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

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Modification of the two existing DIII-D neutral beam lines is proposed to allow off-axis current drive with neutral beam injection (NBI) vertically steered to drive current as far as half the plasma radius off-axis. New calculations indicate very good current drive efficiency (actually better than on-axis due to increased trapped electron fraction) with good localization off-axis as long as *B* and *I* are in the same direction (for a beam steered downward) (Fig. 1). These simulations indicate that even in the presence of fast ion diffusion, significant off-axis current drive (CD) would remain. Self-consistent Advanced Tokamak (AT) scenario modeling using both the scaled, experimental transport model and the theory-based [gyro-Landau fluid (GLF23)] transport model shows that the proposed 10-MW off-axis neutral beam current drive (NBCD) with high power electron cyclotron current drive (ECCD) will allow demonstration of fully noninductive, high β scenario with flat safety factor, $q(\rho)$ with $q_{min} > 2$ (Fig. 2). The modification of the DIII-D NB system will provide flexible scientific tools for understanding transport, energetic particles, heating and CD physics, and validating the off-axis NBCD in support of scenario development for ITER and beyond.

The goal of the DIII-D AT program is to provide the scientific basis for steady-state, high-performance operation for ITER and future tokamak reactors. Research on DIII-D has focused specifically on the high-performance operation, specifically on the high q_{min} scenario development. However, high q_{min} scenario development is limited by an overdrive of the central current by the NBI required for heating. The most expedient solution to this conflict is to modify two of the NB lines to allow full power injection vertically steered to drive current as far as half the plasma radius off-axis. Because of the constraints of the existing poloidal coils and vacuum vessel, the beam must pass through the existing port, implying an oblique injection angle in both the toroidal and vertical directions.

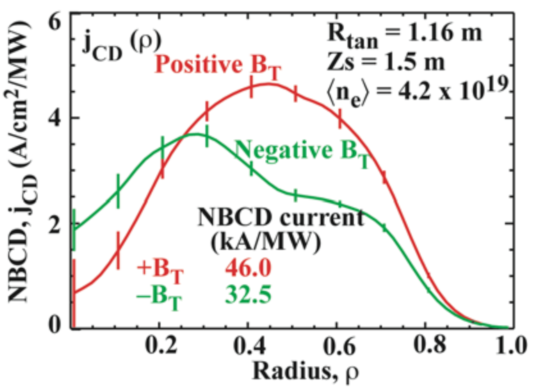

Fig. 1 Calculated off-axis NBCD profiles for DIII-D for positive and negative *B* direction.

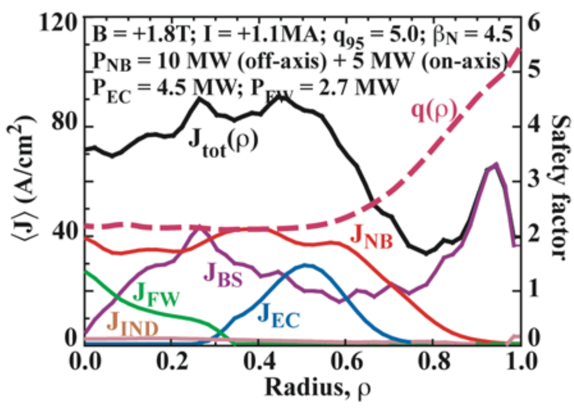

Fig. 2. Profiles of current components and safety factor in a self-consistent, GLF23 simulation using off-axis NBCD.

New calculations to evaluate off-axis CD in DIII-D found a significant difference in both the localization and the magnitude of the off-axis NBCD for co-injection with the direction of *B*. For a downward steered beam, the case with *B* in the same direction as *I* (the +B direction) yields a profile of NBCD that is peaked off-axis at a normalized radius (ρ) of 0.5 and reasonably localized, while the case with *B* in the opposite direction from *I* (the -B direction) yields a broader profile peaked at $\rho \approx 0.3$, as shown in Fig. 1. The magnitude of the current is 40% higher in the case with the +*B* direction. This difference arises primarily from the fact that the beam is much more parallel to the magnetic field lines in the +*B* direction, and from orbit shifts due to change in the ∇B drifts during the slowing-down time. The NBCD efficiency increases off-axis because the trapped electron fraction increases, which reduces the electron shielding of the injected ion current. This is in contrast with ECCD schemes where the increased trapped electron fraction degrades the efficiency. For a given set of density and temperature profiles, the off-axis NBCD efficiency is comparable to that of ECCD at the same radius. The ECCD retains the advantage of higher localization and variability between discharges (and eventually during a discharge). A design goal for the NBI modification is to retain the ability to operate the beams with the same aiming as at present plus the aiming variation possibly over-night.

Off-axis NBCD using vertical steering injection has been reported by JT-60U and ASDEX Upgrade (AUG), and ITER is planned to have an off-axis NB system. We have made assessments for ITER in terms of the *B* direction. Since the nominal *B* and *I* directions are opposite to the DIII-D case with the same direction of *B* and *I*, the localization of the planned downward steered beam would be less localized than for an upward steered beam: the peak CD location increases from $\rho = 0.4$ to 0.5 and the CD increases by 25% for the upward beam compared with the planned downward beam. If a further increase in the off-axis aiming position is contemplated, the effect becomes more important, and either reversal of the *B* direction or the beam steering direction would be recommended. One concern raised by the AUG off-axis NBCD experiment was the possible effects of anomalous fast ion (spatial) transport. Calculations of NBCD profiles with an assumed diffusion of 0.5 m^2/s (constant) show that fast ion diffusion does not alter the feature of off-axis CD, although the magnitude is affected. A prototype NBCD experiment on DIII-D is being planned with a vertically shifted, small plasma in the present configuration to validate the models.

The main focus for steady-state scenario development in DIII-D is the demonstration of fully noninductive current sustainment for the current relaxation time, $\tau_R > 2$, 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* (1.8 T). Demonstration at higher *B* (2.2 T) for the future tokamak reactors requires a significant upgrade to the EC system to supply the off-axis current drive or, alternatively, the off-axis NBCD by vertical steering. In scenario modeling of the $B = +1.8$ 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 fully noninductive high-β scenario with flat $q(\rho)$ above 2 (Fig. 2). 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 current profile for better stability and transport control, and ECCD mitigation of neoclassical tearing modes if necessary. These scenario simulations were carried out with both the scaled experimental transport and the theory-based transport (GLF23) model in the ONETWO transport code.

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