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DIII-D experiments on neutral beam current drive (NBCD) using the new tilted beamline have clearly demonstrated off-axis NBCD as expected from modeling. Two of the eight neutral beam sources have been modified for downward vertical steering to provide significant off-axis current drive for Advanced Tokamak (AT) scenario development. Off-axis current drive is critical in testing the potential of high bootstrap fraction, steady-state operation with a broad current profile at elevated q, especially for the minimum of q > 2. For validation of off-axis NBCD physics, the local NBCD profile driven by the new tilted beams was measured in H-mode plasma and compared with modeling under a range of beam injection and discharge conditions such as the toroidal magnetic field direction, beam injection power, plasma beta (β), and ratio of beam injection energy to electron temperature (E_b/T_e). The full radial profile of NBCD measured by the magnetic pitch angles from the motional Stark effect (MSE) diagnostic (Fig. 1) 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 realistic current drive sources. The beam-stored energy estimated by equilibrium reconstruction and neutron emission data do not show any noticeable anomalous losses of NBCD and fast ions.

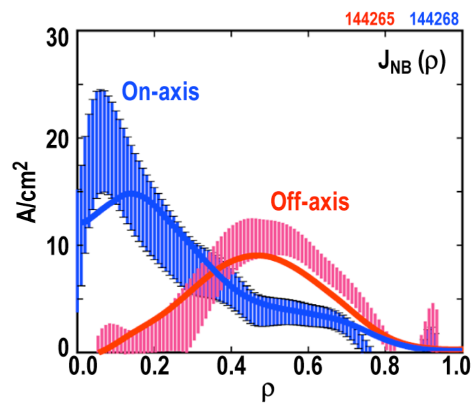

Fig. 1. Measured NBCD profiles for on-axis (blue) and off-axis (red) injection. Solid lines show NUBEAM calculation.

To validate off-axis NBCD physics in great detail, we compare two discharges with on- and off-axis NBCD in otherwise similar discharge conditions to reduce model dependencies and systematic uncertainties of measurements. The plasma current profile determined by the MSE signals shows a definite broadening of the plasma current for off-axis injection. The measured difference between on- and off-axis NBCD at the same electron temperature and density shows good agreement with the NUBEAM modeling even under the presumed uncertainties including Z_{eff} and the neoclassical model of plasma conductivity. Another novel approach using modulation technique finds the NBCD profile directly from the periodic response of the MSE signals to the modulation of the NBCD source created by alternating between left (more tangential) and right (more perpendicular) off-axis beams. The experimental NBCD profile determined from the MSE oscillation is consistent with the NUBEAM modeling. Separate measurement was also made for each process involved in the off-axis NBCD. D-alpha imaging of beam injection into neutral gas yields the neutral beam particle trajectories as well as the off-axis beam ion deposition profile that provides an accurate beam injection model for the new off-axis beams. 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.

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 filed lines. The neutral-particle analyzer (NPA) diagnostic, which detects confined fast ions with a nearly-perpendicular velocity pitch, confirms that reversing the B_T direction modifies significantly the velocity pitch angle distribution of beam ions at their ionization location. The resulting 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), which is in excellent agreement with the NUBEAM modeling. 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. If the signs of the toroidal magnetic field and the plasma current yield the proper helicity, both measurement and calculation indicate that the efficiency is as good as for 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. 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.

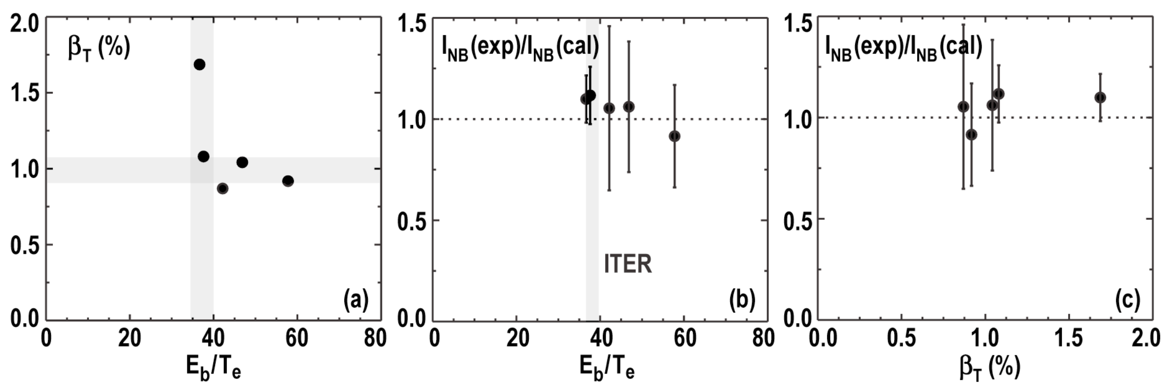

Fig. 2. Comparison of off-axis NBCD between measurement and NUBEAM modeling without anomalous fast ion transport as a function of (b) E_b/T_e and (c) plasma β for a range of E_b/T_e and β (a).

The measured off-axis NBCD is consistent with the NUBEAM modeling without anomalous fast ion transport for a range of plasma β and E_b/T_e, as shown in Fig. 2. The previous experiments in DIII-D using vertically shifted small plasmas and recent modeling suggest that background plasma turbulence might be responsible for additional fast ion transport and thereby for the reduced 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. Disagreement between measurement and the classical model using the shifted small plasmas appears for $E_b/T_e < 35$ or for $\beta_T > 1.4$ %. 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 detailed NB and Electron Cyclotron Heating (ECH) power scan using the new tilted beams indicates no obvious anomaly 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.

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