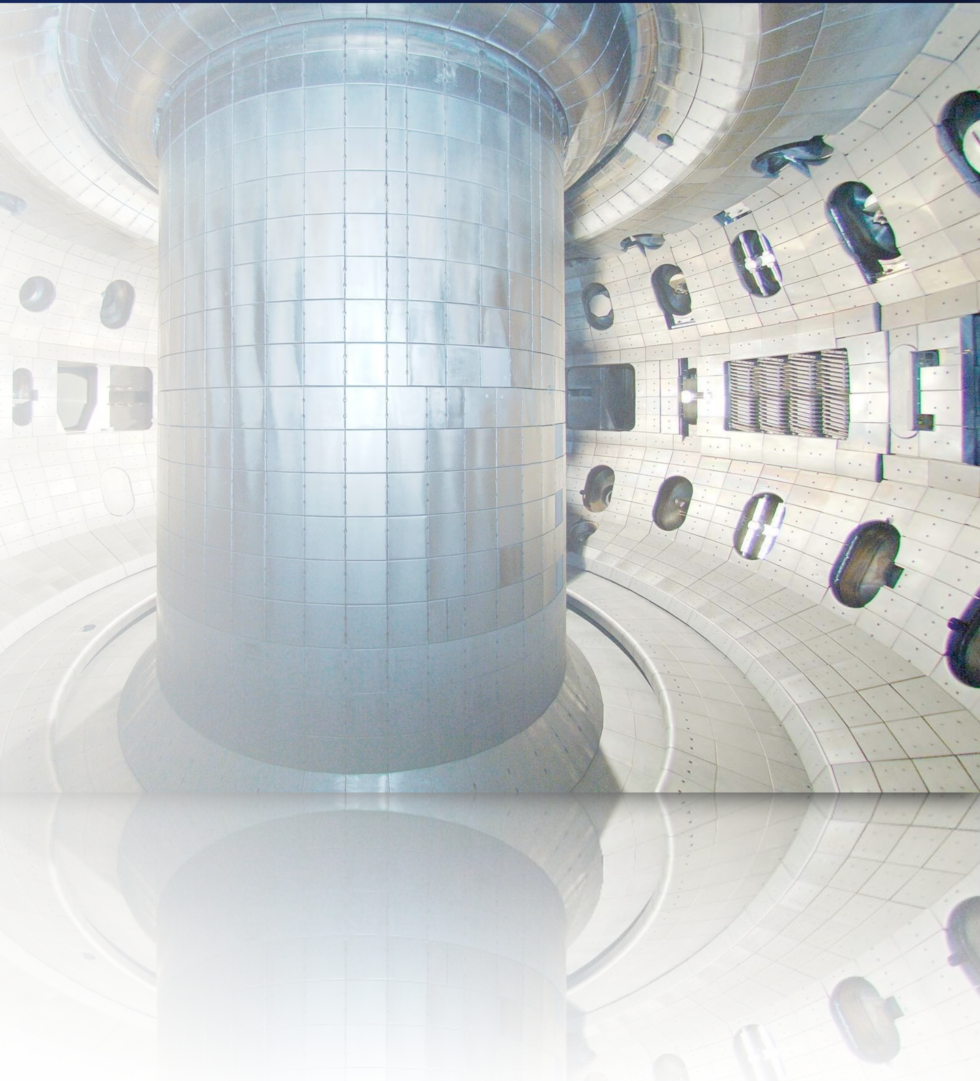
Testing the DIII-D Co/Counter Off-axis Neutral Beam Injected Power and Ability to Balance Injected Torque



by

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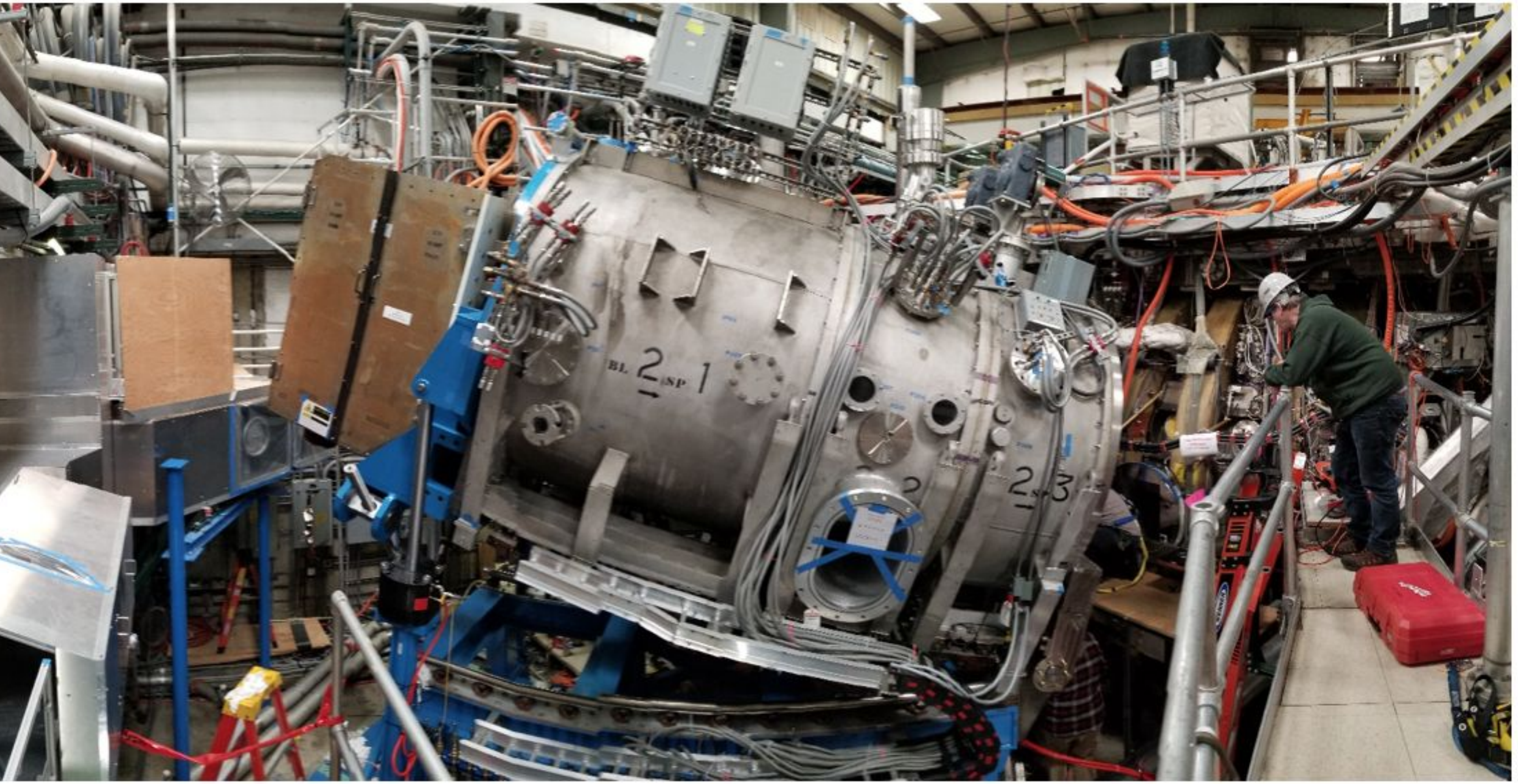
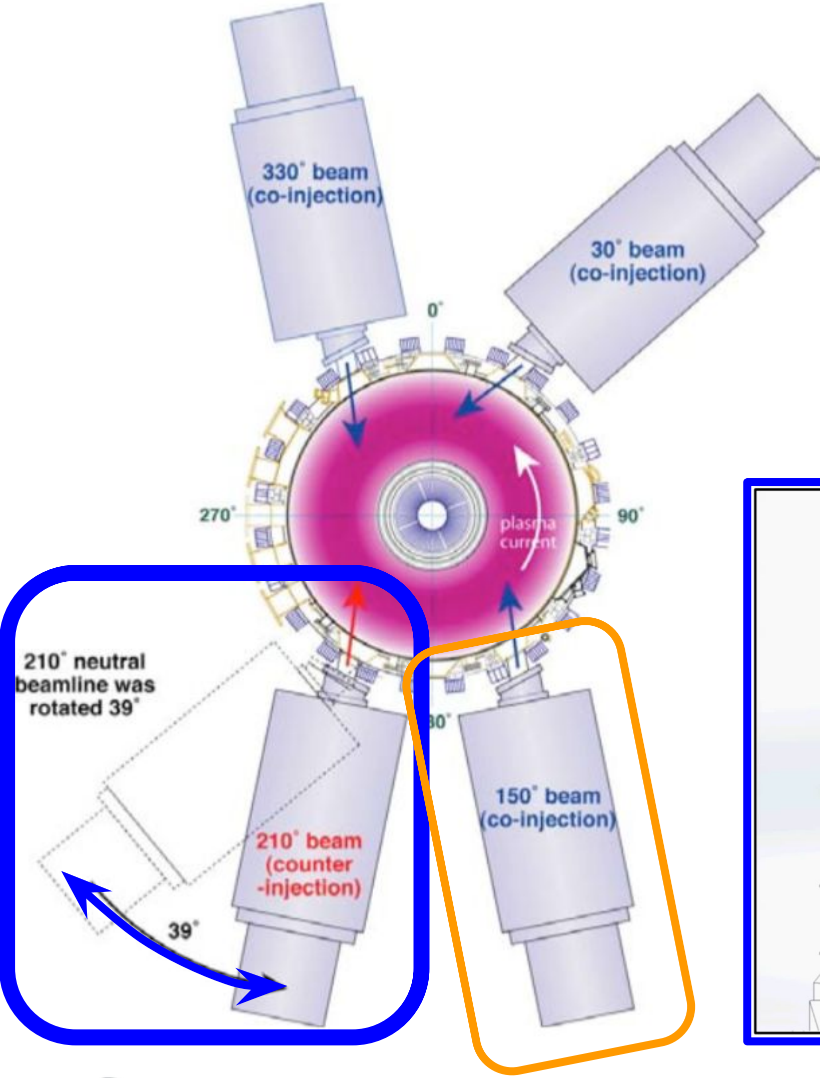
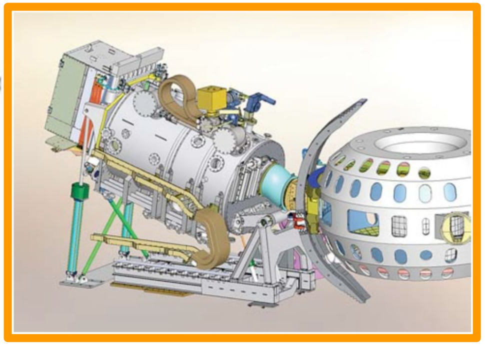
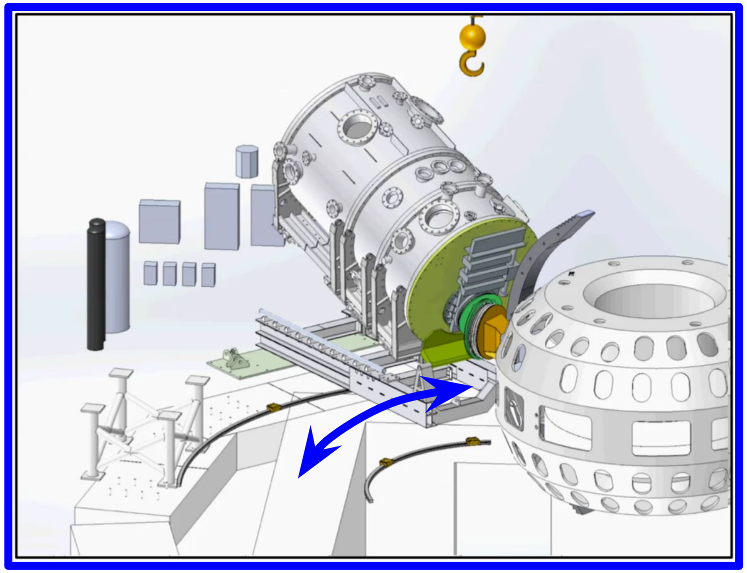
DIII-D has Completed a Major Upgrade to the Neutral Beams that Increases Off-Axis Heating and Current Drive



Steerable 210-Degree Neutral Beam is Latest Upgrade that Opens the Pathway to High β_N Steady-State Operation







- Pre 2006 - all beams in same direction
- 2006 - 210 degree beamline rotated for counter-injection and low torque studies
- 2011 - 150 degree beamline upgraded for continuous tilt off-axis injection up to 16.4 degrees downwards
- 2019 - 210 degree beamline upgraded for fixed off-axis injection and toroidally steerable

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See J.M. Park P1/1009
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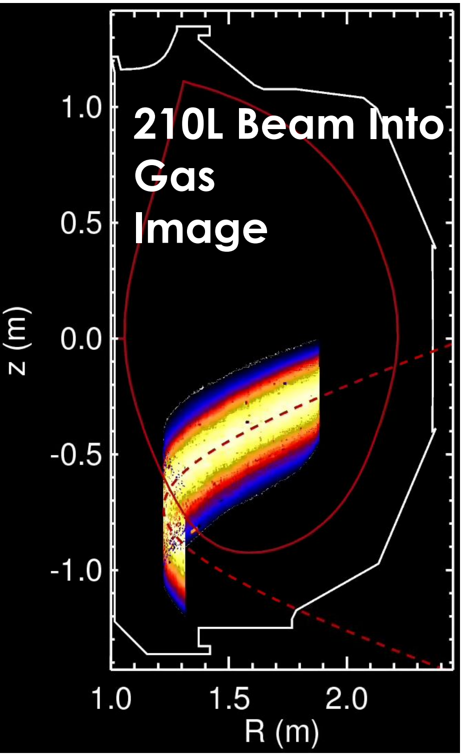
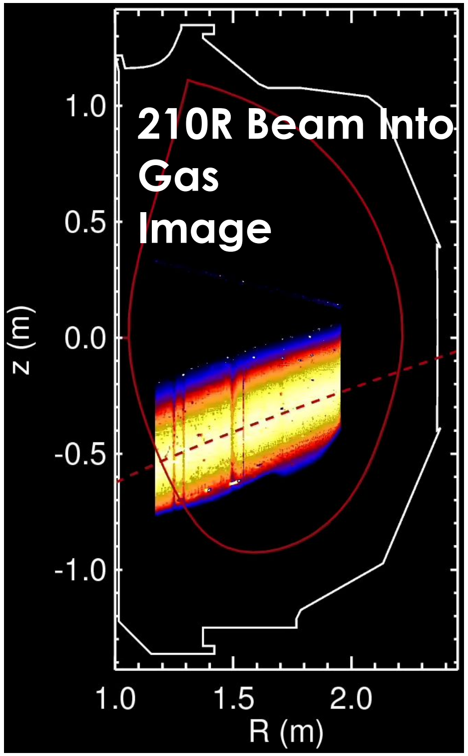
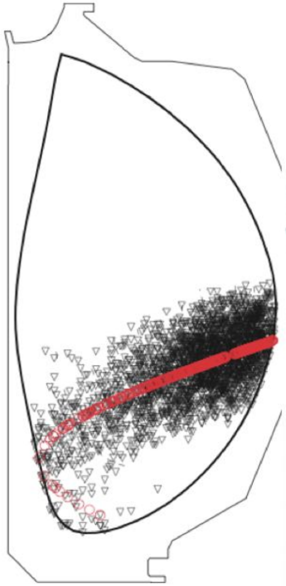
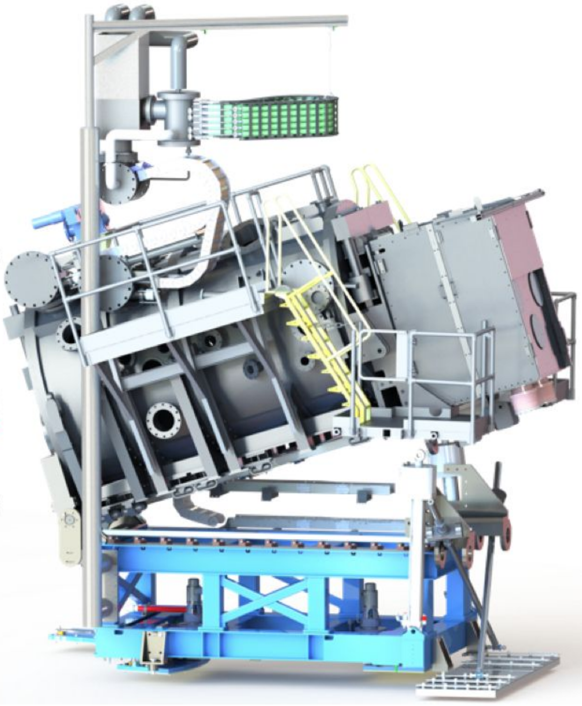
Imaging Of The New 210 Co/Counter Off-Axis Beams Has Been Carried Out To Verify Beam Geometry in Co-I_p Direction



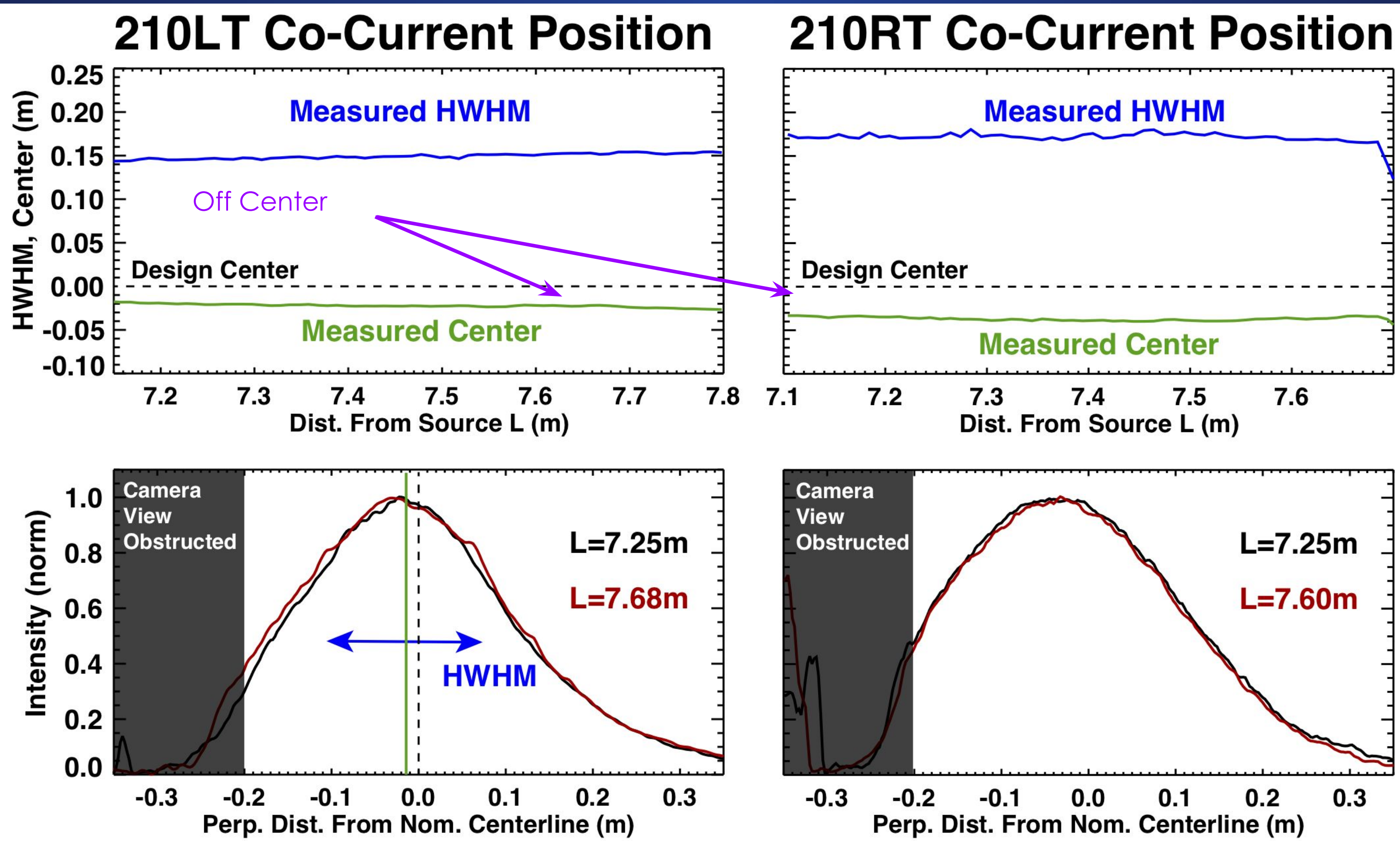






- Images are mapped to beam centerline to obtain size, steering, divergence
- Initial data indicated heating of the top of the drift duct from both sources

Camera Images Guided Aiming of the Neutral Beam to Avoid Interaction with the Neutral Beam Drift Duct, Extending Pulse Length



- Narrowing of the beam vertical shape required to avoid heating of drift duct
- Adjusting gradient grid voltage narrows focus

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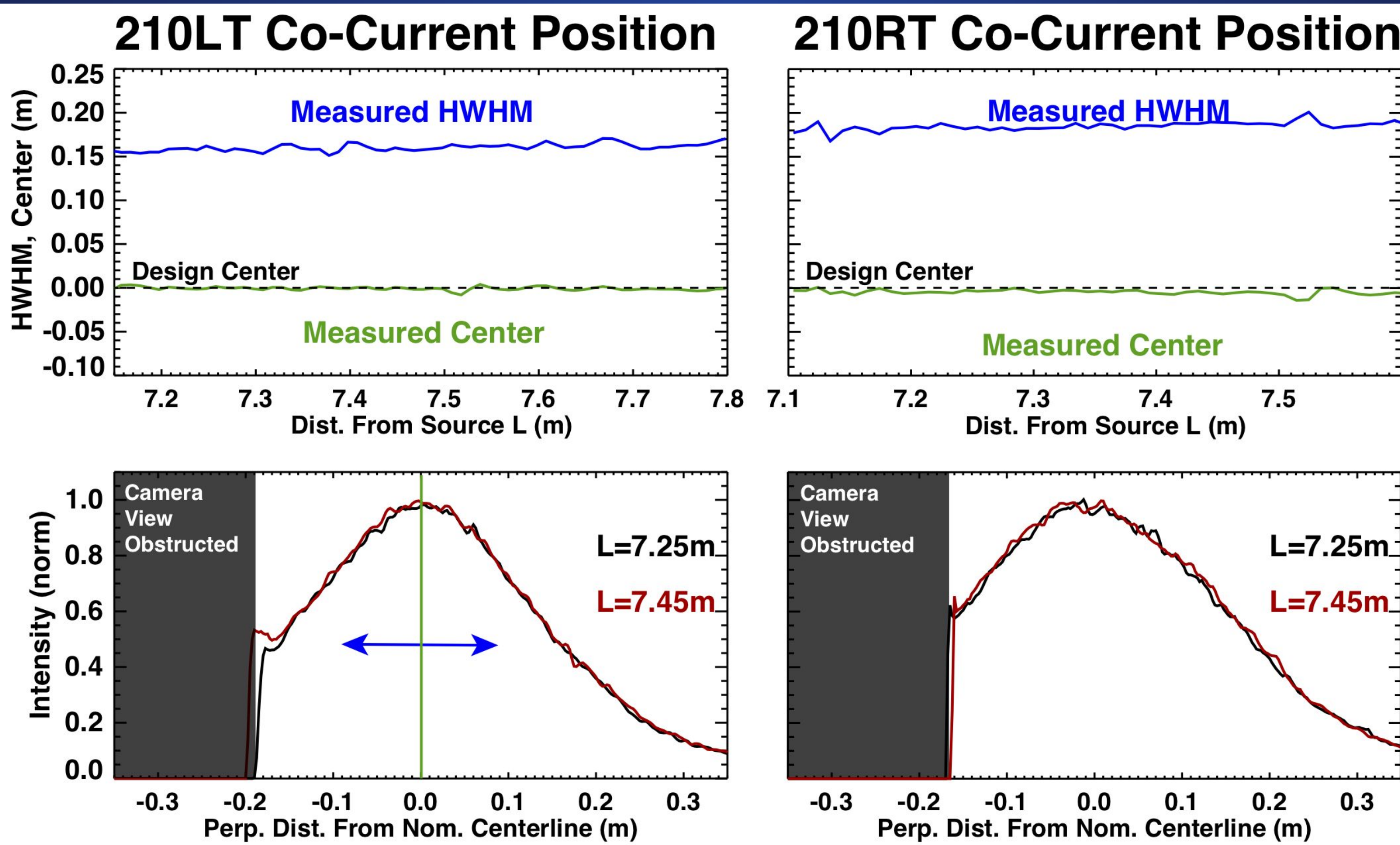
Camera Images Guided Aiming of the Neutral Beam to Avoid Interaction with the Neutral Beam Drift Duct, Extending Pulse Length



Optimized vertical steering and divergence provides clearance

Accurate Efficiencies Required for Power Calculations

$$P_{inj} = I_{acc} V_{acc} \epsilon_{TE} \epsilon_{NE} \epsilon_{RI} \epsilon_{DD} \epsilon_{OL} \epsilon_{tilt}$$

- **I_{acc} is the accelerator current, V_{acc} is the accelerator voltage**
- **Transmission efficiency $\varepsilon_{TE}(p)$ a function of perveance**
  - Determined at the nominal operating voltage and gas feed through water flow calorimetry with bending magnets off so that maximum throughput is obtained
- **Neutralization efficiency $\varepsilon_{NE}(V_{acc}, I_{acc}, \Gamma_N, \Gamma_S)$ a function of accelerator voltage, current, neutralizer Γ_N and source Γ_S gas flow rates**
  - Determined through comparing repeat pulses into calorimeters with bending magnets on and off, and for multiple values of gas flow rates

Accurate Efficiencies Required for Power Calculations (cont'd)

$$P_{inj} = I_{acc} V_{acc} \epsilon_{TE} \epsilon_{NE} \epsilon_{RI} \epsilon_{DD} \epsilon_{OL} \epsilon_{tilt}$$

- **Re-ionization efficiency from neutrals that ionize when encountering neutral gas and are then deflected by the DIII-D toroidal field**
  - Measurements from thermocouples on the armor tiles with and without toroidal field are used to quantify re-ionization losses at $\varepsilon_{RI} = 0.95$
- **The drift-duct (final aperture) includes a collimator structure[18] out-fitted with thermocouples**
  - Although focused, some clipping does occurs and transmission of ε_{DD} = 0.97 has been determined for the on-axis sources
- **An "overlap" efficiency ε_{OL} is included to account for the interaction in the drift duct between the neutrals when two sources are injected simultaneously**
  - The overlap efficiency is time-dependent and reduces the power of both beams with a factor of εOL = 0.97.

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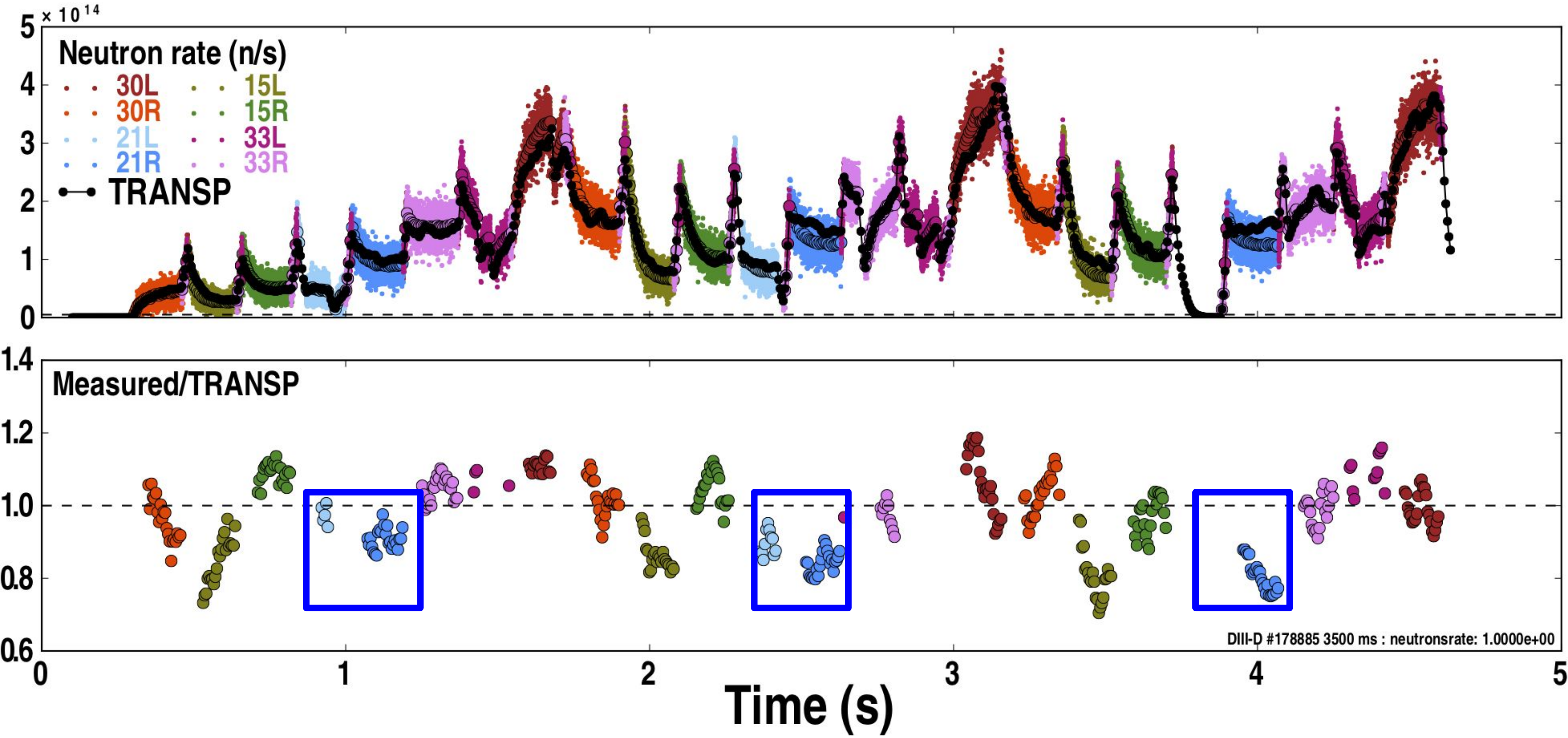
Accurate Efficiencies Required for Power Calculations (cont'd)

$$P_{inj} = I_{acc} V_{acc} \epsilon_{TE} \epsilon_{NE} \epsilon_{RI} \epsilon_{DD} \epsilon_{OL} \epsilon_{tilt}$$

- **Tilt-specific losses as a function of beamline and ion source tilt angles have been included for additional losses when the beam is off-axis, determined by beam ray tracing and CAD renderings of the beam internal structure**
  - Despite ray tracing and renderings, additional losses are seen on tilted beams → Empirical efficiency required
- **A new efficiency has been developed using specialized discharges that incorporates additional difficult-to-quantify losses for off-axis beams only**
  - Accounts for additional losses due to clipping
- **Steady L-mode plasmas used for beam-target dominated neutron-based beam calibration cycling through each source**

Absolute Neutral Beam Power Assessment by Long Steady Pulses Shows 10-15% Reduction in Power Compared to On-Axis



- TRANSP* used to compare measured to expected absolute neutron rate
- Motivates correction due to beam clipping in drift duct

*TRANSP+NUBEAM is taken as accurately capturing the physics of NBI injection and slowing down without uncertainty

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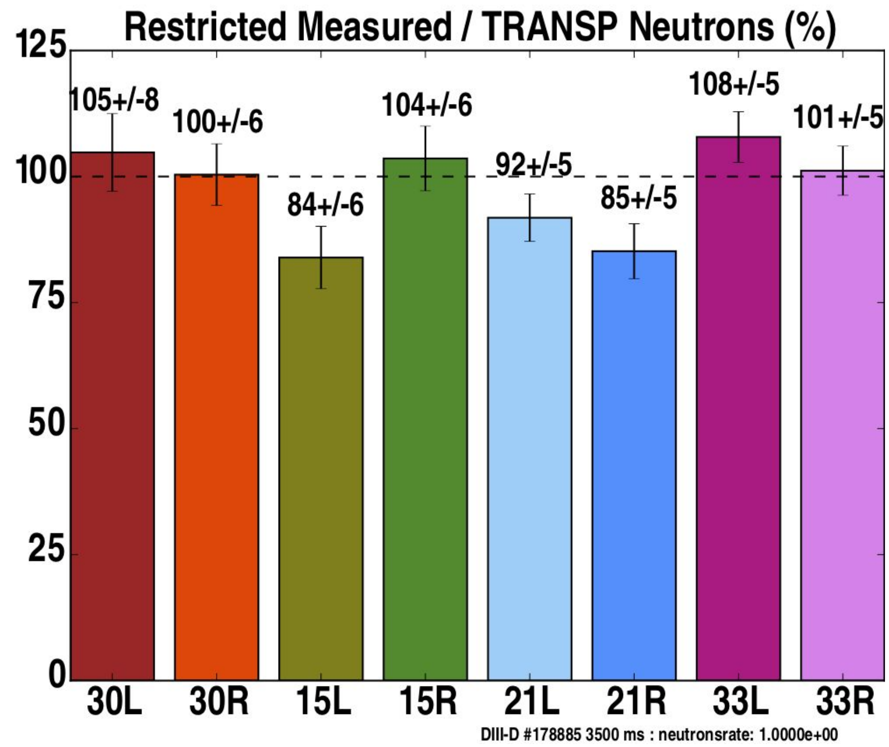
Quantified Power Discrepancies Provide Empirical Corrections

- **Most source powers are accurate**
- **Identified anomalously low power on 15L**
  - Corrected by adjusting gradient grid voltages to optimize transmitted power

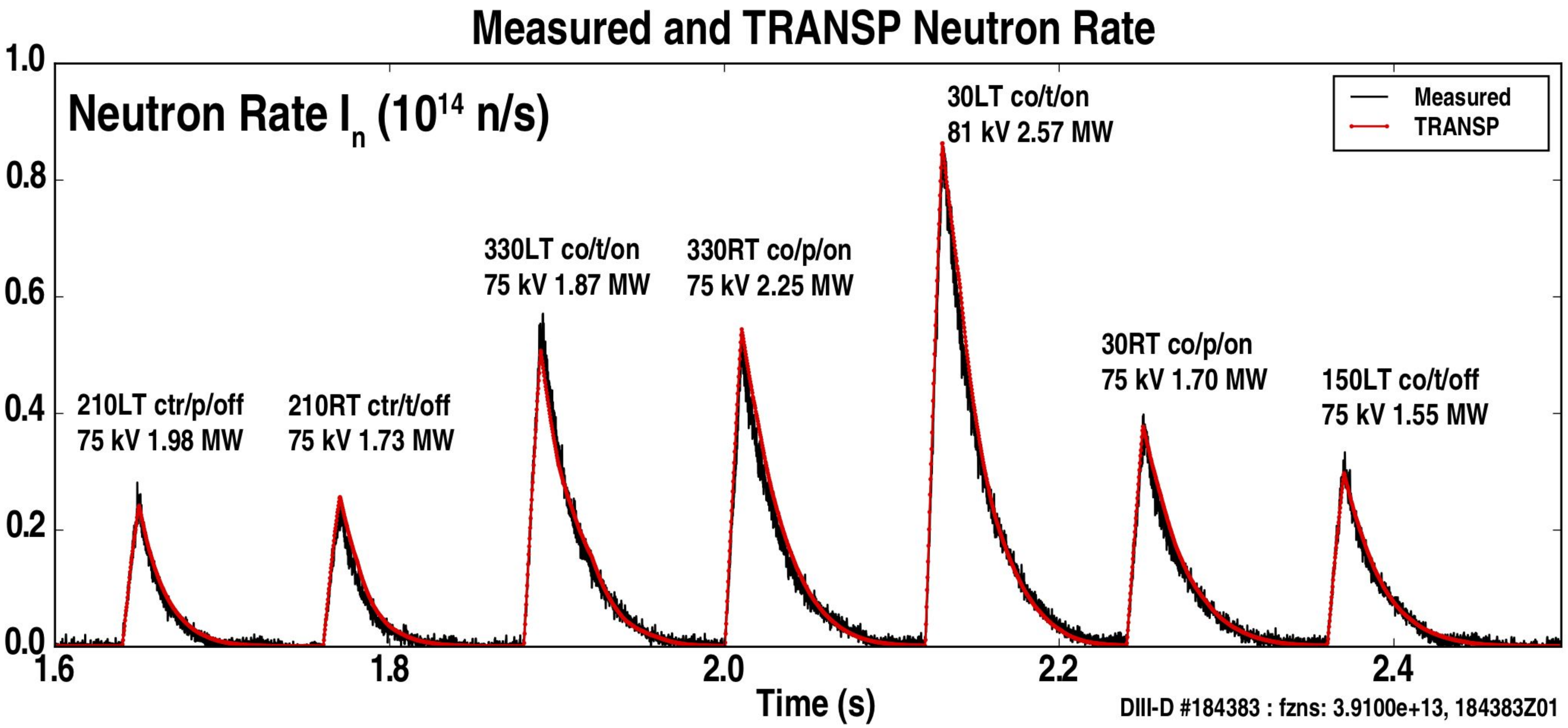


- **Provides opportunity to empirically correct for reductions in power in off-axis sources[1]**

New empirical efficiency introduced for most accurate power reporting

[1]Heidbrink et. al. *Nucl. Fusion*, **52**, 094005 (2012)

Additional Empirical Efficiency Works Equally Well for Beam in Counter-Current Direction



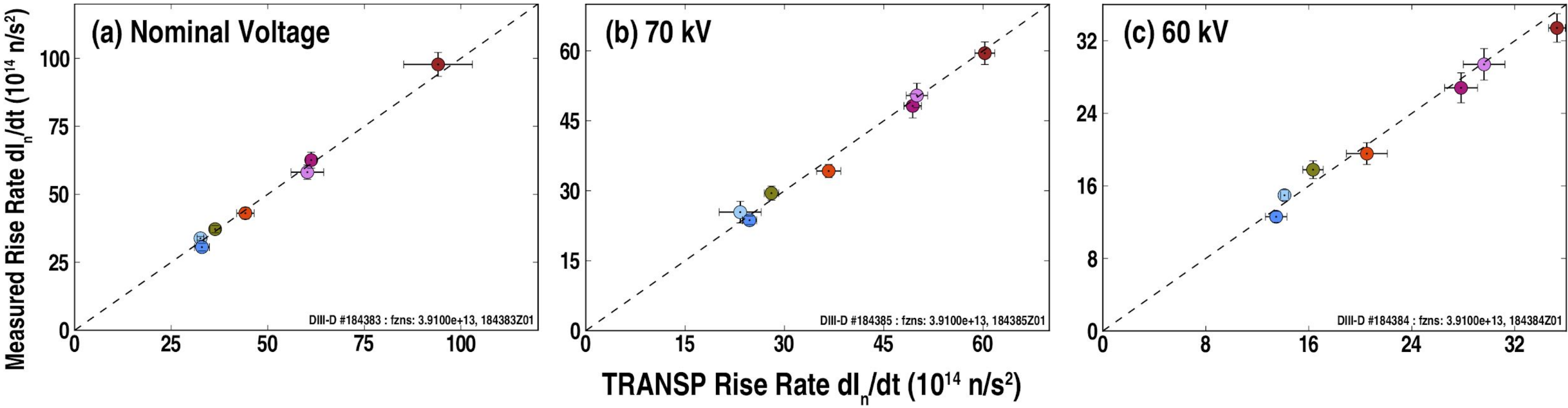
- Empirical efficiency derived in co-I_p position applied to experiments in ctr-I_p position → No discrepancy found

Additional Empirical Efficiency Works Equally Well for Typical Range of Voltages

$$\dot{I}_{\mathrm{n}} \simeq \dot{N}_{\mathrm{b}} n_{\mathrm{d}}$$

$\dot{I}_{\mathrm{n}} = c - I_{\mathrm{n}}/\tau_{\mathrm{n}}$ Rise phase

$\dot{I}_{\mathrm{n}} = -I_{\mathrm{n}}/\tau_{\mathrm{n}}$ Decay phase provides τ_{n}



- Decay phase extracts τ_n, constrained fit to rise phase extracts constant “c” which is proportional to $\dot{N}_b$ in a steady plasma[1]
- No systematic discrepancy found for range of typical voltages between 60-81 keV → Powers are accurate

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[1]Heidbrink, et. al. *Nucl. Fusion* **43** (2003)

Injected Torque Reported for NBI is Mechanical Torque; Absorbed Torque can Differ

- **Mechanical torque T_{inj} by NBI is R×F where F is directed rate of momentum injection**
  - $F = Nmv$, $N=P/eV_{acc}$, $v=(2E/m)^{½}$
  - Each "species" contributes with power fractions $f_p(j)$ for atoms and molecules D^+, D_2^+, D_3^+, mass μ = 1,2,3 for H,D,T

$$T_{inj} = R\sum_{j=1}^{3} f_p(j)\sqrt{2j\mu m_p/eV_{acc}}$$

- **Absorbed torque delivered through collisional slowing down and prompt JxB**
  How does injected vs. absorbed torque differ for co/ctr and on/off axis? → Run high fidelity TRANSP+NUBEAM for all configurations across typical operating voltages into "typical" DIII-D plasma

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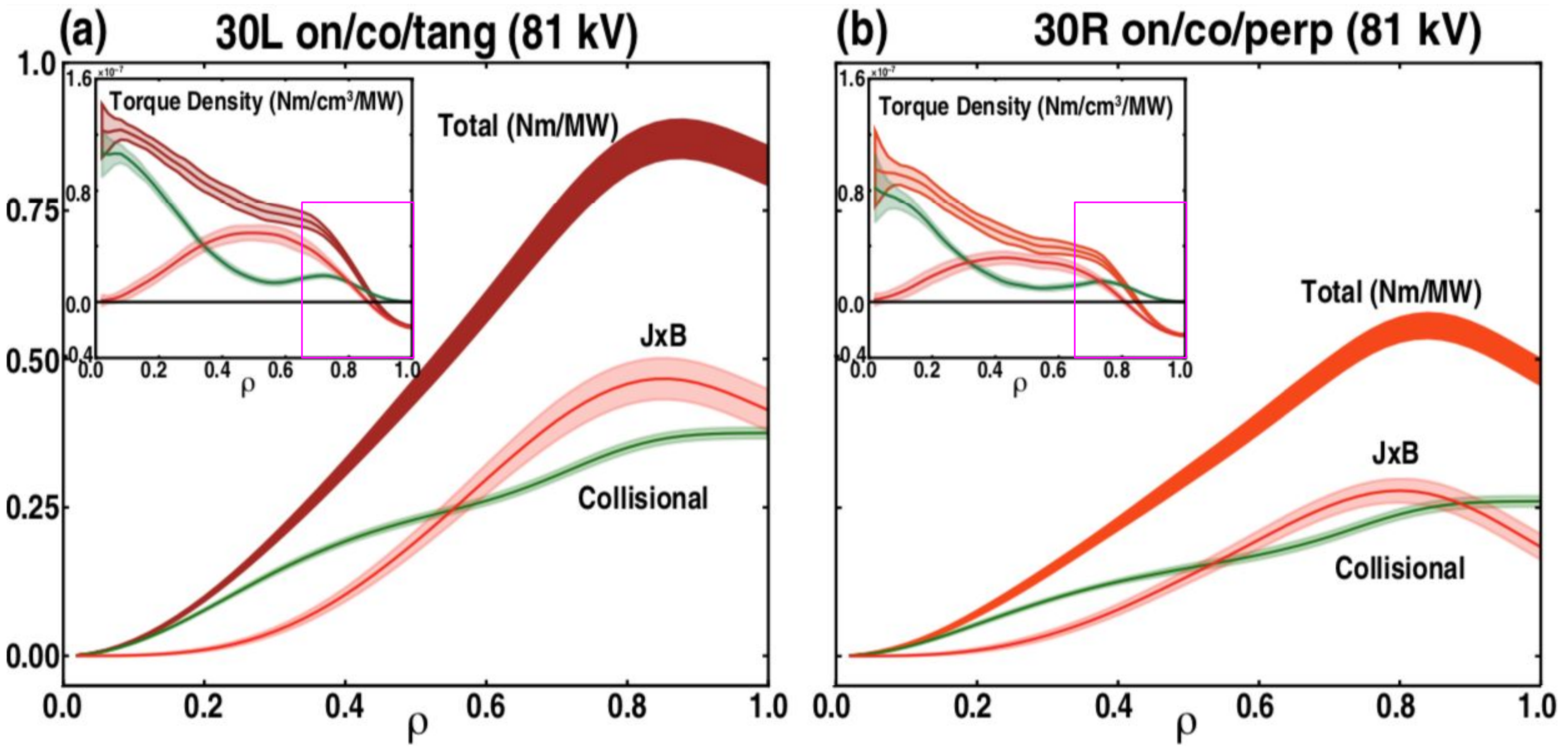
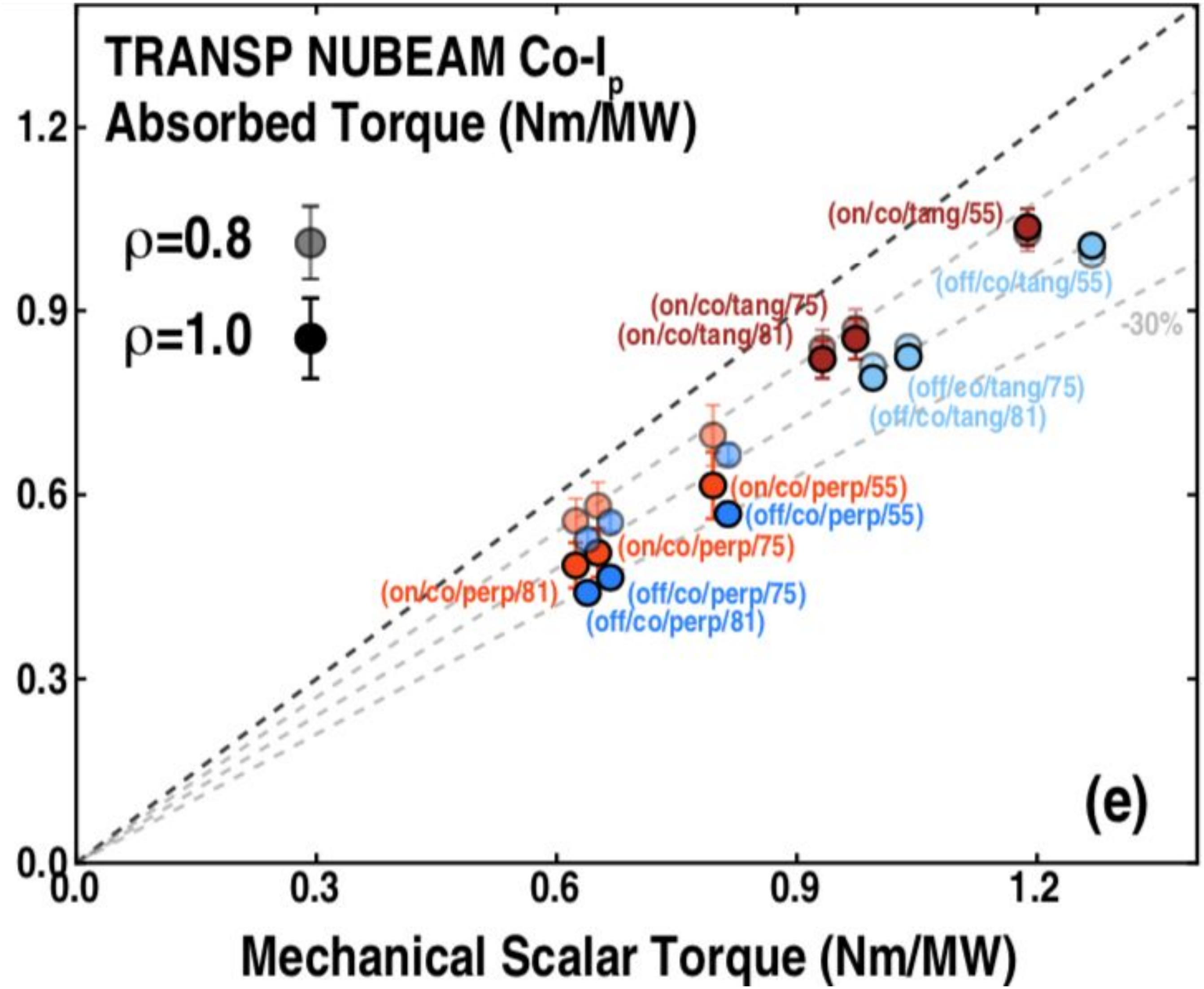
Collisional and J×B Torques of Equal Magnitude for co-Ip Tangential and Perpendicular Injection



- **Edge J×B torque negative, flattening volume integrated torque at large radius**

Total Absorbed Torque for co-Ip Injection 10-30% Below Mechanical Torque

- Minor differences between ρ~0.8 → 1.0
- on/co/tang ~ 10% below
- on/co/perp ~ 10-20% below
- off/co/tang ~ 20% below
- off/co/perp ~ 30% below



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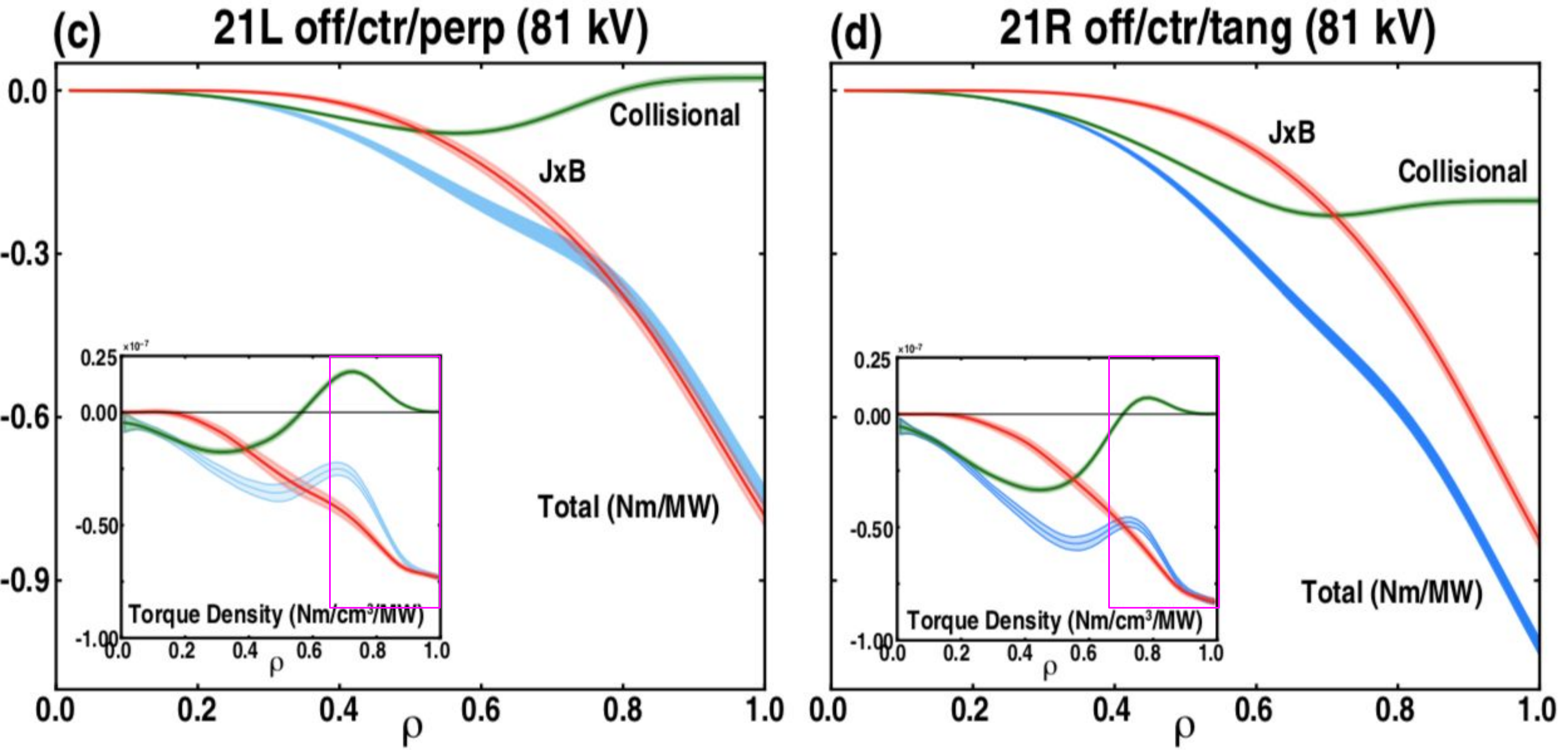
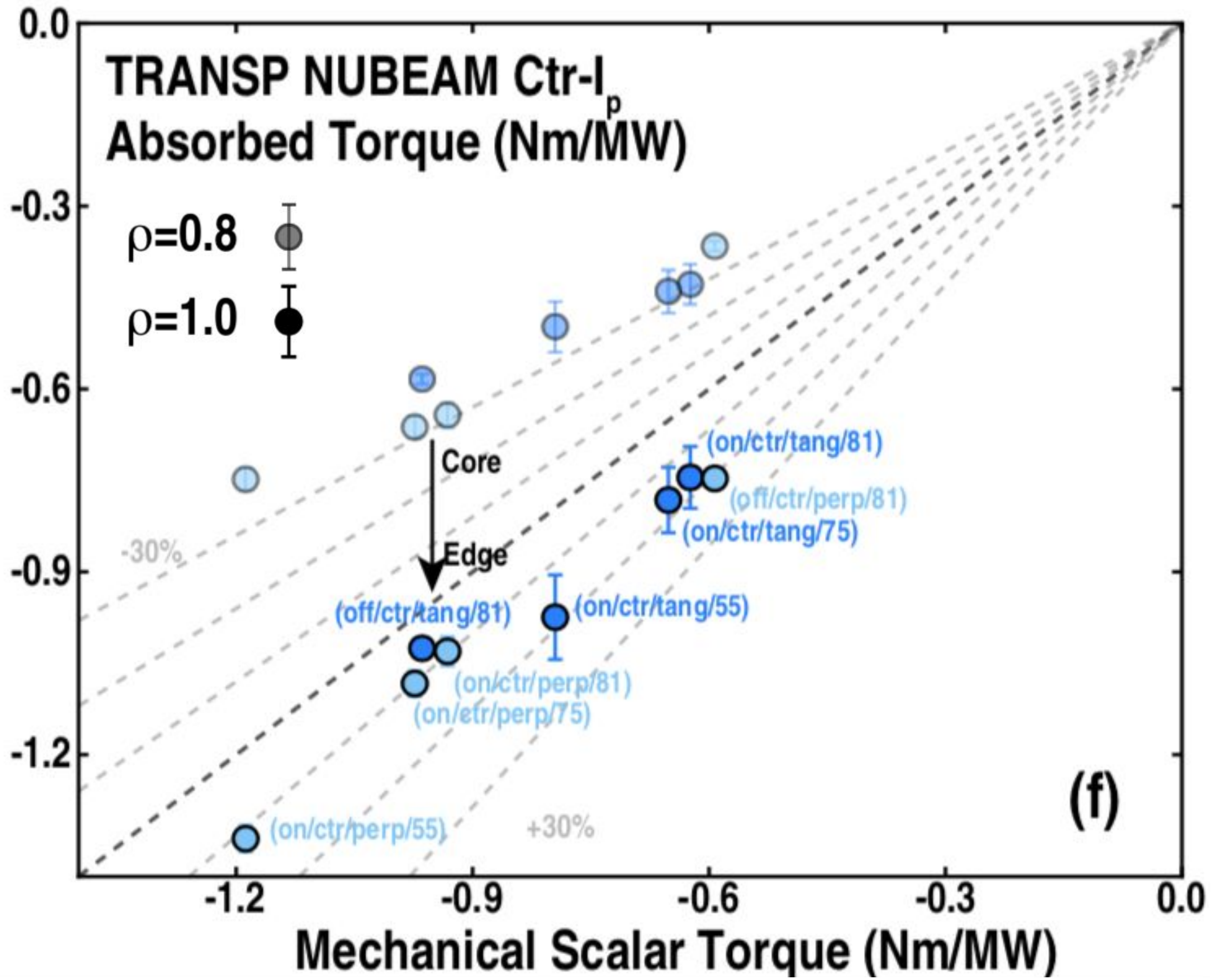
J×B Torque Dominates for ctr-Ip Injection; Dominates in Edge for ctr-Ip Injection



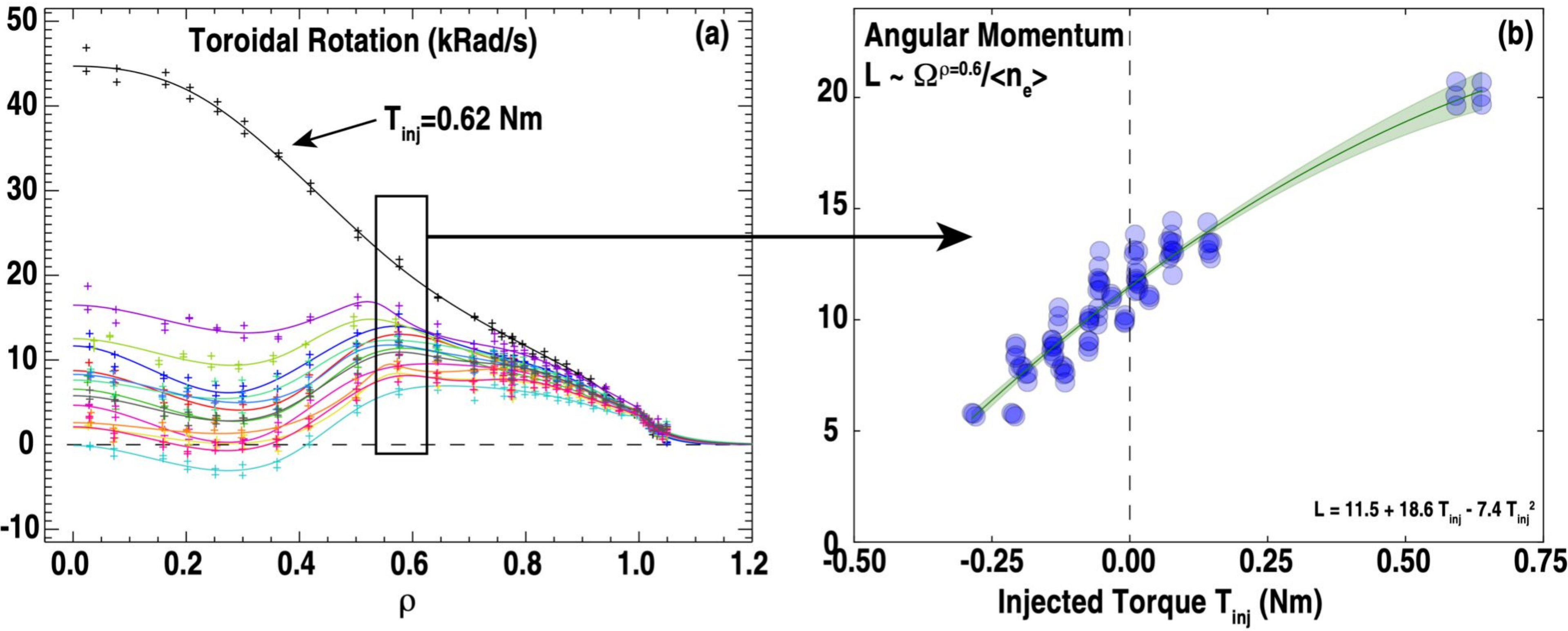
- More torque deposited on fast timescales for ctr-Ip injection

Total Absorbed Torque for ctr-Ip Injection 10-20% Above Mechanical Torque

- Significant differences between ρ~0.8 → 1.0, strong drive for edge shear
- on/ctr/tang ~ 20% above
- on/ctr/perp ~ 10% above
- off/ctr/tang ~ 10% above
- off/ctr/perp ~ 20% above



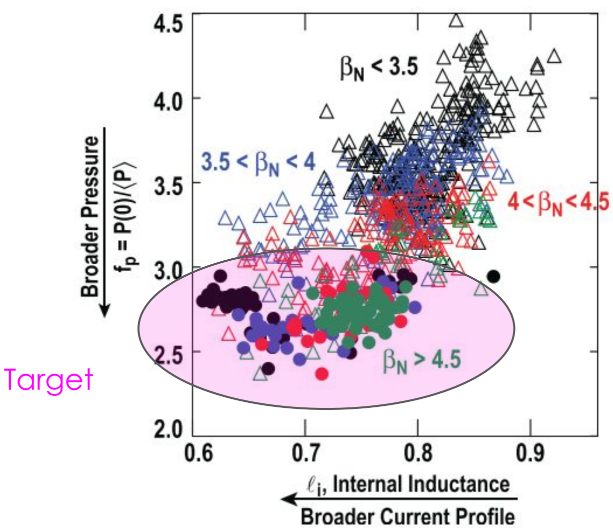
Across Torque Scan Rotation Profile Remains Similar and Near Intrinsic Profile



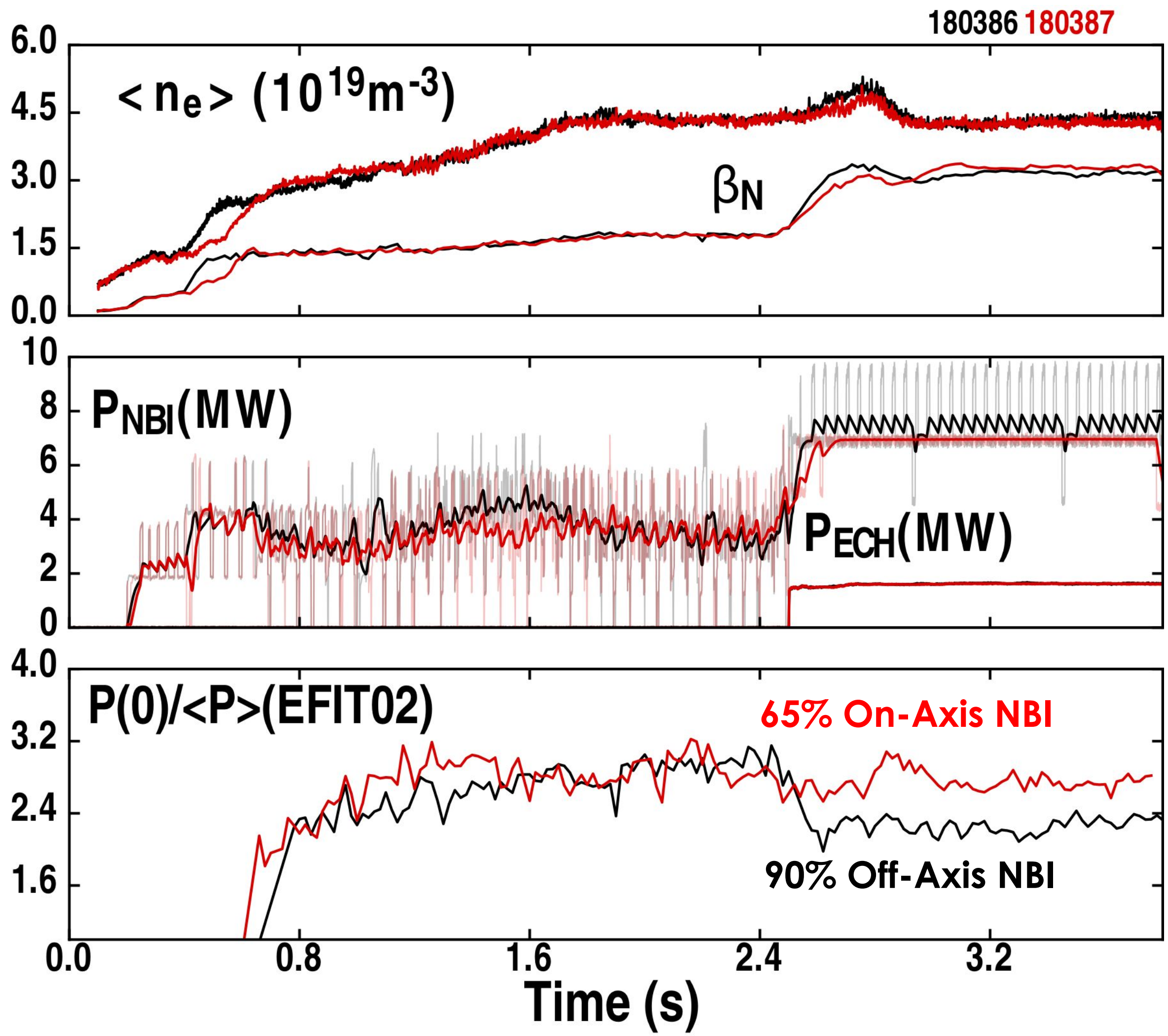
- 12-point scan using 2x2 tang/perp and three voltages

Initial Results: High q_{min} Target Plasma Demonstrates Reduced Pressure Peaking at Same β_N Using Dominantly Off-Axis NBI

- For the first time DIII-D can alternate between on-axis and off-axis injection at meaningful power
- Matched discharges show 15% reduced peaking factor with off-axis NBI
  - At same β_N



Ferron (2013)



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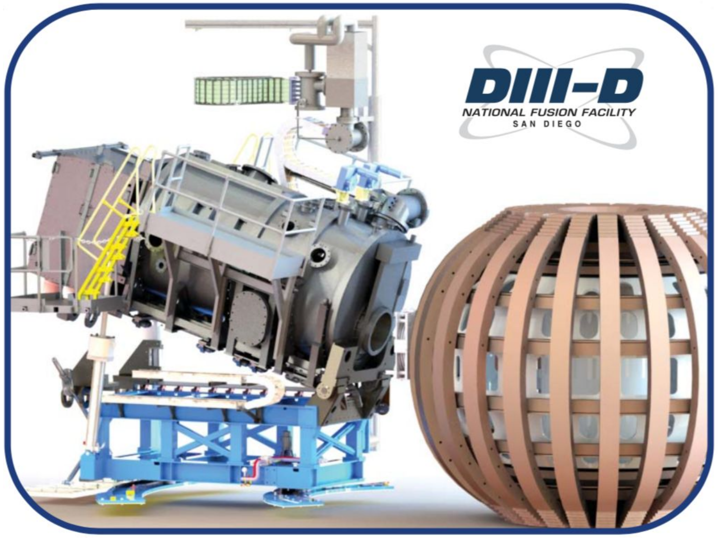
DIII-D Co/Counter Off-axis Neutral Beam Power has been Calibrated and Ability to Balance Injected Torque Retained



- **Beam aiming optimized with visible imaging**
- **Empirical transmission efficiency derived; captures both co-Ip and ctr-Ip operation for 60-81 kV**
  - Currently used in confinement and transport calculations
- **Balanced torque capability retained**
- **Clear pressure broadening when replacing on-axis with off-axis power**