Macroscopic Stability Research for 2009-13

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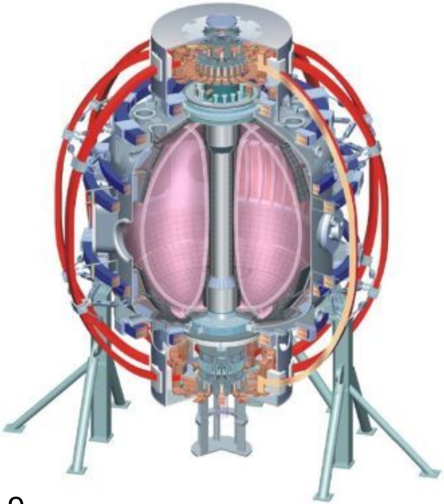
Steven A. Sabbagh

Columbia University

For the NSTX Research Team

NSTX 5 Year Plan Review for 2009-13
Princeton Plasma Physics Laboratory
July 28-30, 2008



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Understanding what profiles and control systems are needed for burning plasmas must occur before such devices

- FESAC US ST mission:
  - *Develop compact, high β, burning plasma capability for fusion energy*

CTF: β_N = 3.8 – 5.9 (W_L = 1-2 MW/m^2) *ST-DEMO: β_N ~ 7.5*

- Both at, or above ideal no-wall β-limit; deleterious effects at ~ ½ $\beta_N^{no\text{-}wall}$

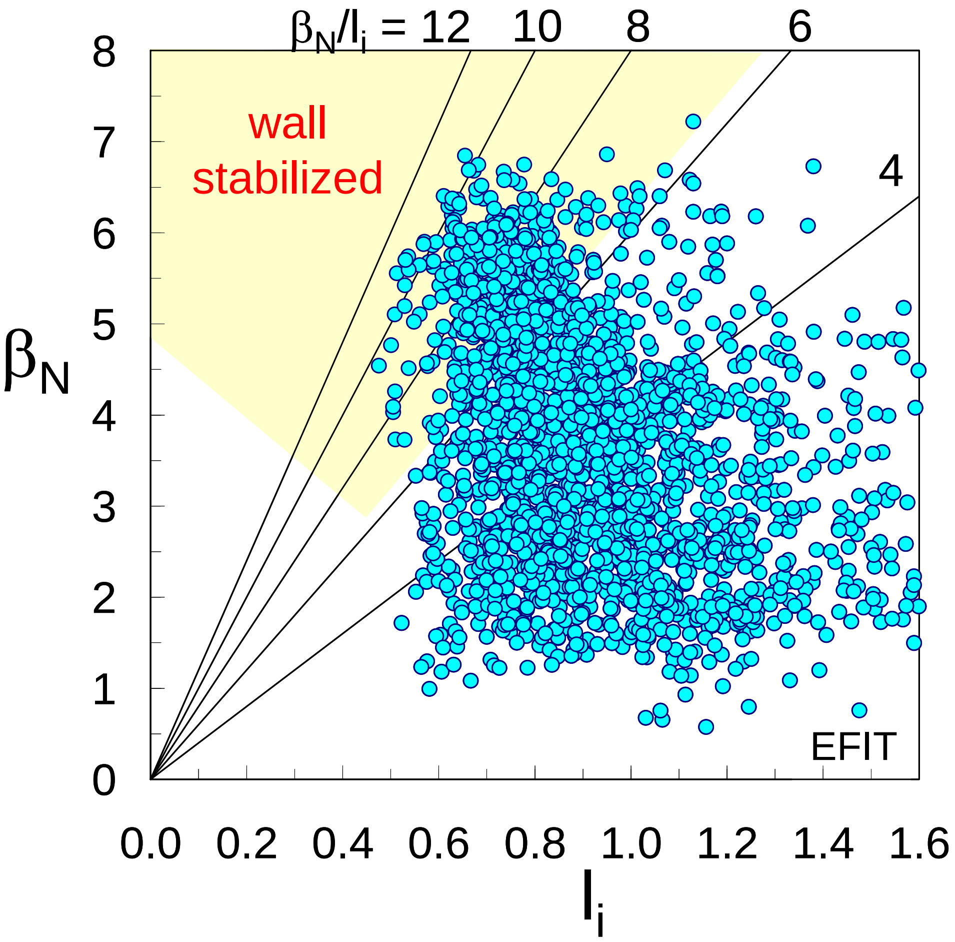
- high β_N accelerates neutron fluence goal - takes 20 years at W_L = 1 MW/m^2)

- Stability Goal (in one sentence)
  - Demonstrate reliable maintenance of high β_N with sufficient physics understanding to extrapolate to next-step devices
- Knowledge base needed to bridge to these devices
  - Demonstration = Control (of modes and plasma profiles):
    - Need to determine what control is needed *before* CTF (for greatest simplicity)
  - Understanding = Vary parameters (+operate closer to burning plasma levels):
    - Collisionality: influences V_ϕ damping
    - Shaping:
    - Plasma rotation level, profile:
    - *q* level, profile:

All influence β-limiting modes: Kink/ballooning, RWM, NTM

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

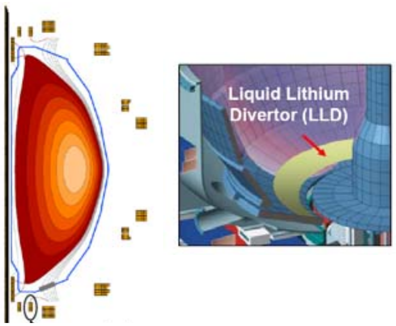


S.A. Sabbagh, et al., *Nucl. Fusion* **46**, 635 (2006).

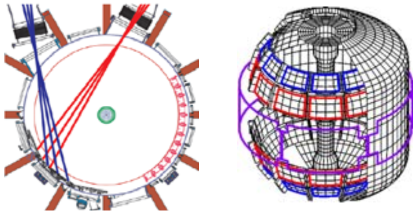
Development of device hardware empowers fundamental stability understanding for robust extrapolation to next-step STs

- Operate at parameters closer to burning plasma (e.g. low ν_i)
  - High plasma shaping (κ ~ 3), low l_i operation
    - Vertical stability, kink/ballooning stability, coupling to passive stabilizers
  - Resistive wall mode (RWM) stabilization
    - Understand physics of passive mode stabilization vs. V_ϕ at reduced ν_i
  - Non-axisymmetric field-induced viscosity
    - Non-resonant and resonant, due to 3-D fields and modes at reduced ν_i

- Control modes and profiles, understand key physics
  - Dynamic error field correction (DEFC)
    - Demonstrate sustained V_ϕ with reduced resonant field amplification, under V_ϕ profile control
  - Resistive wall mode control
    - Increase reliability of active control, investigate multi-mode RWM physics under V_ϕ, q control
  - Tearing mode / NTM
    - Stabilization physics at low A, mode locking physics under V_ϕ, q control
  - Plasma rotation control
    - Sources (2nd NBI, magnetic spin-up) and sink (non-resonant magnetic braking)
  - Mode-induced disruption physics and prediction/avoidance



- Center stack upgrade
- Liquid Li divertor



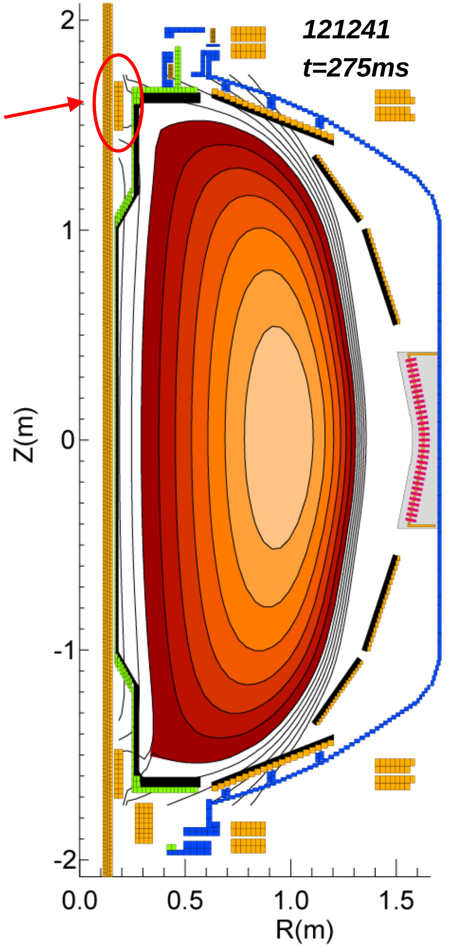
- 2nd NBI (incr.)
- Singly-powered RWM control coils
- coil upgrade (incr.)

Plasma equilibrium goal to access and maintain stable high β_N at high shaping

- Progress
  - Central coil PF1A modified (2005) to allow high shaping
  - Sustained $\kappa < 2.7$, $\delta < 0.8$; transient $\kappa = 3$ with record shaping factor, $S_l \equiv q_{95}(I_p/aB_t) = 41$
    - Note: Present CTF design has $\kappa = 3.07$, lower S_l
  - Highest κ and S_l plasmas reached β_N ~ 6 in 2008

- Plan summary 2009-2011
  - Assess/utilize β feedback control using real-time EFIT and NBI power to avoid fast kink/ballooning disruptions
  - Conduct experiments/analysis to extend high S_l plasmas into wall-stabilized, high $\beta_N > 6$ operating space

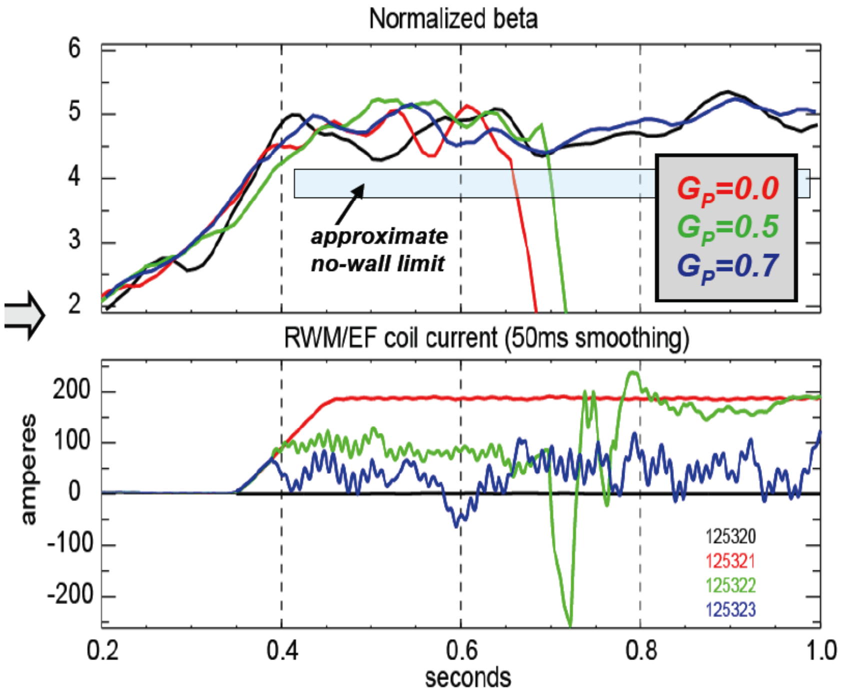
- Plan summary 2012-2013
  - Real-time MSE for evaluation of q in real-time EFIT
  - Utilize/analyze β feedback using stability models; q profile control with 2nd NBI (incremental)
  - Study ST-CTF target shapes (increased A) at low ν_i with favorable profiles, determine sensitivity to variations in l_i, δ



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

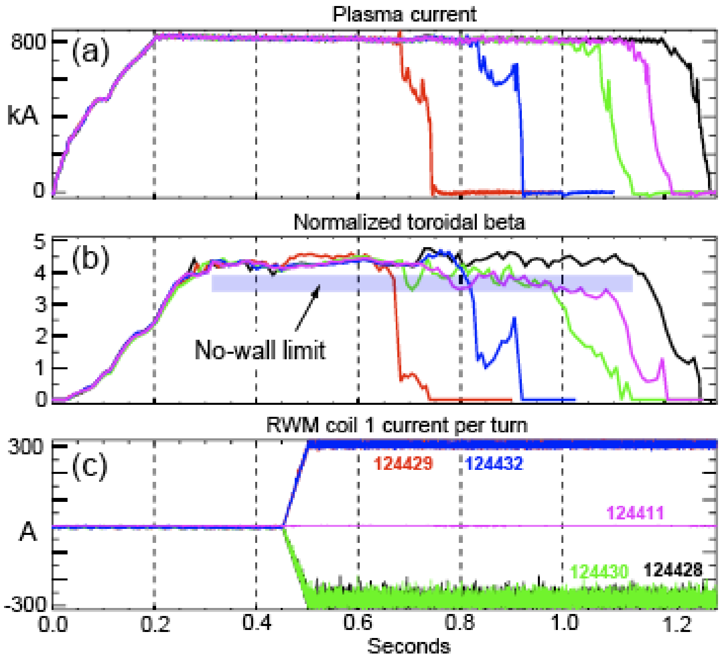
Dynamic Error Field Correction used to increase pulse length

Feedback System Trained for n=1 DEFC



- Apply preprogrammed n = 1 fields
- Adjust feedback gain, phase, so that feedback cancels those currents
- then remove n=1 EF source to correct intrinsic error fields

Important to Correct n > 1 Error Fields



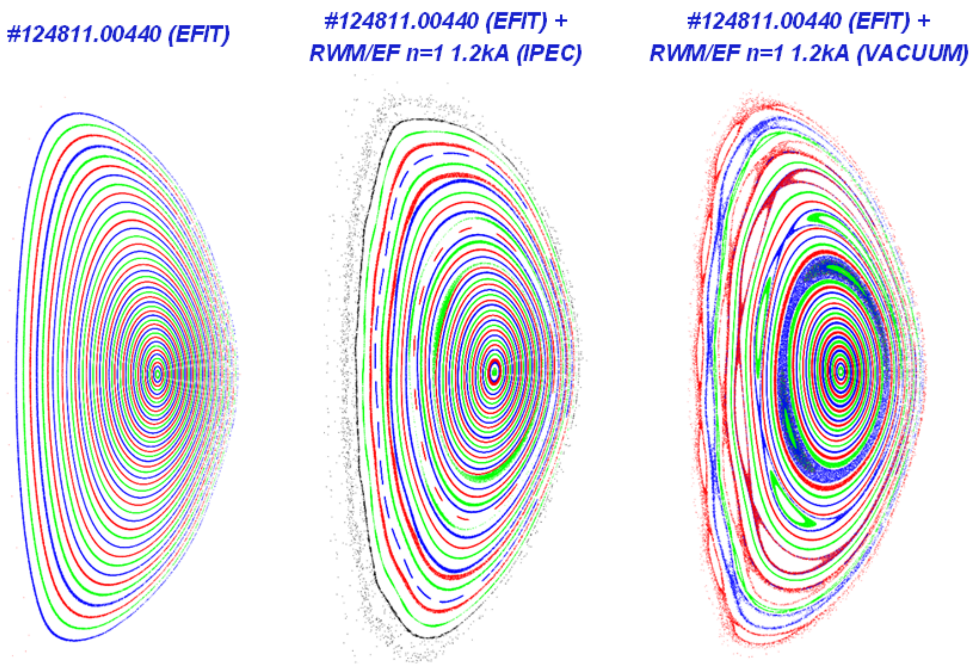
- Pre-programmed n = 3 fields, two phases
- Asymmetric response in rotation, pulse length
  - n = 3 intrinsic error field present (PF5, TF most likely causes)
- n = 2 error fields found to be less important

Goal to make resonant and non-resonant DEFC effective over large range of plasma conditions

- FY2009-10
  - Optimize DEFC control with expanded sensor arrays
    - Plasma response using IPEC
  - Test real-time n=3 correction ($\propto I_{PF5}$)
  - Develop tensor-pressure equilibria with IPEC
- FY2011-2012
  - Modify IPEC to allow magnetic islands. Compare to experiments involving interaction of 3-D applied fields and NTMs.

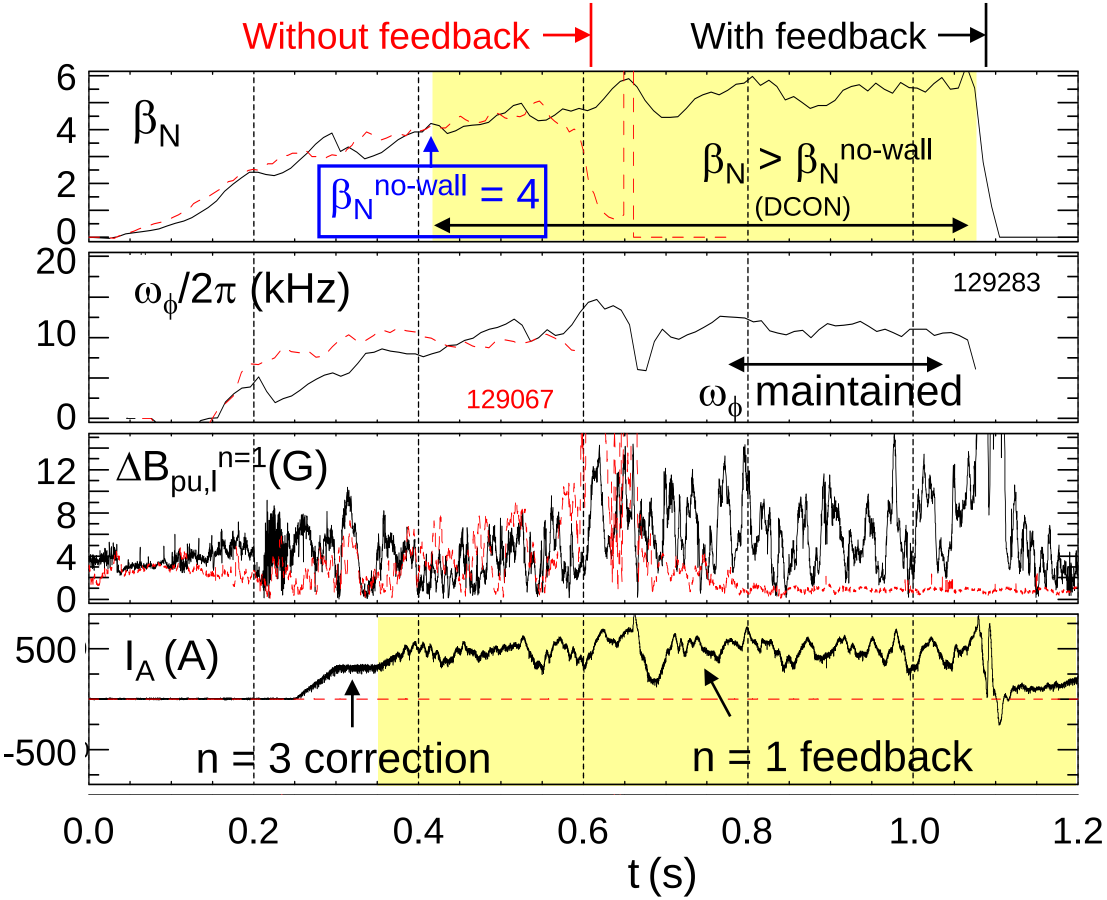
Ideal Perturbed Equilibrium Code (IPEC)

J.-K. Park, et al., Phys. Plasmas **14**, 052110 (2007).



- FY2012-2013
  - Study EF thresholds at $B_T < 1T$, assess intrinsic error fields at higher B_T, I_p
  - Utilize 2nd SPA power supply for greater DEFC spectrum flexibility
  - Utilizing upgraded RWM coil geometry and IPEC modeling, optimize DEFC poloidal mode spectrum for best V_ϕ. Implement appropriate control system upgrades as required.

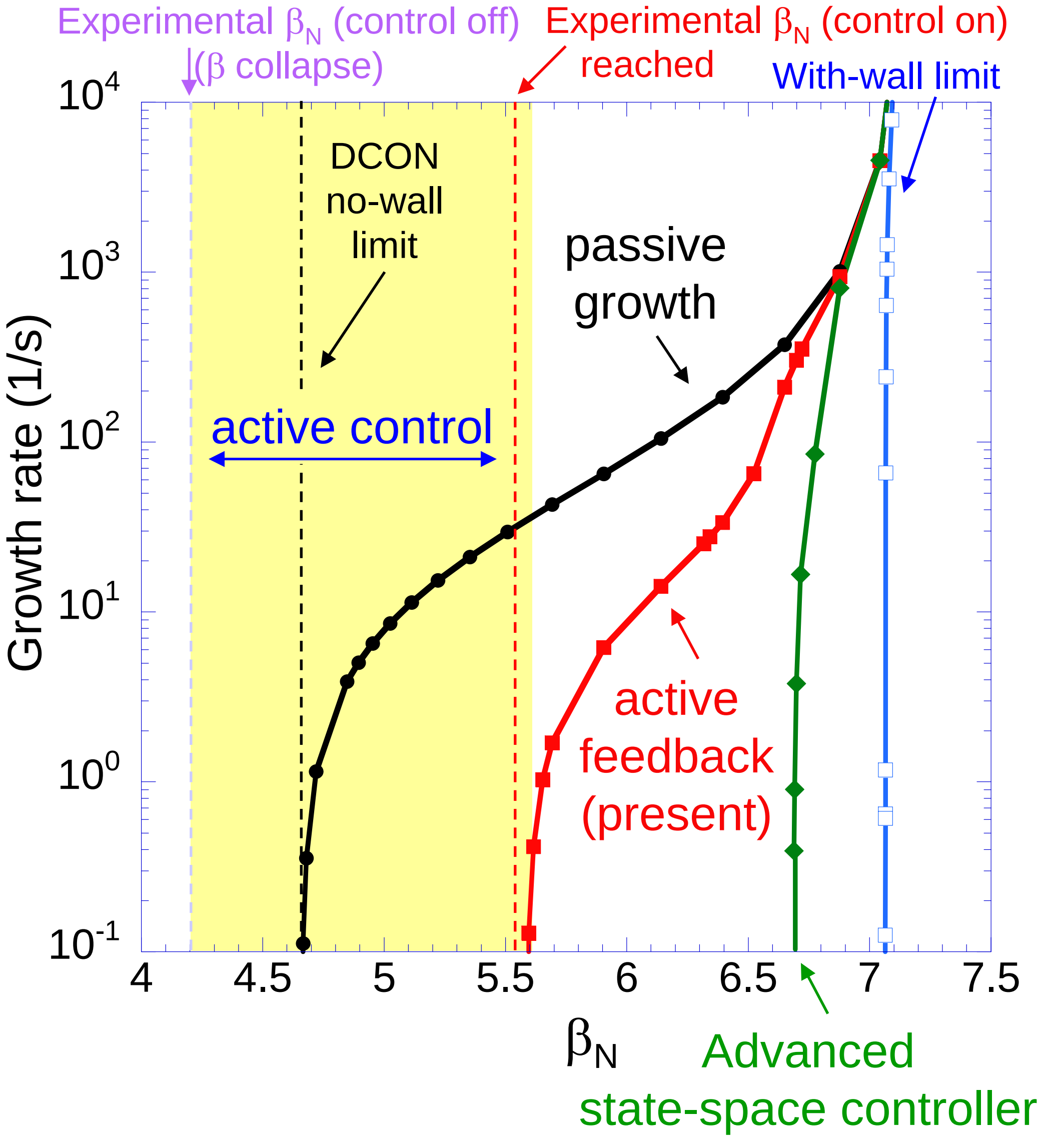
Active RWM control and error field correction maintain high β_N plasma



- NSTX <u>record pulse lengths</u>
  - Up to 1.8s (shown previously)
- n = 1 active control
  - Upper/lower B_p sensors
  - Favorable B_r feedback settings found in 2008
  - Fast response ~ 1 ms
- n = 3 DC field correction
  - best maintains ω_ϕ
  - but - RWMs observed w/o feedback at high ω_ϕ
- n = 1 feedback now being used as tool in many XPs
  - > 200 shots in 2008 with active feedback in 10 XPs
- Present goal to increase reliability, performance
  - Feedback success ~ 74%
    - RWM more likely when NTM stabilized (e.g. by lithium)
    - Poloidal deformation of mode
  - Considering system upgrades

VALEN code reproduces experimental RWM feedback performance

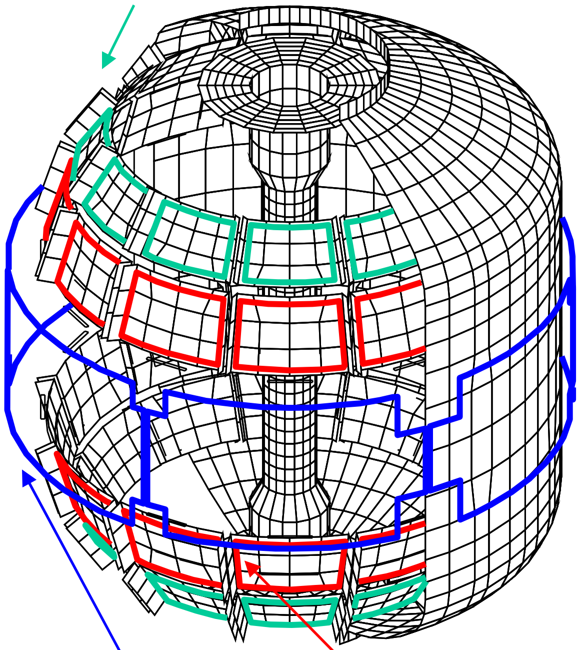
- Model simulates experiments
  - Actual RWM sensors locations
  - Compensation of control field
  - Experimental equilibrium reconstruction (including MSE data)
  - Proportional gain
  - Low V_ϕ results shown
- Advanced control may greatly improve performance
  - Advanced state-space controller may stabilize β_N/β_N^{wall} < 95% (benefit to ITER, next-step ST)
  - Plan to test offline 2009-10; implement for initial RWM control testing 2010-11



Design work for upgraded non-axisymmetric control capabilities has begun

- Capabilities
  - Non-axisymmetric control coil (NCC) – at least four applications
    - RWM stabilization ($n > 1$, higher β_N)
    - DEFC with greater field correction capability
    - ELM control ($n = 6$)
    - $n > 1$ propagation, increased V_ϕ control)
    - Similar to proposed ITER coil design
    - In incremental budget
  - Addition of 2nd SPA power supply unit for simultaneous n > 1 fields
  - Non-magnetic RWM sensors; advanced RWM active feedback control algorithms
  - Alteration of stabilizing plate connections

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

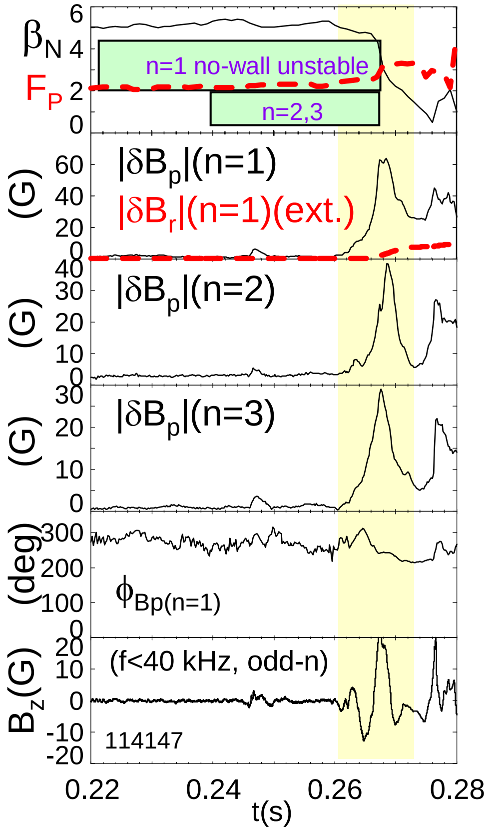


Secondary PP option

Existing coils

Primary PP option

RWM with $n > 1$ RWM observed



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

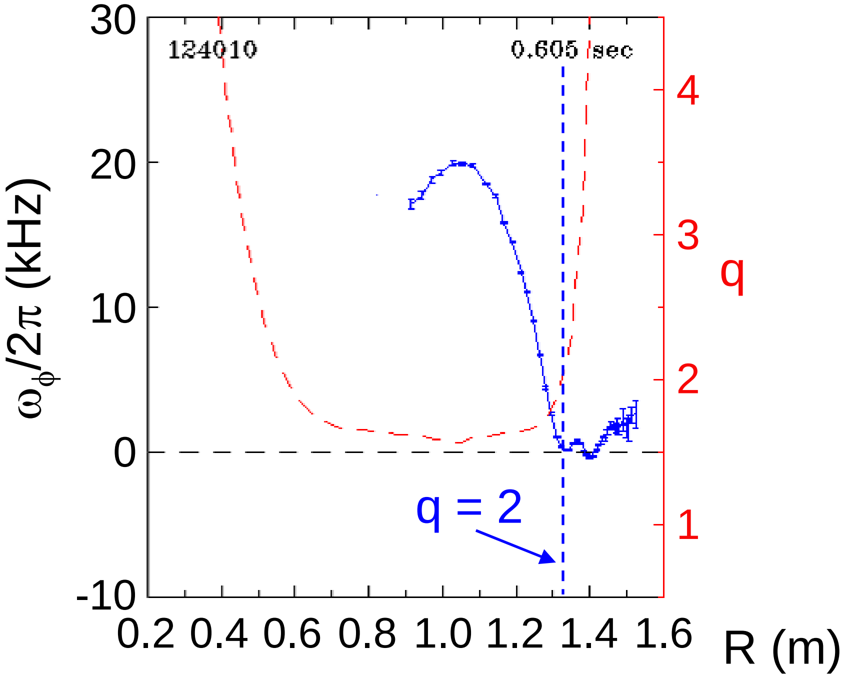
Significant progress planned for RWM control research (i) Active feedback control

- Plan summary 2009-2011
  - Continue use of RWM feedback control as standard tool – build performance statistics
    - Investigate underlying active control physics
  - Continue feedback control parameter optimizations/analysis, using all RWM sensors
    - Determine effectiveness over range of V_ϕ profiles and levels, ν_i level
  - Test advanced state-space active stabilization algorithms offline; implement and perform initial tests for RWM control
  - Determine the role of plasma response during RWM control using IPEC
  - Investigate multiple modes in stabilization, implement methods of decreasing possibility of RWM poloidal deformation
    - Multi-mode VALEN code completed (running NSTX, DIII-D, HBT-EP tests now)
  - Design high-n control coil (NCC); determine need for passive plate modifications

- Plan summary 2012-2013
  - Assess RWM control at reduced ν_i with center stack upgrade; during V_ϕ profile control
  - Analyze initial non-magnetic (SXR) RWM sensor data
    - compare to magnetic sensors; evaluate future use in RWM feedback
  - Implement 2nd switching power amplifier (SPA) to allow independent control of all 6 midplane RWM coils
  - Implement NCC and begin to use for RWM stabilization; $n > 1$ RWM, multi-mode study during $n = 1$ stabilization; compare to theory (incremental)
  - Examine greater range of V_ϕ and q profiles with 2nd NBI, greater non-resonant braking flexibility using 2nd SPA; NCC (incremental)

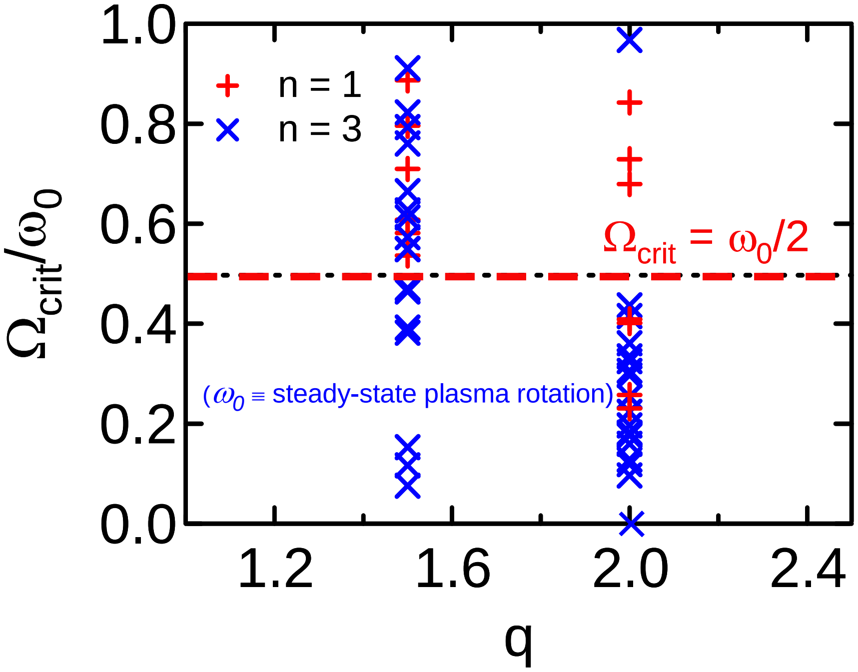
Non-resonant magnetic braking allows V_ϕ modification to probe RWM "critical rotation" and stabilization physics

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



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

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



- Slowest rotation profiles produced in NSTX are at DIII-D balanced-NBI levels
- Ion collisionality profile variation appears to alter experimental Ω_{crit} profile

Kinetic modification of ideal MHD stability theory investigated to explain experiment

- Ideal MHD RWM growth rate formulation
- Kinetic modifications
  - Trapped and circulating ions
  - Trapped electrons
  - Alfven dissipation at rational surfaces
- Stability depends on
  - Integrated Ω_ϕ profile: resonances in δW_K (e.g. ion precession, diamag. drift)
  - Particle collisionality

$$\gamma\tau_w = -\frac{\delta W_\infty + \delta W_K}{\delta W_b + \delta W_K}$$

Hu and Betti, Phys. Rev. Lett **93**, 105002 (2004).

Ω_ϕ profile (enters through ExB frequency)

$$\omega_E = \Omega_\phi^D - \omega_{*i}^D - \frac{v_\theta^D}{2\pi R}\frac{B_\phi}{B_\theta}$$

Trapped ion component of δW_K (plasma integral)

$$\delta W_K^{ti} = \int_0^{\Psi_a} d\Psi \left(\frac{p_s}{1+\frac{T_e}{T_i}}\right)\left(2\sqrt{\pi}\frac{r}{v}\right)\sum_{l=-\infty}^{\infty}\int_{B_0/B_{max}}^{B_0/B_{min}} d\Lambda\left(\frac{\hat{\tau}_b}{2}\right)$$

← Pitch angle integral

$$\times\int_0^\infty\left[\frac{\omega_{*N}+\left(\hat{\varepsilon}-\frac{3}{2}\right)\omega_{*T}+\omega_E-\omega}{\langle\omega_D\rangle+l\omega_b-i\nu_{\text{eff}}+\omega_E-\omega}\right]\hat{\varepsilon}^{5/2}e^{-\hat{\varepsilon}}d\hat{\varepsilon}$$

← Energy integral

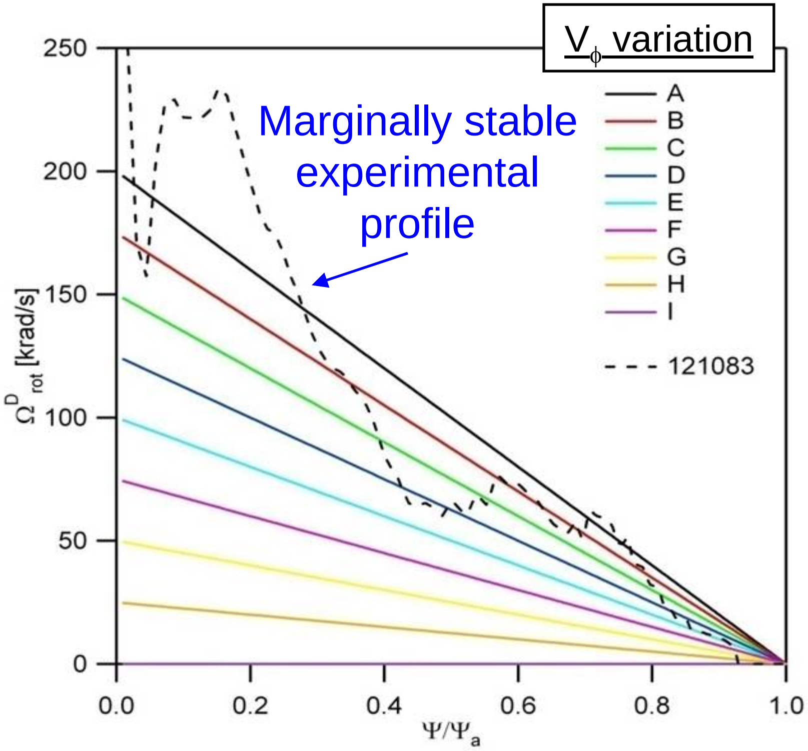
collisionality

$$\times\left|\left\langle\left(2-3\frac{\Lambda}{B_0/B}\right)(\kappa\cdot\xi_\perp)-\left(\frac{\Lambda}{B_0/B}\right)(\nabla\cdot\xi_\perp)\right\rangle\right|^2$$

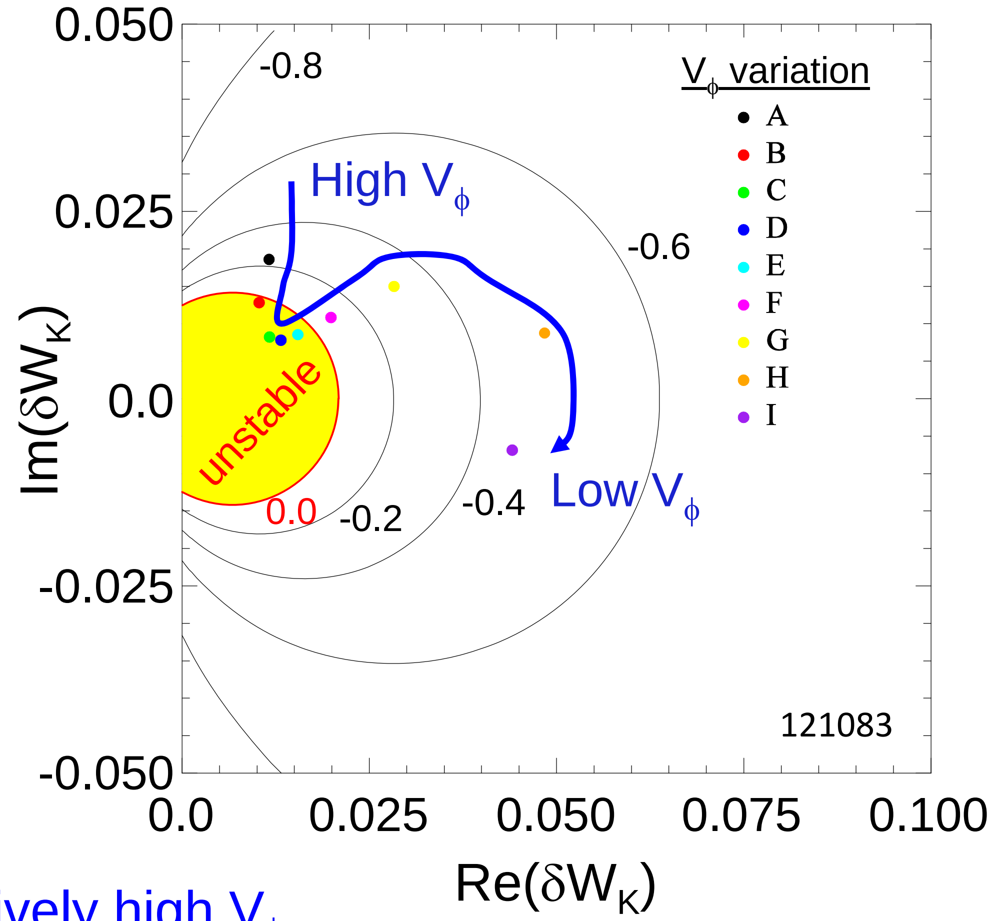
← Mode geometry

Kinetic modifications show RWM unstable region at relatively high V_ϕ - in agreement with experiment

Theoretical variation of V_ϕ



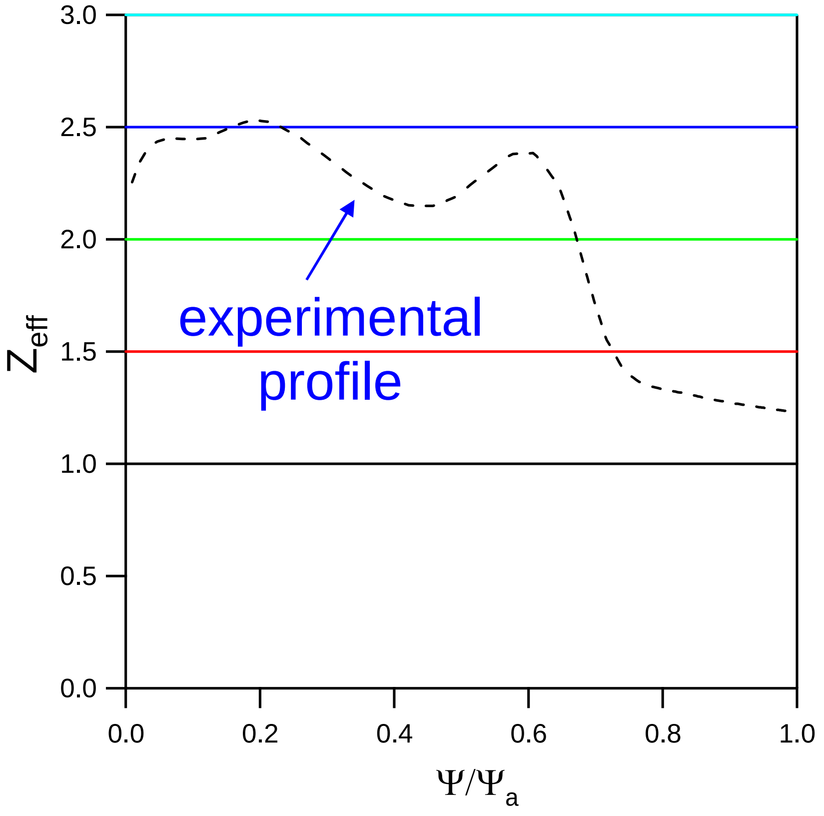
RWM stability vs. V_ϕ (contours of $\gamma\tau_w$)



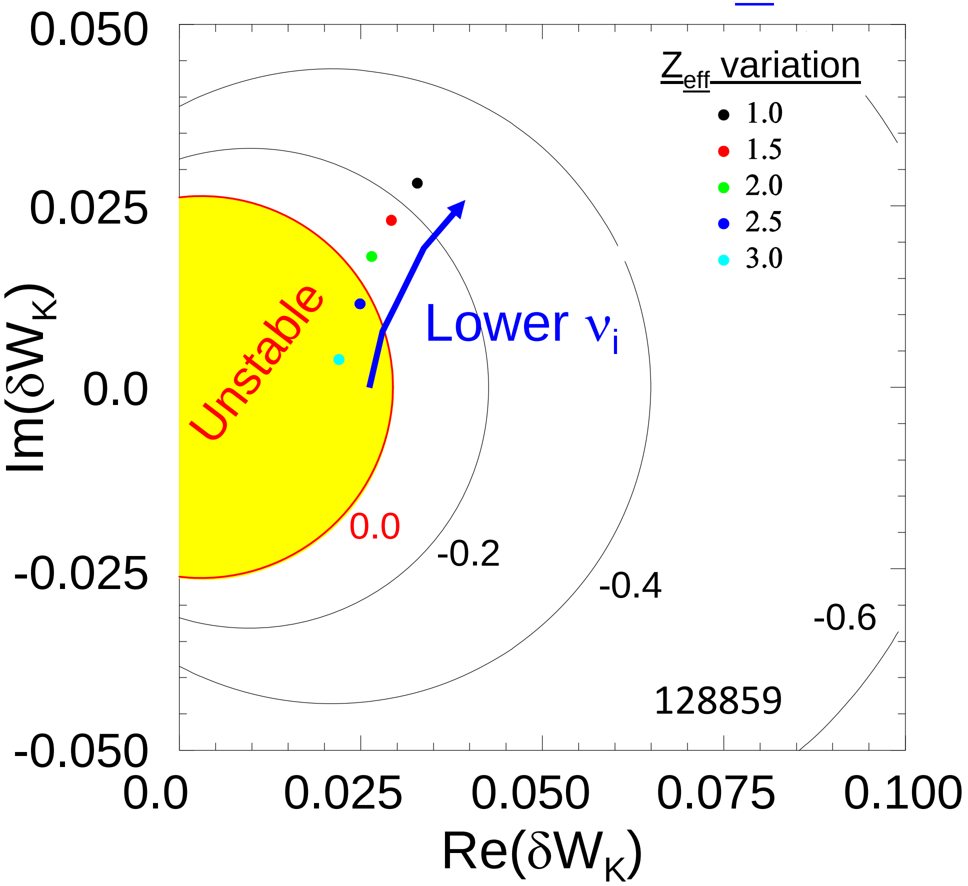
- Marginal stability crossed at relatively high V_ϕ
  - in experiment and theory
  - far greater than thought needed for robust stability in terms of ω_A at $q = 2$

Kinetic stability model shows increase in stability as ion collisionality decreases – under investigation

XP Marginal Z_{eff}; theoretical variation



RWM stability vs. Z_{eff}



- Opposite to results of models using only viscous dissipation
- Determine best theory model by comparing to recent experiments with Li evaporation; further reduced ν_i with upgraded center stack

Significant progress planned for RWM stabilization research (ii) Passive stabilization physics

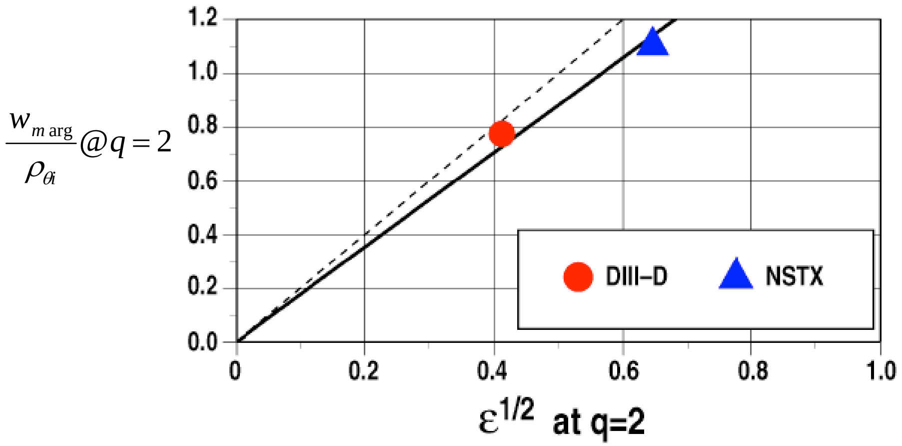
- Plan summary 2009-2011
  - Determine RWM stabilization requirements for broader range of V_ϕ profiles and ν_i allowed by lithium evaporation, liquid lithium divertor
  - Test stability theories against marginal V_ϕ profile database, new parameter scans (2009 milestone)
    - Continue analysis using kinetic δW – Hu-Betti-Manickam code
    - Compare to latest MARS-K implementation (full kinetic effects modeled - Y. Liu)
  - Determine/implement stabilization improvements by altering passive plate electrical reconnections

- Plan summary 2012-2013
  - Examine passive stabilization in low ν_i plasmas created at higher T_i from higher B_t and I_p
  - Examine RWM stabilization during V_ϕ profile feedback control
  - Determine a reliable physics model to confidently predict RWM stabilization as a function of rotation and ion collisionality
  - Test stabilization physics model for greater range of V_ϕ profiles with 2nd NBI, greater non-resonant braking flexibility using 2nd SPA unit; with new NCC (incremental)

Recent experiments and analysis have studied NTM stabilization physics of high-β NSTX plasmas

2/1 Marginal island width for stabilization

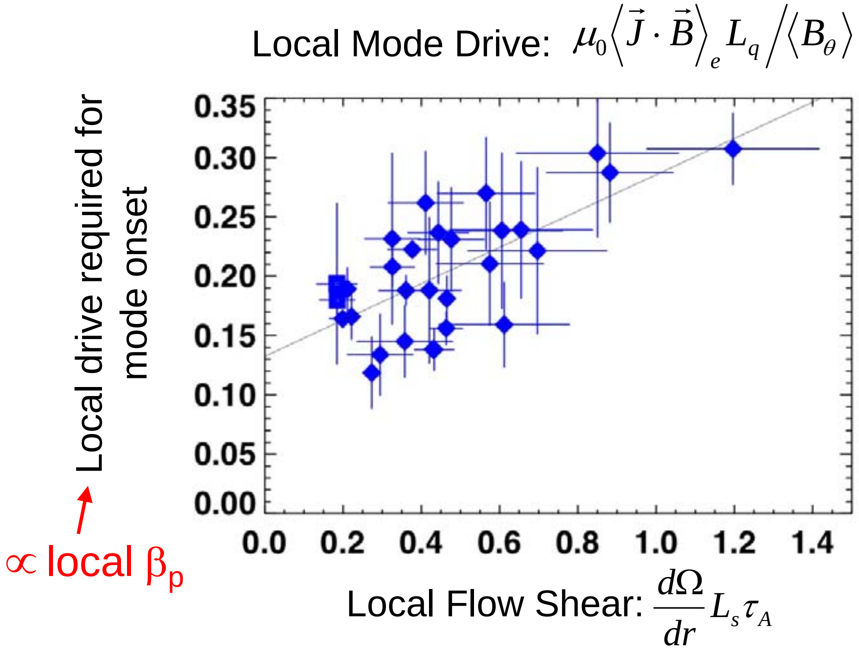
Polarization Threshold Implies $w_{m\,\arg} \propto \sqrt{\varepsilon}\rho_{\theta i}$



- Trend confirms physics of polarization current model
- Expand to additional machines (JET, AUG), and achieve more cases

Collaboration between R.J. La Haye (GA), S. P. Gerhardt (PPPL), R. Buttery (JET), and M. Marschek (AUG)

2/1 onset threshold vs. V_ϕ shear



- Flow shear variation achieved by different NB injection and *n* = 3 braking.
- Similar trends observed in co-/counter mix experiments in DIII-D
- Trend likely due to dependence of Δ' on local flow shear

Establish predictive physics understanding of NTMs

- 2009-2011: Compete Characterization of NTM Onset, Small Island Physics, Restabilization
  - Characterize the role of V_ϕ and the ideal kink limit on NTM onset thresholds
  - Characterize triggering events, including sawtooth triggered 3/2 modes and "triggerless" NTMs with $q_{min} > 1$
  - Finish characterization of the marginal island width for 2/1 and 3/2 modes, including comparisons to conventional aspect ratio devices
  - Understand details of how Li conditioning and DEFC assist in stabilizing 2/1 modes
- 2009-2011: Establish a program of relevant NTM modeling
  - Implement PEST-III calculations of Δ' for realistic NSTX equilibria, including the effects of nearby rational surfaces
  - Utilize initial value codes like NIMROD for more sophisticated treatment of transport near the island or rotation shear effects on mode coupling and island eigenfunction.
- 2012-2013: Develop scenarios that mitigate/eliminate deleterious NTM activity
  - Quantify the benefits of $q_{min} > 2$ operation, and the role of higher order (3/1, 5/2) modes in this case
  - Utilize increased toroidal field (new center stack) to scale $\rho_{\theta i}$ in single device
  - Utilize 2nd beamline for current profile control, possibly allowing Δ' stabilization of NTMs even with $q_{min} < 2$

Collaborations are an essential element of research plan (GA, AUG, JET, U. of Tulsa,…)

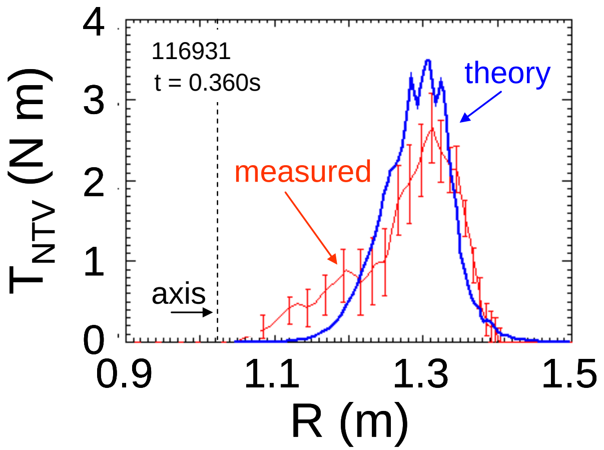
Non-axisymmetric field-induced neoclassical toroidal viscosity (NTV) important for low collisionality ST-CTF, low rotation ITER plasmas

- Significant interest in plasma viscosity by non-axisymmetric fields
  - Physics understanding needed to minimize rotation damping from ELM mitigation fields, modes (ITER, etc.)
  - NTV investigations on DIII-D, JET, C-MOD, MAST, etc. following quantitative agreement on NSTX

- Expand present studies on NSTX
  - Examine larger field spectrum
  - Improve inclusion of plasma response using IPEC
  - Consider expansions of NTV theory
    - Saturation due to E_r at reduced ion collisionality, multiple trapping states, matching theory through collisionality regimes
  - Examine NTV from magnetic islands
    - Stronger dependence on $\delta B/B$
  - Compare to kinetic modeling (e.g. using 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).



Dominant NTV Force for NSTX collisionality…

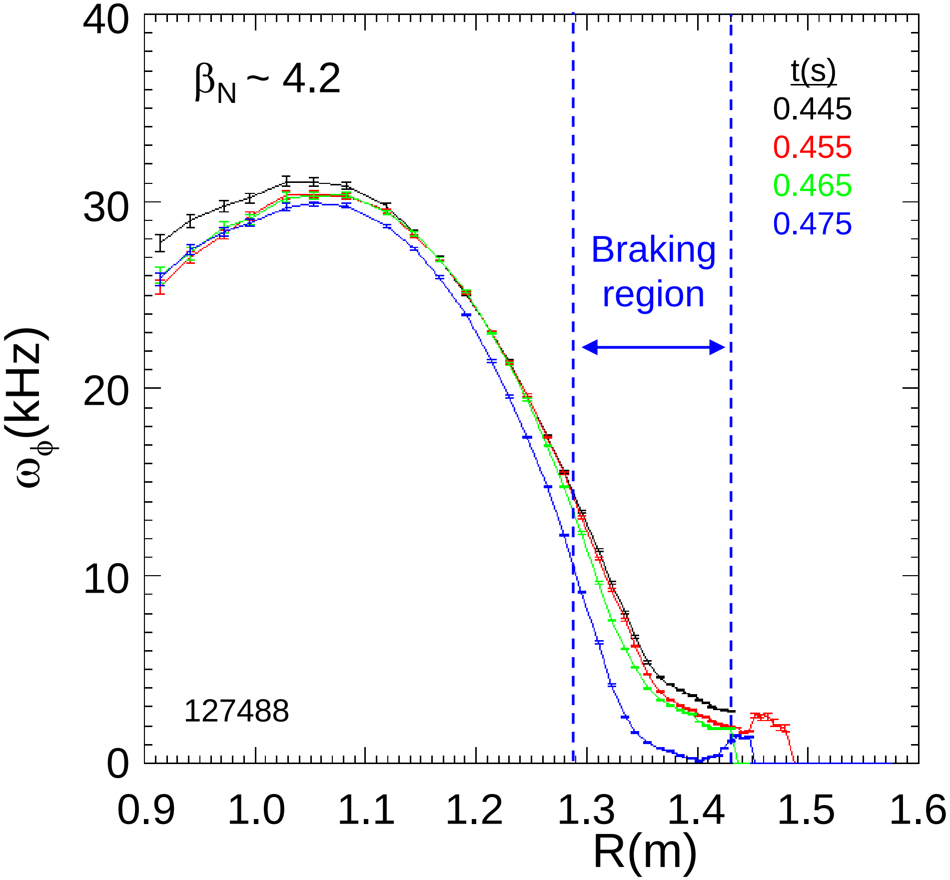
$$\left\langle \hat{e}_t \bullet \vec{\nabla} \bullet \overleftrightarrow{\Pi} \right\rangle_{(1/\nu)} = B_t R \left\langle \frac{1}{B_t} \right\rangle \left\langle \frac{1}{R^2} \right\rangle \frac{\lambda_{1i} p_i}{\pi^{3/2} \nu_i} \varepsilon^{3/2} (\Omega_\phi - \Omega_{NC}) I_\lambda$$

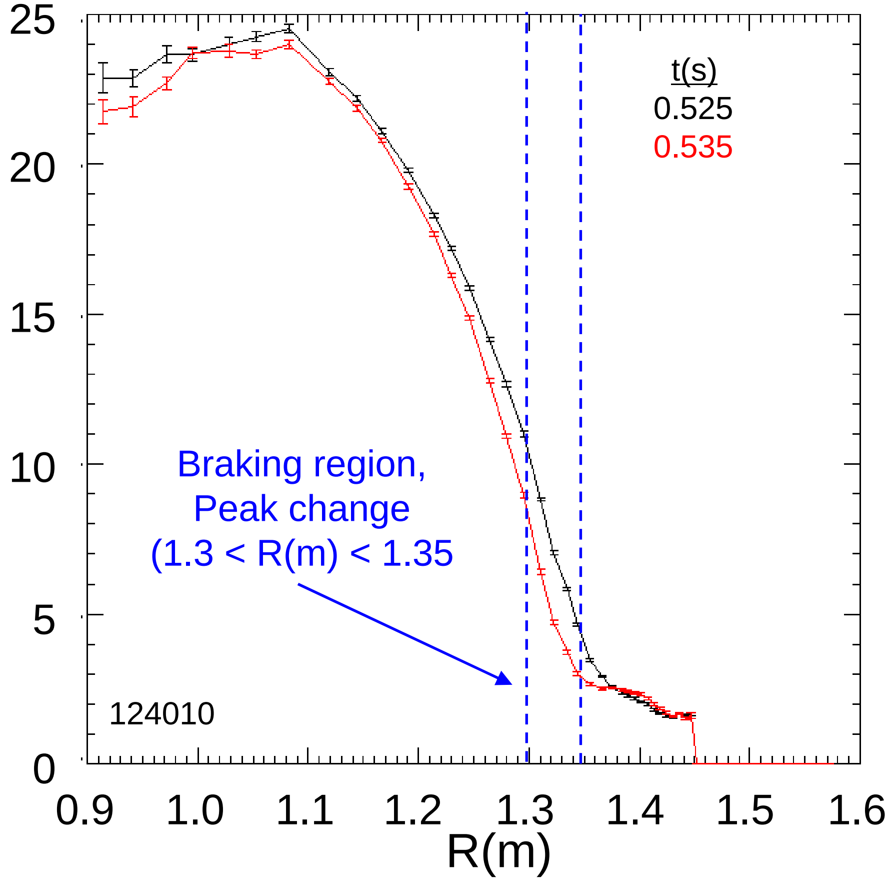
…expected to saturate at lower ν_i

$$\frac{1}{\nu_i} \Rightarrow \frac{\nu_i}{\left(\nu_i^2 + \omega_E^2\right)}$$

Can verify at order of magnitude lower ν_i with center stack upgrade

Clear non-resonant braking observed in recent n = 2 applied field experiments – broader braking profile at lower n


Rotation evolution during n = 2 braking


Rotation evolution during n = 3 braking

- n = 2 configuration has strong n = 4, but essentially no (resonant) n = 1 component
- Recent experiment shows stronger braking with Li evaporation

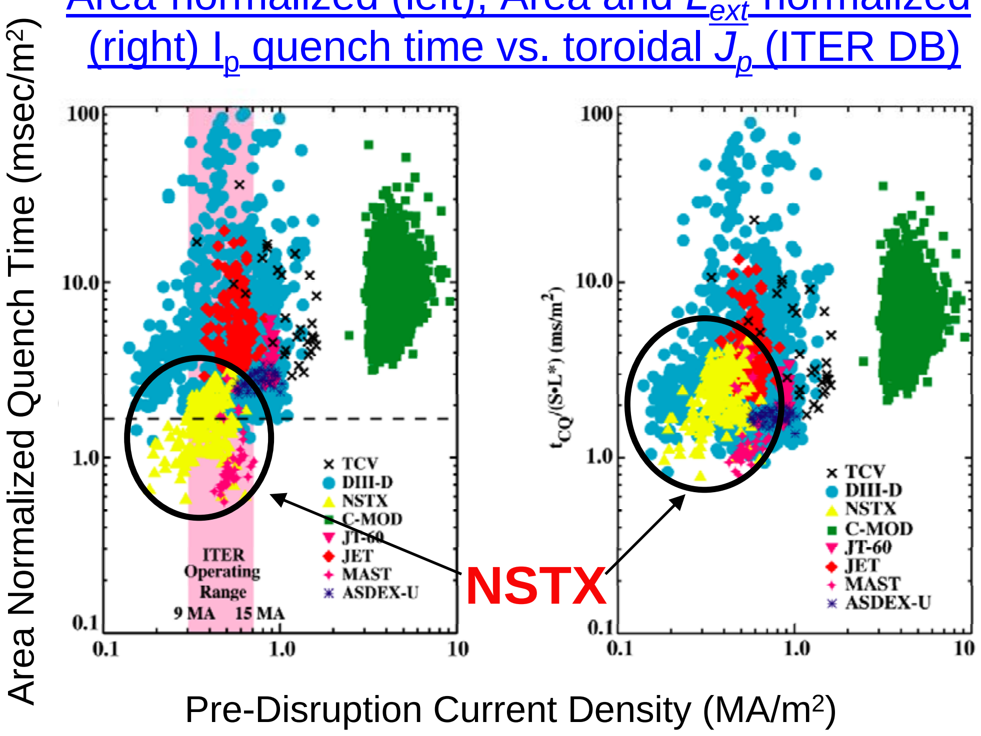
Develop understanding of field-induced plasma viscosity with application to V_ϕ profile control

- Plan summary 2009-2011
  - Continue testing viscosity theory from resonant /non-resonant fields
    - Examine key dependences; alter ν_i using lithium evaporation, LLD
    - joint experiments with other devices (MAST 2008)
    - Improved plasma internal field response using IPEC; influence of magnetic islands
  - Expand analysis to further test theory
    - Saturation due to E_r at reduced ν_i, multiple trapping states, etc.
    - Time-evolved kinetic computations using GTC-Neo; examine saturation at low ν_i
  - Determine range of radial placement of torque possible with NCC design
  - Begin real-time V_ϕ control using CHERS measurements, present NBI as source and n=3 NTV as sink of plasma toroidal momentum
    - Examine effect on modes; initial control of flow shear near for NTM studies

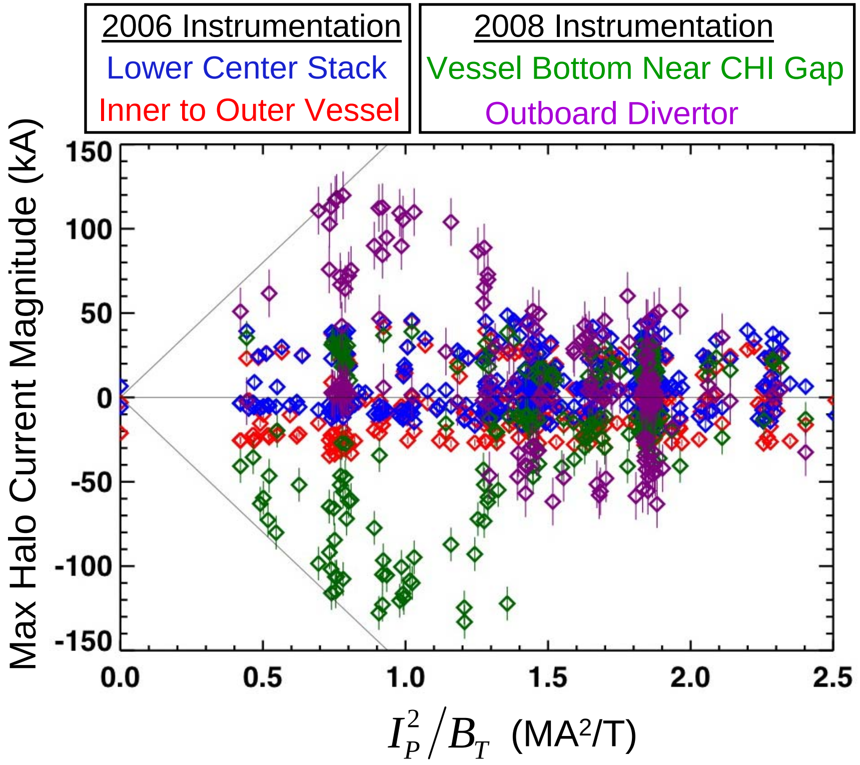
- Plan summary 2012-2013
  - Utilize reduced ν_i plasmas using new center stack to controllably access $1/\nu$ and lower collisionality regimes of NTV theory
  - Use 2nd beam line to vary torque profile at fixed power; include in real-time V_ϕ control
  - Apply greater variation of radial profile of braking torque (for V_ϕ control; test theory)
    - Use 2nd SPA power supply unit; add NCC when available ($n \leq 6$) (incremental)
  - Consider momentum *input* with NCC via non-resonant NTV (proposal)

NSTX Disruption Studies Contribute to ITER, Aim to Predict Disruption Characteristics & Onset For Future Large STs

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



Halo Current Magnitudes and Scaling



- Fastest NSTX disruption quench times of 0.4 ms/m^2, compared to ITER recommended minimum of 1.7 msec/m^2.
- Reduced inductance at high-κ, low-A explains difference

$$\frac{\tau_{L/R}}{S} = \frac{\mu_0}{2\pi\eta}\left[\ln\left(8/\sqrt{\kappa\varepsilon}\right) - 7/4\right]$$

- New instrumentation in 2008 yields significant upward revision of halo current fractions (now up to 20%)
  - reveals scaling with I_P and B_T.
  - Mitigating effect: Largest currents for deliberate VDEs
- Toroidal peaking reduced at large halo current fraction.

Expand these Results For a Complete Characterization of Disruption Dynamics, Including Prediction Methods.

Understand the Causes and Consequencs of Disruptions for Next-step STs and ITER

- 2009-2012: Complete halo current characterization
  - Install arrays of instrumented tiles in outboard divertor, measure currents into LLD trays (2009-10)
  - Utilize CS upgrade to instrument inboard divertor tiles (2011)
  - Understand the halo current paths, toroidal peaking physics, and driving mechanisms, in order to make predicitons for future ST plasmas

- 2009-2011: Complete thermal quench characterization
  - Determine the fraction of stored energy lost in the thermal quench, compared to that in the pre-disruption phase, over a variety or plasmas and disruptions
  - Utilize fast IR thermography to understand time-scale and spatial distribution of the thermal quench heat flux
  - Predict the impulsive heat loading constraints on future ST PFCs

- 2010-2013: Learn to predict and prevent disruptions
  - Develop real-time diagnostics useful for predicting impending disruptions for relevant ST equilibria and instabilities
  - Test predictive algorithms, to determine the simplest, most robust prediction methods
    - Use in conjunction with stability models and mode control systems developed

Experiments in 2008 part of continuing contribution to ITER high priority MHD research

Suggested by

- ELM Mitigation
  - Attempted ELM mitigation with non-axisymmetric field from single row of midplane coils
    - Several field configs. with Chirikov parameter > 1
    - ELM frequency/duration changed, not fully mitigated
    - ELMs mitigated by Li evaporation / triggered by applied field

USBPO, ITER Org.

- Neoclassical Toroidal Viscosity (NTV) Study
  - Following quantitative agreement on NSTX to best determine impact of non-axisymmetric fields from RMP fields on ITER V_ϕ
    - Braking with n = even fields confirm non-resonant effect
    - Stronger NTV damping with Li evaporation (ν_i, or T_i variation?)

USBPO, ITER Org.

- RWM stabilization
  - Active feedback system latency artificially increased to simulate the effect of greater time delays due to ITER blanket

NSTX PAC

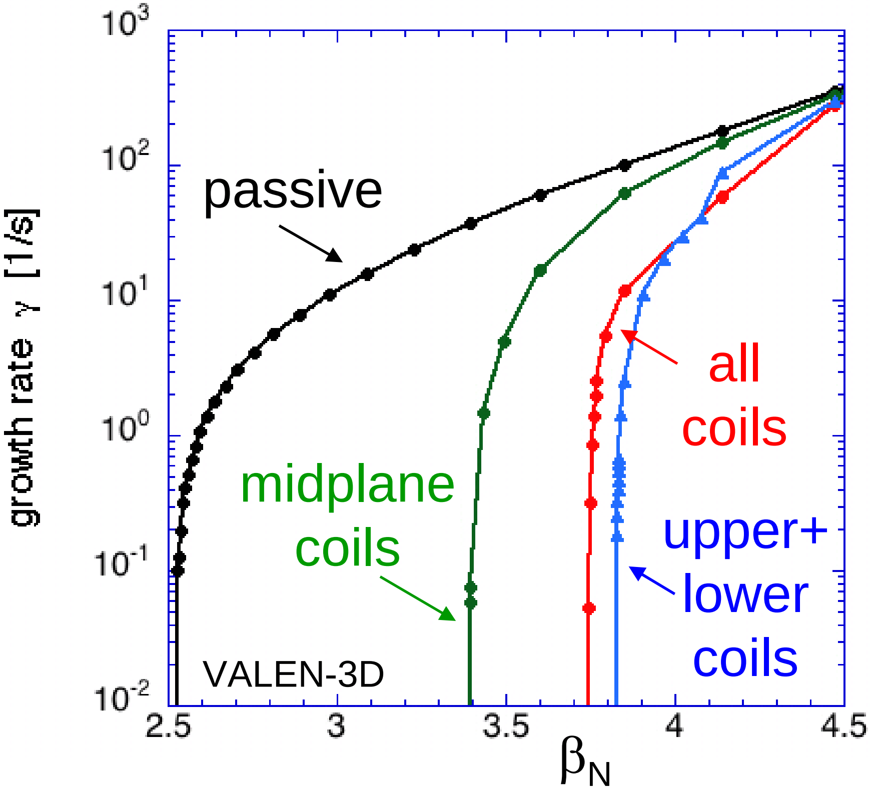
  - Experiment to simulate impartial toroidal coverage of control coils
    - Feedback failed for several phase settings (physics reason TBD)

ITER Org.

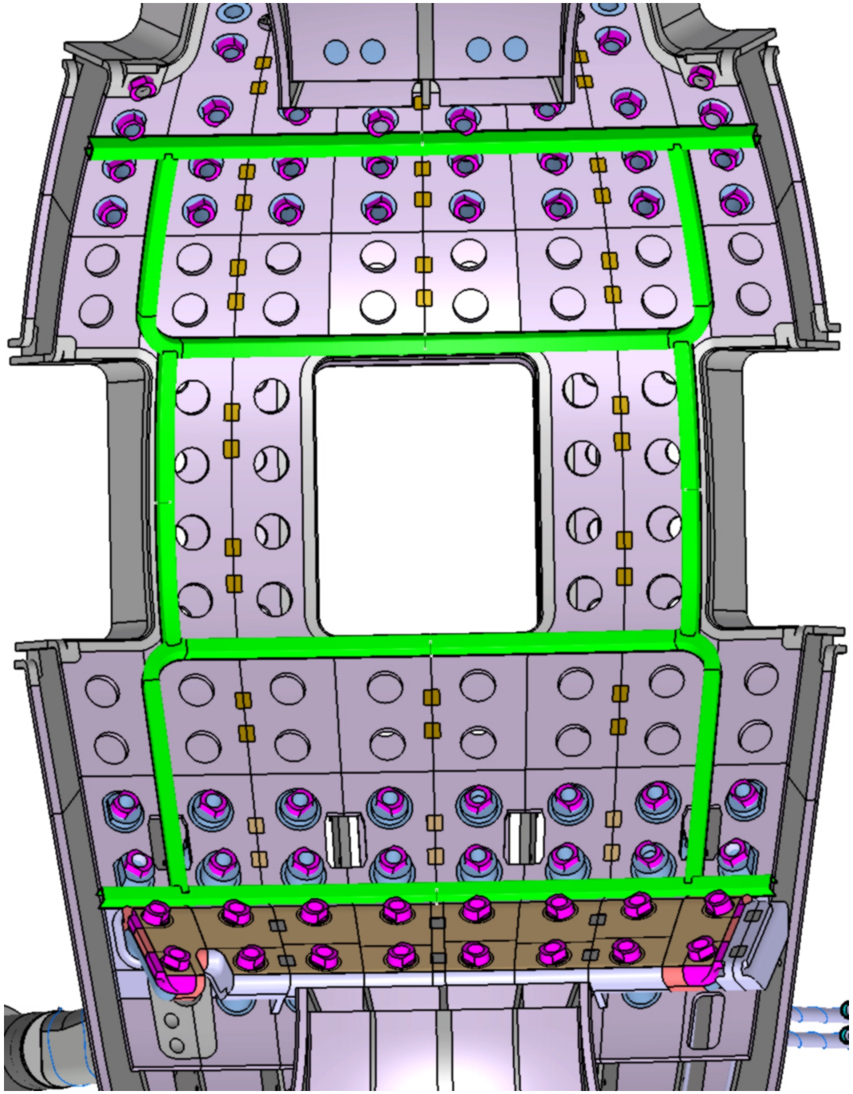
ITER support experiments/analysis to continue in 2009-13

VALEN RWM control models validated on NSTX predict significant β_N increase with proposed ITER internal coil

ITER VAC02 stabilization performance



- 3 toroidal arrays, 9 coils each
- ELM, VS, RWM applications
  - Endorsed by ITER STAC
- Configuration similar to proposed NCC coil upgrade for NSTX

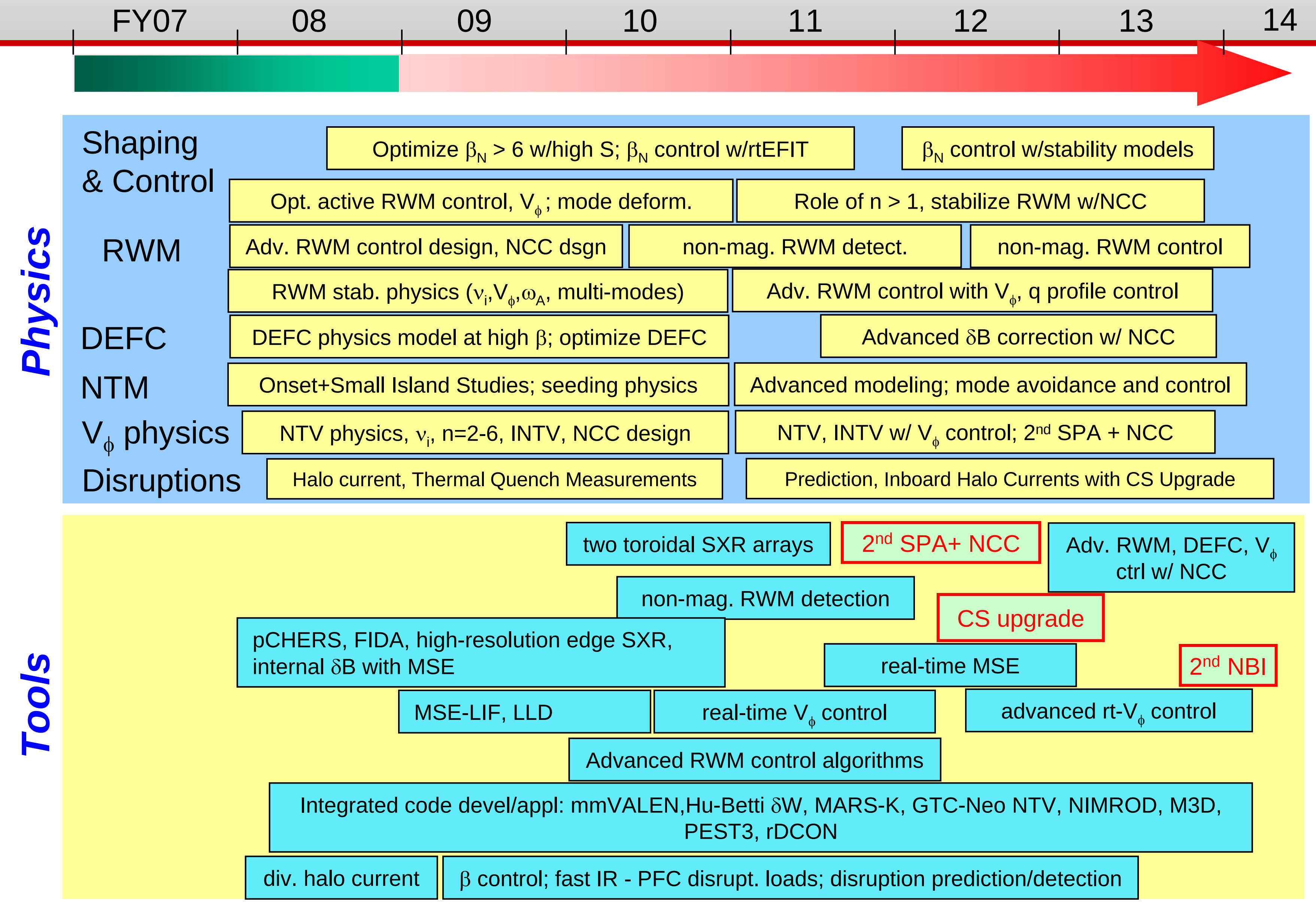


ITER VAC02 design 40° sector

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
- NSTX provides access to best diagnosed high beta plasmas
  - <u>2009-2011</u>: allows significant advances in scientific understanding of ST physics toward next-steps, supports ITER, and advances fundamental science
  - <u>2012-2013</u>: allows demonstration/understanding of reliable stabilization/profile control at lower collisionality – performance basis for next-step STs

Macroscopic Stability Research Timeline (2008-2013)



Physics

Shaping & Control
- Optimize β_N > 6 w/high S; β_N control w/rtEFIT
- β_N control w/stability models
- Opt. active RWM control, V_ϕ; mode deform.
- Role of n > 1, stabilize RWM w/NCC

RWM
- 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
- Onset+Small Island Studies; seeding physics
- Advanced modeling; mode avoidance and control

V_ϕ physics
- NTV physics, ν_i, n=2-6, INTV, NCC design
- NTV, INTV w/ V_ϕ control; 2nd SPA + NCC

Disruptions
- Halo current, Thermal Quench Measurements
- Prediction, Inboard Halo Currents with CS Upgrade

Tools

- two toroidal SXR arrays
- 2nd SPA+ NCC
- Adv. RWM, DEFC, V_ϕ ctrl w/ NCC
- non-mag. RWM detection
- CS upgrade
- pCHERS, FIDA, high-resolution edge SXR, internal δB with MSE
- real-time MSE
- 2nd NBI
- 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-K, GTC-Neo NTV, NIMROD, M3D, PEST3, rDCON
- div. halo current
- β control; fast IR - PFC disrupt. loads; disruption prediction/detection

V1.1