NSTX

Supported by

U.S. DEPARTMENT OF ENERGY | Office of Science

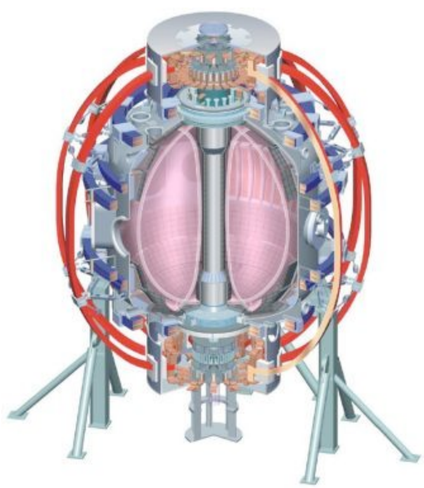
Macroscopic Stability Progress and Plans for 2009-2011 and Beyond

Stefan Gerhardt, PPPL

For the macroscopic stability TSG and the NSTX Research Team

College W&M
Colorado Sch Mines
Columbia U
CompX
General Atomics
INEL
Johns Hopkins U
LANL
LLNL
Lodestar
MIT
Nova Photonics
New York U
Old Dominion U
ORNL
PPPL
PSI
Princeton U
Purdue U
SNL
Think Tank, Inc.
UC Davis
UC Irvine
UCLA
UCSD
U Colorado
U Illinois
U Maryland
U Rochester
U Washington
U Wisconsin

NSTX PAC-25
B318, PPPL
Feb. 19, 2009



Culham Sci Ctr
U St. Andrews
York U
Chubu U
Fukui U
Hiroshima U
Hyogo U
Kyoto U
Kyushu U
Kyushu Tokai U
NIFS
Niigata U
U Tokyo
JAEA
Hebrew U
Ioffe Inst
RRC Kurchatov Inst
TRINITI
KBSI
KAIST
POSTECH
ASIPP
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep
U Quebec

Comprehensive Stability Research Program Planned in Order to Meet ST Programmatic Goals

NSTX Stability Research Goal

Demonstrate reliable maintenance of high β_N equilibria, with sufficient physics understanding to extrapolate to next-step devices

- Understand the role of parameters governing stability
  - Collisionality, shaping, rotation profile, q profile, pressure profile,…
- Determine and develop the necessary control techniques
  - DEFC & RWM feedback, β–control, rotation-control, & q-profile control

Next step devices represent a significant extension in pulse length and performance.

	NSTX	NSTX-U	NHTX	ST-CTF	ST-Demo
Pulse Length (sec)	1-2	5-10	500	2×10^6	2×10^7
β_N	5.7	5.7	5	4-6	7.5
l_i	0.55	0.65	0.6	0.35	0.24

Critical to understand stability physics and control in order to confidently design these devices.

Outline For This Presentation

- Understanding and control of intrinsic instabilities
  - Resistive Wall Modes (RWMs)
  - Neoclassical Tearing Modes (NTMs)
- Stable plasma response to 3D fields
  - Error fields and the associated plasma response
  - Neoclassical Toroidal Viscosity (NTV)
- Disruption prediction and characterization
- New opportunities with the CS upgrade, 2nd beamline, and Nonaxisymmetric Control Coil (NCC)

Research Addresses TAP Macro-Stability Issues for the ST

- **Disruptions**
- **3D Fields**: Error fields, resistive wall modes, edge localized modes, toroidal flow damping.
- **Neoclassical Tearing Modes**

NSTX is Developing Predictive Capability for RWM Stability

- FY09 milestone: "Understand physics of RWM stabilization & control vs. rotation"
  - Continue to test stability theories against marginal V_ϕ profile database:
    - Continue analysis using kinetic δW – MISK code
    - Compare to latest MARS-K implementation (full kinetic effects modeled - Y. Liu)
  - Expand experimental studies of fast-ion stabilization effects on the RWM
    - LITER to control collisionality; possible counter-injection campaign
  - Examine EPMs as RWM triggers in an ST.
    - Utilize the BES diagnostic in 2010-2011 to help understand transition from high-frequency trigger to low frequency RWM.

- Near-term upgrades allow an extended range of rotation and collisionality profiles for FY10 & FY11.
  - Explore RWM physics in plasmas with partial/full HHFW heating
    - Allows a wider range of rotation profiles
    - Modifies the kinetic contributions to δW
    - Full HHFW heating cases would utilize MSE-LIF for equilibrium constraints.
  - Determine RWM stabilization requirements at reduced ν_i allowed by LLD.

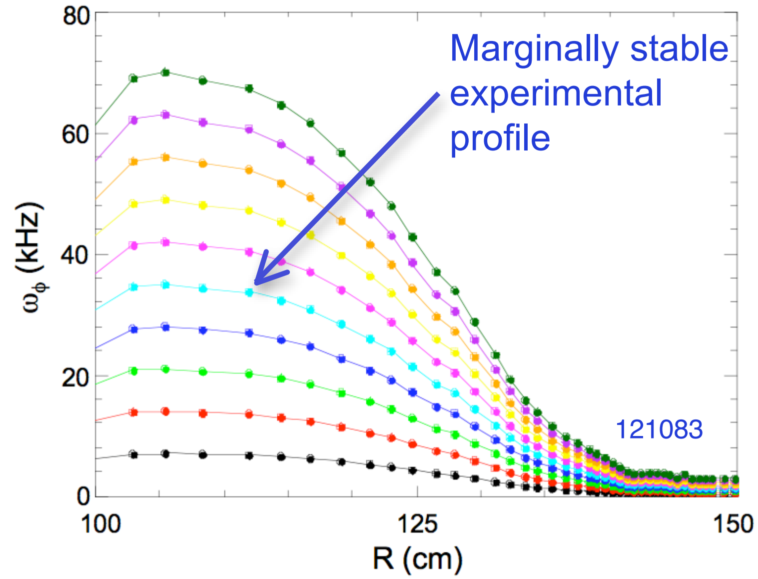
Kinetic Modeling Indicates that RWM Stability is Not a Monotonic Function of Rotation Magnitude

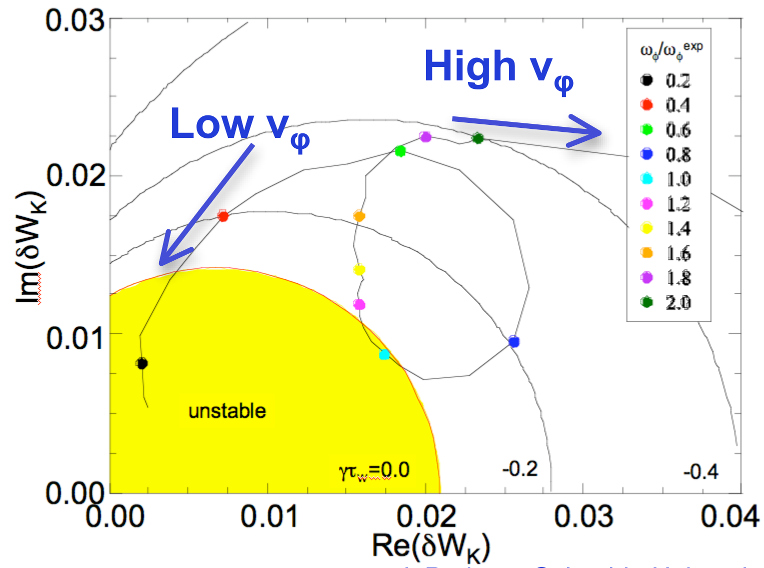
MISK=Modification of Ideal Stability by Kinetic Theory

- Kinetic modifications to ideal MHD[1]:

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

- δW_K depends on:
  - Trapped and circulating ions.
  - Trapped electrons
  - Alfven dissipation
- Stability depends on collisionality, Ω_ϕ profile through resonances in δW_K.
  - No simple "critical rotation speed for RWM stability".
- Example case: Effect of varying the rotating rotation profile on RWM stability.
  - Instability at "intermediate" rotation speeds.
  - Profile yielding instability remarkably close to the experimental marginal profile.



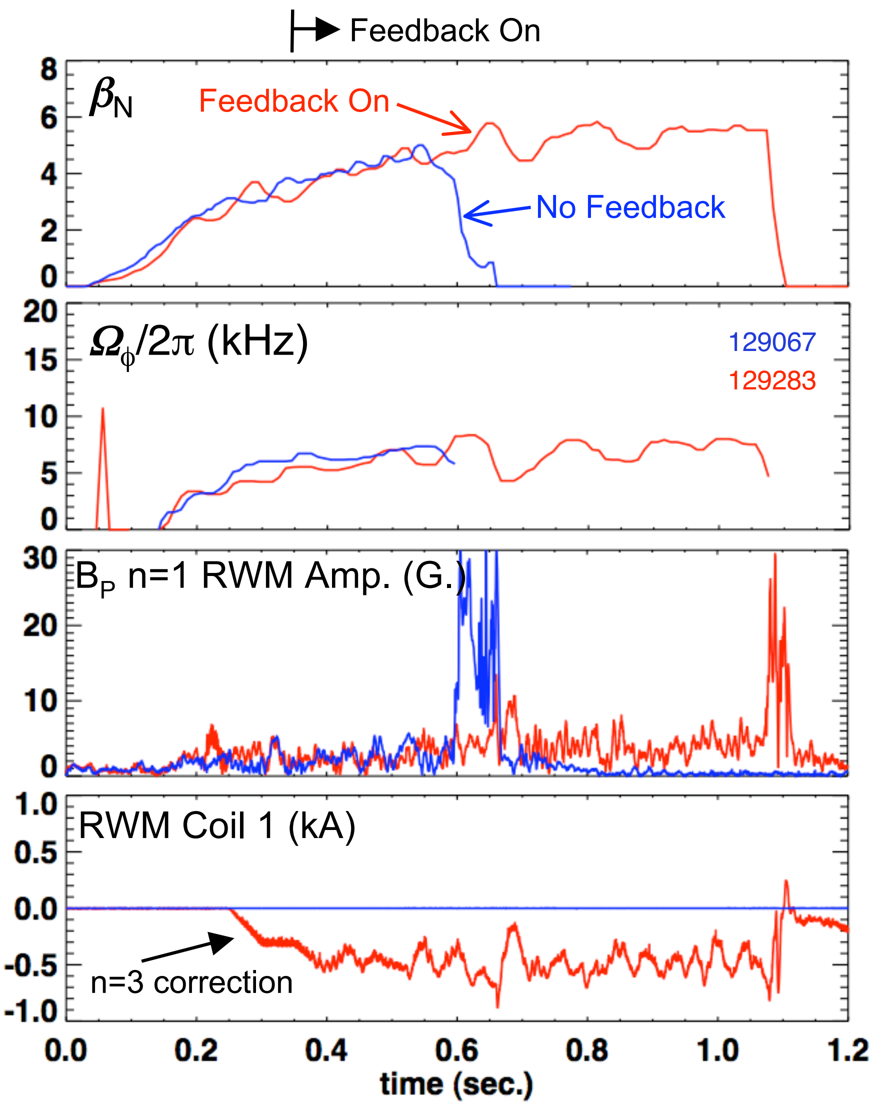


[1] Hu, Betti, and Manickam, PoP 2005

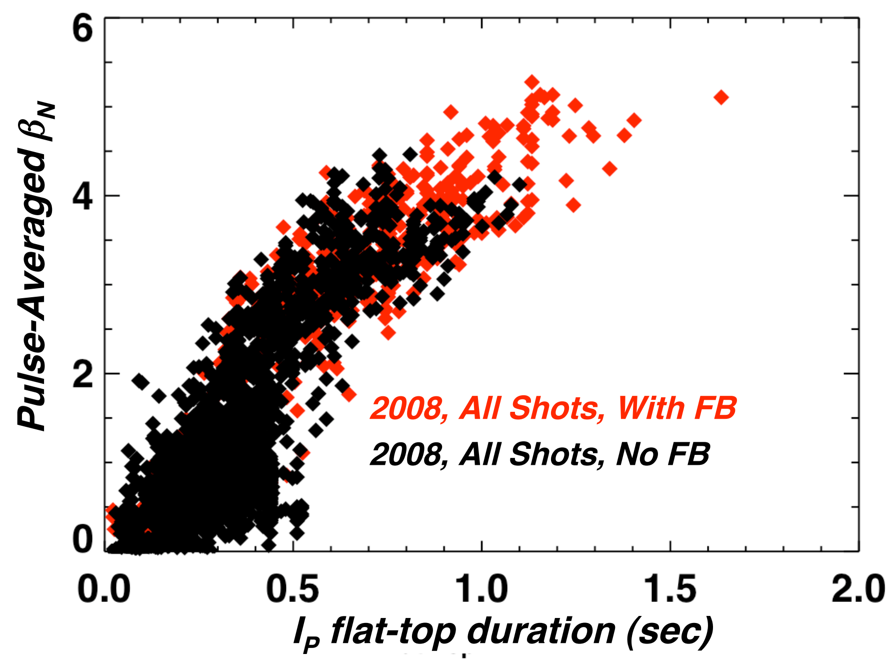
J. Berkery, Columbia University

Static n=3 EF Correction and n=1 Feedback Lead To Dramatically Improved Performance

Control algorithm developed in 2007 (presented to PAC-23), usage became routine in the second half of 2008



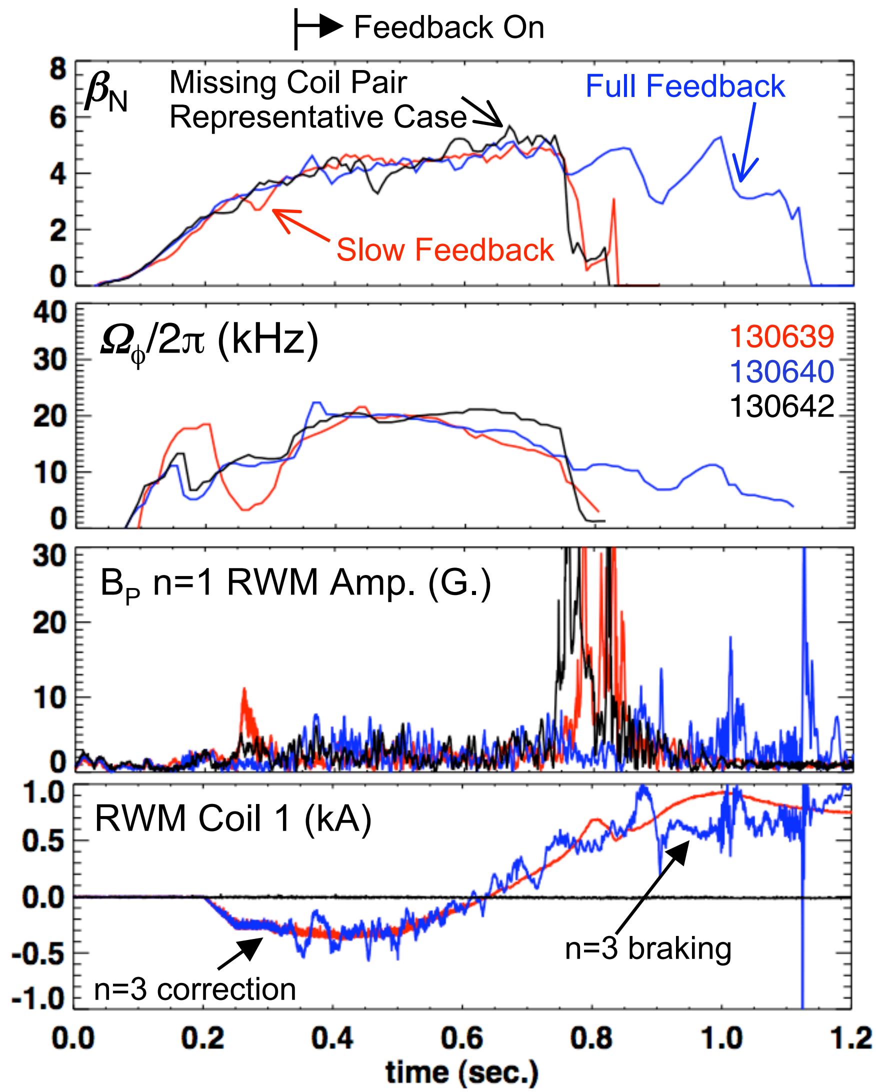
Shots with highest pulse-averaged β_N and longest duration now limited by coil heating limits.



Anticipate that this tool will be commonly used in 2009, across many TSGs

RWM-Feedback Experiments Studied ITER Relevant Cases

- Magnetic braking (n=3) used to achieve low rotation.
- Scan of feedback time scale, to simulate nearby conducting structures or increased latency.
  - Fast feedback allowed sustained high-β_N.
  - 75 ms smoothing time allowed the mode to grow.
- Sustained high-β_N plasmas not possible when an opposing coil-pair is removed.
  - Simulates failure of a coil pair.
  - Multiple feedback phases tried (not shown), but none resulted in sustainment.



MDC-2

PAC 23-15

Direct ITER Support

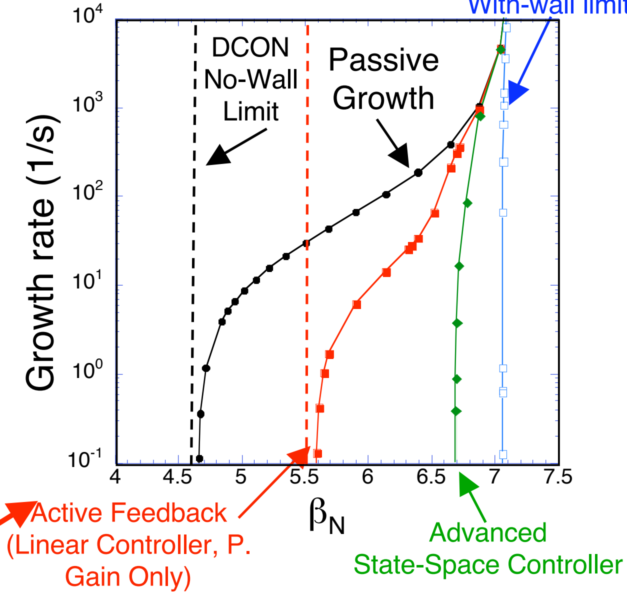
FY-10 Milestone on Disruptivity To Utilize Advanced Mode Avoidance and Control Techniques

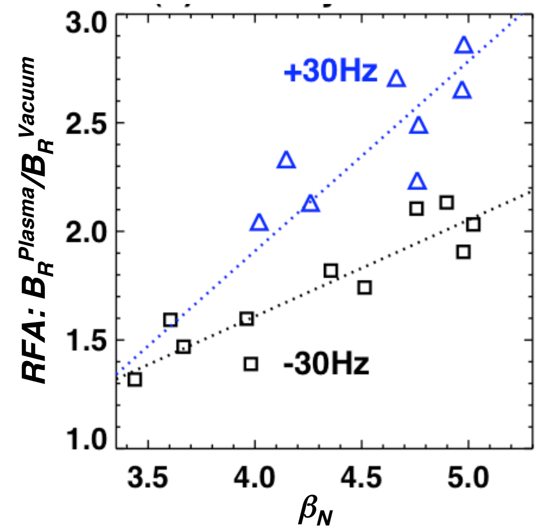
Milestone

Assess sustainable beta and disruptivity, as a function of proximity to the ideal no-wall limit and control techniques.

- Motivation: Even with n=1 feedback:
  - Large excursions in β_N are present.
  - Disruptivity remains unacceptably high for large β_N.
- Directly addresses ST TAP issue on disruptivity.
- Considering implementing a number of control techniques:
  - β_N control via NB modulation.
  - State-space RWM controller.
    - Predicted stable to 95% of $\beta_N^{with\text{-}wall}$
  - Realtime stability boundary detection.
    - Plasma amplification of error fields allows detection of proximity to $\beta_N^{no\text{-}wall}$.

VALEN Low V_ϕ Simulations Shown[1]





MDC-17

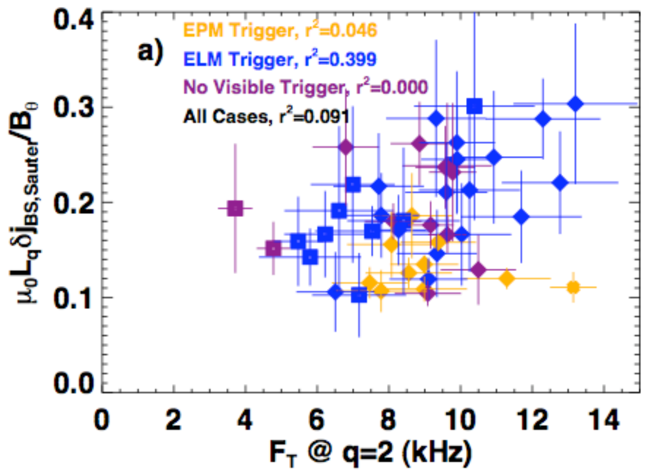
[1] O. Katsuro-Hopkins and J. Bialek, Columbia University

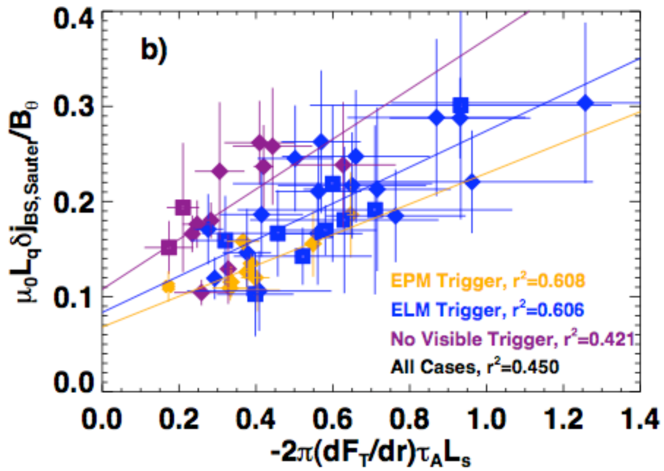
NTM Research Has Focused on Flow Shear and Aspect Ratio Effects

[1] S.P. Gerhardt, et al, accepted for publication in NF

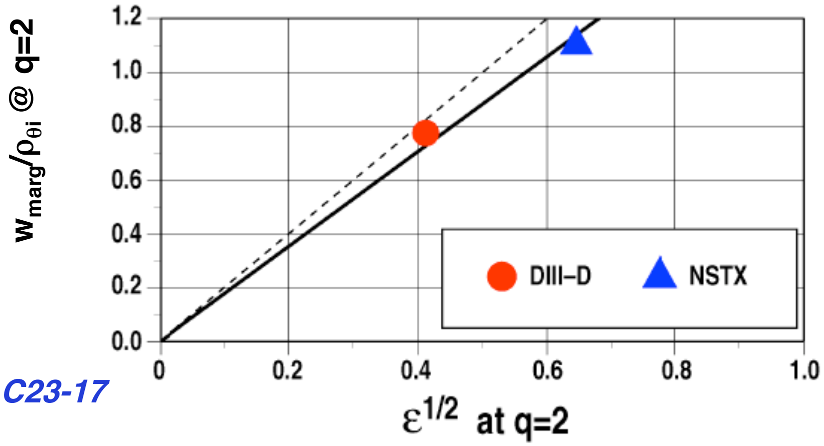
- Neoclassical drive at 2/1 mode onset is a function of normalized rotation-shear, not rotation.[1]
  - Relevant to devices with minimal momentum input.
  - Interpretation: reduced flow shear decreases the classical stability.
- Marginal island width shows a scaling with ion banana width.
  - Suggests small-island physics determined polarization threshold or prevention of bootstrap loss on ion-banana width scale

2/1 Onset Threshold vs. V_ϕ Shear





2/1 Marginal Island Width for Restabilization



PAC23-17

MDC-4,14 *This work done as a collaboration between NSTX staff, R.J. Buttery (UKAEA), R.J. LaHaye (GA), & T. Strait (GA)*

Continue These NTM Studies in FY09-11, Adding Error Field Effects & Modeling

- Marginal island width comparisons with DIII-D allow study of aspect-ratio effects:
  - 2009-2010: Polarization current and finite banana-width effects give a poloidal gyroradius scale size, curvature effects more stabilizing at low aspect-ratio.
- Explore the role of rotation and error fields in modifying 2/1 onset thresholds.
  - DIII-D results: *static* n=1 EFs reduce the onset threshold for *rotating* NTMs.
  - 2009-2010: Study the onset threshold for the 2/1 mode as a function of n=1 EF.
  - 2011: Utilize HHFW-heated H-modes for studies with minimal momentum input.
- Explore the role of Li and DEFC on NTM stability.
  - Many discharges utilizing Li conditioning and DEFC do not strike 2/1 modes.
  - 2009-2010: Assess how triggering and ideal stability are modified by Li.
- Implement improved NTM modeling
  - 2009-2010: Implement PEST-III calculations of Δ' for realistic equilibria.
  - 2010-2011: Utilize initial value codes like NIMROD for more sophisticated treatment of, for instance, transport near an island or rotation shear effects.

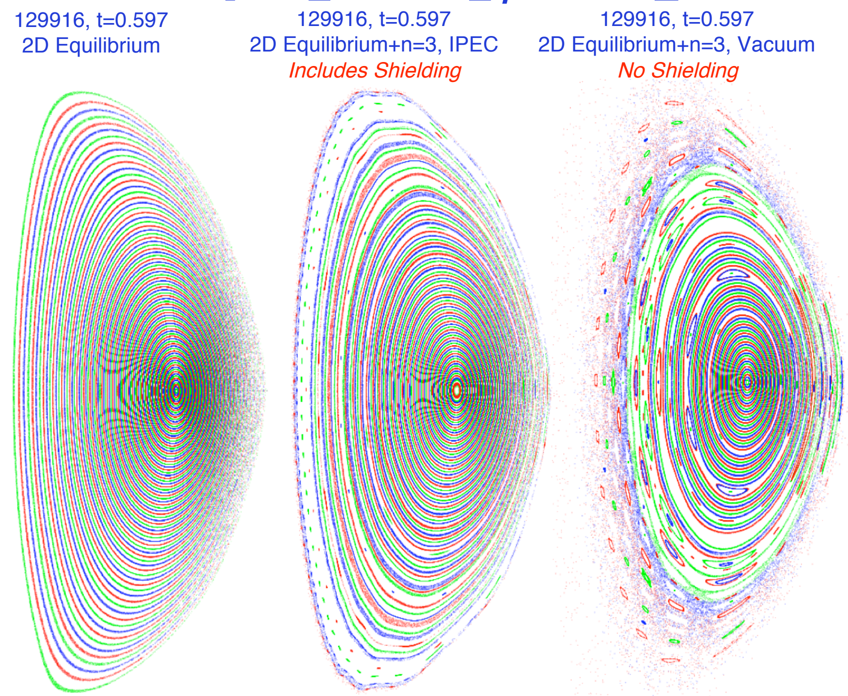
Outline For This Presentation

- Understanding and control of intrinsic instabilities
  - Resistive Wall Modes (RWMs)
  - Neoclassical Tearing Modes (NTMs)
- Stable plasma response to 3D Fields
  - Error fields and the associated plasma response
  - Neoclassical Toroidal Viscosity (NTV)
- Disruption avoidance and characterization
- New stability research opportunities with the CS upgrade, 2nd beamline, and Nonaxisymmetric Control Coil (NCC)

Error Field Program Studies Plasma Response Effects on Error Field Penetration, RMP, and NTV

- Need to understand the self-consistent plasma response to external 3D fields.
  - IPEC calculates the 3D equilibrium with both EFs and shielding currents.
- Useful for a broad range of physics studies:
  - Demonstrated the importance of plasma response for understanding density scaling of locked-mode threshold.
  - Calculation of n≥1 RMP effects.
  - Calculation of neoclassical toroidal viscosity (NTV) with consistent plasma amplification of the 3-D field.

IPEC=<u>I</u>deal <u>P</u>erturbed <u>E</u>quilibrium <u>C</u>ode[1]



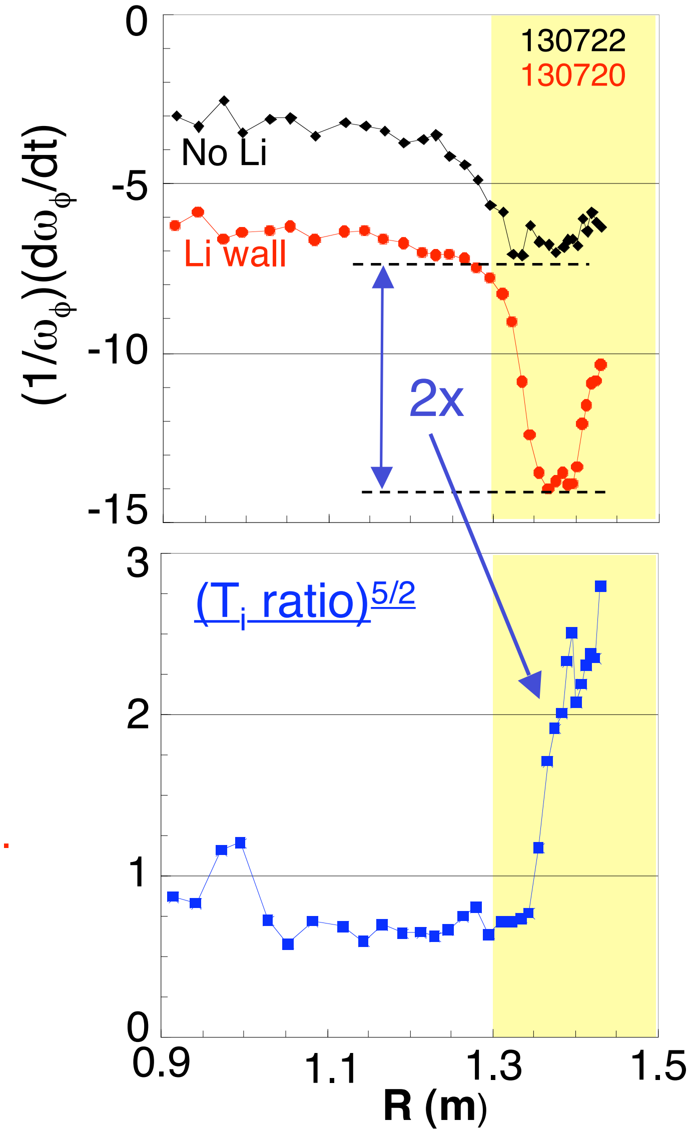
- Plans:
  - 2009: Experiments to study error-field penetration at high-β.
  - 2009-2010: Use IPEC and vacuum calculations to find configurations of RWM coils which can mimic effects of ITER Test Blanket Module (TBM) error fields.
    - Test impact of TBM EF on breakdown, H-mode access, rotation, ELMs,…
  - 2009 and beyond: Continue application of IPEC to RMP ELM suppression experiments.
  - 2009-2010: Expand IPEC to include tensor pressure.
  - 2010-2011: Expand IPEC to allow magnetic islands.

MDC-12

[1] J.K. Park, et al, Phys. Plasmas **14**, 052110 (2007)

NTV Research Demonstrates the Importance of Ion Temperature and 3D Field Spectrum

- Important recent NTV results[1]:
  - Using LITER to vary collisionality, verified $T_i^{5/2}$ dependence of NTV torque in region of max braking.
    - Consistent with $p_i/\nu_i \propto T_i^{5/2}$ scaling.
  - n=2 NTV measured to have broader damping profile than n=3.
- Plans
  - 2009-2010: Continue testing viscosity theory from resonant /non-resonant fields
    - Continued studies of ν_i dependence using lithium evaporation, *LLD.*
    - Improved plasma internal field response using IPEC; influence of magnetic islands.
  - 2010-11: Expand analysis to further test theory
    - Saturation due to E_r at reduced ν_i
    - Time-evolved kinetic computations with GTC-Neo.
  - 2010-2011: Utilize NTV for rotation control.
    - Use NTV from midplane coils for rotation control.
    - Determine range of radial placement of maximal torque possible with NCC design.



MDC-12

[1] S. Sabbagh, et al, IAEA FEC 2008

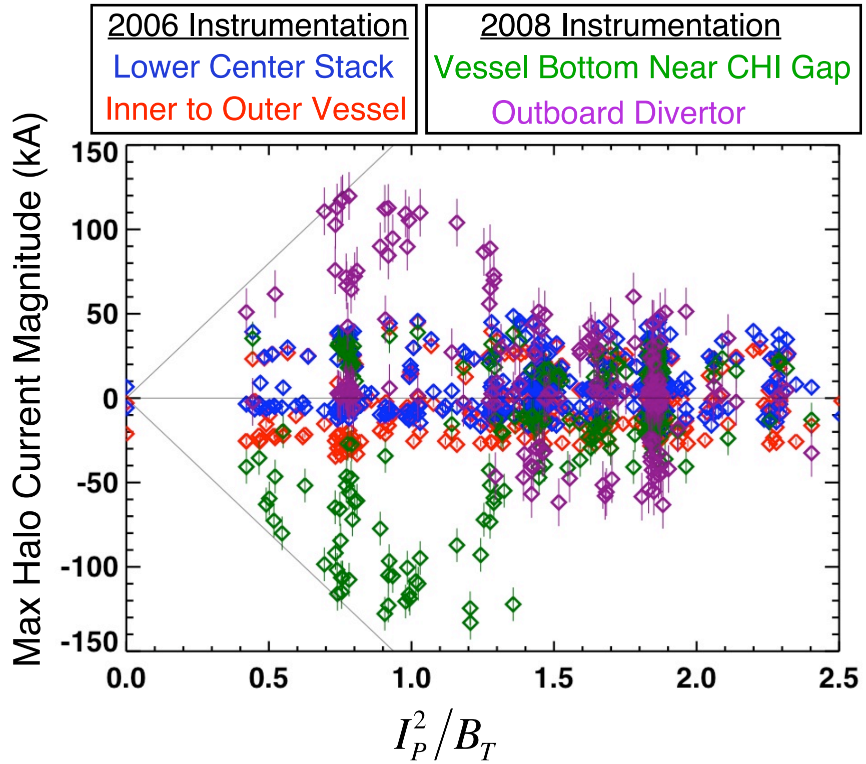
PAC 23-15

Outline For This Presentation

- Understanding and control of intrinsic instabilities
  - Resistive Wall Modes (RWMs)
  - Neoclassical Tearing Modes (NTMs)
- Stable plasma response to 3D Fields
  - Error fields and the associated plasma response
  - Neoclassical Toroidal Viscosity (NTV)
- Disruption avoidance and characterization
- New stability research opportunities with the CS upgrade, 2nd beamline, and Nonaxisymmetric Control Coil (NCC)

Disruption Plans Focus on Characterization and Prediction of Disruptions

- Assess halo currents at low aspect ratio.
  - New instrumentation in 2009 revealed larger halo currents than previously thought.
  - 2009-2010: Upgrade halo current diagnostics (instrumented divertor tiles & currents into LLD tray).
  - 2010-2011: Model halo currents as a function of driving voltages and NSTX geometry.
- Understand thermal quench heat loading.
  - 2009-2010:Utilize (new) fast IR thermography to understand the spatial distribution and timescale of disruption divertor heat flux.
  - 2010-2011: Assess main chamber loading.



- Develop predictive capability
  - (2010-2011) Develop methods for predicting disruptions in high-β, ST plasmas.
    - Extensive realtime measurements (Rotation, RWMs, rtefit) facilitate this effort.
- Assess how lithium PFCs impact disruption physics and disruptivity.
  - Low ionization potential of Li may lead to more rapid current quenches.
  - Li conditioning has tended to reduce rotating MHD, but need to assess how ν_i scaling impacts RWM disruptivity.

MDC-15

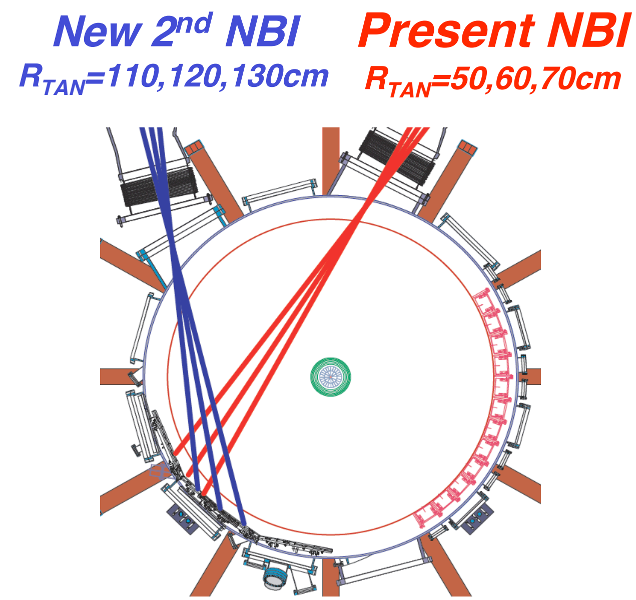
Results from these studies already being used in NSTX-U design activities.

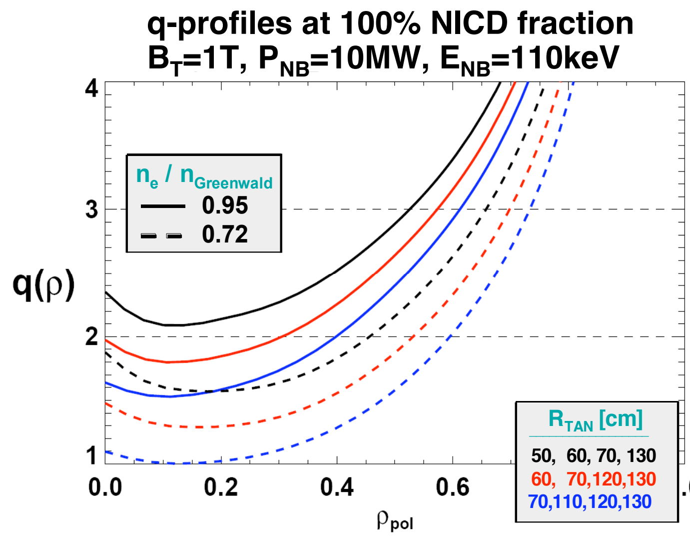
Outline For This Presentation

- Understanding and control of intrinsic instabilities
  - Resistive Wall Modes (RWMs)
  - Neoclassical Tearing Modes (NTMs)
- Stable plasma response to 3D Fields
  - Error fields and the associated plasma response
  - Neoclassical Toroidal Viscosity (NTV)
- Disruption avoidance and characterization
- New stability research opportunities with the CS upgrade, 2nd beamline, and Nonaxisymmetric Control Coil (NCC)

New CS & 2nd NBI Will Dramatically Expand The Range of Stability Studies

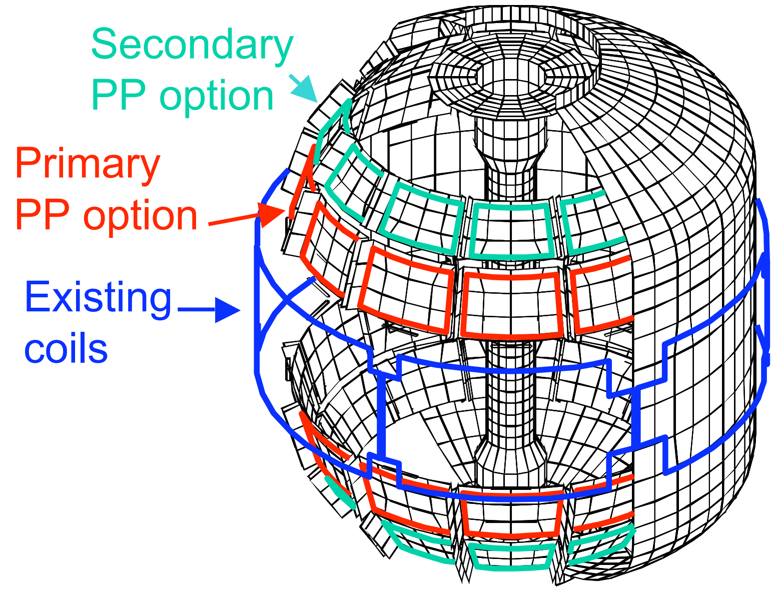
- Resistive Wall Modes & NTV
  - Test of passive RWM stability at significantly reduced ν_i, and with a broader range of rotation profiles.
  - NTV scaling at lower collisionality (ν_i^1, ν_i^0 , ν_i^{-1}?).
  - Determine if rotation-profile control can improve stability for $\beta_N > \beta_N^{no\text{-}wall}$.
  - Explore synergism between RWM, β_N, and rotation control, at a variety of collisionalities.
- Neoclassical Tearing Modes
  - Use NBCD to vary current profile, and the associated classical tearing stability.
  - NTM behavior when the q=2 is excluded.
    - How dangerous will 3/1 modes be?
- Disruption Studies
  - Improved halo current measurements on new CS.
  - Tests of disruption avoidance via advanced control for much longer pulses (up to ~$10^4\tau_w$).
- All three TAP issues (3D-Fields, NTMs, Disruptivity) directly addressed by upgrade.

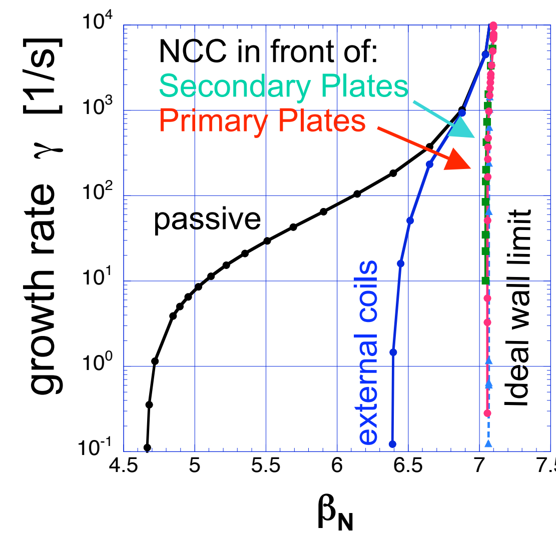




Proposed Nonaxisymmetric Control Coil (NCC) Will Expand Our Knowledge of 3D Effects

- Non-axisymmetric control coil (NCC) – at least four 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 ($n \leq 6$).
  - n > 1 propagation, increased V_ϕ control.
  - Similar to proposed ITER coil design.
  - In incremental budget.
- Addition of 2nd SPA power supply unit:
  - Feedback on n>1 RWMs
  - Independent upper/lower n=1 feedback, for non-rigid modes.
- Design activities are underway:
  - CU group working on assessing the design for RWM stabilization capabilities.
  - GA collaboration is computing Chirkov parameters and field line trajectories for RMP ELM suppression applications.





PAC 23-18

J. Bialek, Columbia University

Stability Research Effort is Addressing the Needs of Next-Step Sets and ITER, Basic Toroidal Plasma Physics

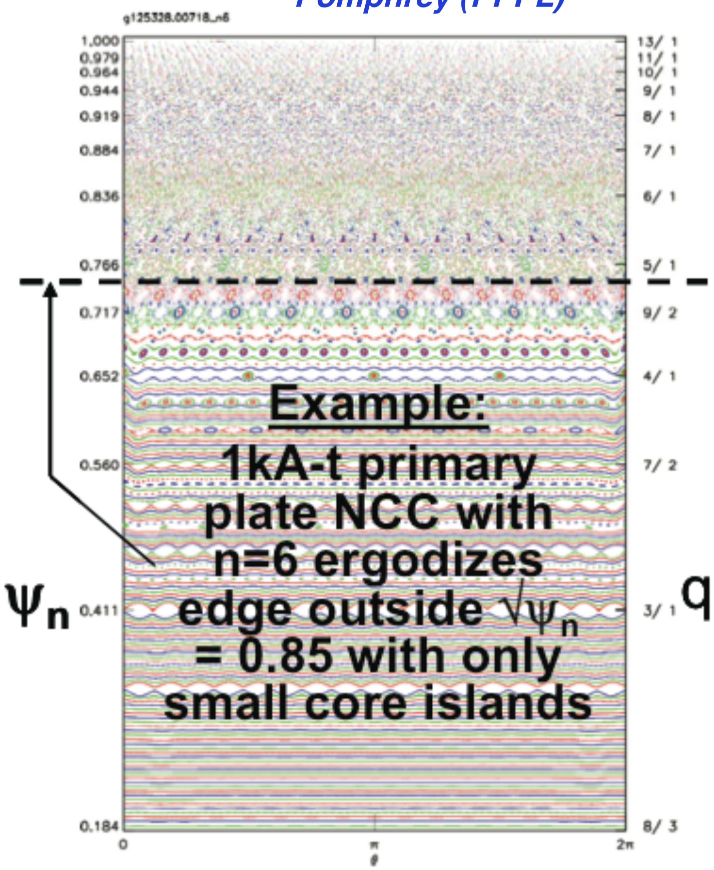
- Research program seeks to sustain high-β plasmas through improved understanding and advanced control.
- Emphasis in subjects critical to the ST development path:
  - Resistive wall mode physics and control
  - Neoclassical tearing mode physics and control
  - Error fields and the associated plasma response
  - Viscosity due to 3-D fields
  - Disruptions
- Important contributions to the broader fusion research effort.
  - ITER specific support tasks.
    - Participation in 6 ITPA joint experiments.
      - See S. Sabbagh's talks at the Oct. ITPA meeting.
      - http://nstx.pppl.gov/DragNDrop/Scientific_Conferences/ITPA/2008/October/MHD/
    - RMP ELM Suppression (discussed in M. Bell's talk)
    - Low rotation RWM control
    - ITER TBM simulation

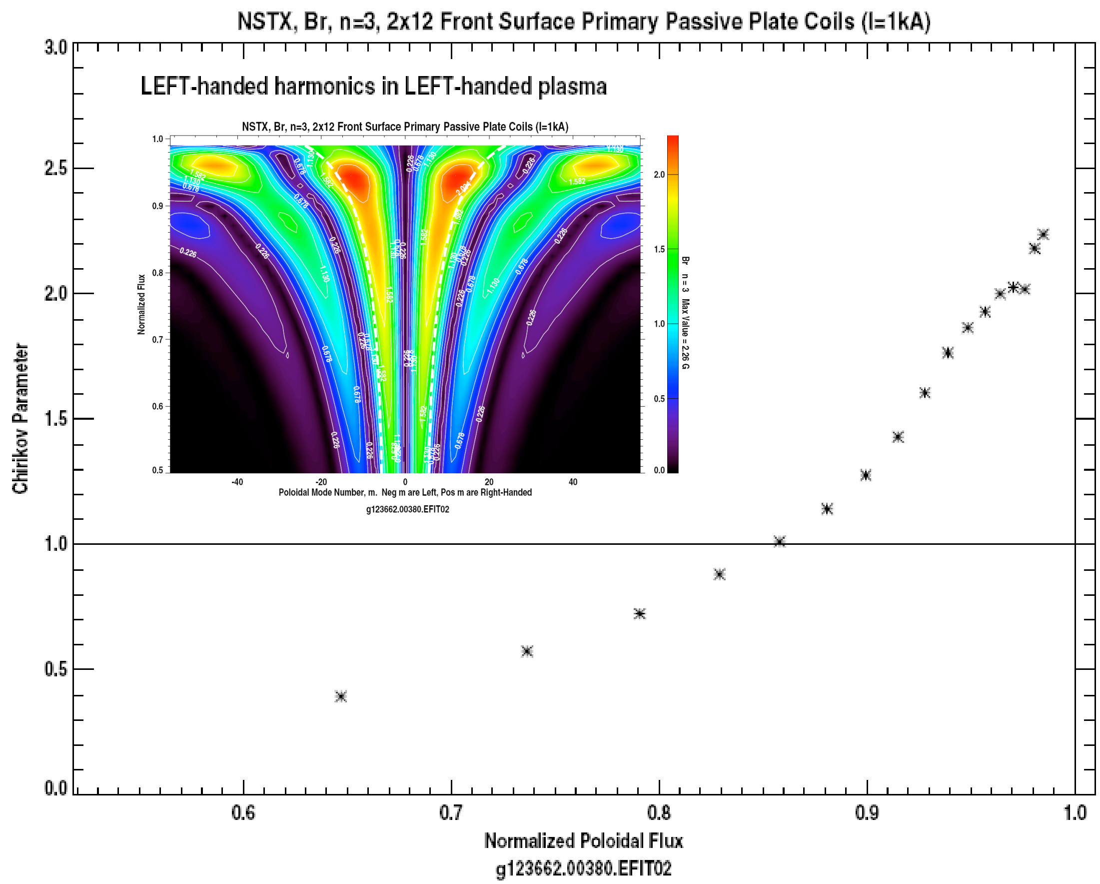
Backup

NCC Coils Add Substantial New Capabilities For RMP Research

- NCC can be configured to ergodize the edge, but with only small core islands.
  - Increased m-spectrum control allows fields to resonate more strongly with edge at higher q
- Further calculations underway as part of General Atomics Collaboration

Pomphrey (PPPL)





Parameters of Next-Step Devices Emphasize the Need for Comprehensive Stability Research

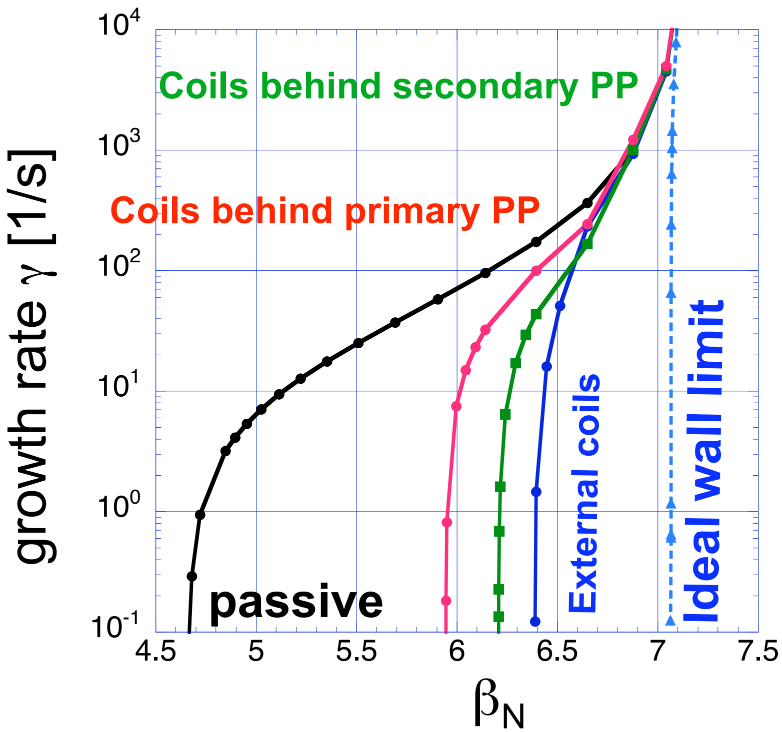
- NHTX: Long pulse ST for PMI Studies
- ST-CTF: High-fluence nuclear testing facility
  - Device designed for β_N beneath the no-wall limit
  - An increased β_N level reduces the time required to achieve neutron fluence goal.
- ST-DEMO: Numbers based on ARIES-ST design

	NSTX	NSTX-U	NHTX	ST-CTF	ST-Demo
Pulse Length (sec)	1-2	5-10	500	2×10^6	2×10^7
κ	2.6	2.6	3	3.1	3.5
β_N	5.7	5.7	5	4-6	7.5
$l_i(1)$	0.55	0.65	0.6	0.35	0.25
$\beta_N/l_i(1)$	10	8.5	8.5	14	31
β_T	14	14	14	18-28	50
f_{BS}	0.54	0.7	0.7	0.5	0.96
e^{lp}	3	7	20	3000	4×10^{12}
$W_{th}/(7A_{Div}\tau^{1/2})$ $(MJ/m^2s^{1/2})$[1]	2	4	25-50	100-200	800-1200

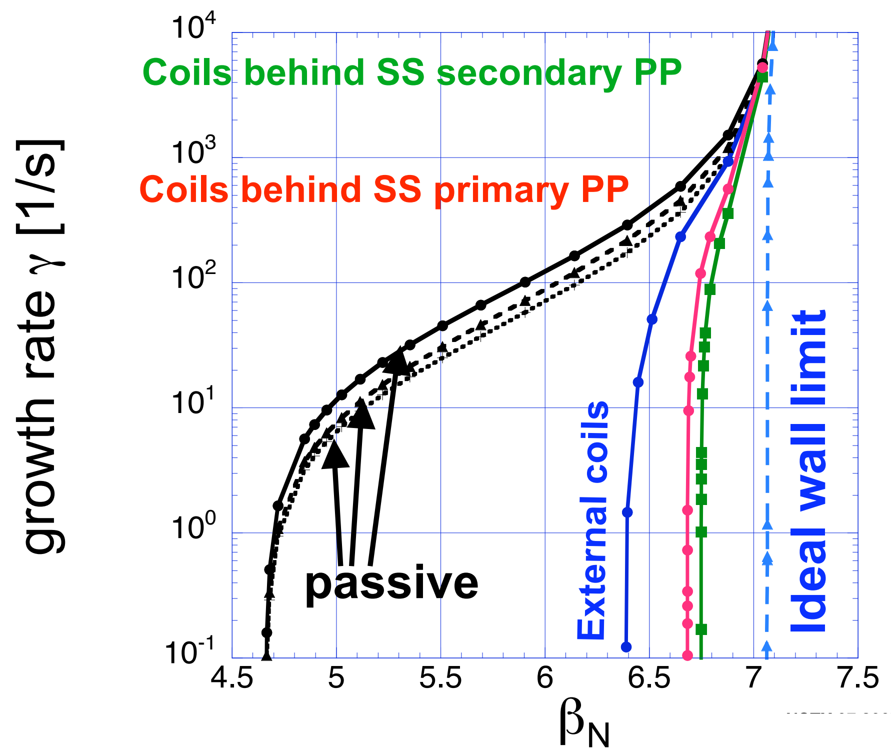
[1] Assumes equilibrium midplane SOL width of ~1cm, flux expansion of 20, no pre-disruption energy loss, and thermal quench times scaling with the minor radius.

VALEN computed RWM stability for proposed RWM control coils upgrade - behind passive plates (PP)

Copper Plates



Stainless Steel Plates

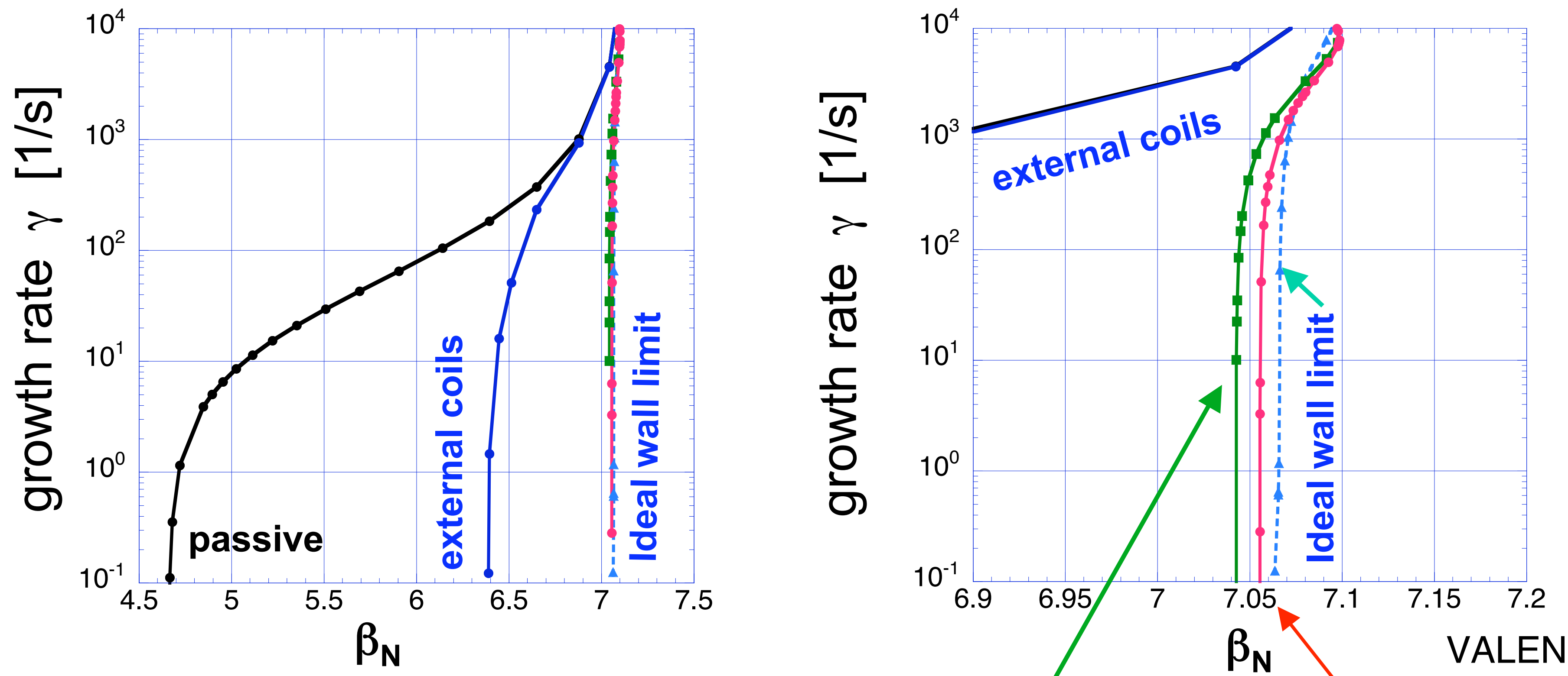


- coils behind copper passive plates perform worse than existing external RWM coil set
- change copper passive plates to SS RWM performs better than existing external coil set

(note: idealized sensors used)

J. Bialek, Columbia University

Proposed control coils on plasma side of copper passive plates computed to stabilize to 99% of $\beta_N^{with\text{-}wall}$



coils on plasma side Cu secondary PP stabilize to $\beta_N = 7.04$

coils on plasma side Cu primary PP stabilize to $\beta_N = 7.05$

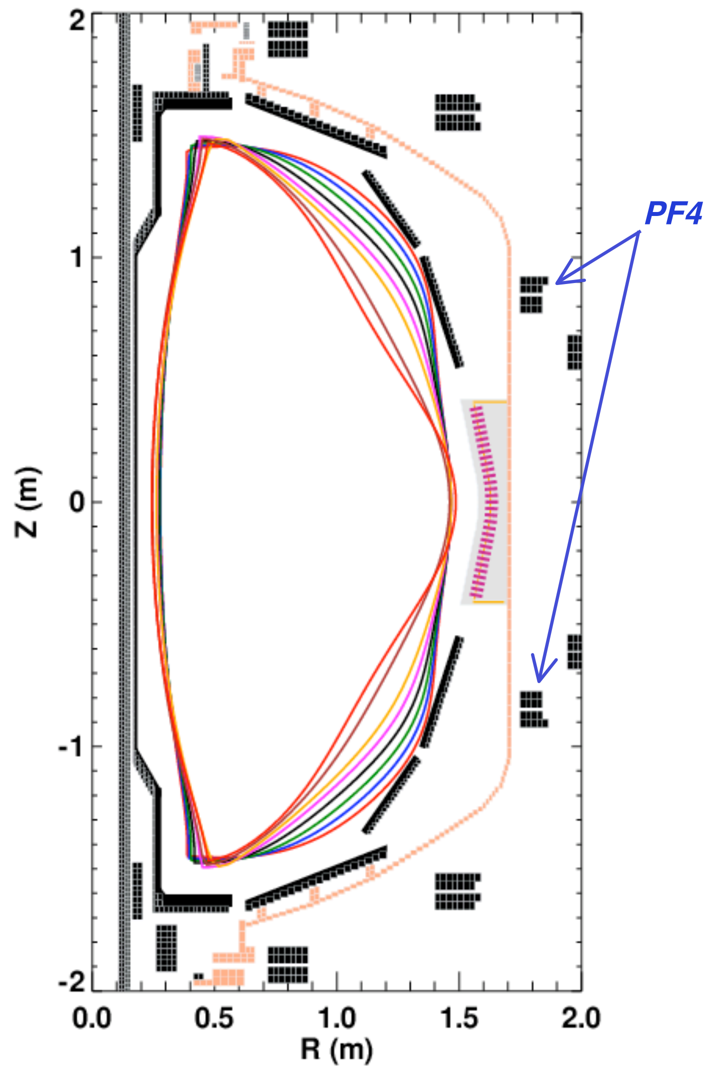
Ideal wall limit $\beta_N = 7.06$

(note: idealized sensors used)

J. Bialek, Columbia University

Future Shaping Research Focusing on How Higher-Order Shaping Influences Edge and Global Stability

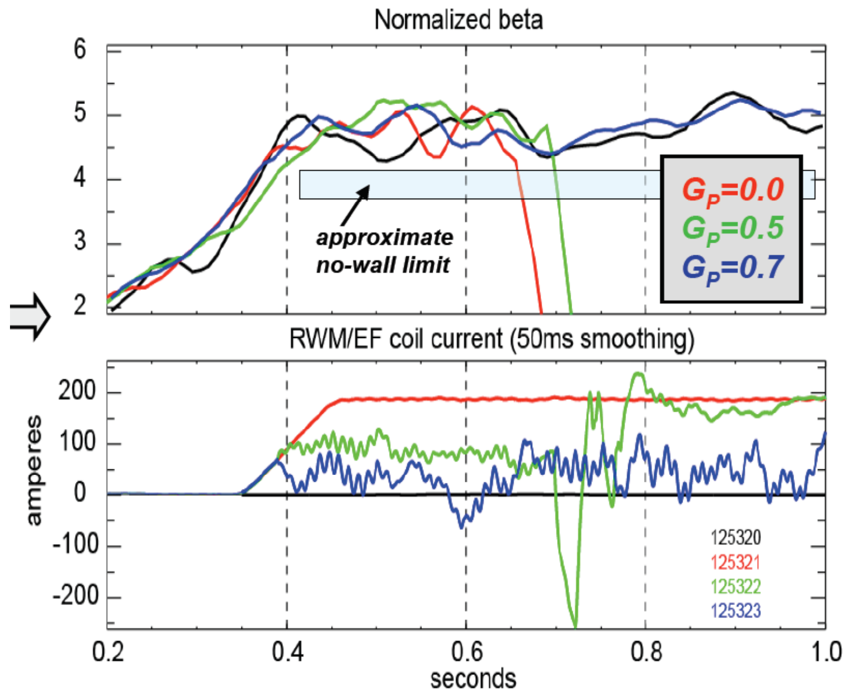
- NSTX has had excellent success with highly shaped plasmas:
  - Achieved world record elongation of κ=2.9
  - Cannot increase κ further without reducing minor radius.
  - Triangularities in the range of 0.7 routine.
- Next shape moment to optimize is squareness (ζ):
  - Reduced squareness was observed to improve n=1 MHD stability.[1]
  - Ballooning stability is likely reduced with increasing squareness…is this a good trade?
- Equilibrium studies show that:
  - ζ scans work best at κ~2.5
  - Require that the PF4 coil be used for during plasma operations (hence, upgrades to PCS code).
  - May be able to do experiment in late 2009 or 2010.



[1] C.T. Holcomb, APS 2008

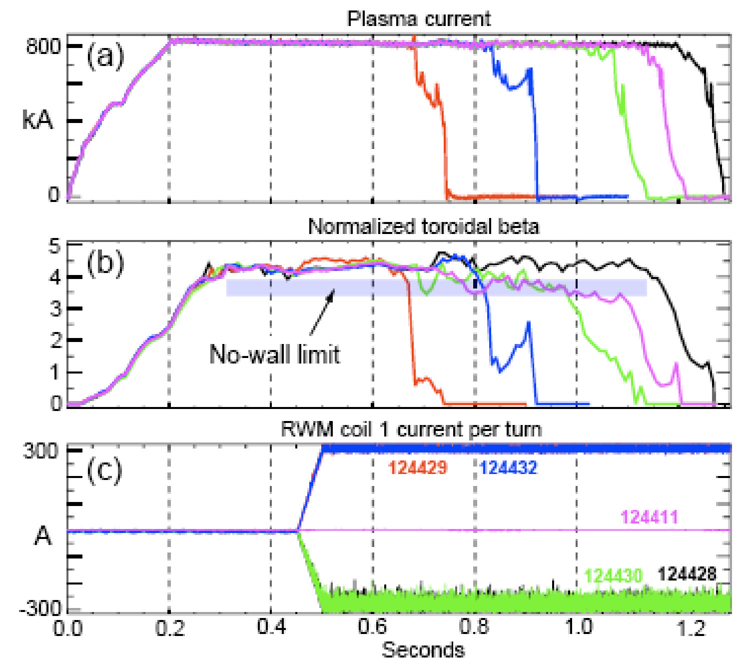
Techniques For Both Dynamic n=1 and Static Non-Resonant EF Correction Have Been Developed…

<u>Feedback System Trained for n=1 DEFC</u>



- 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

<u>Important to Correct n > 1 Error Fields</u>



- 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

PAC-23 Recommendations and Toroidal Alternates Panel Issues

PAC-23 Recommendations

PAC23-15: Complete certain high-priority ITER research tasks (ELM suppression via RMP, NTV physics, and ITER-like RWM coil configuration).

PAC23-16: Make clear identification of stability research priorities in FY08.

PAC23-17: Continue NTM experiments, with a focus on rotation effects.

PAC23-18: Continue design work on internal RWM/RMP coils if NSTX operation will extend past FY10.

Toroidal Alternates Panel Identified 3 Macro-Stability Issues

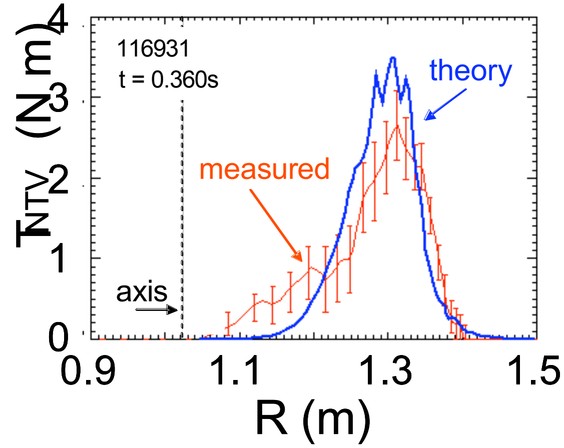
- **3D Fields**: Understand the *physics* requirements and actuators for simultaneous ***EF***, ***ELM***, and ***RWM*** *control.*
- **NTMs**: Assess feasibility of off-axis NBCD to provide NTM suppression through elimination of low-order resonances; otherwise develop EBWCD.
- ***Disruptions:*** Demonstrate disruption-free long pulse operation and improved predictive ability.

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 *δB/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…

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

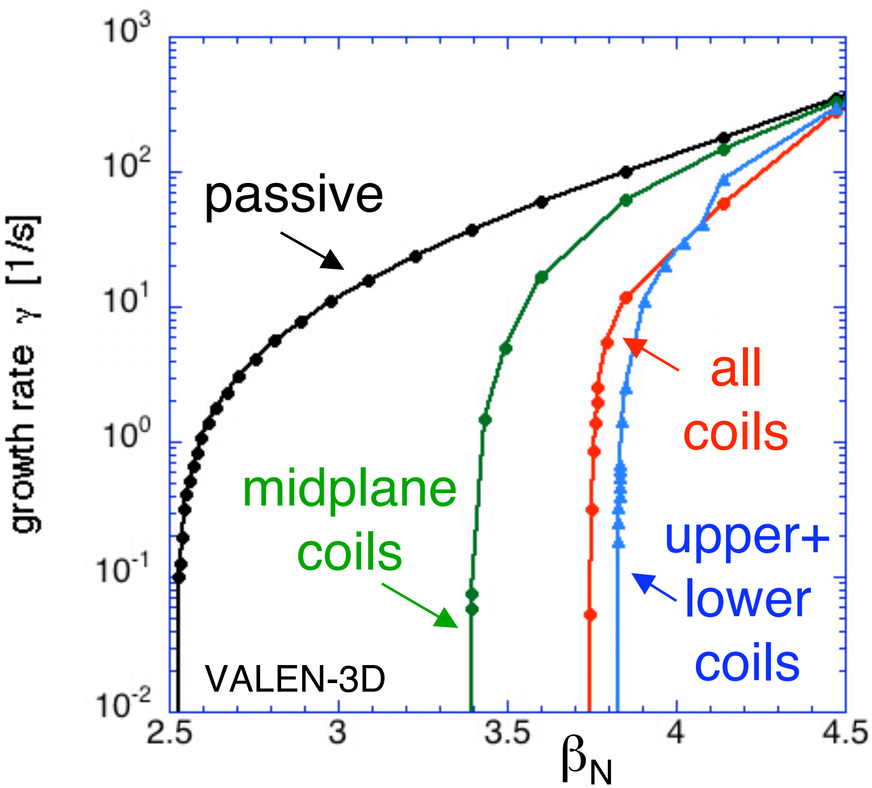
…expected to saturate at lower ν_i

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

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

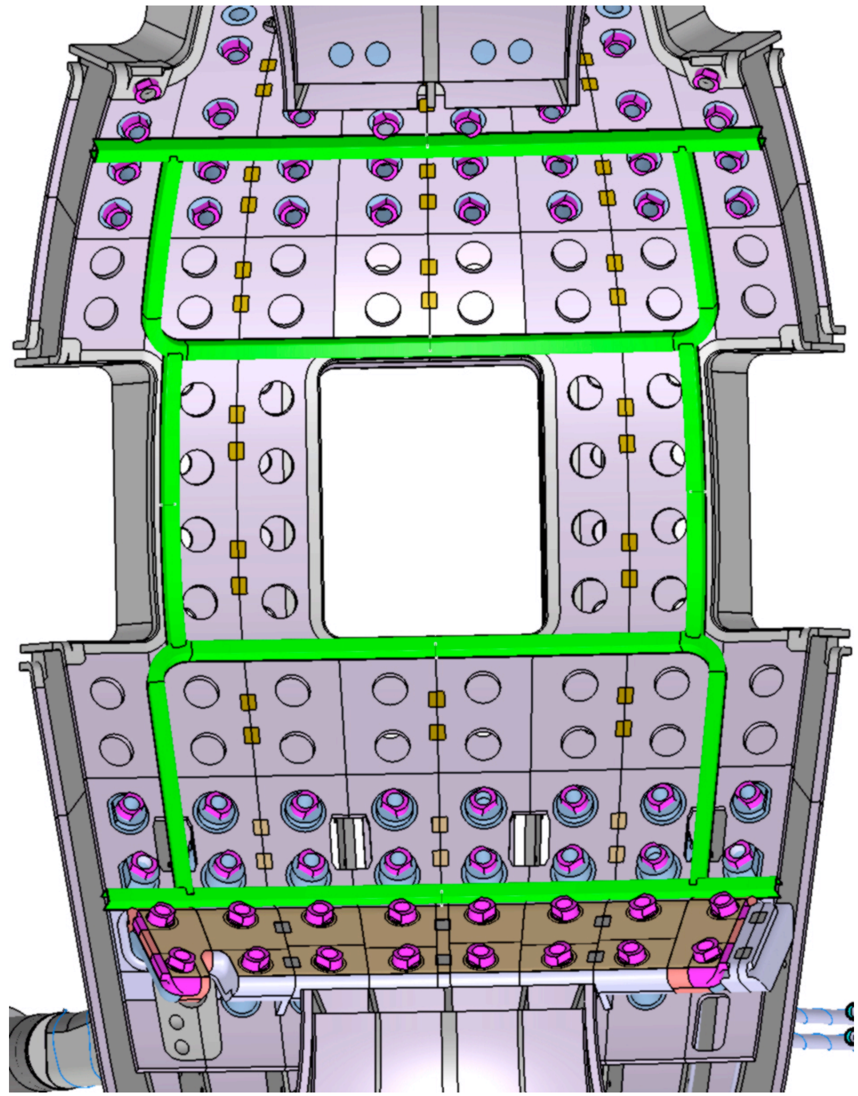
VALEN RWM control models validated on NSTX predict significant β_N increase with proposed ITER internal coil

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

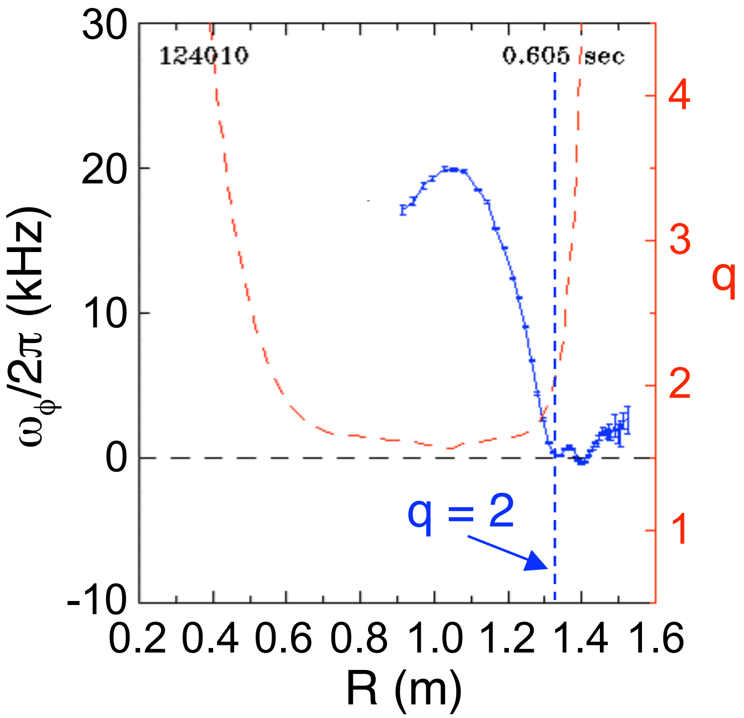
J. Bialek, Columbia University



ITER VAC02 design 40° sector

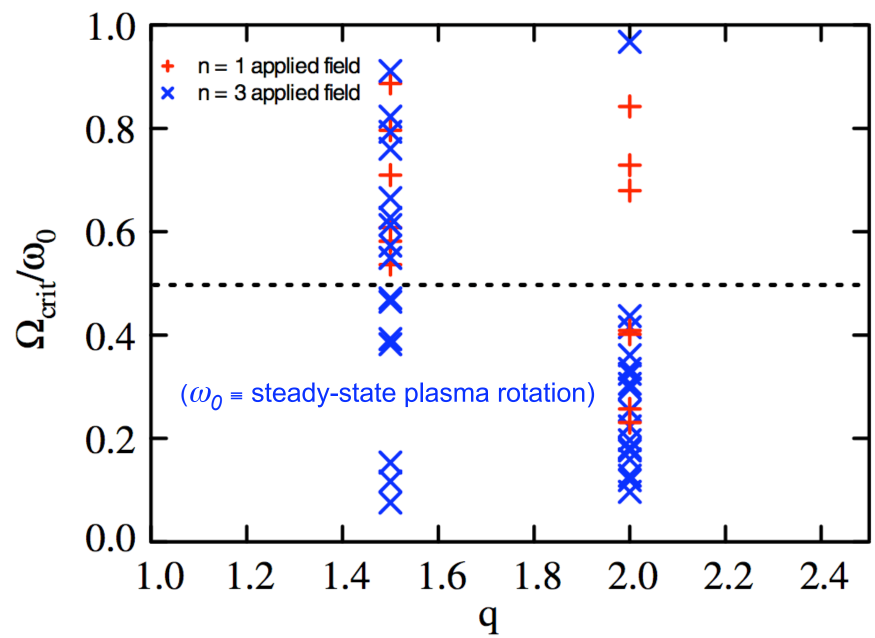
Non-resonant magnetic braking allows V_ϕ modification to probe RWM "critical rotation" and stabilization physics

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



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

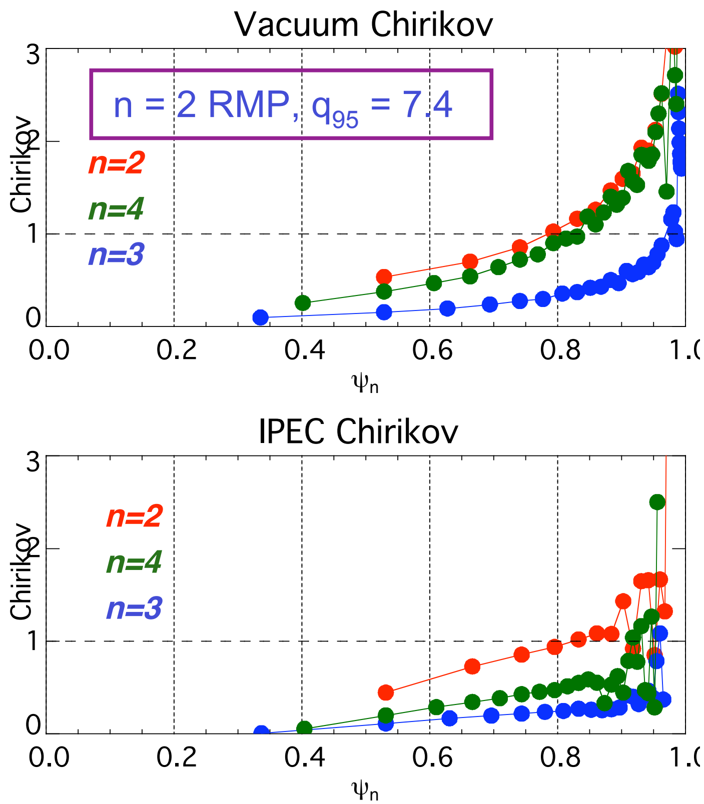
A.C. Sontag, et al., NF **47** (2007) 1005.

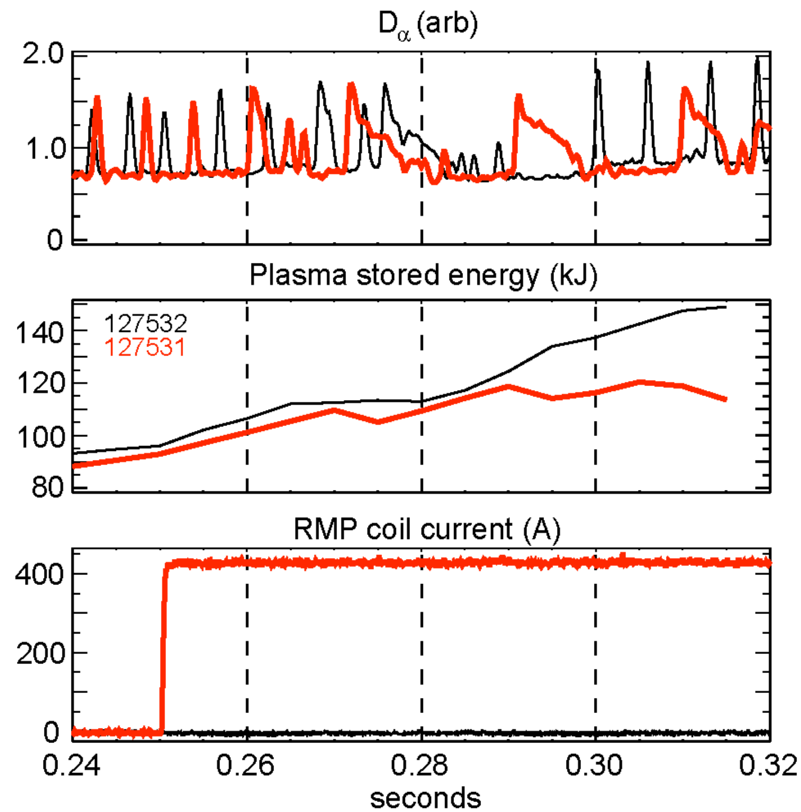


- Slowest rotation profiles produced in NSTX are at DIII-D balanced-NBI levels
- Ion collisionality profile variation appears to alter experimental Ω_{crit} profile

RMP Experiments Modified ELM Properties, But Did Not Suppress ELMs

Research conducted jointly between Macro-Stability and Boundary TSGs.





- This example: n=2 RMP causes ELMs to become larger, at reduced frequency.
- Large ELMs are actually compound ELMs, with multiple filaments and energy bursts.
- Experiments in 2008 tested n=3, n=2+3, AC and DC RMP, with broadly similar results.
- Plan to revisit the n=2+3 configuration at lower q_{95}.
- Note: ELM triggering by RMP also observed, see talk by R. Maingi.

Direct ITER Support

PAC 23-15

Advanced Mode Avoidance and Control Techniques Under Investigation For the FY09-FY11 Period

- β_N control via NB modulation.
  - Operate just below stability limits with immunity to transient confinement improvements.
  - *Should be tested, with β_N from rtefit, in 2009.*
- Improvements in present RWM feedback system
  - 2009: Optimization of mode identification with B_R sensors, in addition to B_P sensors.
  - 2010: Improvements in sensor AC compensation.
- State-space RWM controller
  - Simulation with actual sensor location, NSTX equilibrium, and proportional gain.
  - SS controller may enable $\beta_N/\beta_N^{with\text{-}wall}$ < 95%.
  - *Development of a PCS implementation has begun.*
- Realtime stability boundary detection
  - As β_N exceeds $\beta_N^{no\text{-}wall}$ the plasma responds by amplifying error fields (RFA).
  - Scheme: Apply an n=1 traveling wave, measure with plasma response, adjust the β_N request to achieve a given level of plasma response.
  - *Scoping studies under way.*