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The Role of Neutral Beam Injection Geometry in Advanced Discharge Scenarios on ASDEX Upgrade

A. Staebler, P. Franzen, J. Hobirk, A. Peeters, A.C.C. Sips, and the ASDEX Upgrade Team

Max-Planck-Institut für Plasmaphysik, D-85748 Garching, EURATOM Association

1. The Neutral Beam Injection Geometry on ASDEX Upgrade

The optimisation of advanced tokamak discharges with respect to confinement and stability requires means to control the plasma profiles, in particular the current density or q(r) profile. Since tangential neutral beam injection (NBI) has proven to be an efficient way of non-inductive current drive (CD) a properly chosen injection geometry could help to control q(r).

The NBI system of ASDEX Upgrade consists of two injectors, each equipped with four beams of up to 2.5 MW / beam for deuterium injection (NI-1: 60 kV; NI-2: 93 kV). Recently, the geometry of NI-2 has been significantly modified [1]: a more tangential injection direction of the injector as a whole and a steeper injection angle w. r. t. the horizontal mid-plane of the two more tangential beams are now realised, in order to achieve off-axis beam deposition and CD for these two beams. The new injection geometry is shown in Fig. 1 and compared with the geometry of NI-1. The two off-axis beams have a radius of tangency R_T = 1.29 m which ensures that these beams do not hit the inner wall and that essentially all fast ions are born on passing orbits and therefore can contribute to NBI current drive. For the two more perpendicular beams of NI-2 with R_T = 0.84 m, however, ions starting between $R \approx R_0+a/2$ and R_0+a are initially trapped. It should be noted, that both tangential beams are markedly off-axis only, if the plasma is centred near the midplane. For vertical plasma shifts of around 10 cm the beam coming from below deposits a notable part of the power still near the centre, however, the sum of both tangential beams is peaked off-axis.

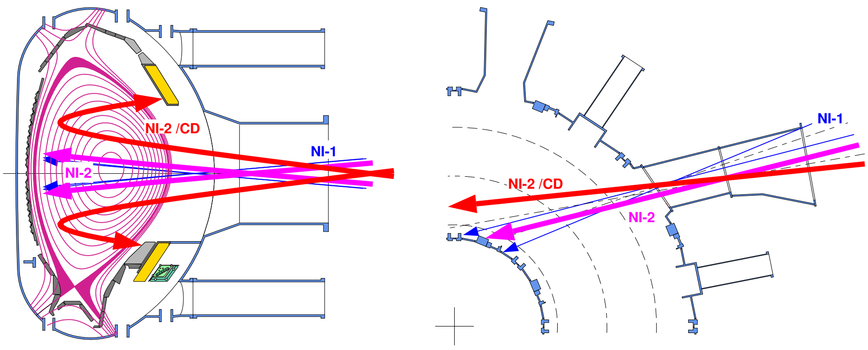

Fig. 1*: Plan and top view of the NI-2 injection geometry (thick lines) compared to NI-1 (thin lines)*

This contribution deals at first with the experimental observations associated with transitions from on-axis to off-axis heating (section 2) and then illustrates how the observed differences are used to optimise different advanced scenarios on ASDEX Upgrade [2] (section 3). Finally, the results will be summarised in section 4.

2. Effects of On-Axis and Off-Axis Heating

In discharges (H-mode, 0.8 MA, 2 T, δ = 0.2, no gas fuelling) where successively all eight beams were switched on for 1 s (P_{NI} = 2.4-2.5 MW) significant differences show up in plasma energy content (0.28-0.37 MJ), in line averaged density ($4.4\text{-}5.3\cdot10^{19}$ m^{-3}) and, especially in the sawtooth behaviour. The density rise observed during off-axis heating is due to density

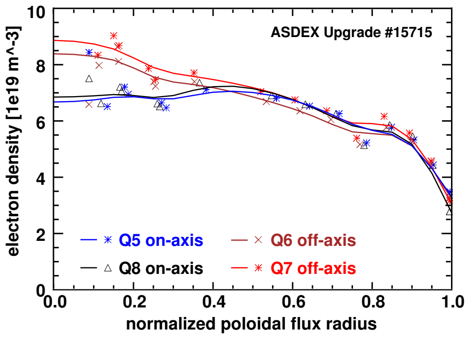

Fig. 2: n_e profiles for a discharge, heated successively with all beams, taken at the end of all phases heated with the NI-2 beams.

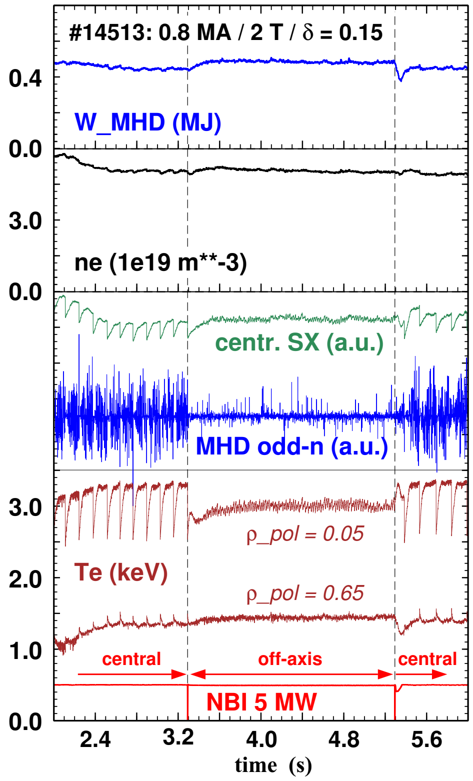

Fig. 3: Transition from on-axis to off-axis heating at 5 MW

peaking as shown in Fig. 2. This observation is consistent with the model presented in ref. [3] which links particle fluxes with heat fluxes: off-axis deposition leads to a low central heat flux and consequently to a reduced central particle flux.

The significant changes in the MHD behaviour of the plasma at a transition from on-axis to off-axis beam heating is shown in Fig. 3 for P_{NI} = 5 MW. During central heating prominent sawteeth are present on the central soft X-ray signal as well as on T_e measured by ECE, and the strong n = 1 mode activity is dominated by sawteeth, a (1,1) mode and fishbones. Sawteeth disappear and the fishbone activity is reduced, immediately after switching to off-axis heating and only a continuous m = 1 activity remains, indicating that the q = 1 surface is still present. The abrupt changes in MHD behaviour, illustrated in Fig. 3, appear on a time scale much faster then the current diffusion time ($\tau_{diff} \approx$ 1 s) obtained in the simulations. This indicates that the observed central MHD is strongly determined by the fast ion distribution for which the slowing down time ($\tau_{sd} \approx$ 50-100 ms) is the relevant time scale.

This discharge (Fig. 3) was part of an effort to study off-axis NBCD [4]. The MSE diagnostic, measuring the j(r) profile, relies on an on-axis heating beam of NI-1 and allows therefore only to detect the difference in current profile induced by the off-axis beams between the end of the first (t = 3.3 s) and the start of the second central heating phase (t = 5.3 s) which then can be compared with code simulations. According to these simulations the expected relative changes in q(r) should well be within the detectable range of the diagnostic, however no significant change of the MSE angels was found – i.e. the predicted off-axis peaked NBI driven current could so far not be verified experimentally. On the other hand, the measured loop voltage can only be reproduced by the simulation when a total beam driven current is taken into account which is of the order of the one calculated by standard models of NBCD. This has been further confirmed by comparing the OH flux consumption of two dischages with the same β_p, one heated with the more tangential off-axis beams the other one with more normal on-axis beams.

3. Off-Axis Beams in Advanced Discharge Scenarios

The study of advanced scenarios on ASDEX Upgrade [2] is concentrated on the one hand on steady state discharges with emphasis either on high confinement at moderate density (Improved H-mode [5]) or on high β_N close to the Greenwald limit (High β_N plasmas [6]), both at weak central shear, and on the other hand on the formation of internal transport barriers (ITB) with reversed central q(r). It will be illustrated in this section how the various characteristics of the NBI system are useful to optimise the performance of these discharges.

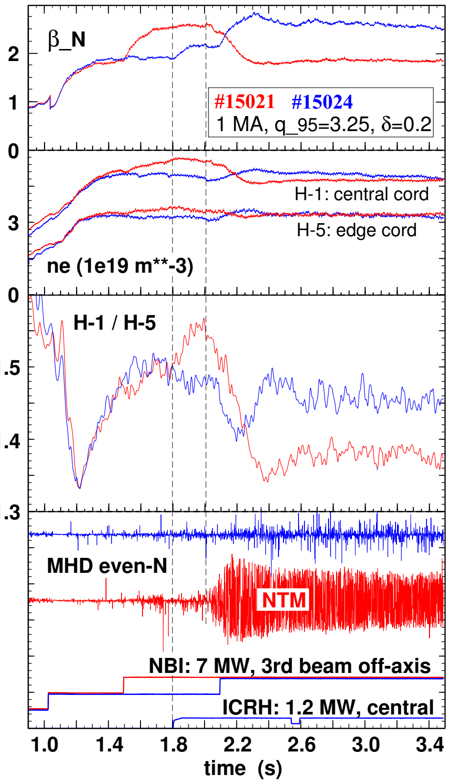

***Fig. 4**: Recipe to achieve stationary improved H-mode plasmas (s. text)*

3.1 Improved H-Mode

The improved H-mode was originally established in low triangularity (δ = 0.2) plasmas with no gas puffing ($n_e/n_{GW}\approx0.3$) at $q_{95}\approx4$ by early NBI heating; $H_{98Py,2}$=1.5 and β_N=2.2 were achieved. These discharges are characterised by the absence of sawteeth, strong fishbone activity and a peaking of the density profile. Recently the parameter range could be extended to lower values of q (q_{95}=3.25) and higher heating power (P_{NI} = 7 MW plus P_{ICRH} = 1.2 MW) with $H_{98Py,2}$= 1.4, β_N=2.6 and $n_e/n_{GW}\approx0.4$ for more than 30 x τ_E limited by the pulse length.

Experimentally, these low-q, higher power discharges could only be obtained stationary when at least one off-axis beam and central ICRH heating was applied. Central ICRH has been shown to flatten density profiles [3]. The path to low-δ, q_{95}=3.25 improved H-mode plasmas is illustrated in Fig. 4 where two discharges heated with three beams are shown. After switching on the third beam, which is off-axis in both cases, sawteeth are suppressed, strong fishbone activity occurs and β_N rises considerably. It should be noted that this type of discharges require more than 5 MW of NBI for sawtooth suppression and strong fishbones. For shot #15021 (Fig. 4) which has no ICRH the density continuously peaks during off-axis heating as illustrated by the relation between the central and an edge cord of the DCN-interferometer (H-1/H-5) until the appearance of a neo-classical tearing mode (NTM) terminate the high confinement phase. Peaked density profiles are vulnerable to NTMs due to the $T\cdot\nabla n$ term of the bootstrap current [3]. If, however, central ICRH is applied before the third beam (#15024), the subsequent off-axis heating only results in sawtooth suppression and strong fishbone activity but now at reduced density peaking and the plasma remains stable at high confinement. For very similar discharges it has been shown that for on-axis instead of off-axis heating by the third beam the sawteeth remains resulting in a NTM after several τ_E, even without density peaking.

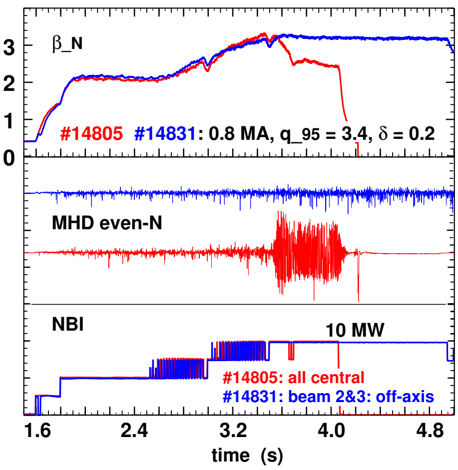

***Fig. 5**: High β_N discharges with on-axis and off-axis heating.*

3.2 High β_N Plasmas

High β_N plasmas are obtained by carefully tuning the rate of rise in heating power and in gas puffing in order to avoid on the one hand NTMs and on the other hand a too strong loss of confinement. Central ICRH is again applied to tailor the density profile. Stationary discharges are achieved with β_N=3.2 and n/n_{GW}=0.85 at δ=0.45 and β_N=3.0 and n/n_{GW}=0.6 at δ=0.2, both with 14 MW of additional heating power.

In the course of developing this type of discharge the effect of using different beams during the rise of the heating power has been studied. Fig. 5 shows two discharges at q_{95} = 3.2 and low triangularity where in one of them only central beam heating was applied, whereas in the other one the 2nd and 3rd beam were off-axis beams. For only central heating, a NTM appears at β_N slightly above 3. With combined on- and off-axis heating, however, the discharge remains stable at the same β_N-value until the end of the heating pulse. It is yet not clear whether the stronger fishbone activity observed for pure central heating or a higher β_p at the q = (3/2) radius is responsible for the NTM. The tendency, however, that discharges which include off-axis beams are less susceptible to NTMs in this scenario had the consequence that high β_N plasmas are obtained routinely with off-axis beams during stepping up the power.

3.3 Internal Transport Barriers

Like on other tokamaks ITBs with NBI heating are produced on ASDEX Upgrade by strong heating ($P_{NI} \geq 7.5$ MW) early during the current ramp at low density. High central ion temperatures well in excess of 20 keV were achieved with profiles showing a clear transport barrier. The ITB phases are so far obtained only transiently. In lower single null (SN) configuration the barrier is destroyed by the first ELM, whereas in upper SN, in L-mode, the peaking of the pressure profile leads to ideal modes at low β_N which terminate the ITB phase.

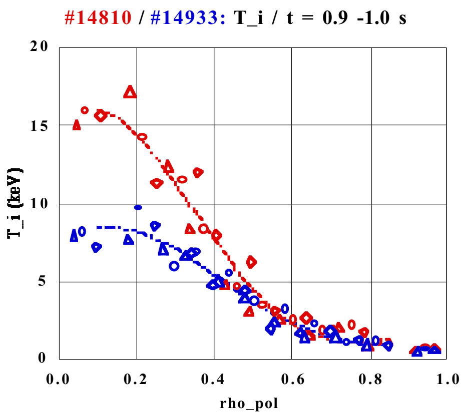

***Fig. 6**: Ti profiles of ITB plasmas; #14810: 3x on-axis beams #14933: 2x on- / 1x off-axis beams*

In order to establish strong ion ITBs sufficient central heating is needed. At the minimum required beam power of 7.5 MW only central beam deposition result in high central T_i. Fig. 6 show profiles of the ion temperature at the start of the current flat-top for two upper SN discharges, one with three on-axis beams, the other with two on-axis and one off-axis beams; P_{NI} = 7.5 MW in each case. This difference results in central T_i which differ by almost a factor of 2. At $P_{NI} \geq 10$ MW the effect of different beam deposition, however, is negligible since then always sufficient central heating is provided, especially as the transport barriers tend to become wider at higher heating power.

4. Summary

Off-axis heating is generally as efficient as on-axis heating for stiff temperature profiles. It leads to more peaked density profiles and significantly influences central MHD: sawteeth and fishbones are suppressed or reduced in amplitude. So far, however, no evidence for clearly off-axis peaked NB current drive was found. It has been shown how the mentioned properties can be utilised to optimise discharges and extend the parameter range in advanced scenarios. Advanced H-modes plasmas (improved H-mode, high β_N) benefit from the impact of off-axis beams on central MHD and from the possibility to control, in combination with central ICRH, the density profile. ITBs however require sufficient on-axis heating for their formation. In summary, the recent modification of the ASDEX Upgrade NBI geometry has made this system an even more flexible tool for plasma heating and profile control.

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