NSTX

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

Columbia U. Group – NSTX 5 Year Plan 2014+ Macrostability TSG - Initial Discussion

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S.A. Sabbagh, J.W. Berkery, J.M. Bialek, Y.S. Park, et al. …

Department of Applied Physics, Columbia University, NY, NY

NSTX 5 Year Plan FY2014+ Discussion
Macrostability TSG

Sept. 7th, 2011

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V1.1

Columbia U. Group proposed DOE research continues from NSTX, aiming toward the Upgrade

- Goal: Improve stabilization understanding and control to sustain plasma, study physics of 3D field effects
  - Greatest disruption probability is not at highest β_N
- NSTX Research / Analysis during Outage (brief outline)
  - Passive stabilization physics
    - Complete unification of kinetic RWM stabilization theory across devices; link δW to active control
    - Apply updated theory/XP comparisons and model to ITER through ITPA MDC-2, MHD WG7
    - Apply/iterate with last set of RWM stabilization physics XPs; analyze RFA for future r/t feedback
  - Active control and stabilization physics
    - Complete testing of RWM state space controller w/2nd SPA, n > 1, etc.; analysis of $B_r + B_p$ PID
    - Further analysis of multi-mode RWM in stability/control, snowflake div. effect, partial coil coverage
  - Neoclassical toroidal viscosity physics and rotation control support
    - Addressing several aspects untested, or contested between devices; XPs at other facilities
    - Apply to model development for r/t V_ϕ control in NSTX
  - ELM stabilization physics
    - Stemming from XP818 and XP1031 – analysis underway
  - NSTX equilibrium reconstruction support and development
  - Many XPs (12) proposed for 2011 and 2012
    - Several of these will be performed in NSTX-U
    - Some physics will be examined in other devices during outage (e.g. DIII-D (9/'11), KSTAR, MAST)

Significant set of NSTX data yet to be analyzed + some new experiments on others devices will supply this effort

Columbia U. Group research naturally merges into preparation for, and research on NSTX-U

- Goal: Test stabilization understanding and control to sustain plasmas closer to FNSF / ST-Pilot and to support Advanced Tokamak / ITER operation
- NSTX-U: preparation and research (initial outline – to be further developed)
  - Passive stabilization physics
    - Rotation (+possible equil. profile) control for RWM stabilization in NSTX-U plasmas (higher A, κ)
    - Passive stabilization via profile control for FNSF / ST-Pilot targets (w/ORNL, PPPL LDRD), ITER
    - Test unified stabilization physics theory in NSTX-U plasmas
  - Active control and stabilization physics
    - Continue in-vessel non-axisymmetric control coil (NCC) design for NSTX-U; partial coil coverage
    - RWM state space controller simulation for 6 RWM coil system, NCC system, FNSF/ST Pilot
    - Multi-mode RWM physics control; effects of snowflake divertor; further B_r + B_p analysis / use
    - Improved disruption avoidance with real-time RFA control / influence of multi-mode physics
  - Neoclassical toroidal viscosity physics and rotation control support
    - Test theory/model developments in long-pulse NSTX-U plasmas
    - Assessment of V_ϕ control for RWM stabilization; analysis to determine further improvements
    - Assessment of 2nd SPA use, NCC use for more highly resolved V_ϕ control
  - ELM stabilization physics
    - Assessment of NCC for dual role ELM / RWM control; continued stability analysis
  - NSTX equilibrium reconstruction support and development
    - Upgrades to allow higher resolution, plan for new diagnostics, support for r/t MSE, etc.

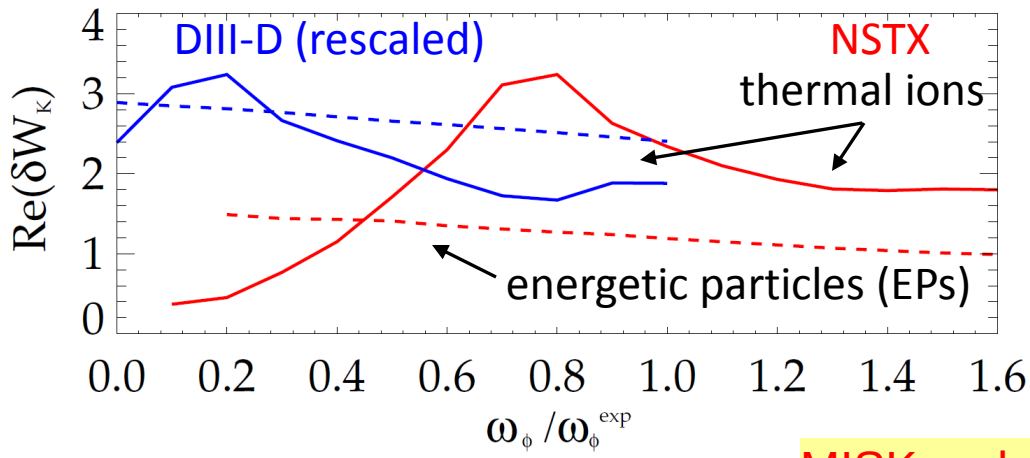
…an incomplete list: a full NSTX-U experimental plan will be developed to supplement the research

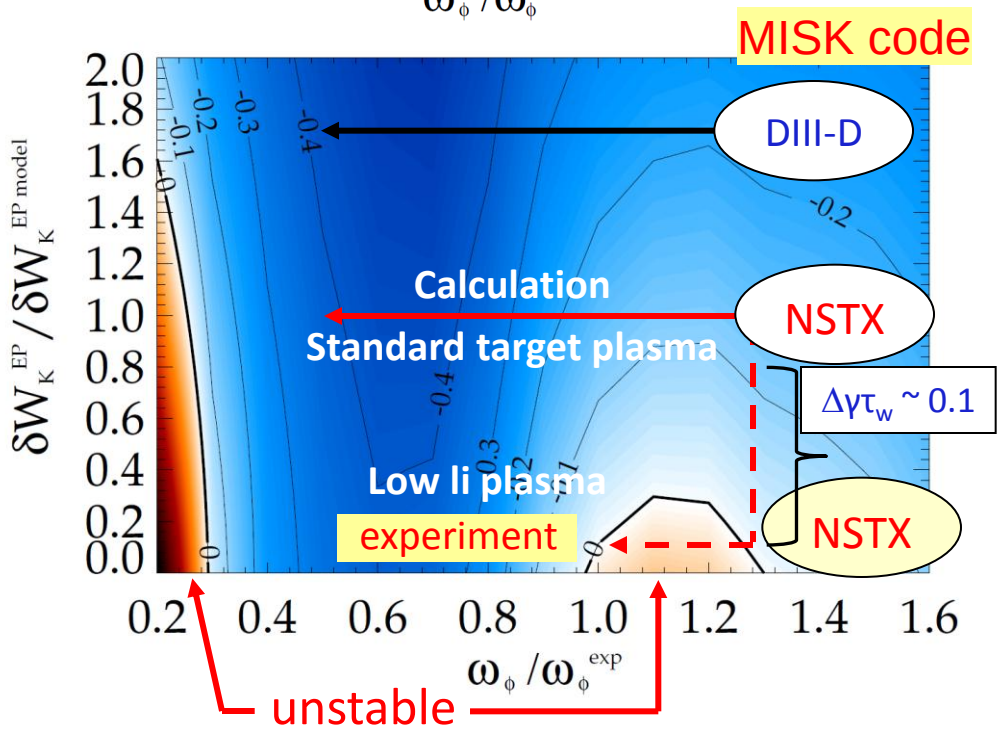
Columbia U. Group research – some suggestions for diagnostics / capabilities to improve analysis / control

- NSTX-U some diagnostic suggestions / ideas (brief outline)
  - Passive stabilization physics
    - Plan for higher resolution real-time V_ϕ (based on V_ϕ, shear profile needs from stability analysis)
    - Continued improvement of equilibrium profiles (TS resolution, MSE, etc.)
    - Fast particle profile diagnostics for all operational regimes (neutron collimator, improved FIDA)
    - SXR at more than one toroidal position
  - Active control and stabilization physics
    - Magnetic RWM sensor upgrades (e.g. coils at midplane, near divertor region to best diagnose mode "bulging", multi-mode RWM spectrum ("divertor mode"))
    - Non-magnetic RWM sensors (past proposal by JHU) – physics development for future devices
    - "Optimized" sensor set based on further RWM state-space controller analysis
    - "Optimized" sensor set for non-axisymmetric control coil (NCC) system for NSTX-U
    - "Optimized" sensor set for real-time RFA control (most sensitive mode during RFA, or during feedback control may not be strongly ballooning)
  - Neoclassical toroidal viscosity physics and rotation control support
    - Plan for higher resolution real-time V_ϕ (based on 6 RWM coil, NCC, 2 NBI ability to change V_ϕ)
    - Some form of density control / reduction (e.g. cryopump to follow further Li tests in NSTX-U)
  - ELM stabilization physics
    - Diagnostic improvements similar to "passive stabilization" above, with emphasis on plasma edge region (especially for current profile constraints)
  - NSTX equilibrium reconstruction support and development
    - Assessment/use of new diagnostics (e.g. MSE-LIF) in NSTX EFIT reconstructions

Supporting slides

Model of kinetic modifications to ideal stability (MISK) can unify RWM stability results between devices





- Stabilization by kinetic effects+ EPs
  - Ion precession drift, bounce resonance, collisions
  - Alfven dissipation at rationals
- NSTX
  - Less EP stability: RWM can cross marginal point as ω_ϕ is varied

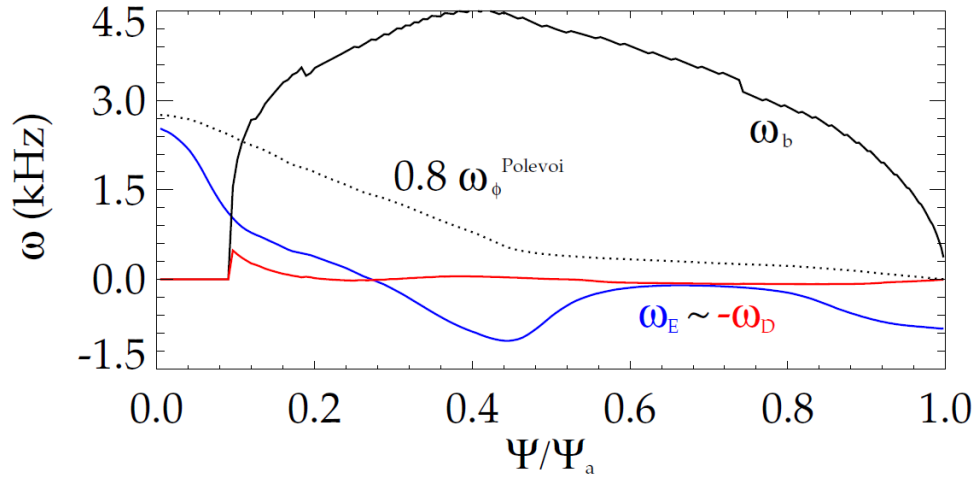
    Sabbagh, et al., IAEA FEC 2010 (EXS/5-5)
- DIII-D
  - More EP stability (~ 2x NSTX): RWM stable at all ω_ϕ
  - RWM destabilized by events that reduce EP population

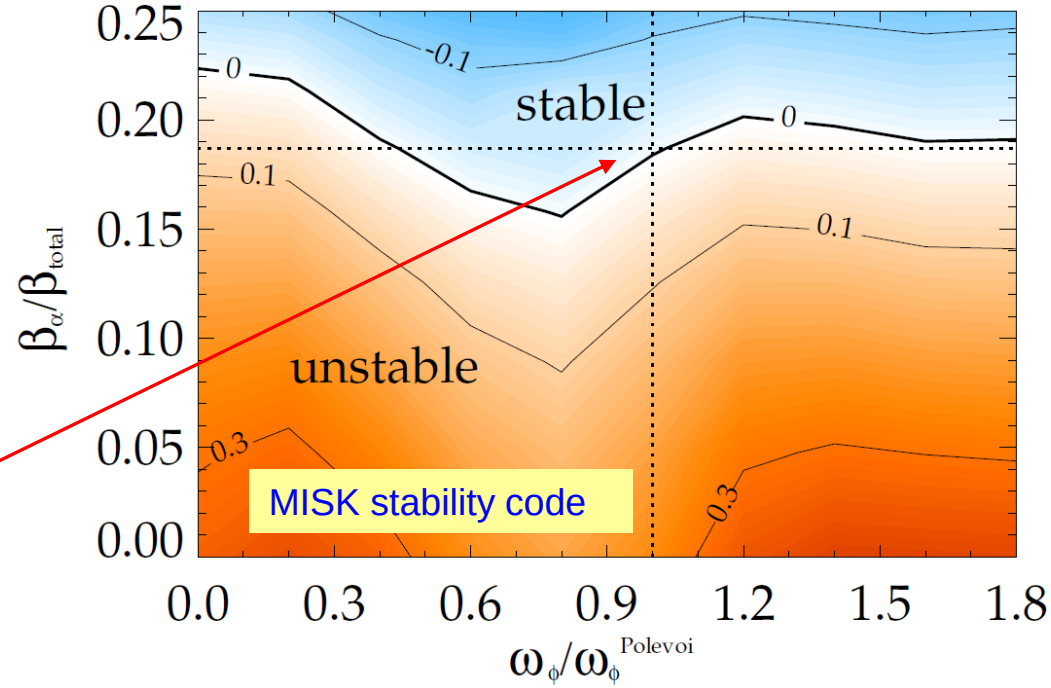
    Reimerdes, et al., IAEA FEC 2010 (EXS/5-4)
- ITER (advanced scenario IV)
  - RWM unstable at expected rotation
  - Only marginally stabilized by alpha particles at 20% over $\beta_N^{no\text{-}wall}$

    Berkery, et al., PoP 17, (2010) 082504

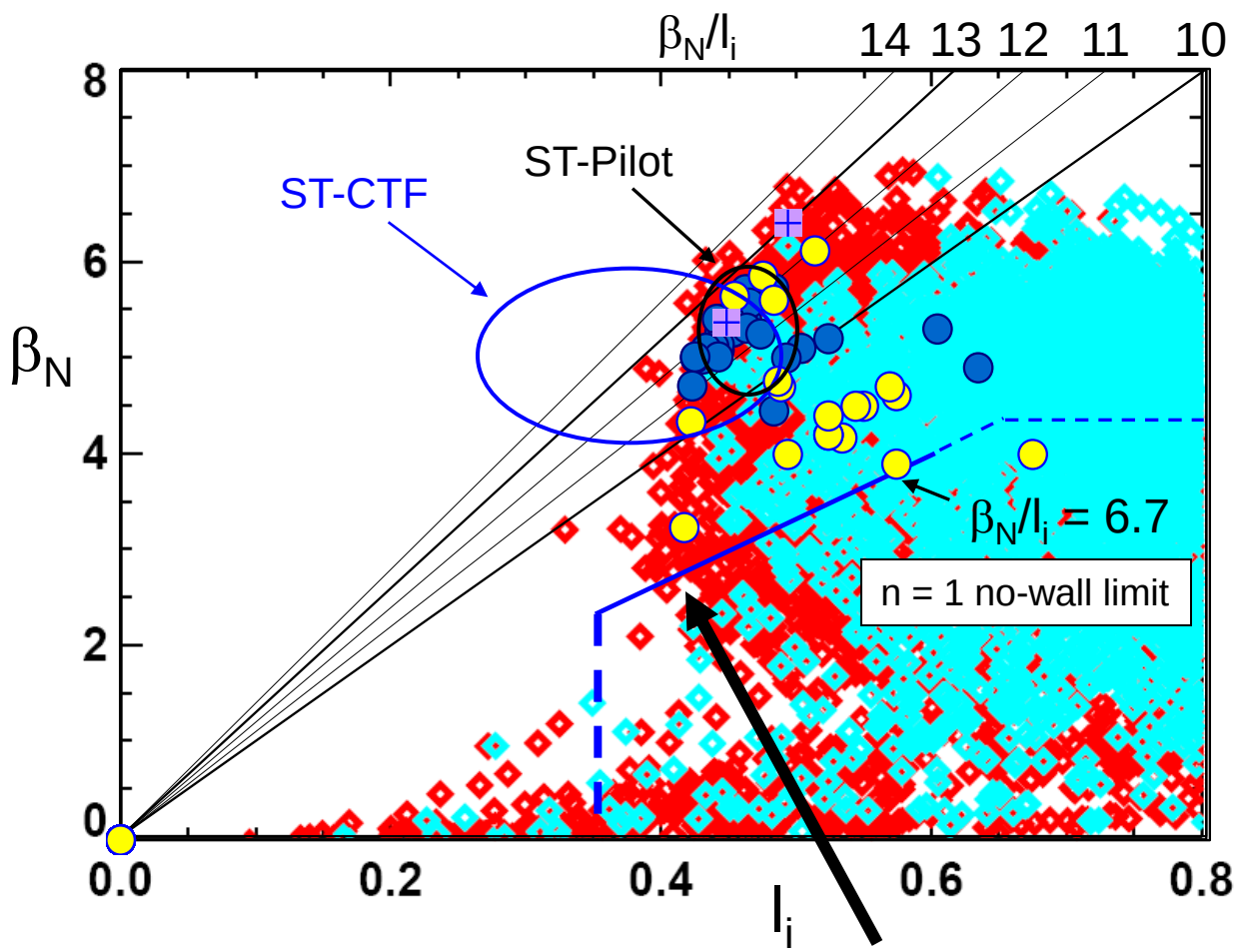
ITER Advanced Scenario IV: RWM stabilized by energetic particles near marginal at $\beta_N = 3$

- Equilibrium
  - With $\beta_N = 3$ (20% above n = 1 no-wall limit)
  - Plasma rotation profile linear in normalized poloidal flux
- Plasma rotation effect
  - Stabilizing precession drift resonance weakly enhances stability near $\omega_\phi = 0.8\ \omega_\phi^{Polevoi}$
- Energetic particle (EP) effect
  - Alpha particles are required for RWM stabilization at <u>all</u> ω_ϕ
  - Near RWM marginal stability at ITER expected $\beta_\alpha/\beta_{total}$ = 0.19 at $\omega_\phi = \omega_\phi^{Polevoi}$





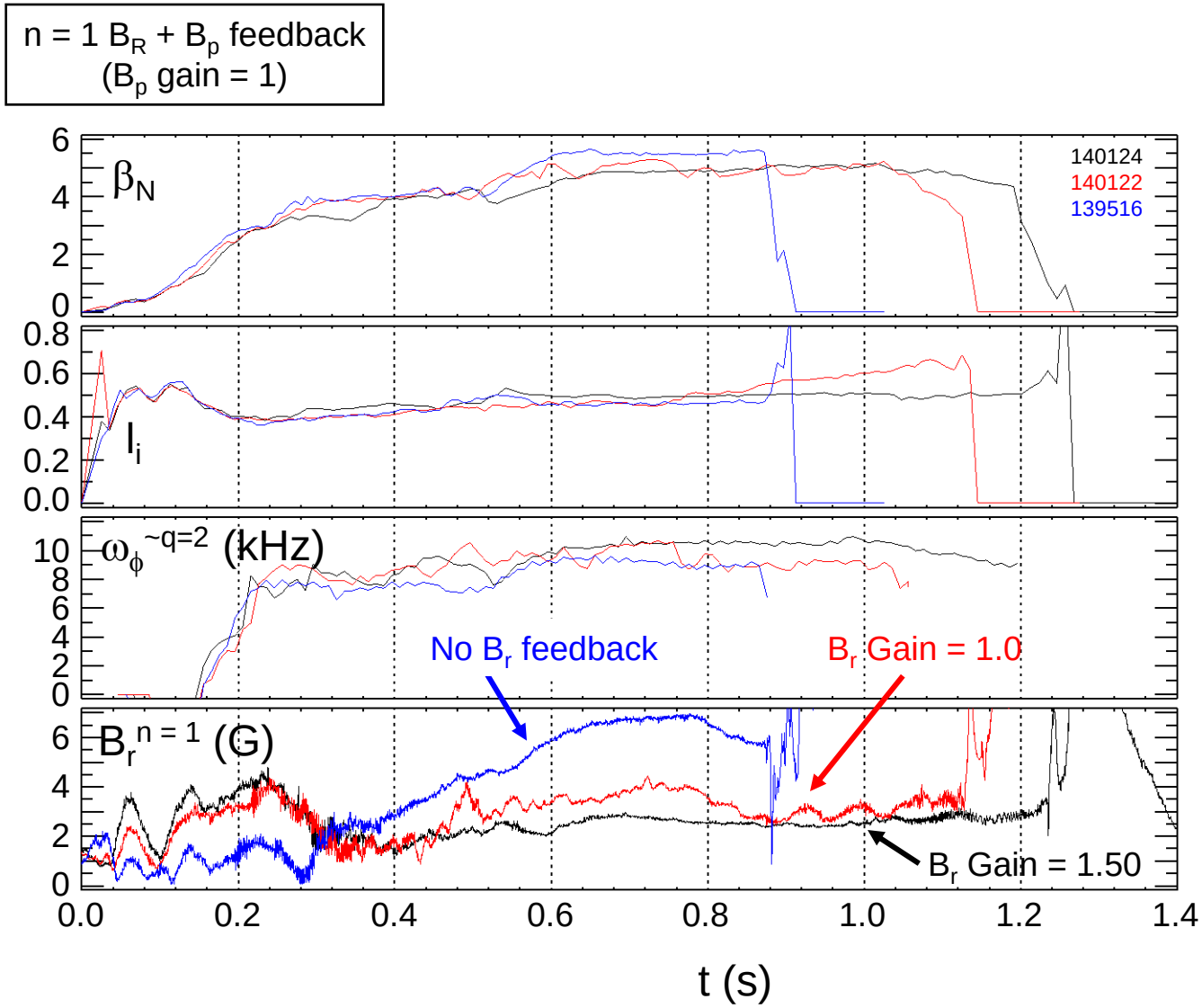
Improvements in stability control techniques significantly reduce unstable RWMs at low l_i and high β_N



- Subset of discharges
  - High $I_p \geq 1.0$MA, $I_{NICD}/I_p \sim 50\%$
- 2009 experiments
  - 48% disruption probability (RWM)
- 2010 experiments
  - n = 1 control enhancements
  - Significantly reduced disruption probability due to unstable RWM
    - 14% of cases with $\beta_N/l_i > 11$
    - Much higher probability of unstable RWMs at lower β_N, β_N/l_i

- Computed n = 1 no-wall limit β_N/l_i,~ 6.7 (low l_i range 0.4 – 0.6)
- Synthetic equilibria variation: n = 1 no-wall unstable at all β_N at $l_i \lesssim 0.38$ (current-driven kink limit)
  - significant for NSTX-U, next-step ST operation

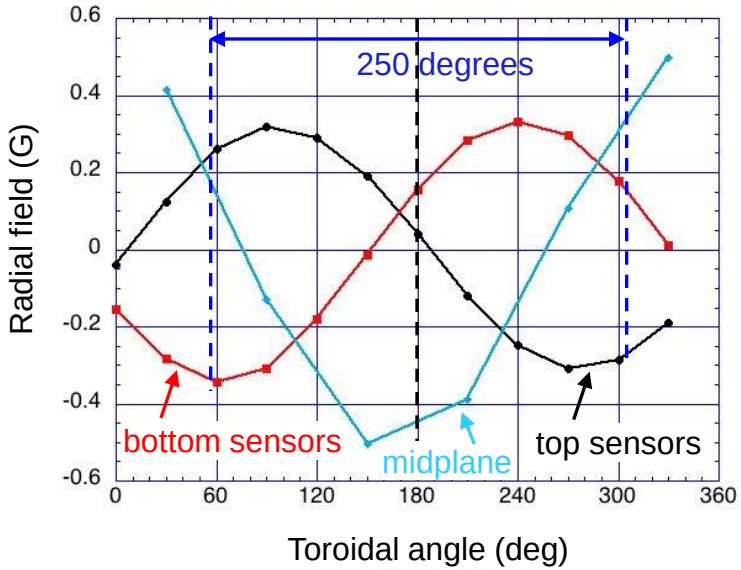
Combined RWM B_R + B_p sensor feedback gain scan shows significantly reduced n= 1 radial error field

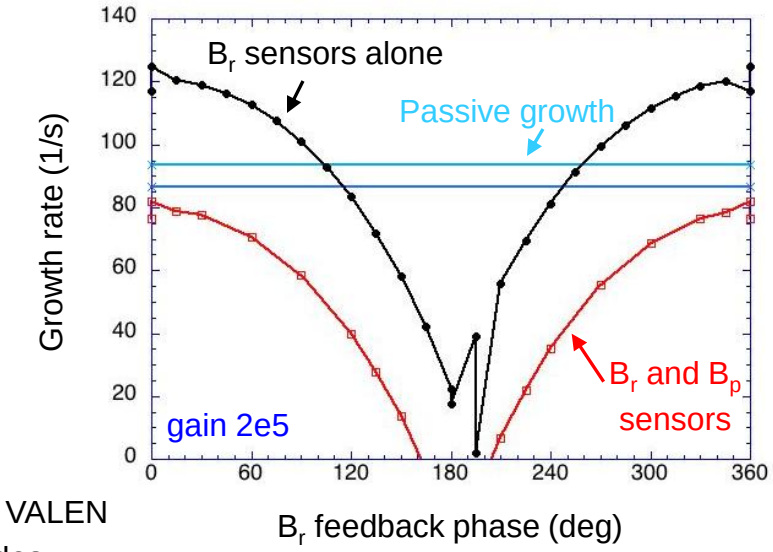


- New B_r sensor feedback gain scan on low l_i plasmas
  - Highest gain attempted (1.5) most favorable
- B_r feedback constrains slow (~10 ms) n = 1 radial field growth
  - Addition of n = 1 B_R sensors in feedback prevents disruptions when $|\delta B_r^{n=1}|$ ~ 9G; better sustains plasma rotation

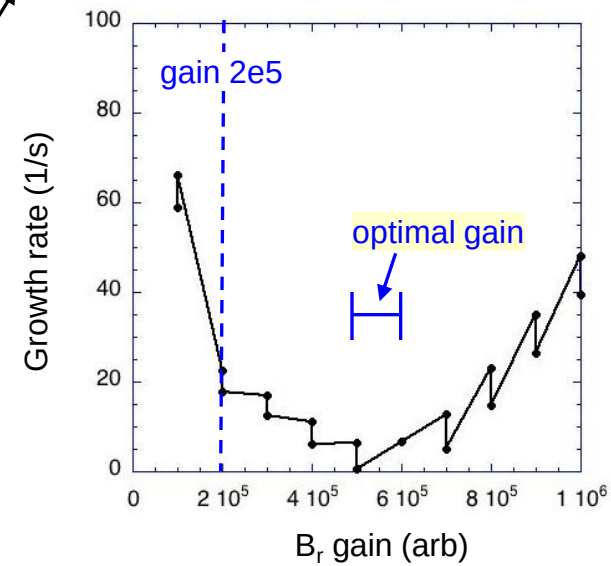
RWM feedback using upper/lower B_p and B_R sensors modeled and compared to experiment

Modeled B_r field at sensors and midplane





DCON, VALEN codes

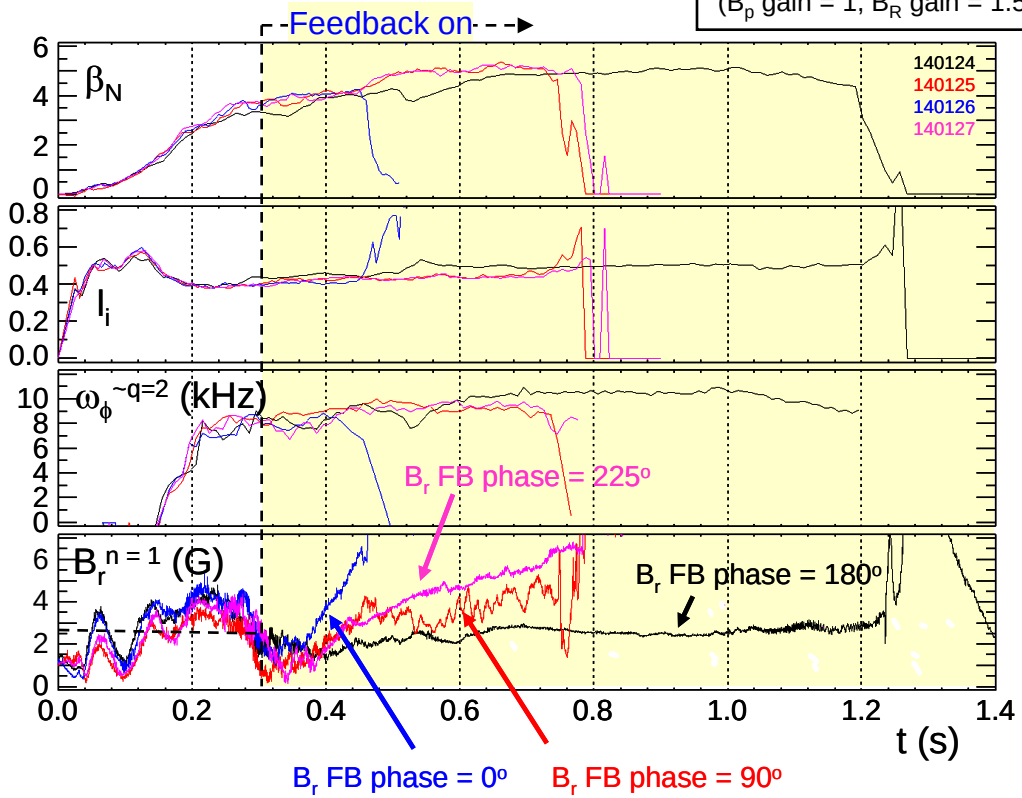


- Both B_r, B_p feedback contribute to active control
  - B_r mode structure and optimal feedback phase agrees with parameters used in experiment
  - B_r feedback alone provides stabilization for growth times down to ~ 10 ms with optimal gain
  - Physics of best feedback phase for B_p sensors in low l_i plasmas under investigation
    - Present analysis mismatches experiment – 3D conducting structure model, plasma response model being investigated

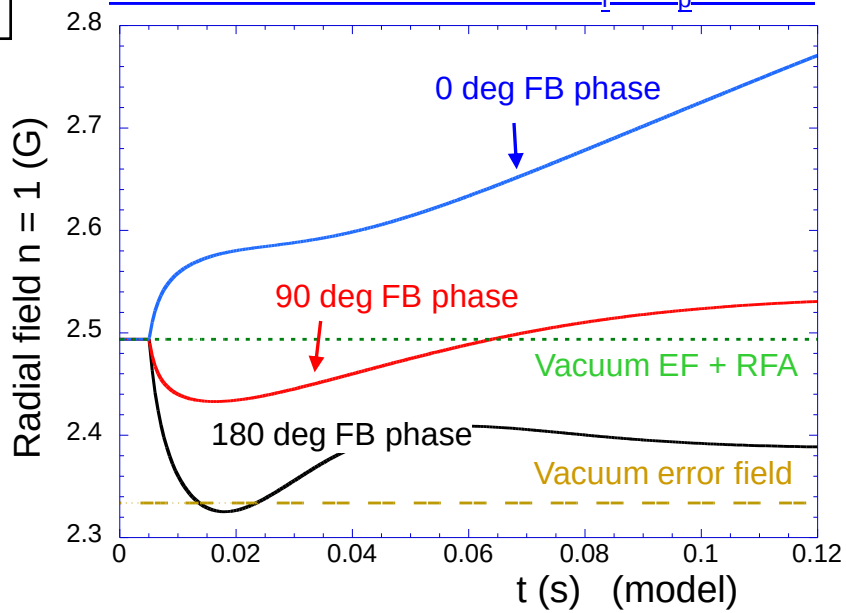
RWM B_r sensor n = 1 feedback phase variation shows superior settings when combined w/B_p sensors; qualitative agreement w/theory so far

NSTX Experiments: B_p + B_R feedback

n = 1 B_R + B_p feedback
(B_p gain = 1, B_R gain = 1.5)



VALEN calculation of NSTX B_r + B_p control

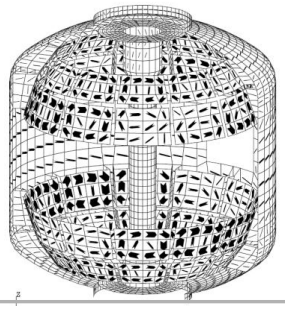


- Favorable B_p feedback settings, varied B_R settings
  - Positive/negative feedback produced at theoretically expected phase values

- VALEN calculation of B_r+B_p feedback follows XP
  - stable plasma (negative "s")
  - initial qualitative result
    - Now running cases to match experiment quantitatively,
    - examining plasma response model

New RWM state space controller implemented to sustain high β_N

Full 3-D model ~3000+ states

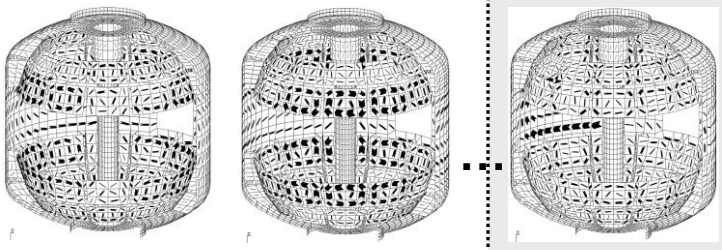


- device R, L, mutual inductances
- instability B field / plasma response
- modeled sensor response

Balancing transformation

State reduction (< 20 states)

RWM eigenfunction (2 phases, 2 states)

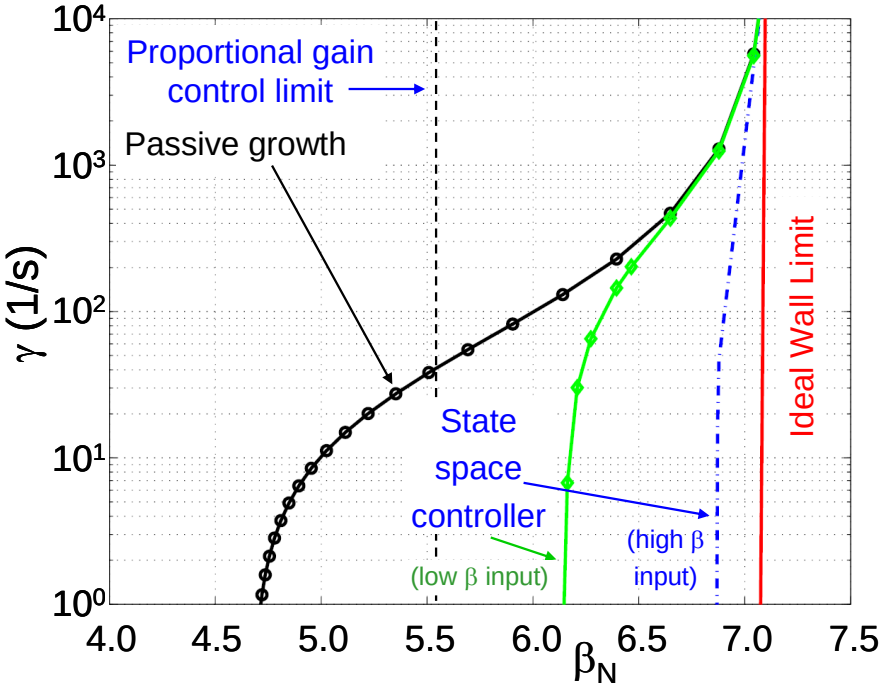


$(\hat{x}_1, \hat{x}_2)$ $\hat{x}_3$ $\hat{x}_4$ $\hat{x}_N$ truncate

- Controller can compensate for wall currents
  - Including mode-induced current
- Potential to allow more flexible control coil positioning
  - May allow control coils to be moved further from plasma, shielded
  - Examined for ITER

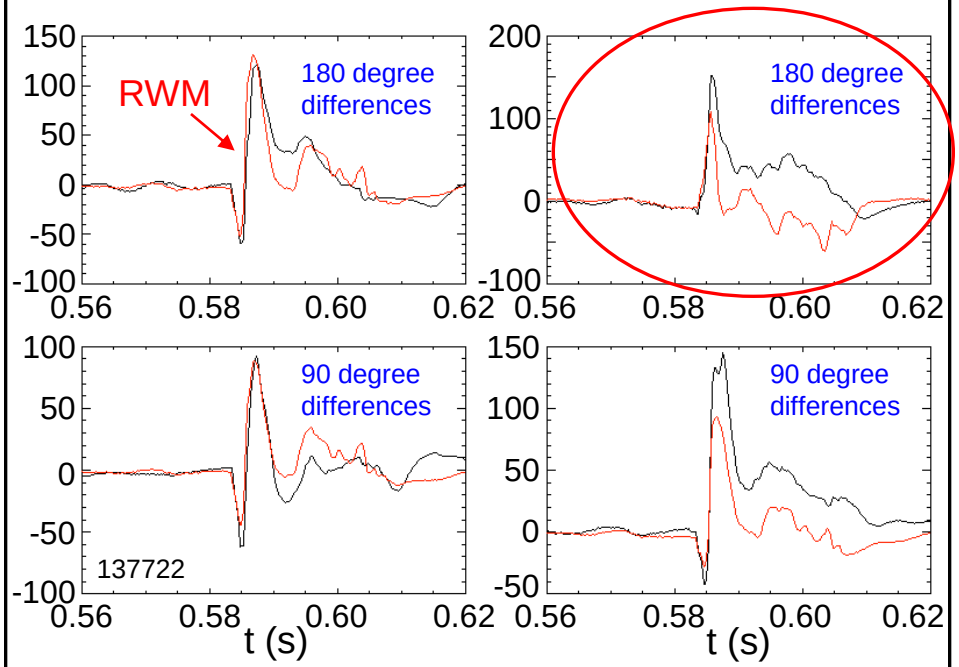
Katsuro-Hopkins, et al., NF **47** (2007) 1157

Theoretical feedback performance (ω_ϕ = 0, 12 states)



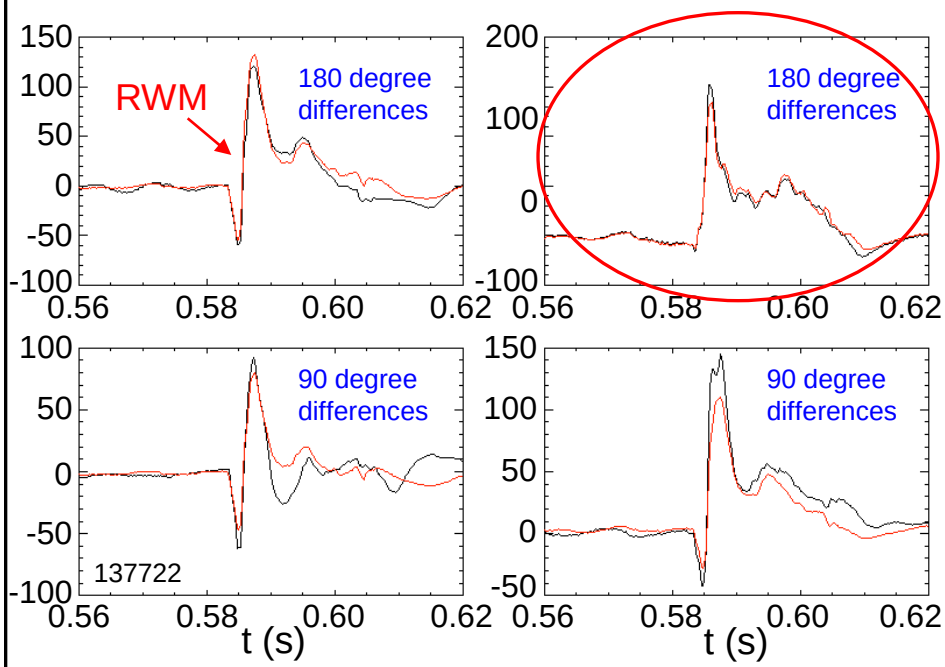
Increased number of states in RWM state space controller improves match to sensors over entire mode evolution

RWM Upper B_p Sensor Differences (G) – 2 States



- Reasonable match to all B_p sensors during RWM onset, large differences later in evolution

RWM Upper B_p Sensor Differences (G) – 7 States

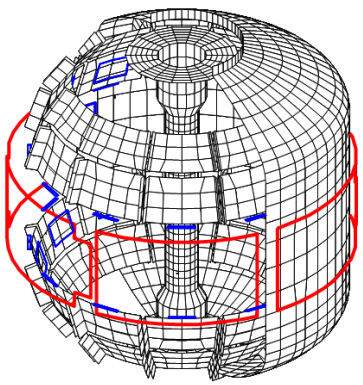


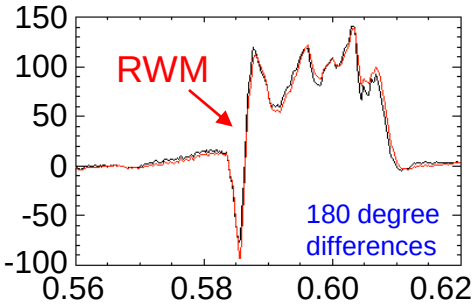
- Some 90 degree differences not as well matched
  - Indicates potential need for an n = 2 eigenfunction state
  - Plan for n = 2 control in 2011

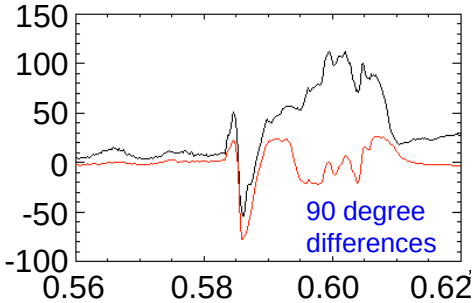
Black: experiment Red: offline RWM state space controller

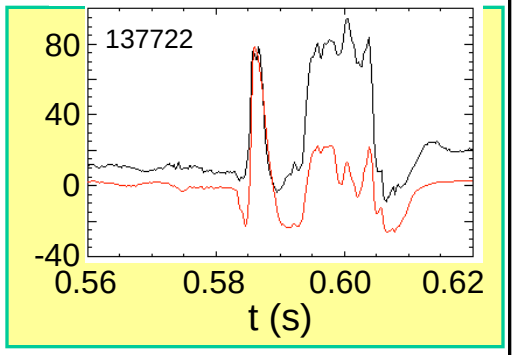
3-D conducting structure detail can improve RWM state space controller match to sensors

RWM Lower B_p Sensor Differences (G) – NO PORT



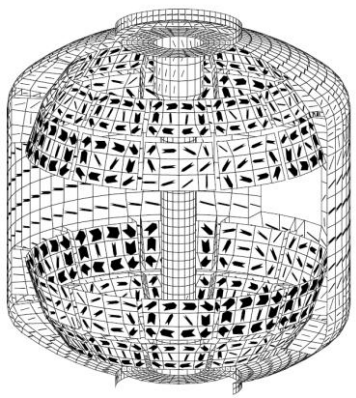


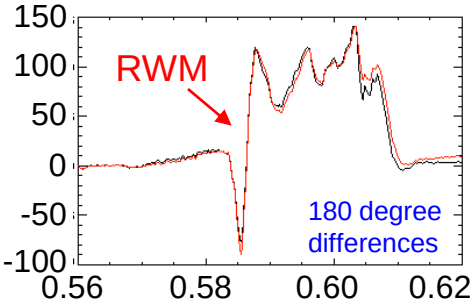


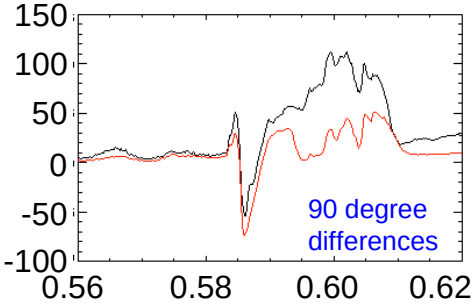


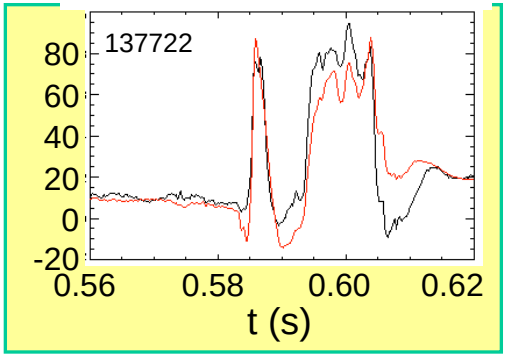
- Some 90 degree differences not well matched
  - Need for n = 2 mode?

RWM Lower B_p Sensor Differences (G) – NBI PORT







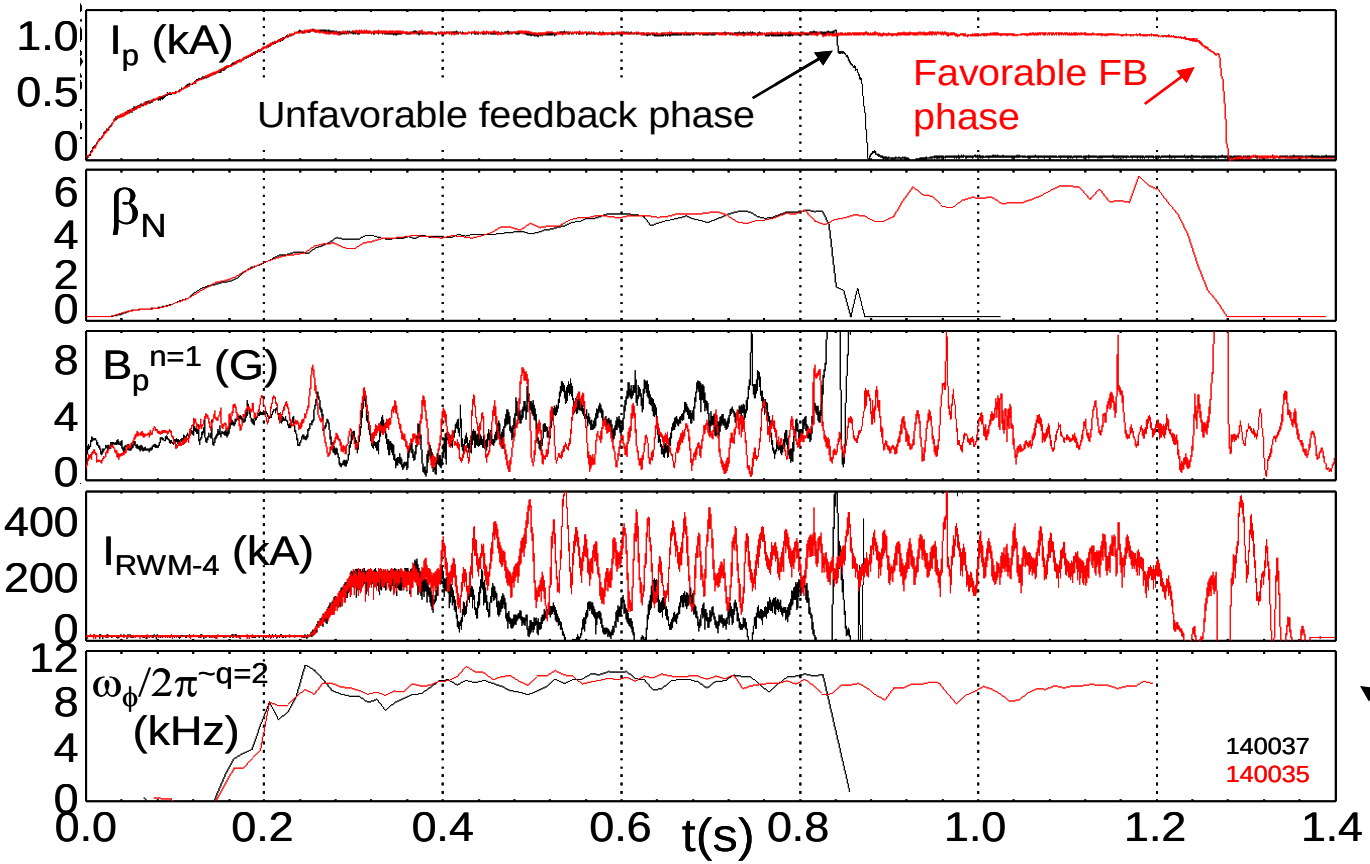


- Adding NBI port leads to greater match on some sensors

Black: experiment Red: offline RWM state space controller

New RWM state space controller sustains high β_N, low l_i plasma

RWM state space feedback (12 states)

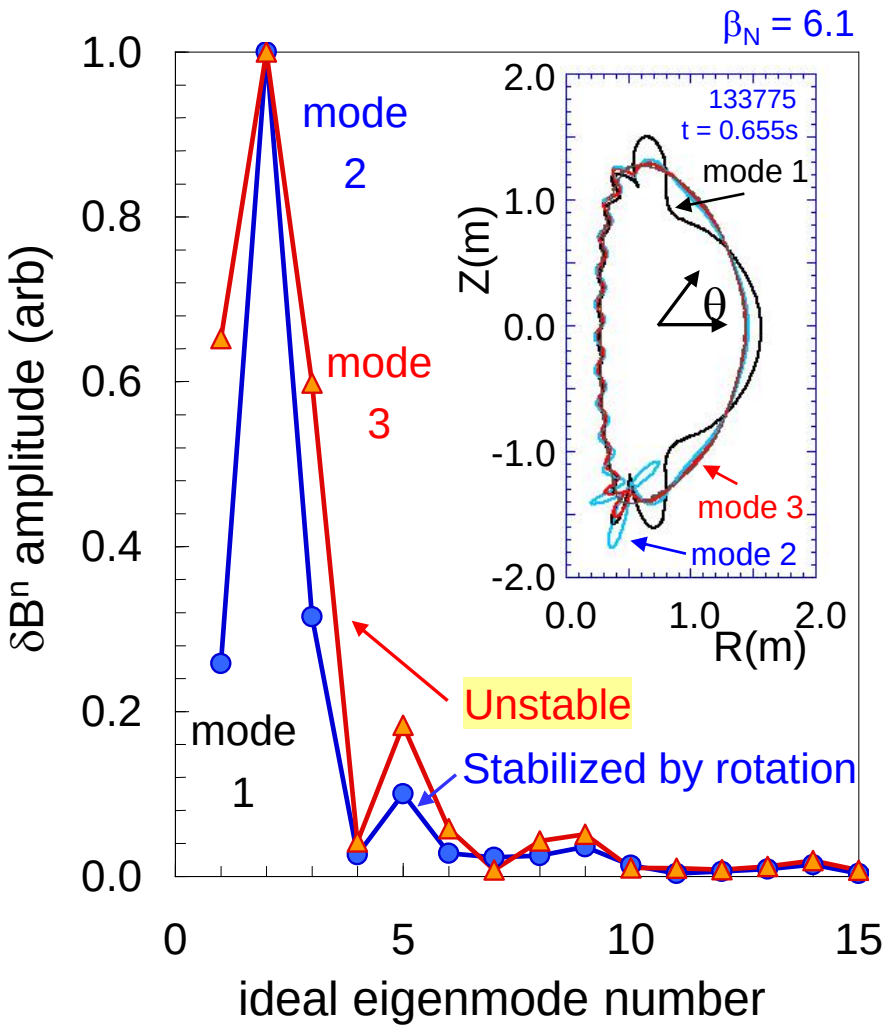


Successful First Experiments

- n = 1 applied field suppression
  - Suppressed disruption due to n = 1 field (See poster for detail)
- Feedback phase scan
  - Best feedback phase produced long pulse, β_N = 6.4, β_N/l_i = 13

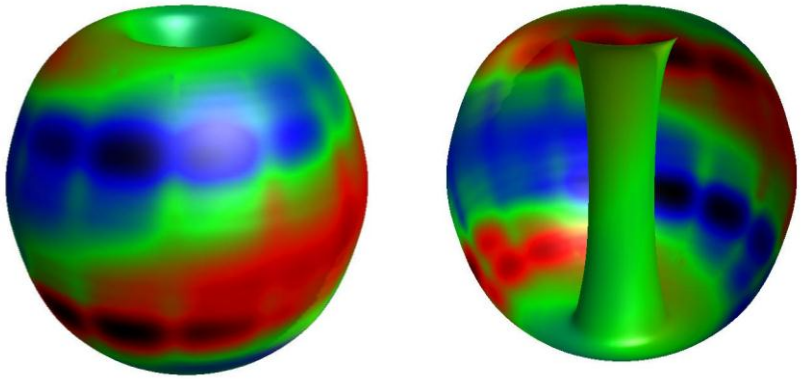
Multi-mode RWM computation shows 2nd eigenmode component has dominant amplitude at high β_N in NSTX stabilizing structure

δB^n RWM multi-mode composition



mmVALEN code

δB^n from wall, multi-mode response



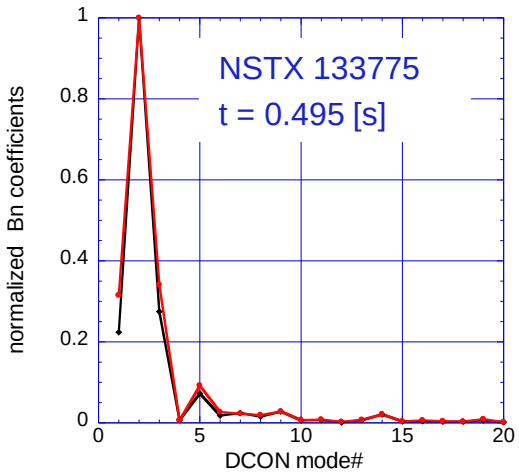
- NSTX RWM not stabilized by ω_ϕ
  - Computed growth time consistent with experiment
  - 2nd eigenmode ("divertor") has larger amplitude than ballooning eigenmode
- NSTX RWM stabilized by ω_ϕ
  - Ballooning eigenmode amplitude decreases relative to "divertor" mode
  - Computed RWM rotation ~ 41 Hz, close to experimental value ~ 30 Hz
- ITER scenario IV multi-mode spectrum
  - Significant spectrum for n = 1 and 2

BP9.00059 J. Bialek, et al.; see poster for detail

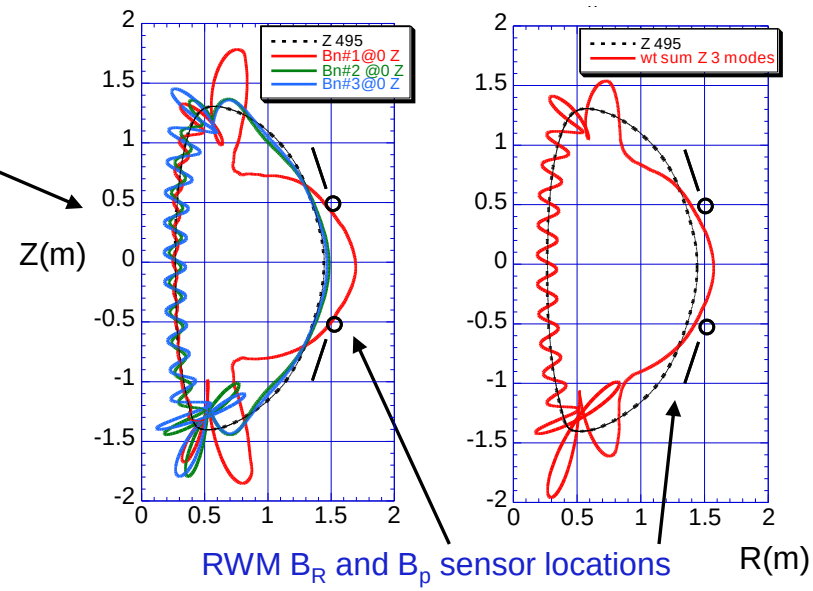
Upgrades of new RWM state space controller will leverage new 2nd SPA power supply to study physics effects

- 2nd SPA power supply allows independent control of the 6 RWM coils
- New RWM state space controller physics studies
  - Addition of n > 1 eigenfunction will then yield n = 1, 2 feedback, and higher n based on observer match to wall states
  - Test controller on various high performance targets
    - (i) fiducial, (ii) low li, (iii) higher A, (iv) snowflake divertor
    - Eigenfunction variations: e.g. does snowflake divertor configuration reduce divertor mode?
  - Compare controller with influence of wall vs. without influence of wall
- XP needs
  - Request: 1 run day
  - n > 1 control requires 2nd SPA, but other studies (e.g. add n = 2) do not require it

n = 1 multi-mode RWM spectrum (mmVALEN)

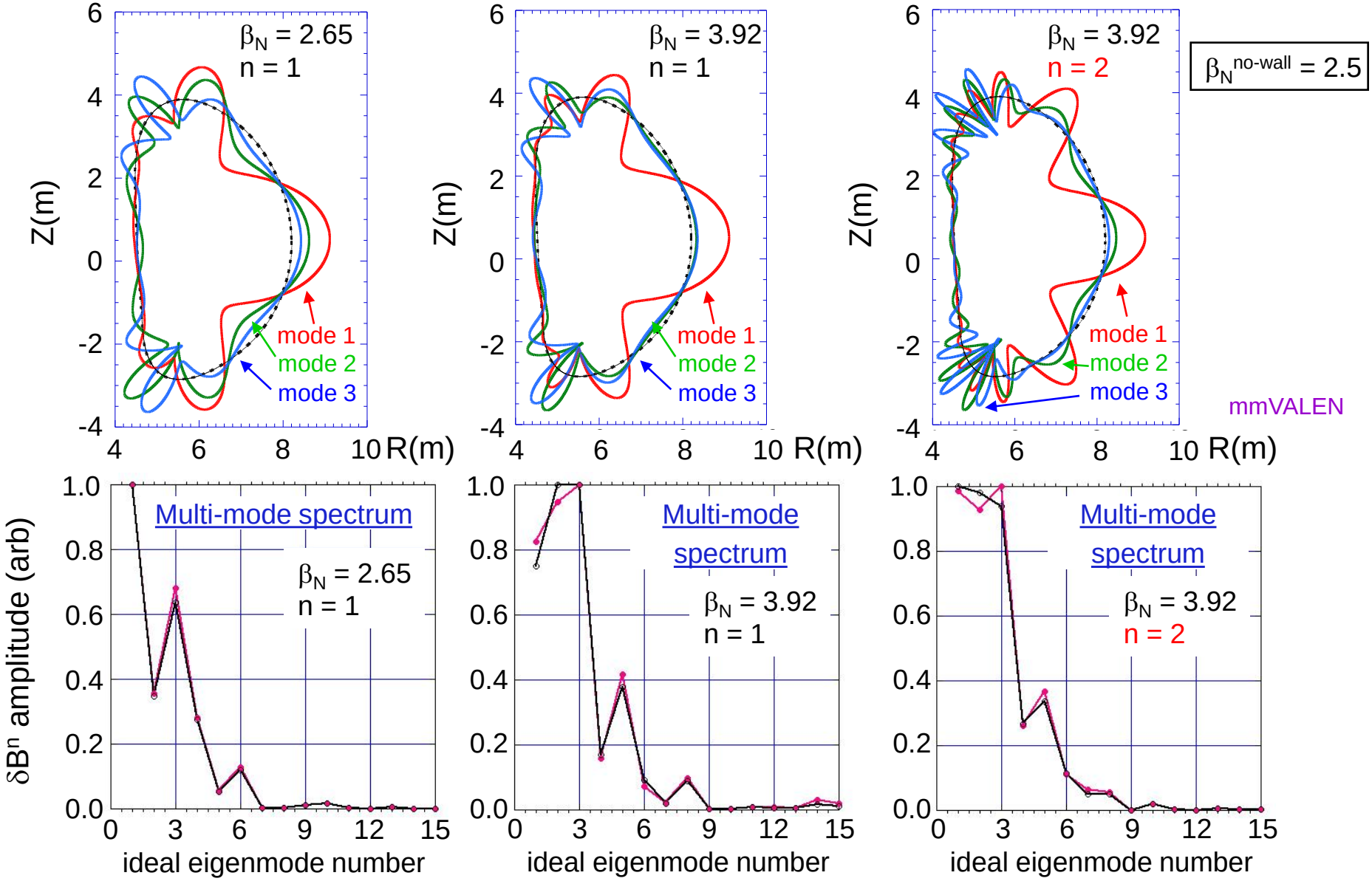


n = 1 ideal eigenfunctions for fiducial plasma



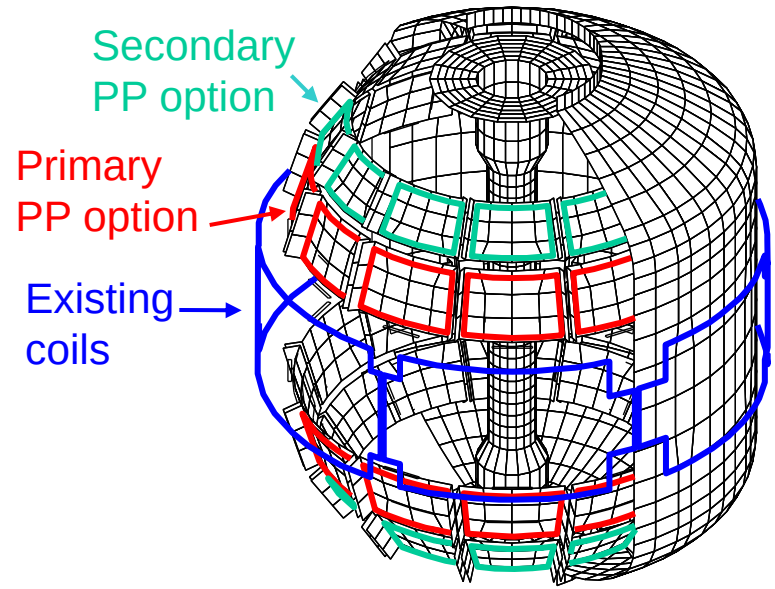
RWM B_R and B_p sensor locations

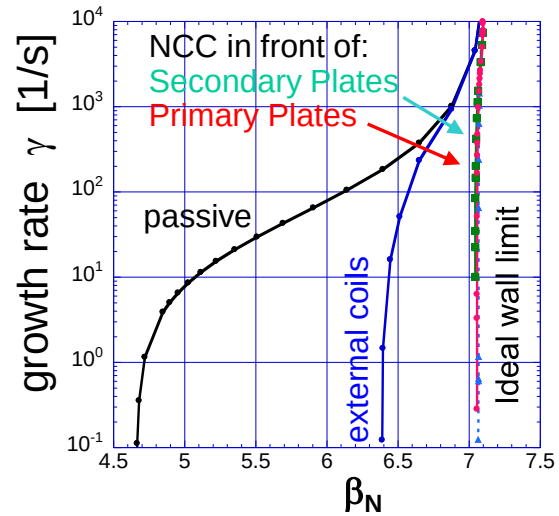
ITER Advanced Scenario IV: multi-mode RWM spectra computation shows significant ideal eigenfunction amplitude for several components



Proposed Nonaxisymmetric Control Coil (NCC) Will Expand Control Capabilities, Understanding of 3D Effects

- Non-axisymmetric control coil (NCC) – at least <u>four</u> applications:
  - RWM stabilization (n>1, up to 99% of n=1 with-wall β_N)
  - DEFC with greater poloidal spectrum capability
  - ELM control via RMP (dominant $n \leq 6$)
  - $n > 1$ propagation, increased V_ϕ control).
  - Similar to proposed ITER coil design.
- Addition of 2nd SPA power supply unit:
  - Feedback on n > 1 RWMs
  - Independent upper/lower n=1 feedback, for non-rigid modes.
- Design activities continue:
  - GA collaboration (T. Evans) computed favorable coil combinations/variations for RMP ELM suppression of NSTX plasmas
  - Columbia U. group assessing design for RWM stabilization capabilities compatible with ELM control



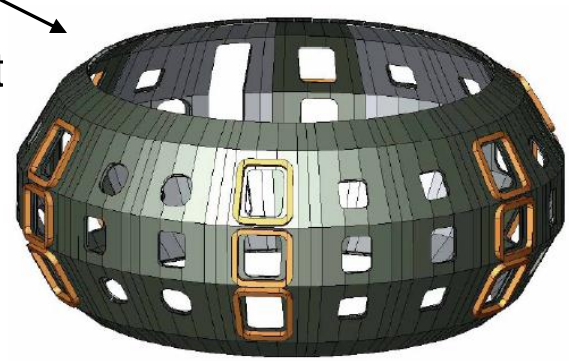


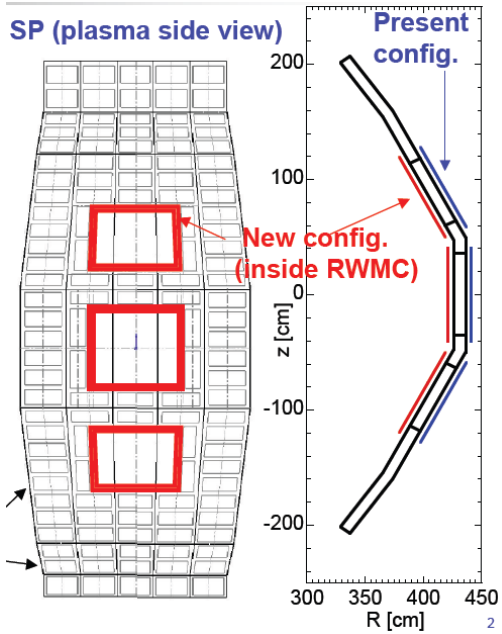
J. Bialek (Columbia U.)

XP: RWM control physics with partial control coil coverage

- Motivation
  - Effect of partial coil coverage (e.g. JT-60SA)*, and impact of internal coil loss (e.g. ITER) may lead to "mode non-rigidity" during RWM feedback – the effect on mode control needs to be understood
  - Provides key physics input for NSTX NCC design**
- Goals / Approach
  - RWM control in NSTX will be attempted with partial coverage of the RWM coils to test the physics of RWM mode rigidity
  - Leverage new independent control of the RWM coils
  - Determine the change in the computed multi-mode RWM spectrum and compare to experiment
  - Compare attempted control with both the RWM PID controller, and RWM state space controller
- Addresses
  - ITPA joint experiment MDC-2, MDC-17, MHD WG7
  - *Collaborative RWM stabilization research with JAEA (for JT-60SA); **physics input for NSTX NCC design

JT-60SA passive plates and RWM control coils





Some comments / suggestions on measurement interval and location of plasma rotation measurements for feedback: non-resonant braking

- Measurement interval
  - For non-resonant breaking at "usual" braking levels (0.6 – 0.9kA, n = 3 braking current), n = 3 braking occurs on 10's of ms timescales
    - See slide 2, left-hand frame BEFORE the faster braking occurs
  - At sufficiently low plasma rotation, NTV strength increases (due to being more strongly in $1/\nu$ regime, and/or superbanana plateau regime). In this case, significant braking observed in 10 ms timescale
    - See slide 2, center frame
  - Ron Bell suggests that a 4 channel system could have 1.5ms time resolution
    - seems like an adequate starting point for analysis, may be a fine target design
- Location of measurements
  - One channel at peak of NTV torque (R ~ 1.35m): maximum NTV actuation
  - One channel near core (R ~ 1.0m) (to guide overall breaking level)
  - From here – decide what we want to control (suggest V_ϕ shear)
    - Would suggest channels at ~ R = 1.3 m, 1.4 m (1.4 m to handle larger plasmas)
    - No channels well outside R = 1.4 m, since no strong NTV due to reduced T_i
  - Could instead use one channel at R ~ 1.2m if one wants to fit a V_ϕ profile
  - OR (perhaps best): if NBI is used as a key actuator, could put measurements where sources B and C deliver peak NBI torque (get position from TRANSP).