Prospects for Off-axis Neutral Beam Current Drive in the DIII-D Tokamak*

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Many Thanks to the Fusion Grid Project

Poster: JP8

Presented at
49th APS-DPP Annual Meeting
Orlando, FL

November 12 - 16, 2007

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ABSTRACT

Off-axis neutral beam (NB) current drive (CD) has the potential to supply substantial off-axis current drive for the demonstration steady-state, advanced tokamak scenarios. A modification being considered for the DIII-D NB system is to tilt the present neutral beam lines by raising the source end by up to 2.0 m. The profile and magnitude of the driven current is calculated using the NUBEAM Monte-Carlo module in TRANSP and ONETWO. When the beam is injected in the same direction as the toroidal field, off-axis CD of ≈45 kA/MW is calculated at with full width half maximum of 0.45. The dimensionless CD efficiency is comparable or somewhat better than that for electron cyclotron current drive at the same location and plasma parameters. The efficiency stays nearly constant in going from on-axis to off-axis CD. The localization and magnitude of the off-axis NBCD are sensitive to the alignment of the NB injection relative to the helical pitch of the magnetic field lines, and thus to the direction of the toroidal field and plasma current. The driven current is still localized off axis for fast ion diffusivities up to 1 . The calculations show that the off-axis NBCD can supply much of the off-axis CD for the steady-state scenarios under consideration, leaving ECCD for fine tuning of the current profile and real-time control.

INTRODUCTION

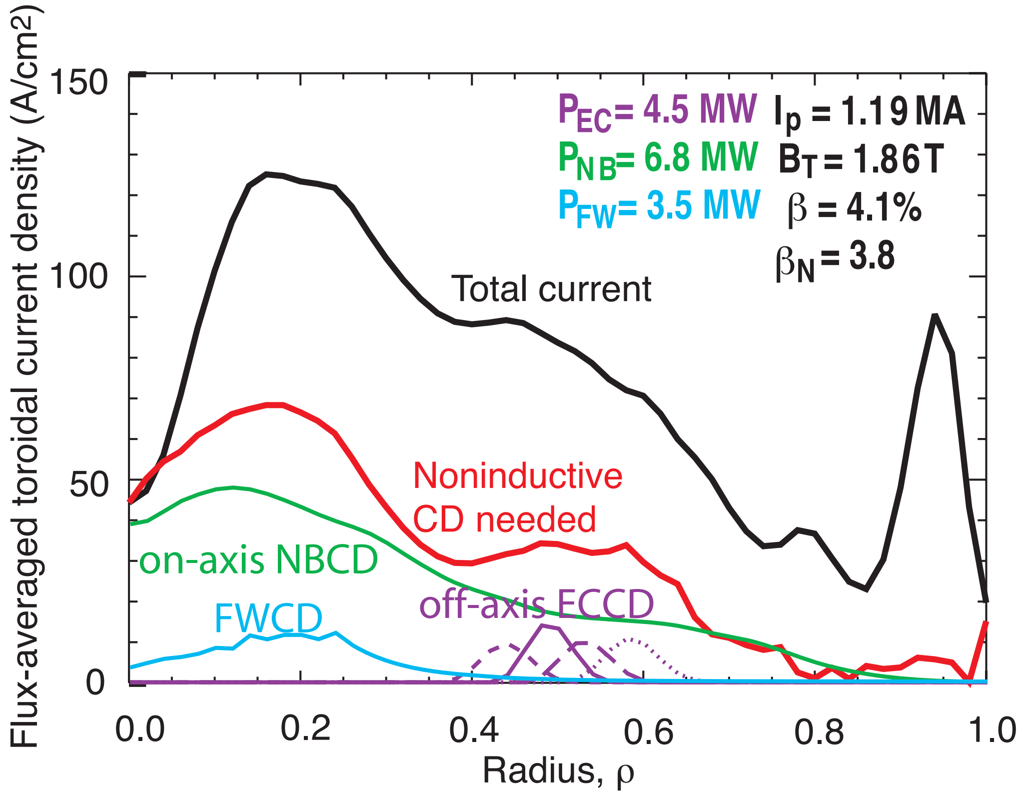
- **Modification to the present NB system is proposed to add flexible steering capabilities to allow raising the source end of the beamline by up to 2.0 m**
- **Off-axis NBCD calculated using orbit-following Monte-Carlo codes:**
  - Calculated off-axis CD ≈45 kA/MW at ρ = 0.5 with FWHM of 0.45
  - Normalized CD efficiency, ζ**,** comparable to or somewhat better than ECCD, and nearly constant in going from on-axis to off-axis
- **Localization of the off-axis NBCD is sensitive to alignment of the NB injection to the pitch of the magnetic field lines, and thus to the relative direction of the B_T and I_p**
  - Possible alternative explanation for the AUG off-axis NBI results
  - Implication to ITER off-axis NBI design
- **Possible strategy for the AT scenario development** is **to use NBCD to get most of the off-axis CD needed and to use ECCD to allow fine tuning of current profiles and real-time control**
  - Explore AT scenarios using off-axis NBCD

OUTLINE

- **Proposal for off-axis NBCD**
  - Modification to the existing (on-axis) NBI
  - Results of Monte-Carlo CD calculation

- **Physics of off-axis NBCD**
  - Why the CD sensitive to the B_T direction?
    - Alternative explanation for the ASDEX-U results
    - Implication to ITER off-axis N-NBI
  - Why the off-axis NBCD so efficient?
  - Possible strategy for AT scenario development?

"Typical" steady-state scenarios requires substantial off-axis CD



- **NEED to enhance the off-axis ECCD for development of steady state, advanced tokamak scenarios**
- **Most of the off-axis CD can be provided by an off-axis NBCD**
- **Broad off-axis CD is preferred**

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PROPOSED OFF-AXIS NBCD SCHEME

Feasibility Studies of Off-axis NBCD Were Carried Out As a Part of the DIII-D 5-year Plan

Design philosophy for the off-axis NBCD:

1. Capable of generating a significant amount of off-axis CD with reasonable localization
2. Applicable to a wide operating range of parameters (e.g., at higher density)
3. Retain the on-axis capability
4. Minimize the extent of the modifications, e.g., by limiting to one degree of motion (vertical)

Range of different NB configurations considered

1. Elevating the beamline (BL) optical axis
   $\Rightarrow$ interference with the F6 coil
2. Turning the sources to horizontal rather than vertical position
   $\Rightarrow$ abandoning due to narrow access port width and large modification of the internal components required)
3. **Proposed scheme**

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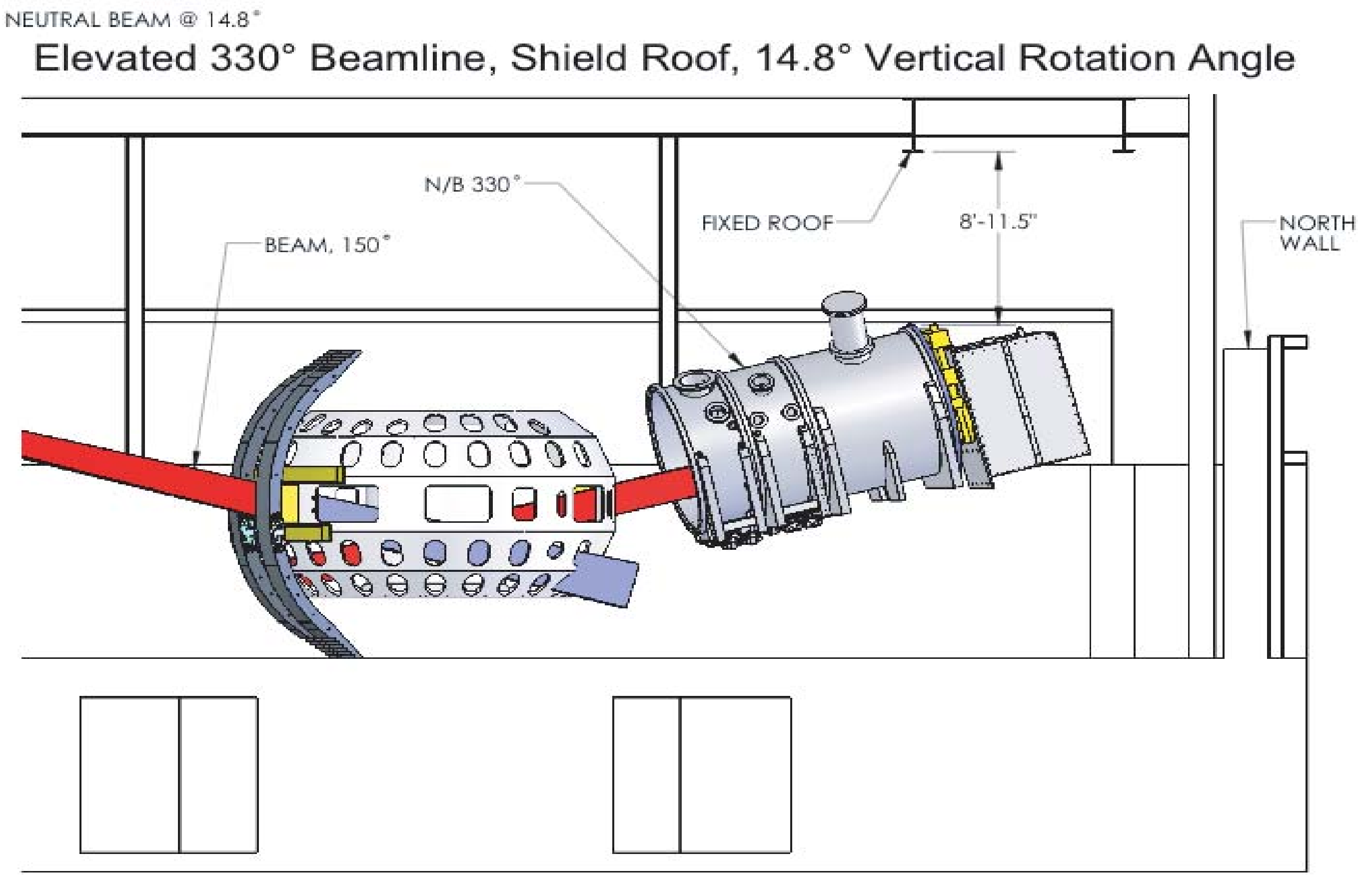
The Proposed off-axis NBCD is achieved by downward steering of beamlines by up to 21 deg (by raising the source end by up to 2.0 m) injecting through the existing midplane port



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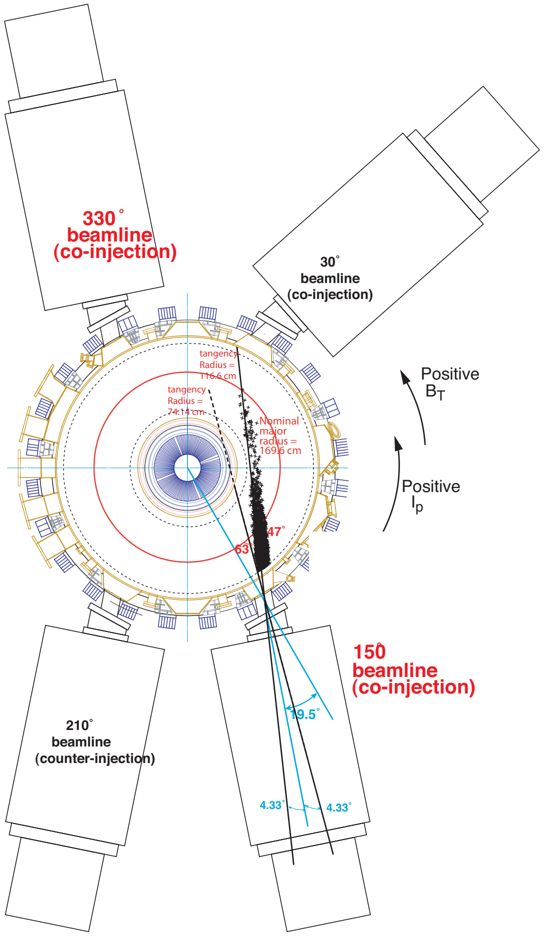
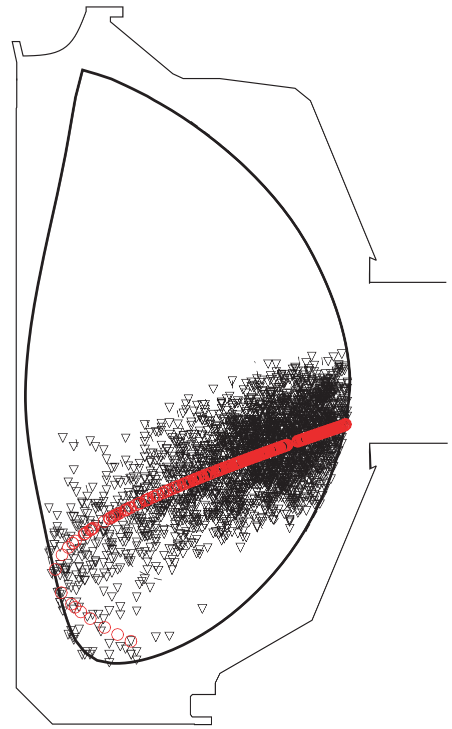
Design Philosophy for Off-axis Modification: Retain On-axis Capability and Limit to One Degree of Motion (Vertical)



Poloidal projection of fast ion birth points on a single toroidal plane



- Off-axis CD has been attempted by JT-60U AUG, and JET

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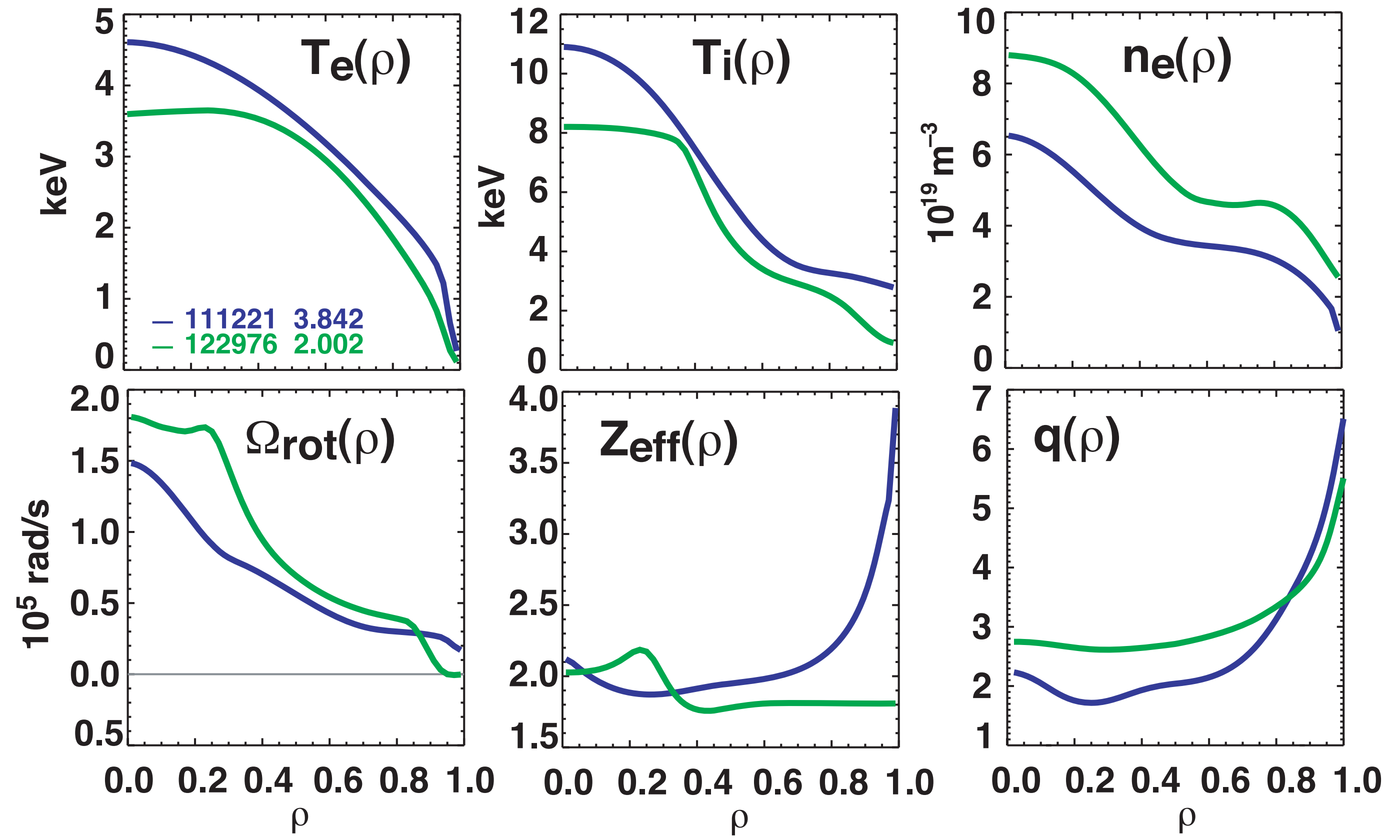
NBCD CALCULATIONS

Simulations Used Two Different Discharges from DIII-D AT Experiments (High and Low Density)



- 111221 (USN, β_N=3.5, 1.9T/1.3MA,nebar=4.1x10^{19}, originally in the 'reversed' B_T)
- 122976 (USN, β_N=4.0, 2.1T/1.6MA, nebar=6.1x10^{19}, originally in the 'normal' B_T)
- Assume to operate in the 'reverse' (≡ 'positive') B_T direction

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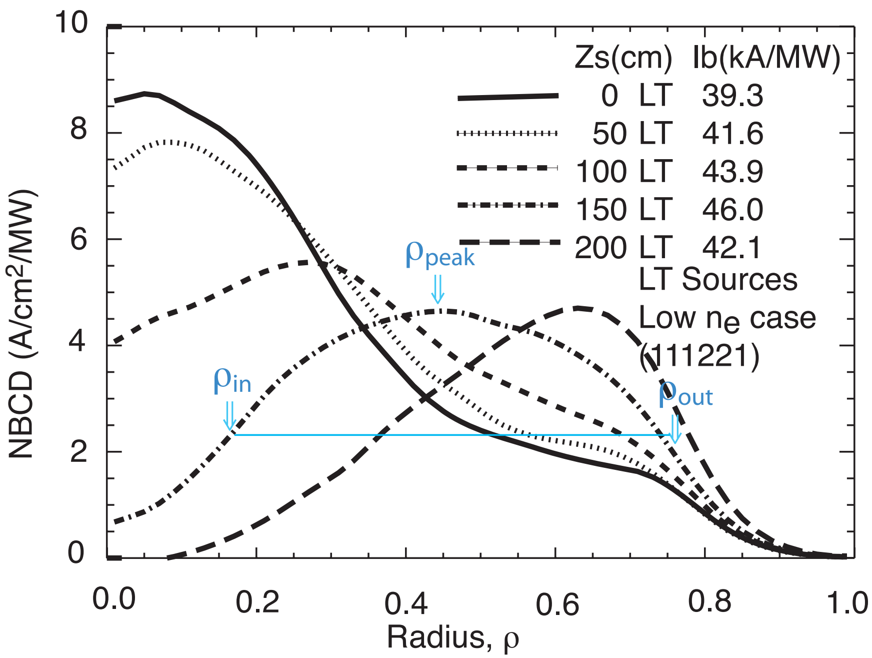
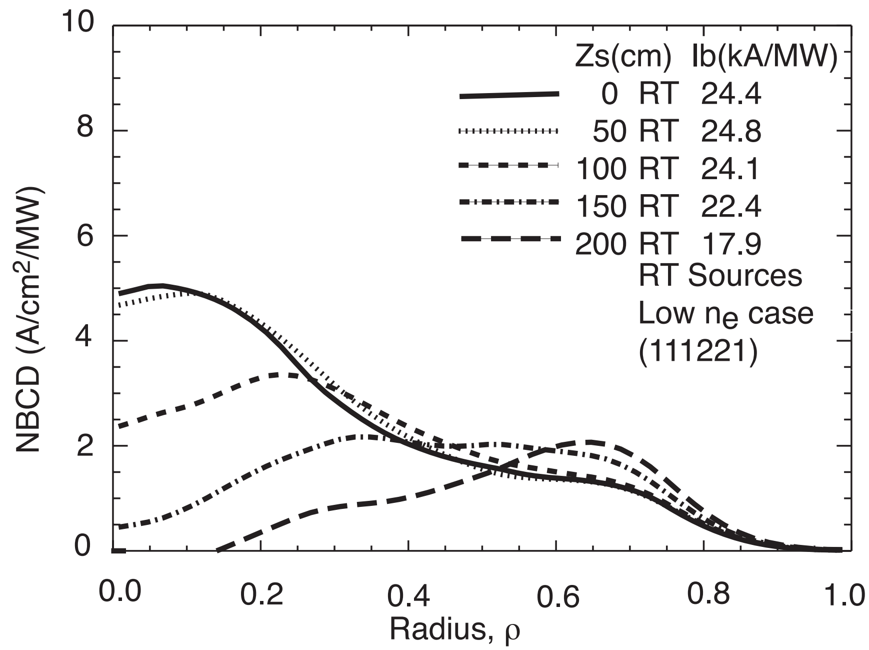
off-axis NBCD profiles for the low density case are calculated by the Monte-Carlo codes





- **The CD profiles shown are those averaged over 30 MC time slices to reduce MC noise in NUBEAM/TRANSP**
- **NUBEAM/ONETWO benchmarked with NUBEAM/TRANSP**
- **$\langle$150LT+150RT$\rangle$ = 34 kA/MW $\Rightarrow$ 340 kA/2BL $\Rightarrow$ f_b = 0.3**

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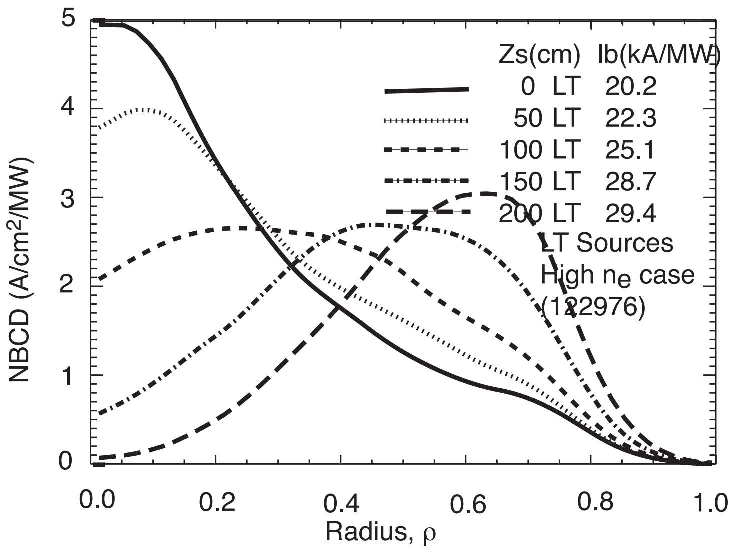
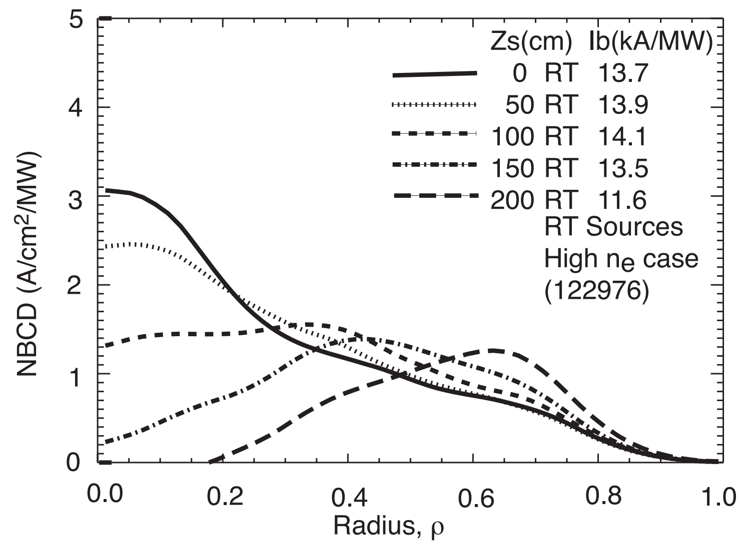
Calculated Off-axis NBCD Profiles for the High Density Case Are Similar to Those for the Low Density Case





- **At higher density (6.2×10^{20} m^{-3}, 1.6MA):**
  $\langle$150RT+150RT$\rangle$ = 20 kA/MW $\Rightarrow$ 200 kA/2BL $\Rightarrow$ f_b = 0.16

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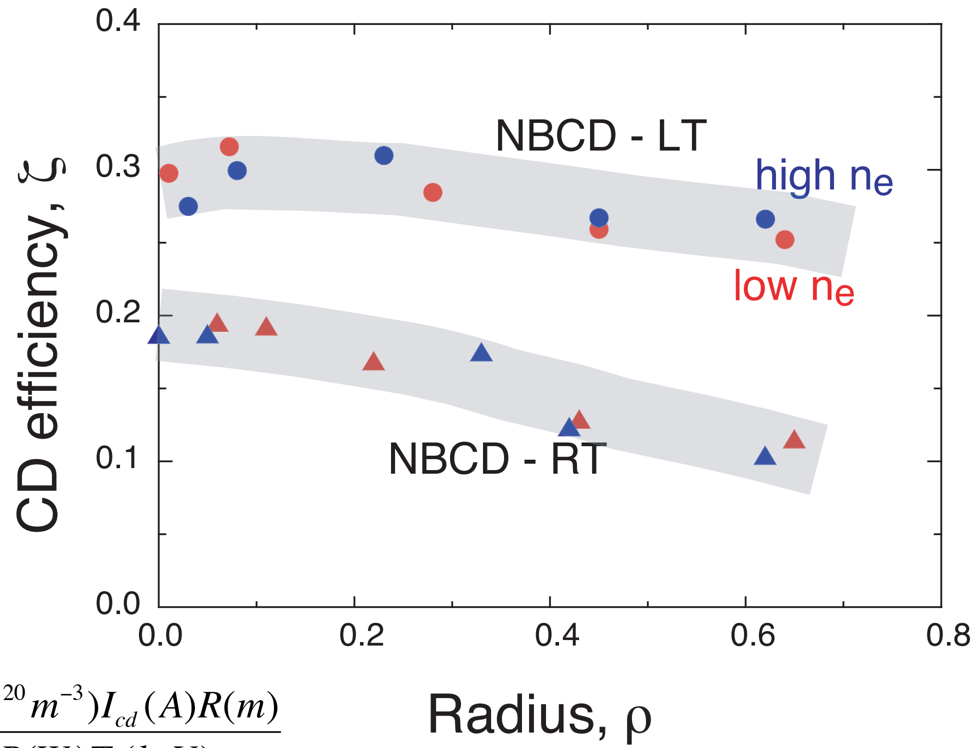
Results of Off-axis NBCD Calculations

Z_s (m)	R_{tan} (m)	$\overline{n}_e$ (10^{13}cm^{-3})	I_b/P_b (kA/MW)	J_{peak} (A/cm^2/MW)	ρ_{peak}	$\rho_{1/2out}$	$\rho_{1/2in}$
0.00	1.16	4.18	39.32	8.70	0.01	0.29	0.00
0.50	1.16	4.18	41.56	7.80	0.07	0.35	0.00
1.00	1.16	4.18	43.86	5.50	0.28	0.70	0.00
1.50	1.16	4.18	45.97	4.60	0.45	0.80	0.08
2.00	1.16	4.18	42.14	4.60	0.64	0.82	0.28
0.00	0.74	4.18	24.40	5.00	0.06	0.34	0.00
0.50	0.74	4.18	24.80	4.90	0.11	0.33	0.00
1.00	0.74	4.18	24.10	3.30	0.22	0.54	0.00
1.50	0.74	4.18	22.40	2.20	0.43	0.79	0.12
2.00	0.74	4.18	17.90	2.00	0.65	0.80	0.43
0.00	1.16	6.21	20.20	4.95	0.03	0.28	0.00
0.50	1.16	6.21	22.27	4.00	0.08	0.39	0.00
1.00	1.16	6.21	25.05	2.62	0.23	0.67	0.00
1.50	1.16	6.21	28.69	2.69	0.45	0.75	0.18
2.00	1.16	6.21	29.45	3.05	0.62	0.78	0.37
0.00	0.74	6.21	13.73	3.06	0.00	0.26	0.00
0.50	0.74	6.21	13.90	2.42	0.05	0.42	0.00
1.00	0.74	6.21	14.07	1.52	0.33	0.66	0.00
1.50	0.74	6.21	13.50	1.38	0.42	0.72	0.18

Dimensionless efficiency of NBCD stays nearly constant



$$\zeta = \frac{e^3}{\varepsilon_0^2}\frac{nI_{cd}R}{PT_e} = 33\frac{n(10^{20}m^{-3})I_{cd}(A)R(m)}{P(W)T_e(keV)}$$

- **Will compare with off-axis ECCD later**

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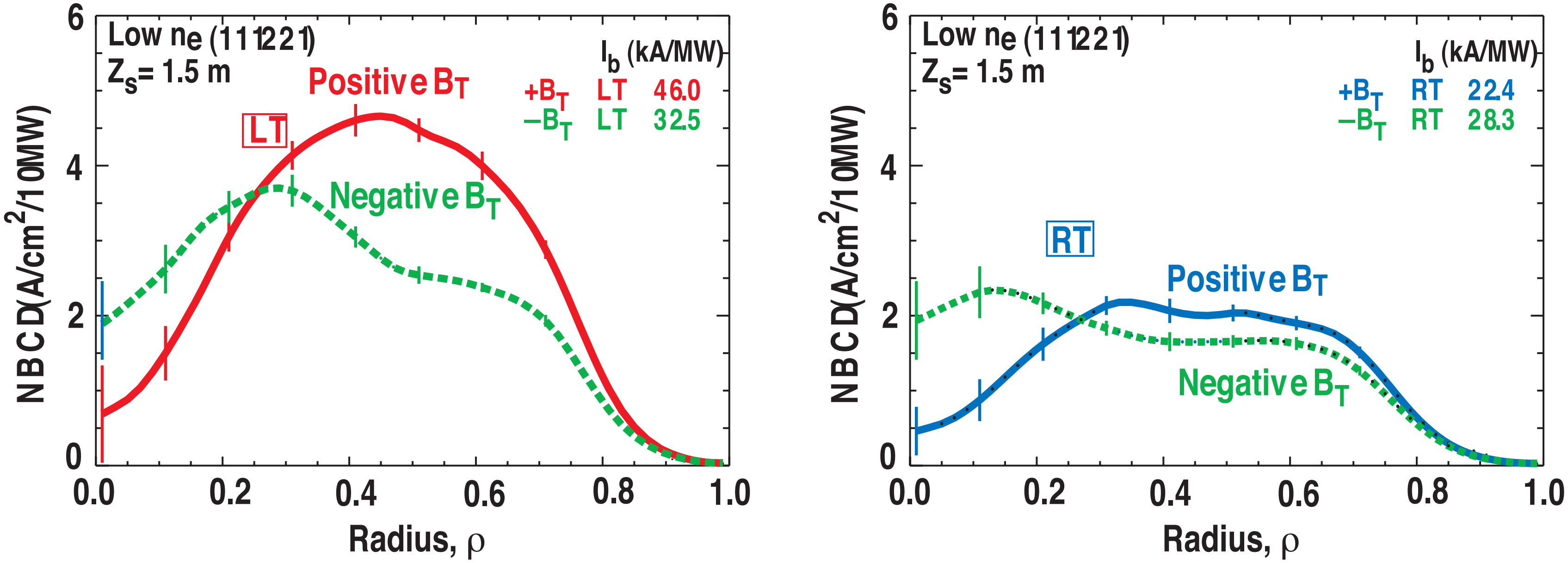
PHYSICS OF OFF-AXIS *NBCD*

Q1: Why is the off-axis NBCD sensitive to the B_T direction?

Characteristics of the Off-axis NBCD Strongly Depend on the B_T Direction -- The 'Positive' B_T Is the Preferred Direction



- The LT beam in the positive B_T direction has the most favorable off-axis CD
- The off-axis feature is significantly lost in the negative B_T direction for both LT and RT beams

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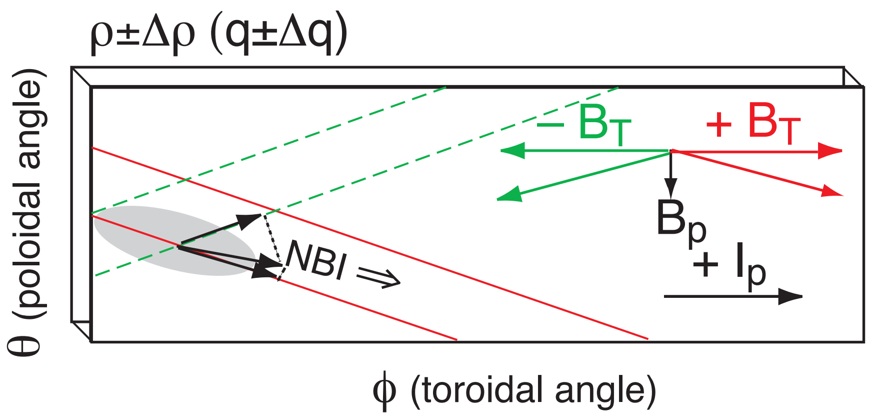
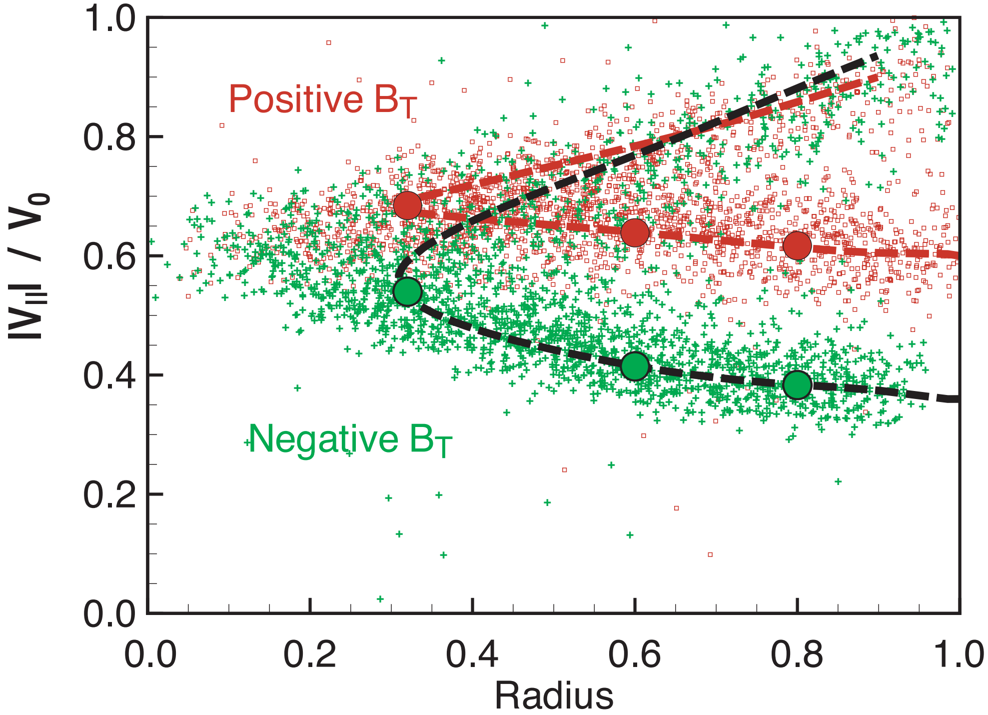
The Sensitivity of the Off-axis NBCD to the B_T Direction Is Due to Alignment of the NB Injection to the Local Pitch of the Magnetic Field Lines



- The downward steered beam is aligned better with the magnetic field line pitch in the $+B_T$ direction than that in the $-B_T$ direction

Better Alignment of Beam Ions With the Magnetic Field Line Pitch in the $+B_T$ Direction Leads to More Parallel Velocity Fraction Than That in the $-B_T$ Direction



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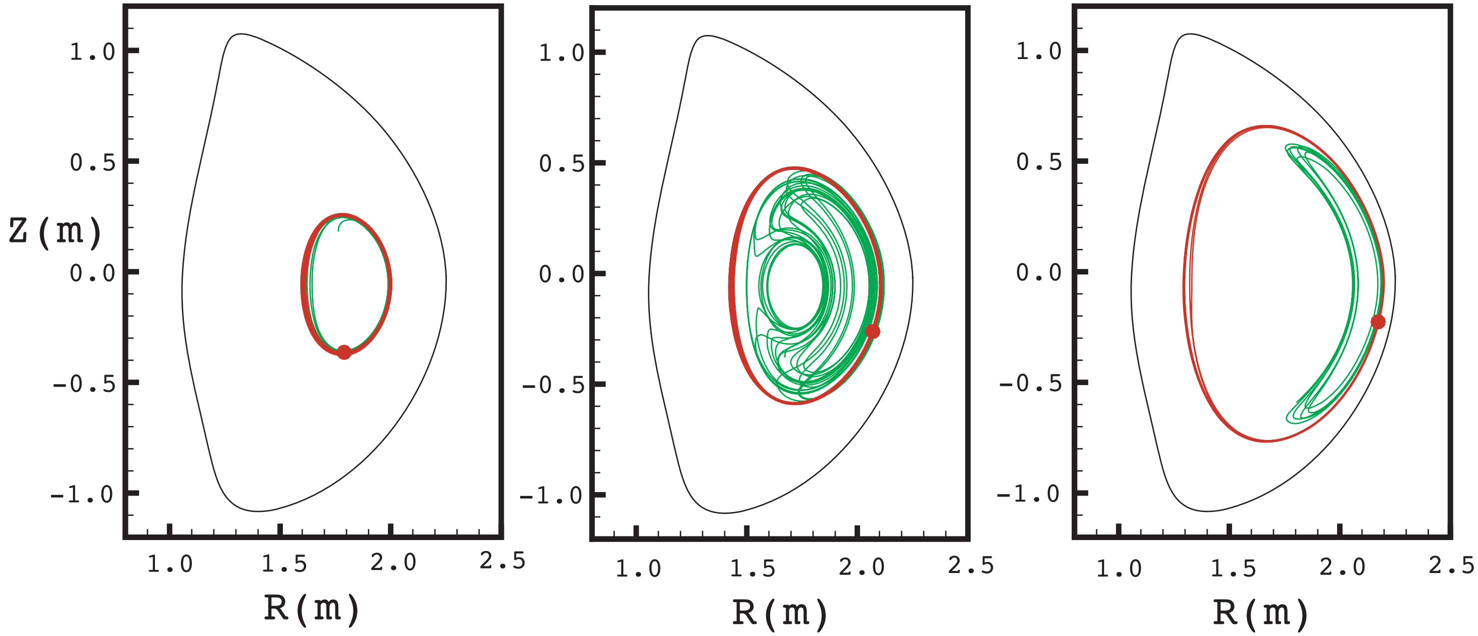
Differences in the Velocity Pitch Angles Lead to Different Orbits, As Illustrated by Samples of Guiding Center Orbits During Initial Stages of Slowing Down

ionization position (dot) , $+B_T$ (red), $-B_T$ (green)



- Beam ions in the $+B_T$ direction stay in the passing particle orbits, achieving the well-localized off-axis CD
- The beam ions borned at the same location but in the $-B_T$ direction stay in more trapped particle orbits due to a larger pitch angle difference
  - **Trapped particles whose guiding center passes through vicinity of the magnetic axis have fat banana**

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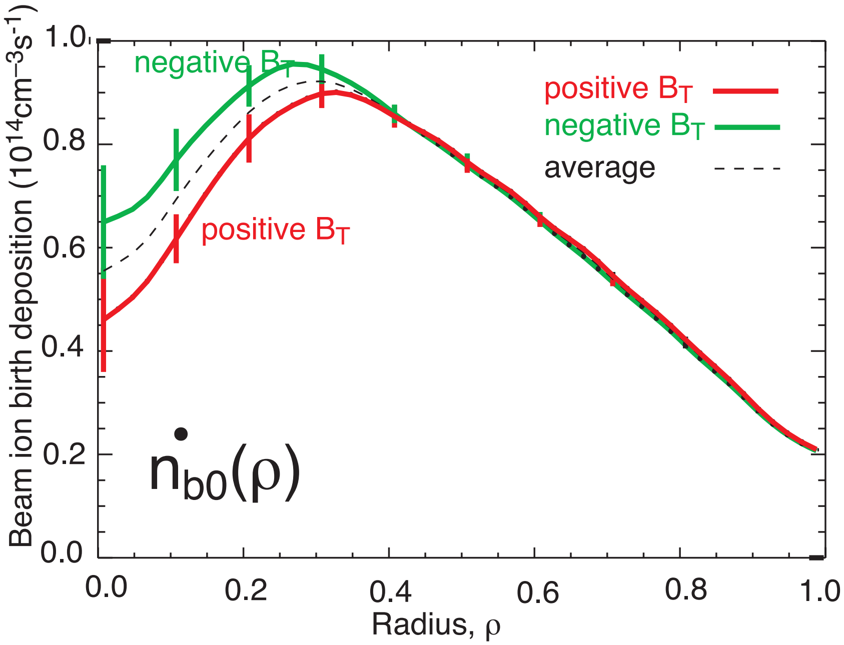
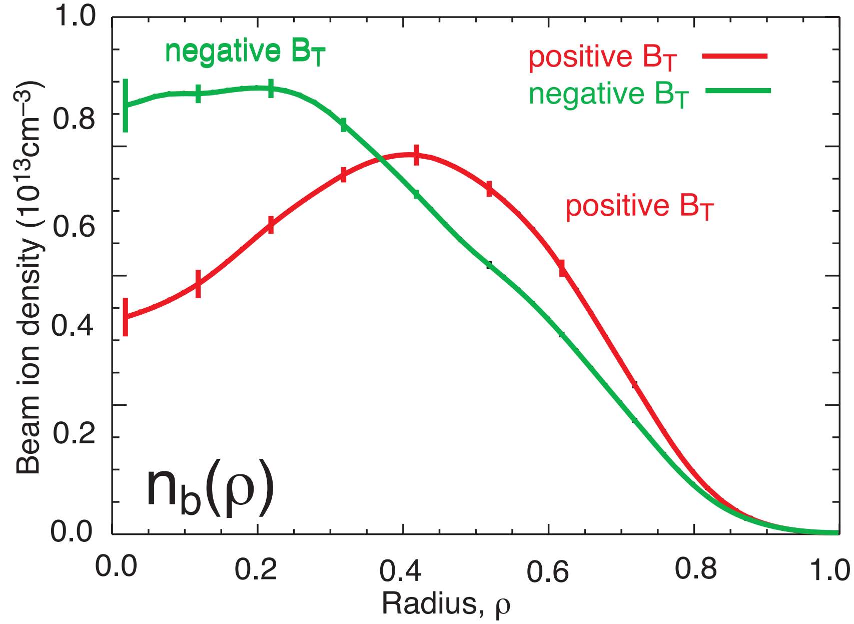
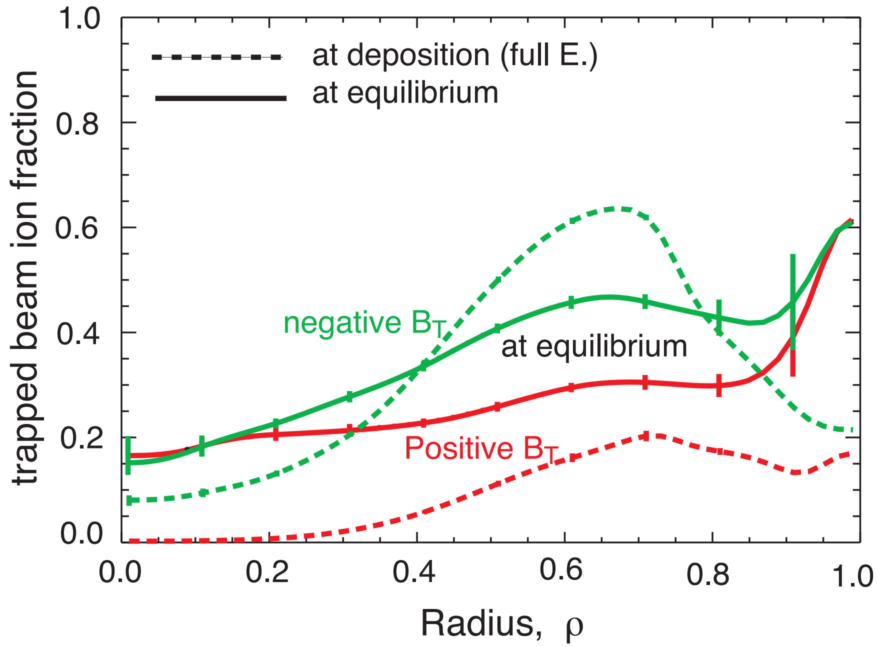
Profiles of Beam Ion Deposition and Density





- **Beam ion deposition profiles reflect more buildup of beam ions at mid radius for the + B_T direction compared with the – B_T direction.**

MC-calculated Fast ion trapping fractions elucidate the effects of the B_T reversal



- **The pitch angle difference at the deposition in the negative direction substantially increases the ion banana fraction at the mid radius initially**
- **As slowing down and pitch-angle scattered, the two cases are more similar, but the difference is still significant for NBCD**

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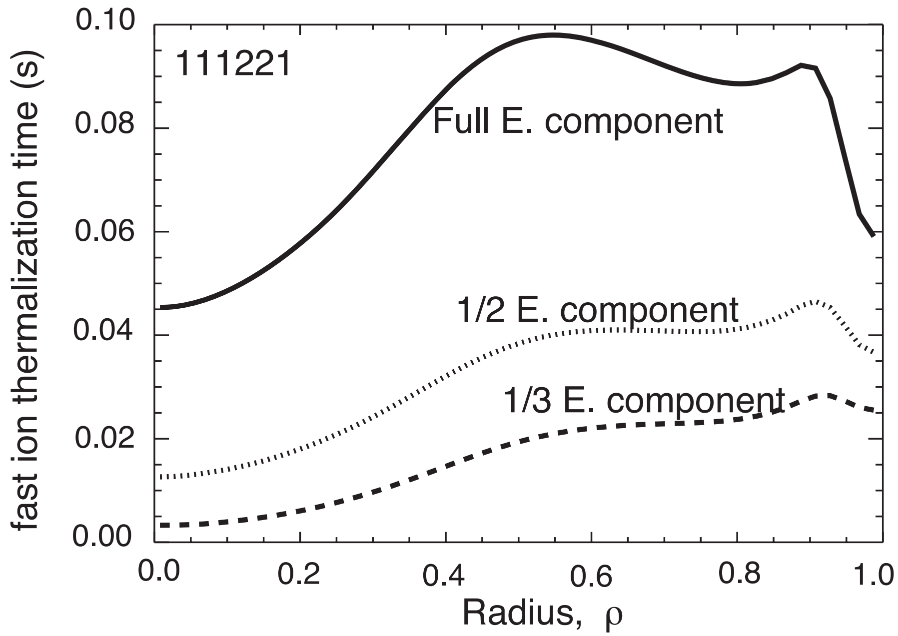
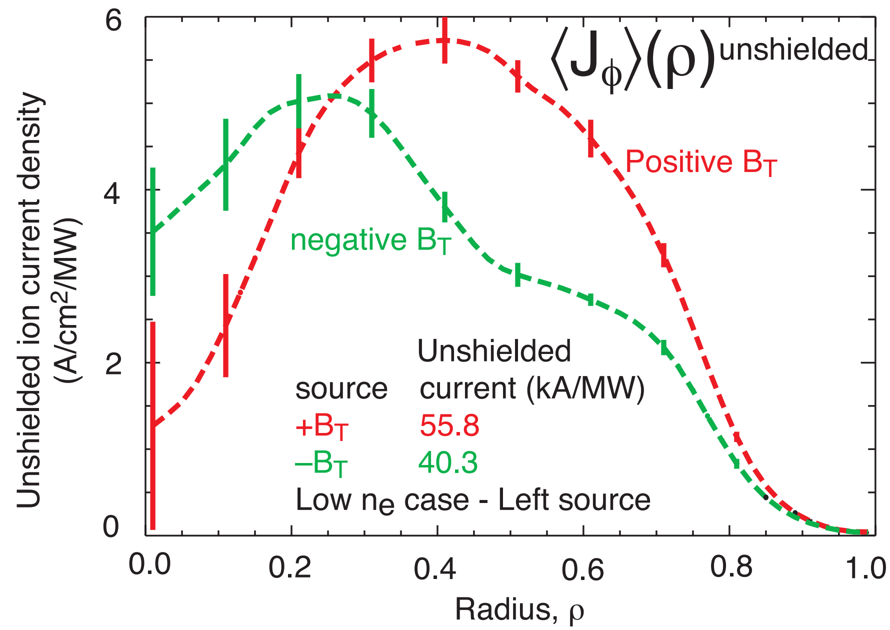
Passing Fast Ions Can More Effectively Build up (or Stack Up) Fast Ion Current As They Circulate Repeatedly Around the Torus Than the Trapped Particles Can





- **The steady state: build up rate of the current due to stacking is balanced by the fast ion loss rate (primarily slowing down through collision with electrons and bulk ions)**

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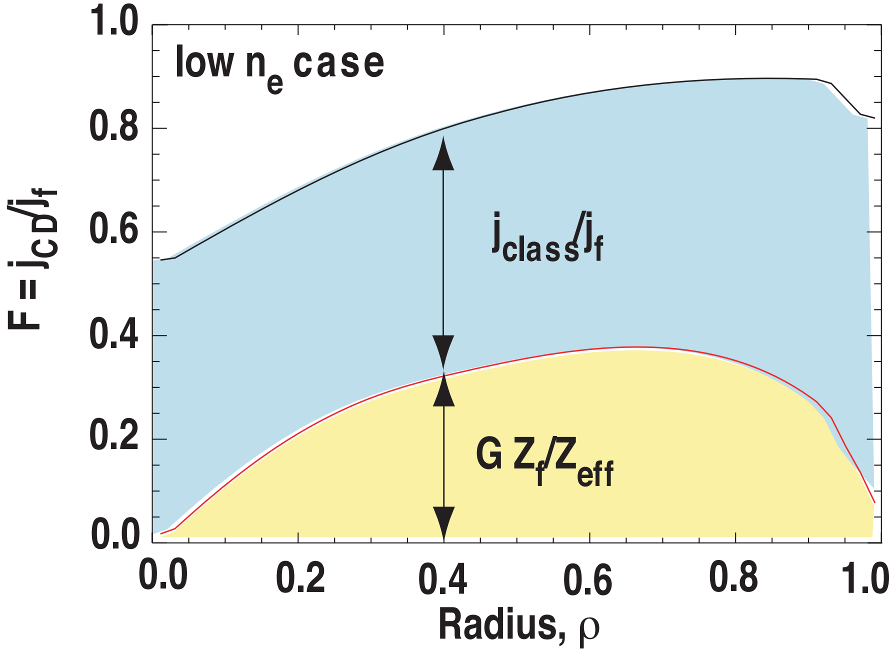
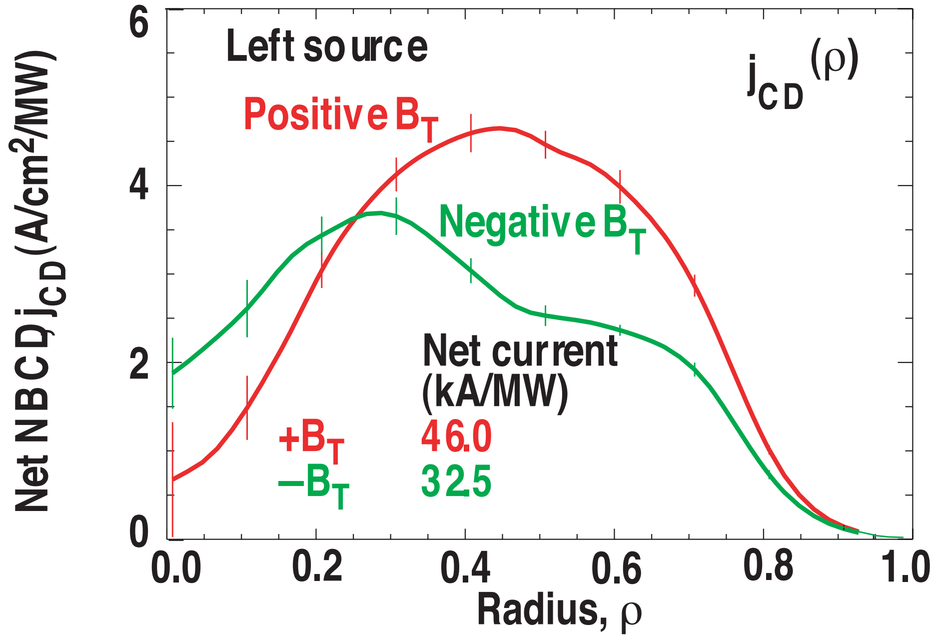
Net NBCD Should Include Reverse (Cancellation) Current Due to Passing Electrons (i.e., exclude Trapped Electrons), Resulting in a Large Difference Between the + B_T and – B_T





$$j_{CD} = j_f[1 - \frac{Z_f}{Z_{eff}}(1-G)] = j_f(1 - Z_f/Z_{eff}) + j_f G Z_f/Z_{eff}$$

$$F = j_{class}/j_f + GZ_f/Z_{eff}$$

$\Uparrow$

Beneficial to the off-axis NBCD

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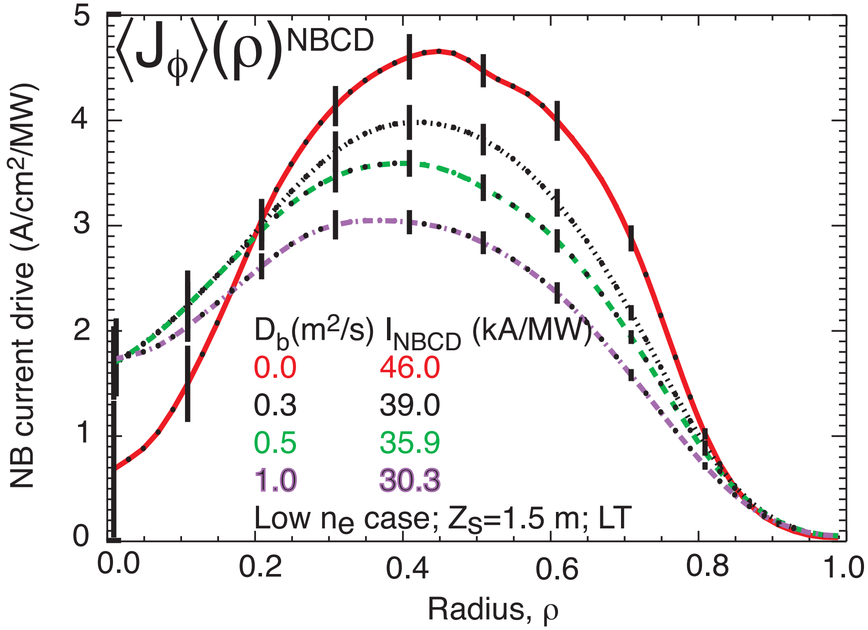
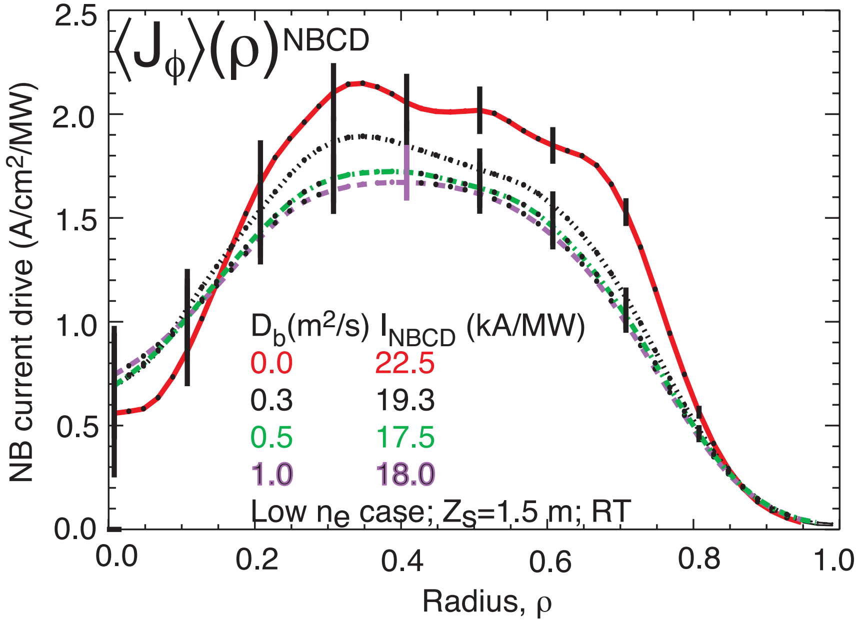
Q2: Effects Of Fast Ion Diffusion?

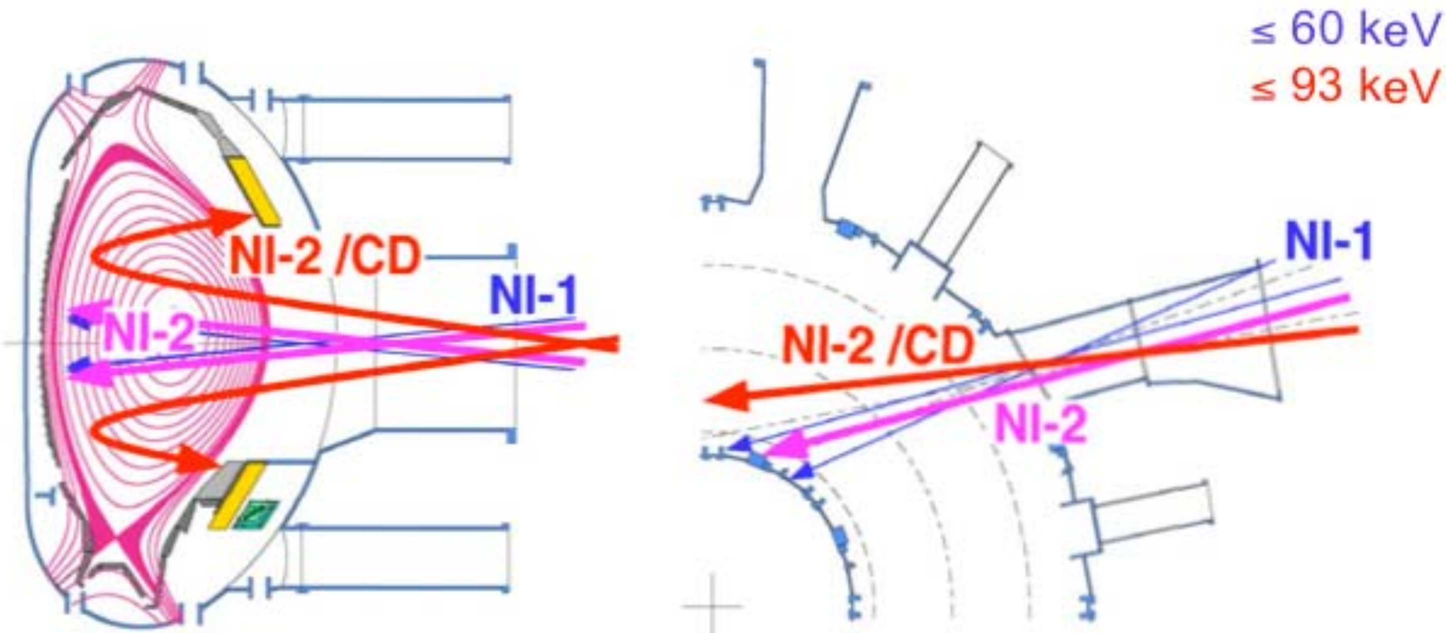
Fast Ion Diffusion Assumed (constant 0.5 m²/s) Does Not Wipe Out the Feature of Off-axis CD





Q3: What Are Situations of Off-Axis *NBCD* in Other Devices?

NBI current drive system on ASDEX Upgrade

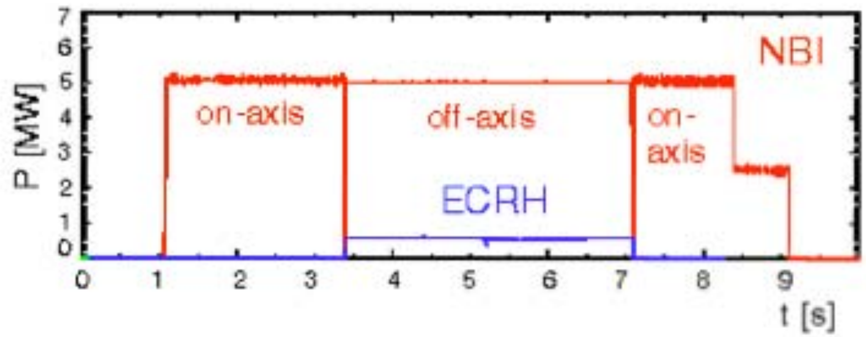


Re-direction of neutral beam injection system

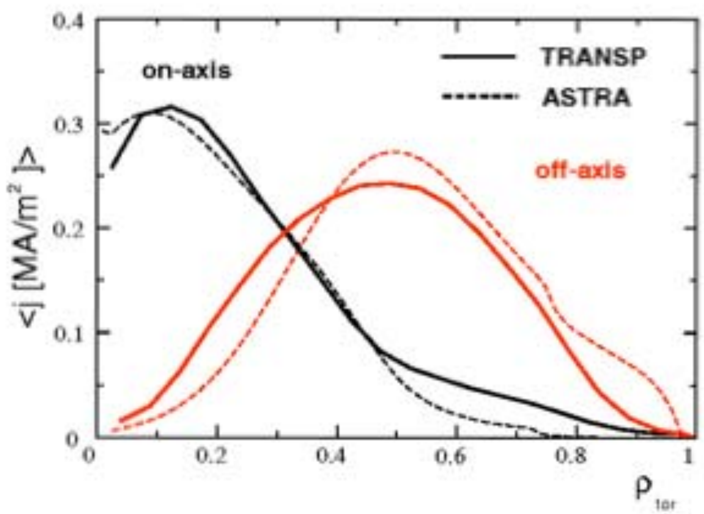
- strong off-axis deposition by tilt of injection angle
- significant current drive at half radius expected

NBI current drive experiments on ASDEX Upgrade

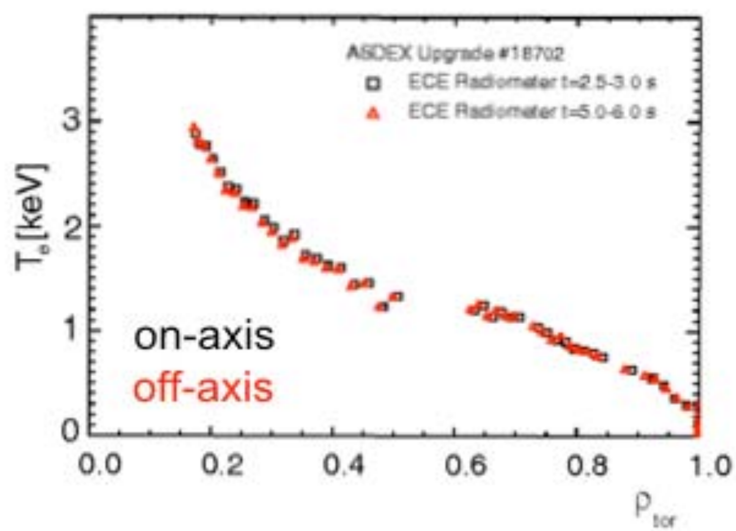
Switching experiments between on-and off-axis beams



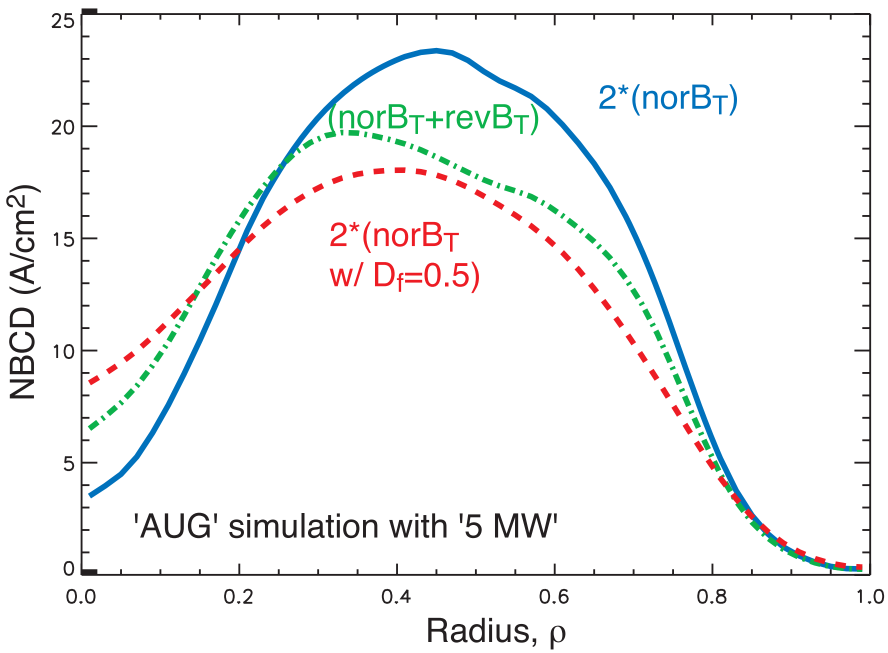
Predicted NBI current profile



Adjustment of T_e profile (ECRH)

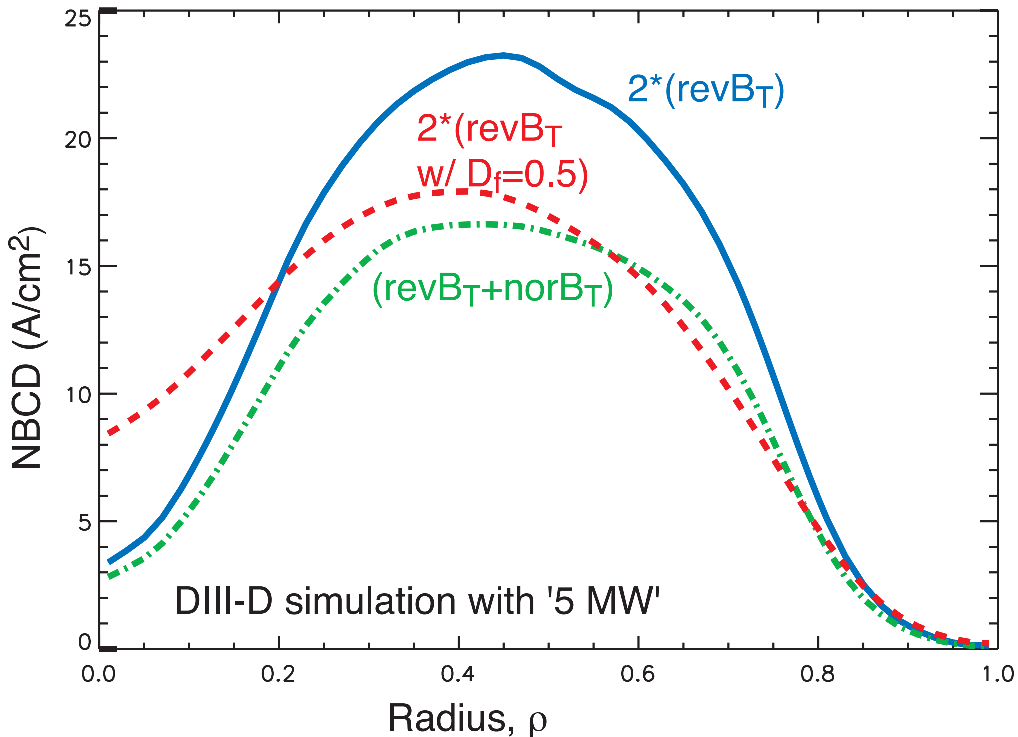


Alternative Explanation for the AUG off-axis NBCD Results



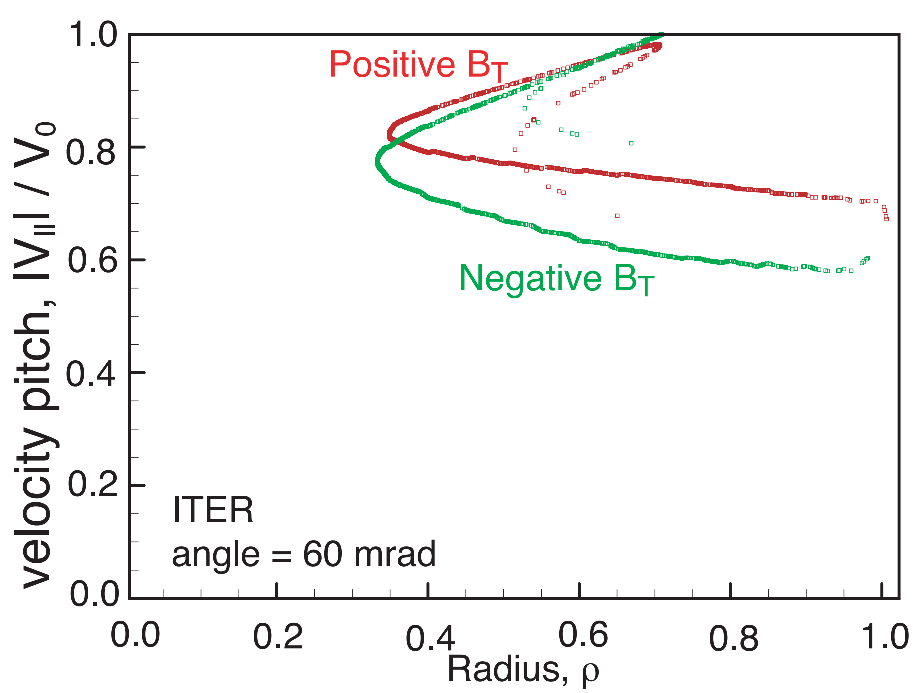
- **The AUG has a pair of upward and downward steered NB sources with operation in the negative B_T direction**
- The total NBI current is NOT expected to be twice the first one
- Although we need to do calculation for the AUG geometry, but we expect substantial central CD from the downward steered beam

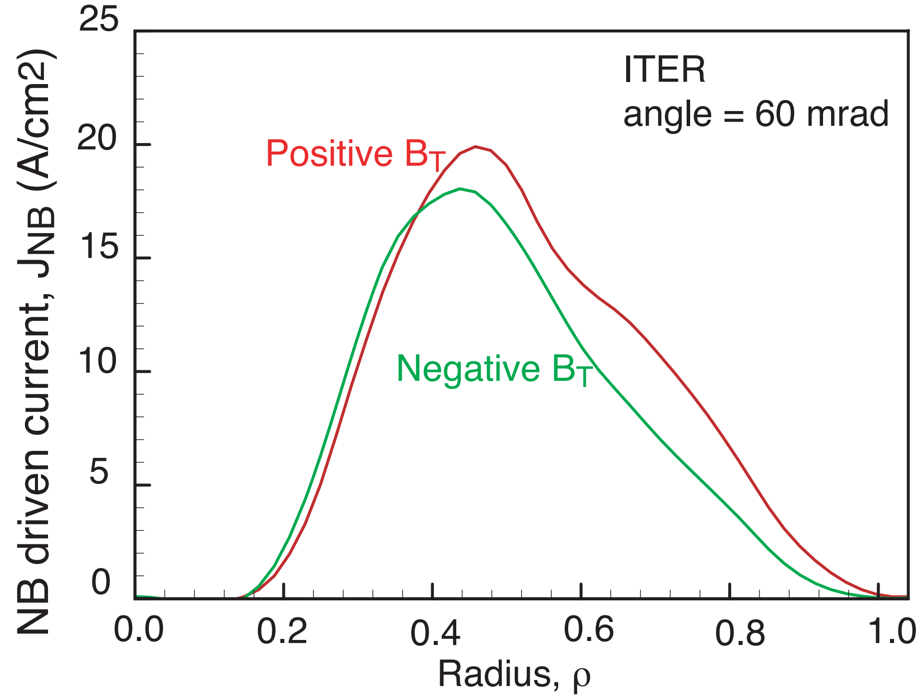
With two beamlines and vertical sources, we should be able to distinguish between the B_T direction and fast ion diffusion effects



- **We need some central CD by NBCD anyway**

Prospect for ITER off-axis NBCD





- **The ITER off-axis N-NBI operates with the downward steered sources (with a substantial offset of NBI port) in the $-B_T$ direction**
- **It appears to be a wrong direction, although the effect is relatively small for the maximum off-axis position that the present design allows (ρ = 0.4)**

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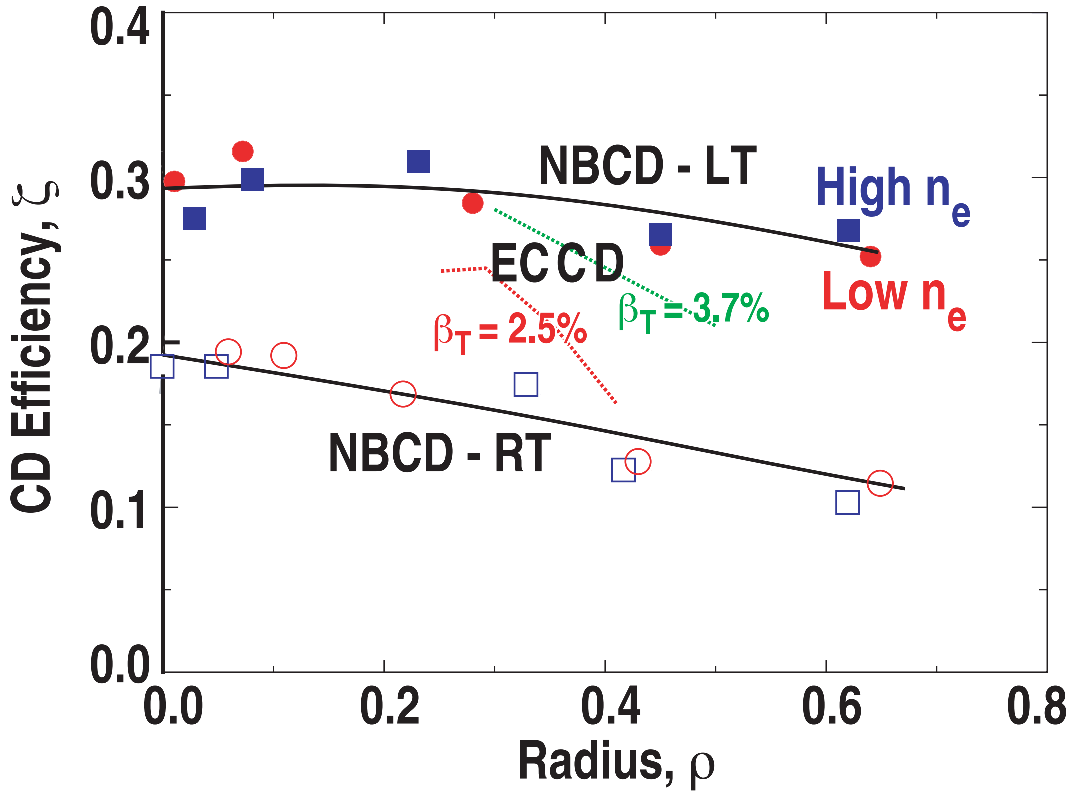
Q4: WHY IS OFF-AXIS *NBCD* SO GOOD OFF-AXIS?

Thanks to the trapped ELECTRON effects, the dimensionless NBCD efficiency does not decrease by going from on-axis to off-axis



$$\zeta = \frac{e^3}{\varepsilon_0^2}\frac{nI_{cd}R}{PT_e} = 33\frac{n(10^{20}m^{-3})I_{cd}(A)R(m)}{P(W)T_e(keV)}$$

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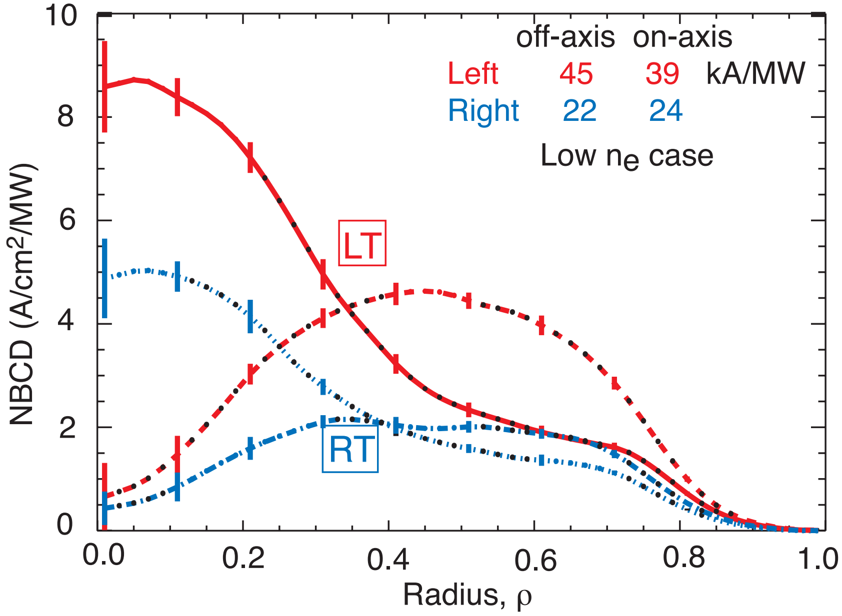
The off-axis NBCD is as efficient as (or even slightly better than) on-axis CD



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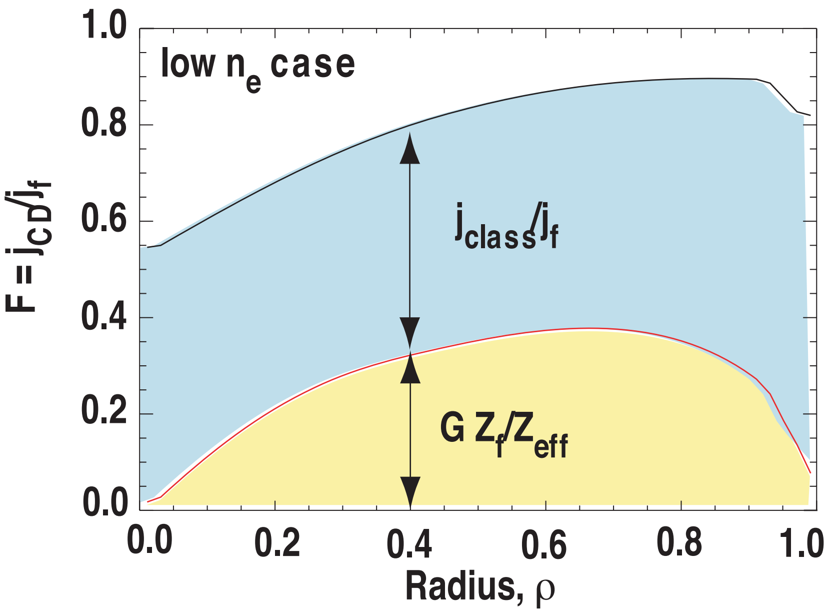
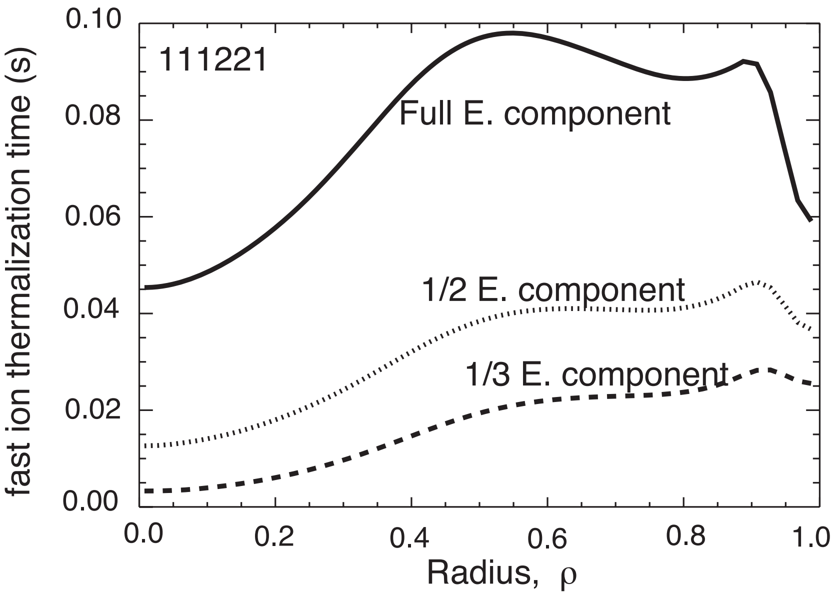
Why Off-Axis NBCD Is So Good Off-axis?





- **Electron trapping is good for NBCD, but bad for ECCD**
- **Plasma response to NBI is the same as bootstrap current (as pointed out by Lin-Liu)**

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STRATEGIES FOR *AT* SCENARIO DEVELOPMENT?

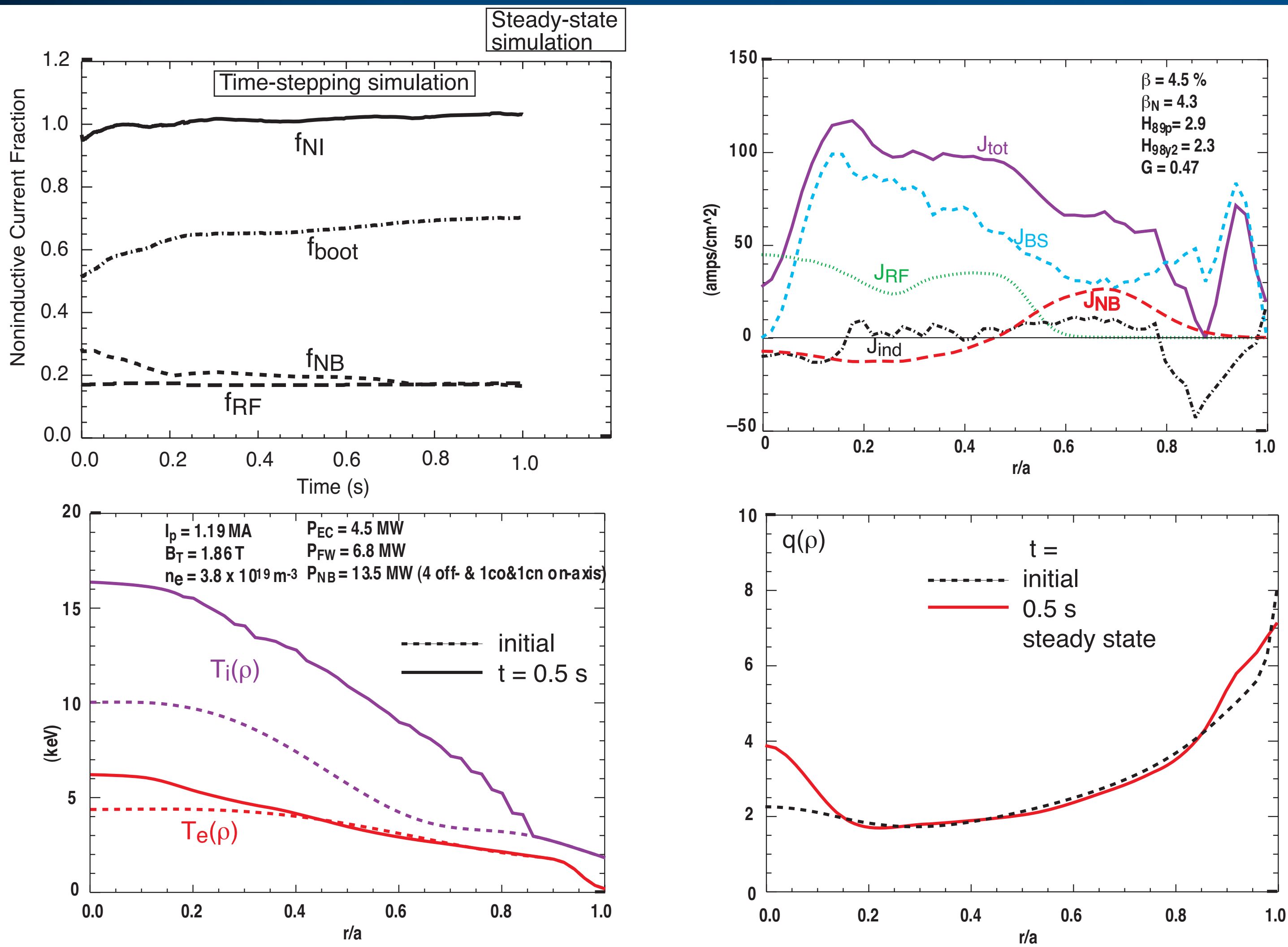
Possible Strategy for the AT Scenario Development in DIII-D Is to Use Both NBCD and ECCD Effectively

- AT scenario development involves trade-offs With NBCD, LHCD, and ECCD
- **ECCD** less efficient but location can be controlled in real time
- **NBCD** more efficient, but only amplitude control possible in real time
- **LHCD** is efficient, but for single-pass case damps at a given temperature, so little control of location

⇒ **Possible strategy:**

- **NBCD** to get most of off-axis CD needed
- **ECCD** to allow fine tuning of J and real-time control

Scenario simulations using off-axis NBCD in DIII-D



CONCLUSION

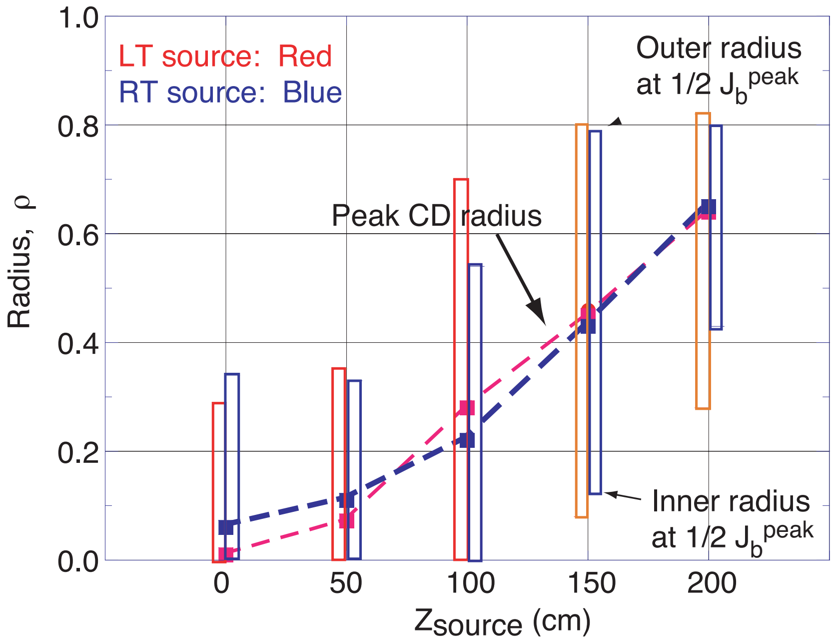
- **Modification to the present NB system is proposed to add flexible steering capabilities to allow raising the source end of the beamline by up to 2.0 m**

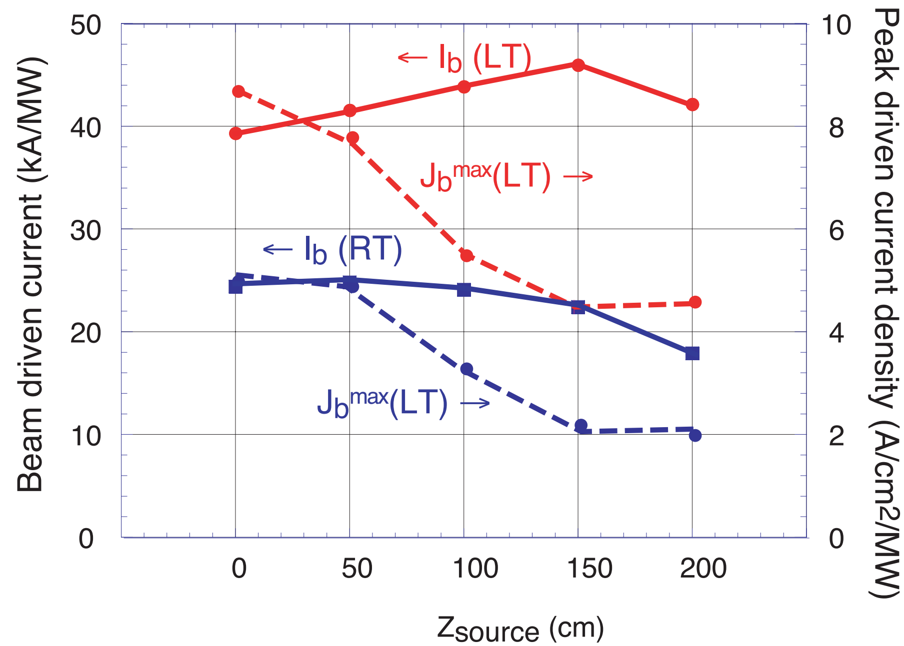
- **Off-axis NBCD calculated shows excellent CD efficiencies:**
  - Calculated off-axis CD ≈45 kA/MW at ρ = 0.5 with FWHM of 0.45
  - Normalized CD efficiency, ζ, comparable to or somewhat better than ECCD, and nearly constant in going from on-axis to off-axis

- **Localization of the off-axis NBCD is sensitive to alignment of the NB injection to the pitch of the magnetic field lines, and thus to the relative direction of the B_T and I_p**
  - Possible explanation for the AUG off-axis NBI results
  - Implication to ITER off-axis NBI design

- **A possible strategy for the AT scenario development is to use NBCD to get most of the off-axis CD needed and to use ECCD to allow fine tuning of current profiles and real-time control**
  - Explore AT scenario using off-axis NBCD

Although Peak Driven Current Density Decreases by X2 As Z_s = 0→1.5 m, the Net Integrated NBCD Actually Increases





- **LT sources are more efficient (~x2) than the RT sources**
- **The peak off-axis CD location and the FWHM for the RT sources are similar to those for the LT sources**

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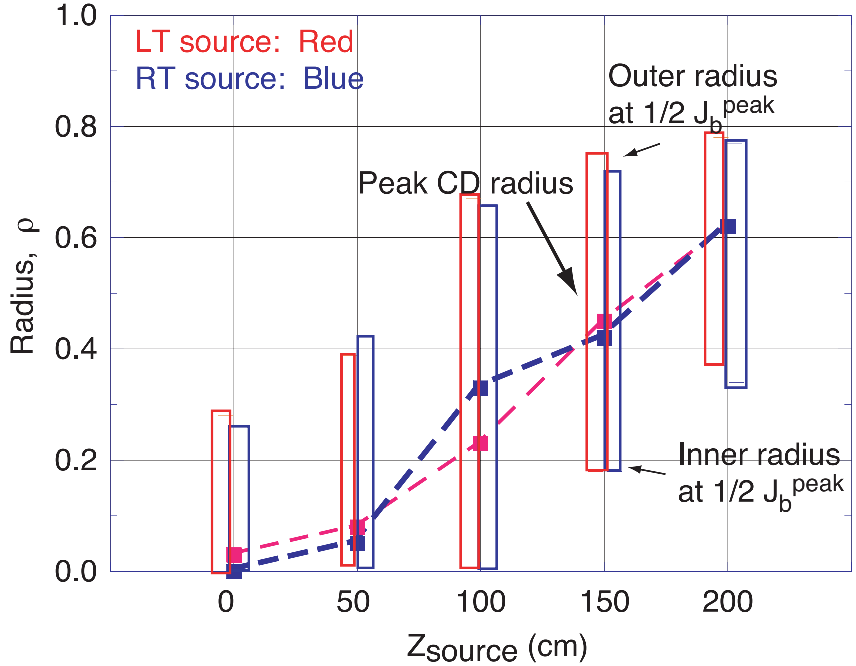
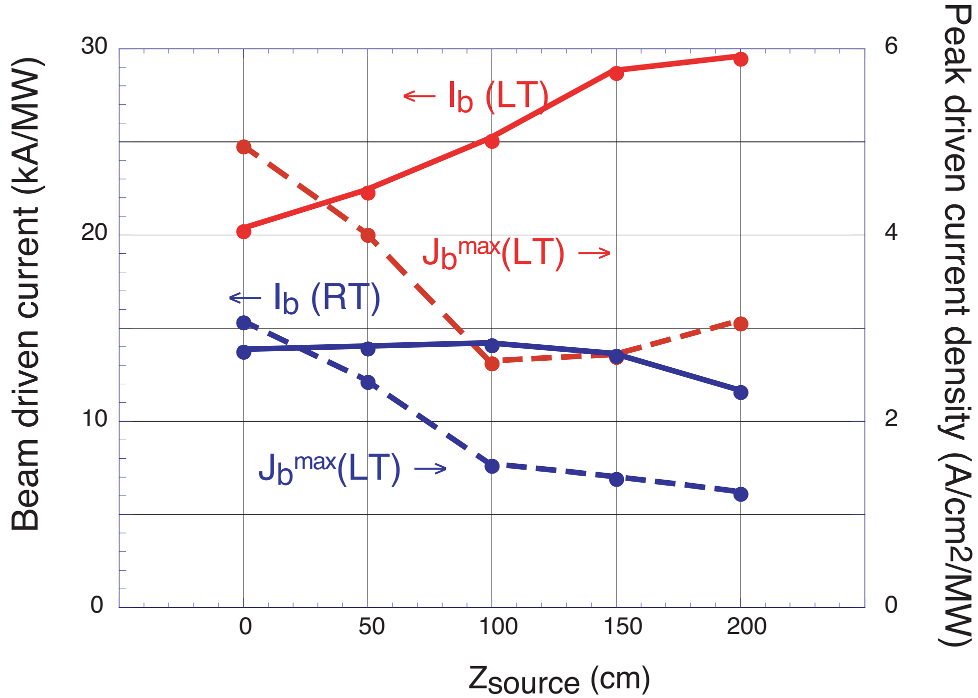
The Results of the High Density Cases Are Similar, With CD Peaked at ≈Same Location





- Beam penetration is not a critical factor for determining the current drive location in the range of densities expected for DIII-D AT operation
- Similar insensitivity obtained in beam voltage (90 kV to 45 kV) variations

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