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Conditions for NBI Current Profile Control on ASDEX Upgrade

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ASDEX Upgrade is now equipped with a flexible NBI heating system, allowing on- and off-axis heating and off-axis current drive [1]. Although in early experiments significant differences between the loop voltages in discharge phases with on-axis heating and off-axis current drive configurations have been found, no evidence of changes in the current profile was observed, in marked contrast to predictions of the ASTRA transport code [2]. These observations were based on MSE measurements and the localisation of MHD modes, and extended over a sufficient time interval to achieve stationarity in the current distribution (> 2s). They have cast significant doubts on the feasibility of ITER scenarios involving current profile control by tangential, off-axis NBI injection.

In order to check if the amount of driven current agrees with the predictions of classical slowing-down models we have performed dedicated experiments, changing the beam distribution between on-axis heating and off-axis current drive. In order to match the electron temperature (and thus the Ohmic current profile) we have added some central electron cyclotron heating during the off-axis NBI phases (Fig. 1). Some central current drive is expected also during the on-axis NBI phase, but a much larger amount of current is predicted to be driven at about half the minor plasma radius during the off-axis NBI phase (see Fig. 2).

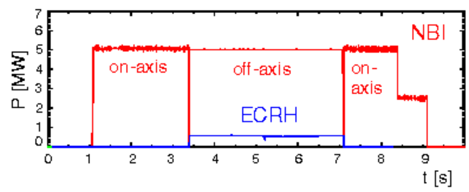


Fig. 1. Time traces of heating power in Discharges with on- and off-axis NBI

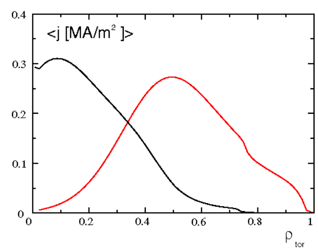


Fig. 2. Radial profiles of the flux surface averaged current density for on- (black) and off-axis (red) NBI.

A set of experiments were conducted in a low triangularity configuration, at a plasma current of 800 kA and with a total NBI heating power of 5 MW. The measured and predicted changes in the inductively driven current, caused by the switch between the NBI sources, is shown in Fig. 3. The experimental values have been derived from the loop voltages at the plasma edge during the on- and off-axis NBI phases, respectively. To achieve stationary conditions also at lower densities, we chose a single phase of on-axis NBI, to allow sufficient time for current profile relaxation (up to 5 s). The measured loop voltage changes are significantly smaller than the predicted ones: especially at low densities/high temperatures, with the discrepancy reaching up to a factor 3. Even at these reduced efficiencies, the remaining NBI current drive (e.g., ≥100 kA for n_e=4 10^{19} m^{-3}) should, however, still suffice to give rise to significant current profile modifications, particularly in situations where strong off-axis current drive is predicted. According to the MSE measurements the q-profiles in the on-and off-axis NBI phases coincide, however, within error bars. Obviously a redistribution is taking place, either of the current itself (e.g., by the observed (1,1) mode activity), or of the driver of the additional current, the fast ions.

To test the hypothesis of an MHD-like current redistribution we have checked the influence of the q-profile and, in particular, the role of the q = 1 surface, varying q at the plasma edge between 4 and 6.2. We did not find any obvious influence of q_a within this range. The measured current drive efficiency at the maximum value of q_a used (q_a =6.2, B_t=2.5 T, I_p=600 kA) was comparable to that observed in the 800 kA discharges, in spite of larger influence of the NBI driven current expected at the lower total current. In the experiments with q_a=4.7 (B_t=2.5 T, I_p=800 kA), marked by black symbols in Fig. 3, some (1,1) mode activity was observed. The q=1 radius in these discharges (ρ_{tor} < 0.1) appears, however, too small to cause a significant redistribution of driven current at about half the minor radius. In the discharges with q_a =6.2 no (1,1) activity was observed at all.

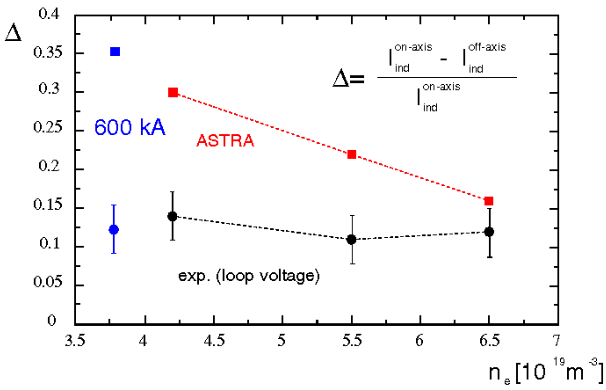


Fig. 3: Comparison of the predicted (red) and measured (black) relative changes in the current driven by the Ohmic transformer between discharge phases of on- and off-axis NBI. Discharge conditions: B_t=2.5T, I_p=800 kA, δ=0.15. P_{NBI} = 5 MW.

A modification of the current profile caused by off-axis NBI current drive was seen when the NBI power was reduced by a factor of two (to 2.5 MW), at otherwise identical discharge parameters (δ=0.15, B_t=2.5 T, I_p=800 kA). Although, due to the reduced NBI power, the driven current predicted was much smaller than in the former case (about 100 kA), a significant shift in the q=1 surface (Fig. 4) and changes in the measured MSE angles were observed, both in quite good agreement with ASTRA simulations.

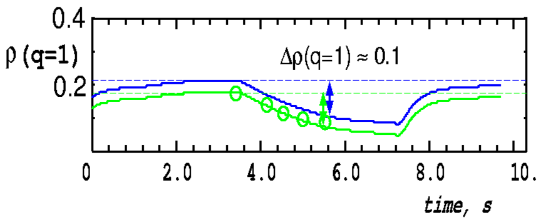
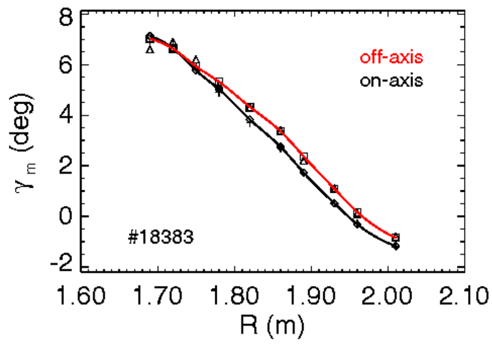


Fig. 4. Shift in the q=1 radius due to off-axis current drive as predicted by ASTRA (blue) and measured by ECE (green circles). Fitting the ASTRA q-profiles to the experiment at a time before the off-axis NBI phase (3.5s), good agreement is found (green line).
NBI power: 2.5 MW, B_t=2.5T, I_p=800 kA, δ =0.15.

Increasing the plasma triangularity, successful current profile modification could be extended even to the 5 MW level of off-axis NBI (traces of heating power as shown in Fig. 1). At the same discharge parameters as above (B_t=2.5 T, I_p=800 kA), but at an increased triangularity of δ=0.4, we observed significant changes in the MSE angles and in the inferred q-profile between the on- and off-axis NBI phases (Fig. 5). Such a q-profile modification is also consistent with the shift of the q=1.5 surface determined from a small (3,2) NTM, seen in the discharge shown in Fig. 5. (This (3,2) mode, however, is itself certainly not responsible for the q-profile modification as the latter was observed also in discharges without MHD activity.)



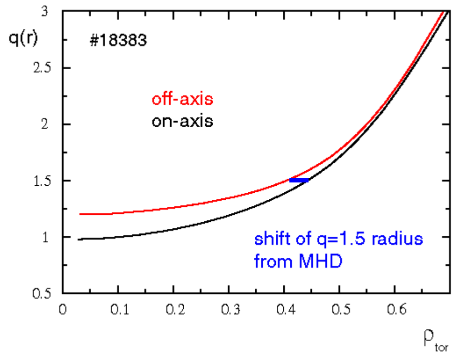
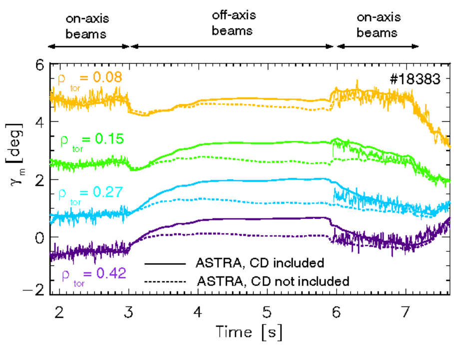


Fig. 5: Comparison of the MSE angles (left) and the resulting q profiles (right) between the discharge phases with on- and off-axis NBI. The q-profile modification is consistent with the shift of the q=1.5 surface as derived from the location of (3,2) MHD activity. NBI power: 5 MW, B_t=2.5T, I_p=800 kA, δ =0.4.

The observed changes in the MSE angles in this case are largely consistent with ASTRA- code simulations. Fig. 6 shows that the predicted current profile relaxation after switching from off-axis to on-axis beams is in quite good agreement with the MSE measurements. This holds particularly for the MSE channels located inside ρ_{tor}=0.3. The changes in the outer MSE channels are significantly smaller than predicted. Thus, the anticipated amount of beam current appears indeed to be driven, albeit localised at smaller radii than calculated by ASTRA. As ASTRA shows a systematic outward displacement of the energy deposition compared to a stand-alone beam deposition code, we are currently setting-up TRANSP simulations to be able to include, e.g., finite orbit and beam diffusion effects into the current drive calculations.



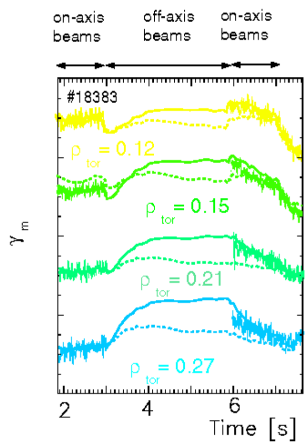


Fig. 6: Time traces of the MSE signal during the on-axis NBI phase compared to the ASTRA predictions including (solid line) and excluding (dashed line) the beam current contribution. Total NBI power: 5 MW, B_t=2.5T, I_p=800 kA, δ =0.4.

The application of further central NBI heating power (+2.5 MW) to such discharges during all phases, makes, however, the observed current profile modification vanish also in these high triangularity cases (Fig. 7).

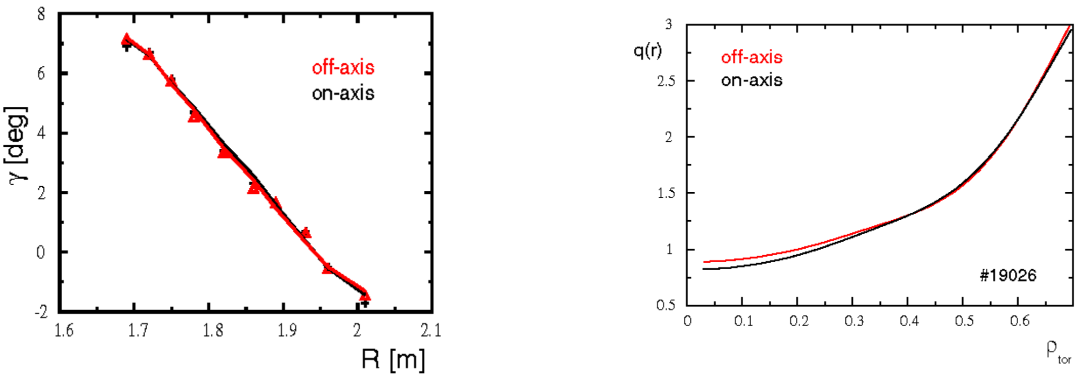


Fig. 7: Comparison of the MSE angles (left) and the resulting q profiles (right) between the discharge phases with on- and off-axis NBI. NBI power: 7.5 MW, B_t=2.5T, I_p=800 kA, δ =0.4.

The last experiment seems to rule out fast particle resonant modes – of which we also had not seen any direct indications in soft X-ray and Mirnov signals - as the origin of spatial redistribution of NB ions, as the added beam has a different spatial and pitch angle distribution and a lower energy. For a more direct proof we have modified the beam voltage of our current drive beams from 93 keV to 69 keV, bringing the deuterium ion velocity below the Alfvén resonance at $v_A/3$. At a comparable heating power the results were virtually identical to those of the higher voltage system.

Summary and Conclusions:

Experiments carried out on ASDEX Upgrade with off-axis NBI current drive show the redistribution and a strong reduction of the additional driven current at higher input powers. Experiments at different q_a, and the frequent absence of measureable MHD activity appear to rule out a dynamo-type re-arrangement of the magnetic field. We have also established that the current re-distribution is closer connected to the passing heat flux than the local fast particle energy density. This, together with the negative outcome of experiments with sub-$v_A/3$ beam velocity, indicates that a diffusive redistribution of fast ions, driven by turbulent fluctuations correlated with the thermal transport, lies at the origin of these observations. The improved performance, at given current drive power, of the high triangularity discharges, in turn, is also in agreement with the observed trend towards better energy confinement in the latter geometry.

A fast particle diffusivity D_f will broaden the current profile over a range $\Delta_f \approx a\sqrt{\tau_s\langle D_f\rangle/(\tau_E\langle\chi\rangle)}$, which for a typical relation of slowing down (τ_s) to energy confinement (τ_E) time: $\tau_s \approx \tau_E/2$ can readily lead to a flattening of the beam driven current density over half the plasma radius, if D_f is assumed approximately equal to the heat diffusivity χ. This diffusive spreading will fill-in the fast particle distribution in the center, but will also bring energetic ions into the outer, cooler regions, where they will undergo a faster slowing-down, resulting in an overall reduced current drive efficiency. It should be noted in this context that this spreading will have a much smaller effect on other measures of the fast ion population, like their β -contribution or the neutron production, as the latter effects weight more strongly the highest velocity phase of the slowing down history.

[1] A. Stäbler et al., Fusion Science and Technology **44** (2003) 730
[2] J. Hobirk et al., 30th EPS conference, St. Petersburg, Russia, 2003, O-4.1B