Off-Axis Neutral Beam Current Drive for Advanced Tokamak

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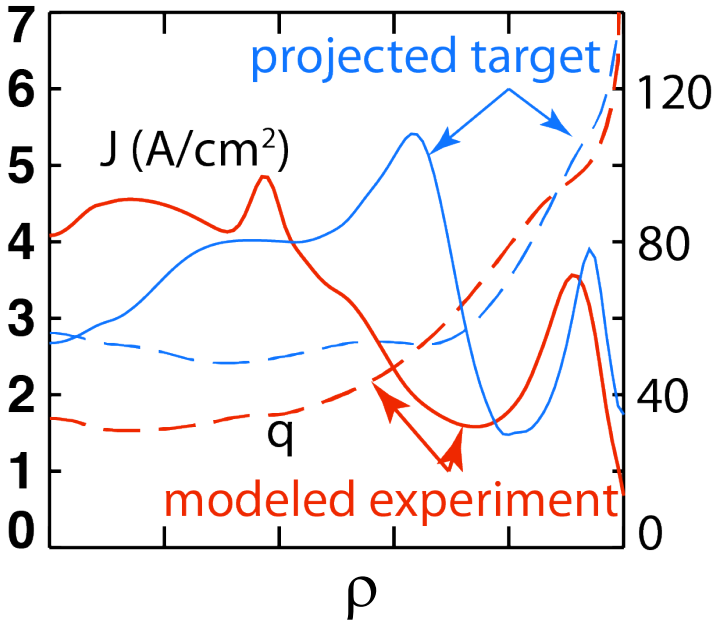
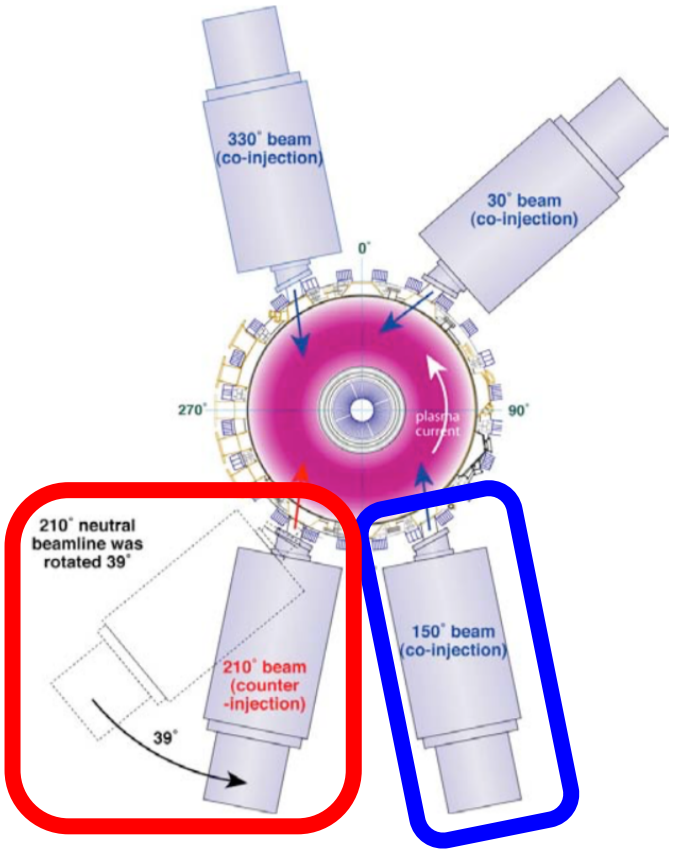
DIII-D Aims at Power-Plant Relevant Steady-State β_N>4 With Broad Current and Pressure Profiles

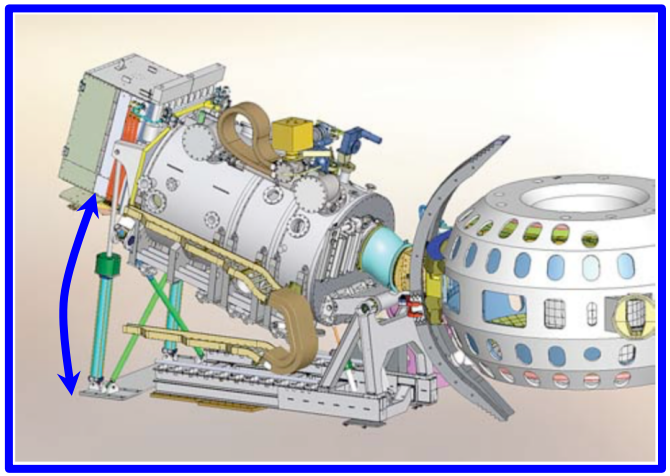
- Off-axis CD plays an essential role in achieving high β_N, high f_{BS} operation by broadening the current and pressure profiles to improve confinement and stability
- IPS-FASTRAN theory-based integrated modeling motivated the upgrade of DIII-D neutral beam H/CD

On-Axis NBI (MW)	Off-Axis NBI (MW)	ECH (MW)	Transport limit β_N	Stability Limit β_N
10.8	3.3	3.2	3.5 (q_{min}=1.5, f_{NI}=0.75)	3.7
9.5	10.7	9	5.1	4.9 (q_{min}>2, f_{NI}=1)

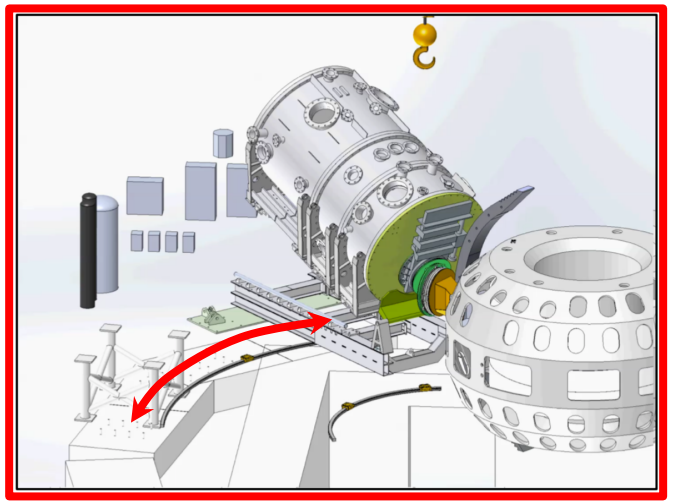


DIII-D has Completed a Major Upgrade to the Neutral Beams that Increase Off-Axis Heating and Current Drive





- Vertically Steerable Off-Axis Neutral Beam



- New toroidally steerable Co-Counter Off-Axis Neutral Beam

See B.A. Grierson poster [P1 Posters 1]

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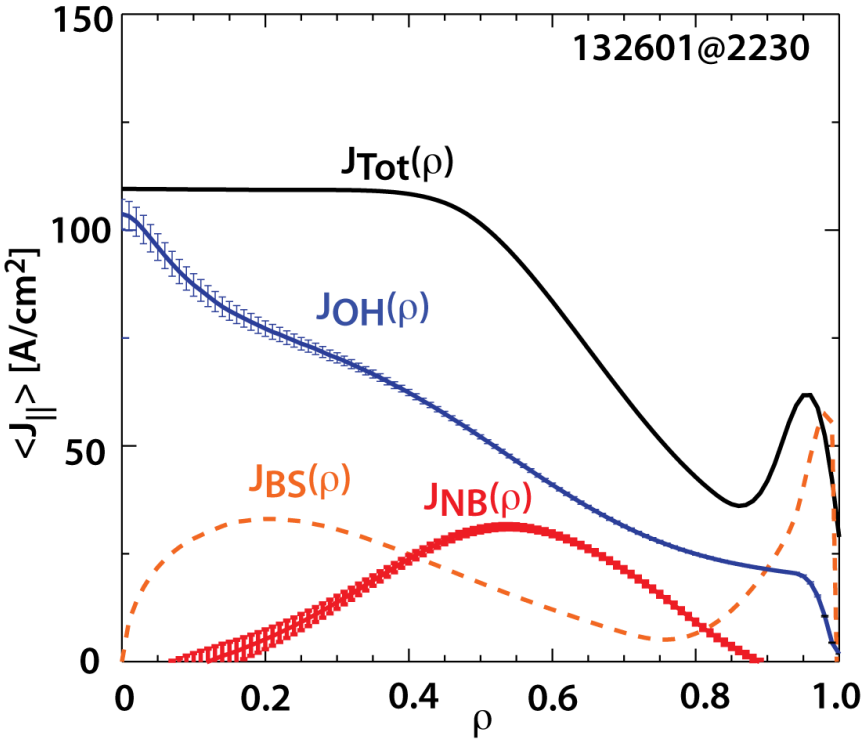
NBCD is Obtained Quantitatively from Evolution of the Equilibria



- **Kinetic equilibria reconstruction using magnetic pitch angles from MSE ⇒ J_{Tot}**
- **Internal loop voltage from time series of equilibria reconstruction ⇒ $J_{OH}=\sigma_{neo}\frac{\partial \psi}{\partial t}$**
- **Bootstrap current from neoclassical theory ⇒ J_{BS}**

$$J_{NB} = J_{Tot} - J_{OH} - J_{BS}$$

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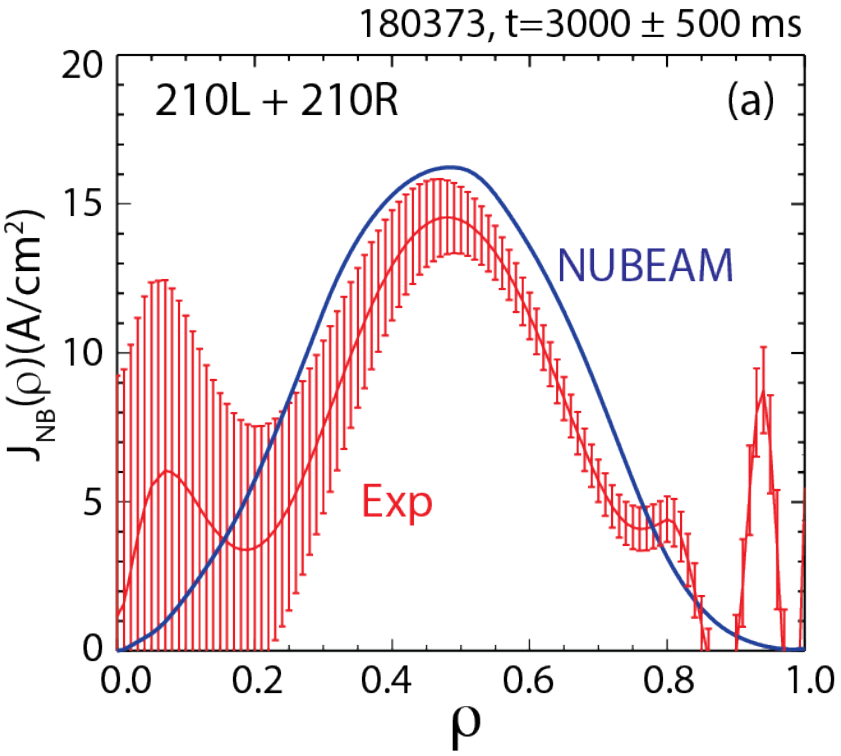
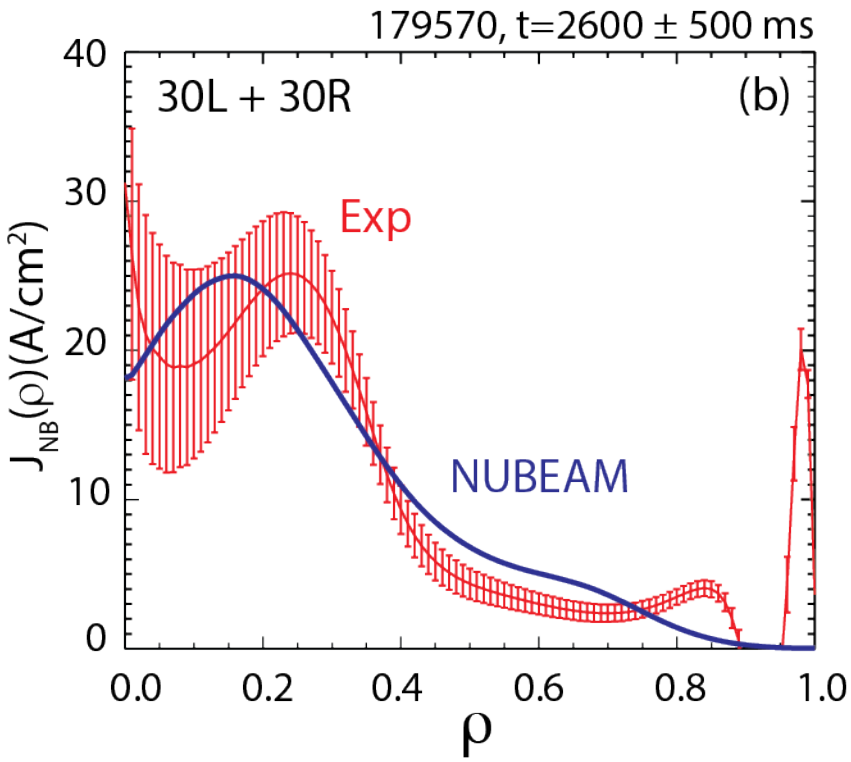
DIII-D Experiments Confirm that New CCOANB Drives Current as Predicted

CCOANB



On-Axis NBCD



- **Reasonably good agreement with classical modeling**
  - Monte-Carlo beam ion slowing down code NUBEAM
  - Without anomalous fast ion transport

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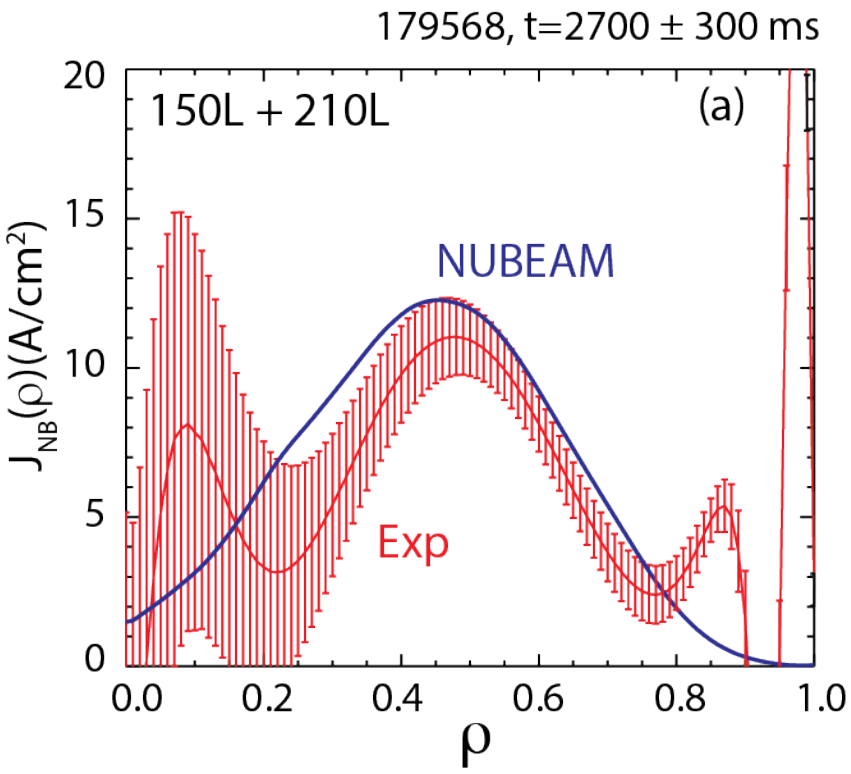
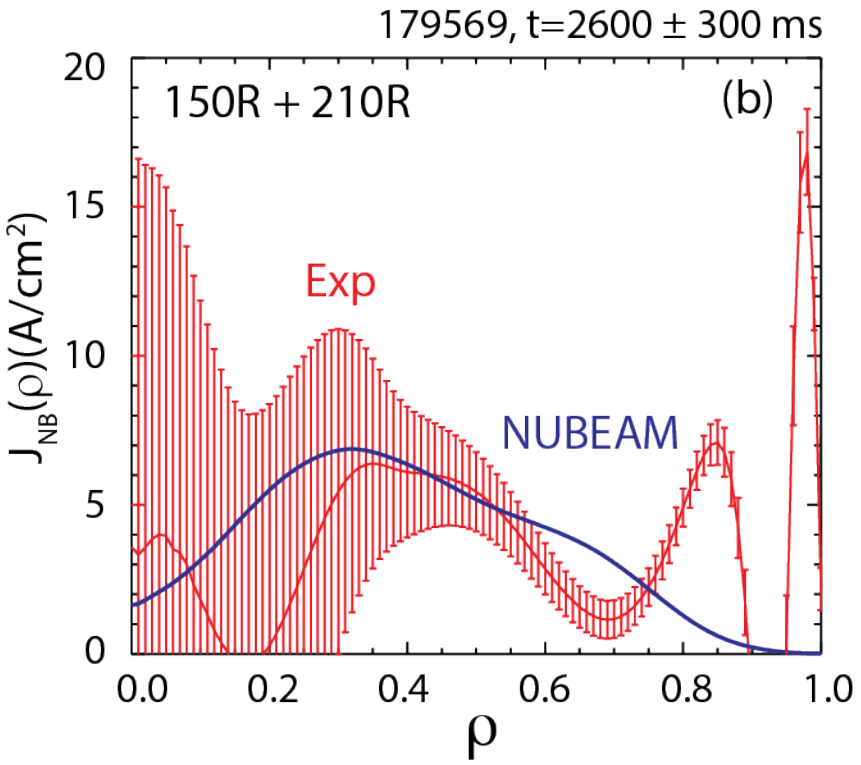
Off-axis NBCD is Sensitive to Beam Injection Alignment to Local Magnetic Field

More Tangential



More Perpendicular



- **Differential NBCD measurement reduces model dependencies and systematic uncertainties**
  - Compare two discharges "Left" (more tangent) and "Right" (more perpendicular) off-axis NBCD

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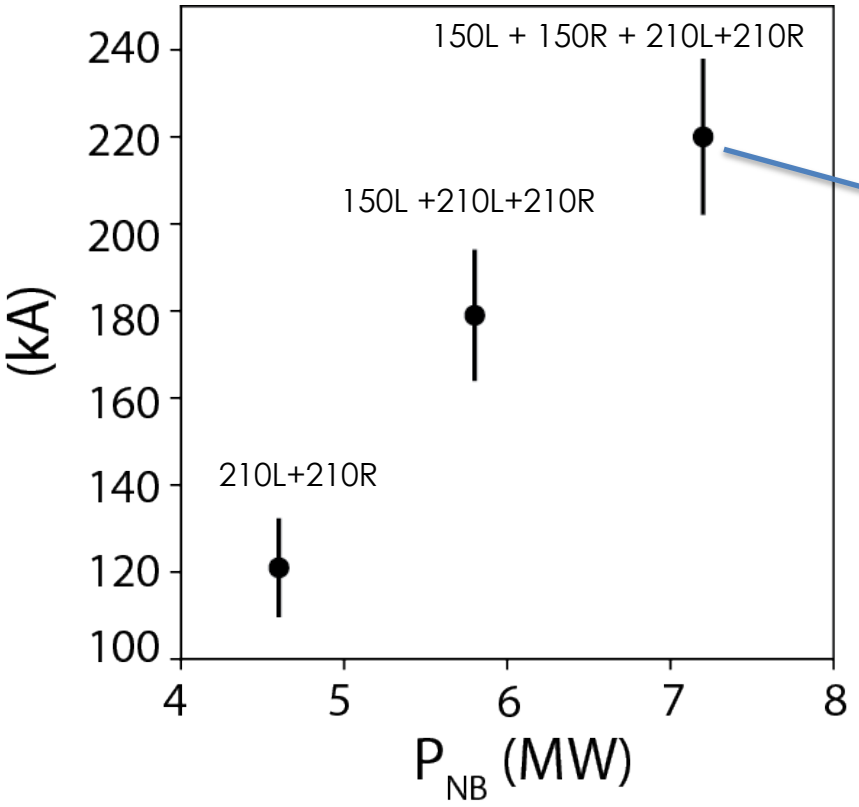
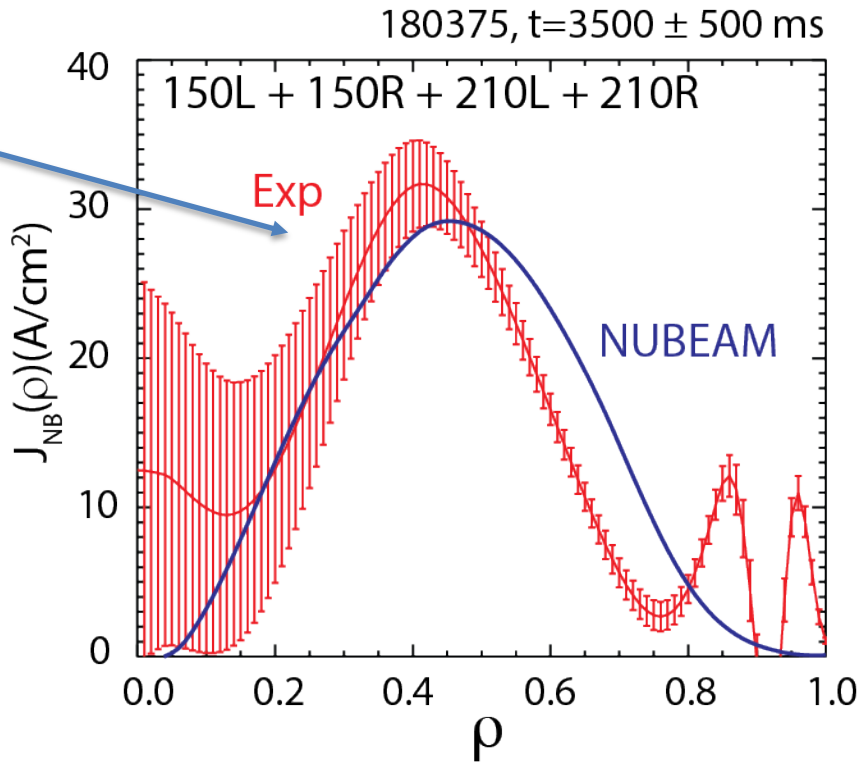
Measured Off-axis NBCD Efficiency Increases with Injection Power

CCOANB + Vertically-Steerable





- **An inward shift of the peak NBCD location for high power off-axis NBCD (~7 MW) in presence of**
  - Estimated beam ion diffusion Db ~ 0.3 m^2/s to match the net driven current and stored energy
    - Related to modest n = 2, 3 MHD instabilities

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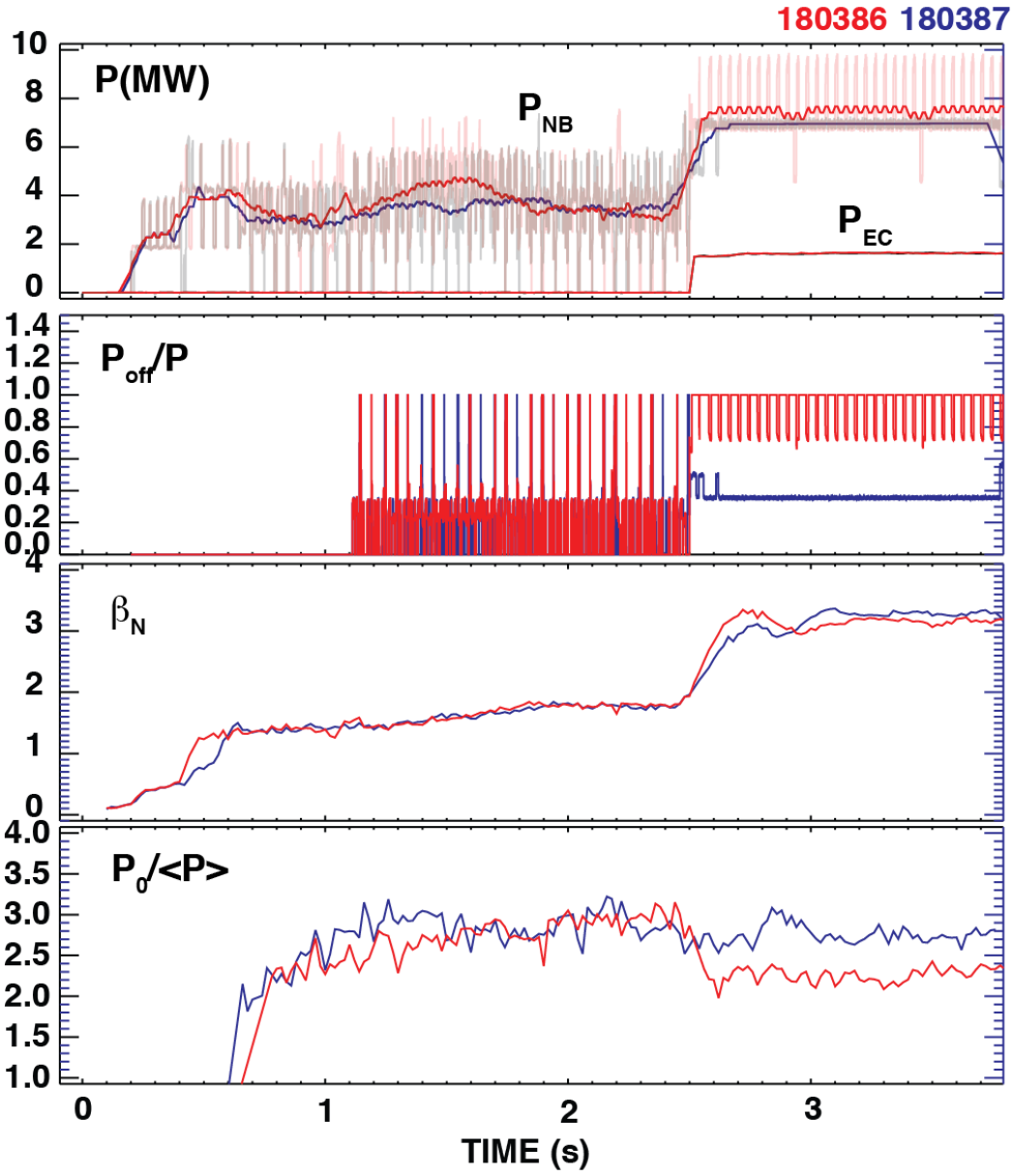
Increased Off-axis NBCD Power Leads to Very Broad Pressure Profiles as Predicted

- Elevated q_{min} target discharge
- Vertically-steerable OANB + on-axis NB
- Dominant off-axis beams (Vertically-steerable + CCOANB) except diagnostic on-axis NB



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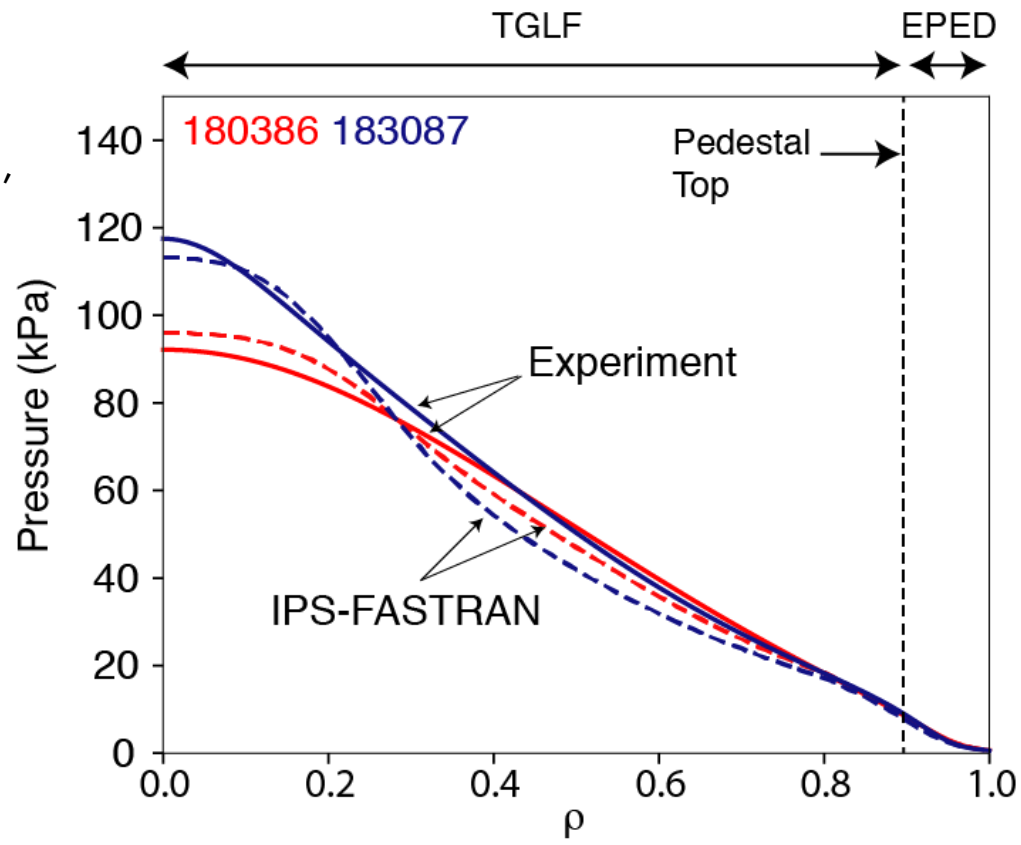
IPS-FASTRAN Reproduces Pressure Profile Broadening Reasonably Well

- **Solve all transport channels**
  - Particle, energy, momentum, current
- **From core to separatrix**
  - TGLF + EPED
- **Self-consistent H/CD**
  - NUBEAM, TORAY-GA
- **Theory-based, limited free parameters**
  - n_e^{ped}, Z_{eff}, Ω_{ped}, D_b



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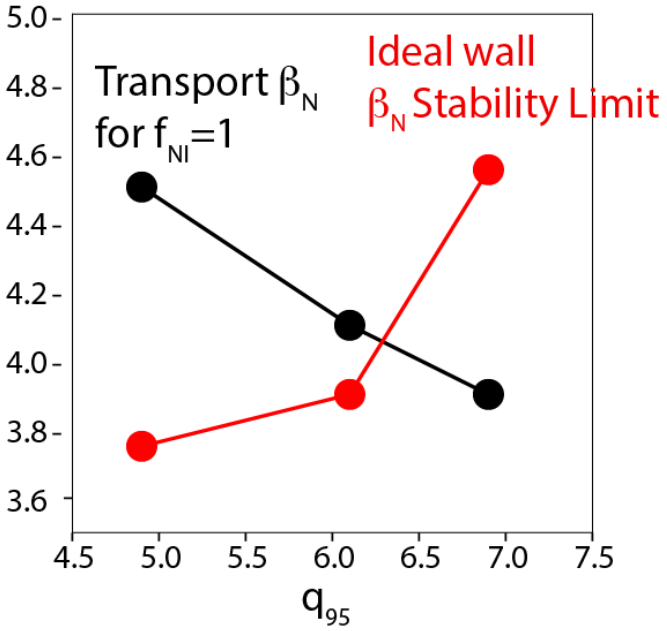
Predict-First Approach Has Been Tested for High q_{min} Scenario with Off-axis NBCD

FASTRAN Predict-FIRST

TGLF+EPED+NUBEAM+TORAY+EFIT+DCON



- **IPS-FASTRAN simulations under a given power constraint for the dedicated Predict-First experiment**
  - P_{ECCD} = 1.5 MW
  - P_{OANB} = 7 MW
- **Multi-dimensional parameter scan searching for the highest stable β_N at f_{NI} = 1**
  - I_p, B_T, pedestal density, ECCD aiming, NB power mix
- **Increasing on-axis NB power on top of all available off-axis NB power until the high qmin discharge hits one of the MHD stability limits, confinement limit, or reaches to f_{NI} = 1**

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Predict-First Approach Has Been Tested for High q_{min} Scenario with Off-axis NBCD

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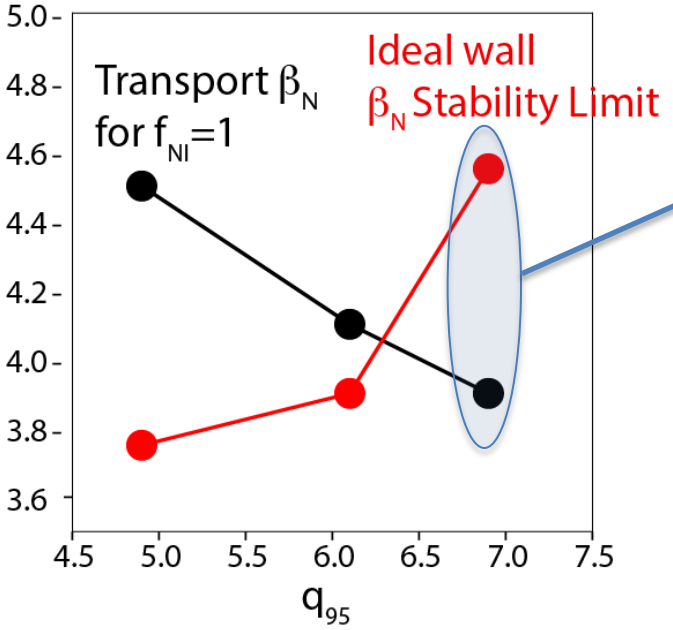

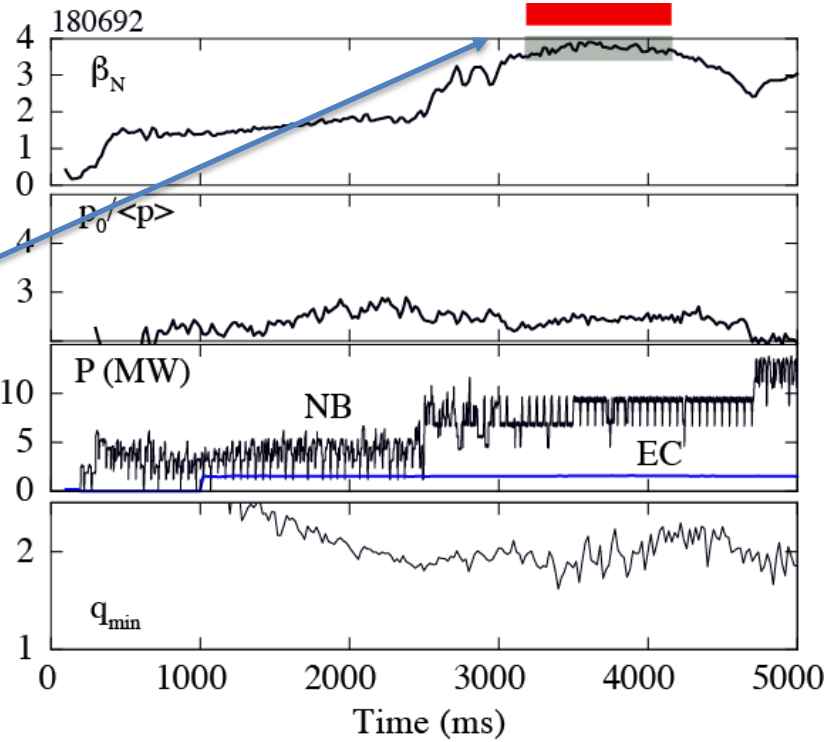

- **Experiment achieved $\beta_N \approx 3.9$, $f_{NI} \approx 0.92$ with a sufficient margin to the n=1 with-wall ideal MHD β_N limit**
- **n=3 TM later in high β_N phase prevented higher β_N operation**

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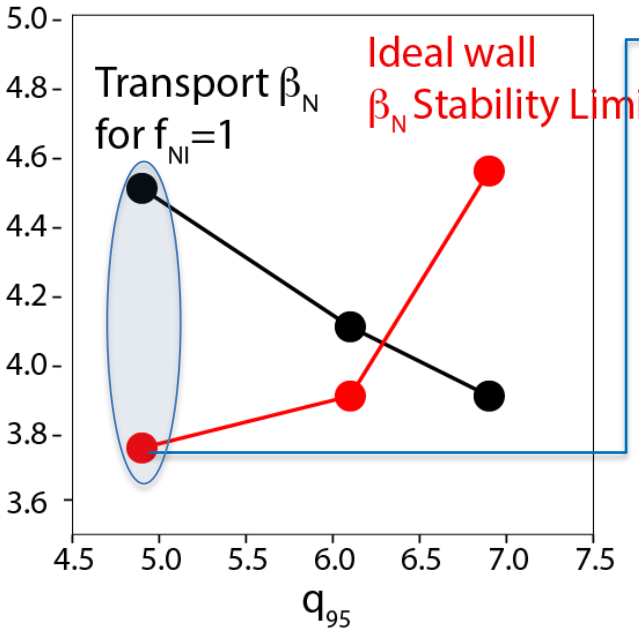
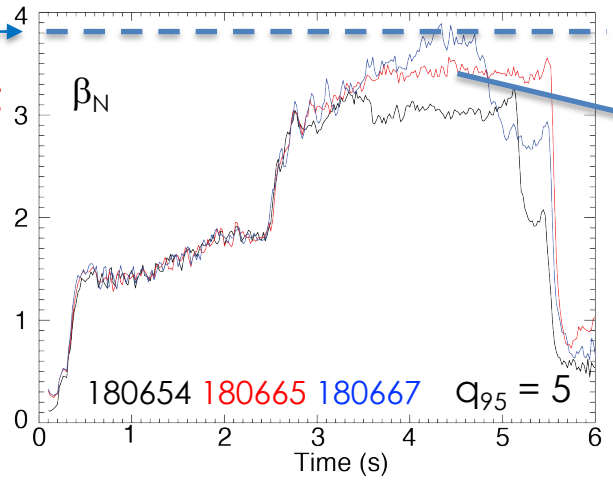
Predict-First Approach Has Been Tested for High q_{min} Scenario with Increased Off-axis NBCD

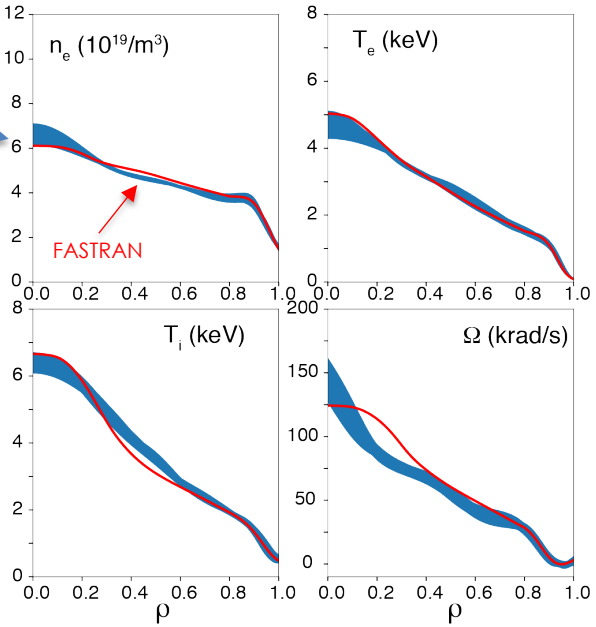
FASTRAN Predict-FIRST → **Experiment with 2nd Off-axis NB** → **Validation**



- Theory-based modeling
- TGLF + EPED+ NUBEAM + TORAY + EFIT + DCON



- On-axis NB power scan at the maximum off-axis NB power to closely mimic FASTRAN Predict-First



- IPS-FASTRAN reproduces experimental profiles with 2nd off-axis beams

Repeated Cycle

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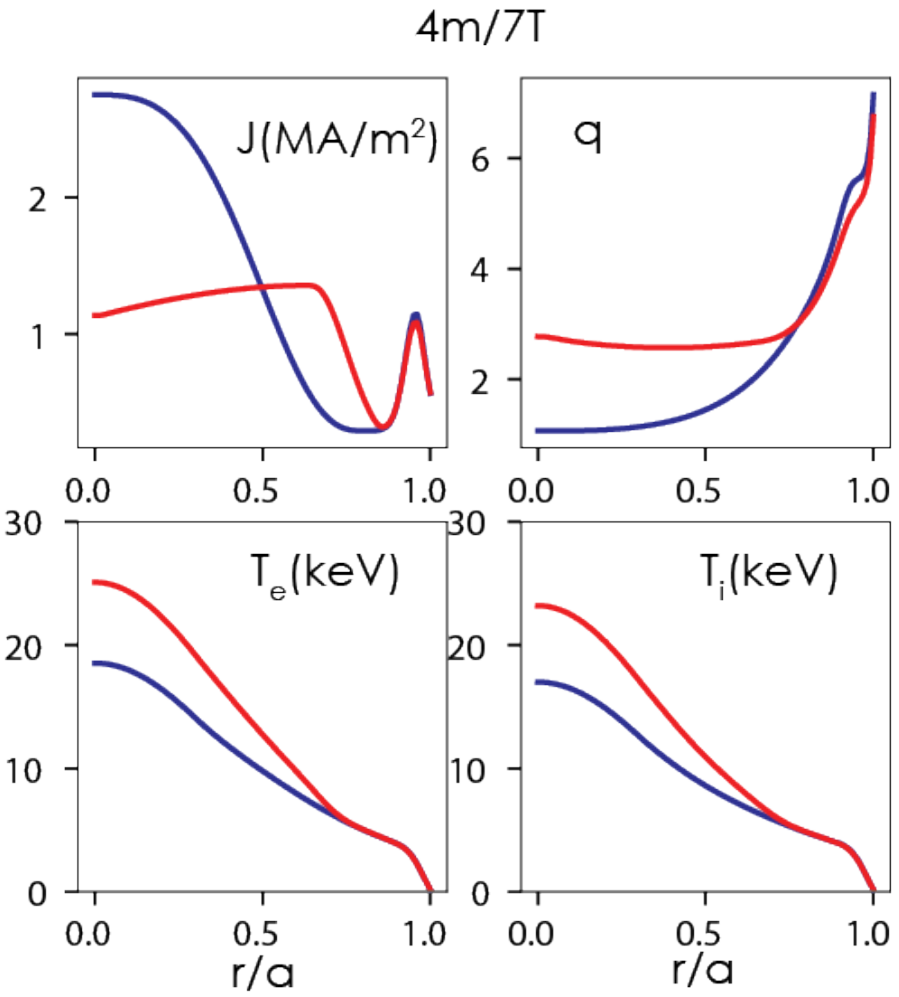
IPS-FASTRAN Prediction for CAT Shows a Significant Improvement of Energy Confinement with a Broad Current Profile

- **Confinement is sensitive to J(ρ)**
  - **Broad J with a weak negative magnetic shear, $q_{min} > 2$**
  - **Monotonic q with $q_0 \approx 1$**
- **H/CD requirement**
  - Broad off-axis CD to fill in $\Delta J = J(\rho) - J_{BS}(\rho)$



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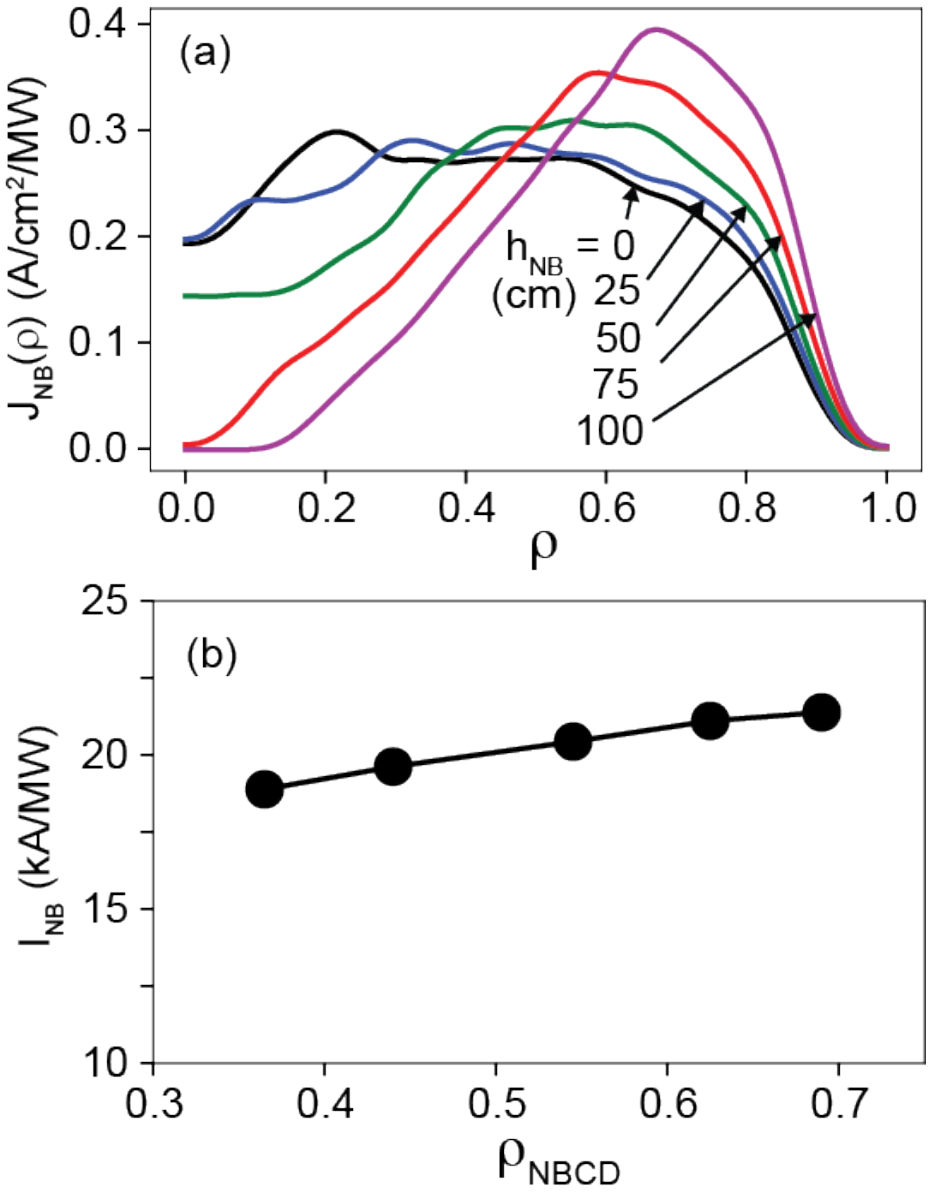
CAT Fusion Pilot Plan: Buttery, Nucl. Fusion **61** 046028 (2021)

Off-axis NBCD Aligns Well with High f_{BS}>0.8 Operation, Maintaining a Broad Current Profile with q_{min}>2

- **Negative beam ion**
  - E_b = 750 keV
  - 56 cm x 120 cm beam size
  - Tangent radius R_T = 4 m
- **Vertical shift for off-axis NBCD**
  - Direction of vertical shift (h_{NB}) was determined for better alignment of NB injection to local B
- **Excellent off-axis NBCD efficiency**
  - NBCD does not lose CD efficiency at a larger radius



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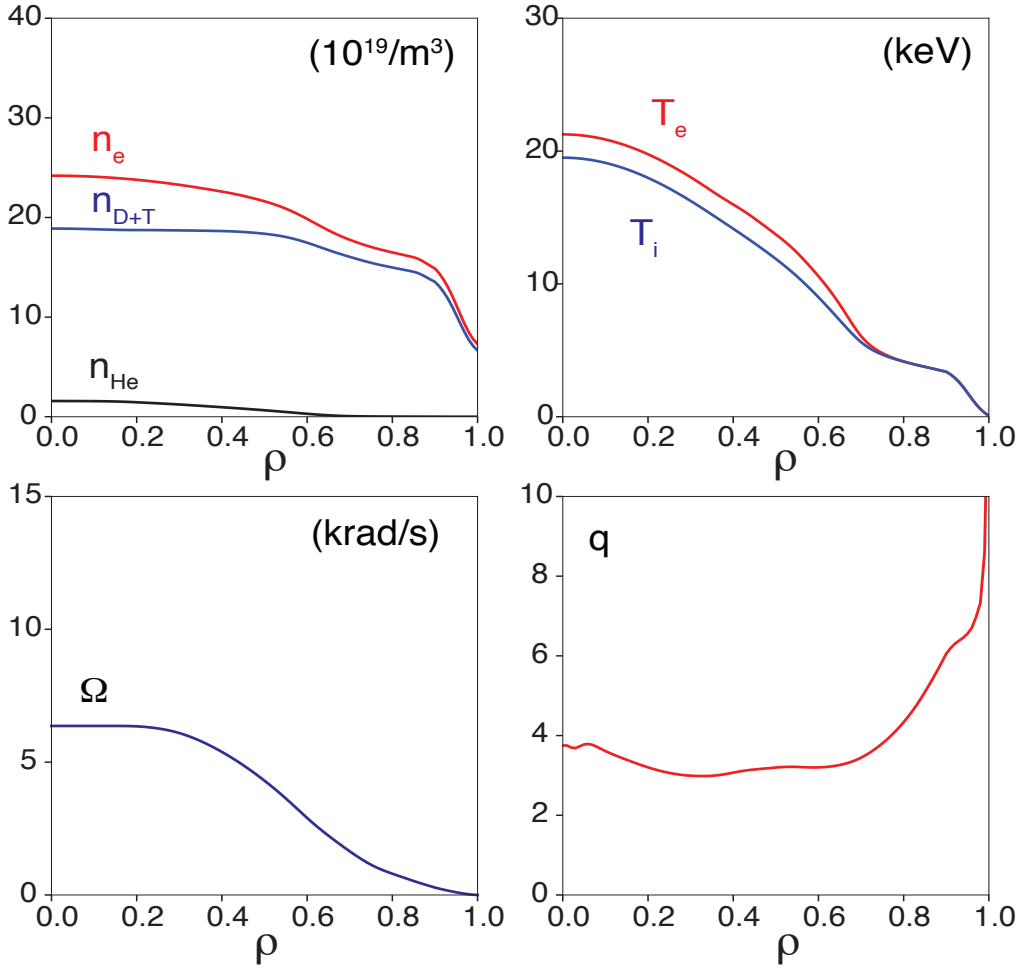
IPS-FASTRAN Predicts A Promising Path To Net Electricity Generation with Off-axis NBCD as a Main H/CD Source

- **200 MW_e net electricity solution**
  - R = 4 m, R/a = 3, B = 7 T
  - β_N = 3.6
  - f_{NI} = 1, f_{BS} = 0.9
  - $n_{e,ped}/n_{GW}$ = 1
- **Off-axis NBCD**
  - P_{NB} = 24 MW
  - Broad CD with peak at ρ = 0.6
- **Helicon CD**
  - P_{HC} = 12 MW @ 1.2 GHz
  - Localized CD at ρ = 0.6



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SUMMARY

- **Off-axis NBCD physics has been validated with increased off-axis injection power up to ~7 MW with the newly available CCOANB capability.**
  - The measured NBCD from CCOANB agrees reasonably well with the classical model NUBEAM for MHD quiescent plasmas.
  - An inward shift of NBCD profile was observed in the presence of low-n resistive instabilities at high injection power, resulting in reduced NBCD compared with the classical prediction.
  - The measured NBCD efficiency increases with injection power even with the anomalous beam ion transport.

SUMMARY

- **IPS-FASTRAN predict-first approach has been tested for high q_{min} scenario with off-axis NBCD.**
  - Dedicated predict-first experiment obtained a discharge with $f_{NI} > 0.9$, $\beta_N \sim 3.9$ at $q_{95} = 6.9$, which is close to the prediction under the constraint of available ECCD power.
  - Additional modeling needs have been identified, especially for the on-set of low-n resistive MHD instabilities and importance of a repeated cycle of scenario design, experimental implementation, and modeling validation.

- **IPS-FASTRAN predicts a promising path to net electricity generation for the CAT Fusion Pilot Plant with off-axis NBCD as a main H/CD source**