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Experimental determination of the NBI power deposition and consequences for NBI current drive

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1. Introduction

The ASDEX Upgrade tokamak (R = 1.65m, a = 0.5m , $\kappa \approx 1.7$) is equipped with a unique possibility for off-axis deposition of the Neutral Beam Injection (NBI). Two of the 8 beams (2.5 MW each) provide power deposition at about mid-radius of the vertical minor radius to drive off-axis current (NBCD) [1]. As presented in [2], the off-axis current drive is weaker than expected, which might be explained by radial diffusion of the injected fast ions, for instance induced by micro-turbulence [3, 4]. Analyses with the TRANSP code [5] indicate that a diffusion of fast ions $\chi_{fi} = 0.5m^2/s$ is sufficient to strongly reduce the off-axis character. This effect seems to occur when the total NBI heating power is above 2.5 MW.

2. Experimental approach and analysis

We present here an experimental investigation of the NBI deposition profile using power modulation of one NBI beam, $16 \leq f_{mod} \leq 35$ Hz and duty cycle 50/50. During their slowing down the fast ions first heat the electrons and drive the NBCD, before they preferentially heat the ions as their energy decreases. The profile of the temperature perturbation induced by the NBI modulation ($\tilde{T}_e$) is expected to reflect that of the power deposited to the electrons (P_e). It is measured with the ECE diagnostic which offers the required resolution in space (1 - 3 cm) and time ($\approx 70\mu s$). We used low density high temperature H-modes to maximize NBCD, as in [2]. The total NBI heating power consisted of 2 beams to which we added one modulated beam (either on-axis or off-axis) leading to a total time averaged heating power of 6.25 MW. For comparison, modulated electron cyclotron heating (MECH) at f_{mod} has also been applied at a radial position close to the maximum of the modulated deposited NBI. These discharges exhibit no measurable MHD activity in the phase with off-axis modulated NBI, whereas a small amplitude 3/2 mode slowly develops during the on-axis modulated phase. The ECH, 2^{nd} harmonic X-mode, provides pure electron heating with 100% absorption and narrow deposition profile [6]. The NBI power deposition has been calculated by TRANSP and FAFNER [7]. In TRANSP, widely used for time-dependent power balance analysis, the modulation of the NBI source has been included and the code run with a time resolution of 2 ms. This yields, in particular, time dependent power deposition and current drive profiles. The calculations have been performed with different values of χ_{fi}. The FAFNER code provides the NBI power deposition and current drive without time dependence. The equilibrium plays a crucial role here and has been treated carefully. In TRANSP, the boundary deduced from the magnetic measurements is provided and the equilibrium is constructed internally taking kinetic and current profile data into account. For the ECE data and for FAFNER, the equilibrium is provided by the CLISTE code [8] constrained by the pressure profile, including fast ions and agrees very well with that from TRANSP.

Power modulation, well-known for transport studies [9] has been widely applied in ASDEX Upgrade using MECH to investigate electron heat transport [10]. Power deposition profiles can be investigated by this method if f_{mod} is sufficiently high, which depends on the deposition width and on heat transport. If the frequency is not high enough, the measured width is determined by the deposition width and by heat diffusion. To analyze the data, we perform the Fourier transform of T_e which yields amplitude and phase of $\tilde{T}_{e,meas}$. The large amplitude of the modulated NBI power excites, at low modulation frequency, a significant movement of the plasma. As the ECE measurement is almost fixed in space, this superimposes a spurious temperature modulation $\tilde{T}_{e,mov}$ in the regions where ∇T_e is not zero. We took this effect into account as follows: the plasma equilibrium has been calculated with a time resolution of 1 ms and the ECE data mapped onto it with the same time resolution. For the (R,z) position of each ECE channel, the values of the normalized radius ρ_t have been calculated for each time point of the equilibrium. Amplitude and phase of the ρ_t variations are extracted by Fourier transform. Taking ∇T_e into account provides $\tilde{T}_{e,mov}$. The vectorial addition of $\tilde{T}_{e,mov}$ and $\tilde{T}_{e,meas}$ yields the actual temperature modulation $\tilde{T}_e$.

3. Results

The experimental data of the modulation of off-axis NBI at 16 and 35 Hz are represented by symbols in Fig. 1. The amplitude of $\tilde{T}_{e,meas}$ and $\tilde{T}_e$ are peaked at about mid-radius, as expected. As explained by our previous experiments with MECH [10], the asymmetry is due to the higher heat flux in the outer region of the deposition in off-axis cases.

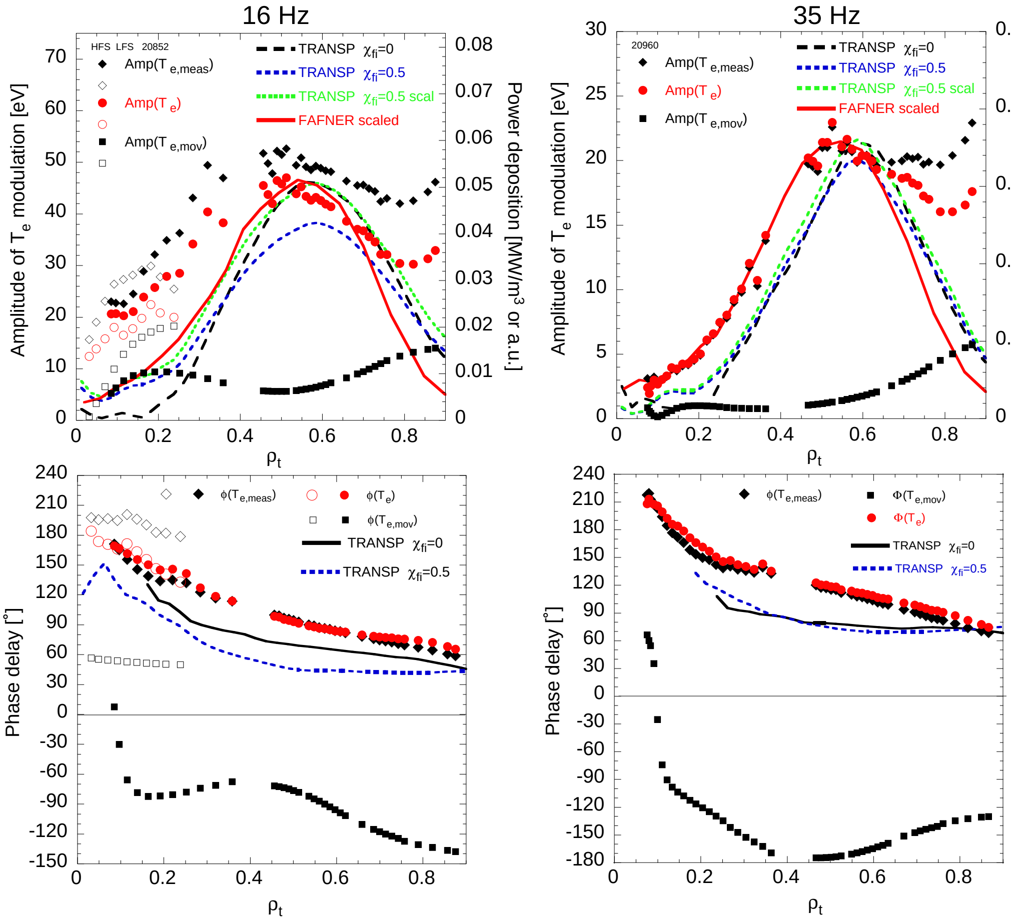

Figure 1: *Amplitude and phase of* $\tilde{T}_e$ *at 16 and 35 Hz. The points correspond to the data as indicated by the legend and in the text. The lines correspond to the power modulation from TRANSP for* $\chi_{fi} = 0m^2/s$ *and* $\chi_{fi} = 0.5m^2/s$*, as well as the scaled data for* $\chi_{fi} = 0.5m^2/s$ *and the FAFNER power deposition.*

The correction taking $\tilde{T}_{e,mov}$ into account is significant at low frequency, but it does not change the overall shape. Note that, as expected, the amplitude of $\tilde{T}_{e,mov}$ for the HFS points is about

2 times larger than on the LFS. The experimental maximum of $\tilde{T}_e$ and that of P_e yielded by TRANSP and FAFNER agree within $\Delta\rho_t \leq 0.05$. At low frequency, the experimental data are clearly broadened by electron heat diffusion, as compared to the 35 Hz case, for which the experimental data agree perfectly with the FAFNER P_e on the inner side of the deposition. The TRANSP P_e lies somewhat outside, but the shape agrees with that of the experiment and FAFNER. The slight difference of the position of the maximum between TRANSP and FAFNER cannot fully be attributed to the small discrepancies in the equilibria. As suggested by a comparison between FAFNER and TRANSP presently being carried out elsewhere, this might be due to different cross-sections of the charge exchange processes and is still under investigation [11].

Finally, it is worth pointing out that modulating an on-axis beam yields amplitude profiles which are clearly peaked in the plasma center and, thus, very different from the off-axis case. However, due to the strong broadening by heat diffusion, such cases do not allow the extraction of much information on the P_e profiles.

The experimental phase delay (Fig. 1 lower plots), calculated with respect to the NBI input power, increases from the edge to the center, following the slowing down time of the fast ions. The phase delay at the maximum of the deposition is $\approx 100^\circ$ at 16 Hz and $\approx 120^\circ$ at 35 Hz. Note that, logically, the LFS phase delay of $\tilde{T}_{e,mov}$ is out of phase with respect to that of $\tilde{T}_e$, essentially because the plasma outwards/inwards shifts follow the turn on/off of the NBI modulation. Coherently, we observe a phase jump of π between the LFS and HFS points of $\tilde{T}_{e,mov}$. It should be underlined that the phase of $\tilde{T}_e$ for the LFS and HFS points overlap, demonstrating that the correction including $\tilde{T}_{e,mov}$ is good. The phase delay of $\tilde{P}_e$ from TRANSP is lower than that of $\tilde{T}_e$ but has a comparable shape. At 16 Hz, for $\chi_{fi} = 0.5m^2/s$ it clearly has a smaller value and the curve exhibits a stronger V shape centered at the maximum of the power deposition. This agrees with the fast ions diffusing during their slowing down process. This effect is negligible at 35 Hz. The physical quantity which reflects transport properties is the phase difference with respect to the *deposited* power, here $\Delta\Phi = \Phi(\tilde{T}_e) - \Phi(TRANSP)$. This delay is known to increase from 0 for $f_{mod} = 0$ up to the asymptotic value of 90° at very high frequencies, as investigated in detail in ASDEX Upgrade with MECH [12]. Here, at 16 Hz, $\Delta\Phi$ is clearly larger when $\chi_{fi} = 0.5m^2/s$ is assumed, whereas at 35 Hz the assumption on χ_{fi} has no effect in the range considered here. Thus, while the cases $\chi_{fi} = 0m^2/s$ yields the expected increase of $\Delta\Phi$ with increasing frequency ($\Delta\Phi = 22^\circ$ at 16 Hz and $\Delta\Phi = 44^\circ$ at 35 Hz), assuming $\chi_{fi} = 0.5m^2/s$ results in a *decrease* of $\Delta\Phi$ with increasing frequency ($\Delta\Phi = 51^\circ$ at 16 Hz and $\Delta\Phi = 44^\circ$ at 35 Hz), in contradiction with the expectations and discussed in the next paragraph.

To assess these observations, we compare the data from MECH with those from NBI modulation. The results for 35 Hz are illustrated in Fig. 2 left plot, which shows the amplitude of $\tilde{T}_e$ for the two methods. Note that, similarly to the NBI case, the amplitude from MECH is asymmetrical, for the reasons indicated above. At this frequency, for MECH, the broadening due to electron heat transport is such that, on the inner part of the power deposition the amplitudes given by MECH and NBI coincide ('MECH scaled' points). This indicates that the width of the $\tilde{T}_e$ amplitude profile for the NBI modulation is dominated by that of P_e. Indeed in Fig. 1 the deposition yielded by FAFNER agrees perfectly with $\tilde{T}_e$ at 35 Hz . The phase of MECH has, as usual in such experiments, a clear minimum corresponding to the maximum of the amplitude. Its value of 48° is close to $\Delta\Phi = 44^\circ$ measured for NBI modulation. This is a very good confirmation that the calculation of P_e is correct and gives confidence to interpret the case at lower frequency. The frequency dependence of the phase delay at the maximum of the deposition is summarized in Fig. 2 right plot. For MECH, the expected increase with

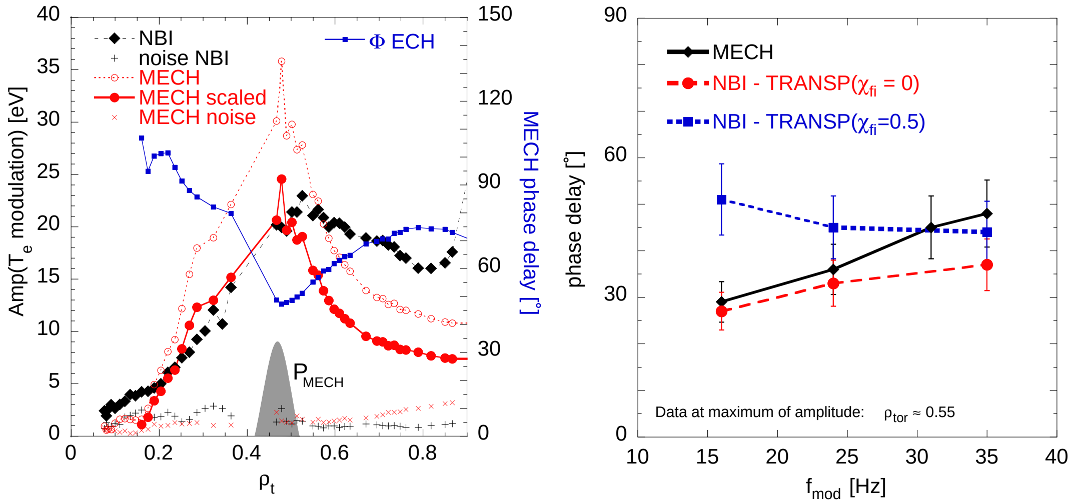

Figure 2: **Left plot:** *Amplitude and phase of MECH* $\tilde{T}_e$ *at 35 Hz, compared to NBI from Fig. 1. MECH points for* $\rho_t < 0.2$ *are in the noise. Red full dots are scaled to the maximum of the NBI case.*
Right Plot: *Phase delay as defined in the text and taken at the maximum of the amplitude versus* f_{mod}.

f_{mod} appears clearly. The NBI modulation data for $\chi_{fi} = 0m^2/s$ agrees closely with them. Assuming $\chi_{fi} = 0.5m^2/s$ exhibits a completely opposite behaviour which seems to contradict the basic physics expectation and thus does not support the assumption of diffusion of fast NBI ions as they preferentially heat the electrons. This is not in contraction with the need of fast ion diffusion to explain the broadening of the off-axis NBCD described in [3, 4] because a fraction of the NBCD is driven by ions with significantly less energy and which might not be sufficiently visible in our modulation experiments.

In conclusion, the analysis of the NBI modulation by FFT of the T_e modulation and time-dependent TRANSP calculations is a reliable method to investigate the NBI power deposition. In the cases presented here, this method does not seem to indicate a diffusion of fast ions during their slowing down time on electrons.

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