Measurement of the NTV offset rotation profile in KSTAR

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presented at the

NSTX-U Physics Meeting

PPPL

September 12th, 2016

Princeton, NJ

(Supported by U.S. DOE grant DE-FG02-99ER54524)

Overview Outline of this Talk

- Two parts to this talk

1. Main part: (Very) recent measurement of NTV offset rotation profile in KSTAR

2. Second separate result: NTV rotation braking with global $n = 1$, non-pitch-aligned 3D field

The NTV Offset Rotation Profile 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

- Outline
  - Goal 1: Use an innovative technique to measure the NTV offset rotation profile on KSTAR for the first time - COMPLETED
    - NTV offset V_ϕ *profile* directly measured
  - Goal 2: Use new counter-I_p target plasma to measure the NTV offset rotation profile on KSTAR – TO BE DONE
    - Reverse-I_p target plasma under development by Jay Kim

Present experiment directly measured the $V_{0\text{-}NTV}$ profile with no NBI momentum

- What did we do?
  - 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 in torque balance
    - Is computed, not directly measured
    - Is typically much larger than the T_{NTV} component due to offset rotation ➔analysis is prone to error
    - The *profile* of T_{NBI} matters – not just zero net input torque from NBI
- Companion experiment to proposed NSTX-U experiment
  - Original, approved proposal XP1062 for NSTX using HHFW (2010 !)
  - Proposal *"NTV steady-state offset velocity at reduced torque with HHFW"* submitted to NSTX-U Research Forum (2015)

Intrinsic Torque due to Neoclassical Toroidal Viscosity (NTV) – a controllable momentum source

- Full Theory (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)
  - The non-ambipolar difference of ion and electron flux due to the application 3D fields yields a so-called “offset rotation profile”, $V_{0\text{-NTV}}$
  - Generally, the local rotation speed can be either in the co- or counter-I_p direction if dominated by electron/ion flux, respectively
    - The electron effect is ignored in most papers on the topic
- 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 $V_{0\text{-NTV}}$ profile: $V_{0\text{-NTV}} = C_2\, dT_i/dr - C_3\, dT_e/dr$ (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 (I)

- 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_l/R)

- Use simple NTV model to express offset rotation

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

Consider simple torque balance equation to further understand expected dynamics (II)

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

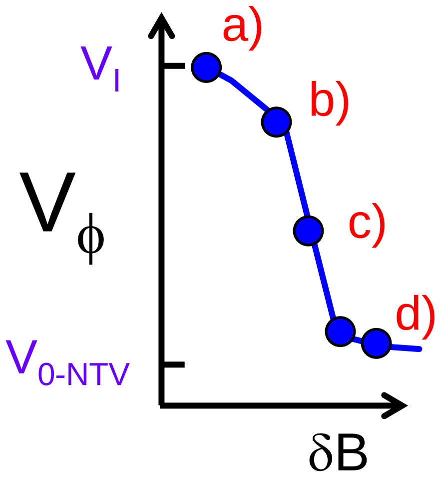
$$\boxed{C_1 \delta B^2 (V_\emptyset - V_{0-NTV}) + \frac{I}{R\tau_{2D}}(V_\emptyset - V_I) = 0}$$

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

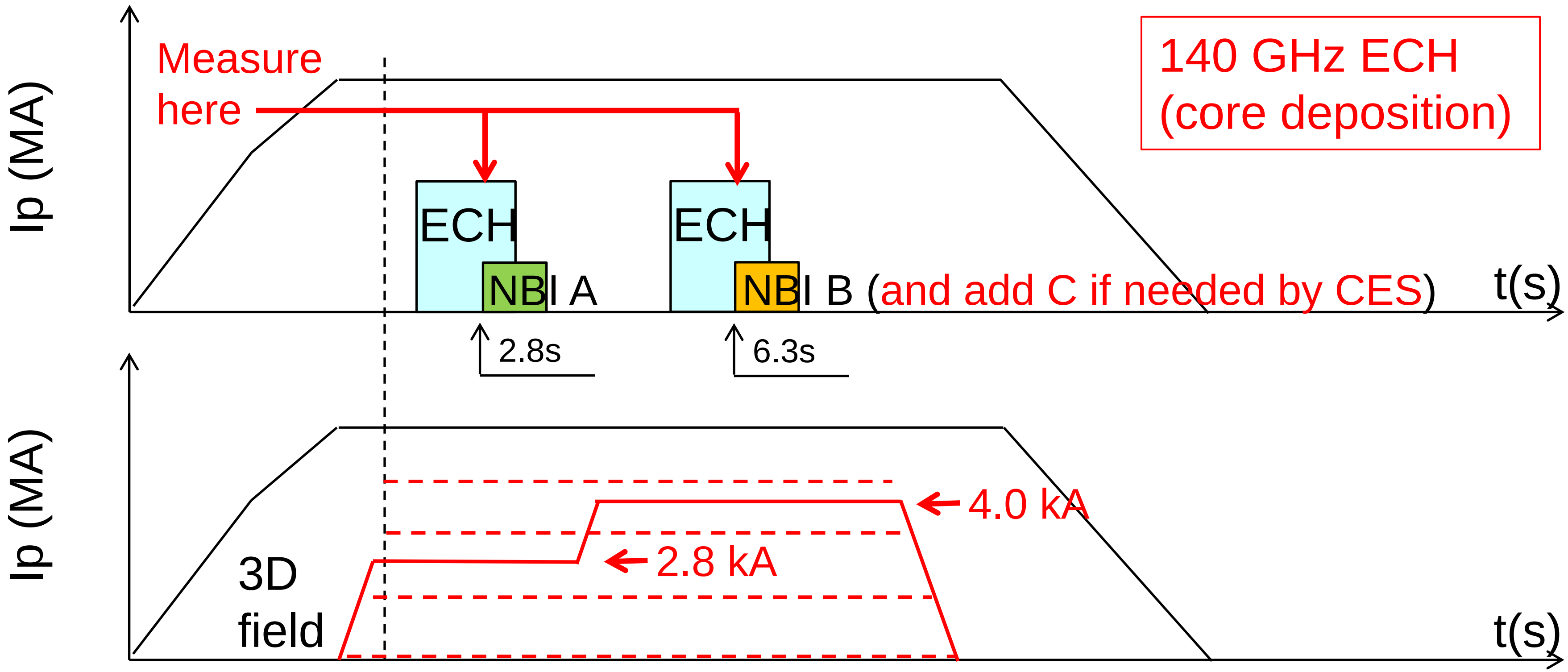
$$V_\emptyset = \left(\frac{C_1 \delta B^2}{C_1 \delta B^2 + I/R\tau_{2D}}\right) V_{0-NTV} + \left(\frac{I/R\tau_{2D}}{C_1 \delta B^2 + I/R\tau_{2D}}\right) V_I$$

(*on each* ψ *surface*)

- Expected dynamics
  - a) <u>δB = 0</u>: $V_\phi = V_I$
  - b) <u>low δB</u>: measured V_ϕ profile close to V_I
  - c) <u>increased δB and ($|V_\phi| >> |V_{0\text{-NTV}}|$)</u>: V_ϕ ➔ $V_{0\text{-NTV}}$
  - d) <u>sufficiently high δB</u>: V_ϕ saturates to $V_{0\text{-NTV}}$



Technique to measure NTV offset V_ϕ profile



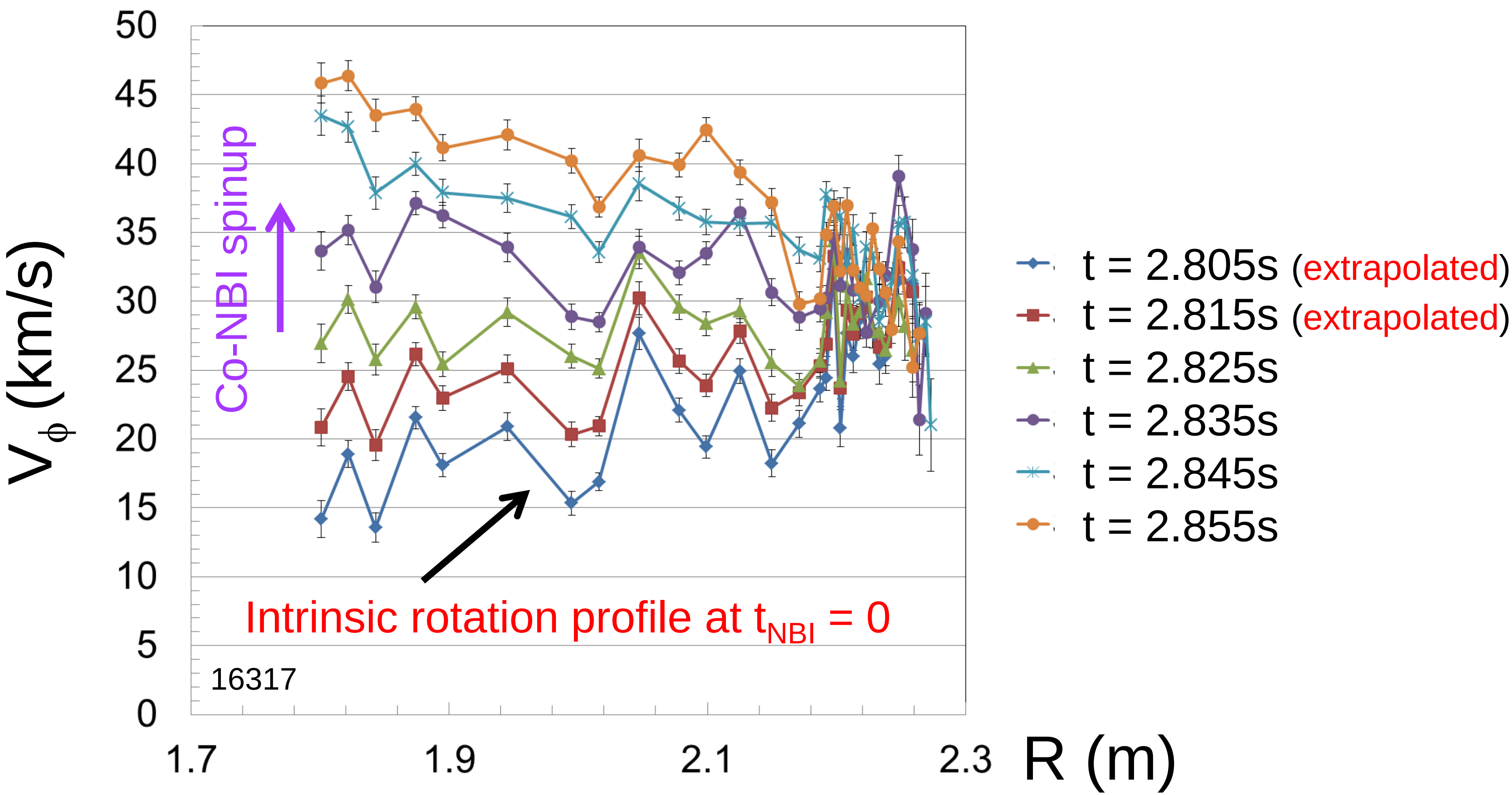
- Brief summary of success (~ 10s long pulses)
  - NBI used as diagnostic worked well – CES has good data – V_ϕ profile measured
  - n = 2 field varied – scans with and without density feedback
    - Without density feedback: 2.0, 2.8, 3.2, 4.0 kA/turn
    - With density feedback: (at least) 1.0, 2.0, 2.4, 2.8, 3.2, 4.0 (δB^2 factor of 16 change)
  - Clear changes to CES measured V_ϕ evolution due to varied n = 2 field strength

Results from first time point measured (2.8s)

Two techniques were used to measure the rotation profile approaching $V_{0\text{-}NTV}$

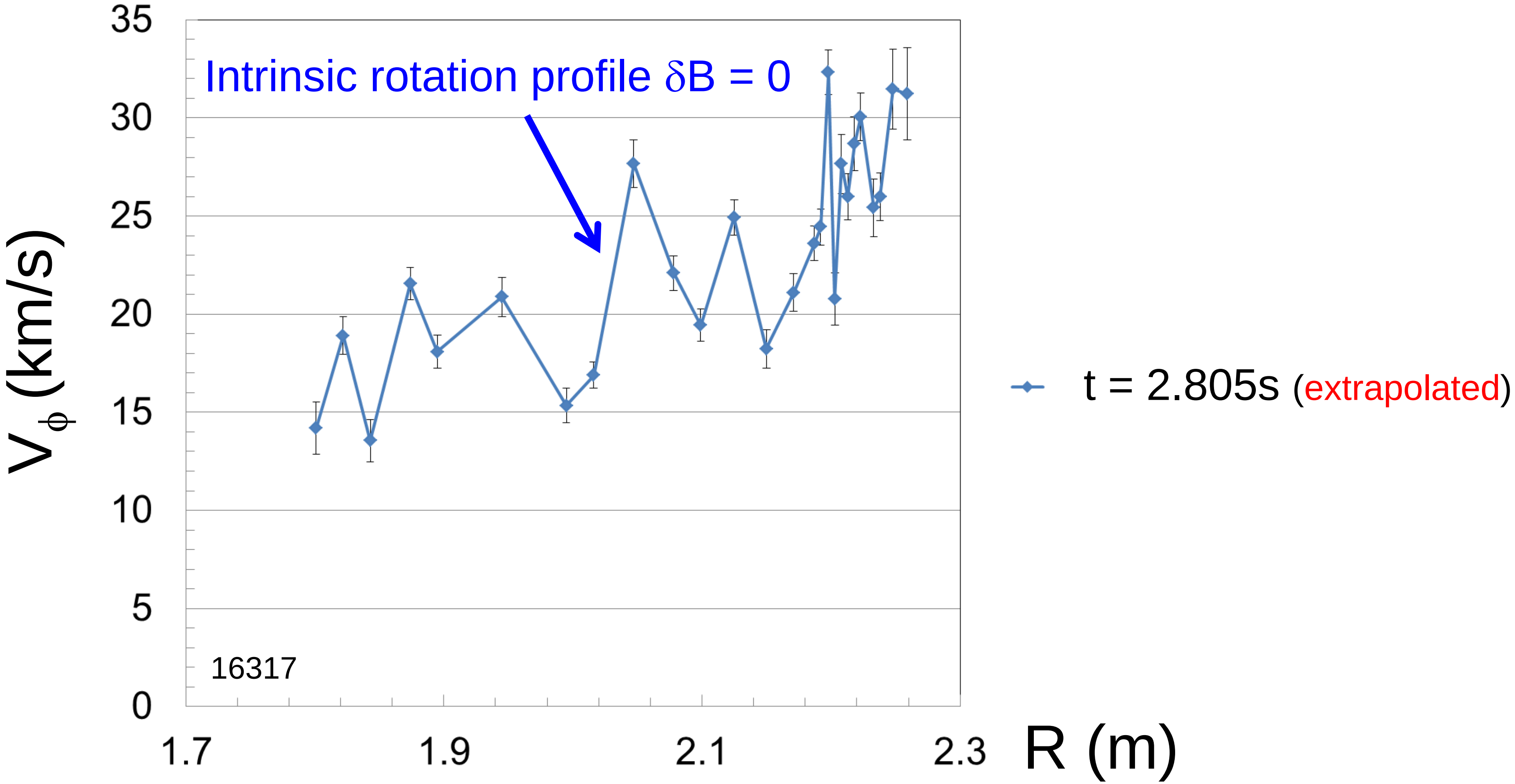
- CES rotation profile extrapolated back to start of NBI
  - Involves an extrapolation 10 - 20 ms earlier in time
  - similar to technique used by Podesta on NSTX (2009) to measure intrinsic rotation in HHFW plasmas
- CES rotation profile analysis re-analyzed to the earliest possible time after the start of NBI
- The best technique to use is still being evaluated
  - CES was re-analyzed just a few days ago
  - Results are qualitatively similar, exact rotation values change a bit
  - Will show results from both techniques

Analysis of CES data and NBI diagnostic technique measures intrinsic V_ϕ from ECH



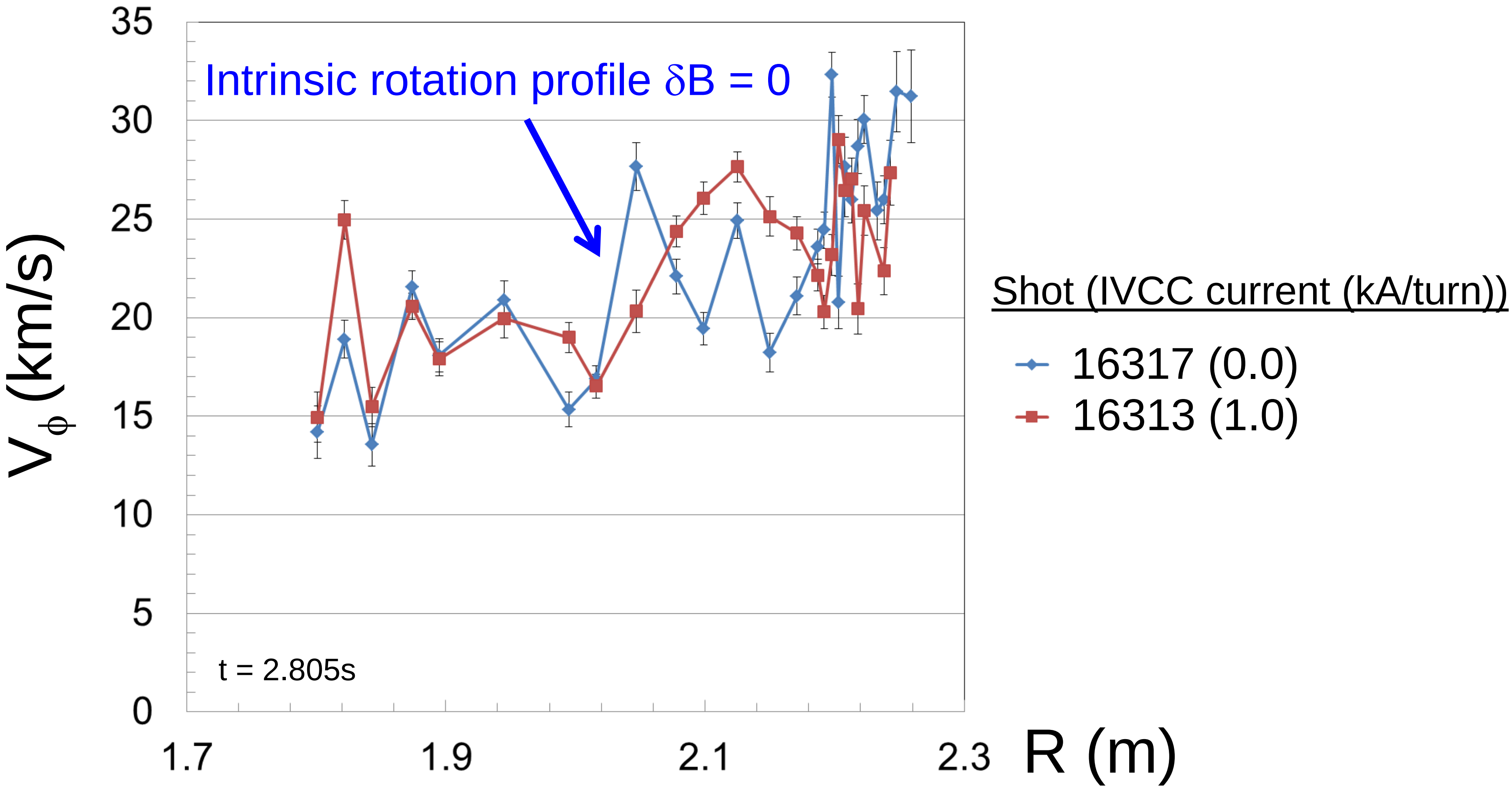
- The excellent (low error) KSTAR CES diagnostic required for this analysis

Condition a): the intrinsic V_ϕ from ECH establishes our $\delta B = 0$ reference V_ϕ profile

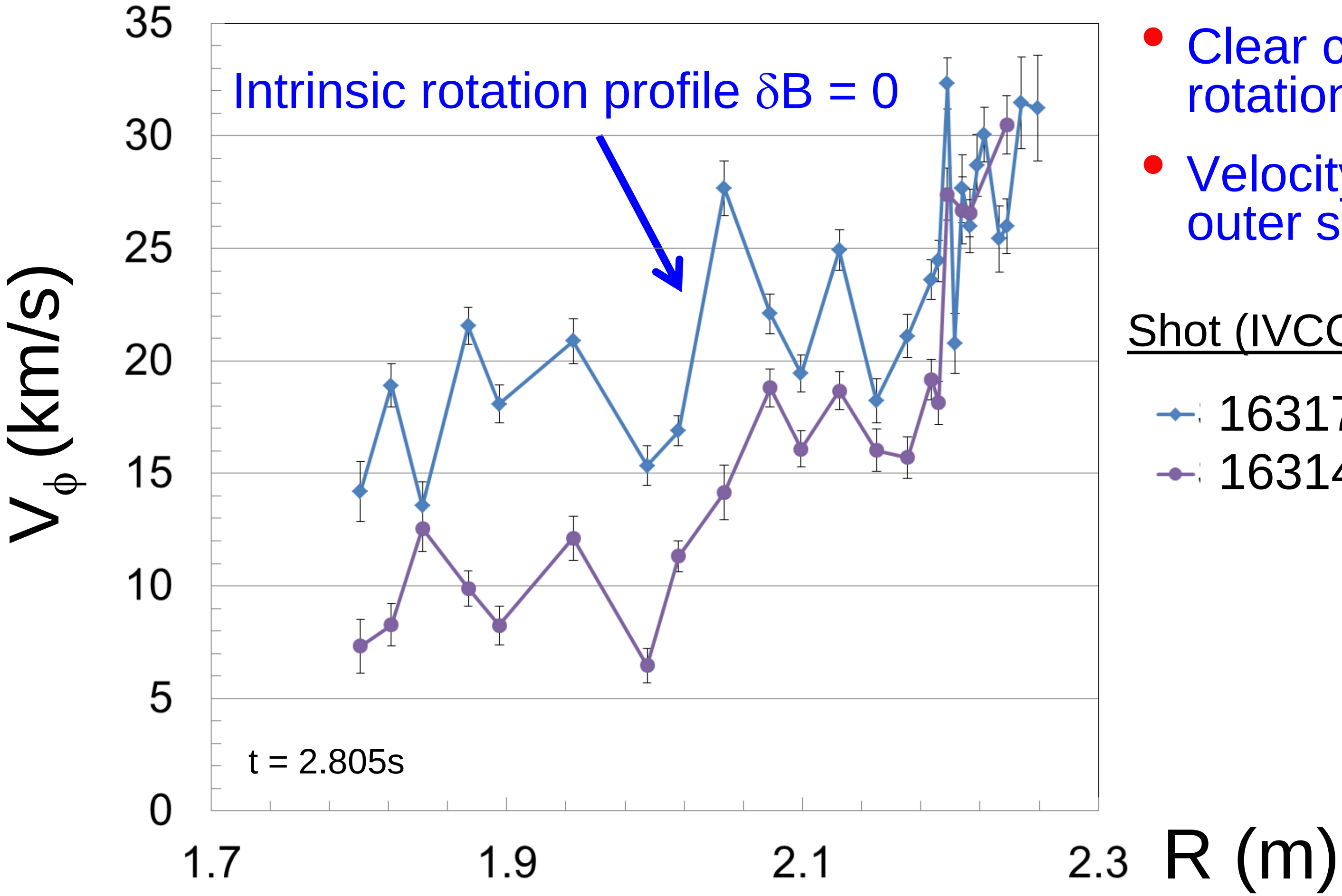


- Note: core rotation speed is FAR slower than with NBI (by ~ factor 5 - 10)

Condition b): at 1.0 kA/turn, δB is small and V_ϕ is close to the V_ϕ with no 3D field



Condition c): at 2.4 kA/turn, δB is sufficiently large to make V_ϕ approach $V_{0\text{-NTV}}$

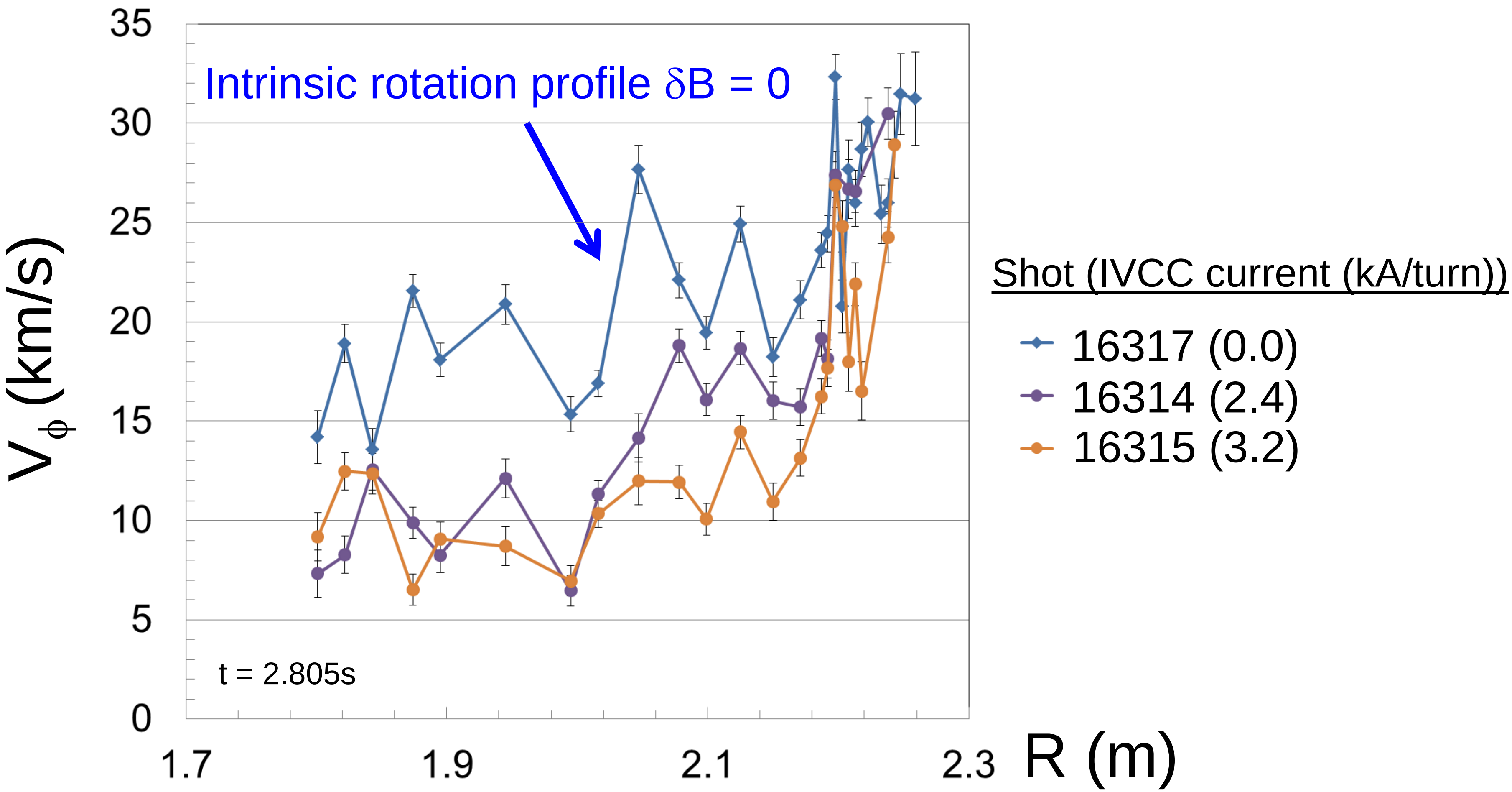


- Clear change in rotation profile
- Velocity increases on outer surfaces

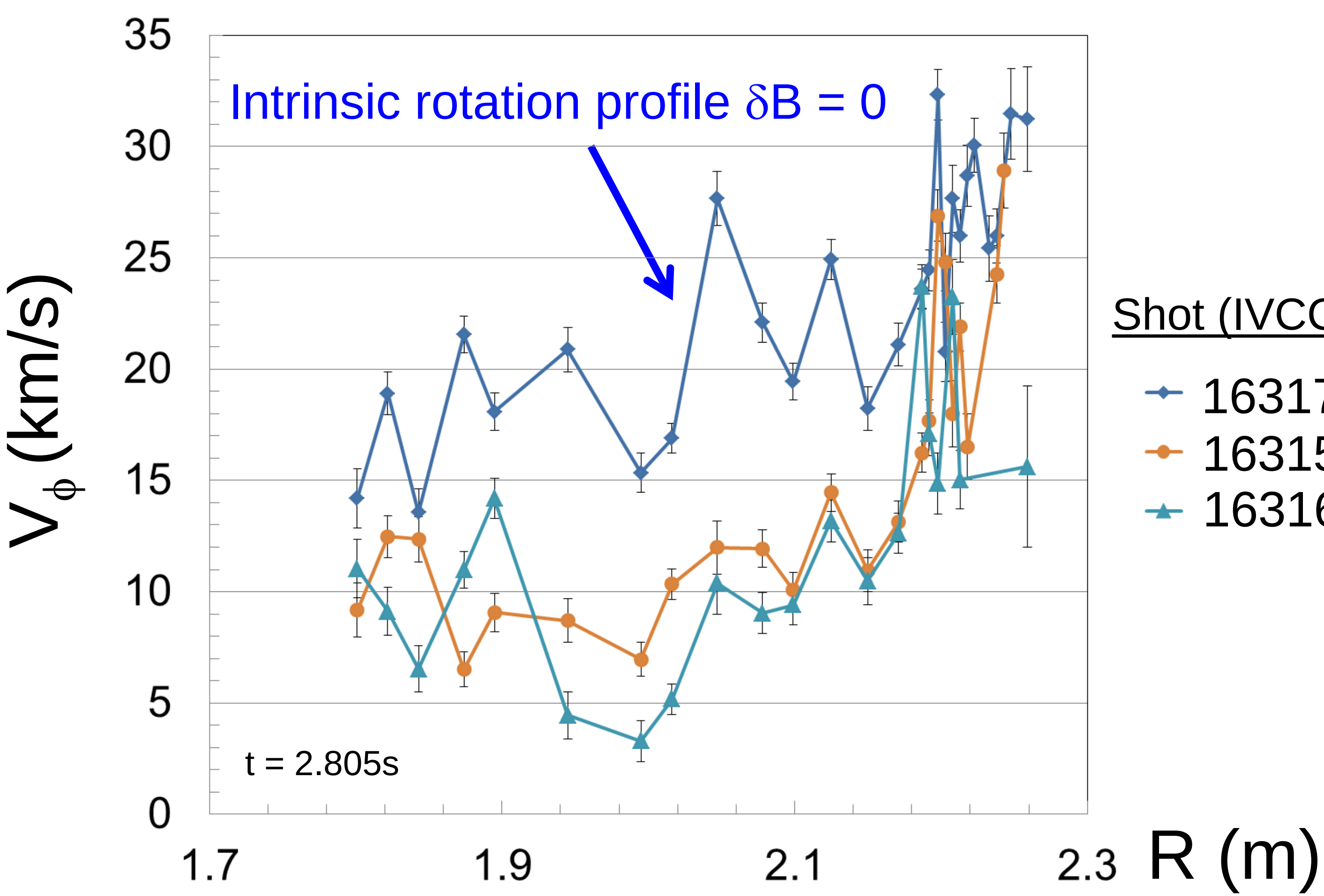
Shot (IVCC current (kA/turn))

- 16317 (0.0)
- 16314 (2.4)

Condition d): at 3.2 kA/turn, δB is sufficiently large to make V_ϕ saturate to $V_{0\text{-}NTV}$ in the core

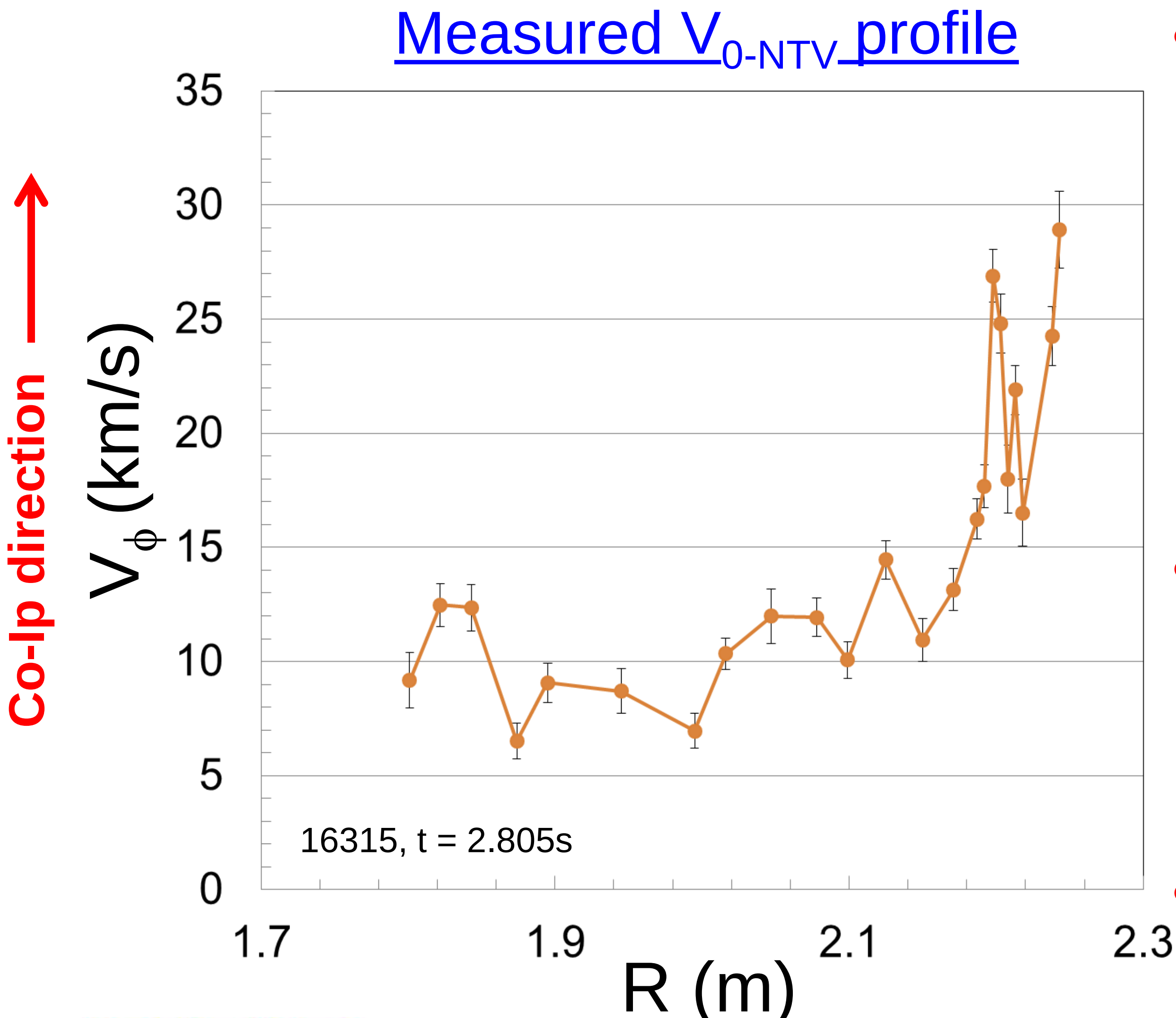


Condition d): at 4.0 kA/turn, δB sufficiently large to make V_ϕ saturate to $V_{0\text{-}NTV}$ in core+outer region



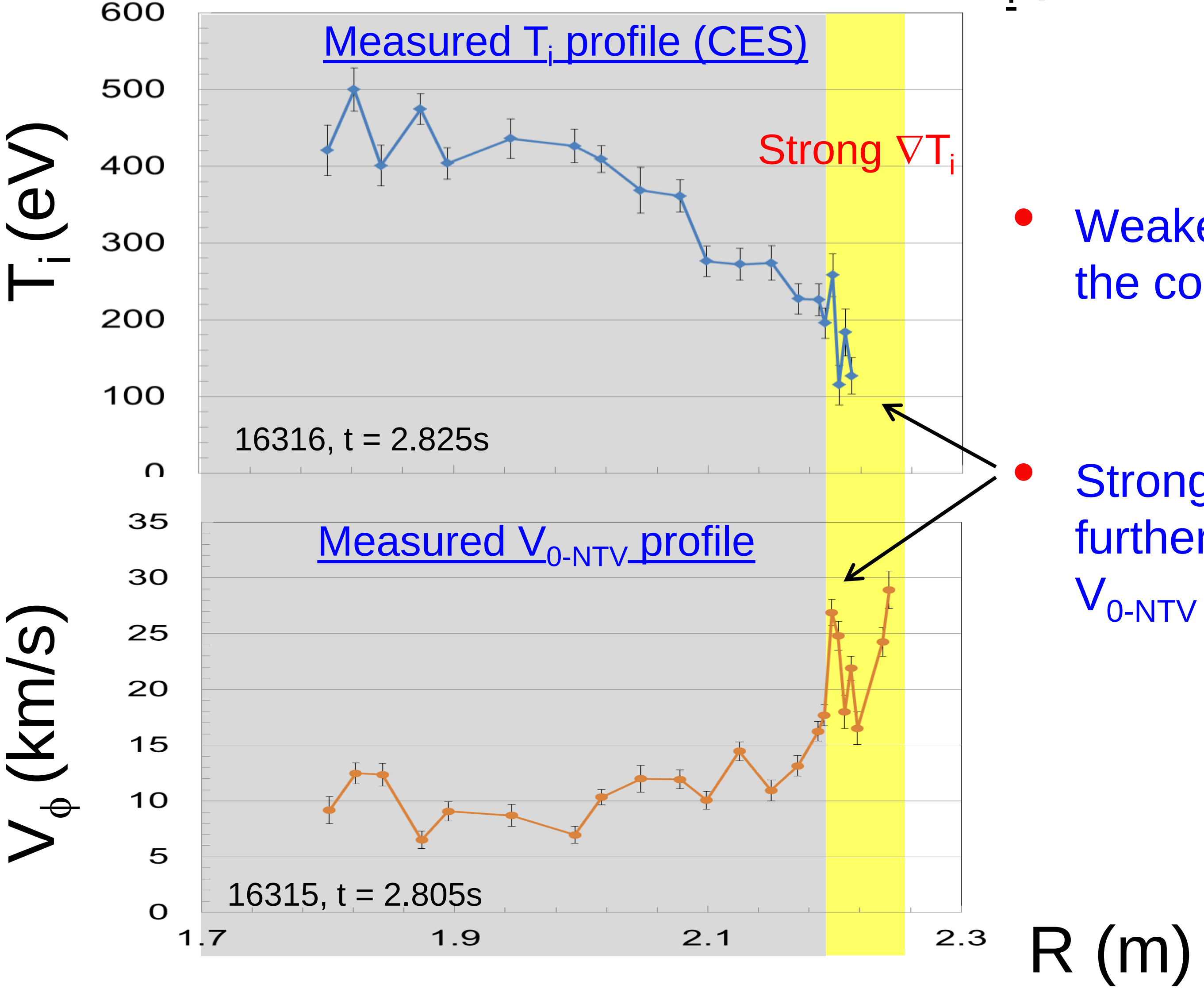
- The saturated rotation profile → $V_{0\text{-}NTV}$

Unique result: resulting saturated $V_{0\text{-}NTV}$ profile is in the co-Ip direction – electron NTV dominates



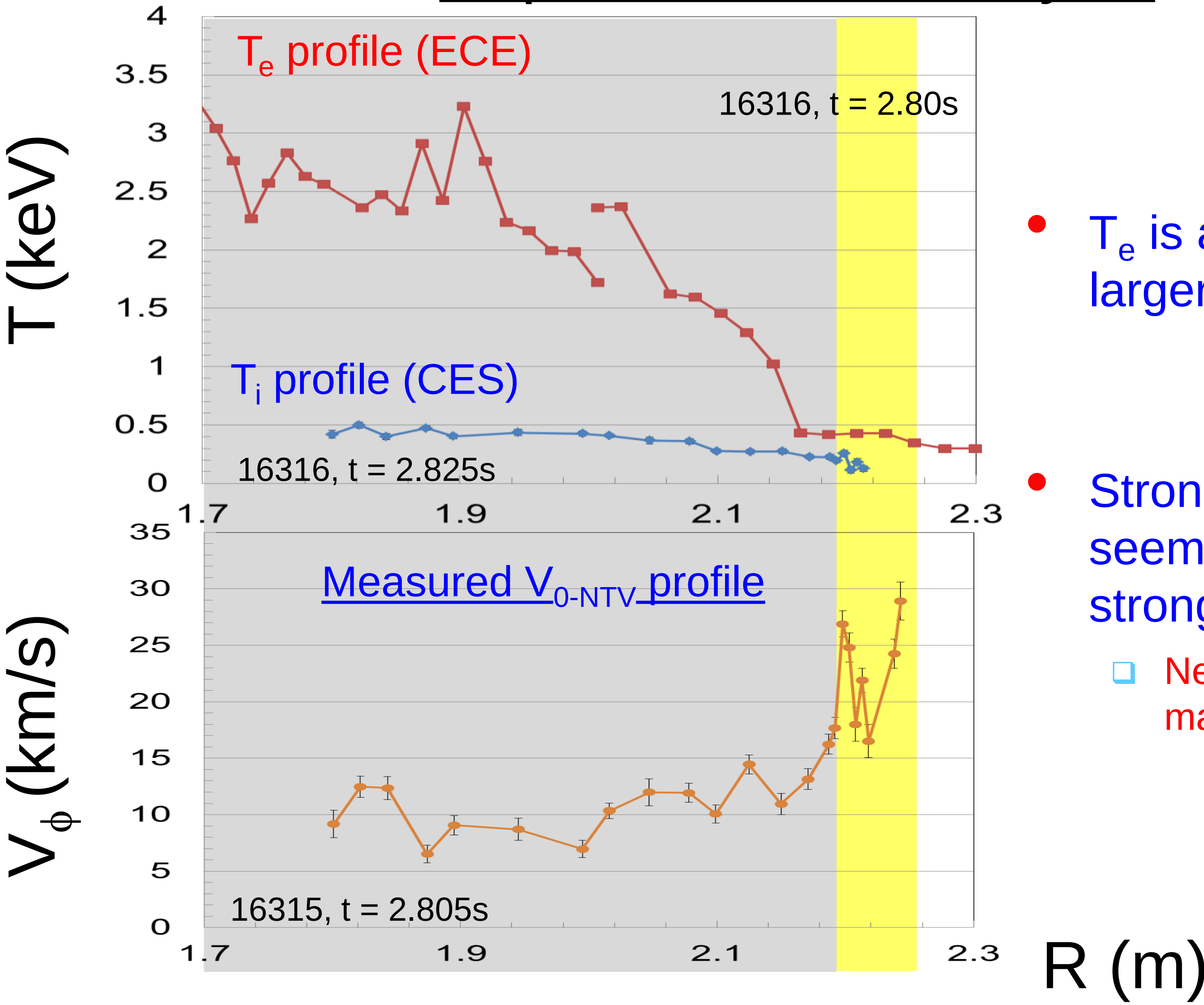
- Consistent w/theory: The ratio of ion to electron NTV torque is $(T_i/T_e)^{3.5}(M_i/M_e)^{0.5}=0.15$
  - electron NTV offset should dominate
  - theory expects $V_{0\text{-}NTV}$ in the **CO-I_p** direction
- First time that
  - NTV offset profile directly measured
  - NTV measured in the co-I_p direction
- Notably strong velocity shear in outer region

Comparison of $V_{0\text{-}NTV}$ profile to gradient in T profile shows a correlation: T_i profile



- Weaker T_i gradient in the core ➔ weak $V_{0\text{-}NTV}$
- Stronger T_i gradient further out ➔ stronger $V_{0\text{-}NTV}$

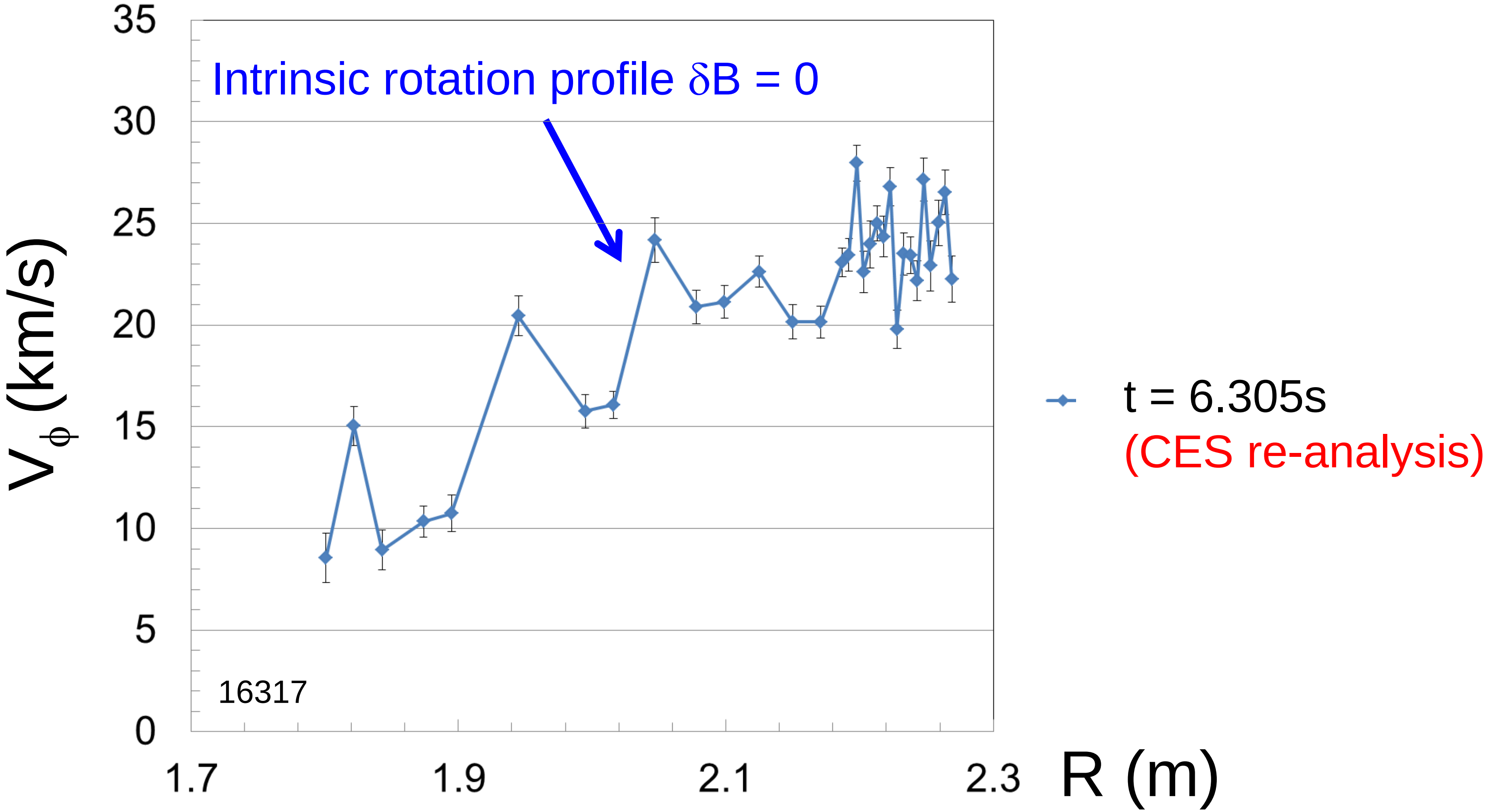
Comparison of $V_{0\text{-}NTV}$ profile to gradient in T_e profile requires further analysis



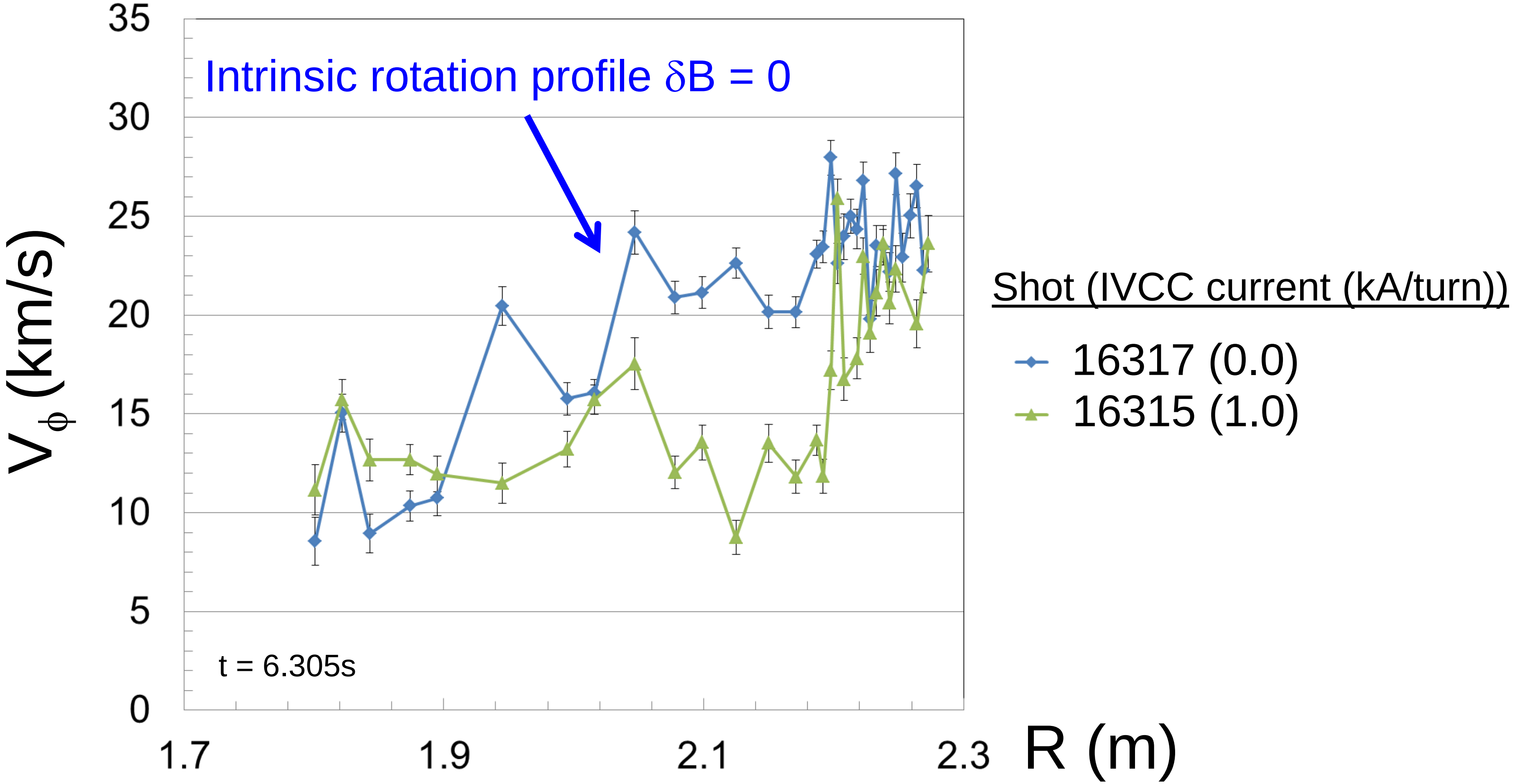
- T_e is about 5 times larger than than T_i
- Stronger T_e gradient seems to be inside stronger $V_{0\text{-}NTV}$ region
  - Need to check the ECE mapping to R

Results from second time point measured (6.3s)

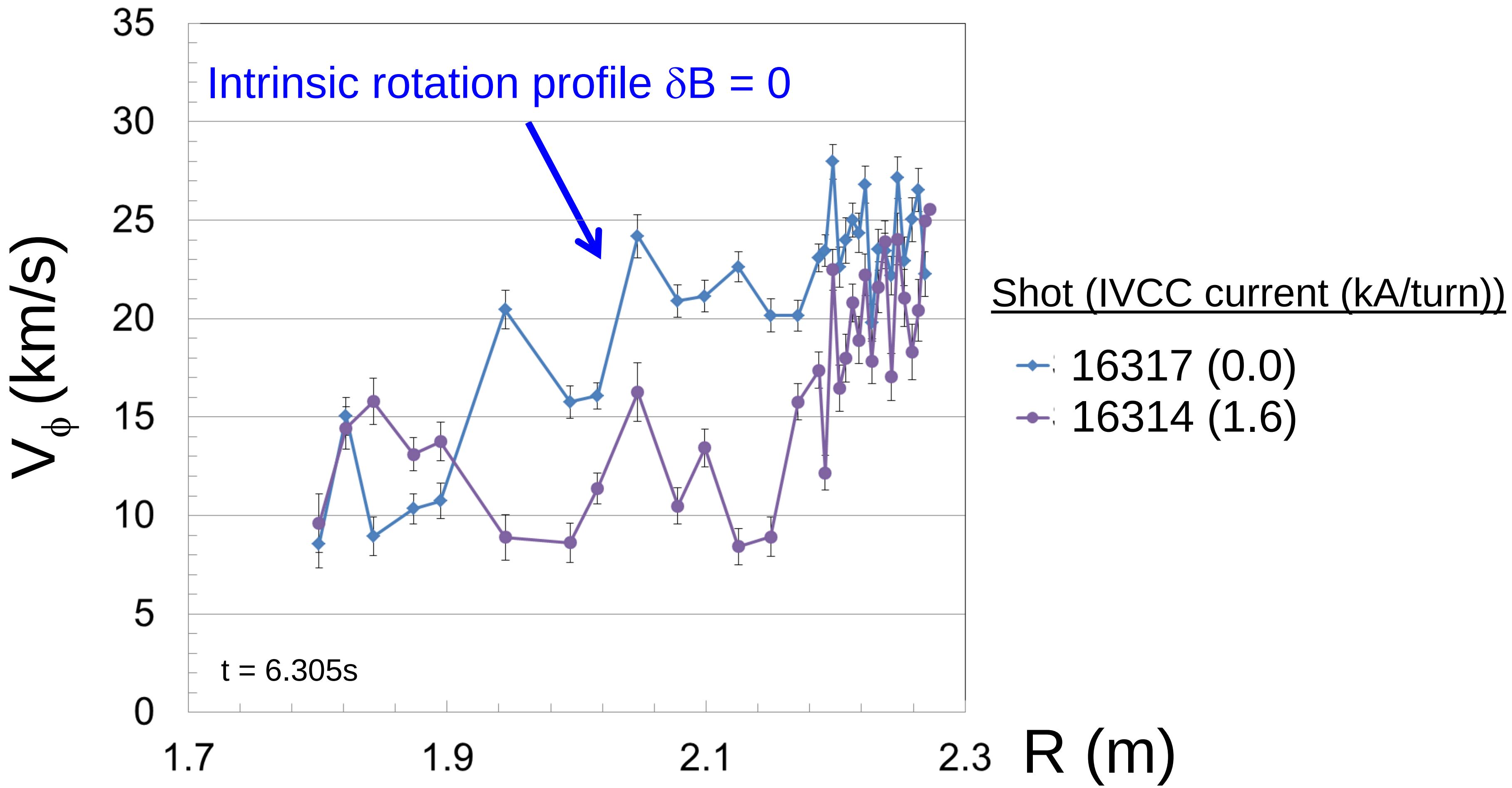
Condition a): the intrinsic V_ϕ from ECH establishes our $\delta B = 0$ reference V_ϕ profile



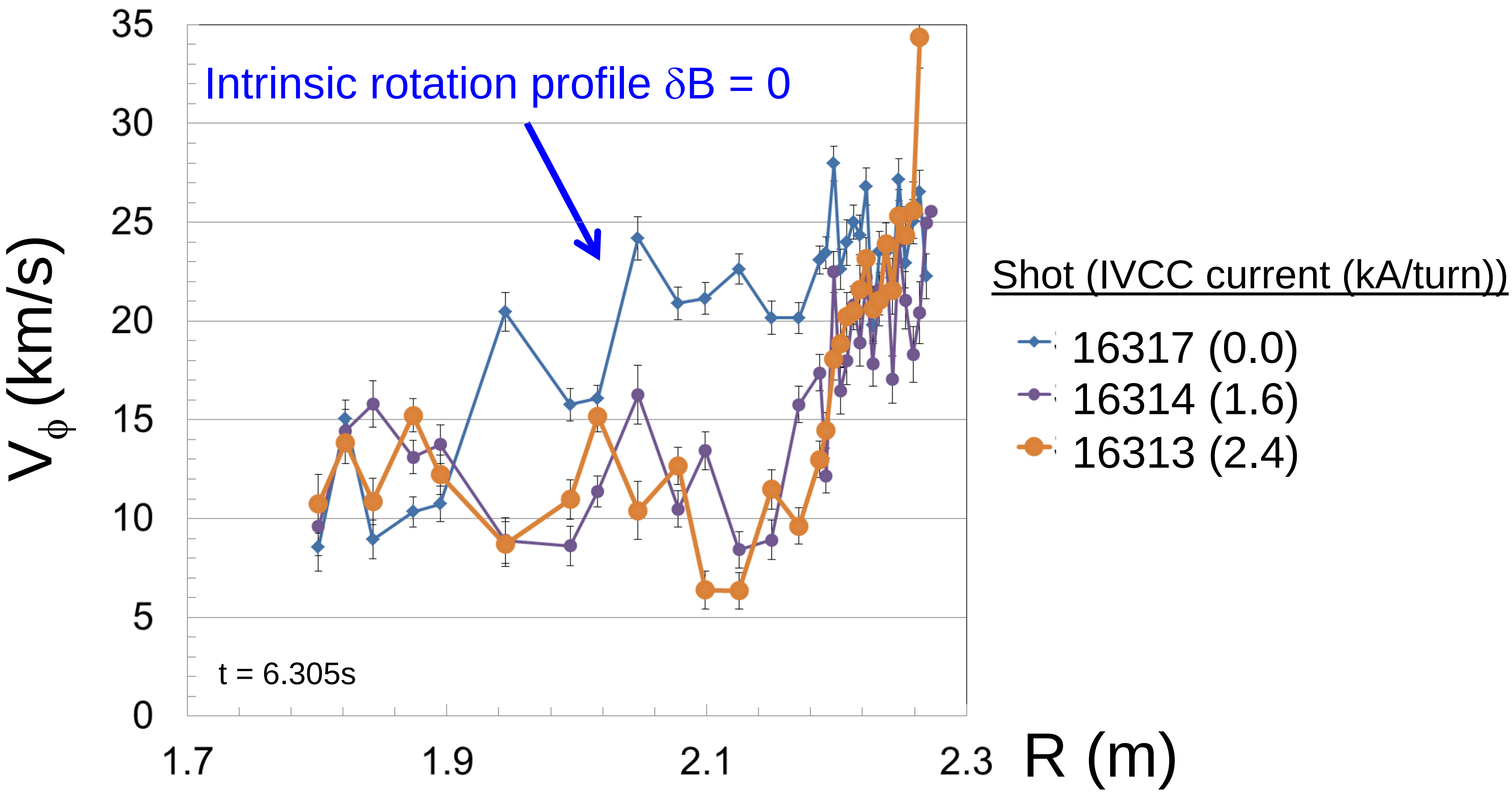
Condition b): at 1.0 kA/turn, δB accelerates the core a small amount, slows further out



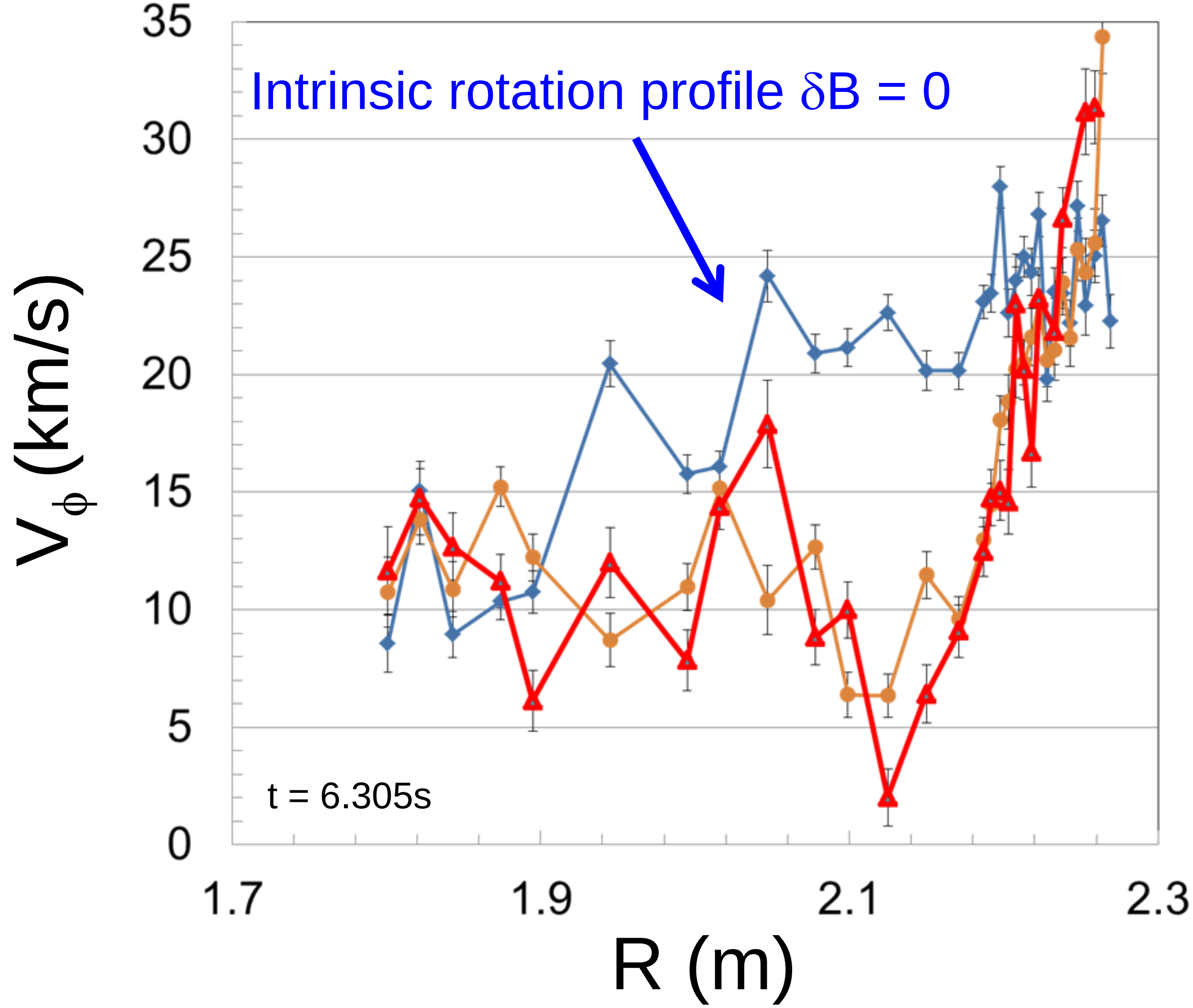
Condition c): at 1.6 kA/turn, core continues to accelerate, while plasma further out slows



Condition d): at 2.4 kA/turn, profile is largely saturated, stronger V_ϕ shear forms at large R



Condition d): at 3.2 kA/turn, much stronger V_ϕ shear at large R is confirmed



Shot (IVCC 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}

15 times greater shear !

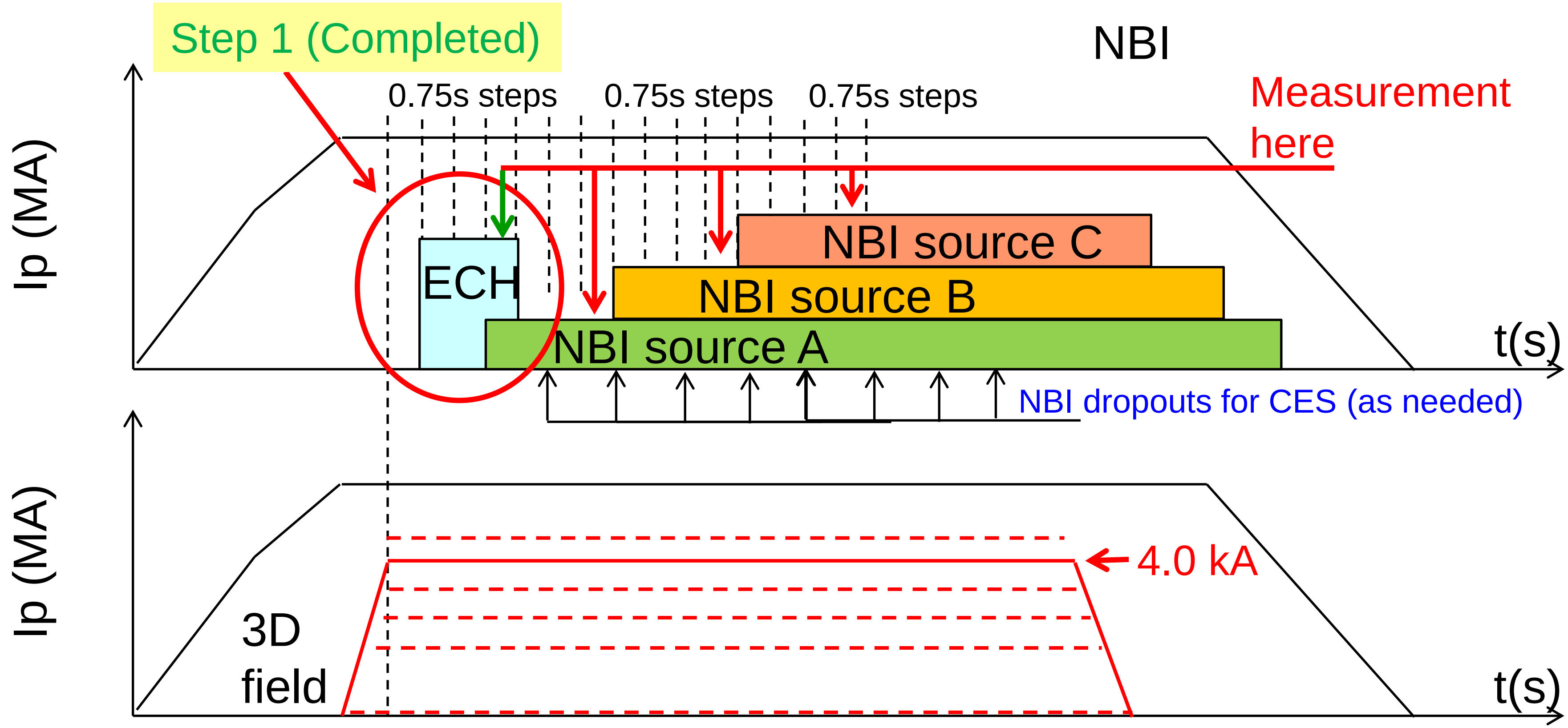
Why are the present results unique and important?

- Why unique?
  - First time that $V_{0\text{-}NTV}$ profile has been directly measured w/ $T_{NBI} = 0$
  - First time $V_{0\text{-}NTV}$ has been measured dominated by electron effects
    - $V_{0\text{-}NTV}$ profile measured in the co-I_p direction for the first time
- Why important?
  - Co-I_p directed $V_{0\text{-}NTV}$ can be higher than ECH-induced co-I_p rotation in edge region
  - Rotation shear in the outer plasma region is 15 times stronger than rotation shear due to ECH
- ITER relevant: $|V_{0\text{-}NTV}|$ is strong compared to ITER modeling
  - ITER 15 MA simulations: 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

Several next-steps to address regarding $V_{0\text{-}NTV}$ understanding

- Perform non-linear least squares fit of V_ϕ vs. δB^2 (at each R)
  - This will quantitatively determine how close measured V_ϕ is to $V_{0\text{-}NTV}$
- $V_{0\text{-}NTV}$ profile scaling with plasma parameters
  - Data from present experiment may provide some answers
- $V_{0\text{-}NTV}$ profile comparison to theory – including electron effects
  - All known experimental publications only consider $V_{0\text{-}NTV} \sim d(Ti)/dr$
- Comparison of present results to ohmic intrinsic rotation
  - Results published by S.G. Lee, et al.
- Run second part of experiment using reversed-I_p plasma

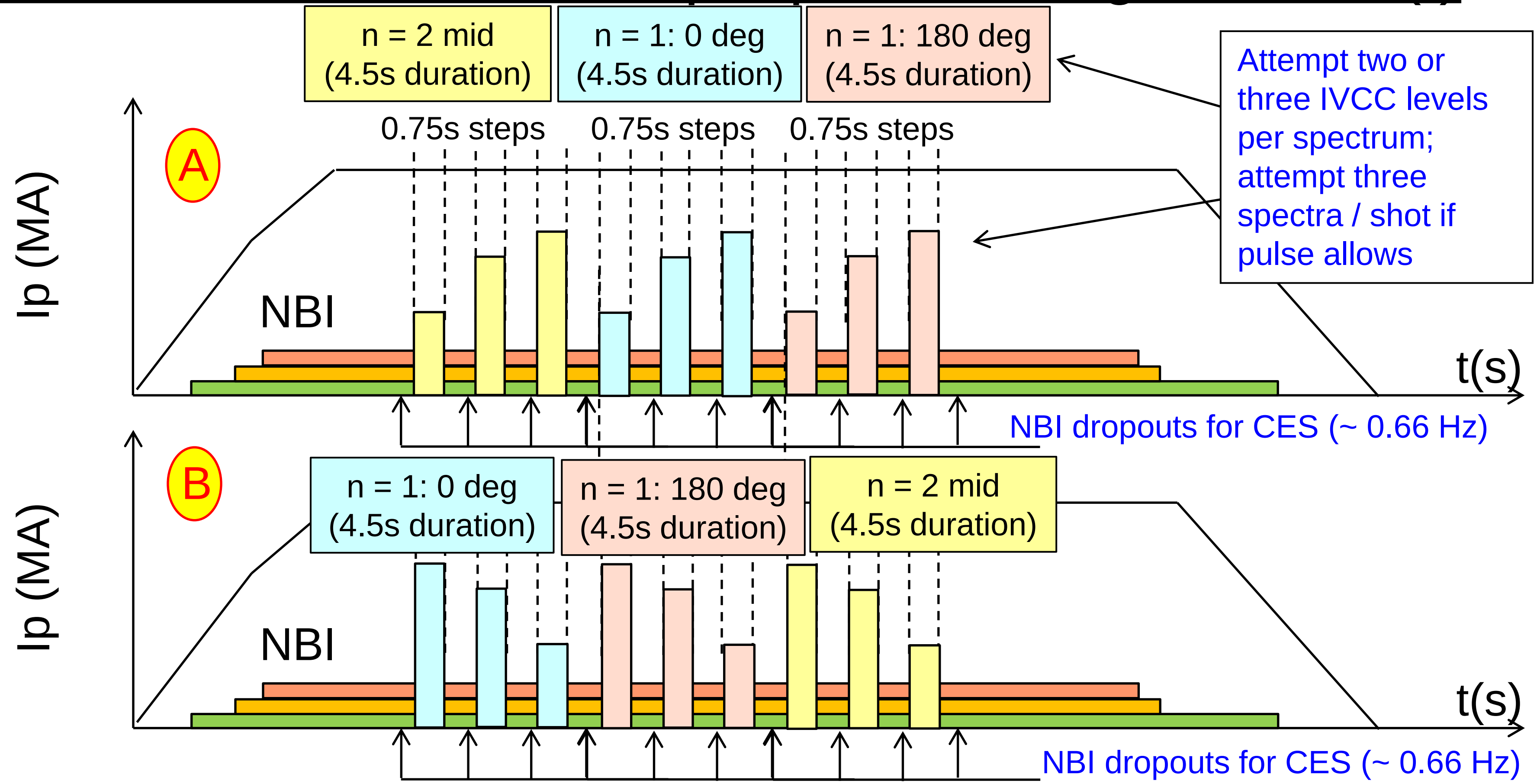
STEP 2: Use Counter-Ip to measure NTV offset V profile



- Set-up Target Plasma Shots
  - For counter-Ip shot (2016) **15884**: Bt = 2.3T, Ip = 0.51 MA, q95 = 6, Ip flattop = 1s - 7s; **ECH set for BEST OUTER HEATING**
- Setup for IVCC 3D fields
  - Step 2B: Start with IVCC = 4.0 kA (n = 2 midplane coils ONLY - like **FIRST STEP** of shots **13433** or **13446**)
  - Step 2D: Start with IVCC = 4.0 kA (n = 2 midplane + n = 1 non-pitch-aligned (0 deg) - like **FIRST STEP** of shot **13436**)

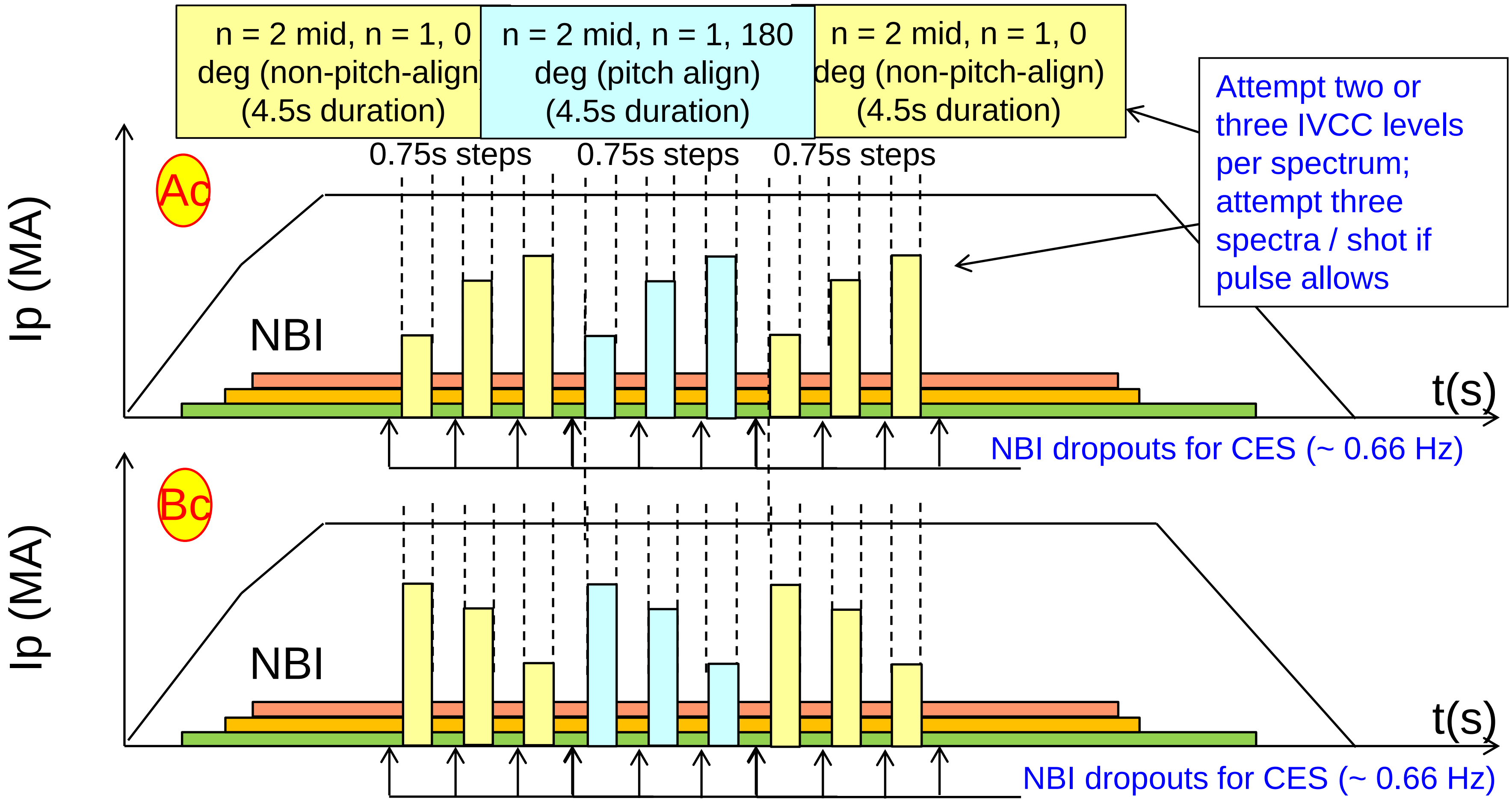
Second separate result: NTV rotation braking with global n = 1, non-pitch-aligned 3D field

STEP 3: Isolate NTV torque profile using fast IPS (I)



- Set-up Shots
  - (2016) Target **15778** (Bt = 1.8T); (2015) Target plasmas **13302** (Bt = 2.0T), **13433** (Bt = 2.6T), **13446** (Bt = 1.8T)
- Setup shots for IVCC timing
  - A Vary applied field magnitude and spectrum (2 or three steps using n = 2 midplane; n = 1 non-pitch-aligned; n = 1 pitch-aligned ➔ shots **13433** , **13446**
  - B Take second shot, changing the order of the IVCC current steps ➔ shots **13434**

STEP 3: Isolate NTV torque profile using fast IPS (II)



- Shots with COMBINED non-resonant field spectra (n = 2 + n =1 non-pitch-aligned)
  - Ac Vary applied field magnitude fixed combined spectrum (n = 2 midplane; n = 1 non-pitch-aligned: ➔ shots **13437**, **13447**
  - Bc Take second shot, changing the order of the IVCC current steps ➔ shots **13436**

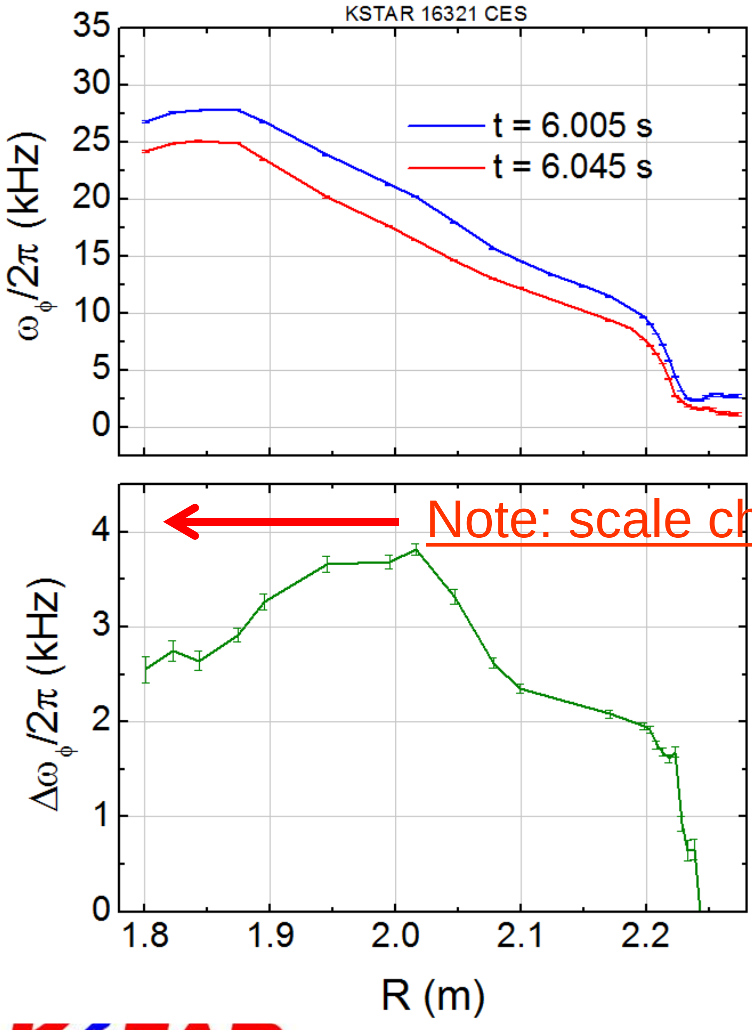
Important new results were ALSO found in "Step 3" of the experiment (7 shots)

- Significantly stronger non-resonant n = 2 NTV braking was found compared to our 2015 experiment, apparently due to high plasma performance (T_i)

- The n = 1 non-pitch-aligned field spectrum – concluded last year to allow non-resonant braking – was found to disrupt the plasma this year
  - Apparently due to higher T_i this year
  - Hypothesis is that stronger non-resonant n = 1 breaking gives way to resonant 3D field penetration and locking
  - Reduces confidence that n = 1 non-resonant field can be reliably used for core plasma rotation control

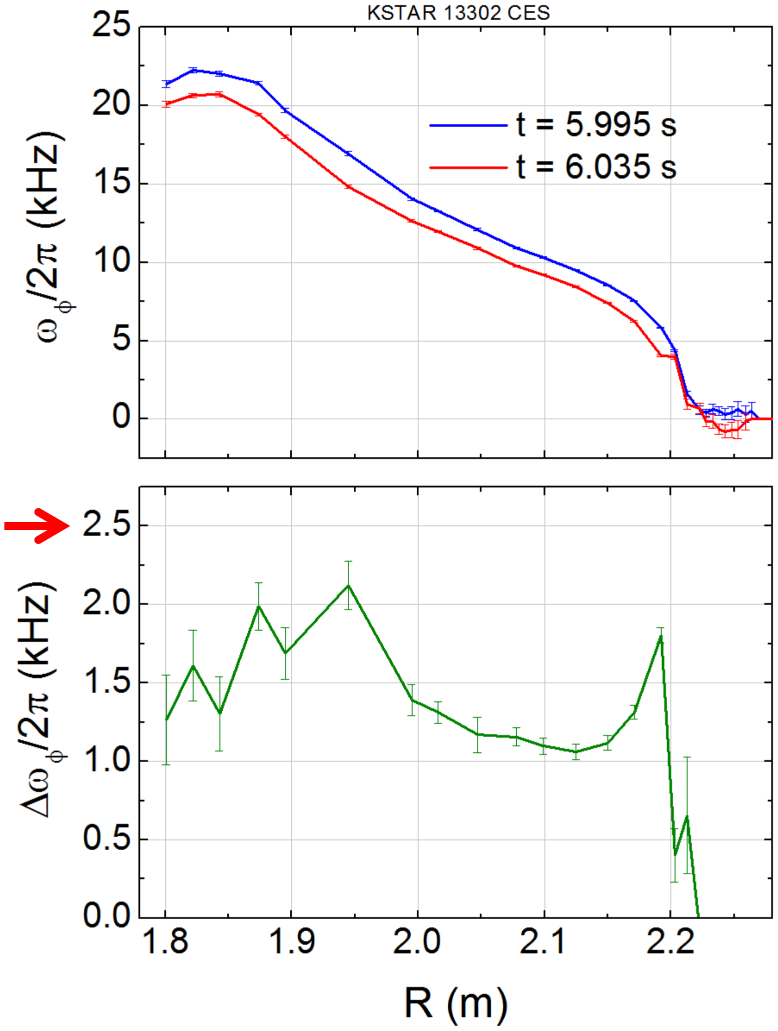
Stronger n = 2 non-resonant NTV in Monday's experiment than in 2015

NTV n = 2 braking (2016)

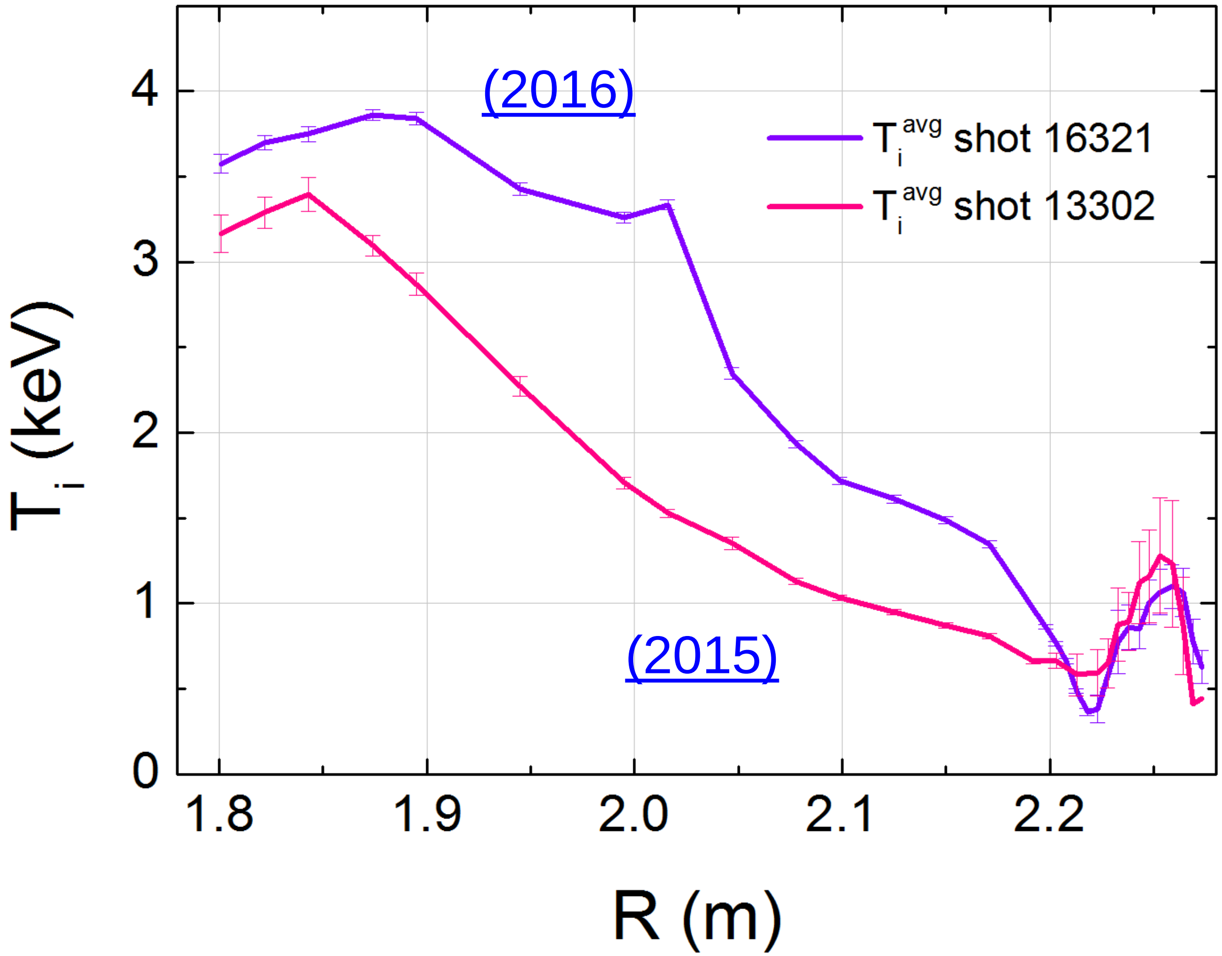


Note: scale change

NTV n = 2 braking (2015)

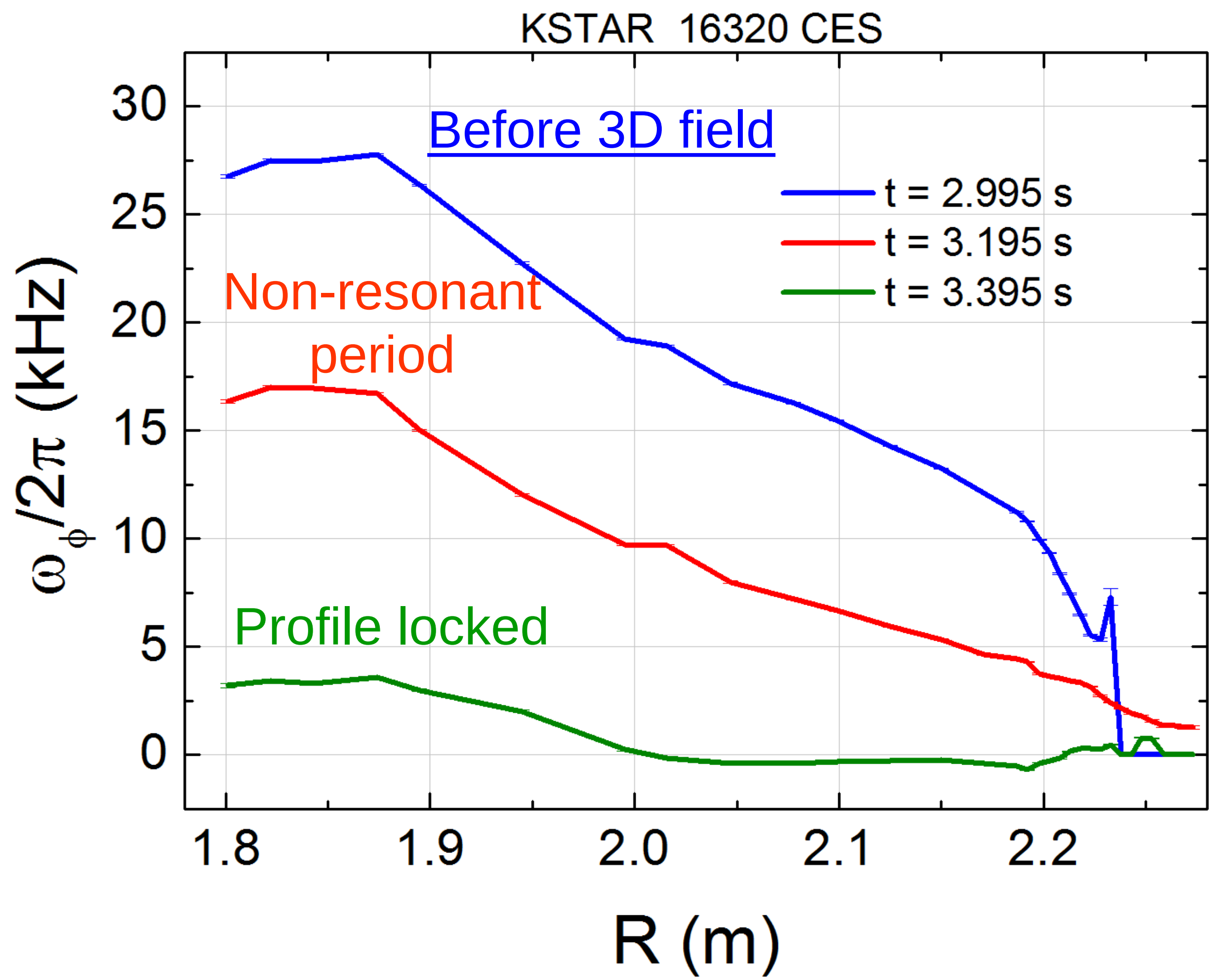


Stronger n = 2 non-resonant NTV during 2016 run apparently due to increased T_i



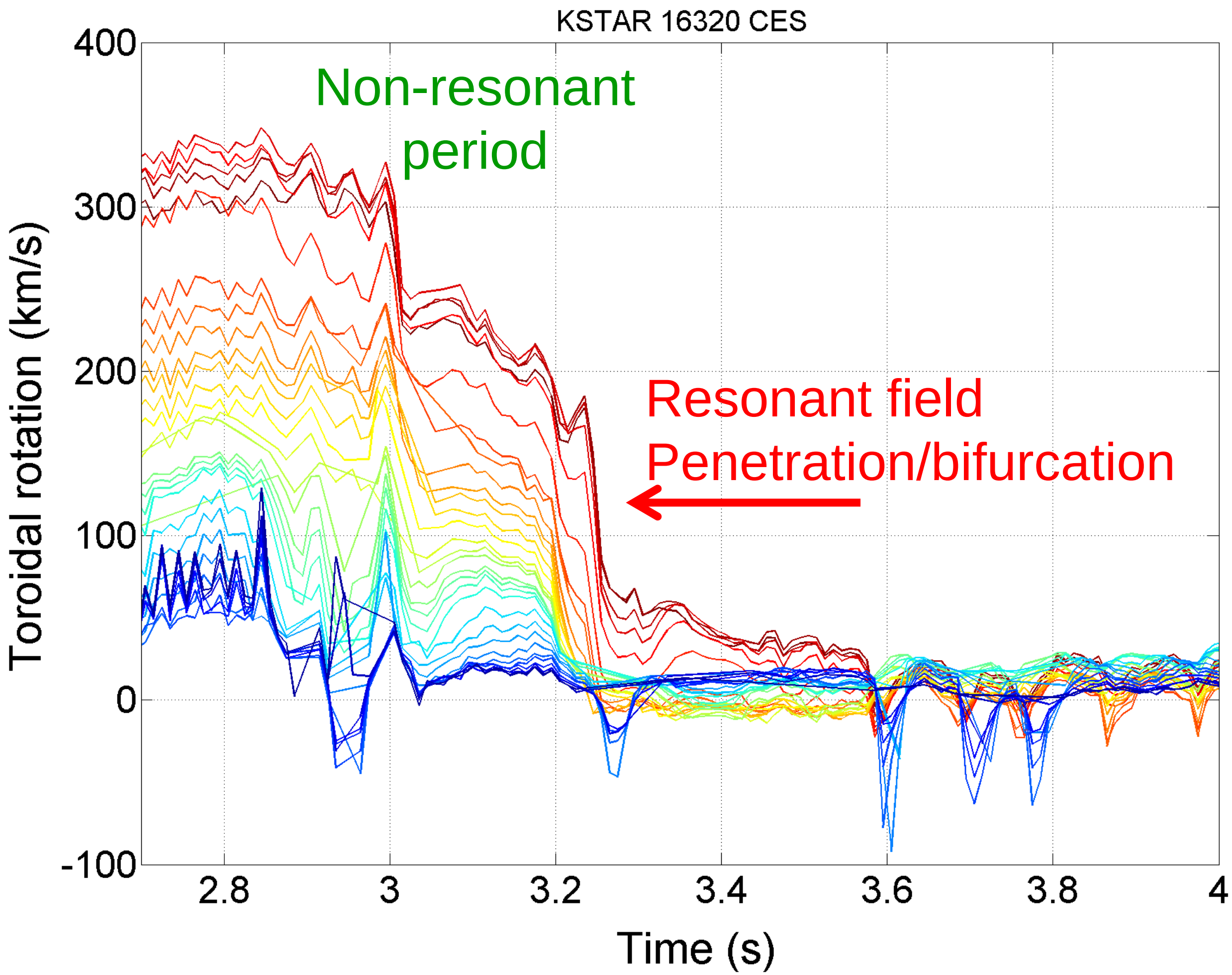
- NTV torque in "1/ν" regime scales as $T_i^{2.5}$

n = 1 non-pitch-aligned 3D field spectrum now apparently leads to resonant field penetration/locking



- NTV braking appears non-resonant to start, but V_ϕ eventually bifurcates

n = 1 non-pitch-aligned 3D field spectrum now apparently leads to resonant field penetration/locking



- NTV braking appears non-resonant to start, but V_ϕ eventually bifurcates

Supporting slides follow

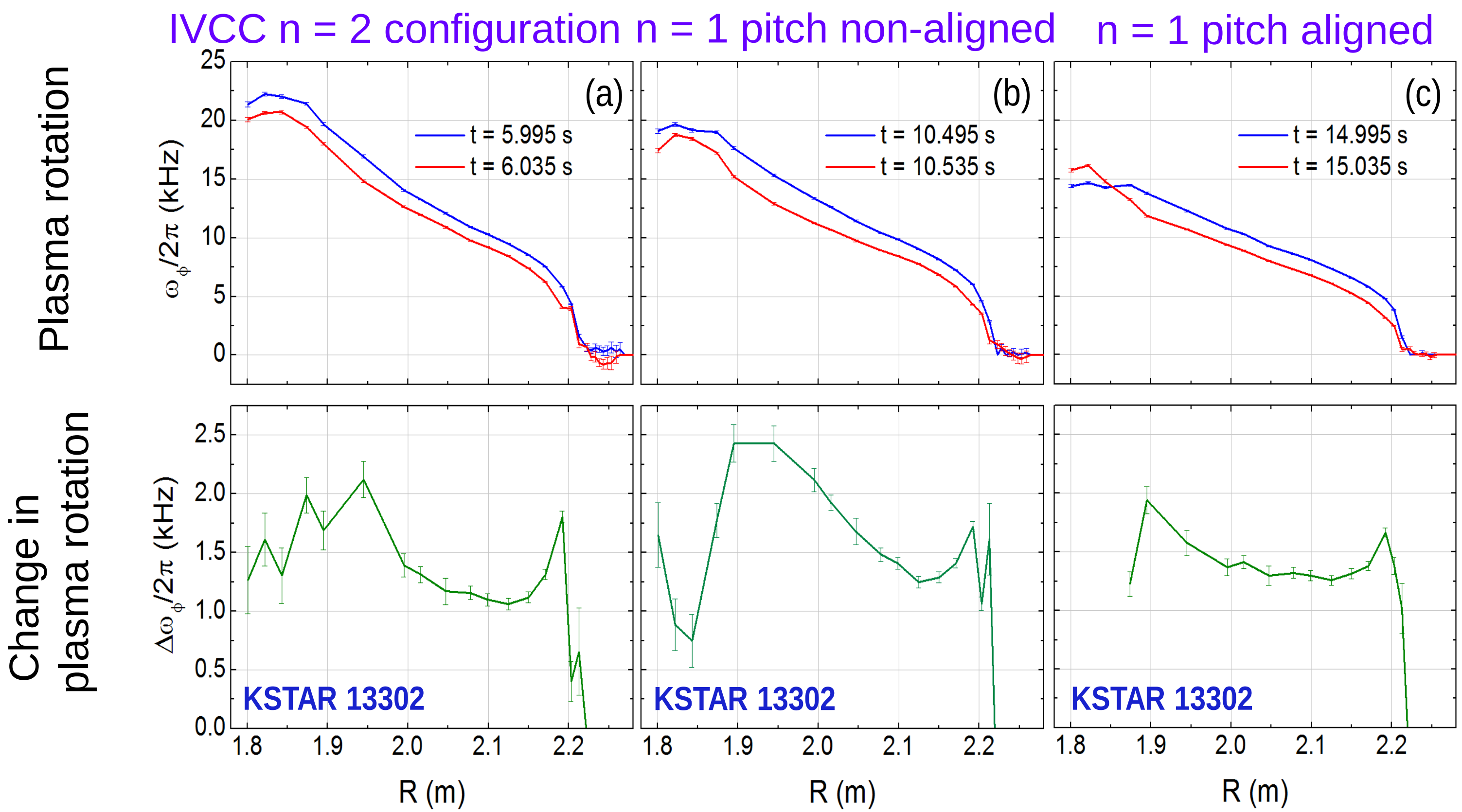
STEP 3: Long-pulse shots that need to be taken

- IVCC setup **13434 (type (B)), 13436 (type (Bc))**
- IVCC setup **13443 (constant current steps)**
- Divertor gas puffing – setup from shots: **13443** (0.6v), **13442** (0.7V)

- $B_t = 1.8$ T
  - Suggested 2016 target is **15778**; reduce I_p to 0.5 from 0.6 MA and match Ip rise time of a shot like 13433, 13434
  - Shots to take:
    - type (B) (IVCC setup 13434), type (Bc) (IVCC setup 13436) (**2 shots**)
    - **NO** divertor gas puff (constant IVCC steps like 13443) (**1 shot**)
    - with divertor gas puff 0.6V (constant IVCC steps like 13443) (**1 shot**)

- $B_t = 2.0$ T
  - Shots to take: (Increase $B_t = 2.0$T from above)
    - **NO** divertor gas puff (constant IVCC steps like 13443) (**1 shot**)
    - with divertor gas puff 0.6V (constant IVCC steps like 13443) (**1 shot**)

MP2015-05-23-001 "*Isolation of NTV torque profile*" on KSTAR established isolated NTV profile using IPS capability



(Y.S. Park, S.A. Sabbagh, Y. Jeon., et al., (approved by U.S. Committee for IAEA FEC 2016)

- 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

➔ Present experiment aims to create distinct NTV profiles ← NOT enough time given for this