Off-Axis Neutral Beam Current Drive for Advanced Tokamak


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

- Off-axis CD plays an essential role in achieving high $\beta_N$, 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.

<table>
<thead>
<tr>
<th>On-Axis NBI (MW)</th>
<th>Off-Axis NBI (MW)</th>
<th>ECH (MW)</th>
<th>Transport limit $\beta_N$</th>
<th>Stability Limit $\beta_N$</th>
</tr>
</thead>
<tbody>
<tr>
<td>10.8</td>
<td>3.3</td>
<td>3.2</td>
<td>3.5 ($q_{min}=1.5$, $f_{NI}=0.75$)</td>
<td>3.7</td>
</tr>
<tr>
<td>9.5</td>
<td>10.7</td>
<td>9</td>
<td>5.1</td>
<td>4.9 ($q_{min}&gt;2$, $f_{NI}=1$)</td>
</tr>
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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]
NBCD is Obtained Quantitatively from Evolution of the Equilibria

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

$J_{\text{NB}} = J_{\text{Tot}} - J_{\text{OH}} - J_{\text{BS}}$
Reasonably good agreement with classical modeling
- Monte-Carlo beam ion slowing down code NUBEAM
- Without anomalous fast ion transport
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
An inward shift of the peak NBCD location for high power off-axis NBCD (~7 MW) in presence of

- Estimated beam ion diffusion $D_b \sim 0.3 \text{ m}^2/\text{s}$ to match the net driven current and stored energy
- Related to modest $n = 2, 3$ MHD instabilities
Increased Off-axis NBCD Power Leads to Very Broad Pressure Profiles as Predicted

- Elevated $q_{\text{min}}$ target discharge
- Vertically-steerable OANB + on-axis NB
- Dominant off-axis beams (Vertically-steerable + CCOANB) except diagnostic on-axis NB
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
  - $n_{e^{ped}}$, $Z_{eff}$, $\Omega_{ped}$, $D_b$

**Diagram:**
- IPS-FASTRAN
- Experiment
- 180386 183087
- Pedestal Top

**Axes:**
- Pressure (kPa)
- $\rho$

**Scale:**
- 0.0 to 1.0
Predict-First Approach Has Been Tested for High $q_{\text{min}}$ Scenario with Off-axis NBCD

- IPS-FASTRAN simulations under a given power constraint for the dedicated Predict-First experiment
  - $P_{\text{ECCD}} = 1.5 \text{ MW}$
  - $P_{\text{OANB}} = 7 \text{ MW}$

- Multi-dimensional parameter scan searching for the highest stable $\beta_N$ at $f_{N_{NI}} = 1$
  - $I_p$, $B_T$, pedestal density, ECCD aiming, NB power mix

- Increasing on-axis NB power on top of all available off-axis NB power until the high $q_{\text{min}}$ discharge hits one of the MHD stability limits, confinement limit, or reaches to $f_{N_{NI}} = 1$
Predict-First Approach Has Been Tested for High $q_{\text{min}}$ Scenario with Off-axis NBCD

**FASTRAN Predict-FIRST**

TGLF+EPED+NUBEAM+TORAY+EFIT+DCON

Transport $\beta_N$ for $f_{NI}=1$

- Ideal wall $\beta_N$ Stability Limit

- Experiment achieved $\beta_N \approx 3.9$, $f_{NI} \approx 0.92$ with a sufficient margin to the $n=1$ with-wall ideal MHD $\beta_N$ limit
- $n=3$ TM later in high $\beta_N$ phase prevented higher $\beta_N$ operation
Predict-First Approach Has Been Tested for High $q_{\text{min}}$
Scenario with Increased Off-axis NBCD

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

- Confinement is sensitive to $J(\rho)$
  - Broad $J$ with a weak negative magnetic shear, $q_{\text{min}} > 2$
  - Monotonic $q$ with $q_0 \approx 1$

- H/CD requirement
  - Broad off-axis CD to fill in $\Delta J = J(\rho) - J_{BS}(\rho)$
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
IPS-FASTRAN Predicts A Promising Path To Net Electricity Generation with Off-axis NBCD as a Main H/CD Source

- **200 MW\textsubscript{e} net electricity solution**
  - $R = 4\ \text{m}$, $R/a = 3$, $B = 7\ \text{T}$
  - $\beta_N = 3.6$
  - $f_{NI} = 1$, $f_{BS} = 0.9$
  - $n_{e,ped}/n_{GW} = 1$
- **Off-axis NBCD**
  - $P_{NB} = 24\ \text{MW}$
  - Broad CD with peak at $\rho = 0.6$
- **Helicon CD**
  - $P_{HC} = 12\ \text{MW} @ 1.2\ \text{GHz}$
  - Localized CD at $\rho = 0.6$
• 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 $q_{\text{min}}$ scenario with off-axis NBCD.
  - Dedicated predict-first experiment obtained a discharge with $f_{\text{Ni}} > 0.9$, $\beta_N \sim 3.9$ 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.