

Influence of Beam Heating Deposition Profiles on the Transport of ASDEX Upgrade Plasmas

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1. Introduction

Recently, the acceleration voltage of the four ion sources of the second neutral beam injector on the ASDEX Upgrade tokamak has been upgraded from 60 kV to around 100 kV in order to increase central plasma heating at high plasma densities. Beam operation under optimum perveance condition is now possible up to 93 kV limited by the power supplies. The maximum beam heating power remained at 2.5 MW per source, resulting in a total NBI power of 10 MW (D^0) at 60 kV from the first injector plus additional 10 MW (D^0) at 93 kV from the upgraded second injector. This allows to investigate the effect of beam energy on various plasma properties at reasonably high heating powers.

On ASDEX Upgrade, a remarkable self-similarity of the T_e - and T_i -profiles in type-I ELMy H-mode discharges was found over a large range of plasma parameters up to rather high densities [1]. This so-called ‘‘profile stiffness’’ was further investigated by heating high density plasmas with the same power but different beam energies resulting in significantly different beam deposition profiles. The experimental results and their analysis are presented in this paper.

2. Experimental Results

The experiments have been performed with plasmas of two different triangularities: (i) at low

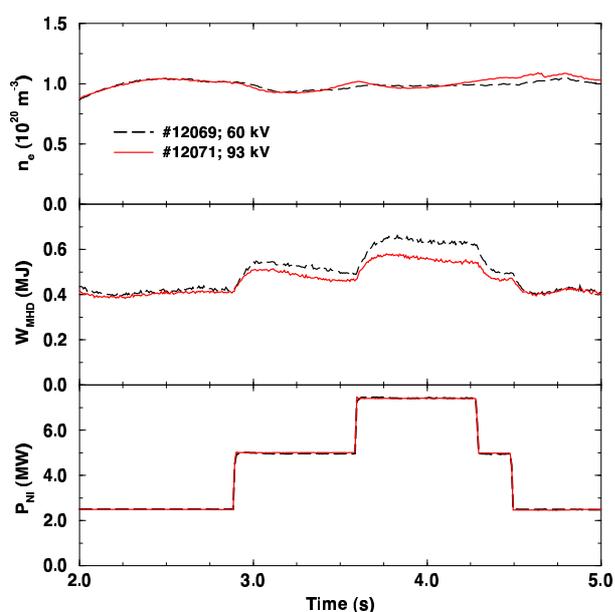


Fig. 1: Line averaged density, energy content and NBI heating power for the $\delta=0.15$ discharges heated with 60 kV and 93 kV beams, respectively.

triangularity ($\delta = 0.15$, measured at the separatrix) with $I_p = 1.2$ MA, $B_t = 2.55$ T, $q_{95} = 3.5$ at $\bar{n}_e \approx 1 \cdot 10^{20} \text{ m}^{-3}$ and (ii) at medium triangularity ($\delta = 0.3$) with 1 MA, 2.05 T and $q_{95} = 4.0$ at $\bar{n}_e \approx 1.2 \cdot 10^{20} \text{ m}^{-3}$. For both beam energies the injection geometry was the same. The rather high densities – necessary to achieve the significantly different deposition profiles for the two beam energies – were obtained and maintained by feedback controlled gas puffing. As shown for the low- δ case in Fig. 1, quasi-stationary phases at different levels of P_{NI} up to 7.5 MW were produced. At all heating powers H-mode plasmas with type-I ELMs are obtained.

In both experiments the deeper penetration of the higher energy beams does not result in a

higher plasma energy content (see Fig. 1 for $\delta = 0.15$): at the maximum heating power, W_{MHD} obtained with the 60 kV beams is surprisingly by typically 10% above the value reached with the 93 kV beams.

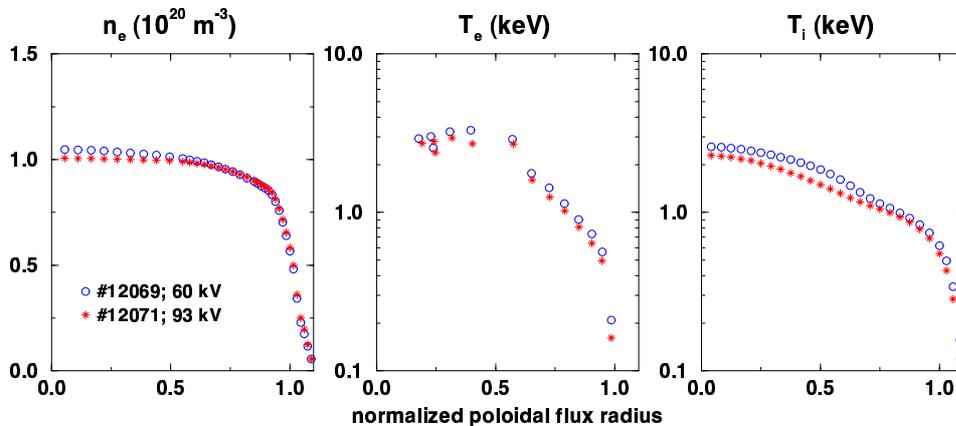


Fig. 2: Density and temperature profiles of the discharges shown in Fig.1 measured during the 7.5 MW heating phase.

The plasma profiles as measured during the phase of 7.5 MW heating are shown in Fig. 2 ($\delta = 0.15$). All profiles are averaged over some 200 ms of the flattop phase, therefore neglecting small changes

due to sawteeth. The neutral beam deposition profiles, calculated for the given plasma profiles by the ASTRA code [2], are shown in Fig. 3. Clearly, the higher energy beams lead to a significantly stronger central heating deposition.

The density profile (Fig. 2), as deduced from a deconvolution of edge measurements with a Li beam and several DCN interferometer channels, is somewhat more peaked for the lower energy beams with a slightly lower pedestal density and higher central density. This observation, though not very pronounced, is reproducible for both triangularities and for all heating powers. No significant differences are found in the sawtooth behaviour. The shape of the electron temperature profiles (see Fig. 2, Thomson scattering data; logarithmic scale) is very similar and

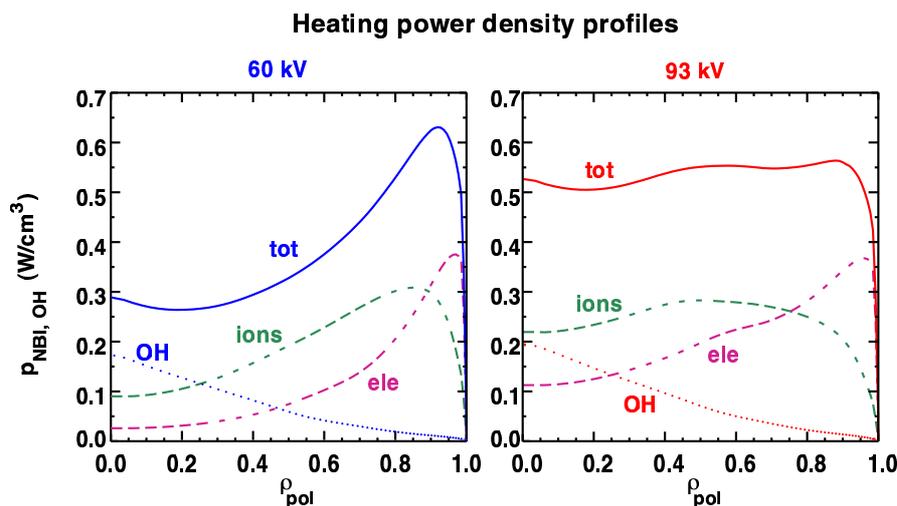


Fig. 3: NBI and ohmic power deposition profiles for the pair of discharges shown in Fig. 1, illustrating the difference in central power deposition due to the different beam energy (NBI power: 7.5 MW).

obviously not affected by the different heating power profiles of the two beam energies. This result was found independently of triangularity. Probably due to the slightly lower pedestal density for the 60 kV beams the pedestal temperature is somewhat higher, thereby maintaining a constant pedestal pressure [1]. As a consequence of

the stiff profile shape, this higher temperature is preserved over the whole plasma. Together with the similarly higher ion temperatures (see Fig. 2, CXR spectroscopy) this accounts for the

differences in the total plasma energy content. It should be noted that the T_i -profile shapes are rather similar, too. MHD activity associated with the presence of fast ions (like fishbones) is small in all discharges considered here.

The above mentioned observation of slightly stronger peaked density profiles and correspondingly higher temperatures – though similar in shape – is also found for NBI heating with the more tangential beams when compared to the heating with the more normal beams at the same beam energy. In this case, the differences are more pronounced. This may be partly due to the differences in fishbone frequency associated with the different injection angles. However, a common feature of the more tangential and the 60 kV beams, respectively, compared to the more normal or the 93 kV beams is their higher angular momentum input. This results in a stronger toroidal rotation, as measured for the tangential/normal comparison. The effect, however, is too small to affect the W_{MHD} -signal. These observations may indicate that the angular momentum input, or the plasma rotation, has some effect on plasma transport. However, the main experimental result to keep in mind is the stiffness of the T_e - and T_i -profiles, independently of the significantly varied heating power profiles at all heating powers.

3. Transport Analysis

Transport analysis of the experiments discussed above were done using the ASTRA code [2] based on the plasma profiles determined during the various stationary phases. The species distribution of the neutral beam power ($E_0:E_0/2:E_0/3$: 62%:29%:9% for 93 kV; 65%:25%:10% for 60 kV) was taken into account. Beam power losses are estimated to be around 20%, mainly

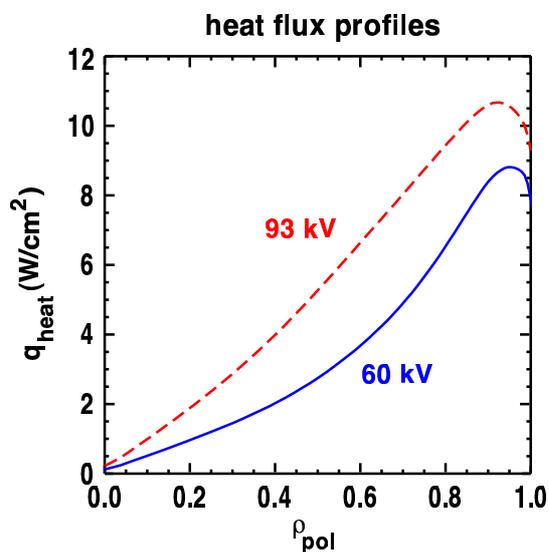


Fig. 4: Heat flux profiles for the 7.5 MW heating phase of the two discharges shown in Fig. 1.

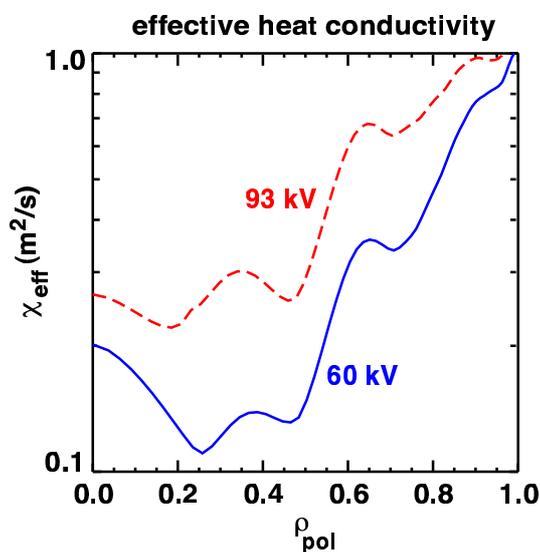


Fig. 5: Profiles of χ_{eff} as calculated by ASTRA during the 7.5 MW heating phase for the pair of discharges given in Fig. 1.

due to beam ionisation in the SOL and due to orbit losses. The contribution of the fast ions to the plasma energy is, even at 7.5 MW, below 10% due to the high density. The data discussed in the following refer to 7.5 MW of NBI heating in the $\delta = 0.15$ discharge for which the power deposition profiles were already shown in Fig. 3. Clearly, the ohmic input to the electrons may

not be neglected in the centre of the plasma. The deduced heat flux profiles are given in Fig. 4. At $\rho_{\text{pol}} = 0.4$ the difference in q_{heat} between 93 kV and 60 kV amounts to a factor of 2. Finally, the resulting effective heat conductivity coefficients are shown in Fig. 5. Across the whole plasma χ_{eff} for 60 kV is below the value for 93 kV beams with a difference of up to a factor of 2 despite of the very similar temperature profiles in both cases. Obviously, the heat conductivity adjusts itself to maintain the observed stiff temperature profiles. Qualitatively the same results have been obtained for the higher triangularity discharge as well as for the lower heating powers. In the later cases, however, the differences in χ_{eff} between the 60 kV and 93 kV beams is less pronounced due to the stronger contribution of ohmic heating.

4. Summary and Discussion

The observation of stiff T_e -profiles in NBI heated plasmas have been reported earlier [3,4,5]. Similar conclusions have been drawn from on-axis/off-axis ECRH experiments on ASDEX Upgrade [6]. The experiments reported here are characterised by having a rather high heating power and by the fact that the only parameter being changed between the two shots to be compared is the beam energy. They clearly show that χ_{eff} strongly reacts on changes of the heating power deposition profile in the sense that the shape of the electron as well as the ion temperature profiles remain maintained. This result was found to be independent of the plasma triangularity. All the experiments refer to H-mode plasmas with type-I ELMs.

In order to describe the above experimental results using a physics based transport model, it is obvious that only such models having a strong tendency to maintain $\nabla T/T$ will be adequate. In a first attempt, the ASTRA code was run in its predictive mode with the transport coefficients as given by the IFS/PPPL model [7] which is based on ITG physics. An adjustment of the calculated and measured temperatures was made at the edge pedestal. The calculated temperature profiles turned out to be rather independent of the different deposition profiles due to the different beam energies – the model obviously reproduces the experimentally observed profile stiffness. For both beam energies, however, the calculated temperatures in the centre of the plasma are by around 30% below the measured values. The reason for this behaviour will be studied further.

Finally, it should be mentioned that the high densities necessary to produce the different deposition profiles restrict the experiments to relatively low edge temperatures and lead to a rather strong coupling of ions and electrons. It remains to be seen whether the situation will be different in a regime of low density and high temperature where the electrons are less coupled to the ions. Experiments pointing in this directions will be performed in the near future.

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