Off-axis Neutral Beam Current Drive for Advanced Scenario Development in DIII-D

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Abstract. Modification of the two existing DIII-D neutral beam lines is proposed to allow vertical steering to provide off-axis neutral beam current drive (NBCD) as far off-axis as half the plasma radius. New calculations indicate very good current drive with good localization off-axis as long as the toroidal magnetic field, B_T, and the plasma current, I_p, are in the same direction (for a beam steered downward). The effects of helicity can be large: e.g., ITER off-axis NBCD can be increased by more than 20% if the B_T direction is reversed. This prediction has been tested by an off-axis NBCD experiment using reduced size plasmas that are vertically shifted with the existing NBI on DIII-D. The existence of off-axis NBCD is evident in sawtooth and internal inductance behavior. By shifting the plasma upward or downward, or by changing the sign of the toroidal field, measured off-axis NBCD profiles, determined from MSE data, are consistent with predicted differences (40%–45%) arising from the NBI orientation with respect to the magnetic field lines. Modification of the DIII-D NB system will strongly support scenario development for ITER and future tokamaks as well as providing flexible scientific tools for understanding transport, energetic particles and heating and current drive.

1. Introduction

Advanced Tokamak (AT) research [1,2] on DIII-D seeks to provide the scientific basis for steady-state, high-performance operation for ITER and future tokamak reactors. For steady-state operation, all of the plasma current must be driven noninductively (without a transformer). The leading approach to the steady-state scenario utilizes the “natural” profile of the bootstrap current [3], which results in a hollow current profile. Since the bootstrap current profile may not perfectly match the current profile needed for desirable fusion performance, a flexible, localized and efficient source of noninductive current is needed for control. Experimentally, such high-performance discharges have been developed; the duration of which, however, is usually limited by the evolution of the current profile to an unstable state [4,5]. Experimental measurements and simulations of these discharges have indicated that these discharges could be extended to near steady state if the current profile were maintained by replacing the remaining ohmic current (30%–40%) near the half radius with externally driven current [6]. The needed off-axis current can be supplied by electron cyclotron current drive (ECCD) or by neutral beam current drive (NBCD) in the co-direction (i.e., CD in the same direction as the plasma current). The "seed" axial current can be supplied by a relatively small amount of on-axis NBCD and/or fast wave current drive (FWCD).

The most expedient solution to get substantial broad off-axis CD in DIII-D is to modify two of the four NB lines to allow vertical steering to drive current as far off-axis as half the plasma radius. This capability should greatly increase the parameter space available for AT scenario development. However, experiments on ASDEX-U reported a lack of localization in off-axis NBI at high power (~5 MW) [7,8]. New calculations indicate very good CD with good localization off-axis as long as the toroidal field, B_T, and plasma current, I_p, are in the same direction (for a beam steered downward) [9]. The effects of the alignment of the neutral beam injection (NBI) relative to the magnetic field pitch can be large: e.g., on ITER [10], off-axis NBCD can be increased by 20% if the direction of B_T is reversed. This prediction has been tested successfully by off-axis NBCD experiments utilizing small cross-section plasmas that are vertically shifted; this places the peak deposition of the neutral beams near the mid-radius of the plasma. By shifting the plasma upwards or downwards, or by changing the sign of B_T, predicted differences in the off-axis NBCD profiles from injecting the beam ions parallel to or across the magnetic field lines have been successfully confirmed.

2. Evaluation of Off-Axis NBCD

DIII-D is equipped with four positive-ion source neutral beamlines with three co and one counter injection. Each beamline consists of two ion sources, which operate at the nominal parameters 81 keV, and inject about 2.5 MW deuterium neutral beam power into the torus. Each has two ion sources (48 cm high x 12 cm wide); the more tangential left (LT) source aimed at the tangency radius of 1.17 m and the less tangential right (RT) source at the radius of 0.74 m for the co-beamlines, while the tangency radius is reversed for the LT and RT source for the counter-beamline. The distance between the source and the intersection of the two beam optical axes at the midplane is 5.5 m [11].

Any modification of the present NBI to provide off-axis NBCD should be: (1) capable of generating a significant amount of off-axis ($\rho \approx 0.5$) CD with reasonable localization; (2) retain the present on-axis NBI capability; (3) minimize the extent of the modifications, e.g., by limiting to one degree of motion (vertical), and (4) applicable to a wide range of operating parameters (e.g., at higher density). We selected the oblique injection by raising the source end by up to 1.5 m (with the beamline optical axis inclined up to ≈15° downward through the midplane port) while retaining the present beamline components [12].

Orbit-following Monte-Carlo calculations were carried out using the NUBEAM module [13] in the TRANSP [14] and ONETWO [15] transport codes to evaluate the performance of the proposed off-axis NBCD system [9]. Two different discharge conditions were chosen from DIII-D AT experiments; a low density discharge (shot 111221) [6], line-average density $\bar{n}_e = 4.2\times10^{19}$ m^{-3}) with the toroidal magnetic field, B_T = 1.91 T, the plasma current, I_P = 1.19 MA, and the normalized beta, β_N = 3.4; a high density discharge (shot 122976) [16] ($\bar{n}_e = 6.2\times10^{19}$ m^{-3}) with B_T = 1.74 T, I_P = 1.34 MA, and β_N = 4.0. Figure 1 shows the calculated profiles of off-axis NBCD for the low density case for the left and right sources. The peak CD location moves off-axis from $\rho = 0$ to 0.45 as the beamline source height (Z_s) is raised by 1.5 m. Although the peak driven current density decreases by about a factor 2 when Z_s is increased from 0 to 1.5 m, the net NB driven current stays constant or somewhat increases. Both the peak and total driven current values are about a factor of 2 higher for the more tangential left source, with similar dependences on Z_s.

The characteristics of off-axis NBCD depend on alignment of beam and magnetic field line. For the co-injection case (and thus, I_P in the positive direction), the beam from the left source in the positive toroidal field (B_T) direction yields the most favorable performance. Figure 2 shows NBCD profiles for the positive and negative B_T directions. In fact, the off-axis CD character and high efficiency are significantly lost for the negative B_T direction.

Here the sign conventions for B_T and I_P are the positive direction is counter clock-wise looking from the top.

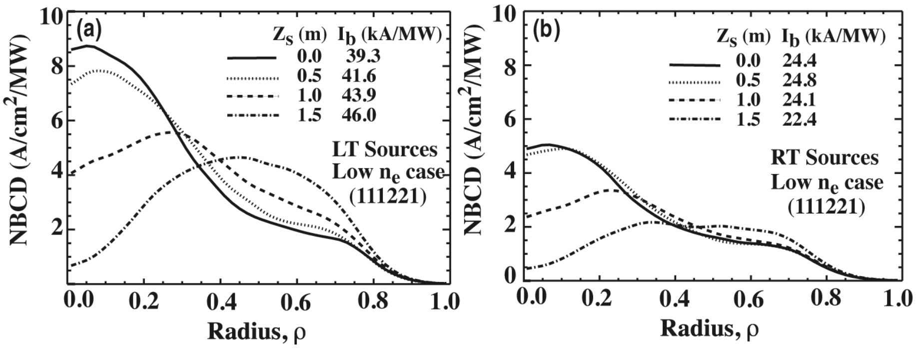

FIG. 1. Calculated off-axis NBCD with different steering angles for low-density (a) left beam, and (b) right beam.

The downward steered beam is aligned better with the magnetic field line pitch in the positive B_T direction than that in the negative B_T (Fig. 3). Therefore the beam ions in the positive B_T direction stay in passing particle orbits, achieving well-localized off-axis CD. The same beam, but with B_T in the negative direction, has a larger pitch angle difference, causing more trapped particle orbits, reducing the parallel ion current off-axis. In addition, the drift surface of the passing particles shift outward (inward) in major radius for the positive (negative) B_T direction, and this contributes fast ion current. Figure 4 shows illustrative examples of early slowing down ("prompt") orbits for two beam ions. Trapped particles whose guiding center passes through the vicinity of the magnetic axis have large banana width, causing more fast ion density near the axis, as seen in Fig. 4(a). A qualitative examination of the CD process confirmed the effect of the reversal of the toroidal field direction, as discussed in Ref. [9].

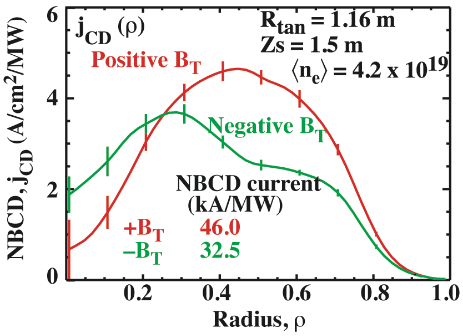

FIG. 2. NBCD profiles for the positive (red) and negative (green) B_T direction with the LT source only.

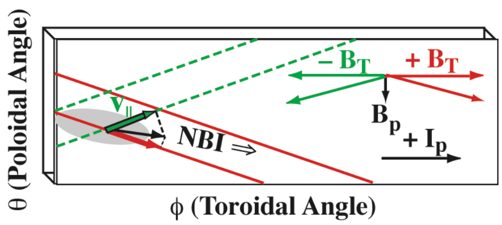

FIG. 3. Beam injection parallel to or slightly across the magnetic field line, depending on the positive (red) and negative (green) toroidal field direction.

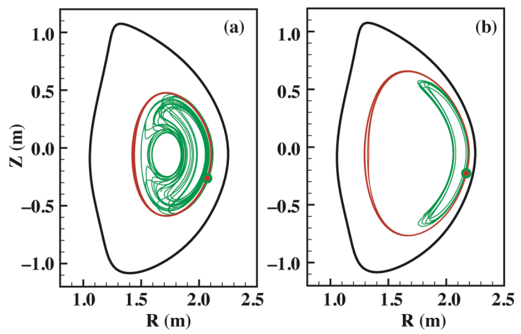

FIG. 4. Examples of prompt orbits for + (red) and – (green) B_T at two birth locations.

3. Prototype Off-Axis NBCD Experiment

To validate the theoretical model, a prototype off-axis NBCD experiment was conducted with specific objectives: (1) to demonstrate the existence of off-axis NBCD; (2) to examine the classical magnetic field alignment effects; and (3) to study effects of anomalous fast ion transport on off-axis NBCD. Off-axis NBCD could be achieved with the existing DIII-D NB geometry by utilizing small-size plasmas that are vertically shifted, placing the peak deposition of the neutral beams near the half-radius of the plasma. Shifting the plasma upwards or downwards, or changing the sign of B_T (Fig. 5), predicted differences arising from the magnetic field alignment effect could be tested. DIII-D has an excellent diagnostic set for studying off-axis NBCD, including motional Stark effect (MSE) polarimetry [17] to measure the driven current profile and multiple fast ion D_α (FIDA) spectroscopy [18] and 2-D FIDA imaging system [19] to measure the beam ion density profiles. The challenge is to get consistent analysis results among various analysis methods, especially to minimize unavoidable uncertainties due to limited diagnostic data inside $\rho \approx 0.4$ when the plasma is vertically shifted. For this reason, each vertically shifted phase was followed by a swift (within 50 ms) shift back to the midplane. Further experimental details will be discussed in Ref. [20].

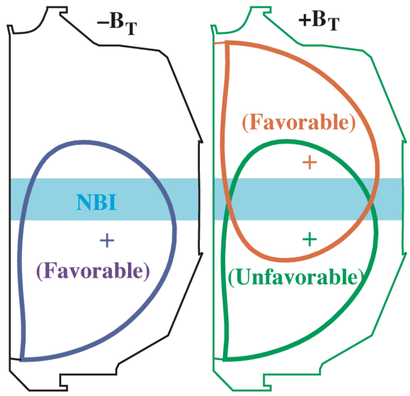

FIG. 5. Prototype off-axis NBCD experiment, mimicking the magnetic alignment effect by changing B_T or vertical shifting (resulting in reversing the poloidal field (B_p) direction).

The global behavior of vertically shifted plasmas with off-axis NBI is consistent with the existence of off-axis CD that increases with co-NB power. In the down-shifted plasma with high enough power in the positive B_T direction, sawteeth were absent in soft x-ray and ECE data, and reappeared well after shifting to on-axis NBI. The internal inductance decreased with increasing power in off-axis NBCD geometry, as expected.

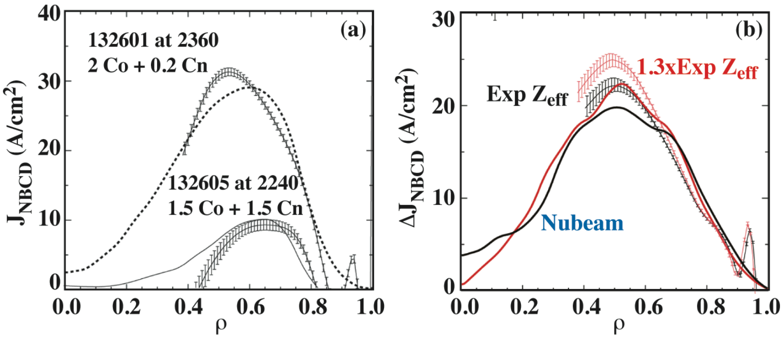

FIG. 6. (a) NBCD analysis for co and balanced NBI discharges, (b) difference in NBCD profiles for co and balanced injection for the shift down with $-B_T$ case. The curves with error bars are measurements and the curves without error bars are modeling.

Measured off-axis NBCD is in good agreement with theoretical predictions. The CD profile analysis benefited from differential NBCD analysis using loop voltage and MSE analysis [21,22] for two discharges with co and balanced NBI with similar β. The systematic sources of error (e.g., Z_{eff}) tend to cancel out in the analysis [Fig. 6(b)]. Including the residual CD in the balanced beam discharge, significantly greater (by ~40%) NBCD was found in cases where favorable alignment was obtained (upward-shifted positive B_T and downward-shifted negative B_T) compared with unfavorable alignment (downward-shifted positive B_T), as shown in the NBCD profiles [Fig. 7(a)] and the surface integrated (over ρ=0.4–1.0) values [Fig. 7(b)].

The MSE pitch angle measurements are in good agreement with MSE signals predicted by TRANSP simulations (Fig. 8). In MSE analysis and simulations, systematic offset errors in the calibration in the individual channels were adjusted to agree with calculated pitch angles including the radial

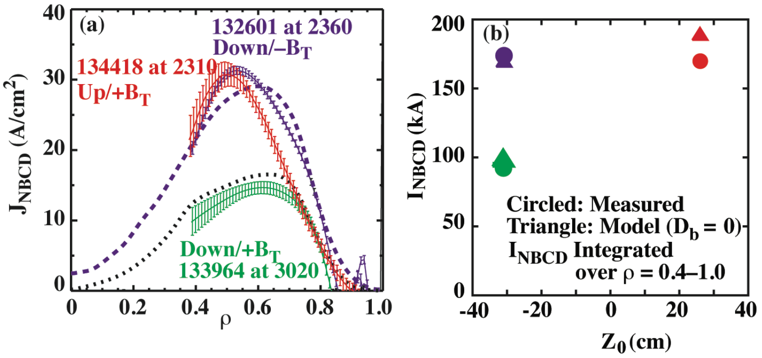

FIG. 7. NBCD (a) profiles [measurements and modeling (dashed)] and (b) integrated current as a function of vertical shift for three different configurations.

electric field (E_r) effects based on the force balance calculation at an early time in another shot. MSE simulations reproduce the MSE signals throughout the discharges, including the large excursion of the vertical shift back to the midplane. Agreement was best with MSE simulations with no fast ion diffusion assumed.

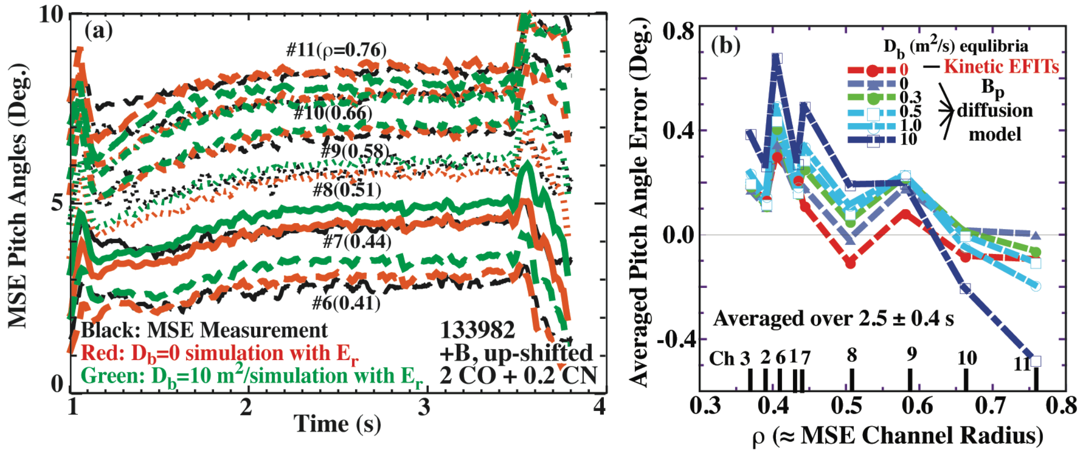

FIG. 8. Comparison between MSE measurement and simulated signals, and errors averaged over 400 ms for different fast ion assumptions.

4. Optimizing Off-Axis NBCD in Tokamaks

We examine in more detail how the pitch angle affects NBCD in the present experiment, and then implications for NBCD in other tokamaks including ITER.

The large difference between favorable and unfavorable magnetic geometry are due primarily to two causes [9]: (a) difference in fast ion trapping fraction, and (b) reduction in electron cancellation current due to trapped electrons. The difference in the magnetic pitch and NB injection direction in the unfavorable geometry substantially increases the ion banana fraction ($f_{i,trap}$) at the mid-radius as seen in Fig. 9(a). As slowing down and pitch angle scattering occur, the difference in $f_{i,trap}$ settles down to ≈10% [Fig. 9(b)], affecting the fast ion current source. Passing fast ions can more effectively build up fast ion current as they circulate repeatedly around the torus than the trapped particle can [23]. Thus, there is substantial difference in fast ion sources [Fig. 9(c)]. The net NBCD should include reverse (cancellation) current due to passing electrons (but not trapped electrons) [24] as shown in Fig. 9(b). Since the electron trapped particle fraction increases with radius, the cancellation electron current decreased with radius, resulting in amplifying the difference in the net NBCD between the favorable and unfavorable configuration. In the favorable configuration, the NBCD efficiency does not decrease with radius. This is not the case for ECCD in which the radial increase in trapped electron population is detrimental.

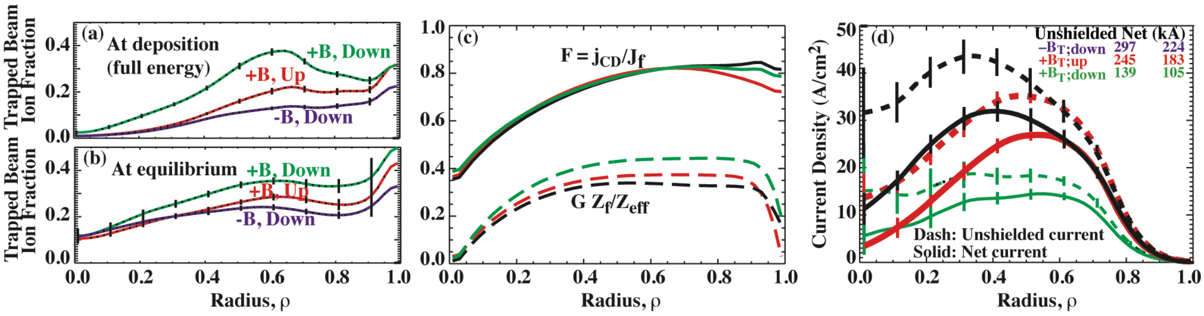

FIG. 9. Reasons of improved CD efficiency off-axis for the three cases shown in Fig. 7: fast ion trapping fraction (a) at deposition and (b) at equilibrium; (c) profile of the shielding factor, consisting of classical contribution and trapped electron contribution; and (d) profiles of the unshielded fast ion current and net NBCD.

Figure 10 shows the dimensionless CD efficiency as a function of the peak CD location. The dimensionless CD efficiency is defined as [25]

$$\xi = \frac{e^3}{\varepsilon_0^2}\left(\frac{IRn_e}{PkT_e}\right) = 33\frac{I(\mathrm{A})R(\mathrm{m})n_e(10^{20}\mathrm{m}^{-3})}{P(\mathrm{W})T_e(\mathrm{keV})} \quad . \tag{1}$$

The ECCD efficiencies are calculated for the profiles of the two discharges using the TORAY-GA code [26]. As expected, the ECCD efficiency is higher for the higher β discharge, but the applicable radial range is narrower due to refraction near the high density cut-off, as shown in Fig. 10. In comparison with the ECCD efficiency, the off-axis NBCD efficiency is somewhat better under the same conditions. Equally important is the fact that it does not decrease as much with radius. The normalized efficiencies of the prototype off-axis NBCD experiment are also shown in the figure.

There are differences between optimization of off-axis NBCD and optimization of fast ion confinement. Even though it is important to improve fast ion confinement which improves the fast ion source term, there are two additional specific requirements for off-axis CD: (a) retaining good off-axis CD localization, and (b) good shielding factor (F = net NBCD/fast ion current). Because of these requirements, it is desirable to operate the B_T/I_P direction such that the guiding center orbit shifting outward to retain off-axis localization (with passing fast ions) and to benefit the radially increasing shielding factor (due to increasing trapped electron fraction). This involves the operation opposite to the optimal fast ion confinement (with the guiding center orbit shifting inward).

Fast ion diffusion places off-axis particles toward the axis, which is similar to the geometry effect of the wrong B_T direction. More analysis of the data is needed to examine the geometry and fast ion diffusion effects in the above experiment. Modeling with an ad-hoc diffusion model shows (Fig. 11) that to first approximation, integrated current decreases a similar fraction for both the favorable and unfavorable case, retaining the off-axis peaking even with anomaly. As for the application to AT plasmas, the effect of a modest amount of fast ion diffusion is not severe.

The magnetic alignment effects are important to interpret off-axis NBCD experiments in tokamaks. AUG, JT60-U and JET all have pairs of upward and downward steered NB sources. Based on the above arguments, only one source out of the pair can produce well-localized off-axis NBCD, while the other source produces more diffused NBCD, depending on the relative directions of I_P and B_T. In the DIII-D case, all sources in the two proposed beamlines are downward steered. DIII-D has sufficient flexibility to choose the I_P and B_T direction to optimize off-axis NBCD.

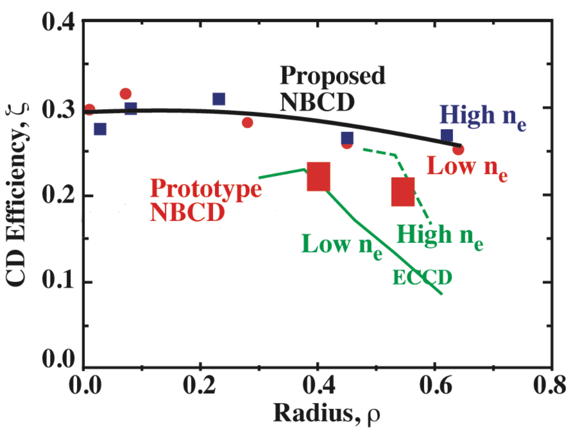

FIG. 10. Dimensionless CD efficiencies for the proposed off-axis NBCD (small symbols) and the present off-axis NBCD experiment (large symbols) and off-axis ECCD (green lines) as functions of peak CD radius on DIII-D.

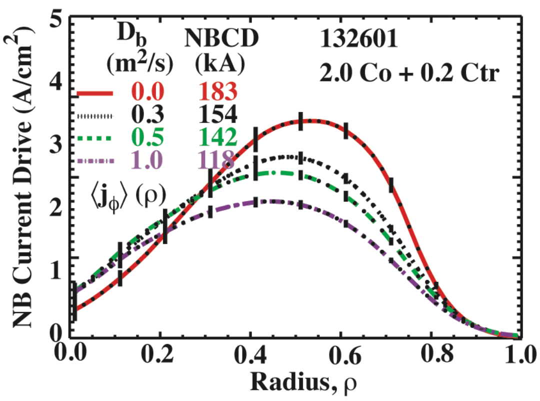

FIG. 11. Effects of ad-hoc anomalous fast ion diffusion on off-axis NBCD.

ITER will have an off-axis NB system, planned with downward steering of the beams and an offset between the mid-plane injection port and the plasma vertical position. Because of the shallow steering (up to 3.4 deg), the geometry effects come primarily from the ∇B drift shifting the orbits of the high energy beam particles outward. Since ITER operates with both the B_T and I_P direction opposite to DIII-D's favorable direction, the downward steered beam in the planned configuration is less favorable for off-axis NBCD. Figure 12 shows the NBCD profiles for the counter-clockwise (CCW) B_T direction as well as the clockwise (CW) B_T direction in ITER for the maximum steering (downward angle of 2.981 deg) in the recent (2007) design [24]. The latter (CW) B_T direction, which is not allowed operationally, has a larger peak CD radius (0.1 in ρ) with a larger driven current (23%). Since the steady state scenario requires the largest possible CD and the NB is the largest CD source, it is highly desirable to operate B_T in the CW direction.

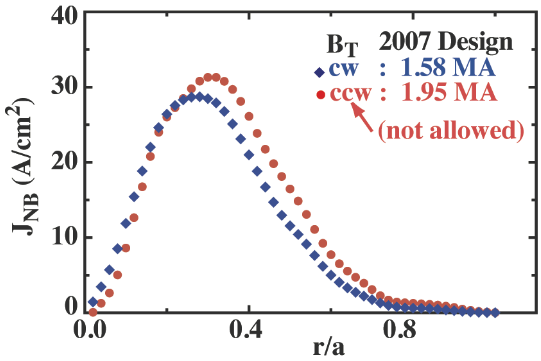

FIG. 12. Calculated off-axis NBCD for both CCW and CW (planned) B_T direction in the 2007 design.

5. Scenario Development Using the Off-axis NBCD in DIII-D

The main focus for steady-state scenario development in DIII-D is the demonstration of fully noninductive current sustainment for the current relaxation time, $\tau_R > 2$ s, at progressively higher pressures to meet the requirements of ITER and future tokamak reactors. DIII-D experiments have demonstrated stationary performance for slightly longer than τ_R at the normalized fusion performance, G=0.3, which is sufficient to meet the ITER physics objective for steady-state operation, for a lower B_T (1.8 T) [6]. Demonstration at higher B_T (2.2 T) for the future tokamak reactors requires a significant increase in power to drive off-axis current, which could be supplied by additional ECCD, or, alternately, off-axis NBCD using vertical steering. In scenario modeling of the B_T = +1.8 T case using the hardware proposed, the combination of off-axis NBCD (10 MW off-axis together with 5 MW on-axis) and high-power ECCD (4.5 MW) leads to a fully noninductive high-β scenario with flat $q(\rho)$ above 2 (Fig. 13). Off-axis NBI provides a broad CD needed at mid-radius that would not be possible with on-axis NBI alone (15 MW total) without over driving the current near the axis. High power ECCD affords tailoring the current profile for better stability and transport control. These scenario simulations were carried out with scaled experimental transport and a theory-based transport (GLF23) model in the ONETWO transport code.

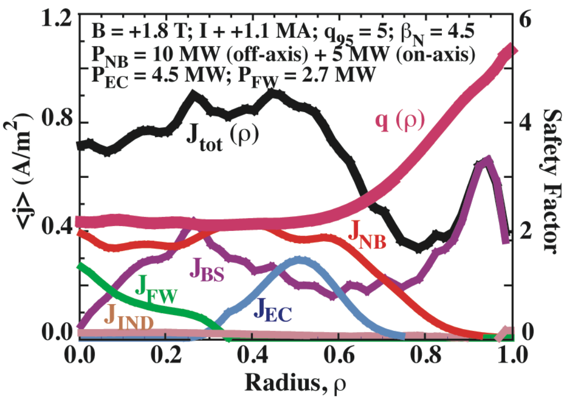

FIG. 13. Profiles of current components and safety factor in a self-consistent GLF-23 simulation using off-axis NBCD for ITER steady-state Demo shot in DIII-D.

6. Conclusion

The prospect for off-axis NBCD in DIII-D to supply a substantial amount of off-axis current drive needed for development of steady state, advanced tokamak scenarios has been studied.

Sensitivity of the magnitude of off-axis NBCD to the beam injection relative to the magnetic pitch has been validated in the DIII-D prototype experiment. The effect is large: ITER off-axis NBCD can be increased by 20% if the direction of B_T is reversed. Therefore, it is desirable to have the capability of operating the desired direction. Modification of the DIII-D NB system will strongly support scenario development for ITER and future tokamak reactors and will provide flexible scientific tools for understanding transport, energetic particles, heating and CD physics.

Acknowledgments

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