Off-axis neutral beam current drive experiments on ASDEX Upgrade and JT-60U

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Neutral beam injection is a very robust tool for heating of high temperature plasmas and is used in most fusion experiments. In theory the neutral beam does not only heat the plasma but drives also current by the injection of fast particles either in the same or opposite direction to the plasma current. The fast particle current is in zeroth order compensated by electrons dragged with the ions. If $Z_{\mathrm{eff}} \neq Z_{\mathrm{beam}}$ then a net current can be created in the classical picture [1]. Despite this effect also the drag forces by the trapped electrons results in an unbalance between electrons and fast ions and create a net current. A more detailed description and a simplified calculation of the driven current profile can be found in [2]. The current drive by neutral beam injection is reported to be within the error bars by some experiments using zero dimensional analysis [3, 4, 5] for example by loop voltage analysis. Also radial resolved analysis has shown that on-axis current drive is within the the error bars using loop voltage profile analysis [6]. Significant changes of a measured current profile, for example by a Motional Stark Effect diagnostic [7] are expected by either on-axis counter current drive or by off-axis co current drive. The latter case is discussed in this paper. Experiments have been carried out in the JT-60U, the ASDEX Upgrade, and also more recently in the JET tokamak (not discussed here) to test the neutral beam current drive model for off-axis injection. The discharges are kept simple, the experiments are done in a stationary phase. An example of a discharge in JT-60U can be found in figure 1. The plasmas discussed here have a small current

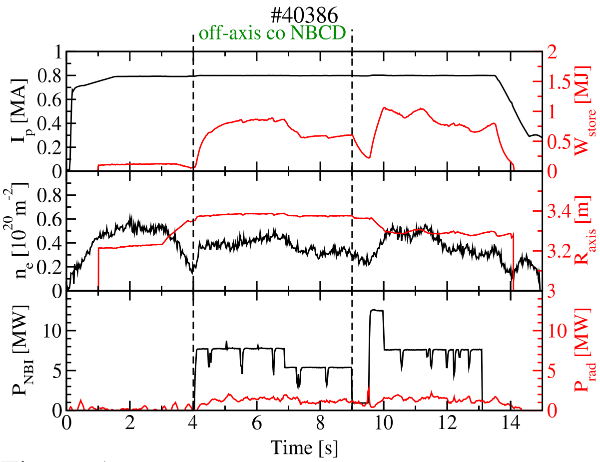

Figure 1: Main time traces for a discharge from JT-60U with strong NB injection in co direction from $t = 4$s to $t = 9$s. It the top graph the plasma current and the stored energy are plotted. In the middle the line integrated electron density (integration length ≈ 5.2m) and the R coordinate of the magnetic axis are represented. Last in the bottom graph the neutral beam injected power and the plasma radiation are drawn.

of $I_P = 800$kA and the experiments are started well after the current ramp up. The current profile was clearly relaxed before neutral beam injection was used. Two types of discharges are done, firstly discharges with changes in the deposition from on- to off-axis to see the change in profile (ASDEX Upgrade and JT-60U) and discharges with only off-axis injection (only JT-60U, because the diffusion time is much longer, approx. 16s) to maximise the effect on the current profile by neutral beam current drive (NBCD). The experiments on JT-60U and ASDEX Upgrade are very similar in many plasma parameters but the electron density for the JT-60U discharges is much lower than for the ASDEX Upgrade discharge. This means that the electron temperature is much higher than for ASDEX Upgrade and the current drive efficiency is also much higher. In figure 2 the evolution of the equilibrium reconstructed q-profile is shown. The change in the profile is very small, almost negligible. Unfortunately the code calculations done for this discharge which predicted a reversed shear after 2s injection this discharge which predicted a reversed shear after 2s injection time are not reliable because the fast particle content is too high to make a useful linear Fokker-Planck calculation. This is not the case for the ASDEX Upgrade discharge from which the measured polarisation angles which are mainly the magnetic pitch angles in a simple geometry of the MSE diagnostic are shown in figure 3. The time duration of 2 sec is long enough for building up stationary profiles in temperature, density and current according to the ASTRA modelling of this discharge. The MSE measurements recorded for this discharge are restricted to the phases of on-axis deposition since MSE relies on an on-axis beam and unfortunately the diagnostic was not calibrated and thus no equilibrium can be reconstructed from these measurements and no q or current profile can be inferred. The measured MSE angles plotted in figure 3

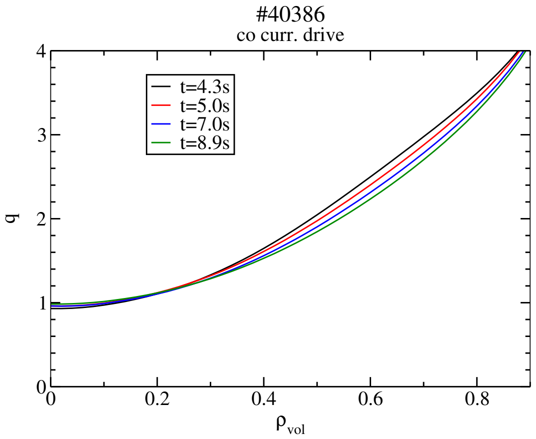

Figure 2: Equilibrium reconstructed q profile development for off-axis NB co injection (4-9s). The MSE measurement used as constraint for the equilibrium reconstruction do not cover the very centre of the plasma (≤ 0.2)

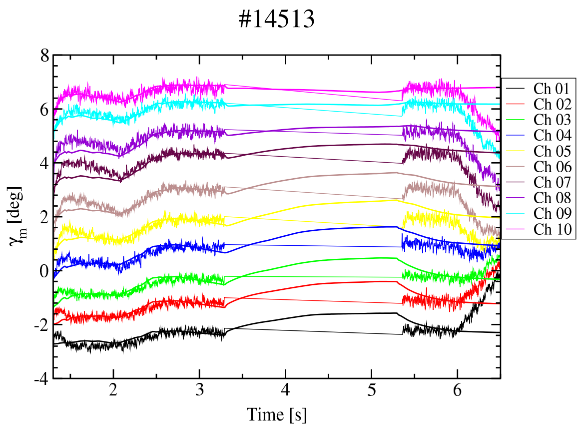

Figure 3: MSE polarisation angles for the discharge shown in the previous figure. From $t = 3.3$s to $t = 5.3$s no data is available. The diagnostic covers the plasma between $\rho_{tor} = 0.1$ and $\rho_{tor} = 0.8$ with a spatial resolution of about 3cm. Channel 1 at the bottom is the most outside channel and No. 10 the most inside. The peak of the off-axis neutral beam injection is at channel 5. The noisy time traces are the measurement. ASTRA calculations are shown as thick lines.

are offset corrected to the angles calculated by ASTRA [8] at $t = 2.8$s. The differences between the calculated and the measured angle at the beginning of the injection phase can be attributed to a wrongly modelled plasma energy in this phase. The larger differences at the end of the discharge ($t > 6$ s) in the MSE angles are due to the fact that the current ramp down is not included in the modelling and shows that the diagnostic is sensitive to the changes in poloidal field. The MHD activity in this discharge shows sawteeth and fishbones at the $q = 1$ surface at $\rho_{tor} \approx 0.36$ during on-axis deposition. With off-axis tangential injection the sawtooth oscillation stops but a continuous (1,1) mode starts at the same radial location as the sawtooth precursors were before. This indicates that the position of the q=1 surface does not change. Frequency and position of this (1,1) mode is stable for the whole of the 2s interval. After switching back to the central deposition the sawteeth reappear in less than 10 ms which is too fast to be a result of a current diffusion process over a large spatial range. The constant location of the $q = 1$ surface determined by the MHD activity is in full agreement with the given interpretation of the measured MSE angles but again in contradiction to the modelling. In a next step, two nearly identical discharges, one with the more normal on-axis and one with the tangential off-axis beams, have been compared. As shown in figure 5 the slope of the current in the ohmic transformer changes when changing the injection geometry. This difference in ohmic transformer current slope can be used to infer the total current driven by the off-axis tangential beams if all other current sources are given. In this analysis, the slight variation (less than 5%) in the plasma parameters (T_e, Z_{eff}, n_e) between the two discharges have been taken into account in ASTRA to determine the difference in resistivity. Using the bootstrap current from the ASTRA calculation the driven current by the tangential on-axis beams is calculated to $I_{NBI} = 247$kA from the difference in slope of the

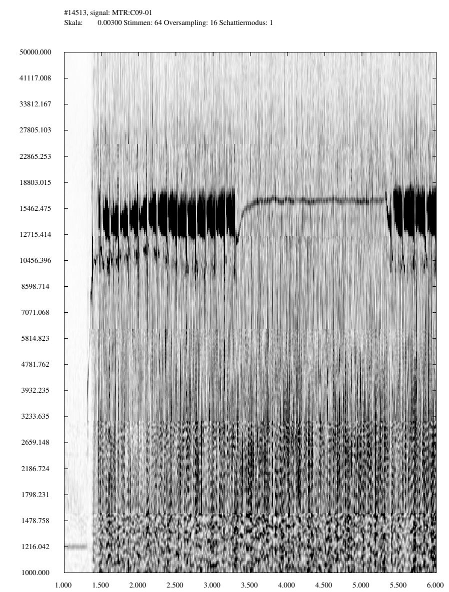

Figure 4: Wavelet plot of the MHD activity in ASDEX Upgrade discharge. The wavelet plot shows the amplitude of a certain MHD activity in darkness, the frequency is on the y axis, and the time is on the x axis. The type of MHD changes with off-axis injection and with turning off the off-axis injection. The mode number and position does not change.

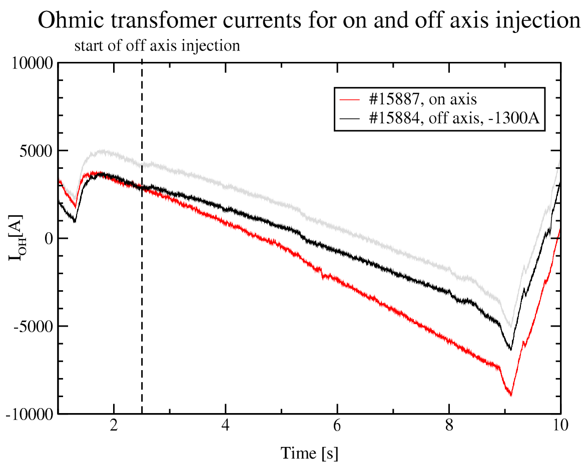

Figure 5: Equilibrium reconstructed q profile development for off-axis NB co injection.

ohmic transformer current, which is in reasonably good agreement with the $I_{NBI} = 300$kA calculated by ASTRA. This shows that a total current of the order of the expected one is driven by the tangential beams. The experiments discussed here are not fully conclusive. The current driven by the neutral beams can be verified by analysing the ohmic transformer current but the predicted influence of this driven current on the current profile is not confirmed by the MSE measurement nor by the MHD activity. These findings might indicate that a fast transport process moves the fast particles from the off-axis position to somewhere else. To be more specific, a transport process is needed which results in a neutral beam current profile very similar to the ohmic current profile, for example like in the on-axis injection case where no significant change in the q-profile between the ohmic phase and the on-axis injection phase could be found. A likely candidate would be a Alfvén like MHD activity but up to now no indications are found for this kind of MHD. The sawteeth could be another candidate for a fast particle transport but they disappear (together with the fishbones) when changing the neutral beam deposition and they are, therefore, not able to influence the fast particle distribution any more. Further more in the experiments on JT-60U no sawteeth are present and in some other discharges no MHD at all could be found, nevertheless no clear effect on the total current profile by the off-axis co NBCD could be obeserved yet. Up to now, no single discharge on ASDEX Upgrade has clearly indicated an influence of the off-axis injection on the MSE measurements, even though very different MHD activities may be present (like tearing modes). Apart from MHD one could speculate about an anomalous transport leading to a redistribution of the fast particles (like ion temperature gradient modes) or about a kind of stiffness in the current profile. The last explanation, however, is very unlikely because ECCD (and lower hybrid current drive) clearly has an influence on the plasma current profile. Further experimental investigations are needed to clarify these findings.

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