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Current Profile Modification by off-axis NBI on ASDEX Upgrade

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NBI has established itself as a robust, largely parameter independent heating method, with the capability, to drive also substantial plasma current at high enough T_e. Particularly for advanced tokamak regimes, control not only of the magnitude, but also of the spatial distribution of the driven currents is essential, and is an important element of the present ITER planning. ASDEX Upgrade is equipped with a flexible NBI heating system, allowing on- and off-axis heating and current drive to test such scenarios. Experiments using this system reported previously [1] showed measurable changes in the current profile only for modest total heating powers. Above a certain threshold - depending on plasma shape - however, neither MSE signals nor the location of MHD resonant surfaces showed any detectable changes. We show in this paper that the observed total driven current agrees very well with results of TRANSP-code [2] analyses. At low heating power this agreement extends also to the spatial distribution of the driven current. At high heating power one has to assume anomalous broadening of the driven current, consistent, for example, with an anomalous diffusion of the slowing-down fast particles.

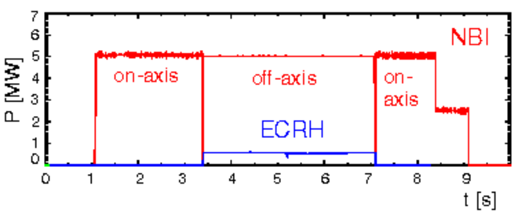

Fig. 1: Time traces for heating power in a typical NBI current redistribution discharge. The off-axis NBI is complemented by ECRH to keep the electron temperature approximately constant in time.

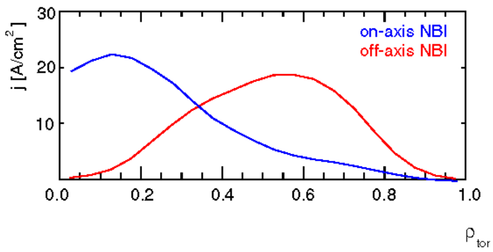

Fig. 2: Typical profiles for the NBI driven current density during on-axis (blue) and off-axis injection phases (red), as predicted by TRANSP.

A typical scenario for NBI current-redistribution experiments is illustrated in Fig. 1. Following current ramp-up we pass through a sequence: on-axis/off-axis/on-axis beam injection, with the length of the phases chosen to allow approach to resistive equilibrium. The off-axis injection is complemented by central ECRH, adjusted in power to keep the

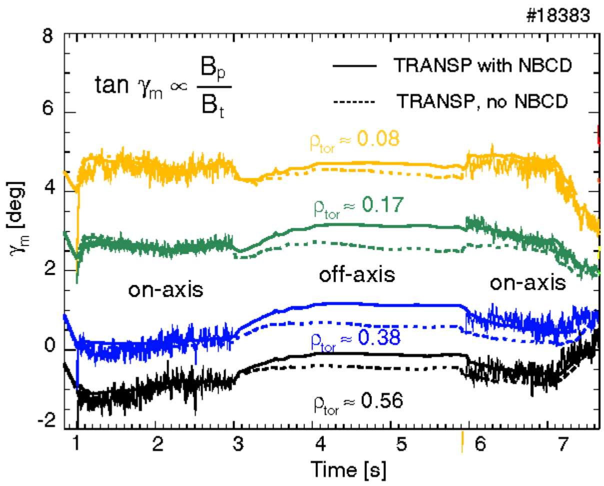

Fig. 3: Measured time traces of the MSE diagnostic at different radii compared to TRANSP predictions including (solid line) and excluding NBI current drive. Discharge parameters: I_p=800 kA, B_t=2.5 T, δ=0.4, P_{NBI}=5 MW, q_{95} = 5.0.

electron temperature, and hence the resistivity, approximately constant in time. All experiments reported in the following were in type-1 ELMy H-mode regime. The two off-axis beam-sources, with a beam voltage of 93keV and a total power of up to 5 MW have a tangency radius of 1.29 m (nominal major radius of ASDEX Upgrade: 1.65m) and are inclined vertically to be tangent, in a poloidal cut, to the half-minor radius flux surface. The on-axis beam sources (total power up to 15 MW) operate at 60 keV (4 sources) and 93keV (2 sources) respectively. The MSE system is linked to operation of one of the more radially directed 60 keV sources (tangency radius 0.93m). Fig. 2 shows typical profiles for the NBI driven current density during the on-axis and off-axis injection phases, as predicted by TRANSP.

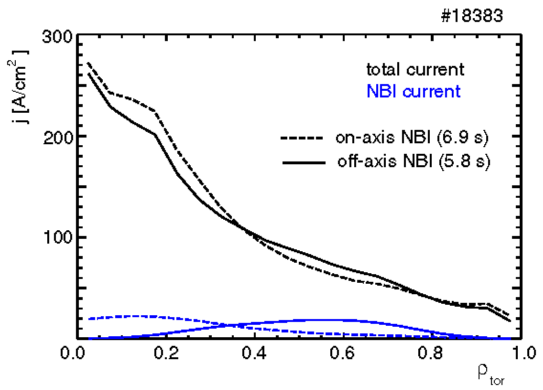

Fig. 4a: TRANSP results for NBI (blue) and total (black) current density profiles at the end of the off-axis (solid) and the on-axis phase (dashed) for the discharge shown in Fig. 3.

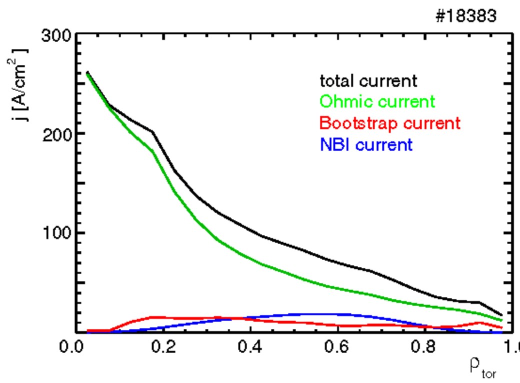

Fig. 4b: Contributions to the total current density at the end of the off-axis phase (5.8 s) for the discharge shown in Fig. 3, as resulting from TRANSP modeling.

At sufficiently low total heating power the measured time traces of the MSE signal correspond very well to the TRANSP prediction (Fig. 3). At high triangularity (δ~0.4), this regime extends up to our full off-axis power capability. As the MSE system is linked to an on-axis beam, only the signal during on-axis phases can be directly compared with the modelling results. It is evident, however, that the experimental MSE traces correspond - over the whole radius range - far better to signals reconstructed from TRANSP-runs including the NBI current drive with full nominal efficiency than to those neglecting it. Fig. 4a shows the modelled NBI and total current densities for two time instances, at the end of the off-axis

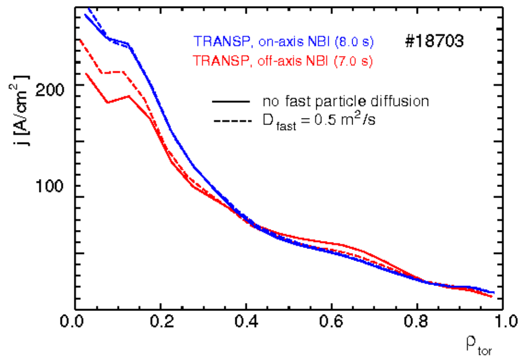

Fig. 6a: TRANSP current density profiles at the end of the off-axis (red) and the on-axis phase (blue) for the discharge of Fig. 5, with (dashed) and without (solid) fast particle diffusion.

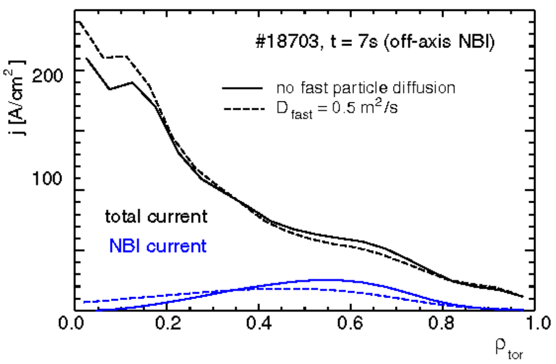

Fig. 6b: TRANSP results for NBI (blue) and total (black) current density profiles for off-axis NBI, without (solid) and with (dashed) artificially introduced fast particle diffusion.

and the second on-axis phase. Such changes in the current density profiles for low power discharges are also confirmed by the observed shift in the resonance location of occasionally appearing MHD activity. The different contributions to the plasma current density resulting from the TRANSP analysis at the end of the off-axis phase are shown in Fig. 4b.

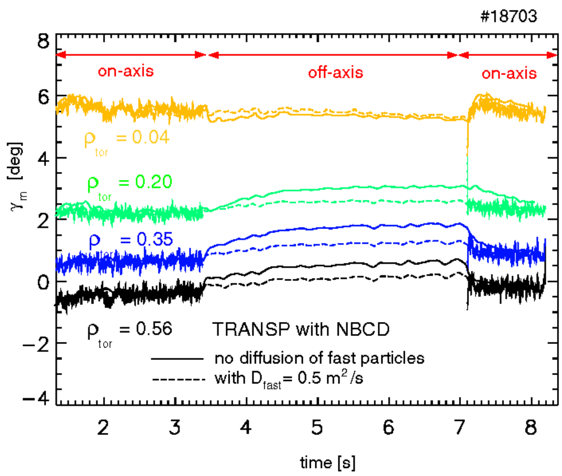

Fig.5: Measured time traces of the MSE diagnostic at different radii compared to TRANSP predictions including NBI current drive, without (solid) and with (dashed) artificially introduced fast particle diffusion. Discharge parameters: I_p=600 kA, B_t=2.5 T, δ=0.2, P_{NBI}=5 MW, q_{95} = 6.2.

In the high heating power regime (which for low triangularity (δ~0.2)is reached with less than 5 MW) the current profile changes measured by the MSE system fall significantly short of the predictions of the TRANSP code (Fig.5). The agreement can be substantially improved by introducing an artificial diffusion of the slowing down fast particles, assuming a diffusivity D_{fast} ≈ 0.5m^2/s. Fig. 6a shows the TRANSP current density profiles at the end of the off-axis and on-axis injection phases, computed both with and without fast particle diffusion. The consequences of fast particle diffusion on the NBI-driven current density distribution are illustrated in Fig. 6b for the off-axis case.

The predicted total driven current, as monitored by the loop voltage, agrees quite well with TRANSP simulations throughout all power regimes, even without the assumption of additional fast particle diffusion. The latter is, anyway, expected to affect the net-current drive efficiency only through higher order effects (e.g. by displacing particles into regions with different slowing-down rate). Nevertheless, simulations with fast particle diffusion appear to give also in this respect a slightly better fit (Fig. 7).

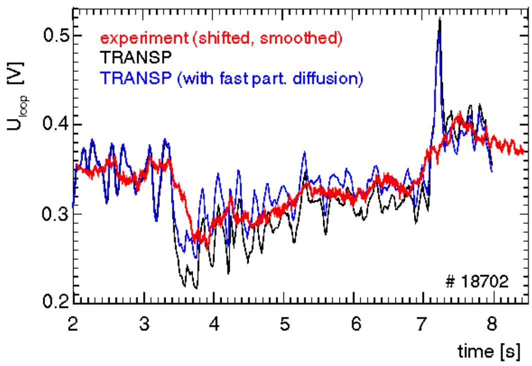

Fig.7: TRANSP prediction for the loop voltage without (black) and with (blue) fast particle redistribution compared with measured loop voltage (smoothed, and constant offset added). Discharge parameters: I_p=800 kA, B_t=2.5 T, δ=0.2, P_{NBI}=5 MW, q_{95} = 4.6.

Obvious candidate mechanisms for a fast-particle re-distribution are Alfven-type waves or other MHD activity. To rule out m/n = 1/1 type MHD activity of fishbone or sawtooth type we have carried out the NBI current re-distribution experiments also at q_{95} values corresponding to vanishing (1/1) activity, with similar results for the observed and modelled NBI current distribution. In fact, the discharge shown in Figs. 5 and 6 corresponds to $q_{95} > 6$. To rule out a possible role of Alfven waves, we had previously already carried out experiments varying the resonance conditions for such waves, e.g. by reducing the beam velocity below $v_A/3$, without change in the observed behaviour. We also have found no direct evidence for Alfven wave activity, in spite of a dedicated search with Mirnov, SXR and recently also reflectometry and interferometry diagnostics. It should also be noted that observations of Alfven activity for $v_{||} < v_A/3$ in other experiments appear to be restricted so far to hollow-q profiles (see e.g. [3]), a situation not pertinent to our experiments.

[1] J. Hobirk et al. 30th EPS conference, St. Petersburg, Russia, 2003, O-4.1B; S. Günter et al., 31st EPS conference, London, UK, 2004, O1.02

[2] A. Pankin et al., Comp. Phys. Comm. 159, No. 3, 2004, 157

[3] R. Nazikian et al., 20th IAEA FEC, Vilamoura, Portugal, 2004, IAEA-CN-116/EX/5-1

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