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NSTX MHD Research in ITPA, RWM stabilization, and non-axisymmetric field-induced viscosity

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U Maryland
U Rochester
U Washington
U Wisconsin

S.A. Sabbagh, J.W. Berkery, J.M Bialek, S.P. Gerhardt, and many others...

Columbia U. – NSTX Collaboration Group
and
NSTX Macroscopic Stability Topical Science Group

PPPL MHD Science Focus Group Meeting
December 12th, 2008

PPPL

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
ENEA, Frascati
CEA, Cadarache
IPP, Jülich
IPP, Garching
ASCR, Czech Rep
U Quebec

Outline

- ITPA MHD High Priority tasks (Lausanne ITPA mtg. – Oct. 2008)
- NSTX 2009 Research Forum XPs and ITPA
- NSTX Research on RWM Stabilization
- NSTX Research on non-axisymmetric field-induced viscosity

High Priority ITPA MHD Stability Research Areas (10/2008)

(Lausanne)

- Largest single problem: disruptions (and runaways)
  - Suggest that NSTX research approach this several ways: (i) database/empirical, (ii) causal mode physics, (iii) control/avoidance
    - Embodied in different joint experiments
- Priority areas noted and discussed
  - Vertical stabilization for ITER
  - Disruptions (control, mitigation, and loads)
    - e.g.: address runaway issue – with RMPs as a possible technique to avoid mode locking during dusruptions, which leads to worse heat loss issues
    - Disruption database – further development
  - NTMs (many subtopics)
  - Error field effects
    - Quantify effects of error fields, specify multi-mode error correction requirements and error field thresholds at medium to high beta (note: present EFCCs are only n = odd capable)
  - RWM control
    - Mode stabilization physics
    - Control system: need specifications for noise, voltage/current required for power supplies, frequency response, control of large transient events
    - first priority is dynamic correction of error fields; second priority is correction of RFA and RWM control at higher beta
  - Magnetics diagnostics for ITER (J. Lister - special presentation)
    - Focus on compensation of ferromagnetic materials, effective positioning, redundancy

Prioritized Macroscopic MHD TSG 2009 XPs (12/9/08)

Could utilize COUNTER-INJECTION capability

- XP Idea presentations (23 ideas)
  - Continued Search for the n=3 EF Source in NSTX (Gerhardt) 0.5 days
  - Optimization of Squareness for Improved Stability & τ_E at High β_N (SPG) 1.0 days
  - Error Field Threshold Study in high-beta plasmas (J.-K. Park) 0.5 days
  - Influence of fast particles in Resistive Wall Mode Stabilization (Berkery) 1.0 days
  - Effect of RWM Stabilization on Background Plasma (Delgado-Aparicio) 0.5 days
  - NTV physics at varied $\nu_i^*/q\omega_E$ and search for offset rotation (Sabbagh) 1.0 days
  - Error field influence on 2/1 NTM onset through rotation (Buttery) 0.75 days
    - NSTX/DIII-D Aspect Ratio Comparison of 2/1 NTM Physics (LaHaye) 0.75 days
    - Effects of Impurities and Wall Conditioning on NTM Stability (Volpe) 0.5 days
  - Improving $\langle\beta_N\rangle_{pulse}$ vs. rotation under RWM Feedback (Sabbagh) 1.0 days

7.5 days

  - Global MHD and ELM stability at low, near-integer n*q (Sabbagh) 1.0 days
  - Disruption Mitigation in NSTX using CHI (Raman) 0.5 days

9 days

ITER
  - Formation and suppression of disruption runaway beams (Gerhardt) 1.0 days
  - Effect of toroidally localized field perturbations: ITER support (Sabbagh) 1.0 days

  - Physics of RWM Triggers During Active Feedback Control (Sabbagh) 1.0 days
    - Assessment of kinetic modeling on fishbone driven-RWM (Okabayashi)
  - Achieving High I_p/I_{TF} by Wall and Rotational Stabilization (Jarboe) 1.0 days
  - XP743: Island-induced Neoclassical Toroidal Viscosity (NTV) (Sabbagh) 1.0 days
  - RWM Stabilization Physics Investigation in Counter-injection (Berkery) 1.0 days
  - NSTX/DIII-D RWM joint XP - Verify Common Physics Basis (Berkery) 1.0 days
  - Measurements of Transient Heat Fluxes During Global MHD (Gerhardt) 1.0 days
  - Exploration of Different FB Timescales for Optimal Performance (SPG) 1.0 days
  - Real-time Techniques for Disruption Soft-Landing (Gerhardt)

Run time guidance: 7 – 9 run days

Run days: 18.0 days

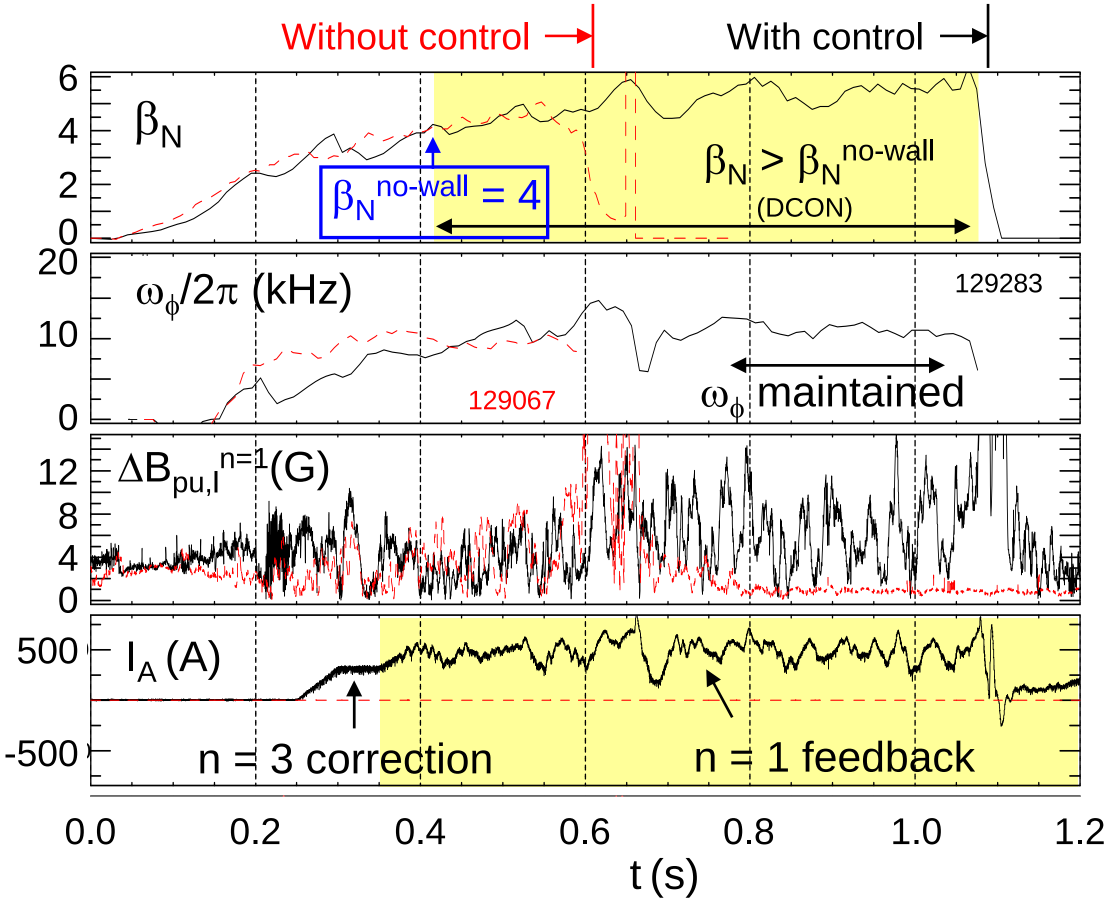
ITPA MHD Stability Group - Joint Experiments: NSTX

- MDC-1: Disruption mitigation by massive gas jets
- MDC-2: Joint experiments on resistive wall mode physics
- MDC-4: NTM Physics – aspect ratio comparison
- MDC-5: Comparison of sawtooth control method for NTM suppression
- MDC-12: Non-resonant magnetic braking
- MDC-13: Vertical stability physics and performance limits in highly elongated plasmas
- MDC-14: Rotation effects on NTMs
- MDC-15: Disruption database development
- MDC-16: Runaway electron generation, confinement, and loss
- MDC-17: Physics-based disruption avoidance
- - MHD risks associated with the Test Blanket Modules
- PEP-23: Quantification of requirements for ELM suppression by RMP

new

- NSTX 2009 Forum Macro TSG XP proposal address these tasks
  - red: addressed in 1st tier proposals; purple: 2nd tier; blue: ITER-specific run time

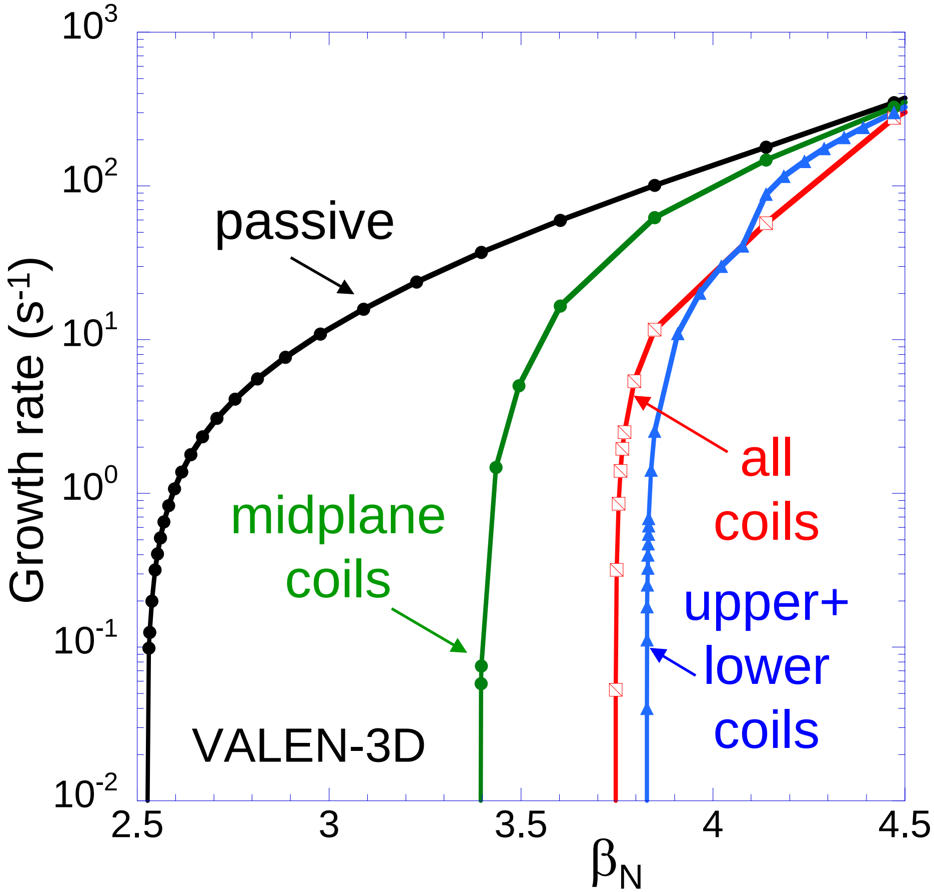
Active RWM control and error field correction maintain high β_N plasma



- n = 1 active, n = 3 DC control
  - n = 1 response ~ 1 ms < $1/\gamma_{RWM}$
  - $\beta_N/\beta_N^{no-wall}$ = 1.5 reached
  - best maintains ω_ϕ
- NSTX record pulse lengths
- Without control, plasma more susceptible to RWM growth, even at high ω_ϕ
- Approach in 2009 experiment
  - Run at highest performance with Li conditioning
  - Vary plasma rotation levels to determine $\langle\beta_N\rangle_{pulse}$ reached
    - Some data already from 2008
  - Include B_r sensors for control
    - Find best re-zeroing time(s)
  - Request 1.5 days + piggyback

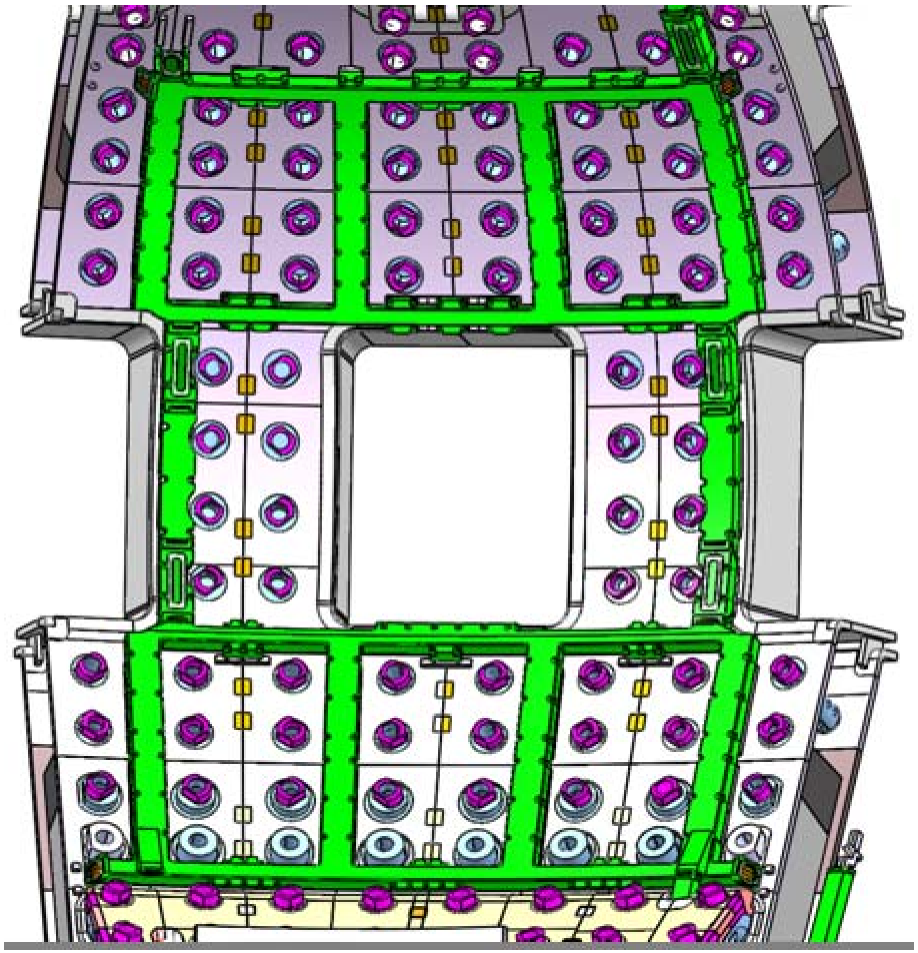
Significant β_N increase expected by internal coil proposed for ITER

ITER VAC02 stabilization performance



- 50% increase in β_N over RWM passive stability
- Multi-mode VALEN developed; being tested (Bialek)

ITER VAC02 design (40° sector)



3 toroidal arrays, 9 coils each

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

- Simple critical ω_ϕ 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 ω_ϕ profile: resonances in δW_K (e.g. ion precession drift)
  - Particle collisionality

ω_ϕ profile (enters through ExB frequency)

Trapped ion component of δW_K (plasma integral)

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

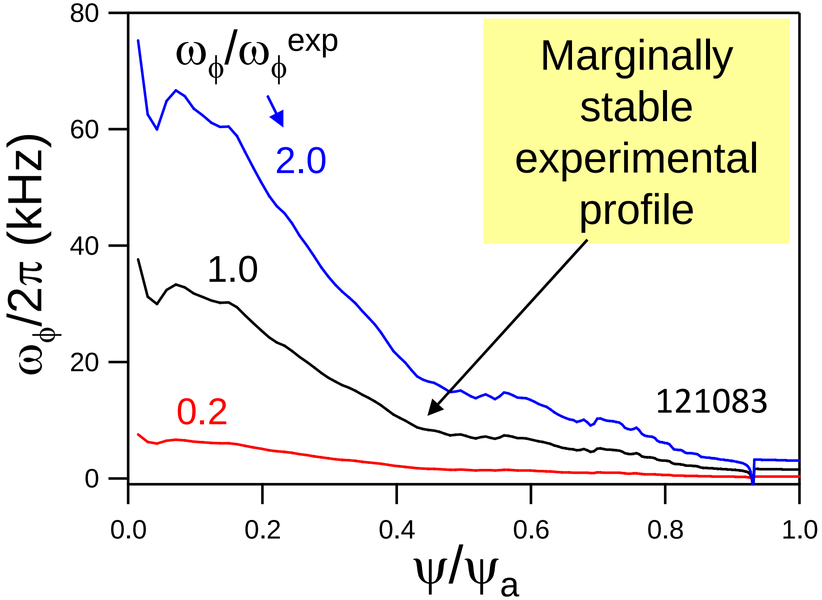
← Energy integral

precession drift — bounce — collisionality

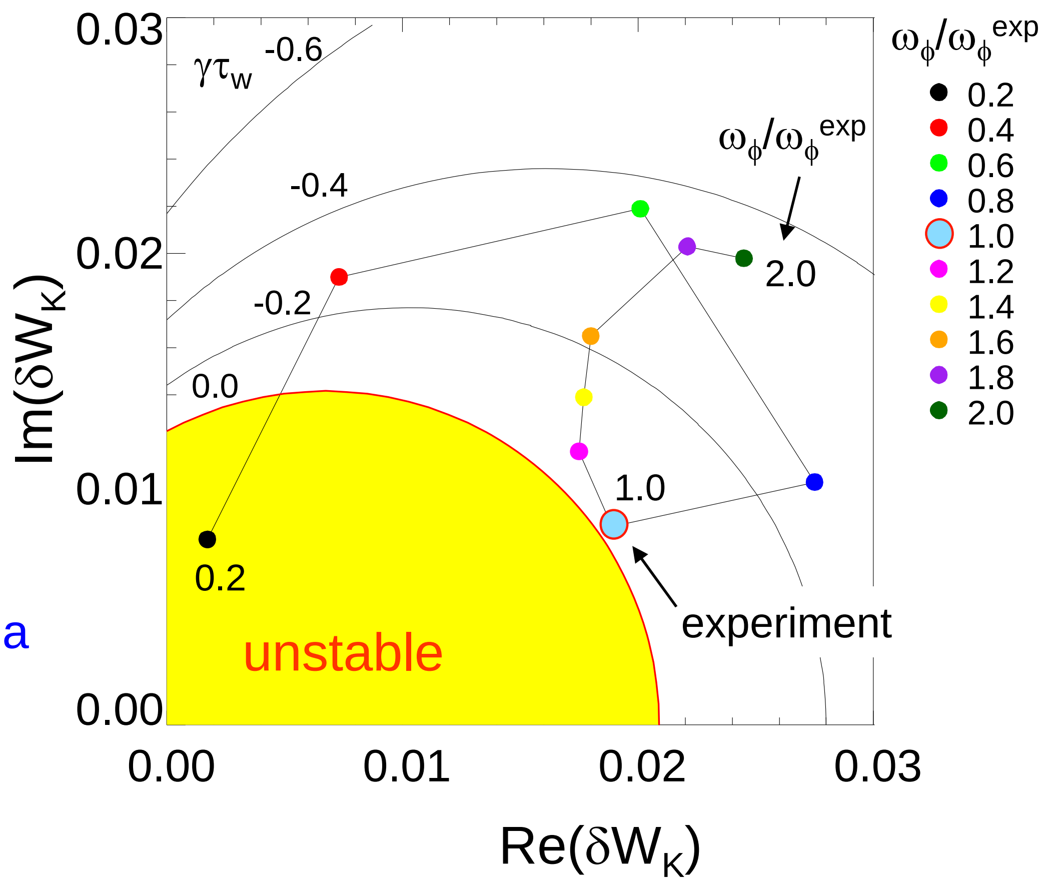
J.W. Berkery

Kinetic modifications show decrease in RWM stability at relatively high V_ϕ – consistent with experiment

Theoretical variation of ω_ϕ



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



- Marginal stable experimental plasma reconstruction, rotation profile ω_ϕ^{exp}
- Variation of ω_ϕ away from marginal profile <u>increases</u> stability
- Unstable region at low ω_ϕ

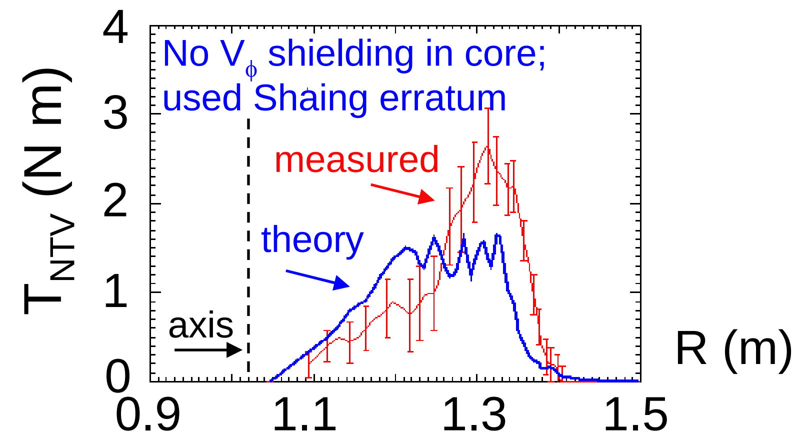
J.W. Berkery

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
  - Larger field spectrum
  - Plasma response w/IPEC
    J.K. Park, APS 2008 invited
  - Include developments in NTV theory
    - Reduction, or saturation due to E_r at reduced ion collisionality, multiple trapping states, matching theory through collisionality regimes, PIC models, GTC-NEO, etc.
  - Examine NTV from islands (INTV)
  - First Tier experiment to examine in 2009; + proposal to investigate INTV

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).

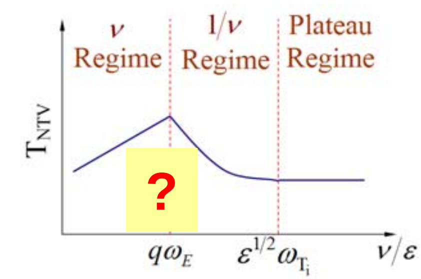


Dominant NTV Force for NSTX collisionality…

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

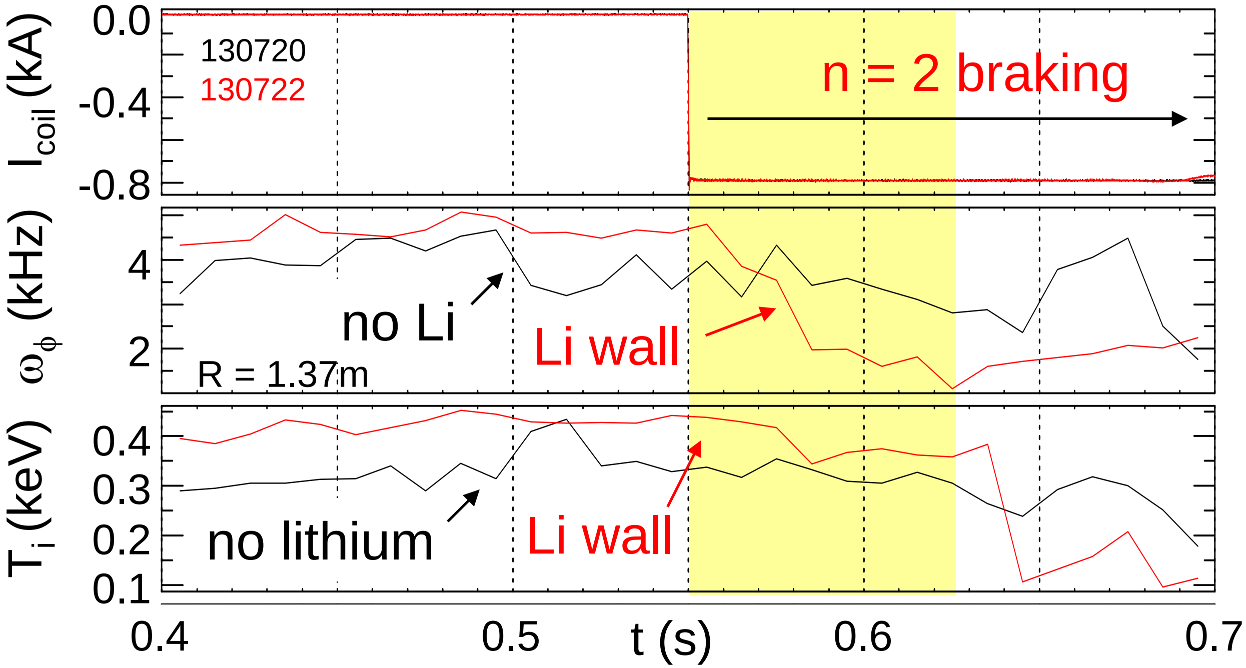
…expected to saturate at lower ν_i

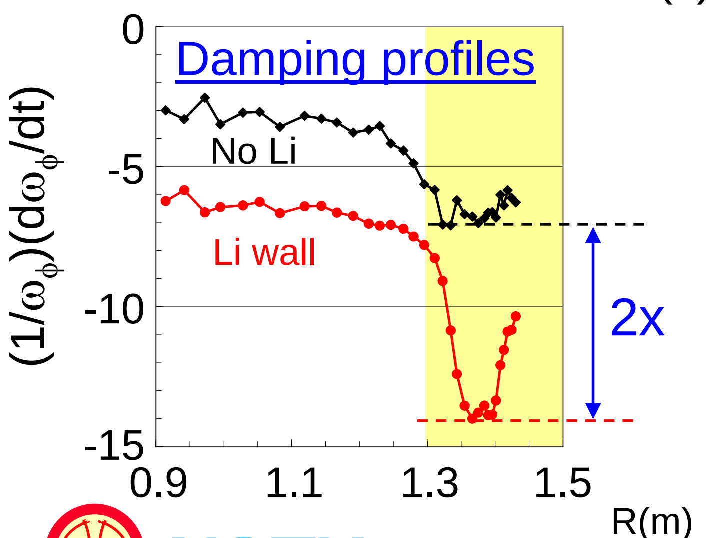
$$\frac{1}{\nu_i} \Rightarrow \frac{\nu_i}{\left(\nu_i^2 + \omega_E^2\right)}$$

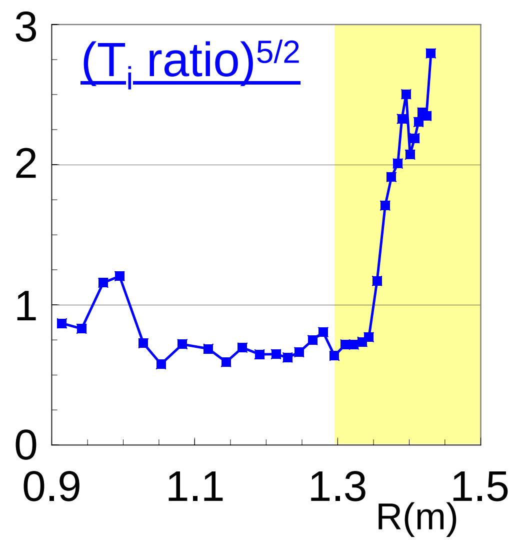


NSTX

Stronger non-resonant braking at increased T_i







- Observed NTV braking using n = 2 field
- 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$^{5/2}$ = $(0.45/0.34)^{5/2}$ ~ 2
  - Consistent with measured $d\omega_\phi/dt$
- Approach in 2009 XP
  - Enter main braking phase from different "steady-state" $q\omega_E$ levels
  - Reach steady ω_ϕ to determine offset; use counter-injection if available
  - Change T_i gradient to determine if offset ω_ϕ changes
  - Request 1 run day

NSTX

Research plan focuses on bridging the knowledge gaps to next-step STs; contributing 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 β 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