NSTX-U

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Physical Characteristics of Neoclassical Toroidal Viscosity in Tokamaks for Rotation Control and the Evaluation of Plasma Response

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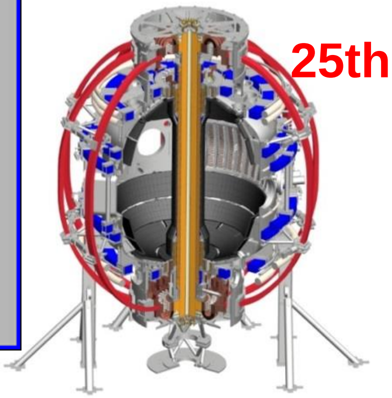

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The physical characteristics of NTV investigated in tokamaks for rotation control and the evaluation of plasma response

❑ Motivation

- ❑ Low magnitude ($\delta B/B_0 \sim O(10^{-3})$) 3D magnetic fields are used favorably used in tokamaks (e.g. ELM suppression, MHD mode control)
- ❑ 3D fields of this magnitude can produce neoclassical toroidal viscosity (NTV), which can:
  - Alter plasma rotation
  - Significantly reduce fusion gain, Q, by increased alpha particle transport ($\delta B/B_0 \sim O(10^{-4})$)

K.C. Shaing, et al., Nucl. Fusion **54** (2014) 033012

K.C. Shaing, et al., IAEA FEC 2014 Paper TH/P1-11

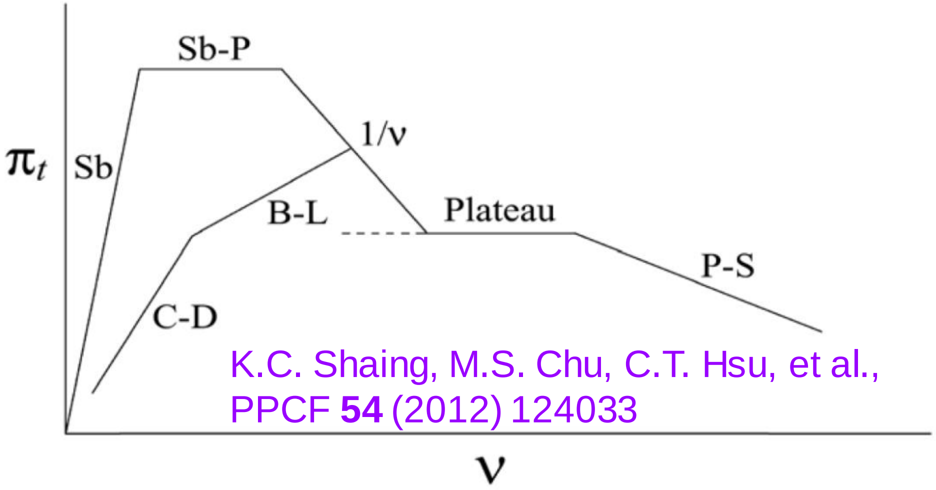
- ❑ Therefore, it is important to understand NTV in tokamaks, backed by accurate (~$O(1)$) quantitative modeling

❑ Outline

- ❑ NTV physical characteristics
- ❑ NTV comparison of theory to experiment
- ❑ NTV experiments and assessment of plasma response
- ❑ Application of NTV to plasma rotation control for NSTX-U

Neoclassical Toroidal Viscosity (NTV) can be studied through the application of 3D fields in tokamaks

- Theory: NTV strength varies with plasma collisionality ν, δB^2, rotation



K.C. Shaing, M.S. Chu, C.T. Hsu, et al., PPCF **54** (2012) 124033

NTV force in “1/ν” collisionality regime

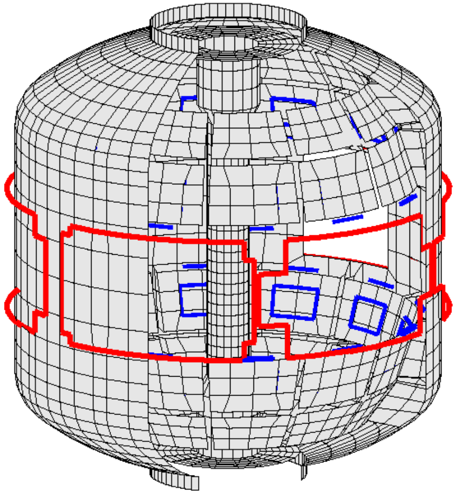
$$\left\langle \hat{e}_t \bullet \vec{\nabla} \bullet \overleftrightarrow{\Pi} \right\rangle_{(1/\nu)} = B_t R \left\langle \frac{1}{B_t} \right\rangle \left\langle \frac{1}{R^2} \right\rangle \frac{\lambda_{1i} p_i}{\pi^{3/2} \nu_i} \varepsilon^{3/2} (\omega_\phi - \omega_{NC}) I_\lambda$$

$T_i^{5/2}$

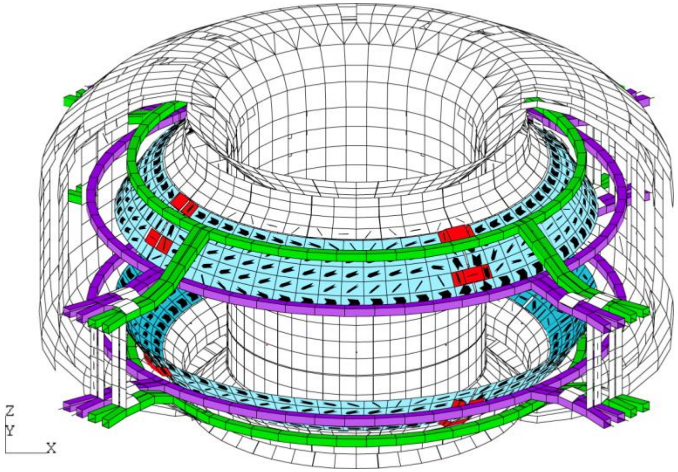
plasma rotation

K.C. Shaing, et al., PPCF **51** (2009) 035004

NSTX 3D coils



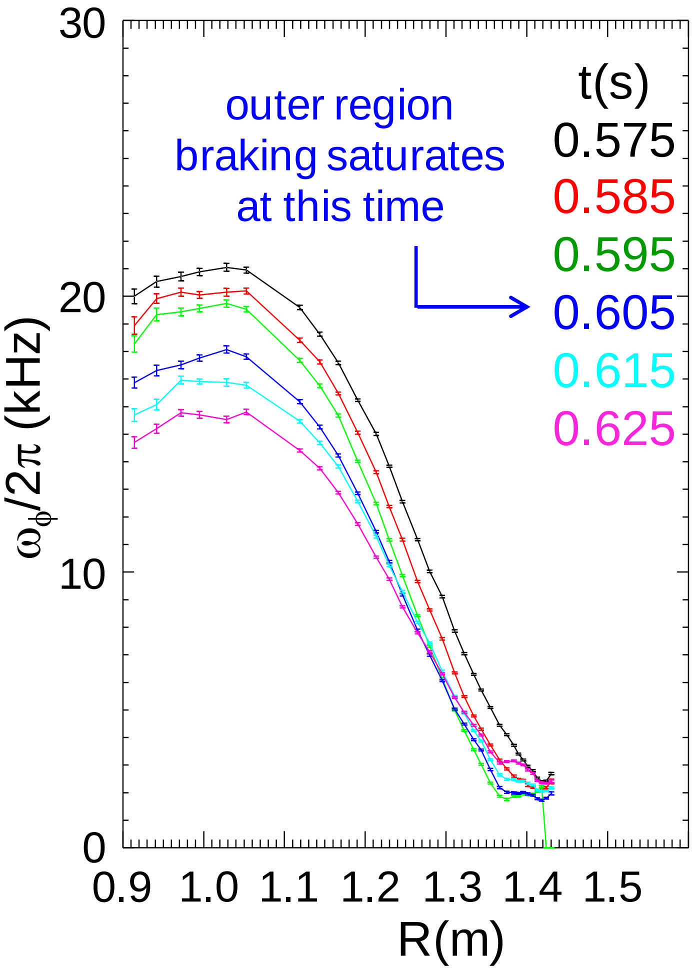
KSTAR 3D coils



NTV physical characteristics are generally favorable for rotation control

- ❑ Non-resonant NTV characteristics (e.g. in NSTX and KSTAR)
  - ❑ 3D field configurations with dominant toroidal mode number *n* > 1 can alter the plasma rotation profile, ω_ϕ, without mode locking
  - ❑ Experimentally, NTV torque is radially extended, with a relatively smooth profile
  - ❑ NTV changes continuously as the applied 3D field is increased
  - ❑ T_{NTV} is not simply an integrated torque applied at the plasma boundary, but a radial profile – e.g. ω_ϕ shear can be changed
- ❑ These aspects are generally favorable for rotation control; give potential mode control
- ❑ Questions remain
  - ❑ e.g. Is there hysteresis when ω_ϕ is altered by NTV?

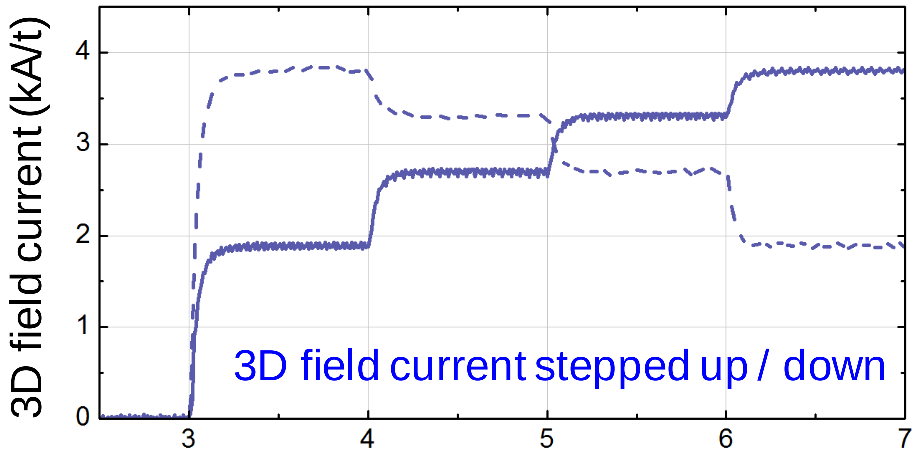
<ins>ω_ϕ alteration by n = 2 applied field configuration in NSTX</ins>

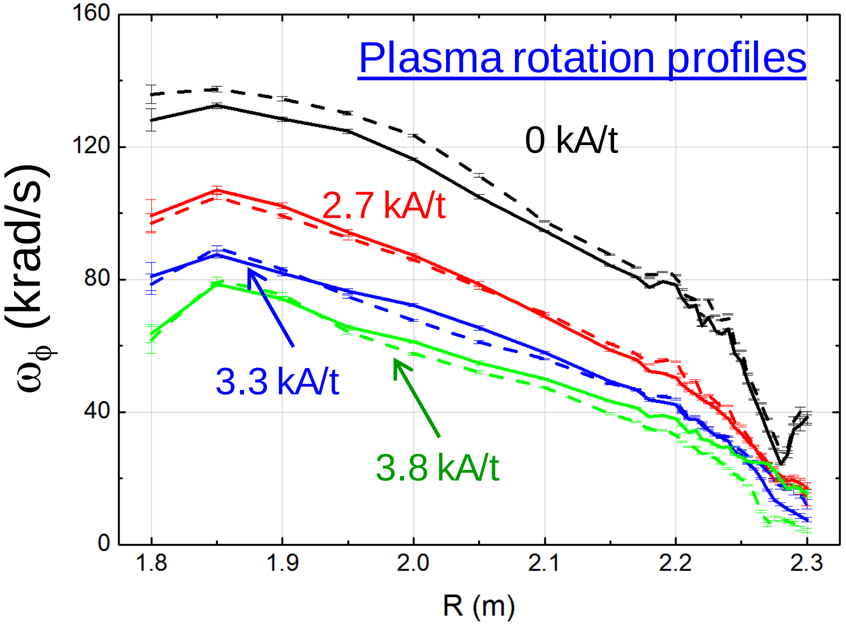


outer region braking saturates at this time

KSTAR experiments show essentially no hysteresis in steady-state ω_ϕ profile vs. applied 3D field strength

KSTAR non-resonant (“n = 2”) NTV experiments

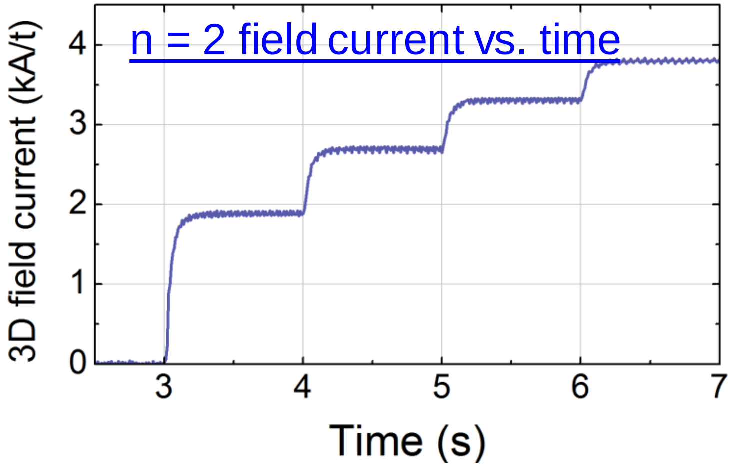


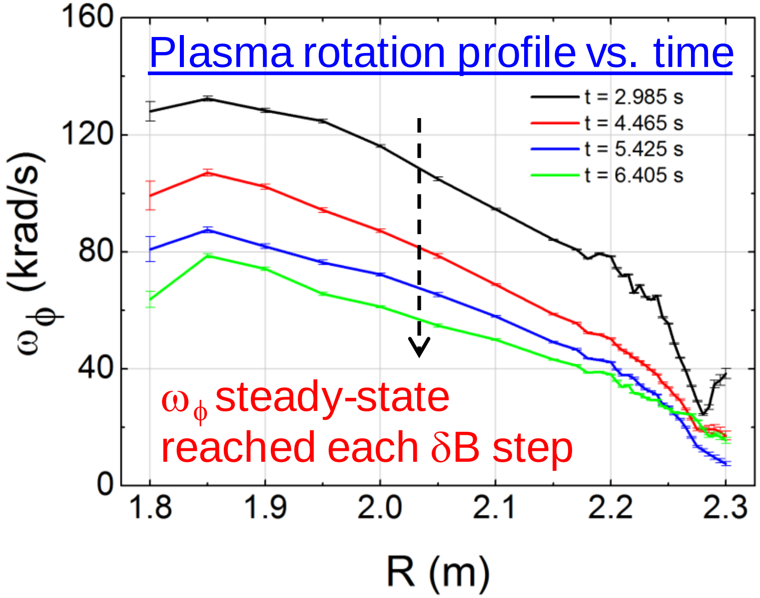


- Experiment run to produce various steady-state ω_ϕ with different 3D field evolution
- The steady-state rotation profile reached is generally independent of the starting point of ω_ϕ
  - depends just on the applied 3D field current level
  - important for rotation control
- Absence of hysteresis further confirmed in very recent experiments with 6 steps in 3D field current

KSTAR

Neoclassical Toroidal Viscosity varies as δB^2, and $T_i^{2.27}$ in KSTAR experiments, expected by theory

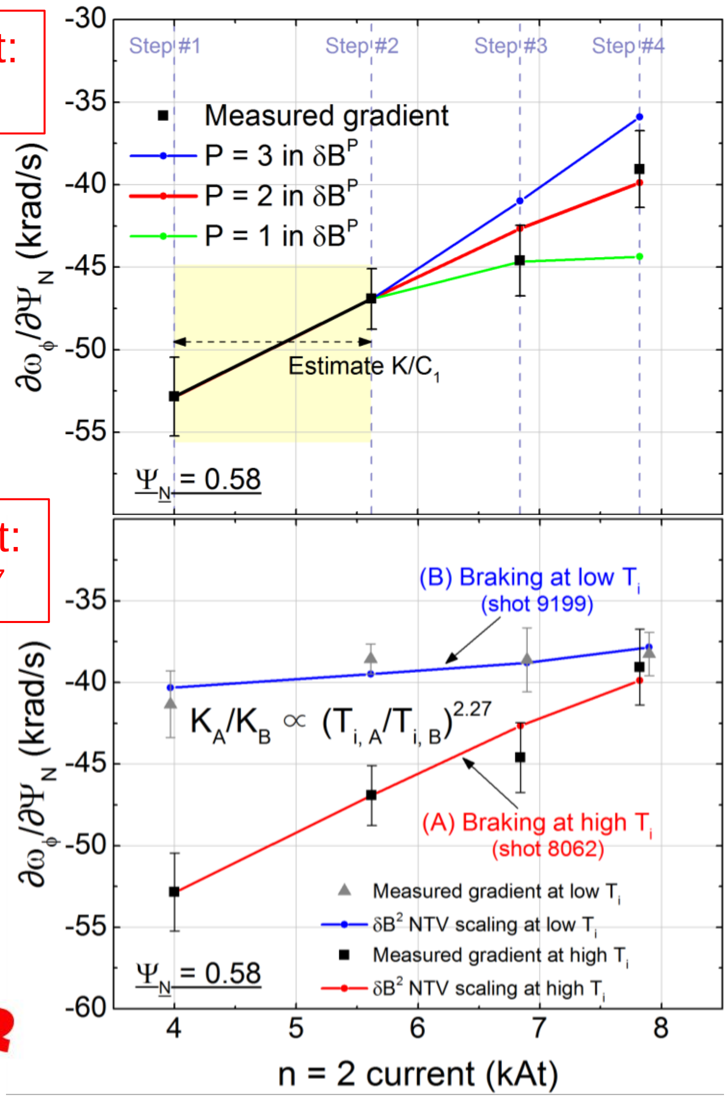




ω_ϕ steady-state reached each δB step

Best fit: $\propto \delta B^2$

Best fit: $\propto T_i^{2.27}$



- NTV torque T_{NTV} expected to scale as δB^2 and $T_i^{2.5}$ in the "1/ν regime"

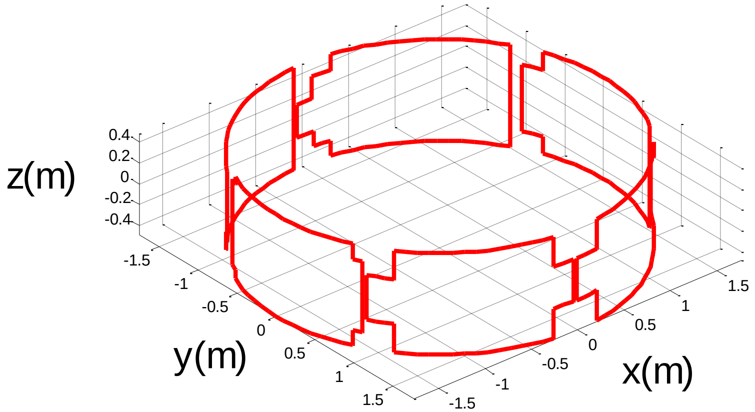
Y.S Park, et al., IAEA FEC 2014: EX/P8-05 (Fri. PM)

3D field perturbation experiments conducted to measure the T_{NTV} profile in NSTX

- High normalized beta plasma targets typically chosen
  - Typically near or above n = 1 no-wall limit (for higher T_i)
- Apply or otherwise change 3D field on a timescale significantly faster than the momentum diffusion time, τ_m
  - Analysis before/after 3D field application isolates T_{NTV} in the momentum diffusion equation; $-dL/dt = T_{NTV}$
- *dL/dt* measured experimentally and compared to theoretically computed T_{NTV} on this timescale
  - *dL/dt* profile can change significantly on timescales > τ_m, (diffuses radially, broadens, leads to significant error compared to T_{NTV})
- Focus on non-resonant applied 3D field configurations
  - To avoid driving MHD modes
  - Resonant fields (e.g. n = 1) are more strongly screened by plasma

Theoretical NTV torque density profiles, T_{NTV} are computed for NSTX using theory applicable to all collisionality regimes

Non-axisymmetric coils fully modelled in 3D



- **NTV analysis of NSTX – data interfaced to NTVTOK**

  (Y. Sun, Liang, Shaing, et al., NF **51** (2011) 053015)

  - Use Shaing's "connected NTV model", covers all ν, superbanana plateau regimes
    (K.C. Shaing, Sabbagh, Chu, NF **50** (2010) 025022)
  - Full 3D coil specification and δB spectrum, ion and electron components computed, no aspect ratio assumptions

3D field definition

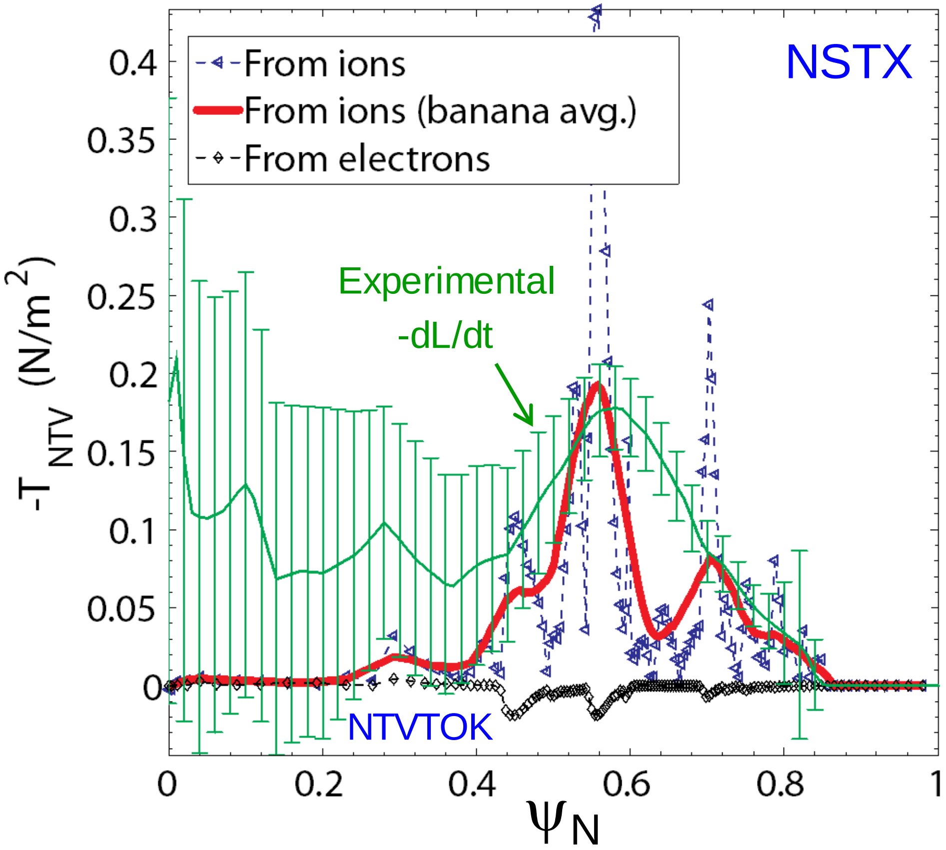
$$\delta B = \vec{b}\bullet\left(\vec{B}/B\right)+\left(\vec{\xi}\bullet\nabla B\right)$$

plasma displacement

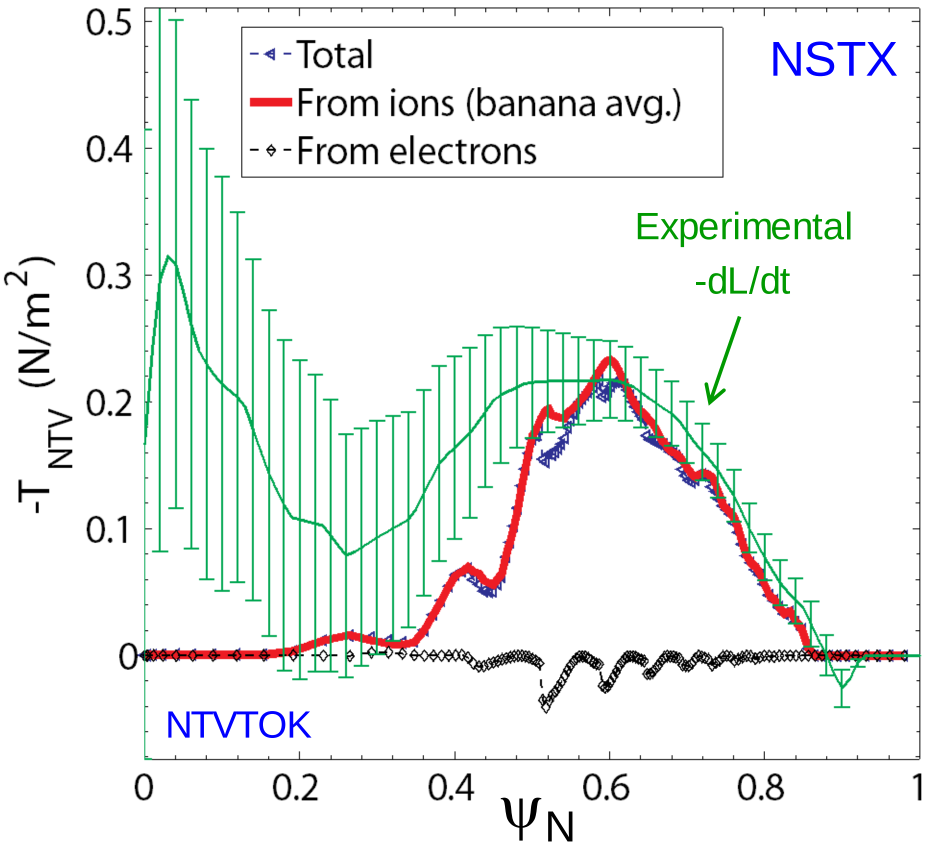
- General considerations
  - In tokamaks, ξ not typically measured, can lead to large error
  - "Fully-penetrated field constraint" used to define ξ $\left(\vec{B}_{2D}\bullet\nabla\vec{\xi}=\vec{b}\right)$
    - Singularities avoided by standard finite island width assumption
  - For NSTX, $|\xi|$ ~ 0.3 cm << $\varepsilon^{0.5}\rho_i$, therefore, ion banana width-averaging is used for ion channel
    - Can explain why strong resonant peaks in NTV profile are not observed in experiment

Measured NTV torque density profiles quantitatively compare well to computed T_{NTV} using fully-penetrated 3D field

n = 2 coil configuration



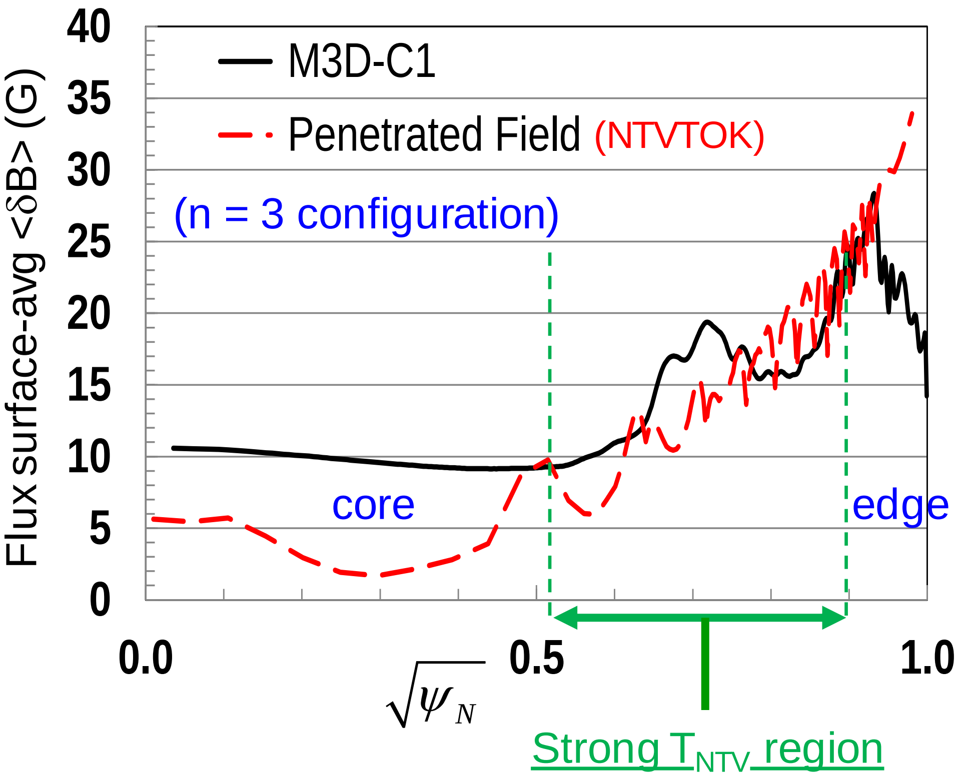
n = 3 coil configuration



- T_{NTV} (theory) scaled to match *peak* value of measured *-dL/dt*
  - Scale factor ($(dL/dt)/T_{NTV}$) = 1.7 and 0.6 (for cases shown above) – O(1) agreement
  - O(1) agreement using “fully-penetrated 3D field” indicates that plasma response is *not* strongly amplified from this “vacuum field assumption” ($T_{NTV} \sim \delta B^2$)

Plasma response from fully-penetrated 3D field used in NTV experimental analysis matches M3D-C^1 single fluid model

Surface-averaged δB from fully penetrated model vs. M3D-C^1 single fluid model



- NTV experimental data is a strong quantitative constraint on plasma response of δB
  - Because the measured NTV scales as $T_{NTV} \propto \delta B^2$,
- Level of agreement varies along the profile
  - Good agreement between NTVTOK / M3D-C^1 single fluid models in strong NTV region
  - M3D-C^1 core <δB> larger than NTVTOK
    - Core mode in M3D-C^1
  - M3D-C^1 edge <δB> smaller
    - Experimental T_{NTV} too small in this region to constraint δB

Non-resonant NTV and NBI used as actuators in state-space rotation feedback controller designed for NSTX-U

- Momentum force balance – ω_ϕ decomposed into Bessel function states

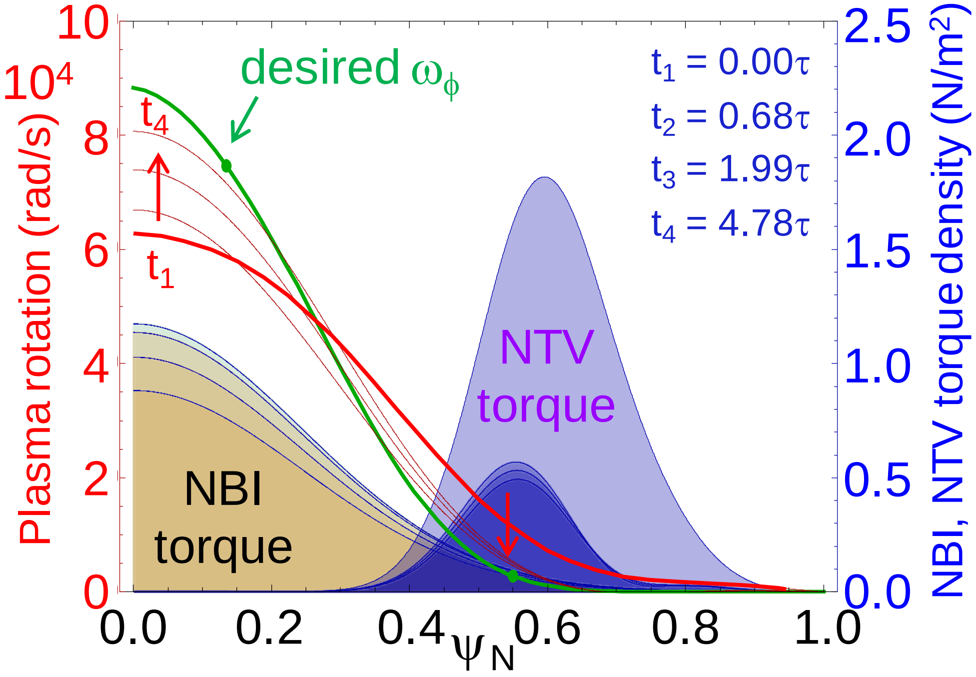
$$\sum_i n_i m_i \left\langle R^2 \right\rangle \frac{\partial \omega}{\partial t} = \left(\frac{\partial V}{\partial \rho} \right)^{-1} \frac{\partial}{\partial \rho} \left[\frac{\partial V}{\partial \rho} \sum_i n_i m_i \chi_\phi \left\langle \left(R \nabla \rho \right)^2 \right\rangle \frac{\partial \omega}{\partial \rho} \right] + T_{NBI} + T_{NTV}$$

- NTV torque:

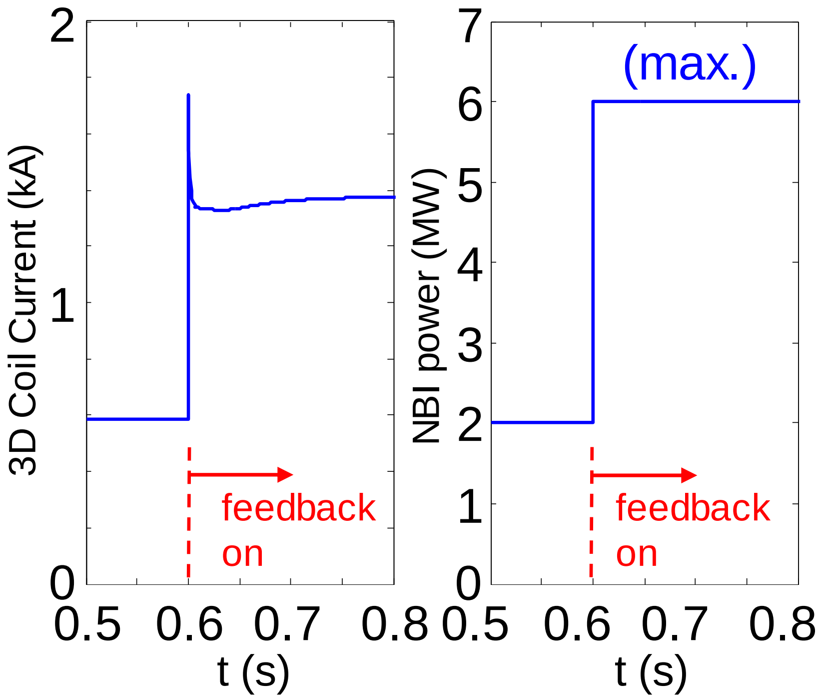
$$T_{NTV} \propto K \times f\left(n_{e,i}{}^{K1} T_{e,i}{}^{K2} \right) g\left(\delta B(\rho) \right) \left[I_{coil}{}^{2} \omega \right]$$

(non-linear)

Rotation evolution and NBI and NTV torque profiles



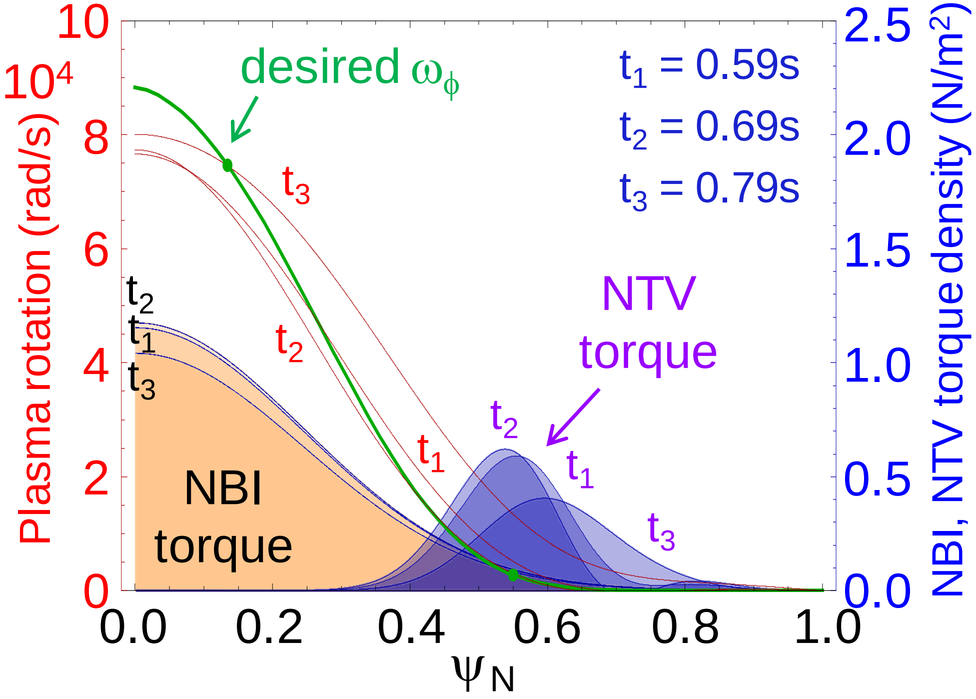
3D coil current and NBI power (actuators)



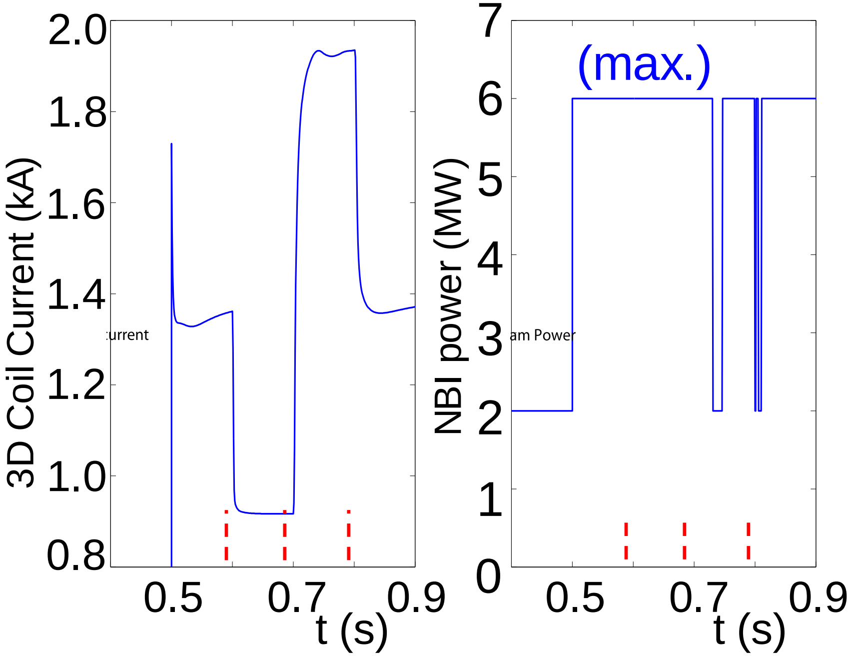
I. Goumiri (PU), S.A. Sabbagh (Columbia U.), D.A. Gates, S.P. Gerhardt (PPPL)

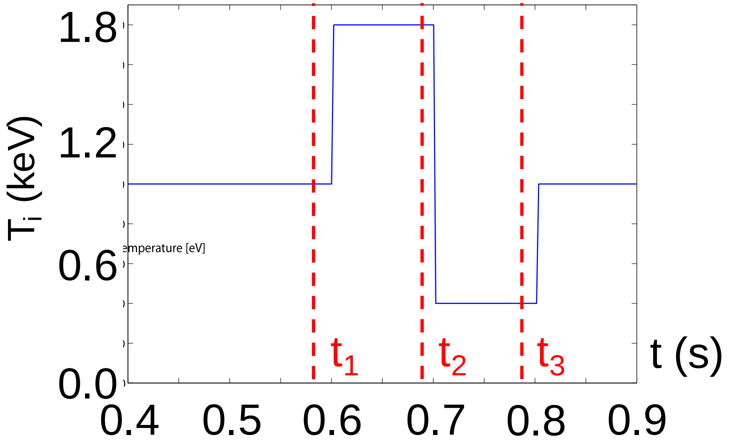
When T_i is included in NTV rotation controller model, 3D field current and NBI power can compensate for T_i variations

Rotation evolution and NBI and NTV torque profiles



3D coil current and NBI power (actuators)





$$T_{NTV} \propto K \times f\left(n_{e,i}^{\;K1} T_i^{K2}\right) g\left(\delta B(\rho)\right)\left[I_{coil}^{\;2}\omega\right]$$

K1 = 0, K2 = 2.5

- NTV torque profile model for feedback dependent on ion temperature

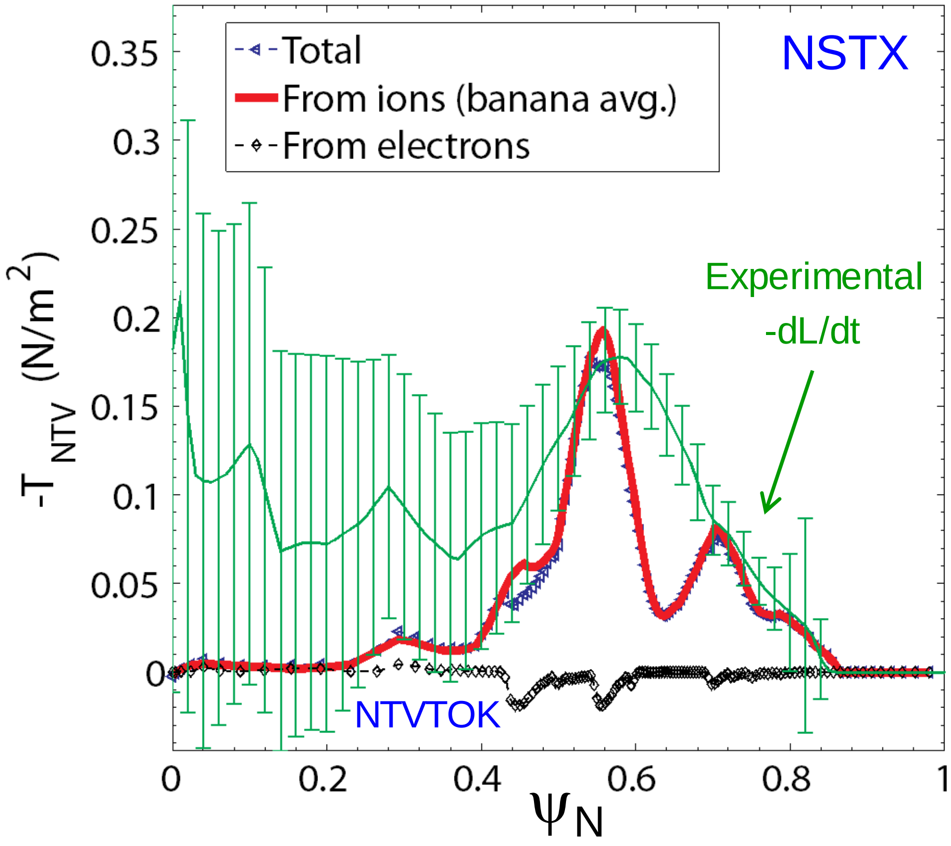
Physical characteristics of NTV are investigated in tokamaks for rotation control and the evaluation of plasma response

- ☐ Experiments on NSTX and KSTAR show that non-resonant NTV torque T_{NTV} from applied 3D field is a radially extended, relatively smooth profile
- ☐ Analysis of KSTAR shows $T_{NTV} \propto (\delta B_{3D})^2$; $T_{NTV} \propto T_i^{2.27}$; no hysteresis on the rotation profile when altered by non-resonant NTV (key for control)
- ☐ 3D field perturbation experiments in NSTX using both n = 2 and n = 3 field configurations measure the T_{NTV} profile
- ☐ The measured T_{NTV} profile quantitatively compares well between experiment and Shaing's "connected NTV theory" K.C. Shaing, et al., NF **50** (2010) 025022)
- ☐ Non-resonant T_{NTV} profile in NSTX is quantitatively consistent with "fully-penetrated field" assumption of plasma response
- ☐ Surface-averaged 3D field profile from M3D-C^1 single fluid model consistent with field used for quantitative NTV agreement in experiment
- ☐ Rotation controller using NTV and NBI designed/tested for NSTX-U

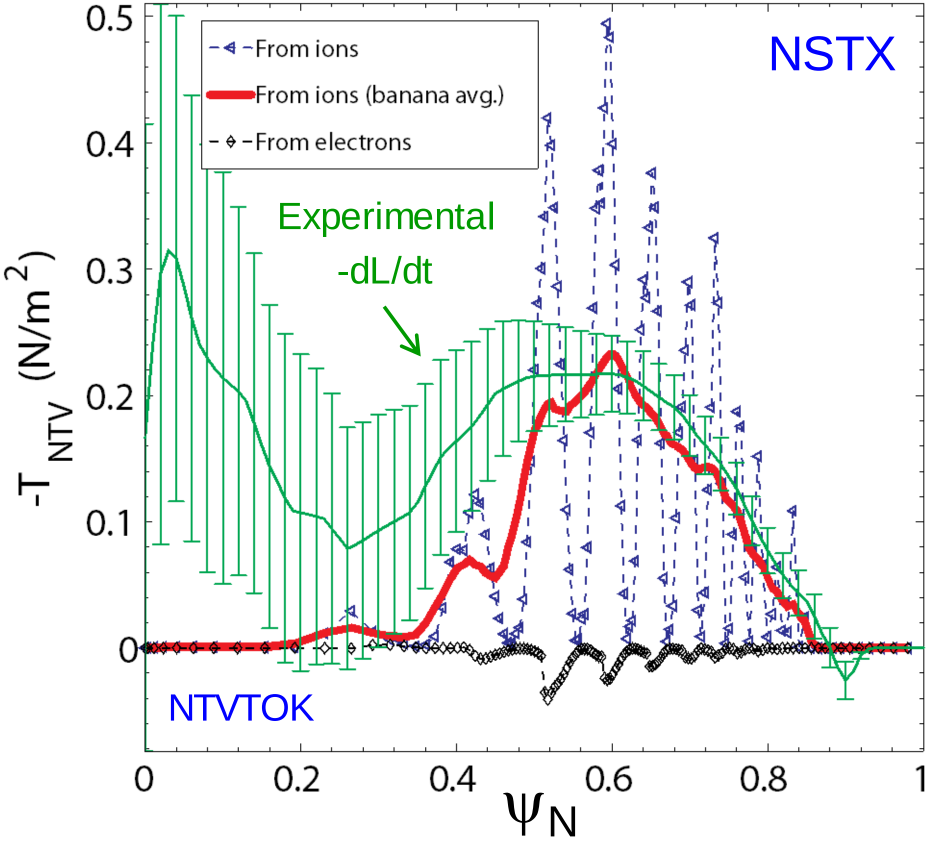
Extra slides for poster

Measured NTV torque density profiles quantitatively compare well to computed T_{NTV} using fully-penetrated 3D field

n = 2 coil configuration



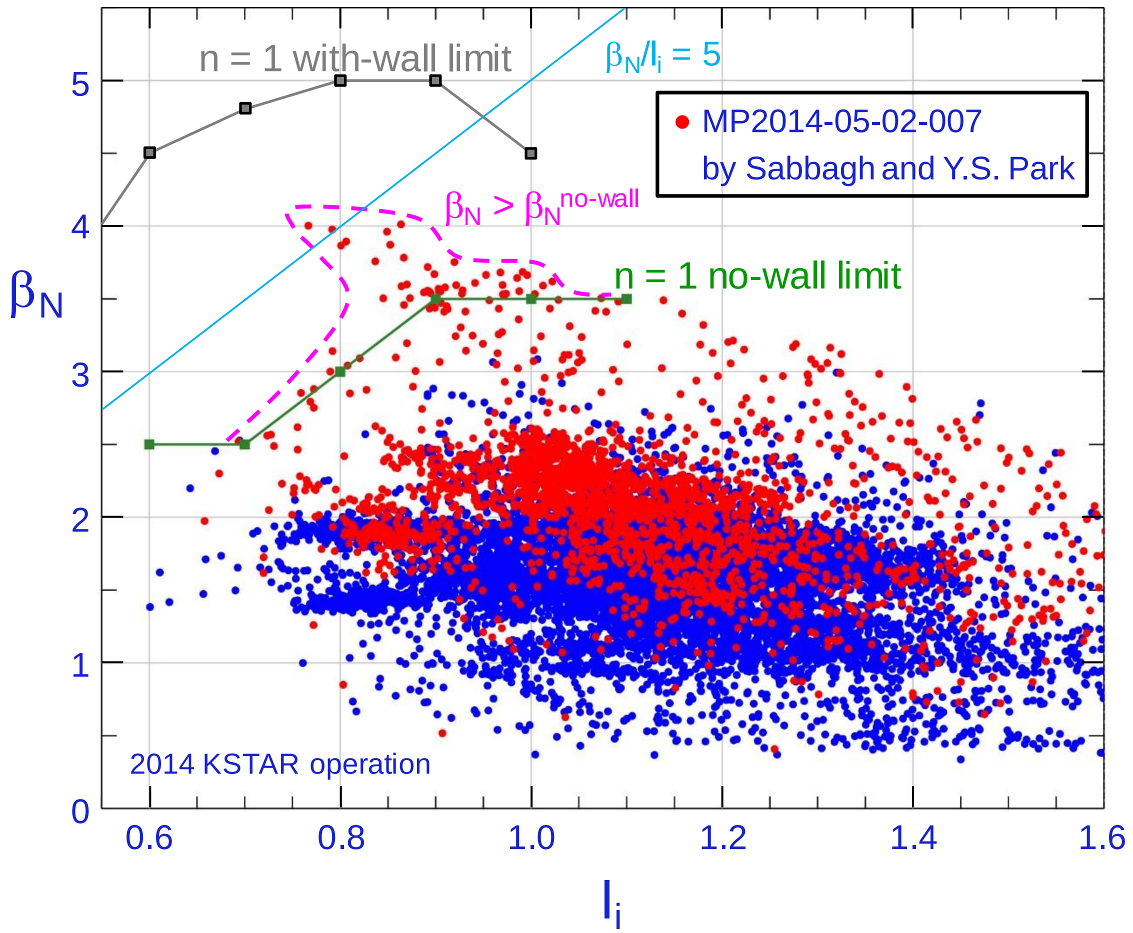
n = 3 coil configuration



- T_{NTV} (theory) scaled to match *peak* value of measured *-dL/dt*
  - Scale factor ($(dL/dt)/T_{NTV}$) = 1.7 and 0.6 (for cases shown above) – O(1) agreement
  - O(1) agreement using "fully-penetrated 3D field" indicates that plasma response is <u>*not*</u> strongly amplified from this "vaccum field assumption" ($T_{NTV} \sim \delta B^2$)

Very recently, high beta plasmas transiently reached β_N = 4 in 2014 campaign

KSTAR operating space containing ~11,500 equilibria



- Values obtained using fully converged KSTAR EFIT reconstructions
- High values reached transiently at lowered B_t
    - B_T in range 0.9 - 1.2 T
    - β_N up to 4 with l_i ~ 0.8 for duration longer than τ_E ~60 ms in these discharges
    - β_N/l_i = 5 is ~ 40% over the computed n = 1 ideal MHD no-wall limit
- Adding newly available 3rd neutral beam source may further increase the operating performance in the ongoing device campaign

Y.S Park, et al., IAEA FEC 2014 paper EX/P8-05 (Fri. PM)

S.W. Yoon, et al., IAEA FEC 2014 paper OV/3-4 (Tues. AM)

Non-resonant Neoclassical Toroidal Viscosity (NTV) physics will be used for the first time in rotation feedback control

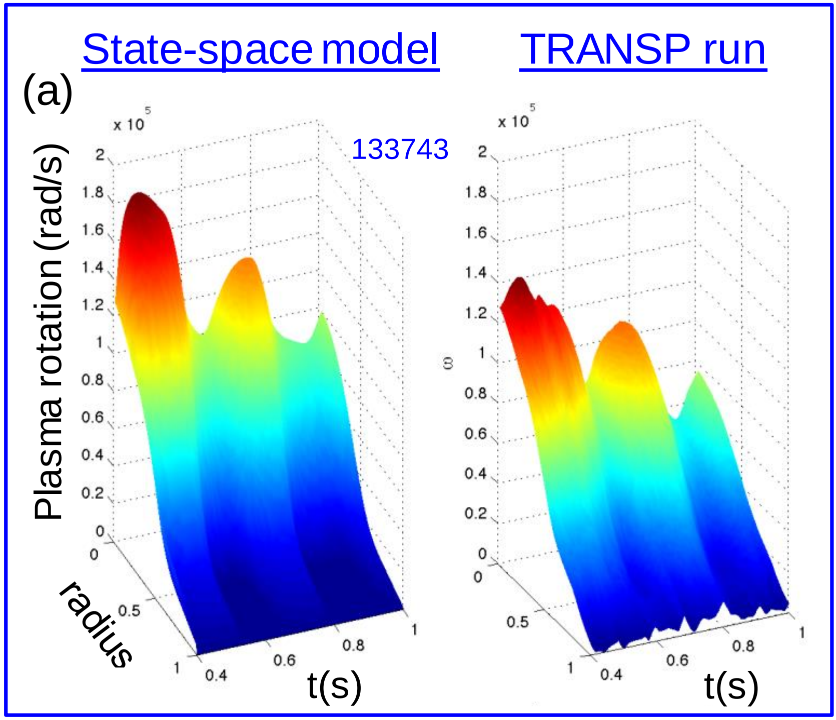
- Momentum force balance – ω_ϕ decomposed into Bessel function states

$$\sum_i n_i m_i \left\langle R^2 \right\rangle \frac{\partial \omega}{\partial t} = \left(\frac{\partial V}{\partial \rho} \right)^{-1} \frac{\partial}{\partial \rho} \left[\frac{\partial V}{\partial \rho} \sum_i n_i m_i \chi_\phi \left\langle \left(R \nabla \rho \right)^2 \right\rangle \frac{\partial \omega}{\partial \rho} \right] + T_{NBI} + T_{NTV}$$

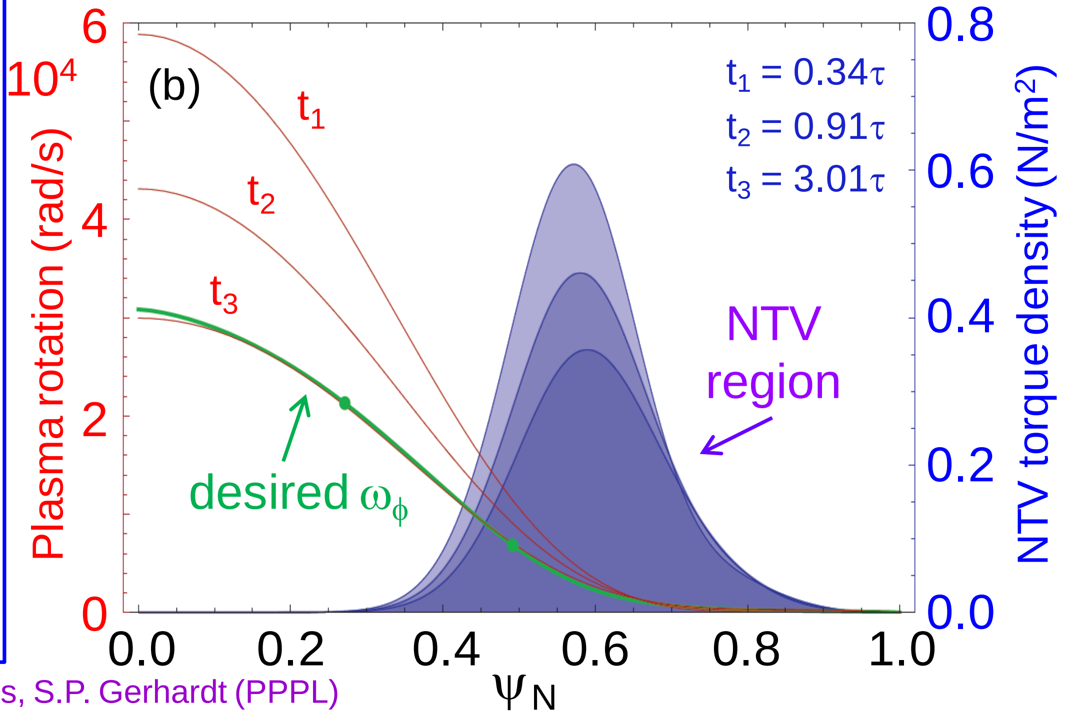
- NTV torque:

$$T_{NTV} \propto K \times f\left(n_{e,i}{}^{K1} T_{e,i}{}^{K2} \right) g\left(\delta B(\rho) \right) \left[I_{coil}{}^2 \omega \right]$$

(non-linear)

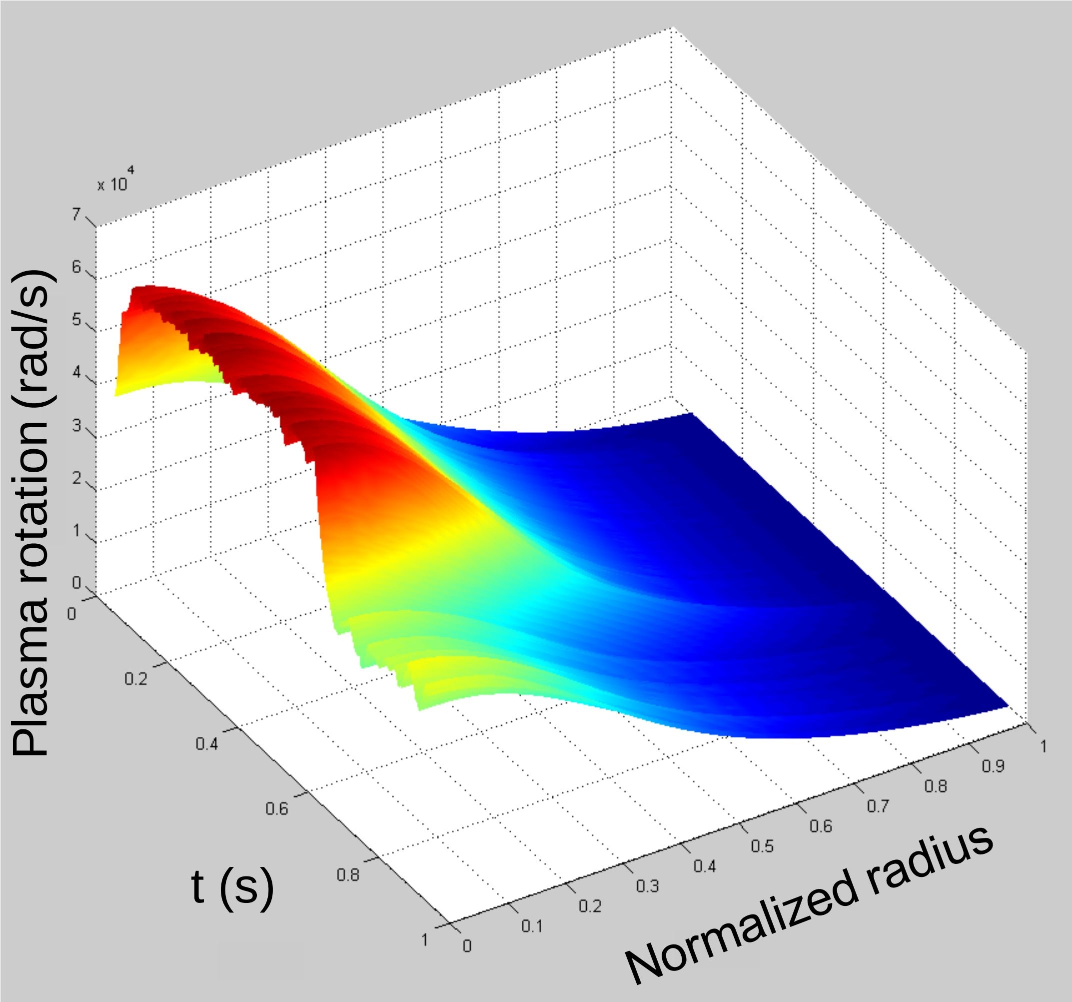


Feedback using NTV: "n=3" $\delta B(\rho)$ spectrum



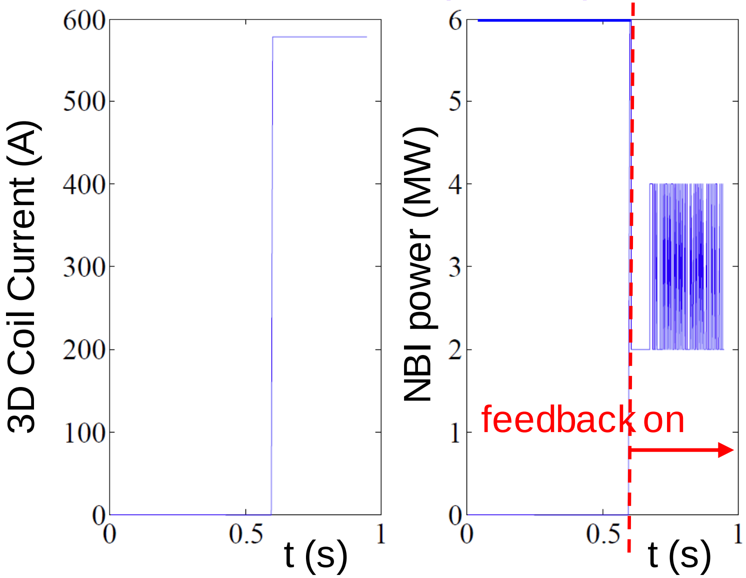
I. Goumiri (PU), S.A. Sabbagh (Columbia U.), D.A. Gates, S.P. Gerhardt (PPPL)

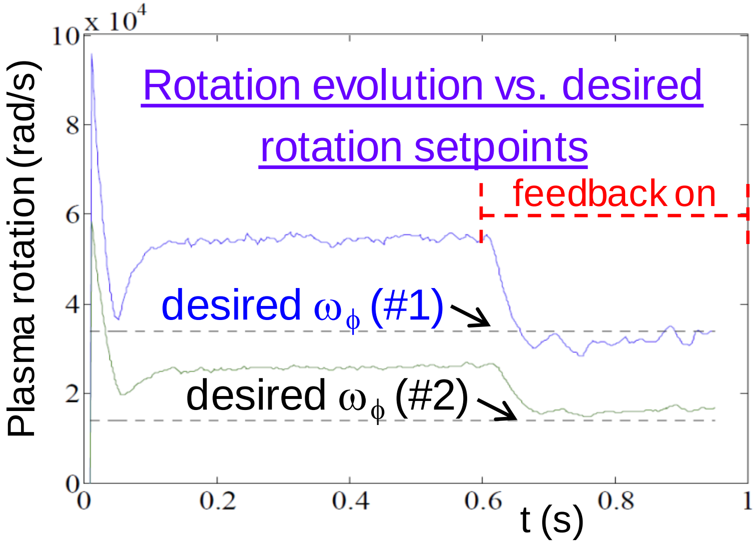
Plasma rotation control has been demonstrated for the first time with TRANSP using NBI and NTV actuators



This case uses pre-programmed 3D coil current and NBI feedback

3D coil current and NBI power (actuators)





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Extra slides

Several ordered publications by K.C. Shaing, et al. led to the "Combined" NTV Formulation

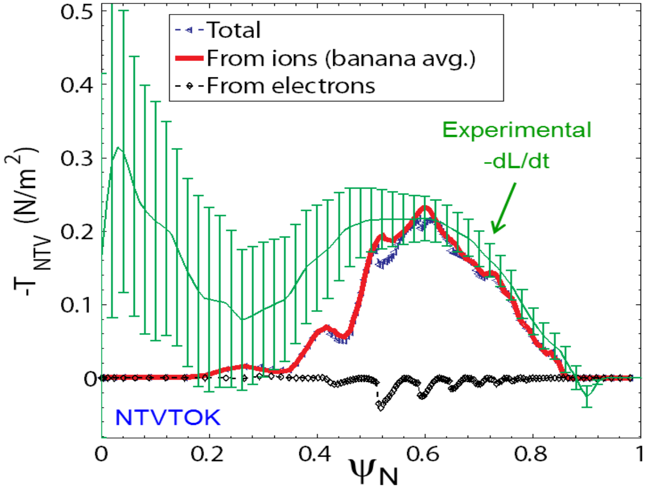
❑ Publications (chronological order)	❑ Topic
1) K.C. Shaing, S.P. Hirschman, and J.D. Callen, Phys. Fluids **29** (1986) 521.	➢ Plateau transport
2) K.C. Shaing, Phys. Rev. Lett., **87** (2001) 245003.	➢ Island NTV
3) K.C. Shaing, Phys. Plasmas **10** (2003) 1443.	➢ Collisional, $1/\nu$ regimes
4) K.C. Shaing, Phys. Plasmas **13** (2006) 052505.	➢ Banana, $1/\nu$ regimes
5) K.C. Shaing, S. A. Sabbagh, and M. Peng, Phys. Plasmas **14** (2007) 024501.	➢ Multiple trapping
6) K.C. Shaing, S. A. Sabbagh, M.S. Chu, et al., Phys. Plasmas **15** (2008) 082505.	➢ Orbit squeezing
7) K.C. Shaing, P. Cahyna, M. Becoulet, et al., Phys. Plasmas **15** (2008) 082506.	➢ Coll. b'dary layer, $\nu^{0.5}$
8) K.C. Shaing, S. A. Sabbagh, and M. S. Chu, PPCF **51** (2009) 035004.	➢ Low ν regimes
9) K.C. Shaing, S. A. Sabbagh, and M. S. Chu, PPCF **51** (2009) 035009.	➢ Superbanana plateau
10) K.C. Shaing, S. A. Sabbagh, and M. S. Chu, PPCF **51** (2009) 055003.	➢ Superbanana regime
11) K.C. Shaing, M. S. Chu, and S. A. Sabbagh, PPCF **51** (2009) 075015.	➢ Bounce/transit/drift res.
12) K.C. Shaing, M. S. Chu, and S. A. Sabbagh, PPCF **52** (2010) 025005.	➢ $J_{bootstrap}$ w/resonances
13) K.C. Shaing, S. A. Sabbagh, and M. S. Chu, Nucl. Fusion **50** (2010) 025022.	➢ Combined NTV formula
14) K.C. Shaing, J. Seol, Y.W. Sun, et al., Nucl. Fusion **50** (2010) 125008.	➢ ∇B drift in CBL analysis
15) K.C. Shaing, M. S. Chu, and S. A. Sabbagh, Nucl. Fusion **50** (2010) 125012.	➢ Flux/force gen. coords.
16) K.C. Shaing, T.H. Tsai, M.S. Chu, et al., Nucl. Fusion **51** (2011) 073043.	➢ SBP regime refinement
17) K.C. Shaing, M.S. Chu, C.T. Hsu, et al., PPCF **54** (2012) 124033.	➢ NTV brief overview

EX/1-4: Physical Characteristics of Neoclassical Toroidal Viscosity in Tokamaks for Rotation Control and the Evaluation of Plasma Response

Highlights

- ❑ Experimental NTV characteristics
  - ❑ NTV experiments on NSTX and KSTAR
  - ❑ NTV torque T_{NTV} from applied 3D field is a radially extended, relatively smooth profile
  - ❑ Perturbation experiments measure T_{NTV} profile
- ❑ Aspects of NTV for rotation control
  - ❑ Varies as δB^2; $T_{NTV} \propto T_i^{5/2}$ in primary collisionality regime for large tokamaks
  - ❑ No hysteresis on the rotation profile when altered by non-resonant NTV is key for control
  - ❑ Rotation controller using NTV and NBI tested for NSTX-U; model-based design saves power
- ❑ NTV analysis to assess plasma response
  - ❑ Non-resonant NTV quantitatively consistent with fully-penetrated field assumption
  - ❑ Surface-averaged 3D field profile from M3D-C^1 single fluid model consistent with field used for quantitative NTV agreement in experiment

Perturbation experiments measure NTV torque profile and compare to theory



Rotation controller using NTV and NBI