Global MHD Mode Stabilization and Control for Tokamak Disruption Avoidance

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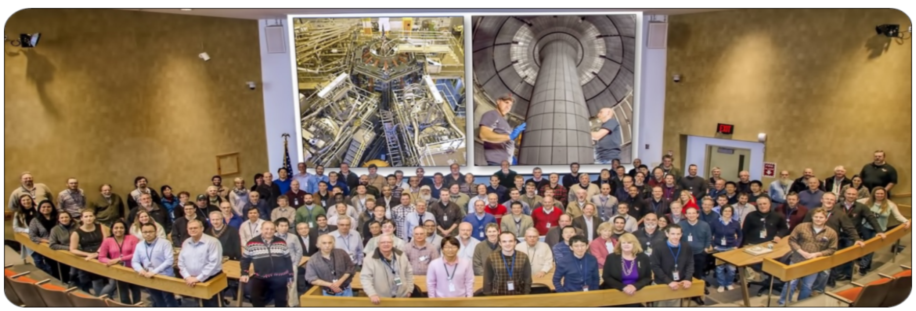
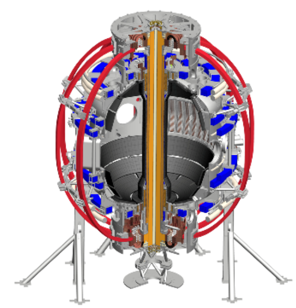




Disruption avoidance is a critical need for future tokamaks; NSTX-U is focusing stability research on this

- The new "grand challenge" in tokamak stability research
  - Can be done! (JET: < 4% disruptions w/C wall, < 10% w/ITER-like wall)
    - ITER disruption rate: < 1 - 2% (energy load, halo current); << 1% (runaways)

- Strategic plan: utilize/expand stability/control research success
  - Synergize and build upon disruption prediction and avoidance successes attained in present tokamaks

- FESAC 2014 Strategic Planning report defined "*Control of Deleterious Transient Events*" highest priority (Tier 1) initiative

- NSTX-U will allow focused research on disruption prediction and avoidance with quantitative measures of progress

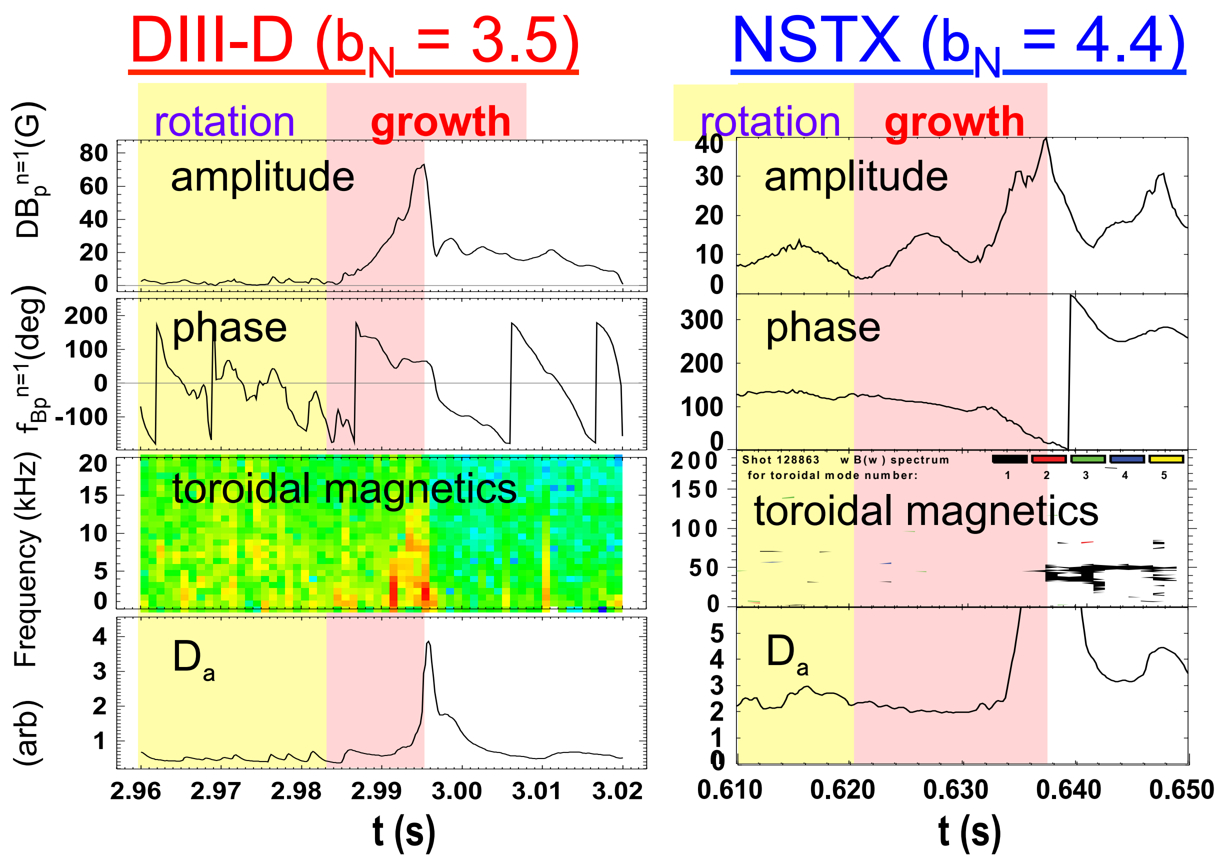
Research in today's presentation is part of NSTX-U's evolving capabilities for disruption prediction/avoidance

Sensor/predictor (CY available)	Control/Actuator (CY available)
Low frequency MHD (n=1,2,3): 2003	Dual-component RWM sensor control (closed loop: 2008)
Low frequency MHD spectroscopy (open loop: 2005)	Control of β_N (closed loop: 2007)
r/t RWM state-space controller observer (2010)	Physics model-based RWM state-space control (2010)
Real-time rotation measurement (2016)	Plasma rotation control (NTV rotation control open loop: 2003) (+NBI closed loop ~ 2017)
Kinetic RWM stabilization initial real-time model (2016-17)	Safety factor control (closed loop ~ 2016-17)
MHD spectroscopy (real-time) (in NSTX-U 5 Year Plan)	Upgraded 3D coils (NCC) (in NSTX-U 5 Year Plan)

- +New Disruption Event Characterization and Forecasting code, initial results

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



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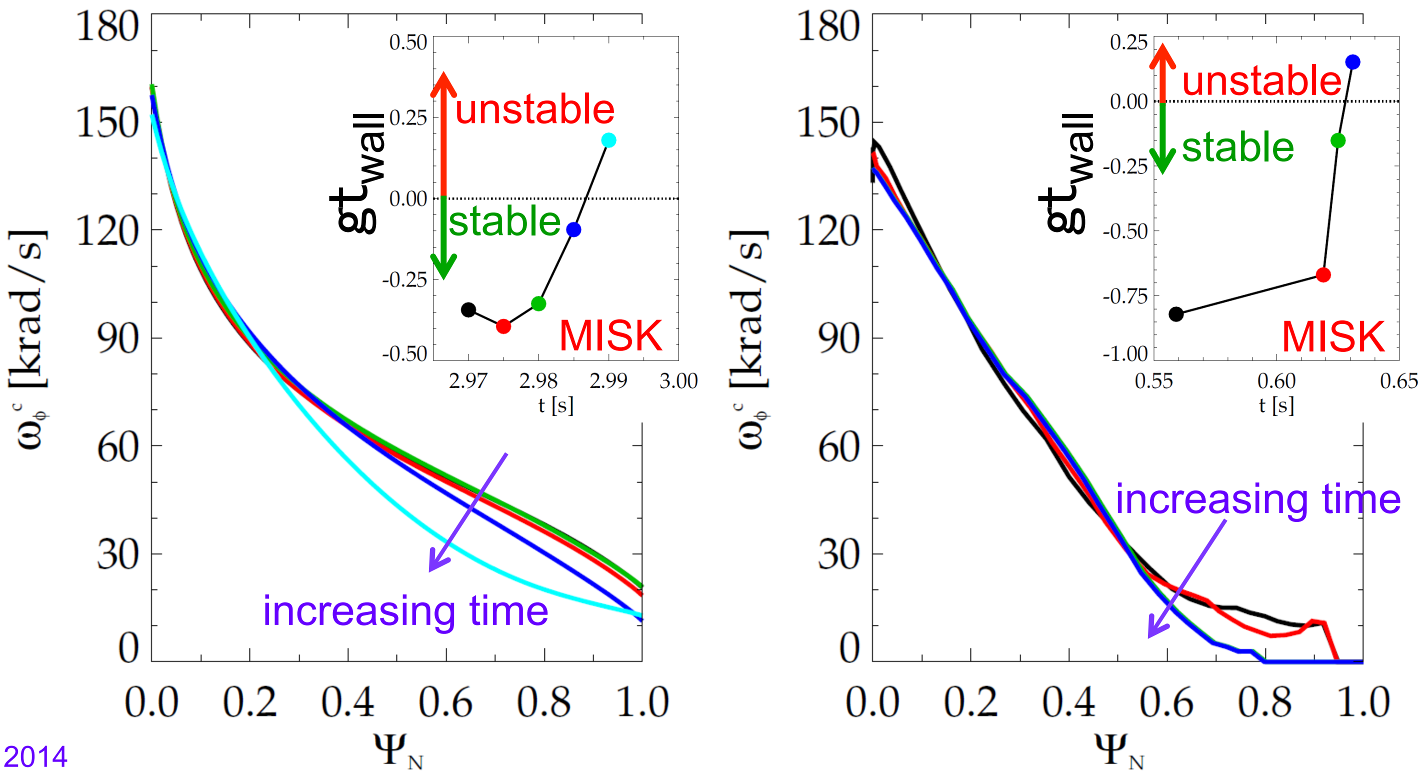
Evolution of plasma rotation profile leads to linear kinetic RWM instability as disruption is approached

- 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)



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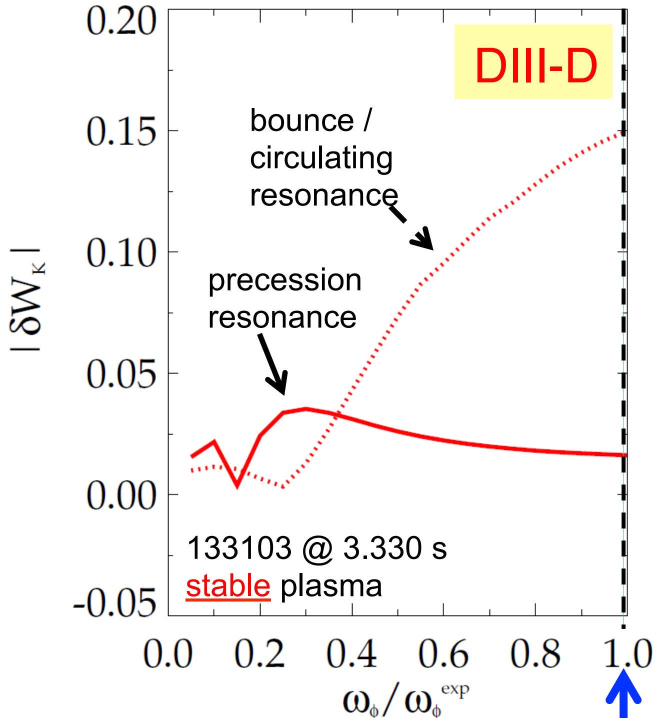
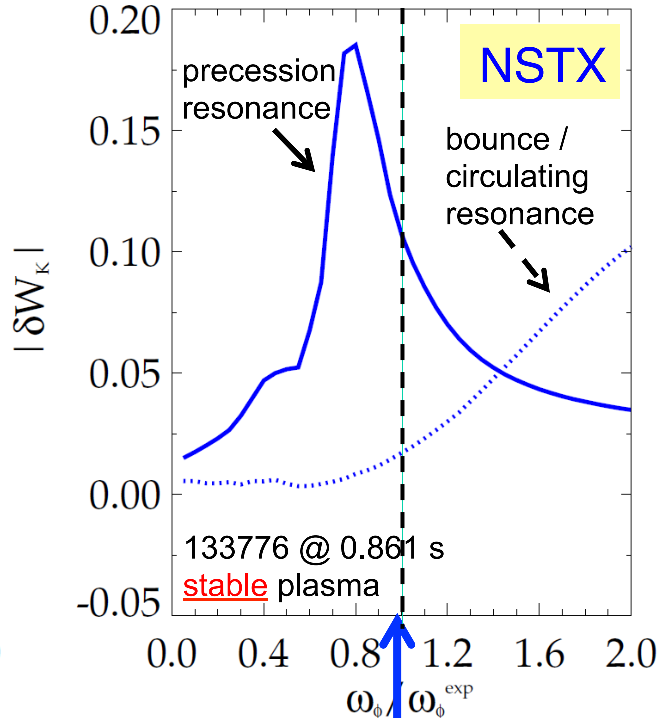
Bounce resonance stabilization dominates for DIII-D vs. precession drift resonance for NSTX at similar, high rotation

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



DIII-D experimental rotation profile



NSTX experimental rotation profile

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 and NBI to maintain stable profiles

- Momentum force balance – w_f decomposed into Bessel function states

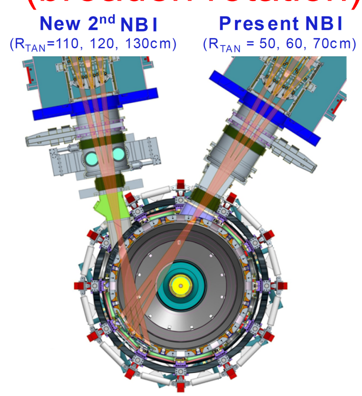
$$\sum_i n_i m_i \langle R^2 \rangle \frac{\partial \omega}{\partial t} = \left(\frac{\partial V}{\partial \rho}\right)^{-1} \frac{\partial}{\partial \rho}\left[\frac{\partial V}{\partial \rho} \sum_i n_i m_i \chi_\phi \left\langle (R \nabla \rho)^2 \right\rangle \frac{\partial \omega}{\partial \rho}\right]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

- NTV torque:

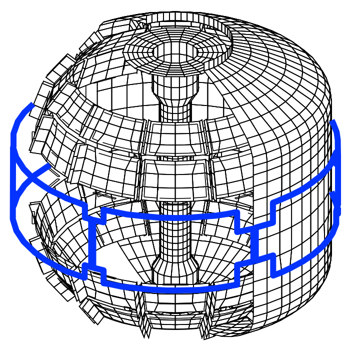
$$T_{NTV} \propto K \times f\left(n_{e,i}^{K1} T_{e,i}^{K2}\right) g\left(\delta B(\rho)\right)\left[I_{coil}^{2} \omega\right] \quad \text{(non-linear)}$$

Momentum Actuators

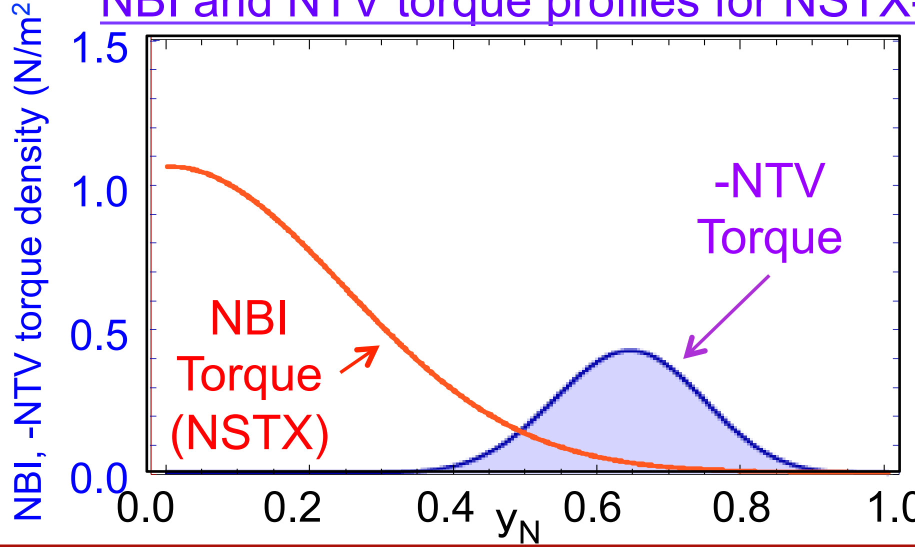
New NBI (broaden rotation)



3D Field Coil (shape w_f profile)



NBI and NTV torque profiles for NSTX-U



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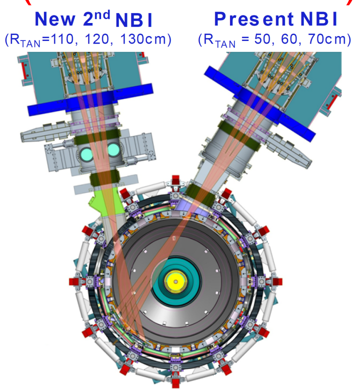
Momentum Actuators

New NBI (broaden rotation)



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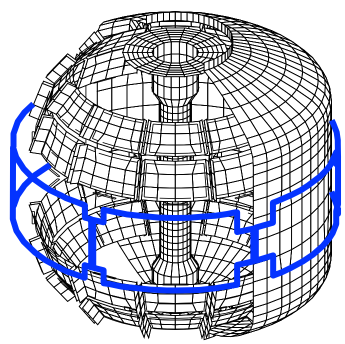

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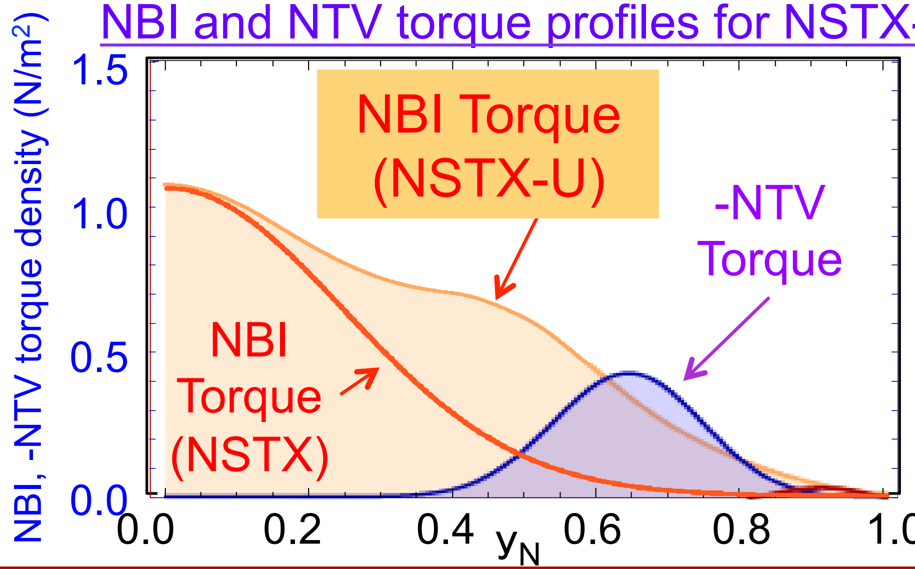
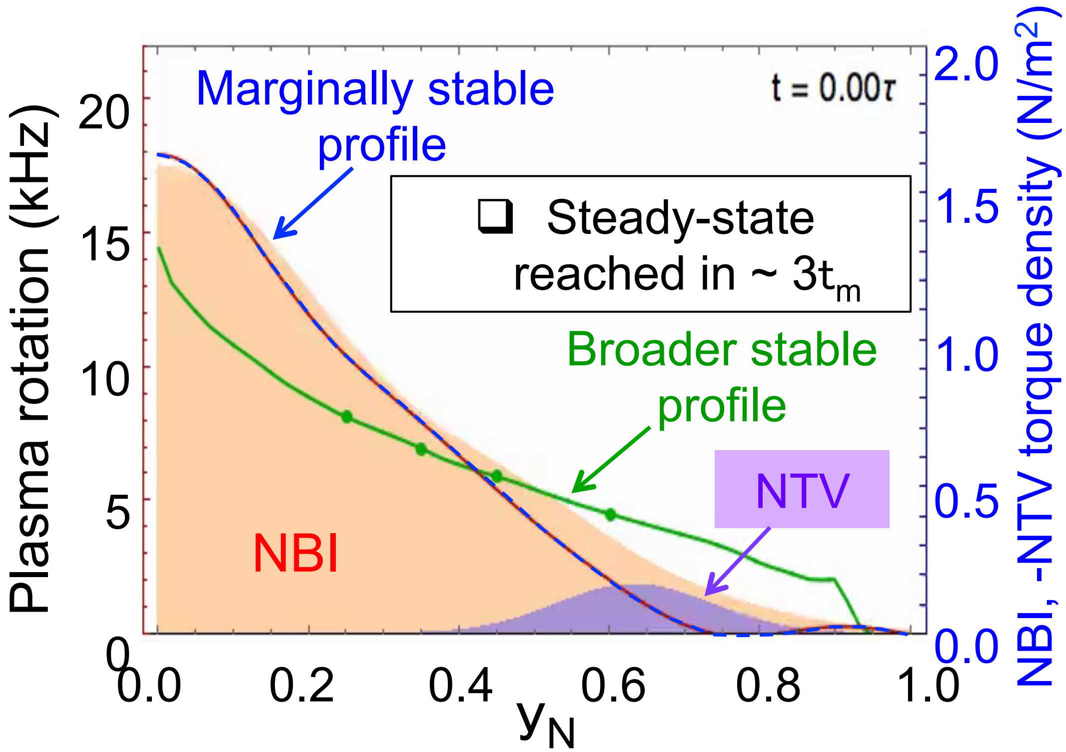
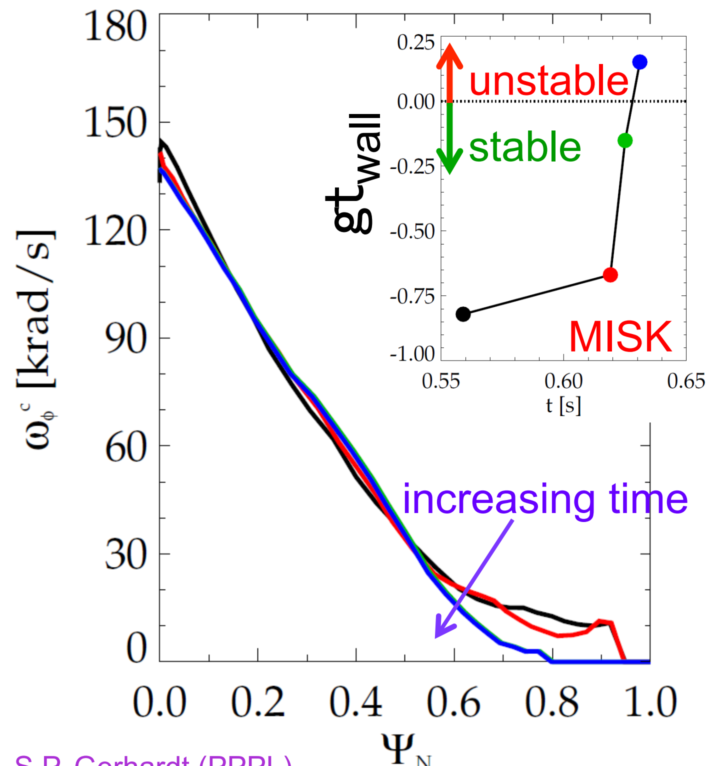


State space rotation controller designed for NSTX-U can evolve plasma rotation profile toward global mode stability

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

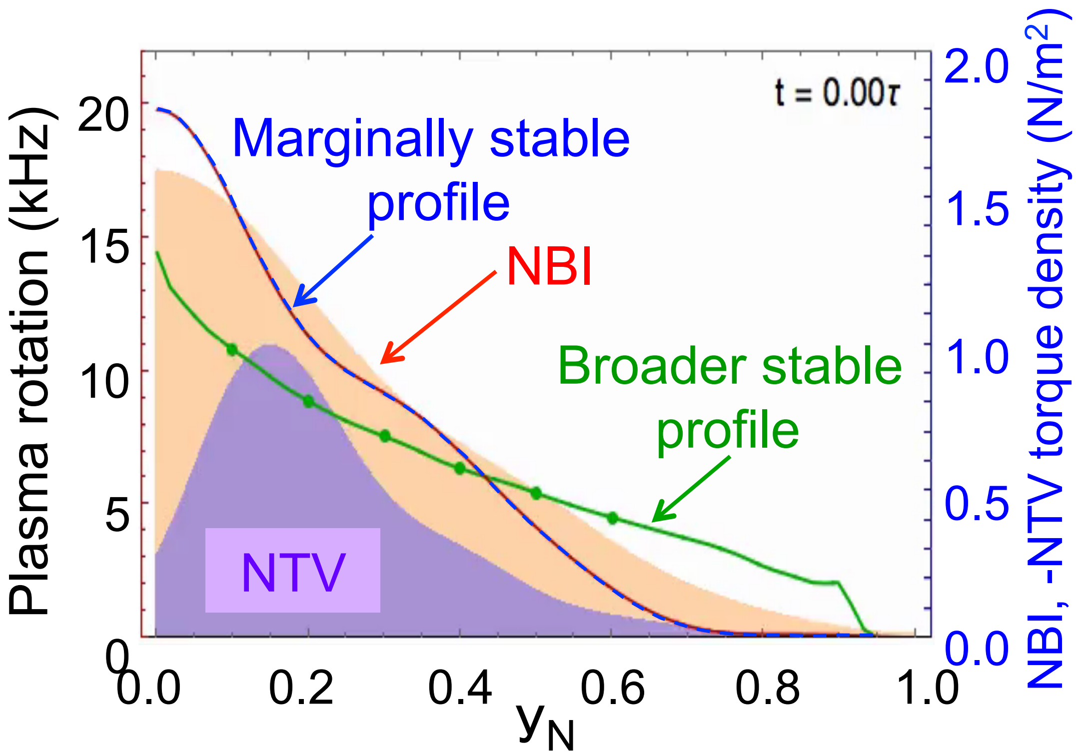


Recall: NSTX (major disruption)



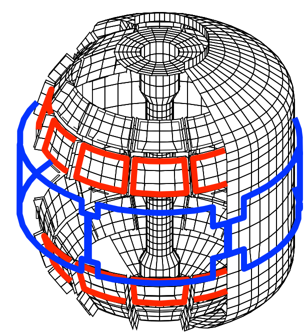
I. Goumiri (Princeton student), S.A. Sabbagh (Columbia U.), C. Rowley (P.U.), D.A. Gates, S.P. Gerhardt (PPPL)

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



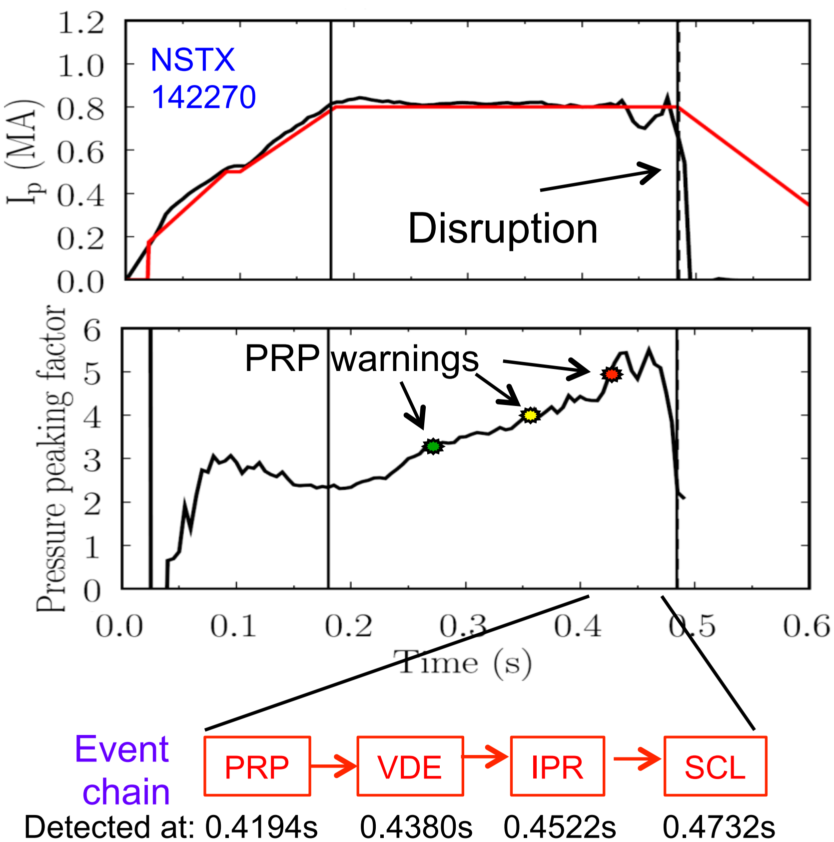
- NSTX-U w_f control with
  - 6 NBI sources
  - Greater core NTV from planned NCC upgrade
- Better performance
  - Faster to target t ~ 0.5t_m
  - Matches target w_f better

Planned NCC upgrade



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

Disruption Event Characterization And Forecasting Code (DECAF) yielding initial results (pressure peaking example)



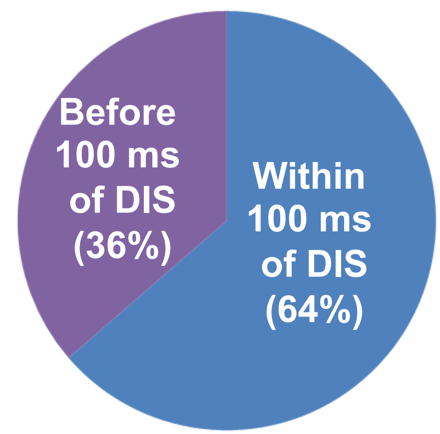
- 10 physical events presently defined in code with quantitative warning points
  - Builds on characterization work of de Vries
    P.C. de Vries *et al*., Nucl. Fusion **51** (2011) 053018
  - Builds on warning algorithm of Gerhardt
    S.P. Gerhardt *et al*., Nucl. Fusion **53** (2013) 063021
  - New code written (in Python) to be easily expandable, portable to other tokamaks

- Example: Pressure peaking (PRP) disruption event chain identified by code
  1. (PRP) Pressure peaking warnings identified first
  2. (VDE) VDE condition subsequently found 19 ms after last PRP warning
  3. (IPR) Plasma current request not met
  4. (SCL) Shape control warning issued

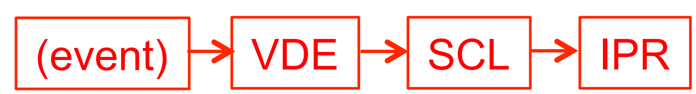
Initial DECAF results detect RWM events when applied to dedicated 44 shot NSTX disruption database

- Several events were detected for all shots
  - DIS: Disruption occurred
  - RWM: RWM event warning
  - VDE: VDE warning (42 shots)
  - IPR: Plasma current request not met
  - LOQ: Low edge q warning
- Very simple RWM event criteria
  - RWM $B_P^{n=1}$ lower sensor amplitude used
  - Simple criterion + no threshold optimization yet ➔ "false positive" rate is high; adjust criteria to reduce it
- Code already sees common disruption event chains
  - (event)➔VDE➔SCL➔IPR occurs in 52% of the shots

RWM event warning timing
(simple criterion, not optimized)



Common event chain

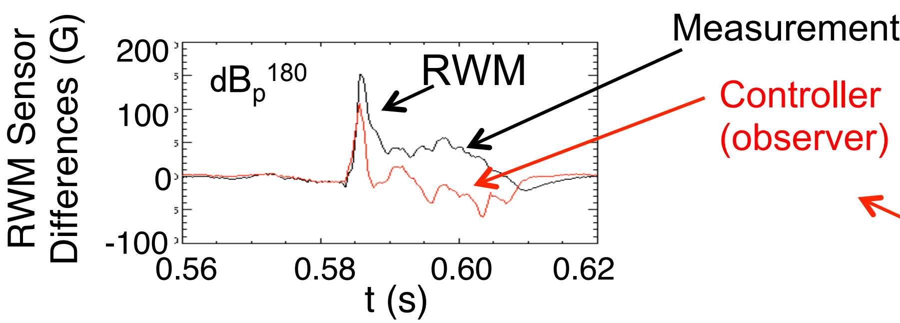


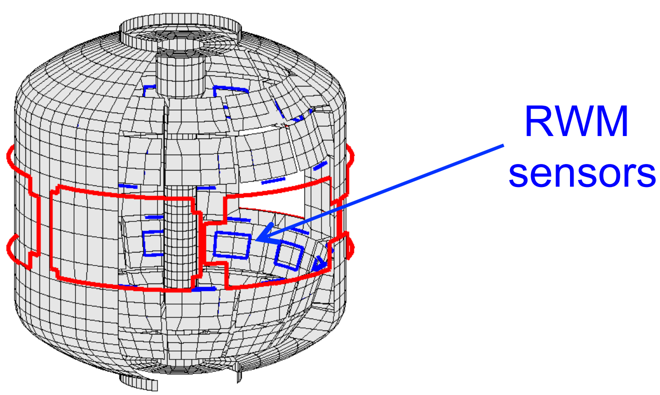
Also see poster by **M. Parsons PP12.00118 (Wed 2 pm)** for related work on supervised machine learning for disruption prediction

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 b_N = 6.4, b_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

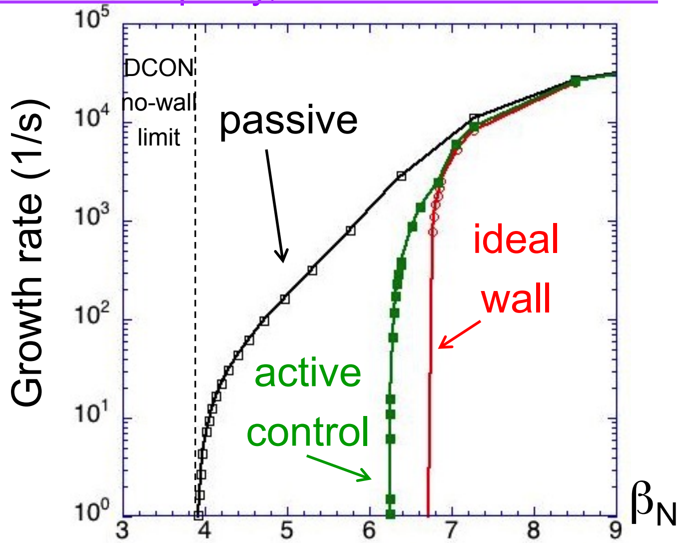
Global MHD mode stabilization understanding and control will synergize in NSTX-U for disruption avoidance

- Physics Understanding
  - Unification of DIII-D / NSTX experiments and analysis gives improved RWM understanding for disruption avoidance
  - Complementarity found: at similar high rotation, kinetic RWM stabilization physics is dominated by bounce orbit resonance in DIII-D, and by ion precession drift resonance in NSTX
  - Disruption Event Characterization and Forecasting code initial results identify RWM events and disruption event chains
- Stability Control
  - Rotation profile control has potential to steer away from unstable profiles
  - Model-based active RWM state-space controller can also be used as synthetic diagnostic for disruption warning
  - Further improvements to rotation profile control, active mode control possible with planned NCC 3D coil upgrade

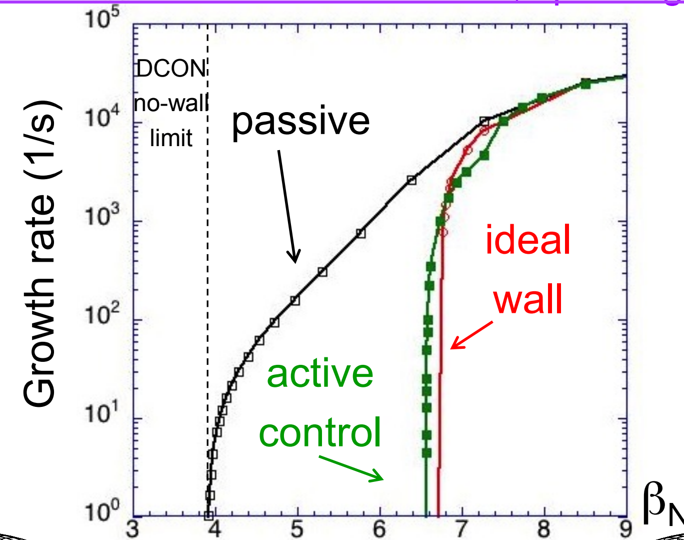
Supporting slides follow

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 $b_N/b_N^{no\text{-}wall} = 1.58$
  - NCC 2x12 coils, optimal sensors: active control to $b_N/b_N^{no\text{-}wall} = 1.67$