NSTX-U

Supported by U.S. DEPARTMENT OF ENERGY Office of Science

NSTX-U Columbia U. Group Research Plan Summary (2014-2018)

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NSTX-U Collaborator Research Plan Meeting
PPPL – LSB B318
May 5, 2014

Coll of Wm & Mary
Columbia U
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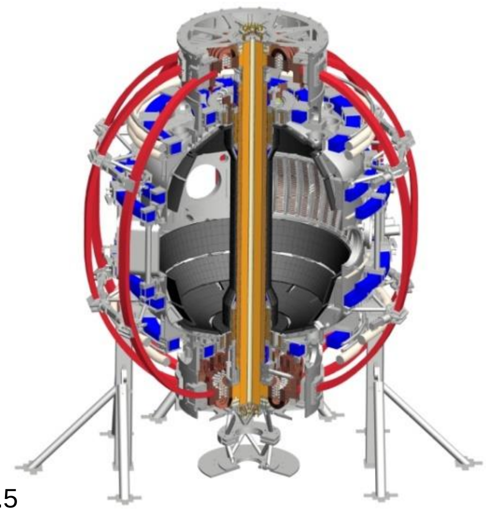

Culham Sci Ctr
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V1.5

Columbia U. Group research plan for NSTX-U aims at mode control for disruption prediction / avoidance

- Physics areas as written in DOE proposal
  1. Global mode active control
     - Model based RWM state-space active control, use of observer for disruption avoidance, comparison to PID, internal mode control scopic study, etc.
  2. Global mode stabilization at low collisionality
     - Test kinetic RWM theory at low ν, maintain stability, etc.
  3. Applied NTV research and physics-based rotation control
     - NTV dependence on ν, NTV offset, application to rotation control to avoid beta-limiting instabilities (incl. at low V_ϕ)
  4. RFA and MHD spectroscopy for disruption avoidance
     - Including simple models to be used in real-time
  5. NCC physics design and usage for disruption control

Disruption categorization (NSTX database)

- % Having strong low frequency n = 1 magnetic precursors
  ➔ 55%
- % Associated with large core rotation evolution
  ➔ 46%

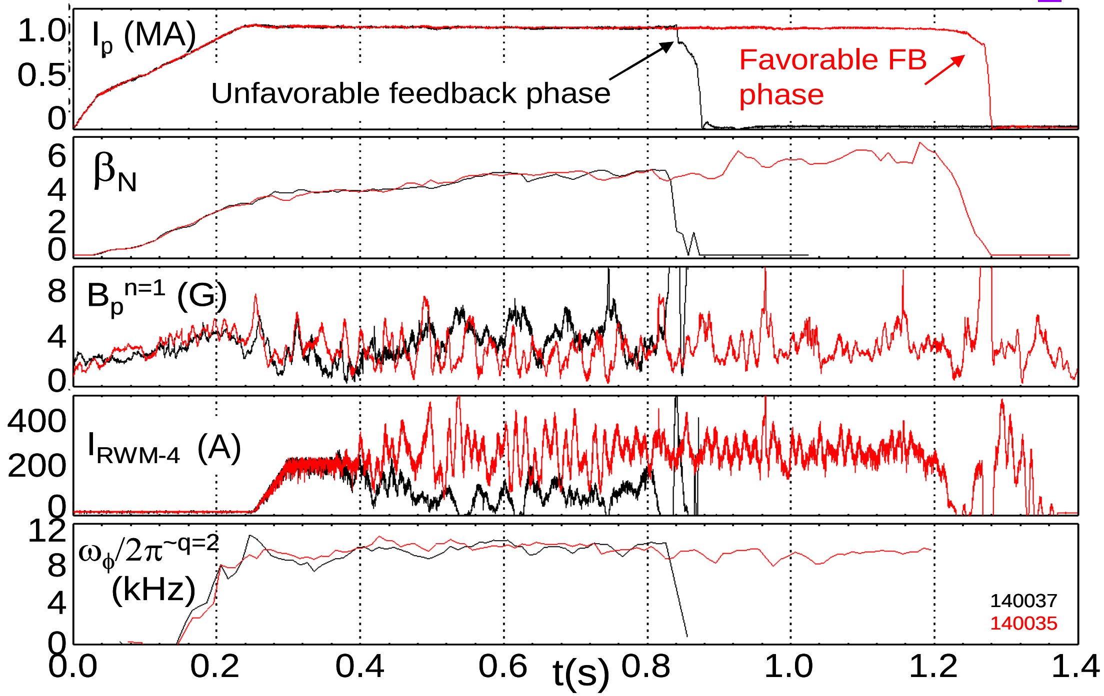
S. Gerhardt et al., NF 53 (2013) 063021

Research plans and needs for this year (FY2014) in preparation for NSTX-U operations in FY2015

- Present attention is on NSTX analysis / paper publication
  - Two papers accepted for publication in 2014
  - One presently under review
  - 2 – 3 further NSTX papers expected before the start of NSTX-U Ops
- Transition to computational analysis preparation ~ mid 2014
  - RWM State-space Controller generalization – to be available on “Day 0”
    - Offline IDL version of code already generalized
    - Changes to r/t version to be made. Small PCS programming support will be needed
  - NSTX EFIT (of course, “Day 0”)
    - Plan to upgrade to faster processing to support increased between-shots spatial resolution / time resolution (eta 2014-2015); present code available as default
    - New code components acquired Dec 2013; new dedicated prototype 32 core CPU computer online at PPPL (planned to be expanded); consistent with PPPL IT plan
  - NSTX rotation control
    - Continuing work with PU student (I. Goumiri) on rotation control algorithm
    - Present quantitative NTV analysis of Columbia U. NSTX experiments supports this, and the paper publication goals above

Model-based RWM state space controller including 3D plasma response and wall currents used at high β_N in NSTX

RWM state space controller in NSTX at high β_N

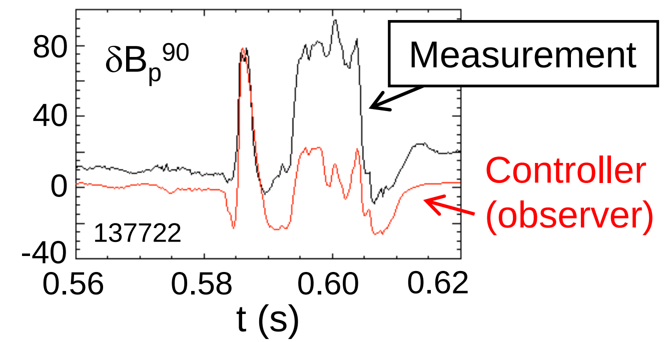


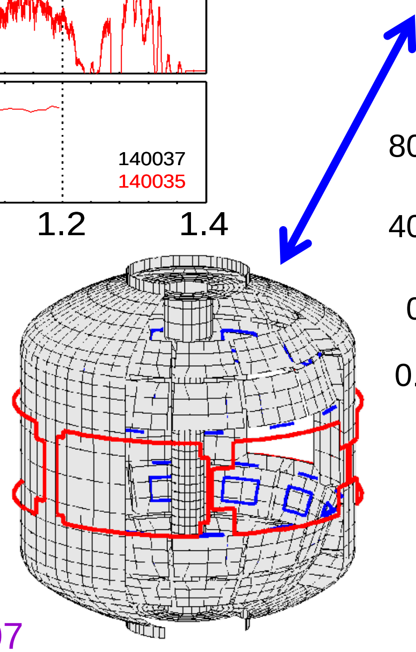
- Potential to allow more flexible control coil positioning
  - May allow control coils to be moved further from plasma, and be shielded (e.g. for ITER)
    Katsuro-Hopkins, et al., NF 47 (2007) 1157

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

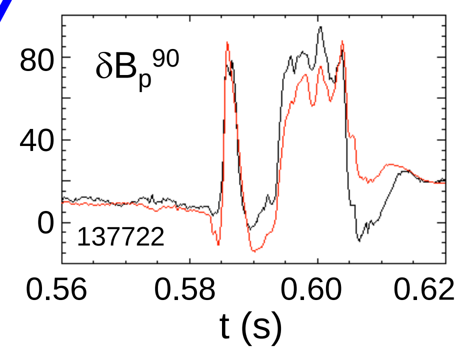
Effect of 3D Model Used

No NBI Port





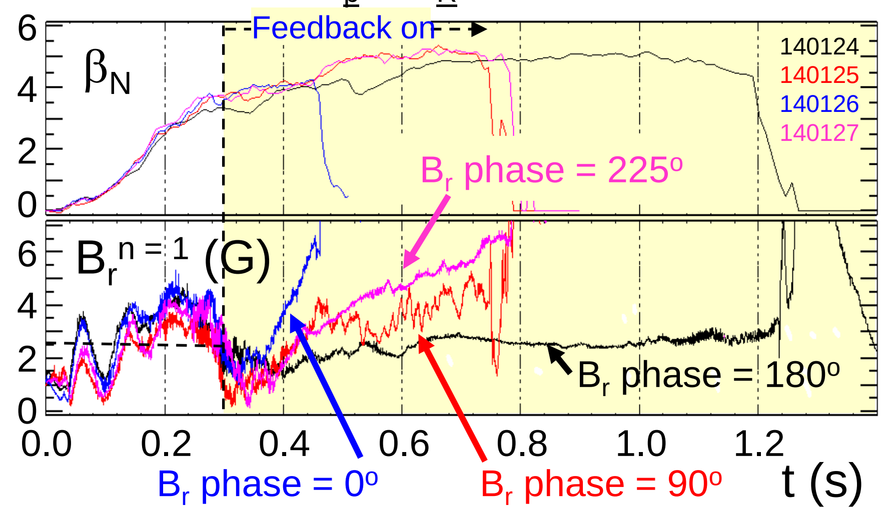
With NBI Port



- 3D detail of model is important to improve sensor agreement

Dual-component PID (B_r + B_p) and model-based RWM state-space (RWMSC) active control will enable long pulse, high β operation

- 2014:
  - Expand/analyze RWMSC for 6 coil control and n > 1 physics

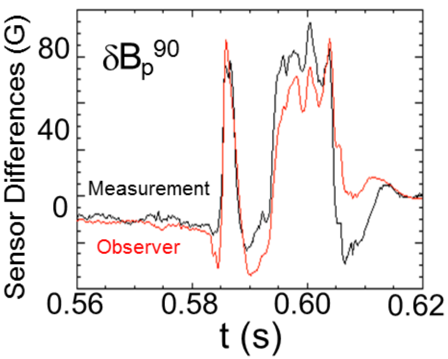


- 2015 and 2016:
  - Establish B_r + B_p active control capability in new machine, use with snowflake divertor
  - Examine RWMSC with:
    - independent actuation of six coils
    - multi-mode control with n up to 3
    - rotational stabilization in the model

RWMSC

Advantages:

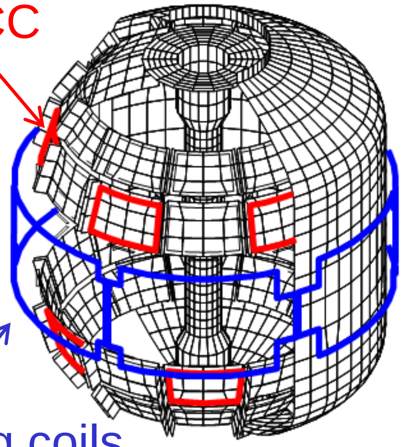
potential for use of external coils with less power



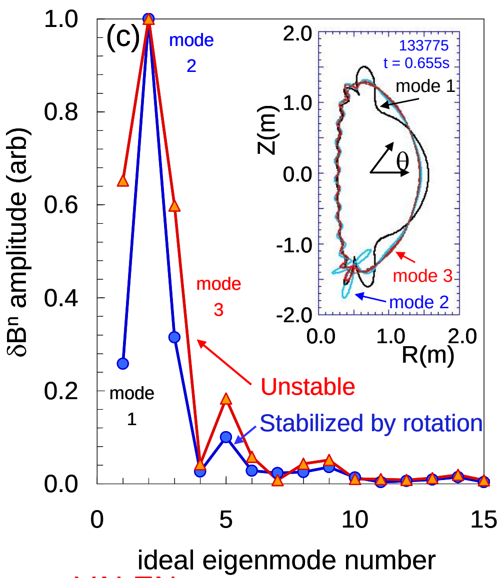
- 2017 and 2018:
  - Upgrade for NCC, utilize model-based active control with the new NCC to demonstrate improved global MHD mode stability and very low plasma disruptivity, producing highest-performance, longest-pulse plasmas

NCC will greatly enhance physics studies and control; Enhanced magnetics near divertor will measure multi-modes

- Years 2017 and 2018:
  - Implement improvements to active feedback of n =1-3 modes via RWMSC control allowed by the NCC
  - Utilize rotation profile control capabilities allowed by the NCC to demonstrate reduced disruptivity by actively avoiding global instability boundaries



Multi-mode n = 1 ideal eigenfunction for fiducial plasma

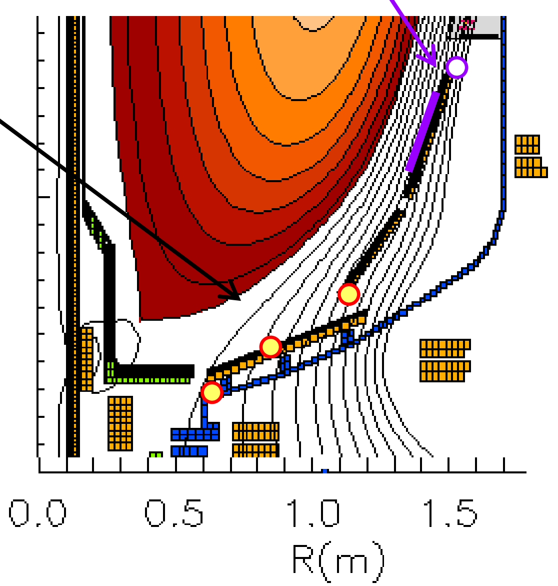


mmVALEN

Proposed new sensor locations

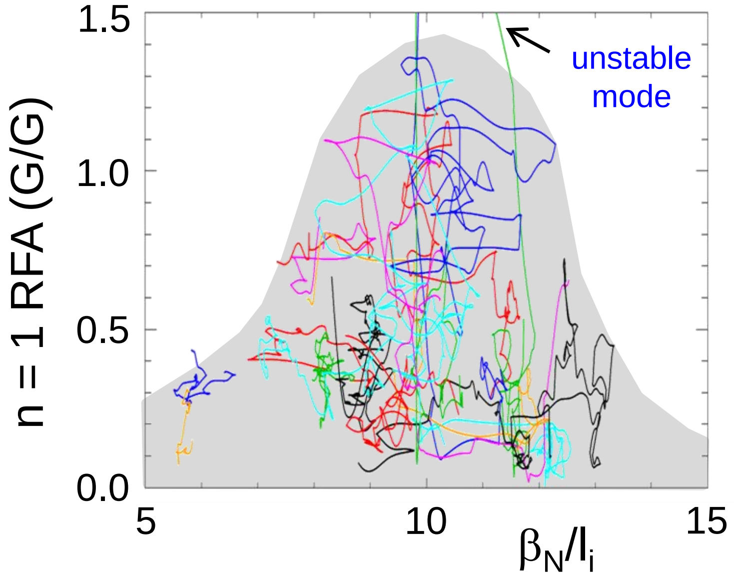
- Mode diagnosis:
  - If two modes are near marginal, need to be able to distinguish
  - Measure increased amplitude near divertor (3D analysis shows >2x increase over present sensors)
  - Similar results in ITER simulations
- Significant toroidal phase change would be measured
  - Can help constrain the RWMSC

Present sensor locations



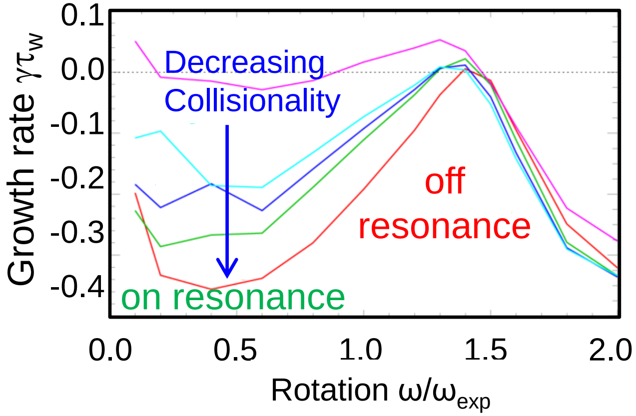
MHD spectroscopy shows improved stability at high β_N/l_i; kinetic RWM stability to be studied at lower ν in NSTX-U

Resonant Field Amplification (RFA) vs. β_N/l_i



J.W. Berkery, et al., Phys. Plasmas (2014)

Theory: RWM γ vs. ν and ω_ϕ

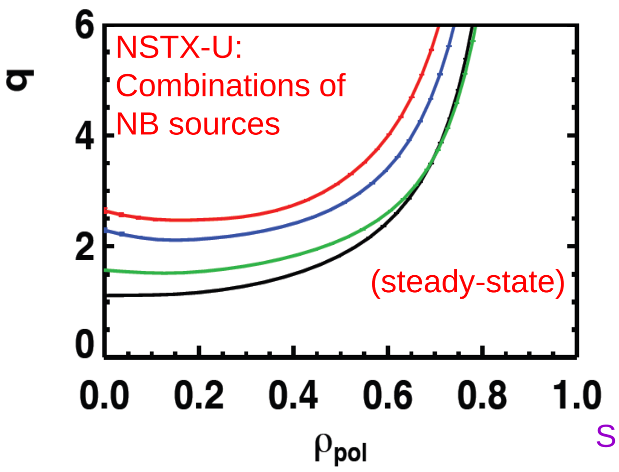


J.W. Berkery, et al., PRL **106** (2011) 075004

- Mode stability directly measured in experiment using MHD spectroscopy
  - Decreases up to β_N/l_i = 10, increases at higher β_N/l_i
  - Agrees with larger NSTX disruption database

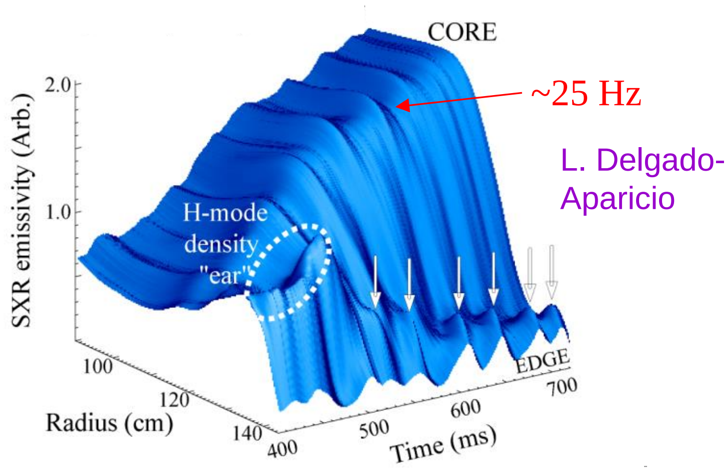
- 2015 and 2016:
  - Investigate the dependence of stability on reduced ν through MHD spectroscopy; compare to kinetic stabilization theory
- 2017 and 2018:
  - Utilize rotation control, NCC, and cryo-pump (for reduced ν) to change proximity to kinetic resonances for RWM control

Scoping study planned to determine / improve stability of internal (global) MHD modes



S.P. Gerhardt

Low frequency mode activity measured with multi-energy soft X-ray



L. Delgado-Aparicio

- Years 2015 and 2016:
  - Measure (global) internal modes non-magnetically with ME-SXR, examine vs. r/t model with RWMSC observer
- Years 2017 and 2018:
  - Examine time-evolution of global mode internalization using newly-installed, additional toroidally-displaced ME-SXR diagnostic
  - Combine results with rotation and q control to demonstrate improved RWM/internal MHD mode stability

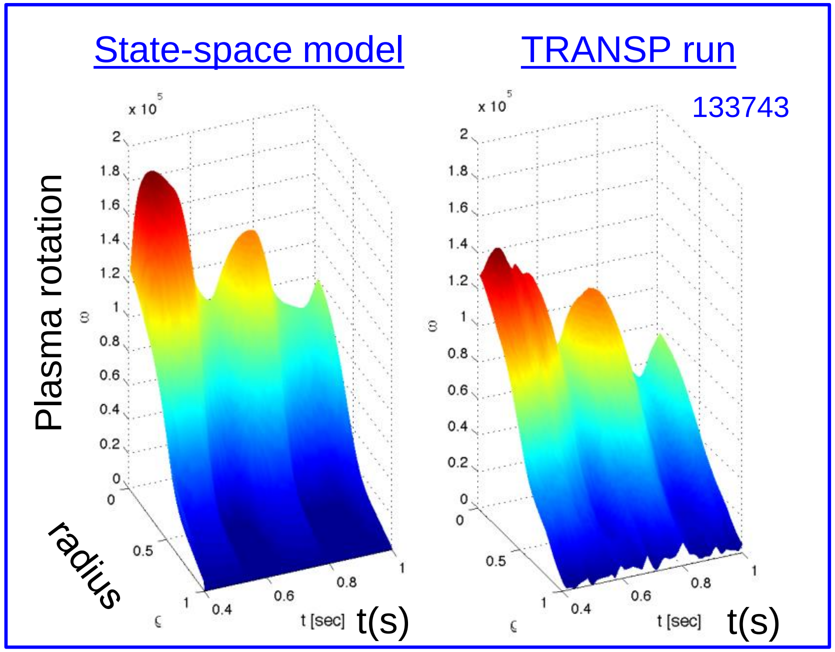
Columbia U. group actively supporting model-based, state-space rotation controller designed to NTV profile as actuator

- Momentum force balance – ω_ϕ decomposed into Bessel function states

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

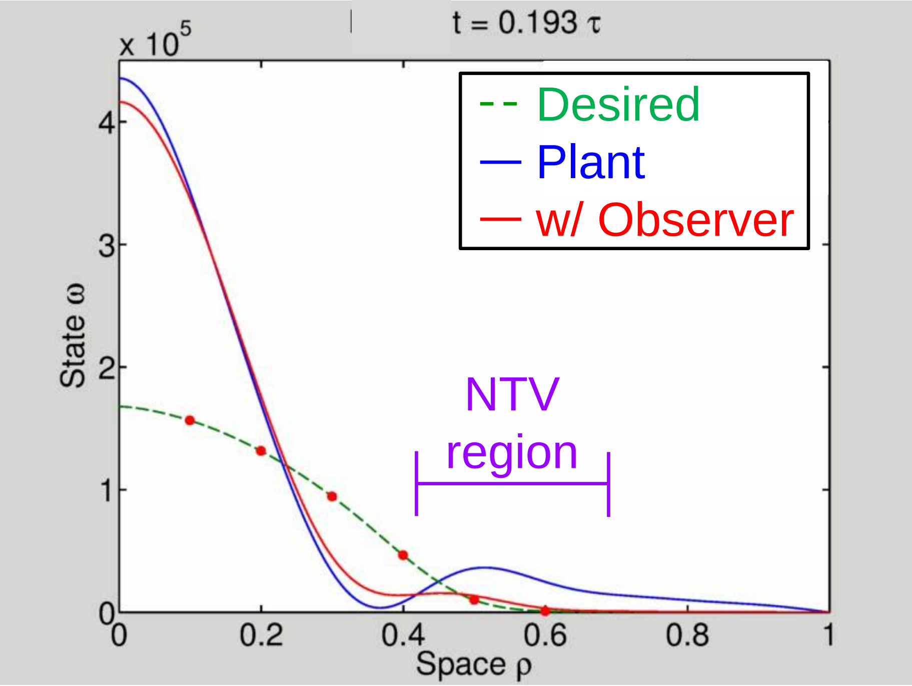
- NTV torque:

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



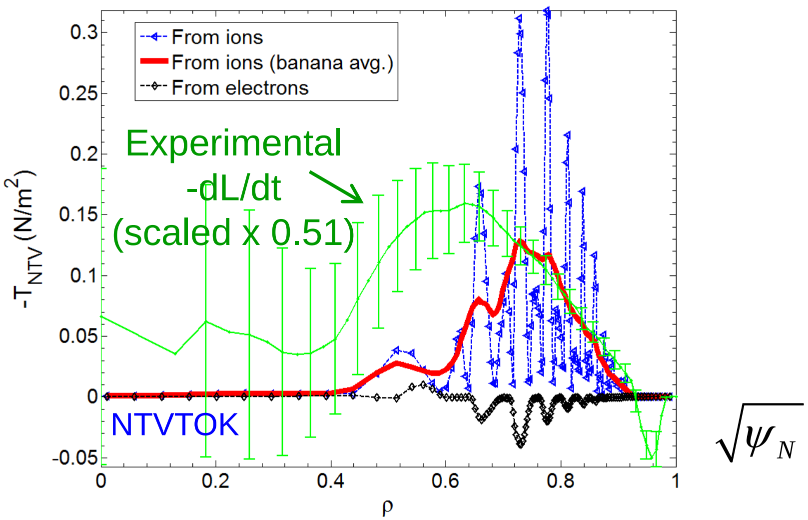
I. Goumiri (PU) (from Sabbagh, et al. APS DPP 2013)

Feedback using NTV: "n=3" $\delta B(\rho)$ spectrum



Columbia U. group investigating neoclassical toroidal viscosity (NTV) at reduced ν, important for rotation control

NTV torque profile (n = 3 configuration)



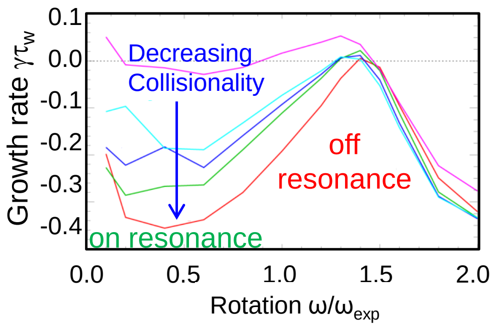
- **New analysis: NTVTOK code**
  (Sun, Liang, Shaing, et al., NF **51** (2011) 053015)
  - Modified for NSTX, incl. Shaing's connected NTV model, covers all ν, superbanana plateau regimes
    (Shaing, Sabbagh, Chu, NF **50** (2010) 025022)
  - Full 3D coil spec, ions & electrons, all A
  - Initial plasma response models include "vacuum field assumption" and M3D-C[1] single and two-fluid models (with Evans/Ferraro)

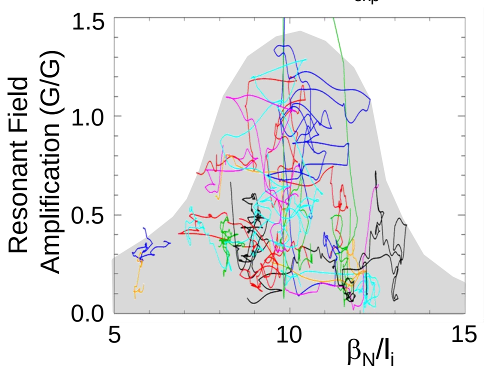
- 2014:
  - Presently analyzing existing Columbia U. NTV experimental data on ν dependence and other NTV characteristics
- Years 2015 and 2016:
  - Assess NTV profile and strength at reduced ν of NSTX-U, examine NTV offset rotation at long pulse
  - Utilize initial real-time model of NTV profile for use in NSTX-U plasma rotation control system
- Years 2017 and 2018:
  - Utilize NCC, demonstrate low rotation profile operation (ITER-like) in steady-state with closed-loop rotation control

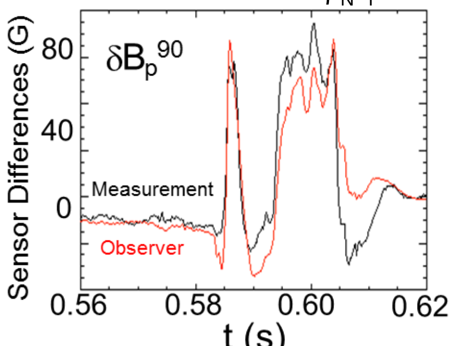
Columbia U. group will strongly contribute to disruption prediction in NSTX-U by multiple means

Predictors → ***Disruption Warning System*** → ***Mitigation***

Predictors → ***Control Algorithms*** → ***Avoidance Actuators***







Kinetic Physics

- Evaluate simple physics criteria for global mode marginal stability in real-time

MHD Spectroscopy

- Use real-time MHD spectroscopy while varying rotation, q_{min}, and β_N to predict disruptions

→ ***q, v_ϕ, β_N control***

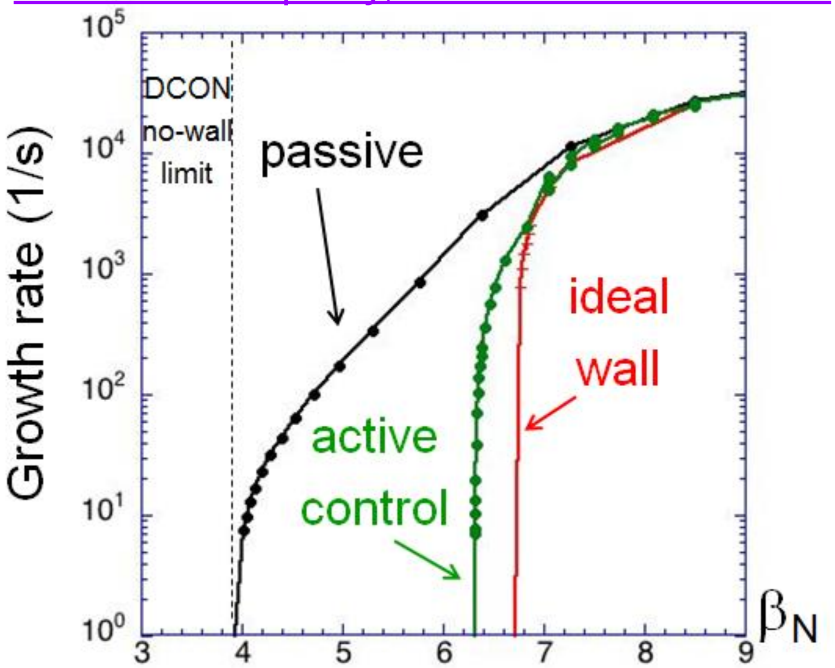
RWMSC observer

- Compare mismatch between the RWMSC observer and sensor measurements, and disruption occurrence

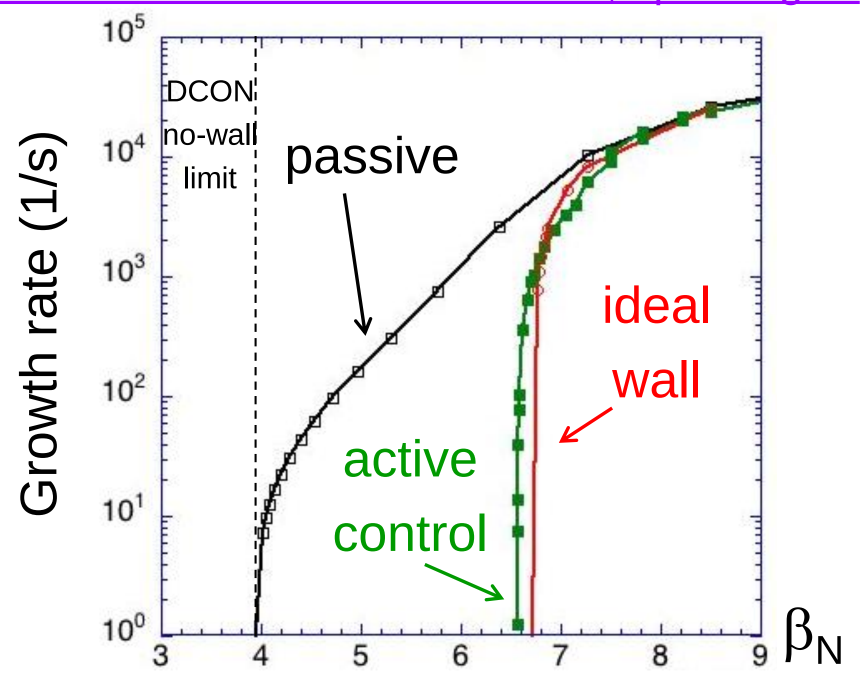
→ ***3D fields, feedback***

Columbia U. group continues to assess RWM active control capability of the NCC

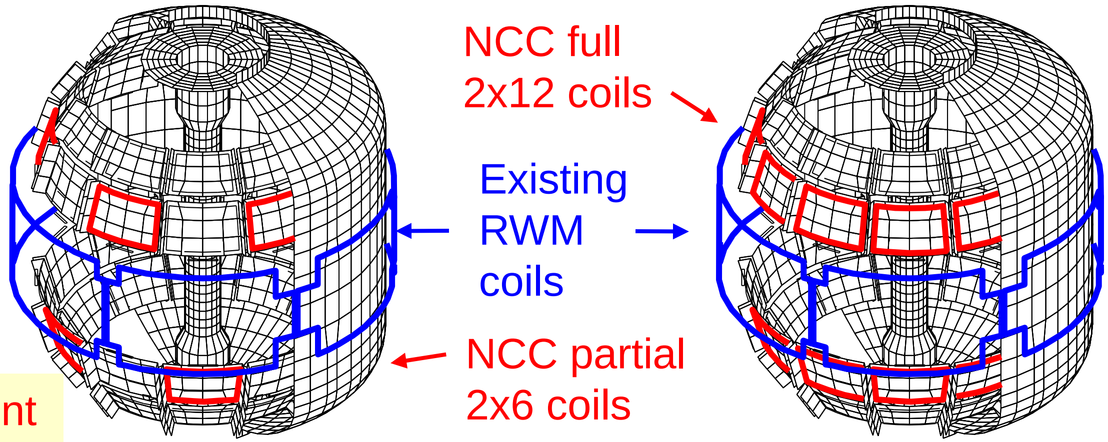
NCC 2x6 odd parity, with favorable sensors



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 $\beta_N/\beta_N^{no\text{-}wall} = 1.61$
  - NCC 2x12 coils, optimal sensors: active control to $\beta_N/\beta_N^{no\text{-}wall} = 1.70$
  - (RWM coil $\beta_N/\beta_N^{no\text{-}wall} = 1.25$)
- Design now needs sensor assessment



Columbia U. group will contribute to disruption prediction in NSTX-U by multiple means

- 2014:
  - Continue "benchmarked" MISK code analysis of kinetic RWM stabilization on NSTX database
  - Evaluate initial simple physics model for marginal stability based on kinetic stability physics (suitable for r/t use)
- Years 2015 and 2016:
  - Measure NSTX-U plasma stability using MHD spectroscopy vs. key variables and compare to theory
  - Compare the mismatch between the RWMSC observer model and sensor measurements, and disruption occurrence
- Years 2017 and 2018:
  - Implement real-time evaluations of kinetic stability model, MHD spectroscopy, and RWMSC observer disruption prediction for input to profile control algorithms; use NCC for RWM active mode control

Some Columbia U. group experiments proposed for last NSTX campaign are appropriate to run in NSTX-U

Columbia U. Group 2011-12 Macrostability TSG experiments

- Macrostability TSG (proposed for 2011)
  - XP1144: RWM stabilization/control, NTV V_ϕ alteration of higher A ST targets (Sabbagh)
  - XP1145: RWM state space active control physics (independent coil control)(Sabbagh)
  - XP1146: RWM state space active control at low plasma rotation (Y-S Park)
  - XP1062: NTV steady-state rotation at reduced torque (HHFW) (Sabbagh)
  - XP1111: RWM PID optimization (Sabbagh)

- Macrostability TSG (proposed for FY 2012)
  - XP1149: RWM stabilization dependence on energetic particle profile (Berkery)
  - XP1147: RWM control physics with partial control coil coverage (JT-60SA) (Y-S Park)
  - XP1148: RWM stabilization physics at reduced collisionality (Berkery)
  - XP1150: Neoclassical toroidal viscosity at reduced ν (independent coil control) (Sabbagh)

- (of course) further experiments specific to NSTX-U will be proposed

Ideas to enhance participation in NSTX-U research/program by U.S. Universities, early-career researchers, and students

- Columbia U. Group at PPPL has always encouraged students and young researchers (total of 8 since we started)
  - Most recent example: co-advising PU student I. Goumiri
  - Last Columbia Ph.D. student on NSTX was W. Zhu (Ph.D. 2009)
- Key issue in bringing in Columbia students is funding
  - Tony Peebles gave excellent summary of significant limitations of present DOE solicitations to universities vs. solicitations to national labs (see Tony's talk)
  - Abed Balbaky (Columbia SEAS EE student) recently very helpful in supporting Columbia reseach plan for NSTX; could not continue at present funding level
    - Wrote important modifications to low frequency MHD spectroscopy software
    - Supported last paper by J. Berkery, et al.; co-author on two NSTX papers
  - At present, co-advising PU students is most logical (*doesn't help home dept.*)
- With sufficient funding, there are many avenues
  - Additionally need exciting/attractive work atmosphere to attract students – difficult to even get office space at the moment
  - CU off-campus students face other challenges (e.g. housing / travel costs)