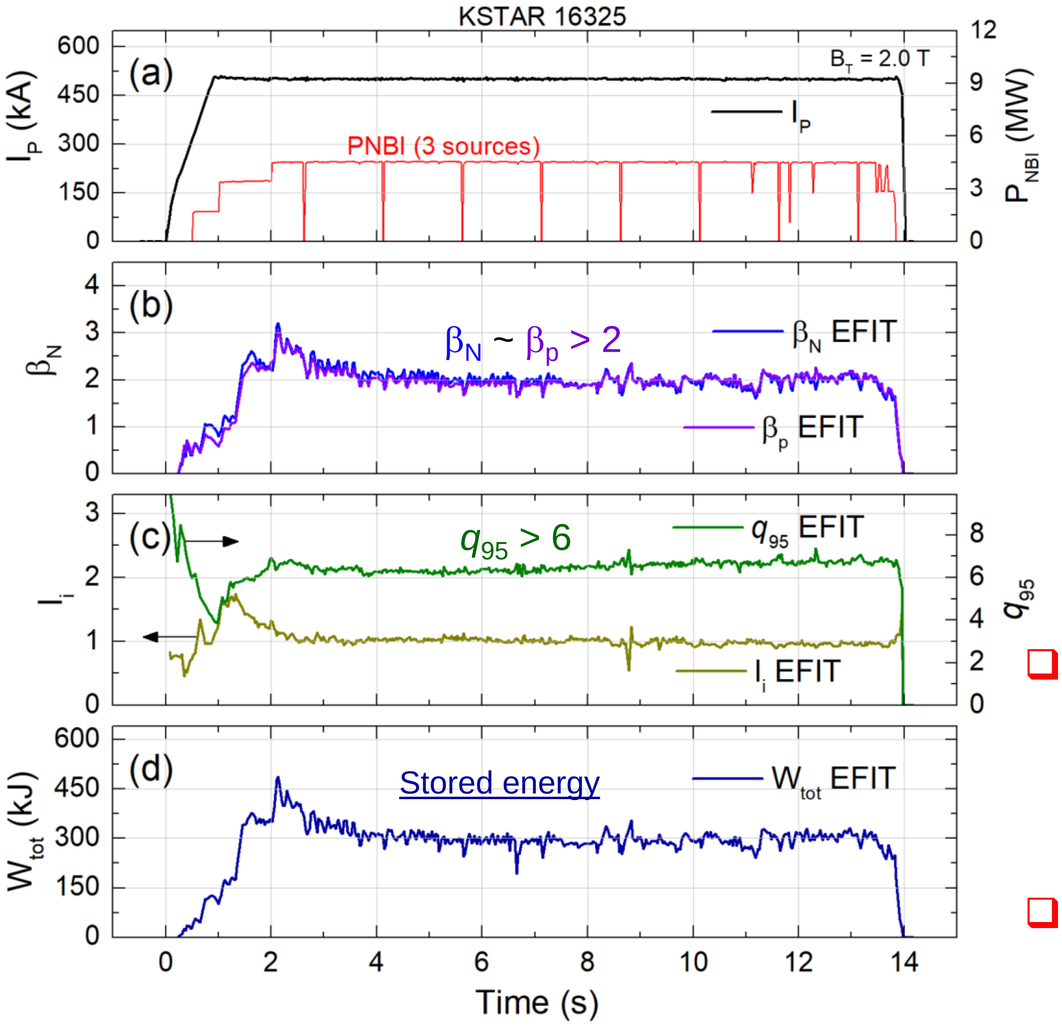
(M3D-C[1]: S.C. Jardin, *et al.*, J. Comput. Phys. **226** (2007) 2146)

High β_N > 3 equilibria limited by rotating MHD

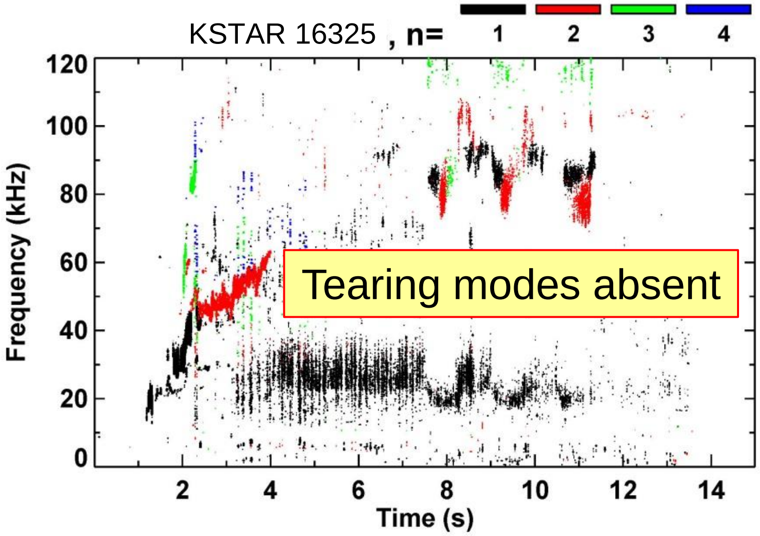


- High β_N plasmas were significantly extended to longer pulse by utilizing improved plasma control
- Sustained high β_N^{avg} = 3.3 achieved for 3 s
  - I_p ~ 450 kA, B_T = 1.2 T, q_{95} = 4.0-4.5, W_{tot} = 270 kJ
- 2/1 tearing mode onset at high β_N phase
  - Consequently reduces β_N and W_{tot} by ~35%
  - Measured mode amplitude >20 G (2G at weak activity)

Comparative equilibria having higher q_{95} shows significantly different MHD stability (shot 16325)



Magnetic probe spectrogram



Tearing modes absent

- Plasma operation at elevated B_T produced equilibria having higher q_{95} and β_p
- Unlike shot 16295, discharge doesn't experience major beta-limiting MHD activity

Several stability codes are being used to analyze KSTAR kinetic equilibrium reconstructions

- Ideal MHD analysis (kink/ballooning, resistive wall modes)
  - Ideal DCON (A. H. Glasser, Phys. Plasmas **23** (2016) 072505)
  - PEST (R.C. Grimm, J.M. Greene, and J.L. Johnson, Methods in Comp. Phys. **16** (1976) 253

- Kinetic MHD analysis (kinetic kink, resistive wall modes)
  - MISK (B. Hu, R. Betti, and J. Manickam, Phys. Plasmas **12** (2005) 057301)
    (J.W. Berkery, S.A. Sabbagh, et al., Phys. Rev. Lett. **104** (2010) 035003)

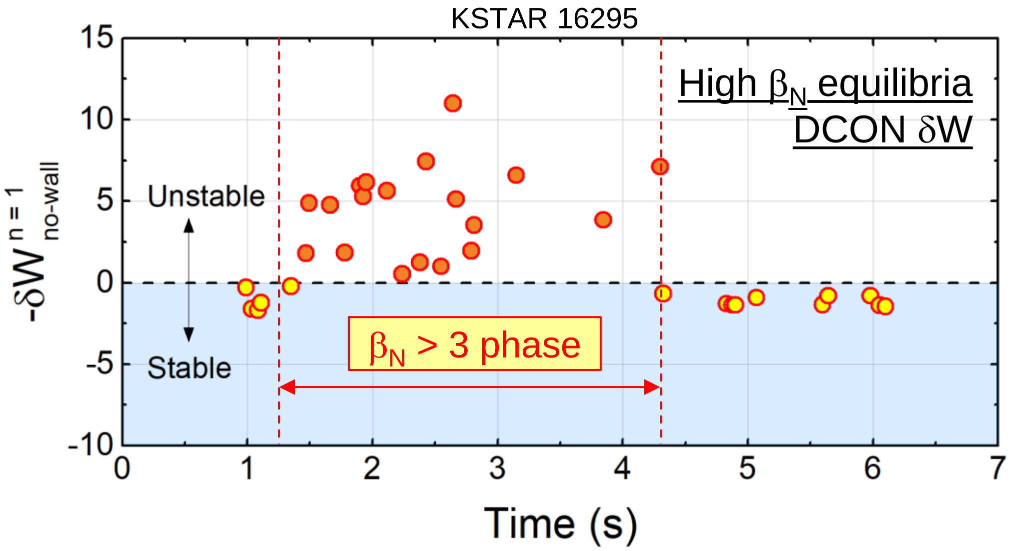
- Tearing modes
  - Resistive DCON (A.H. Glasser, *et al*., Phys. Plasmas **23** (2016) 112506)
  - M3D-C^1 (S.C. Jardin, *et al*., J. Comput. Phys. **226** (2007) 2146)

INITIAL EMPHASIS on determining the quality of equilibrium convergence needed for reliable stability analysis

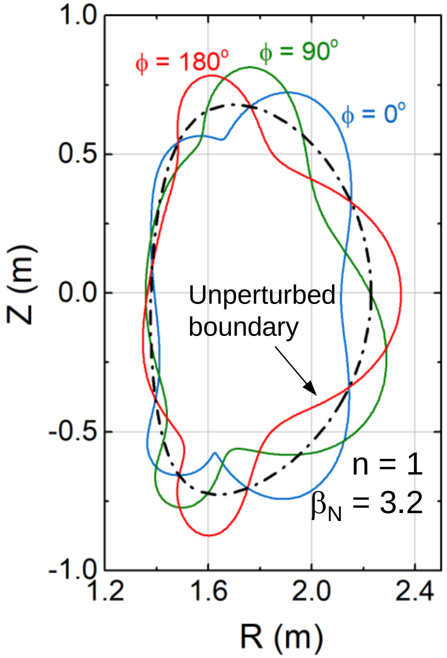
➔ see poster by Y. Jiang (CU) Tuesday

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

DCON analysis, ideal n = 1 mode, no-wall boundary condition



DCON computed δB_n of unstable n = 1 mode at *t* = 2.356 s



- At observed high β_N phase, DCON calculates unstable n = 1 mode with no-wall ($\beta_N > \beta_N^{\text{no-wall}}$)
- Hypothesis: global kink / resistive wall modes stabilized by kinetic effects

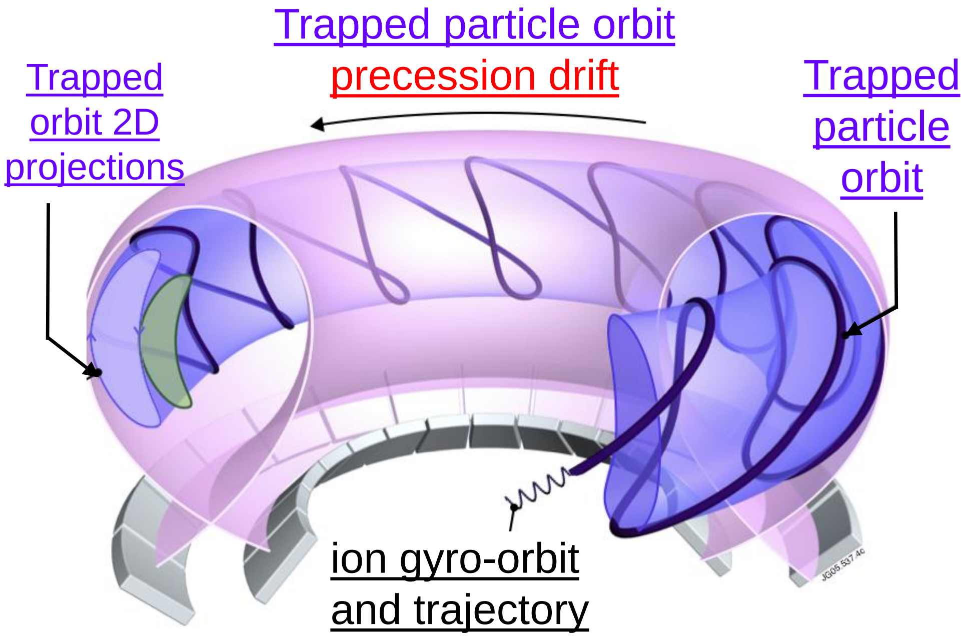
DCON: A.H. Glasser, Phys. Plasmas **23** (2016) 072505

Calculations of kinetic modifications to ideal stability examined with the MISK code

- Kinetic modification to ideal MHD

$$\gamma\tau_w = -\frac{\delta W_\infty + \delta W_K}{\delta W_{wall} + \delta W_K}$$

- Stability depends on
  - Trapped / circulating ions, trapped electrons
  - Particle collisionality
  - Energetic particle (EP) population
  - Integrated ω_ϕ profile matters: broad rotation resonances in δW_K



(Fig. adapted from R. Pitts et al., Physics World (Mar 2006))

plasma integral over particle energy

$$\delta W_K \propto \int \left[\frac{\omega_{*N} + \left(\hat{\varepsilon} - \frac{3}{2}\right)\omega_{*T} + \omega_E - \omega - i\gamma}{\langle\omega_D\rangle + l\omega_b - i\nu_{eff} + \omega_E - \omega - i\gamma}\right]\hat{\varepsilon}^{\frac{5}{2}} e^{-\hat{\varepsilon}}\, d\hat{\varepsilon}$$

precession drift bounce collisionality ω_ϕ profile (enters in ω_E)

NSTX CALCULATIONS: Some references:

J. Berkery *et al.*, PRL **104** (2010) 035003

S. Sabbagh, *et al.*, NF **50** (2010) 025020

J. Berkery *et al.*, PRL **106** (2011) 075004

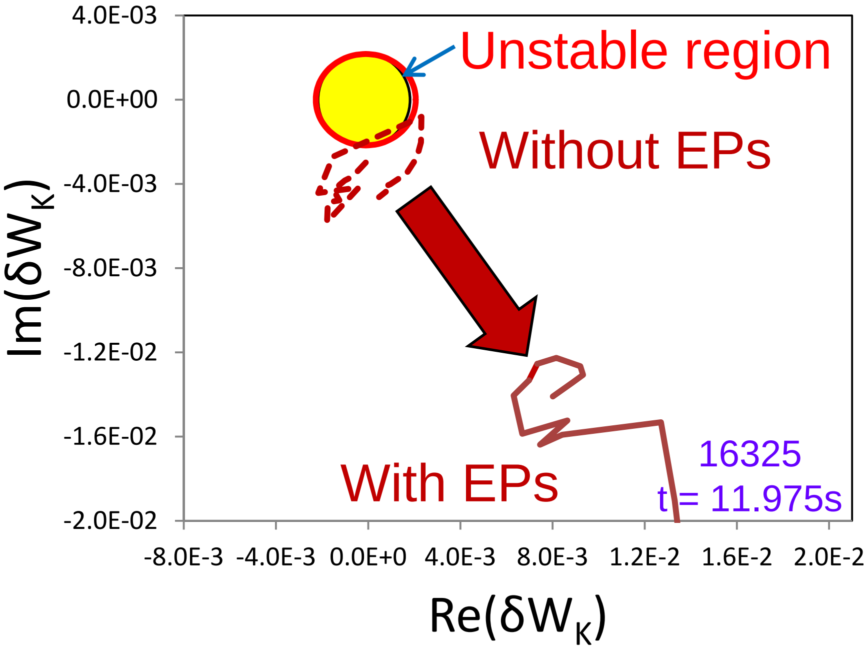
S. Sabbagh *et al.*, NF **53** (2013) 104007

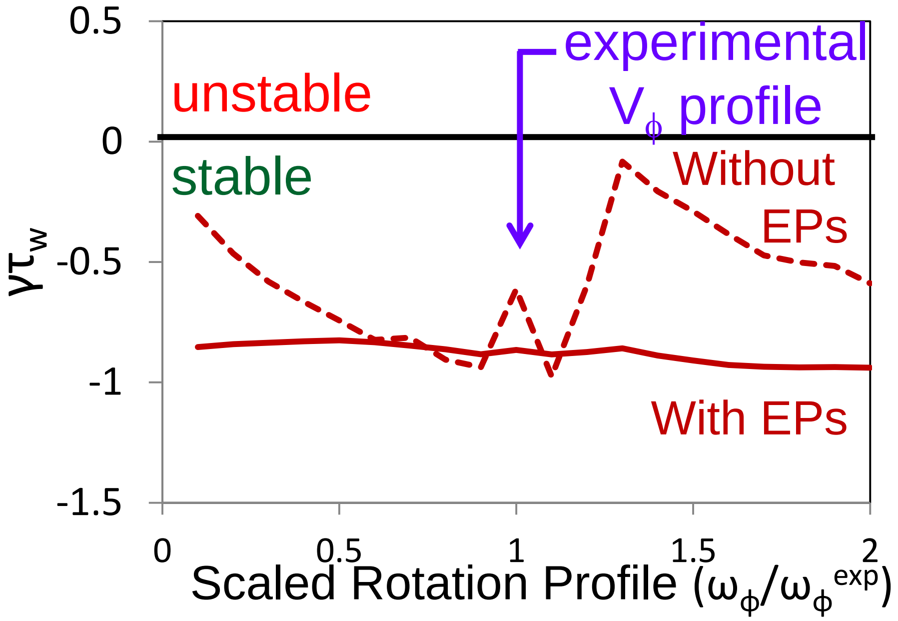
J. Berkery *et al.*, PoP **21** (2014) 056112

J. Berkery *et al.*, NF **55** (2015) 123007

J. Berkery, *et al.*, NF **24** (2017) 056103

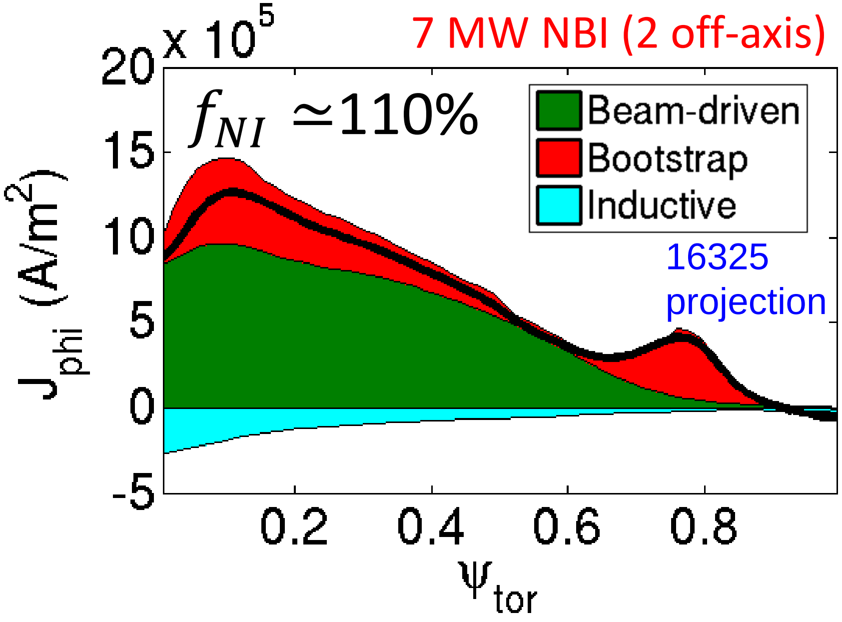
MISK kinetic RWM stability analysis shows stability, significant stabilizing effect of energetic particles





- Resistive wall modes (RWM) computed to be stable (consistent with experiment)
  - Close to marginal stability when examining variation of experimental rotation profile and without considering energetic particles
  - Additionally, energetic particles contribute large stabilizing effect

TRANSP analysis shows new off-axis NBI sources can broaden current profile somewhat



TRANSP 16325	2016 actual	4 NBI (mid-plane)	4 NBI (2 off axis)
NIC fract. (%)	71%	103%	110%
β_N	2.7	3.65	3.65
l_i	0.9	0.96	0.92
$T_i(0)$ (keV)	4.5	6.3	5.6
$T_e(0)$ (keV)	3.6	3.3	3.3
$n_e(0)$ (10^{19}m^{-3})	3.2	5.5	5.5
$f_{Greenwald}$	0.5	0.5	0.5
H_{98y2}	1.25	1.25	1.25

➔ see poster by J.H. Ahn (Columbia U.) on Tuesday for further KSTAR TRANSP analysis

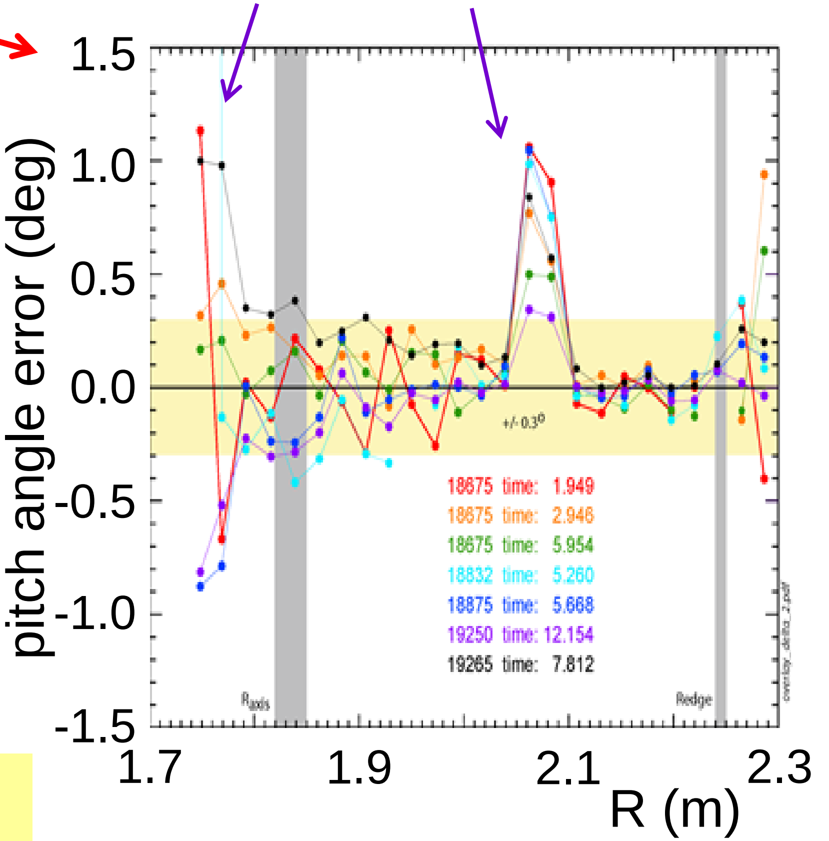
Kinetic equilibrium / stability analysis will continue to improve thru Columbia / PPPL / MIT Collaboration

- Transferred 10 channel MSE background light polychrometer from C-Mod to KSTAR (4/2017)
  - Investigating improvement of MSE measurement by background light subtraction
  - DOE has funded 15 additional BL polychrometer channels (for 2018)
- Collaborative interaction to further improve Thomson scattering data
- Continued improvement of kinetic equilibrium reconstruction / stability analysis
  - E.g. Improved modeling / planned neural net delivery of fast particle pressure P_{fast}

➔ All supporting the main disruption prediction and avoidance research goals

(S.D. Scott (PPPL), et al.,)

Pitch angle can be troublesome on some channels due to neglect of background light subtraction



Broadened disruption prediction and avoidance research centered around DECAF is progressing for future tokamaks

- DECAF code is rapidly developing
  - Initial published results showed strong promise of new, automated "event chain-based" research paradigm
  - DECAF event objects expanded in capability now include event criteria histories; <u>innovation continues</u> (e.g. direct coupling of events)
  - Models defining events are highly flexible (e.g. can include diagnostic comparisons, physics models, machine learning tools/techniques)
- Physics-based approach on multiple devices key to success
  - Understanding is key to disruption forecasting extrapolability, reliability
  - New DOE funding for disruption prediction/avoidance on MAST; KSTAR research including kinetic equilibria, stability, TRANSP analysis
  - Research includes active mode detection/control, directed experiments
- "DECAF database" has begun
  - Storage of intermediate results, est. growth to 100's of TB ("big data"!)