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GENERAL ATOMICS

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ABSTRACT

DIII-D experiments on neutral beam current drive (NBCD) using the new tilted beamline have clearly demonstrated off-axis NBCD as expected from modeling, alleviating concerns of NBCD loss due to microturbulence. The local NBCD profile was measured in H-mode plasma and compared with modeling under a range of beam injection and discharge conditions. The full radial profile of NBCD measured by the magnetic pitch angles from the motional Stark effect (MSE) diagnostic shows a clear hollow NBCD with the peak NBCD location at ρ~0.45, which is in good agreement with the classical model calculation using the Monte-Carlo beam ion slowing down code, NUBEAM. Time evolution of the MSE signals is consistent with transport simulation with modeled current drive sources. The beam-stored energy estimated by equilibrium reconstruction and neutron data do not show any noticeable anomalous losses of NBCD and fast ions. The measured magnitude of off-axis NBCD is very sensitive to the toroidal magnetic field (B_T) direction that modifies the alignment of the off-axis beam injection to the local helical pitch of the magnetic field lines. The NBCD profile for the B_T direction in poor alignment shows substantially reduced NBCD (~45%) as well as inward shift of the peak NBCD location ($\Delta\rho$~0.1). This dependency of the off-axis NBCD efficiency on the B_T direction is crucial to optimum use of the off-axis beams not only for DIII-D but also for ITER. Detailed NB and Electron Cyclotron Heating (ECH) power scans to vary the ratio of beam injection energy to electron temperature (E_b/T_e) at fixed β and vary β at fixed E_b/T_e, around the anticipated ITER parameters, imply that ITER is not likely to suffer from loss of NBCD efficiency due to additional transport from microturbulence.

1. INTRODUCTION

Two of the eight neutral beam sources in DIII-D have been modified for downward vertical steering to provide significant off-axis current drive for Advanced Tokamak (AT) scenario development [1]. Off-axis current drive is critical in testing the potential of high bootstrap fraction, steady-state operation with broad current and pressure profiles at elevated q, especially for the minimum of q (q_{min}) > 2 [2,3]. A previous experiment using vertically shifted small plasmas [4] with the beams injected to the mid-plane to move current off-axis indicates that the efficiency of off-axis NBCD is as good as on-axis NBCD because the increased fraction of trapped electrons reduces the electron shielding of the injected ion current, in contrast with electron current drive schemes where the trapping of electrons degrades the efficiency. The magnitude of off-axis NBCD is very sensitive to the toroidal magnetic field direction due to a change of the beam injection alignment relative to the local helical pitch of the magnetic field lines [5]. The measured off-axis NBCD increases approximately linearly with the injection power, although a modest amount of fast ion diffusion is needed to explain an observed difference in the NBCD profile between the measurement and calculation at high injection power P_{NB} > 7 MW [4,6]. Although the previous experiments using vertically shifted small plasmas demonstrated robust off-axis NBCD, the diagnostic coverage was limited to determine a full range of the NBCD profile from the off-axis injection and its hollowness.

This paper describes experiments on DIII-D evaluating on- and off-axis neutral beam current drive (NBCD) in greater detail using the new tilted beamline to establish the physics basis for the off-axis NBCD and to develop predictive modeling capabilities to estimate the range of applicability, which is particularly important for steady state mission.

2. OFF-AXIS NBCD MEASUREMENT

The off-axis NBCD profiles are measured in H-mode plasma with an upper-biased double null shape shown in Fig. 1, as used in AT discharges for steady state scenario development in DIII-D [2]. Typical parameters for the experiment are major radius R = 1.7 m, minor radius a = 0.6 m, elongation κ = 1.77, upper triangularity δ = 0.6, toroidal magnetic field strength B_T = +2.0 T, and plasma current I_p = +0.9 MA. The positive direction of B_T is used for the experiment described in this section for better alignment of NBI to local B_T that is known to allow good NBCD efficiency from the previous modeling and experiment [4,5]. Here, the sign conventions for B_T and I_p are that the positive direction is counterclockwise looking down from above. The off-axis beams are injected in the direction of the plasma current. Injection of the beams at the off-axis mid-radius target (ρ~0.5, where ρ is the normalized minor radius proportional to the square root of the toroidal flux) requires a combination of both beamline vertical tilt and ion source tilt. Maximum tilting of the beamline and ion source is used at 16.5 deg and 35 min, respectively to aim the beams downward low enough to reach the off-axis target.

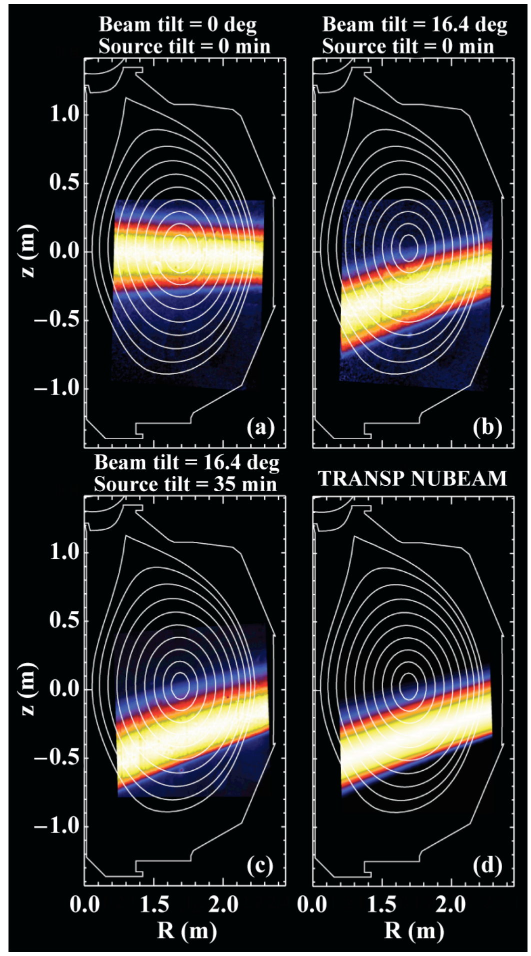

FIG. 1. D_α image of off-axis beam injection into neutral deuterium gas depending on beamline and source tilt (a), (b), (c). Comparison with NUBEAM modeling is shown in (d) for the case of maximum tilt (c). Equilibrium flux surfaces with the plasma shape used in NBCD measurement are plotted for reference.

For comparison with modeling, the Monte-Carlo beam ion slowing down code, NUBEAM [7] has been used with an improved description of beam injection that takes into account the beam ion scraping-off at the collimators inside the beamline as well as at the port box. Figure 1 shows fast framing camera images of D_α emission during beam into neutral deuterium gas injection [8,9] for a range of beamline and source tilts. These images yield the beam vertical profile as well as verify beam trajectories relative to design values. With no beam or source tilt, the off-axis beamline functions as the other on-axis co-sources. As the beam and source are tilted, the centerline trajectory moves lower as expected. From Fig. 1(c), it is clear that a small amount of clipping occurs on the lower portion of the beam when the beam is tilted downward. The clipped beam particles are lost to both the internal collimators and the port box.

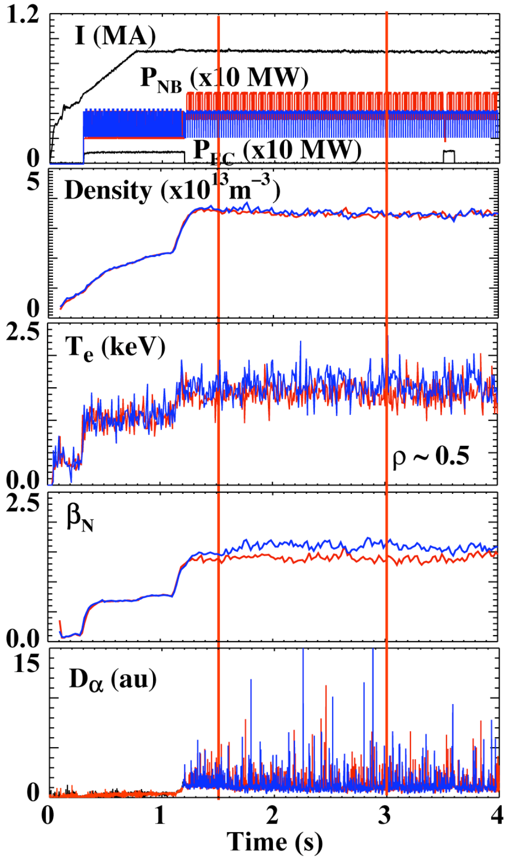

FIG. 2. Time trace of typical plasma parameters to compare two similar discharges without (blue) and with (red) off-axis injection.

The lost power estimated from the modeling is ~10% of the total source power when the beam is tilted at its maximum angle. Figure 1(d) shows the results of TRANSP/NUBEAM modeling with the source geometry taken from engineering drawings and a vertical divergence adjusted to best match the experimental beam profiles. The ion source is described by four individual rectangular sources to represent a strongly focused ion source as newly built in the off-axis beams [1]. The TRANSP/NUBEAM model reproduces well the measured vertical beam profile, steering, and clipping throughout the entire tilt range.

To validate off-axis NBCD physics in great detail, we compare two discharges primarily with on- and off-axis NBCD in otherwise similar conditions to reduce model dependencies and systematic uncertainties of measurements. The time evolution of the main plasma parameters for such a pair of discharges is illustrated in Fig. 2. For the period of current drive analysis ($t > 1.5$ s), both discharges are maintained without any large-scale MHD activity (for example, Alfvén eigenmodes, sawteeth) except for edge localized modes (ELMs). The electron density (n_e) and temperature (T_e) are kept the same in both cases by adjusting the beam power for the on-axis injection case. Diagnostic beams for the motional Stark effect (MSE) polarimetry, fast ion D_α, and charge exchange recombination (CER) are imposed on top of the current drive beams in a form of balanced (co- and counter-) injection. For off-axis injection, a substantial change is observed in magnetic pitch angles measured by the MSE diagnostic when compared to the on-axis injection at the same n_e and T_e (as shown in Fig. 3). Since the plasma conductivity is the same from the beginning to the end of the discharge in both cases, any change of current profile evolution should result from the NBCD difference. The plasma current profile directly determined by the MSE signals [10] shows a definite broadening of the plasma current for off-axis injection, indicating clear evidence of off-axis NBCD. The radial profile of total pressure determined by the equilibrium reconstruction is also broader for off-axis injection. Dedicated fast-ion D_α (FIDA) measurement in MHD-quiescent L-mode plasmas also show an off-axis peak in the fast ion profile for off-axis injection [11].

The time evolution of MSE signals is consistent with the off-axis NBCD predicted by NUBEAM without anomalous transport effects. In Fig. 4, the measured MSE signals are compared at different radii with the signals calculated by the coupled transport-equilibrium simulation of the poloidal flux evolution with realistic current drive sources using ONTWO [12], EFIT [13] and NUBEAM [7]. Good agreement is found between the measured pitch angles and those from simulations. If the expected off-axis NBCD is not included, the simulations deviate significantly from measured signals.

The beam-stored energy estimated by equilibrium reconstruction does not show any noticeable anomalous losses of NBCD and fast ions, while neutron data deviates from the simulation. The thermal pressure p_{th} from the n_e, T_e, T_i, and carbon density measurements is subtracted from the total pressure p_{Tot} from MSE equilibrium reconstruction to obtain the fast ion pressure profile p_f, which is consistent with NUBEAM modeling. Separate measurement was also made to check the confinement of off-axis beam ions [11]. Short beam blips into MHD quiescent Ohmic plasmas yield measurements of the number of injected confined beam ions (from rise of neutron emission) and collisional slowing down of beam ions (from neutron rate decay). For off-axis injection, the decay of the neutron rate is in good agreement with the classical beam ion slowing down calculation, but the magnitude of the initial rise is smaller than predicted.

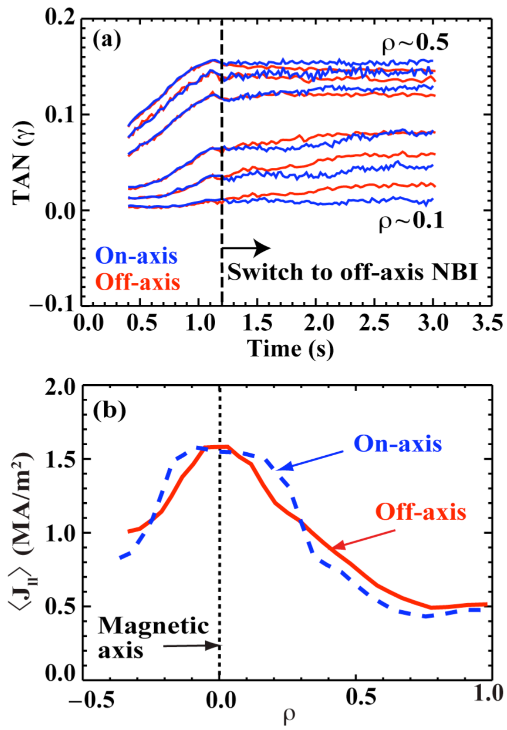

FIG. 3. Comparison of (a) time evolution of MSE signals and (b) plasma current density between on (blue) and off (red) axis injection.

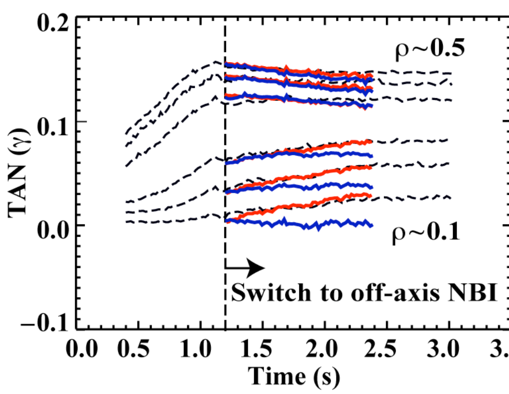

FIG. 4. Comparison of measured (dashed) and simulated (solid) evolution of the magnetic field pitch angles, including off-axis NBCD (red) and excluding off-axis NBCD (blue) in coupled transport (ONETWO) and equilibrium (EFIT) MSE simulation with NUBEAM.

The local NBCD profile is obtained quantitatively from the time evolution of poloidal magnetic flux [4] using Ohm's law. The total parallel current J_{Tot} is determined from kinetic EFIT equilibrium reconstruction using the magnetic pitch angles from the MSE polarimetry and the external magnetic signals, where the current profile in the edge pedestal is used as a constraint that is deduced from a time-dependent simulation of poloidal flux evolution using the ONETWO transport code. The internal loop voltage profile is obtained from a time series of equilibrium reconstructions by taking the time derivative of the poloidal flux, $d\psi/dt$ which provides the Ohmic current profile $J_{OH}=\sigma_{Neo}d\psi/dt$, where σ_{Neo} is the neoclassical conductivity from the NCLASS model [14]. The beam driven current is given by $J_{NB}=J_{Tot}-J_{OH}-J_{BS}$, where the bootstrap current J_{BS} is calculated by Sauter model [15]. The measured $J_{NB}(\rho)$ in Fig. 5 shows a clear hollow NBCD profile with the peak at about half radius ρ~0.45 for the off-axis beam injection, which agree reasonable well with the NUBEAM modeling without anomalous transport. The net driven current normalized to the total co-current injection NB power is 16.2 kA/MW and 18.4 kA/MW for on- and off-axis injection, respectively in these specific cases at relatively low β. The off-axis NBCD efficiency is as good as on-axis NBCD mainly because the increased fraction of trapped electrons reduces the electron shielding in the outer radius region. The decreased electron shielding in the outer radius region compensates for the shorter slowing down of off-axis beam ions due to lower T_e to maintain the NBCD efficiency of off-axis injection as high as or even higher than that of on-axis injection.

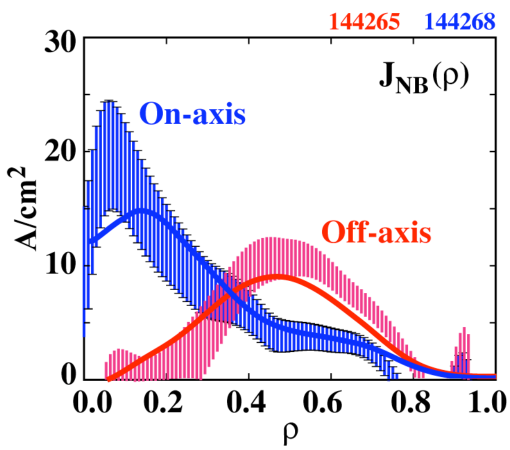

FIG. 5. Measured NBCD profiles for on (blue) and off (red) axis injection. NUBEAM modeling is shown with solid line.

Figure 6 shows the measured difference in the NBCD profile between on- and off-axis injection, ΔJ_{NB}=J_{NB}(off)-J_{NB}(on), compared with the NUBEAM modeling at the same electron temperature and density. This differential current drive analysis significantly reduces systematic sources of error such as model dependency and uncertainties in measurement. Relatively good agreement is found even under the presumed uncertainties including Z_{eff} and the neoclassical models of plasma conductivity and bootstrap current, since J_{OH} and J_{BS} tend to cancel out in this analysis. However, the discrepancy between measurement and modeling, especially at ρ > 0.4 (“large” off-axis NBCD) suggests further improvement of NUBEAM modeling including an improved description of fast ion bootstrap current in the orbit-following beam ion slowing down calculation and/or a neoclassical model of electron response to fast ions. Separate measurement of fast ion bootstrap current and electron shielding are planned in a future experiment on DIII-D.

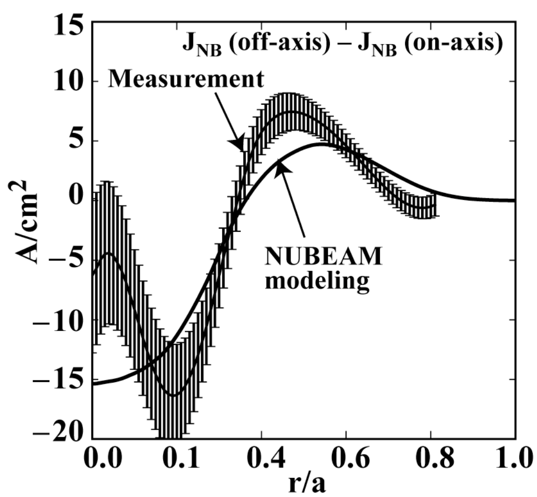

FIG. 6. Measured difference in the NBCD profile between on- and off-axis injection (with error bars), ΔJ_{NB}=J_{NB}(off)-J_{NB}(on), compared with the NUBEAM modeling (solid line).

Another novel approach using a modulation technique [16] finds the NBCD profile directly from the periodic response of the MSE signals to the modulation of the NBCD sources created by alternating between left and right off-axis beams. The left (more tangential) beam drives significantly more current than the right (more perpendicular) beam, while the plasma parameters can be maintained fixed especially to minimize oscillation of the plasma conductivity

$\tilde{\sigma}_{Neo}/\sigma_{Neo} << 1$. The beams are modulated at 6.7 Hz injecting each beam about one beam slowing down time (~75 ms). The experimental NBCD profile is determined by inserting the MSE oscillations into the Fourier transformed poloidal flux diffusion equation, as shown in Fig. 7. The real part of the NBCD profile J_{NB} plotted in Fig. 7(a) is the component that is in phase with the modulated NBCD source. The imaginary part of J_{NB} shown in Fig. 7(b) is the out of phase component that is expected to be zero [16]. The measured off-axis NBCD profile using this modulation technique is consistent with the NUBEAM modeling when an ad hoc oscillation of plasma motion (0.7 mm) is included in this analysis.

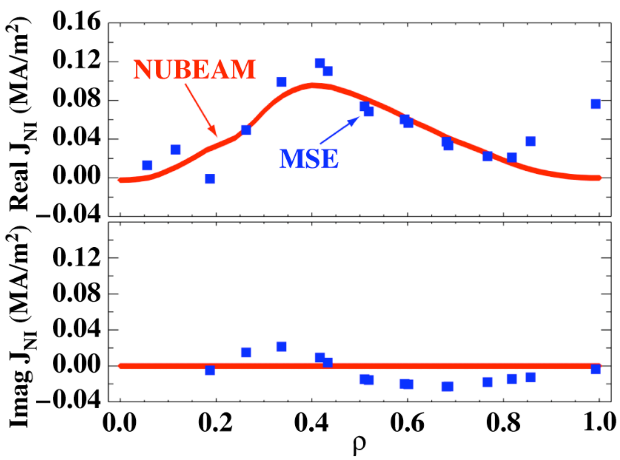

FIG. 7. Measured off-axis NBCD profile using modulation technique (symbol). NUBEAM modeling is shown with solid line.

3. MAGNETIC FIELD ALIGNMENT EFFECTS

The measured magnitude of off-axis NBCD is very sensitive to the toroidal magnetic field direction ($\pm B_T$) that modifies the alignment of the off-axis beam injection to the local helical pitch of the magnetic field lines. The neutral-particle analyzer (NPA) diagnostic [11], which detects confined fast ions with a nearly perpendicular velocity pitch, confirms that reversing the B_T direction significantly modifies the velocity pitch angle distribution of beam ions at their ionization location [4,5]. The magnetic trapping of beam ions and their detailed orbits during slowing down play an important role in the classical off-axis NBCD physics, since only the passing beam ions contribute to the fast ion current and the trapped fraction increases generally with the minor radius. The minus B_T direction is found to generate beam ions with higher perpendicular velocity components. The resulting NBCD profile for the B_T direction in this poor alignment shows substantially reduced NBCD (~45%) as well as inward shift of the peak NBCD location ($\Delta\rho$~0.1), which is in excellent agreement with the NUBEAM modeling as shown in Fig. 8. The discharge in the $-B_T$ direction shows lower q_{min}, higher ℓ_i, and early sawteeth start time compared with the discharge in the $+B_T$ direction, which is consistent with lower NBCD efficiency. The calculated beam ion profile in the $-B_T$ direction also shows inward shift in its peak location. Only when the signs of the toroidal magnetic field and the plasma current yield the proper helicity, both measurement and calculation indicate that the efficiency of off-axis NBCD is as good as for on-axis NBCD as described in Section 2. Dependency of the off-axis NBCD efficiency on the toroidal field direction is crucial to the optimum use of the off-axis beams not only for DIII-D but also for ITER.

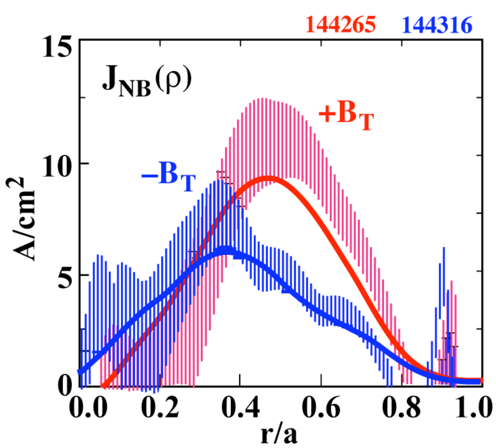

FIG. 8. Dependency of measured off-axis NBCD on toroidal field direction.

4. ANOMALOUS FAST ION TRANSPORT

Anomalous fast ion transport tends to degrade the efficiency of off-axis NBCD and its localization. Previous experiments in DIII-D using vertically shifted small plasmas showed that the measured NBCD deviates from the theoretical calculation unless anomalous fast ion transport is included ($D_b \neq 0$) for the highest injected power case in the NB power scan [4]. The integrated beam-driven current I_{NB} is smaller than the calculated value by 20% at P_{NB} = 7.2 MW. The radial profile of radiance from the vertical FIDA spectrometers as well as the neutron rate deviate from the classical model simulation, though these measurements agree with the classical model for the lower power cases. The fast ion pressure estimated by equilibrium reconstruction is smaller than the theoretical calculation with D_b=0 at the highest NB power, indicating that deviation of the measured I_{NB} from the classical model for this case is correlated with fast ion loss by additional anomalous transport that increases with the injection power. The measured NBCD profile fits best with the theoretical calculation with D_b = 0.3 m^2/s (an ad hoc diffusion model with a spatially uniform coefficient) that is roughly consistent with a theory-based beam ion diffusion due to microturbulence [6]. This experimental observation and recent modeling suggest that background plasma turbulence might be responsible for additional fast ion transport and thereby for the reduced 20% off-axis NBCD efficiency. A theoretically predicted scaling of beam ion diffusion depends on E_b/T_e for electrostatic turbulence or β for electromagnetic turbulence [17,18]. Disagreement between measurement and the classical model using the shifted small plasmas appears for $E_b/T_e < 35$ or for $\beta_T > 1.4\%$ [19]. It was difficult, however, to conclude which parameter is important since E_b/T_e and β are almost linearly coupled in the previous NB power scan.

The measured off-axis NBCD using the new tilted beamline is consistent with the NUBEAM modeling without anomalous fast ion transport for a range of beam injection and discharge conditions, including on/off-axis, parallel/perpendicular injections, variations in beam energy, injection power, toroidal field direction, plasma β and E_b/T_e, as shown in Fig. 9. To separate the effects of plasma β and E_b/T_e, the detailed NB and Electron Cyclotron Heating (ECH) power scan has been carried out, which includes the total beam injection and ECH power up to 10 MW and 2.7 MW, respectively. For the NB power scan, balanced on-axis beams are superimposed to the co-current off-axis beams. No obvious anomaly in the measured NBCD has been found either with variation of E_b/T_e at fixed β or with variation of β at fixed E_b/T_e, around the anticipated ITER parameters, implying that ITER is not likely to suffer from the loss of NBCD efficiency due to additional transport from microturbulence.

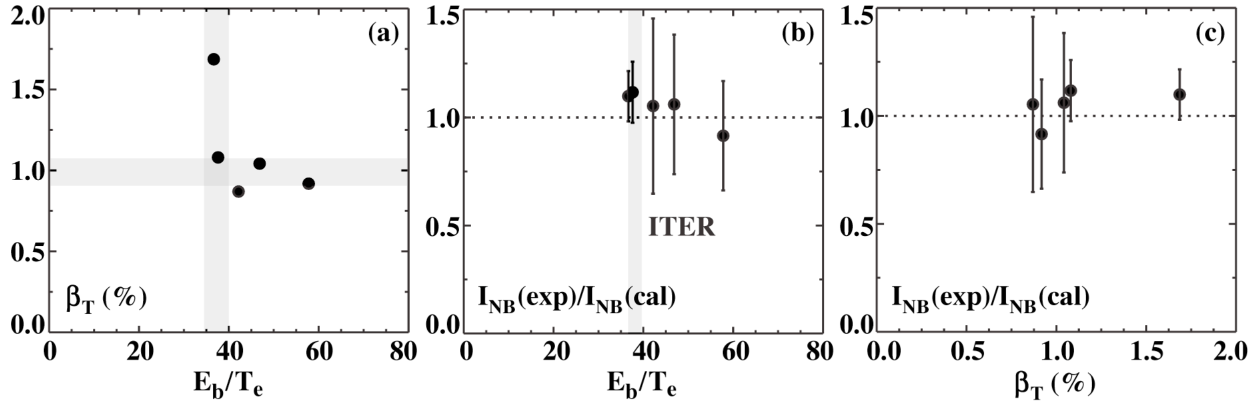

FIG. 9. Comparison of off-axis NBCD between measurement and NUBEAM modeling without anomalous fast ion transport as a function of (b) E_b/T_e and (c) plasma β for a range of E_b/T_e and β (a).

5. CONCLUSION

DIII-D neutral beam has been successfully modified for off-axis injection, providing heating and current drive for physics studies. Beam emission, fast ion population and current drive are all consistent with off axis NBI. The measured off-axis NBCD is very sensitive to the toroidal field direction that modifies the alignment of the off-axis beam injection to the local helical pitch of the magnetic filed lines. The NBCD profile for the B_T direction with poor alignment shows substantially reduced NBCD as well as an inward shift of the peak NBCD location. This dependency of the off-axis NBCD efficiency on the toroidal field direction is crucial to the optimum use of the off-axis beams not only for DIII-D but also for ITER. The measured off-axis NBCD is consistent with NUBEAM modeling without anomalous fast ion transport for a range of beam injection and discharge conditions including on- and off-axis injection, toroidal field direction, beam injection power, injection energy, plasma β and E_b/T_e. No obvious anomaly was found either with variation of E_b/T_e at fixed β or with variation of β at fixed E_b/T_e, around the anticipated ITER parameters, indicating ITER is not likely to suffer from the loss of NBCD efficiency due to additional transport from microturbulence.

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