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# Macroscopic Stability Research on NSTX and a ReNeWed Future

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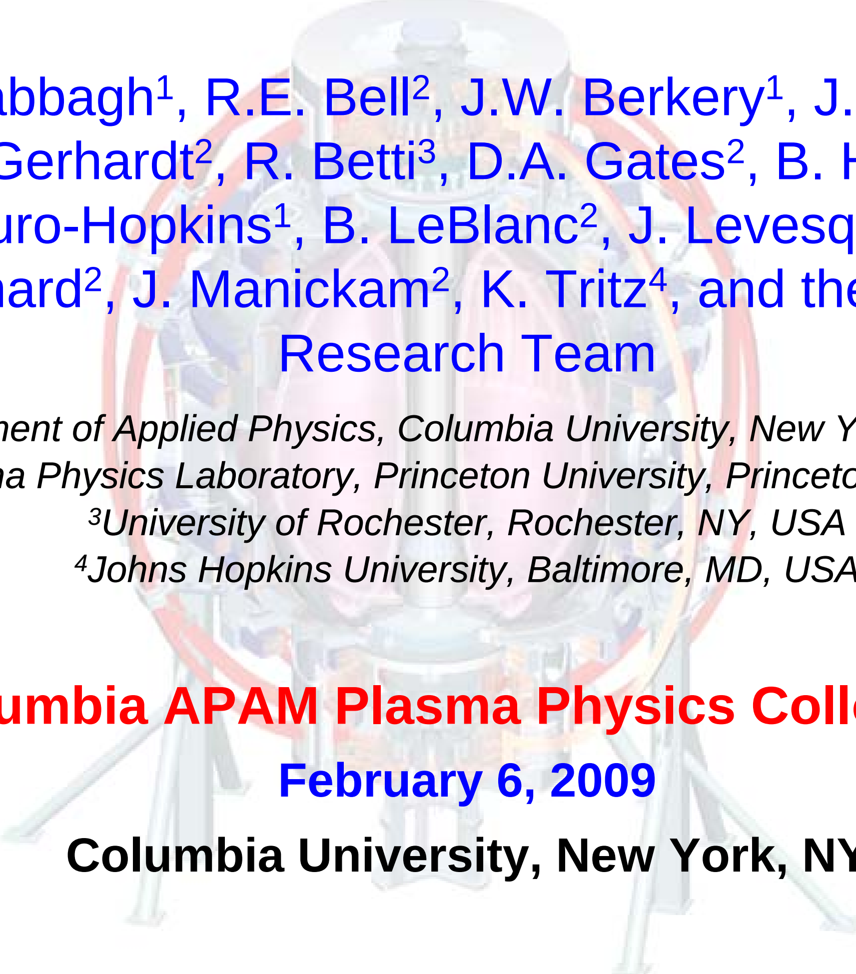

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**Columbia APAM Plasma Physics Colloquium**

**February 6, 2009**

**Columbia University, New York, NY**

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# Key Research Challenge: Develop Stability and Control Understanding to Produce Continuous High Beta Plasmas

- Motivation
  - Future spherical torus (ST) magnetic fusion devices plan to run at high ratios of plasma pressure to magnetic field (beta) and with effectively continuous operation
  - Mega-Ampere level high beta ST plasmas have been reached
  - Attention now turns to stability physics understanding and mode control to maximize steady-state high beta conditions, minimize beta excursions, and largely eliminate disruptions
- Outline
  - Present macroscopic stability research on NSTX
  - Related research / device upgrades planned for next five years
  - Developing longer-term "ITER-era“ research plan through DOE's ReNeW process
    - community input strongly encouraged
    - conduits for your input and collaborative discussion

# Understanding what profiles and control systems are needed for burning plasmas best occurs before such devices are built

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

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

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

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

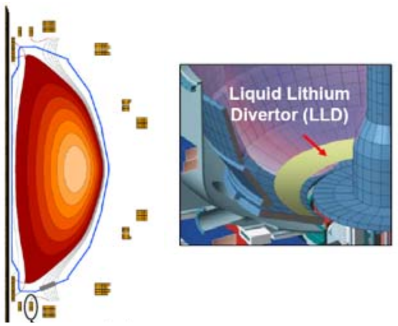
- Stability Goal (in one sentence)
  - Demonstrate reliable maintenance of high $\beta_N$ with sufficient physics understanding to extrapolate to next-step devices
- Knowledge base needed to bridge to these devices; + physics for ITER
  - Demonstration = Control (of modes and plasma profiles):
    -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

}

***All influence $\beta$-limiting modes:***
***Kink/ballooning, RWM, NTM***

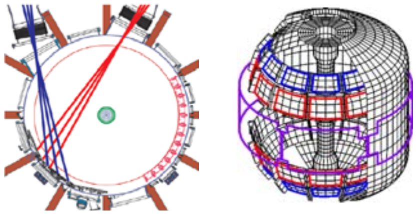
# Development of device hardware empowers fundamental stability understanding for robust extrapolation to next-step STs

- Operate at parameters closer to burning plasma (e.g. order of magnitude lower $\nu_i$ (PTRANSP) )
  - High plasma shaping ($\kappa \sim 3$), 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. $V_\phi$ at reduced $\nu_i$
  - Non-axisymmetric field-induced viscosity
    - Non-resonant and resonant, due to 3-D fields and modes at reduced $\nu_i$



- New center stack ($B_t$ = 1T, $I_p$ = 2 MA)
- Liquid Li divertor

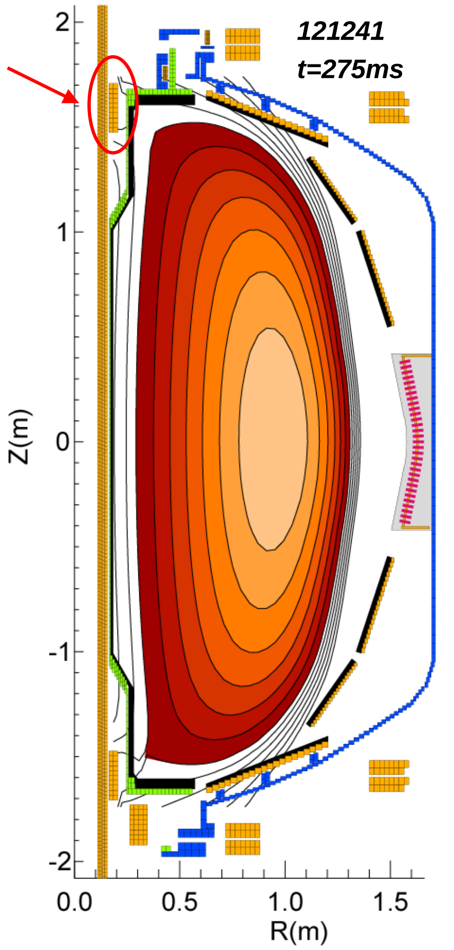
- Control modes and profiles, understand key physics
  - Dynamic error field correction (DEFC)
    - Demonstrate sustained $V_\phi$ with reduced resonant field amplification, under $V_\phi$ profile control
  - Resistive wall mode control
    - Increase reliability of active control, investigate multi-mode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



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

# Plasma equilibrium goal to access and maintain stable high $\beta_N$ at high shaping

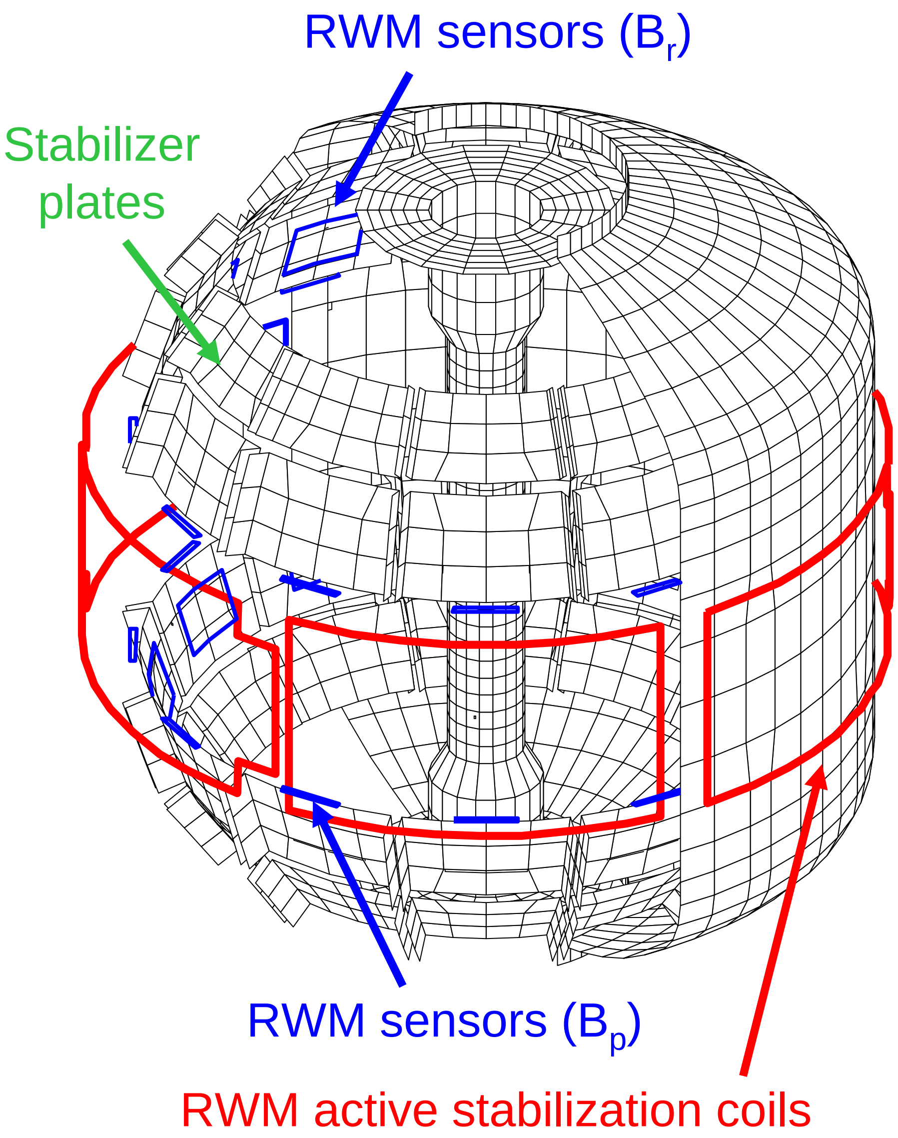
- **Progress**
  - Central coil PF1A modified (2005) to allow high shaping
  - Sustained $\kappa < 2.7$, $\delta < 0.8$; transient $\kappa = 3$ with record shaping factor, $S_l \equiv q_{95}(I_p/aB_t) = 41$
    - Note: Present CTF design has $\kappa = 3.07$, lower $S_l$
  - Highest $\kappa$ and $S_l$ plasmas reached $\beta_N \sim 6$ in 2008
- **Plan summary 2009-2011**
  - Assess/utilize $\beta$ feedback control using real-time EFIT and NBI power to avoid fast kink/ballooning disruptions
  - Conduct experiments/analysis to maintain 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 $\beta$ feedback using stability models; $q$ profile control with 2nd NBI (incremental)
  - Study ST-CTF target shapes (increased A) at low $\nu_i$ with favorable profiles, determine sensitivity to variations in $l_i$, $\delta$



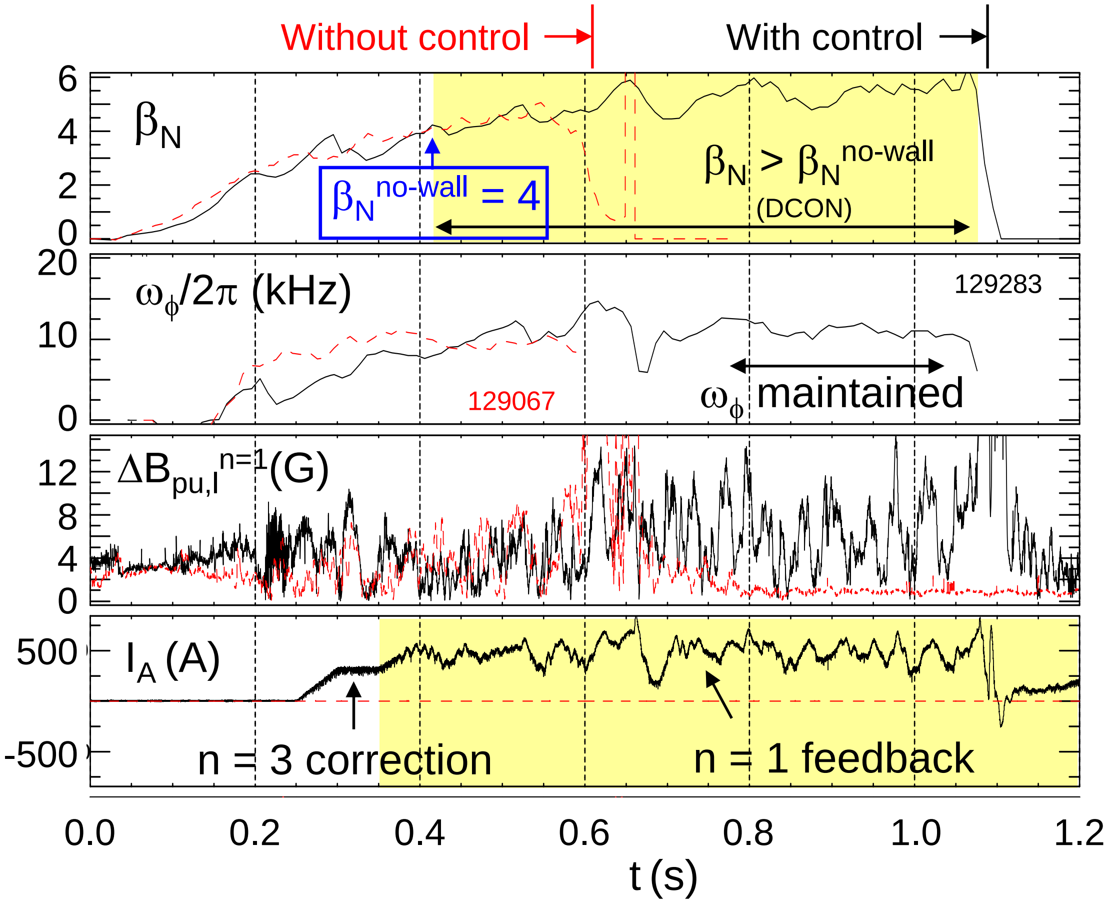
D.A. Gates, et al., *Nucl. Fusion* **47**, 1376 (2007).

# NSTX equipped for passive and active RWM control

- Stabilizer plates for kink mode stabilization
- External midplane control coils closely coupled to vacuum vessel
- Varied sensor combinations used for feedback
  - 24 upper/lower $B_p$: ($B_{pu}$, $B_{pl}$)
  - 24 upper/lower $B_r$: ($B_{ru}$, $B_{rl}$)



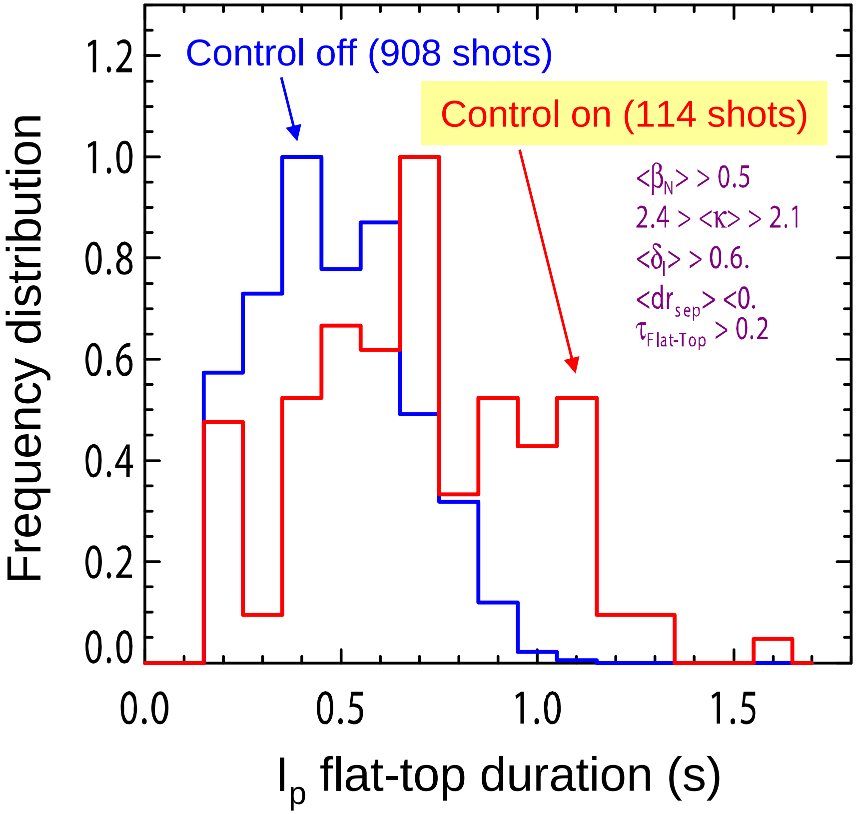
# Active RWM control and error field correction maintain high $\beta_N$ plasma

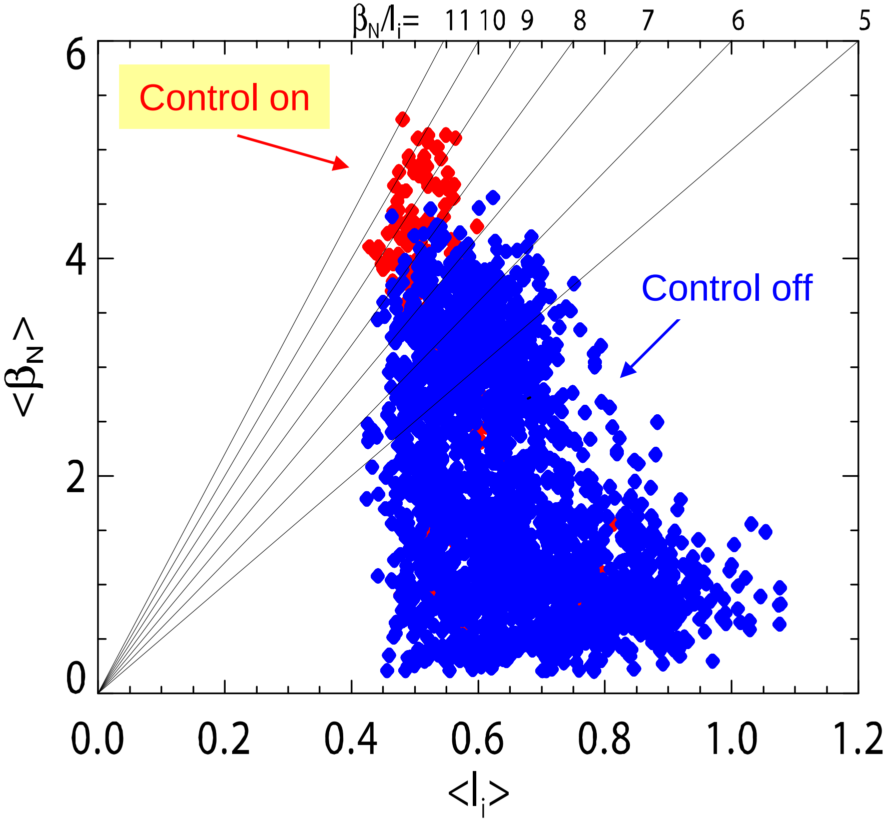


- n = 1 active, n = 3 DC control
  - n = 1 response ~ 1 ms < $1/\gamma_{RWM}$
  - $\beta_N/\beta_N^{no\text{-}wall}$ = 1.5 reached
  - best maintains $\omega_\phi$
- NSTX record pulse lengths
  - limited by magnet systems
  - n > 0 control first used as standard tool in 2008
- Without control, plasma more susceptible to RWM growth, even at high $\omega_\phi$
  - Disruption at $\omega_\phi/2\pi$ ~ 8kHz near q = 2
  - More than a factor of 2 higher than marginal $\omega_\phi$ with n = 3 magnetic braking

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

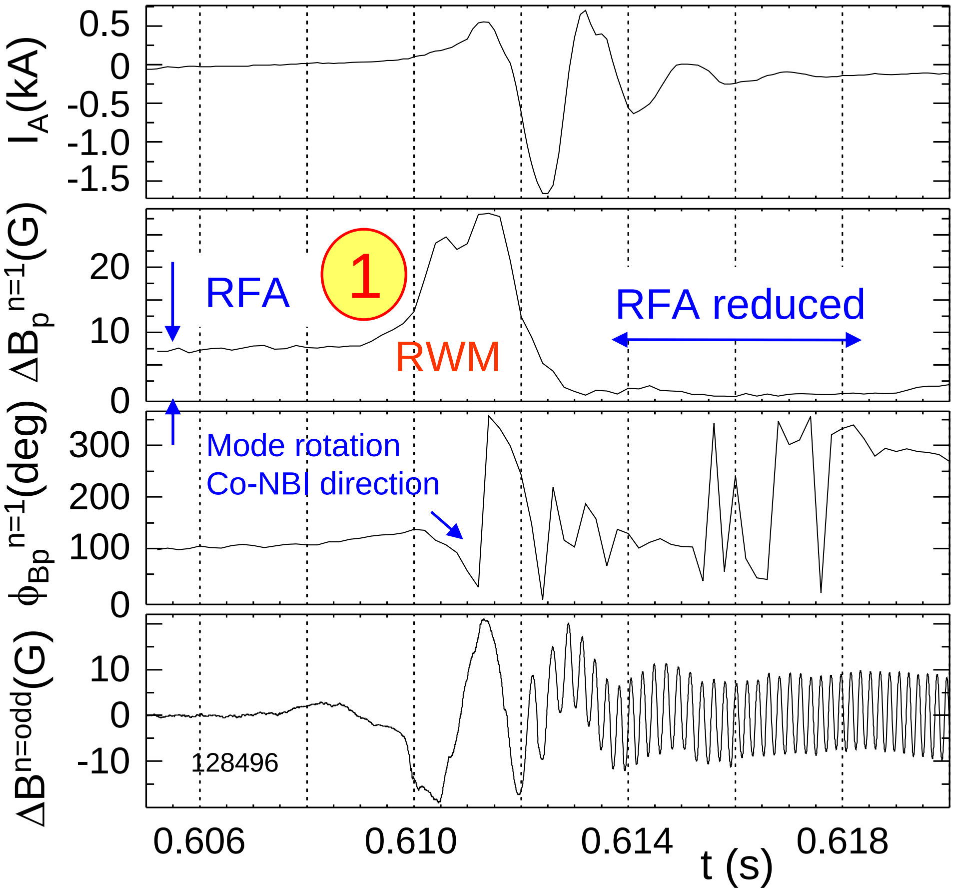
# Probability of long pulse and $\langle\beta_N\rangle_{pulse}$ increases significantly with active RWM control and error field correction





- ❑ Standard H-mode operation shown
  - ❑ $I_p$ flat-top duration > 0.2s (> 60 RWM growth times)
- ❑ Control allows $\langle\beta_N\rangle_{pulse} > 4$
  - ❑ $\beta_N$ averaged over $I_p$ flat-top

# During n=1 feedback control, unstable RWM evolves into rotating global kink



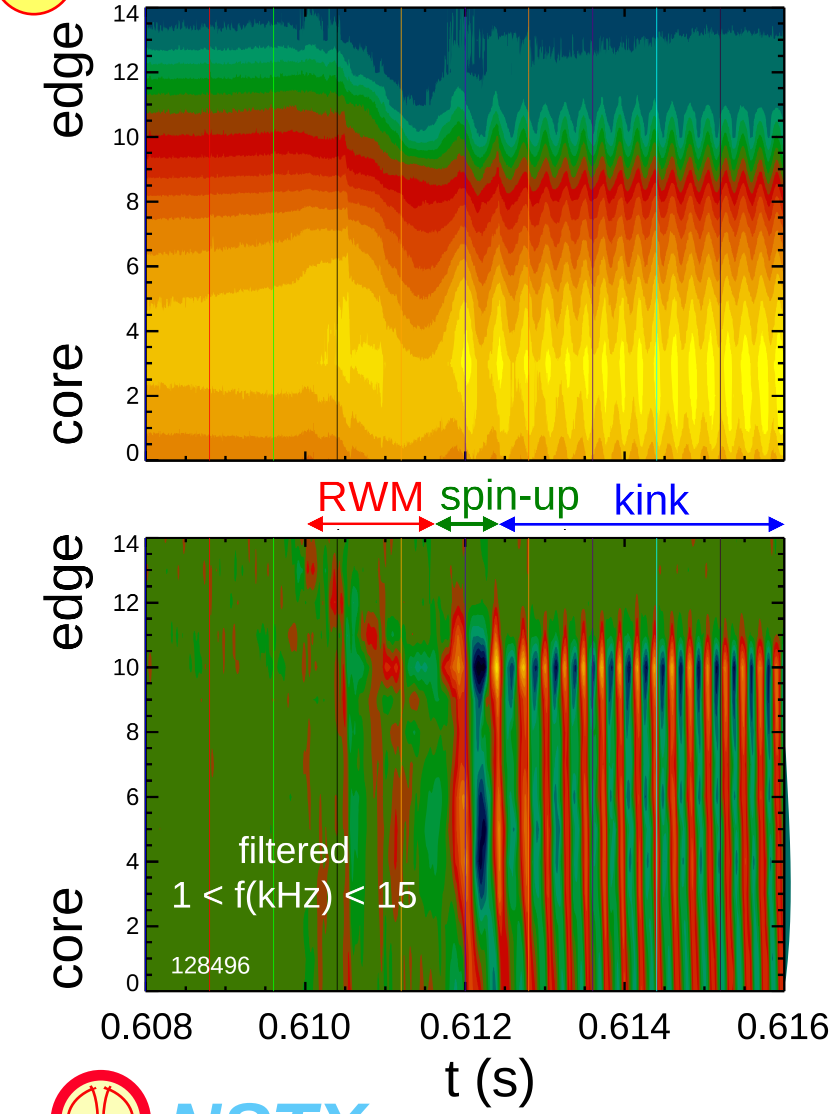
① RWM grows and begins to rotate

- With control off, plasma disrupts at this point
- With control on, mode converts to global kink, RWM amplitude dies away
- Resonant field amplification (RFA) reduced

- Conversion from RWM to rotating kink occurs on $\tau_w$ timescale
- Kink either damps away, or saturates
    - Tearing mode can appear during saturated kink

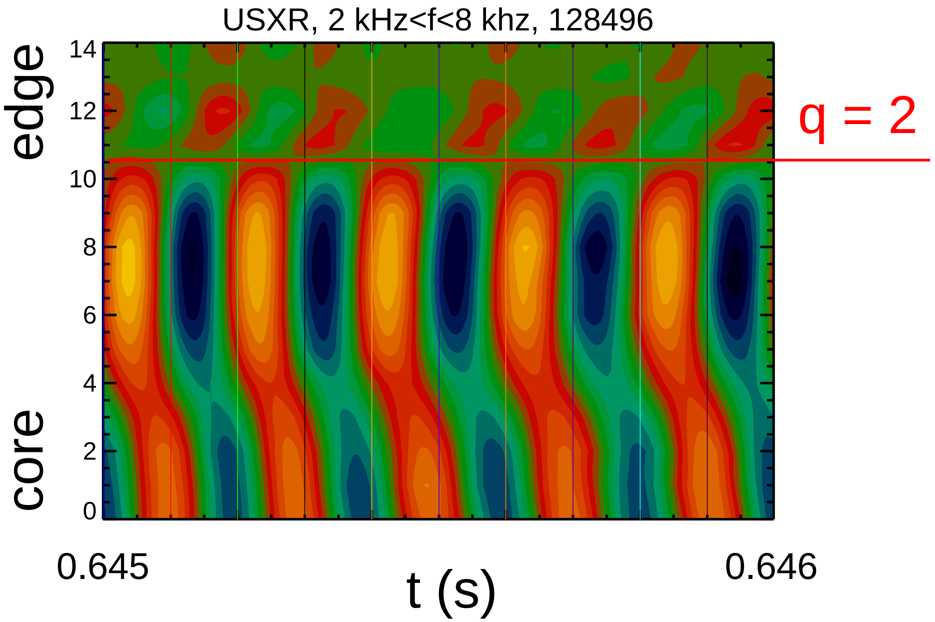
# Soft X-ray emission shows transition from RWM to global kink

## ① Transition from RWM to kink



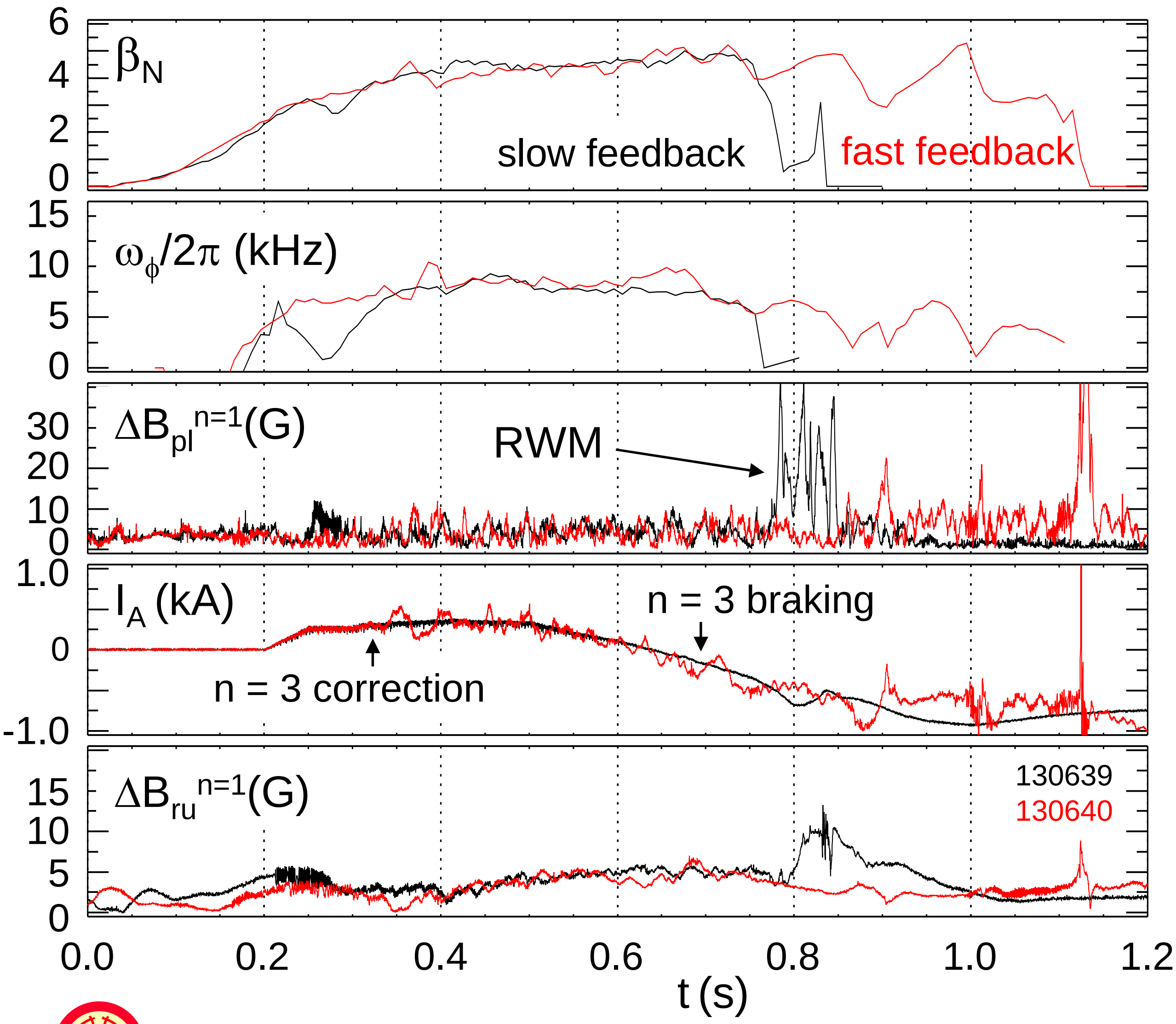
## ② Tearing mode appears during kink

RWM onset time + 35 ms



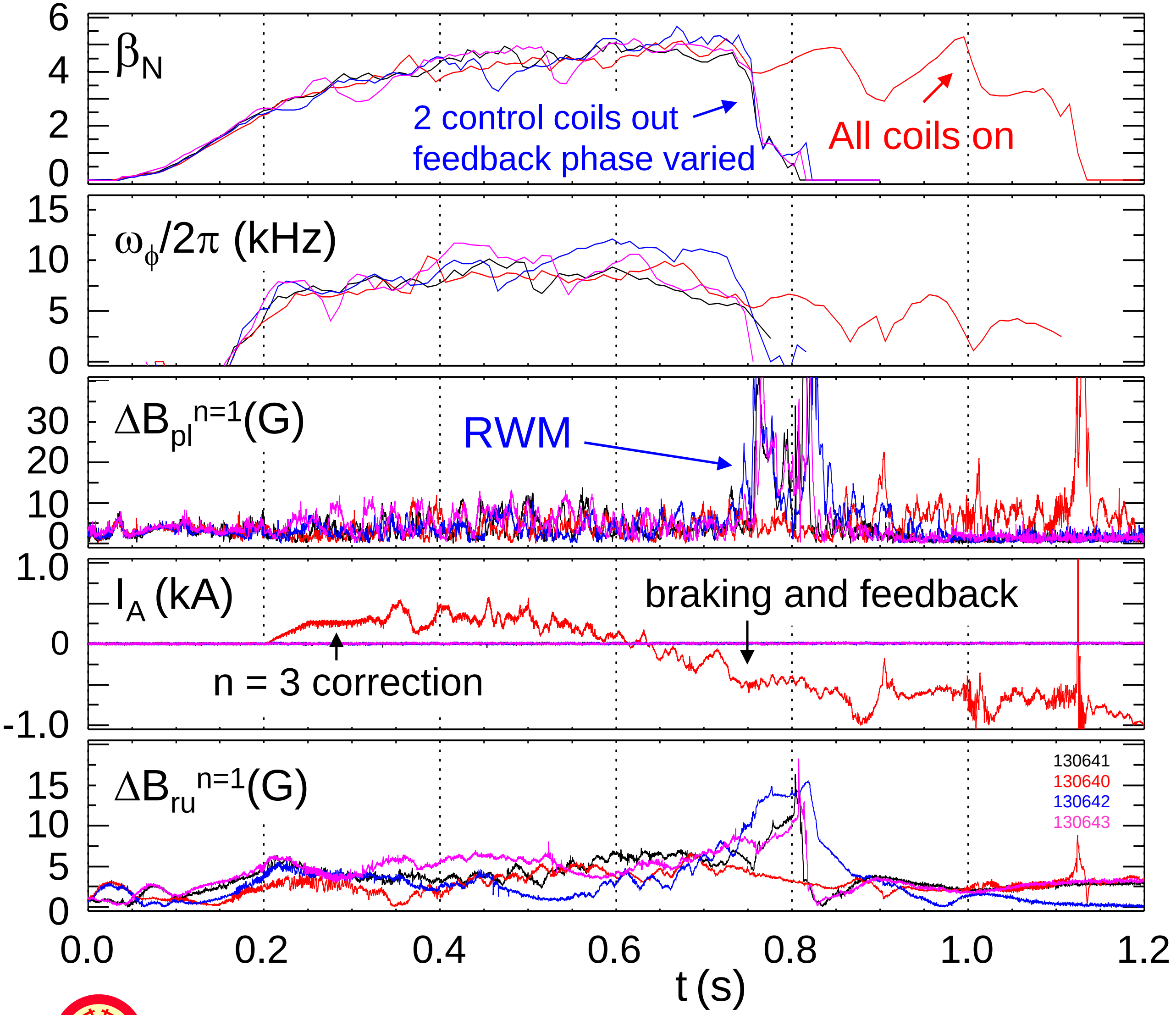
- Initial transition from RWM to saturated kink
- Tearing mode appears after 10 RWM growth times and stabilizes

# Low $\omega_\phi$, high $\beta_N$ plasma not accessed when feedback response sufficiently slowed



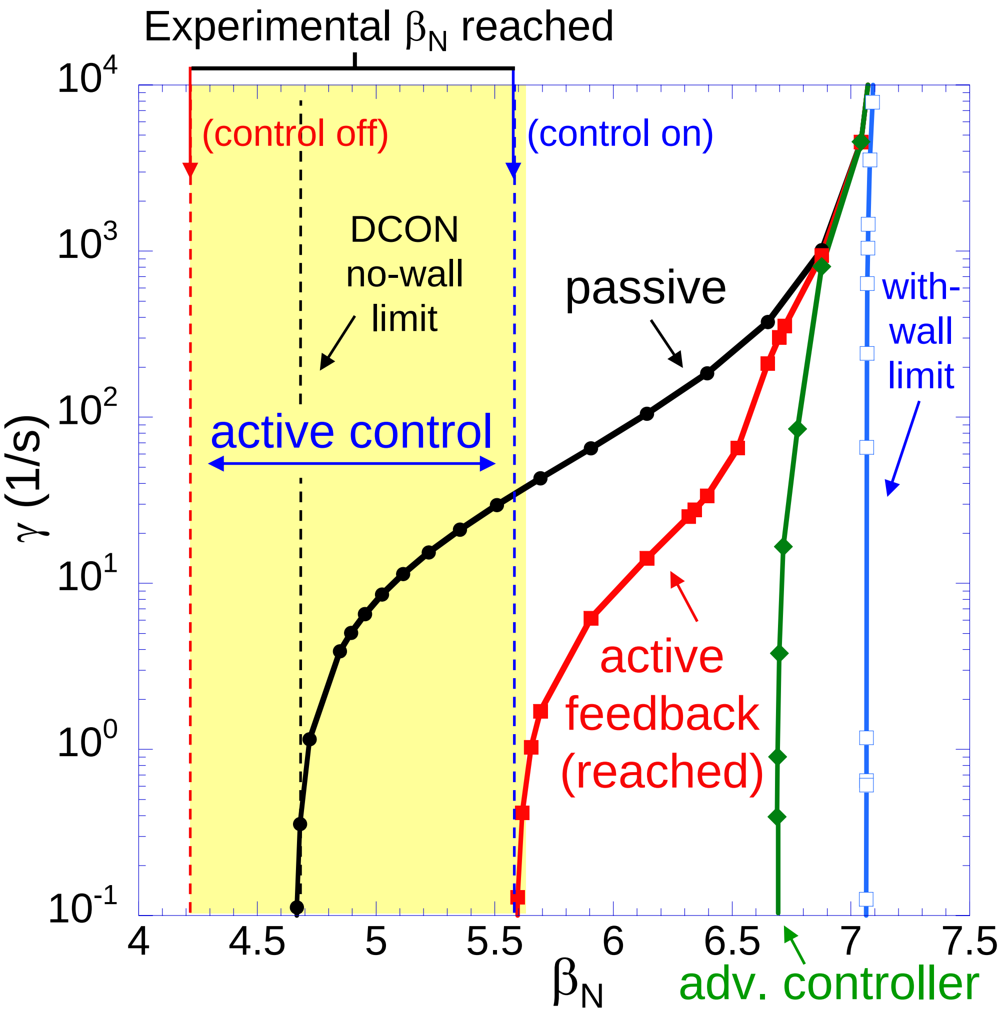
- Low $\omega_\phi$ access for ITER study
  - use n = 3 braking
- n = 1 feedback response speed significant
  - "fast" (unfiltered) n = 1 feedback allows access to low $V_\phi$, high $\beta_N$
  - "slow" n = 1 "error field correction" (75ms smoothing of control coil current) suffers RWM at $\omega_\phi \sim$ 5kHz near q = 2

# Low $\omega_\phi$, high $\beta_N$ plasma not accessed when two feedback control coils are disabled

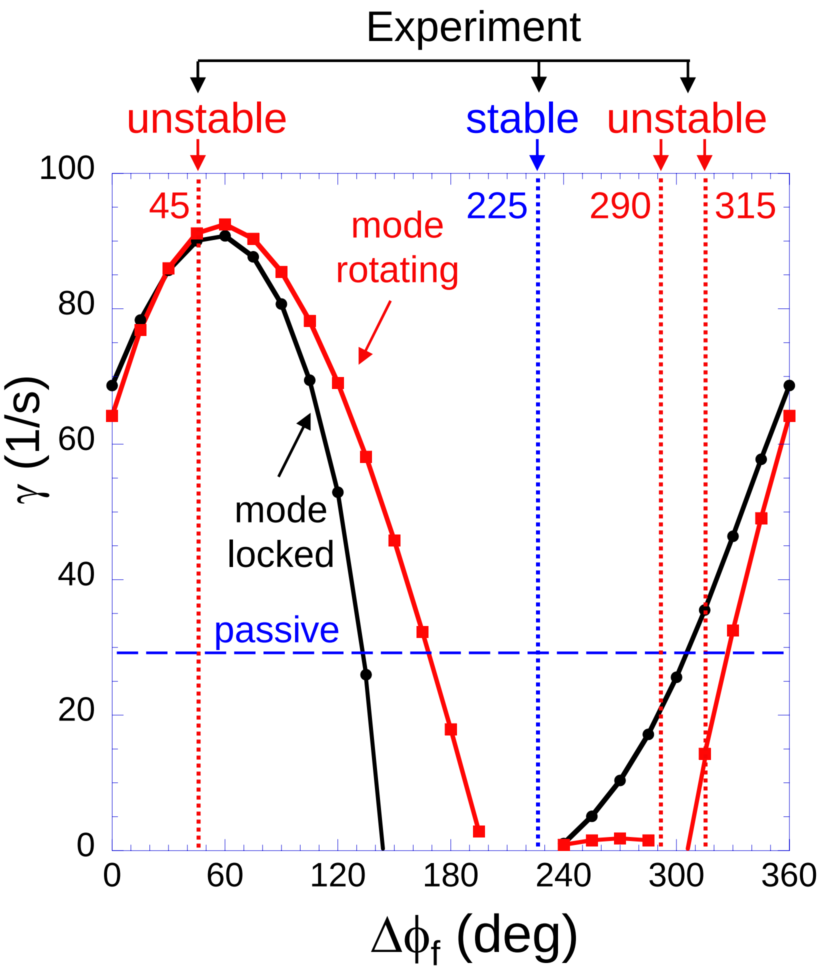


- Low $\omega_\phi$ access for ITER study
  - use n = 3 braking
- n = 1 feedback doesn't stabilize plasma with 2 of 6 control coils disabled
  - scenario to simulate failed coil set in ITER
  - Feedback phase varied, but no settings worked
  - RWM onset at identical time, plasma rotation

# Experimental RWM control performance consistent with theory



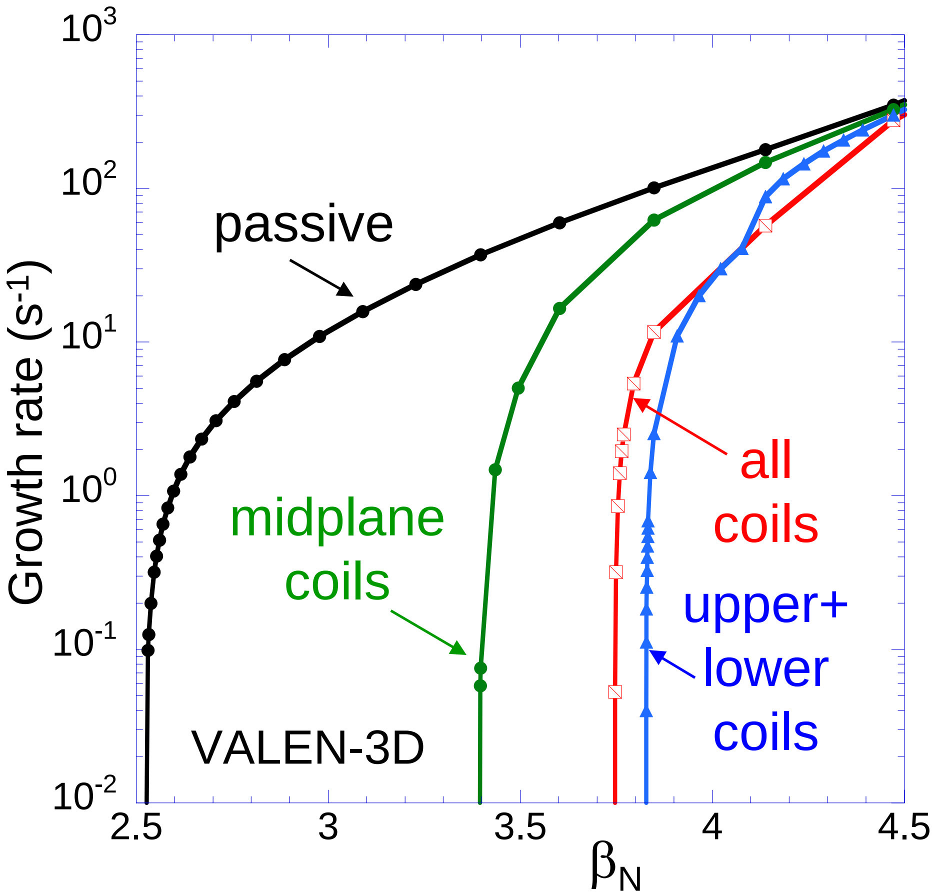
- VALEN code with realistic sensor geometry, plasmas with reduced $V_\phi$



- Feedback phase scan shows superior settings

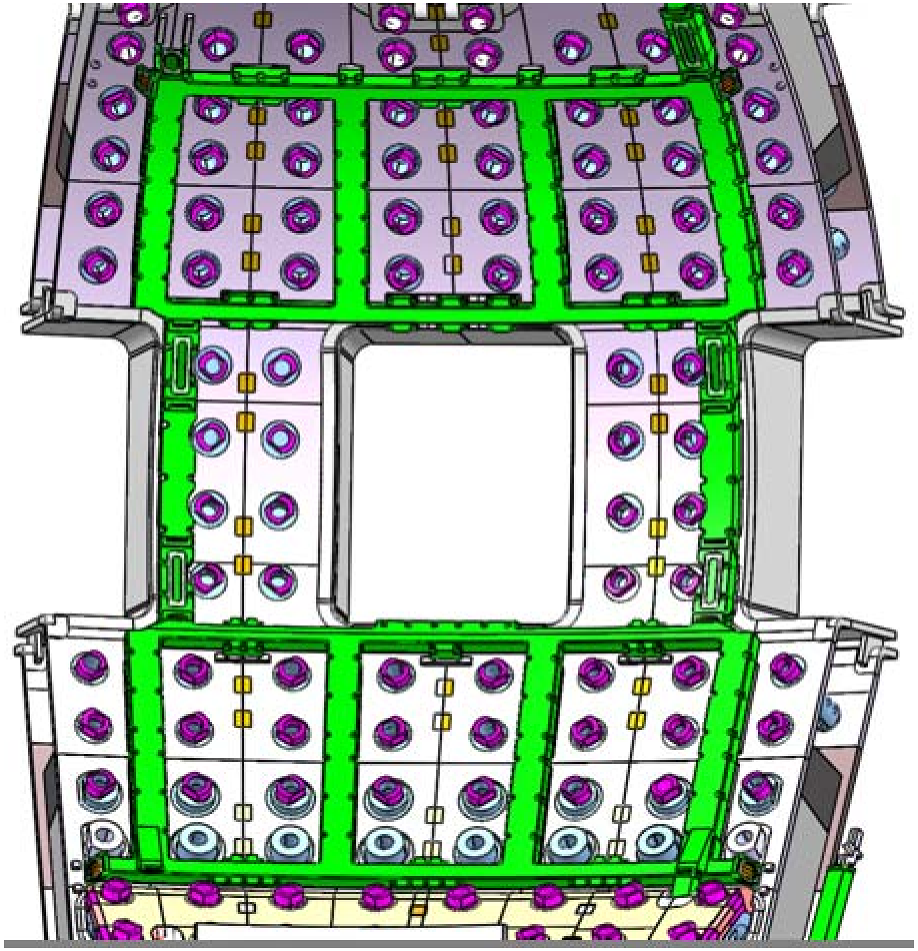
# Significant $\beta_N$ increase expected by internal coil proposed for ITER

## ITER VAC02 stabilization performance



- ❑ 50% increase in $\beta_N$ over RWM passive stability

## ITER VAC02 design (40° sector)



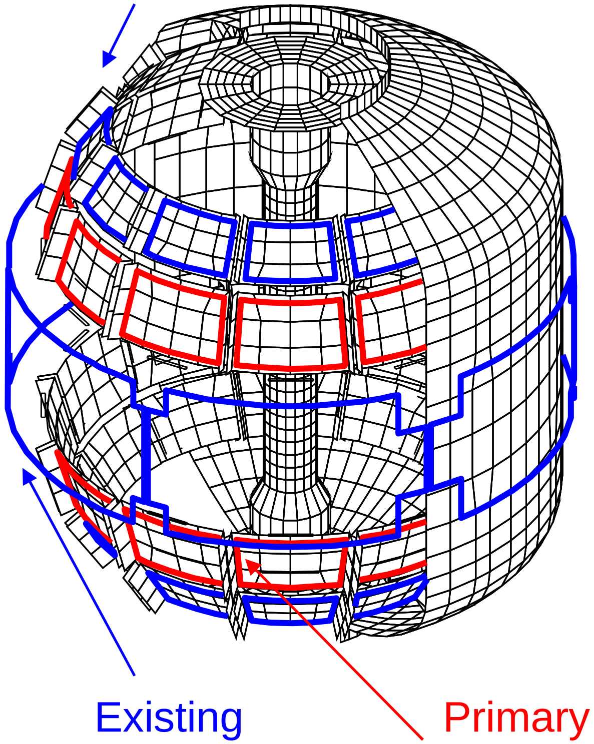
3 toroidal arrays, 9 coils each

# 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 $\beta_N$)
    - DEFC with greater field correction capability
    - ELM control ($n$ = 6)
    - $n$ > 1 propagation, increased $V_\phi$ 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)

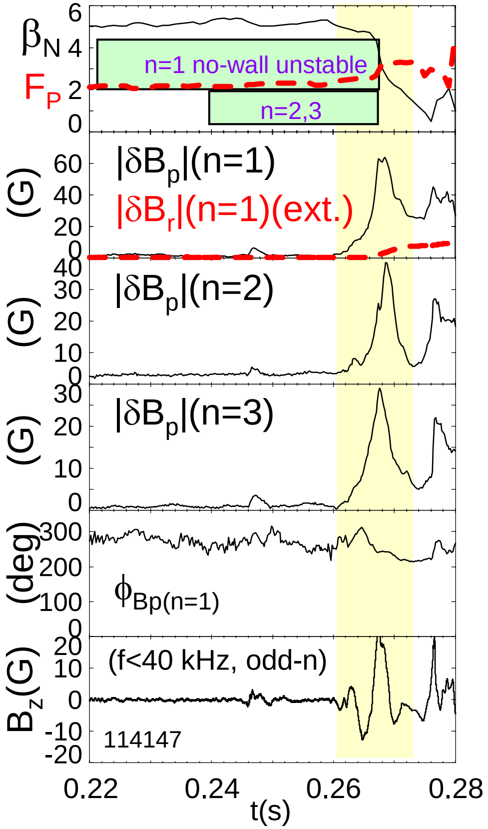
Secondary PP option



Existing coils

Primary PP option

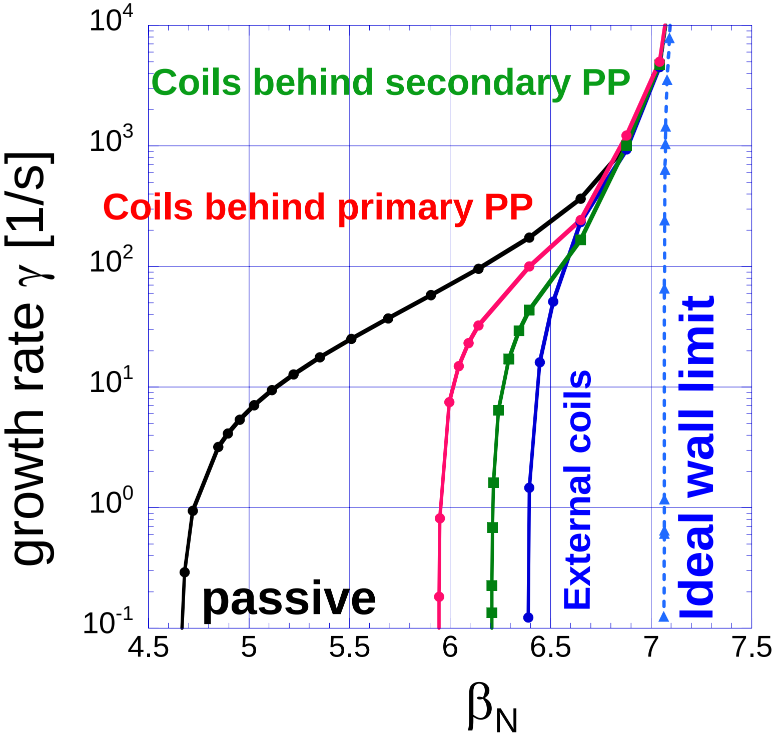
RWM with $n$ > 1 RWM observed



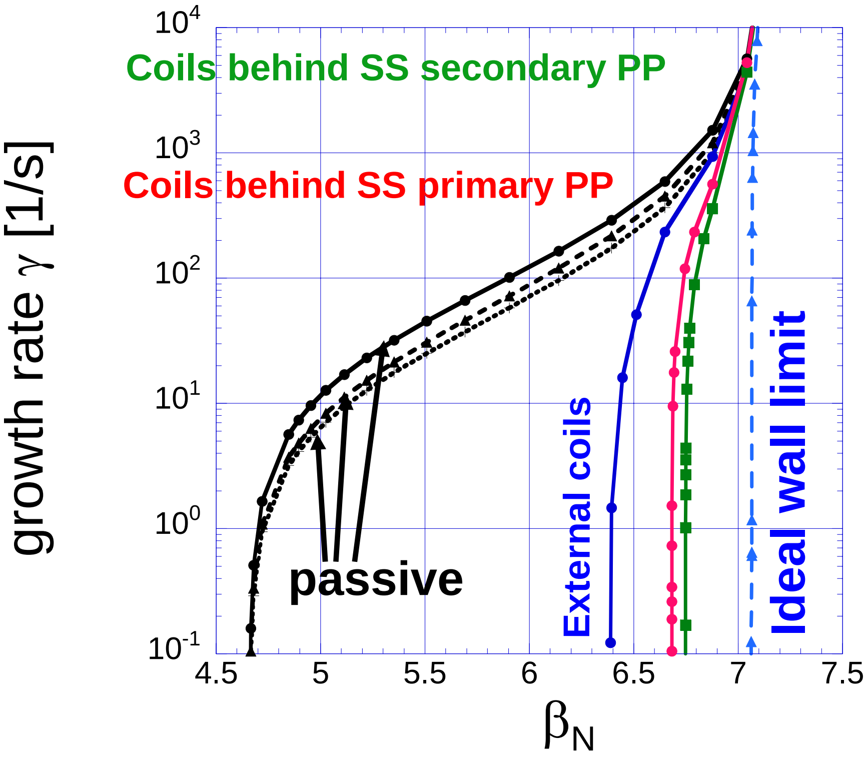
(Sabbagh, et al., Nucl. Fusion **46**, 635 (2006). )

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

**Copper Plates**



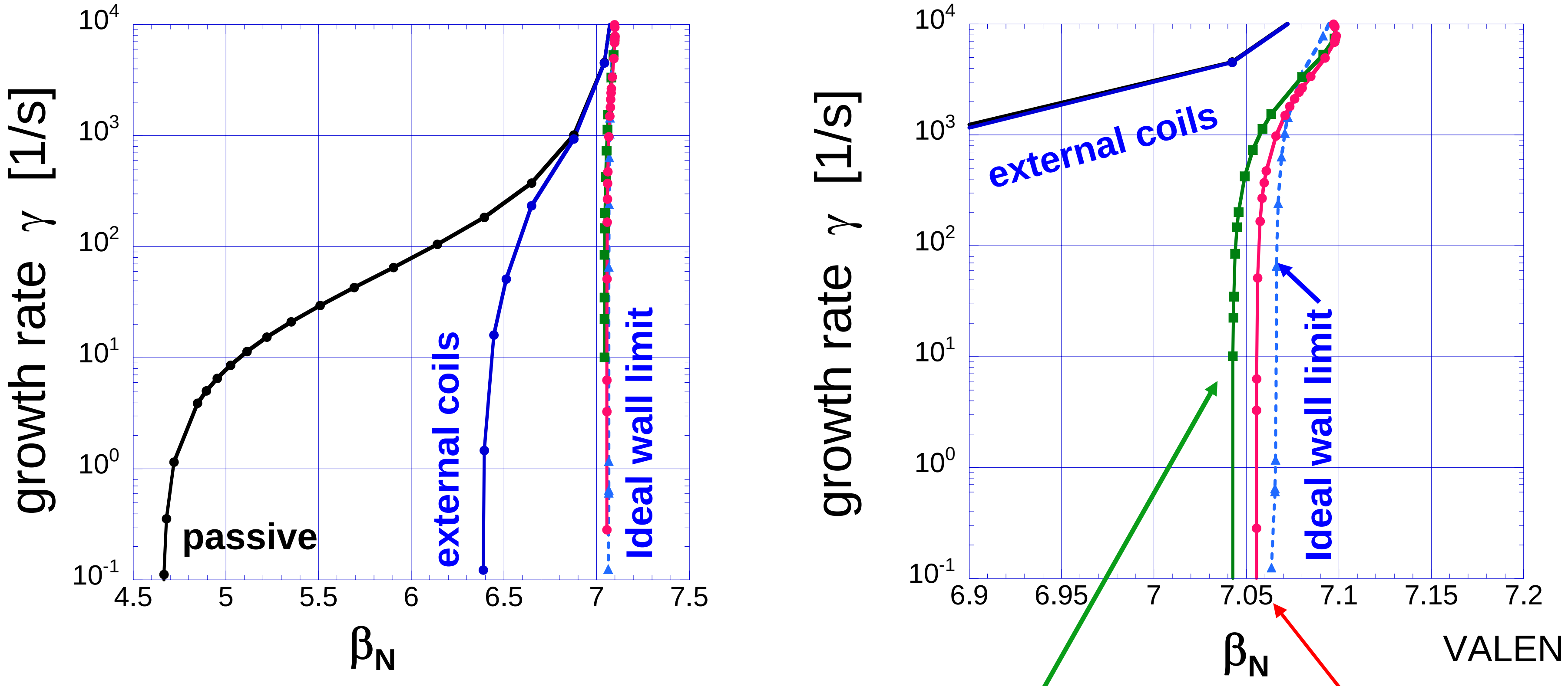
**Stainless Steel Plates**



- 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)

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



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)

# Modification of Ideal Stability by Kinetic theory (MISK code) investigated to explain experimental RWM stabilization

- Simple critical $\omega_\phi$ threshold stability models or loss of torque balance do not describe experimental marginal stability Sontag, et al., Nucl. Fusion **47** (2007) 1005.
- Kinetic modification to ideal MHD growth rate
  - Trapped and circulating ions, trapped electrons
  - Alfven dissipation at rational surfaces

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

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

- Stability depends on
  - Integrated $\omega_\phi$ profile: resonances in $\delta W_K$ (e.g. ion precession drift)
  - Particle collisionality

$\omega_\phi$ profile (enters through ExB frequency)

Trapped ion component of $\delta W_K$ (plasma integral)

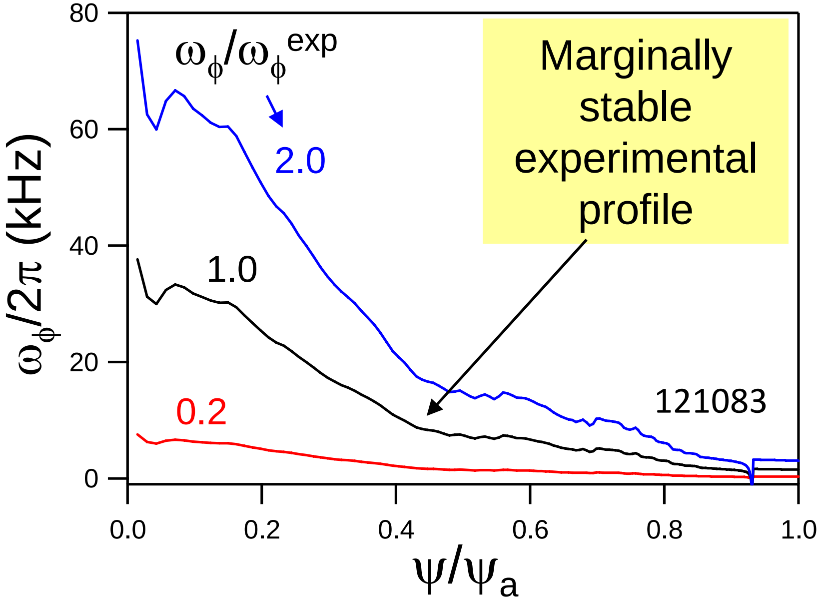
$$\delta W_K \propto \int \left[ \frac{\omega_{*N} + \left(\hat{\varepsilon} - \frac{3}{2}\right)\omega_{*T} + \omega_E - \omega - i\gamma}{\langle\omega_D\rangle + l\omega_b - i\nu_{eff} + \omega_E - \omega - i\gamma} \right] \hat{\varepsilon}^{\frac{5}{2}} e^{-\hat{\varepsilon}} d\hat{\varepsilon}$$

← Energy integral

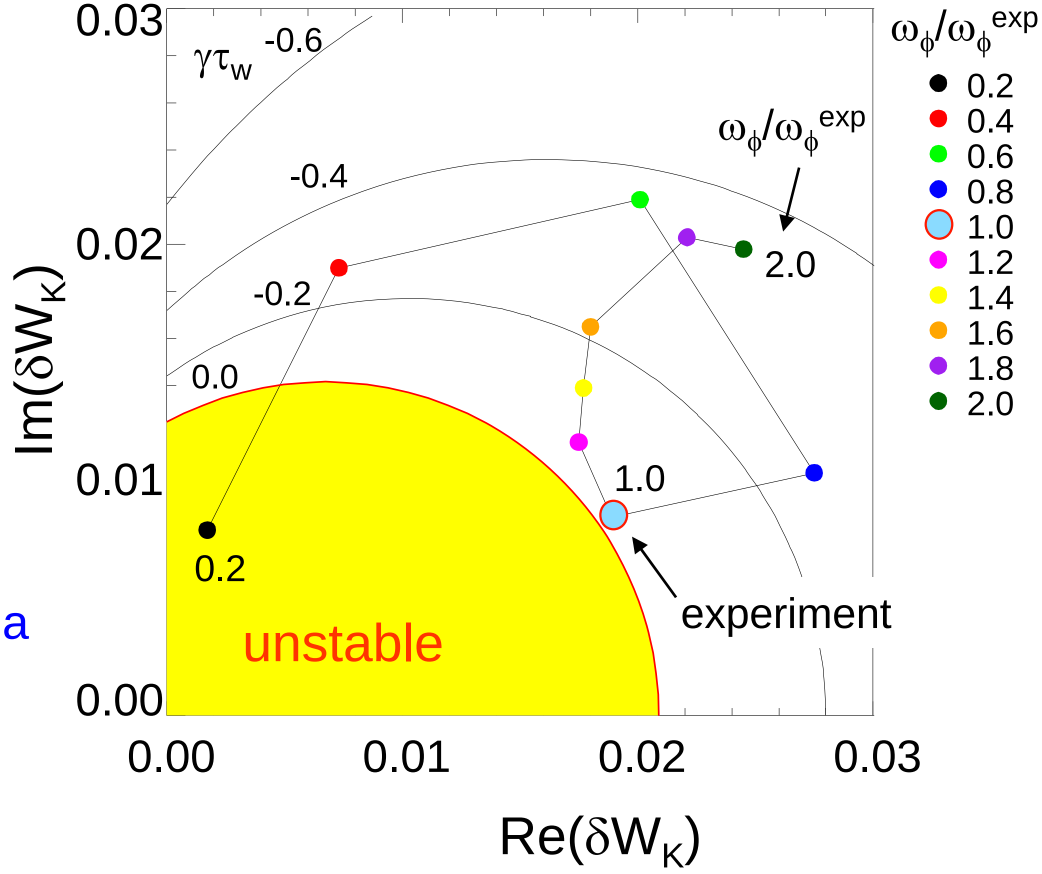
precession drift bounce collisionality

# Kinetic modifications show decrease in RWM stability at relatively high $V_\phi$ – consistent with experiment

## Theoretical variation of $\omega_\phi$



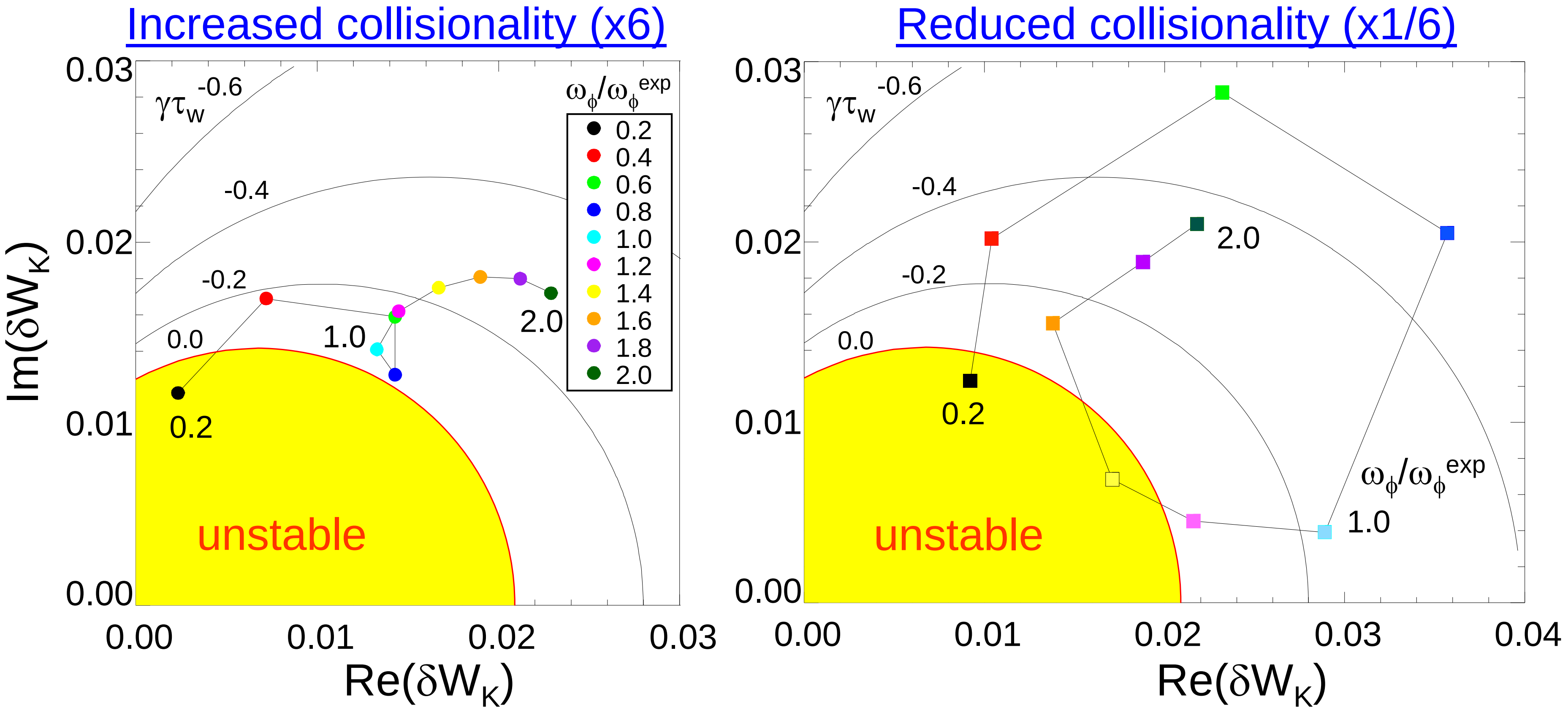
## RWM stability vs. $V_\phi$ (contours of $\gamma\tau_w$)



- Marginal stable experimental plasma reconstruction, rotation profile $\omega_\phi^{exp}$
- Variation of $\omega_\phi$ away from marginal profile increases stability
- Unstable region at low $\omega_\phi$

NSTX

# Kinetic model shows overall increase in stability as collisionality decreases



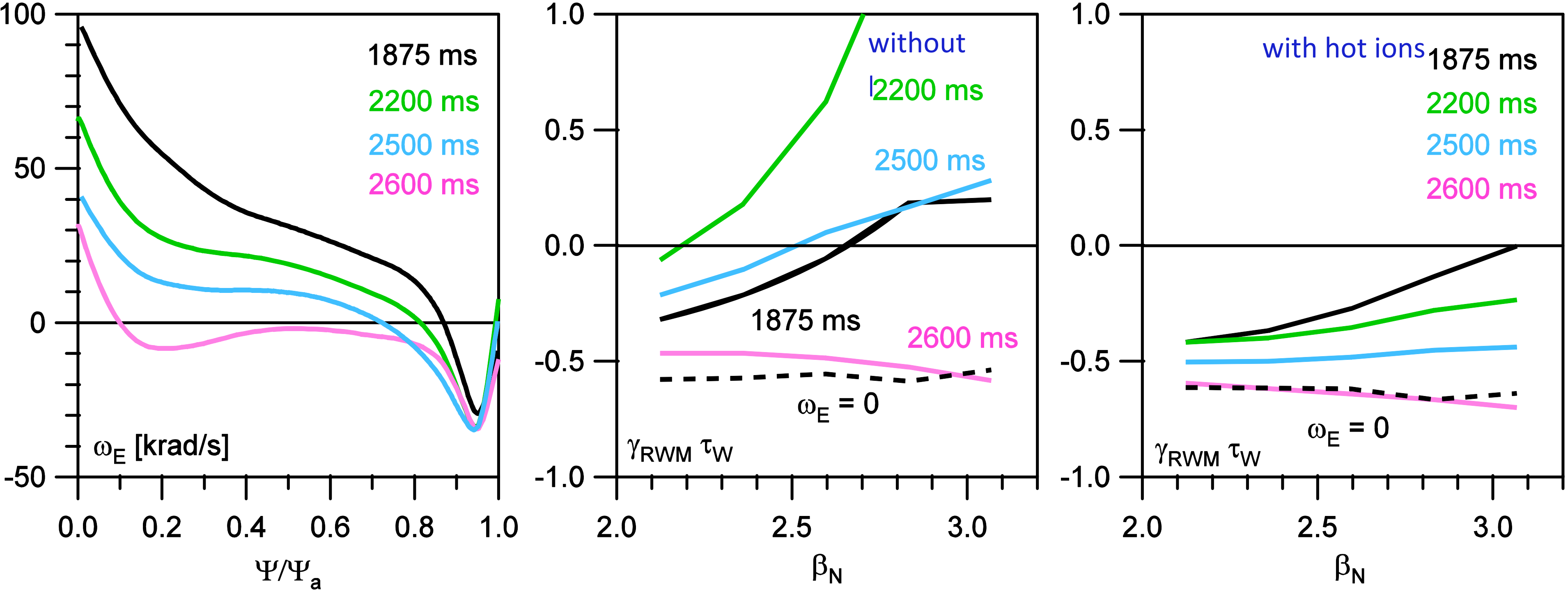
Increased collisionality (x6)

Reduced collisionality (x1/6)

- ❑ Vary $\nu$ by varying T, n at constant $\beta$
- ❑ Simpler stability dependence on $\omega_\phi$ at increased $\nu$
- ❑ Increased stability at $\omega_\phi/\omega_\phi^{exp} \sim 1$
- ❑ Unstable band in $\omega_\phi$ at increased $\omega_\phi$

NSTX

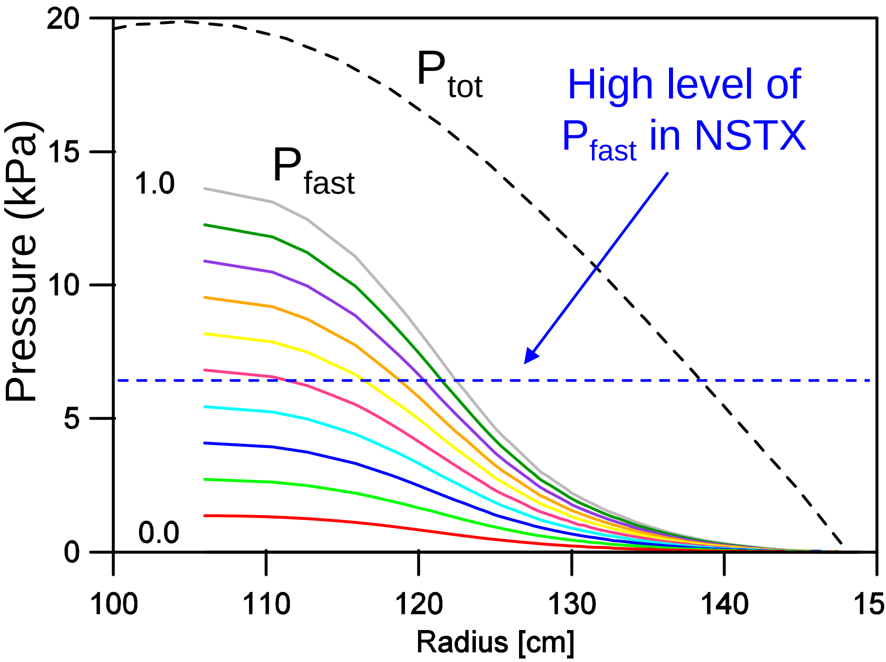
# Hot ions have a strongly stabilizing effect on DIII-D

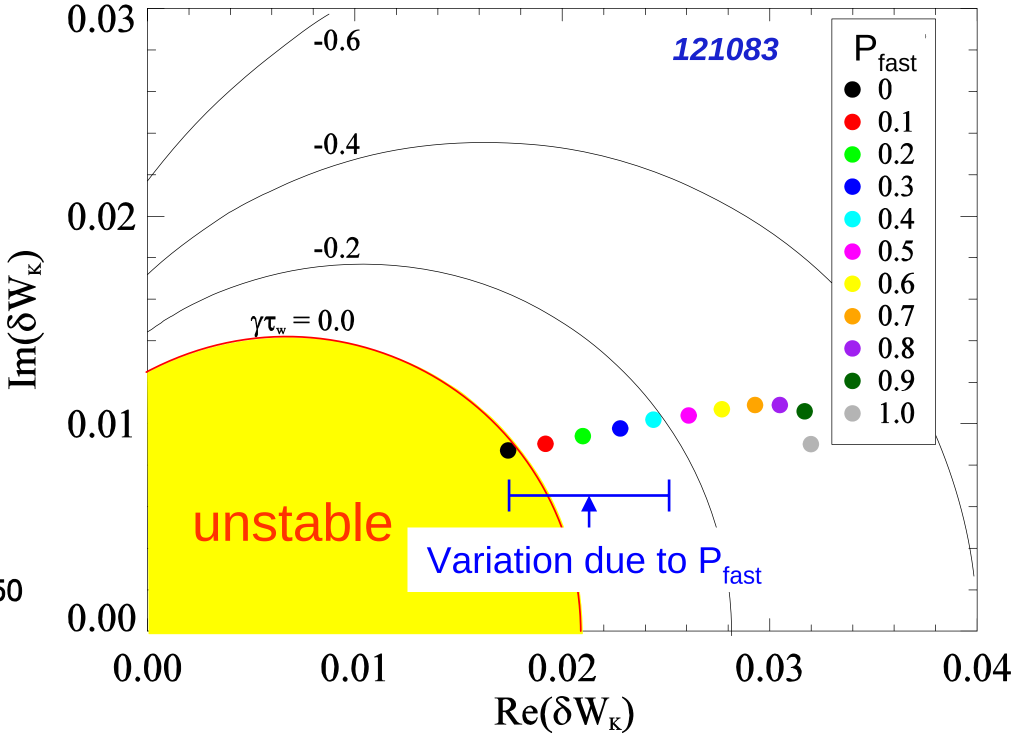


- MISK show band of instability at moderate rotation without hot ions, but complete stability with hot ions: $\Delta(\gamma\tau_w) \sim 1.0$
  - DIII-D shot 125701 @ 2500ms and rotation from 1875-2600ms
- This may explain why DIII-D is inherently more stable to the RWM than NSTX
  - energetic particle modes might “trigger” RWM by fast particle loss (JT-60U IAEA 08)

*(J.W. Berkery, Mode Control Mtg. 2008)*

# NSTX RWM stability with hot ions under evaluation

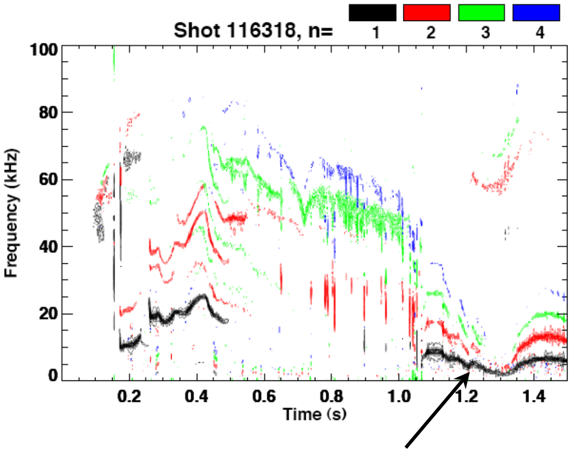


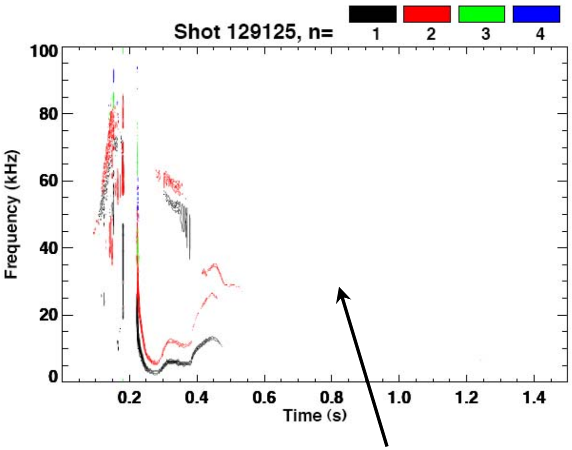


- Direct effect on calculated growth rate using test profiles (based on TRANSP analysis) for hot ion pressure: $\Delta(\gamma\tau_w) \sim 0.2$
  - Stability using TRANSP runs of RWM marginally stable plasmas now underway
- TRANSP hot ion population smaller at edge in NSTX vs. DIII-D – may explain why RWM apparently less stable in NSTX

# Lithium wall conditioning, n=1 RWM control, n=3 error correction also shown to control (eliminate) tearing modes

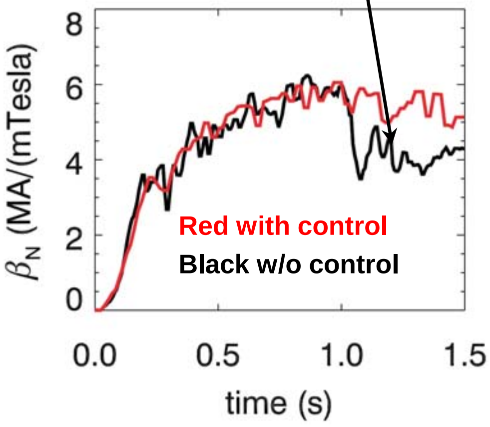
- ***MHD spectrogram w/o n=1 feedback and n=3 correction***
- ***MHD spectrogram with lithium, n=1 feedback and n=3 correction***



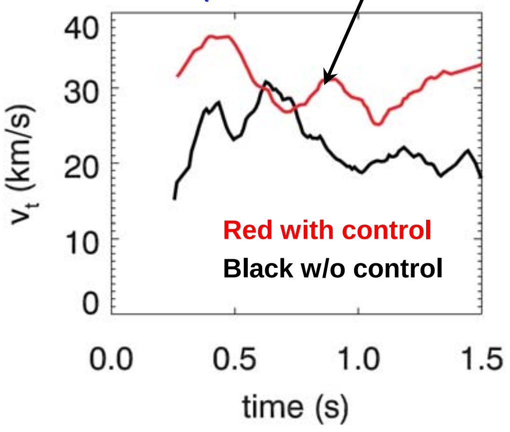


**n=1 mode drops $\beta$**

**No MHD, $\beta$ and rotation maintained**



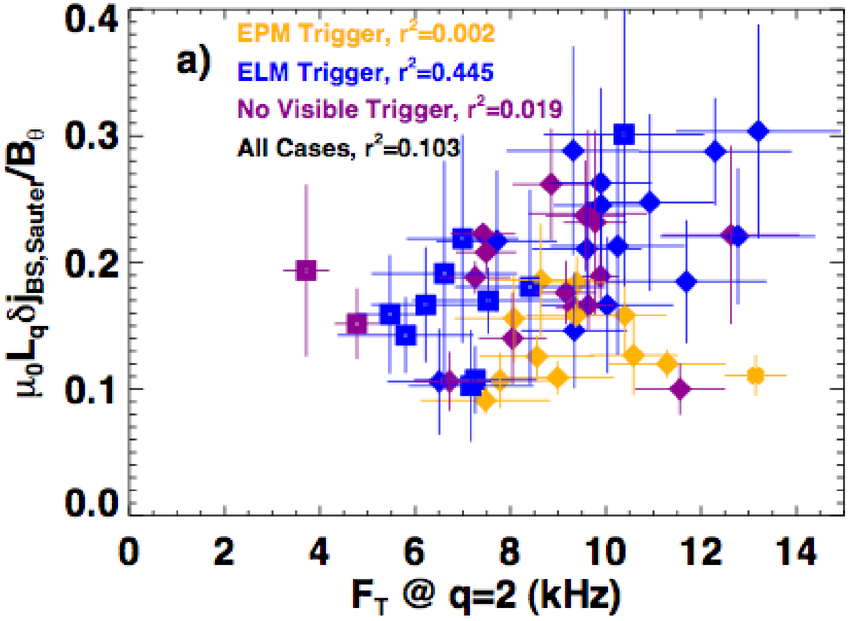
*CHERS $v_t$ at R = 139cm*



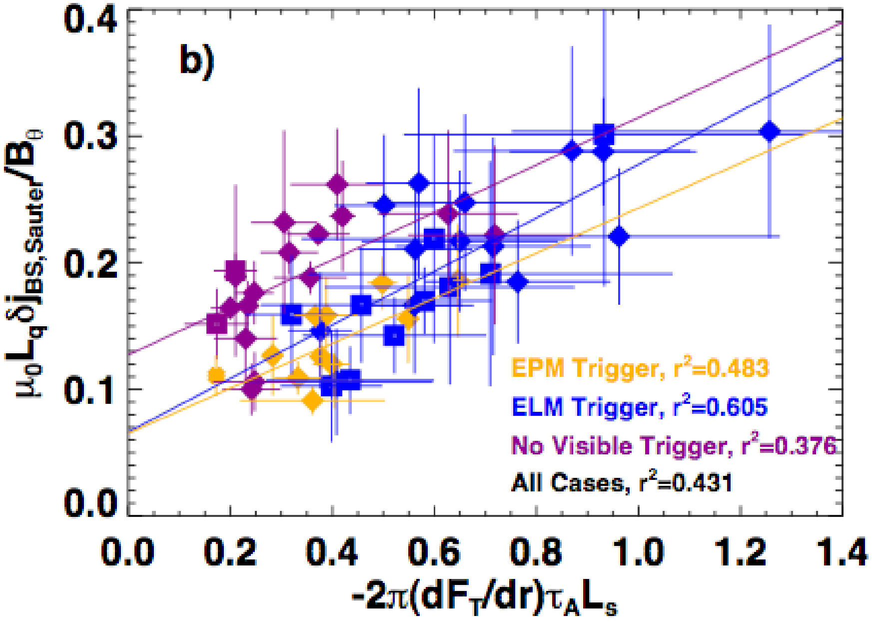
- ❑ Physics of tearing mode elimination still under investigation
    - ❑ Full suppression of modes not seen on all shots
- ❑ If lithium wall conditioning a key element, liquid lithium divertor might be used for NTM control

# Required drive for NTM onset better correlated with rotation shear than rotation magnitude

*NTM Drive at Onset Only Poorly Correlated with q=2 (Carbon) Rotation*



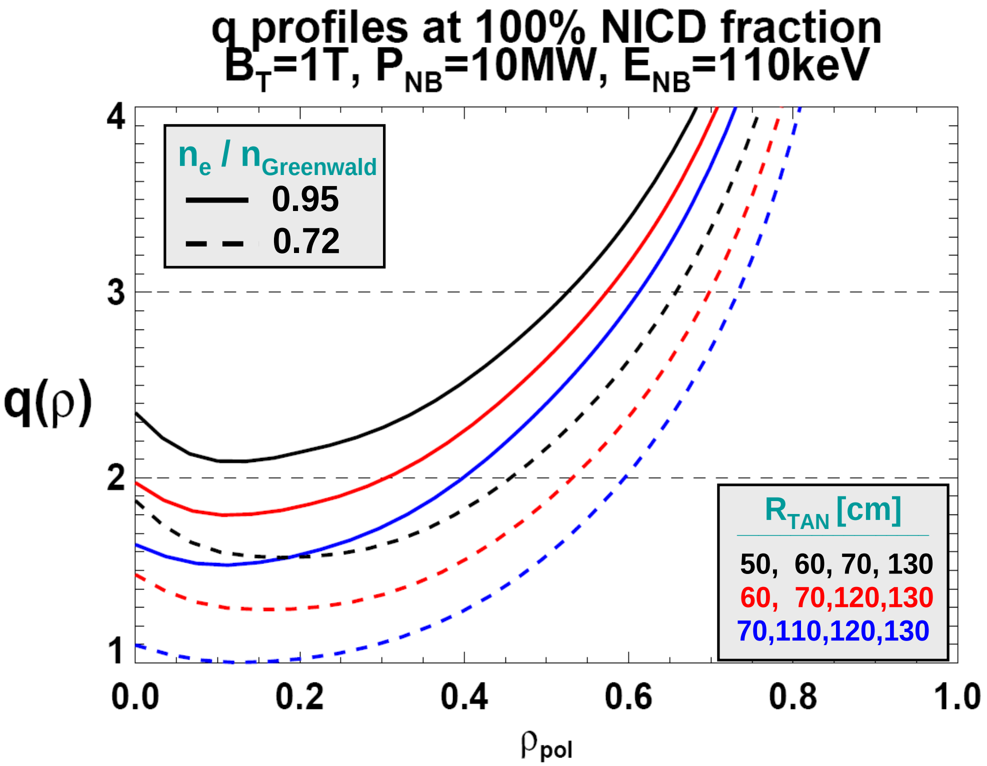
*NTM Drive at Onset Better Correlated with Local Flow Shear*



- For fixed $V_\phi$, order of increasing onset drive: EPM triggers, ELM triggers, and “Triggerless”
- All trigger types have similar dependence on flow shear
  - Dependence likely to related to intrinsic tearing stability, not triggering

S.P. Gerhardt, submitted to Nucl. Fusion

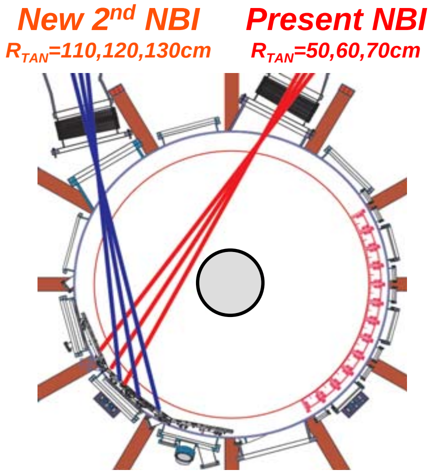
# $2^{nd}$ NBI and $B_T$ = 1T with center stack upgrade to be used for study and control MHD modes (and much more…)



- $q_{min}$ > key rationals 1.5, 2 to be used for NTM control

Above: $\beta_N$=5, $\beta_T$=10%, $I_P$=0.95MA

$\beta_N$=6.1, $\beta_T$=16%, $q_{min}$ > 1.3, $I_P$=1MA at $B_T$=0.75T possible



- Fully non-inductive scenarios require $2^{nd}$ NBI (7-10MW of NBI heating) for $H_{98} \leq 1.2$
  - $\tau_{CR}$ will increase from 0.35 → 1s if $T_e$ doubles at lower $n_e$, higher $B_T$
  - Need 3-4 $\tau_{CR}$ times for J(r) relaxation → 5s pulses → need $2^{nd}$ NBI

# Establish predictive physics understanding of NTMs

- 2009-2011: Compete Characterization of NTM Onset, Small Island Physics, Restabilization
  - Characterize the role of $V_\phi$ 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 $\Delta'$ 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 $\Delta'$ 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

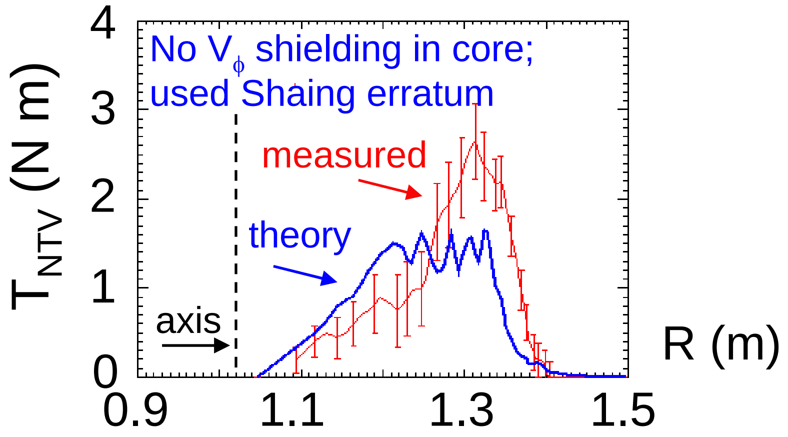
- ❑ Significant interest in plasma viscosity by non-axisymmetric fields
  - ❑ Physics understanding needed to minimize rotation damping from ELM mitigation fields, modes (ITER, etc.)
  - ❑ NTV investigations on DIII-D, JET, C-MOD, MAST, etc.

    e.g. A.M. Garofalo, APS 2008 invited (DIII-D)
- ❑ Expand studies on NSTX
  - ❑ Examine larger field spectrum
  - ❑ Improve inclusion of plasma response using IPEC

    J.K. Park, APS 2008 invited talk
  - ❑ Consider developments in NTV theory
    - Reduction, or saturation due to $E_r$ at reduced ion collisionality, multiple trapping states, bounce/precession resonances, superbanana regime, etc.
    - Some effects suggest continued increase in viscosity at reduced $\nu_i$
  - ❑ Examine NTV from magnetic islands

## Measured *d(IΩ<sub></sub>*$_p$*)/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…

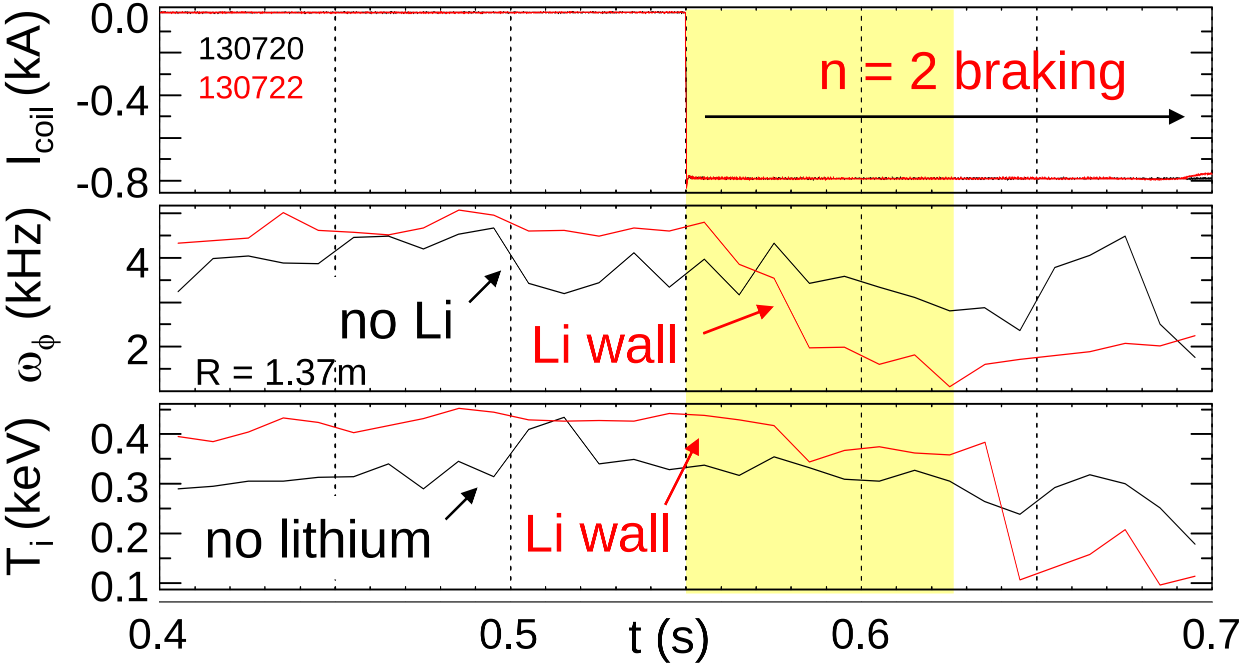
$$\left\langle \hat{e}_t \bullet \vec{\nabla} \bullet \overleftrightarrow{\Pi} \right\rangle_{(1/\nu)} = B_t R \left\langle \frac{1}{B_t} \right\rangle \left\langle \frac{1}{R^2} \right\rangle \frac{\lambda_{1i} p_i}{\pi^{3/2} \nu_i} \varepsilon^{3/2} (\Omega_\phi - \Omega_{NC}) I_\lambda$$

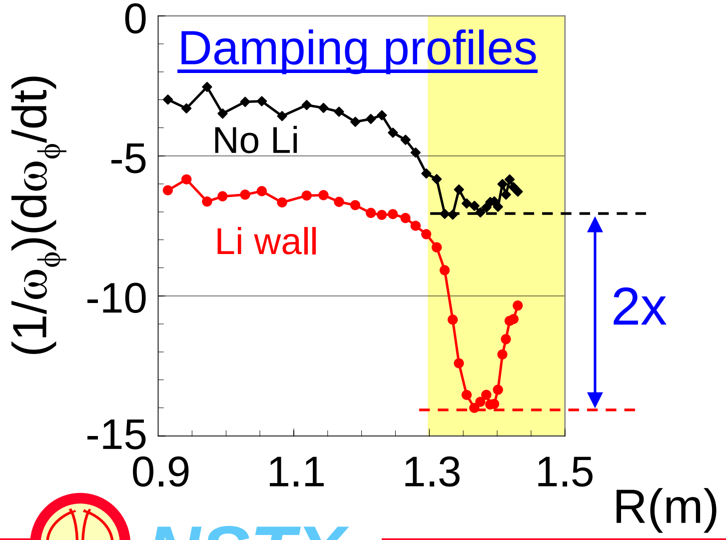
…will it saturate, decrease at lower $\nu_i$ ?

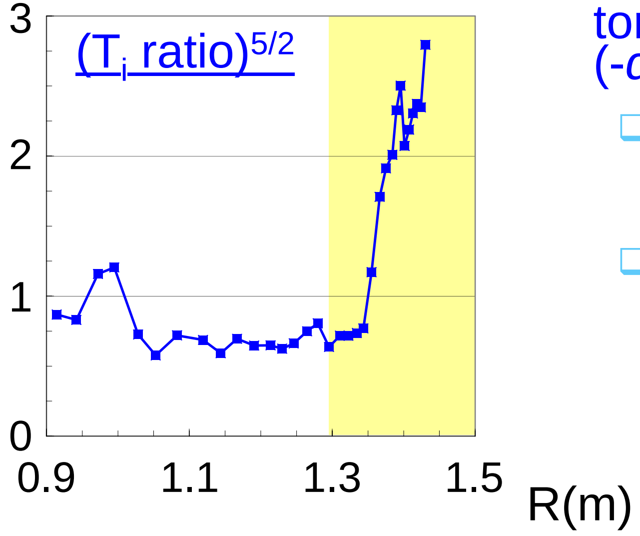
$$\frac{1}{\nu_i} \Rightarrow \frac{\nu_i}{\left(\nu_i^{\,2} + \omega_E^{\,2}\right)}$$

Can examine at order of magnitude lower $\nu_i$ with center stack upgrade

# Stronger non-resonant braking at increased $T_i$



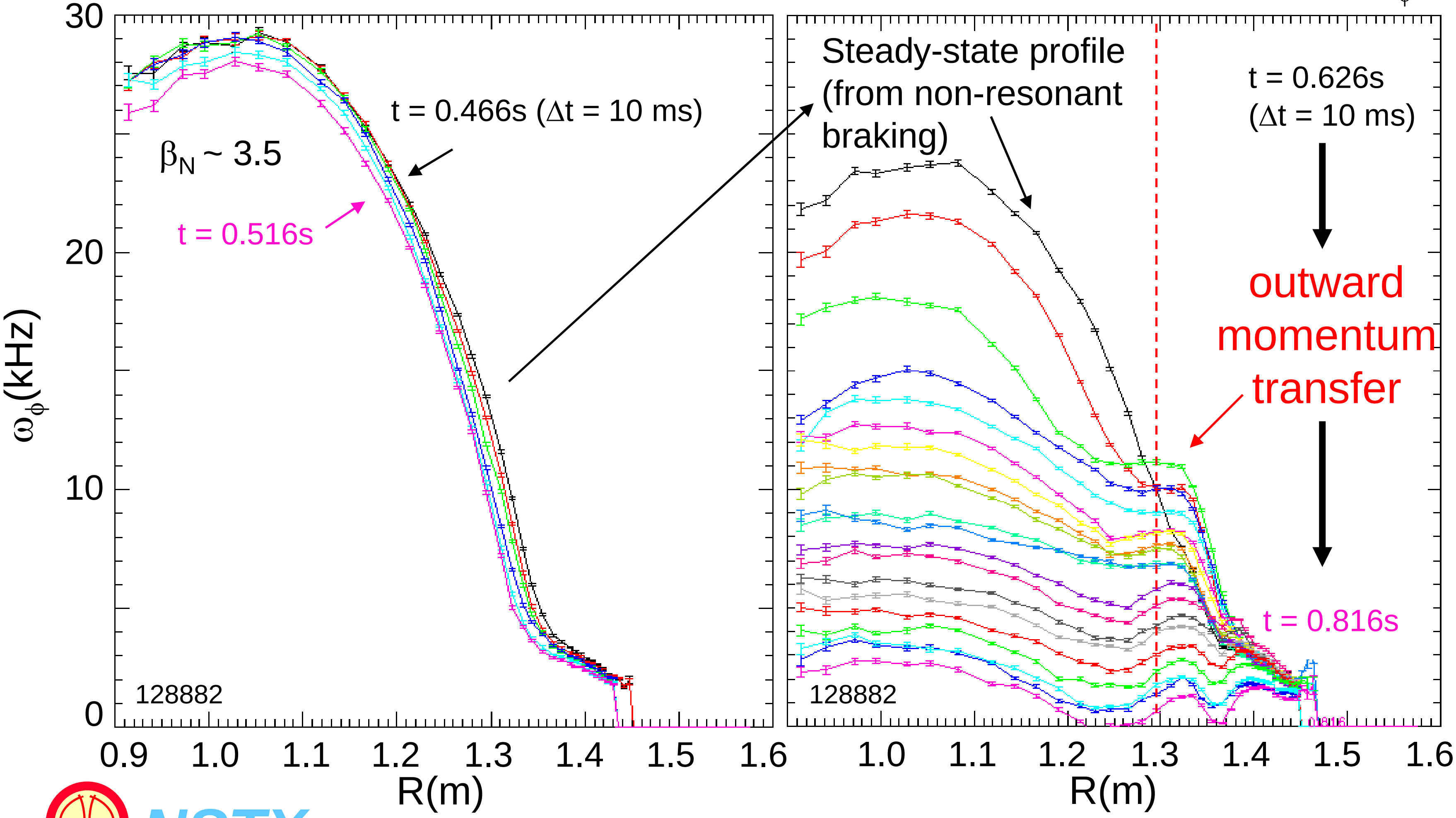




- Observed non-resonant braking using n = 2 field
- Examine $T_i$ dependence of neoclassical toroidal viscosity (NTV)
- Li wall conditioning produces higher $T_i$ in region of high rotation damping
- Expect stronger NTV torque at higher $T_i$ ($-d\omega_\phi/dt \sim T_i^{5/2}\,\omega_\phi$)
  - At braking onset, $T_i$ ratio$^{5/2}$ = $(0.45/0.34)^{5/2} \sim 2$
  - Consistent with measured $d\omega_\phi/dt$ in region of strongest damping

# n = 2 non-resonant braking evolution distinct from resonant

- Non-resonant:
  - broad, self-similar reduction of profile
  - Reaches steady-state (t = 0.626s)
- Resonant:
  - Clear momentum transfer across rational surface
  - evolution toward rigid rotor core
  - Local surface locking at low $\omega_\phi$



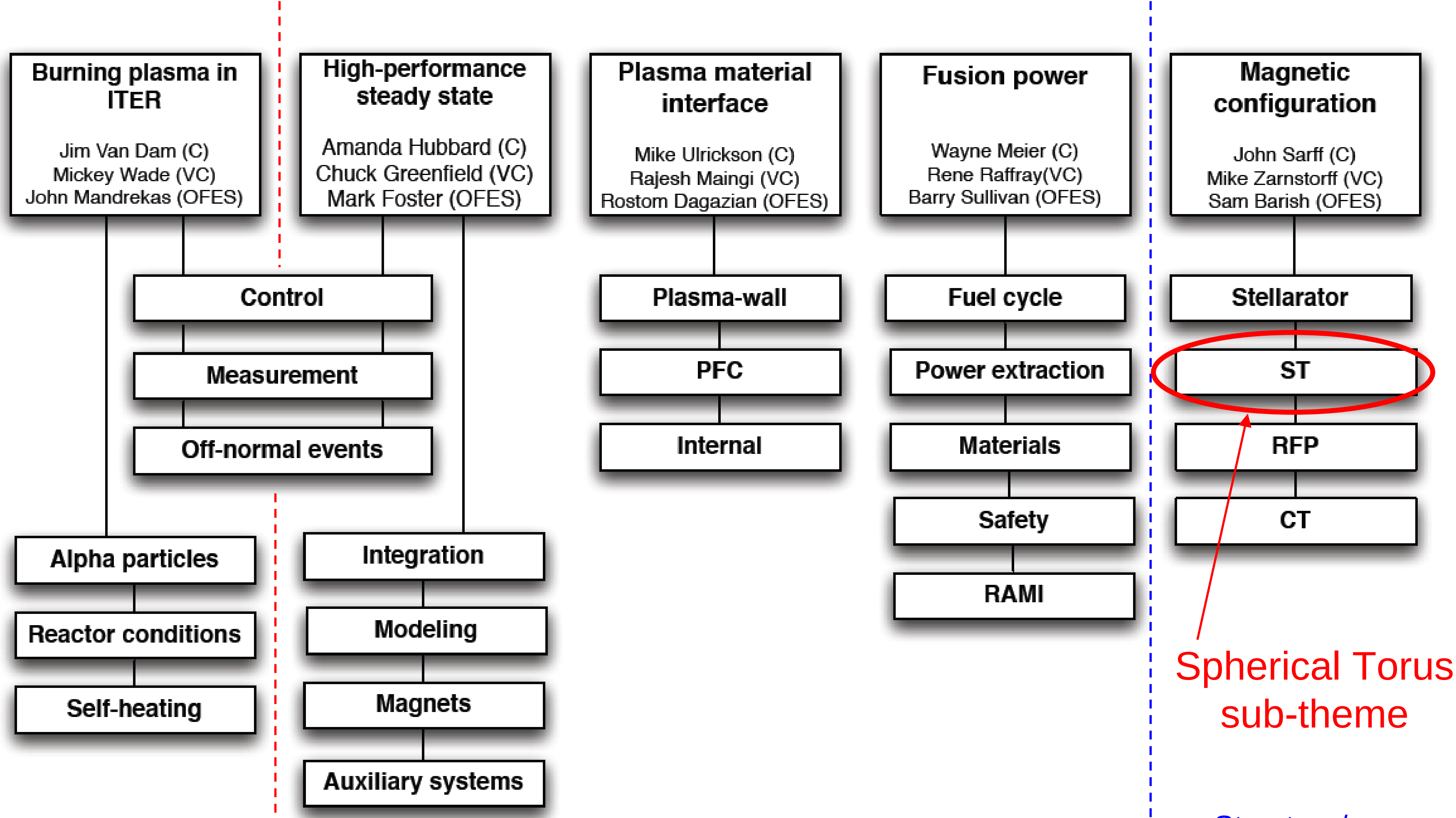
# High β ST research plan focuses on bridging the knowledge gaps to next-step STs; contributes to ITER

- 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 $\beta$ operational regime
  - Specific ITER support tasks
- NSTX provides access to well diagnosed high beta ST plasmas
  - 2009-2011: allows significant advances in scientific understanding of ST physics toward next-steps, supports ITER, and advances fundamental science
  - 2012-2013+: allows demonstration/understanding of reliable stabilization/profile control at lower collisionality – performance basis for next-step STs

# DOE ReNeW process to define “ITER-era” (20 yr) research program

- ReNeW: Research Needs Workshop
  - To inform the Office of Fusion Energy Sciences (OFES) in preparing a strategic plan for research in each major area of the Fusion Energy Sciences Program
  - To allow U.S. fusion community to explain research goals, methods to achieve them
    - Including communication to new administration
  - MAIN WEB PAGE: http://burningplasma.org/renew.html
- Document
  - Vol 1: Define scientific research needed to fill “gaps” in present understanding
    - “gaps” defined in / modified from Greenwald report, FESAC TAP reports
    - Divided into 5 “themes” comprising magnetic fusion research
  - Vol 2: Define (~ 15) “research thrusts” that will carry out this research
  - Basis for detailed program plan to be constructed by OFES

# ReNeW organized into 5 fusion research themes



- **Burning plasma in ITER**
  Jim Van Dam (C)
  Mickey Wade (VC)
  John Mandrekas (OFES)
  - Control
  - Measurement
  - Off-normal events
  - Alpha particles
  - Reactor conditions
  - Self-heating
- **High-performance steady state**
  Amanda Hubbard (C)
  Chuck Greenfield (VC)
  Mark Foster (OFES)
  - Control
  - Measurement
  - Off-normal events
  - Integration
  - Modeling
  - Magnets
  - Auxiliary systems
- **Plasma material interface**
  Mike Ulrickson (C)
  Rajesh Maingi (VC)
  Rostom Dagazian (OFES)
  - Plasma-wall
  - PFC
  - Internal
- **Fusion power**
  Wayne Meier (C)
  Rene Raffray(VC)
  Barry Sullivan (OFES)
  - Fuel cycle
  - Power extraction
  - Materials
  - Safety
  - RAMI
- **Magnetic configuration**
  John Sarff (C)
  Mike Zarnstorff (VC)
  Sam Barish (OFES)
  - Stellarator
  - ST
  - RFP
  - CT

Spherical Torus sub-theme

Structure/gaps
Energy Policy Act task group report

Structure/gaps
Priorities, Gaps, and Opportunities Panel Report
("Greenwald Report")

Structure/gaps
FESAC Toroidal Alternates Panel Report

Reports available at: http://burningplasma.org/renew.html

# ReNeW ST Panel is on Schedule to Complete Tasks

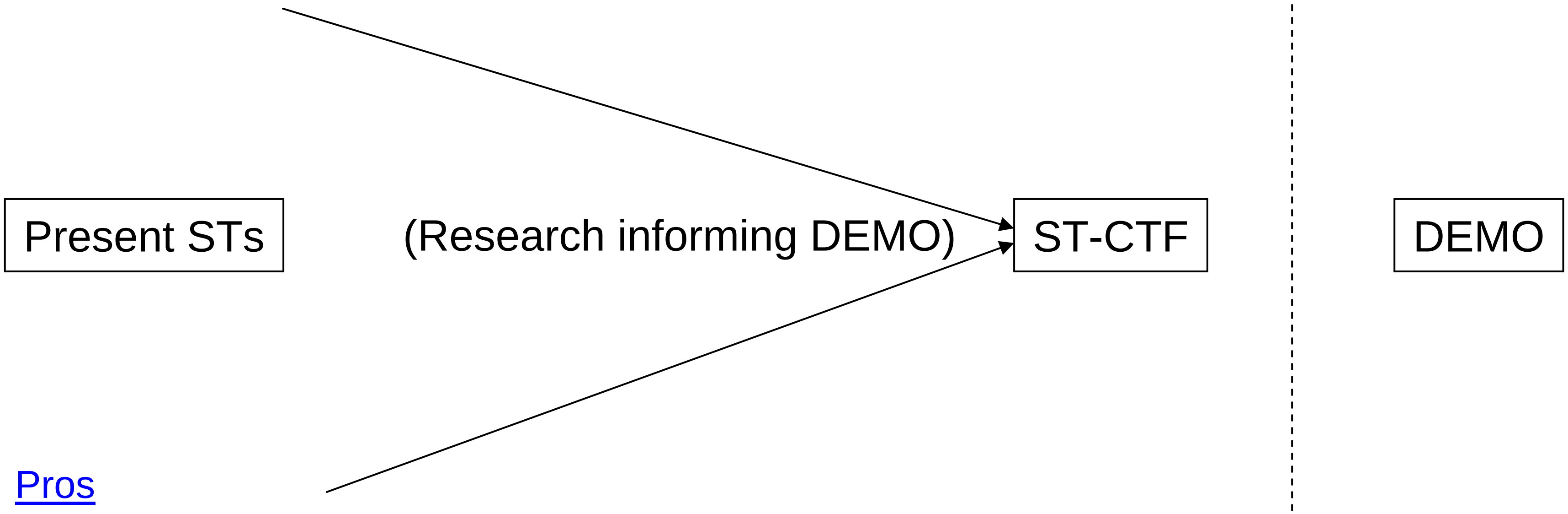
- Tasks through March 16-19 Workshop
  - Solicit community input: (First call for input DONE – continue to engage community)
  - Review issues as described in TAP panel report: (DONE: embodied in community distributed draft of ST section V1.7)

********** WE ARE HERE **********

  - Identify scientific research needed to address the issues
    - Review and expand on research outlined in the TAP panel report
    - Draft write-up of research requirements, make available to community
    - Fold in community input on research requirements
  - Develop draft “research thrusts” for discussion at March workshop

- FESAC TAP Report Mission statement: *Establish the ST knowledge base to be ready to construct a low aspect ratio component testing facility that provides high heat flux, neutron flux, and duty factor needed to inform the design of a demonstration fusion power plant.*

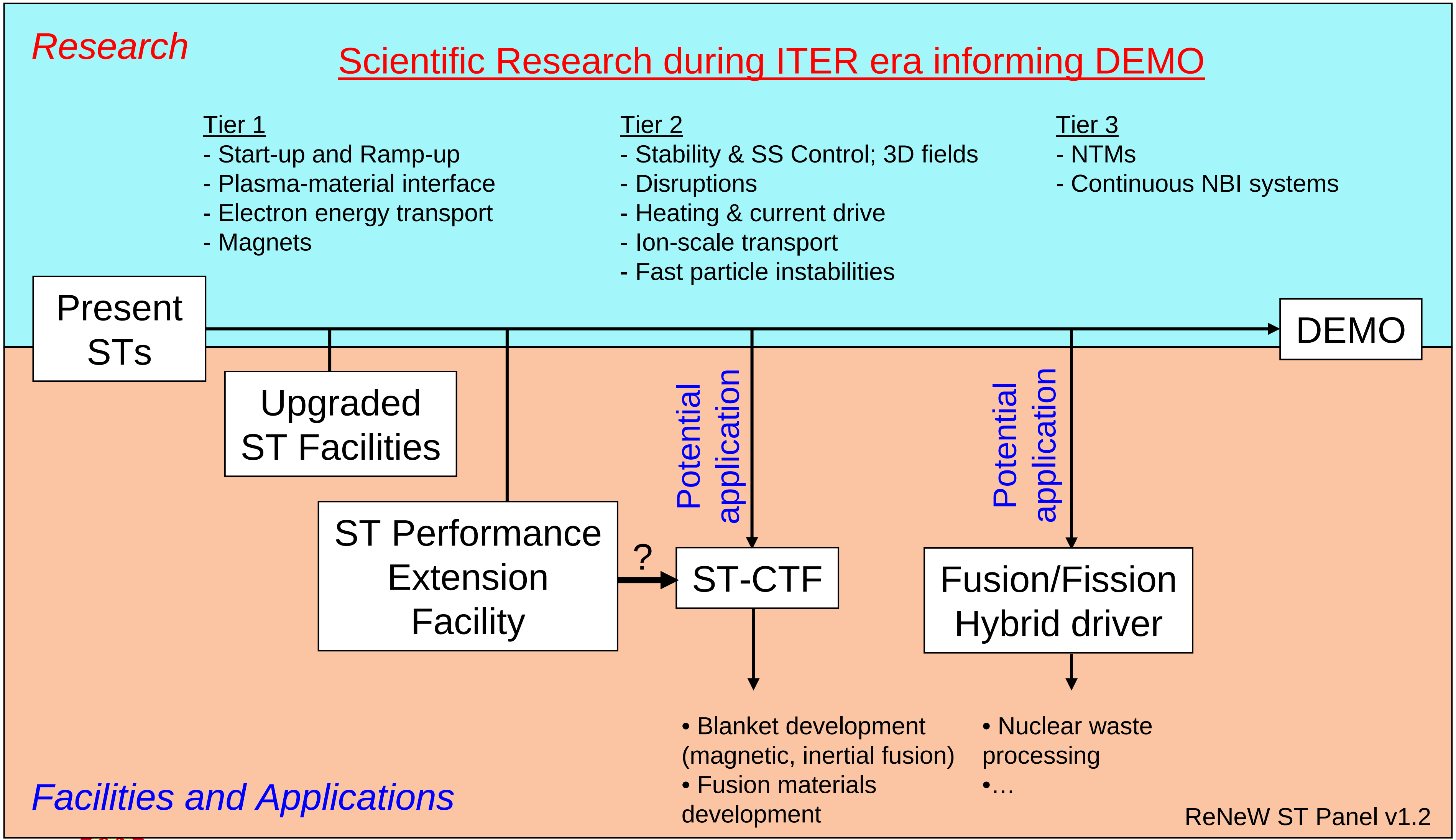
# Interpretation of the FESAC TAP document by some people in the community



- Pros
  - ST-CTF focus
- Cons
  - Alienates a significant part of the community (research plan has been characterized by some (to quote) as a “dead end”), so loses potential constituency
  - Many have complained that several physics issues have been “swept under the rug”, even at the level of an ST-CTF device
  - Interpreted as above, it doesn’t maximize cross-cutting with other magnetic fusion research

Key point: Let’s engage the community and make appropriate, small changes to strengthen these weak points.

# (STRAWMAN) U.S. ST Research Vision consistent with Present ST Mission Statement



*Research*

## Scientific Research during ITER era informing DEMO

Tier 1
- Start-up and Ramp-up
- Plasma-material interface
- Electron energy transport
- Magnets

Tier 2
- Stability & SS Control; 3D fields
- Disruptions
- Heating & current drive
- Ion-scale transport
- Fast particle instabilities

Tier 3
- NTMs
- Continuous NBI systems

- Blanket development (magnetic, inertial fusion)
- Fusion materials development

- Nuclear waste processing
- …

*Facilities and Applications*

ReNeW ST Panel v1.2

# Several Conduits for Participation in ReNeW Process

- ReNeW Forum (web bulletin board)
  - Contribute to open discussions; start your own discussions
  - Registration instructions: http://burningplasma.org/forum/
    - Request authorization to ReNeW Forum: e.g. email: sabbagh@pppl.gov
  - ST topic: https://burningplasma.org/forum/index.php?showforum=114
- ST Group: Direct input to/discussion of evolving draft ST section of document
  - Posted: https://burningplasma.org/forum/index.php?showtopic=653
- Submit short white papers describing your ideas on how to resolve key issues, support/define research thrusts
  - Download directions at: http://burningplasma.org/renew.html
- Participate in March 2009 Workshops
  - Links to websites with info/registration at: http://burningplasma.org/renew.html
- Directly contact panel members
  - ST Group: 10 Panel members (see next page); more than 30 advisors

# ReNeW Spherical Torus Panel Members

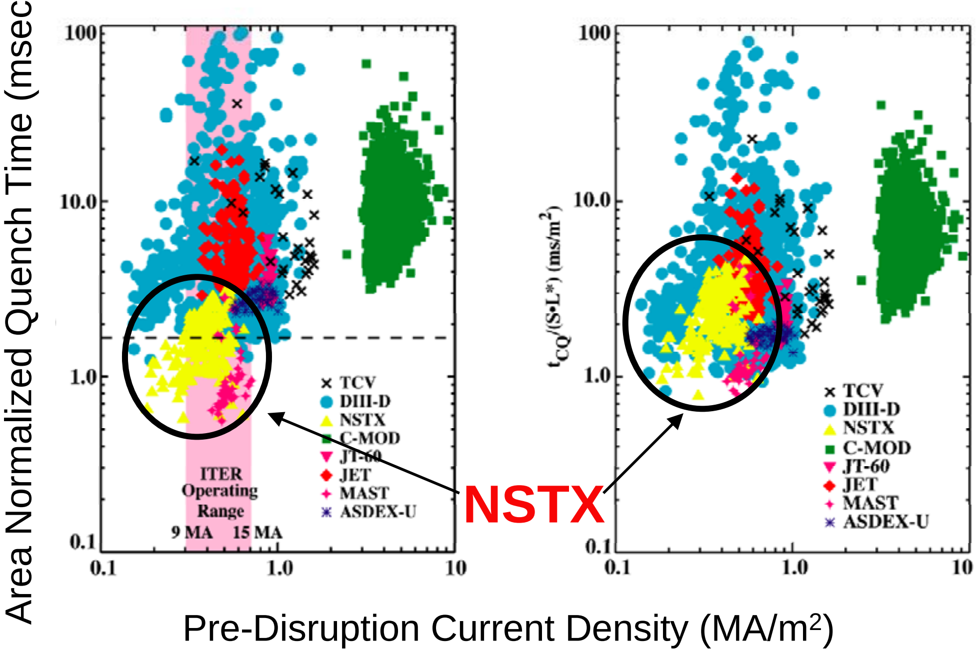
| Member | Institution | telephone | email |
|---|---|---|---|
| Steve Sabbagh | Columbia U. | (609) 243-2645 | sabbagh@pppl.gov |
| Aaron Sontag | ORNL | (865) 574-1179 | sontagac@ornl.gov |
| Vlad Soukhanovskii | LLNL | (609) 243-2064 | vlad@llnl.gov |
| M. Kotschenreuther | U. Texas | (512) 471-4367 | mtk@mail.utexas.edu |
| Dan Stutman | Johns Hopkins U | (410) 516-7929 | stutman@pha.jhu.edu |
| Dick Majeski | PPPL | (609) 243-3112 | dmajeski@pppl.gov |
| Jon Menard | PPPL | (609) 243-2037 | jmenard@pppl.gov |
| Nikolai Gorelenkov | PPPL | (609) 243-2552 | ngorelen@pppl.gov |
| Chris Hegna | U. Wisconsin | (608) 263-0810 | hegna@engr.wisc.edu |
| Martin Peng | ORNL | (865) 368-0917 | pengym@ornl.gov |

- ❑ Contact any panel member for authorization to access the ReNeW Forum (website bulletin board)
- ❑ Full advisor list posted at:
  https://burningplasma.org/forum/index.php?showtopic=636

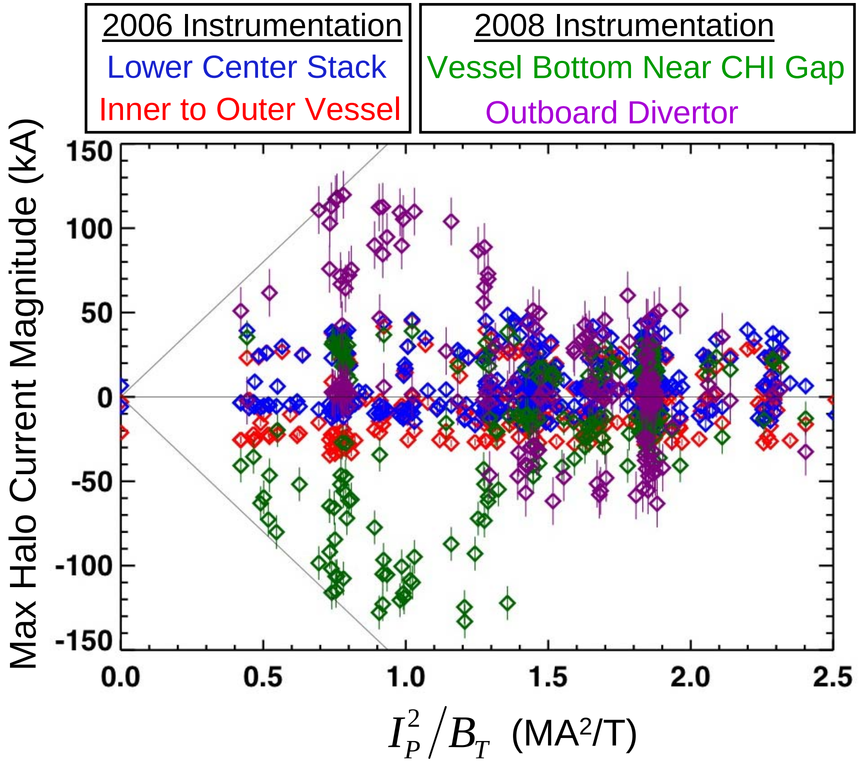
# Backup Slides

# 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/m², compared to ITER recommended minimum of 1.7 msec/m².
- 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
  - 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: 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: 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