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Isolation of Neoclassical Toroidal Viscosity Profile Under Varied Plasma and 3D Field Conditions in Low and Medium Aspect Ratio Tokamaks*

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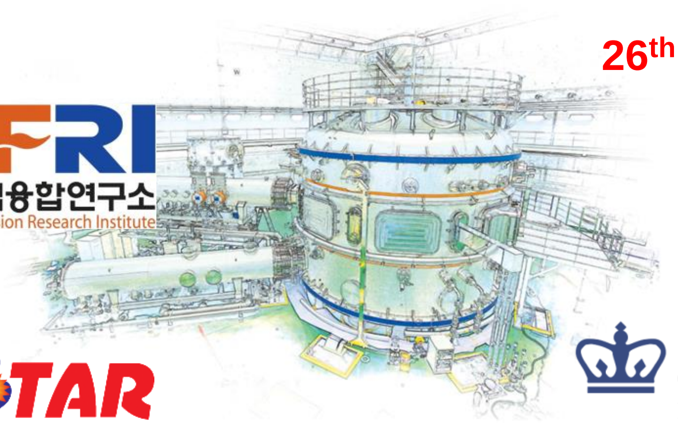

KSTAR

26th IAEA Fusion Energy Conference

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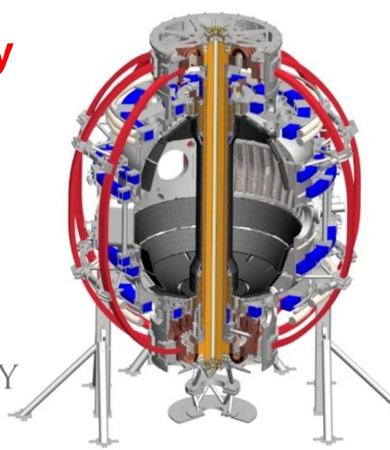
Kyoto, Japan

COLUMBIA UNIVERSITY IN THE CITY OF NEW YORK



PPPL

NSTX-U

V1.2

**This work supported by the US DOE contract DE-AC02-09CH11466, DE-FC02-04ER54698, and DE-FG02-99ER54524*

Key physical characteristics of NTV are investigated in low and medium aspect ratio tokamaks

Motivation

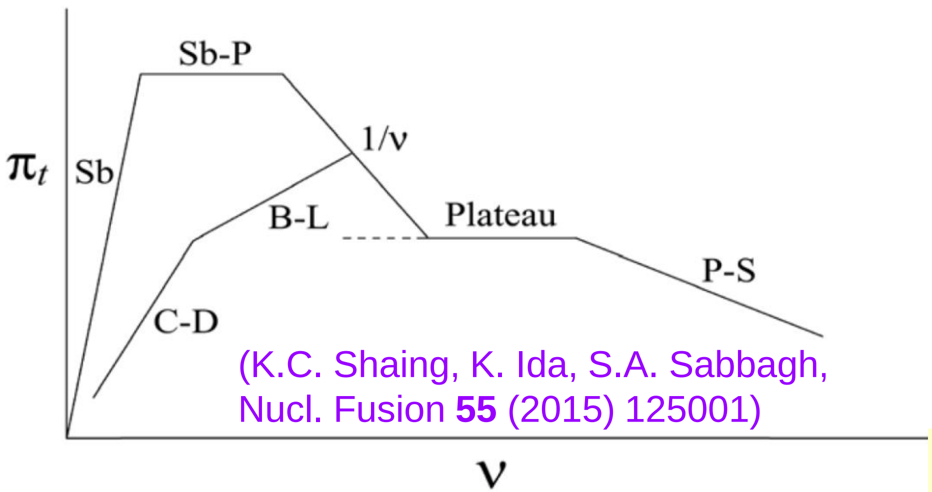
- Low magnitude ($\delta B/B_0 \sim O(10^{-3})$) 3D magnetic fields are used favorably used in tokamaks (e.g. ELM suppression, MHD mode control)
- 3D fields of this magnitude can produce neoclassical toroidal viscosity (NTV), which can:
  - Alter plasma rotation non-resonantly (without mode locking)
  - Potentially create stabilizing plasma rotation, V_ϕ, V_ϕ shear (e.g. in ITER)
- Therefore, it is important to understand NTV in tokamaks, backed by accurate (~$O(1)$) quantitative modeling

Outline

- NTV profile isolation experiments in NSTX and KSTAR
- NTV comparison of theory to experiment in NSTX
- Recent NTV offset rotation experiments in KSTAR (Sept 2016)

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, K. Ida, S.A. Sabbagh, Nucl. Fusion **55** (2015) 125001)

NTV force in "1/ν" collisionality regime

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

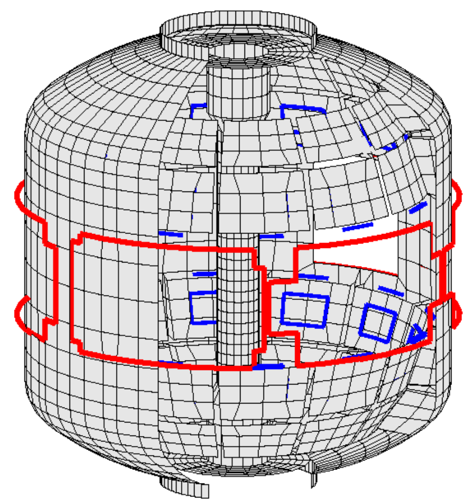
NTV "offset" rotation

$T_i^{5/2}$

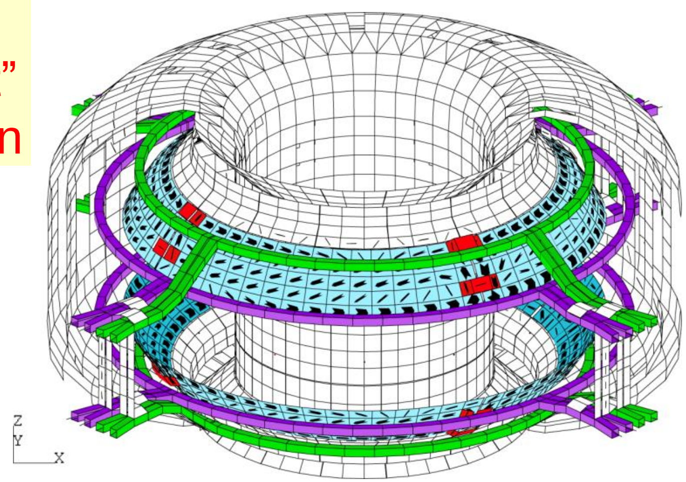
plasma rotation

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

NSTX 3D coils



KSTAR 3D coils (IVCC)

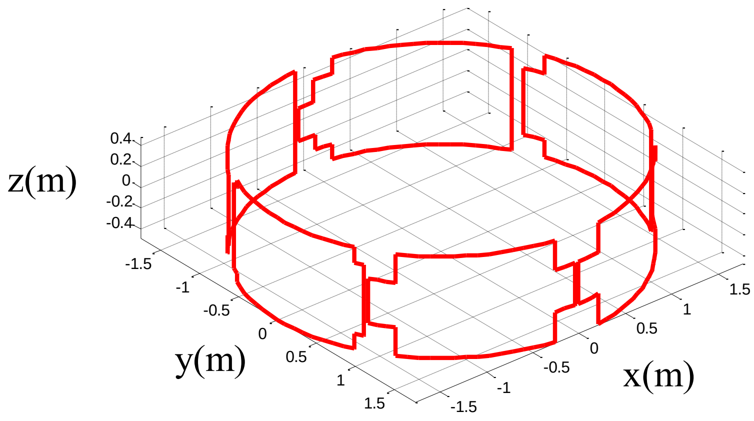


3D field perturbation experiments conducted to isolate and measure the T_{NTV} profile in NSTX and KSTAR

- 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})
- Emphasize non-resonant applied 3D field configurations
  - Use n = 2 and 3 field configurations to avoid driving MHD modes
  - n = 1 field configurations with different pitch investigated in KSTAR

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

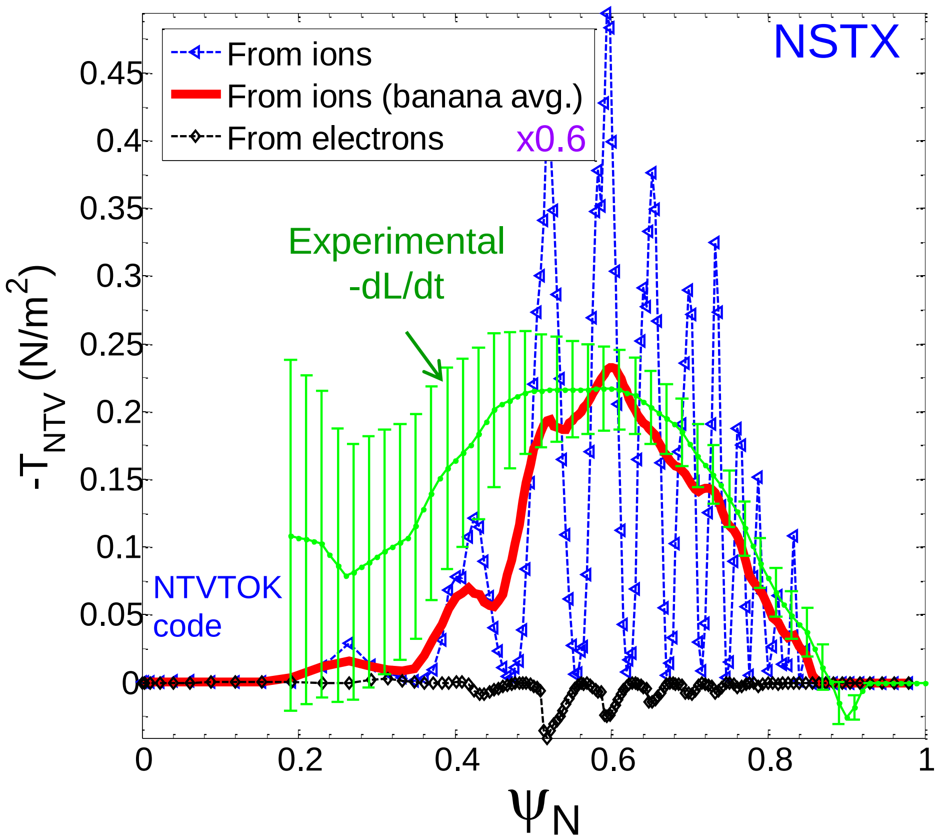
$$\delta B = \vec{b} \bullet \left(\vec{B} / B \right) + \left(\vec{\xi} \bullet \nabla B \right)$$

↑ plasma displacement

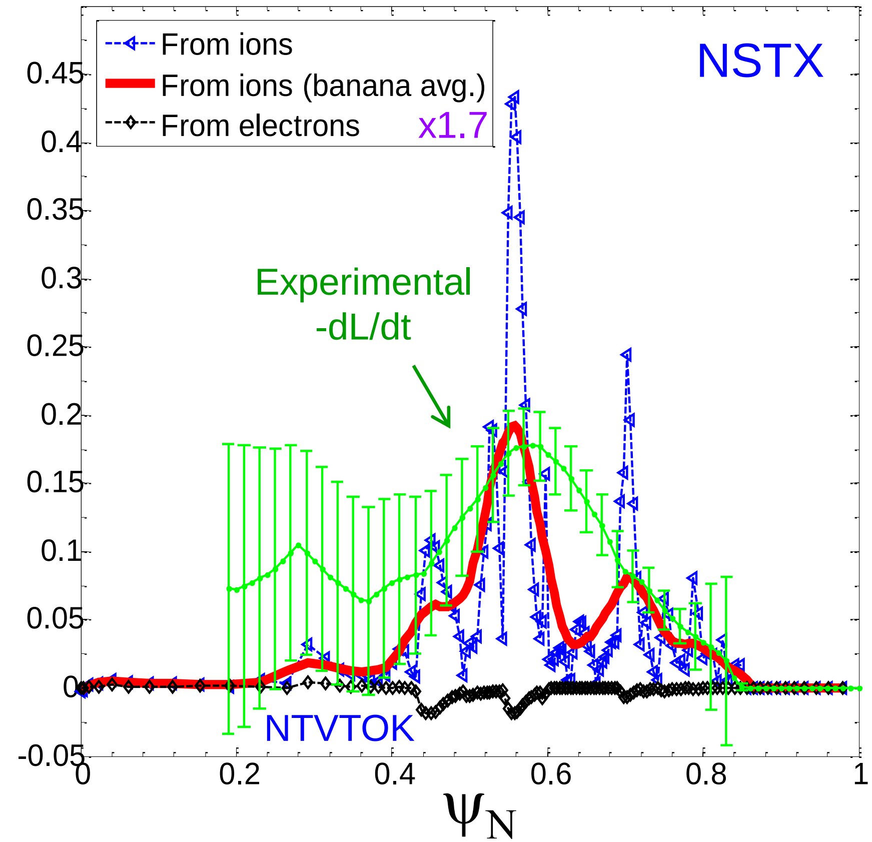
- General considerations
  - In tokamaks, ξ not typically measured, can lead to large error
  - "Fully-penetrated field constraint" used to define ξ $\left(\vec{B}_{2D} \bullet \nabla \vec{\xi} = \vec{b} \right)$
    - Singularities avoided by standard finite island width assumption
  - For NSTX, $|\xi|$ ~ 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 = 3 coil configuration



n = 2 coil configuration

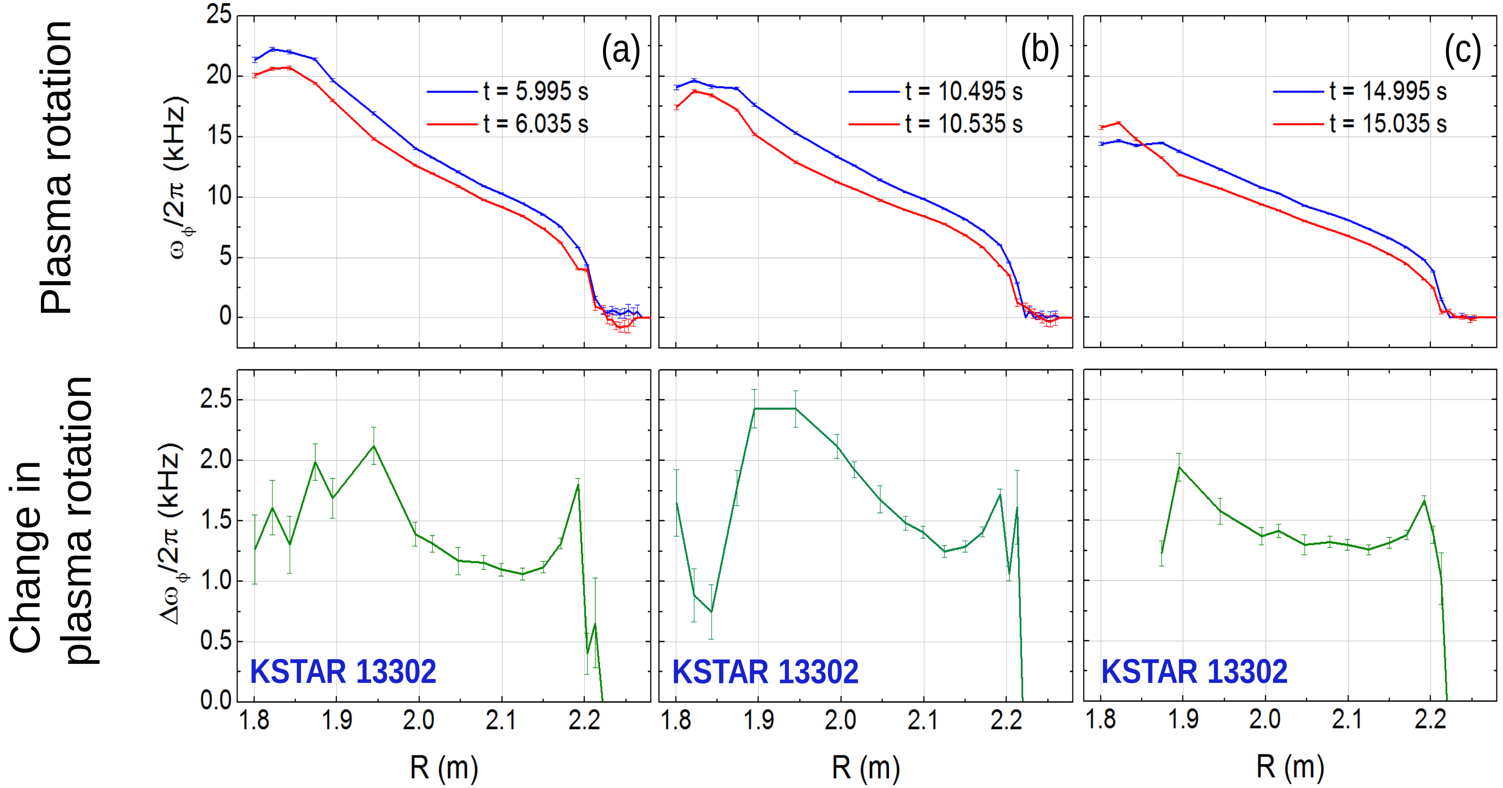


- T_{NTV} (theory) scaled to match *peak* value of measured *-dL/dt*
  - Scale factor $((dL/dt)/T_{NTV})$ = 0.6 and 1.7 for cases shown above – O(1) agreement
- Banana orbit-averaging reduces computed resonant perturbation effects

K.C. Shaing, and S.A. Sabbagh, et al., Phys. Plasmas **23** (2016) 072511

KSTAR experiment using different 3D field spectra established isolated NTV profile using fast power supply

IVCC n = 2 configuration   n = 1 pitch non-aligned   n = 1 pitch aligned



- Results show non-resonant NTV characteristics; broad NTV torque profile
  - $\Delta\omega_\phi$ does not change sign across profile (non-resonant); $\Delta\omega_\phi$ ~ 0 near plasma edge
  - 3D field spectrum varied: similar $\Delta\omega_\phi$ profiles, n = 1 pitch non-aligned has largest NTV
- KSTAR n = 2 NTV experiments do not exhibit hysteresis (linear behavior)

See recent NTV review paper: K.C. Shaing, K. Ida, S.A. Sabbagh, et al., Nucl. Fusion **55** (2015) 125001

The NTV Offset Rotation Profile, V_0^{NTV}, was recently directly measured in KSTAR

- **Motivation**
  - Plasma rotation highly important for tokamak stability and confinement
  - Future fusion devices are envisioned to have far less momentum input
  - ➔ If sufficiently strong, this rotation could provide stabilization and improved performance in ITER and future devices
- **Experiment overview**
  - Used ECH for plasma heating, avoided issues of strong NBI torque
  - Measured intrinsic rotation using NBI as a diagnostic beam for CES
- **Issues related to experiments with NBI torque**
  - T_{NBI} term is
    - Computed, not directly measured
    - Typically much larger than the T_{NTV} component due to offset rotation ➔analysis is prone to error
    - The T_{NBI} *profile* matters – not just zero net input torque from NBI

Intrinsic Torque due to Neoclassical Toroidal Viscosity (NTV) – a controllable momentum source via 3D field

(K.C. Shaing, K. Ida, S.A. Sabbagh, Nucl. Fusion **55** (2015) 125001)
(Y. Sun, K. Liang, K.C. Shaing, et al. Nucl. Fusion **51** (2011) 053015)

- Full Theory
  - The non-ambipolar difference of ion and electron flux due to the application 3D fields yields a so-called “offset rotation profile”, V_0^{NTV}
  - Generally, the local rotation speed can be either in the co- or counter-I_p direction if dominated by electron/ion flux, respectively

- Highly Simplified Theory
  - Consider a highly simplified theory to help understand characteristics
  - Simplified NTV torque profile: $T_{NTV} = C_1\, \delta B^2 (V_\phi - V_{0\text{-}NTV})$
  - Simplified V_0^{NTV} profile: $V_0^{NTV} = C_2\, dT_i/dr - C_3\, dT_e/dr$ (for future analysis)
    - Electron effects can dominate at low collisionality – important for ITER
  - Unlike “intrinsic rotation”, the T_{NTV} can be controlled by the applied 3D field spectrum and strength

Consider simple torque balance equation to further understand expected dynamics when measuring V_0^{NTV} profile

- Simple torque balance $$\frac{dL}{dt} = T_{NTV} + T_{NBI} + T_{RF} + T_{Intrinsic} - \frac{L}{\tau_{2D}}$$

  (e.g. W. Solomon, et al., Phys. Plasmas **17** (2010) 056108, Equation 8)

- Consider equations with/without 3D field (in steady-state)

$$T_{NTV} + (T_{RF} + T_{Intrinsic}) - \frac{L}{\tau_{2D}} = 0$$ (with 3D field ➔ L ➔ IV/R)

$$(T_{RF} + T_{Intrinsic}) - \frac{L(0)}{\tau_{2D}} = 0$$ (without 3D field ➔ L(0) ➔ IV_I/R)

- Use simple NTV model to express offset rotation

$$T_{NTV} = C_1 \delta B^2 (V_\emptyset - V_{0-NTV})$$

As 3D field strength increases, V_ϕ evolves from $V_{intrinsic}$ toward a saturated profile V_0^{NTV}

- **Combine equations**
  - Assume (T_{RF} + $T_{intrinsic}$) not function of 3D field; use simple T_{NTV} model

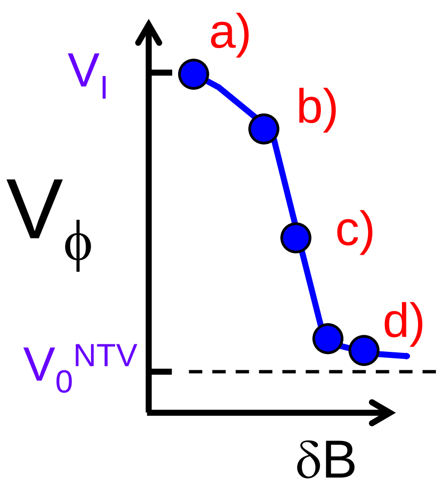
$$C_1 \delta B^2 (V_\emptyset - V_{0-NTV}) + \frac{I}{R\tau_{2D}}(V_\emptyset - V_I) = 0$$

- (V_I is the toroidal velocity measured without 3D field applied)
- I ➔ moment of inertia

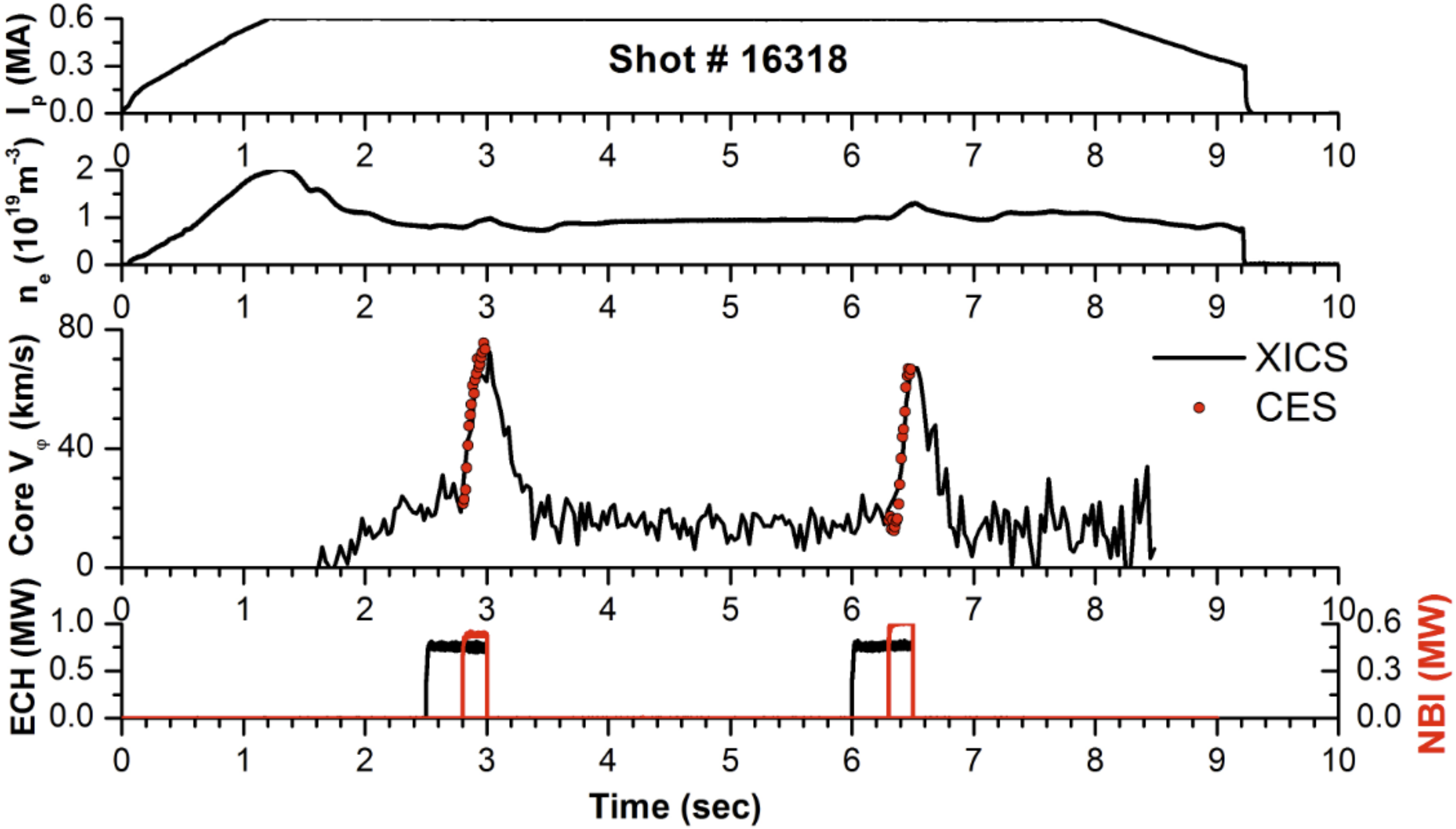
$$V_\emptyset = \left(\frac{C_1 \delta B^2}{C_1 \delta B^2 + I/R\tau_{2D}}\right) V_{0-NTV} + \left(\frac{I/R\tau_{2D}}{C_1 \delta B^2 + I/R\tau_{2D}}\right) V_I$$

(on each ψ surface)

- **Expected dynamics (4 different "conditions")**
  a) $\delta B = 0$: $V_\phi = V_I$
  b) low δB: measured V_ϕ profile close to V_I
  c) increased δB and ($|V_\phi| >> |V_0^{NTV}|$): V_ϕ ➔ V_0^{NTV}
  d) sufficiently high δB: V_ϕ saturates to V_0^{NTV}

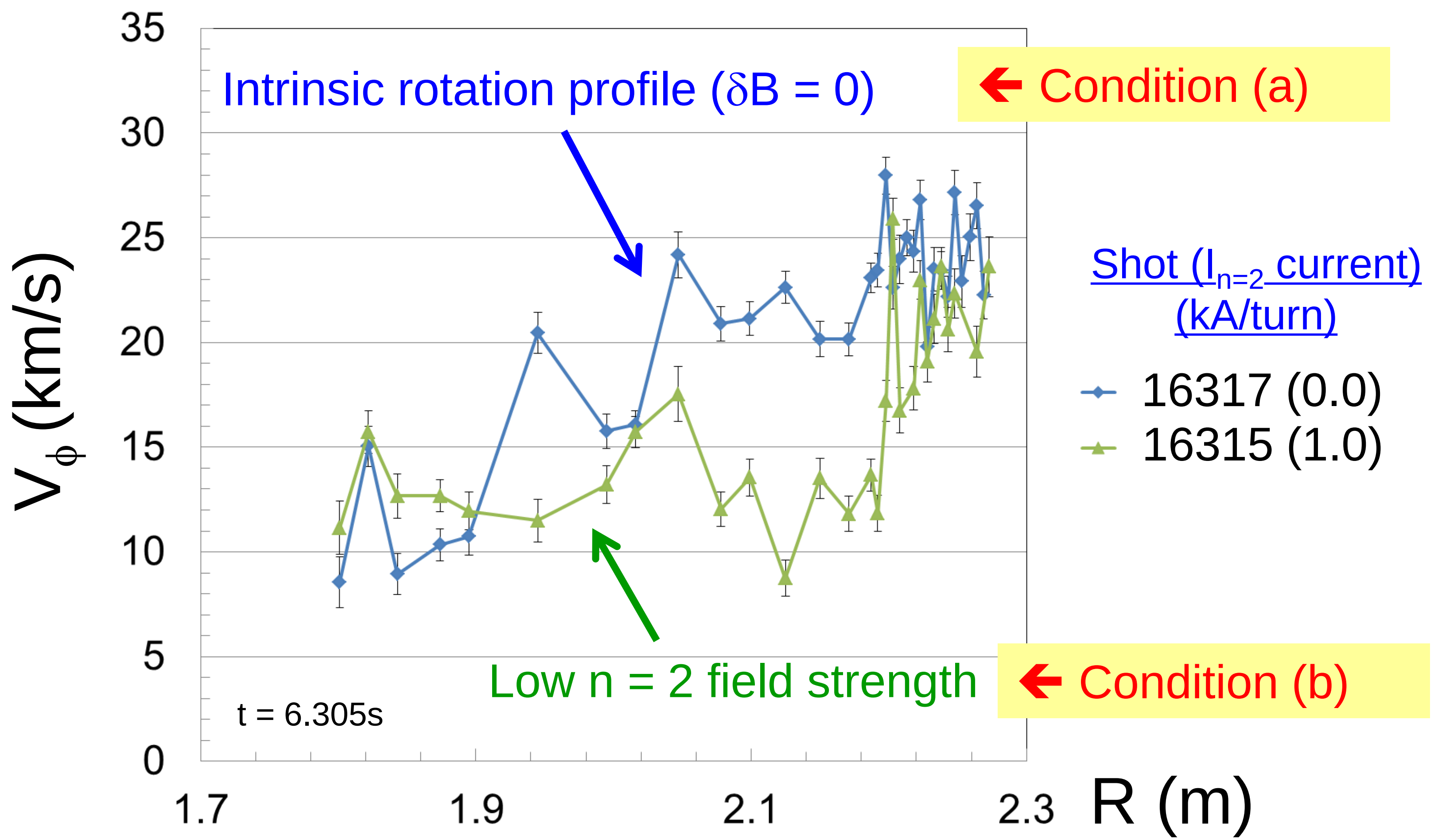


Target plasma with CES and XCIS measurement of plasma toroidal velocity (apply n = 2 field to this)



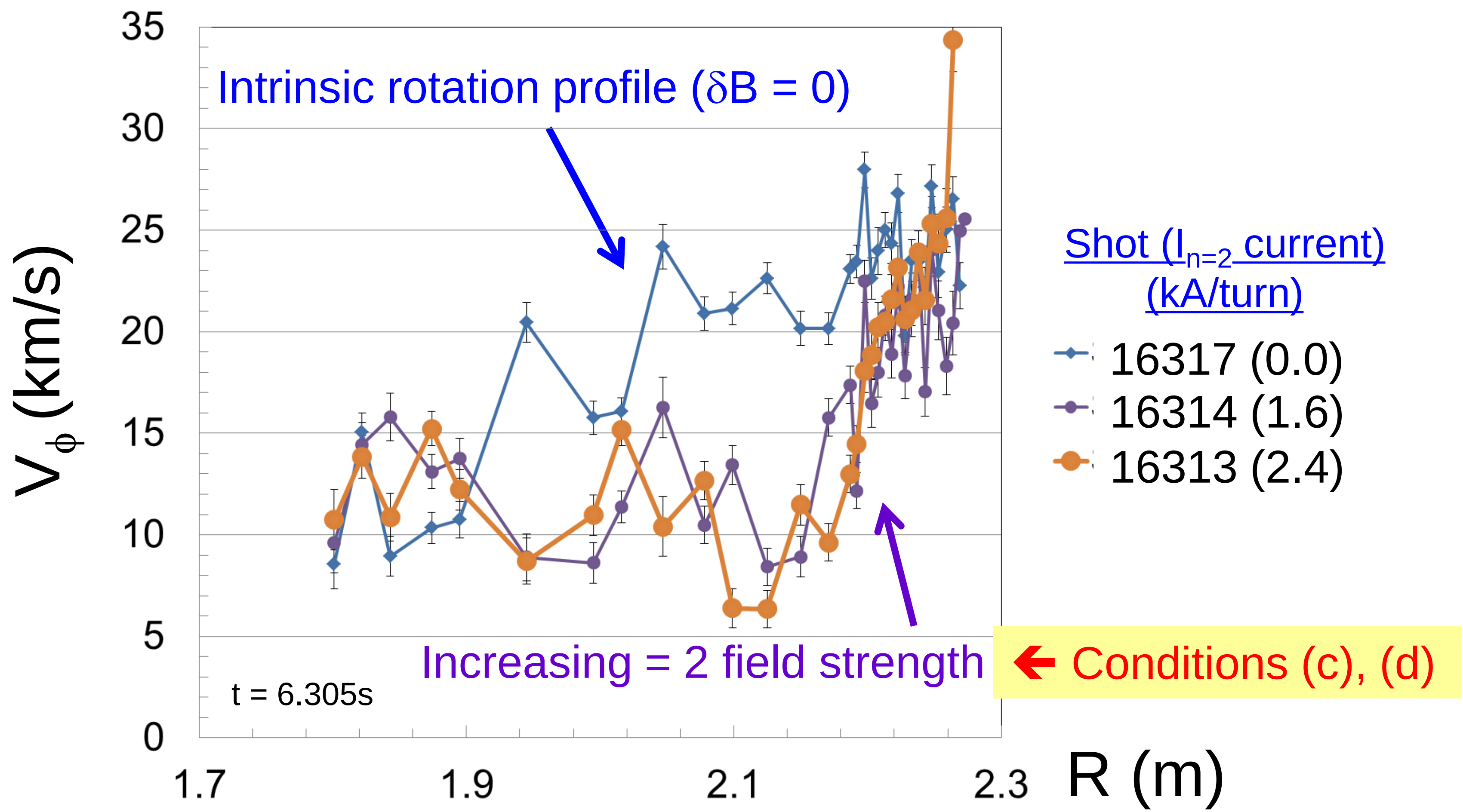
- X-ray crystal (XCIS) and charge exchange spectroscopy (CES) data agreement shows that plasma velocity is well described by the early CES time point
- NBI spins plasma in co-NBI direction – NOT ALWAYS true with 3D field!

Comparison of measured intrinsic rotation profile ($\delta B = 0$) and low level of applied n = 2 field clearly alters V_ϕ



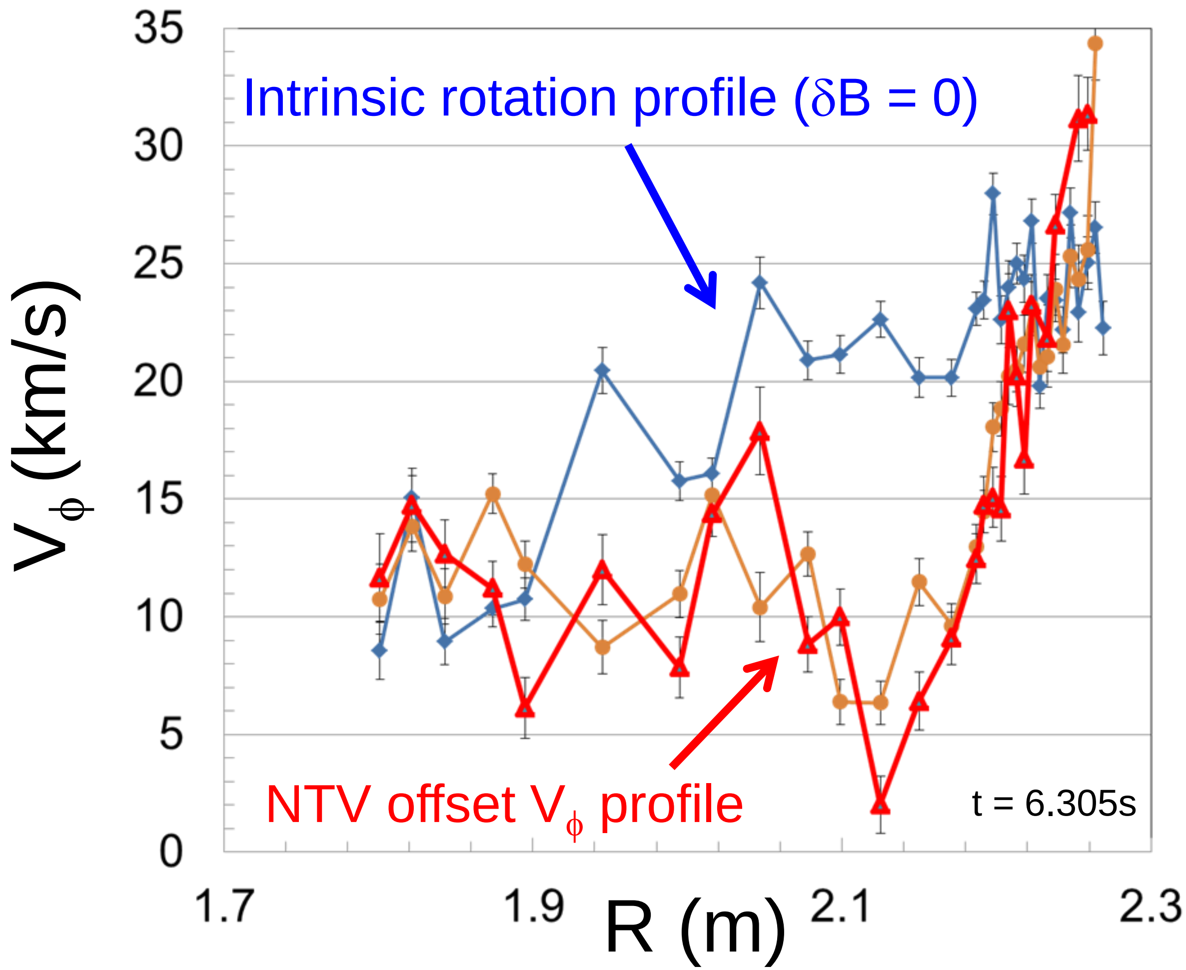
- Intrinsic rotation is defined as measured rotation profile with no applied 3D field
  - Note: ECH applied in this case, but ohmic cases were run as well

Increasing the applied n = 2 field strength leads to the saturation of the V_ϕ profile expected for NTV offset profile



- More than 2.2x increase in δB^2 in this step, with almost no change to V_ϕ profile
- NTV drag with V_ϕ profile >> V_0^{NTV} would produce change (more than 2.2x torque)

Final saturated NTV offset V_ϕ profile has much stronger V_ϕ shear at large R compared to the intrinsic rotation profile



15 times greater shear !

Shot ($I_{n=2}$ current) (kA/turn)

- 16317 (0.0)
- 16313 (2.4)
- 16312 (3.2)

Average shear (R > 2.14m)

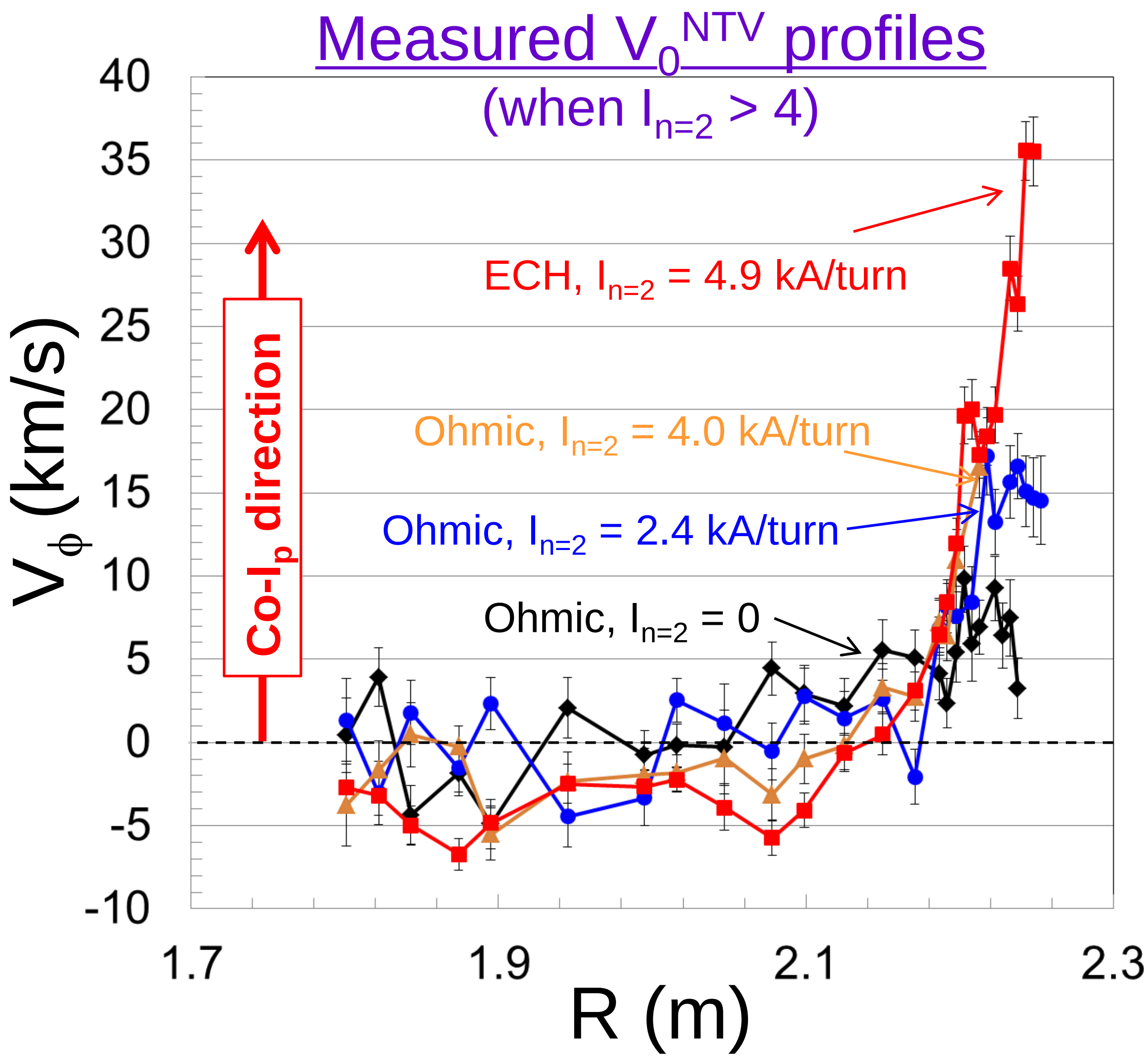
- $V^{-1}(dV/dr)$ (ECH) = 1.1 m^{-1}
- $V^{-1}(dV/dr)$ ($V_{0\text{-}NTV}$) = 15.4m^{-1}

- NTV offset V_ϕ profile has 15 times greater shear at large R
- Saturated profile at highest applied n = 2 current confirms increased V_ϕ at large R

The present results are potentially significant for ITER to provide strong plasma rotation and shear in outer plasma

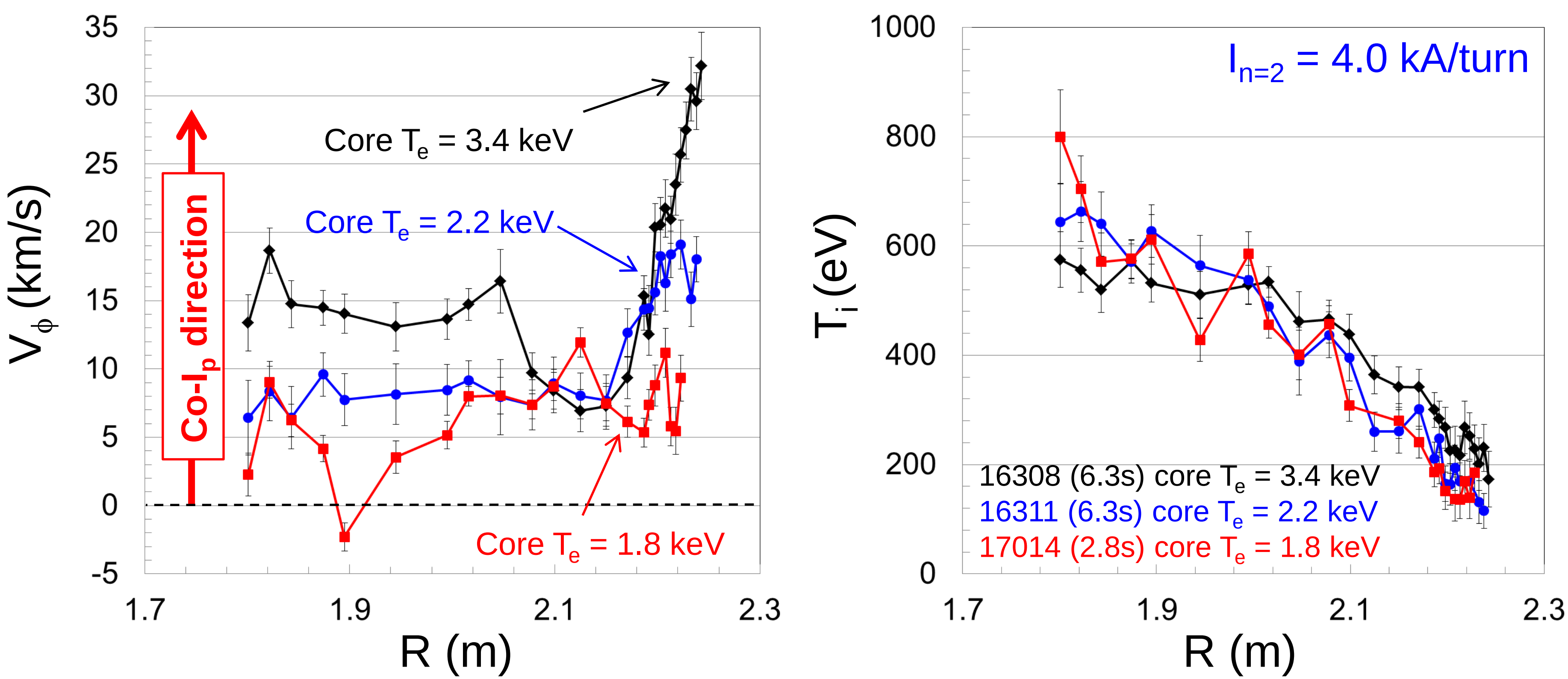
- Why unique?
  - First time that V_0^{NTV} profile has been directly measured w/ $T_{NBI} = 0$
  - First time V_0^{NTV} has been measured dominated by electron effects
    - V_0^{NTV} profile measured in the co-I_p direction
- Why important?
  - Co-I_p directed V_0^{NTV} can be higher than ECH-induced co-I_p rotation in edge region and is *controllable*
  - Rotation shear in the outer plasma region is 15 times stronger than rotation shear due to ECH
- ITER relevant: $|V_0^{NTV}|$ strong compared to simulations
  - ITER 15 MA ASTRA simulation: Ω_ϕ ~ 2 krad/s in edge region
  - Recent KSTAR experiment: Ω_ϕ > 12 krad/s in edge region (scaling?)
  - Potential to greatly increase rotation shear in outer plasma region

The NTV offset effect is produced in ohmic plasmas, and is observed to be *accentuated* by ECH heating



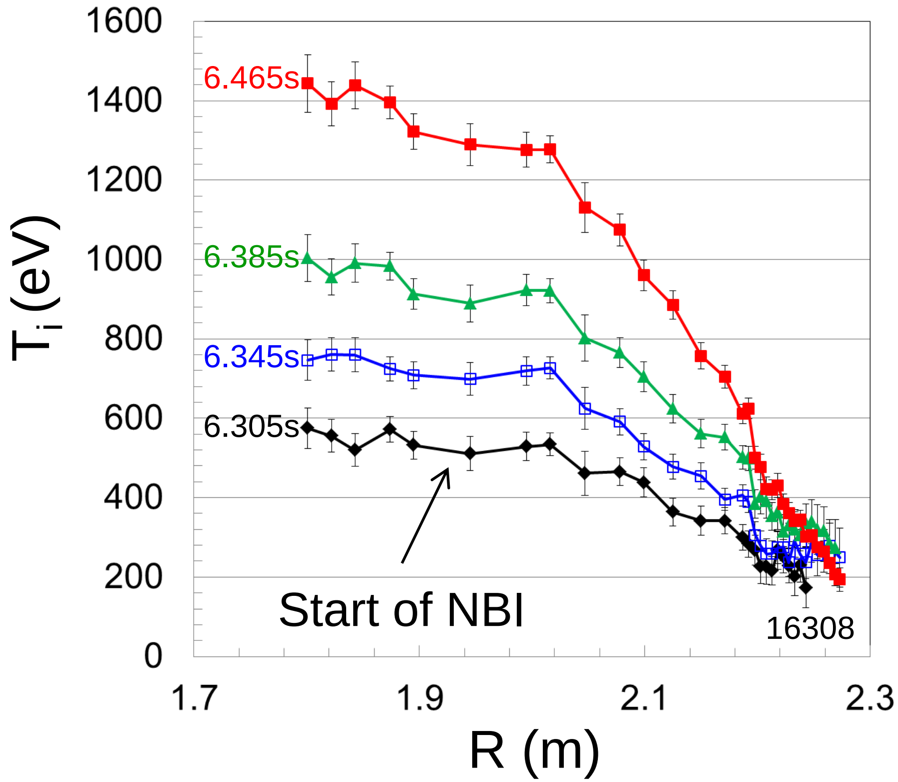
- Ohmic plasma V_ϕ ~ 0 in core, weak further out
- Applied n = 2 field increases V_ϕ ~ in outer region
  - Effect appears saturated at 4kA/turn (but no CES data outside R = 2.213m)
- Stronger n = 2 field + ECH heating clearly yields counter-I_p rotation in core, co-I_p rotation in outer region
  - Ctr-I_p only possible by V_0^{NTV}
  - Large outer V_ϕ shear

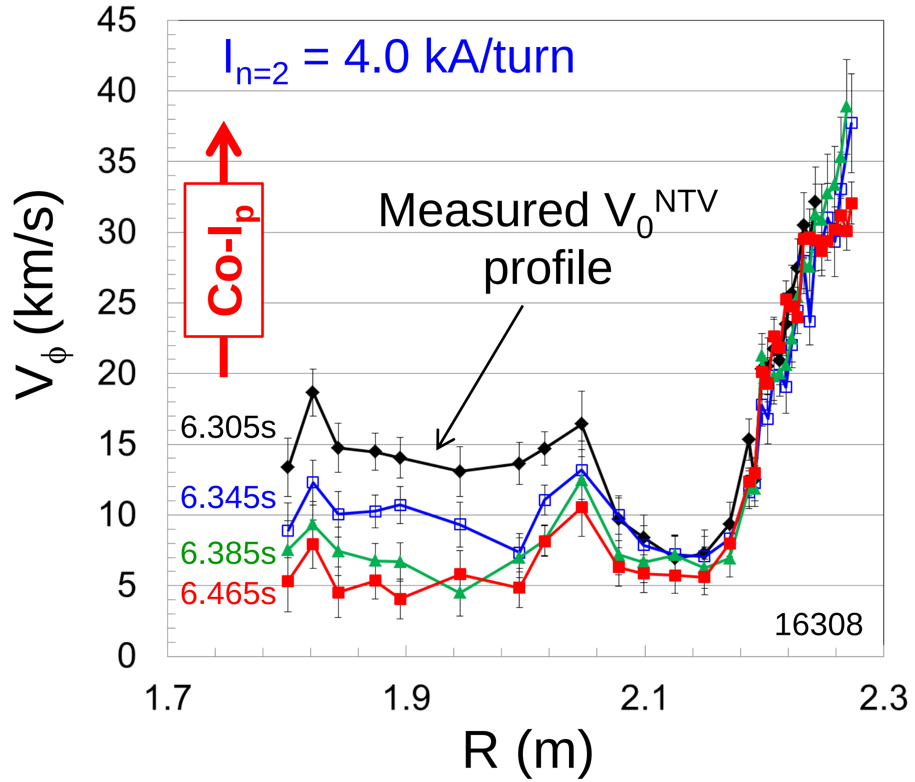
Varying plasma temperature shows V_0^{NTV} more strongly in co-I_p direction when T_e is higher



- Applied current for n = 2 field constant (4 kA/turn)
- Plasma temperature varied by altering density
- Results qualitatively follow NTV theory
  - V_0^{NTV} is more strongly in co-I_p direction when T_e is higher

co-NB injection produces *less co-rotation* away from V_0^{NTV} as T_i increases in strong 3D field





- Core plasma spins **down** with 3D field constant if δB, T_i are sufficiently high
- Outer plasma velocity remains at V_0^{NTV} profile value
- Non-intuitive result is consistent with NTV: Higher T_i increases NTV drag and/or makes NTV offset rotation migrate toward counter-NBI direction

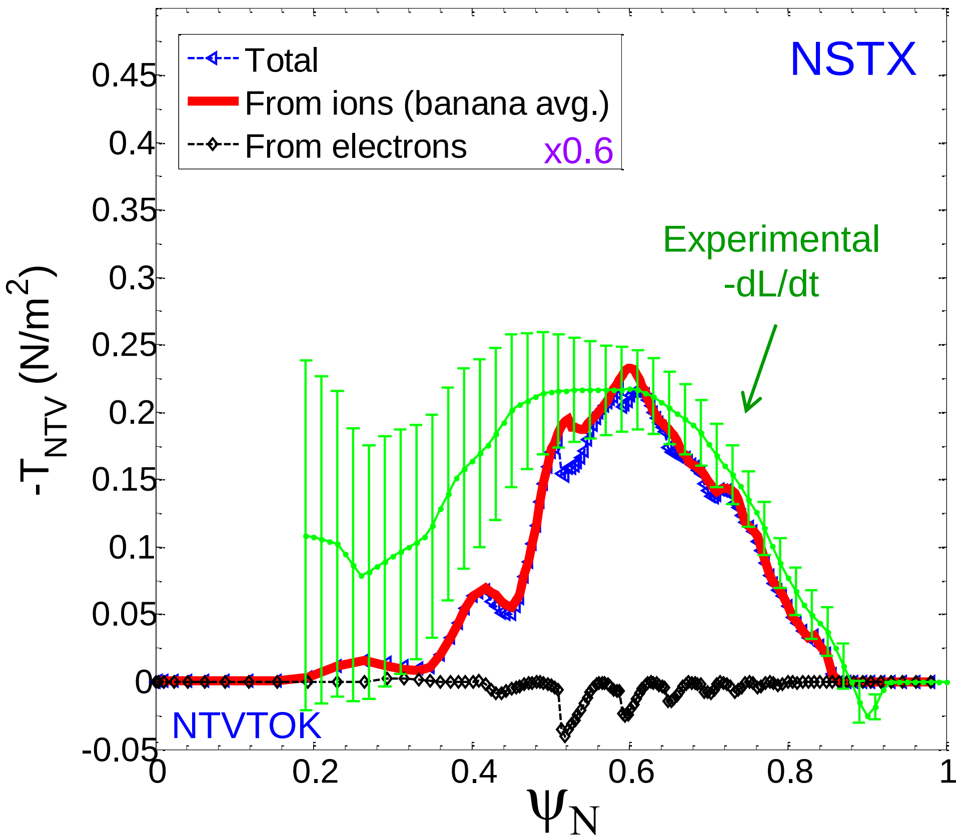
Experiments on NSTX and KSTAR isolated the NTV profile, and KSTAR XPs directly measured the offset rotation profile

- Measured, isolated NTV torque density profiles created in KSTAR / NSTX, quantitatively compare well to theoretical T_{NTV} using fully-penetrated 3D field (NSTX)
- The NTV offset rotation profile was recently directly measured in KSTAR
  - Incl. plasmas dominated by electron effects – measured in co-I_p direction
  - shown to reverse sign in the core region to counter-I_p outside of error bars - can only happen if the NTV offset rotation profile is non-zero (not drag)
- Relatively strong rotation and rotation shear were generated in outer region of the plasma by V_0^{NTV} - potentially highly important to ITER
  - Suggests use of ITER ELM coils to generate rotation/shear
- The $|V_0^{NTV}|$ is strongest and in co-I_p direction in outer part of plasma and remains steady in higher temperature plasmas
  - $|V_0^{NTV}|$ shown to decrease as temperature (temperature gradient?) decreases
- ANALYSIS CONTINUES on both NTV isolation analysis (e.g. plasma parameter and 3D spectrum dependence), NTV offset rotation profile comparison to theory

Supporting Slides Follow

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

n = 3 coil configuration



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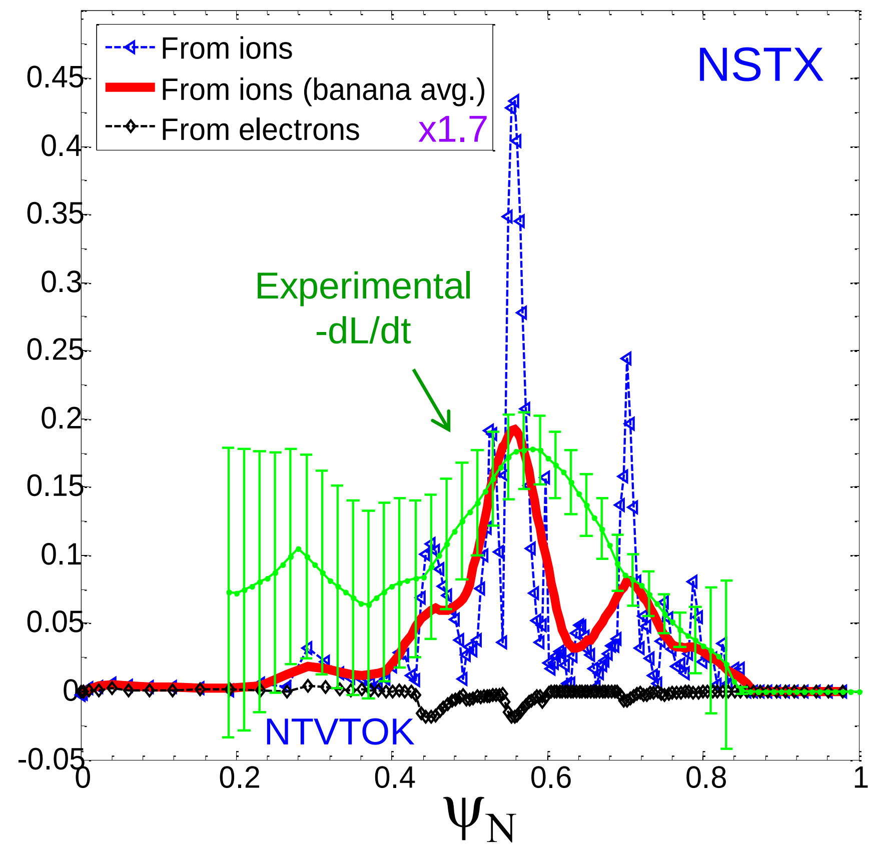

- T_{NTV} (theory) scaled to match *peak* value of measured *-dL/dt*
  - Scale factor (*(dL/dt)/*T_{NTV}) = 0.6 and 1.7 for cases shown above – O(1) agreement
- Banana orbit-averaging reduces computed resonant perturbation effects

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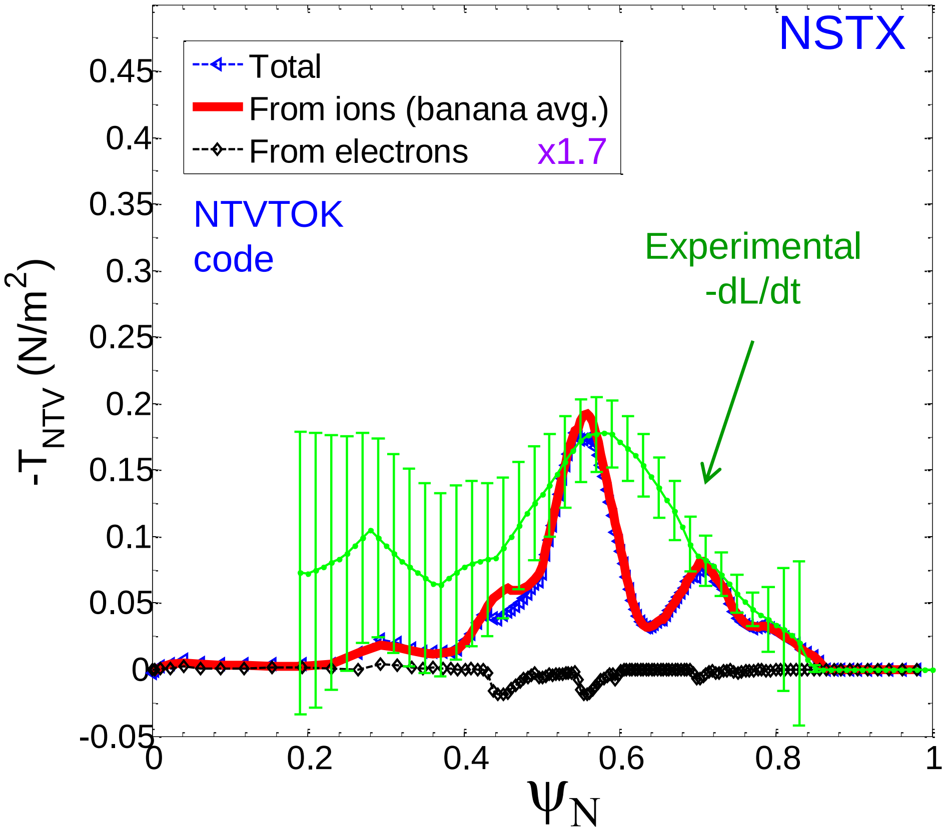

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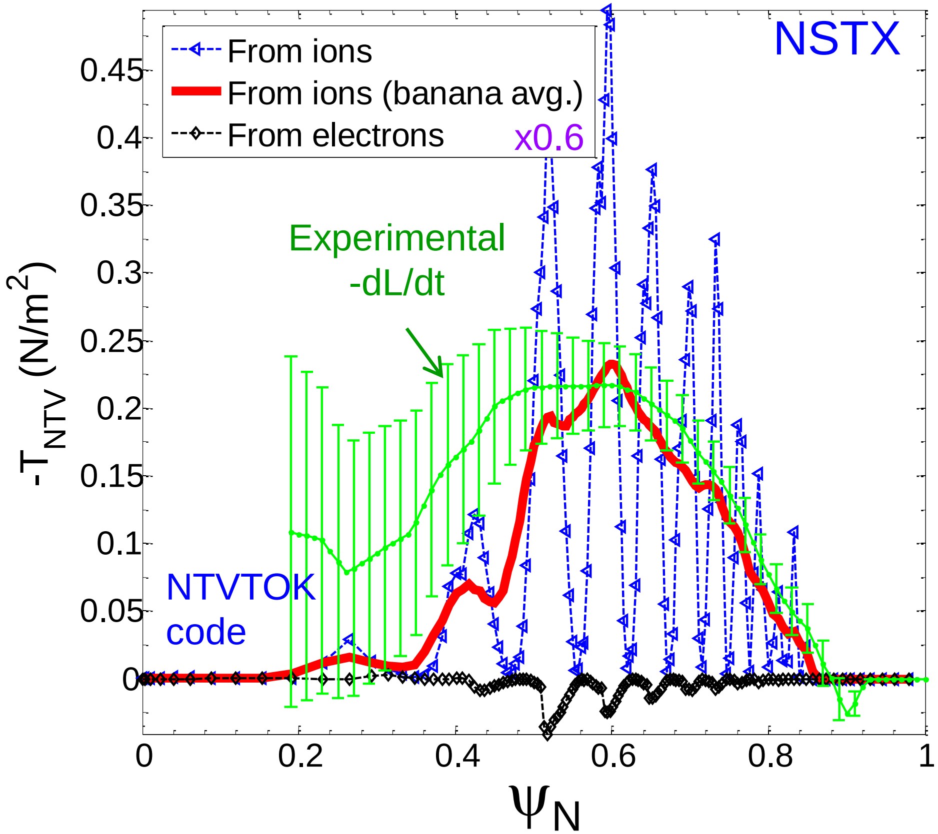

- T_{NTV} (theory) scaled to match *peak* value of measured *-dL/dt*
  - Scale factor ($(dL/dt)/T_{NTV}$) = 1.7 and 0.6 for cases shown above – O(1) agreement
- Banana orbit-averaging reduces computed resonant perturbation effects

K.C. Shaing, and S.A. Sabbagh, et al., Phys. Plasmas **23** (2016) 072511