A PROPOSAL FOR OFF-AXIS HEATING AND CURRENT DRIVE WITH NBI ON ASDEX UPGRADE

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1. Introduction

The study of advanced tokamak scenarios in connection with divertor operation will be a major part of the ASDEX Upgrade programme during the next years. For a bootstrap current fraction of 70%, quasi-stationary tokamak operation at $I_P \approx 0.8$ MA with flat or reversed magnetic shear requires a non-inductively driven current of about 250 kA – peaked off-axis at around r/a ≈ 0.5 with a rather broad profile – in a plasma with $\bar{n}_e = 4 \cdot 10^{19}$ m^{-3} and $T_e(a/2) =$ 2 keV [1]. Presently, ASDEX Upgrade is equipped with two neutral beam injectors each delivering 10 MW (60 kV) D^0 beams to the plasma. One of these injectors will be upgraded to 100 kV later this year. It will be shown that moderate changes of this injector will be sufficient to fulfil the above mentioned requirements for off-axis current drive, even though NBI has not been considered as suitable candidate for off-axis current drive so far.

2. Optimization of beam geometry and parameters for off-axis current drive

Off-axis current drive by NBI requires (i) tangential injection in order to avoid trapping of fast ions and (ii) off-axis deposition of the fast ions. The four ion sources of an ASDEX Upgrade injector are arranged in a rectangle with the individual beams inclined by ±4.90° with respect to horizontal. In their present geometry one pair of beams is injected with a radius of tangency (R_T) of 0.53 m, the other one with $R_T = 0.93$ m into a plasma with $R_0 = 1.65$ m and a = 0.50 m. As a consequence, ions born at R > 1.75 m (for $R_T = 0.53$ m), and R > 1.95 m (for $R_T = 0.93$ m), respectively, are trapped. Efficient current drive, therefore, calls for a more tangential injection which can be achieved by turning the injector as a whole. Taking into account the space restrictions around the tokamak and allowing for a sufficiently wide port for beam transmission led to the choice of $R_T = 1.29$ m for the more tangential pair of beams. In this case only a negligible part of the fast ions will be born on trapped orbits.

Since injection with $R_T = R_0 + a/2 = 1.90$ m is impossible, off-axis beam deposition can only be achieved by having the beams travel through the plasma further above/below the midplane, i.e. by further inclining the beams and/or moving the beam sources further away from the plasma (see Fig. 1.). Keeping $R_T = 1.29$ m and $R(P_0)$ fixed the following cases have been studied in some detail:

(a) $\beta = 4.90°$, $\Delta x = -0.5$ m, i.e. present internal geometry;
(b) $\beta = 5.71°$, $\Delta x = 0$;
(c) $\beta = 6.65°$, $\Delta x = +1.0$ m.

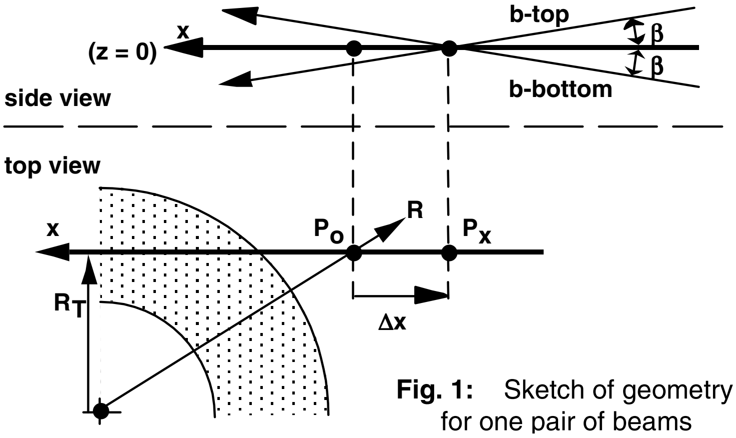

Fig. 1: Sketch of geometry for one pair of beams

Fast ion deposition profiles H(r) were calculated using the FAFNER code [2] which allows to model the exact beam geometry together with the optics of individual beams. A standard equilibrium and measured density and temperature profiles of an ASDEX Upgrade plasma were taken. The resulting deposition profiles are normalized such that integration over the plasma cross section gives the total injected power minus shine through. Fig. 2 shows H(r) for the three cases mentioned above. It is assumed that the two sources are injecting 2.5 MW each and that the plasma center is close to z = 0. Obviously, off-axis deposition peaked around $\rho = 0.5$ is achieved for $\beta = 6.65°$, $\Delta x = +1.0$ m.

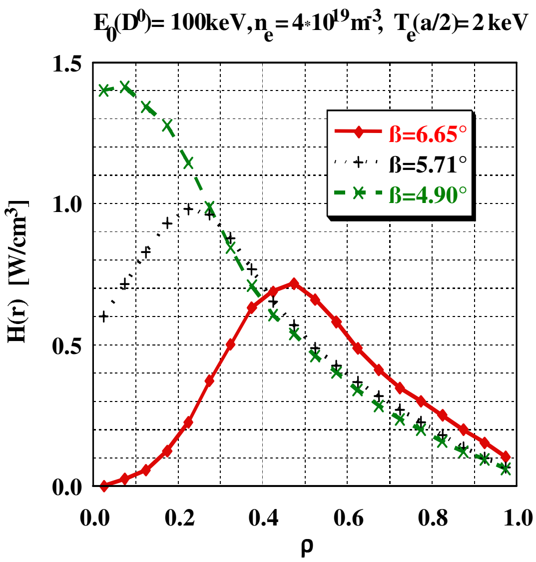

Fig. 2: NBI deposition profiles for three different injection geometries

It is interesting to note that this H(r) is rather independent of plasma and beam parameters. Changing beam penetration by increasing n_e and/or E_{beam} by a factor of 2.5 does not change the position of the off-axis maximum.

The relation between beam deposition and beam driven current for given plasma parameters was studied using the ASTRA code [3]. The input parameters for this code were carefully adjusted such that the resulting deposition profiles are in fair agreement with the above mentioned FAFNER results. Normalized profiles of H(r) and the resulting driven current densities for fixed plasma parameters ($\bar{n}_e = 4 \cdot 10^{19}$ m^{-3}, $T_e(a/2) = 2$ keV) are compared in Fig. 3. If differences close to the edge are neglected, where trapped orbits effects and enhanced losses are to be expected, H(r) and j_{NBCD} closely follow each other, independently of the region where most of the beam ions are deposited. The integrated beam driven current I_{NBCD}, however is higher for central current drive, reflecting the T_e-dependence of the NBCD efficiency.

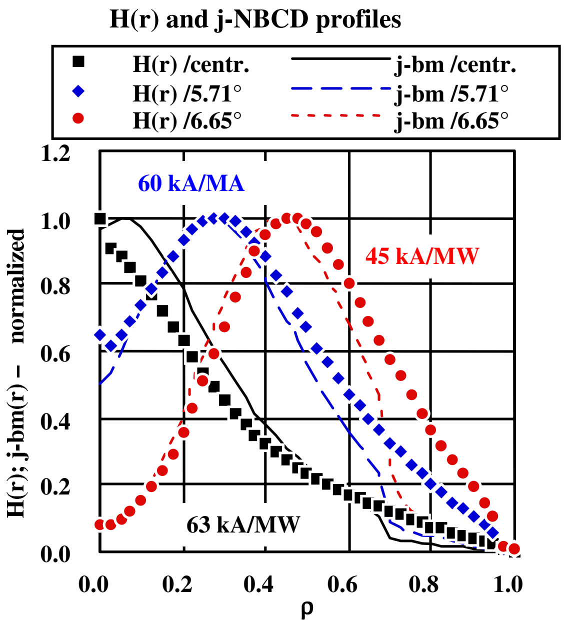

Fig. 3: NBI deposition profiles compared to neutral beam current drive profiles *($n_e = 4 \cdot 10^{19}$ m^{-3}, $T_e(0)$ = 4 keV, $T_e(a/2)$ = 2 keV)*

The parametric dependence of I_{NBCD} was determined by varying E_{beam}, n_e, T_e, and Z_{eff} in different ASTRA runs. The expected $I_{NBCD} \propto 1/n_e$-dependence was verified. Increasing Z_{eff} from 1.5 to 2.5 results in a 10% increase of I_{NBCD}. Further results for the $\beta = 6.65°$,

Δx = +1.0 m case are summarized in Table 1. As long as T_e at the position of maximum current drive stays relatively low ($T_e(a/2) \approx 2$ keV) the current drive efficiency of 100 keV and 250 keV D^0 beams is similar. The benefit of higher beam energies, however, becomes evident for higher electron temperatures.

Table 1: I_{NBCD} / P_{NI} [kA/MW]
($\beta = 6.65°$, $Z_{eff} = 1.5$, $\bar{n}_e = 4 \cdot 10^{19}$ m^{-3})

$T_e(a/2)$	E_{beam} [keV]	
[keV]	100	250
2	51	45
4	71	98

So far it has been assumed that the plasma center is kept close to z = 0. However, ASDEX Upgrade equilibria are possible for a wide range of vertical plasma positions. In addition, there are boundary conditions set by, for example, the divertor shape or the ICRH antennae. The dependence of beam deposition on a vertical shift of the plasma with respect to the beams is therefore of great interest. Fig. 4 (left) shows that the deposition profiles of the individual (top or bottom) beams vary strongly with the vertical plasma position. Deposition maxima between $\rho \approx 0.3$ and 0.6 are obtained when shifting the plasma by $\Delta z = 0.12$ m. However if both beams

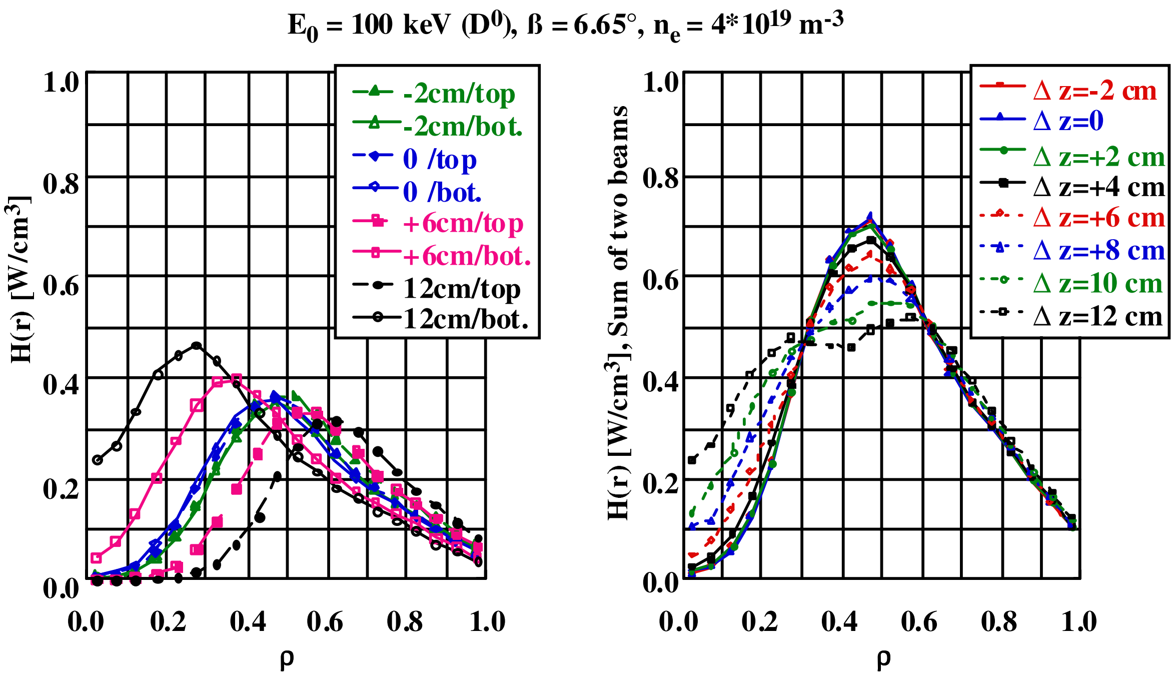

Fig. 4: H(r) for individual beams (left) and for top plus bottom beam (right) for varying the vertical plasma position

are injected simultaneously with equal power, the sum of both H(r) profiles remains remarkably robust against vertical plasma position (Fig. 4, right).

3. Choice of neutral beam parameters

Based on the results presented in the previous section the choice of neutral beam parameters proposed for the advanced tokamak experiments on ASDEX Upgrade is rather obvious:

- Tangential injection (R_T = 1.29 m) with a beam geometry characterized by $\beta = 6.65°$, Δx = +1.0 m results in an off-axis deposition at around $\rho = 0.5$ and consequently in an off-axis current drive over a wide range of plasma parameters and vertical positions.
- A beam energy of $E(D^0) = 100$ keV is adequate as long as T_e at $\rho = 0.5$ remains around 2 keV.

– A neutral power of 5 MW at 100 keV (D^0) is sufficient to drive 250 kA in a plasma with the parameters given above (see Table 1). The expected power of the envisaged 100 kV beams is 2.5 MW per beam, however, some 30% of this power is in the $E_0/2$- and $E_0/2$-components. Calculations have shown that this leads to a reduction of the driven current by around 10%. Therefore, re-arranging the two tangential 100 kV beams to the current drive geometry as outlined above will marginally result in the required beam driven current.

4. Necessary Modifications to the NBI system

The optimization of beam geometry was performed taking into account the space restrictions of the ASDEX Upgrade tokamak as well as under the boundary conditions that as many as possible of the existing components can be re-used and that the remaining two sources of the modified injector are still available for central plasma heating. The necessary modifications to the system can be summarized as follows: (i) R_T = 1.29 m for the more tangential beams is achieved by an appropriate re-orientation of the injector; (ii) β = 6.65°, Δx = +1.0 m requires to move the injector as a whole some 0.50 m further away from the tokamak and to increase the vertical distance as well as the inclination of the two tangential ion sources with respect to horizontal from ±0.60 m to ±0.70 m and from ±4.90° to ±6.65°, respectively.

The connection between the injector in its new position and the ASDEX Upgrade vessel has of course to be rebuilt. This includes – as the most delicate part – a new port to be welded into the vessel, a modified interface between port and injector box as well as changes of the support structure of the PF coil system. Some effort will additionally be necessary to adapt the environment of the injector to its new position.

The ion sources are mounted to the injector box via an ion source flange which determines the position and the aiming of the sources. A new ion source flange is therefore required. Inside the injector the ion removal system (bending magnet and ion dumps) and the calorimeter are specifically aligned to the internal beam geometry. Detailed calculations have shown that no changes to the magnet are required, that the ion dumps have to be shifted vertically as a whole but that the calorimeter assembly has to be rebuilt in order to cope with the power load of the new beam geometry. More details on all these technical modifications are given in Ref. [4].

5. Summary

Turning one of the ASDEX Upgrade injectors into a more tangential injection direction and modifying only the geometry of the two tangential beams lead to a NBI system which can be used flexibly for off-axis heating and current drive as required to study advanced tokamak scenarios on ASDEX Upgrade. The two remaining beams of this injector are still available for central heating. Only moderate changes of the existing hardware are necessary to achieve this purpose.

References

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