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Stability Research on MAST/-U supporting Disruption Prediction and Avoidance and the RWM in MAST

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NFRI
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National Fusion Research Institute

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

NSTX-U Physics Meeting

3 December 2019

Princeton, NJ

MAST-U

KSTAR

NSTX-U

V1.2

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

Collaborative stability research is being conducted on MAST/-U supporting disruption forecasting (Columbia group)

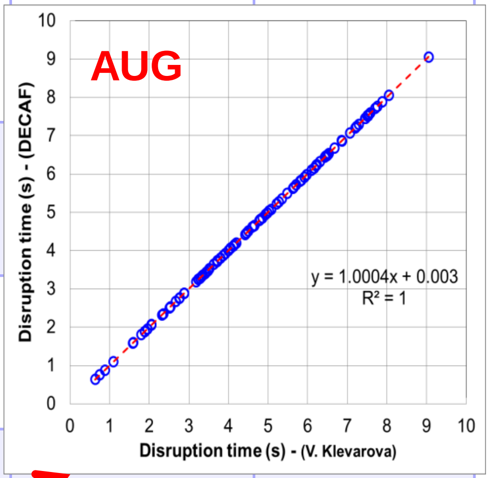
- Overview: ST research conducted during NSTX-U recovery
  - Take opportunity to engage with MAST-U program addressing physics studies / experiments supporting disruption prediction
  - Interface to MAST database for disruption prediction / avoidance research (disruption event characterization and forecasting (DECAF)
  - Plan to bring research back to NSTX-U, now expanded to encompass the present larger scope of disruption prediction / avoidance

- Talk Outline
  - Quick update of DECAF database access to world tokamaks (a full talk!)
  - Importance of conducting stabilizing structure for global mode stabilization
  - Observation of the resistive wall mode in MAST
  - Expectations of RWM stabilization in MAST-U
  - Magnetic / kinetic / MSE equilibrium reconstructions for MAST/-U
  - Further research: KSTAR high β_N, 100% non-inductive CD; real-time effort

DECAF now connected to databases from multiple machines, expanding analysis

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

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



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

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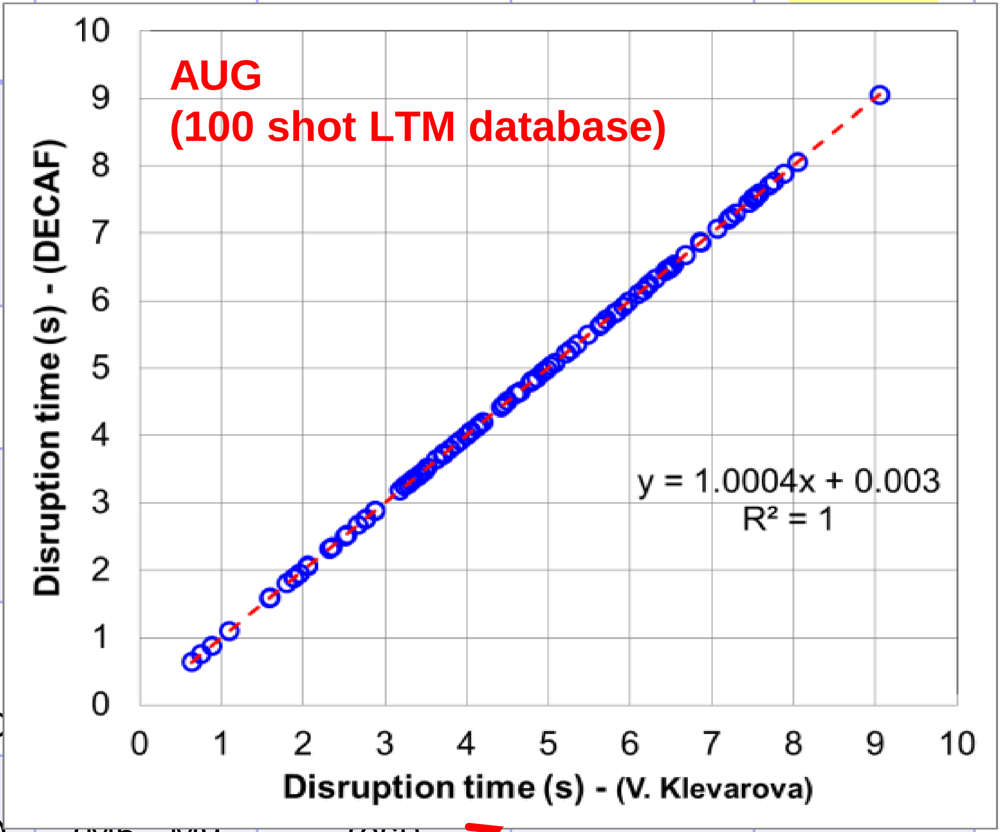

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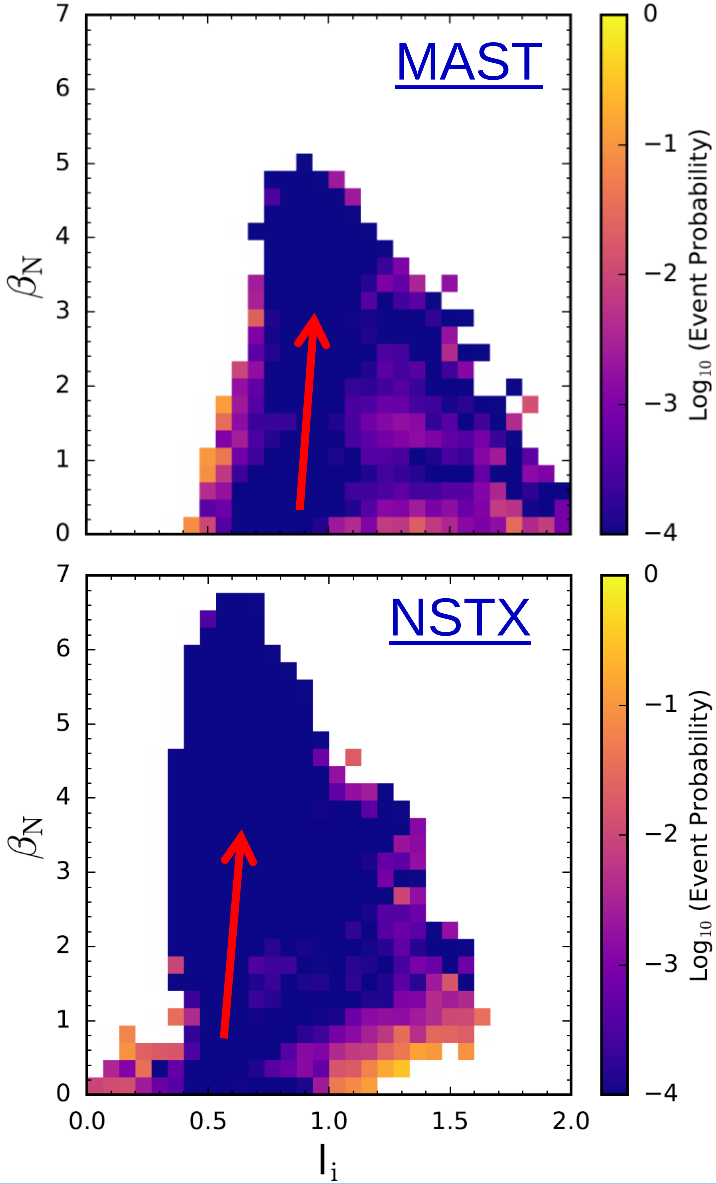
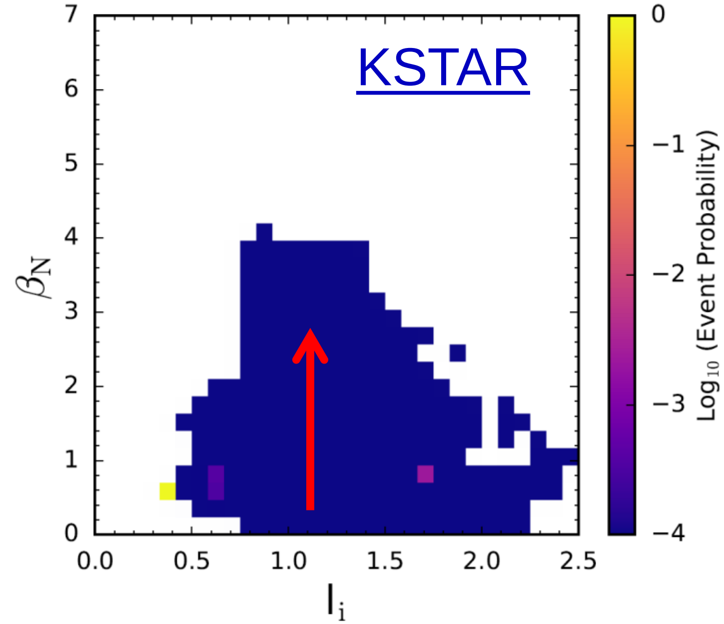
  - 100 shot LTM disruption database by V. Klevarova analyzed for DIS

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

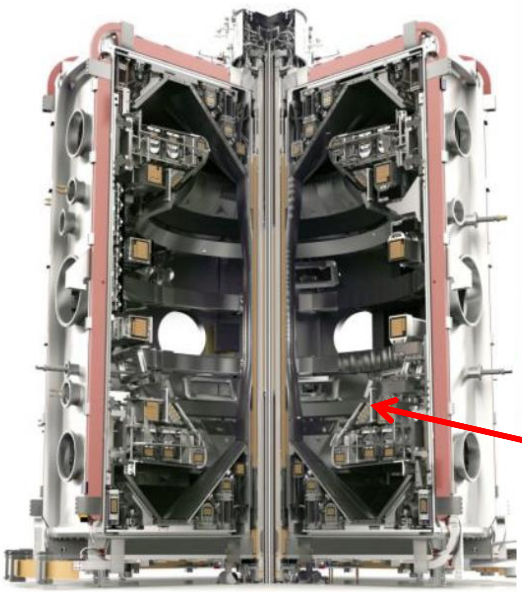




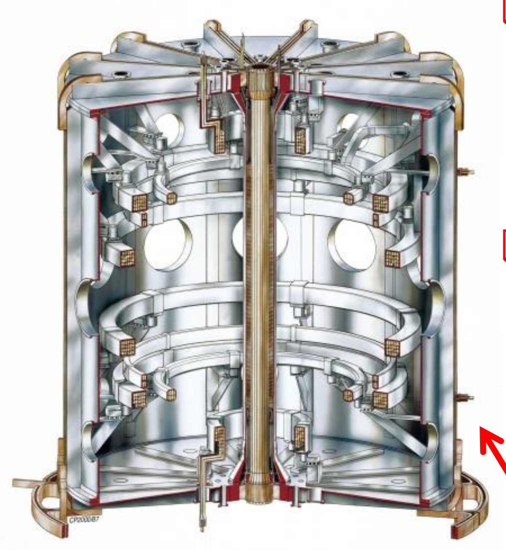
- DECAF analysis of DIS event
  - Shots analyzed at 10 ms intervals
- Analysis during I_p flat-top
  - MAST: 8,902 plasmas analyzed
  - NSTX: 10,432 plasmas analyzed
  - KSTAR: 1,309 plasmas analyzed

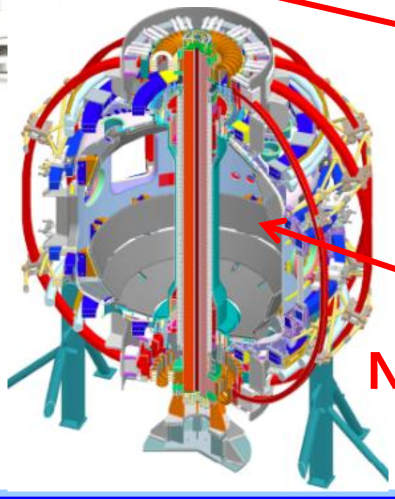
Recent DECAF supporting effort: key funded DOE study to determine effect of conducting structure on ST stability

MAST-U



MAST

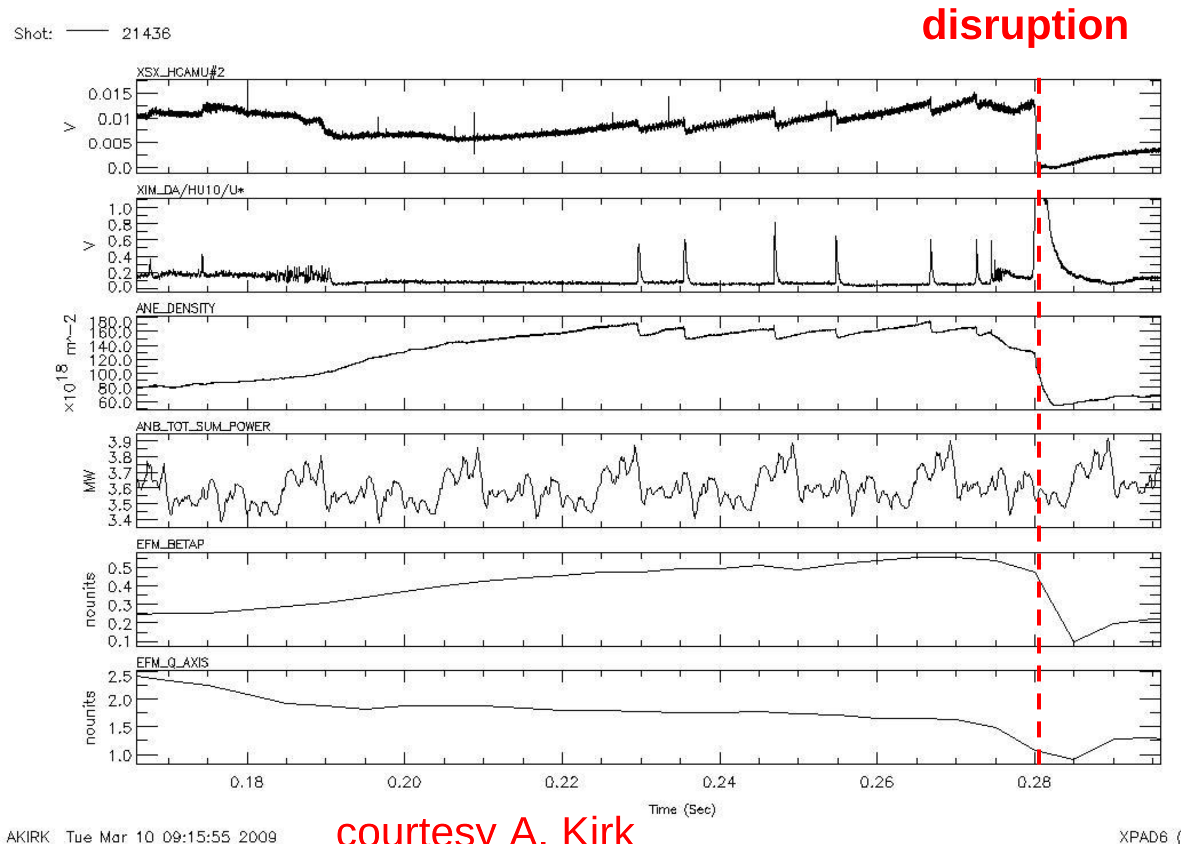




NSTX

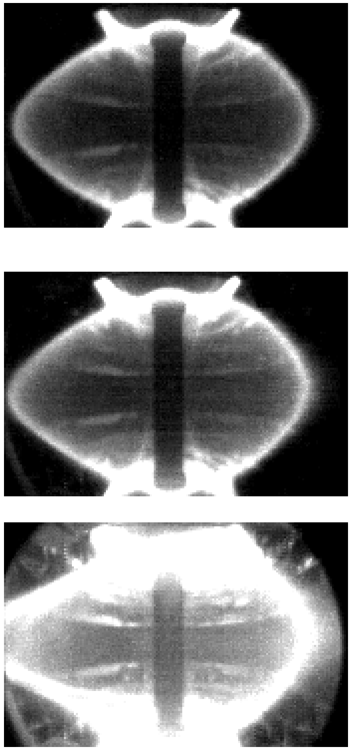
- Effect of wall is "theoretical"
  - High power ST devices can't easily remove conducting wall
- MAST and MAST-U provide unique global mode boundary conditions allowing joint device (experimental) study
  - MAST: Least amount of mode stabilizing conducting structure; PF coil jackets provide stability?
  - MAST-U: Divertor plates add substantial stabilizing structure
  - NSTX: 4 toroidal rows of ¾" copper stabilizing plates

Apparent global mode "egg shape event" has been noted by A. Kirk regarding loss of H-mode



courtesy A. Kirk

Fast camera images (21436, t ~ 0.280s)

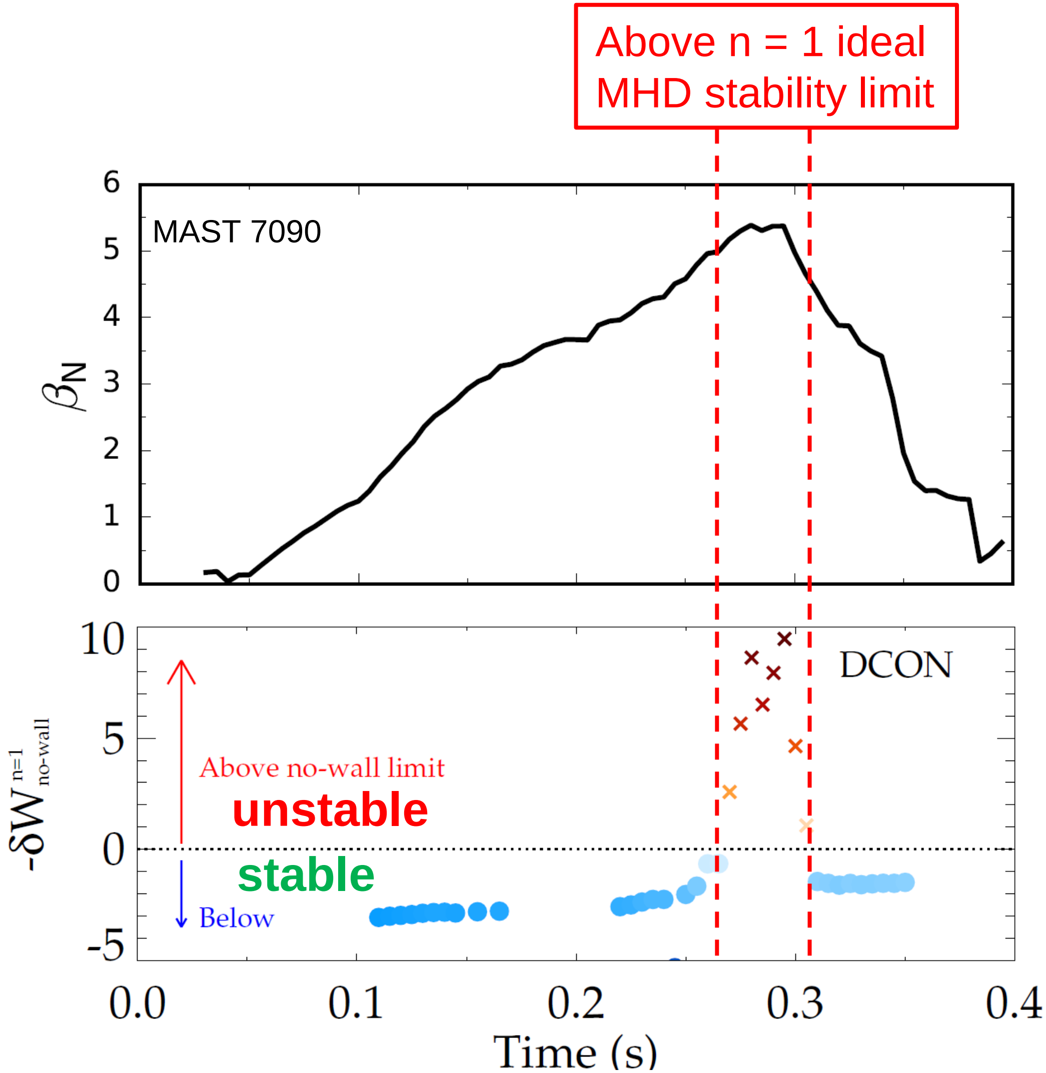


Mode locked toroidally, expands radially

- Several shots display asymmetric, global events
  - Consider that the "egg shape events" are global MHD ➔kink/ballooning/resistive wall modes (RWM)

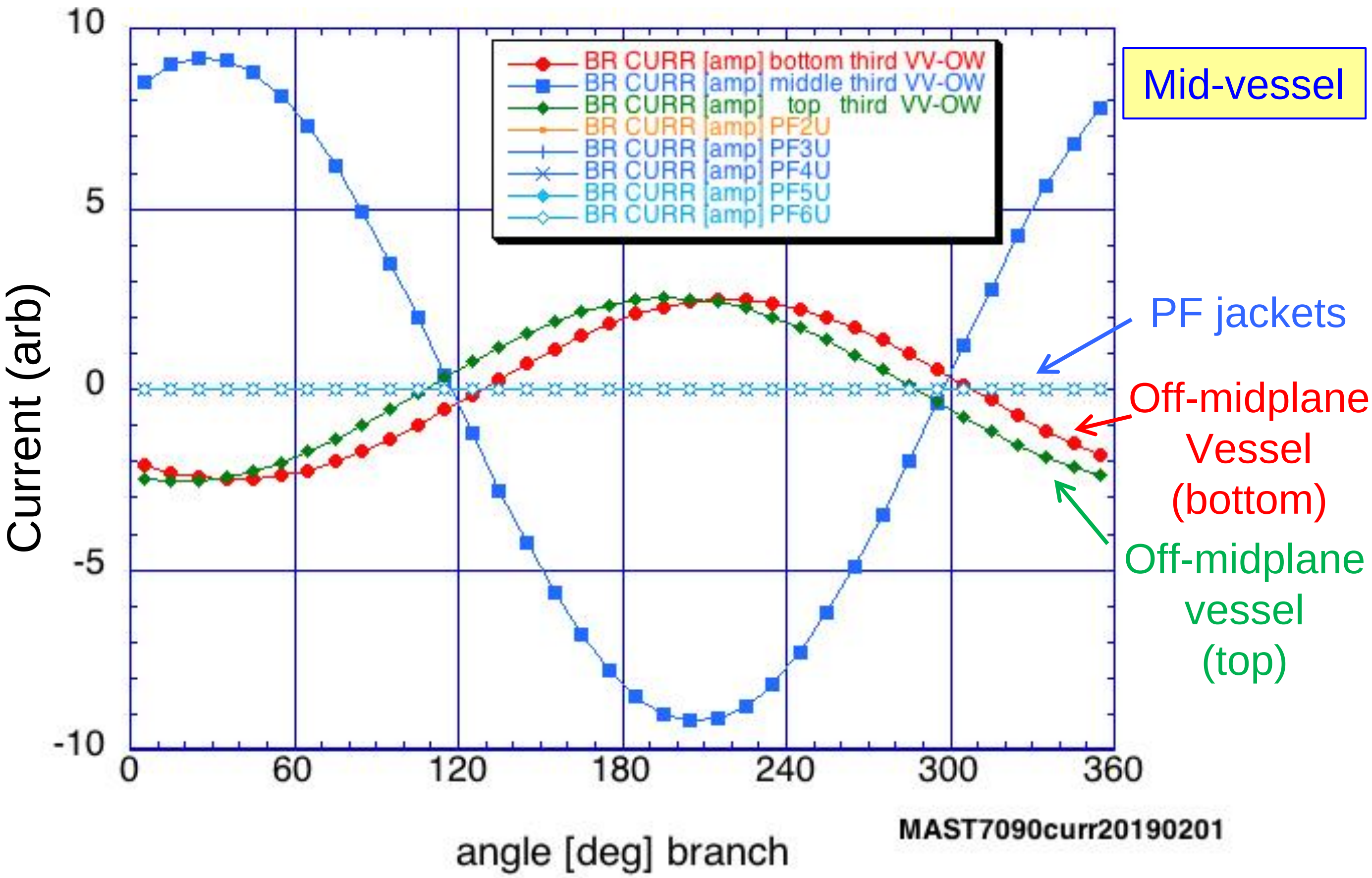
    Q: does this follow "standard" theory?

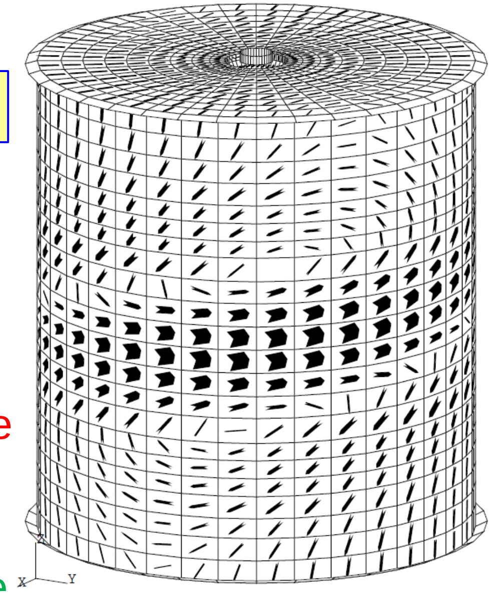
MAST plasmas have exceeded n = 1 MHD no-wall limit based on magnetic equilibrium reconstructions

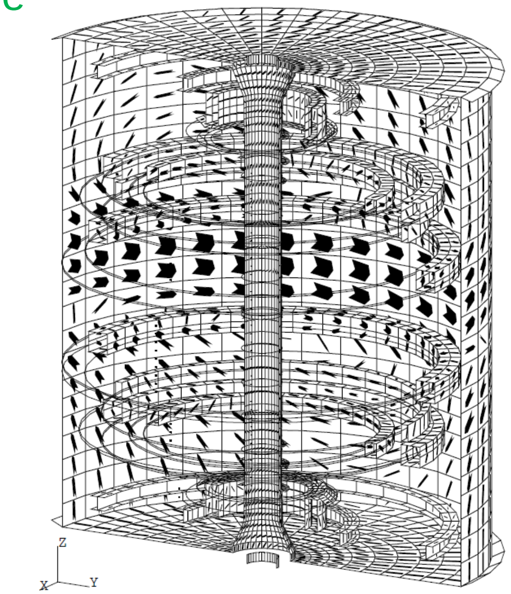


- MAST plasma 7090
  - Plasma with I_p ramp-down to increase β_N (Gryaznevich)
- Initial DCON calculation with magnetics-only EFIT++
  - Above the no-wall limit at high beta
  - No-wall limit higher than DECAF estimate – can we do better with improved equilibria?
- Note: quantitative analysis of MAST plasmas w/ “egg-shape” events will require kinetic equilibrium reconstructions

Mode-generated current in MAST vacuum vessel is responsible for kink stabilization, *not* PF jackets

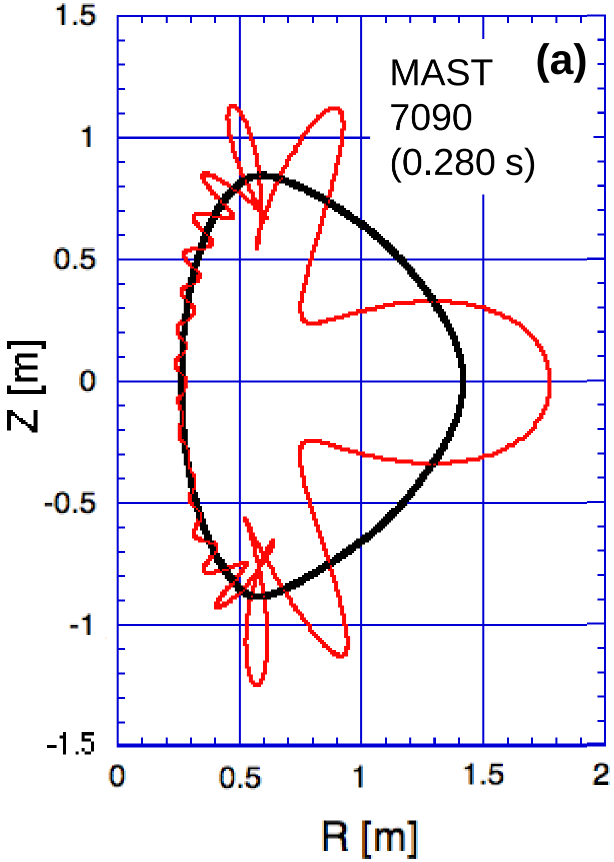




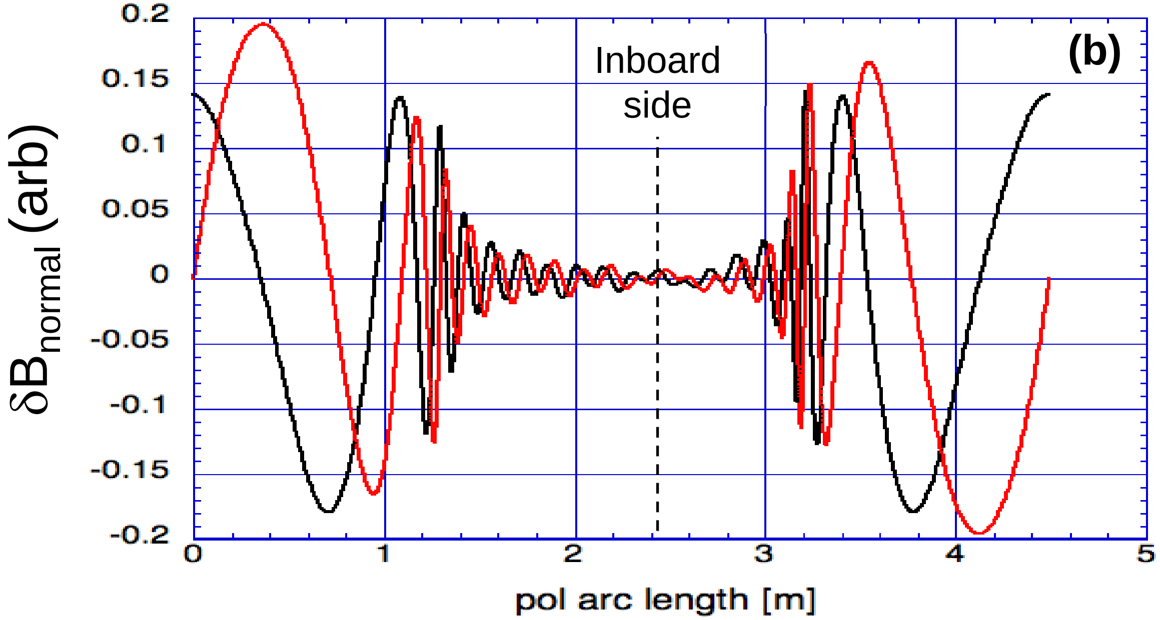


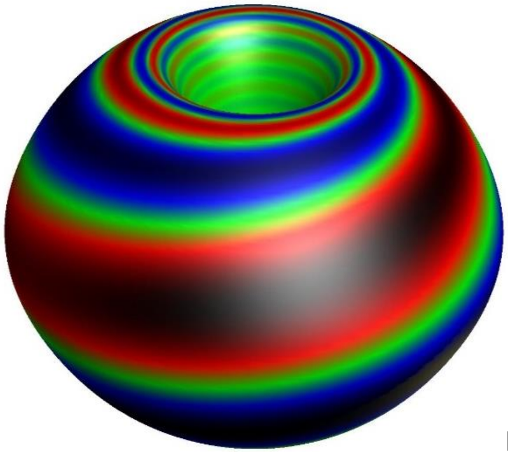
- Present MAST vessel model with no 3D structure (yet)
  - Consistent with Fitzpatrick theory of wall effect
  - Midplane ports will alter mode-generated eddy currents

DCON and VALEN codes show the structure of unstable mode above the no-wall limit



Poloidal variation of n = 1 mode





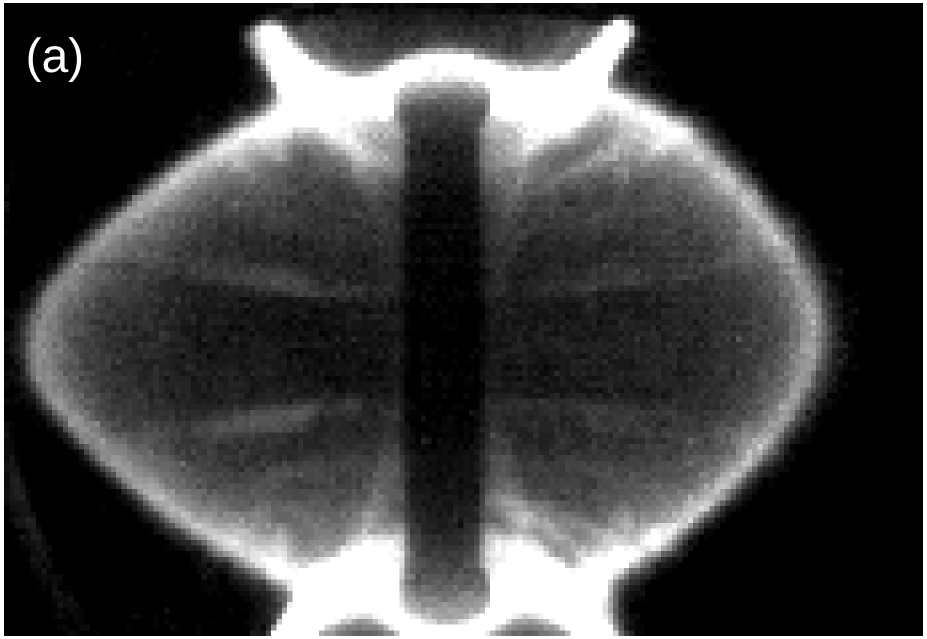
B-normal contours for n = 1 mode on flat plasma surface

MAST 7090 (0.280 s)

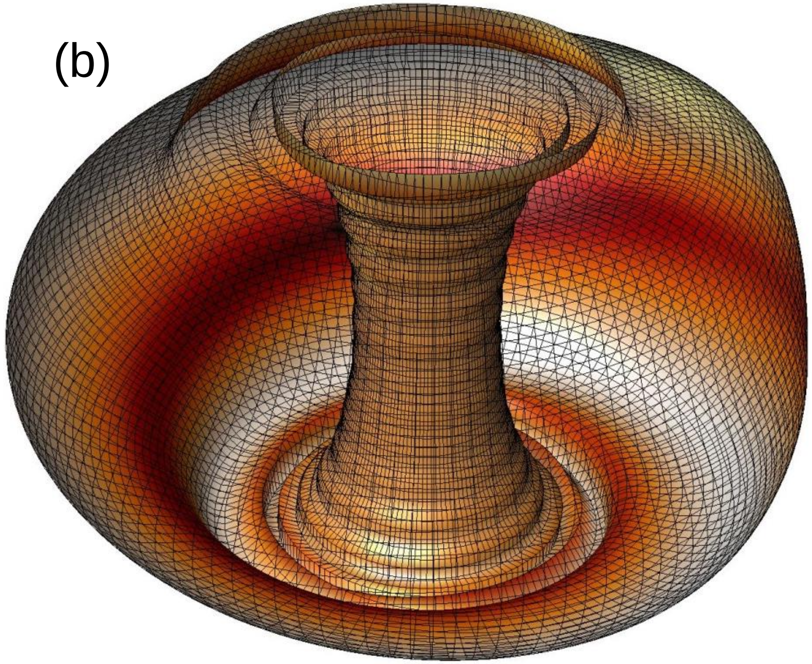
- DCON / VALEN computes eigenfunction:
  - (a) Poloidal projection of mode δB_{normal}
  - (b) Poloidal variation of unstable mode δB_{normal} at the plasma boundary

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

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



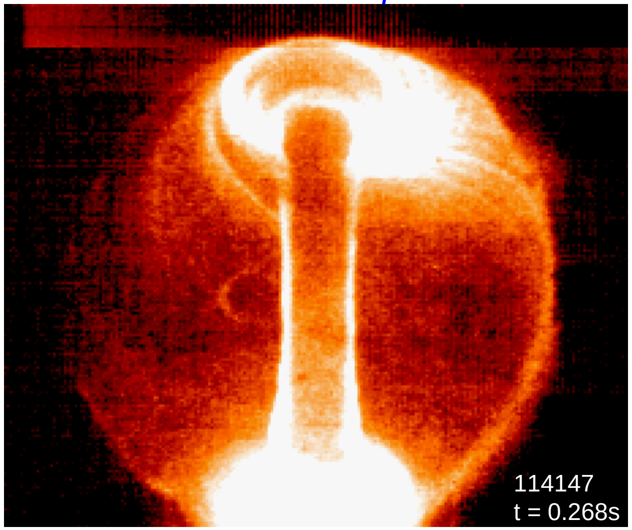
VALEN analysis (n = 1 RWM)
(using MAST 7090)



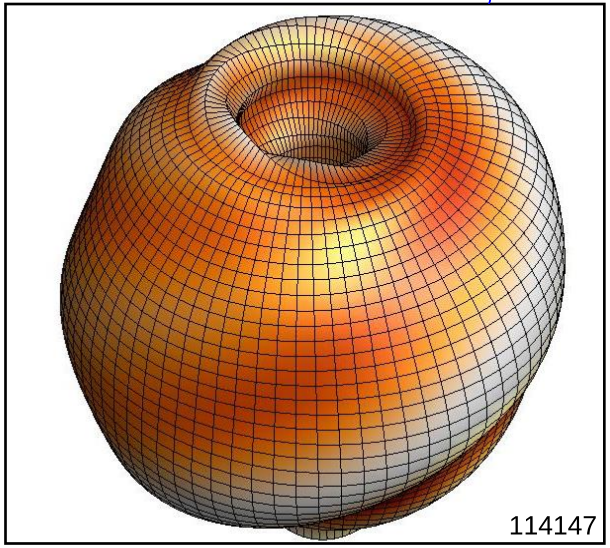
- Analysis of RWM eigenfunction in VALEN resembles MAST fast camera image, some subtle differences
  - More flattened appearance in analysis may be due to present assumption of pure n = 1 mode in model
  - Magnetics-only equilibrium used, and from a different plasma (7090)

NSTX fast camera shows scale/asymmetry of theoretical RWM in experiment

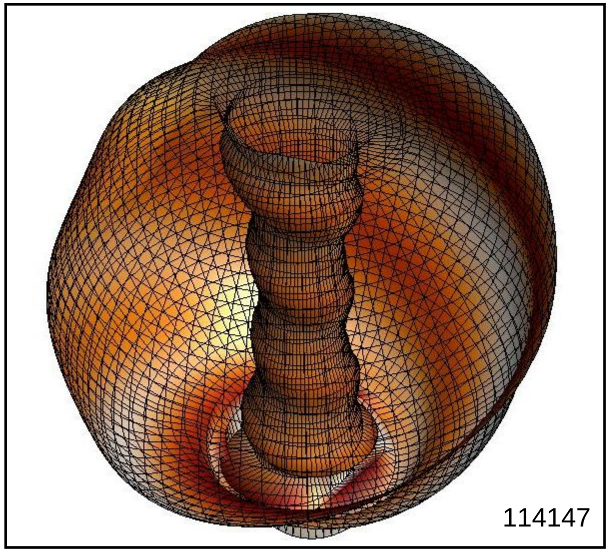
RWM with ΔB_p = 92 G



Theoretical ΔB_ψ (x10) with n=1-3 (DCON)

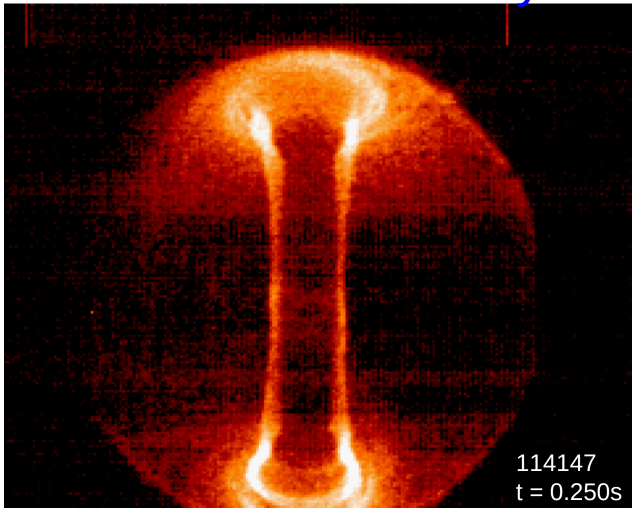


(exterior view)



(interior view)

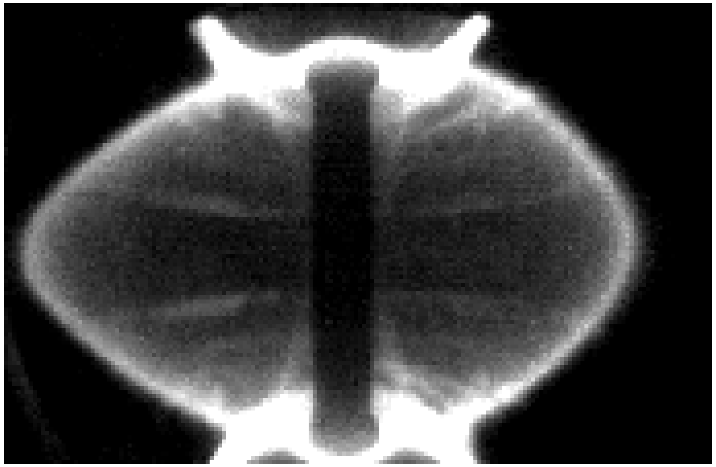
Before RWM activity



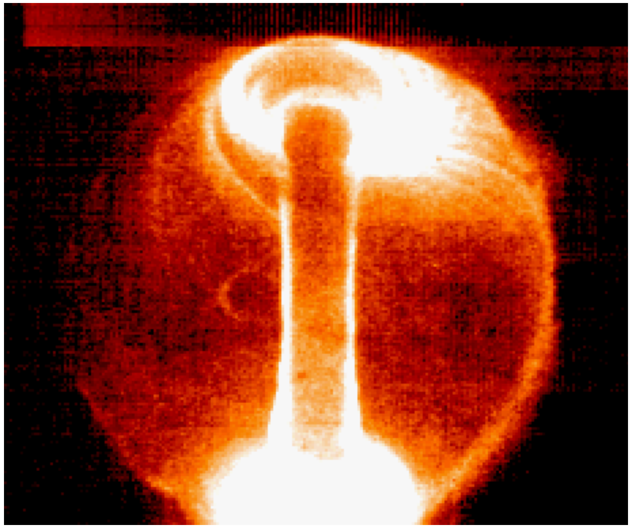
- Visible light emission is toroidally asymmetric during RWM Sabbagh, et al., Nucl. Fusion 46 (2006) 635
- DCON theory computation displays mode
  - uses experimental equilibrium reconstruction
  - includes n = 1 – 3 mode spectrum
  - uses relative amplitude / phase of n spectrum measured by sensors – RECONSTRUCTION!

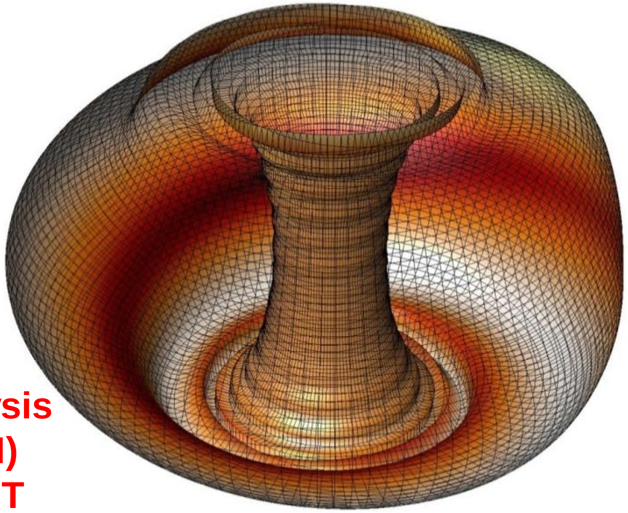
Wall effect changes mode shape as well as mode growth rate – now shown experimentally!

MAST 21436, t ~ 0.280s



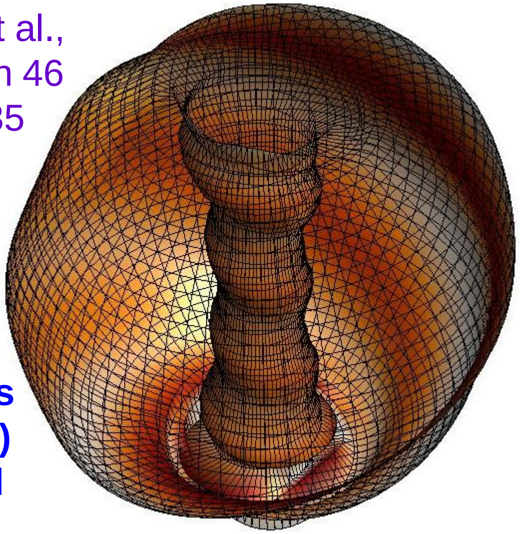
NSTX 114147, t ~ 0.268s





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

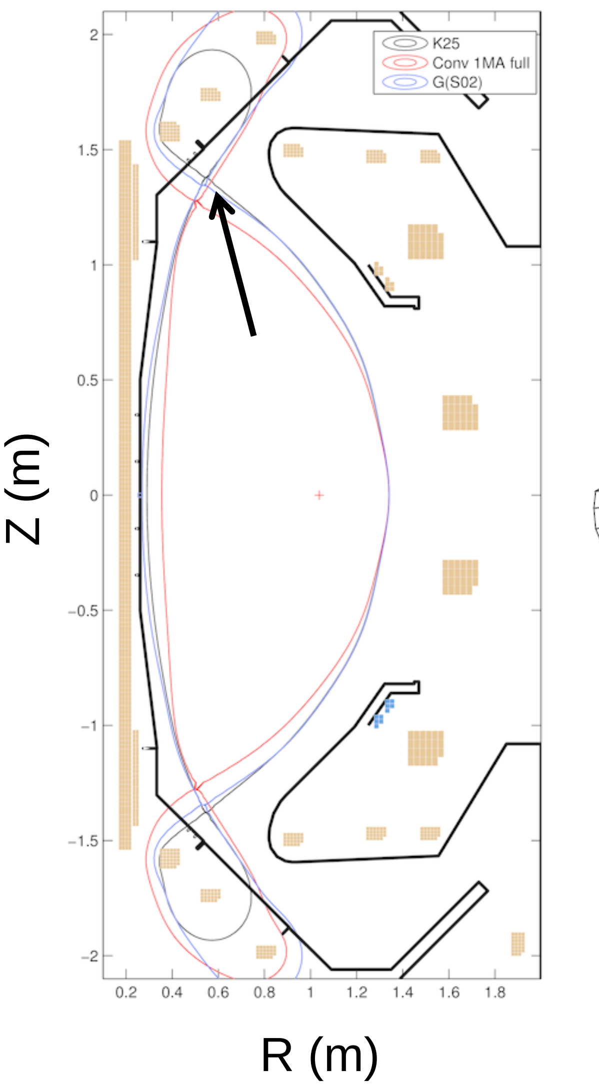
Sabbagh, et al., Nucl. Fusion 46 (2006) 635

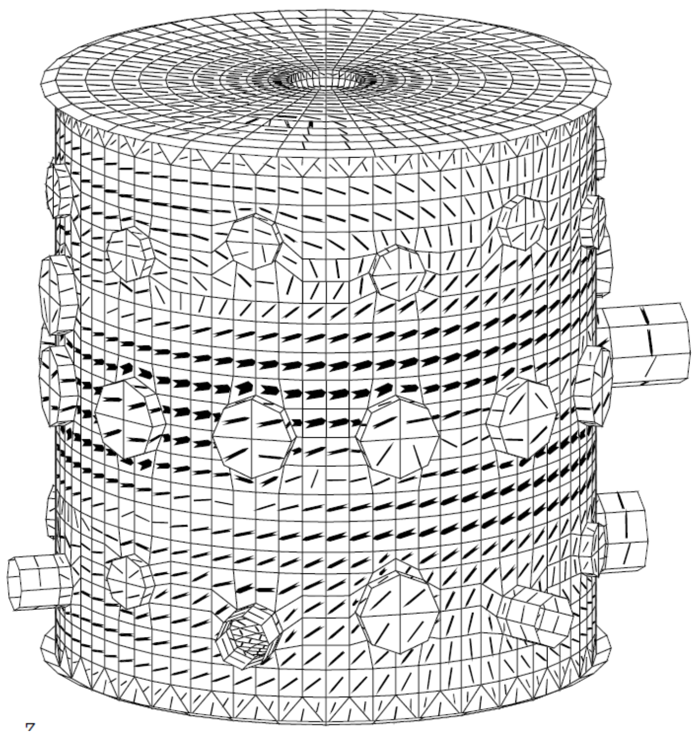


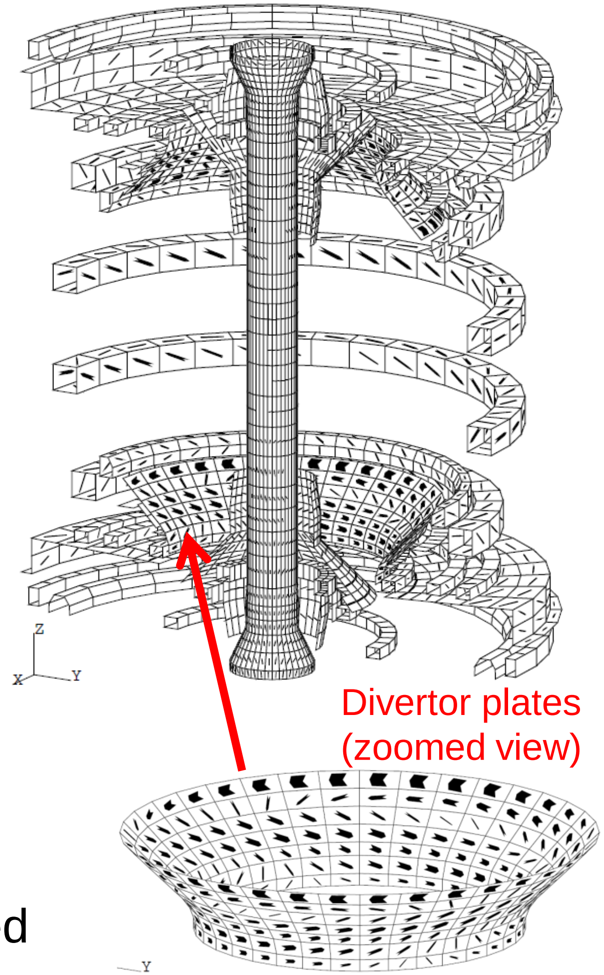
VALEN analysis (n = 1,2,3 RWM) (reconstructed 114147)

MAST-U: mode-generated current for kink stabilization now computed for design equilibria

K-25 equilibrium used as basis

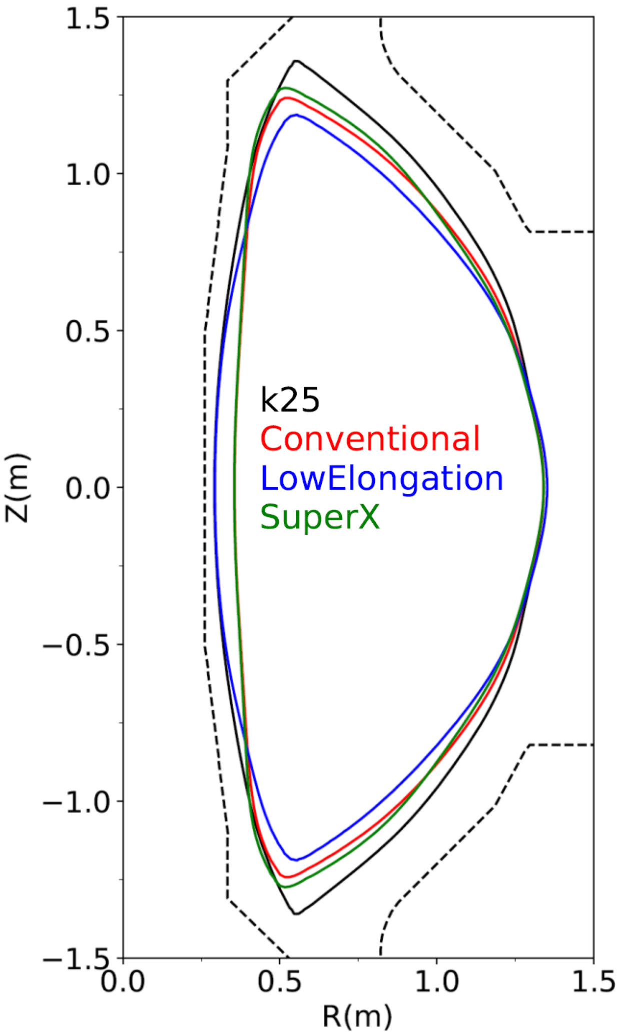


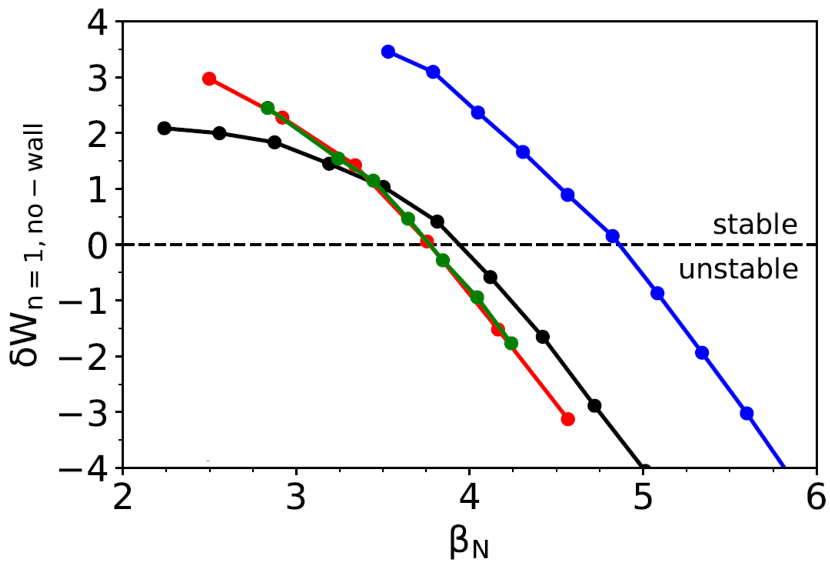


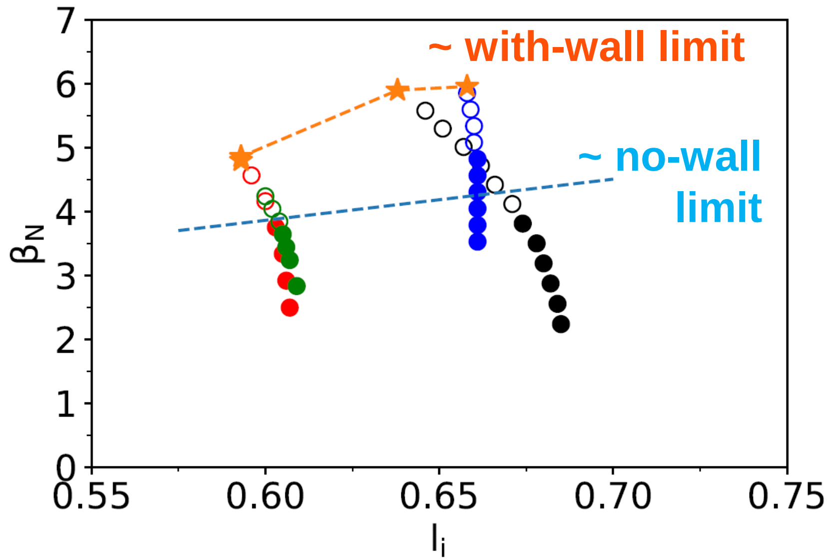


- MAST-U model with 3D conducting structure
  - Ports alter mode-generated eddy currents
  - Mode-induced currents are significant in divertor plates

DCON analysis of MAST-U projected equilibria shows range of no-wall limit starting at $\beta_N \sim 3.7$

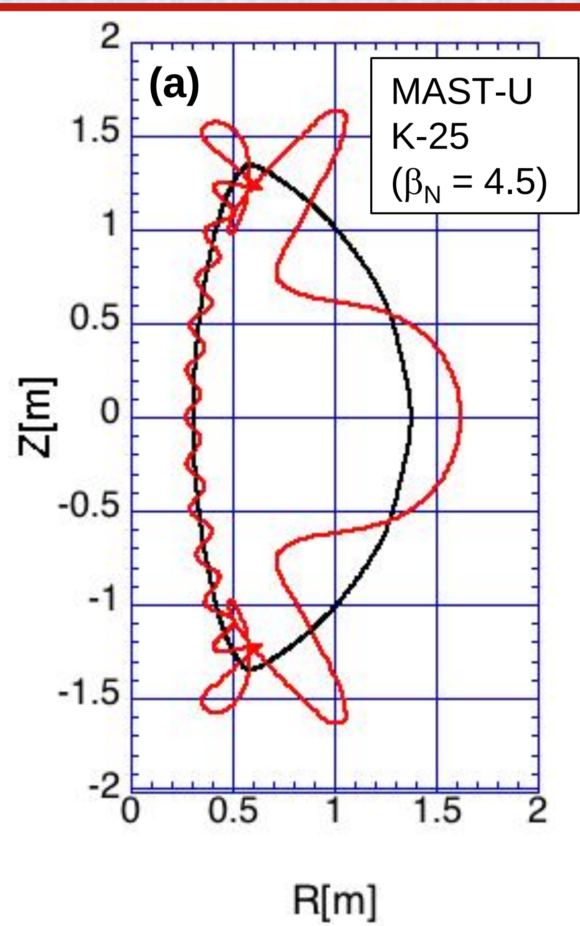




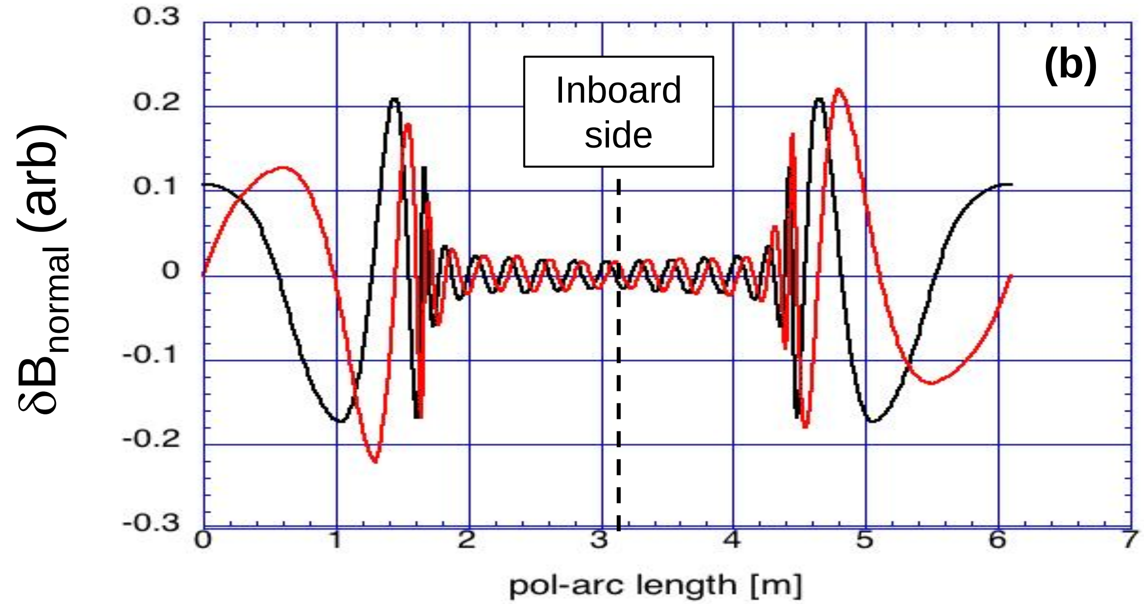


- DCON stability calculations of CHEASE pressure-scaled equilibria

DCON and VALEN codes show the structure of a MAST-U unstable mode above the no-wall limit



Poloidal variation of n = 1 mode



- DCON / VALEN computes eigenfunction:
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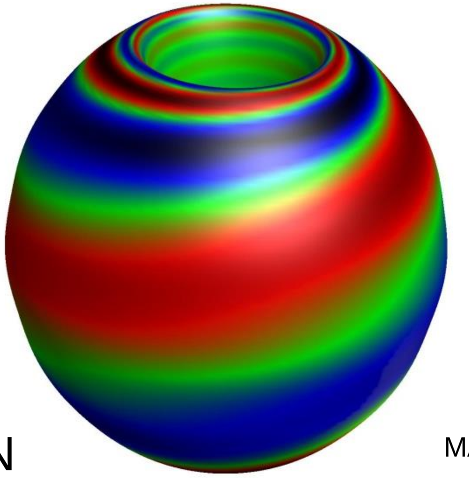
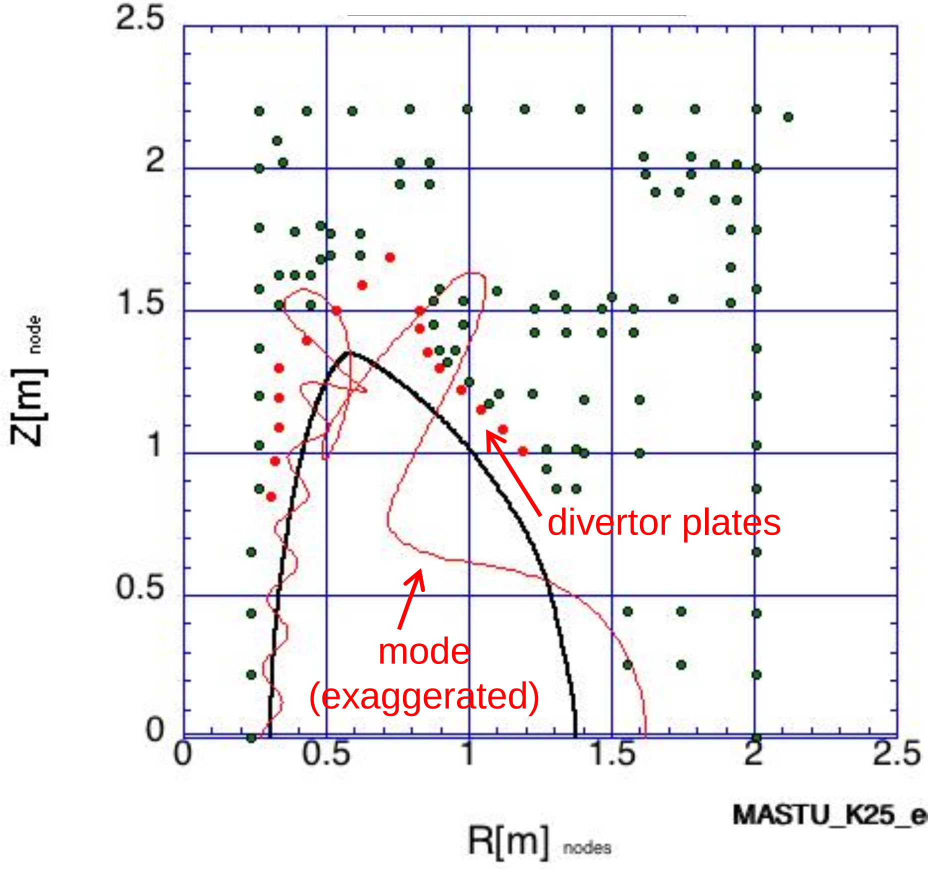
VALEN



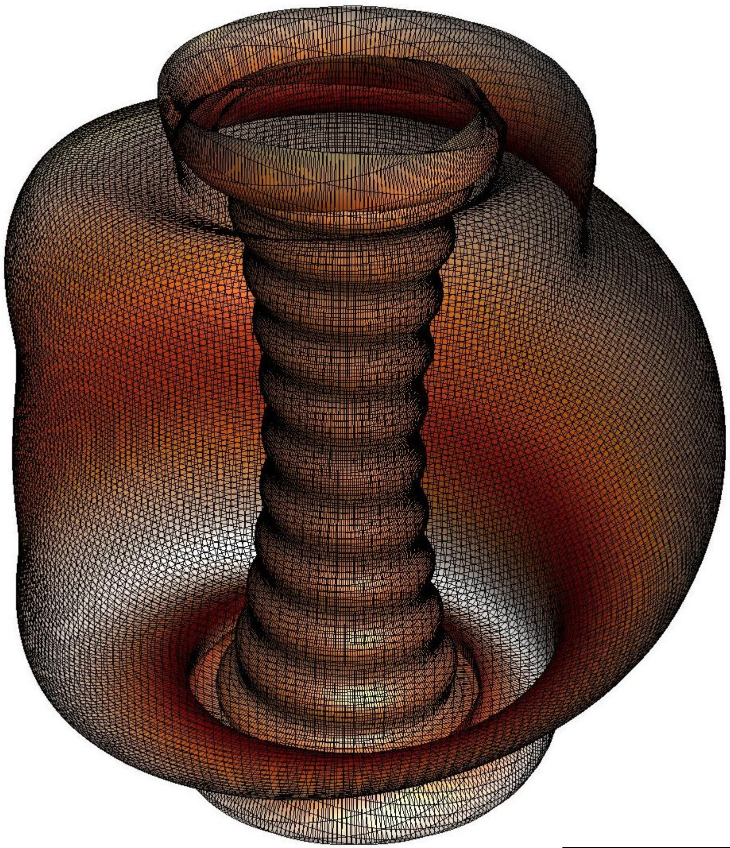
B-normal contours for n = 1 mode on flat plasma surface

MAST-U K-25 (β_N = 4.5)

The MAST-U global mode computed using design equilibrium couples well to divertor plate at high β_N



Computed mode eigenfunction (n = 1 RWM) (using MAST-U design equil. K-25, β_N = 4.5)

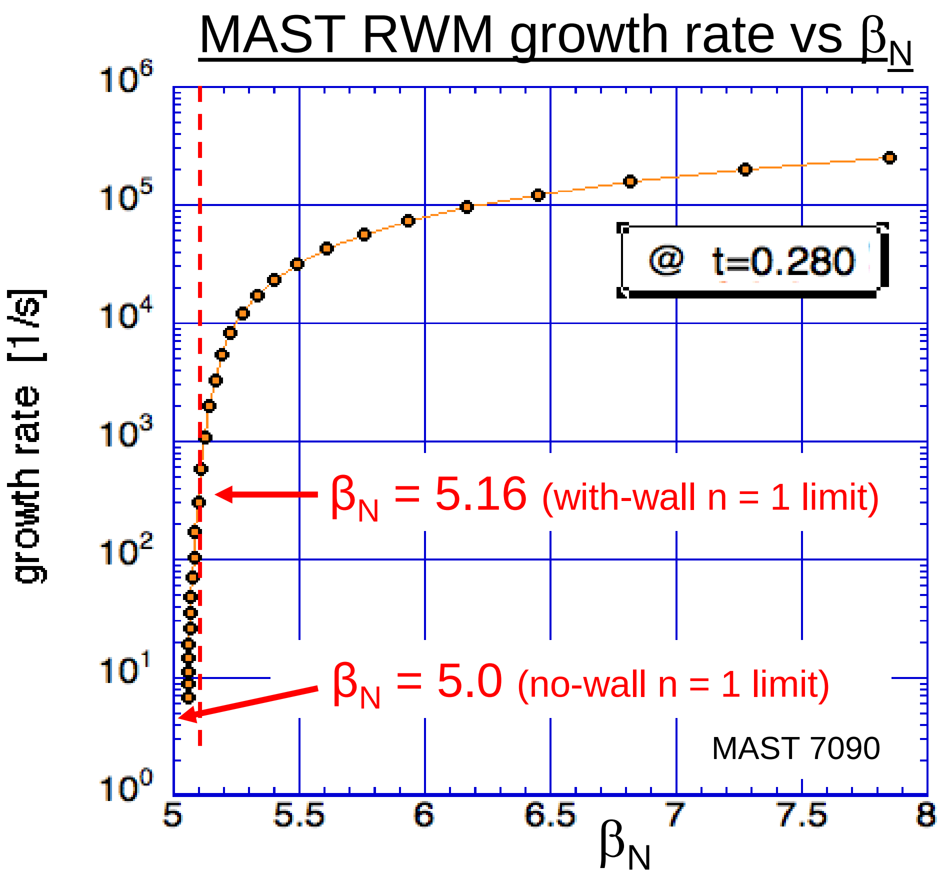


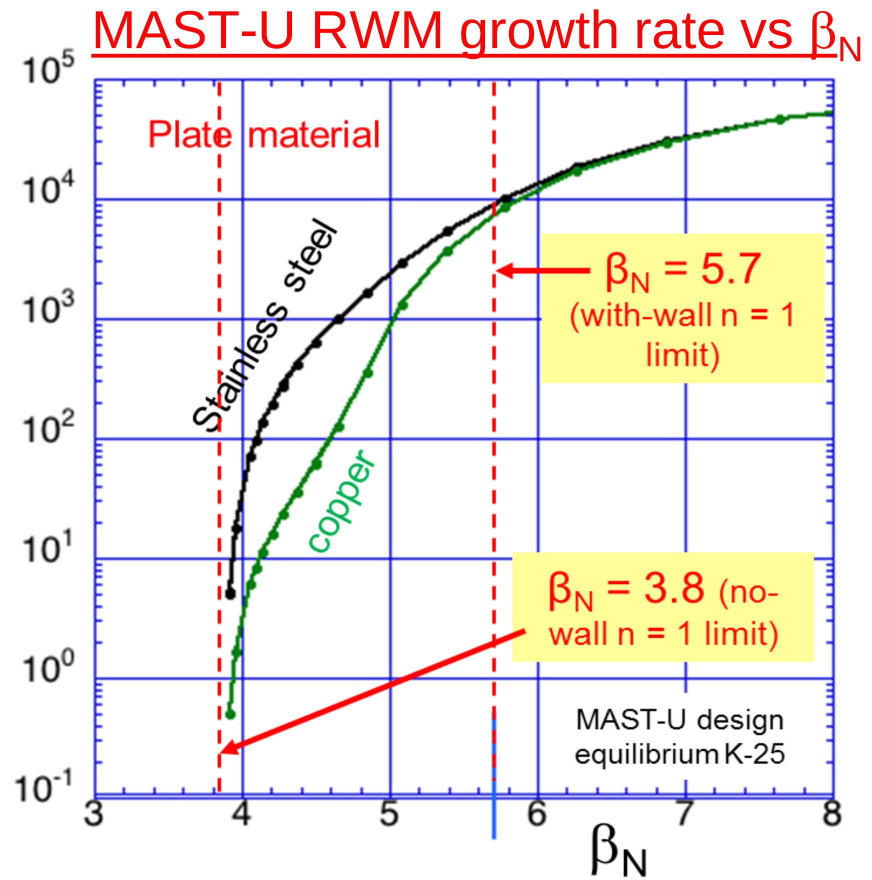
- DCON / VALEN eigenfunction: MAST-U
  - Long poloidal wavelength on outboard side
  - Significant mode perturbation in the region of the divertor plates at high β_N

Less "egg-shaped" in MAST-U due to divertor plates

MAST-U
K-25
(β_N = 4.5)

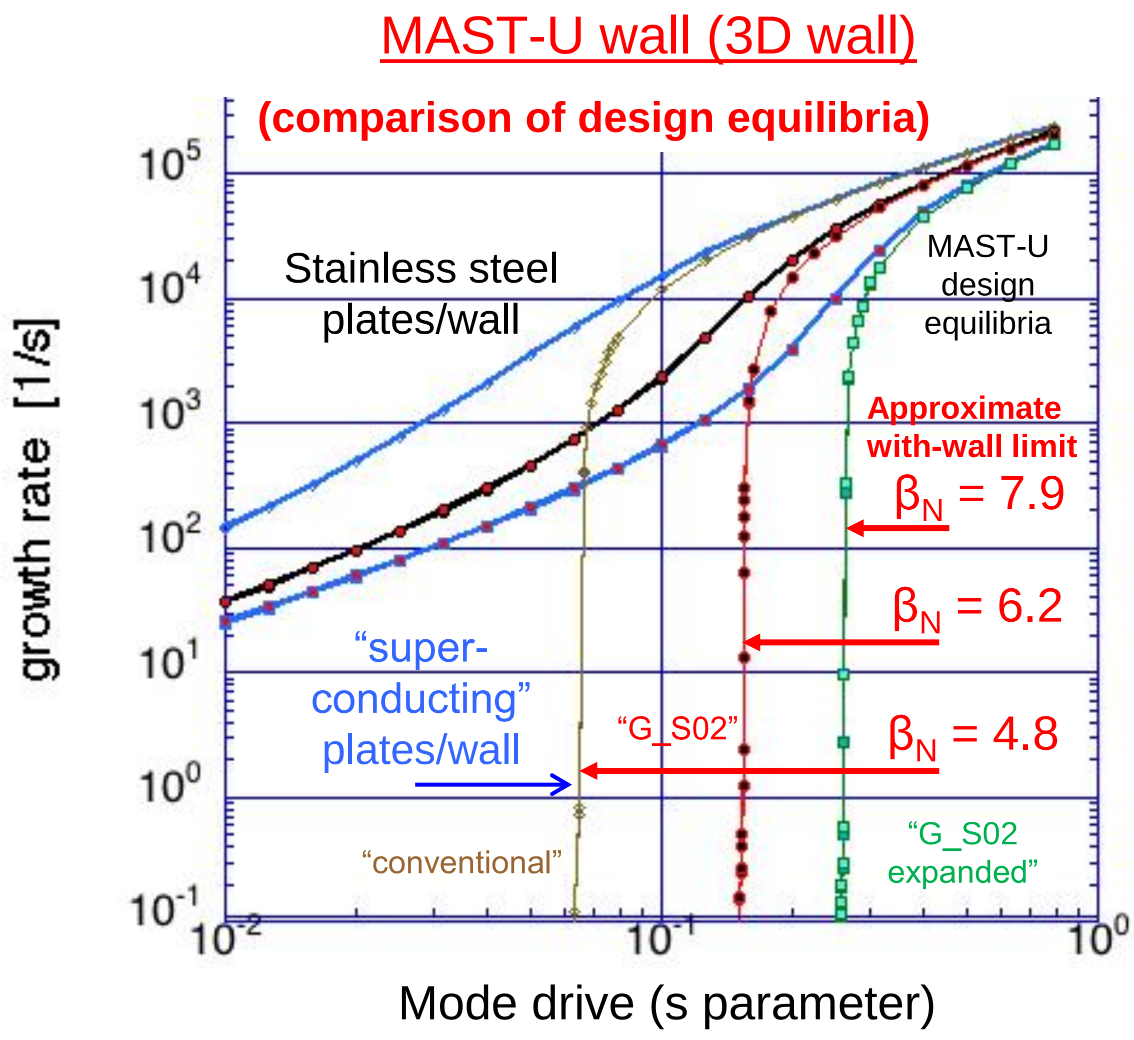
VALEN analysis shows a significantly larger window between the no-wall/with-wall β_N limits for MAST-U





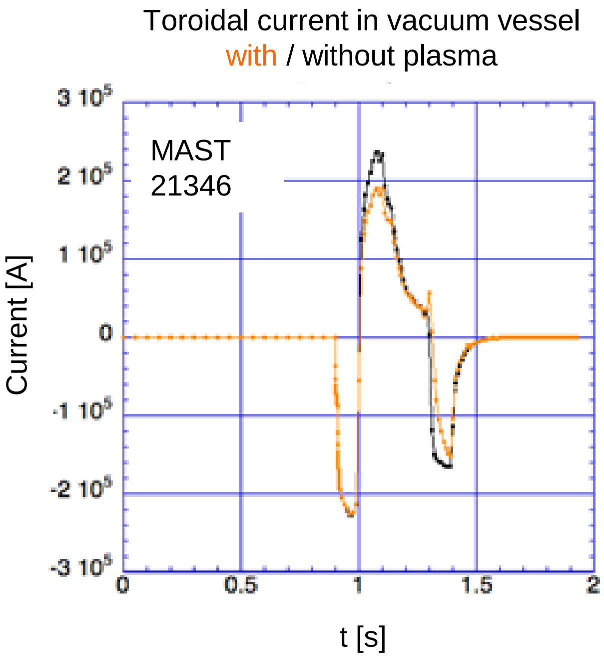
- Due to greater passive conducting structure in MAST-U (divertor plates)
  - Computed wall stabilized $\Delta\beta_N$ window only for MAST 0.15 (➔ 3% of β_N operational space)
  - Computed $\Delta\beta_N$ window is 1.9 for MAST-u (for K-25 case) ➔33% of β_N operation space (result not optimized – greater stabilization with plasma in closer proximity to the wall)

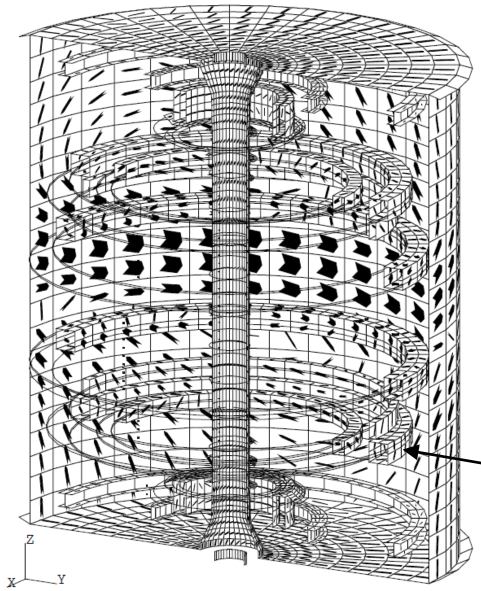
VALEN analysis of other MAST-U design equilibria show a range of with-wall β_N limits

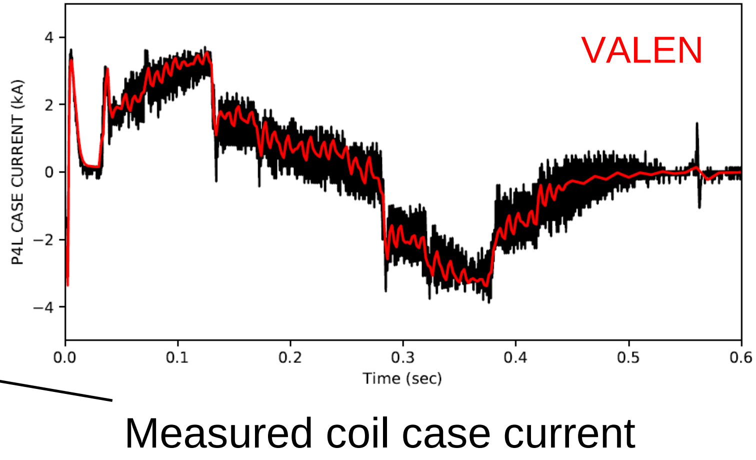


- MAST-U design equilibrium variation
  - Original equilibria from A. Thornton
  - The β_N was scaled from original equilibria to produce β_N scans
  - Note: plasma profiles are not optimized – scaled from the design equilibria
- Greater stabilization in part due to greater plasma boundary coupling to wall

Equilibrium reconstruction of MAST now conducted; currents in the conducting structure included

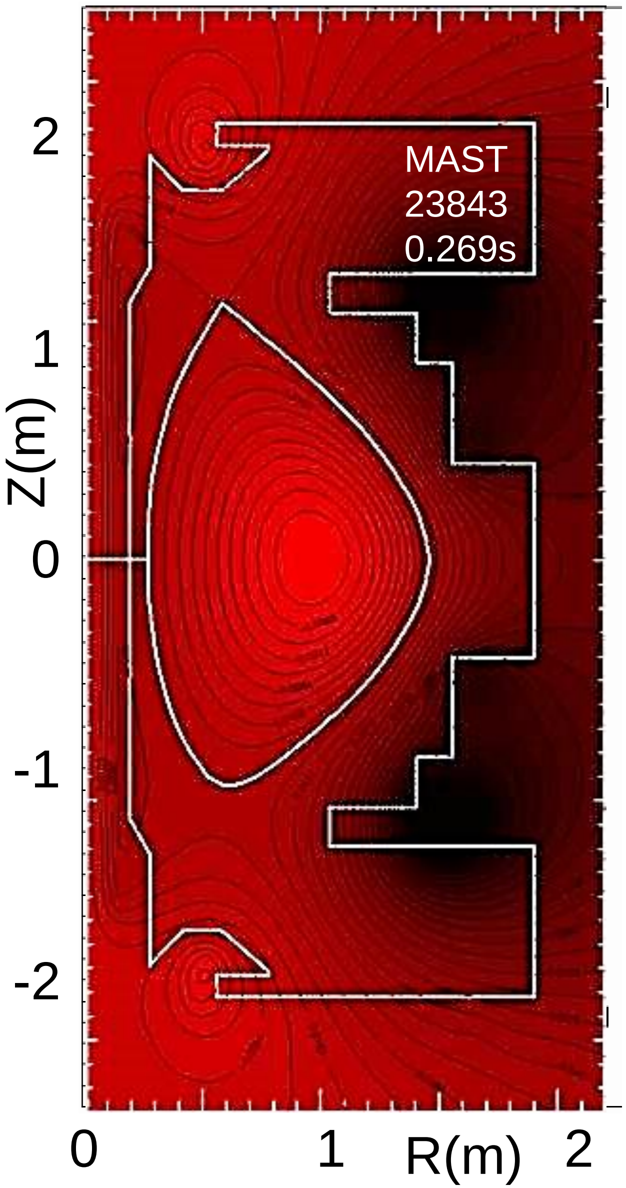




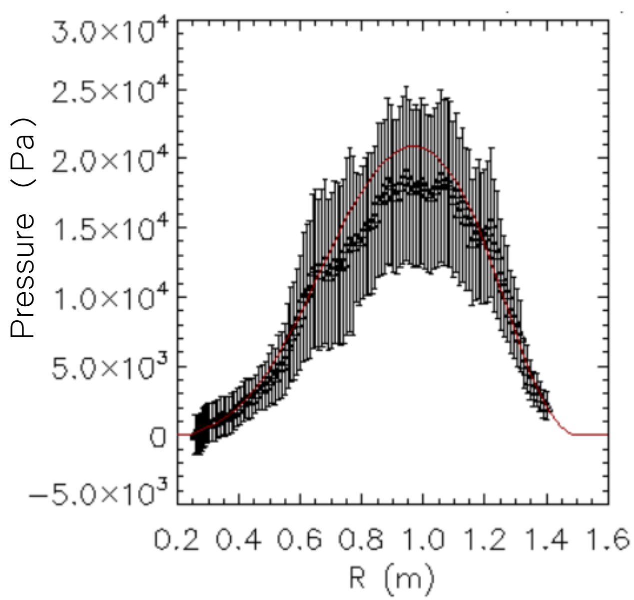


- 3D wall models of MAST/-U created in VALEN
  - Time-domain calculations performed using experimental currents in coils with/without plasma current for MAST discharges
  - Net toroidal and poloidal currents in the conducting structure, and eddy current patterns were determined
  - VALEN prediction matches measured coil case currents

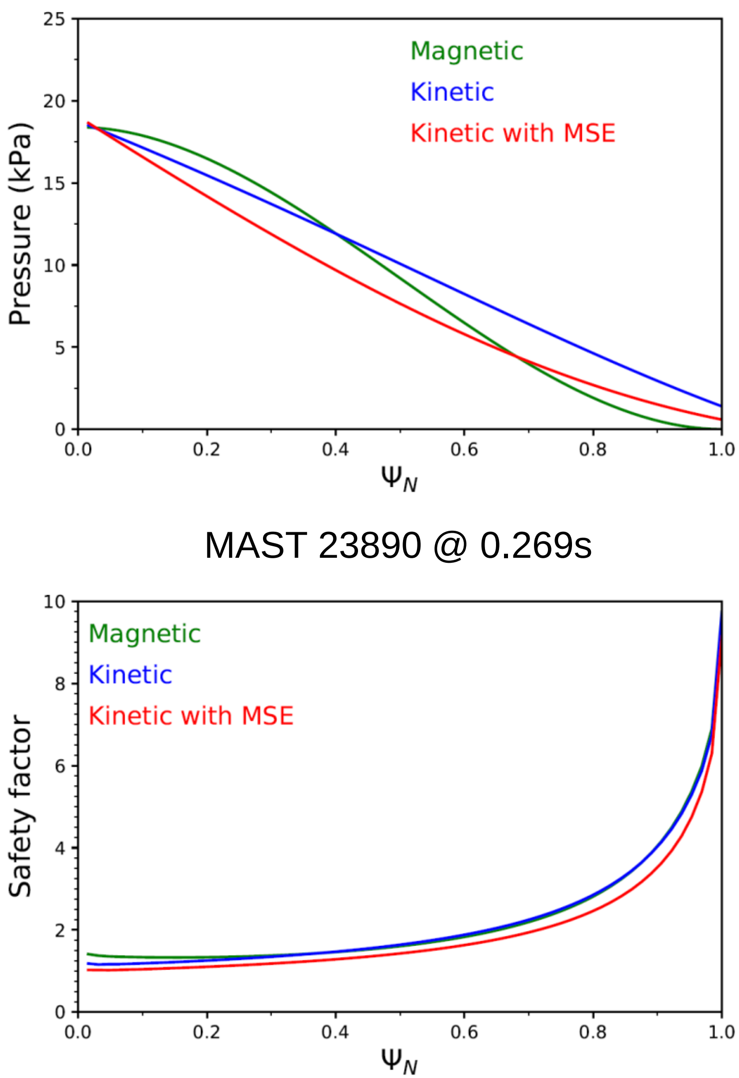
Three levels of MAST kinetic equilibrium reconstructions are now being processed (Columbia U. collaboration)



- All necessary elements set up
  - Conducting structure model (MAST & MAST-U)
  - Data retrieval automated for magnetics, kinetics
  - Analysis models tested
- First reconstructions being processed now
  - Vacuum shots confirm consistency of data/model
  - Magnetic reconstructions to ensure validity
  - Kinetic reconstructions with Thomson, charge exchange, MSE

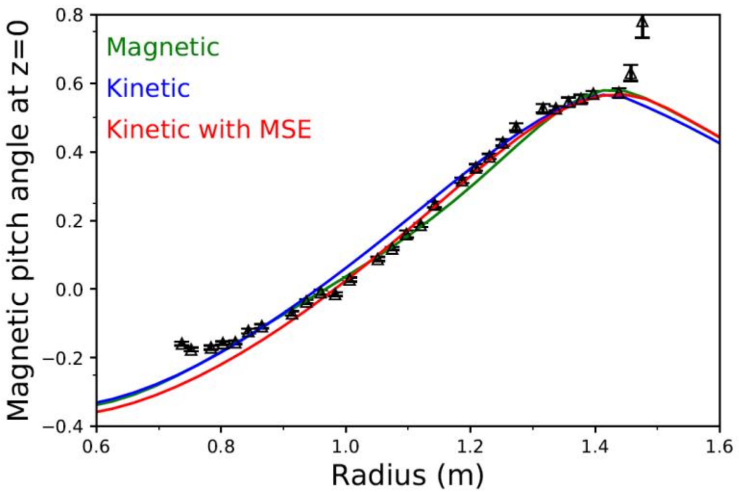


Three levels of diagnostic inclusion allows the refinement of equilibrium reconstructions



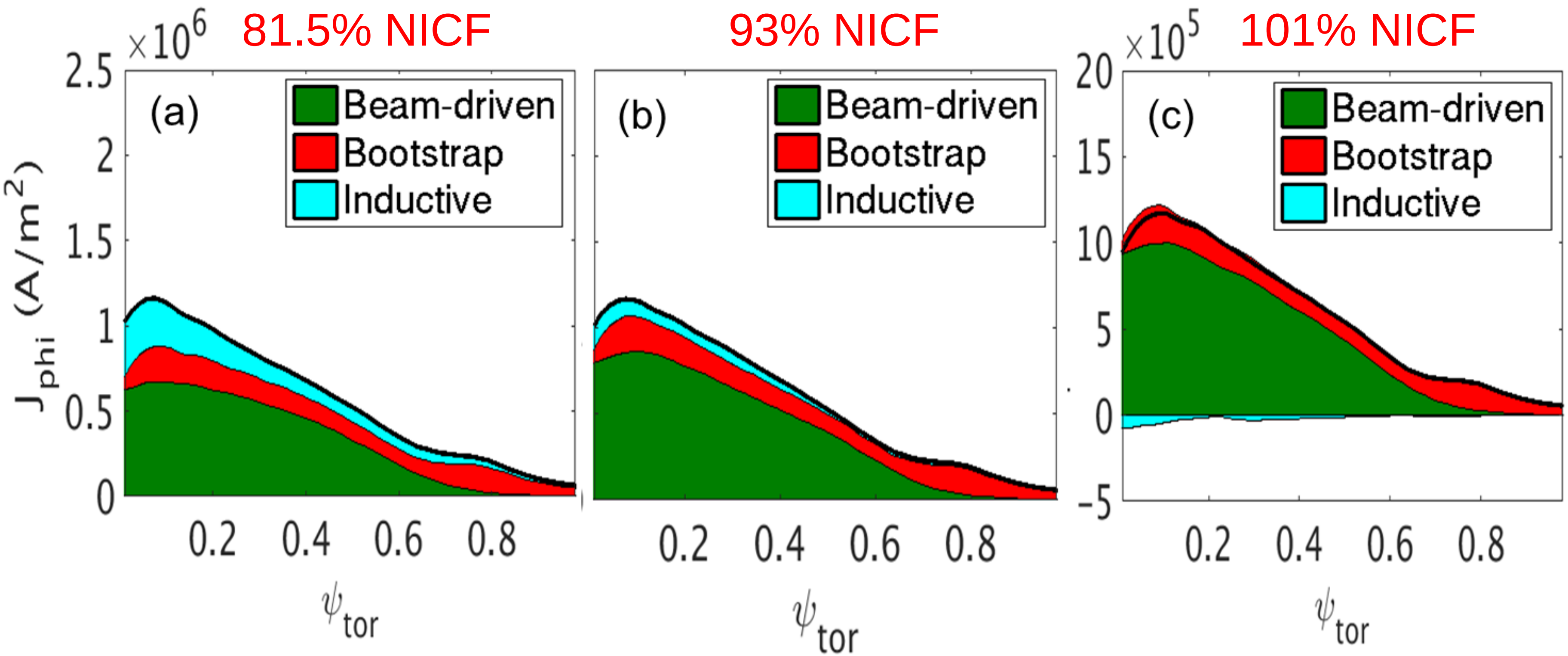
MAST 23890 @ 0.269s

- Magnetic, Kinetic, and Kinetic with MSE
  - More data allows greater detail in pressure and q profiles
  - Already good agreement with MSE-measured pitch angle before including it
  - All reconstruction levels now being "polished" for best analysis robustness



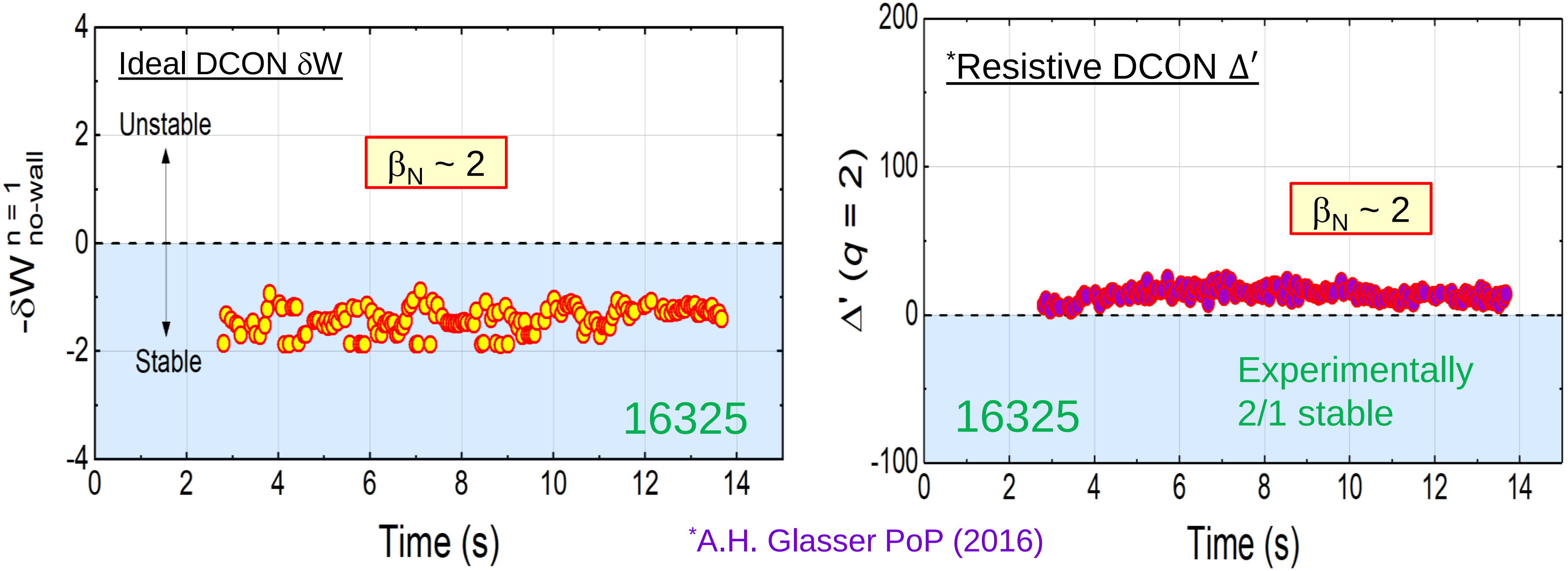
"Predict-first" KSTAR TRANSP analysis shows expected high performance plasmas at > 80% NICF

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



- High non-inductive current fraction predicted for 6.5, 7.5, 8.5 MW NBI
  - The β_N ranges from 3.0 – 3.5; based on KSTAR plasmas with NICF ~70%
- Aim to generate a substantial database of long pulse, high NICF plasmas in 2020 - 2021 KSTAR runs for disruption prediction studies

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

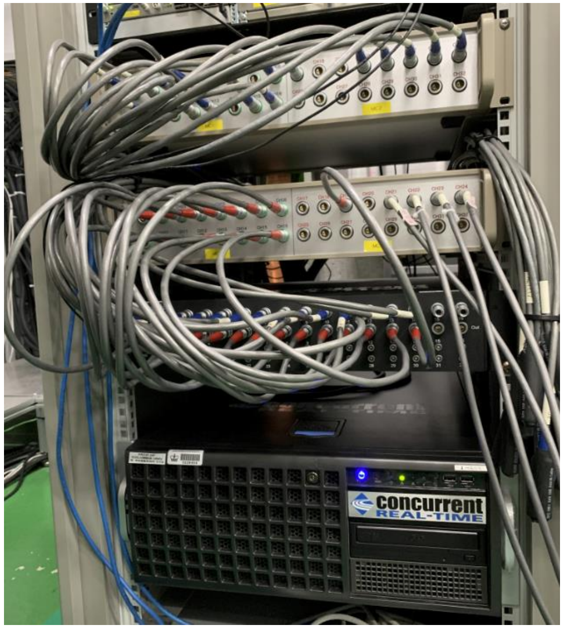


*A.H. Glasser PoP (2016)

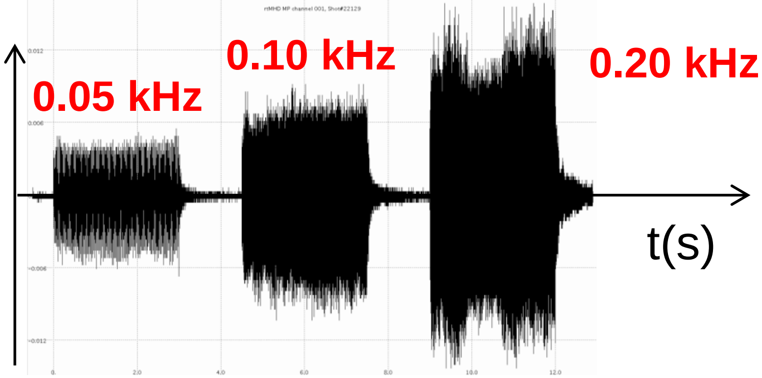
- Classical tearing stability index, Δ′, computed at q = 2 surface using outer layer solutions
- At higher q_{95}, Δ′ is mostly positive predicting unstable classical tearing mode
  - Indicates neoclassical effects, additional physics needed to reproduce XP
  - KEY POINT: Conclusions regarding Δ' evolution can be made!

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

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

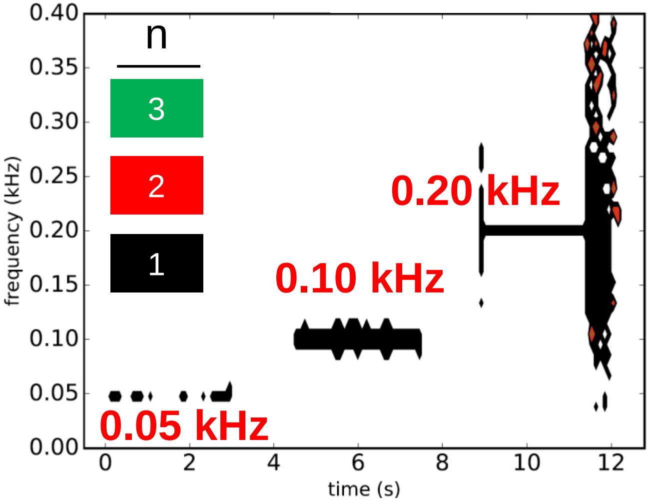


Real-time magnetic probe data acquired
(14 toroidal probes: **n = 1 rotating field applied)**

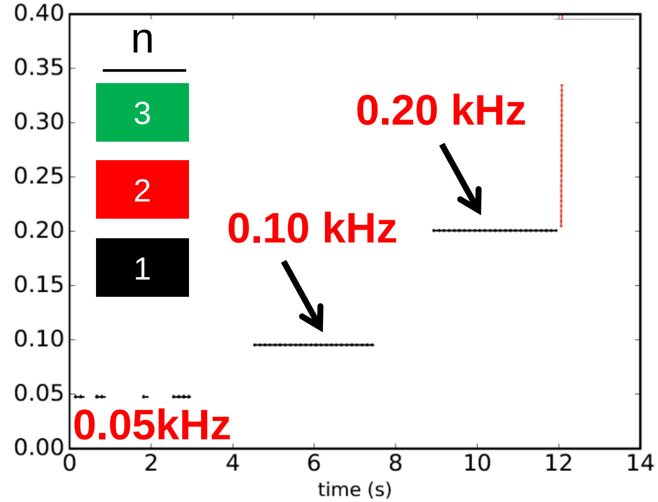


Offline DECAF analysis of real-time signals

DECAF spectrogram



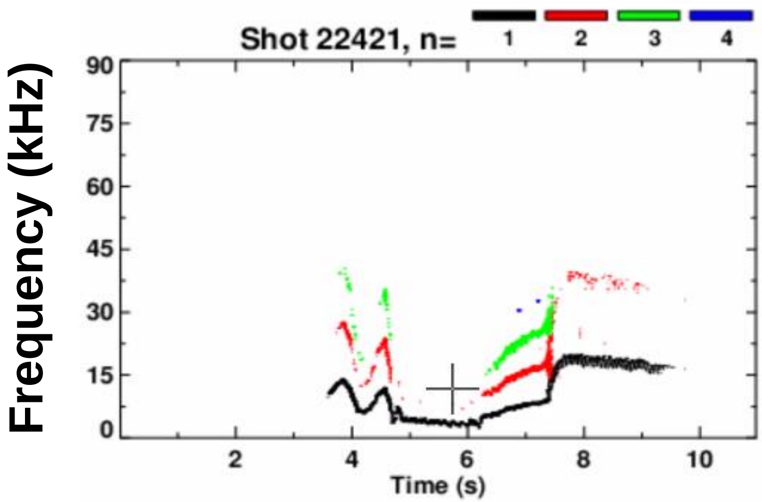
DECAF mode decomposition

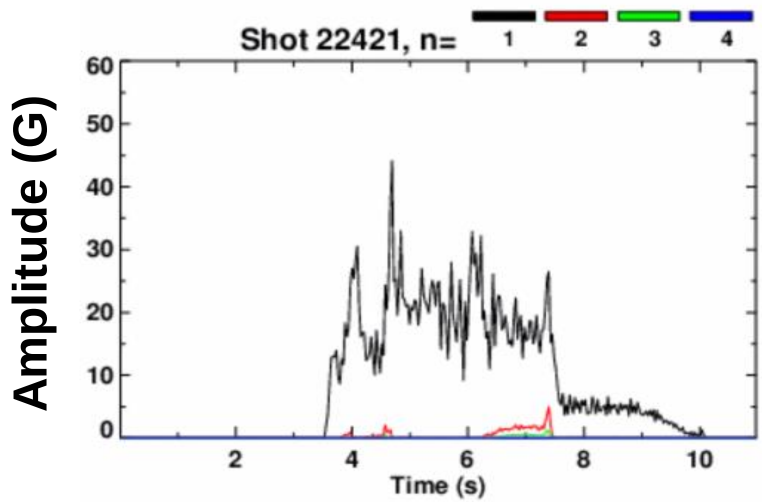


- **NEXT**: Expand to real-time computation of MHD, other DECAF algorithms

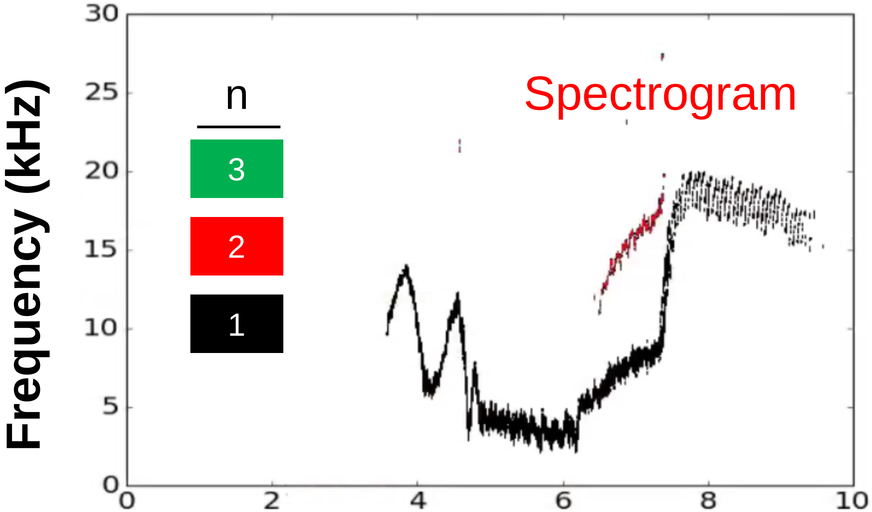
KSTAR real-time MHD computer now taking data for plasma shots in 2019 run campaign

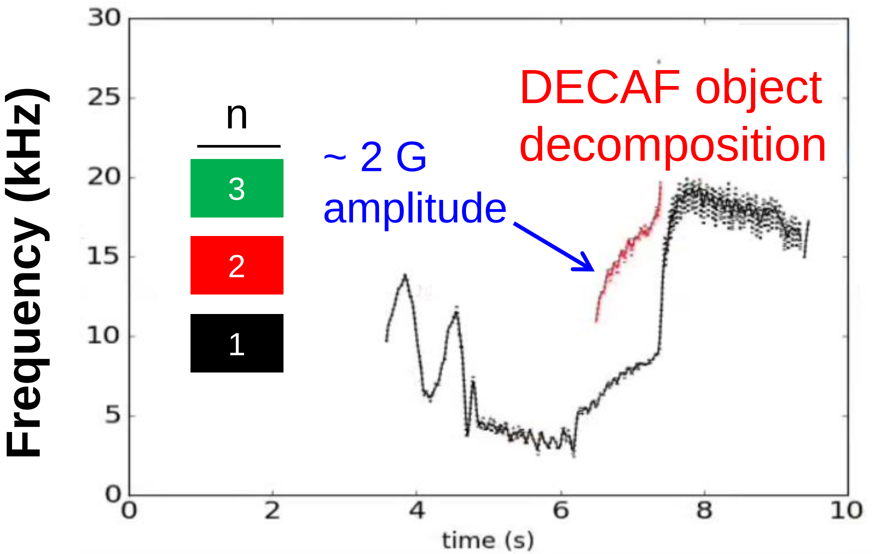
Offline data, native code analysis





Real-time data, DECAF analysis (offline)





New KSTAR DPA grant “fills in” the desired real-time (r/t) diagnostic capability for r/t DECAF

- Real-time measurement of rotating / locking MHD: DONE
  - < 300 kHz; upgrade to higher frequency for energetic particle modes
- Real-time and offline Motional Stark Effect - IN PROCESS
  - Real-time implementation of MSE; includes δB profile measurement
- Real-time plasma rotation profile - IN PROCESS (11/19/19)
  - MP: discussion potential upgrade of fibers for high transmission
  - MP: requests access to raw data (spectra) from present CES system
  - In-kind funding contribution from KSTAR for fibers / device mount
- Real-time T_e profile - IN PROCESS (11/19/19)
  - Met with K.D. Lee – discussed strawman design for system
- Real-time T_e fluctuation profile – IN PROCESS (11/18/19)
  - Met with M. Choi – discussed strawman design for system

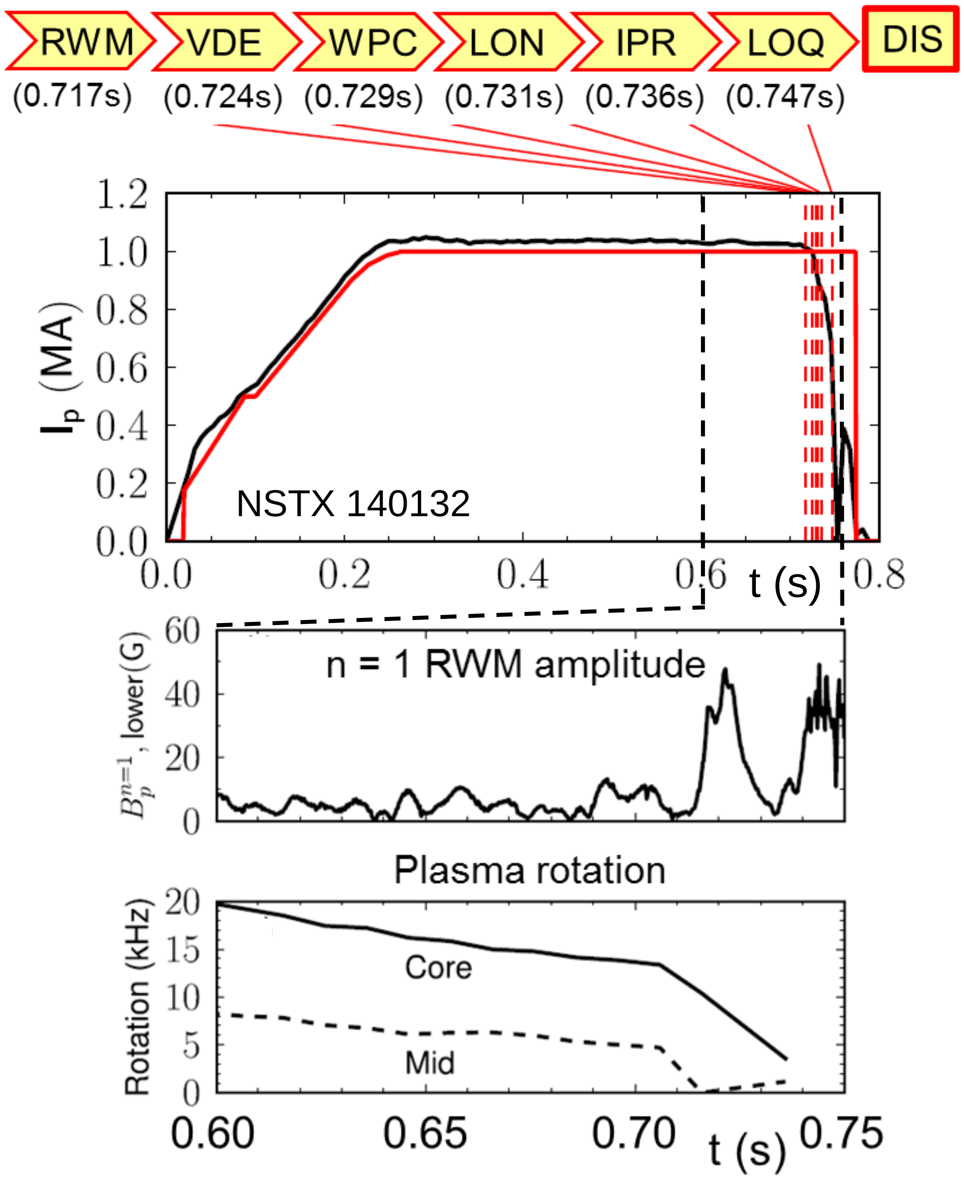
COLUMBIA PPPL NOVA PHOTONICS

Collaborative MAST stability research supports the overall research focus on disruption avoidance

- Comparison of MAST RWM to NSTX provides first direct experimental evidence of effect of wall on mode characteristics in similar high performance tokamaks
  - MAST vacuum vessel, *not* PF coil jackets, is primary stabilizing element
- The RWM has been observed on MAST
  - Calculations / experimental observations to date support this
  - Mode eigenfunction shape and growth rate are significantly altered by location of conducting structure
- Now, compute stability w/ kinetic equilibrium reconstructions with MSE to assess quantitative stability agreement w/ theory
- Mode stability at high β_N can to be significantly improved by conducting structure in the divertor plates of MAST-U
- Research also being conducted on KSTAR: high β_N, 100% non-inductive CD, MHD stability, large real-time control effort

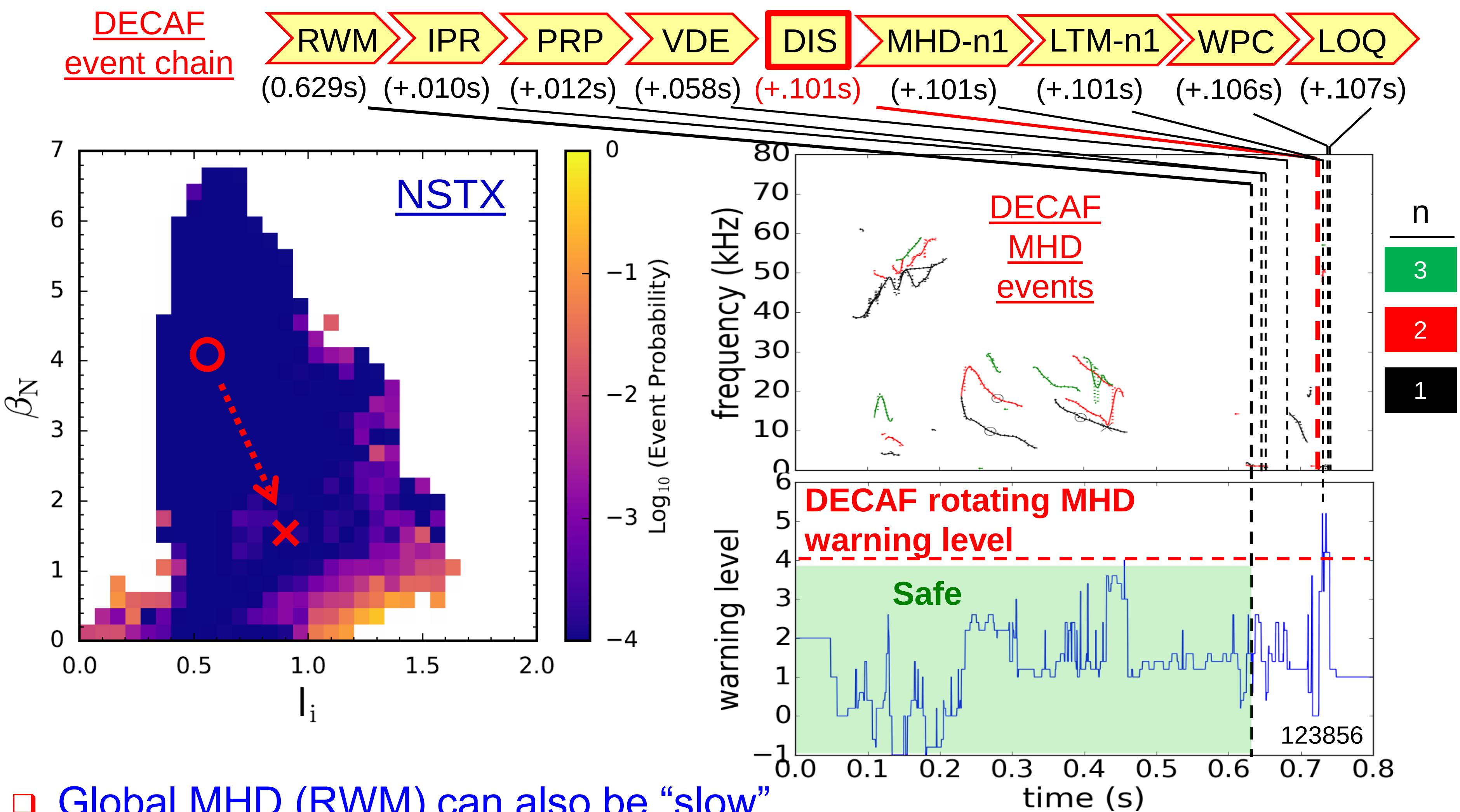
Supporting slides follow

DECAF determines disruption triggers and automatically generates event chains



- 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)

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



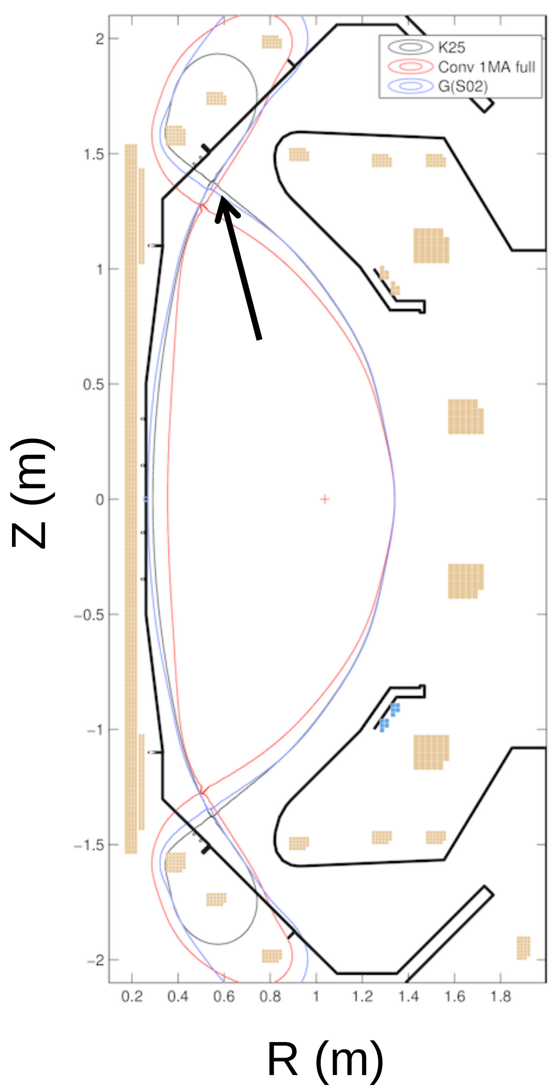
- Global MHD (RWM) can also be "slow"
  - Rotating MHD warning level decreases after 0.46s ➔ DANGEROUS for RWM onset!
  - H – L back transition (PRP) drags out time to disruption (> 100 ms – transport timescale)

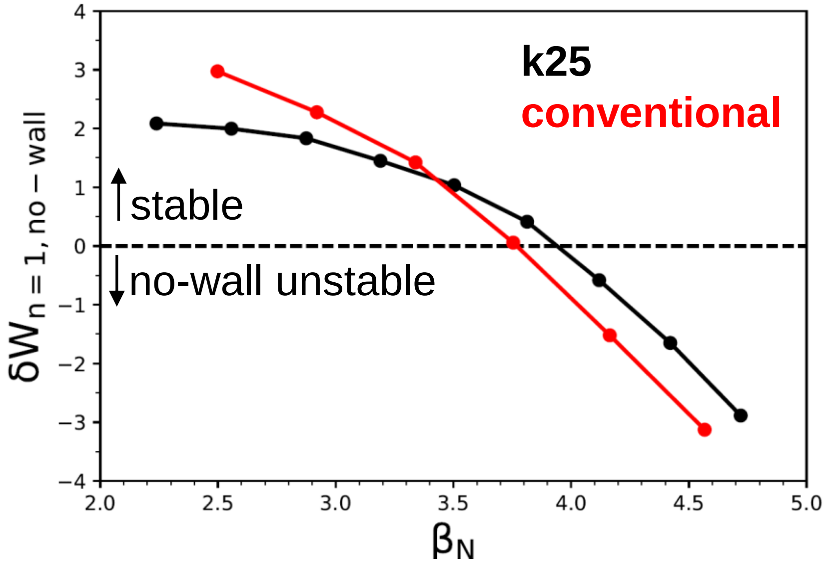
DECAF is fueled by coordinated research that continues to validate/develop physics models

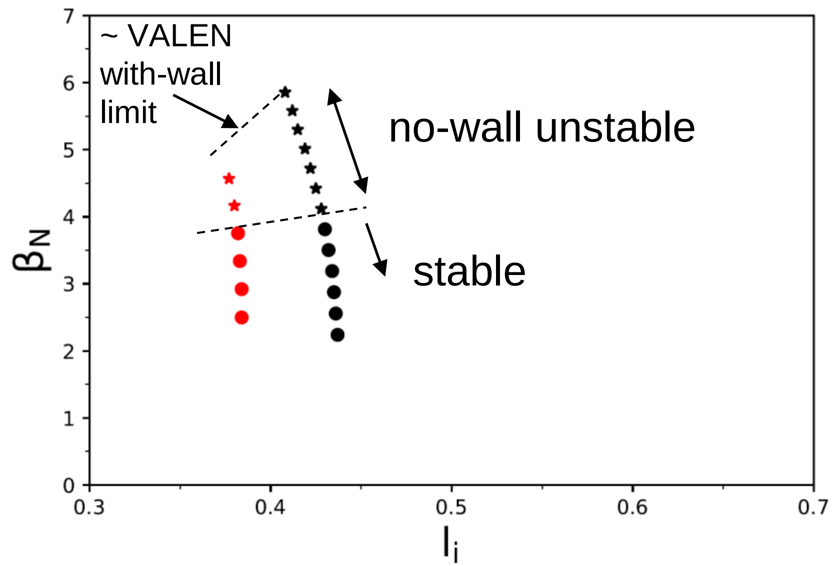
- Global MHD
  - Detection: available magnetic diagnostics, plasma rotation, equilibrium
  - Forecasting: Kinetic MHD model has high success in NSTX, DIII-D
- Resistive MHD
  - Detection / forecasting: available magnetic diagnostics, plasma rotation
  - Forecasting: starting examination of MRE ➔ start 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

DCON analysis of scaled MAST-U design equilibria shows a no-wall limit of β_N just below 4

K-25 equilibrium used as basis

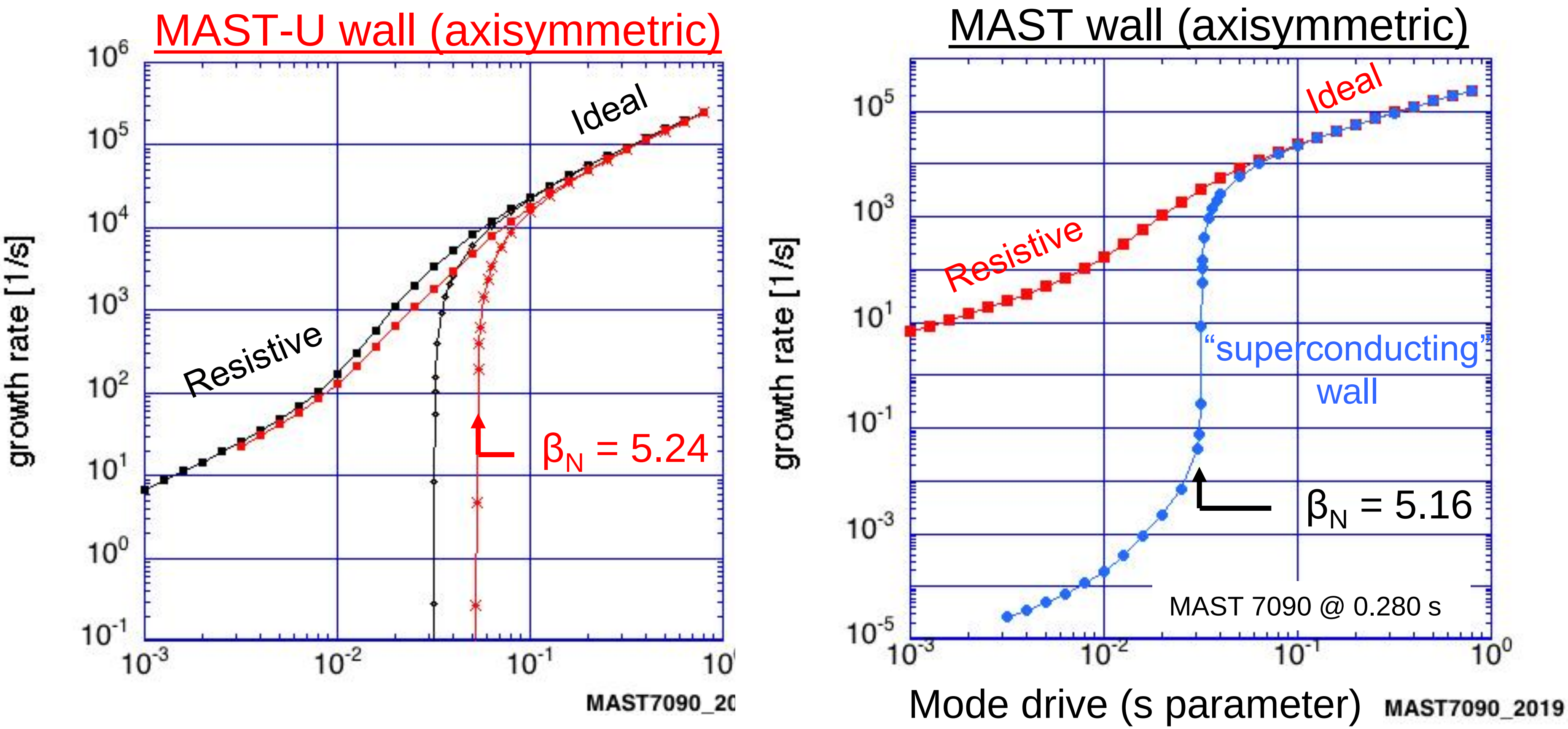






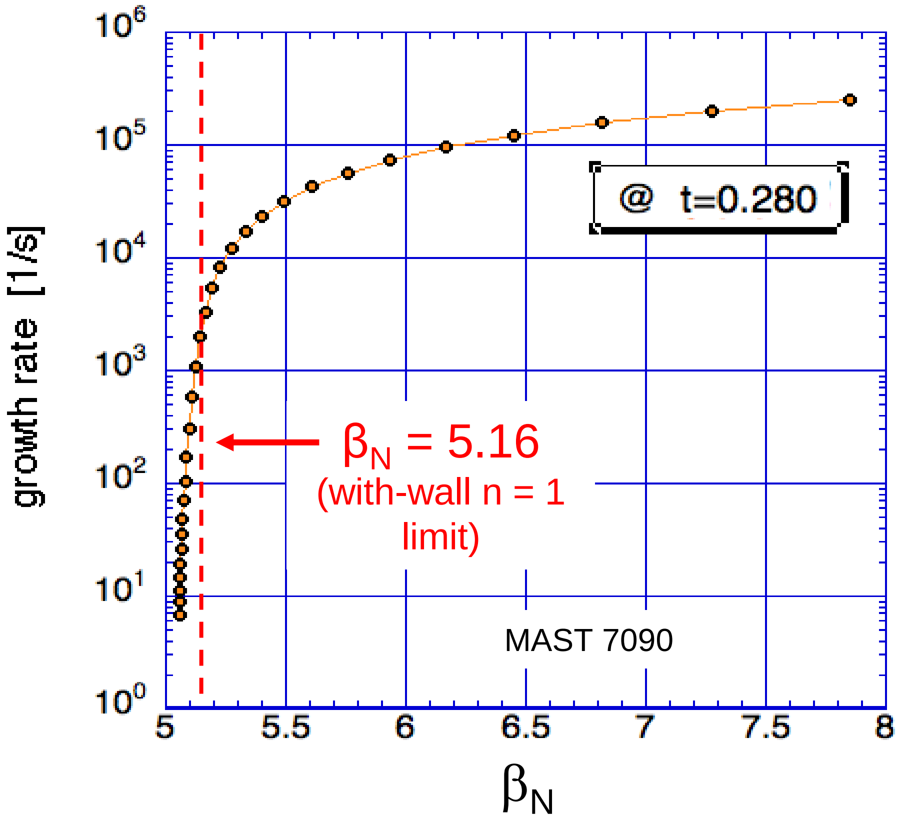
- Fixed boundary equilibrium scans based on several MAST-U design equilibria
- DCON stability calculations of CHEASE pressure-scaled equilibria

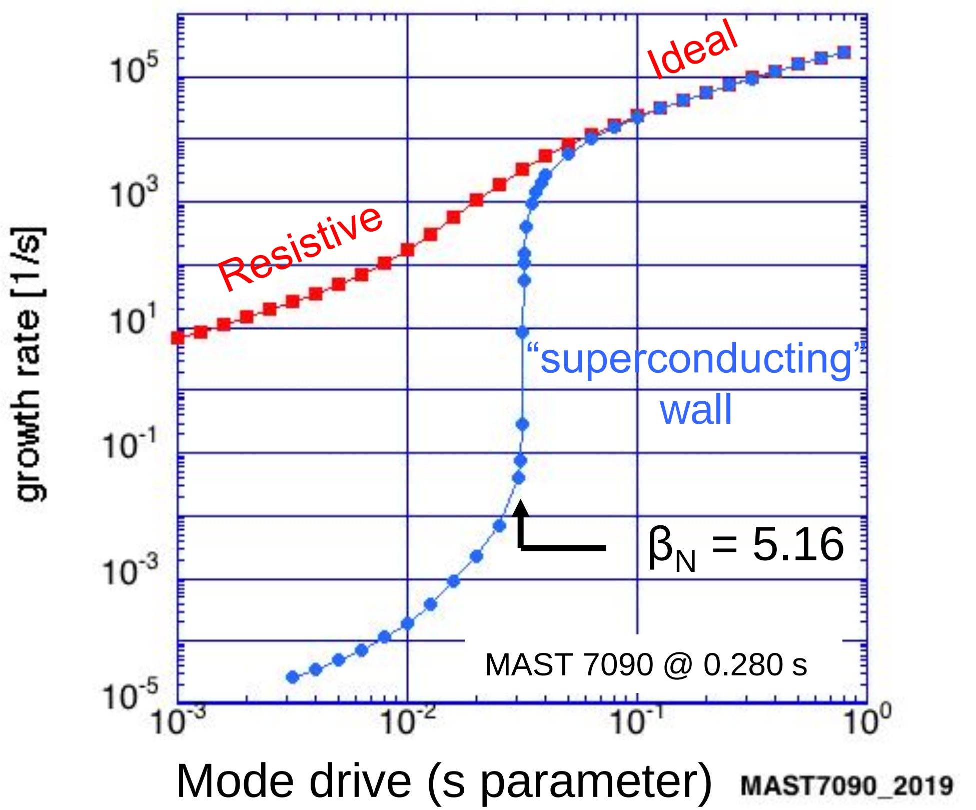
Initial VALEN analysis - MAST plasma with MAST-U vessel and conducting structure



- Initial analysis using MAST-U conducting structure with *MAST* plasma
- VALEN computes with-wall limit β_N = 5.24 (up from from 5.16)
  - NOTE: this is an initial assessment – not using more closely coupled MAST-U plasma, and not using MAST-U mode structure (greater effect of divertor plates?)

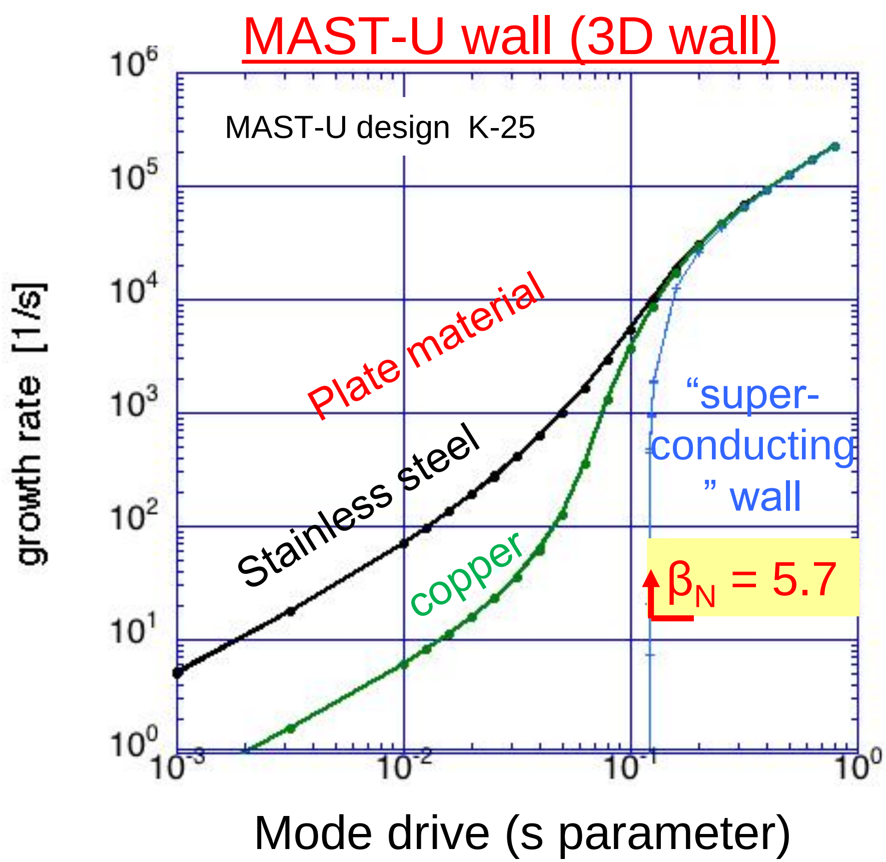
VALEN analysis indicates a small window between the no-wall and with-wall β_N limits for MAST

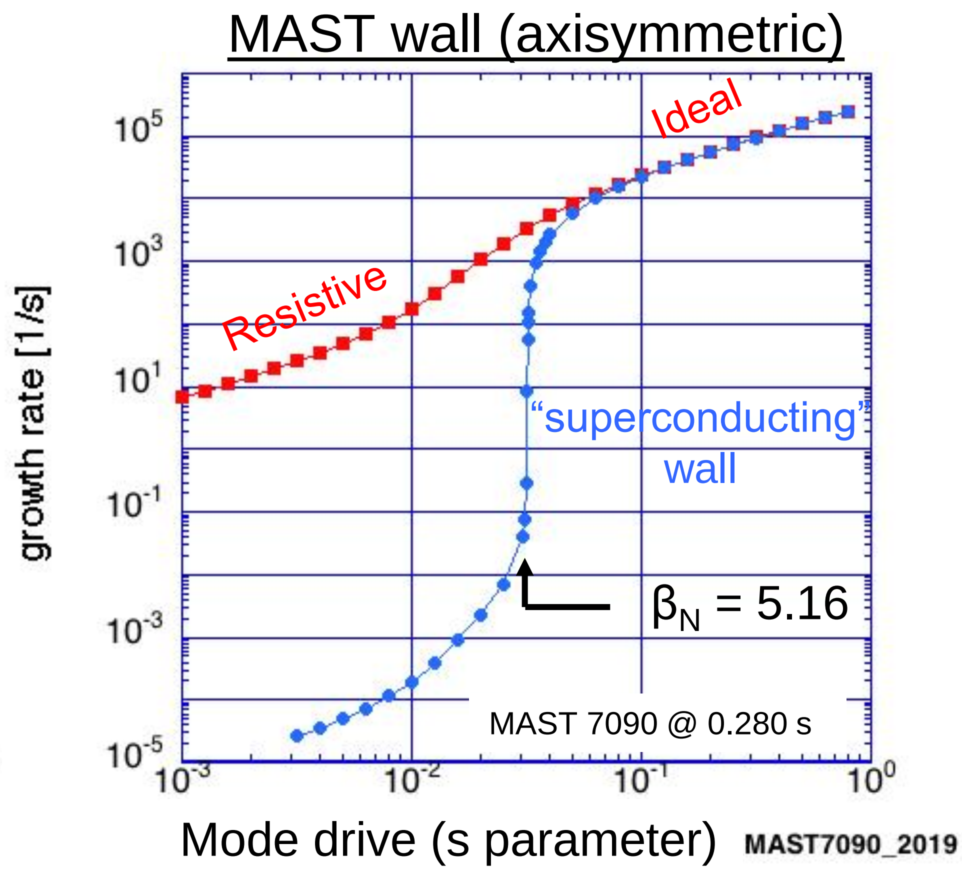




- VALEN scan shows the no-wall limit occurs at β_N just above 5 in this case
- VALEN computed with-wall limit β_N = 5.16 is just above the no-wall limit
  - MAST conducting structure offers little stabilization in present calculation
  - Best to recompute mode eigenfunction and stability using kinetic reconstructions

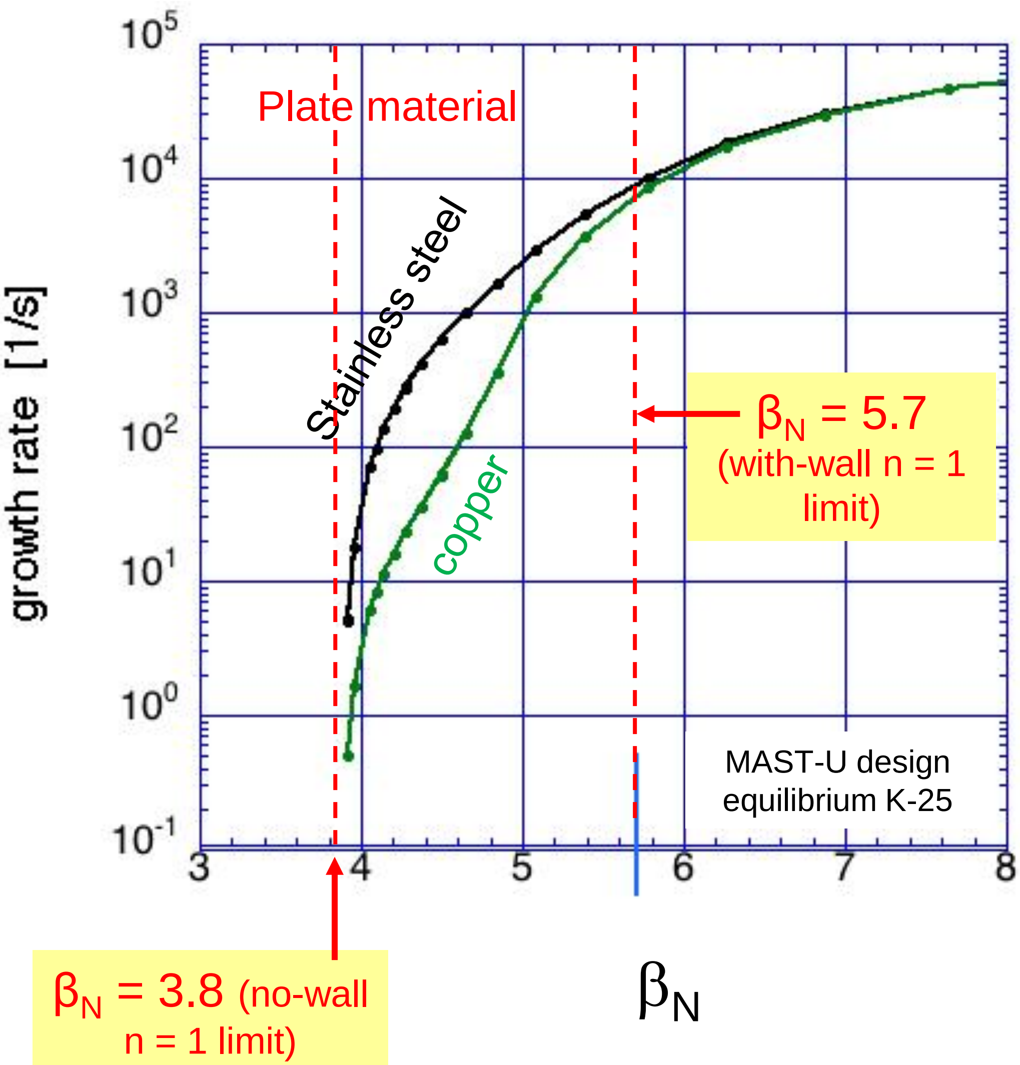
VALEN analysis of MAST-U design plasma with 3D vessel and conducting structure





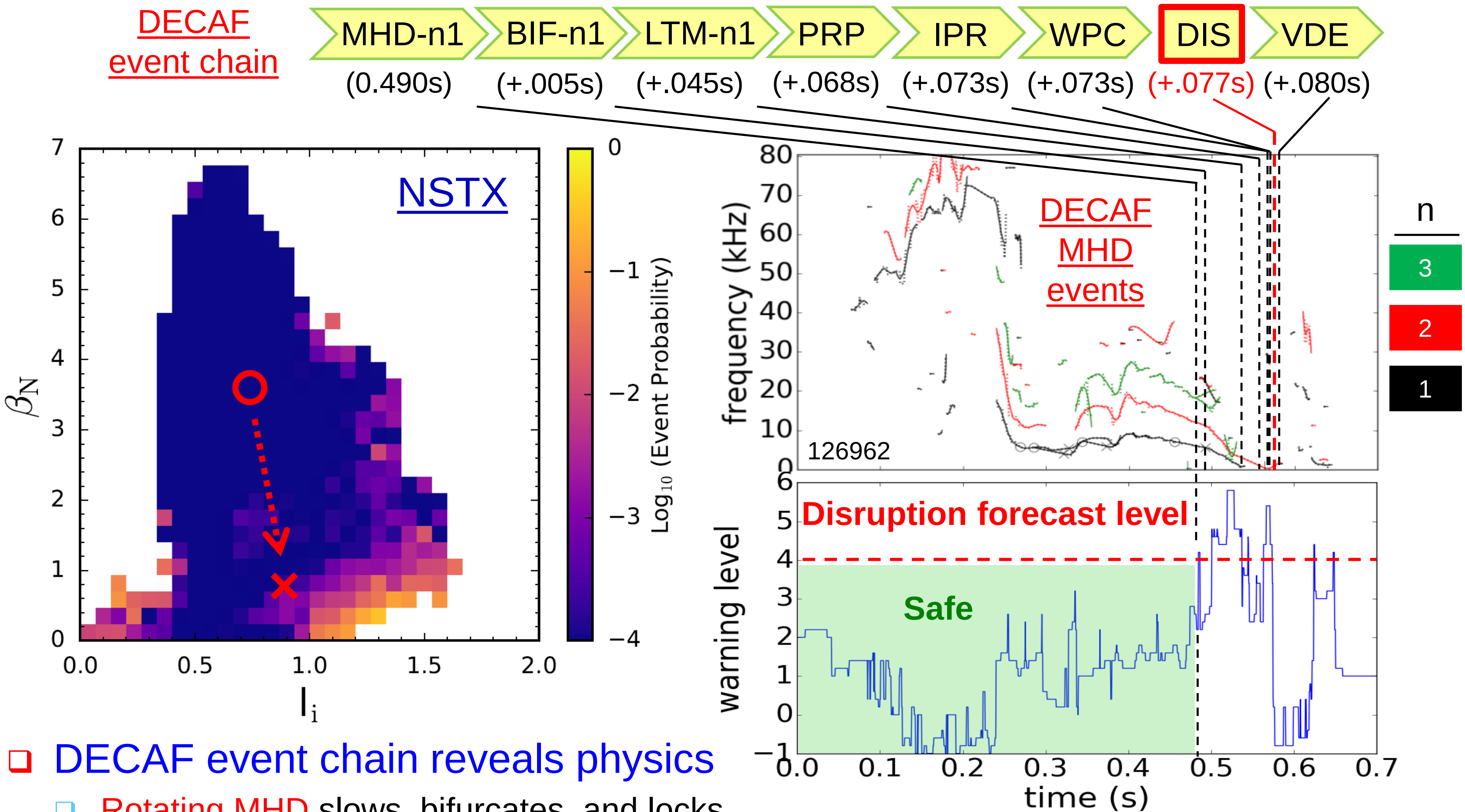
- Analysis using MAST-U conducting structure, MAST-U design plasma K-25
- VALEN computes with-wall limit β_N = 5.7 (up from 5.16 in MAST)
  - Significant stabilizing effect of divertor plates, copper reduces growth rate 10x
  - Improved coupling of plasma boundary to plates increases with-wall stability limit

VALEN analysis shows a significantly larger window between the no-wall/with-wall β_N limits for MAST-U



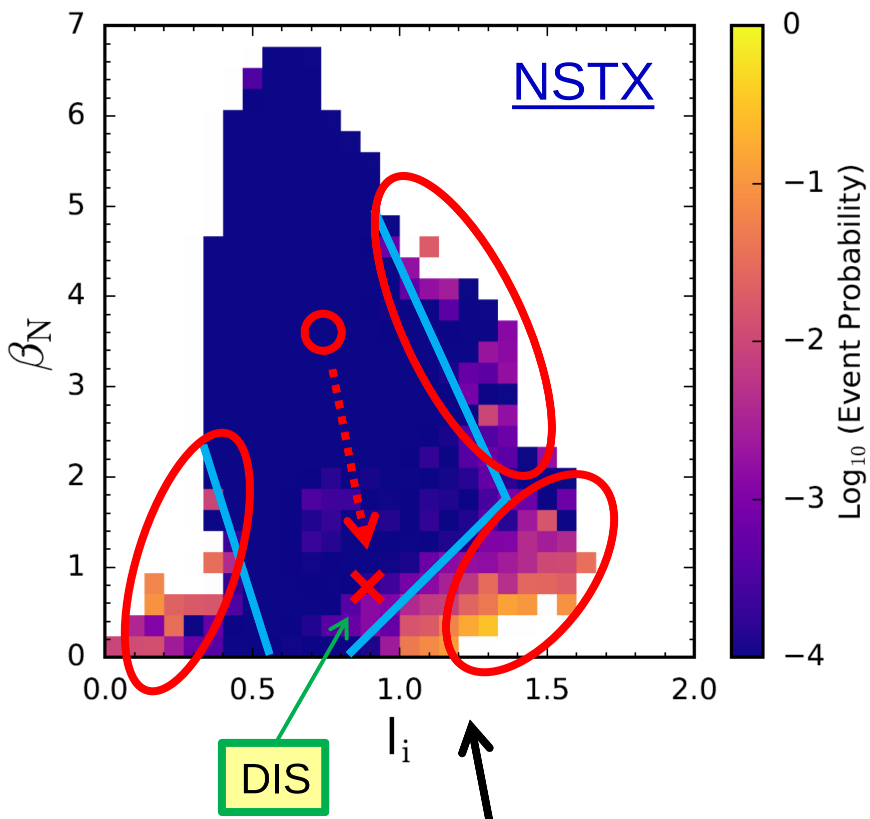
- Recall: MAST high β_N window
  - The VALEN computed $\Delta\beta_N$ window was only 0.15 (➔ 3% of the β_N operational space)
- VALEN computed MAST-U high β_N > no-wall β_N limit is significantly larger than MAST
  - Due to greater passive conducting structure in MAST-U
  - The VALEN computed $\Delta\beta_N$ window is 1.9 (for K-25 case)
    ➔33% of β_N operation space
  - Result is *not* optimized

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



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

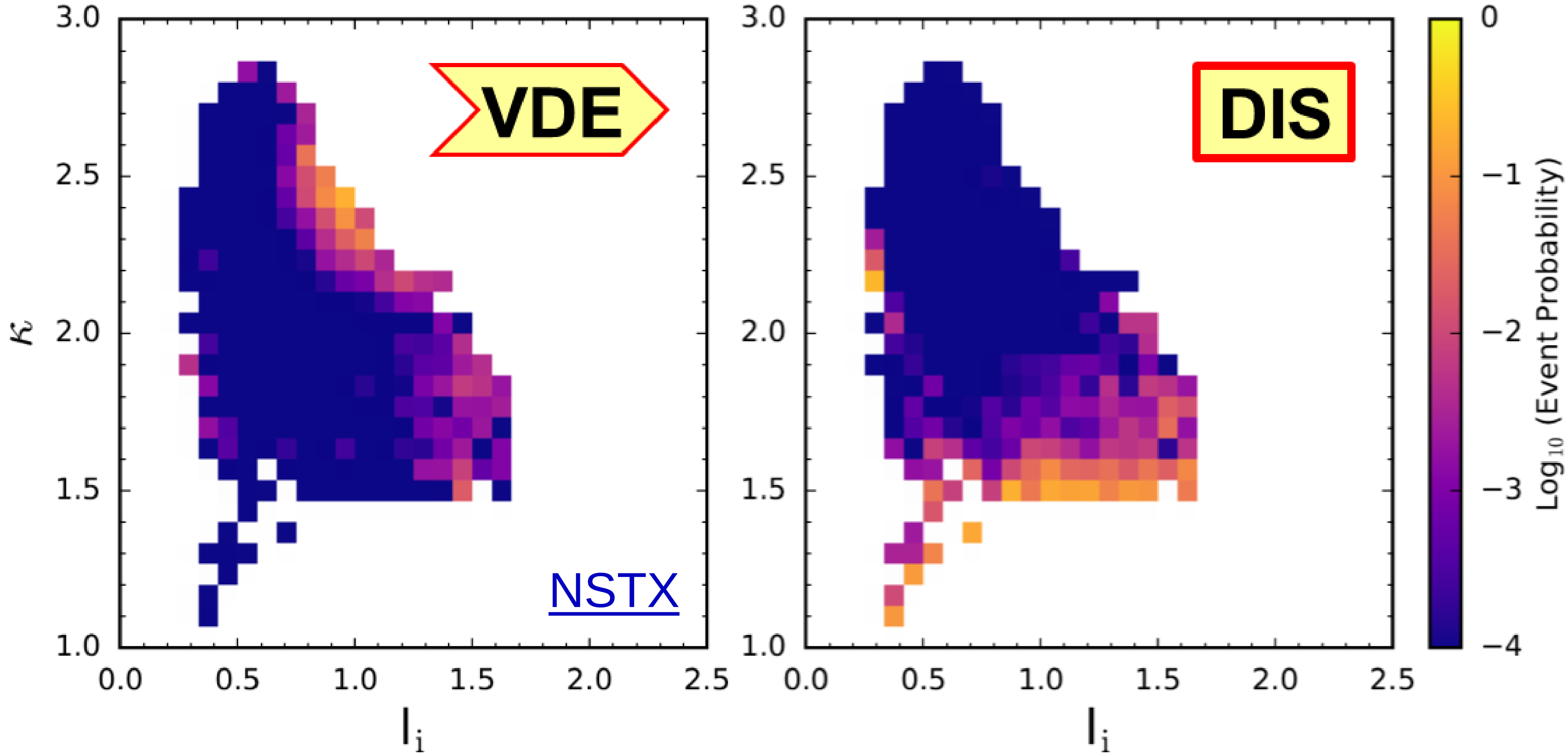
DECAF provides early disruption warning and understanding of disruption event chains beyond disruptivity plots



- Example: What are the most important regions to study on this plot?
  - Studies usually focus on the high event probability regions
  - "Black box" 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 issue detected and when disruption happens

- Answer: the circle ○ marks 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 cross ✕)

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