NSTX-U

NSTX-U is sponsored by the
U.S. Department of Energy Office of Science
Fusion Energy Sciences

Macroscopic Stability Research - NSTX-U

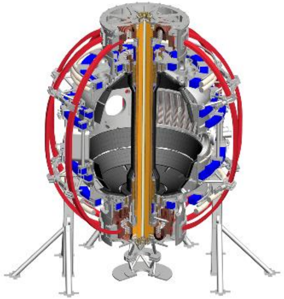
S.A. Sabbagh, for the NSTX-U Team

NSTX-U PAC-39 Meeting
PPPL
January 9th, 2018

COLUMBIA UNIVERSITY
IN THE CITY OF NEW YORK

PPPL

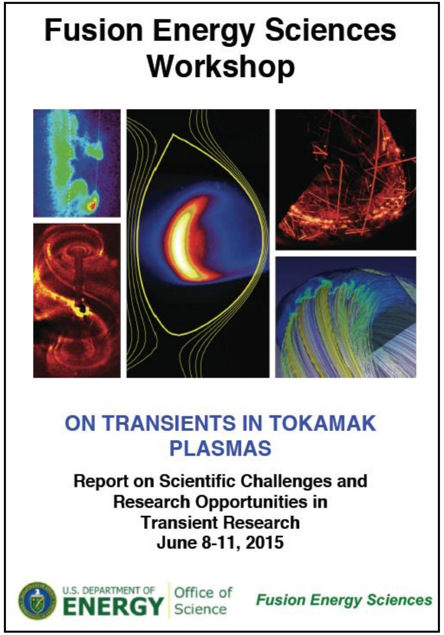
V2.0



NSTX-U restart will provide critical macrostability research of compact, high β plasmas with world-leading capabilities

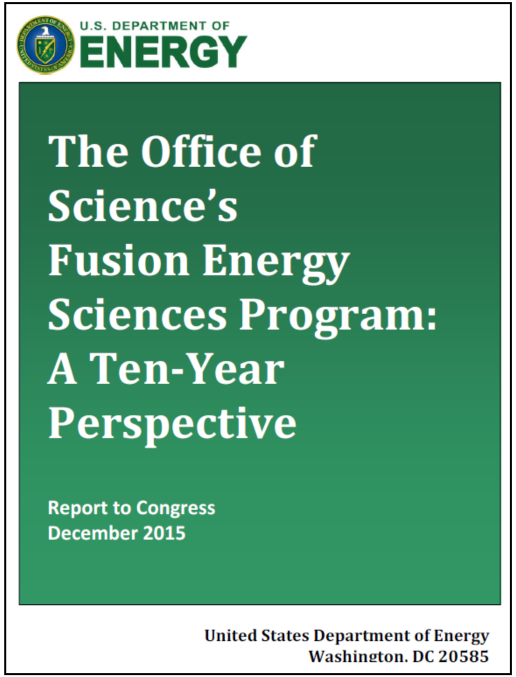
- **Overview:**
  - NSTX-U research is critical to the U.S. DOE FES priorities, needs to continue ASAP
  - Significant investment in NSTX/-U data leverages unique, high β compact tokamak physics data and research for key theory validation, confident extrapolation of models
- **Outline:**
  - U.S. Program high priority needs defined by DOE and NSTX-U essential role
  - Unique aspects/findings of NSTX research stimulating world-leading NSTX-U research
  - Capabilities for disruption prediction and avoidance research at high beta
  - Recent NSTXU researcher efforts to support ITER through ITPA
  - Results from NSTX-U initial operation supporting more rapid progress on restart

Avoidance/control of transient events are one of two highest DOE FES priorities in macrostability research



Charge 2,3

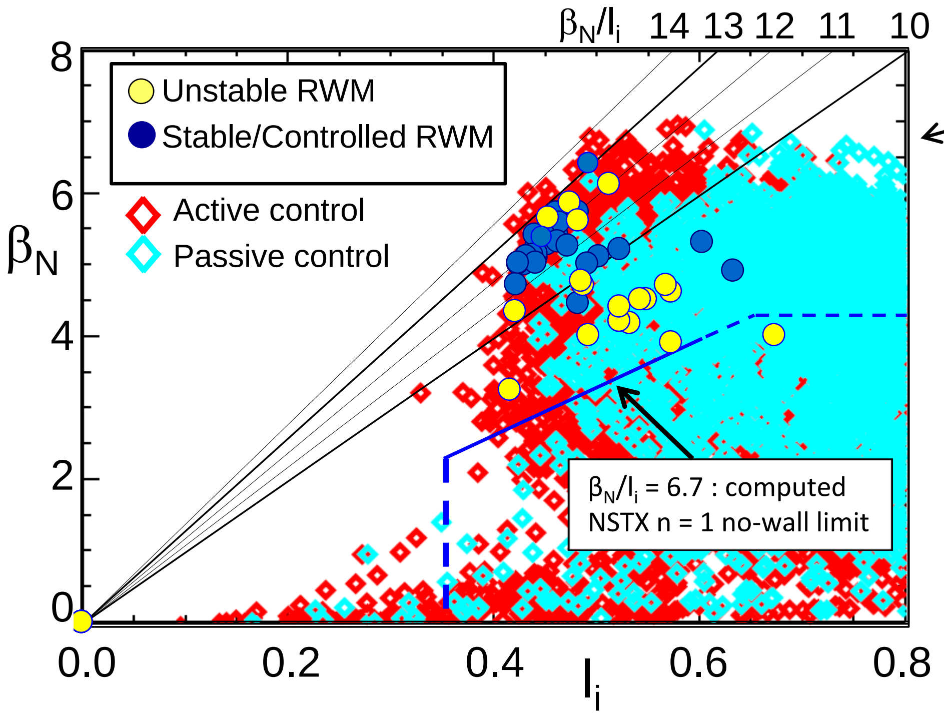
- **Workshop on Transients Report**
  - Broad community process addressing critical disruption and ELM challenges; identified as critical ITER needs
  - Disruption prediction / avoidance / mitigation Thrusts/Pursuits include:
    - Experimentally validated theoretical understanding of disruption chain events
    - Predicted thresholds and control for disruption avoidance and mitigation
    - Leverage national/international multi-device data for best extrapolability



- **FES Program 10 Year Perspective (NSTX-U uniqueness)**
  - "Exploration of the impact of (device aspect ratio) can inform much of fundamental science pertaining to magnetic confinement."

NSTX reaches uniquely high β_N, low l_i range of operation, and the highest β_N/l_i is *not* the least stable

Charge 2,3



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

➔ Key MAST-U complementarity: stability physics *without* stabilizing wall

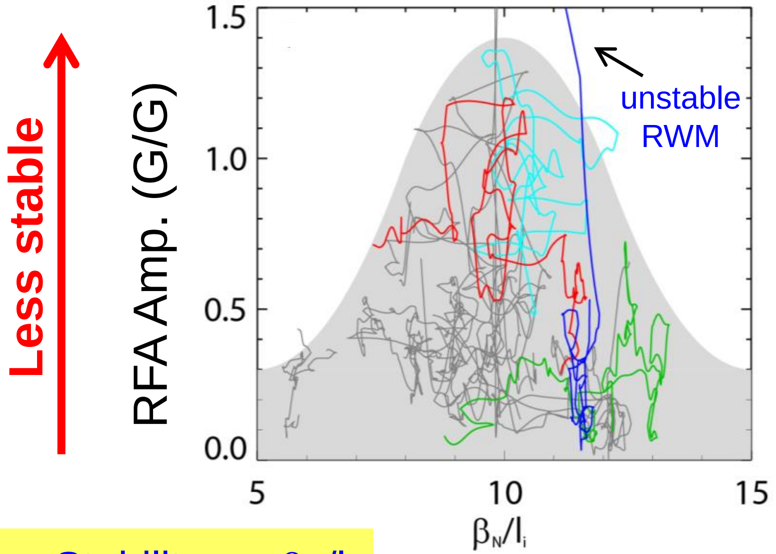
- Unique high β_N > 7, β_N/l_i > 14 reached!
  - In dedicated experiment (shown), disruptivity was higher at "intermediate" values of β_N/l_i
  - In larger database, disruptivity decreases at higher levels of β_N/l_i
- Research leverages NSTX-U capabilities
  - Compact ST field geometry (incl. high shaping)
  - Stabilizing conducting wall (copper)
  - Reduced collisionality (I_p, B_T increase)
  - Plasma rotation and current profile control
  - Adv. control of high β_N ST eigenmodes (see backup)

➔ Combined to produce highest sustained β_N with broad, self-consistent non-inductive current profile (low l_i)

$$f_{BS} \sim A^{1/2}\left(\frac{\beta_N}{l_i}\right)\left(\frac{R_0}{R_M}\right)q_{cyl}$$

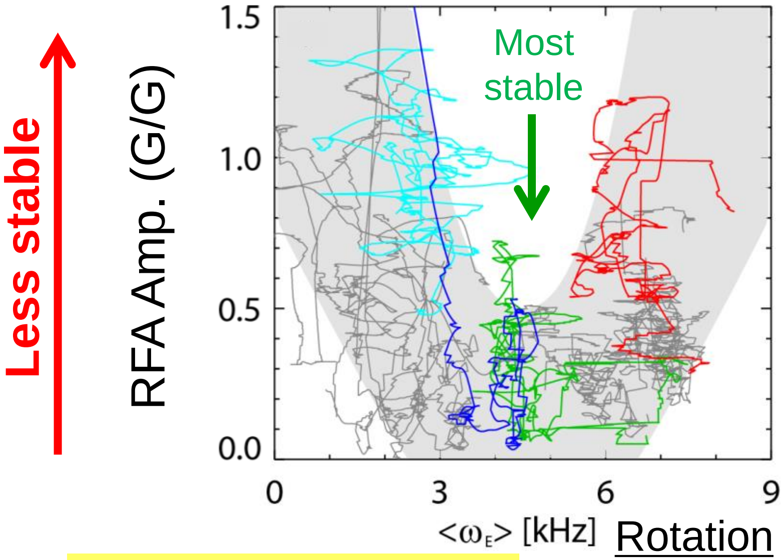
Experiments directly measuring global stability using MHD spectroscopy (RFA) understood by kinetic RWM theory

Resonant Field Amplification (RFA) vs. β_N/l_i



RFA vs. rotation (ω_E)

Charge 1



- Stability vs. β_N/l_i
  - decreases up to $\beta_N/l_i = 10$, ***increases*** at higher β_N/l_i
  - Consistent with kinetic stabilization

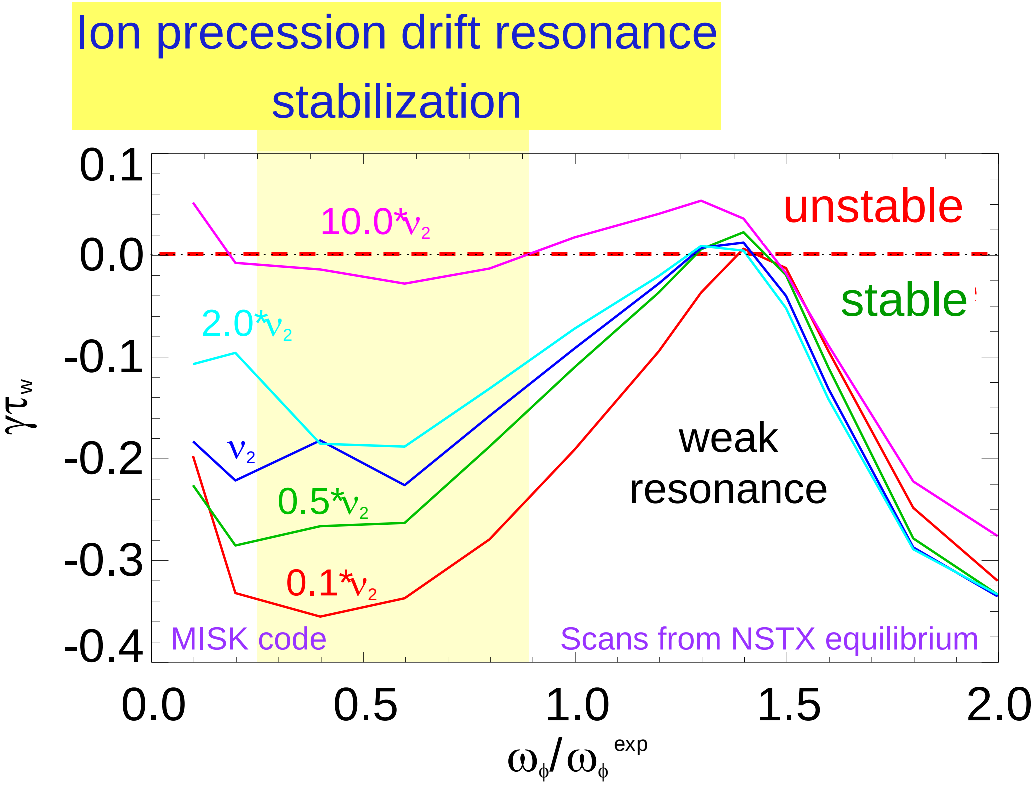
- Stability vs. rotation
  - Largest stabilizing effect from ion precession drift resonance with ω_ϕ

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

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

Kinetic modifications completely change the understanding and scaling of mode stability at reduced collisionality

Charge 1,3,4



- Past models/ideas
  - Collisions provide stabilization
  - stability decreased with decreasing ν
  - Unfavorable for ITER
- Present model
  - Collisions spoil broad stabilizing resonances
  - Mode stabilization vs. ν depends on rotation profile ω_ϕ
    - At strong resonance: mode stability **increases** with decreasing ν

➔ Key next step: verify extrapolation to low ν in NSTX-U

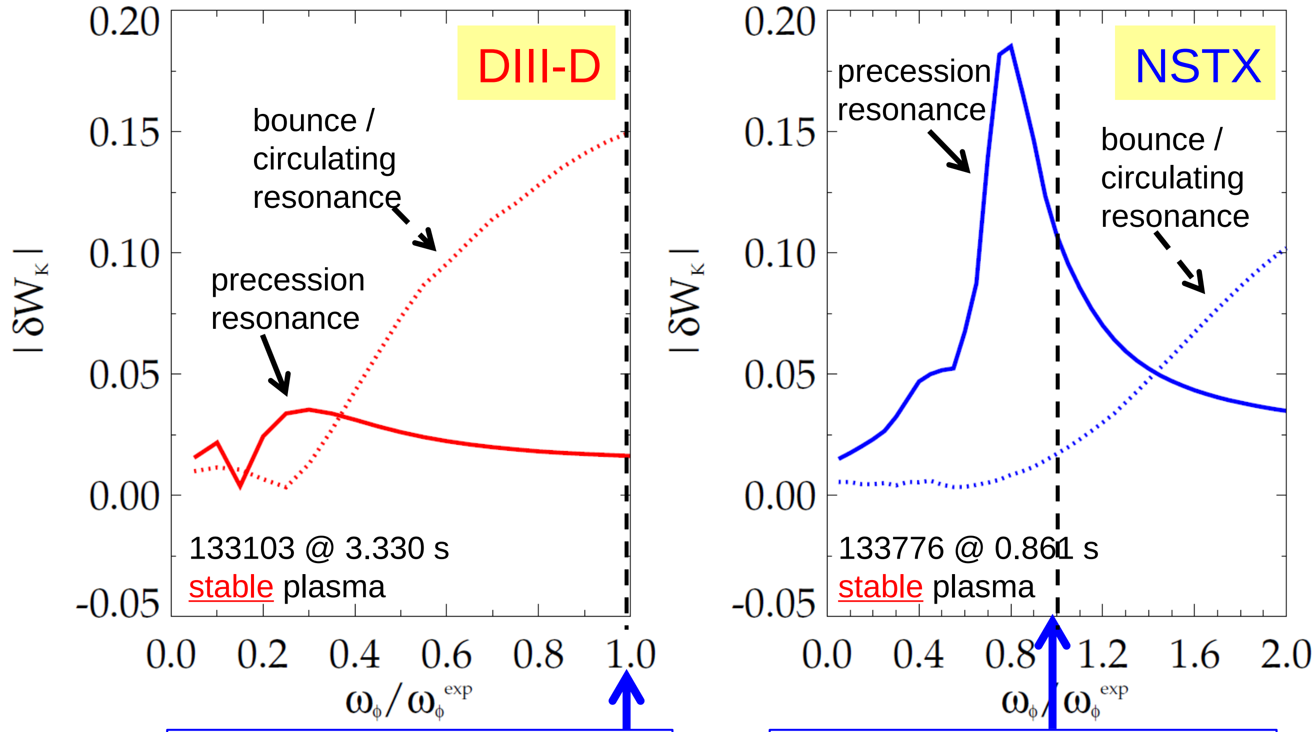
J.W. Berkery, et al., Phys. Rev. Lett. **106** (2011) 075004

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

NSTX shows dominant precession drift resonance stabilization vs. bounce resonance for DIII-D in joint XP at similar, high rotation

$|\delta W_K|$ for trapped resonant ions vs. scaled experimental rotation (MISK code)

Charge 1



DIII-D experimental rotation profile

NSTX experimental rotation profile

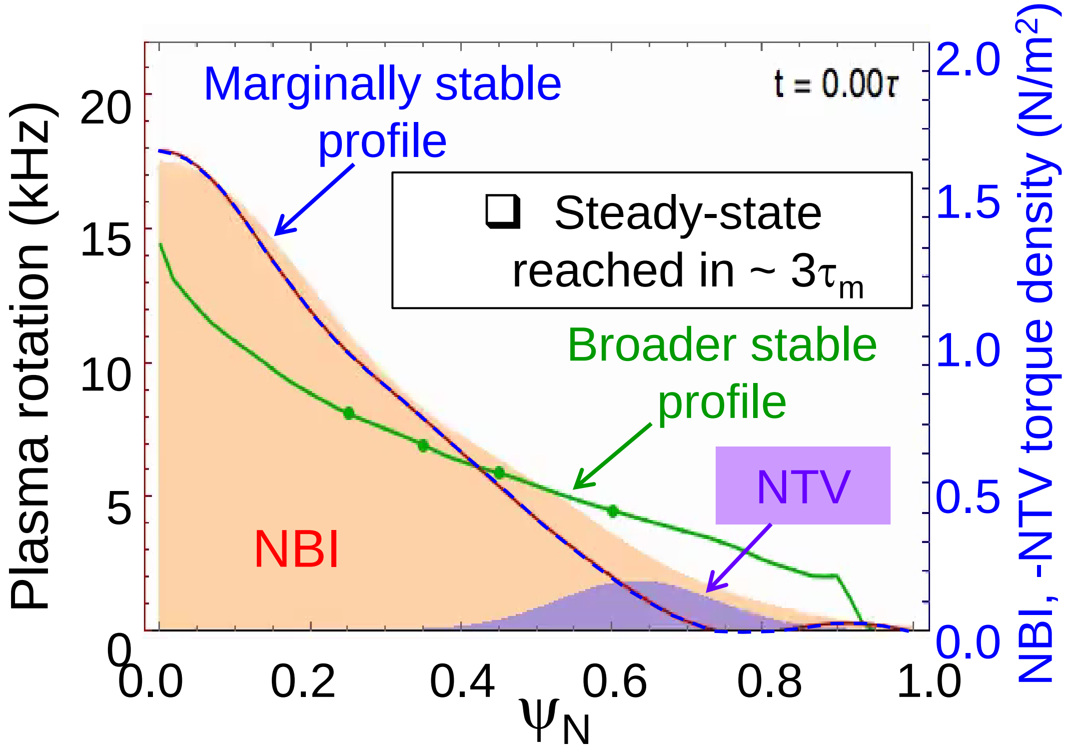
- Also, computed kinetic RWM stability matches disruption onset in both machines over wide rotation range (using same analysis tools) (see backup slide)

Some NSTX / MISK analysis references

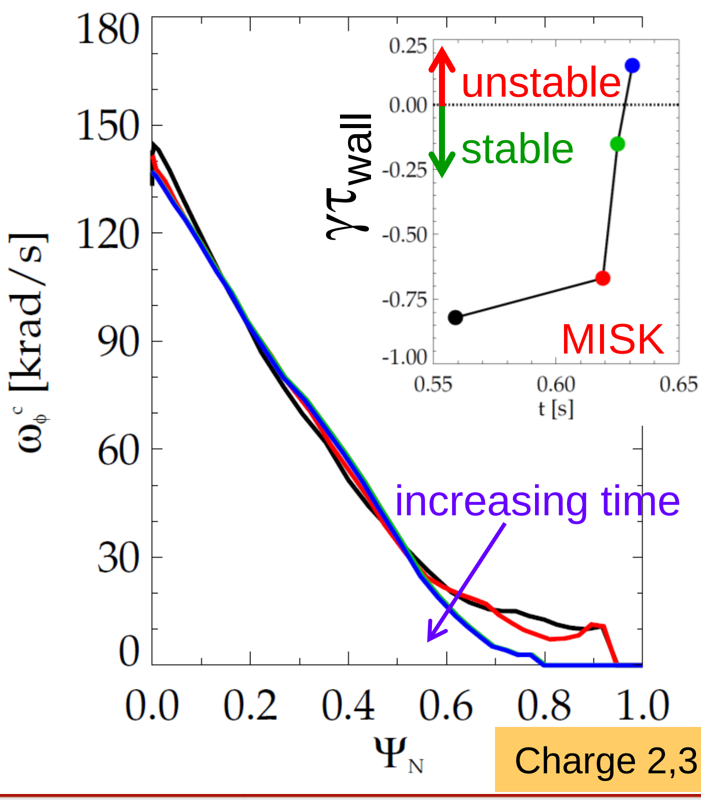
- J. Berkery *et al.*, PRL **104**, 035003 (2010)
- S. Sabbagh, et al., NF **50**, 025020 (2010)
- J. Berkery *et al.*, PRL **106**, 075004 (2011)
- S. Sabbagh *et al.*, NF **53**, 104007 (2013)
- J. Berkery *et al.*, PoP **21**, 056112 (2014)
- J. Berkery *et al.*, PoP **21**, 052505 (2014)
- J. Berkery *et al.*, NF **55**, 123007 (2015)

State space rotation controller designed for NSTX-U using non-resonant NTV (3D field) and NBI to maintain stable profiles

NSTX-U (6 NBI sources and n = 3 NTV)



ω_ϕ evolution in NSTX (disruption)



I. Goumiri, C. Rowley, S.A. Sabbagh, et al, PoP 24 (2017) 056101

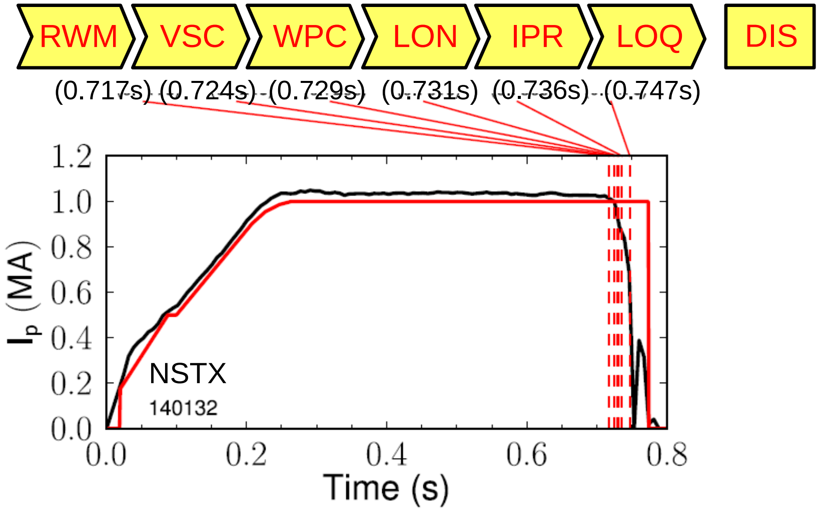
Charge 2,3

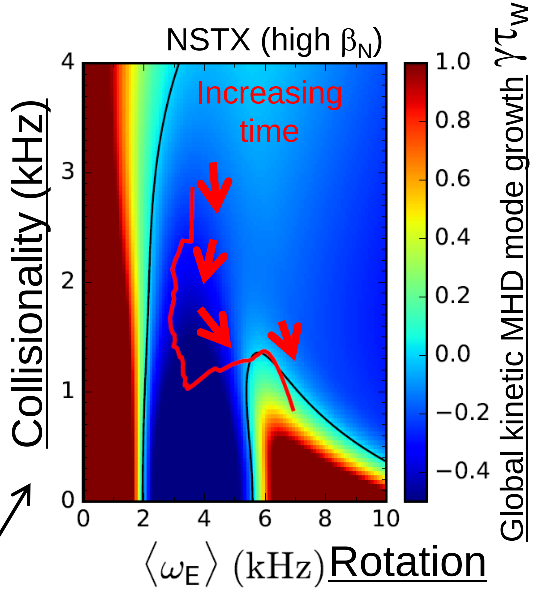
Automated Disruption Event Characterization and Forecasting innovation to enable disruption avoidance

Automated disruption event chain analysis

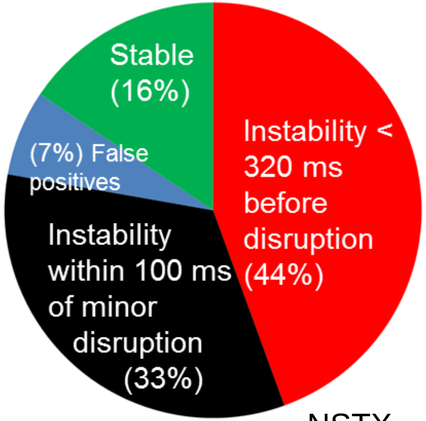
Disruption forecasting

Charge 1,2,3,4





Predicted instability statistics



Cue disruption avoidance systems

- Physics-based disruption forecasting, compared to experiment
- Recent automated rotating MHD module for TM analysis (see backup)
- Portable code for collaborative (inter)national multi-device studies (including NSTX/-U, KSTAR, DIII-D, TCV); supports NSTX-U r/t event handler

DECAF code

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

In aggregate, NSTX-U provides key capability for disruption avoidance research of unique high beta, compact ST plasmas

Predictor/Sensor (CY available)	Control/Actuator (CY available)	Physics Research
- Rotating and low freq. MHD (n=1,2,3) 2003	- Dual field -component RWM sensor control (closed loop 2008)	NTM, RWM
- Low freq. MHD spectroscopy (open loop 2005); - Kinetic RWM modeling (2008)	- Control of high β_N ST plasmas (closed loop 2007)	Kink/ballooning, RWM
- Real-time physics-based RWM state-space controller observer (2010)	- Physics model-based RWM state-space control of ST modes (2010)	NTM, RWM (ballooning), VDE
- Real-time V_ϕ measurement (2016 NSTX-U)	- Plasma V_ϕ control (by NTV 2004) - NTV + NBI rotation control (closed loop)	NTM, Kink/ballooning, RWM
- Reduced Kinetic RWM stabilization model (2016) - Automated MHD identification (2017) - Real-time MHD spectroscopy (5 Year Plan) - Real-time kinetic stabilization model (new) - Real-time rotating MHD identification (new)	- Safety factor, l_i control (closed loop) - NTV + NBI rotation control (closed loop) - Upgraded 3D coils (NCC): improved V_ϕ and mode control (in 5 Year Plan)	NTM, RWM Kink/ballooning, VDE

Capability

Existing

Recent

Upcoming

Routine use of existing systems (reliability shown)

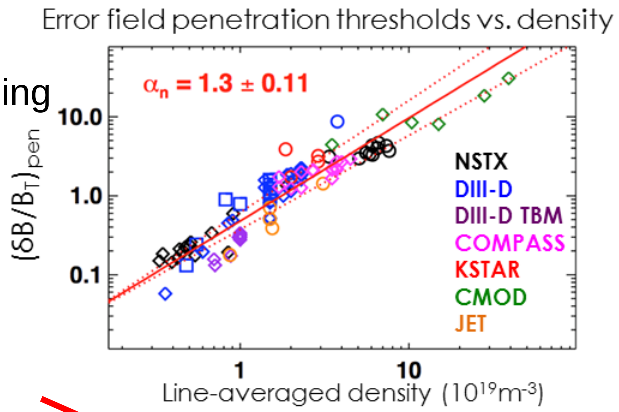
Charge 2,3,4

NSTX-U researchers are leading international efforts to support ITER in macrostability analysis

Charge 1,2,3

- **Error fields (ITPA MDC-19)** J.-K. Park et al.
  - On-going effort to predict ITER error field (EF) tolerance using MHD response metrics
  - Resonant n = 1 EF criterion (2017)

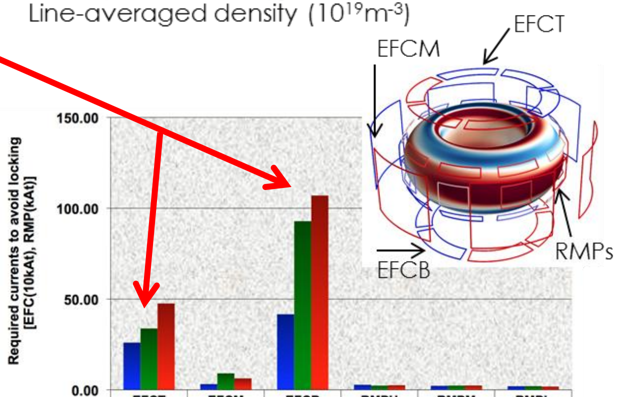
$(dB/B_T)_{pen} = 0.0006 (n_e) 1.3 B_T^{-1.7} R^{0.7} \beta_N^{-0.78}$



- **3D field coil effectiveness (ITPA MDC-19)** J.-K. Park et al.
  - Top / bottom ex-vessel coils are found to be 10 times less efficient to control n=1, 2 resonant fields than other coils

- **Halo currents (ITPA MHD WG-6)** C. Myers, et al.
  - Multi-machine database (NSTX, DIII-D, C-Mod, JET, AUG) examining halo current magnitudes, asymmetries, rotation

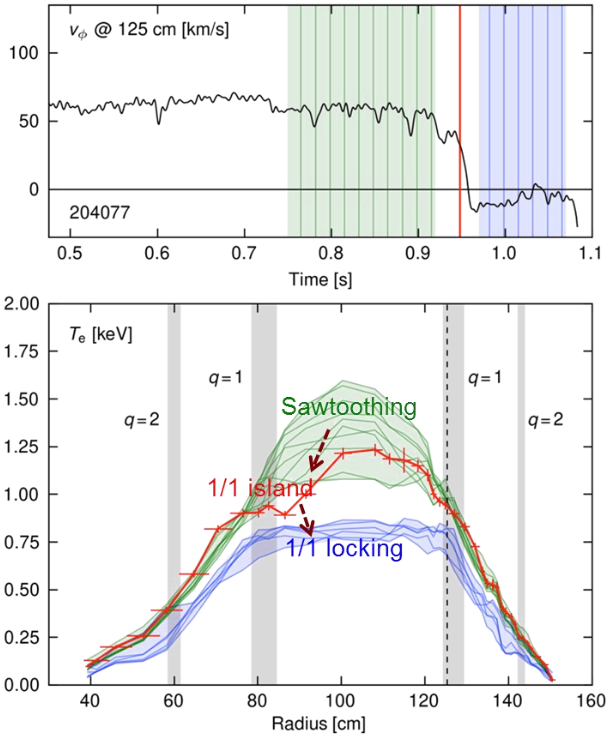
- **Global mode stability/control (MDC-21)** S. Sabbagh, J. Berkery, et al.
  - Extensive kinetic RWM analysis code benchmarking effort
  - Alpha particles, and/or active control required for RWM stabilization at all ω_ϕ in advanced scenario $\beta_N = 2.9$



	EFCT (10kAt)	EFCM (10kAt)	EFCB (10kAt)	RMPU (kAt)	RMPM (kAt)	RMPL (kAt)
Scen2_Flat	26.00	3.13	41.60	2.77	2.19	1.98
Scen2_Burn	33.77	9.06	92.88	2.32	2.32	2.01
Scen4_Burn	47.56	6.29	107.00	2.52	2.38	1.78

Macrostability research from initial NSTX-U operation provides key insight for rapid progress upon restart

Observation of direct 1/1 mode locking

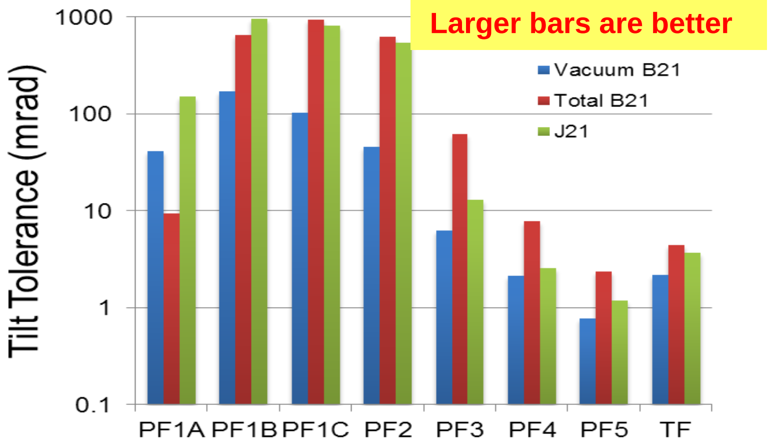


(C. Myers et al., submitted to PRL (2017))

- Error field rapidly characterized

Charge 1,2,3

  - EF partly corrected using 3D field coils
  - IPEC, M3D-C[1] plasma response modeling implicated TF misalignment as likely primary source of locking
    - TF misalignment identified, will be corrected
  - Codes now being used to set alignment tolerances for all coils (J.-K. Park, N. Ferraro)



Condition: resonant 2/1 Field < RMP coil at 1 kA-t

Summary (I): NSTX-U recovery paves the way back to world-leading research on unique, compact high β plasmas

- Charge 1: Quality/importance of recent NSTX/NSTX-U research results
  - Kinetic RWM stabilization research fundamentally changed physics understanding of experimental stability, importance of rotation profile, extrapolation to reduced collisionality (2016 Landau-Spitzer Award)
  - Direct measurement of plasma stability through RFA verified key understanding of greater stability at uniquely high β_N/l_i
  - Physics-based disruption prediction/avoidance research (DOE high priority) established

- Charge 2: Uniqueness / timeliness for the world program
  - Unique (in the world) high β_N, β_N/l_i operational regime provides critical theory validation
  - Global MHD stability, error field/plasma response, applied 3D field research directly serve ITER, KSTAR, et al. now; will continue
  - Disruption prediction/avoidance research expanded to collaborations on world tokamaks

Summary (II): NSTX-U recovery paves the way back to world-leading research on unique, compact high β plasmas

- **Charge 3: How/whether NSTX-U will be world-leading after restart**
  - Disruption prediction and avoidance research is world-leading, highest priority, remains active – plan to be significantly advanced by restart
  - Advanced control technique plan for disruption avoidance will remain world-leading on restart, collaborations to keep effort active
  - Unique low A, high β_N joint experiments w/ tokamaks can resume in timely fashion on restart

- **Charge 4: How recent findings influence the future NSTX-U program**
  - NSTX-U 5 Year Plan remains largely intact (e.g. study of kinetic RWM stabilization paradigm at low ν, w/ greatly varied / controlled rotation profile remains strongly relevant)
  - Advanced control techniques are planned; if recommended, recovery period provides opportunity for early development / implementation - restart research ASAP
  - Disruption prediction research plan can be even more aggressive (e.g. real-time MHD ID)
  - 3D field coil upgrade remains important for NTV rotation, adv. mode control, ELM studies

Backup Slides Follow

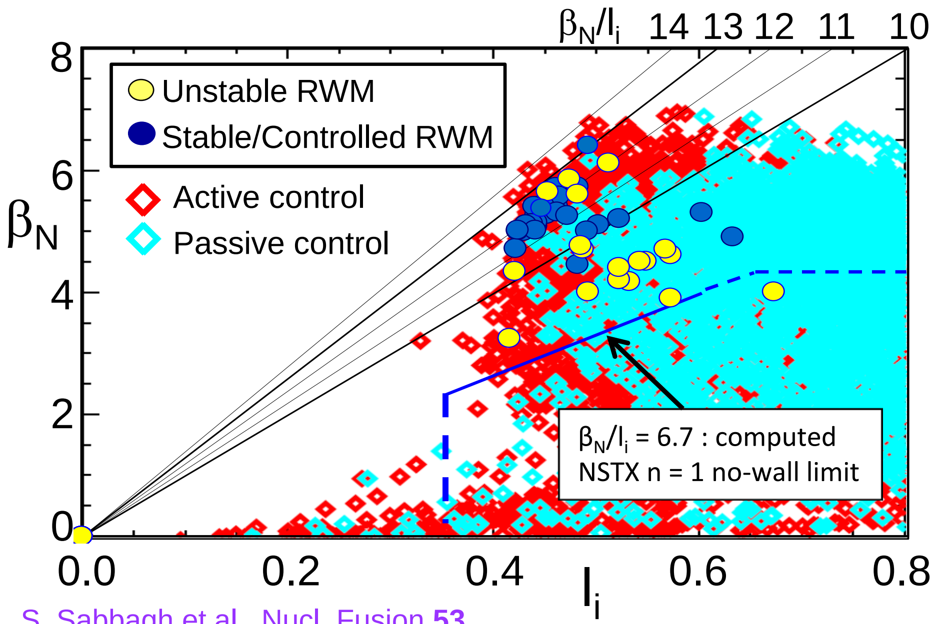
High priority research elements of recent Strategic Planning Meetings align strongly with NSTX-U Macro research

- Madison meeting:
  - Uniquely high level of consensus in critical Macrostability research areas including
    - Compact tokamak design (high field utilization)
    - Disruption-free (very low disruption rate)
    - Fully/highly non-inductive stable operation

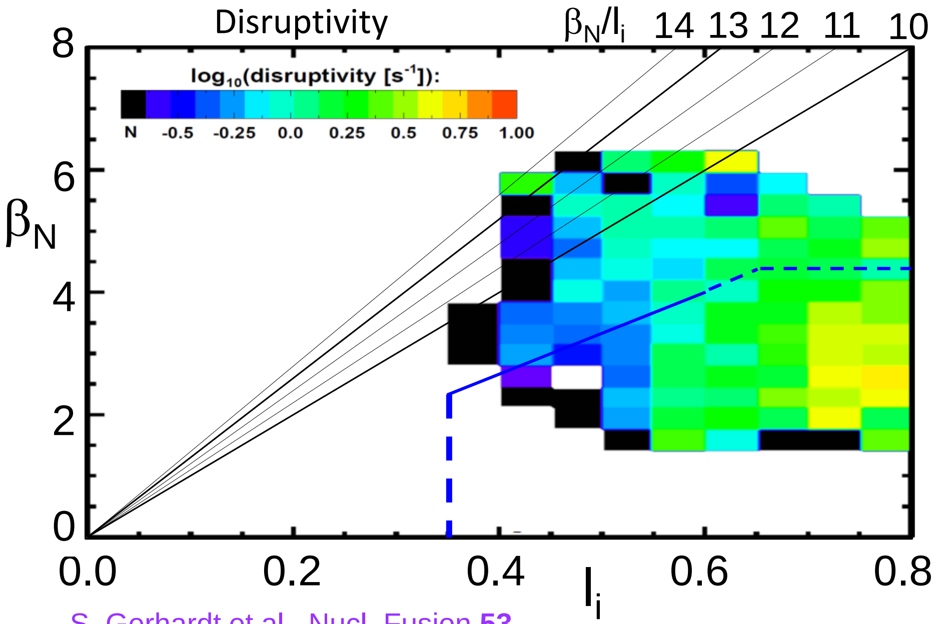
- Austin meeting:
  - Innovations stated (Working Group-SA3) align with NSTX-U research, including
    - Physics understanding of low A advantages
    - Disruption event characterization and forecasting
    - Disruption avoidance through profile, active mode control
    - Stability physics of self-consistent, fully/highly non-inductive operation

NSTX reaches uniquely high β_N, low l_i range of operation, and the highest β_N/l_i is *not* the least stable

Charge 2,3



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



S. Gerhardt et al., Nucl. Fusion **53**, 043020 (2013)

- Unique high β_N > 7, β_N/l_i > 14 reached!
  - In dedicated experiment (shown), disruptivity was higher at “intermediate” values of β_N/l_i
- In the larger database, disruptivity decreases at higher levels of β_N/l_i
  - ➔ Key MAST-U complementarity: physics of stability *without* stabilizing wall

Global mode stability forecasting: build from success of drift kinetic theory modification to MHD as a model

- Kinetic modification to ideal MHD

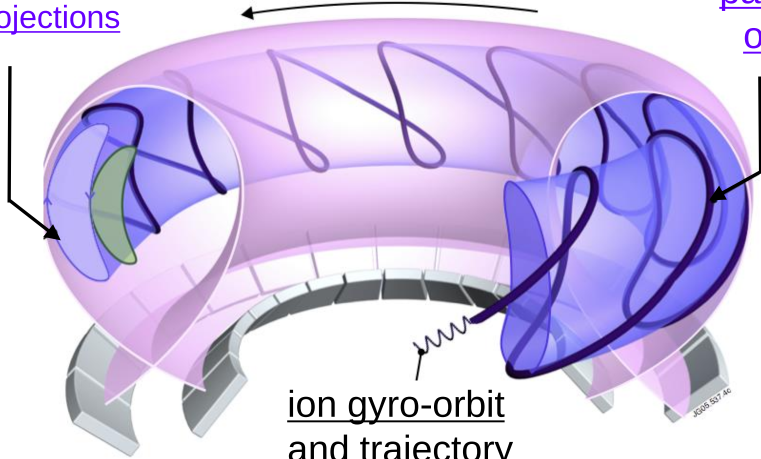
$$\gamma\tau_w = -\frac{\delta W_\infty + \delta W_K}{\delta W_{wall} + \delta W_K}$$

- Stability depends on
  - Trapped / circulating ions, electrons
  - Collisionality; Energetic particles
  - Integrated ω_ϕ profile matters!!! : broad rotation resonances in δW_K

plasma integral over particle energy

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

precession drift bounce collisionality ω_ϕ profile (enters in ω_E)



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

Just some references:

B. Hu, R. Betti, et al., PoP 12 (2005) 057301

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

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

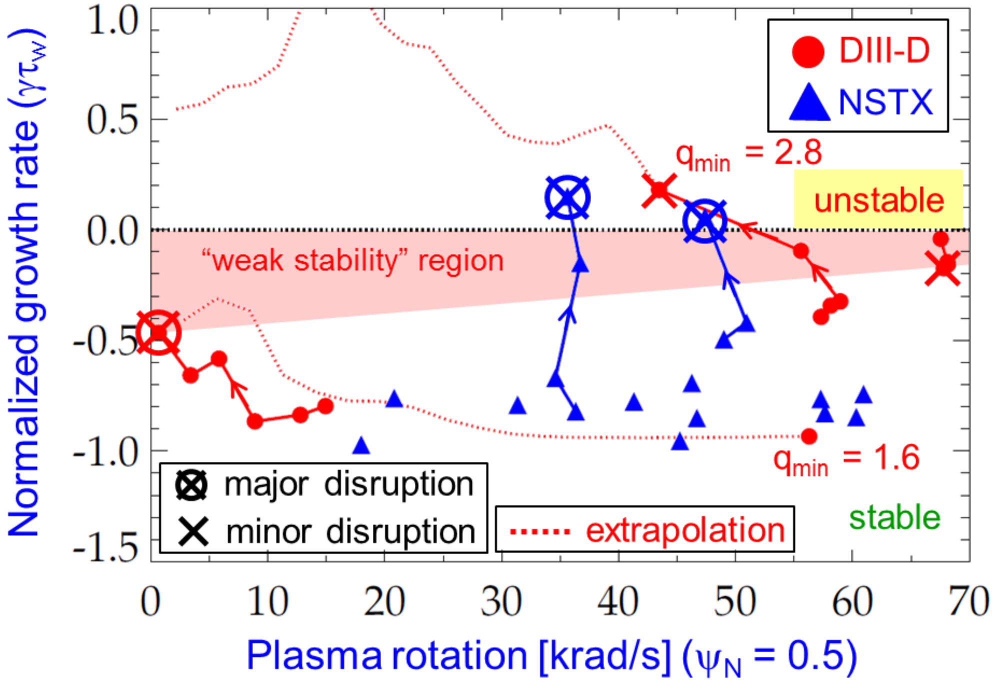
J. Berkery *et al.*, PRL **106** (2011) 075004

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

Kinetic RWM stability evaluated for DIII-D and NSTX plasmas, reproduces dedicated experiments over wide rotation range

- **Summary of results**
  - Plasmas free of other MHD modes can reach or exceed linear kinetic RWM marginal stability
  - Bursting MHD modes can lead to non-linear destabilization before linear stability limits are reached
  - Extrapolations of DIII-D plasmas to different V_ϕ show marginal stability is bounded by $1.6 < q_{min} < 2.8$

Kinetic RWM stability analysis for experiments (MISK)



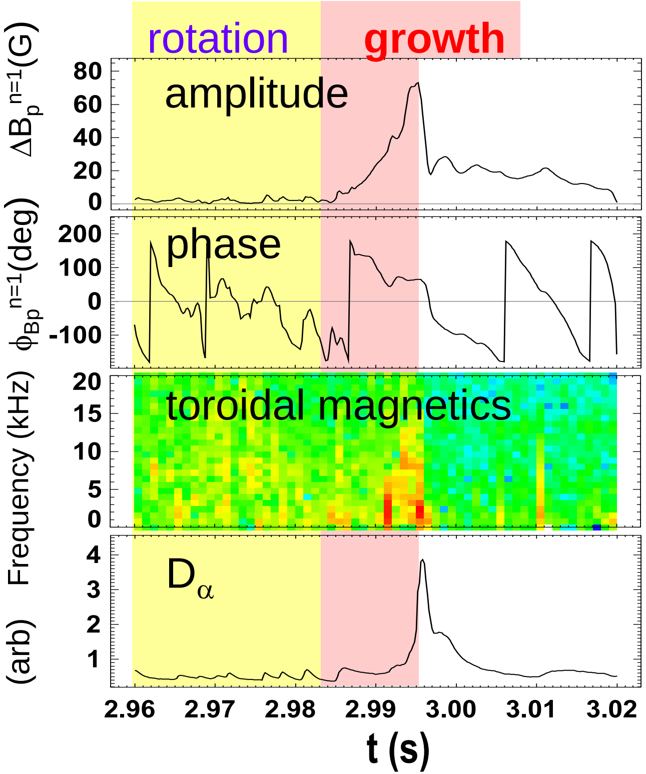
S. Sabbagh et al., APS Invited talk 2014

Charge 1

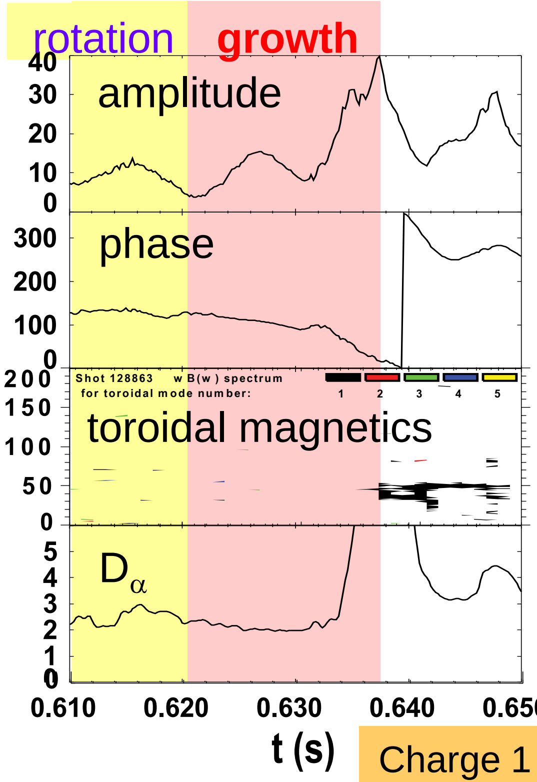
Joint NSTX / DIII-D experiments and analysis gives unified kinetic RWM physics understanding for disruption avoidance

- RWM Dynamics
  - RWM rotation and mode growth observed
  - No strong NTM activity
  - Some weak bursting MHD in DIII-D plasma
    - Alters RWM phase
  - No bursting MHD in NSTX plasma

DIII-D ($\beta_N = 3.5$)



NSTX ($\beta_N = 4.4$)



Charge 1

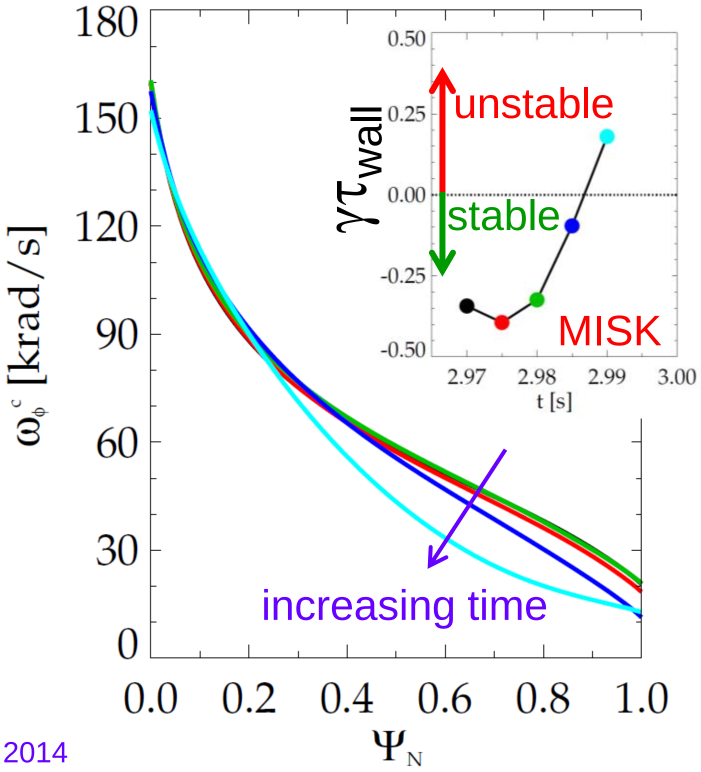
S. Sabbagh et al., APS Invited talk 2014

Evolution of plasma rotation profile leads to linear kinetic RWM instability as disruption is approached

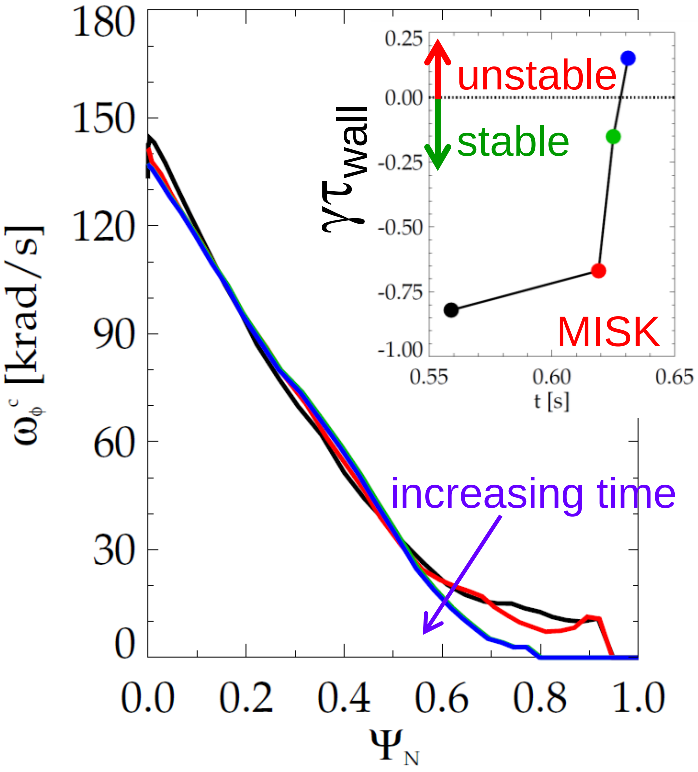
Charge 1

- Kinetic RWM stabilization occurs from broad resonances between plasma rotation and particle precession drift, bounce/circulating and collision frequencies

DIII-D (minor disruption)



NSTX (major disruption)



S. Sabbagh et al., APS Invited talk 2014

State space rotation controller designed for NSTX-U using non-resonant NTV and NBI to maintain stable profiles

Charge 2,3

- Momentum force balance – ω_ϕ decomposed into Bessel function states

$$\sum_i n_i m_i \langle R^2 \rangle \frac{\partial \omega}{\partial t} = \left(\frac{\partial V}{\partial \rho} \right)^{-1} \frac{\partial}{\partial \rho} \left[\frac{\partial V}{\partial \rho} \sum_i n_i m_i \chi_\phi \left\langle (R \nabla \rho)^2 \right\rangle \frac{\partial \omega}{\partial \rho} \right] + T_{NBI} + T_{NTV}$$

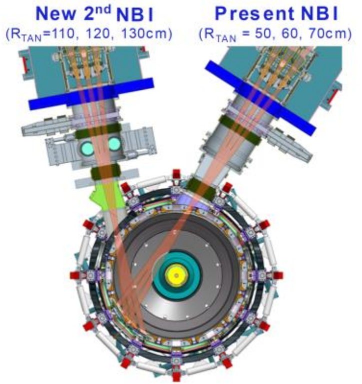
- NTV torque:

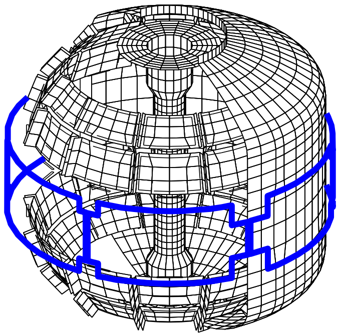
$$T_{NTV} \propto K \times f\left(n_{e,i}{}^{K1} T_{e,i}{}^{K2}\right) g\left(\delta B(\rho)\right) \left[I_{coil}{}^2 \omega \right] \quad \text{(non-linear)}$$

Momentum Actuators

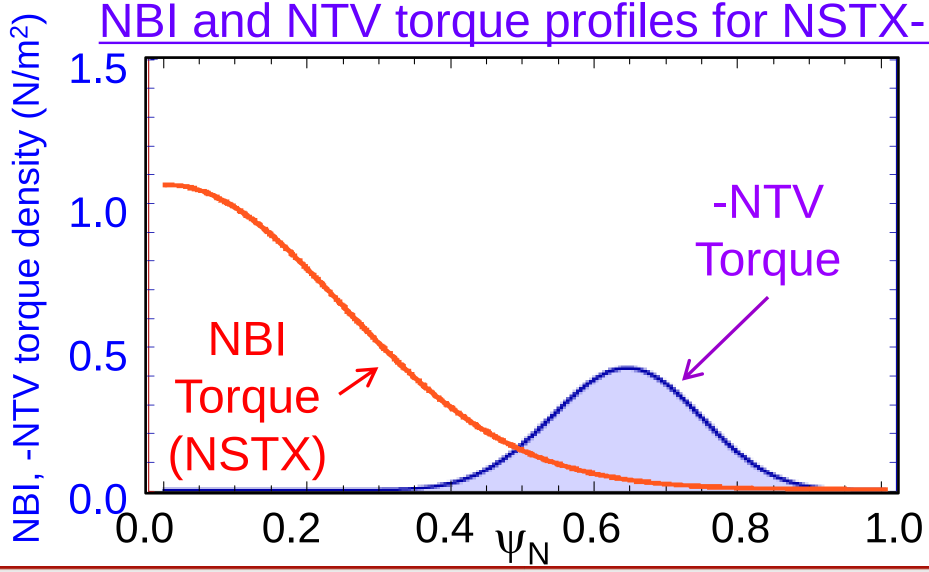
New NBI
(broaden rotation)

3D Field Coil
(shape ω_ϕ profile)





NBI and NTV torque profiles for NSTX-U



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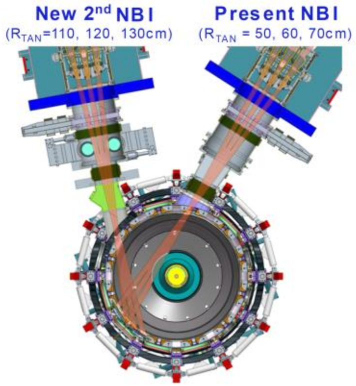
- NTV torque:

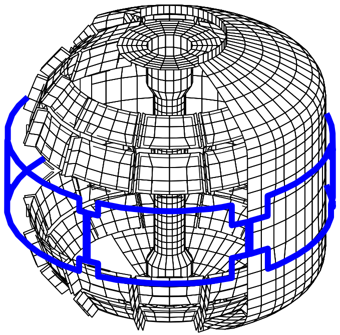
$$T_{NTV} \propto K \times f\left(n_{e,i}{}^{K1} T_{e,i}{}^{K2} \right) g\left(\delta B(\rho) \right) \left[I_{coil}{}^2 \omega \right]$$ (non-linear)

Momentum Actuators

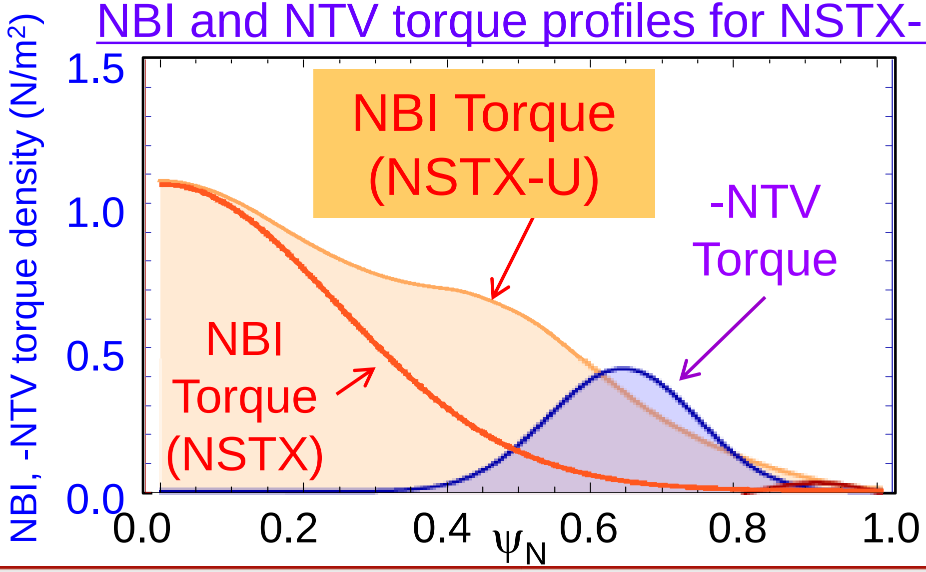
New NBI
(broaden rotation)



3D Field Coil
(shape ω_ϕ profile)

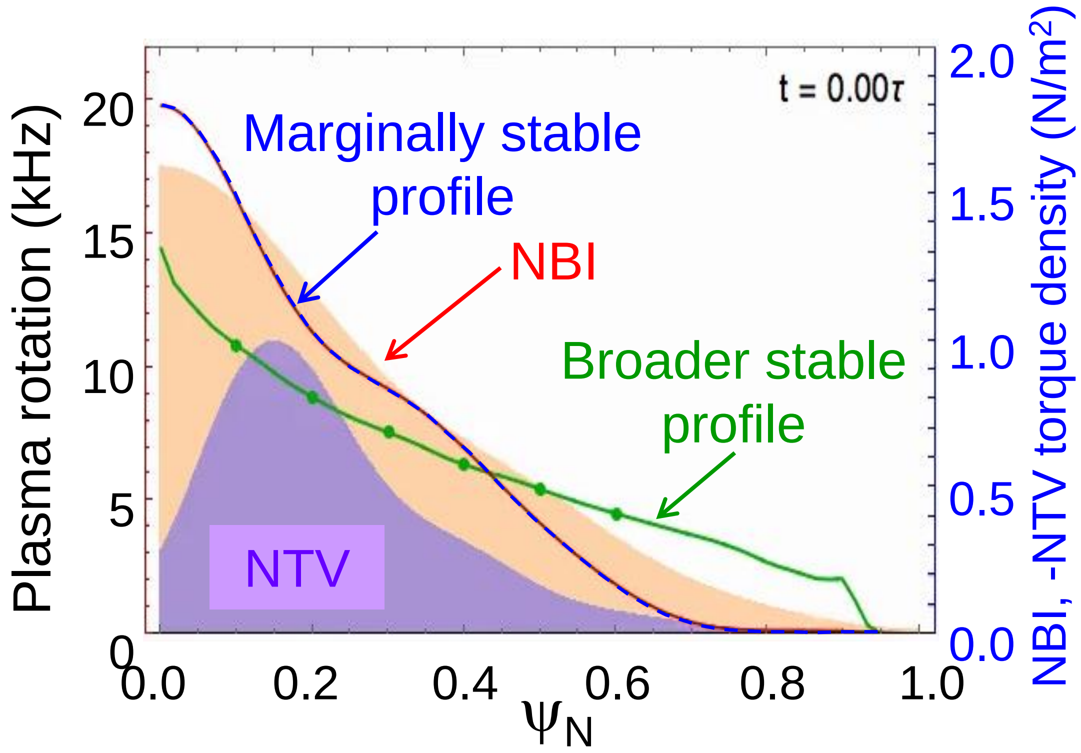


NBI and NTV torque profiles for NSTX-U



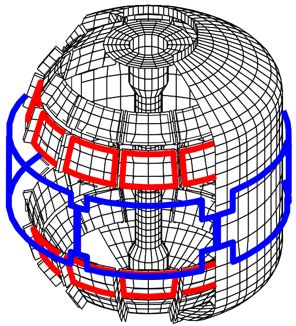
With planned NCC coil upgrade, rotation controller can reach desired rotation profile faster, with greater fidelity

Charge 2,3



- NSTX-U ω_ϕ control with
  - 6 NBI sources
  - Greater core NTV from planned NCC upgrade
- Better performance
  - Faster to target t ~ $0.5\tau_m$
  - Matches target ω_ϕ better

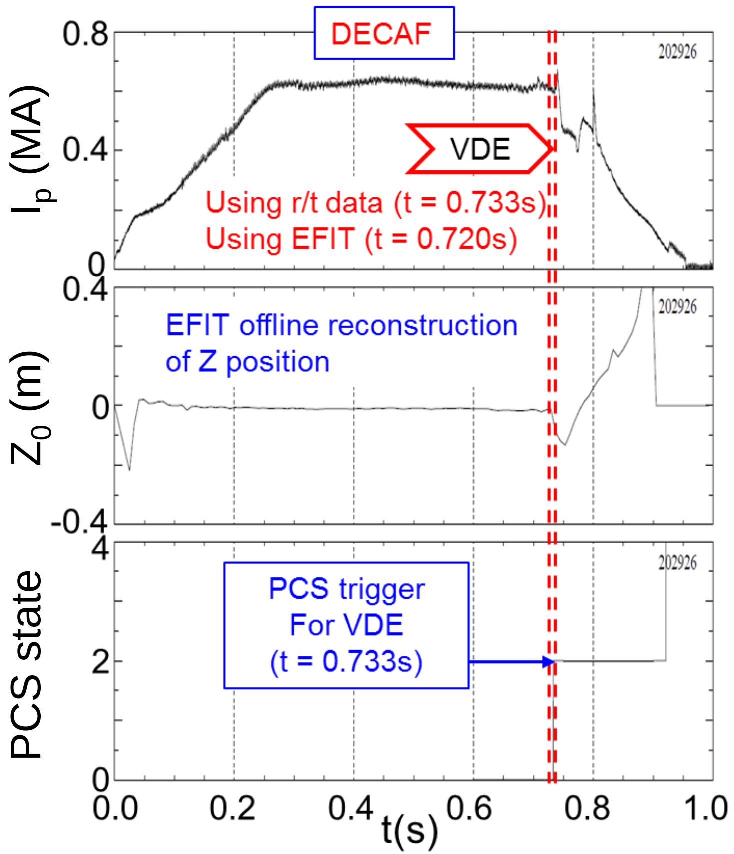
Planned NCC upgrade



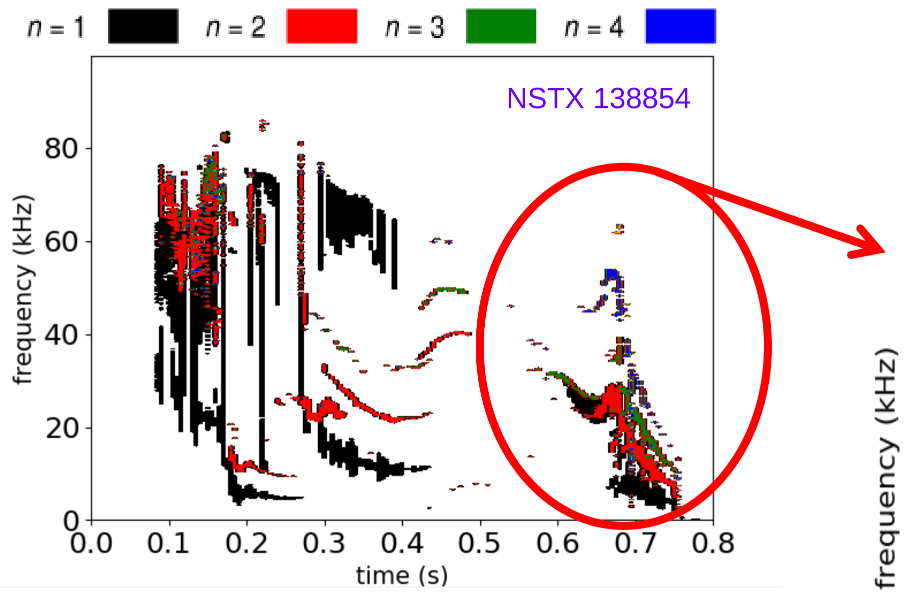
- Also, calculations show that NCC can allow RWM control up to ideal MHD wall limit

DECAF replicates the triggers found in new real-time plasma shutdown / event handler capability of NSTX-U

- Important capability of DECAF: compare analysis using offline vs. real-time data
- Plasma Shutdown Handler conditions are analogous to DECAF events
  - Control system loss of vertical control ➔ DECAF VDE
- DECAF comparison: VDE event
  - Matches Plasma Control System when r/t signal is used (1 criterion)
  - VDE event 13 ms earlier using offline EFIT signals (3 criteria: Z_0, dZ_0/dt, $Z_0 \times dZ_0/dt$)

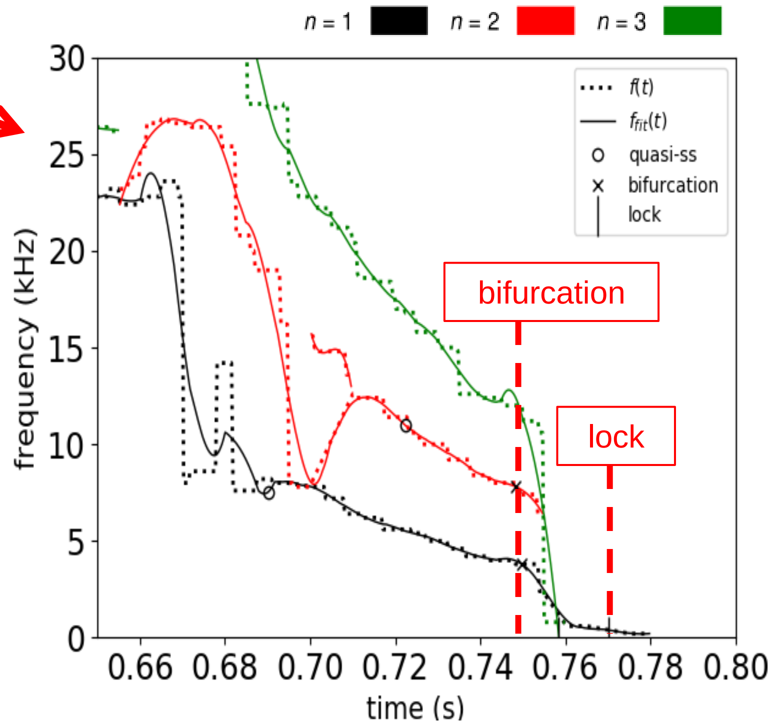


Automated identification of MHD mode bifurcation and locking recently developed for the DECAF code



Zoomed-in View

Charge 3,4

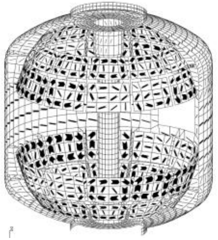


- Required capability to automatically analyze ubiquitous rotating MHD
- Code is completely portable, kept fairly simple, potential future real-time processing

Physics-based RWM state-space controller sustains high β_N, low l_i plasma; NSTX-U with allow independent coil control

Charge 2,3

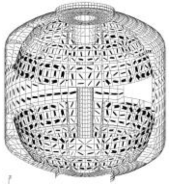
Full 3-D model ~3000+ states



Balancing transformation

State reduction (< 20 states)

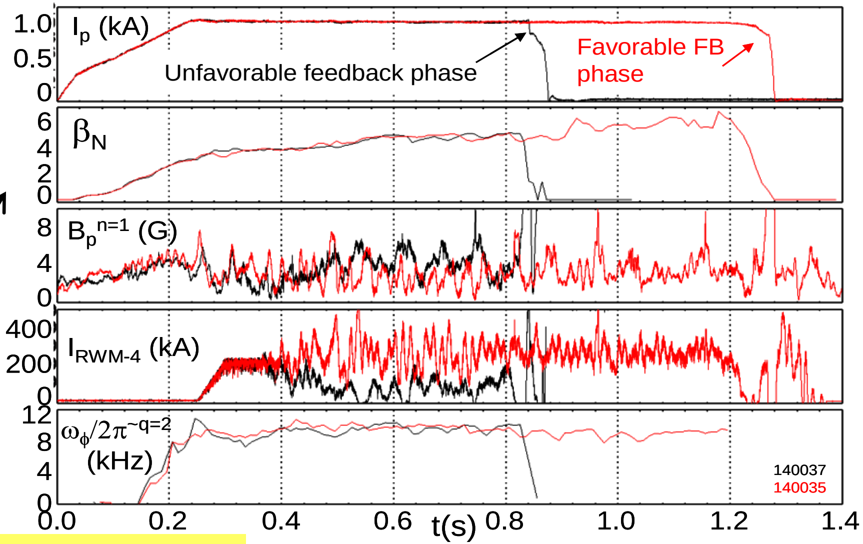
RWM eigenfunction (2 phases, 2 states) $(\hat{x}_1, \hat{x}_2)$ +



+ $\hat{x}_3$

$\hat{x}_4$ …

- Controller model compensates wall currents
  - Includes plasma mode-induced current model (DCON)
  - Potential to allow control coils to be moved further from plasma and be shielded (e.g. ITER)
- Straightforward inclusion of multiple modes in controller



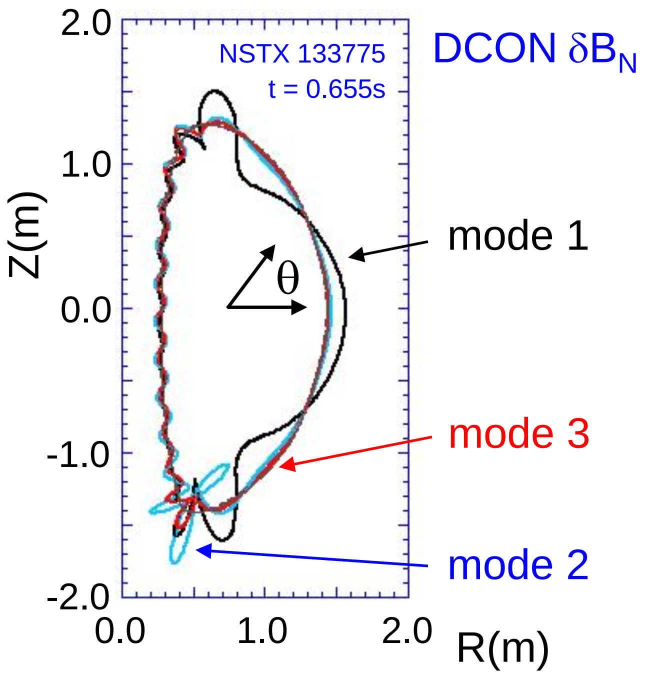
➔ USED on NSTX to sustain high β_N > 6 operation

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

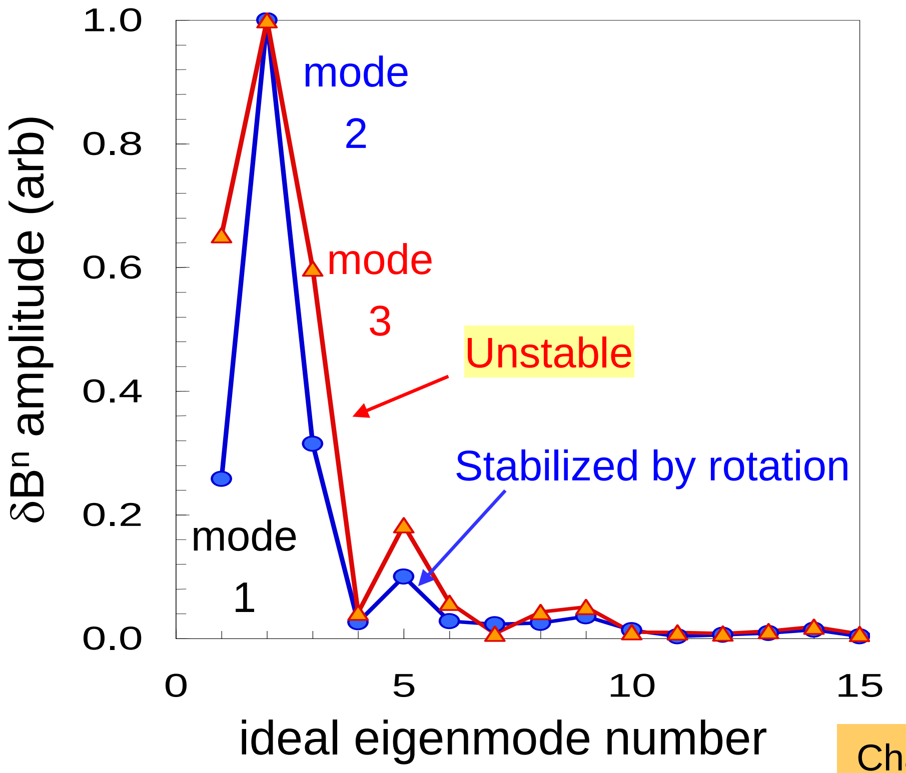
High β_N ST global eigenmodes have unique shape, multi-mode character; computed 2^{nd} eigenmode component has dominant amplitude

Computed n = 1 eigenmodes

(β_N = 6.1)



δB^n RWM multi-mode composition



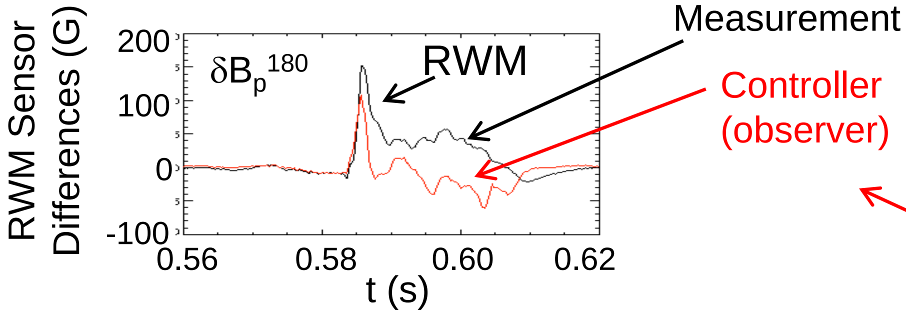
mmVALEN code

Charge 2,3

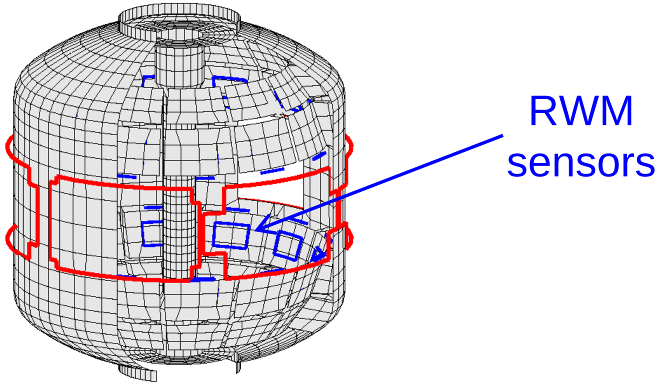
In addition to active mode control, the NSTX-U RWM state space controller will be used for real-time disruption warning

- RWM state space controller used for RWM control in NSTX - long pulse plasmas reached high stability parameters $\beta_N = 6.4$, $\beta_N / l_i = 13$

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



- The controller "observer" produces a physics model-based calculation of the expected sensor measurements – a real-time synthetic diagnostic

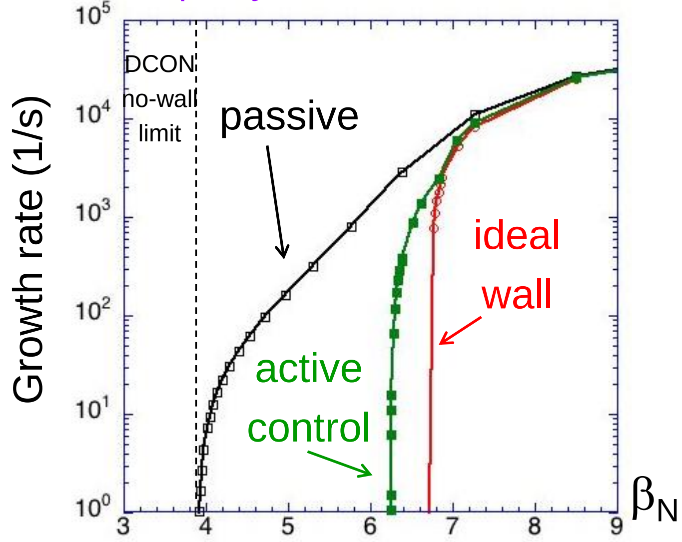


- If the real-time synthetic diagnostic poorly matches the measured sensor data, a real-time disruption warning signal can be triggered
  - Technique will be assessed using the DECAF code

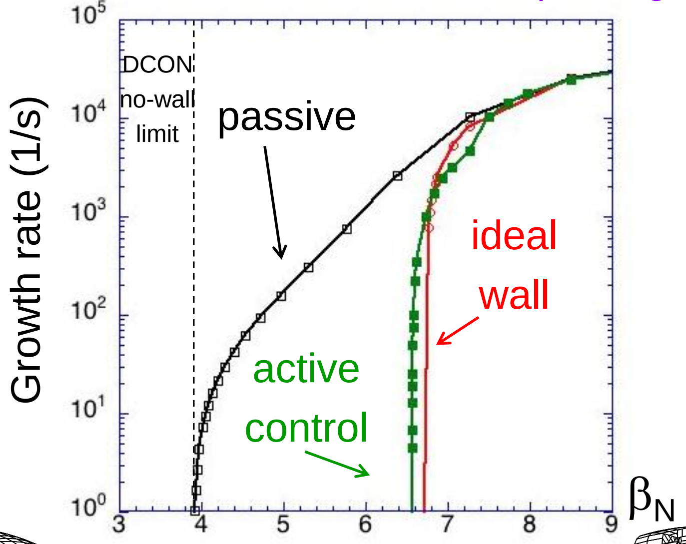
Charge 2,3

Active RWM control design study for proposed NSTX-U 3D coil upgrade (NCC coils) shows superior capability up to ideal wall limit

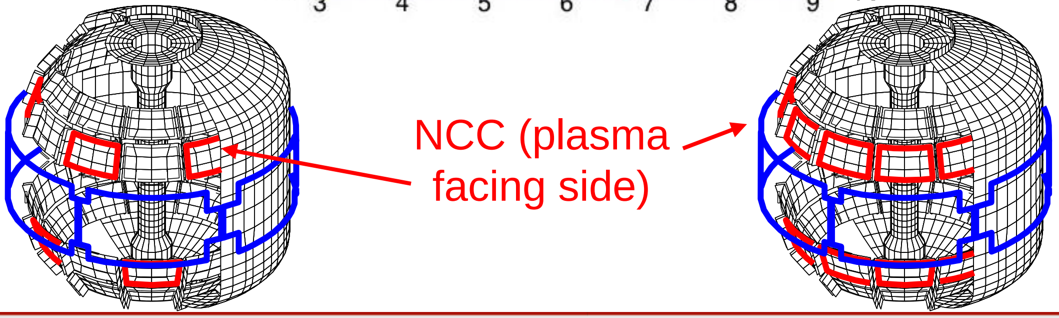
NCC 2x6 odd parity, with favorable sensors



NCC 2x12 with favorable sensors, optimal gain



- Full NCC coil set allows control close to ideal wall limit
  - NCC 2x6 odd parity coils: active control to $\beta_N/\beta_N^{no\text{-}wall} = 1.58$
  - NCC 2x12 coils, optimal sensors: active control to $\beta_N/\beta_N^{no\text{-}wall} = 1.67$

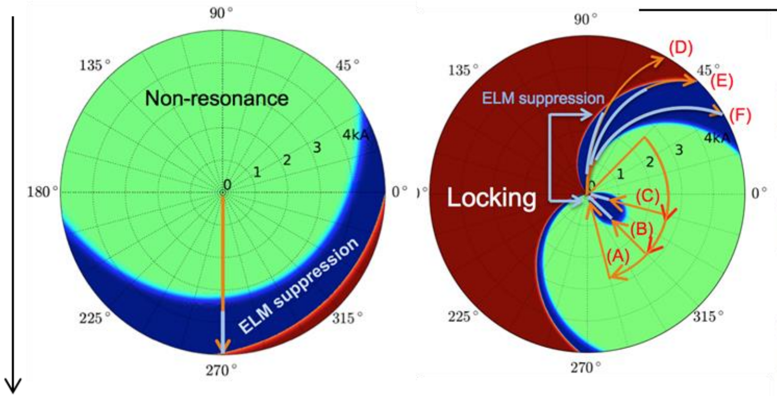


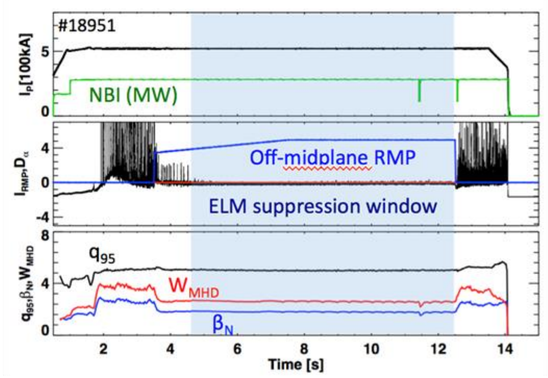
Successful predicition of RMP optimization with partial coil sets and for new targets in 2017 KSTAR campaign

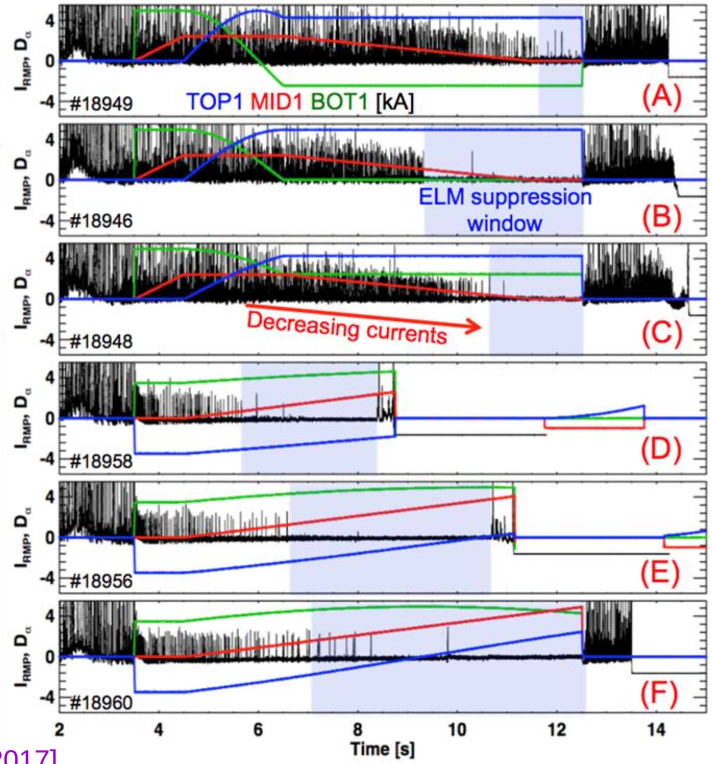
Charge 1, 3

First off-midplane n=1 RMP

RMP optimization for 2017 KSTAR



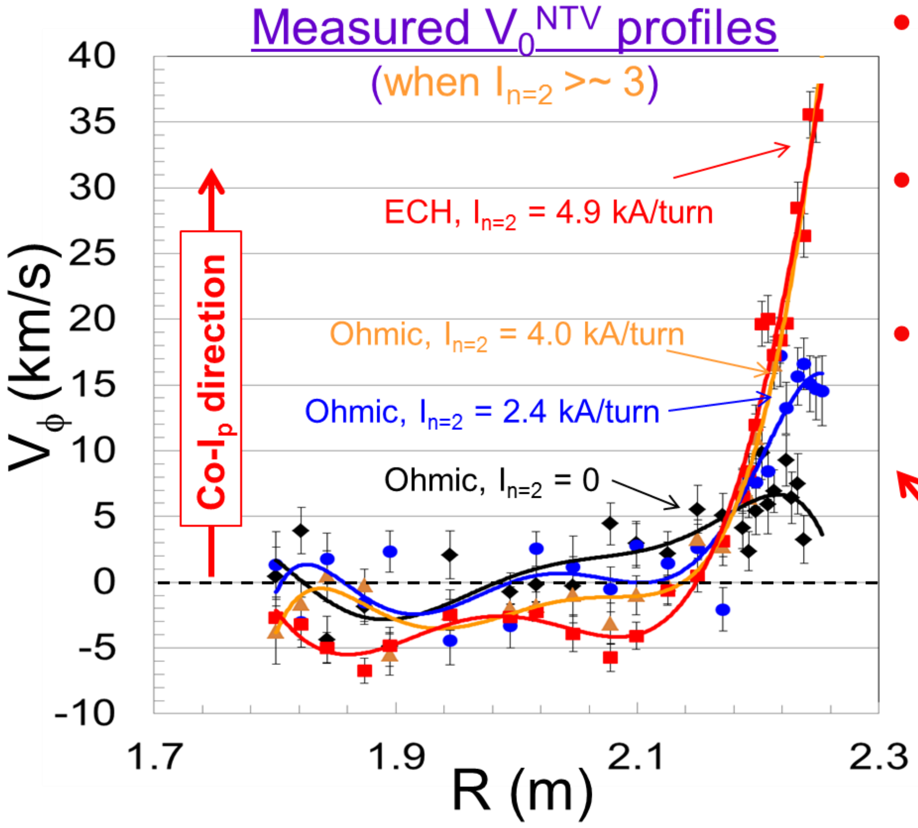




[J.K. Park, KSTAR 2017]

Generalized Neoclassical Toroidal Viscosity (NTV) Offset rotation profile V_0^{NTV} measured in KSTAR

Charge 1, 3



- Co-I_p rotation generated
  - First time co-I_p rotation by NTV directly measured
- Co-I_p direction of V_0^{NTV} consistent w/ dominance of electron channel
- Potential aid for ITER
  - ITER simulations: $\Omega_\phi \sim$ 2 krad/s in outer region
  - Recent KSTAR result: $\Omega_\phi >$ 12 krad/s in outer region
  - Also, 15 times stronger rotation shear generated with applied 3D field

➔ Initially proposed on NSTX-U, potential for joint experiment/analysis with KSTAR

(S.A. Sabbagh, Y.S. Park, J. Kim, W. Ko, et al.)