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Macroscopic Stability Physics (MHD) Research - Applied Stability Control Understanding

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Columbia University

For the NSTX Research Team

NSTX PAC Meeting

January 23, 2008

Princeton Plasma Physics Laboratory

Princeton, NJ

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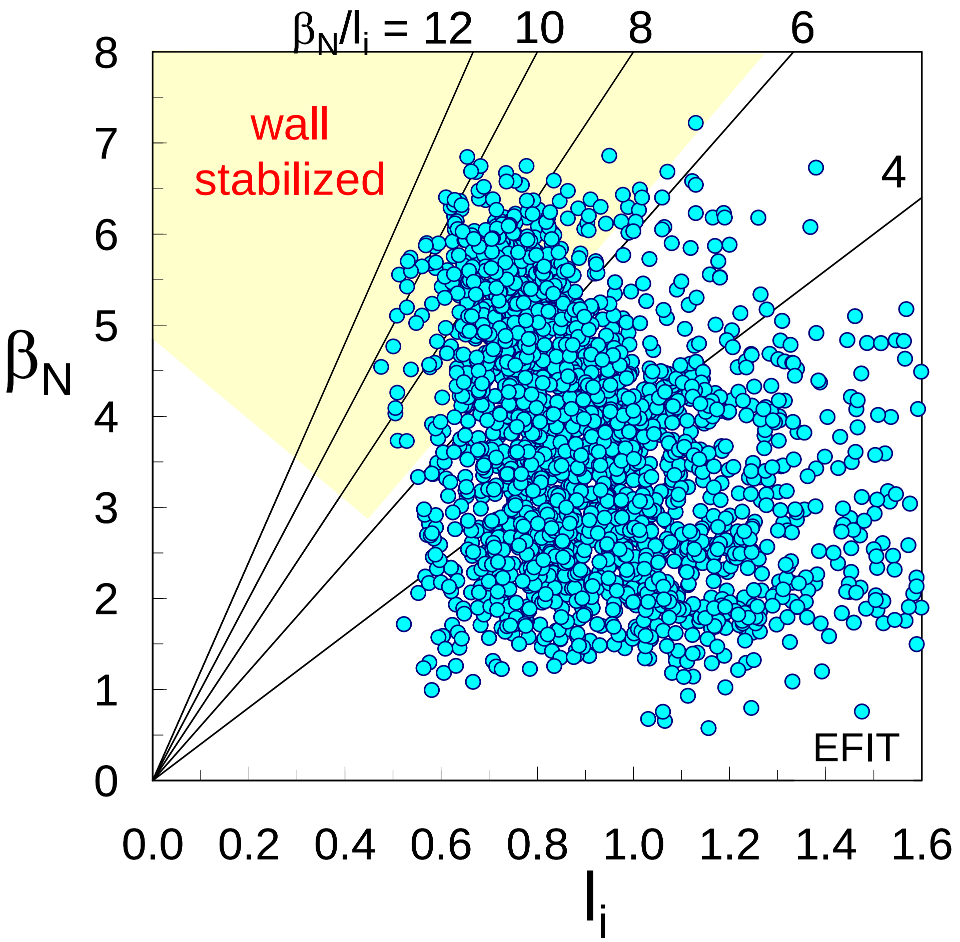
Advanced tokamak operation demonstrated in a mega-Ampere class spherical torus

- High β operational space
  - Ultra-high β_t = 39%, near unity in core
  - Broad current and pressure profiles
  - $\beta_N > 7$, $\beta_N/l_i > 11$
  - Wall-stabilized, $\beta_N/\beta_N^{no\text{-}wall} >$ 50% at highest β_N
- Future research moves to develop predictive capability and control for *steady-state operation near with-wall β limit*
  - Extrapolate to next step device with high confidence



S.A. Sabbagh, et al., *Nucl. Fusion* **46**, 635 (2006).

Continued development of active control tools / fundamental understanding will enable robust extrapolation to next step STs

- High plasma shaping ($\kappa \sim 3$), low l_i operation
  - Vertical stability, kink / ballooning mode stability, coupling to passive stabilizers
- Resistive wall mode (RWM) stabilization
  - Increase reliability of active control, investigate multimode RWM physics
  - Understand physics of passive mode stabilization
- Dynamic error field correction (DEFC)
  - Reduction of RFA, demonstrate sustained V_ϕ, preferably with V_ϕ profile control
- Tearing mode / NTM
  - Stabilization physics at low A, mode locking physics, resonant/non-resonant plasma viscosity
- Non-axisymmetric field-induced viscosity / plasma rotation control
  - Non-resonant and resonant, due to RWM, RFA, NTM, error fields, applied 3-D fields for ELM mitigation
  - Control: Source (2^{nd} NBI, magnetic spin-up) and sink (non-resonant magnetic braking)
- Mode-induced disruption physics and prediction/avoidance

Stability group has responded to all PAC-21 recommendations

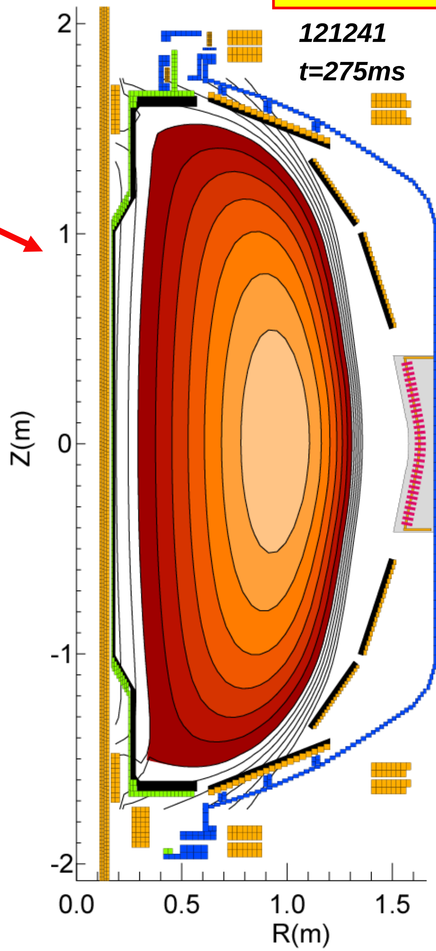
- PAC21-4a: pursue understanding non-axisymmetric field shielding
  - Resonant fields: Locked mode study results consistent with Cole theory (APS 07 invited talks). Plasma response needed to understand q scaling.
  - Non-resonant fields: shielding not needed for quantitative experimental agreement with theory
- PAC21-4b: encourages NTM studies, but not at expense of RWM
  - We did both: RWM study and ran two NTM XPs; start of an expanded study of mode seeding and stabilization in 2008
- PAC21-5: suggests NSTX contribution to ITPA disruption database
  - Present contributions to be supplemented by new diagnostic data in 2008
- PAC21-6: pursue optimal configuration / control, push to steady-state
  - Beta control in '09 – might not close loop in '08 with NBI, rt-MSE pushed out to '11, V_ϕ control pushed out to '11 minimum
- PAC21-36: RWM control system upgrades operation closer to β_N^{wall}
  - New "non-axisymmetric control coil" (NCC) planned 2011 upgrade; pursue advanced state-space control algorithm in 2010 timeframe

Access and maintain high β_t and β_N at high shaping

Contributes to: *NHTX, ST-CTF development*

PAC21-6

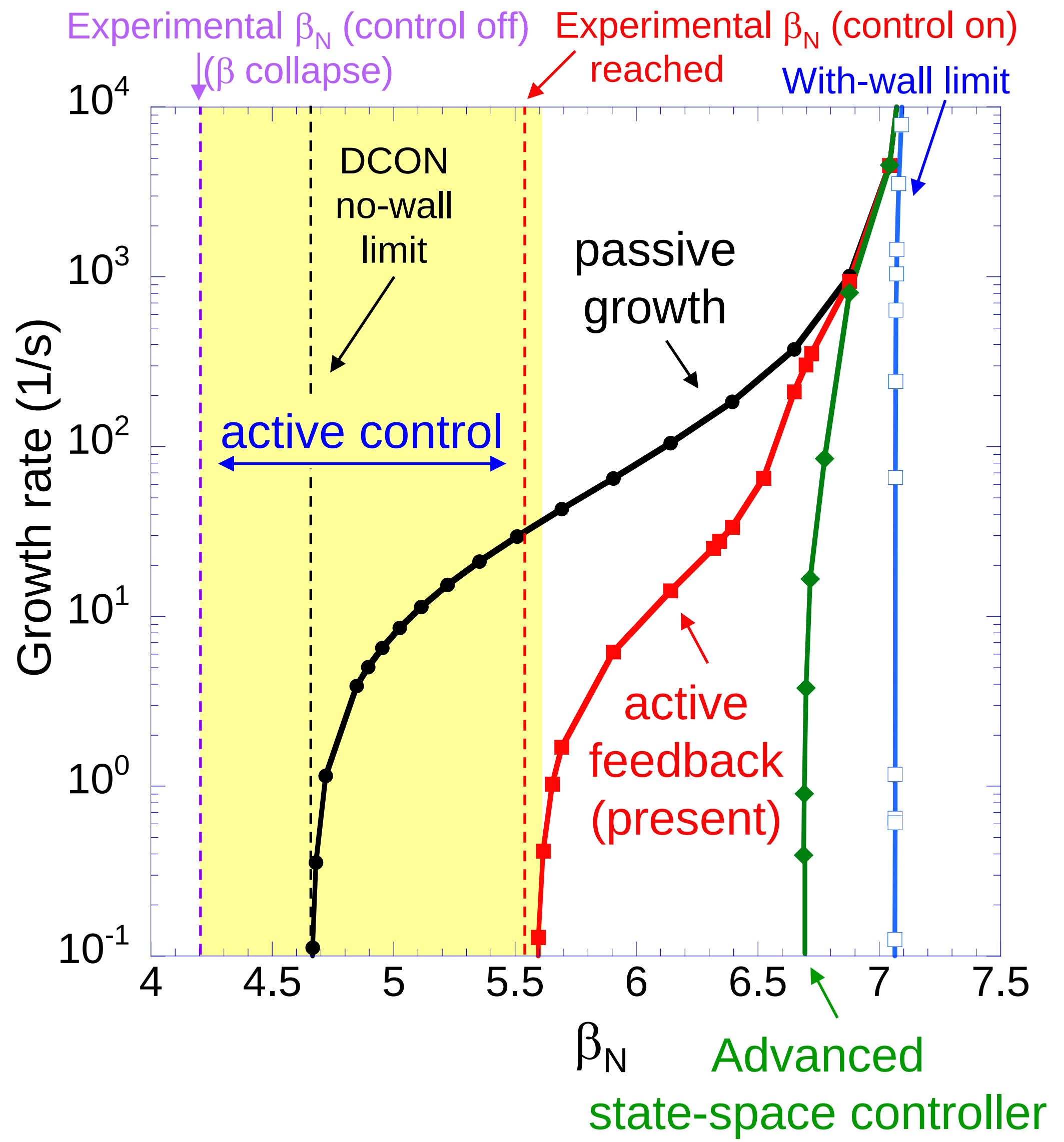
- Present status / issues
  - Sustained $\kappa < 2.6$, $\delta < 0.8$; transient $\kappa = 3$ with record shaping factor, $S \equiv q_{95}(I_p/aB_t) = 41$
  - Highest κ and S plasmas suffer β collapse at $\beta_N \sim 4 \sim$ computed ideal $\beta_N^{\text{no-wall}}$
- Plan summary 2008-2010
  - Operate with upgraded control computer. Test β feedback control using diamagnetic loop sensor and NBI power.
  - Research to extend high S plasmas into wall-stabilized, high $\beta_N > 6$ operating space, understand stabilization
- Reduction to 2 year program provides only enough time for initial understanding of stability at extreme shaping; eliminates integration with full β and V_ϕ feedback
- Plan summary 2011-2013
  - Integration of β feedback into real-time EFIT, improve strike point control for Li divertor.
  - real-time MSE w/real-time V_ϕ for real-time EFIT, β feedback using stability models; profile control with 2[nd] NBI



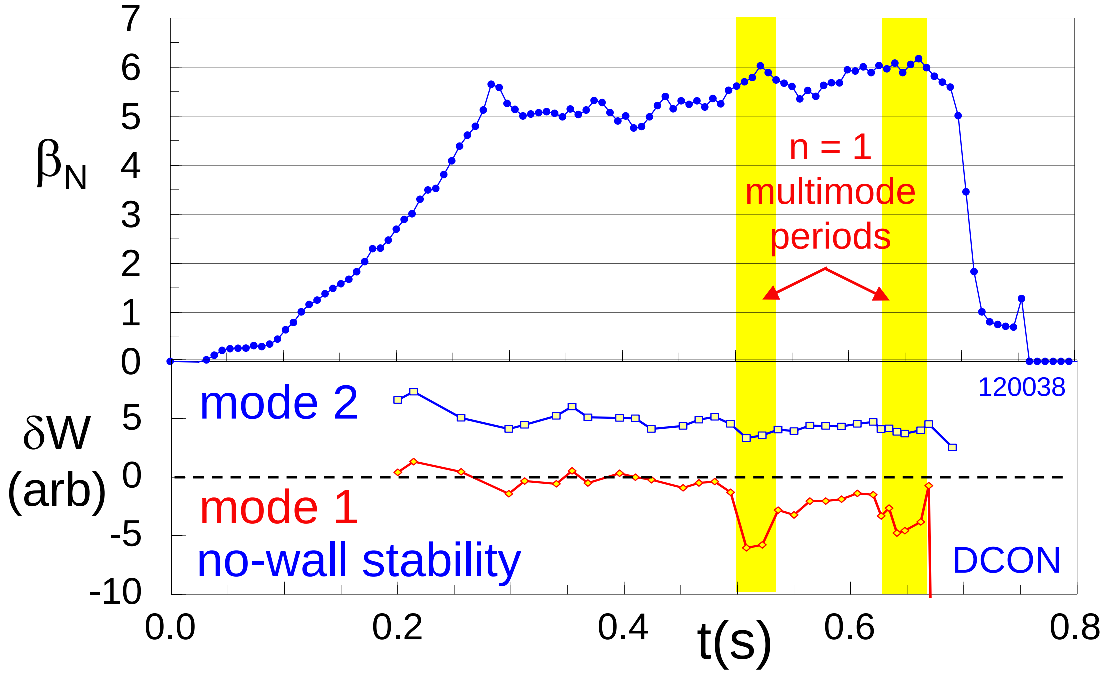
D.A. Gates, et al., *Nucl. Fusion* **47**, 1376 (2007).

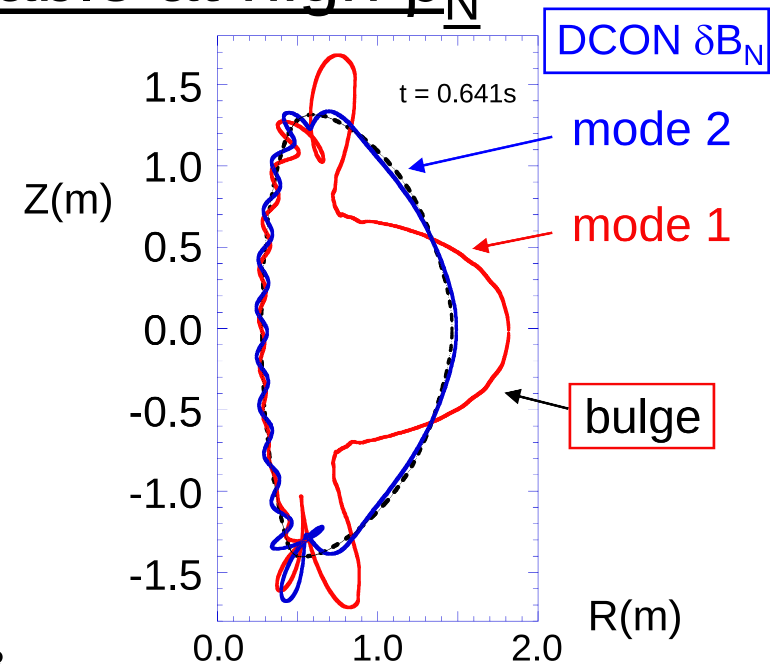
VALEN code reproduces RWM feedback performance

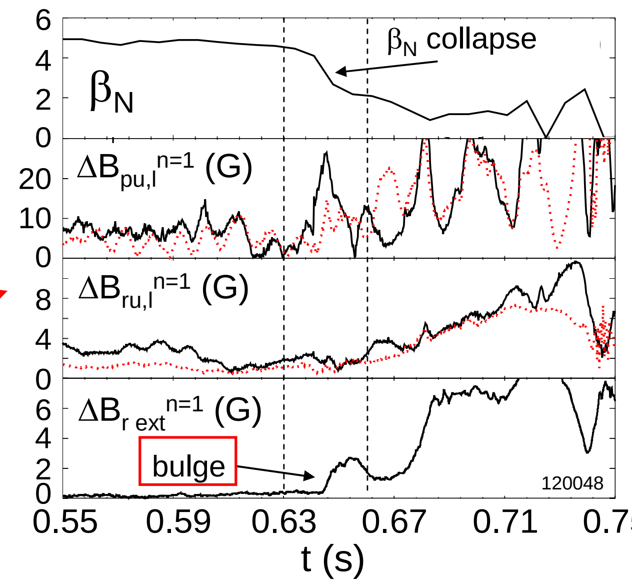
- New model simulates experiment
  - Upper B_p sensors located as on device
  - Compensation of control field from sensors
  - Experimental equilibrium reconstruction (including MSE data)
  - Proportional gain
- Advanced control may greatly improve performance
  - Advanced state-space controller with B_{pu} sensors may stabilize $\beta_N/\beta_N^{wall} < 95\%$ (benefit to ITER, next-step ST)
  - Plan to test offline in 2008, implement for initial RWM control testing 09-10



Multimode theory applicable at high β_N







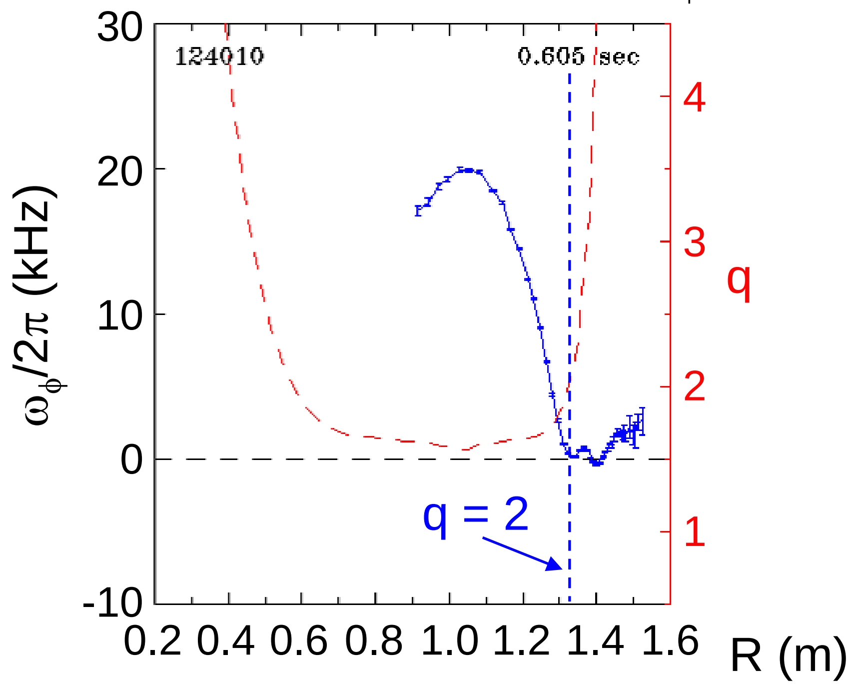
- Boozer multimode criterion for n = 1 met at high β_N (PoP 10 (2003) 1458.)
  - $|\delta W|$ smallest for 2nd n = 1 eigenfunction
- Multiple n > 1 RWM also observed in NSTX (Sabbagh, et al., Nucl. Fusion **46** (2006) 635.)
- Multiple n = 1 modes may explain observations
  - Upper/lower sensor phases do not always match single mode
  - Poloidal deformation of mode during feedback (mode "non-rigidity")

S.A. Sabbagh, et al., PRL **97** (2006) 045004.

NSTX

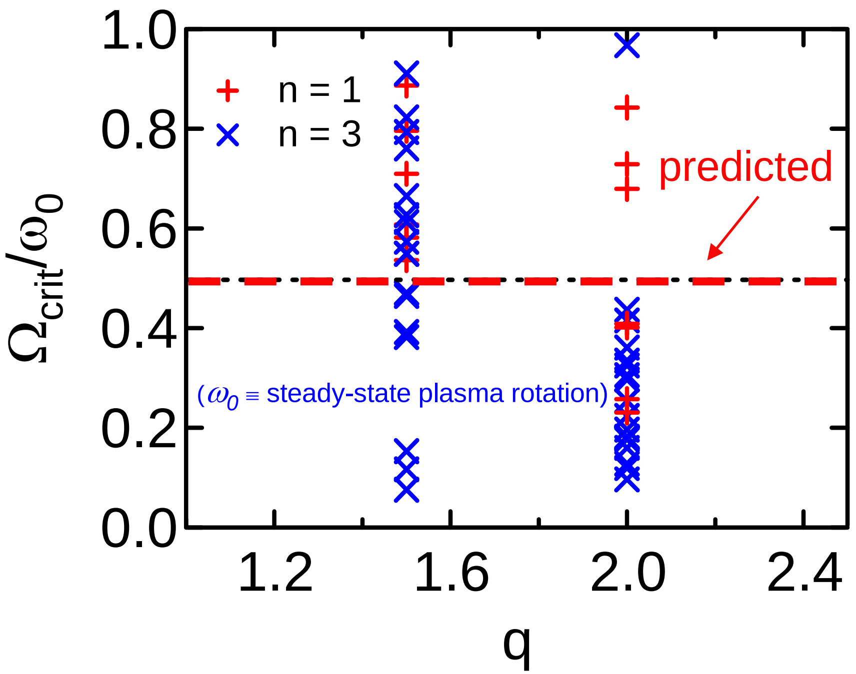
Non-resonant magnetic braking allows V_ϕ modification to probe RWM critical rotation and stabilization physics

- Scalar plasma rotation at q = 2 inadequate to describe marginal stability
  - Plasma stable $\beta_N > \beta_N^{no\text{-}wall}$, $\omega_\phi^{q=2} = 0$



- Ω_{crit} doesn't follow simple $\omega_0/2$ rotation bifurcation relation

A.C. Sontag, et al., NF **47** (2007) 1005.



- Ion collisionality profile variation appears to alter Ω_{crit} profile
- RWM stability at low rotation profile not yet found unless (i) active RWM control applied, (ii) internal rotating mode with $\omega \sim \omega_\phi$ present

Significant progress planned for RWM stabilization research

***Contributes to**: ITPA MDC-2, USBPO coil design, 2008 Joule, 09-10 NSTX milestones*

PAC21-36

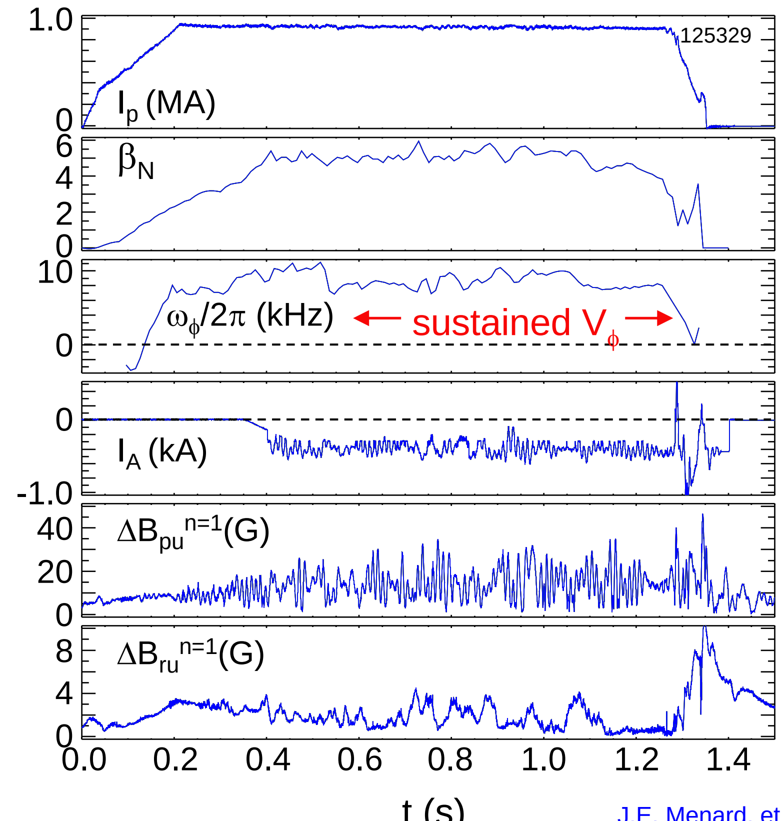
- Plan summary 2008-2010
  - Determine RWM stabilization requirements for broader range of V_ϕ profiles
  - Test present MHD theories against present profile database, new parameter scans (2009 milestone)
    - Kinetic modification of ideal MHD δW – Hu-Betti-Manickam code (ported locally, setting up test runs now)
    - Compare to latest MARS-F implementation (full kinetic effects modeled - Y. Liu)
  - Continue proportional feedback parameter variation, all RWM sensors used for feedback
  - Test advanced state-space active stabilization algorithms offline; implement and perform initial tests for RWM control
  - Investigate multiple modes in stabilization, implement methods of decreasing possibility of RWM poloidal deformation
    - Multi-mode VALEN code now completed (running NSTX, DIII-D, and HBT-EP test cases now)
  - Design high-*n* control coil (NCC) – 12 coils toroidally (n/a if research plan limited to 3 years)
  - Implement initial non-magnetic (SXR) RWM sensors, study mode identification
- Reduction to 2 year program greatly compromises ability to reach conclusions in these areas, eliminates testing of state-space RWM control; eliminates study of passive stabilization under active V_ϕ profile control
- Plan summary 2011-2013
  - Start NCC use for RWM stabilization; $n > 1$ RWM, multimode study during $n = 1$ stabilization
  - Implement real-time mode ID with non-magnetic RWM sensors; use in feedback control
  - Examine greater range of V_ϕ profiles with 2nd NBI, greater non-resonant braking flexibility using NCC
  - Examine RWM stabilization during V_ϕ profile feedback control

Dynamic Error Field Correction used to maintain V_ϕ, high β_N

Contributes to: *ITPA MDC-2, 2010 milestone*

- Plan summary 2008-2010
  - Investigate sources / physics of dynamic error field, resonant field amplification
  - Investigate correction of *n* = even fields (primarily *n* = 2, 4, also n = 6 with limited scope)
  - Feedback on upper and lower arrays of both B_r and B_p sensors
- Reduction to 2 year program eliminates research/understanding from improved capability/flexibility of DEFC planned
- Plan summary 2011-2013
  - Independent control of $n \leq 6$ fields with expanded power supply capability (midplane coil) to sustain plasma rotation and high β_N
  - Significantly expanded correction capability (e.g. ability to vary poloidal spectrum of field) using new NCC

I_p = 0.9 MA record pulse length
n = 1 feedback (All RWM B_p sensors, optimal phase) and n = 3 error correction



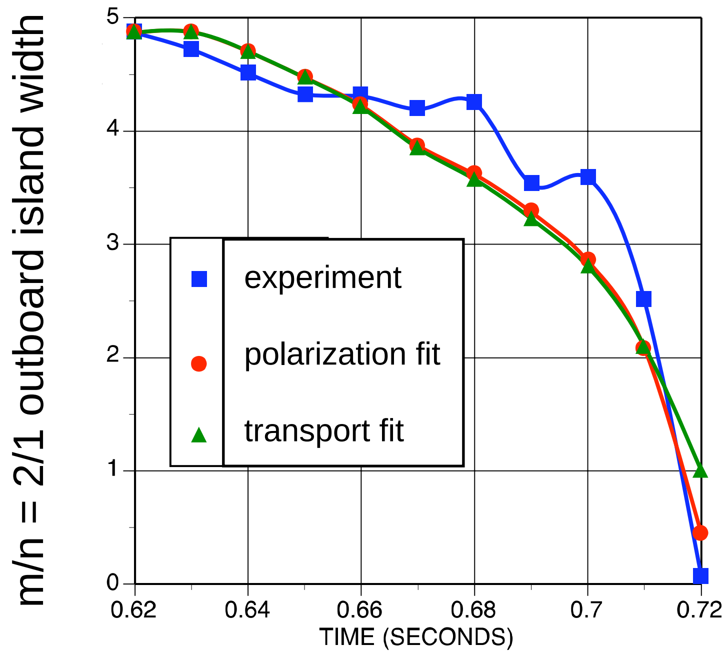
J.E. Menard, et al. APS DPP Invited Talk (2007)

Comparison XPs to investigate *A* effects on tearing stability

PAC21-4b

2/1 Marginal island width for stabilization

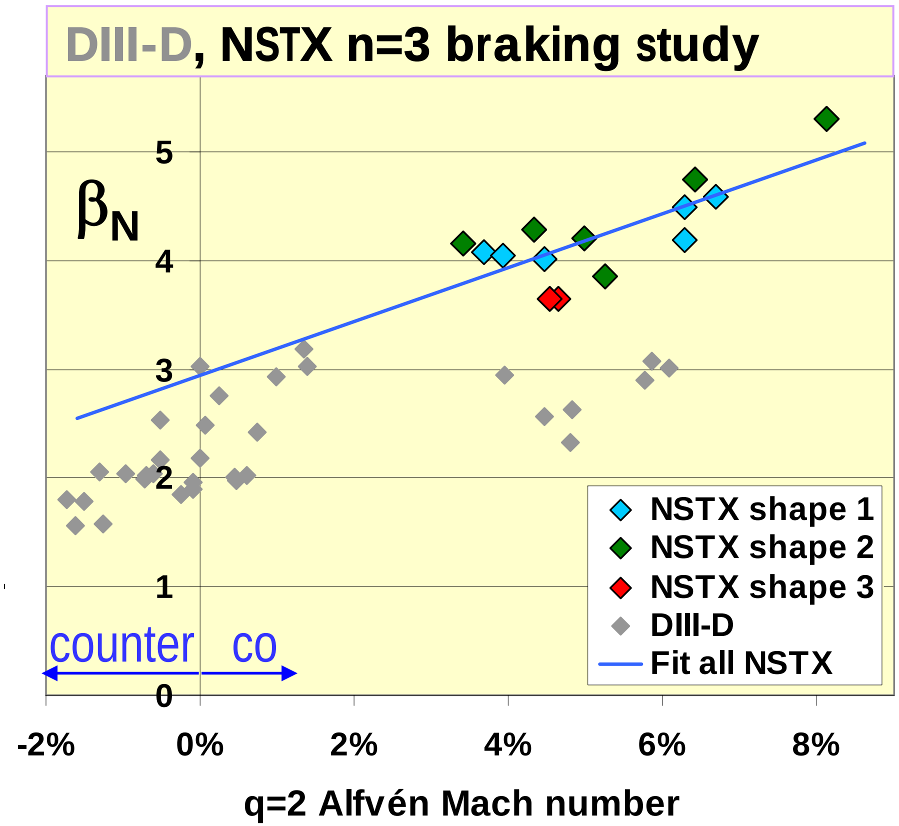
(R. LaHaye, et al., NSTX XP 739 (2007).)



- $W_{marg}/\varepsilon^{0.5}\rho_{\theta i}$ ratio ~ 2 in tokamaks
  - AUG, DIII-D, JET data for 3/2 mode
- First result shows $W_{marg}/\varepsilon^{0.5}\rho_{\theta i}$ also ~ 2 for NSTX (2/1 mode) (!)
  - NSTX W_{marg} = 3.5 cm; DIII-D: 3.1 cm

2/1 onset β_N vs. toroidal rotation

(E.J. Strait, et al., NSTX XP 740 (2007).)



- Similar % fall in β_N per % Mach
- Further analysis to examine *A*, V_ϕ shear effects

Investigate explicit *A* dependences on tearing stability

***Contributes to:** ITPA MDC-3, ITPA MDC-4, 2008 Joule, 2010 NSTX milestone*

- Plan summary 2008-2010
  - Compare mode characteristics/stability of sawtooth seeded 2/1, 3/2 modes to spontaneous modes
    - Compare to higher *A*
    - Determine further seeding mechanisms
  - Increase simulation capacity: modified Rutherford equation at low-*A*
    - PEST3, rDCON, NIMROD, M3D
  - Begin NTM onset β_N experiments vs. ρ*, ν*, V_ϕ, V_ϕ shear
- Reduction to 2 year program significantly limits scope of experiments, integrated comparison of theory/experiment
- Plan summary 2011-2013
  - Complete NTM onset β_N study vs. ρ*, ν*, V_ϕ, V_ϕ shear; stability near β_N^{wall}
  - Comparison of NTM experiments to theory/simulation developed
  - Develop discharges that avoid mode, minimize mode impact via profile control (e.g. q, V_ϕ, shear) with 2nd NBI, NCC
  - Assess EBWCD results for potential stabilization

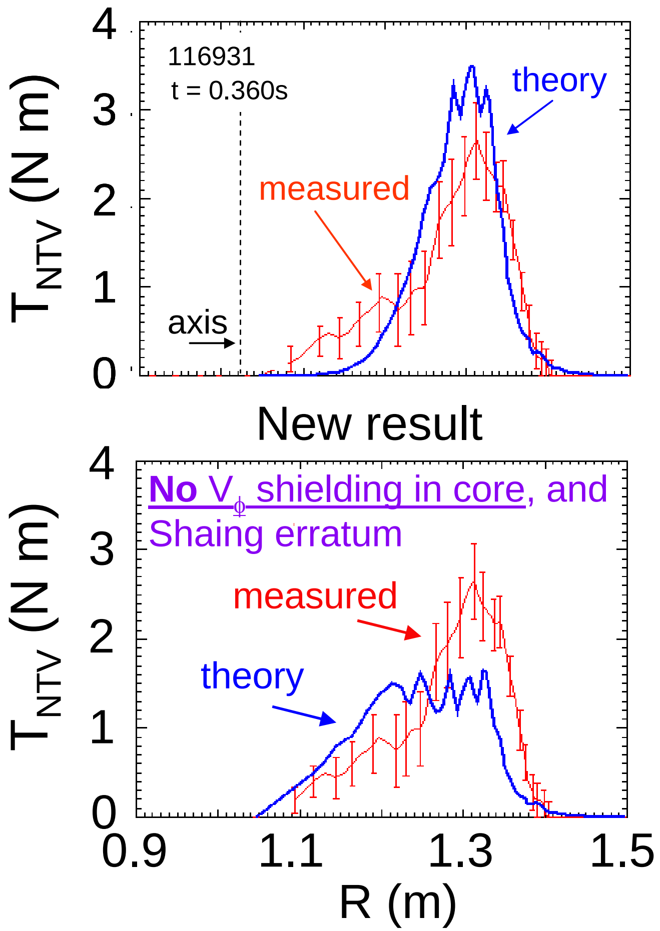
Control V_ϕ profile using knowledge of plasma viscosity

PAC21-4a

- Significant interest in plasma viscosity due to non-axisymmetric fields
  - Physics understanding needed to minimize rotation damping from ELM mitigation fields (ITER, etc.)
  - New Neoclassical Toroidal Viscosity (NTV) investigations on DIII-D, JET, C-MOD, MAST, etc. following quantitative agreement on NSTX
- Expand present studies on NSTX
  - New capability to examine larger n spectrum (e.g. n = 2,4, limited capability for n = 6)
  - Consider expansions of NTV theory
    - Saturation due to E_r, multiple trapping states, errata
    - No V_ϕ shielding needed in core when recent Shaing erratum included
  - Examine NTV from magnetic islands
  - Compare to kinetic modeling using new GTC-Neo upgrade (W. Wang)

Measured $d(I\Omega_p)/dt$ profile and theoretical NTV torque (n = 3 field) in NSTX)

W. Zhu, et al., *Phys. Rev. Lett.* **96,** 225002 (2006).



Control V_ϕ profile using knowledge of plasma viscosity

Contributes to: *ITPA MDC-2, ITPA MDC-12, 2008 Joule, 2010 NSTX milestone*

- Plan summary 2008-2010
  - Continue testing viscosity theory from resonant /non-resonant fields
    - Greater *n* spectrum (e.g. even parity fields)
    - Focus on key parameters: ν_i, q, β_N, V_ϕ, n ; joint experiments with other devices
    - Influence of magnetic islands (INTV)
  - Expand analysis to further test theory
    - Impact of multiple trapping states
    - Time-evolved computations using GTC-Neo; examine saturation at low ν_i ; compare to present theory
  - Influence NCC design (eliminated in 3 year termination plan)
- Reduction to 2 year program limits research to study of NTV and INTV theories with present machine capability - no real-time V_ϕ control demonstration and verification
- Plan summary 2011-2013
  - 2nd beam line to vary torque at fixed power
  - Use NCC to test viscosity theories ($n \leq 6$)
  - Real-time V_ϕ control using CHERS sensors, basic sources and sinks of plasma toroidal momentum
  - Real-time V_ϕ control using additional momentum sources
  - Attempt momentum *input* with NCC via non-resonant NTV

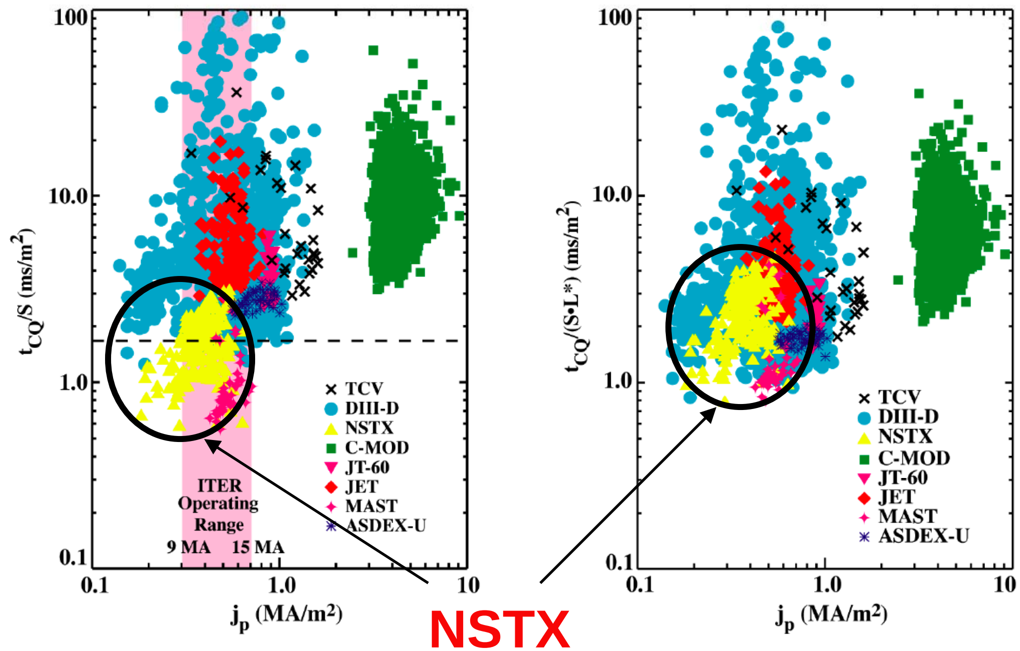
Analyze disruption characteristics, causal modes, avoidance

Contributes to: *NHTX, ST-CTF development*

PAC21-5

- Plan summary 2008-2010
  - Further characterize modes that lead to disruptions, operational boundaries
  - Current quench rate study (ITPA)
  - Greater halo current diagnostics in the lower divertor, for magnitude and toroidal peaking studies. Initial IR camera studies.
  - Studies of heat flux deposition patterns and timing vs. disruption type and discharge parameters (e.g. q_{95}, dr_{sep})
- Reduction to 2 year program eliminates disruption avoidance via plasma control; might drop entirely
- Plan summary 2011-2013
  - Precursor studies for disruption prediction
  - Detection of impending disruptions based on real-time measurements
    - RFA, stability model based detection

Area-normalized (left), Area and L_{ext}-normalized (right) I_p quench time vs. toroidal J_p (ITER DB)



J.C. Wesley et al., *21st IAEA Fusion Energy Conference* (Chengdu, China 2006), paper IT/PI-21.

2008 Run Plan includes specific ITER support XPs

Suggested by

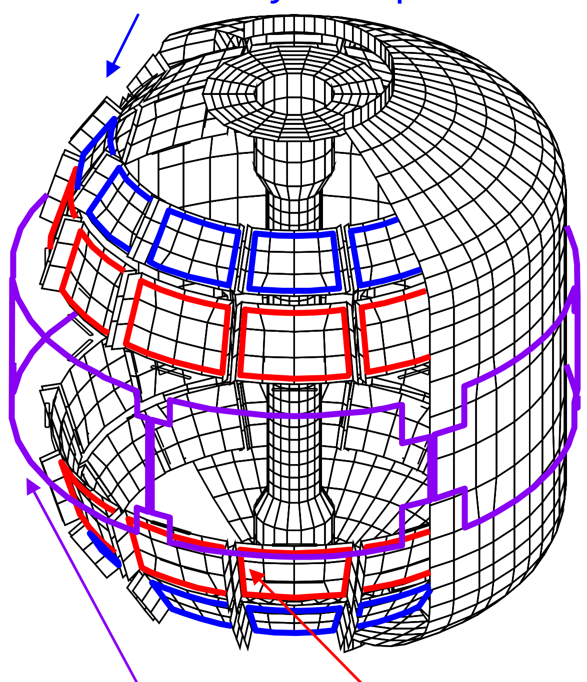
- ELM Mitigation
  - "Joint" ELM mitigation experiment to address "challenge" of demonstrating ELM mitigation with a single row of midplane coils ← USBPO, ITER Org.
- Neoclassical Toroidal Viscosity (NTV) Study
  - Several experiments following quantitative agreement on NSTX to best determine impact of non-axisymmetric fields from ELM/RWM coils, error fields on ITER rotation ← USBPO, ITER Org.
  - Experiments include n = even fields, ν_i variation, INTV
- RWM stabilization
  - Experiment to artificially vary active feedback system latency to simulate the effect of greater time delays due to ITER blanket ← NSTX PAC
  - Experiment to simulate ITER port plug RWM stabilization coil geometry by eliminating current in one coil during feedback ← ITER Org.

New capabilities planned for 2011 – 2013 research

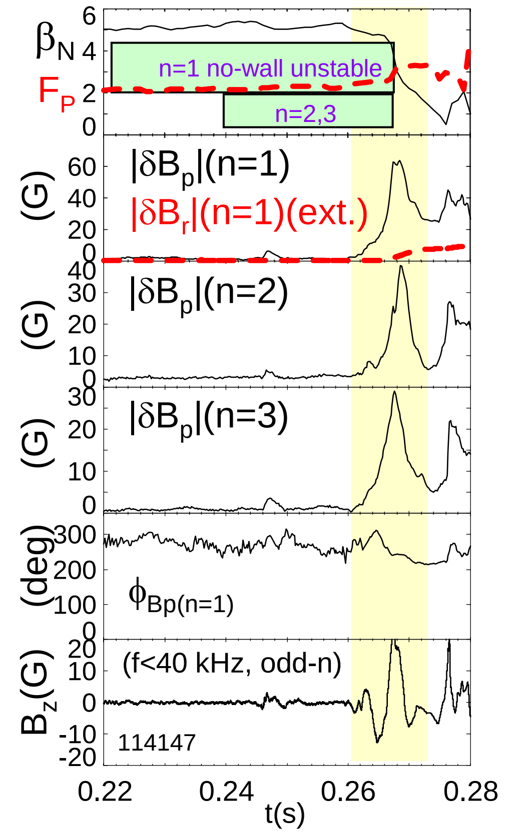
(ALL Eliminated if operations limited to 3 years)

- Capabilities
  - 2nd NBI
    - q profile variation
    - momentum source variation
  - Non-axisymmetric control coil (NCC) – at least four applications
    - RWM stabilization (n > 1, higher β_N)
    - DEFC with greater field correction capability
    - ELM mitigation (n = 6)
    - V_ϕ control increase; n > 1 propagation)
  - Non-magnetic RWM sensors; advanced RWM active feedback control algorithms (ITER, etc.)
  - Alteration of stabilizing plate materials / electrical connections

Proposed Internal Non-axisymmetric Control Coil (NCC) (12 coils toroidally)



RWM with n > 1 RWM observed



(Sabbagh, et al., Nucl. Fusion **46**, 635 (2006).)

U.S. leads the world in high β ST research and is in position to bridge the gap to next-step STs

- Macroscopic stability research direction
  - Transition from establishing high beta operation to reliably and predictably sustaining and controlling it – required for next step device
- Research provides critical understanding for tokamaks
  - Stability physics understanding applicable to tokamaks including ITER, leveraged by unique low-*A*, and high β operational regime
  - Specific ITER support tasks on schedule for 2008 run
- NSTX provides access to best diagnosed high beta plasmas
  - 2008-2010 Run: allows significant advances in scientific understanding of ST physics, supports ITER, and advances fundamental science
  - Curtailed 2 Year Run: does not allow completion of key scientific investigations; significant loss of control demonstration/research
  - 2011-2013 Run: allows demonstration/understanding of reliable stabilization/profile control - performance basis for next-step STs

Macroscopic Stability Research Timeline (2008-2010)

V1.0

FY07 | 08 | 09 | 10 | 11 | 12 | 13 | 14

Physics

- **shaping**: Run β_N > 6 w/high S; β_N control w/diag loop ctrl
- **RWM**:
  - Opt. active RWM control, V_ϕ; mode deform.
  - Adv. RWM control design
  - non-mag. detect.
  - RWM stab. physics (ν_i,V_ϕ,ω_A, multi-modes)
- **DEFC**: DEFC physics model at high β; optimize DEFC
- **NTM**: low A studies (W_{marg}, V_ϕ, ρ*,ν*); seeding physics
- **V_ϕ physics**: NTV physics, ν_i, n=2-6, INTV
- **Disruptions**: Characterize disruption/modes; low A sims.

Tools

- two toroidal SXR arrays
- non-mag. RWM det.
- pCHERS, FIDA, high-resolution edge SXR, internal δB with MSE
- rt- MSE
- MSE-LIF, LLD
- rt-V_ϕ
- Adv. RWM cntl. alg.
- Code devel/appl: mmVALEN,,Hu-Betti δW, MARS-F, GTC-Neo NTV, NIMROD, M3D, etc.
- div. halo current
- β control; fast IR, PFC loads

Base Plan
+10% incr.

Macroscopic Stability Research Timeline (2008-2013)

V1.0

FY07 | 08 | 09 | 10 | 11 | 12 | 13 | 14

Physics

shaping
- Run β_N > 6 w/high S; β_N control w/diag loop ctrl
- β_N, SP control w/ rtEFIT
- β_N control w/stability models

RWM
- Opt. active RWM control, V_ϕ; mode deform.
- Role of n > 1, stabilize RWM w/NCC
- Adv. RWM control design, NCC dsgn
- non-mag. RWM detect.
- non-mag. RWM control
- RWM stab. physics (ν_i,V_ϕ,ω_A, multi-modes)
- Adv. RWM control with V_ϕ, q profile control

DEFC
- DEFC physics model at high β; optimize DEFC
- Advanced δB correction w/ NCC

NTM
- low A studies (W_{marg}, V_ϕ , ρ^*,ν^*); seeding physics
- Test models low A; mode avoidance min. impact

V_ϕ physics
- NTV physics, ν_i, n=2-6, INTV, NCC design
- NTV, INTV w/ real-time V_ϕ control; with NCC

Disruptions
- Characterize disruption/modes; low A sims.
- Disruption prediction, detection, avoidance

*10% incr. puts 2nd NBI earlier, NCC later

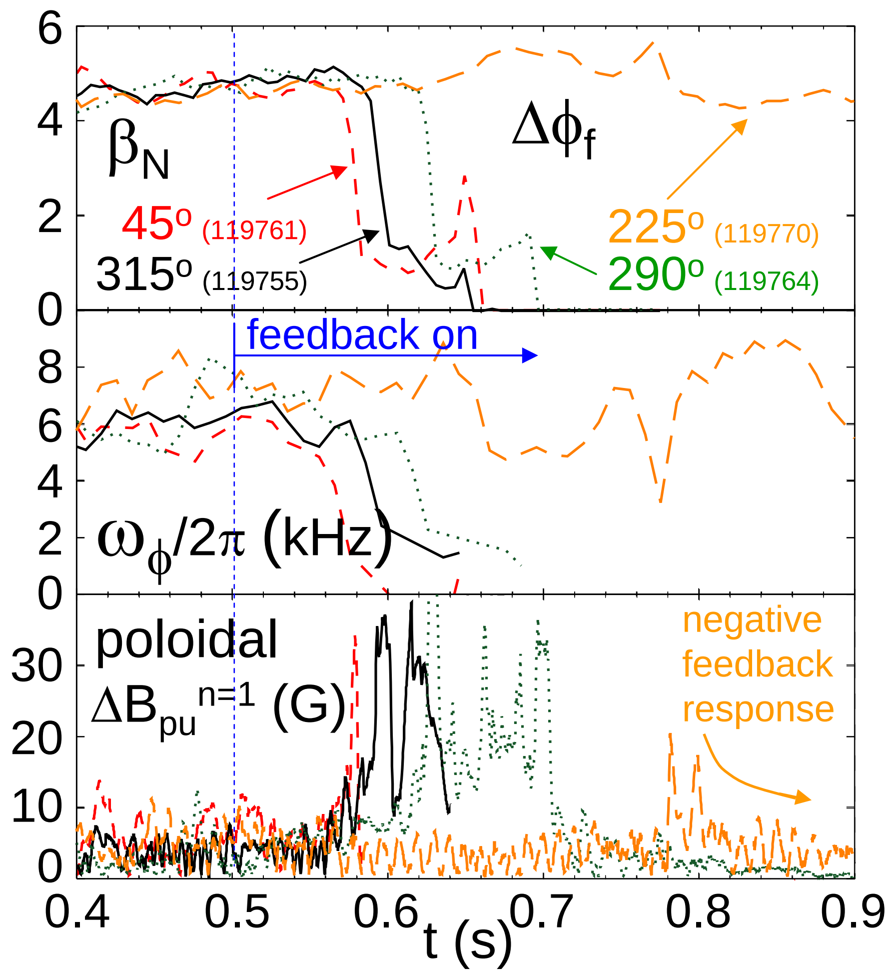
Tools

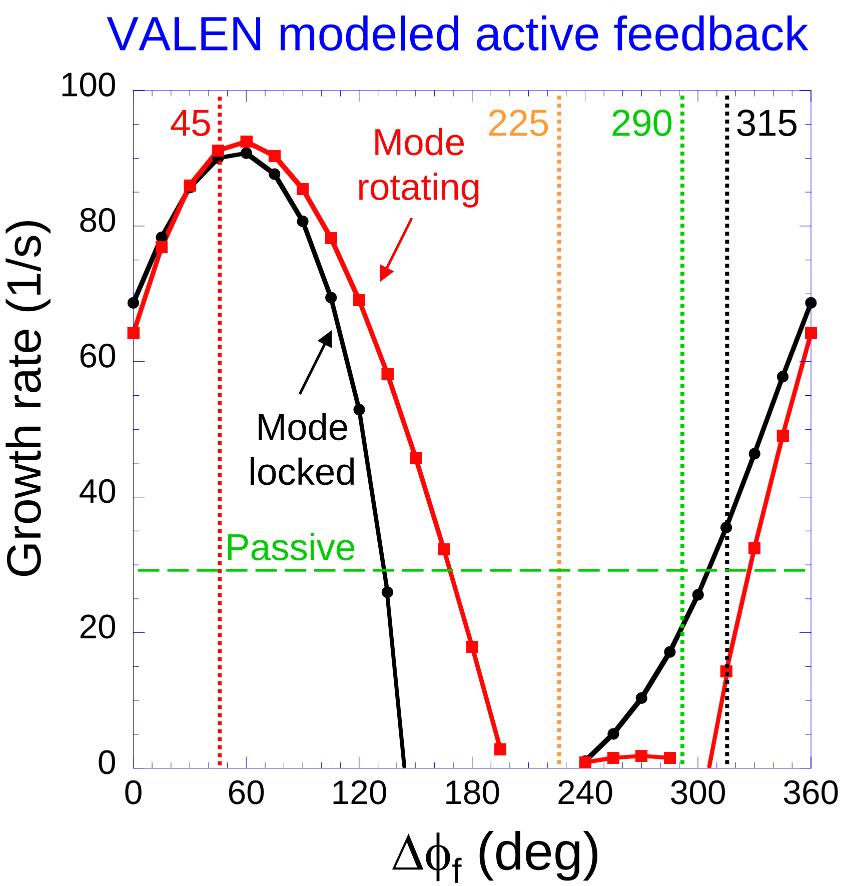
- two toroidal SXR arrays
- NCC install
- Adv. RWM, DEFC, V_ϕ ctrl w/ NCC
- non-mag. RWM detect.
- neut. collim.
- non-mag. RWM control
- pCHERS, FIDA, high-resolution edge SXR, internal δB with MSE
- real-time MSE
- 2nd NBI
- q control
- MSE-LIF, LLD
- real-time V_ϕ control
- advanced rt-V_ϕ control
- Advanced RWM control algorithms
- Integrated code devel/appl: mmVALEN,Hu-Betti δW, MARS-F, GTC-Neo NTV, NIMROD, M3D, PEST3, rDCON

Base Plan
+10% incr.*
- div. halo current
- β control; fast IR - PFC disrupt. loads; disruption prediction/detection

Backup slides

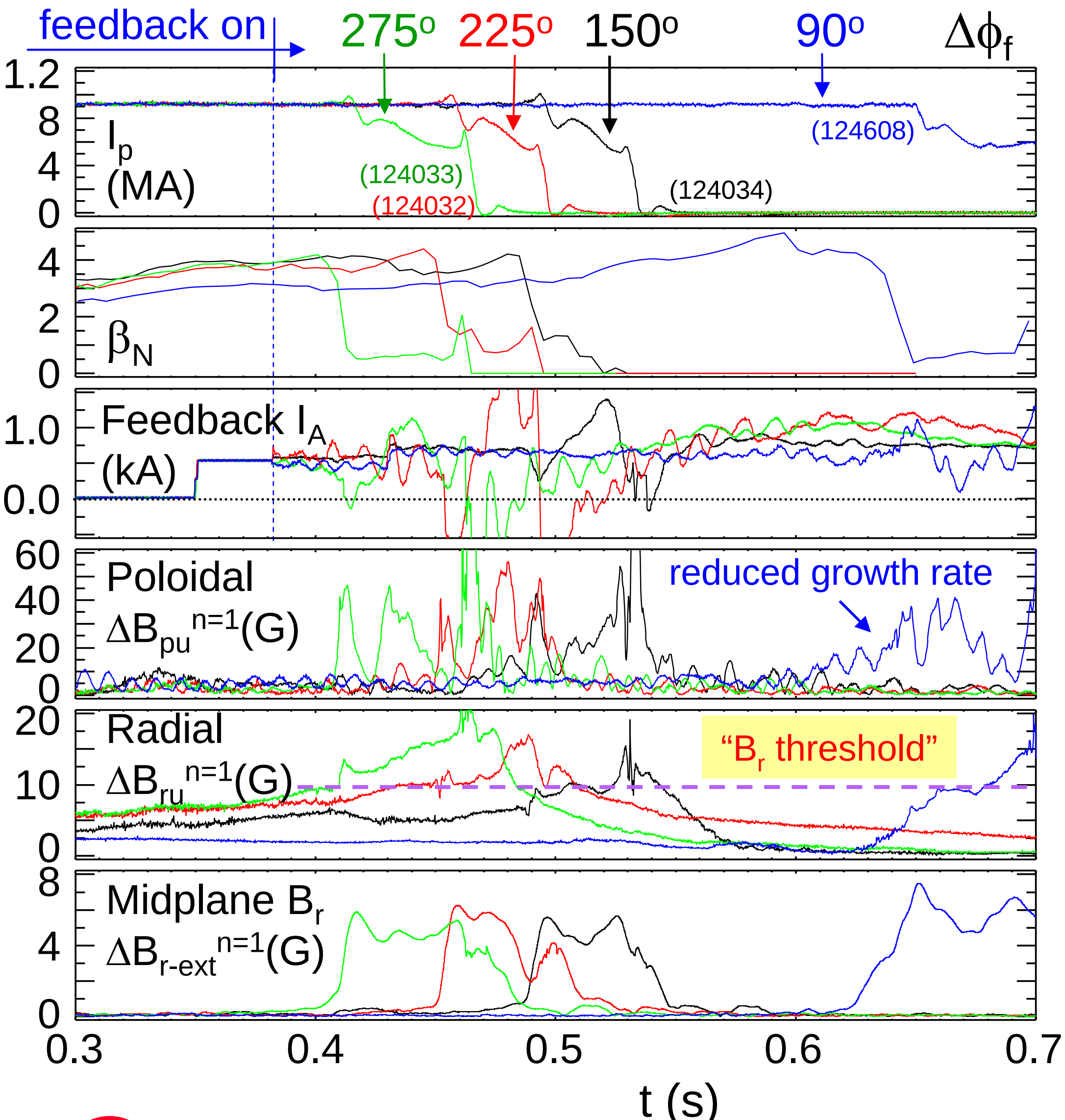
Varying relative phase shows positive/negative feedback





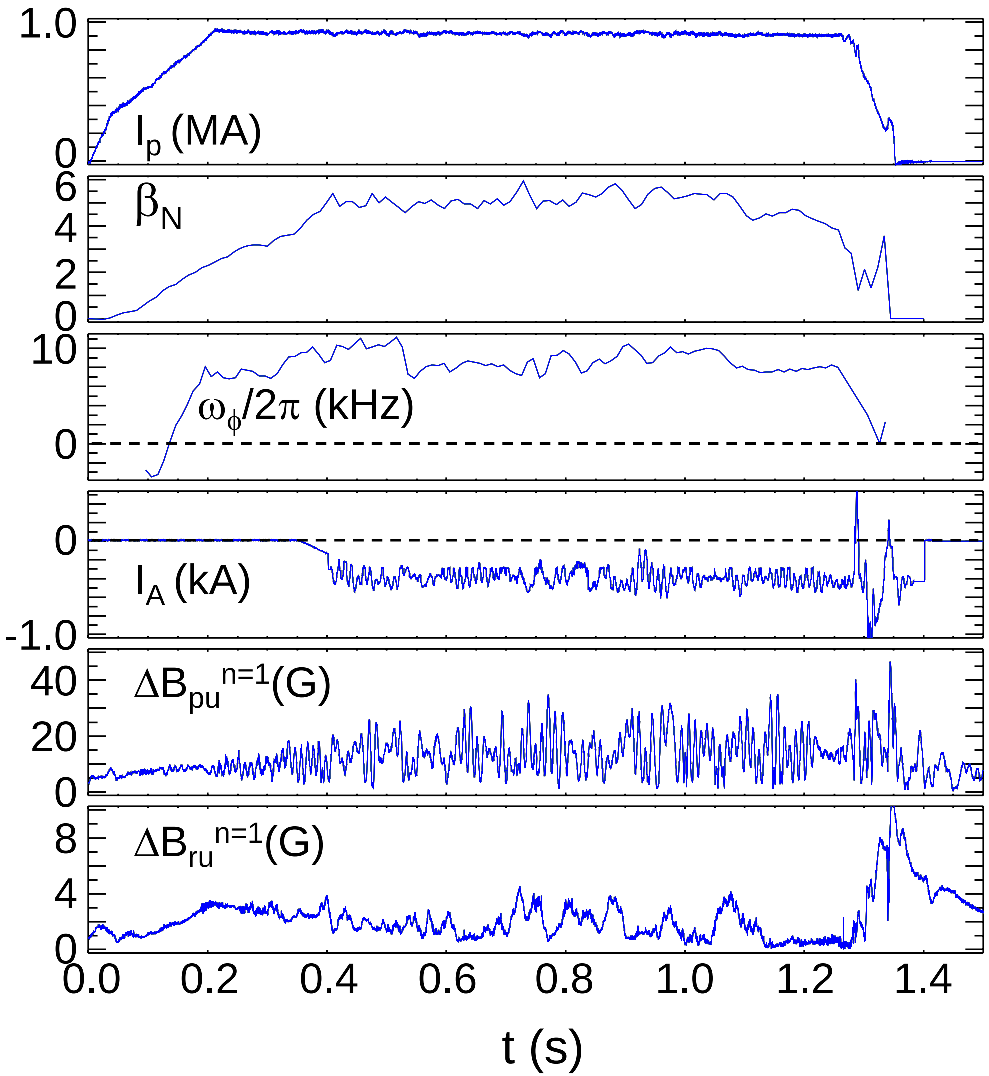
- Feedback control current has relative phase $\Delta\phi_f$ to measured ΔB_{pu}
  - Internal plasma mode seen at $\Delta\phi_f$ = 225°, damped feedback system response
- Phase scan shows superior settings for negative feedback
  - Agreement between theoretical and experimental feedback behavior

Combination of upper/lower B_p sensors reduces RWM growth



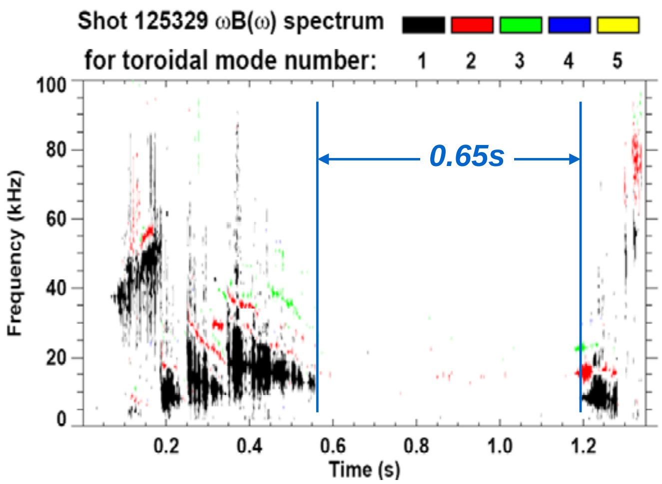
- Feedback phase scan using B_{pu} and B_{pl}
  - Best phase shown 90°, not optimal configuration
    - Reduction in $\Delta B_{pu}^{n=1}$ growth rate
  - Spatial phase offset between upper/lower B_p sensor flux can improve feedback
- Control using B_{pu} and B_{pl} also reduces ΔB_r
  - Correlation of β_N collapse and $\Delta B_{ru}^{n=1}$ amplitude
  - Attempted feedback on ΔB_r - RWM control not reliable
    - Reduced ΔB_r successfully
    - Fast n = 1, 2 RWM onset ($\gamma\tau_w$ ~ 1) occurs

Feedback control modifications used successfully at moderate ω_ϕ

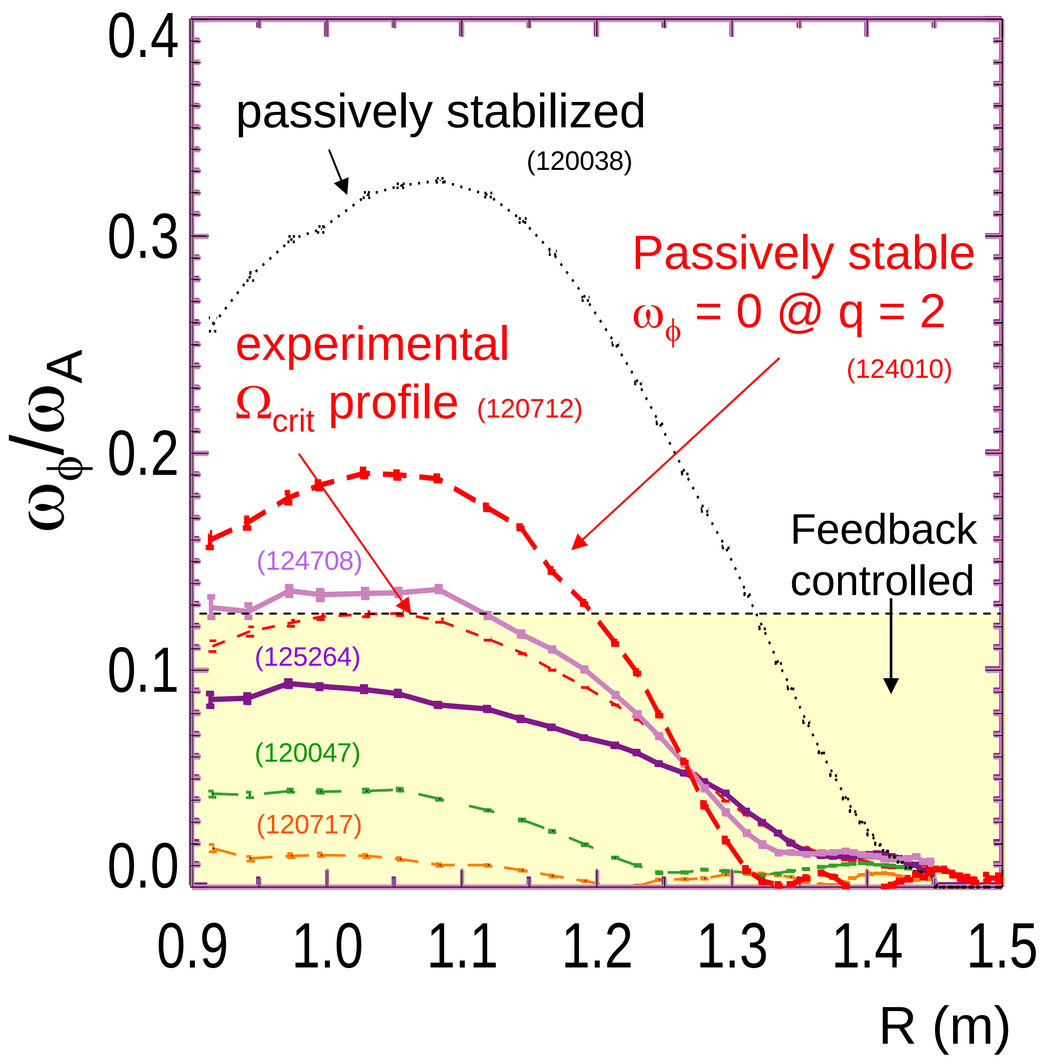


J.E. Menard, et al. APS DPP Invited Talk (2007)

- NSTX record pulse length at I_p = 0.9 MA
  - Feedback used combined upper/lower B_p sensors with spatial phase offset
  - Moderate, sustained ω_ϕ keeps ΔB_r in check
  - n = 3 DC field phased for field correction, maintains ω_ϕ
  - n = 1 rotation mode suppressed, helps maintain ω_ϕ



Large variation of V_ϕ produced to study RWM passive stabilization physics



- High rotation typically stable, but not always
  - Apparent RWM observed at high core rotation
  - Need to understand instability mechanism
- Stability at intermediate rotation depends on profile
  - Passively stable plasma with $\omega_\phi = 0$ at $q = 2$ has slower edge and faster core rotation
- Compare experimental database to present theory
  - Hu-Betti kinetic δW theory
  - New MARS-F code (full kinetic model)