Decoupling the Effects of Momentum and Power Input From Neutral Beam Injection

by

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With contributions from

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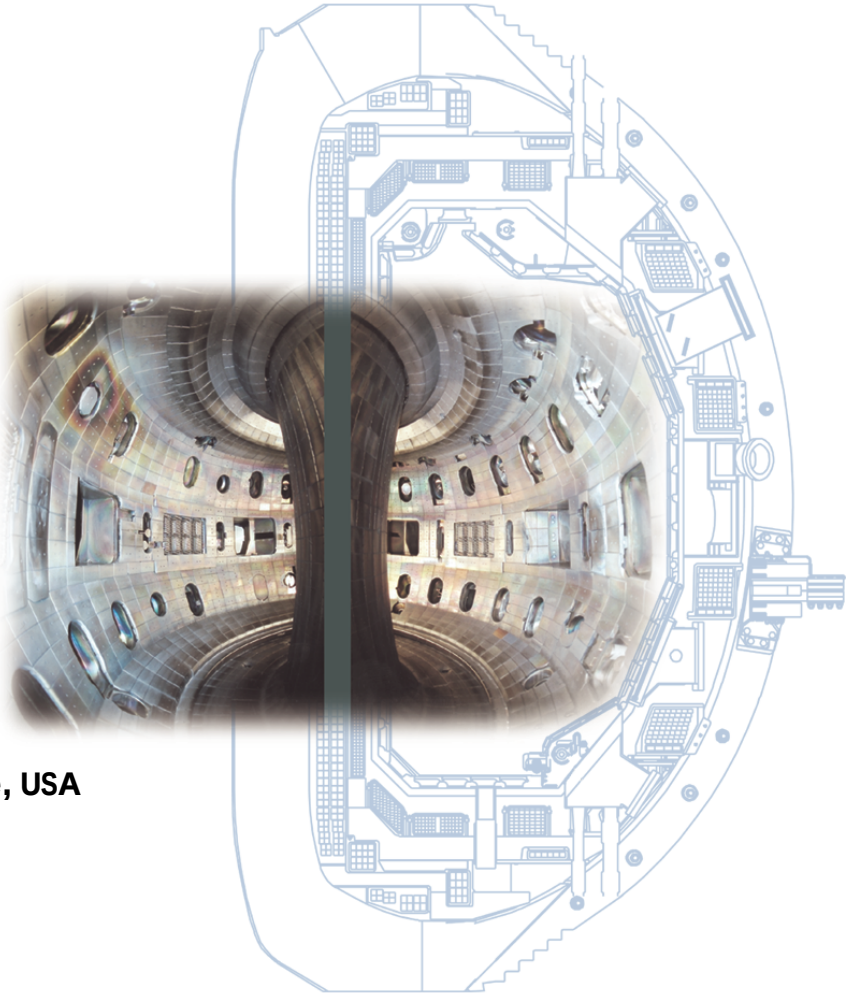

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DIII-D NATIONAL FUSION FACILITY SAN DIEGO

PPPL PRINCETON PLASMA PHYSICS LABORATORY

Motivation for Momentum Confinement Studies

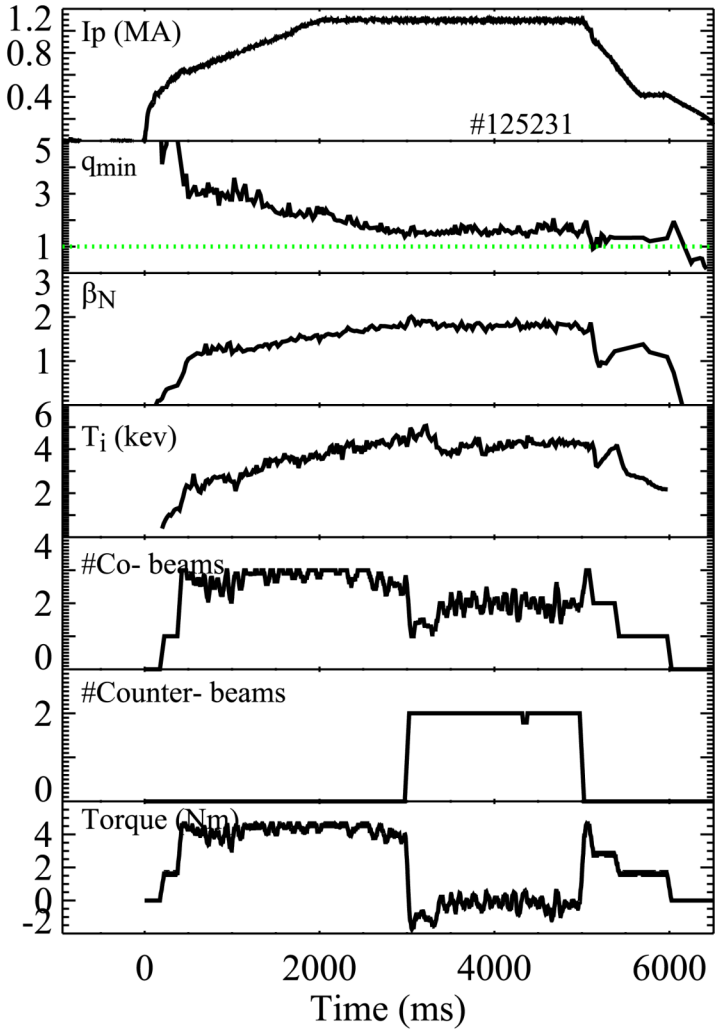
- **Rotation in ITER is expected to be much lower than the usual values in today's experiments**

- **There are many unknowns associated with rotation**
  - How exactly does the rotation scale with the momentum input?
  - How well do enhanced confinement regimes hold up at lower rotation?
  - Do we get enough $E \times B$ shear at low toroidal rotation to suppress turbulence?

- **New counter neutral beam capabilities on DIII-D allow us to begin to address some of these questions**

Momentum Transport Was Investigated Ising *Advanced Tokamak* Plasma Startup

- **Elevated q_{min} conditions stay above 1 for ~ 5 s**
  - no sawteeth
- **Torque scans performed at constant b_N**
  - Use plasma control system (PCS) beta feedback control
  - Beta feedback as proxy for T_i
- **As vary number of counter sources, PCS adjusts number of co-sources to maintain requested beta level**



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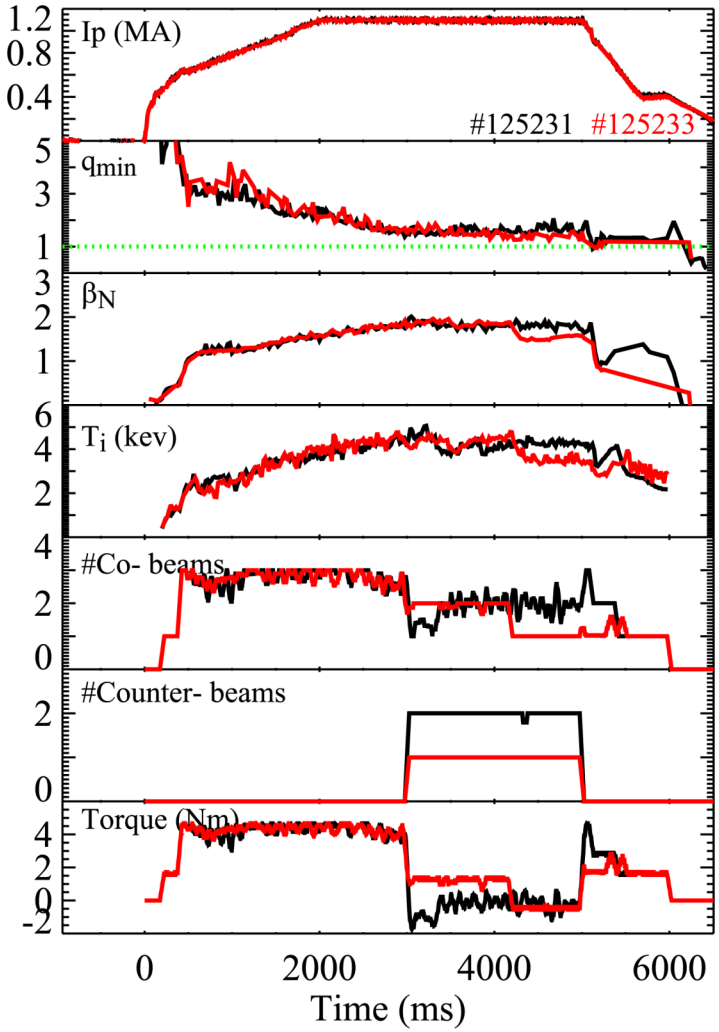
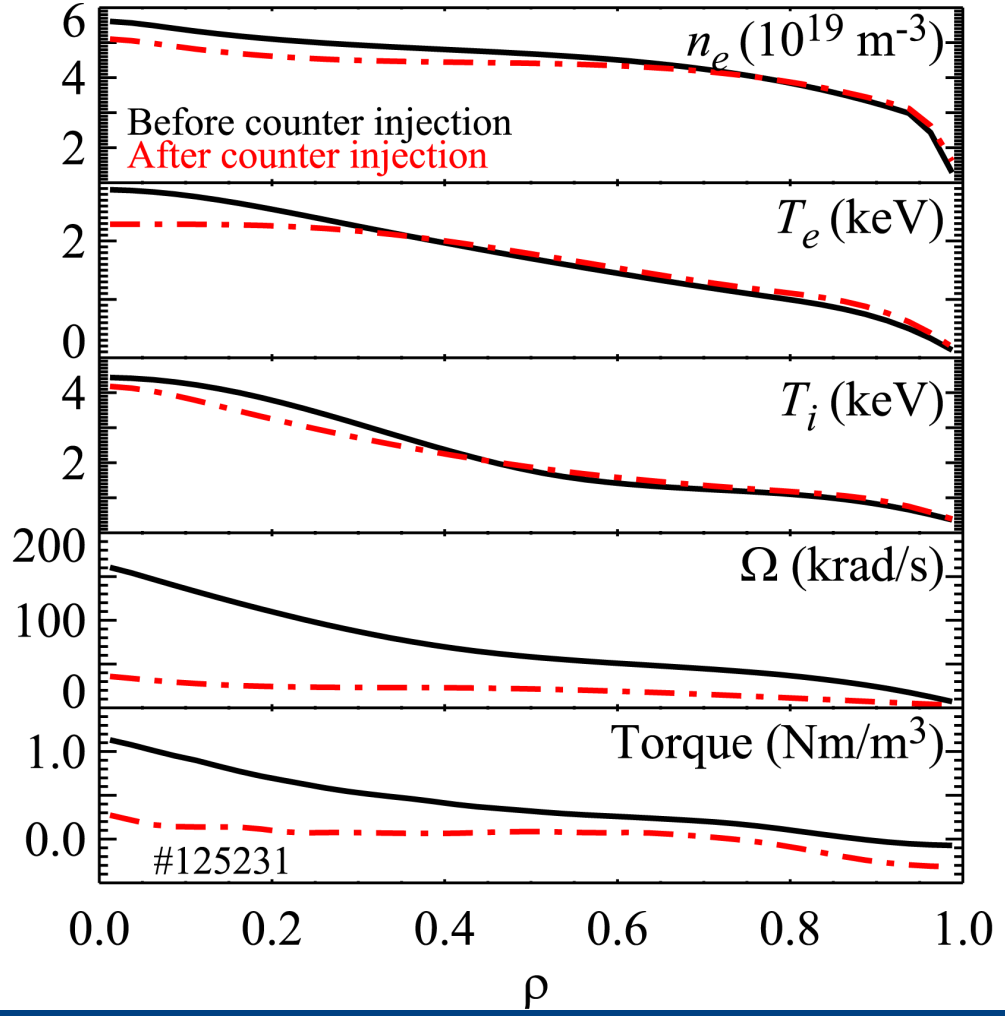


Change in Net Torque by Counter NB Mainly Affects Just the Rotation Profile

- **Introduction of counter beams reduce rotation by approx factor 4**
- **Only minor changes to other plasma profiles**
- **Transport analysis performed with TRANSP**



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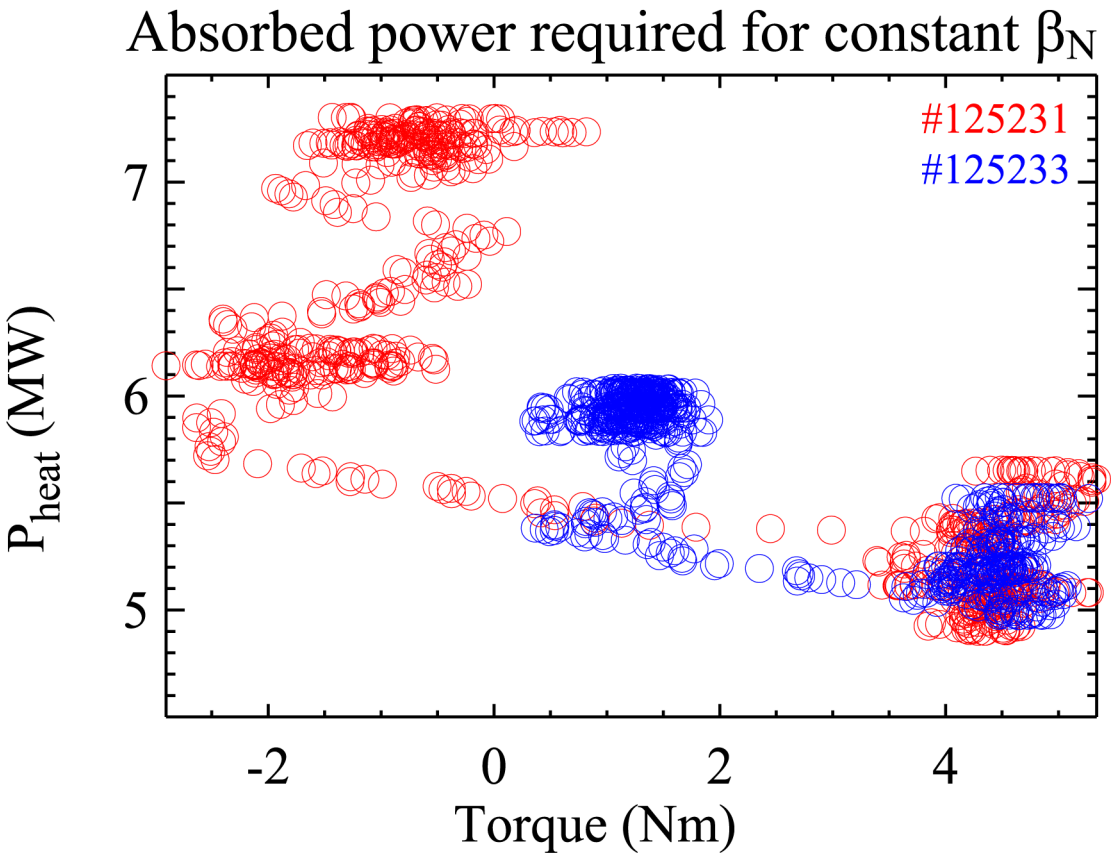
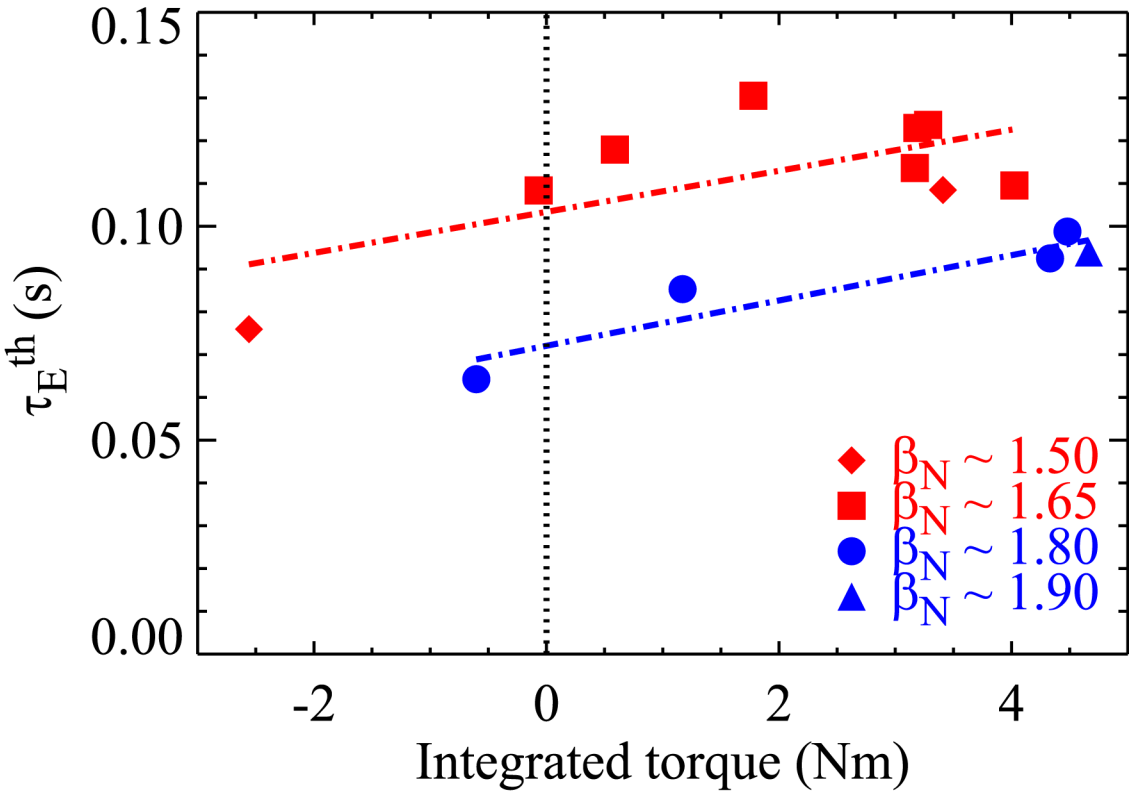
Power Requirements to Maintain Constant b_N Increase With Reduced Torque

- **Time record of absorbed beam power vs integrated torque from TRANSP**
- **Clear increase in power requirements as torque is reduced by introduction of counter beams**



Energy Confinement is Degraded with Counter Beams

- **Systematic decrease in energy confinement time as torque is reduced by counter beam**
- **Observations compatible with reduction in *E* x *B* shear**
- **Presumably, at some point, this trend must reverse**
  - Reverse I_p plasmas can have good confinement (eg QH-mode)



Momentum Confinement Time Characterized by Simple Model of Angular Momentum

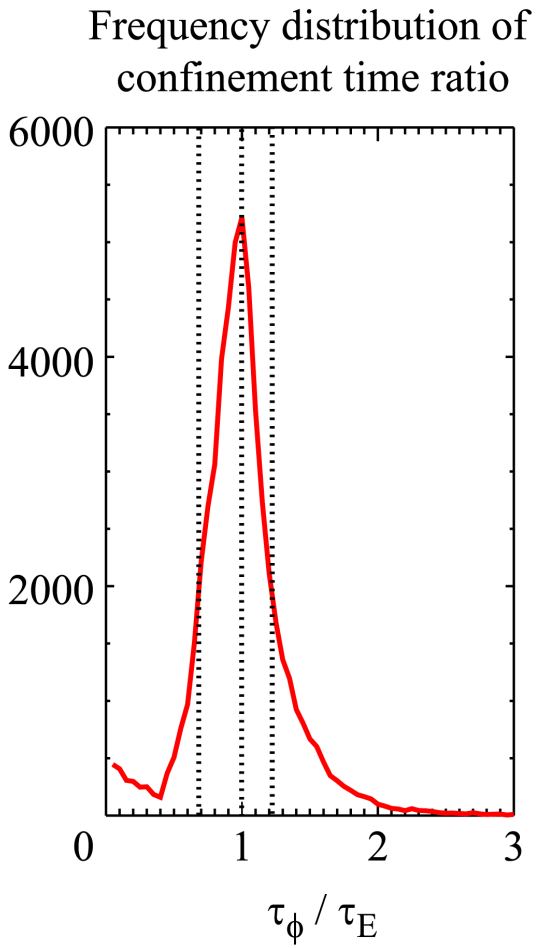
- **Momentum confinement time t_f represents decay of angular momentum *L*. For momentum source (torque) *T* :**

$$\frac{dL}{dt} = T - \frac{L}{t_f}$$

- **If torque comes from neutral beam injection, then in steady state:**

$$t_f \sim L / T_{NB}$$

- **Ratio of momentum to energy confinement typically found to be ~1 across many machines**

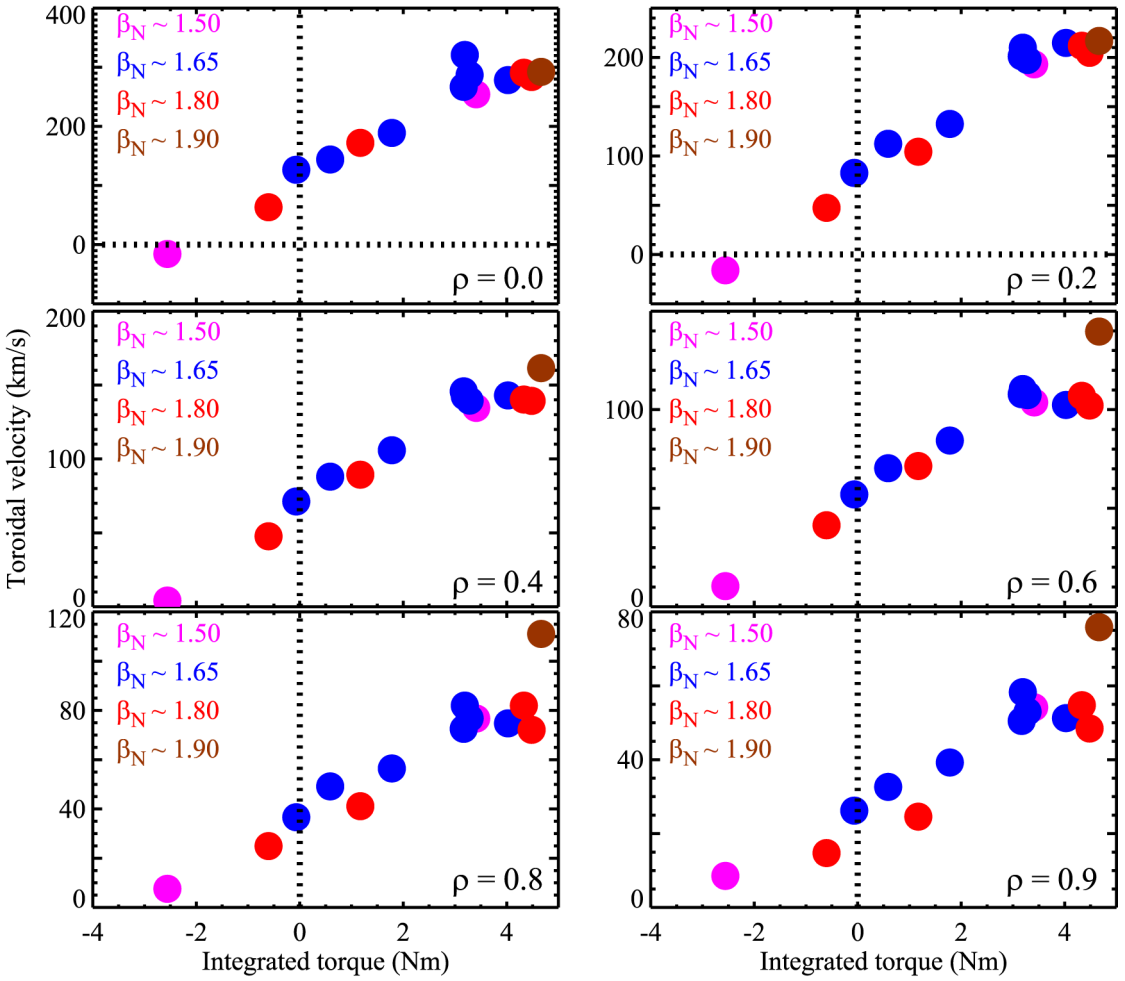


J.S. deGrassie et al, Nucl. Fus. **43**, 142 (2003)

Torque Scans Show that Toroidal Velocity Varies Fairly Linearly with Total Integrated Torque

- **No obvious variation with b_N**
- **Perhaps a little flattening at large torque**
- **Rotation not zero with zero torque**
  - "Intrinsic rotation"

  [See deGrassie GI1.00005]



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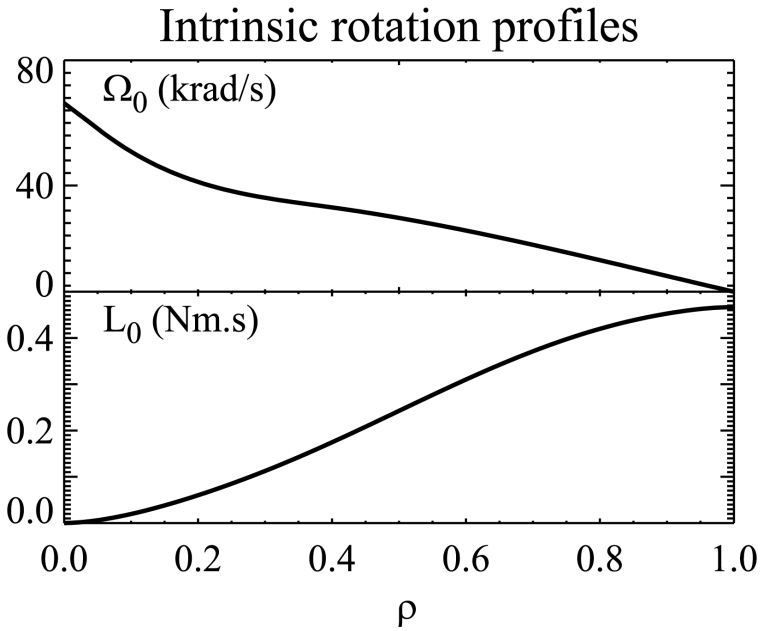
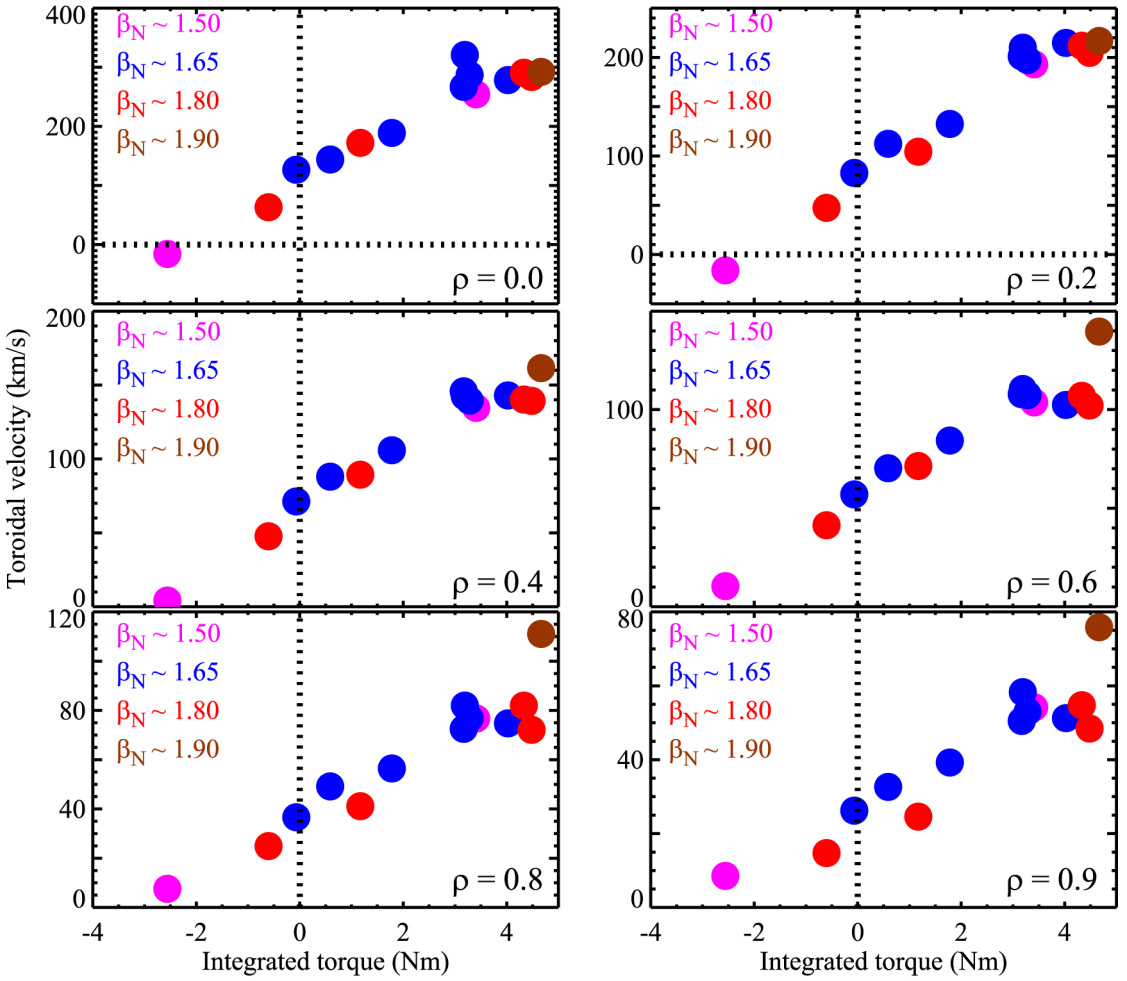
Intrinsic Rotation Profile Can Be Interpolated From the Torque Scan Data

- **Very large intrinsic rotation on axis**



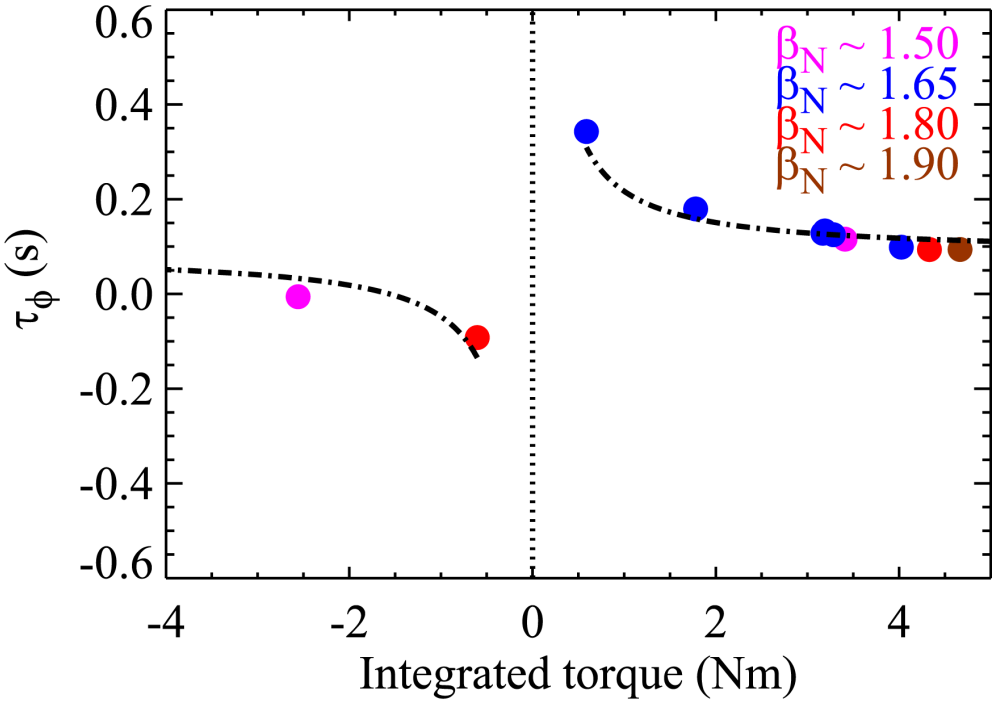


If Intrinsic Rotation is Neglected, Erroneous Momentum Confinement Times are Deduced

- **Large intrinsic rotation gives 1/torque dependency to momentum confinement**

$$t_f \sim L/T$$

- **If *L* doesn't go to zero with *T*, then t_f blows up**
- **If *L* positive when *T* negative, get negative t_f**

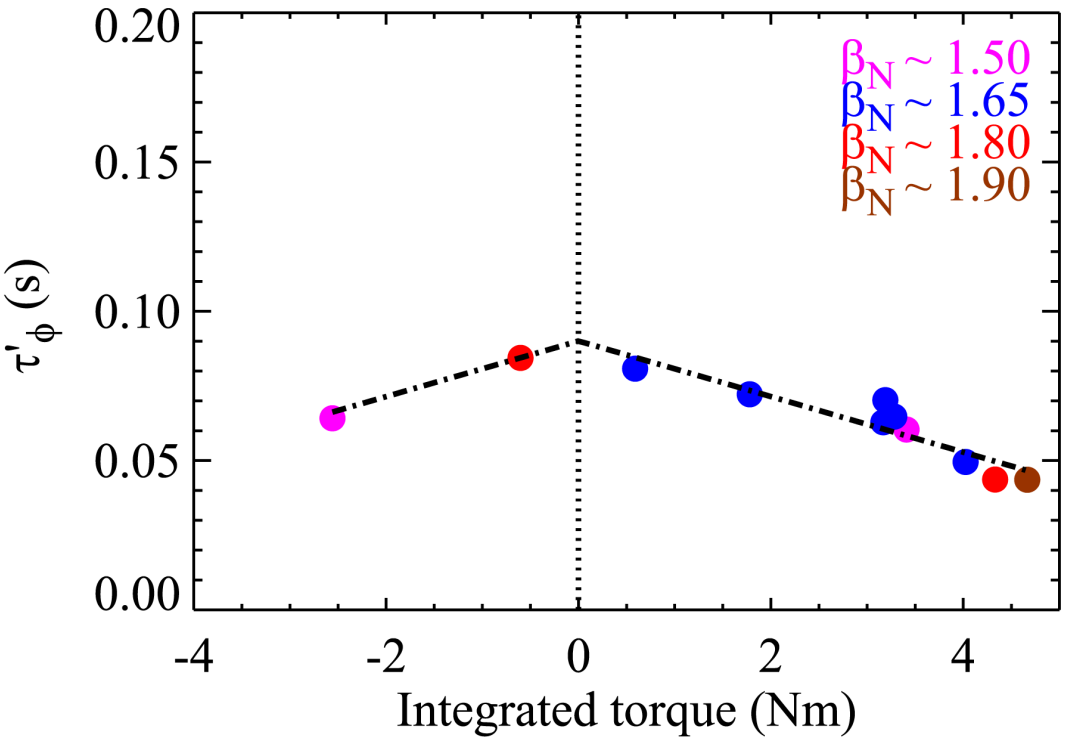


Momentum Confinement Shows Torque Dependence After Accounting for Intrinsic Rotation

- **Reanalyze momentum confinement times after subtracting intrinsic rotation**
  - Leaves rotation driven by neutral beam torque (incremental momentum confinement)

$$t'_f \sim \frac{L - L_0}{T_{NBI}}$$

- **1/Torque dependency disappears as expected**
- **However, residual dependence on torque/rotation remains**
  - Momentum confinement degrades with increased torque

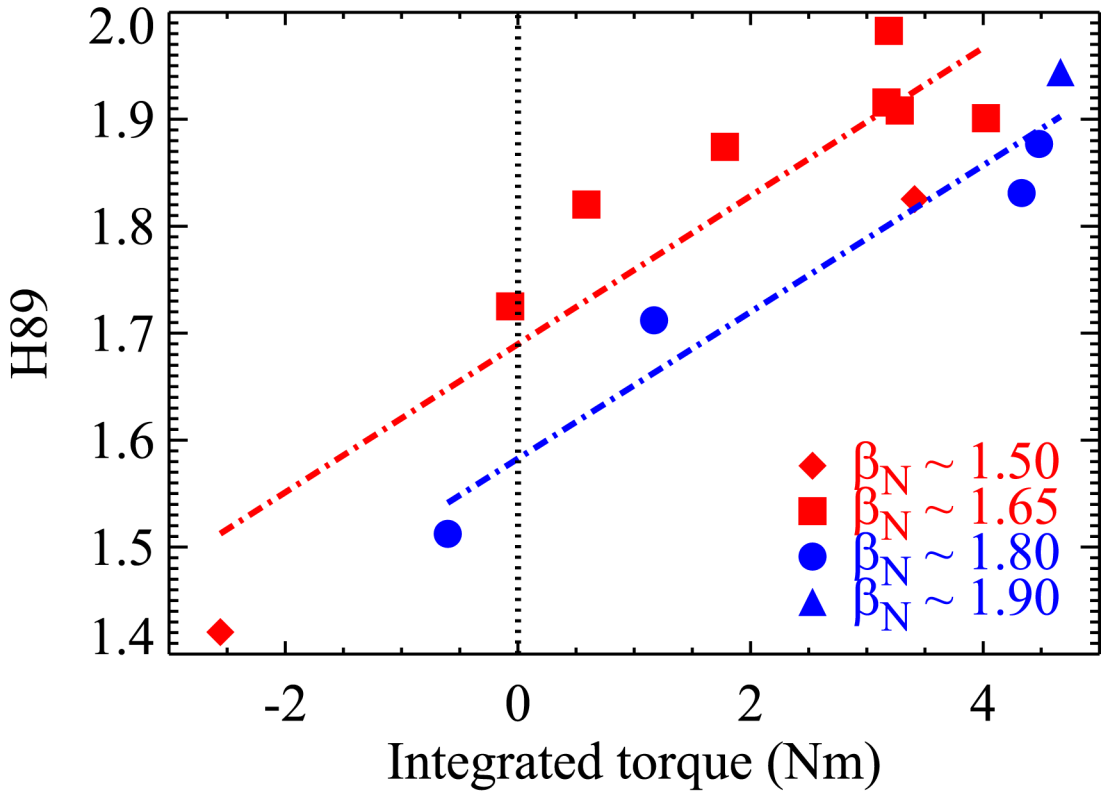


Summary

- **Power requirements to maintain given b_N increase with reduced torque**
- **Energy confinement is degraded as counter neutral beams introduced / net torque reduced**
- **Intrinsic rotation needs to be considered for momentum confinement studies**
- **Momentum confinement degrades with increase to net torque**
  - Comparable to degradation in energy confinement with power
  - Momentum confinement time appears insensitive to β_N

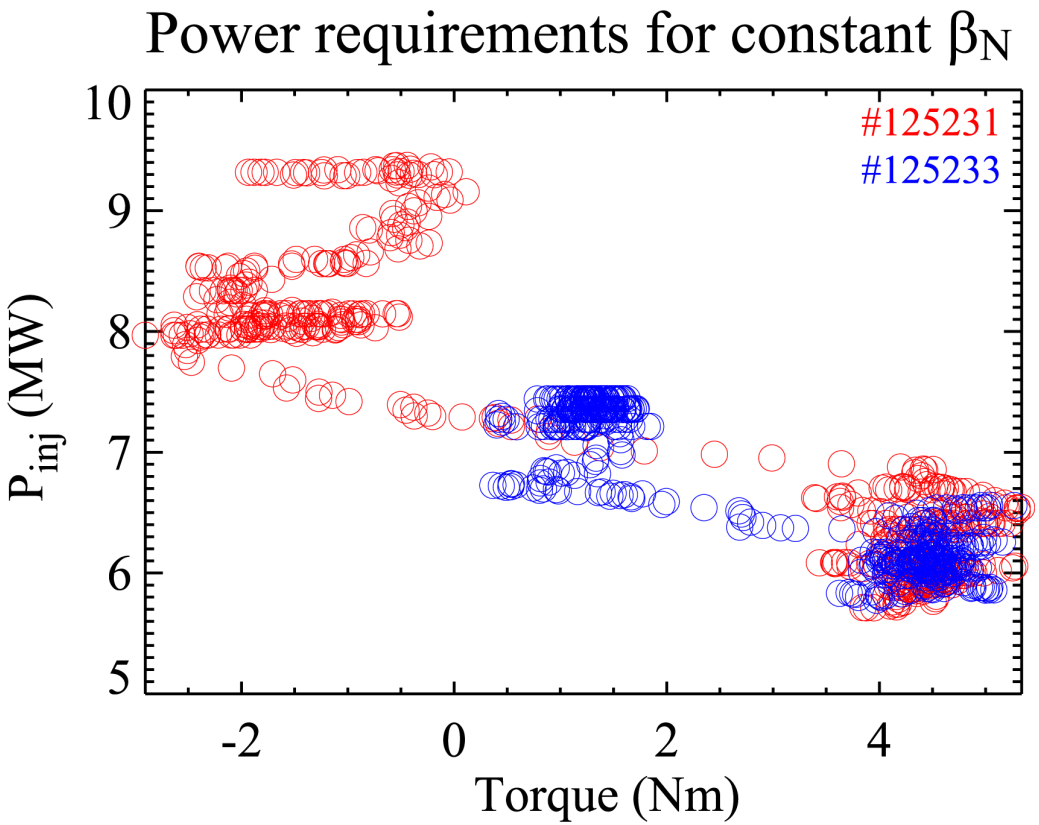
H-Factor is Degraded With Counter Beams

- **Systematic decrease in H-factor as torque is reduced by counter beam**

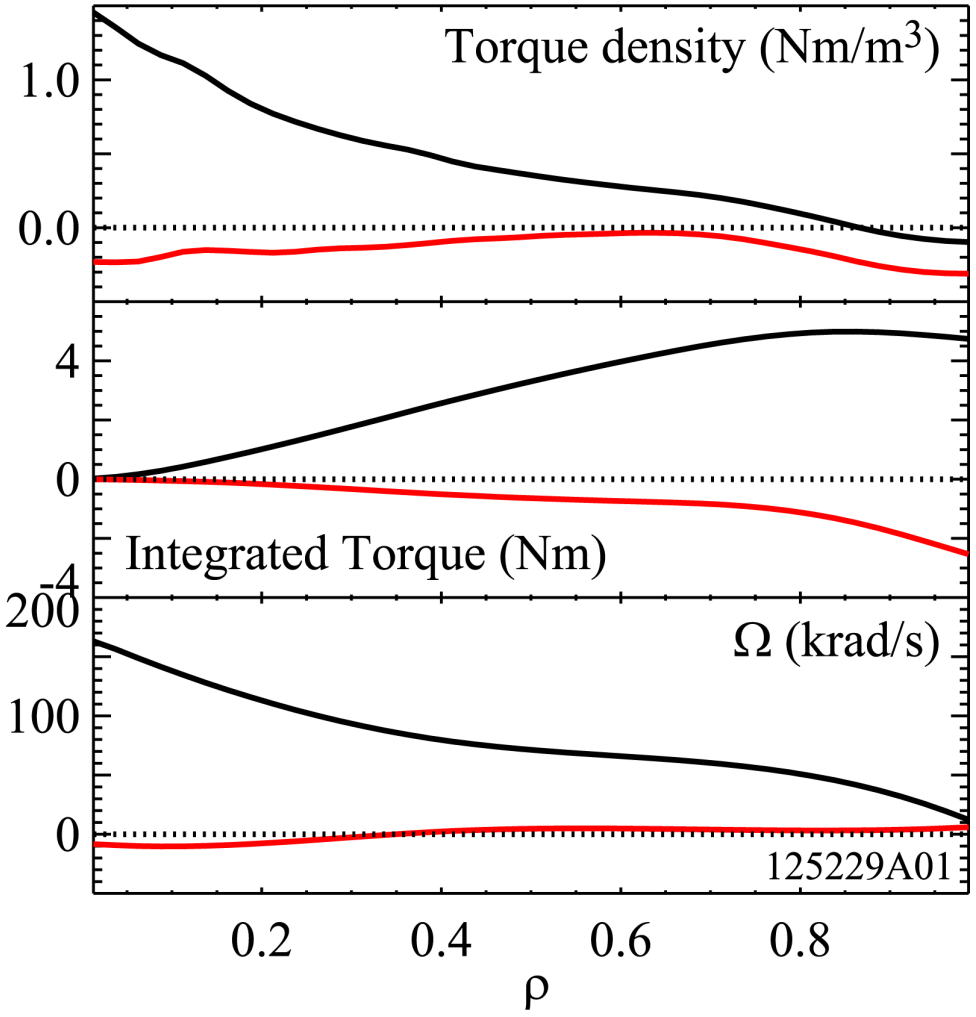


Power Requirements to Maintain Constant b_N Increase With Reduced Torque

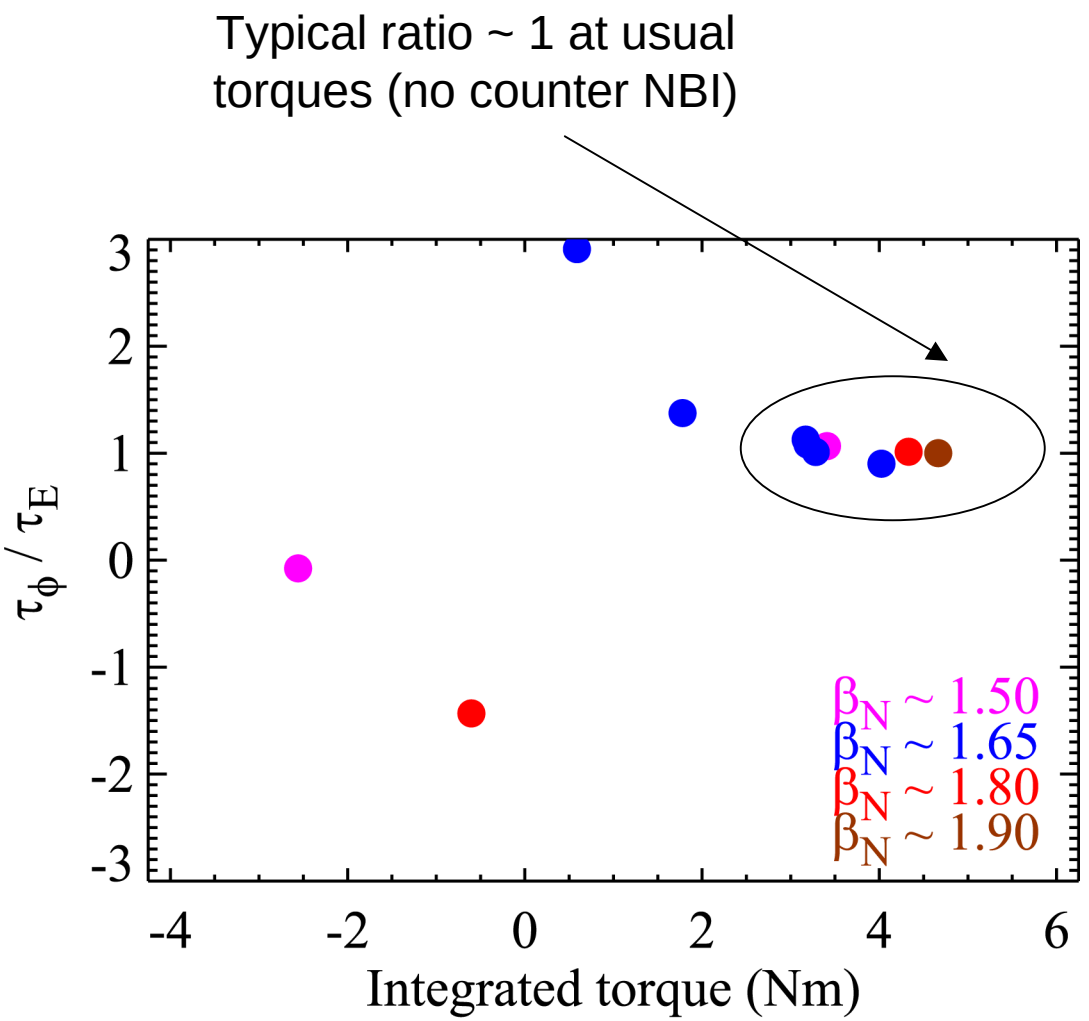
- **Time record of injected power vs integrated torque from TRANSP**
- **Clear increase in power requirements as torque is reduced by introduction of counter beams**



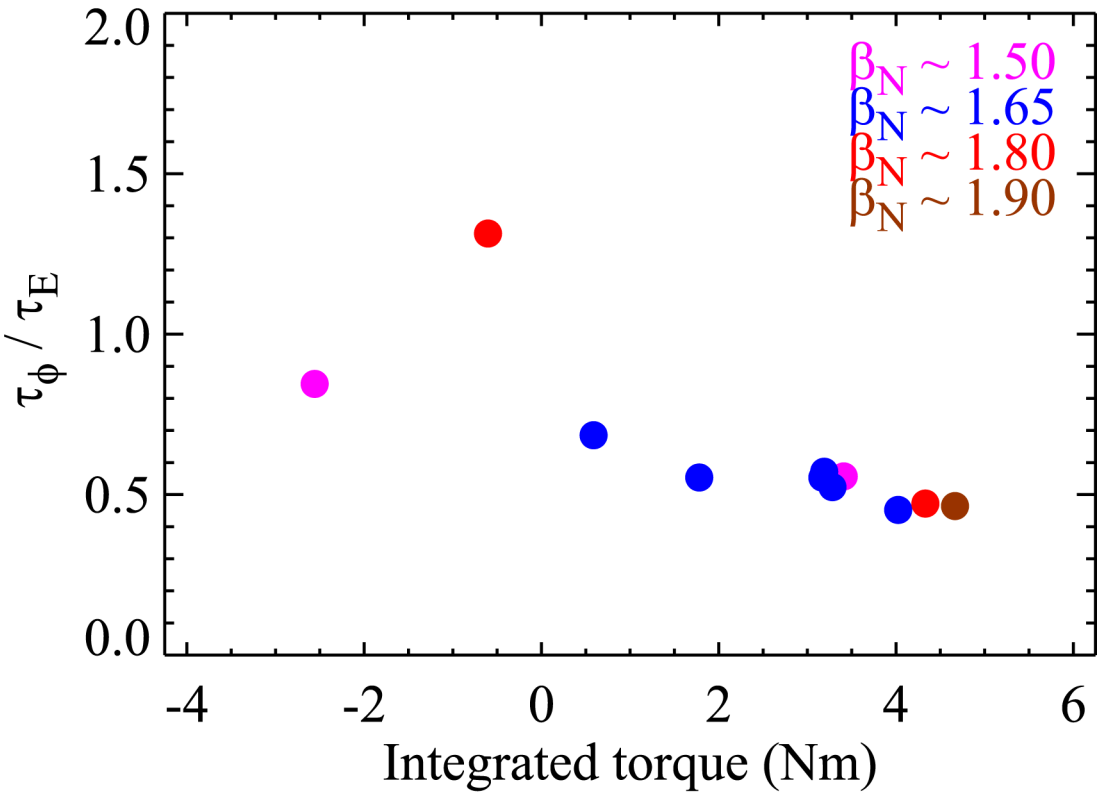
- **Rotation is close to zero, but torque is negative everywhere across plasma**



- **Ratio of momentum confinement time to energy confinement time straight from TRANSP**
- **Ignores intrinsic rotation**

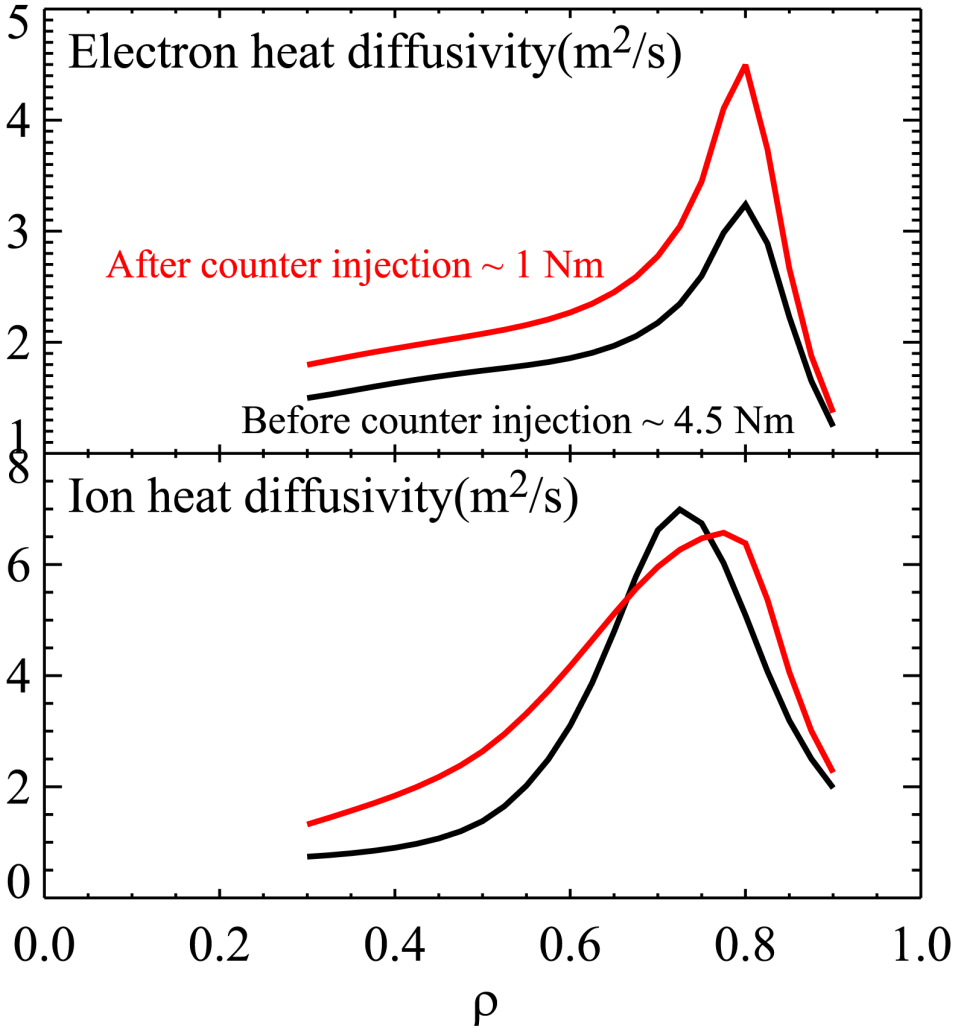


- **Ratio drops ~ factor of two at large torque after including intrinsic rotation**
- **Not obvious variation with torque**



Counter Beam Injection Leads to Increases in Electron and Ion Heat Diffusivities

- **Transport analysis performed with TRANSP**
- **Electron and ion heat diffusivities enhanced at reduced torque**



Analysis of Energy Confinement Shows Dependence on Rotation

- **Analysis of energy confinement time for all shots this year show the same general trend**
  - Using central rotation as representation of torque
- **On counter rotation side, see similar degradation in confinement as approach zero rotation**
- **Linear fit to the data show that co-rotation outperfor counter-rotation**
- **Observations consistent with reduction in ExB shear**