Validation of Kinetic Turbulent-Neoclassical Theory for Edge Intrinsic Rotation in DIII-D Plasmas

by

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in collaboration with

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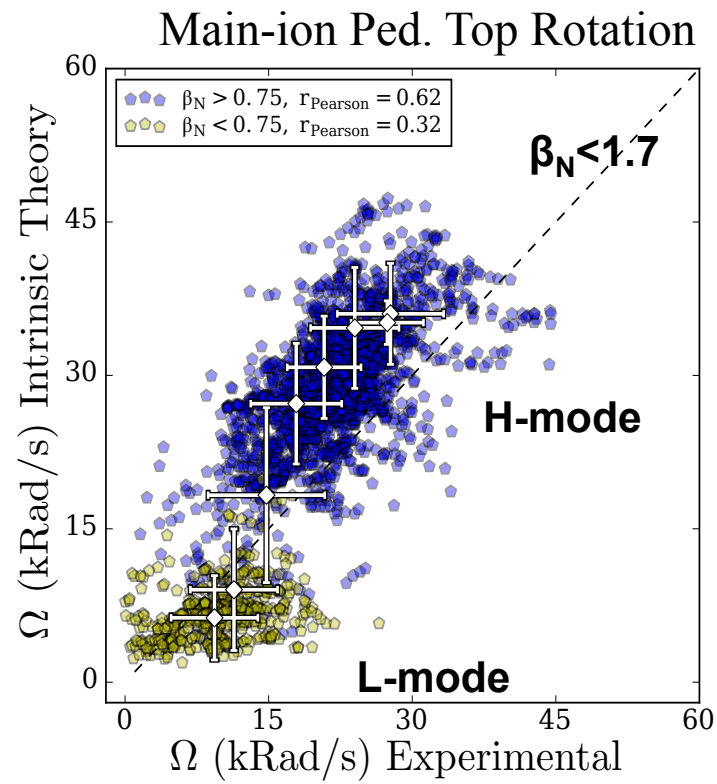
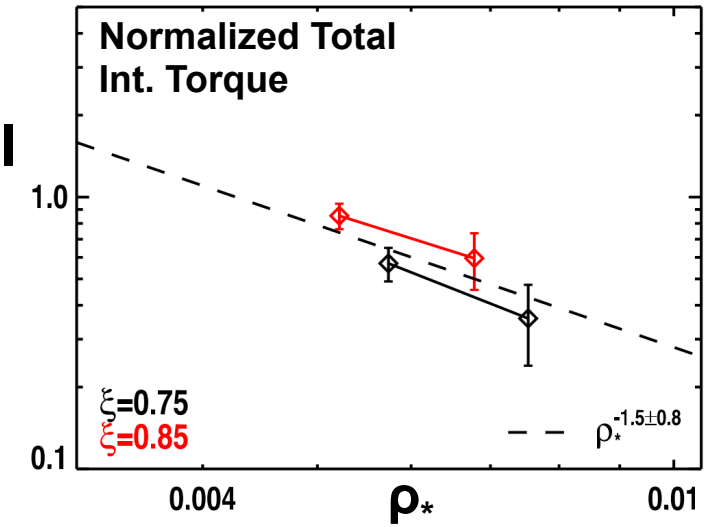


Toroidal Rotation is Beneficial to the Performance of Tokamaks

- **Rotation and shear improve confinement and stability**
- **In tokamaks, in the absence of external momentum sources the plasma spins with an *intrinsic* toroidal velocity.**
- **In ITER, rotation is expected to be strongly influenced by *intrinsic* sources[1,2].**

C Chrystal, PoP (2017)



[1] BA Grierson IAEA (2016)
[2] C Chrystal PoP, 24, 056113 (2017)

Capturing the Physics of Edge Momentum Transport has been a Challenge for Predicting the Rotation Profile

Previous Related Theory Models:

- Neoclassical models : drastically under-predict momentum transport i.e. $\chi_\varphi << \chi_i$. Experiments show $\chi_\varphi \sim \chi_i$, suggesting turbulence dominated transport of momentum.
- Turbulent models : primarily focus on *core*, use quasilinear formulation to identify residual stress, momentum pinch.
- Orbit loss models : neglect turbulent transport which can strongly modify the loss-cone-predicted rotation.

Stoltzfus-Dueck Theory Model:

- Predicts the *value* and *direction* for intrinsic rotation at the pedestal top.
- Prediction can be used as BC for *predictive simulations*.

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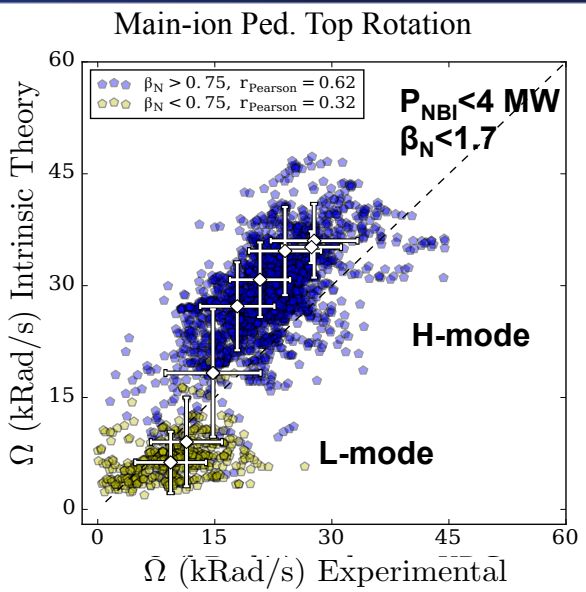
Main Results

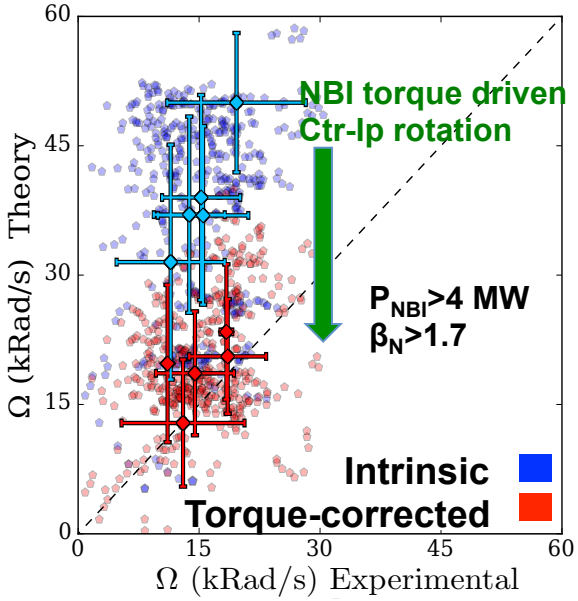
A) Intrinsic rot. Theory (T. Stoltzfus-Dueck):

- **for moderate β_N theory prediction in reasonably good agreement with exp. pedestal top rotation**
- **At high β_N, exp. rotation degrades with increasing β_N, in contrast with theory prediction**



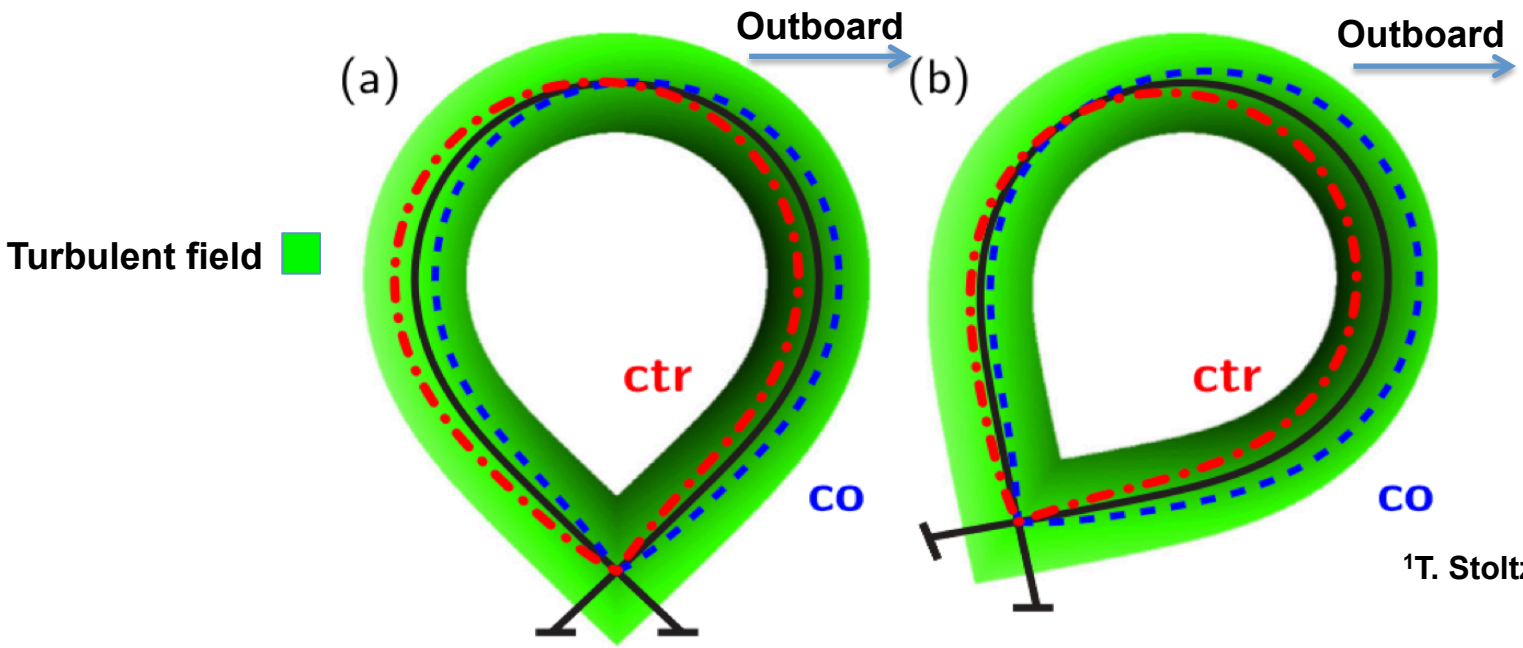
B) General rot. theory - finite torque:

- **At high β_N, finite ctr-Ip JxB torque resulting from NBI generated fast ion orbit loss reduces the net co-Ip rotation**
- **Ctr-Ip rotation shift is calculated using a reduced edge momentum transport model + TRANSP/NUBEAM**



Intrinsic Rotation Theory Model

Stoltzfus-Dueck Model[1] Predicts Value, Direction of Velocity at Core-Edge Boundary



[1]T. Stoltzfus-Dueck PRL 2012

How is the intrinsic rotation generated?

- **For typical outboard ballooning turbulence:**

  ctr-Ip passing ions experience a stronger drift-orbit-averaged turbulent diffusion than co-Ip ions.

  → ctr-Ip ions are depleted at a higher rate

  → co-Ip intrinsic rotation of the plasma

A Central Result: Steady State Momentum Balance Equation at the Pedestal Top

Density flux

Angular momentum flux

Co-Ip torque applied to plasma core

$$\tau = v_{\mathrm{rig}}\Gamma_p + \Pi$$

Outward momentum flux through pedestal

- Π **(Rotation drive) represents a "residual stress".**

- **Intrinsic rotation is a special case:**

$$\tau = 0 \longrightarrow v_{\mathrm{int}} = -\frac{\Pi}{\Gamma_p}$$

Model Yields An Explicit Formula for Flux-Surf.-Avg. Main-ion Toroidal Velocity at Pedestal Top

Passing fraction f_{pass} ~ 29 % for typical DIII-D ped. top

Theory Prediction

edge safety factor

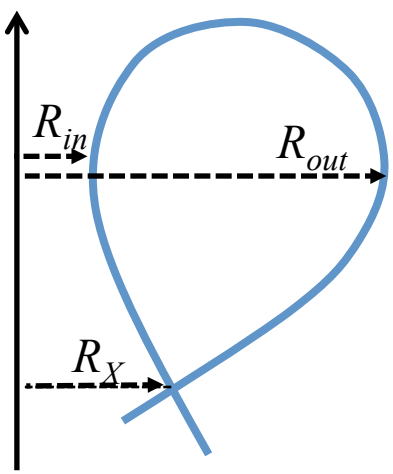
$$v_{\rm int} \approx \boxed{f_{\rm pass}} \times 0.104(0.5d_c - \overline{R}_X)\frac{q}{L_{\tilde{\phi}}({\rm cm})}\frac{T_i|_{\rm pt(eV)}}{B_T({\rm T})}{\rm km/s}$$

Ballooning in/out asymmetry

normalized X-pt major radius:

$$\overline{R}_X = \frac{2R_X - (R_{out} + R_{in})}{R_{out} - R_{in}}$$

radial decay length of potential fluctuations



- **Strong dependence on X-pt location (Validated on TCV for Ohmic L-modes[1])**
- **v_{int} captures observed features of edge intrinsic rotation:**
  - **Reproduces Rice scaling (q/B_T~1/Ip)**
  - **Predicts co-Ip vel. for typical inboard X-pt**

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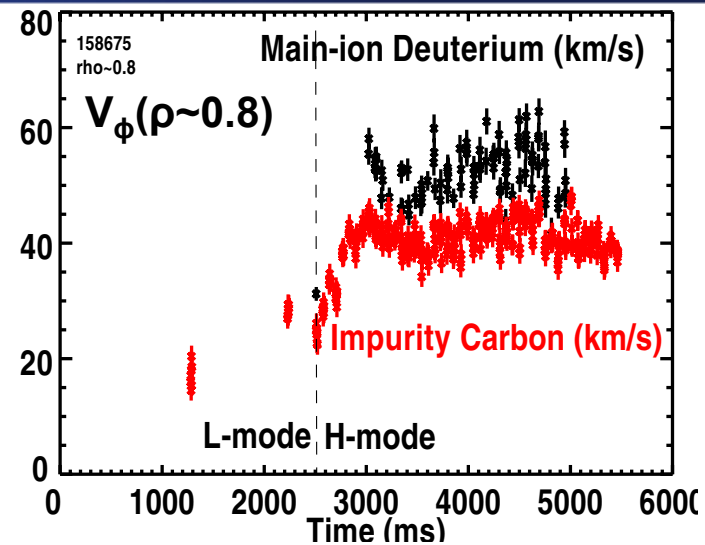
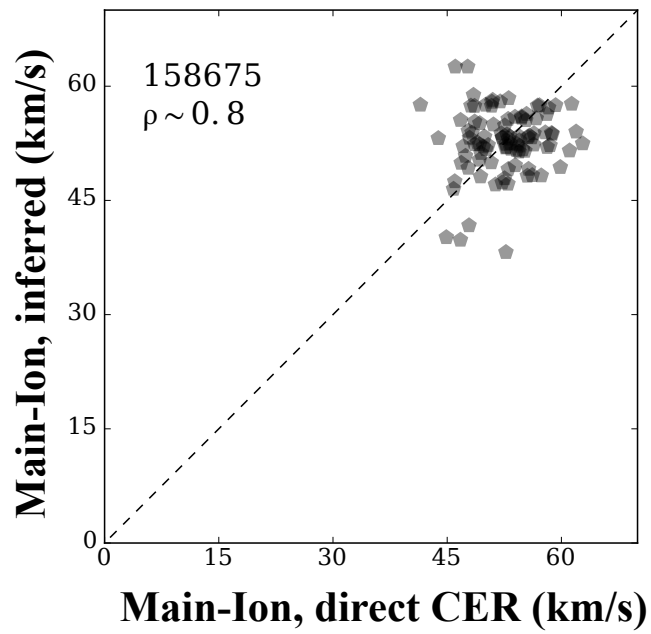
Developing the Rotation Database

Exp. Main-ion Rotation is Inferred From Impurity Measurements

- $\Omega_C < \Omega_D$ → Impurity rotation not suitable for theory validation.
- Main-ion rot. (Ω_D) inferred from measured impurity rot. on LFS (Ω_C) by analytically calculating their Neoclassical offset.[1]
- Ω_C corrected for PS flow to obtain rigid rot.
- Ω_D validated with direct CER measurements for a limited number of discharges





[1]Kim, Diamond, Groebner, PoP, 1991

Validation of Model is Performed Across Wide Range of Plasma Conditions

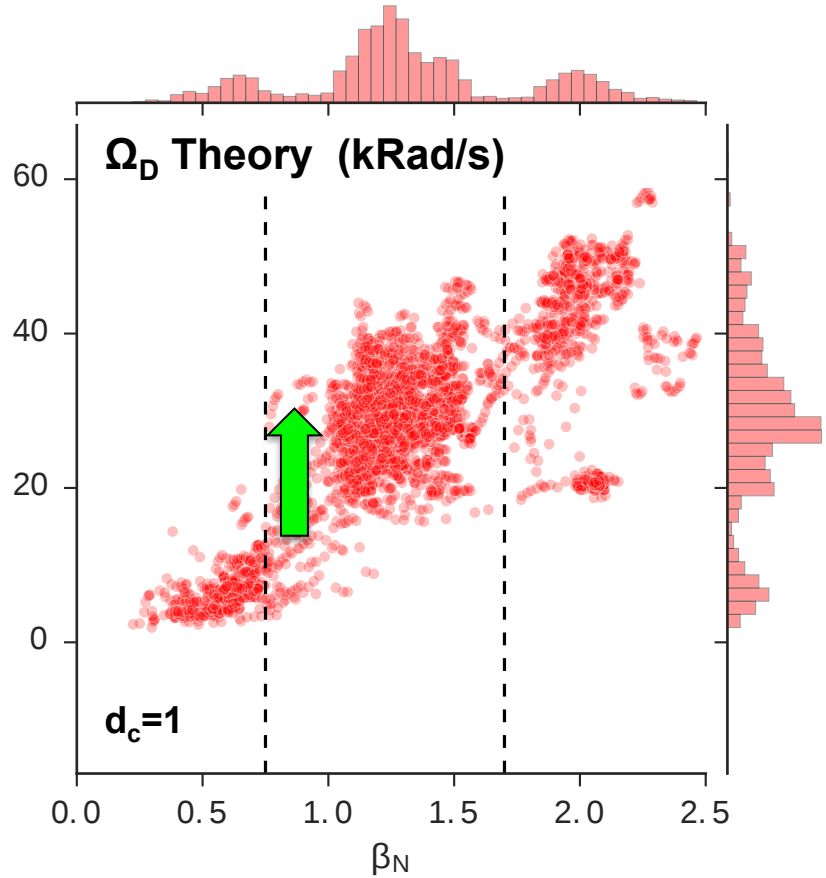
Database

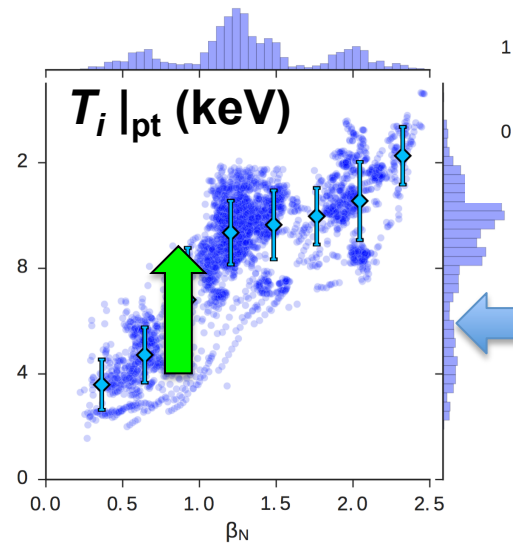
Main-ion, flux surface averaged ped. top rot.:

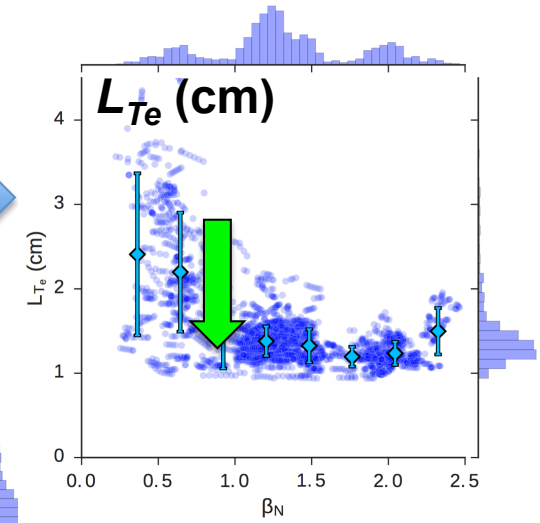
44 low-torque discharges ($|\tau|<0.5$ N.m),
~14000 CER measurements, L and H mode,
β_N up to 2.5, USN and LSN,
Forward and Reverse Ip,
ECH and balanced NBI heating

- **Potential fluctuations measurements not available ; L_{Te} used as a substitute for L_ϕ. (from experiments $L_\phi \sim 1\text{-}2\ L_{Te}$)**
- **Pedestal top radial location identified from fit to T_e**
- **X-pt poloidal location is approximately constant for entire database, with X-pt on the inboard side.**

Theory Predicts Monotonic Increase in Rotation with β_N





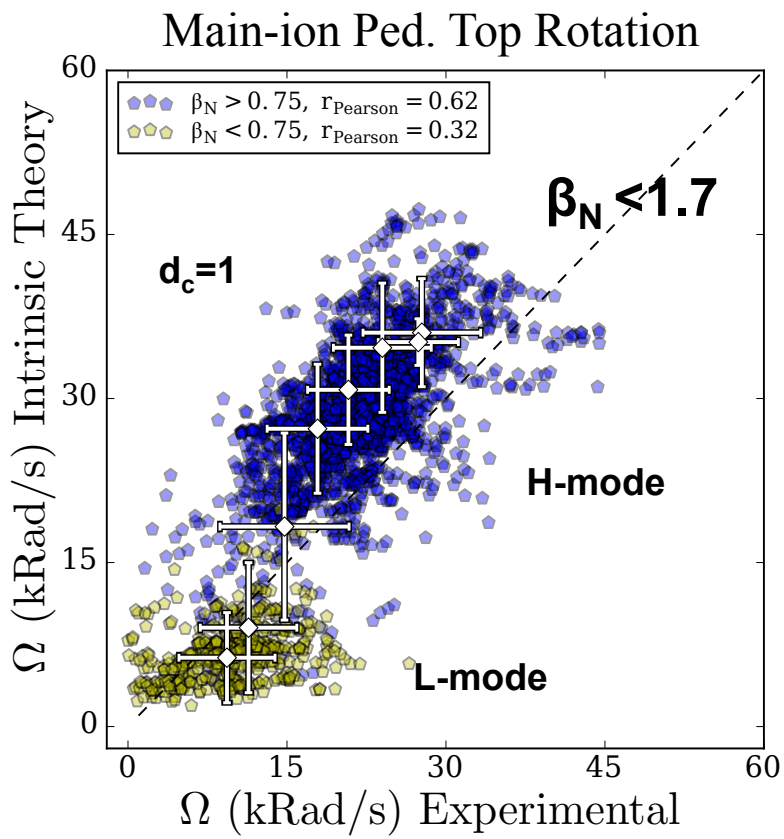


L_{Te} drops from ~ 3 to ~1.2cm

T_i |pt grows from ~ 0.5 to ~1 keV

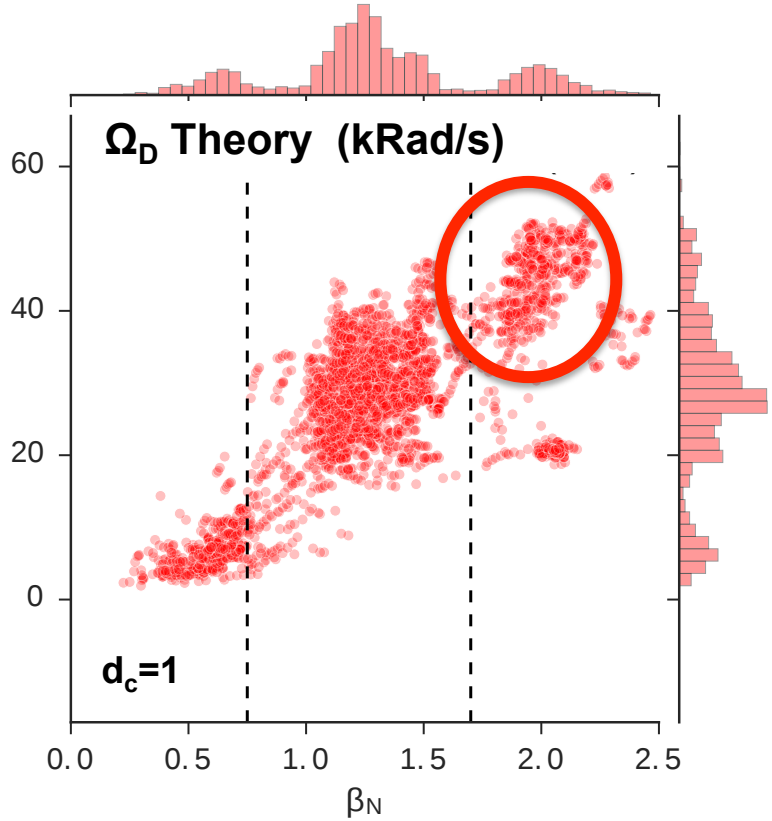
- Theory prediction is independent from rotation measurements.
- d_c=1 for moderate out-board ballooning used for whole database.
- Co-Ip spin-up at L-H transition is captured by the increase in Ti|pt and decrease of L_{Te} resulting from steepening of gradients.

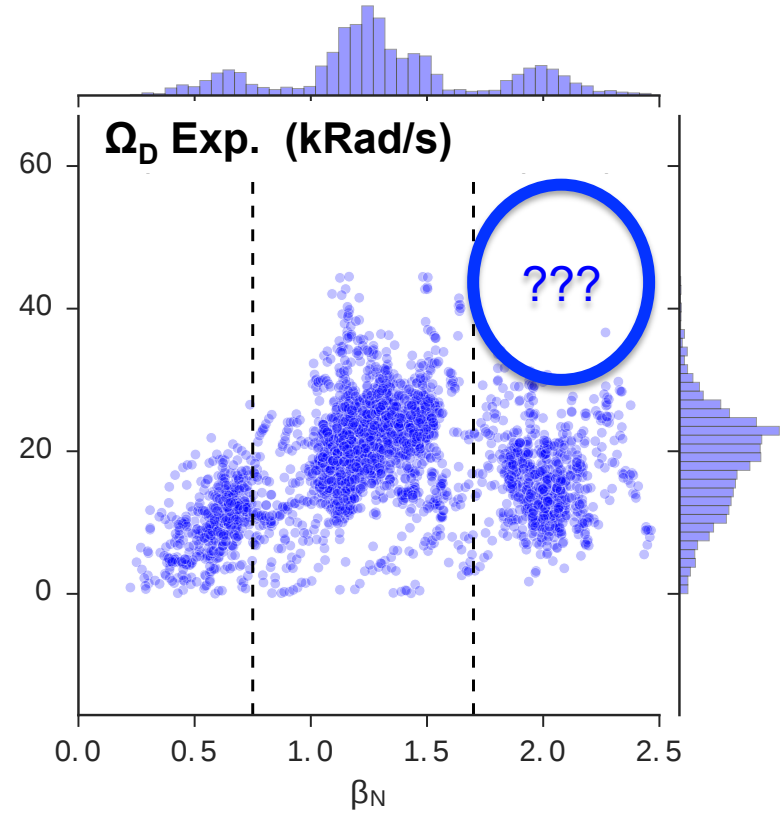
for Moderate β_N, Theory in Reasonably Good Agreement with Experiments



- **For L-mode further fine-tuning can be made by fitting for the optimum ballooning parameter d_c ,(d_c~ *1.6, stronger ballooning for L-mode than H-mode*).**
- **For ITER baseline, theory predicts a ped. top intrinsic rotation of ~ 4 kRad/s. (Chrystal PoP 2017 predicted ~ 7 kRad/s).**

at High β_N, Intrinsic Theory Does Not Predict the Observed Rotation Degradation

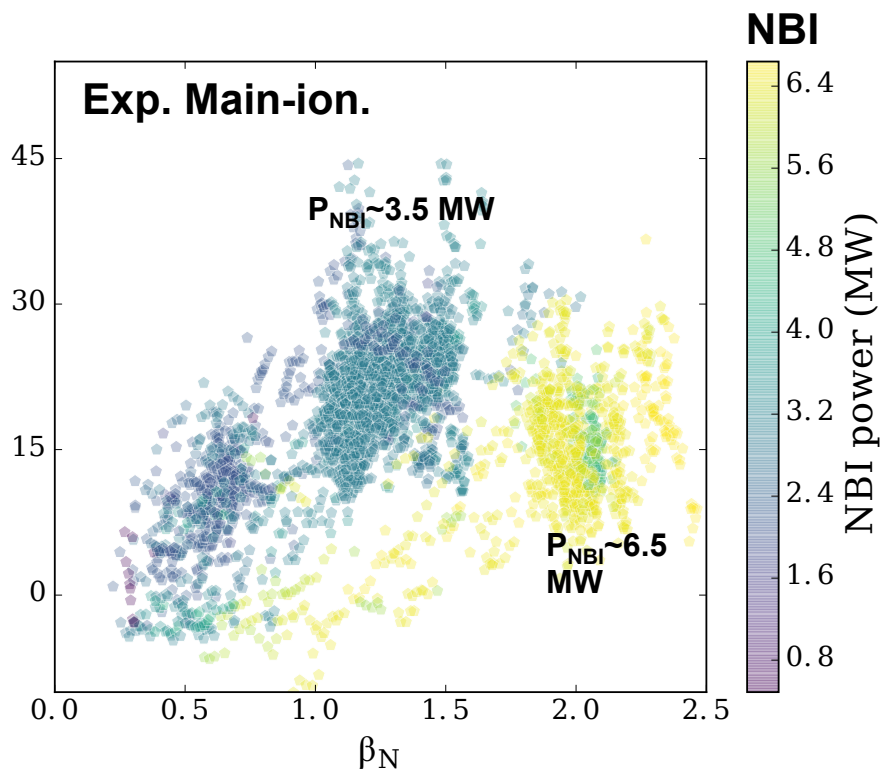


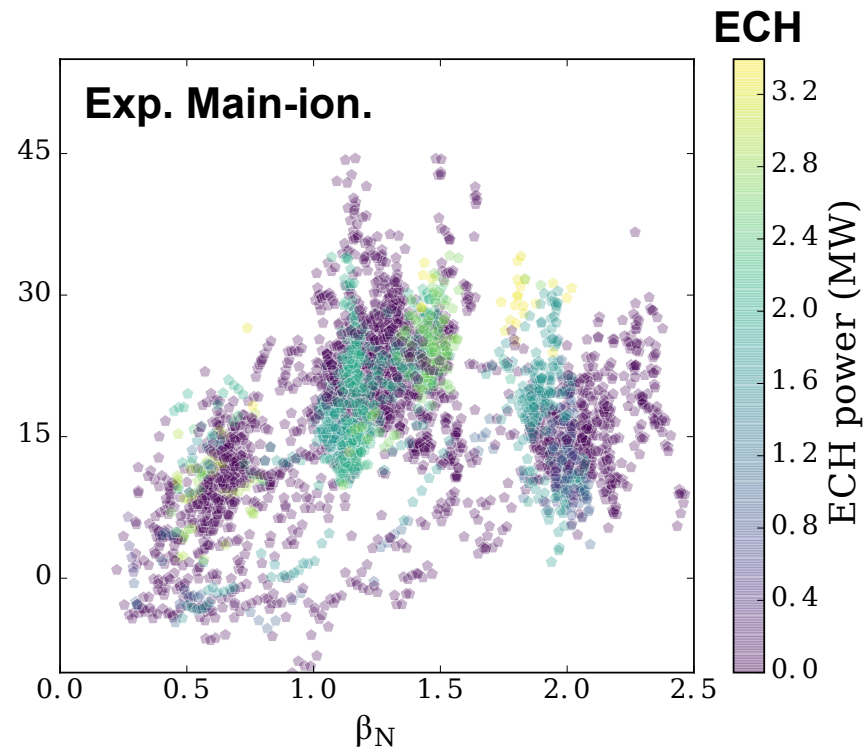


- **Disagreement at high β_N → problematic if model will be used for high performance conditions.**

Why is there a disagreement at high β_N??

Parameter Range with Large Disagreement with Theory is Isolated at High P_{NBI}

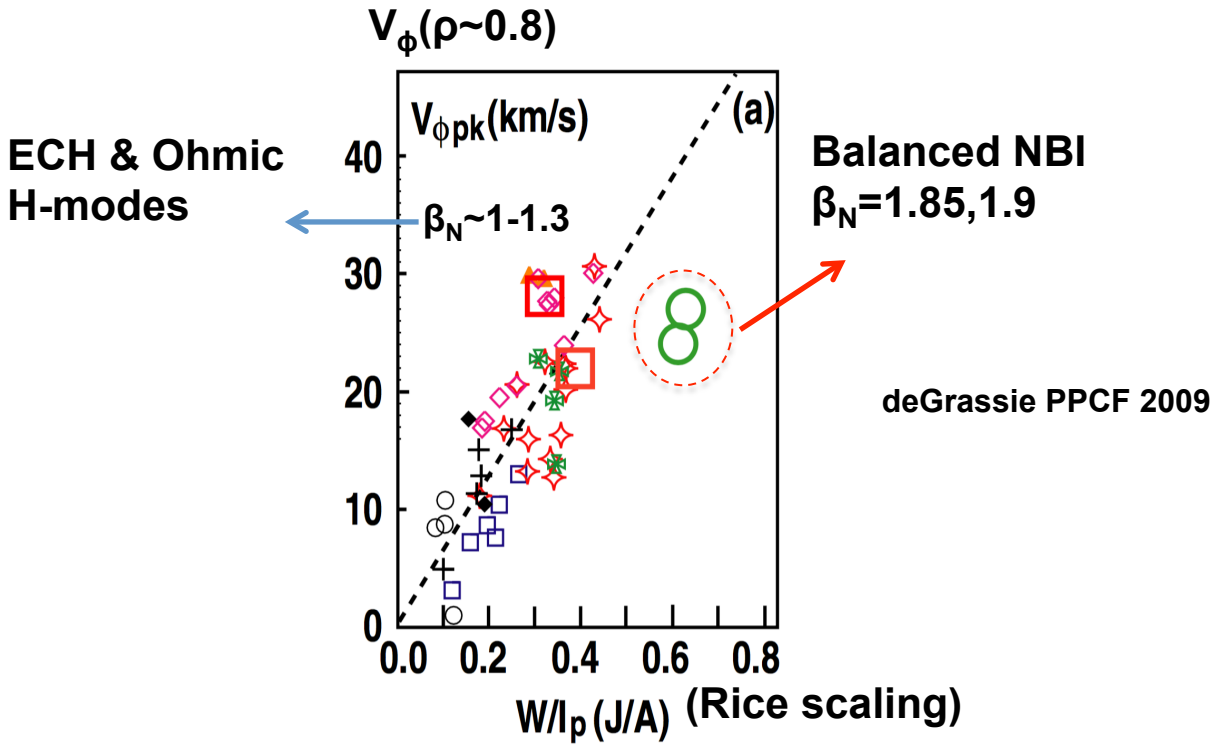




- P_{NBI}>4 MW rotation velocities are lower than P_{NBI}<4 MW.
- P_{ECH} is not correlated with rot. degradation.

This Database Connects with Previous Mystery of Main-Ion Rotation Degradation at High P_{NBI} in DIII-D

- D^+ rotation degradation at high β_N is consistent with previous reports in DIII-D for He^{2+}.



For High P_{NBI} , Large Ctr-Ip Torque in the Edge (>1 N.m) Leads to Rot. Degradation

$\mathbf{j_f} = -\mathbf{j_i}$ → $\mathbf{j_i} \times \mathbf{B}$ torque on plasma

$$\frac{d}{dt}\int \rho R V_\varphi dV = -\dot{N} e \Delta\psi$$

- Transport and friction losses

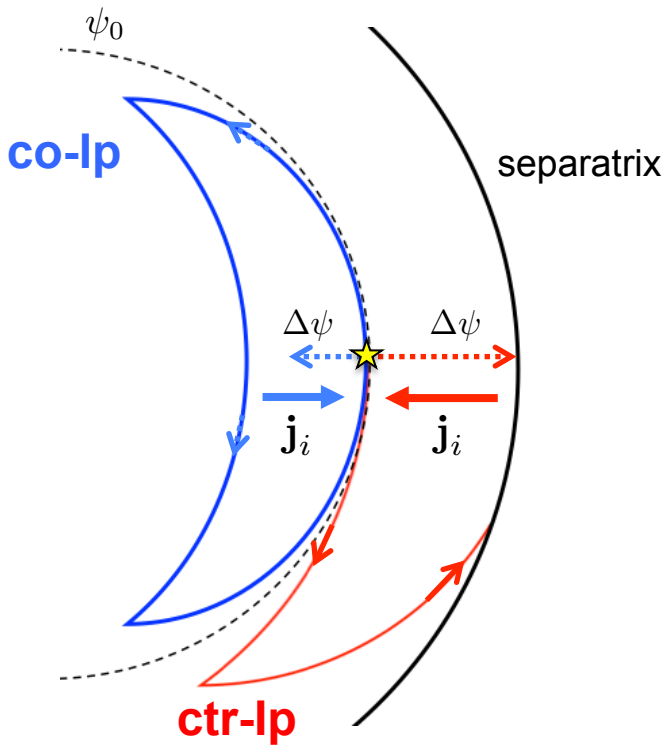
- **In the absence of collisions canonical angular momentum is conserved**

$$p_\varphi = m_i R v_\varphi - e\psi$$

- **Radial displacement:**

co-Ip $e\Delta\psi = -m_i R_0 v_{\varphi 0} < 0$ **(banana orbit)**

ctr-Ip $e\Delta\psi = m_i R_s v_{\varphi s} - m_i R_0 v_{\varphi 0} > 0$ **(lost orbit)**



When both directions of NBI are applied and are "nominally balanced", the total torque absorbed by the plasma can be net ctr-Ip, due to fast ion prompt loss[1]

[1]Helander PoP 2005

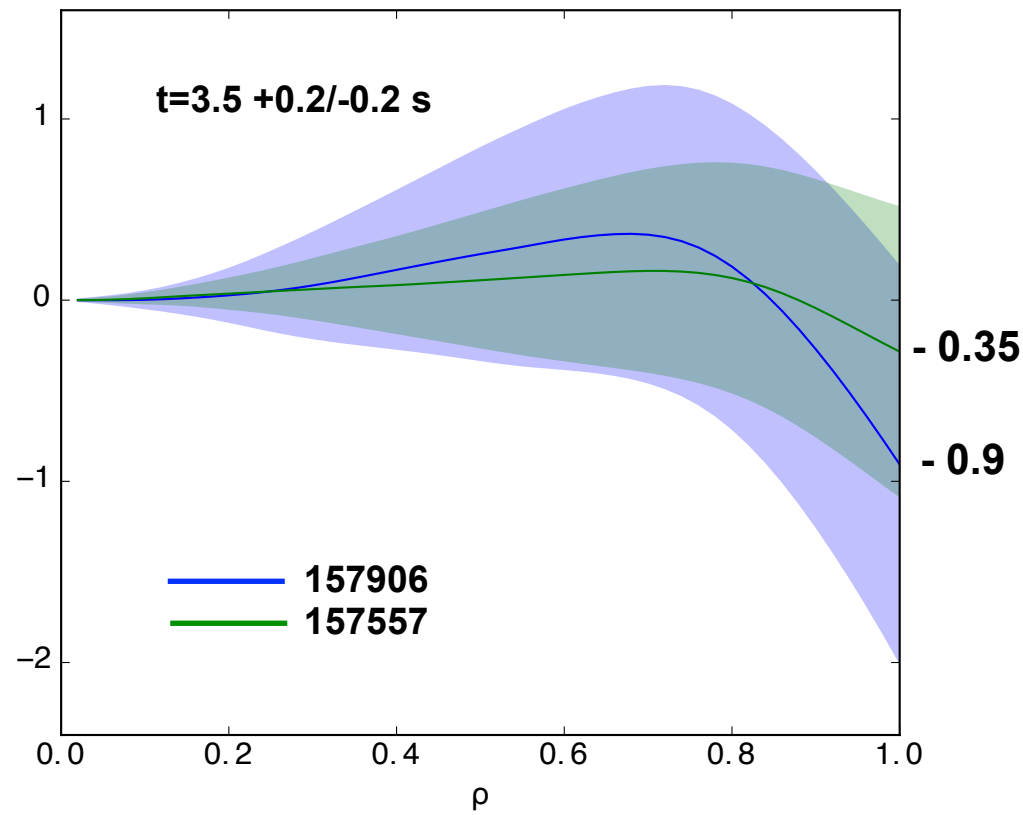
TRANSP/NUBEAM Calculation Performed for Entire Database

Discharge 157557:
β_N ~ 1.2 (moderate)
P_{NBI}~ 3.25 MW

Discharge 157906:
β_N ~ 2 (high) → degraded rot.
P_{NBI}~ 6.5 MW

- **Torque deposited in core(edge) is co-Ip (ctr-Ip)**
- **Note: NBI alternates between co&ctr; at CER measurement times prompt edge torque can be larger or smaller than average.**

Vol. integrated absorbed torque (N.m), calculated by TRANSP



Calculating the Rotation With Finite Torque is Required for Both Validation and Future Predictions

- **Simplified momentum evolution equation for the edge:**

$$\frac{d\omega_\tau}{dt} = -\frac{\omega_\tau}{t_\phi^{\text{edge}}} + \frac{\tau_{\text{edge}}}{I_{\text{edge}}} \quad \Longrightarrow \quad \omega_\tau(t) = \int_{-\infty}^{t} \mathrm{e}^{-(t-t')/t_\phi^{\text{edge}}} \frac{\tau_{\text{edge}}(t')}{I} dt'$$

- **Edge momentum transport time:** $t_\phi^{\text{edge}} \sim \frac{L_{\text{ped}}^2}{\chi_\phi^{\text{edge}}} \approx \frac{L_{\text{ped}}^2}{\text{Pr}\ \chi_i^{\text{edge}}}$
  - **Theory of turbulent transport predicts χ_i and χ_φ to be comparable: the Prandtl number, $\text{Pr} = \chi_\varphi/\chi_i$ is expected to be close to unity**

$$\chi_\phi^{\text{edge}} \approx \text{Pr}\chi_i^{\text{edge}}$$

  - **Pr estimated analytically[1] ; a single value used for DB**
  - χ_i^{edge} **is estimated using** Q_i^{edge} **(heat flux through edge) computed by TRANSP.**

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[1]T. Stoltzfus-Dueck PRL 2012

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For High P_{NBI}, Calculated Net Torque in the Edge (τ_{edge}) is Ctr-Ip and Large (>1 N.m)

Net torque in the edge:

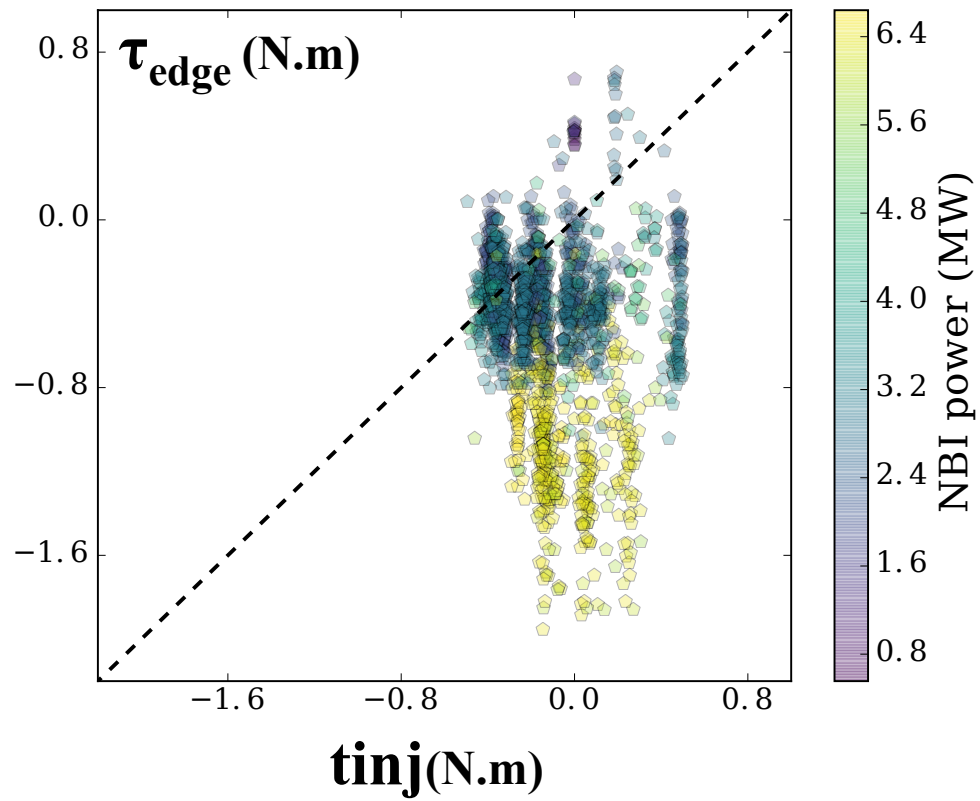
(using TRANSP/NUBEAM)

Ctr-Ip torque is collisionless J x B, promptly absorbed in edge.

Co-Ip torque is deposited in the core, transported to the edge slowly t~ $t_\phi^{\rm core}$; smoothed out in the process.

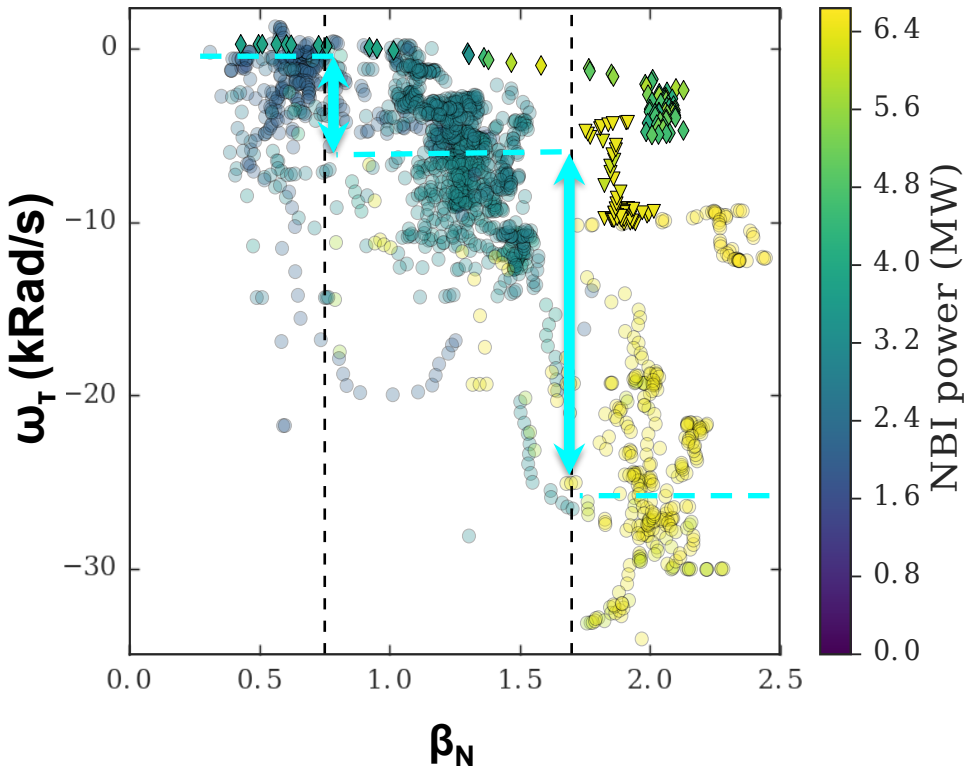
$$\tau_{\rm edge} = \tau_{\rm edge}^{\rm fast} + \tau_{\rm core}^{\rm slow}$$

prompt **averaged over** $t_\phi^{\rm core}$



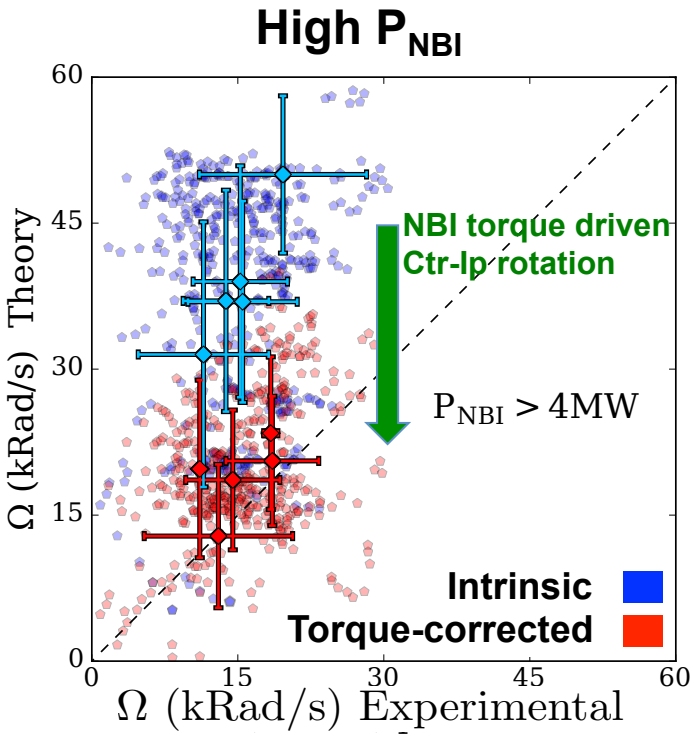
For P_{NBI} > 4 MW, while calculated torque ejected from beam holes is |tinj|< 0.5, net edge torque can be <-1 N.m

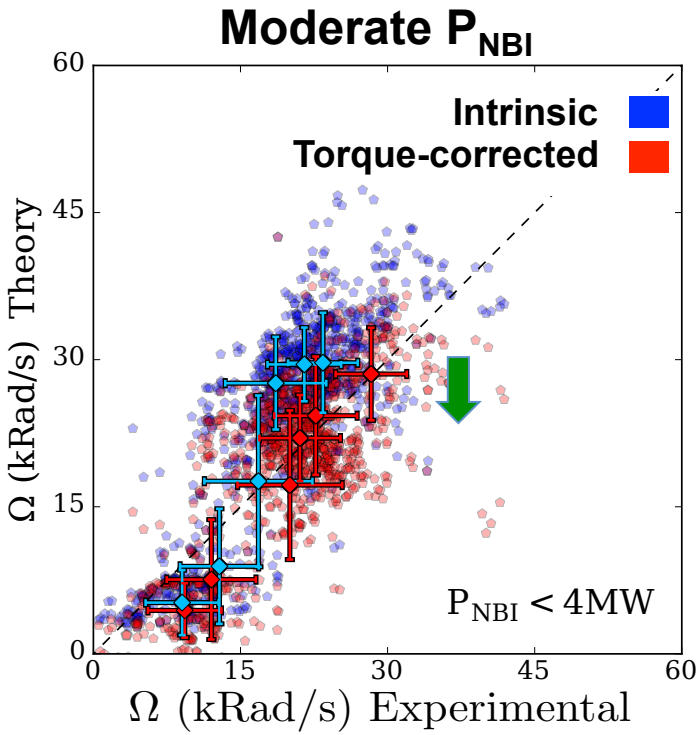
Calculated Ctr-Ip Rotation Shift is Large for High β_N



- **Large ctr-Ip torque at high P_{NBI} (~ -1 N.m) ➡ ω_T ~ - 30 kRad/s**
- **Finite rotation change for moderate-β_N H-mode (~ - 7 kRad/s)**

NBI Torque Correction to Intrinsic Theory Improves the Predicted Rotation





- **Torque corrected rotation (red) is much closer than intrinsic values (blue) to the experimental rotations (ω_T ~ - 30 kRad/s).**
- **Torque correction brings the theory prediction for H-mode closer to the experimental values (ω_T ~ - 7 kRad/s).**

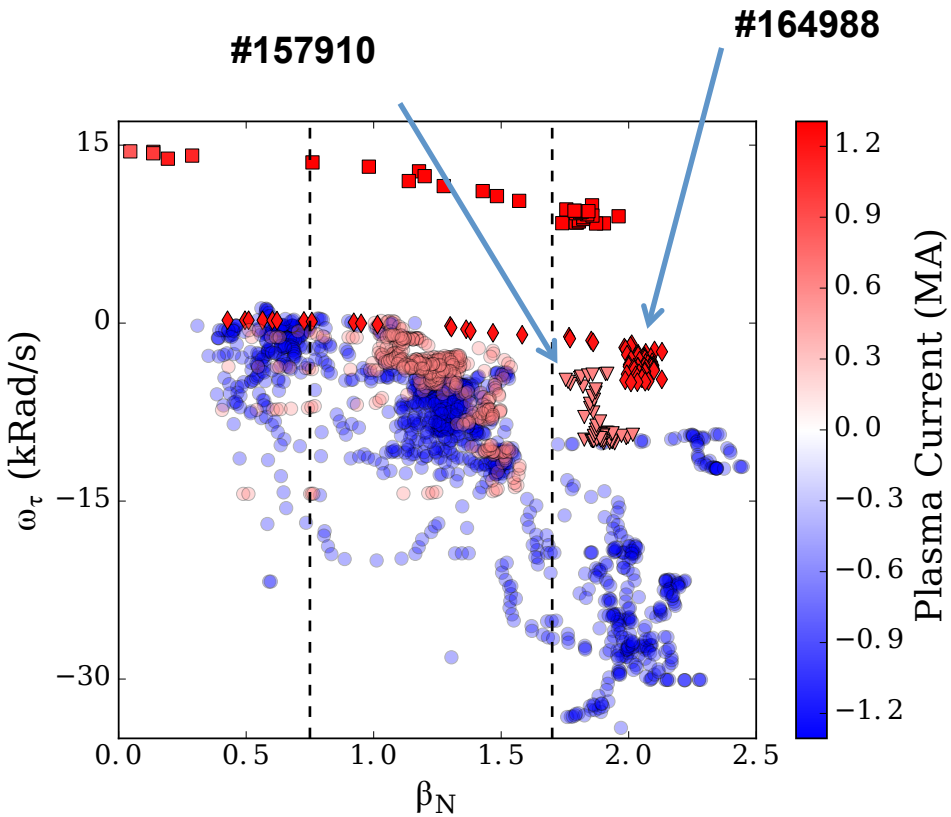
A New Rotation Model, Tested in Low-Torque DIII-D Plasmas, is Available for Predictive Simulations

- **Pedestal top rotation prediction shows good agreement for DIII-D low-torque rotation database.**
- **Model now includes finite NBI torques → uses simple inputs available to modeling codes.**
- **Future Research :**
  - **Using direct measurements of turbulent fluctuation profiles, ballooning (in/out asymmetry) for L- and H-mode, for more accurate predictions.**
  - **Exploring ELMs and 3D fields effect on momentum/rotation.**
  - **Exploring the intrinsic rotation generation in higher collisionality regimes**

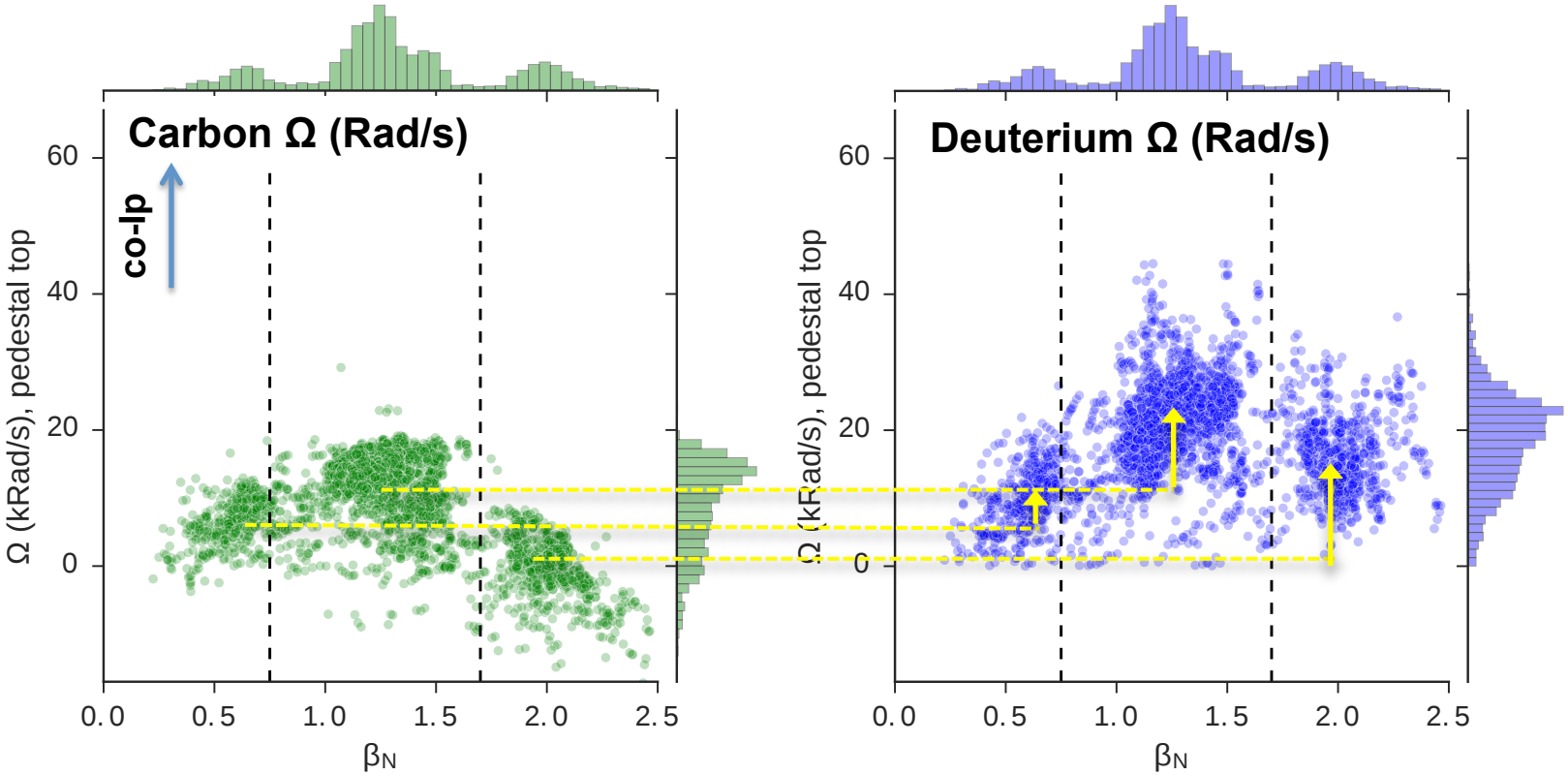
Supplemental Slides

Rotation degradation – Current Dependence

- Forward Ip discharges 157910 and 164988 have the lowest ω_T , comparable to the values in moderate β_N range
- Edge CER measurements use the 330 beams.
- 330 beam is in positive tor. direction; contributes a co-Ip(ctr-Ip) torque when Ip is directed forward(reverse).
- Discharge 164988 has largest Ip ~1.25 MA; smaller radial steps result in less orbit loss.

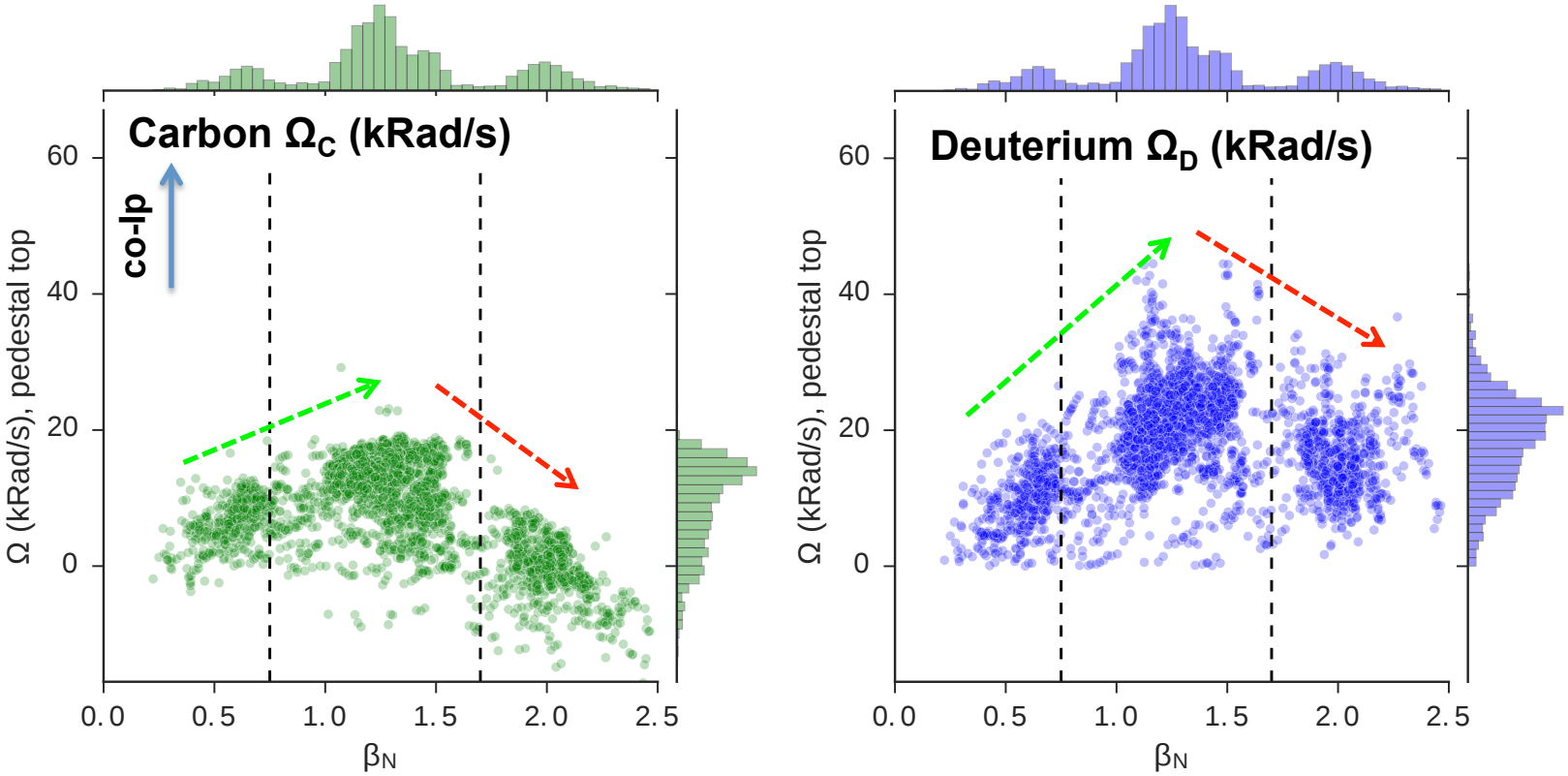


Important to Correct For Difference Between Impurity and Main-ion Toroidal Rotation



- **Main-ion rotation > carbon rotation, consistent w/ direct CER.**
- **L-to-H transition at β_N~0.75.**

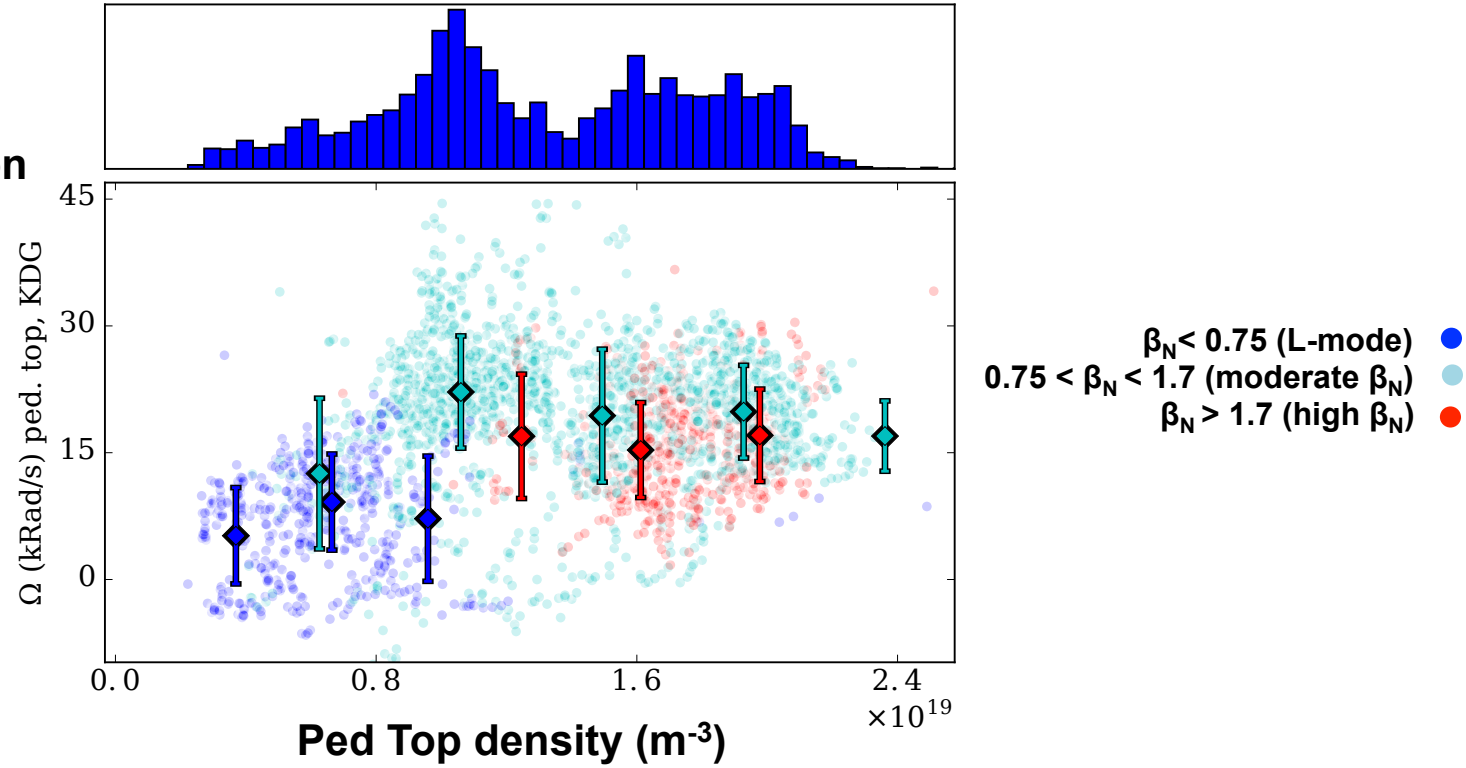
Impurity and Main-Ion Both Show Degraded Rotation at High β_N



- **Rot. increases in L-to-H transition.**
- **From medium to high β_N H-modes (crossing β_N~1.7) rot. decreases for both carbon and deuterium (due to finite NBI edge torque)**

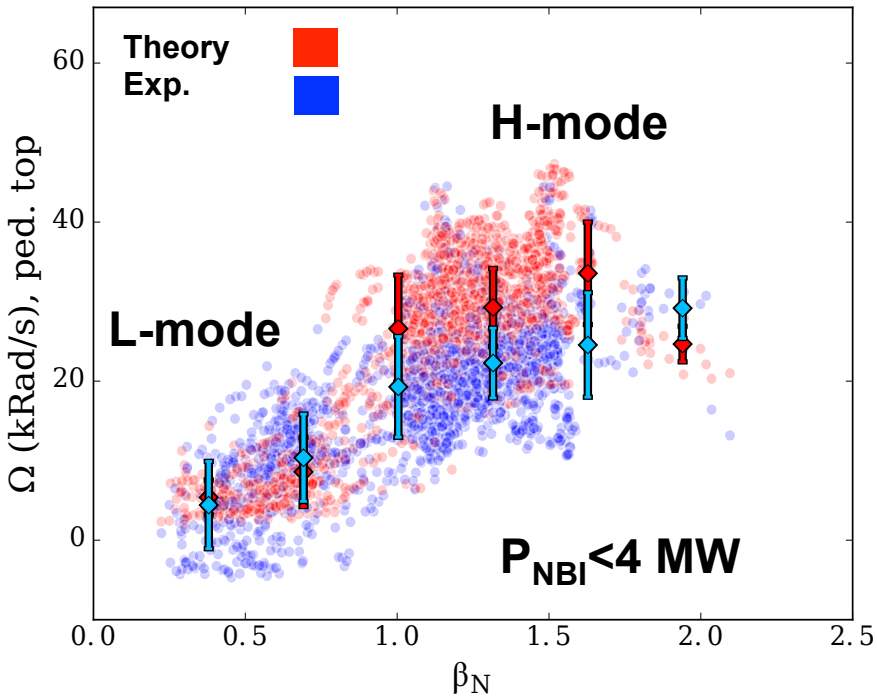
Exp. Main-Ion Rotation is Independent of Ped. Top Density

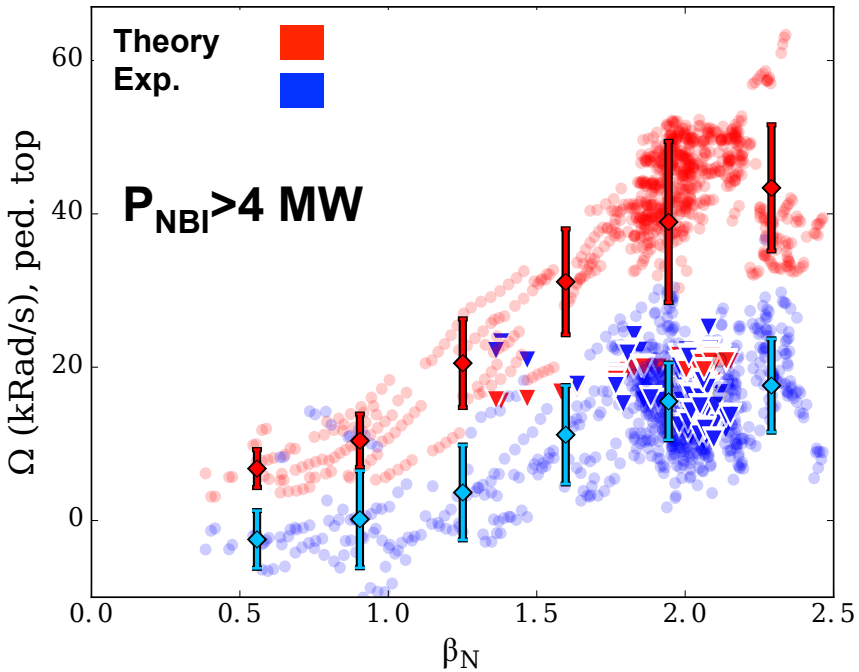
Exp. main-ion rotation



- For each β_N range in database, main-ion rotation is independent of pedestal-top main-ion density.
- Theory prediction is also independent of density.

Parameter Range with Large Disagreement with Theory is Isolated at High P_{NBI}





- Good agreement at moderate P_{NBI}
- For high P_{NBI} theory prediction is significantly larger than exp.