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# Towards a Better Understanding of Neutral Beam Current Drive and Steady State Operation

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Non-inductive current drive is essential for future tokamak reactors to reach longer pulses or even steady state operation. The common non-inductive current drivers are the wave heating systems and neutral beam injection besides the intrinsic bootstrap current. The focus of this study is on the effect of anomalous transport on on- and off-axis neutral beam current drive (NBCD) and on highly non-inductive discharges. Such discharges were performed on ASDEX Upgrade at a plasma current of 600 kA and 800 kA with at least 95 % of non-inductively driven current, mainly driven by (off-axis) NBCD and bootstrap current.

**ASDEX Upgrade**

ASDEX Upgrade [1] is a well suited machine for current drive studies. Its flexible heating systems and comprehensive diagnostics present the possibility to tailor the current profile by neutral beam current drive and electron cyclotron current drive (ECCD) while simultaneously monitoring its evolution by motional Stark effect polarimetry (MSE) [2] as well as the radial fast ion distribution by fast ion $D_\alpha$ spectroscopy (FIDA) [3]. Additionally an imaging MSE and a Faraday rotation polarimetry system is available. The neutral beam injection (NBI) system hosts four 60 keV and four 93 keV beams, each with a maximum power of 2.5 MW. The beam geometries can be seen in Fig. 1a) and b). Noteworthy is the geometry of beams 6 and 7. These beams have a higher current drive efficiency because they inject tangentially. They also create their fast ions and the associated current further off axis. Additionally four gyrotrons, each with a nominal power of 800 kW, provide electron cyclotron resonance heating (ECRH) and current drive (ECCD) from steerable launchers.

**Off-axis neutral beam current drive**

Indication of anomalous fast ion transport during off-axis neutral beam current drive at ASDEX Upgrade was first reported by Günter et al. [4]. There the evolution of the measured MSE angles, which are directly related to the current profile, differed from that predicted by neoclassical TRANSP [5] simulations. The data could however be matched by assuming $0.5\,\mathrm{m^2/s}$ anomalous fast ion diffusion in the simulations which was explained by microturbulence. A later FIDA-based study using comparable discharges [6] came to the contradictory conclusion that the radial NBI fast ion distribution underlying NBCD was very well in agreement with the neoclassical TRANSP prediction.

The discharges performed to resolve this discrepancy retained the main structure of the former studies. As shown in Fig. 1c) 5 MW of on-axis NBI were replaced by 5 MW of off-axis NBI and back. Additionally, NBI beam 3 was on throughout the whole discharge to enable continuous MSE and FIDA coverage, as both diagnostics rely on this beam. With the higher NBI

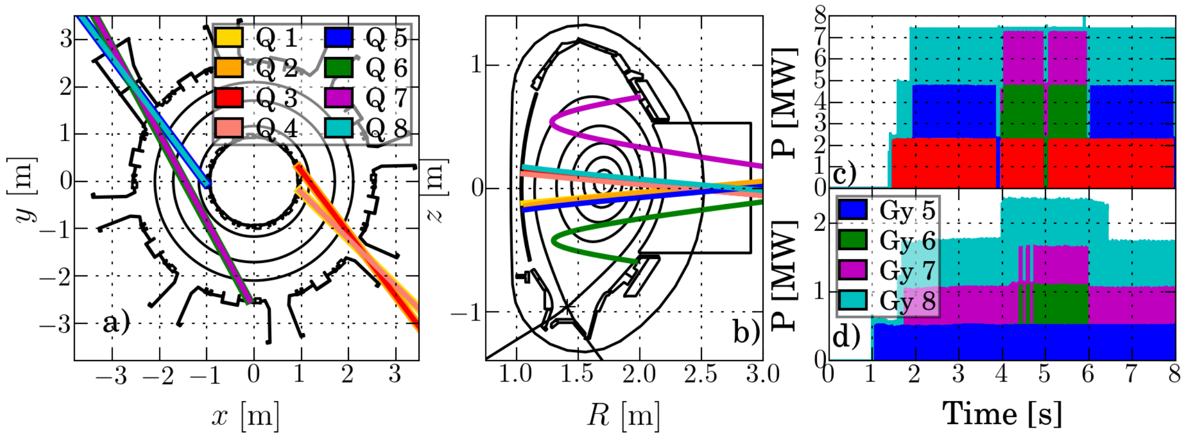


Figure 1: *a) Top-down and b) poloidal view of ASDEX Upgrade and the NBI geometry. c) NBI heating scheme (4–6 s off-axis) and d) ECRH timing for discharge #31453.*

power compared with the previous studies an NTM would appear which was avoided using ECCD preemptively with one gyrotron. Another gyrotron for central co-ECCD prevented sawteeth and tungsten accumulation. The last two gyrotrons operated in real time $T_e$ control mode, avoiding a drop of the central electron temperature while switching NBI from on- to off-axis. The ECRH heating scheme can be seen in Fig. 1d).

Figure 2 a) shows the evolution of the measured and TRANSP-simulated MSE angles. Lacking absolute calibration, the simulation of each line of sight is shifted by a constant angle in such a way that the angle averaged over the time intervals from 3.3 to 3.7 s and 7.3 to 7.7 s matches the measurement. The angles from all radial channels change at the switch from on- to off-axis NBI. Whereas in the central channels ($\sim \rho_{\mathrm{pol}} = 0.2$) the angle decreases the edge channels see an increase ($\sim \rho_{\mathrm{pol}} = 0.6$). These changes can be explained by a combination of varying Shafranov shift due to the different beam geometries of the sources used and the redistribution of the current from the center to closer to the edge. In Fig. 2a) the measured angles are also compared with those simulated with TRANSP. There are a number of differences in the simulations with respect to those reported in [4]: Firstly, an error in the sign of the radial electric field for MSE calculations in TRANSP was corrected [7], affecting mainly the channels $\sim \rho_{\mathrm{pol}} = 0.6$ by about $\sim 0.1^{\circ}$. Secondly, the NBI geometry was reviewed based on infrared measurements, leading to corrections of some beam positions in the cm range. This improves agreement in the temporal evolution (see 2–3 s). Thirdly, besides these mere corrections, instead of assuming a flat diffusion coefficient of $0.5\,\mathrm{m}^2/\mathrm{s}$ a $\rho$-, time-, and energy-dependent diffusion coefficient was estimated using the formulae given by Pueschel at al. [8]. The calculated values are between 0.05 (off-axis phase) and $0.45\,\mathrm{m}^2/\mathrm{s}$ (on-axis phase, central). Within the errors the agreement with the measurement is quite good for all corrected TRANSP simulations. As Fig. 2a) shows, it is not possible to resolve the difference between neoclassical transport and the low levels of expected anomalous fast ion diffusion based on the MSE data.

Figure 2b) and c) shows corresponding radial FIDA profiles and TRANSP simulations. In the on-axis case b) the agreement is better with the assumption of anomalous fast ion diffusion. In the off-axis case c) none of the simulations fits perfectly. Whereas all underestimate the center

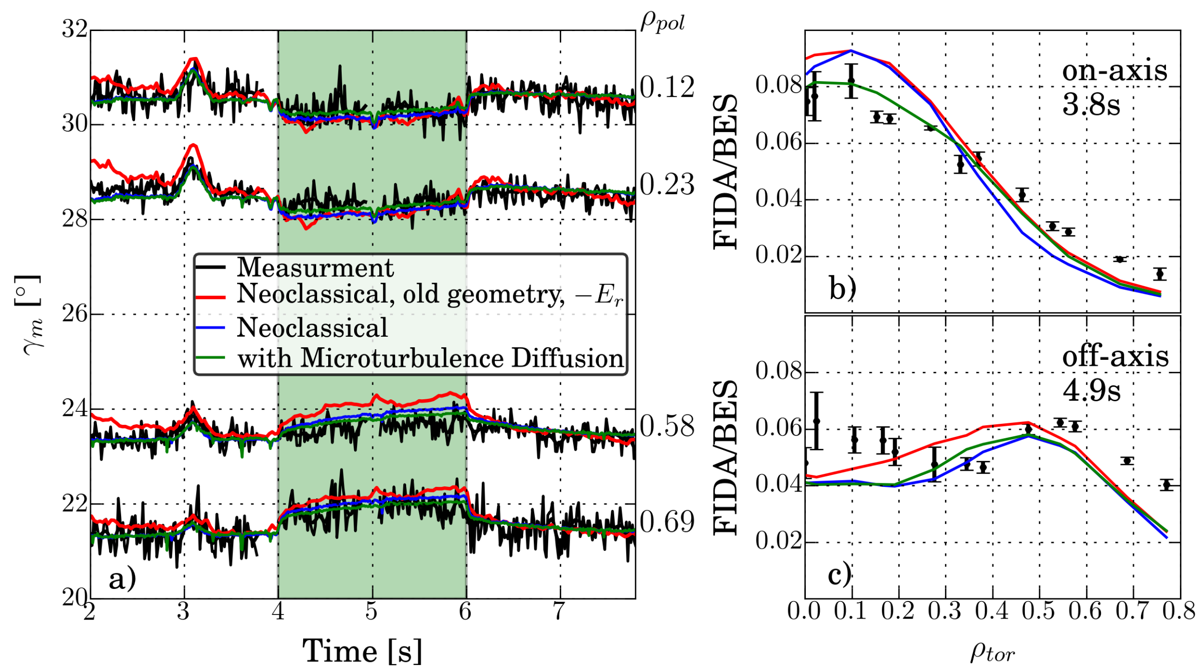


Figure 2: *a) MSE angles. Off-axis phase marked in green. Radial measured and modeled FIDA profiles b) on-axis, c) off-axis.*

and the edge, the corrected simulations fit slightly better at intermediate $\rho_{\text{tor}}$. The light anomalous fast ion diffusion of $\sim 0.1\,\text{m}^2/\text{s}$ predicted for the off-axis case leads to a slight broadening of the peak. As of now the discrepancies in the off-axis case remain an open question.

**High non-inductive current fraction**

To investigate conditions that could lead to a steady state tokamak, scenarios were designed [9] with practically fully non-inductive current drive. By simultaneously maximizing the neutral beam driven current and the bootstrap current ASDEX Upgrade discharges with nominal current of 600 kA and 800 kA were achieved with at least 95% $\pm$ 5% non-inductive current. The plasma current composition predicted by TRANSP [5] consists of $\sim 45\,\%$ NBCD, $\sim 40\,\%$ bootstrap current and $\sim 10\,\%$ ECCD, the rest being inductive. To reach the high bootstrap and neutral beam driven current fractions, high electron temperatures, low densities and a hollow current profile were necessary. With $\beta_{\text{pol}}$ feedback control the NBI power was kept close to the maximum feasible level below the stability limit. In Fig. 3a) the simulated current distribution of the 600 kA discharge is shown. After an inductive ramp up, $\beta_{\text{N}}$ was increased from 1.4 to 2.2 in the time from 2.5 to 3.5 s by increasing the NBI power up to 10 MW. At the same time a hollow current profile is formed due to off-axis ECCD which leads to a large increase of the bootstrap current. From around 4 s the inductive current, calculated as the difference between the plasma current and all non-inductive currents, becomes negative. This contradicts the non-negative loop voltage. The most likely reason is a slight overestimation of the non-inductive currents due to uncertainties in the experimentally determined quantities that enter this calculation, additionally the anomalous fast ion transport described above could play a role. Additionally a comparison

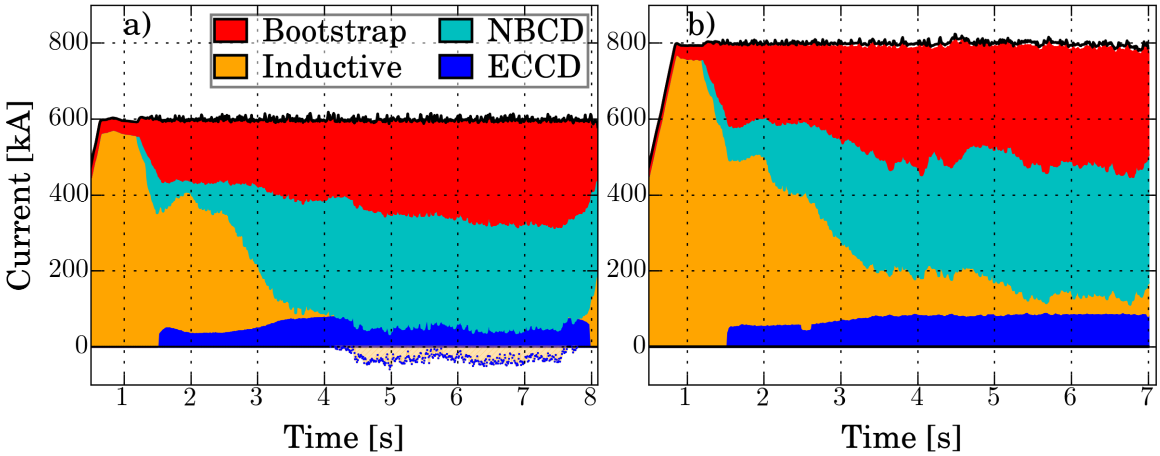


Figure 3: *TRANSP predicted current Distribution a) 600 kA (#33379) and b) 800 kA (#33134)*

with an equilibrium reconstruction constrained by MSE and polarimetry was made [9].

The 800 kA case (Fig. 3b)) is quite similar. Here the maximum $\beta_N$ is 2.7 and therefore 12.5 MW of NBI heating was now required. Additionally, the current in the central solenoid was kept constant from 4.5 s onwards, setting inductive current drive to zero. The plasma current stays almost constant at $\sim$ 800 kA ($-20$ kA in 2.5 s) and the remaining inductive current decays slowly while being compensated by an increase in bootstrap current. Unfortunately the discharge duration is limited to 7 s due to high heat loads. In combination with current diffusion time scale of several seconds this is too short to reach full steady state.

## Summary

The earlier apparent contradiction between FIDA and MSE measurements in off-axis NBCD discharges disappeared due to corrections to the analysis. Nevertheless, the fast ion distribution with off-axis NBI could not yet be properly reproduced by simulation. As a step towards steady state tokamak operation discharges at 600 kA and 800 kA with close to fully non-inductive current drive were demonstrated at ASDEX Upgrade.

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