Columbia U. Group – NSTX-U Macrostability TSG XPs

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Y.S. Park, (et al…)

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NSTX-U Research Forum

February 25th, 2015

PPPL

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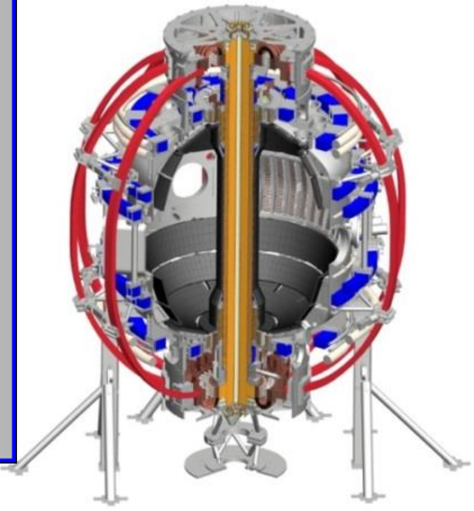

- *Culham Sci Ctr*
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V1.2

Columbia U. Group 2015 Macrostability TSG XPs (Short Summary)

- XPs (related XPs assigned numbers for "2011 run")
  - RWM stabilization dependence on neutral beam deposition angle (~XP1149) (Berkery)
  - RWM stabilization physics at reduced collisionality (~XP1148) (Berkery)

- -

  - RWM state space active control physics (independent coil control) (~XP1145) (Sabbagh)
  - RWM control physics with partial control coil coverage (JT-60SA) (~XP1147) (Y-S Park)
  - RWM PID control optimization based on theory and experiment (~XP1111) (Sabbagh)
  - RWM state space active control at low plasma rotation (~XP1146) (Y-S Park)
  - Neoclassical toroidal viscosity - reduced ν (independent coil control) (~XP1150) (Sabbagh)
  - NTV steady-state rotation at reduced torque (HHFW) (~XP1062) (Sabbagh)
  - Multi-mode error field correction using the RWMSC (to follow initial EFC XP)
  - NTM Entrainment in NSTX-U (Y.S. Park)
- Piggyback XPs
  - Disruption PAM characterization, measurements, and criteria (Sabbagh, for DPAM WG)

<u>NOTE</u>: - some shot plans <u>already scoped out</u> in web submissions (not repeated here)

- run day requests mostly assume leveraging "2nd NBI XP", "Ip/Bt scaling XP"

XP: RWM state space active control physics (independent coil control) – Sabbagh, et al.

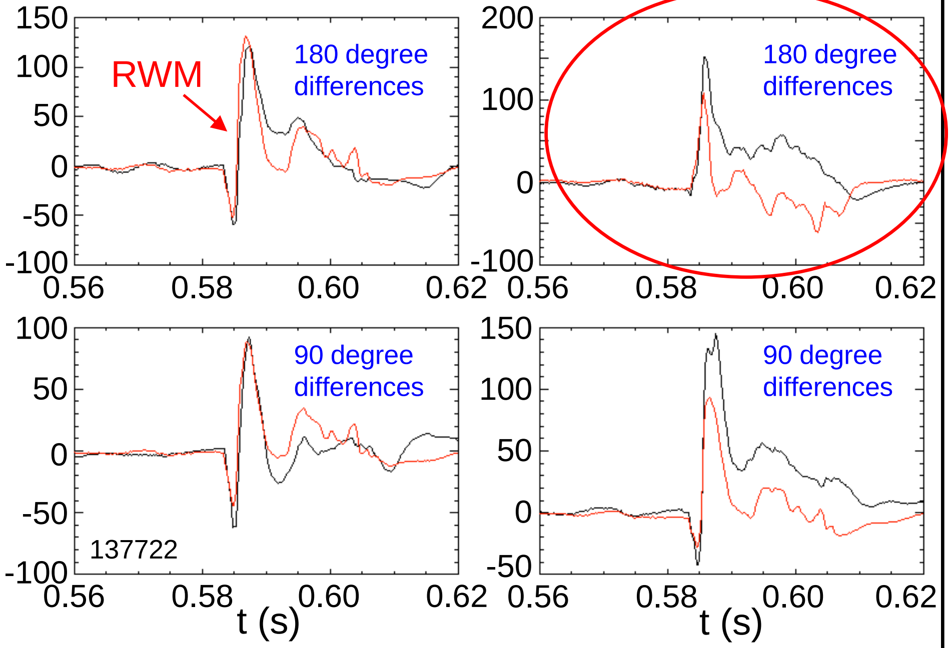
- Motivation
  - RWM state space controller (RWMSC) allowing influence of conducting structures, plasma mode shape / response expected to improve control performance, allows greater shielding of control coils needed in future devices
  - Improve capability of present NSTX-U RWMSC by using new 2nd SPA, more plasma modes, etc.

- Goals / Approach
  - Examine control aspects of different high performance target plasmas
    - Key step to prepare the RWMSC for general use in the future
  - Determine control physics advantages of including influence of wall, choice of input eigenfunction set, inclusion of $n > 1$ eigenfunctions
  - Determine effect of control with 6 independent RWM coils
  - Determine influence of reducing effect of conducting structure
  - Examine influence of adding $n = 1$ RWM PID control using B_r sensors

- Addresses
  - NSTX Research Milestones R(15-3),JRT-16
  - ITPA joint experiments MDC-17, MDC-21

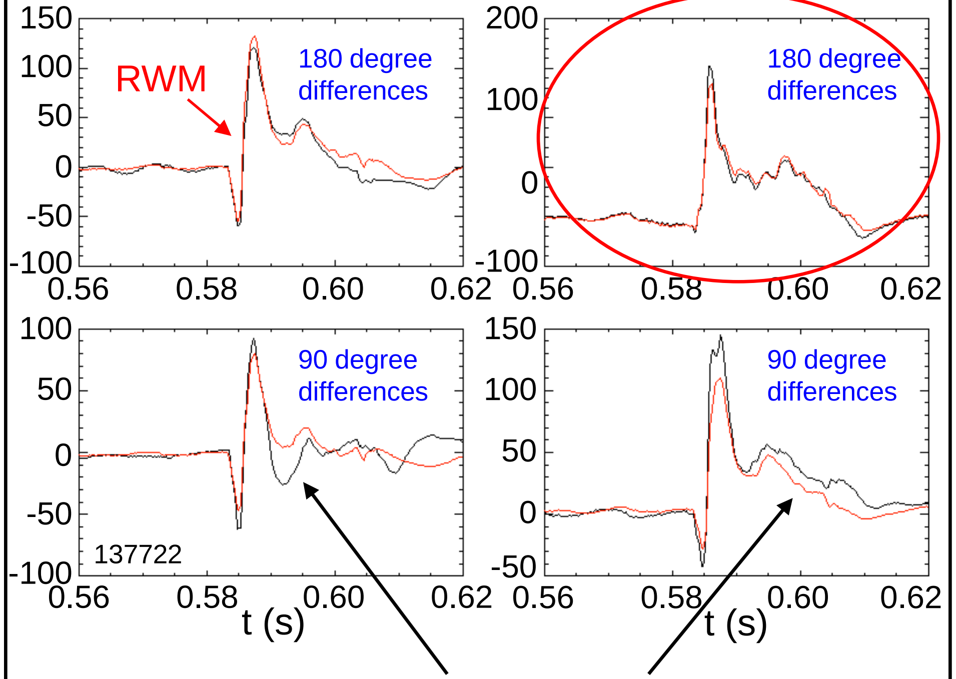
Increased number of states in RWM state space controller improves match to sensors over entire mode evolution

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



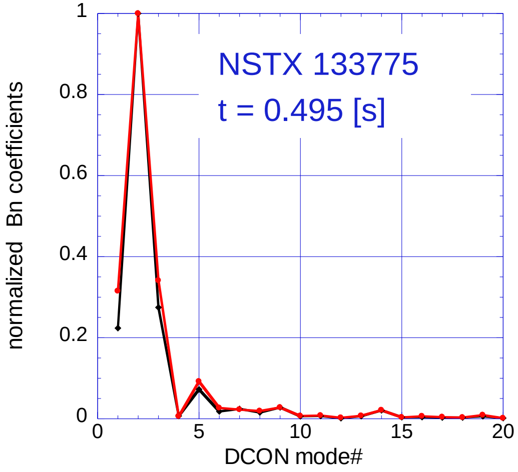
- Some 90 degree differences not as well matched
    - Indicates potential need for an n = 2 eigenfunction state
    - Attempt n = 2 control in 2015

Black: experiment Red: offline RWM state space controller

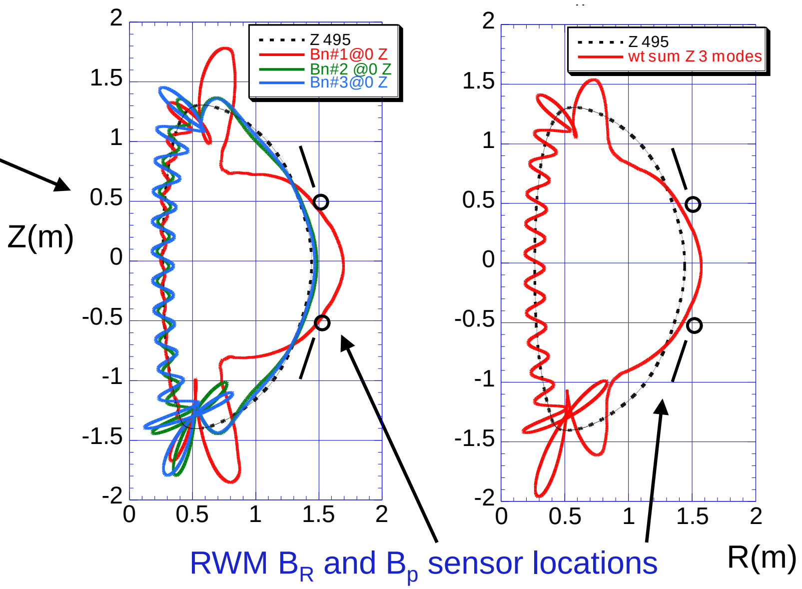
Upgrades of new RWM state space controller will leverage new 2nd SPA power supply to study physics effects

- 2nd SPA power supply allows independent control of the 6 RWM coils
  - We need new phase and gain scans (test new control matrices) – this was not performed in 2011
- 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
    - E.g. (i) fiducial, (ii) low li, (iii) 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: 1.5 run days

n = 1 multi-mode RWM spectrum (mmVALEN)



n = 1 ideal eigenfunctions for fiducial plasma



RWM B_R and B_p sensor locations

XP: RWM control physics with partial control coil coverage – Y.S. Park, et al.

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
- NSTX active RWM control failed with 2 coils missing

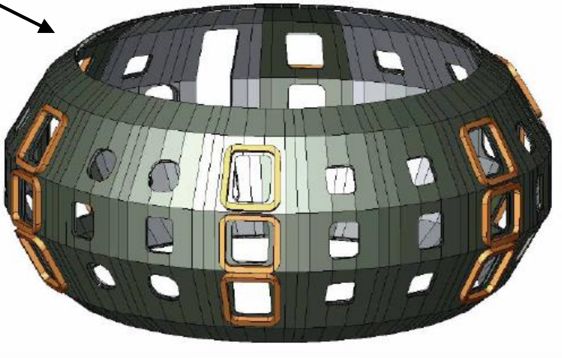
Goals / Approach

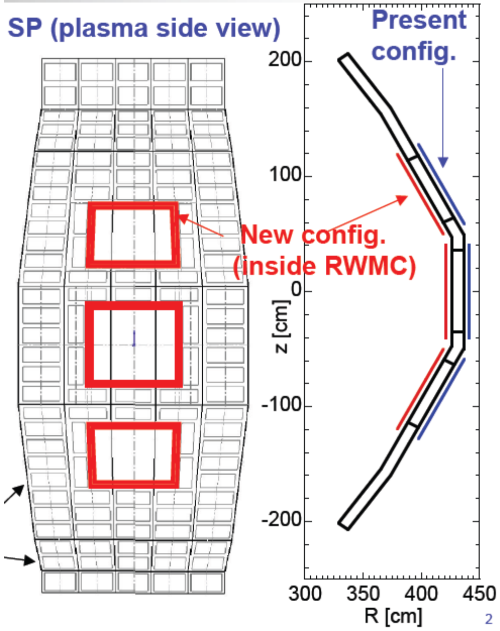
- RWM control in NSTX will be attempted with partial coverage of the RWM coils to test the physics of RWM mode rigidity
- Leverage new independent control of the RWM coils
- Determine the change in the computed multi-mode RWM spectrum and compare to experiment
- Compare attempted control with both the RWM PID controller, and RWM state space controller

Addresses

- *Collaborative RWM stabilization research with JAEA (for JT-60SA) – IEA joint research task
- ITPA joint research MDC-17, MDC-21

JT-60SA passive plates and RWM control coils





Request:
1 run day

XP: RWM PID control optimization based on theory and experiment – Sabbagh, et al.

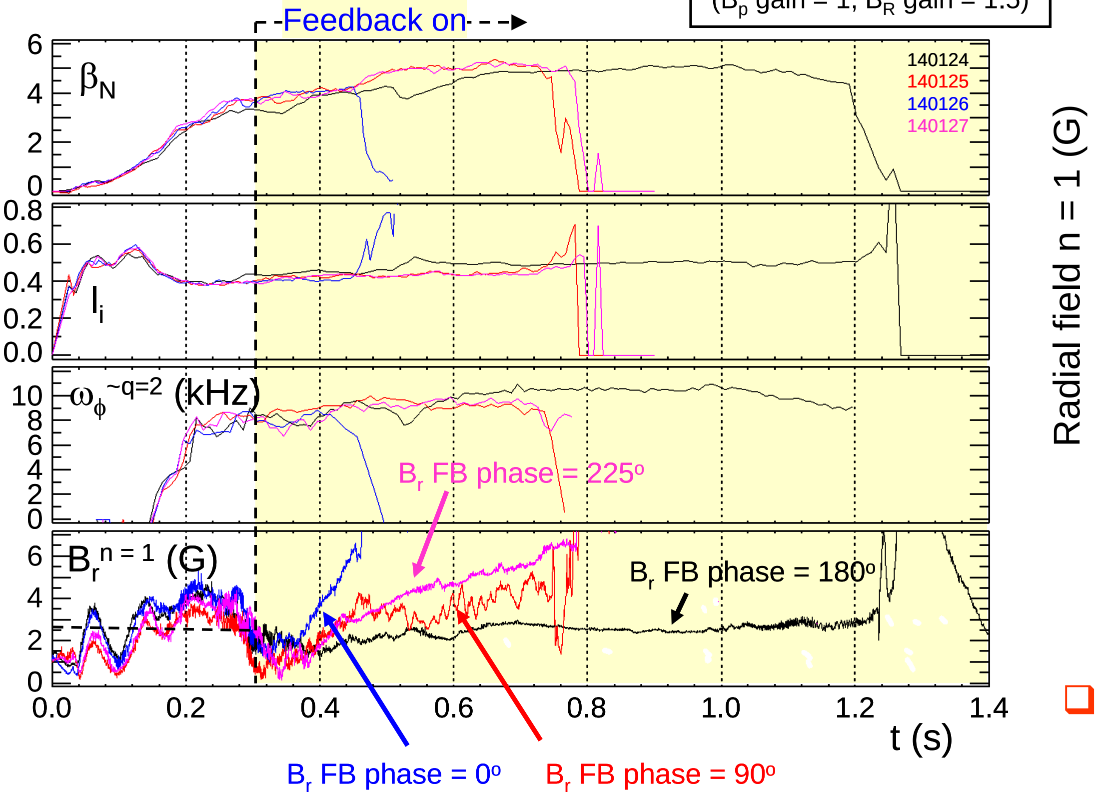
- **Motivation**
  - Experiments using n = 1 RWM control in 2010, and subsequent analysis using the VALEN code show that some settings for control using dual B_R and B_p sensor feedback were optimal, others could have been improved
  - Active RWM PID control settings need to be re-optimized for NSTX-U
  - Support general NSTX-U experiments by optimizing RWM PID control
- **Goals / Approach**
  - Optimize n = 1 RWM PID control focusing on scans of key parameters
    - Vary B_p feedback phase, B_R feedback gain – which differ in the most in the analysis from the experimental settings
    - B_p sensor gain will also be examined in this experiment (never scanned with r/t AC compensation).
    - Perform on high performance target plasmas (fiducial; low l_i; snowflake)
- **Addresses**
  - General support for NSTX-U high beta experiments, R(15-3), JRT-16
  - ITPA joint experiment MDC-17

Request: 0.5 – 1.0 run days (depends on desired targets, number of parameter variations/shot)

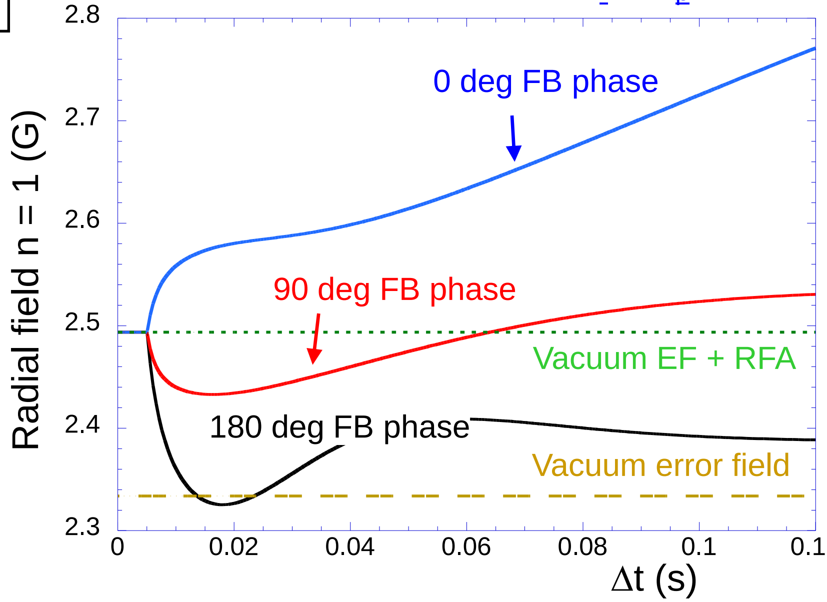
RWM B_r sensor n = 1 feedback phase variation shows superior settings when combined w/B_p sensors; good agreement w/theory so far

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 (experimental) 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”)
  - Now examining plasma response model variation
    - impact of “s”, and diff. rotation (“α”) on results

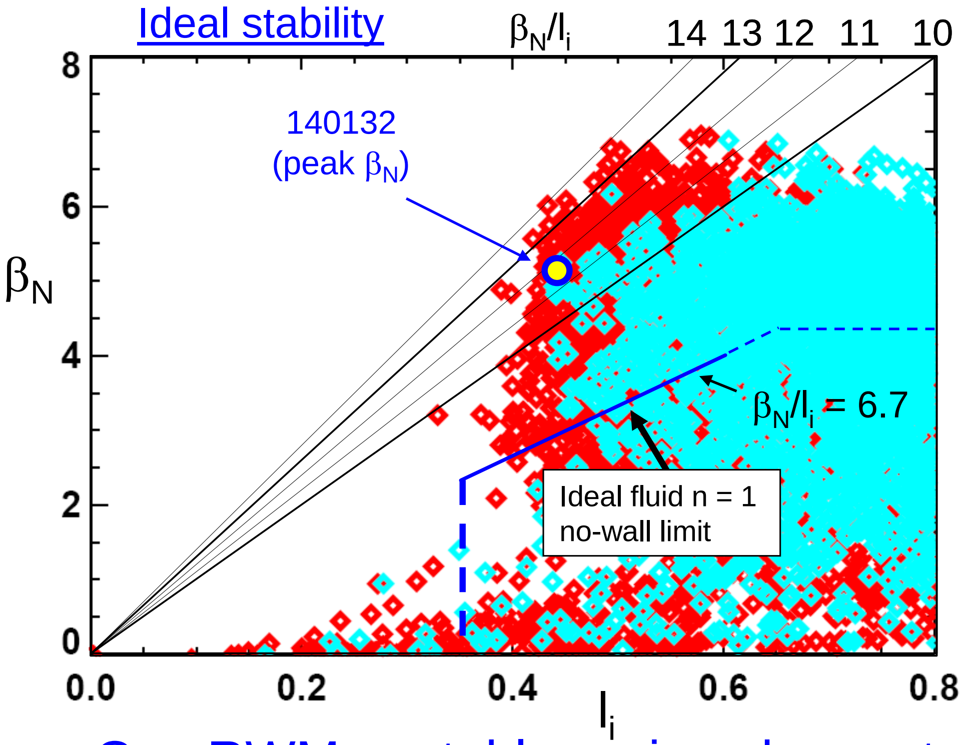
XP: RWM state space active control at reduced plasma rotation – Y.S. Park, et al.

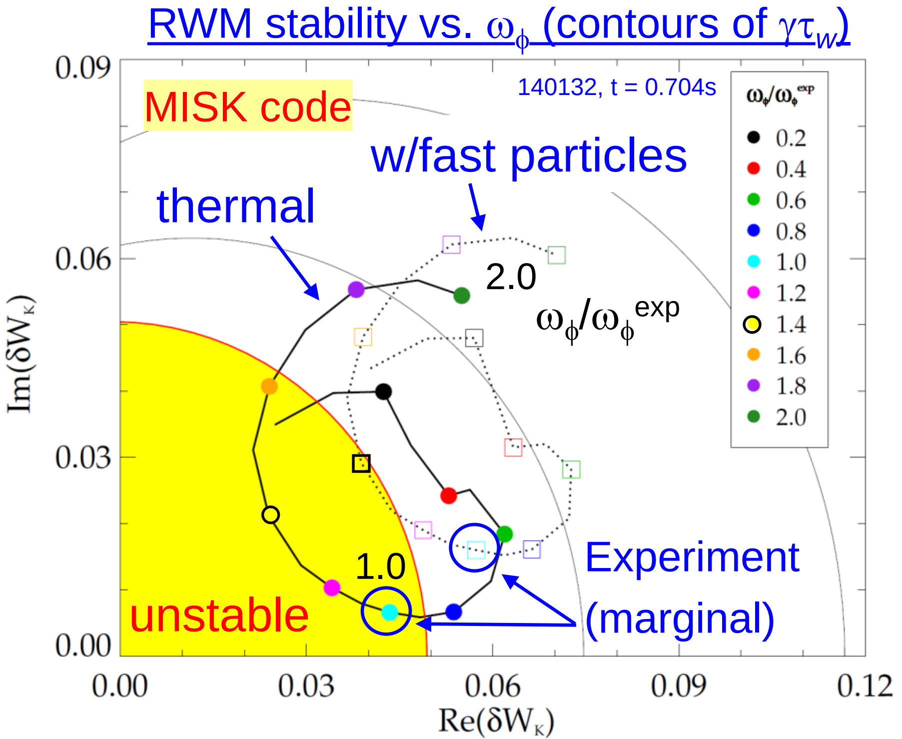
- Motivation
  - Present theory shows ITER advanced scenario plasmas are kinetic RWM unstable just above the n = 1 no wall limit, and alpha particle stabilization is required; Amount of kinetic resonance stabilization at low rotation is uncertain

- Goals / Approach
  - Demonstrate RWM control over a greater range of plasma rotation using RWM state space control (incl. (i) low ω_ϕ, (ii) intermediate ω_ϕ at marginal stability)
  - Determine control physics differences of varying input eigenfunction set (including allowance of n > 1 eigenfunctions) at various ω_ϕ
  - Vary key controller parameters to examine influence on stability
  - Test compatibility with applied fields for NTV rotation damping
    - Ensure controller doesn't reduce n = 2, n = 3 braking field significantly
  - Examine influence of adding n = 1 RWM PID control using B_r sensors

- Addresses
  - NSTX Research Milestones R(15-3)
  - ITPA joint experiment MDC-17, MDC-21

Kinetic stability calculations show reduced stability in low l_i target plasma as ω_ϕ is reduced; also at low ω_ϕ


Ideal stability


RWM stability vs. ω_ϕ (contours of $\gamma\tau_w$)

- Can RWM unstable regions be controlled using the RWMSC, including low rotation?
  - Ideal stability analysis shows high margin over no-wall limit
    - RWM stabilization by kinetic effects large
  - MISK: RWM marginal stability at various ω_ϕ
    - Demonstrate control in these regions!

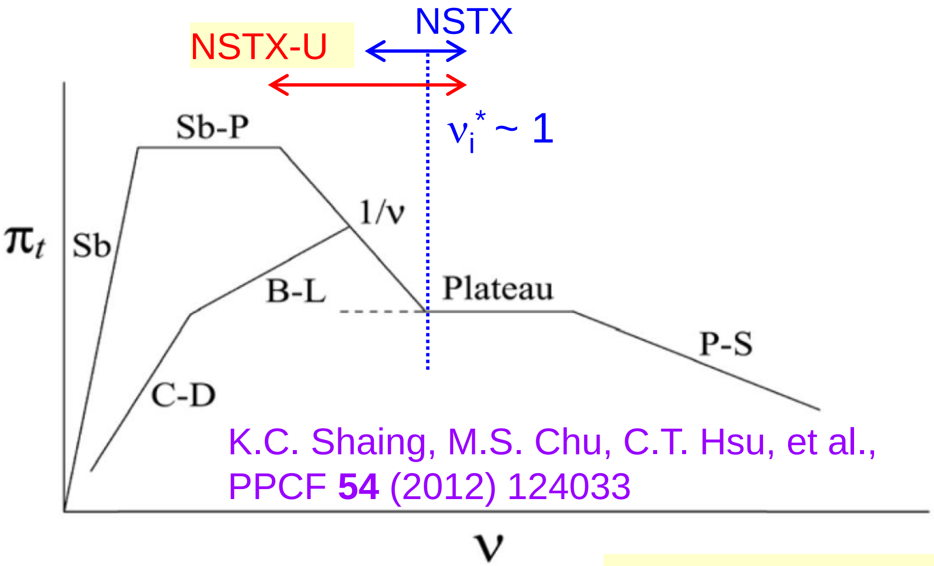
- Find RWMSC matrices most effective for control
  - Includes n > 1 control, variation of eigenfunctions used in controller, etc.

- Request: 1 run day

XP: Neoclassical toroidal viscosity at reduced collisionality (independent coil control) – Sabbagh, et al.

- Motivation
  - Experimentally, the dependence of neoclassical toroidal viscosity (NTV) at low collisionality is not well known
  - Understanding important for NSTX-U V_ϕ control, other tokamaks, future devices
- Goals / Approach
  - Examine the dependence of NTV on ion collisionality
    - expected to increase with decreasing ν_i from present experiments, and theory
  - Determine if superbanana plateau increase of NTV depends on ν_i
  - Operate with pre-programmed n = 2, 3 applied fields for V_ϕ feedback control testing at reduced ν_i
- Addresses
  - NSTX Milestones R(15-3), closed-loop rotation control with 3D fields
  - ITPA joint experiment MDC-21

NTV strength varies with plasma collisionality ν, δB^2, rotation



K.C. Shaing, M.S. Chu, C.T. Hsu, et al., PPCF **54** (2012) 124033

NTV force in “1/ν” collisionality regime

$$\left\langle \hat{e}_t \bullet \vec{\nabla} \bullet \overleftrightarrow{\Pi} \right\rangle_{(1/\nu)} = B_t R \left\langle \frac{1}{B_t} \right\rangle \left\langle \frac{1}{R^2} \right\rangle \frac{\lambda_{1i} p_i}{\pi^{3/2} \nu_i} \varepsilon^{3/2} (\omega_\phi - \omega_{NC}) I_\lambda$$

“offset” rotation

$T_i^{5/2}$

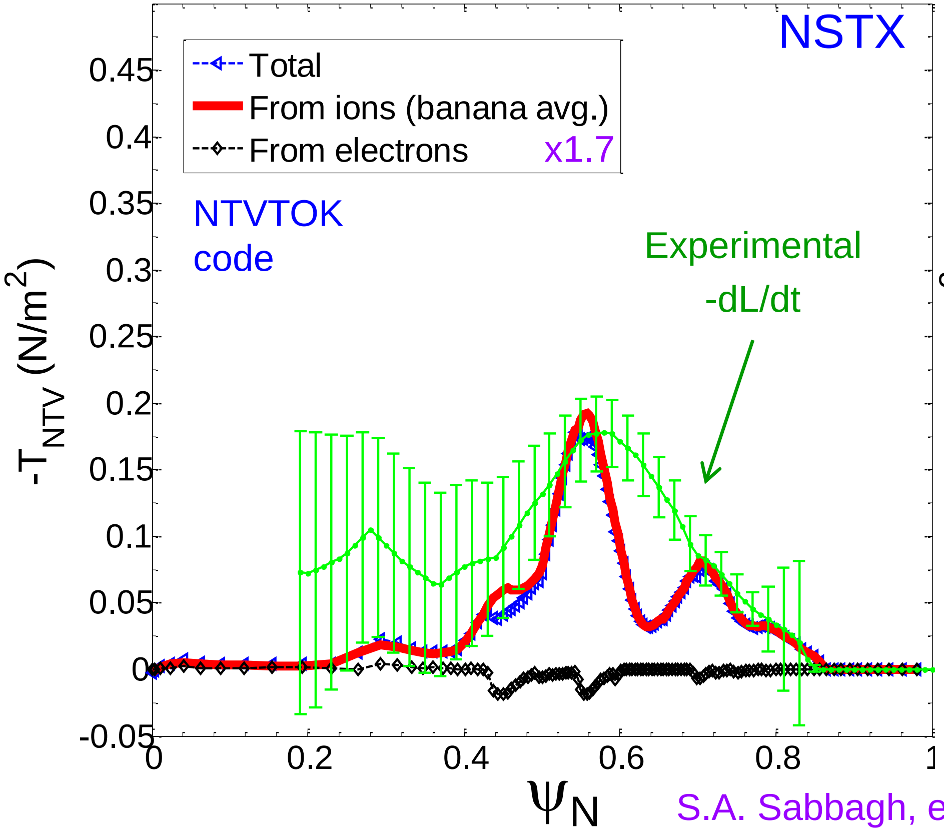
plasma rotation

1/aspect ratio (compare to KSTAR)

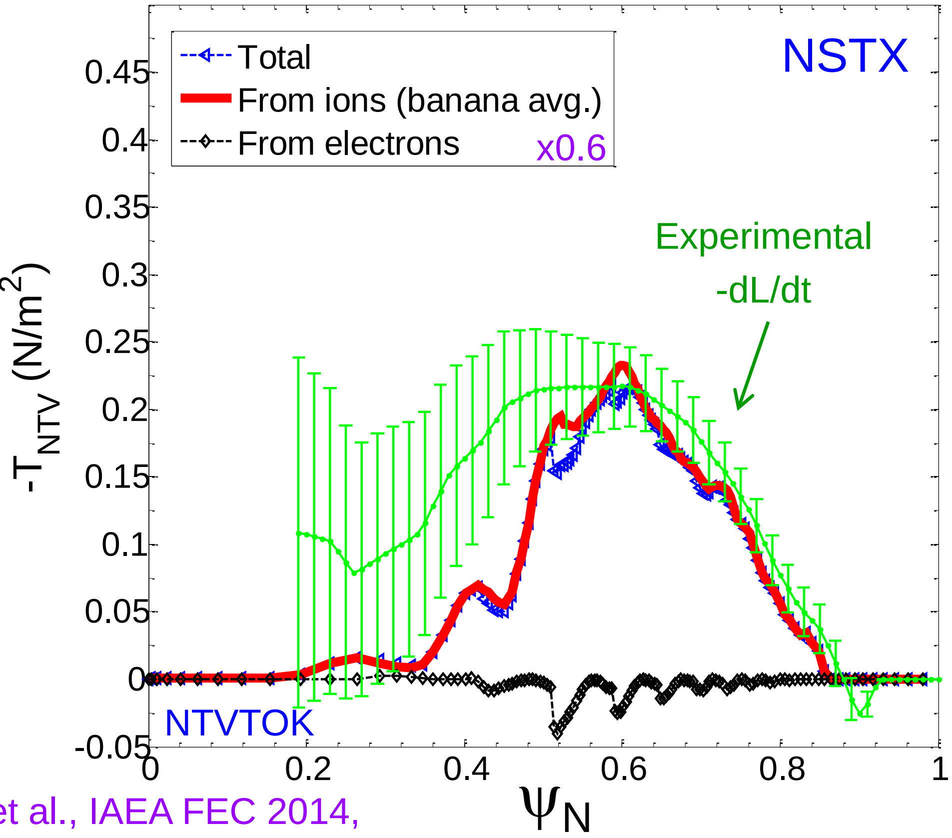
K.C. Shaing, et al., PPCF **51** (2009) 035004

Measured NTV torque density profiles quantitatively compare well to computed T_{NTV} – NTVTOK code interfaced to NSTX-U

n = 2 coil configuration



n = 3 coil configuration

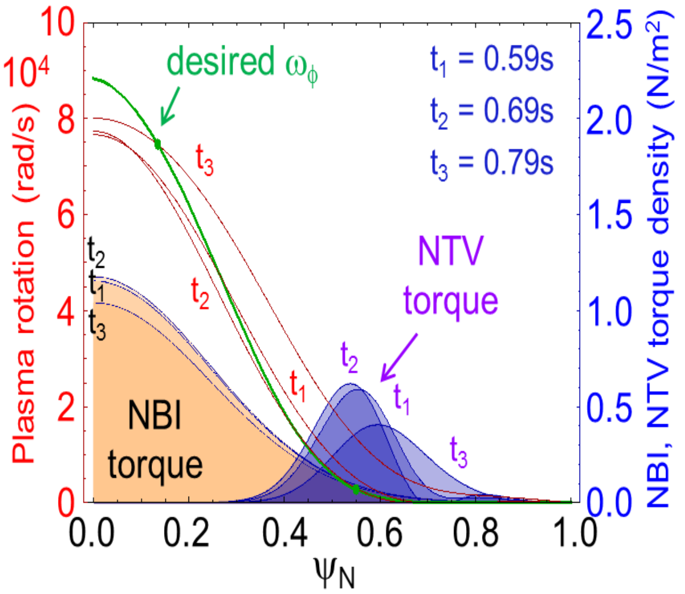


S.A. Sabbagh, et al., IAEA FEC 2014, paper EX/1-4

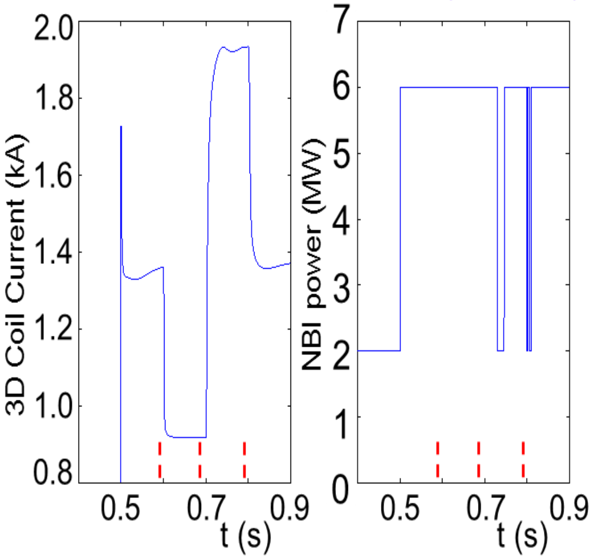
- Scale factor ($(dL/dt)/T_{NTV}$) = 1.7 and 0.6 (for cases shown above) – O(1) agreement
- Comparison to full Shaing, et al. theory with NTVTOK code (applicable for all collisionality (as shown above) is possible to compute between shots for NSTX-U
- Comparisons will also be made to other NTV codes (e.g. by J-K. Park, K. Kim, Z. Wang)

NTV experiment at reduced ν is a key step for closed-loop V_ϕ feedback using 3D fields in NSTX-U

Rotation evolution and NBI and NTV torque profiles

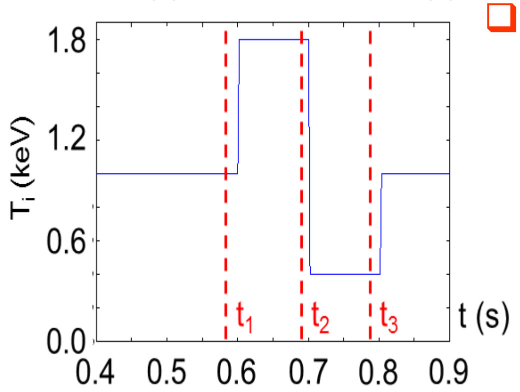


3D coil current and NBI power (actuators)



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

K1 = 0, K2 = 2.5



- NTV torque profile model for feedback dependent on ion temperature

I. Goumiri (PU), S.A. Sabbagh (Columbia U.), D.A. Gates (PPPL)

S.A. Sabbagh, et al., IAEA FEC 2014, paper EX/1-4

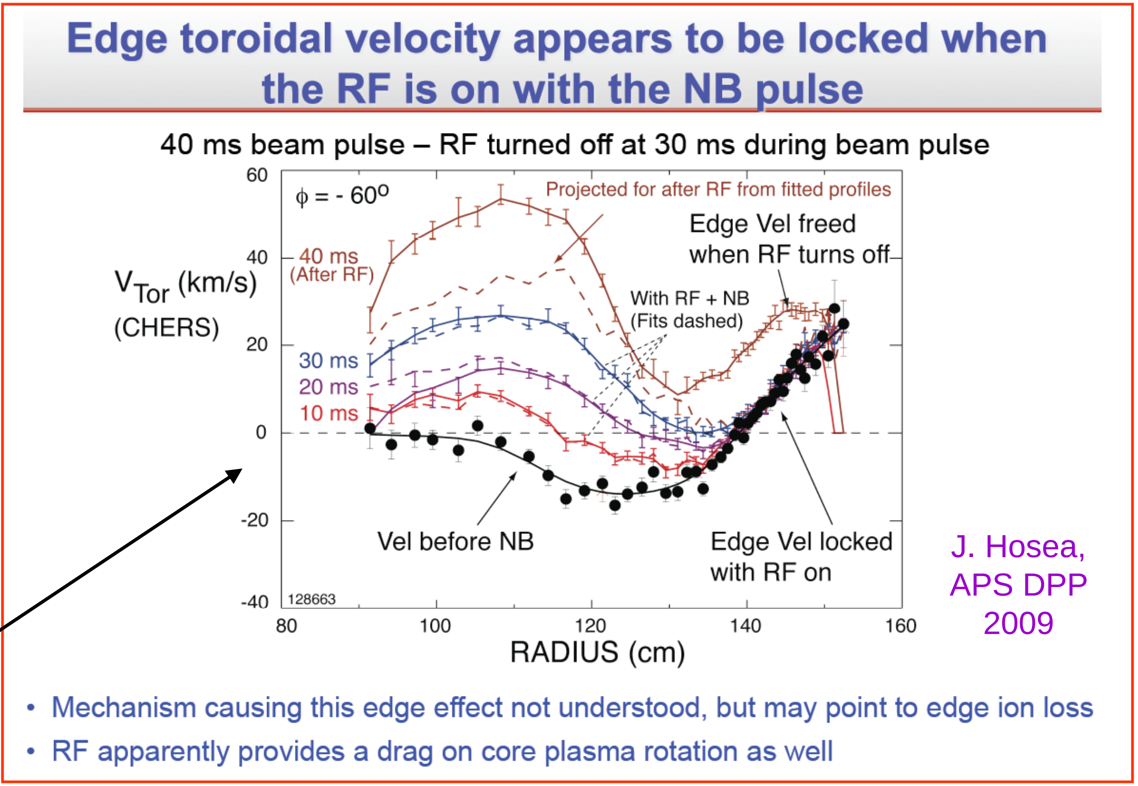
- Expect stronger NTV torque at higher T_i ($-d\omega_\phi/dt \sim T_i^{5/2}\,\omega_\phi$)
  - Initially shown in NSTX
    S.A. Sabbagh, et al, NF **50** (2010) 025020
  - Shown in our recent KSTAR XPs
    Y.S. Park, et al, IAEA FEC 2014, paper EX/P8-05
- Present XP
  - Operate with larger change in ν_i
  - Attempt to reach quasi-steady-state ω_ϕ for each ν_i
  - Use braking fields envisioned for V_ϕ FB
- Request: 1 run day

XP: NTV steady-state offset velocity at reduced torque with HHFW – Sabbagh, et al.

- Motivation
  - Measure and understand neoclassical toroidal viscosity (NTV) steady-state offset velocity physics to gain confidence in extrapolation of the effect to future devices
    - Background: NSTX low ω_ϕ NTV experiments with co-NBI + non-resonant magnetic braking do not show NTV steady-state offset velocity to be in the counter-I_p direction (e.g., shown in DIII-D (Garofalo, PRL 2008), claimed consistent with theory)
- Goals
  - Complete XP1062, partially run in 2010 (**but excluded HHFW portion of shot list**)
  - Determine NTV offset rotation in plasmas with no, varied NBI torque (HHFW heated)
    - Use demonstrated technique to measure ω_ϕ in RF plasmas
    - Use n = 3 applied field, compare to results with n = 2 applied field configuration
  - Demonstrate for the first time NTV with strong electron component
  - Key code validation in new regime: for the NTVTOK code, and other NTV codes
  - Determine if low ω_ϕ (low ω_E superbanana plateau (SBP) regime) can be reproduced during the NBI portion of these discharges with non-resonant braking
    - Can attempt to measure NTV steady state offset velocity this way as well when varying non-resonant applied field magnitude
- Addresses
  - NSTX Milestone R(15-3)
  - Desire to understand potential sources of momentum input for ITER

Zero input torque ω_ϕ profile diagnosed in 2009 RF XPs

- Determine NTV offset rotation – RF approach
  - Generate ω_ϕ with RF at highest T_i, W_{tot} possible, diagnose similar to Hosea/Podesta 2009
  - Repeat for different *initial* values of n = 3 (and/or 2) field, determine if pre-NBI ω_ϕ changes
  - Note that if NTV offset is indeed only in counter-I_p direction, the ω_ϕ profile will change (it's presently counter in core, co at the edge
- Attempt to maintain near-zero ω_ϕ during NBI phase
  - New way to enter/sustain low ω_E SBP regime



Edge toroidal velocity appears to be locked when the RF is on with the NB pulse

40 ms beam pulse – RF turned off at 30 ms during beam pulse

- Mechanism causing this edge effect not understood, but may point to edge ion loss
- RF apparently provides a drag on core plasma rotation as well

J. Hosea, APS DPP 2009

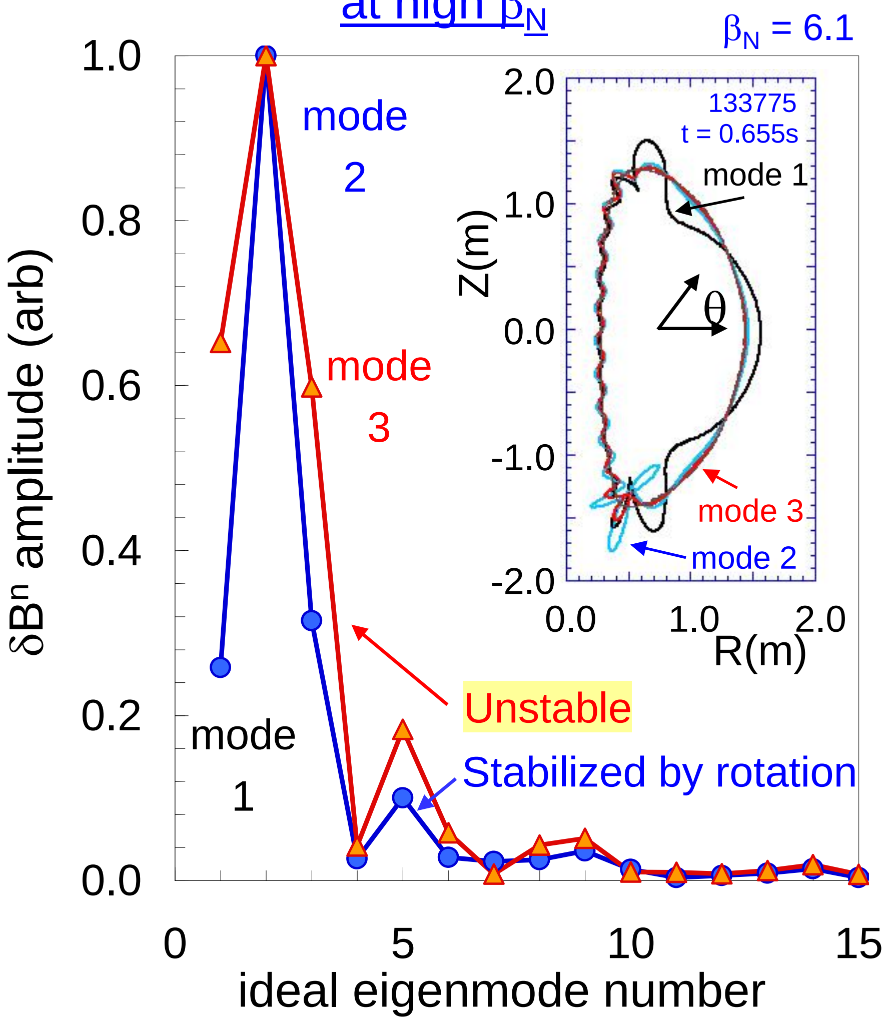
- Since SBP regime yields maximum NTV
  - Entering it by lowering ω_ϕ yielded an observed increase in NTV without mode locking (2009-10)
  - Conversely, attempt to measure decrease in NTV as SBP regime is exited
- Request: 0.5 – 1.0 run days (depends on goals, and leveraging RF+NBI development)

XP: Multi-mode error field correction with the RWM state-space controller (RWMSC) – Sabbagh, et al.

- Motivation
  - Produce multi-mode error field correction for the first time using the inherent capability of the RWMSC to include multiple modes (different n; different poloidal spectra)
  - High interest for ITER and other tokamaks
- Goals / Approach
  - Demonstrate reduction of applied n = 1, 2, 3 error fields
    - Test the need for matching *n* values between applied field and modes
    - Test the influence of wall states in the error field reduction effectiveness
  - Demonstrate reduction of NSTX-U intrinsic error fields
    - Use “best” set of RWMSC control matrices determined from above step (including n > 1, and sufficient number of wall states)
  - Demonstrate reduction of dynamic error fields (at higher β_N)
    - Determine if increase of plasma permeability is required in control model for best performance at increased β_N
- Addresses
  - Milestone R(15-3), JRT-16
  - ITPA joint experiment MDC-17, MDC-19, MDC-21

Multi-mode RWM computation shows 2nd eigenmode component has dominant amplitude at high β_N (vs. 1st eigenmode dominant at lower β_N)

NSTX δB_n RWM multi-mode spectrum at high β_N



mmVALEN code

- Multi-mode error field correction experiment differs from RWM active control experiments
  - Theoretically, the multi-mode spectrum is simplified away from RWM marginal stabilty points
    - Are different control matrices needed for the best error field correction compared to RWM control at marginal stability?
  - Compare effect on RWM PID and RWMSC for error field correction
    - PID should be more subject to failure by n > 1 mode content, error in tracking toroidal phase
    - State space controller with n > 1 eigenfunctions and wall effects is expected to provide greater EFC

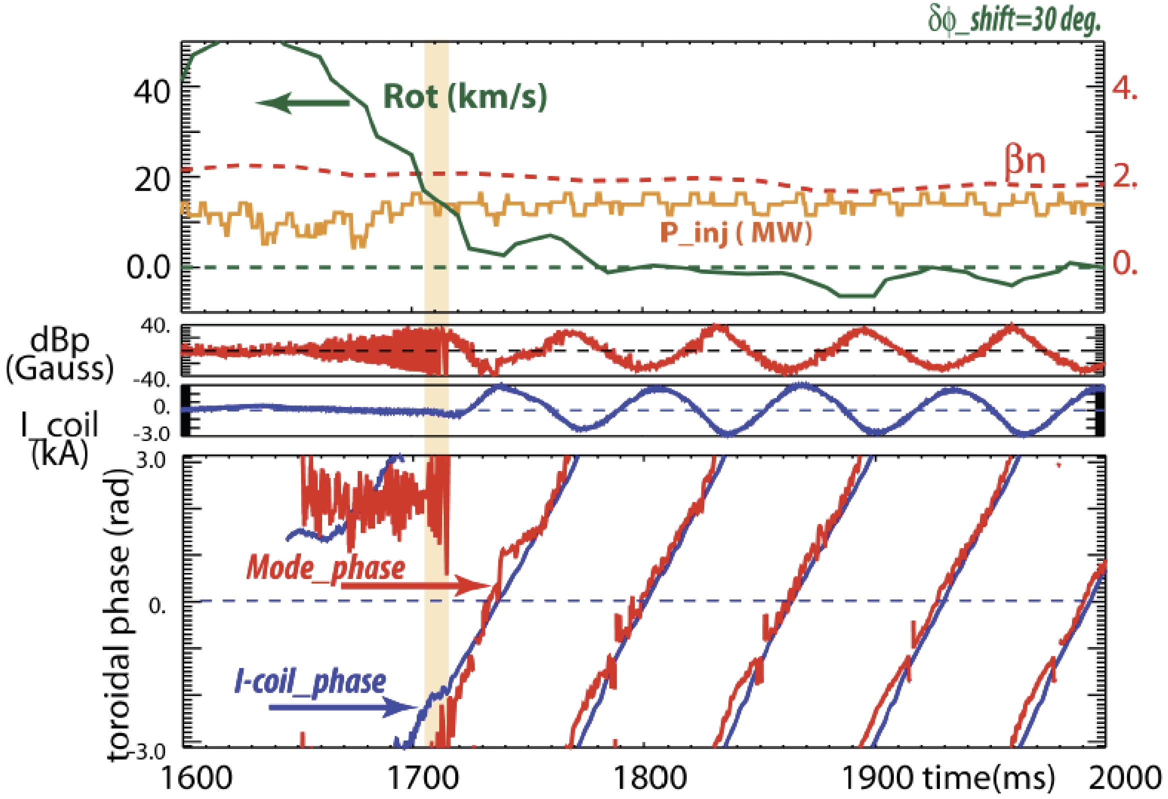
- Request: 1 run day (should run after PID EFC experiment (by C. Myers))

XP: NTM Entrainment on NSTX-U – Y.S. Park, et al.

- Motivation
  - NTM "entrainment", in which tearing modes are partially controlled to avoid locking, can be used for disruption avoidance (or at least in conjunction with controlled shutdown)
- Goals / Approach
  - Attempt entrainment for the first time on NSTX-U with a somewhat novel technique
    1. Slow NTM (attempt both 3/1, and 2/1 modes) using non-resonant NTV (n = 3) to slow the plasma
    2. With NTM slowed to near, or below the critical rotation speed for mode locking, apply an n = 1 AC field to attempt to keep the NTM rotating at low frequency ~ 50Hz (far slower speed than the critical mode rotation speed for locking)
    3. Attempt to use n = 1 "slow" feedback with a phase that sustains the n = 1 mode rotation to avoid mode lock
- Addresses
  - NSTX-U Milestones R(15-3), JRT-16
  - ITPA joint experiment MDC-8, MDC-17, MDC-22

Present entrainment experiment would be similar (could be compared to) past DIII-D experiments

Tearing mode entrainment with n = 1 feedback in DIII-D



M. Okabayashi, et al., ITPA MHD Stability meeting, April, 2013

- Will entrainment be different at varied aspect ratio, higher edge q shear?
  - DIII-D / NSTX-U comparison
  - Also NSTX-U / KSTAR (A = 3.5) comparison (we will propose XP on KSTAR in 2015)
- A key motivation for NSTX-U is disruption avoidance by mode locking avoidance
- Request: 0.5 – 1.0 run days

Piggyback XP: Disruption PAM (DPAM) Characterization, Measurements, and Criteria - Sabbagh, for the DPAM WG

Motivation

- Serve NSTX-U DPAM Working group main goal: Satisfy gaps in understanding prediction, avoidance, and mitigation of disruptions in tokamaks, applying this knowledge to move toward acceptable levels of disruption frequency/severity using quantified metrics

Goals / Approach

- Initial discussion held at first DPAM Working Group meeting

  (see http://nstx.pppl.gov/DragNDrop/Working_Groups/DPAM/2015)
- Start early in NSTX-U operation to
  - Characterize NSTX-U disruptions (similar to P. deVries, et al. approach taken on JET)
  - Quantify results with measurements (similar to S. Gerhardt, et al. pioneering work on NSTX)
  - Expand disruption determination/avoidance models - as stated in NSTX-U 5 Year Plan
- Tools are presently being developed for this purpose
- Analysis will be conducted/communicated to/by NSTX-U DPAM WG meetings, planned as a multi-year effort
- This step is expected to be conducted in piggyback – NO RUN TIME request

Addresses

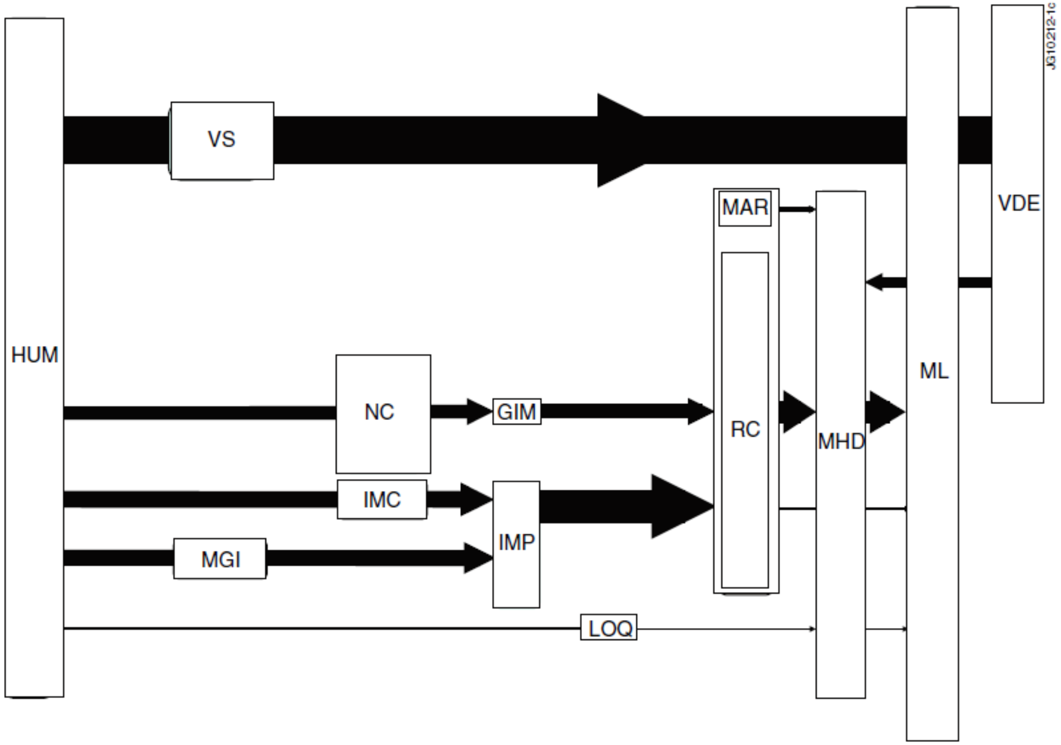
- NSTX-U Milestones: R(15-3), JRT-16, NSTX-U DPAM WG charges
- ITPA joint experiment MDC-21, MDC-22

Example of disruption physics elements interconnected to describe paths toward disruption

- Elements
  - Provide a logical and quantifiable set of components in the disruption chain, with underlying physics

- Connections
  - Shows interrelations of the elements, arrow thickness showing relative probability of path
  - Can have multiple inputs / outputs

Example: Disruption Elements and Connections Diagram (JET)



P.C. de Vries *et al.*, Nucl. Fusion **51**, 053018 (2011)

Supporting slides follow

(Incomplete) List of physics elements tied to disruption prediction, avoidance (individual involvement) – 1/30/15 mtg

- Impurity control (NC)
  - bolometry-triggered shutdown (SPG); "tailoring" radiation-induced TM onset (LD, DG)
  - change plasma operational state / excite ELMs, etc. (TBD – perhaps JC)
- Greenwald limit (GWL)
  - density/power feedback, etc. (DB)
- Locked TM (LTM)
  - TM onset and stabilization conditions, locking thresholds (JKP,RLH,ZW)
  - TM entrainment (YSP)
- Error Field Correction (EFC)
  - NSTX-U EF assessment and correction optimization (CM,SPG)
  - NSTX-U EF multi-mode correction (SAS, YSP, EK)
- Current ramp-up (IPR)
  - Active aux. power / CD alteration to change q (MDB, SPG)
- Shape control issues (SC)
  - Active alteration of squareness, triangularity, elongation – RFA sensor (SPG,MDB)
- Transport barrier formation (ITB)
  - Active global parameter, V_ϕ, etc. alteration techniques (SAS,JWB,EK)
- H-L mode back-transition (HLB)
  - Active global parameter, V_ϕ, etc. alteration techniques (SAS,JWB,EK)
- Approaching vertical instability (VSC)
  - Plasma shape change, etc. (SPG, MDB)
- Resistive wall mode (RWM)
  - Active global parameter, V_ϕ, etc. alteration techniques (SAS,JWB)
  - Active multi-mode control (SAS,YSP,KT)
- Ideal wall mode (IWM)
  - Active global parameter, V_ϕ, etc. alteration techniques (JEM)
- Internal kink/Ballooning mode (IKB)
  - Active global parameter, V_ϕ, etc. alteration techniques (SAS,JWB)
  - Active multi-mode control (SAS, YSP, KT)

Abbreviations:
JWB: Jack Berkery
AB: Amitava Bhattacharjee
DB: Devon Battaglia
MDB: Dan Boyer
JC: John Canik
LD: Luis Delgado-Aparicio
DG: Dave Gates
SPG: Stefan Gerhardt
MJ: Mike Jaworski
EK: Egemen Kolemen
RLH: Rob La Haye
JEM: Jon Menard
CM: Clayton Myers
JKP: Jong-Kyu Park
YSP: Young-Seok Park
RR: Roger Raman
SAS: Steve Sabbagh
KT: Kevin Tritz
ZW: Zhirui Wang
TBD: (To be decided)

- Interest from Theory
  - Amitava Bhattacharjee, Allen Boozer, Dylan Brennan, Bill Tang have requested involvement