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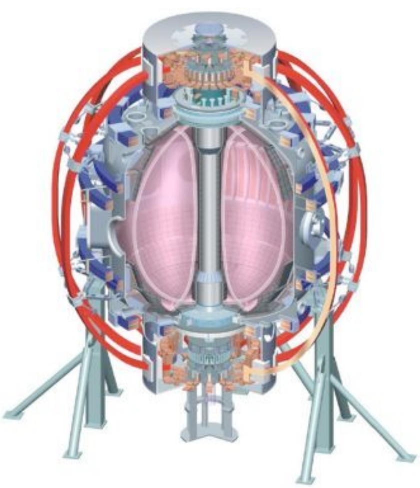
Macroscopic Stability Progress and Plans for 2009-2011 and Beyond

Stefan Gerhardt, PPPL

For the macroscopic stability TSG and the NSTX Research Team

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



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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	$2x10^6$	$2x10^7$
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
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- Stable plasma response to 3D fields
  - Error fields and the associated plasma response
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- 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.

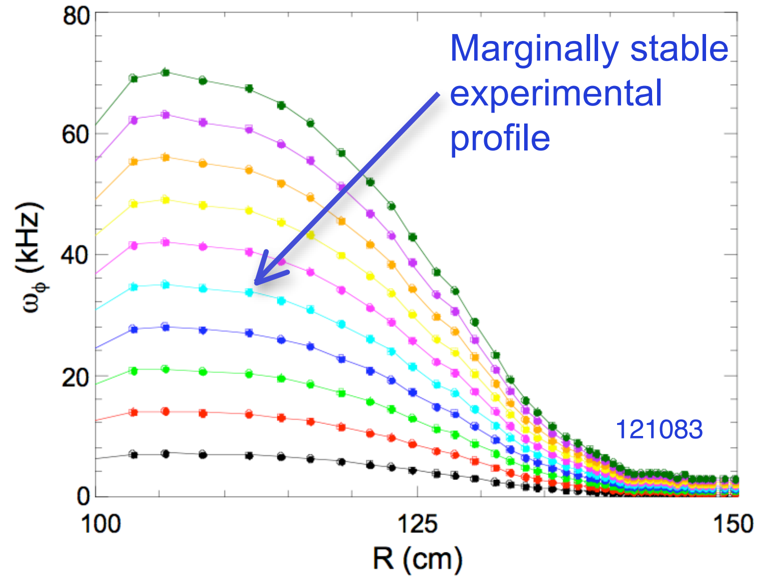
Kinetic Modeling Indicates that RWM Stability is Not a Monotonic Function of Rotation Magnitude

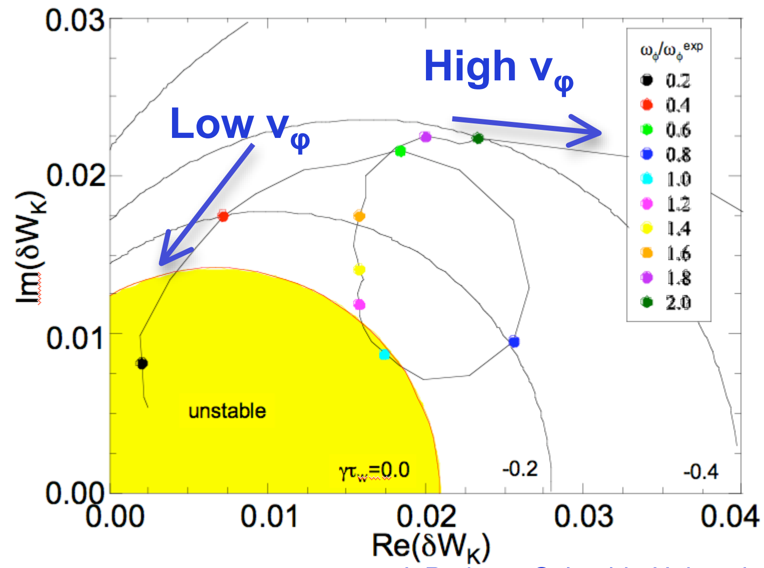
MISK=Modification of Ideal Stability by Kinetic Theory

- 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.



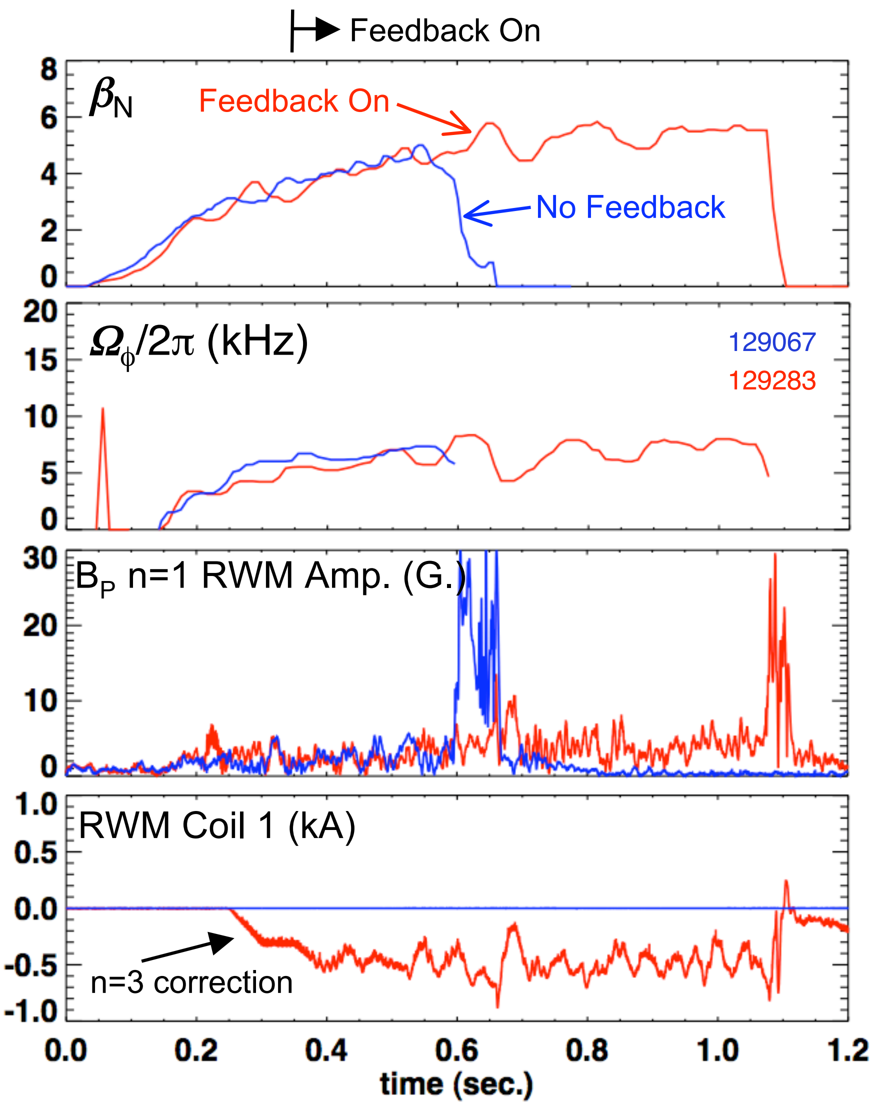


[1] Hu, Betti, and Manickam, PoP 2005

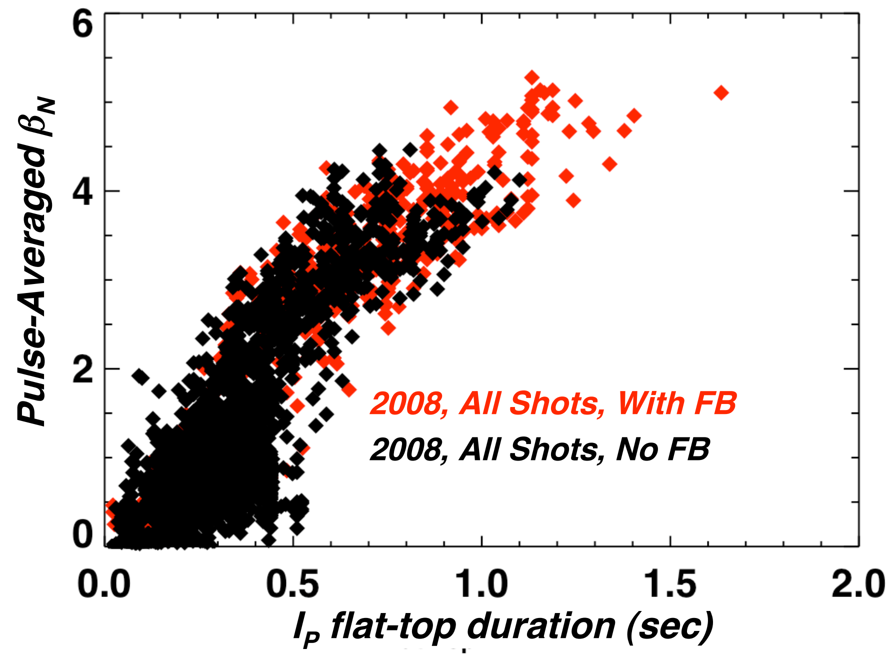
J. Berkery, Columbia University

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



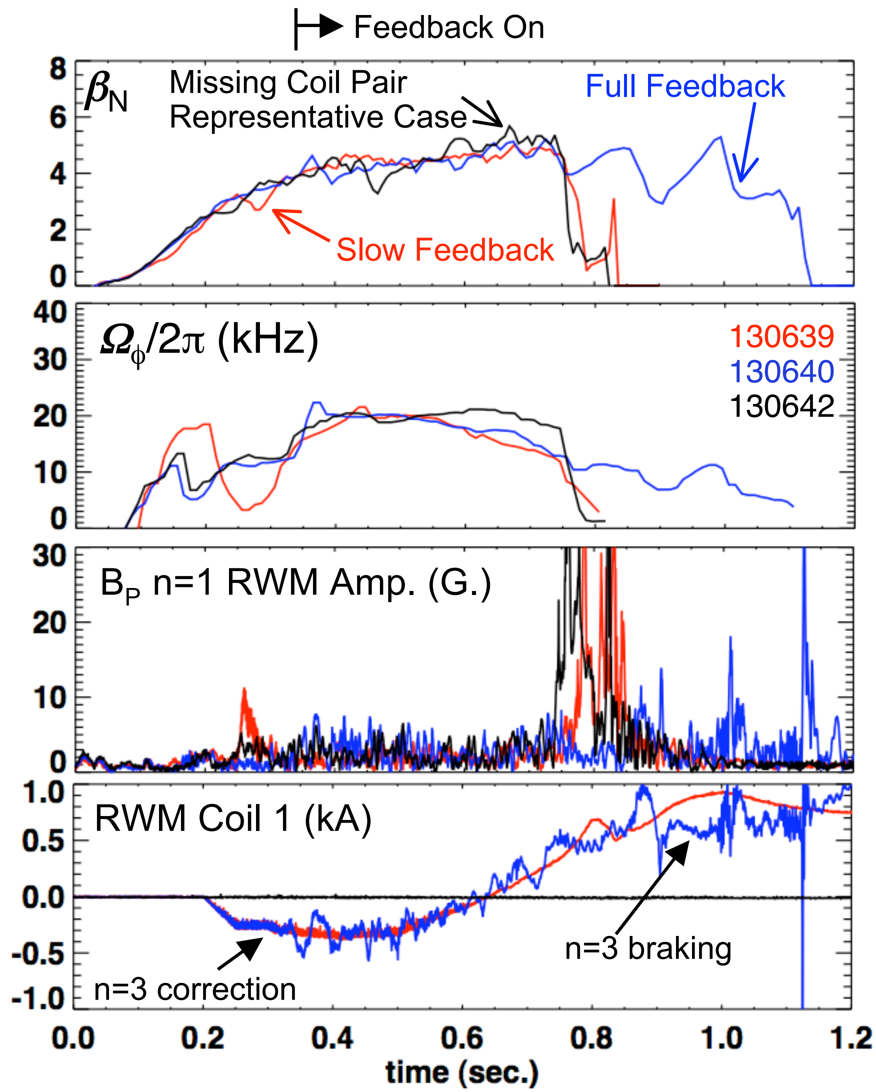
Shots with highest <u>pulse-averaged β_N</u> and longest duration now limited by coil heating limits.



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.



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Direct ITER Support

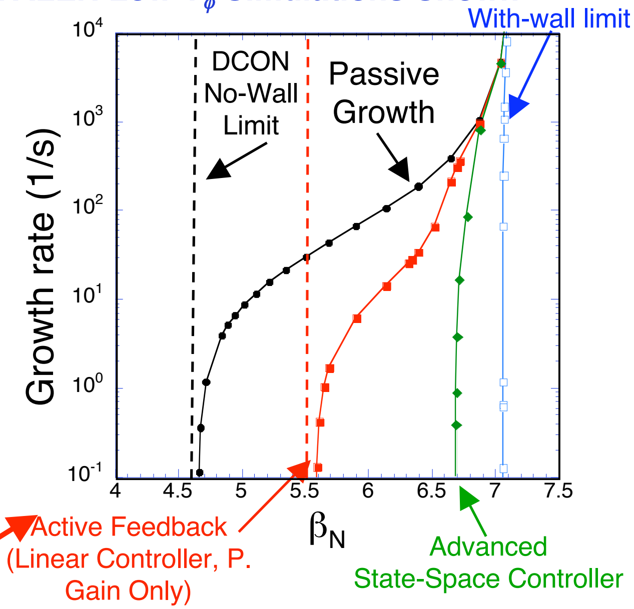
FY-10 Milestone on Disruptivity To Utilize Advanced Mode Avoidance and Control Techniques

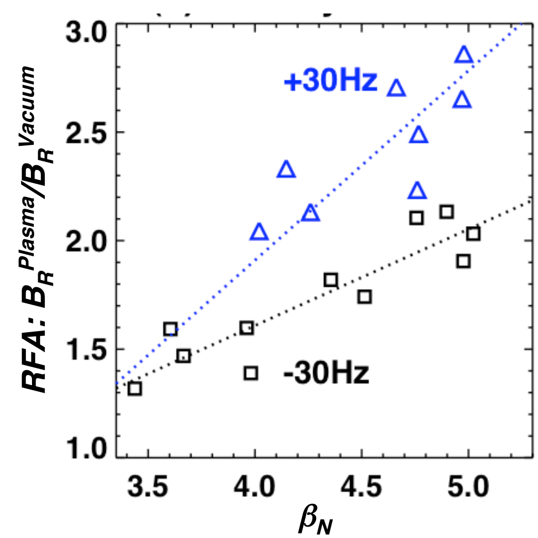
Milestone

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]





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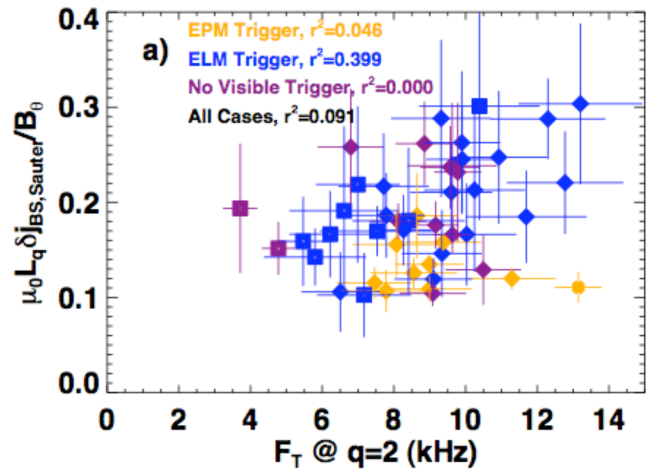
[1] O. Katsuro-Hopkins and J. Bialek, Columbia University

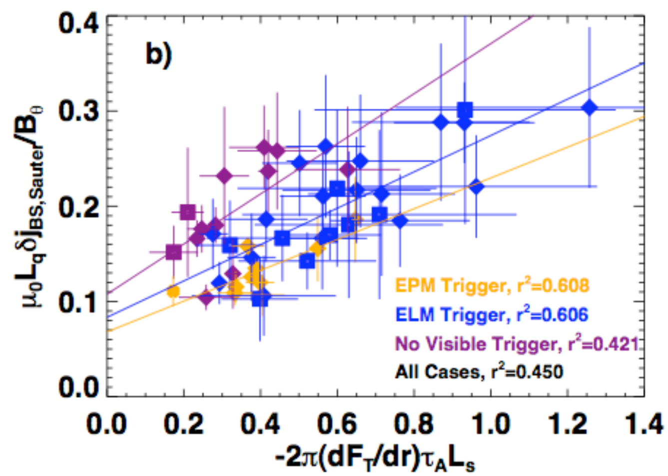
NTM Research Has Focused on Flow Shear and Aspect Ratio Effects

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

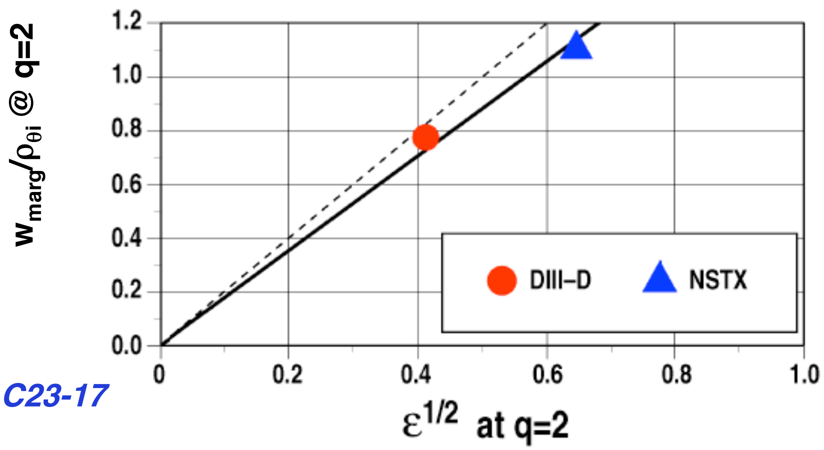
- Neoclassical drive at 2/1 mode onset is a function of normalized rotation-shear, not rotation.[1]
  - Relevant to devices with minimal momentum input.
  - Interpretation: reduced flow shear decreases the classical stability.
- Marginal island width shows a scaling with ion banana width.
  - Suggests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



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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.

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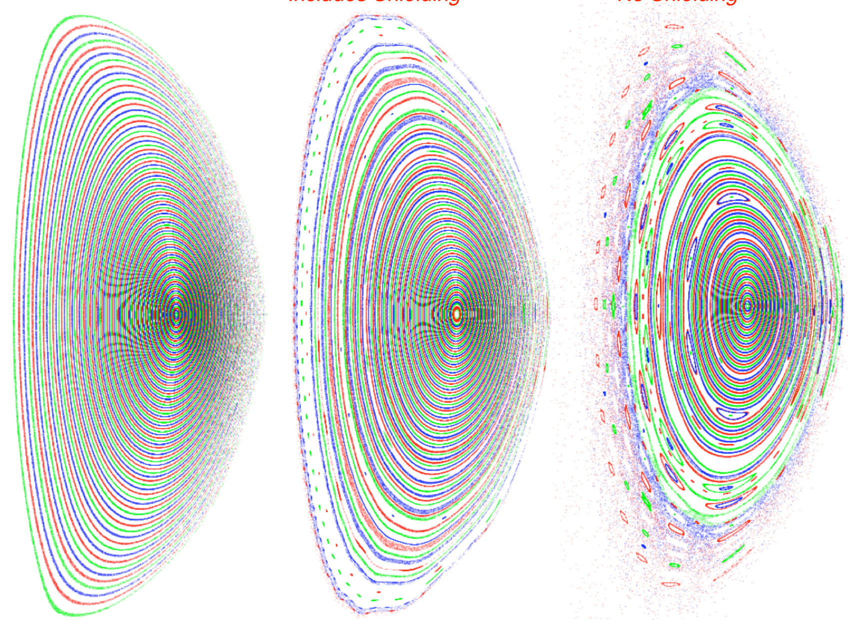
Error Field Program Studies Plasma Response Effects on Error Field Penetration, RMP, and NTV

- 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=Ideal Perturbed Equilibrium Code [1]

129916, t=0.597 2D Equilibrium | 129916, t=0.597 2D Equilibrium+n=3, IPEC *Includes Shielding* | 129916, t=0.597 2D Equilibrium+n=3, Vacuum *No Shielding*



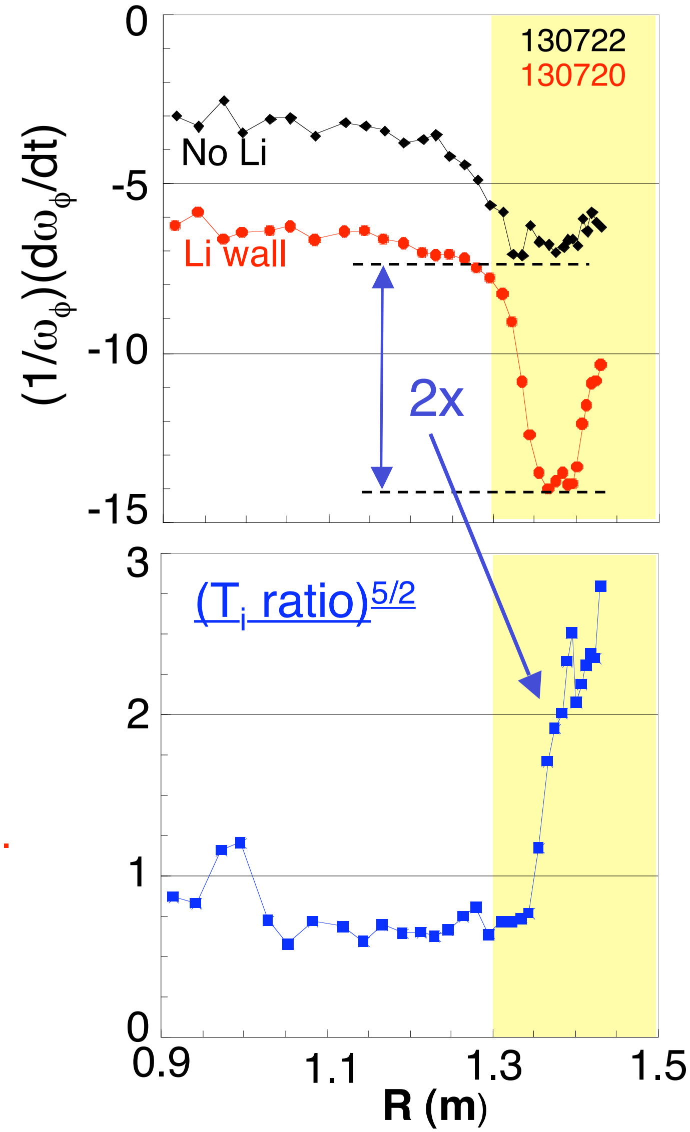
- Plans:
  - 2009: Experiments to study error-field penetration at high-β.
  - 2009-2010: Use IPEC and vacuum calculations to find configurations of RWM coils which can mimic effects of ITER Test Blanket Module (TBM) error fields.
    - Test impact of TBM EF on breakdown, H-mode access, rotation, ELMs,…
  - 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.



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

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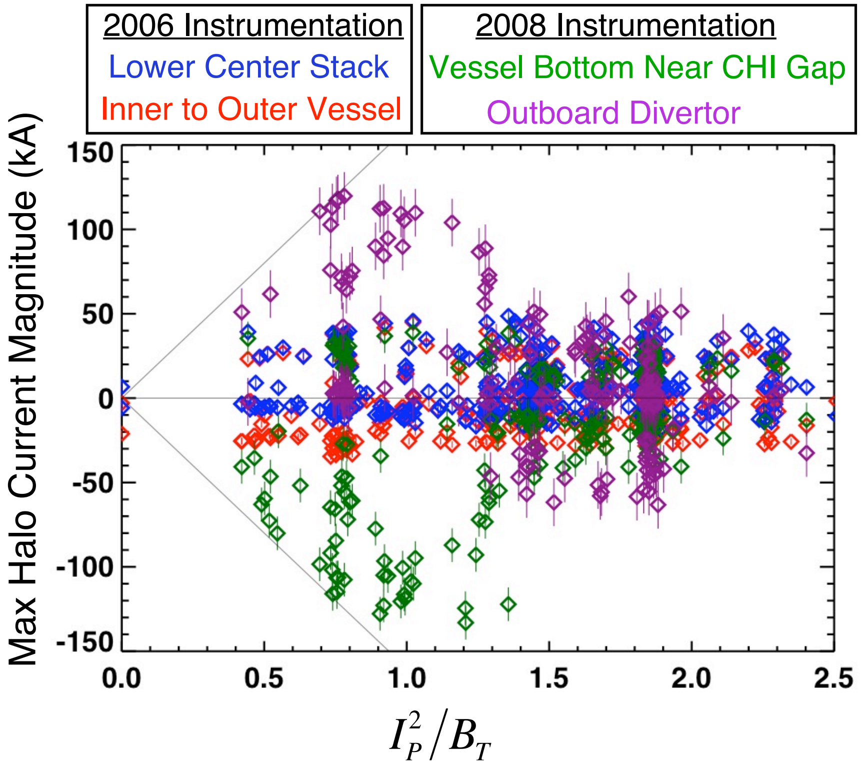
Disruption Plans Focus on Characterization and Prediction of Disruptions

- 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.

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

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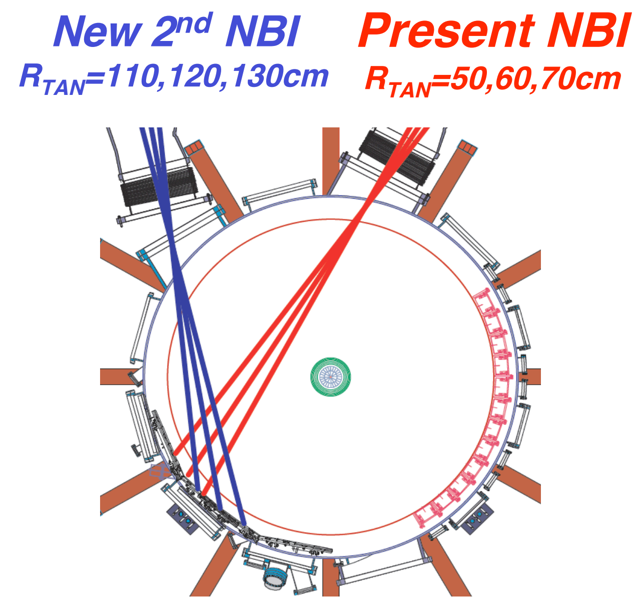
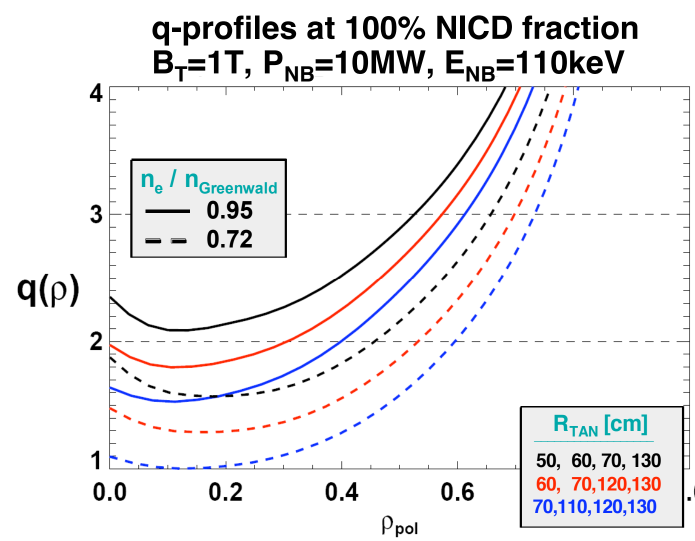
New CS & 2nd NBI Will Dramatically Expand The Range of Stability Studies

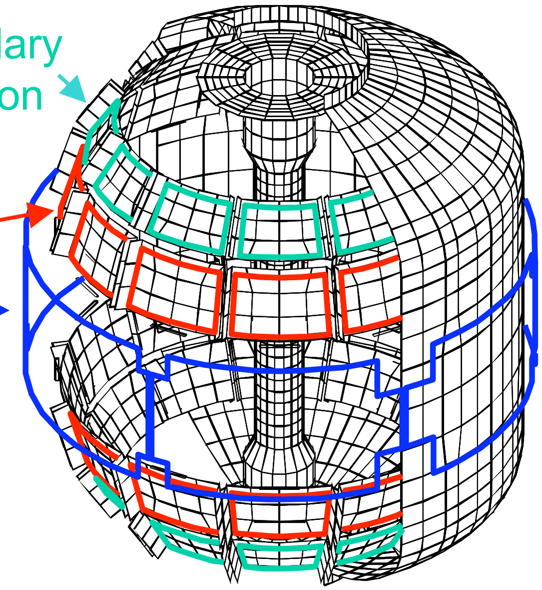
- Resistive Wall Modes & NTV
  - Test of passive RWM stability at significantly reduced ν_i, and with a broader range of rotation profiles.
  - NTV scaling at lower collisionality (ν_i^1, ν_i^0 , ν_i^{-1}?).
  - Determine if rotation-profile control can improve stability for $\beta_N > \beta_N^{no\text{-}wall}$.
  - 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.

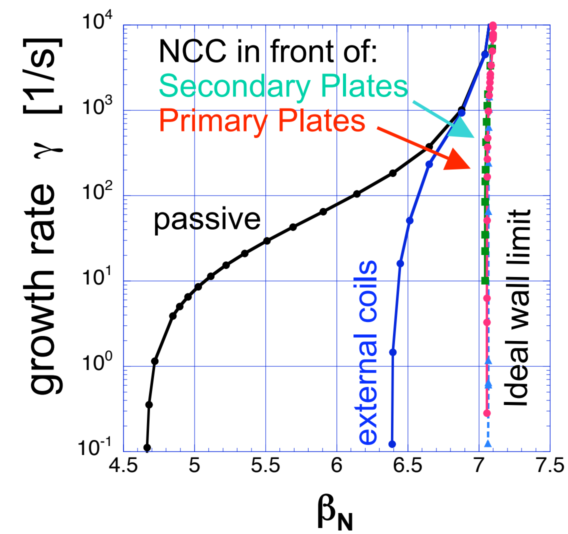




Proposed Nonaxisymmetric Control Coil (NCC) Will Expand Our Knowledge of 3D Effects

- Non-axisymmetric control coil (NCC) – at least <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 ($n \leq 6$).
  - 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