Macroscopic Stability Progress and Plans

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for the NSTX Research Team

NSTX PAC-29
PPPL B318
January 27th, 2011

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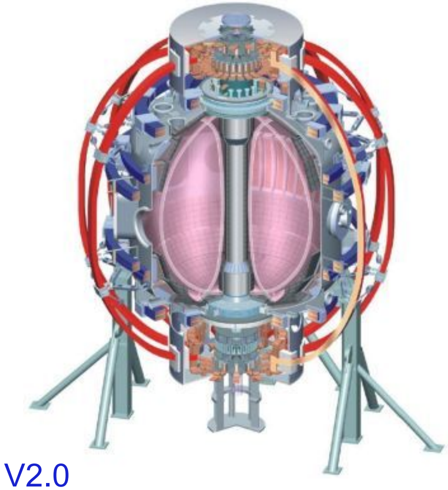

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NSTX Macrostability research is addressing needs for maintaining long-pulse, high performance STs

- Goals (aligned with 3 of 4 OFES vision research themes - highlighted)
  - Maintain high β_N stability and validate predictive capability to allow confident extrapolation to ST applications (e.g. FNSF/CTF, ST-Pilot)
  - Research/develop plasma dynamics and control for steady-state, and understand optimal use/scaling of 3D magnetic fields/effects
  - Evolve research toward lower l_i and collisionality (closer to levels of future ST applications); varied, low V_ϕ (ITER)

- Outline
  - Macrostability research addressing milestones
  - ITER/ITPA MHD stability group participation
  - Results supporting FY10 milestone and PAC-27 recommendations
  - 2011-2013 research plans

PAC 27-##

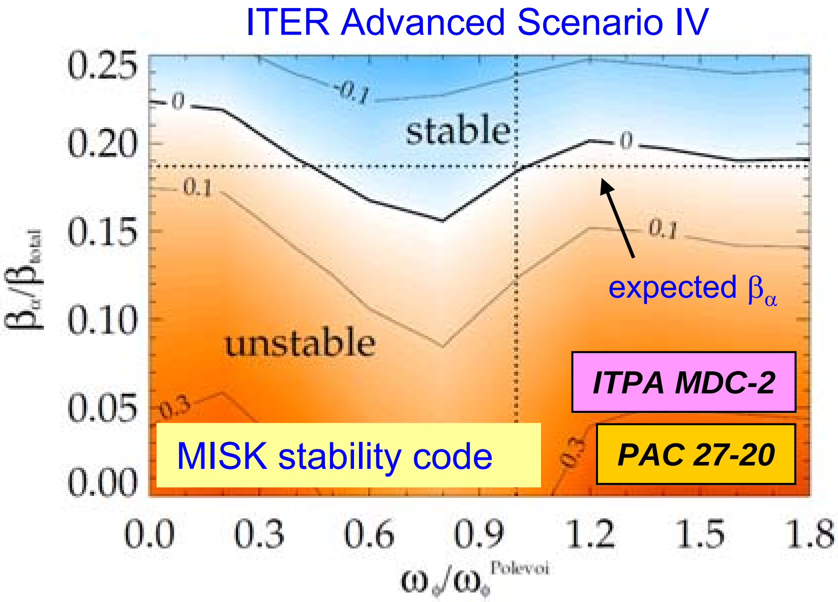
ITPA ###

Results/plans supporting PAC-27 recommendations, ITPA MHD stability group tasks, NSTX Milestones ***(I)R(##-#)*** , are labeled throughout

Macrostability research continues to follow an established plan guided by NSTX-U, future ST, and ITER physics needs (ITPA)

- Research plan contributes to a wide range of milestones
  - *Assess sustainable beta and disruptivity near and above the ideal no-wall limit:* Milestone R(10-1) (2010)
  - *Assess ST stability dependence on A and shaping* **R(11-2)**
  - *Examine H-mode pedestal stability response to 3D fields* **R(11-4)** **PAC 27-19**
  - *Assess dependence of MHD mode stabilization on ν^** **R(12-3)**
  - *Investigate 3D magnetic braking physics, V_ϕ control at low ν^** **IR(12-1)** **PAC 27-19**

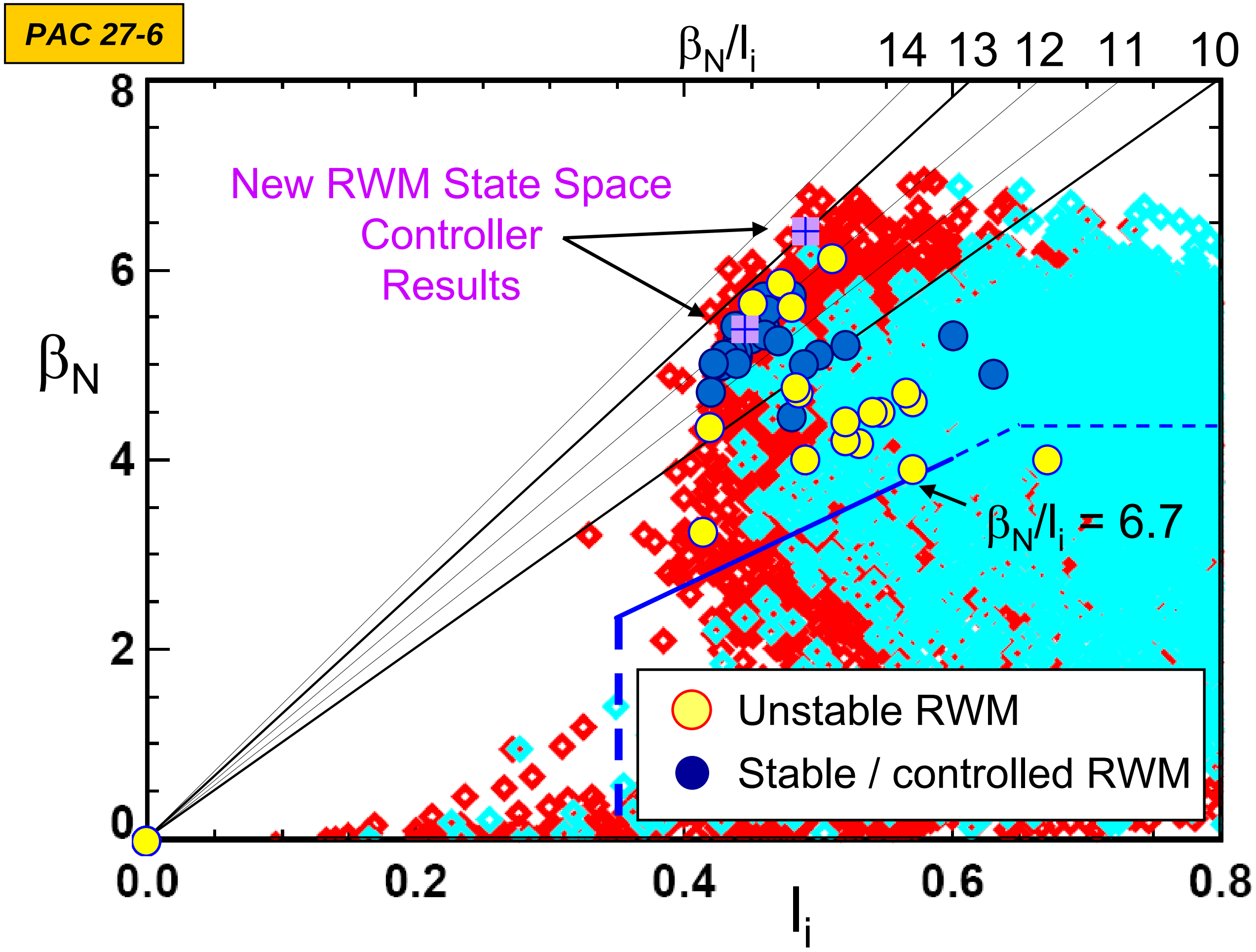
- Active ITPA participation
  - Contributed to 8 ITPA MHD joint experiments, 4 working groups
    - Sabbagh appointed ITPA MHD MDC-2 leader; WG7 co-leader (RWM physics)
    - ITER AS-IV stability requires α particles
  - NSTX / DIII-D joint NTM study (La Haye)
  - Expanded ITPA disruption database, halo current study (Gerhardt) **ITPA MDC-15**
  - ITER IPEC error field task agreement completed (Menard, J-K Park)



J.W. Berkery, et al., Phys. Plasmas **17**, 082504 (2010)

R10-1 Milestone: Improvements in stability control techniques significantly reduce unstable RWMs at low l_i and high β_N

PAC 27-6



- 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

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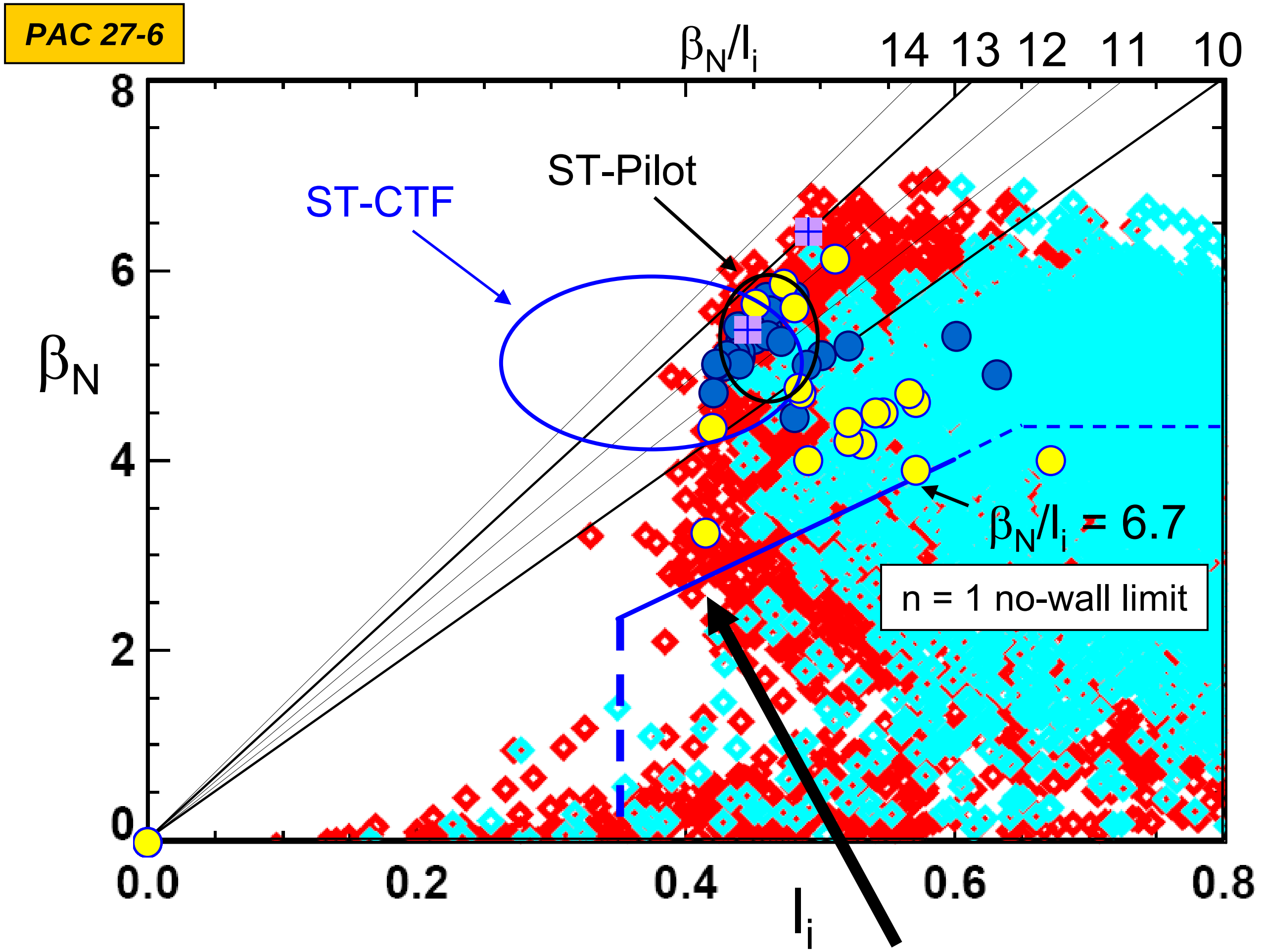

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- Computed n = 1 no-wall limit β_N/l_i,~ 6.7 (low l_i range 0.4 – 0.6)
- Synthetic equilibria variation: n = 1 no-wall unstable at all β_N at $l_i \lesssim 0.38$ (current-driven kink limit)
  - significant for NSTX-U, next-step ST operation

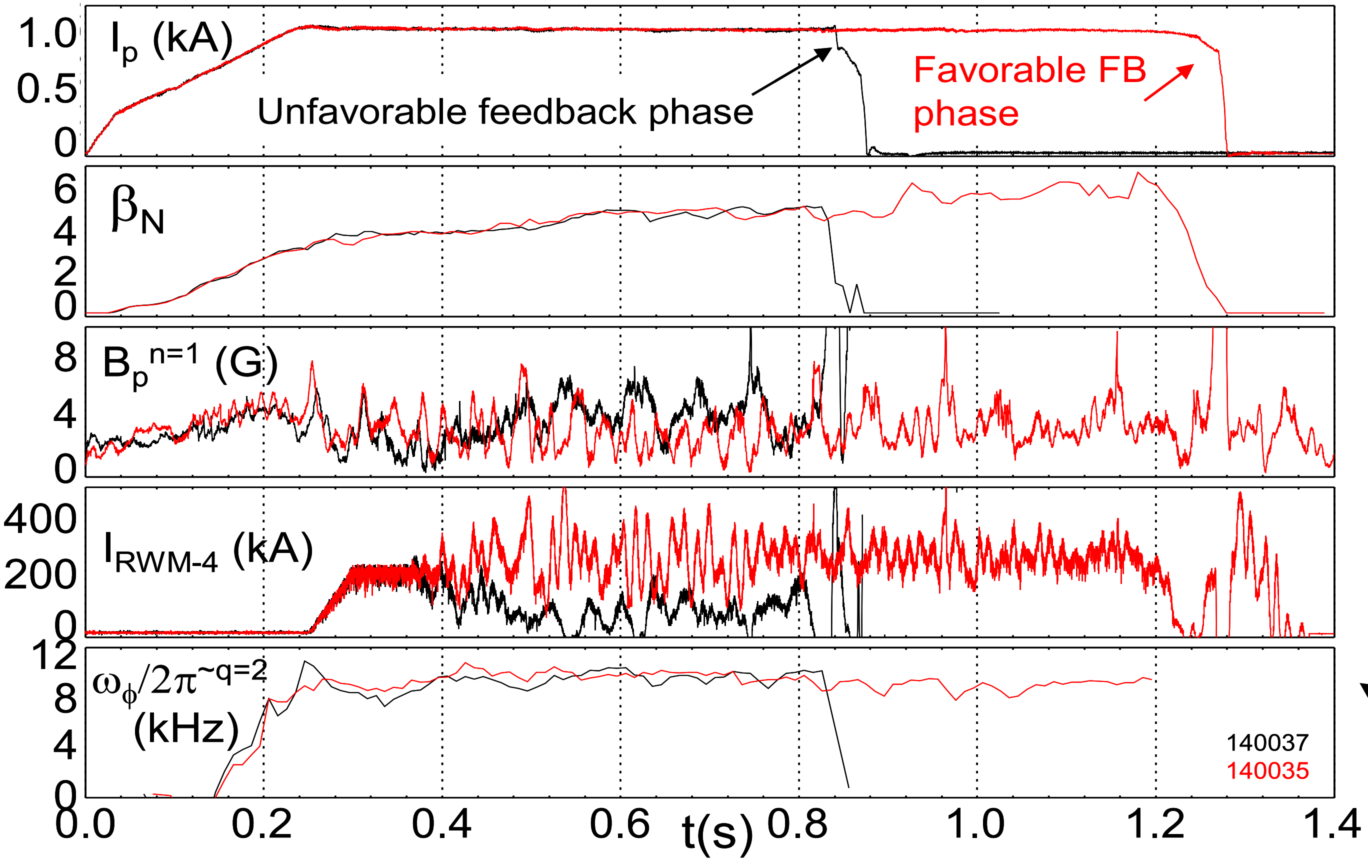
PAC 27-19

New RWM state space controller implemented in 2010 sustains high β_N, low l_i plasma

PAC 27-6

ITPA MDC-17

RWM state space feedback (12 states)



Successful First Experiments

- ❑ n = 1 applied field suppression
  - ❑ Suppressed disruption due to n = 1 field
- ❑ Feedback phase scan
  - ❑ Best feedback phase produced long pulse, $\beta_N = 6.4$, $\beta_N/l_i = 13$

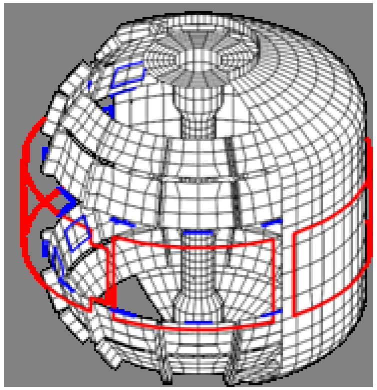
- ❑ RWM PID control system also enhanced: combined upper/lower B_r + B_p sensors used in feedback yield best reduction of n = 1 field amplitude, improved stability
  - ❑ Detail in backup slides; improved real-time RWM sensor TF pickup, AC compensation

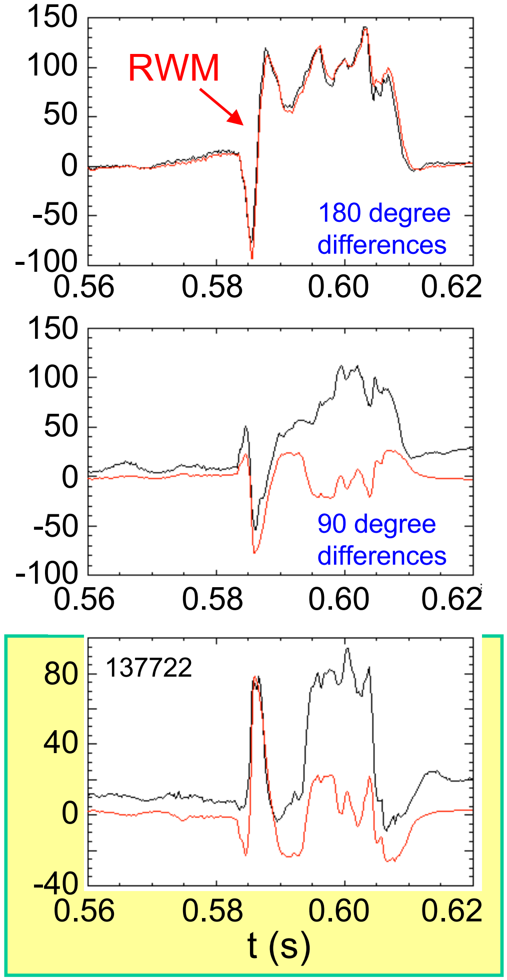
Accurate 3-D conducting structure and 3-D mode detail can improve RWM state space controller match to sensors

ITPA MDC-17

PAC 27-20

RWM Lower B_p Sensor Differences (G) – NO PORT



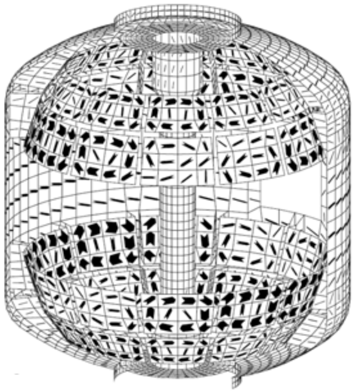


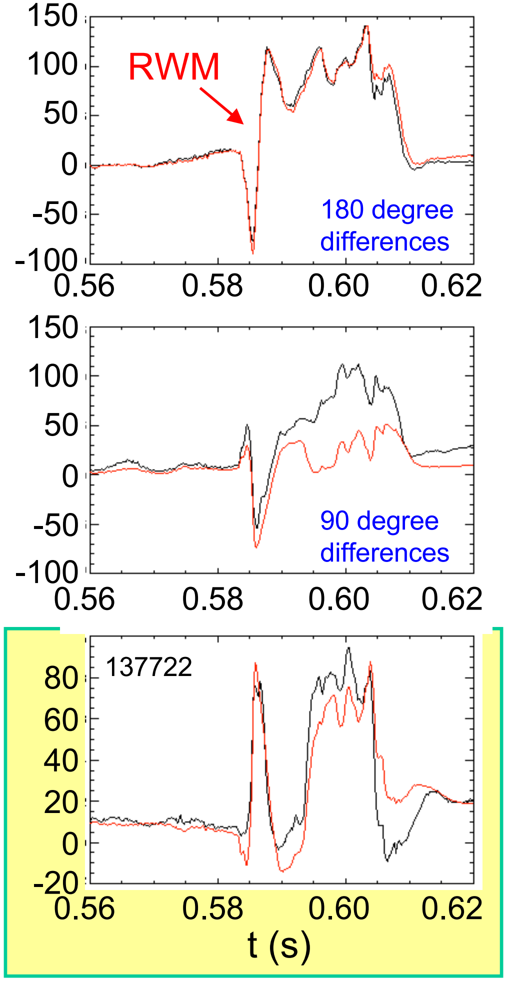
- ❑ Some 90 degree differences not well matched
  - ❑ Need n=2 mode?

R(11)-2

Sabbagh, et al. APS DPP 2010 (invited)

RWM Lower B_p Sensor Differences (G) – NBI PORT





- ❑ Adding NBI port leads to greater match on some sensors
- ❑ New multi-mode VALEN code determines full RWM spectrum
  - ❑ See backup slides

Black: experiment   Red: offline RWM state space controller   (see backup slides for controller detail)

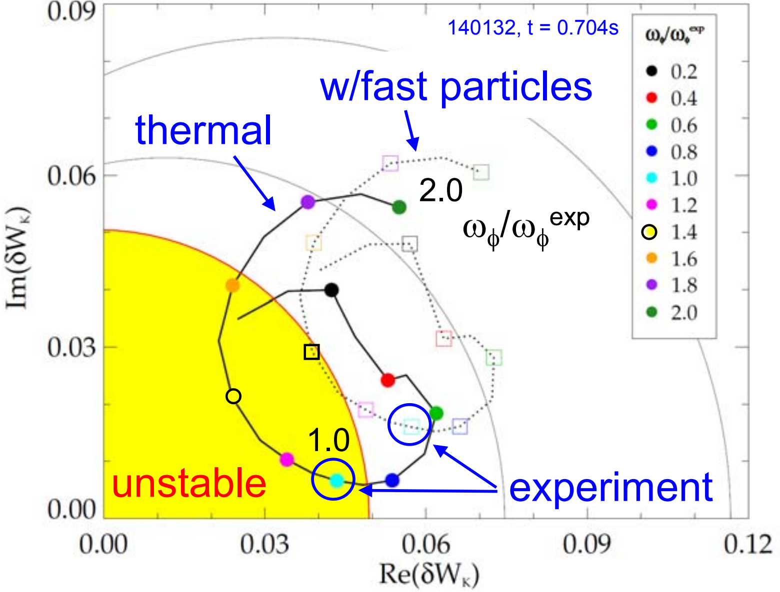
Reduced stability in low l_i target plasma as ω_ϕ reduced, RWM instability is approached; stability also reduced at higher A

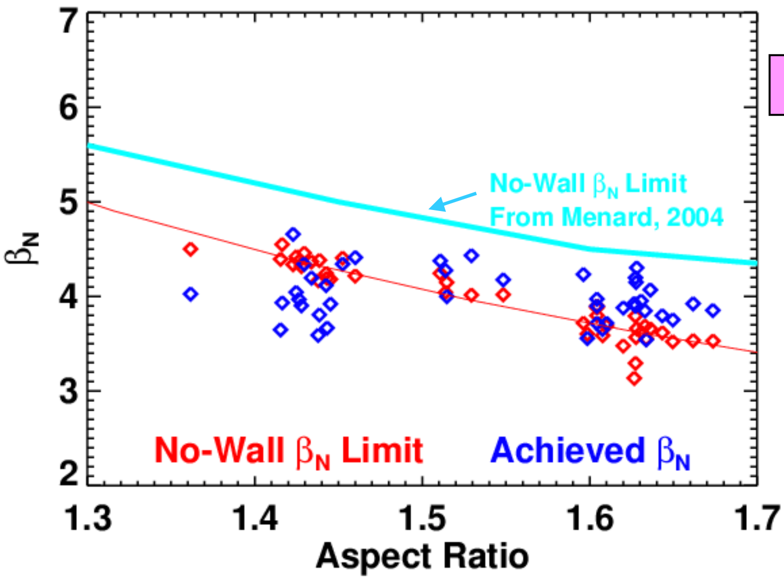
R(11-2)

ITPA MDC-2

PAC 27-19

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





- ❑ MISK shows plasma stable at time of minimum l_i, and marginally stable at RWM onset (l_i = 0.49)
- ❑ Reduction of calculated n = 1 no-wall β_N limit in increased aspect ratio plasmas

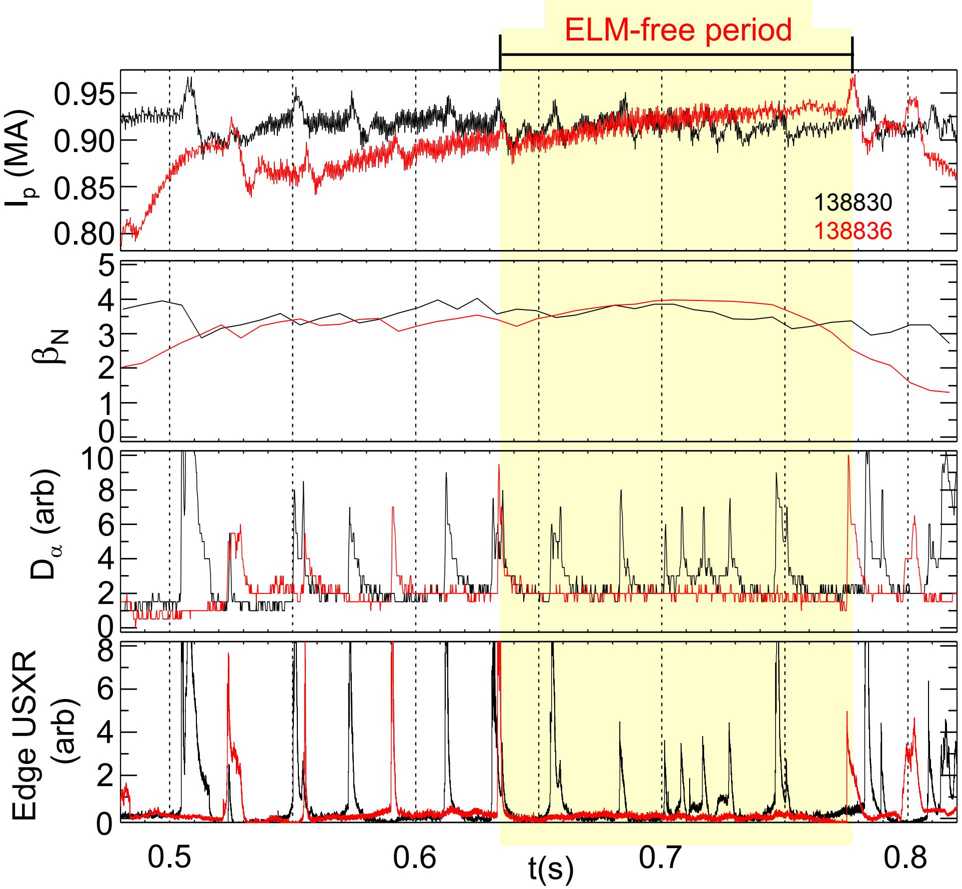
- ❑ **Plans 2011** – Milestone R(11-2)
  - ❑ Determine maximum sustainable high β_N in plasmas closer to NSTX-U, next-step ST devices (A ~ 1.7, κ ~ 3, low l_i), test present stabilization physics models / control systems
  - ❑ Extend initial experiments at higher A to higher κ, $\langle\beta_N\rangle_{pulse}$, lower l_i, use improved n = 1 PID/state space control. Compare to ideal (DCON), RWM stability limits (MISK, VALEN).
    - *Addition of 2nd SPA for independent RWM coil currents (enhanced RWM state-space controller, more flexible ω_ϕ control via NTV)*

tools

Macrostability TSG to support ITER milestone R11-4 by examining/modeling plasma response to 3D fields

R(11-4)

- **Plans 2011**: Milestone R(11-4)
  - Use IPEC to determine equilibrium variations due to 3D fields, variation of Chirikov criterion with plasma response, validate rotation damping / correlate to particle transport
  - Explore higher-n ideal stability calculations with improved 2D tools; utilize new tools (M3D-C^1) for stability, determine key physics differences of stable/unstable plasmas



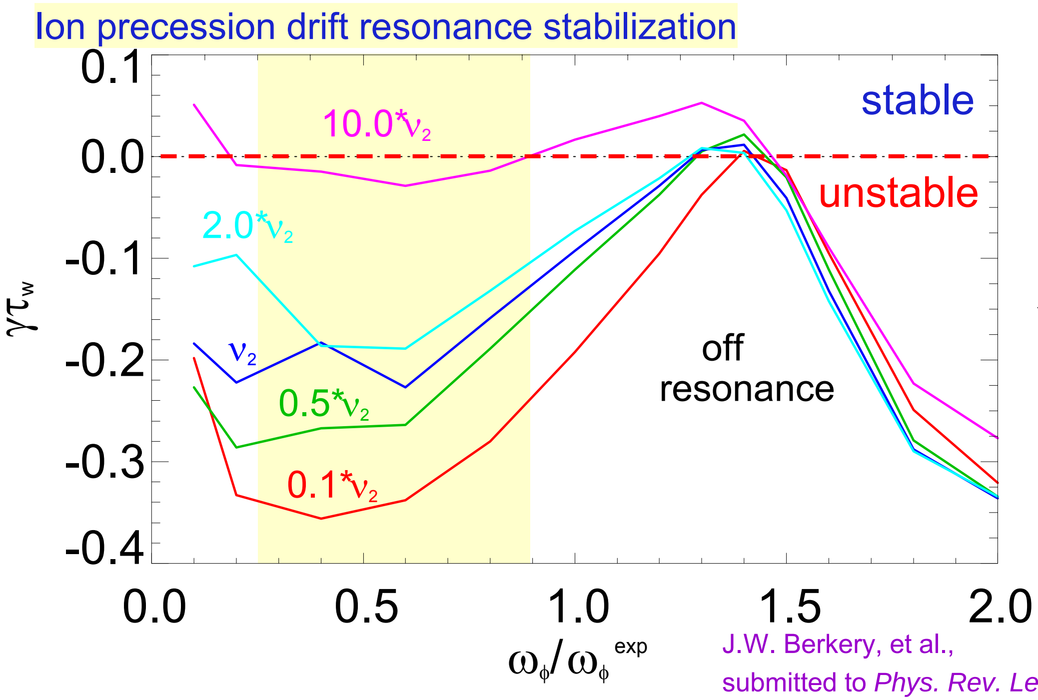
- ELM stabilization: 3D field + positive current ramp
  - Did not stabilize with negative current ramp
  - Plasma without 3D fields did not stabilize with I_p ramps
    - Modification to equilibrium, change in q profile, resonance effect ?

ITPA PEP-25

Physics of reduced collisionality is critical to extrapolating steady, high β_N operation to NSTX-U, future STs

R(12-3)

ITPA MDC-2, 12



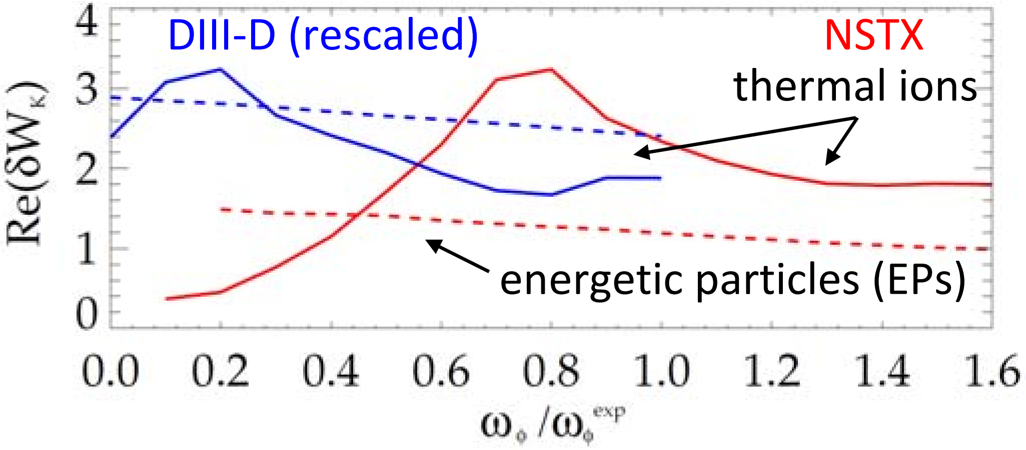
J.W. Berkery, et al., submitted to *Phys. Rev. Lett.*

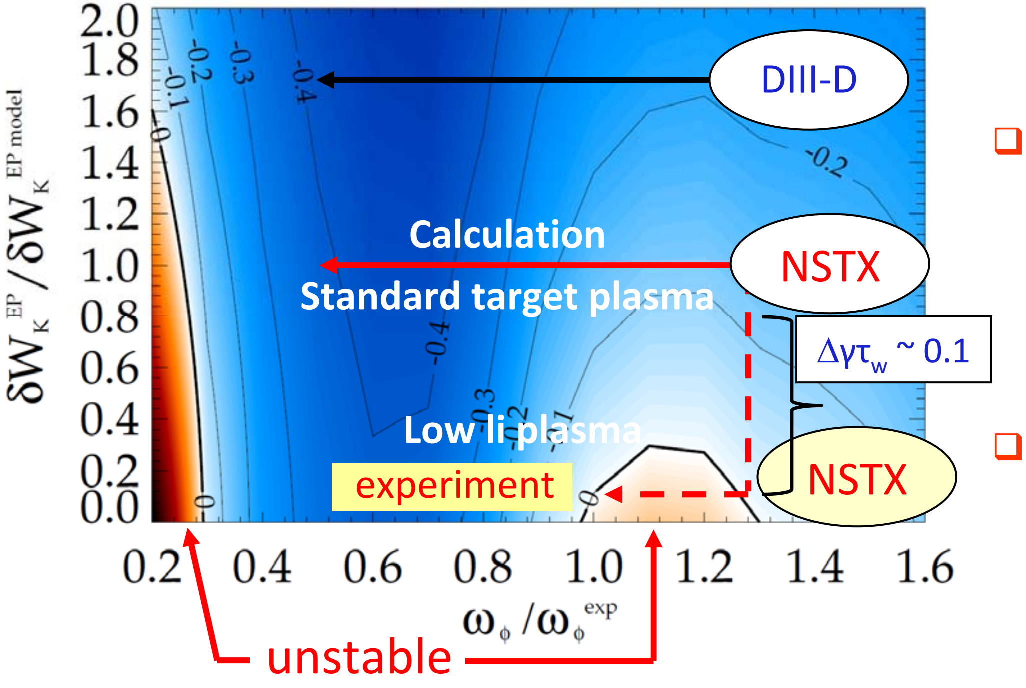
- RWM Stability physics
  - Past models – stability increases with ν
  - Present model shows effect of ν depends on ω_ϕ
    - Collisions spoil stabilizing resonance effect
    - little effect off resonance
- Rotation control with 3D magnetic fields (NTV) strongly dependent on ν

PAC 27-19

- **Plans 2011-2012** – Milestone R(12-3)
  - Develop low n_e start-up scenarios free of locked modes, leading to reduced ν
    - Continue initial success (2010) with lower, varied startup gas
    - Optimize early error field correction, revise vacuum response/IPEC plasma response
    - Attempt n = 1 PID and state-space feedback
    - Test multi-machine error field threshold scaling at reduced density
  - Test MISK, multi-mode VALEN stability models in prep. for NSTX-U, future STs
  - Determine saturation of 1/ν dependence of NTV braking torque at low ν

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





- 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 alphas at 20% over no-wall limit

PAC 27-20

- **Plans 2011-2012** **R(12-3)** **ITPA MDC-2**
  - Theory development and multi-device benchmarking (ITPA)
  - Formal IEA analysis task (JT-60U)
  - Joint experiment proposed (DIII-D)

Measure of the marginal island width gives information on small island stabilizing physics

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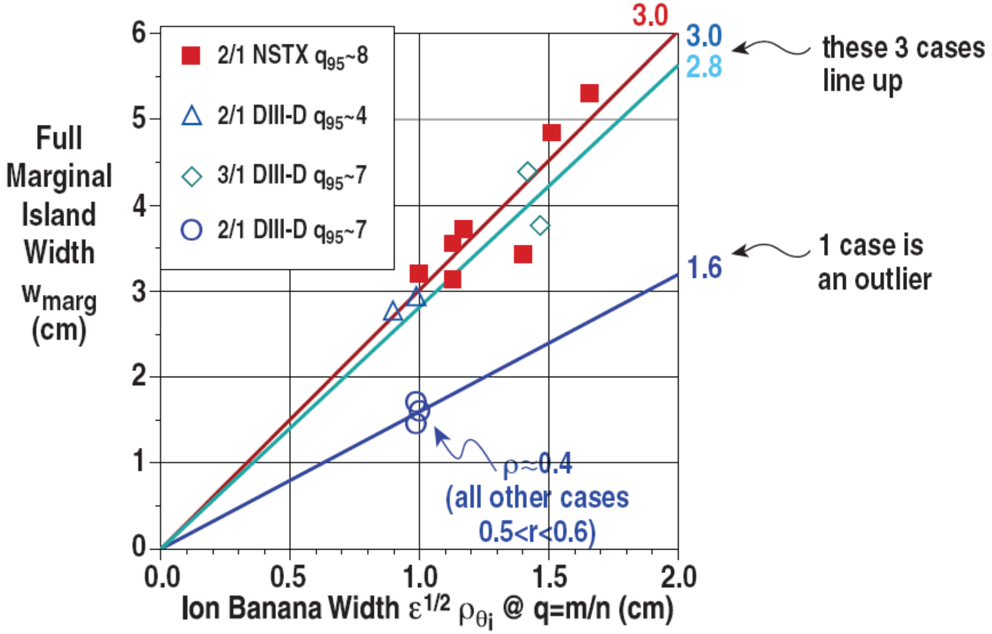
ITPA MDC-4, 14



- **Empirically, marginal island width three times ion banana width**
  - ★ **except outlier is DIII-D 2/1 mode closer to axis at higher q95**

DIII-D NATIONAL FUSION FACILITY

La Haye, et al. APS DPP 2010; ITPA MHD 2010

NSTX

296-10/RJL/jy

- ❑ Balance of terms in modified Rutherford equation shows that curvature term dominates over Δ’ for NSTX plasmas; curvature term negligible for DIII-D plasmas
- ❑ Studies of error field threshold scaling for mode locking in H-modes (Buttery; J-K Park)
- ❑ **Other plans 2011-12**: Extend present mode locking density, and NTV offset rotation studies to low torque (RF) plasmas **PAC 27-19**

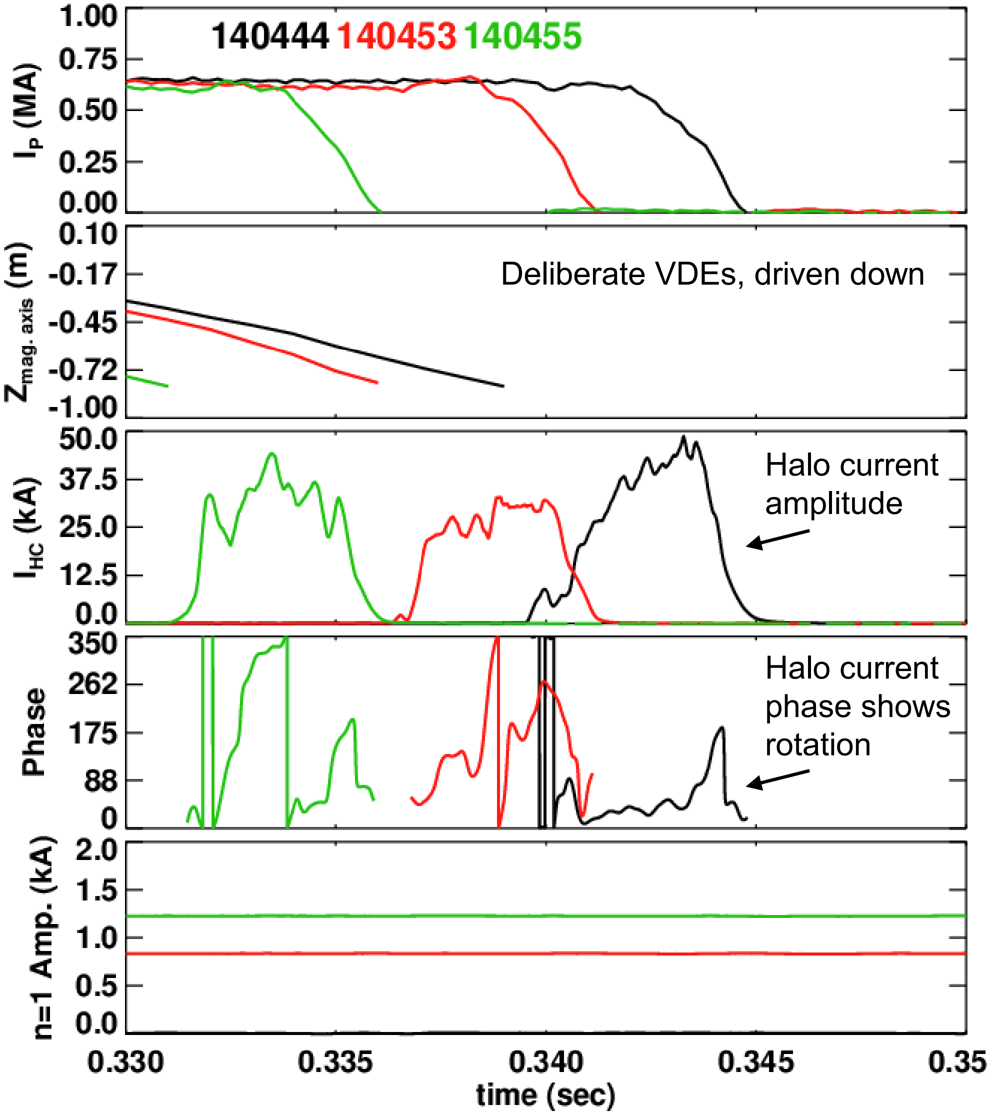
3D nature and toroidal rotation of halo currents (HC) measured using new toroidal array of shunt tiles

PAC 27-20

ITPA MDC-5, WG6

- Halo current characteristics key for ITER
  - vessel forces due to n = 1 currents can be excessive
  - forces from currents can be reduced if growth rate reduced

  Strauss, et al. APS DPP 2010
- Raw data / Fourier analysis both show rotation of current
  - n = 1 pattern rotates ~1 kHz in counter-I_p direction
  - Applied n = 1 DC fields: HC continues to rotate in first XP →
- **Plans 2011-12**: Study/attempt to influence n = 1 halo current
  - Expand initial work with n = 1 fields, try n = 3 field
  - Test use of divertor gas
  - Test rotation vs. stored energy



Macrostability research in 2010 – 2013 addresses stability physics understanding for NSTX-U, steady-state high performance STs, ITER

- 2010: Improved stability control/physics understanding to maintain high β_N
  - Improved n = 1 RWM, β_N control to sustain high β_N at varied V_ϕ levels, reduced l_i; first use of RWM state-space control; RWM stabilization physics compared NSTX/DIII-D
  - NSTX/DIII-D NTM marginal island width for restabilization 3x $\varepsilon^{0.5}\rho_{\theta i}$ for both devices, significance of curvature term very different between devices (A effect)
- 2011-12: Understand 3-D field effects, reduce ν, study impact on stability
  - Study plasmas closer to NSTX-U, next-step ST devices (A ~ 1.7, κ ~ 3, low l_i , ν), test present stabilization physics models / control, unify with tokamaks
  - Incremental milestone: show V_ϕ control, use to test stability, real-time NTV – see backup
- 2013+ (outage period): Analysis supporting NSTX-U, next-step STs, ITER
  - Analysis/design: includes stability/control analysis of NSTX-U plasma (higher A, κ, low l_i)
  - Finalize expanded 3D coil set design (ELM, RWM, V_ϕ control + physics) - see backup
  - Code development/testing: includes non-ideal IPEC shielding models, with inner layer physics (GPEC), expanded MISK model, compare to M3D-C^1 with RWM physics
  - Joint experiments: DIII-D/MAST/KSTAR: RFA, RWM physics/control, NTV physics
  - NSTX-U prep: Update control systems/physics models for NSTX-U analysis/operations

Working with data from NSTX + other experiments (e.g. DIII-D, JT-60U), and ITPA to understand MHD physics for NSTX-U and future ST development, ITER

Backup slides

Further step to extrapolating steady, high β_N: Observed sensitivity of RWM stability on plasma rotation motivates planned V_ϕ control

- Macrostability FY12 Milestone IR(12-4) (incremental)
  - *Investigate magnetic braking physics and develop toroidal rotation control at low collisionality (joint with ASC group)*

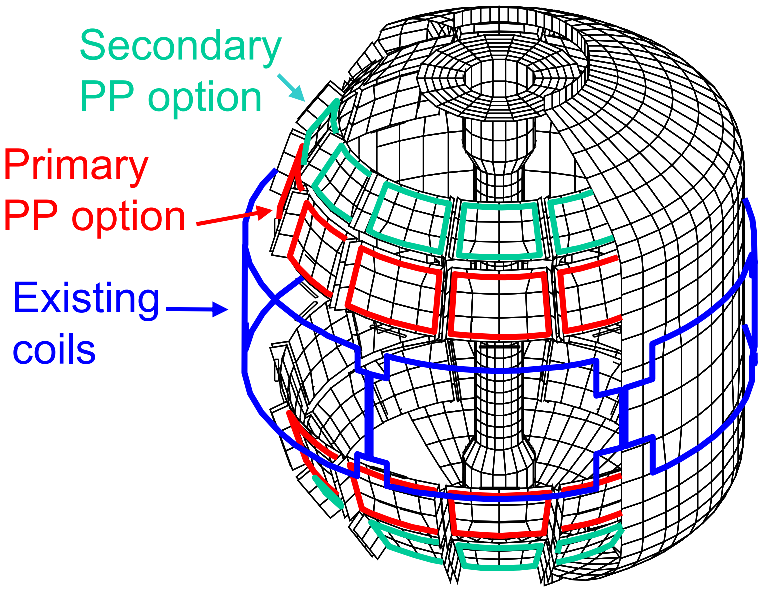
tools

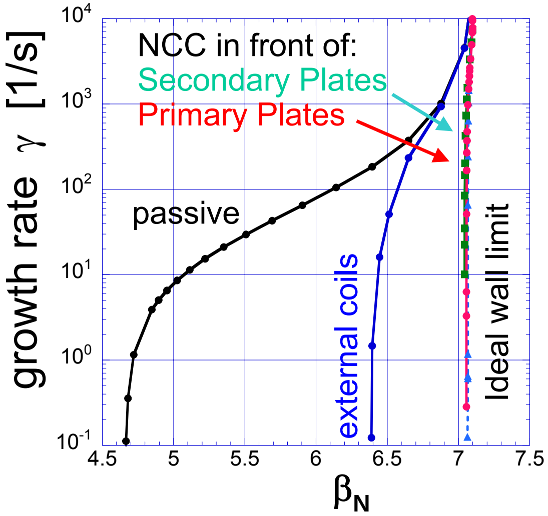
    - *2nd SPA for independent RWM coil currents (more flexible V_ϕ control)*
    - *Real-time V_ϕ measurement (up to 4 radial positions) and real-time control*
  - Approach/Plans:
    - Use real-time V_ϕ measurements as sensors to actuate NBI and 3D magnetic fields (tailored braking torque by NTV) for V_ϕ feedback control
    - Bring together key scalings of resonant and non-resonant (NTV) damping physics to support real-time model of V_ϕ control at varied ν
    - Explore influence of NTM stability by changing V_ϕ and V_ϕ shear near the $q = 2$ surface
    - Explore avoidance of decreased RWM stability with planned V_ϕ control at various levels of collisionality

Will provide required understanding of rotation control for greater plasma stability needed to reduce disruption probability in NSTX-U and future STs

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.)

Macroscopic Stability TSG 2010 XPs – Year-end Status

Author	Proposal Title	NSTX Forum Allocations / Priority			XP / Status
J. Park	Error field threshold study at high-beta - reduced torque	1.0	1	0.50	XP1018
Menard	Effects of non-res. fields on low/moderate beta locking threshold	1.0	1	0.50	
Buttery	Error field threshold scaling in H mode - next step devices	1.0	1	0.50	XP1032
Gerhardt	Optimization of beta-control - disruptivity	1.0	1	0.50	XP1019
Berkery	Determination of, navigation through weak RWM stability Vphi(psi)	1.0	1	1.00	XP1020
Reimerdes	Measuring resonance frequencies relevant for RWM stabilization	1.0	1	-	
McLean/Gerhardt	Halo current study w/ extended diagnostic capability + LLD	1.0	1	1.00	XP1021
Y-S. Park	RWM state-space control in NSTX	1.0	1	1.00	XP1022
Sabbagh	Optimized RWM feedback for high <betaN>pulse at low nu and li	1.0	1	1.00	XP1023
Gerhardt	Comparison of RFA suppression using different sensors	1.0	2	1.00	XP1060
Buttery	2/1 NTM stability (and EF sensitivity) vs q profile	1.0	2	0.50	XP1061
Sabbagh	NTV physics: low collisionality and maximum variation of OmegaE	1.0	2	0.50	XP1062
Berkery	RWM stabilization by energetic particles	1.0	3	1.00	
J. Park	Resonant Field Amplification of n=2 and n=3 applied fields	1.0	3	1.00	
La Haye	Effect of rotation on amplitude of 3/2 NTMs	1.0	3	1.00	
Y. Park	Passive/active stability of kink,RWM, Vf control: KSTAR Joint	1.0	3	1.00	
Sabbagh	Global MHD / ELM stability vs edge current, n*qped, edge nu	1.5	ITER	0.50	XP1031
Sontag	Peeling-ballooning stability and access to QH-mode in NSTX	1.5	ITER	0.50	XP1063
Gerhardt	Optimization of beta-control XMP	0.5	CCE	0.50	XMP65
Menard	Influence of LLD-induced collisionality, profile on ST stability	1.5	CCE	1.50	XP1055 (team)
Goldston	RF Amplification of EHOs in Lithium-pumped ELM-Free Plasmas		CCE		XP1068

Group review	Team review	XP signoff	Started	Near Complete	Completed

NSTX Macroscopic Stability TSG – ITPA areas of contribution

ITPA Joint Experiments / Joint Analysis

MDC-2	Joint experiments on resistive wall mode physics
MDC-4	Neoclassical tearing mode physics - aspect ratio comparison
MDC-5	Comparison of NTM avoidance by sawtooth control
MDC-12	Non-resonant magnetic braking
MDC-13	Vertical stability physics/performance limits in high κ plasmas
MDC-14	Rotation effects on neoclassical tearing modes
MDC-15	Disruption database development
MDC-17	Physics-based disruption avoidance

ITPA MHD Group – Working Groups

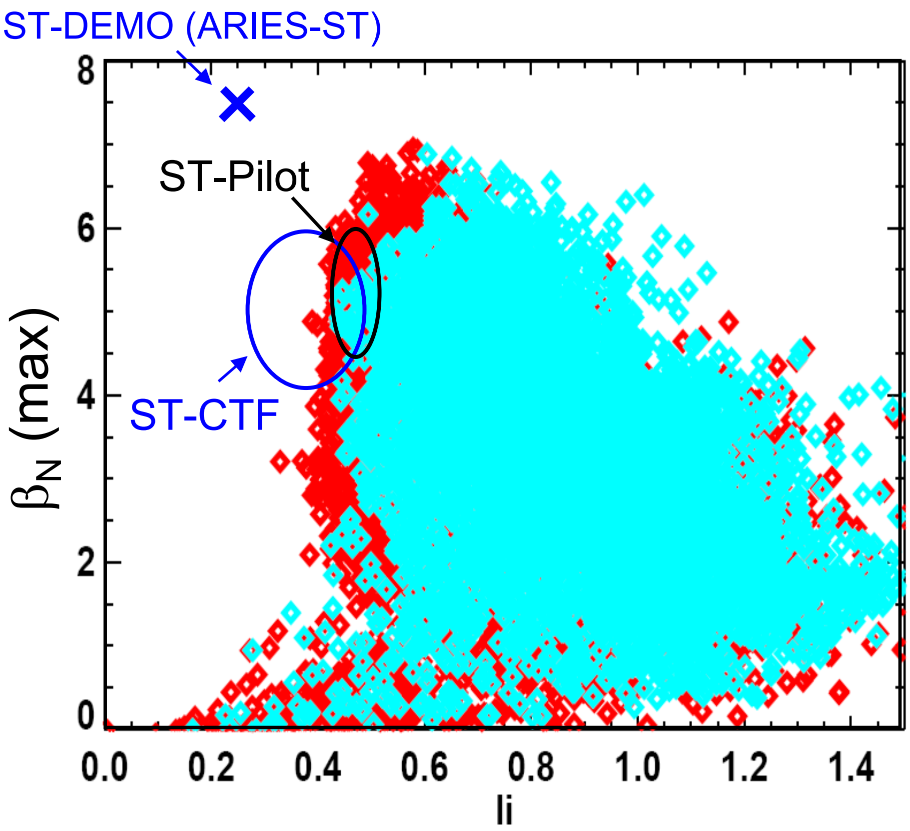
- MHD WG1 Waveforms of current in error field correction coils
- MHD WG4 Diagnostic requirements for MHD stability control
- MHD WG6 Sideway forces on vacuum vessel and magnets by disruptions
- MHD WG7 RWM feedback control (new)

Operation has aimed to produce sustained low l_i and high pulse-averaged β_N

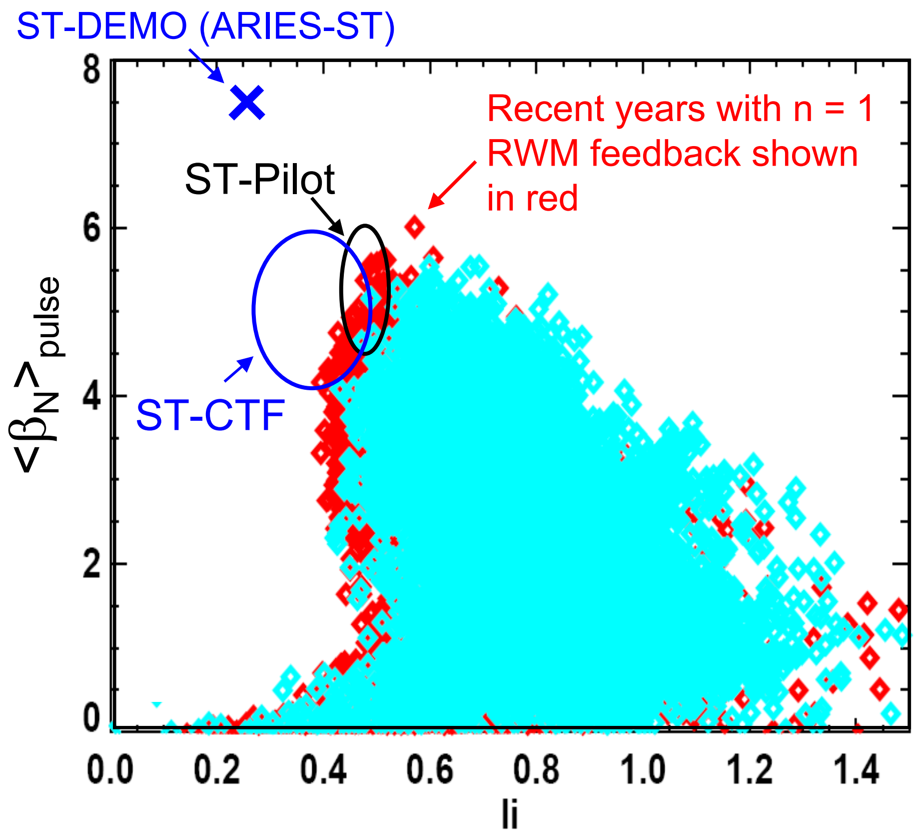
PAC 27-6

- NSTX R10-1 Milestone
  - *Assess sustainable beta and disruptivity near and above the ideal no-wall limit*

β_N vs. l_i (maximum values)

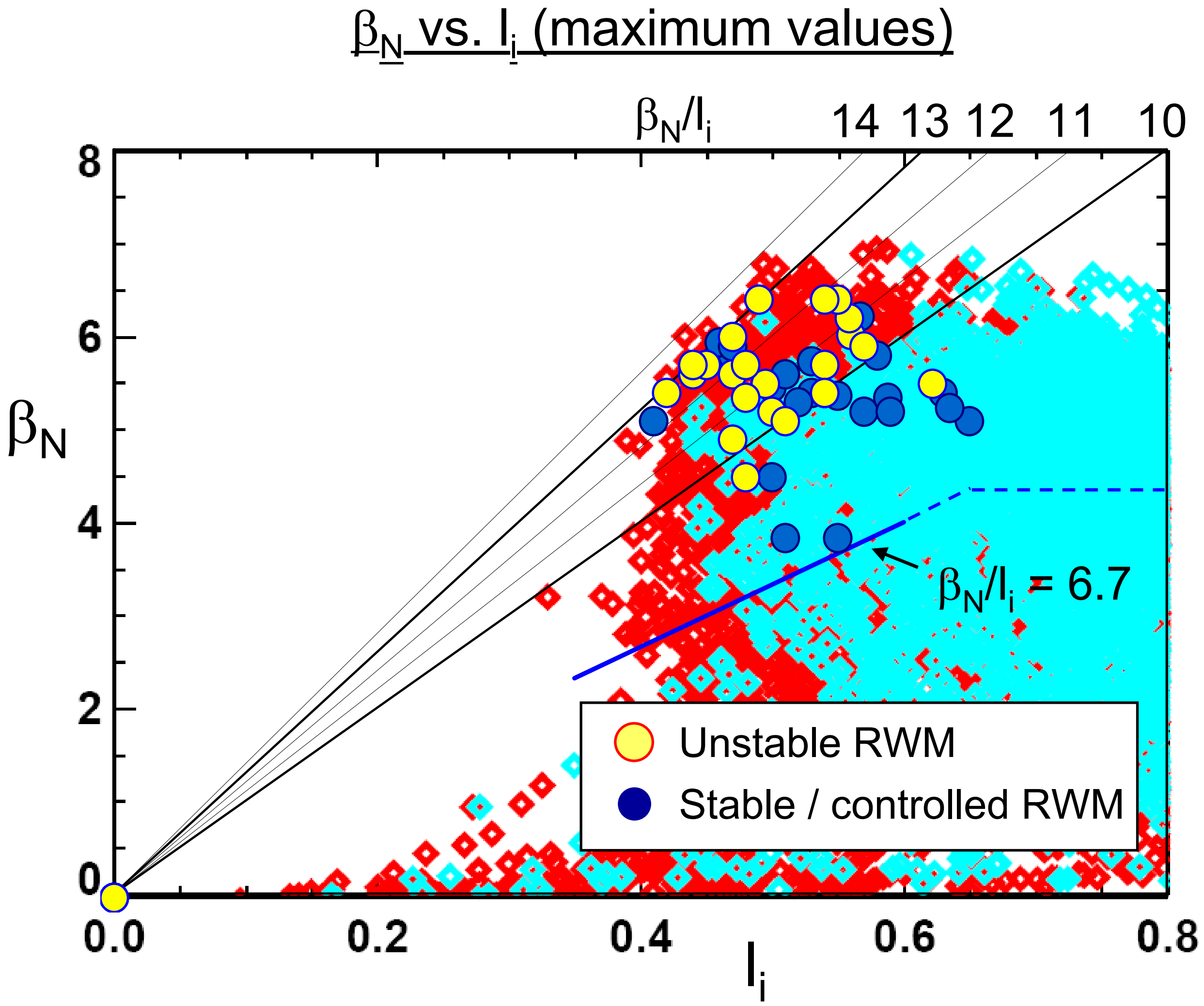


β_N vs. l_i (pulse-averaged values)



- Reached low l_i, high $<\beta_N>_{pulse}$ suitable for next-step ST fusion devices

Global stability examined for experiments aimed to produce sustained low l_i and high β_N at high plasma current

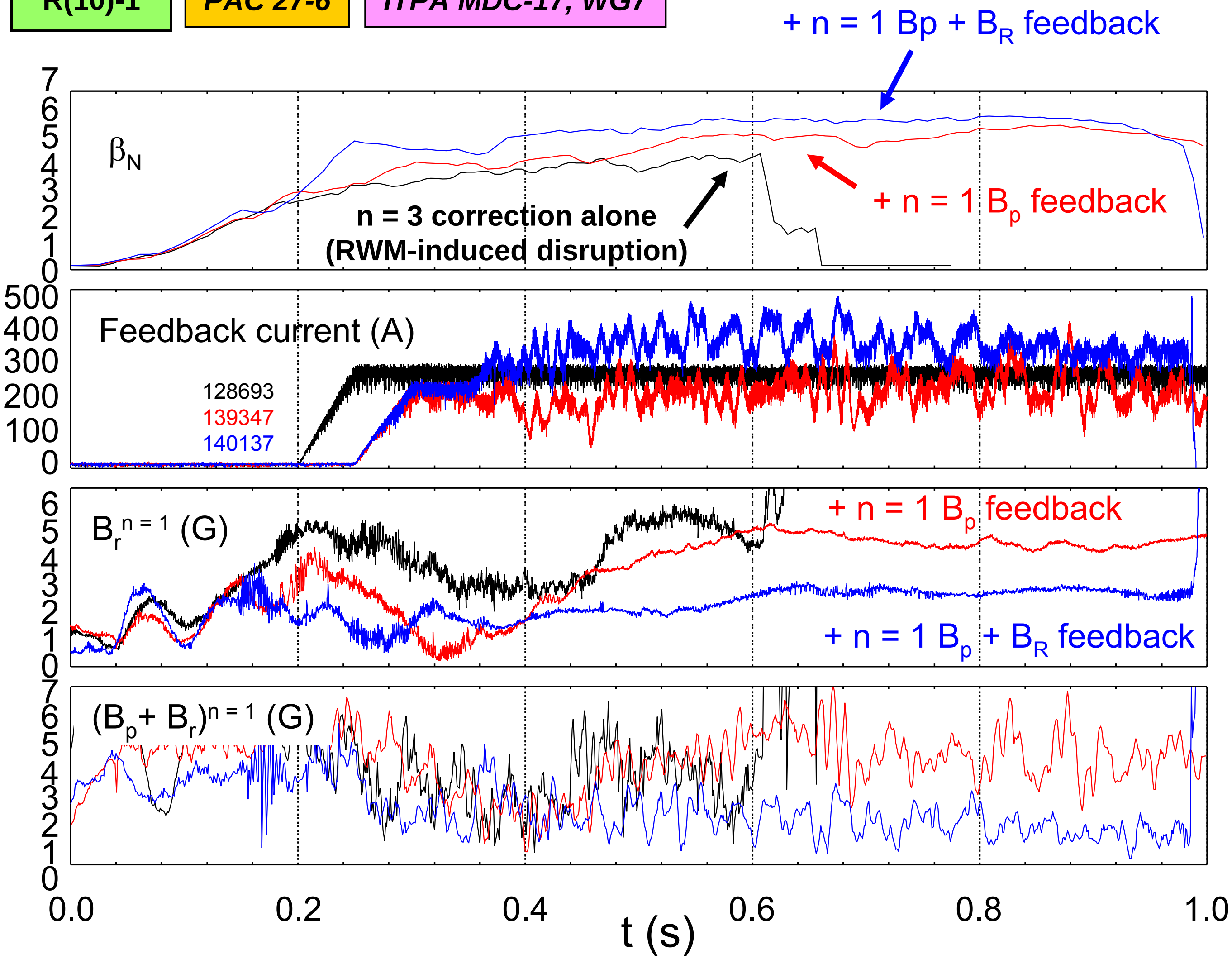


β_N vs. l_i (maximum values)

- High $I_p \geq$ 1.0MA, high non-inductive fraction ~ 50%
- Initial experiments
  - Yielded low l_i
  - Access high β_N/l_i
  - High disruption probability
- Instabilities leading to disruption
  - Unstable RWM
    - 48% of cases run
  - Locked tearing modes

Use of combined B_r + B_p RWM sensor n= 1 feedback yields best reduction of n = 1 field amplitude / improved stability

R(10)-1 ***PAC 27-6*** ***ITPA MDC-17, WG7***

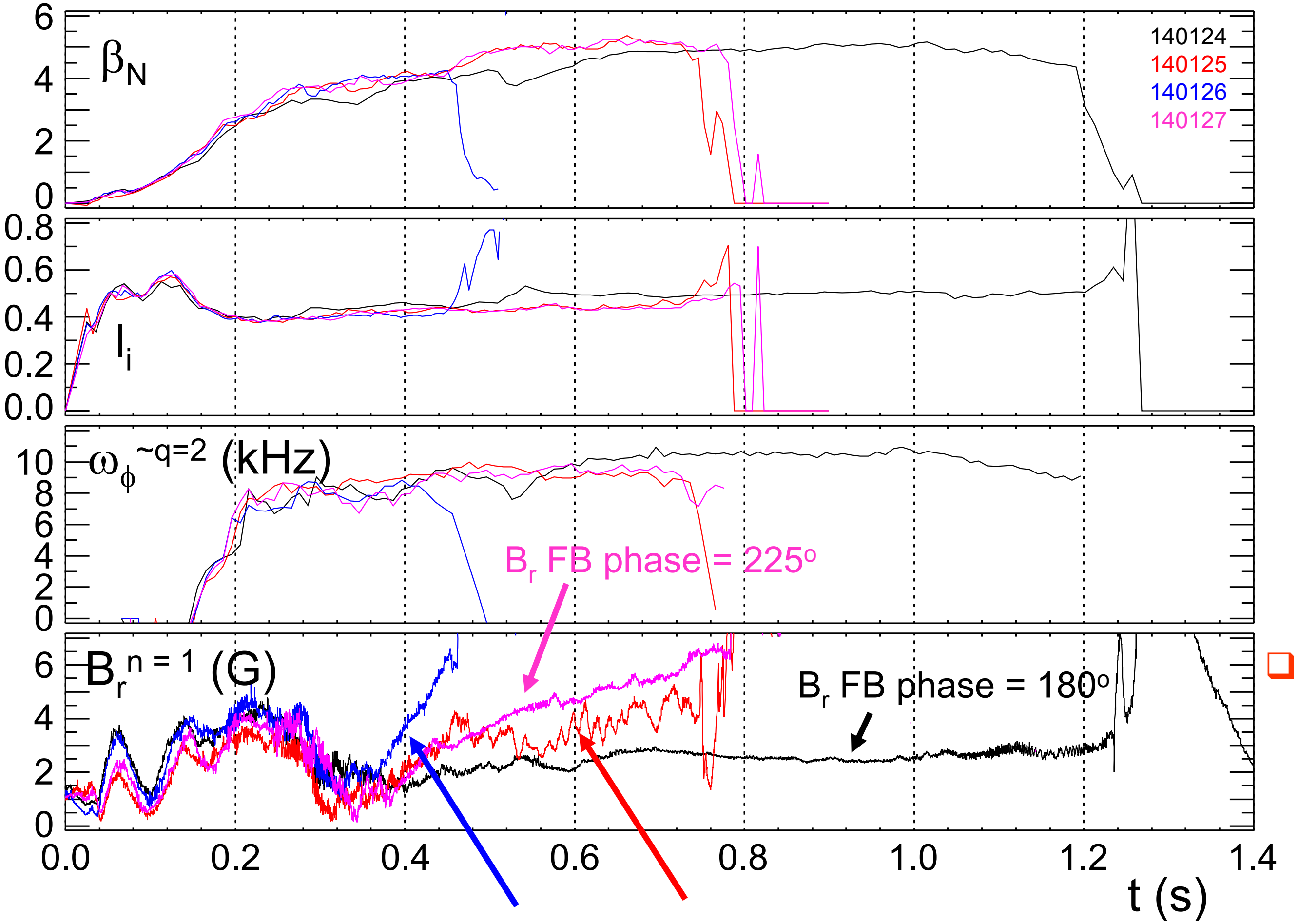


- Combination of DC error field correction, n = 1 feedback
  - Dedicated scans to optimize B_r, B_p sensor feedback phase and gain
  - n = 3 DC error field correction alone subject to RWM instability
  - n = 1 B_p sensor fast RWM feedback sustains plasma
  - Addition of n = 1 B_R sensors in feedback reduce the combined B_p + B_r n = 1 field to low level (1–2 G)

RWM B_r sensor n = 1 feedback phase variation shows clear settings for improved feedback when combined with B_p sensors

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

R(10)-1 | ***PAC 27-6*** | ***ITPA MDC-17, WG7***



B_r FB phase = 225°

B_r FB phase = 180°

B_r FB phase = 0°

B_r FB phase = 90°

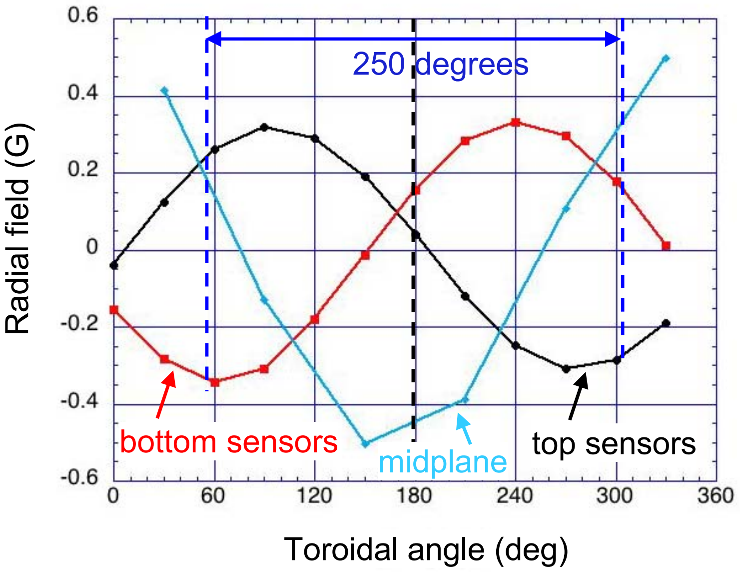
- Recent corrections to B_r sensors improve measurement of plasma response
    - Removed significant direct pickup of time-dependent TF intrinsic error field
    - Positive/negative feedback produced at theoretically expected phase values
- Adjustment of B_p sensor feedback phase from past value further improved control performance

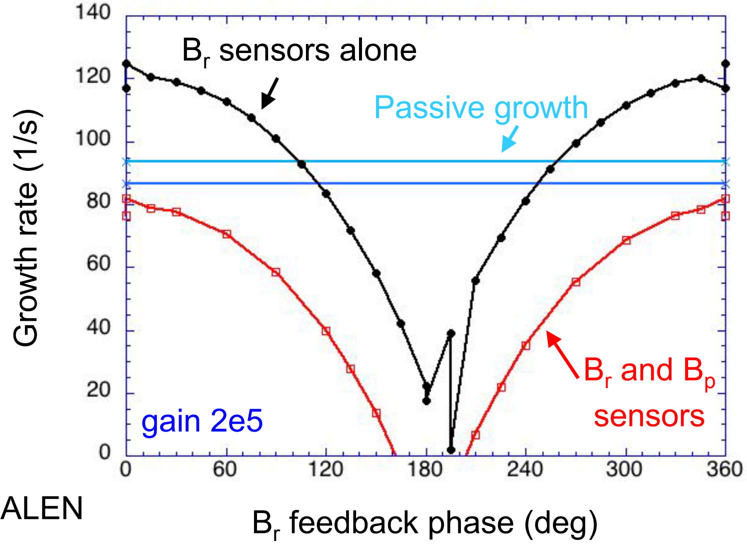
RWM feedback using upper/lower B_p and B_R sensors modeled and compared to experiment

R(10)-1

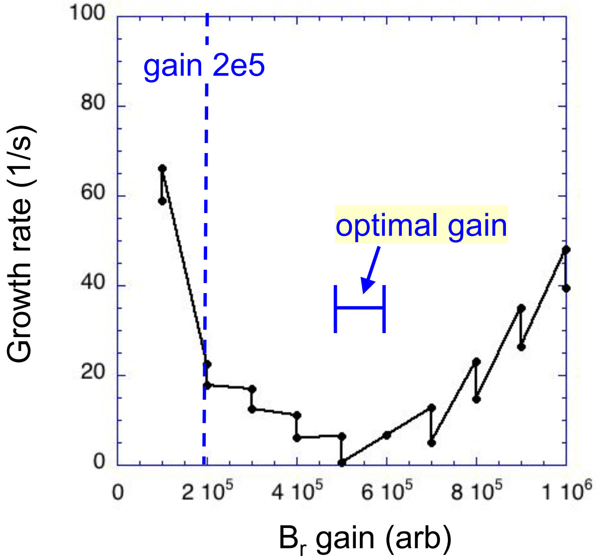
ITPA MDC-17

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

New RWM state space controller implemented in 2010 to sustain high β_N

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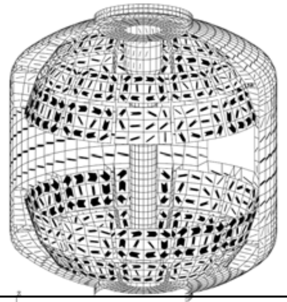
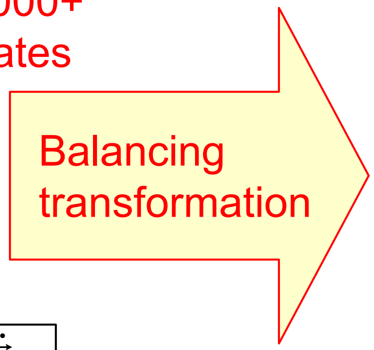
PAC 27-20

R(10)-1

Full 3-D model ~3000+ states

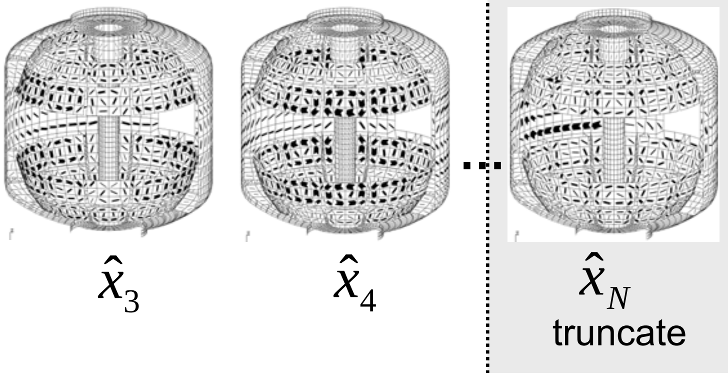




State reduction (< 20 states)

RWM eigenfunction (2 phases, 2 states)

$(\hat{x}_1, \hat{x}_2)$



$$\vec{x} = \left(\vec{I}_w \quad \vec{I}_{cc} \quad I_p\right)^T; \quad \vec{u} = \dot{\vec{I}}_{cc}$$

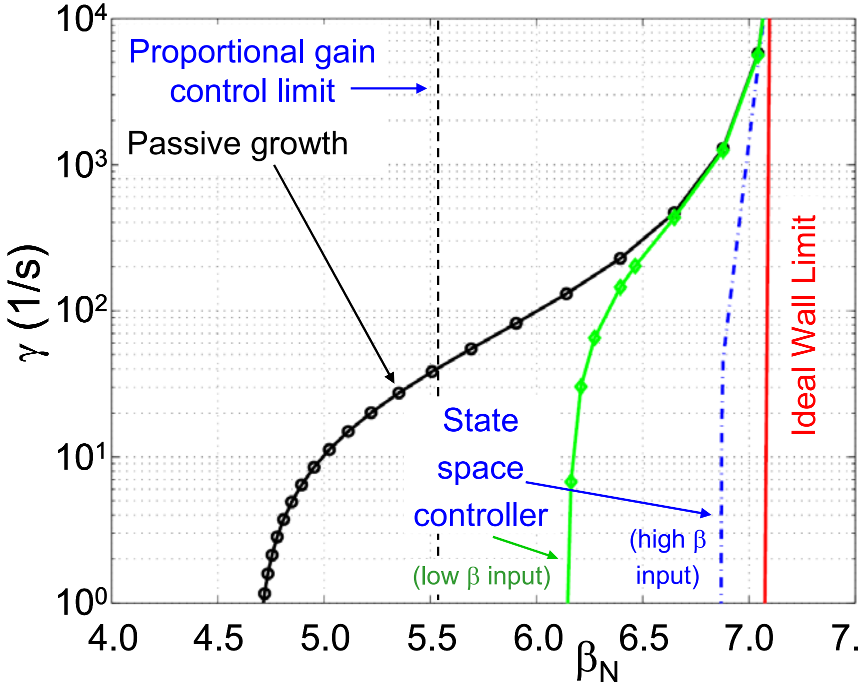
$$\overleftrightarrow{A} = -\overleftrightarrow{L}_1^{-1}\overleftrightarrow{R}; \quad \overleftrightarrow{B} = \overleftrightarrow{L}_1^{-1}\overleftrightarrow{L}_2$$

$$\vec{y} = \vec{\Phi}_{sensors}; \qquad \overleftrightarrow{C} = \overleftrightarrow{M}$$

- 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)



NSTX RWM state space controller advances present PID controller

- PID (our present, successful workhorse)
  - n = 1 phase/amplitude of RWM sensors provides input to controller
  - feedback logic operates to reduce n = 1 amplitude
  - No a priori knowledge of mode structure, physics, controller stability

- State space control
  - States reproduce characteristics of full 3-D model: conducting structure, plasma response, and feedback control currents via matrix operations
  - Observer (computes sensor estimates)
    - RWM sensor estimates provided by established methods (Kalman filter)
      - Allows error specification on measurements and model – full covariance matrix
    - Difference between sensor measurements and state space estimates are used to correct the model at each time point; useful as an analysis tool
  - Controller (computes control currents)
    - Controller gain computed by established methods: gains for each coil and state
  - State space method amenable to expansion

State Derivative Feedback Algorithm used for Current Control

- State equations to advance

$$\dot{\vec{x}} = A\vec{x} + B\vec{u} \qquad \vec{u} = -K_c\vec{x} = \dot{I}_{cc}$$

$$\vec{y} = C\vec{x} + D\vec{u}$$

Control vector, *u*; controller gain, K_c

Observer est., *y*; observer gain, K_o ; $D = 0$

K_c , K_o computed by standard methods
(e.g. Kalman filter used for observer)

Advance discrete state vector

$$\hat{\vec{x}}_t = A\vec{x}_{t-1} + B\vec{u}_{t-1};\ \hat{\vec{y}}_t = C\hat{\vec{x}}_t$$

"time update"

$$\vec{x}_{t+1} = \hat{\vec{x}}_t + A^{-1}K_o(\vec{y}_{sensors(t)} - \hat{\vec{y}}_t)$$

"measurement update"

- State derivative feedback: superior control approach

$$\dot{\vec{x}} = A\vec{x} + B\vec{u} \qquad \vec{u} = -\hat{K}_c\dot{\vec{x}} \longrightarrow \vec{I}_{cc} = -\hat{K}_c\vec{x}$$

$$\dot{\vec{x}} = ((\mathrm{I} + B\hat{K}_c)^{-1}A)\vec{x}$$

  - new Ricatti equations to solve to derive control matrices
– still "standard" solutions in control theory literature

    e.g. T.H.S. Abdelaziz, M. Valasek., Proc. of 16th IFAC World Congress, 2005

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

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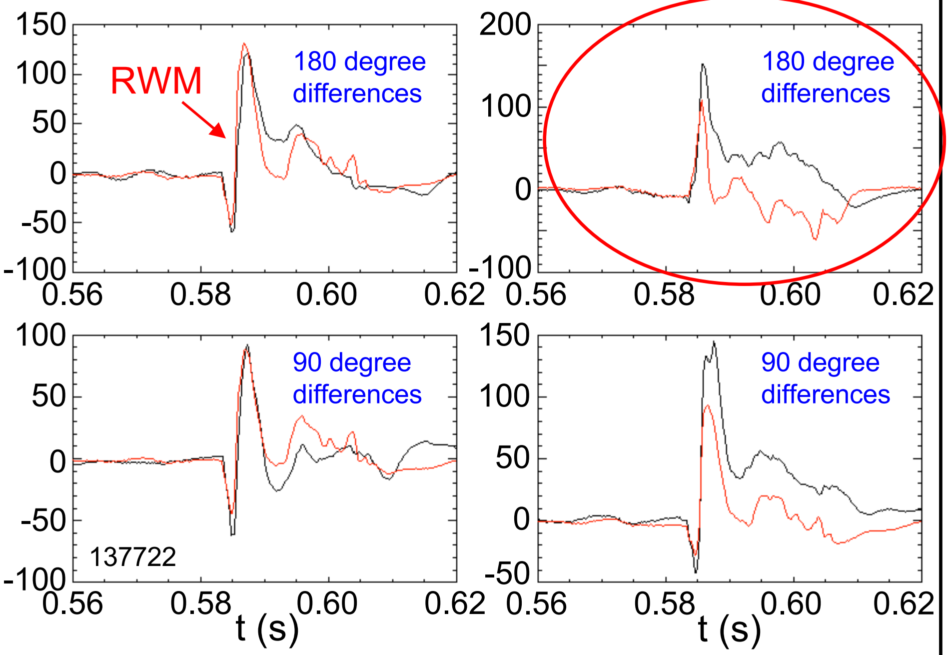
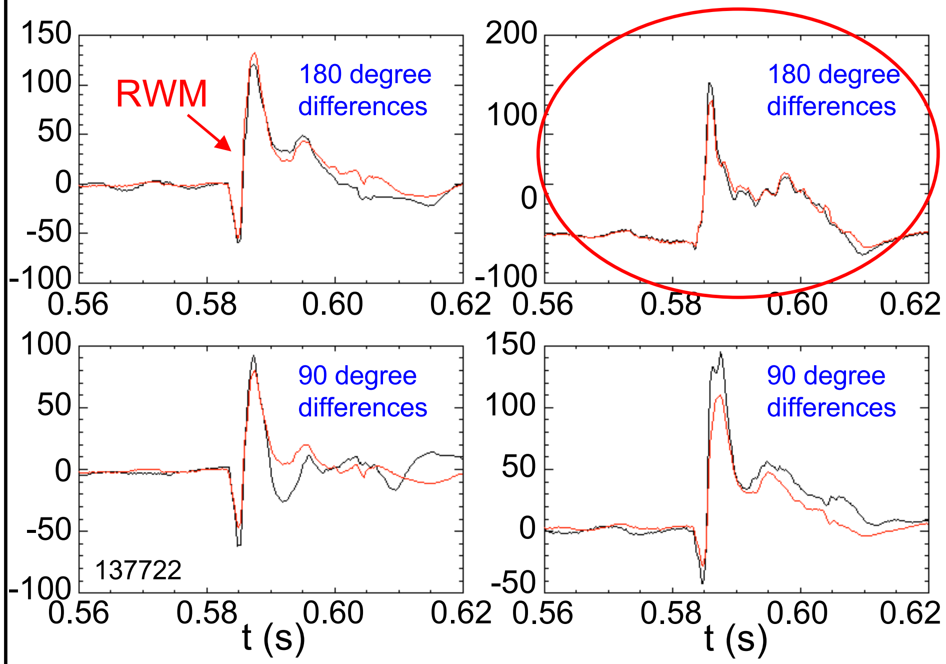
R(10)-1

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
  - May indicate the need for an n = 2 eigenfunction state

Black: experiment Red: offline RWM state space controller

RWM state space controller sustains otherwise disrupted plasma caused by DC n = 1 applied field

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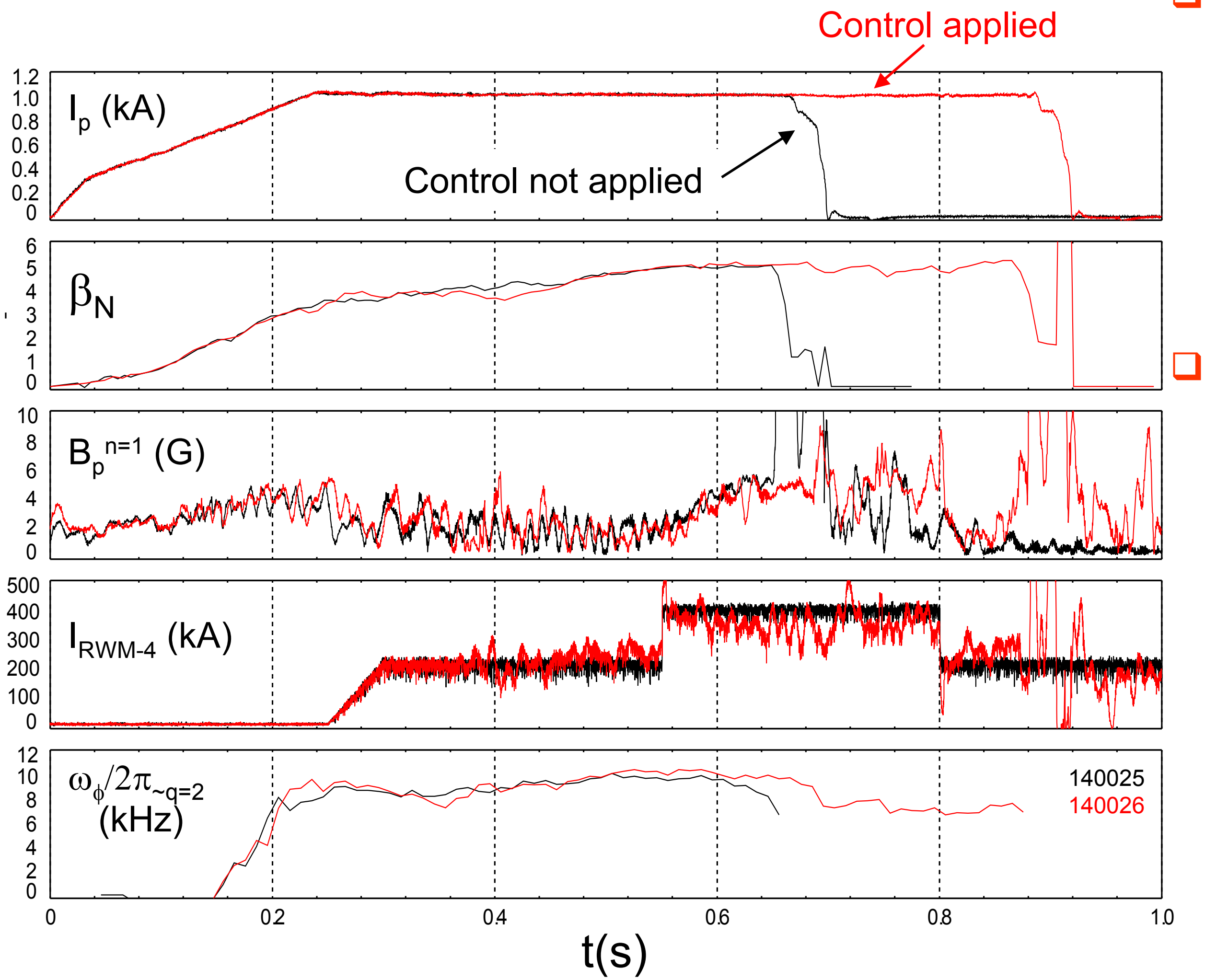
R(10)-1



- n = 1 DC applied field
  - Simple method to generate resonant field amplication
  - Can lead to mode onset, disruption
- RWM state space controller sustains discharge
  - With control, plasma survives n = 1 pulse
  - n = 1 DC field reduced
  - Transients controlled and do not lead to disruption
  - NOTE: initial run – gains NOT optimized

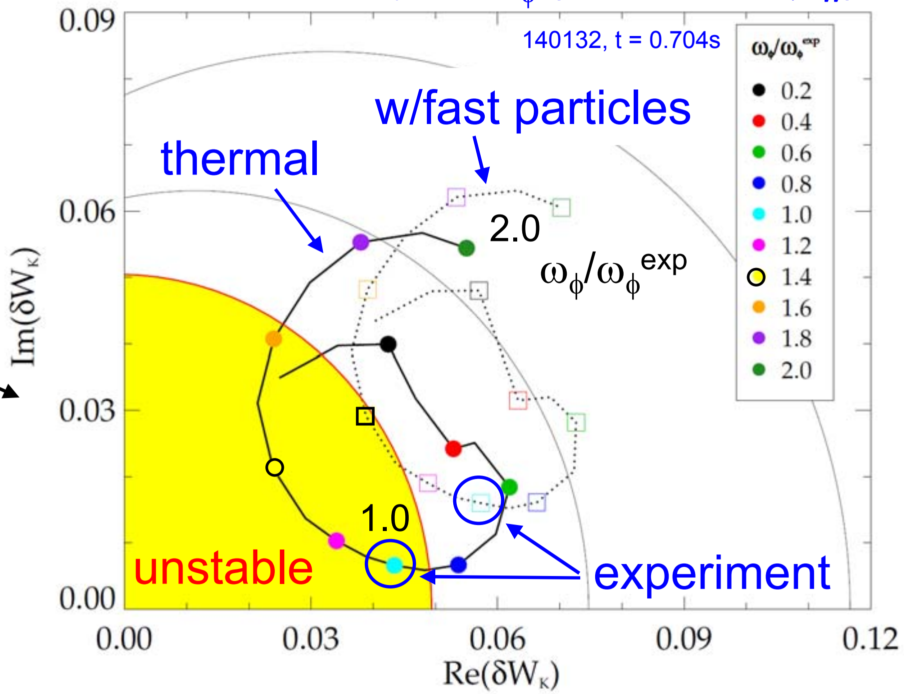
Reduced stability in low l_i target plasma as ω_ϕ is reduced, RWM instability is approached

R(11)-2

PAC 27-19 **ITPA MDC-2**

- Stability evolves
  - MISK computation shows plasma to be stable at time of minimum l_i
  - Region of reduced stability vs. ω_ϕ found before RWM becomes unstable (l_i = 0.49)
    - Co-incident with a drop in edge density gradient – reduces kinetic stabilization

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



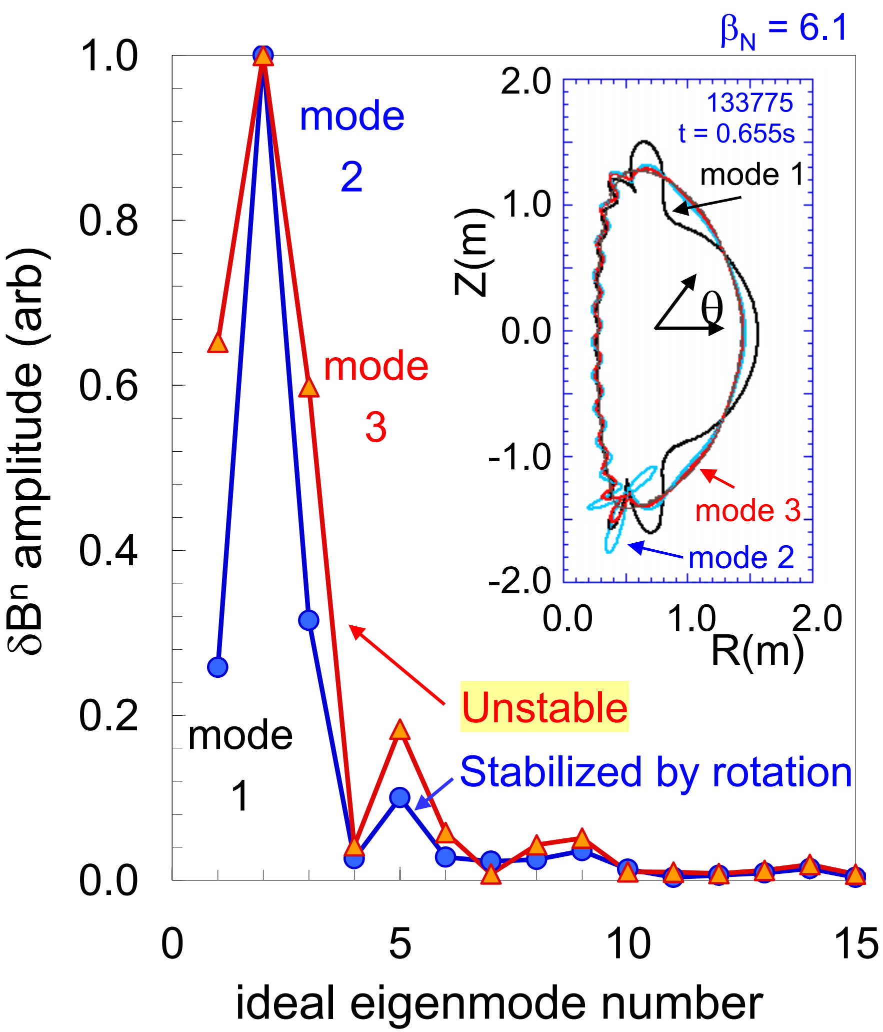
- Plans 2011 – Milestone **R(11-2)**
  - Determine maximum sustainable high β_N in plasmas closer to NSTX-U, next-step ST devices (A ~ 1.7, κ ~ 3, low l_i), test present stabilization physics models / control systems
  - Extend initial experiments at higher A to higher κ, $\langle\beta_N\rangle_{pulse}$, lower l_i, use improved n = 1 PID/state space control. Compare to ideal (DCON), RWM stability limits (MISK, VALEN).

tools

- *Addition of 2nd SPA for independent RWM coil currents (enhanced RWM state-space controller, more flexible ω_ϕ control via NTV)*

Multi-mode RWM computation shows 2nd eigenmode component has dominant amplitude at high β_N in 3D stabilizing structure

δB^n RWM multi-mode composition



mmVALEN code

- ❑ 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 experiment ~ 30 Hz
- ❑ ITER scenario IV multi-mode spectrum
  - ❑ Significant spectrum for n = 1 and 2

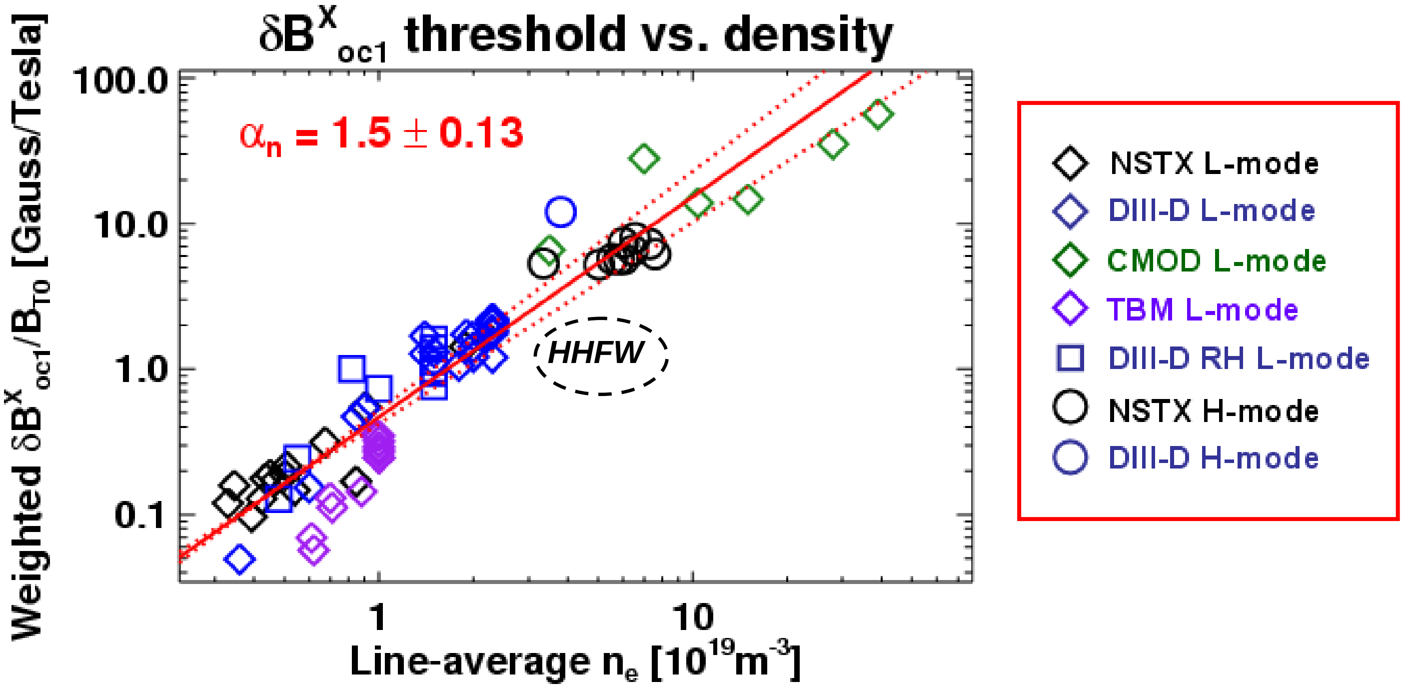
PAC 27-20

- ❑ Plans 2011-2012
  - ❑ Physics study for RWM state-space controller - test if greater eigenmode content improves controller performance

IPEC computed total resonant field unifies linear dependence of mode locking threshold on density among devices

ITPA MDC-2

$$\frac{\delta B^{x}_{oc1}}{B_{T0}} \le 0.4\times 10^{-4}\left(n[10^{19}m^{-3}]\right)^{1.5}\left(B_{T0}[T]\right)^{-1.9}\left(R_0[m]\right)^{1.2}\beta_N^{-1.1}$$



- ❑ Continued effort to consolidate error field threshold scaling in tokamaks
- ❑ Error field threshold in HHFW plasmas will be tested (2011)

ITER IPEC error field task agreement completed

(J.E. Menard, J-K Park)

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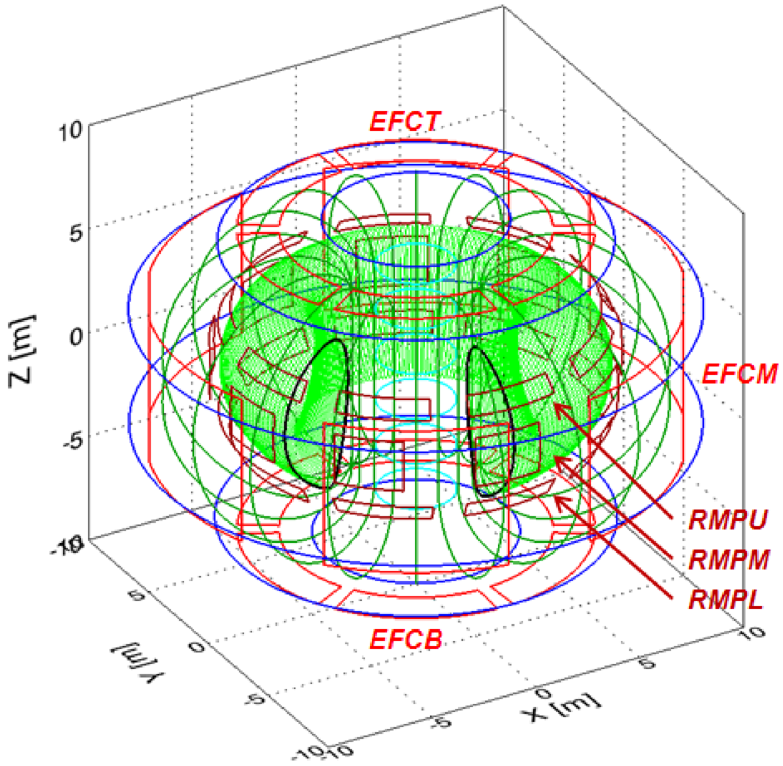


- ITER EFC and RMP coil capabilities for error field corrections were studied using NSTX, DIII-D, and CMOD locking database

<u>Key conclusions:</u>

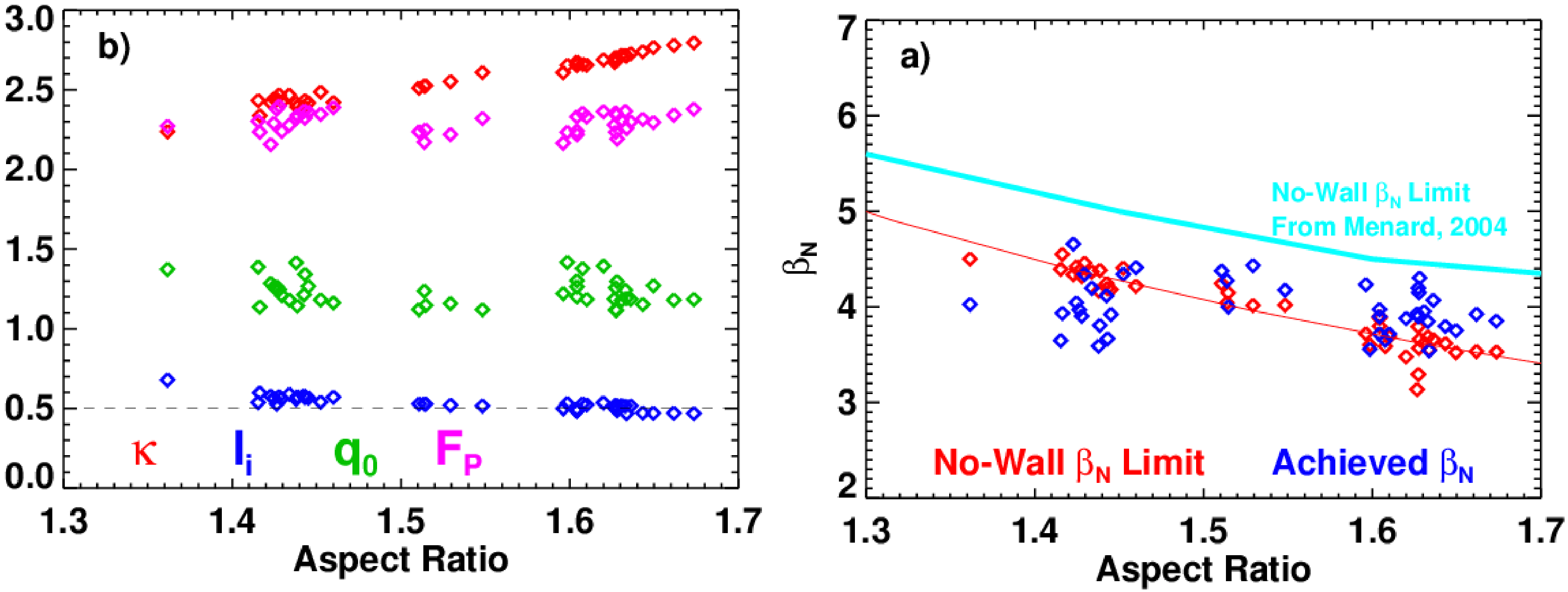
- EFCT and EFCB coils are inefficient for locking mitigation
- EFCT and EFCB coils can help NTV reduction, but RMP coils can do much better with higher efficiency
- Optimized configurations for both locking mitigation and NTV reduction
  - **EFCM+RMPU+RMPL (71+23+23 kAt)**
  - **EFCM+EFCT+EFCB (95+164+257kAt)**
  - **EFCM only (132kAt)**

Significant Reduction of the Calculated No-Wall β_N Limit in Large-Aspect Ratio Scenarios

R(11-2)

PAC 27-19

- Use actual equilibria, reconstructed with MSE, Te-Isotherm, magnetics
- For each reconstructed equilibria
  - Scale pressure profile up and down many times, and compute fixed boundary equilibria (CHEASE)
  - Compute δW for each one, find β_N where $\delta W=0$ (DCON).
- Repeat for many time slices, sort those with similar q_0
- l_i tended to decrease with A, but no clear trend in pressure peaking (F_P)
- Experiment did not actively push the β_N limit…high-priority task in FY-11/12

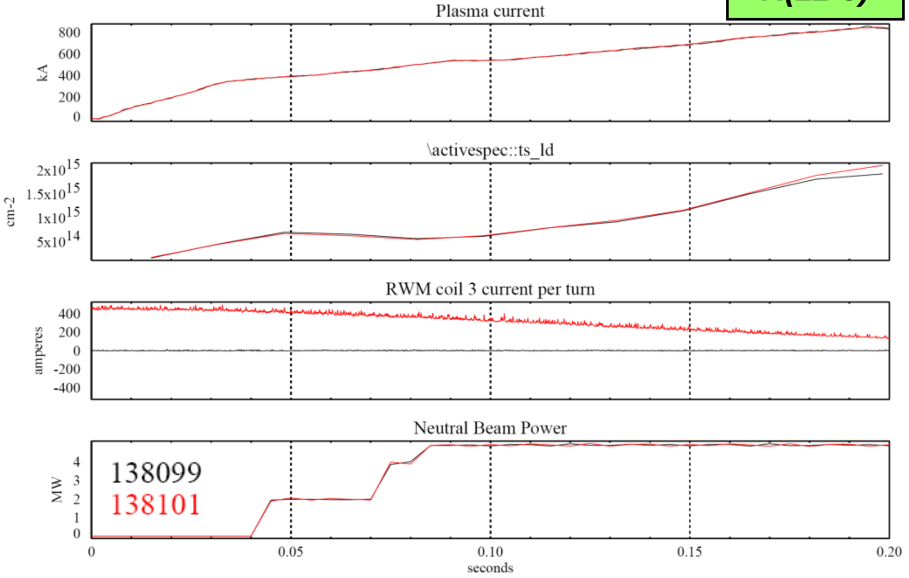


Low density plasmas with and without early EFC show early EFC increases rotation 10-20% for t=120-180ms

R(12-3)

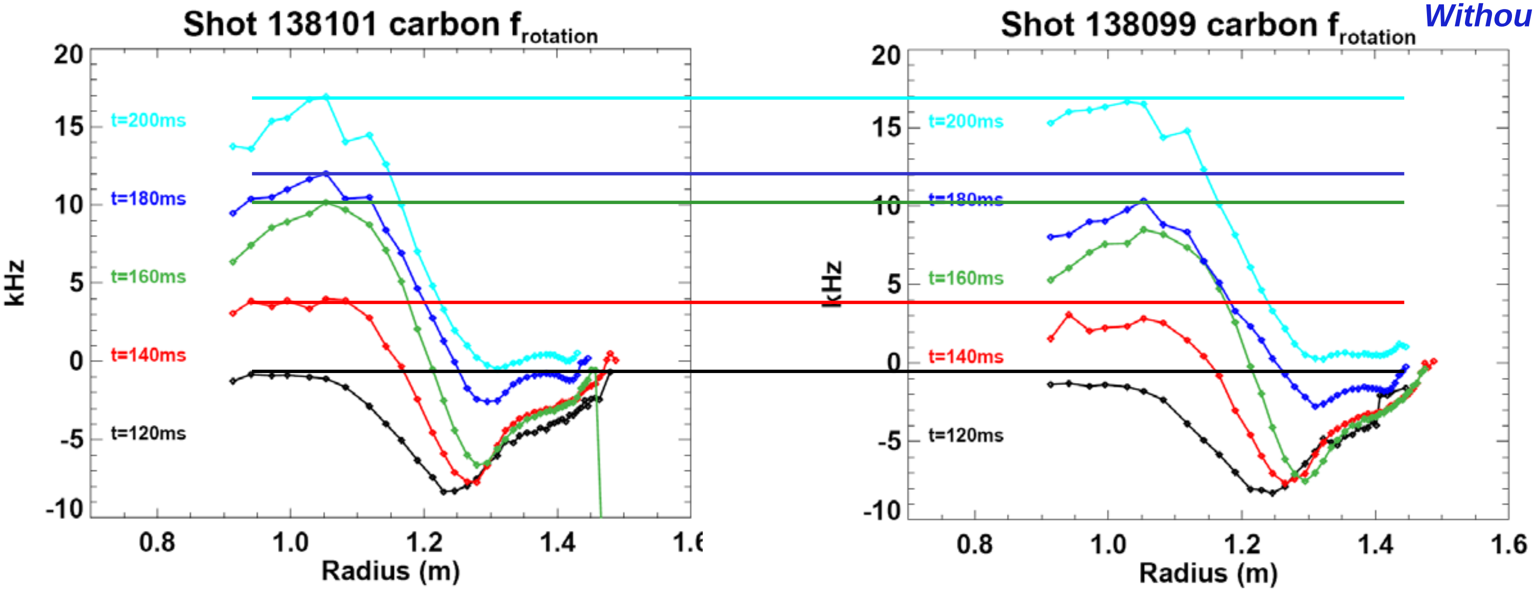
- Delay of early H-mode by reduced early fueling reduces density by 30-40% at t=0.2s (vs. reference)
  - Similar to what typically happens with increased LITER evaporation

- Additional EFC <u>phase</u>, amplitude scans (in 2011) might be able to further increase rotation at reduced density.



With Correction

Without Correction



β_N Controller Implemented Using NB Modulations and rtEFIT β_N

- ❑ Controller implemented in the General Atomics plasma control system (PCS), implemented at NSTX.
- ❑ Measure β_N in realtime with rtEFIT.
- ❑ Use PID scheme to determine requested power:

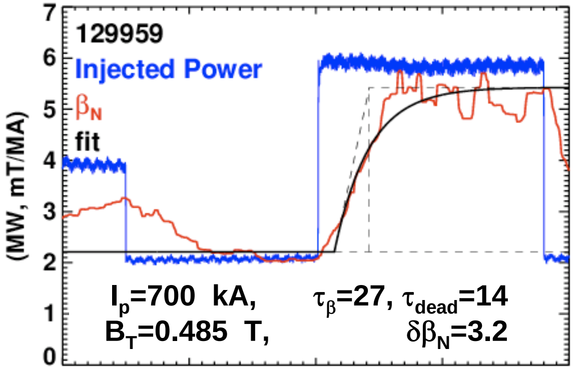
$$e = \beta_{N,reqeust} - LPF\left(\beta_{N,RTEFIT};\tau_{LPF}\right)$$

$$P_{inj} = P_{\beta_N}\overline{C}_{\beta_N}e + I_{\beta_N}\overline{C}_{\beta_N}\int edt + D_{\beta_N}\overline{C}_{\beta_N}\frac{de}{dt}$$

$$\overline{C}_{\beta_N} = \frac{I_P V B_T}{200\,\mu_0 a\,\tau}$$

- Use Ziegler-Nichols method to determine P & I.
  - Based on magnitude, delay, and time-scale of the β_N response to beam steps.
- Convert “analog” requested power to NB modulations.
  - – Minimum modulation time of 15 msec.

Determination of Gains Using Ziegler-Nichols Method



Constant-β_N During I_P and B_T Scans