Title
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Permalink
https://escholarship.org/uc/item/3dn4z52s

Journal
Nuclear Fusion, 51(8)

ISSN
0029-5515

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Publication Date
2011-08-01

DOI
10.1088/0029-5515/51/8/083020

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Peer reviewed
Experimental investigation and validation of neutral beam current drive for ITER through ITPA Joint Experiments

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Received 25 February 2011, accepted for publication 14 June 2011
Published 12 July 2011
Online at stacks.iop.org/NF/51/083020

Abstract
Joint experiments investigating the off-axis neutral beam current drive (NBCD) capability to be utilized for advanced operation scenario development in ITER were conducted in four tokamaks (ASDEX Upgrade (AUG), DIII-D, JT-60U and MAST) through the international tokamak physics activity (ITPA). The following results were obtained in the joint experiments, where the toroidal field, \( B_t \), covered 0.4–3.7 T, the plasma current, \( I_p \), 0.5–1.2 MA, and the beam energy, \( E_b \), 65–350 keV. A current profile broadened by off-axis NBCD was observed in MAST. In DIII-D and JT-60U, the NB driven current profile has been evaluated using motional Stark effect diagnostics and good agreement between the measured and calculated NB driven current profile was observed. In AUG (at low \( \delta \sim 0.2 \)) and DIII-D, introduction of a fast-ion diffusion coefficient of \( D_b \sim 0.3–0.5 \text{ m}^2 \text{s}^{-1} \) in the calculation gave better agreement at high heating power (5 MW and 7.2 MW, respectively), suggesting anomalous transport of fast ions by turbulence. It was found through these ITPA joint experiments that NBCD related physics quantities reasonably agree with calculations (with \( D_b = 0–0.5 \text{ m}^2 \text{s}^{-1} \)) in all devices when there is no magnetohydrodynamic (MHD) activity except ELMs. Proximity of measured off-axis beam driven current to the corresponding calculation with \( D_b = 0 \) has been discussed for ITER in terms of a theoretically predicted scaling of fast-ion diffusion that depends on \( E_b/T_e \) for electrostatic turbulence or \( \beta_t \) for electromagnetic turbulence.

(Some figures in this article are in colour only in the electronic version)

1. Introduction and background of neutral beam current drive (NBCD) validation efforts

NBCD is the main current drive source in ITER. In order to reach a steady-state operation scenario free from low \( m \) and \( n \) magnetohydrodynamic (MHD) activity (e.g. the neo-classical tearing mode (NTM), etc) that is resonant on low \( q \) rational surfaces, it is expected that \( q_{\text{min}} \gtrsim 1.5 \). Off-axis current drive is essential to sustain such weak or reversed magnetic shear. The negative ion-source based NB (N-NB) injector has been designed with off-axis steering capability in ITER, and the characteristics of off-axis NBCD are of great concern to achieve a \( Q = 5 \) steady-state operation scenario in ITER. Concerning on-axis NBCD, the measured NBCD profile at \( E_b \) up to 370 keV using an ITER-relevant N-NB system in JT-60U showed good agreement with calculations [1, 2]. A recent NSTX experiment also confirmed the good agreement for on-axis NBCD into MHD-free plasma [3]. However, there has been no result on the off-axis NBCD profile, which is more important for current profile control in the steady-state operation scenario. ASDEX Upgrade (AUG) first reported off-axis NBCD from the viewpoint of current profile tailoring, where the measured off-axis NBCD current did not agree with calculations and was smaller than the calculation [4] in
Table 1. Operation parameters and summary of the off-axis NBCD joint experiments.

<table>
<thead>
<tr>
<th>Device</th>
<th>ASDEX Upgrade (AUG)</th>
<th>DIII-D</th>
<th>JT-60U</th>
<th>MAST</th>
</tr>
</thead>
<tbody>
<tr>
<td>( I_p ) (MA)</td>
<td>0.6–0.8</td>
<td>0.9</td>
<td>1.2</td>
<td>0.5–0.8</td>
</tr>
<tr>
<td>( B_t ) (T)</td>
<td>2–2.5</td>
<td>2.1</td>
<td>3.7</td>
<td>0.4–0.5</td>
</tr>
<tr>
<td>( R_p ) (m)</td>
<td>∼1.65</td>
<td>∼1.7</td>
<td>∼3.3–3.4</td>
<td>∼0.85</td>
</tr>
<tr>
<td>( a ) (m)</td>
<td>∼0.5</td>
<td>0.55</td>
<td>∼0.8–0.9</td>
<td>∼0.65</td>
</tr>
<tr>
<td>Triangularity ( \delta_{tr} )</td>
<td>0.2–0.42</td>
<td>0.58</td>
<td>0.25–0.45</td>
<td>∼0.35</td>
</tr>
<tr>
<td>( E_b ) (keV)</td>
<td>93</td>
<td>81</td>
<td>65</td>
<td>85, 350(N-NB)</td>
</tr>
<tr>
<td>( r/a ) of off-axis NBCD peak in calculation</td>
<td>∼0.55</td>
<td>∼0.5</td>
<td>∼0.3 (N-NB)–0.5</td>
<td>∼0.5</td>
</tr>
</tbody>
</table>

The way of realizing Up/downward-steered Up/down-shift Downward-steered Up/down-shift off-axis NBCD off-axis beams of the plasma off-axis beams of plasma

Codes for comparison TRANSP NUBEAM,TRANSP OFMC TRANSP

Summary of results Agreement (but \( D_b = 0.5 \text{ m}^2 \text{s}^{-1} \)) Agreement in \( j_{BD} \) Agreement in \( j_{BD} \) Broader \( j \) profile by off-axis NBCD

The way of realizing off-axis NBCD

The way of realizing Up/downward-steered Off-axis beams of the plasma Downward-steered Off-axis beams of plasma

Codes for comparison TRANSP NUBEAM,TRANSP OFMC TRANSP

Summary of results Agreement (but \( D_b = 0.5 \text{ m}^2 \text{s}^{-1} \)) Agreement at low \( \delta = 0.2 \) and 5 MW (heating power) Agreement in \( j_{BD} \) (but \( D_{ns} = 0.3 \text{ m}^2 \text{s}^{-1} \) at 7.2 MW (heating power)) Agreement in \( j_{BD} \) over a wide range of \( E_b \)

Figure 1. Beam lines for off-axis NBCD in four devices and their position with respect to plasma. AUG and JT-60U have exclusive off-axis beam lines, while DIII-D and MAST realized off-axis NBCD by vertical shift of the plasma.

The case of strong heating into a low \( \delta \) plasma. Later, the difference was attributed to possible diffusive redistribution of fast ions by turbulence [5]. JT-60U also investigated the off-axis NBCD and found good agreement between measurement and calculation of the off-axis NBCD current, but found a difference in the NBCD location [6]. Thus, joint experiments were conducted through the international tokamak physics activity (ITPA) to validate off-axis NBCD capability. This paper reports on the results of the joint experiments conducted in four tokamaks, AUG, DIII-D, JT-60U and MAST. Since it is known that MHD activity bring about redistribution of fast ions and modify the NBCD capability, these joint experiments were conducted in plasmas without MHD activity (e.g. sawteeth, fishbones, NTMs, Alfvén eigenmodes) except ELMs.

2. Experimental conditions of off-axis NBCD

Operation parameters of the devices for off-axis NBCD (as well as on-axis NBCD for comparison) are shown in table 1. Beam ions are deuterium in all discharges shown here for all devices. Positive-ion based NBs (\( E_b < 100 \text{ keV} \)) are used in all devices, as well as N-NB (\( E_b \sim 350 \text{ keV} \)) in JT-60U. Plasma size, shape and magnetic field vary, and the way off-axis NB injection is realized varies from device to device; use of off-axis steered NBs in AUG (up/downward) and JT-60U (downward), and vertical shift of the plasma in DIII-D (up/downward) and MAST (downward). Figure 1 shows the beam lines for off-axis NBCD in all devices and their relative position to the plasma. Locations of off-axis NBCD using positive-ion based NB (P-NB) are intended to be about a half minor radius (\( r/a \sim 0.5 \)) in all devices. In addition, off-axis NBCD at \( r/a \sim 0.3 \) was performed in the JT-60U N-NB case, which is closer to the off-axis steering NBCD in ITER. Since half of the N-NB (lower ion source injected upwards) is almost on-axis (figure 1(c)), only the other half (upper ion source injected downwards) was used for this study. MHD activity that redistributes fast ions is avoided during NBCD analysis by adjusting operation scenarios, for example, high \( q_{95} \) operation (up to \( \sim 6 \)) and/or pre-heating during current ramp-up to delay current penetration. In all devices, the NB driven current or change in the current profile by NB driven current is measured directly using motional Stark effect (MSE) diagnostics. The measured results are compared with theoretical calculations that are different between devices, as shown in table 1. There was a detailed benchmarking study between some NBCD codes using parameters of the reference ITER steady-state scenario [7], where the calculated beam driven current profiles by the NUBEAM [8] (for DIII-D) and OFMC [9] (for JT-60U) codes give clear discrepancy in NB driven current (see figure 2 in [7]). After careful investigation of the two codes, it was found that the homogeneous Coulomb logarithm in the collision operator in the OFMC code is the main cause of the discrepancy in the benchmark. NB driven current by both codes agreed after revising the OFMC code.
3. Experimental results

Plasma parameters (electron density $n_e$, electron temperature $T_e$ and ion temperature $T_i$) during off-axis NBCD are summarized in figures 2(a) and (b). The parameters are measured at the NBCD location $\rho_{CD}$ defined as the peak location of the beam driven current density in each calculation. Figures 2(c) and (d) show the relation of off-axis NBCD beam energy $E_b$, off-axis NBCD power $P_{NB(off-axis)}$ and total heating power $P_{total}$. Thanks to the joint experiments, wide dynamic ranges of the local plasma parameters as well as global parameters (table 1) have been achieved. Figures 2(e) and (f) show $n_e$ and $T_e$ as a function of $P_{total}$. Roughly speaking, higher $T_e$ was obtained at larger $P_{total}$. In the off-axis NBCD discharge at $n_e \sim 4 \times 10^{19} \text{m}^{-3}$, the current density profile broadened less than at lower $n_e$, showing a reduction in the off-axis beam driven current with increasing $n_e$, qualitatively consistent with theory.

A more direct comparison of the beam driven current profile, $j_{BD}$, was performed in DIII-D [11] and JT-60U, using loop-voltage-profile analysis [12]. Figure 4 shows the comparison between measurement and calculation in JT-60U (2.0 MW off-axis NBCD in 6.0 MW total power) and DIII-D (5.2 MW off-axis NBCD in 5.7 MW total power), as well as ITER-like slightly off-axis NBCD ($\rho_{CD} \sim 0.3$) using N-NB (1.8 MW, $\sim 350$ keV) in 12 MW total power in JT-60U. The codes used for the calculations in JT-60U and DIII-D are OFMC and NUBEAM, respectively. Characteristic profile shapes and magnitudes of the beam driven current density in calculations are well validated by the measurements in figure 4.

In MAST, the radial profile of the plasma current density was measured in a nearly ohmic discharge as well as off-axis NBCD discharges [10]. A significant change in the MSE polarization angle (proportional to the magnetic field pitch angle viewed from the MSE optics) between ohmic and off-axis NBCD discharges was observed in figure 3(a). The resulting plasma current density profile broadened in the off-axis NBCD phase relative to the ohmic phase at similar $n_e \sim 2 \times 10^{19} \text{m}^{-3}$, as shown in figure 3(b). In the off-axis NBCD discharge at higher $n_e \sim 4 \times 10^{19} \text{m}^{-3}$, the current density profile broadened less than at lower $n_e$, showing a reduction in the off-axis beam driven current with increasing $n_e$, qualitatively consistent with theory.

The codes used for the calculations in JT-60U and DIII-D are OFMC and NUBEAM, respectively. Characteristic profile shapes and magnitudes of the beam driven current density in calculations are well validated by the measurements in figure 4.
the off-axis NBCD phase, as described later. In figure 5(a), agreement of \( I_{BD} \) between measurements and calculations is obtained within their error bars for each machine except for the two DIII-D discharges with the largest \( I_{BD} \). The two discharges have the highest heating power (6.3 MW and 7.2 MW) in DIII-D data in figure 2(d). Agreement of the NBCD location is fine for all data, as shown in figure 5(b), although it is difficult to define their error bars. Current drive efficiencies in the calculations are shown in figures 5(c) and (d) in order to show the operation regime from the viewpoint of the current drive. Dimensional current drive efficiency is defined as \( \eta_{CD} = \frac{I_{BD} \rho n_e R_p}{P_{NB off-axis}} \), and normalized current drive efficiency is \( \zeta_{CD} = \eta_{CD} \rho^2 / (e R_p T_e) \), where \( R_p \) is the major radius and \( n_e \) and \( T_e \) are at \( \rho_{CD} \). Beam driven current \( I_{BD} \) is the same as plotted in figure 5(a).

NBCD current is theoretically predicted to depend on the NB injection angle to the magnetic field line [14, 15]. In order to study the effect of NB injection angle, the direction of the toroidal magnetic field \( B_t \) and the vertical shift of the plasma were scanned in DIII-D, as shown in figure 4(c). The measured beam driven current is almost the same between the up-shifted plasma with positive \( B_t \) (Up/\( +B_T \)) and the down-shifted plasma with negative \( B_t \) (Down/\( -B_T \)), since the NB injection angles to the magnetic field line are the same. In contrast, a significant decrease in the beam driven current was observed in the case of off-axis NBCD in the down-shifted plasma with positive \( B_t \) (Down/\( +B_T \)). These results validate the theoretical prediction. Alignment of the NB injection angle to the magnetic field line in ITER was discussed in [14].

**Figure 3.** (a) MSE polarization angle and (b) total current density \( j_{\text{total}} \) profile measured by MSE in MAST for nearly ohmic (\#20123) and NBCD phases (\#20118: higher \( n_e \); \#20096: lower \( n_e \)), showing the difference in \( j_{\text{total}} \) broadened by off-axis NBCD.

4. **Discussion**

In the joint experiments described above, measurement of off-axis NBCD has been performed when there is no MHD activity except ELMs. In many cases, off-axis NBCD in a range \( r/a \sim 0.3–0.5 \) agrees with theoretical calculations without introducing anomalous diffusion of fast ions. In some devices and conditions (in AUG with low \( \delta \) and in DIII-D), reasonably small \( D_b \sim 0.3–0.5 \text{ m}^2 \text{s}^{-1} \) are required to obtain agreement between measurement and calculation at higher heating power (or off-axis NBCD power). After the work in AUG [5], there have been several theoretical works recently in the field of gyrokinetic simulation, simulating fast-ion transport induced by microturbulences [21–24]. The scalings of fast-ion diffusion coefficients based on the
Figure 4. Comparison of the beam driven current density profile between measurement (solid curves with error bars) and calculation (broken curves). (a) JT-60U P-NB \( \sim 85 \text{ keV} \), (b) JT-60U N-NB \( \sim 350 \text{ keV} \), (c) DIII-D \( \sim 81 \text{ keV} \). Good agreement is observed both in JT-60U and DIII-D. In DIII-D (figure 4(c)), NB injection angles to the magnetic field are scanned by changing the direction of the vertical shift and the direction of the toroidal magnetic field but at the same off-axis NBCD power (three cases are shown).

Figure 5. (a) Comparison of measured beam driven current \( I_{BD} \) and the calculated one (no radial diffusion of fast ions is taken into account) in AUG, DIII-D and JT-60U. \( I_{BD} \) for both measurements and calculations are integrated in a range \( r/a = 0.2-0.8 \) in figure 4 for JT-60U. (b) Comparison of NBCD location \( \rho_{CD} \) between measurement and calculation, defined as the peak location of the beam driven current density profile. (c) Current drive efficiency as a function of \( T_e \) at NBCD location. (d) Normalized current drive efficiency as a function of NBCD location. Definition of the symbols is the same as in figure 2.

Simulations are qualitatively similar to each other. The electrostatic diffusion of fast ions in the background plasma with microturbulence approaches the diffusion of thermal ions when the ratio of beam energy to the electron temperature of the background plasma \( (E_b/T_e) \) becomes smaller [21–24]. Since the thermal-ion diffusivity is, in general, larger off-axis than on-axis, the effect of microturbulence on fast-ion diffusion is significant for off-axis NBCD. In the case of electromagnetic diffusion, the diffusion coefficient is independent of the beam energy and increases with plasma beta [24]. In this section, we discuss off-axis NBCD in ITER along such theoretical works, using the results in the ITPA joint experiments. It should be noted that the ITER operation scenarios have usually been developed using integrated codes with NBCD packages assuming no anomalous fast-ion diffusion. Achievement of ITER baseline scenarios within its heating and current drive capability was discussed using such integrated codes in detail in some references (e.g. [25, 26] for recent analysis). Thus, validity of the NBCD packages assuming no anomalous fast-ion diffusion under the ITER condition is important and is examined here. In the following discussions, we examine the measured beam driven current
where good agreement between the measurement and the calculation was obtained. In addition, off-axis steering of ITER N-NB is intended for \( \rho_{\text{CD}} \sim 0.2–0.3 \), so the electrostatic effect of microturbulence is relatively smaller there than for \( \rho_{\text{CD}} \sim 0.5 \) in the joint experiments due to the smaller thermal-ion diffusion at \( r/a \sim 0.2–0.3 \) (e.g. see figure 4 of [16]). However, we must note that \( E_b/T_c \) in two AUG discharges shown in figure 7 are similar in the range 68–79, where the lower \( \delta \) discharge (figure 7(a)) requires \( D_b = 0.5 \text{ m}^2 \text{ s}^{-1} \) but the higher \( \delta \) discharge (figure 7(b)) requires no anomalous fast-ion diffusion. The value \( E_b/T_c \sim 68 \) is much larger than that where DIII-D requires \( D_b \sim 0.3 \text{ m}^2 \text{ s}^{-1} \) (\( E_b/T_c \sim 30 \) for 7.2 MW heating case in figure 6). Thus, we must keep in mind that there could be more hidden parameters, such as geometric ones like \( \delta \).

In figure 9, data in the joint experiments are examined from the electromagnetic effect of turbulence on fast-ion diffusion as well. Figure 9(a) shows the relation between toroidal beta \( \beta_t \) as a measure of electromagnetic effect as a function of inverse of \( E_b/T_c \) as a measure of electrostatic effect in the database. Note that \( \beta_t \) and \( T_c/E_b \) (or \( T_c \)) are almost linearly coupled in DIII-D and \( \beta_t \) in JT-60U is restricted to low values for its high toroidal field. Figures 9(b) and (c) show measured \( I_{\text{BD}} \) normalized by the corresponding calculations with \( D_b = 0 \) assumed as a function of \( \beta_t \) for low and high-triangularity discharges, respectively. No clear dependence on \( \beta_t \) is seen in the low-triangularity case for \( \rho_{\text{CD}} \sim 0.5 \) data (figure 9(b)). For the high-triangularity case (figure 9(c)), there is a degradation of the proximity with an increase in \( \beta_t \) as predicted by theory. Disagreement appears in two DIII-D discharges for \( \beta_t > 1.4\% \); however, this evidently comes from the correlation between \( \beta_t \) and \( E_b/T_c \) in DIII-D. Although there is a wide dynamic range in \( \beta_t \) (0.2–1.3\%) for almost the same \( T_c/E_b = 0.028 \) between DIII-D and JT-60U for the high-triangularity case, it is difficult to conclude which parameters are important. In addition, in the AUG discharges with similar \( E_b/T_c \sim 68–79 \) (or \( T_c/E_b = 0.015–0.013 \)), a higher \( \beta_t \) discharge (1\% at high-triangularity in figure 7(b)) requires \( D_b = 0 \), while a lower one (0.6\% at low-triangularity in figure 7(a)) requires \( D_b = 0.5 \text{ m}^2 \text{ s}^{-1} \), if difference in triangularity is ignored. Thus, it seems it is difficult to understand from the viewpoint of electromagnetic diffusion of fast ions alone. Further theoretical understanding of fast-ion transport and/or simulation work on realistic ITER geometry and parameters is necessary. From the experimental viewpoint, separation of \( \beta_t \) and \( E_b/T_c \), as well as direct measurement of turbulent fluctuations (not merely a measure of turbulence \( E_b/T_c \) and \( \beta_t \)), are necessary for further study. It should be noted that \( \beta_t \) in ITER steady-state operation scenario (\#4 type-I) is about 4\%, which is higher than the range in these joint experiments.

5. Summary

The following results were obtained in the ITPA joint experiments, where the toroidal field, \( B_t \), covered 0.4–3.7 T, the plasma current, \( I_p \), 0.5–1.2 MA, and the beam energy, \( E_b \), 65–350 keV. The current profile was broadened by off-axis NBCD in MAST. In DIII-D and JT-60U, the NB driven current profile has been evaluated using MSE diagnostics and good agreement between the measured and calculated

\[ I_{\text{BD}} \] not the profile \( I_{\text{BD}} \), in comparison with the corresponding calculations, since \( I_{\text{BD}} \) well represents anomalous fast-ion diffusion at least when \( D_b \) is spatially uniform as shown in figure 6.

Figure 8(a) shows the relation between the off-axis beam energy \( E_b \) (at injection) and \( T_c \) at the NBCD location \( \rho_{\text{CD}} \) in the joint experiments, as well as one of the candidates for the ITER steady-state operation scenario (\#4 type-I) [27, 28] for \( \rho_{\text{CD}} \sim 0.2–0.3 \). The parameter \( E_b/T_c \) is estimated to be 37–40 for ITER conditions, and the results of joint experiments distribute around this value. In the joint experiments, lower \( E_b/T_c \sim 37–40 \) near the ITER conditions are mostly obtained at higher \( T_c \) discharges with higher heating power in figure 2(f). Figures 8(b) and (c) plot the measured NBCD current normalized by the corresponding calculations for \( D_b = 0 \) as a function of \( E_b/T_c \) in low- and high-triangularity discharges, respectively. The low-triangularity discharge is in \( \delta = 0.20–0.26 \) and the high-triangularity discharge is in \( \delta = 0.42–0.44 \) (for AUG and JT-60U) and 0.58 (for DIII-D). Separation of discharges depending on the triangularity is based on the AUG results in figure 7. It is considered that the ratio \( I_{\text{BD}}(\text{exp})/I_{\text{BD}}(\text{cal}) \) represents proximity to the \( D_b = 0 \) condition. In the high-triangularity case (figure 8(c)), degradation of the proximity with a decrease in \( E_b/T_c \) below 40 is observed, whose trend is as expected from the electrostatic diffusion of fast ions. Disagreement between measurement and calculation appears for \( E_b/T_c < 35 \) in two DIII-D discharges, which is below the ITER condition. It seems the proximity is worse in the low-triangularity case (figure 8(b)) than high-triangularity case (figure 8(c)) for the \( \rho_{\text{CD}} \sim 0.5 \) dataset. According to [28], the \( \delta \) of the ITER scenario is 0.39, which is closer to \( \delta \) in the high-triangularity case than in the low-triangularity case. Joint experiments for off-axis NBCD at \( r/a \sim 0.5 \) with high-triangularity (figure 8(c)) show agreement of \( I_{\text{BD}} \) between measurement and calculation with \( D_b = 0 \) around \( E_b/T_c \sim 37–40 \) (the upper bound by DIII-D and the lower bound by DIII-D and JT-60U). The off-axis NBCD profile for JT-60U is shown in figure 4(a).
Figure 7. Waveforms of MSE polarization angles in two AUG discharges at the same off-axis NBCD and heating powers (5 MW and 5.6 MW, respectively), but different triangularities (a) 0.2 and (b) 0.4. Since MSE diagnostic data are not available during off-axis NBCD in AUG, TRANSP simulation data adjusted before the start of off-axis NBCD are compared with MSE data after the end of off-axis NBCD. In the lower triangularity discharge, MSE measurements are not properly simulated for the $D_b = 0.5 \text{ m}^2 \text{s}^{-1}$ (solid curves). Better agreement between measurement and simulation was obtained for $D_b = 0.5 \text{ m}^2 \text{s}^{-1}$ (dotted curves). (b) In another higher triangularity discharge, MSE measurements are well simulated assuming $D_b = 0$ (solid curves). Dotted curves correspond to no NBCD effect being taken into account in the simulation.

Figure 8. (a) Conditions of off-axis NBCD experiments on beam energy $E_b$ and $T_e$. (b), (c) Measured off-axis beam driven current normalized by the theoretical calculation (no radial diffusion of fast ions is taken into account) as a function of a parameter $E_b/T_e$. Low-triangularity case (b) and high-triangularity case (c). The grey shaded line shows the parameter range in $E_b/T_e$ in ITER scenario #4 (type-I) [27, 28] at $\delta = 0.39$. N-NB in JT-60U is for $\rho_{CD} \sim 0.3$ and the others are for $\rho_{CD} \sim 0.5$. Definition of the symbols is the same as in figure 2.

Figure 9. (a) Relation between toroidal beta $\beta_t$ and inverse of $E_b/T_e$ in the joint experiments. (b), (c) Measured off-axis beam driven current normalized by the theoretical calculation (no radial diffusion of fast ions is taken into account) as a function of $\beta_t$. The low-triangularity case (b) and the high-triangularity case (c). Toroidal beta is $\sim$4% in the ITER scenario #4 (type-I) [27, 28] at $\delta = 0.39$. N-NB in JT-60U is for $\rho_{CD} \sim 0.3$ and the others are for $\rho_{CD} \sim 0.5$. Definition of the symbols is the same as in figure 2.
NB driven current profile was observed. In AUG (at low $\delta \sim 0.2$) and DIII-D, introduction of a fast-ion diffusion coefficient of $D_b = 0.3$–0.5 m$^2$ s$^{-1}$ in the calculation gave better agreement at high heating power (5 MW and 7.2 MW, respectively), suggesting anomalous transport of fast ions by turbulence. It was found through these ITPA joint experiments that NBCD related physics quantities reasonably agree with calculations (with $D_b = 0$–0.5 m$^2$ s$^{-1}$) in all devices when there is no MHD activity except ELMs. Proximity of measured off-axis beam driven current to the calculation with $D_b = 0$ has been discussed for ITER in terms of a theoretically predicted scaling of fast-ion diffusion that depends on $E_b/T_e$ or $\beta_t$. The assumption $D_b = 0$ is usually employed in NBCD packages in integrated codes for ITER operation scenarios development so that the validity of the assumption is essential particularly for achievement of ITER steady-state operation. In the high-triangularity case with $\delta = 0.42$–0.58, degradation of the proximity has been observed for $E_b/T_e < 35$ and $\beta_t > 1.4%$ in DIII-D discharges; however, both of the parameters are coupled in DIII-D and identification of an essential parameter for the possible turbulent transport is not possible in this joint experiment. In addition, the fast-ion diffusion coefficient required to obtain a match between the measurements and calculations in AUG differs depending on $\delta$ even at similar $E_b/T_e$. Thus, we must keep in mind that there could be more hidden parameters, like $\delta$. Further theoretical understanding of fast-ion transport and/or simulation work on realistic ITER geometry is necessary. From the experimental viewpoint, separation of $\beta_t$ and $E_b/T_e$, as well as direct measurement of turbulent fluctuations (not merely a measure of turbulence $E_b/T_e$ and $\beta_t$) are necessary for further study. The range of $E_b/T_e$ in the joint experiment is sufficient but $\beta_t$ is not for ITER steady-state operation scenario (#4 type-I) with $E_b/T_e = 37$–40 at $\rho_{CD} \sim 0.2$–0.3 and $\beta_t \sim 4%$. The database obtained in the ITPA joint experiments here will provide such future work with a good touchstone of benchmarking with experimental measurements.

Acknowledgments

One of the authors (TS) thanks Dr T. Oikawa, Dr T. Fujita, Dr K. Hamamatsu, Dr K. Shinohara, Dr M. Honda and Mr M. Suzuki for their support in improving NBCD codes (OMFC and ACCOME). Also T.S. thanks Dr J. Snipes for his cooperation in improving this manuscript.

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