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Toroidal Orbit-Following Simulation of Ion Temperature Measurements from NBI Tail Distribution in ASDEX Upgrade

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Abstract. Toroidal orbit-following simulations of neutral particle analyser (NPA) measurements are performed using the ASCOT code in real ASDEX Upgrade magnetic geometry. The method of evaluating the ion temperature from the distribution tail slopes of high-energy ions from neutral beam injection (NBI) is tested for ASDEX Upgrade.

Introduction. Obtaining accurate ion temperature profiles is a bottleneck in the data analysis of tokamak discharges. Particularly the central temperature is difficult to obtain in high performance discharges using conventional methods. Therefore it is quite common to assume that the electron and ion temperatures are the same, which may not be the case in high performance discharges.

It has been shown [1] that, in neutral beam heated discharges, the ion distribution function above the injection energy can be expressed as $f_{tail}(E) \sim \exp(-E/T_{eff})$, where

$$T_{eff} \approx \frac{T_i + (E/E_c)^{3/2} T_e}{1 + (E/E_c)^{3/2}} \quad [2]. \tag{1}$$

Here, T_i and T_e are the ion and electron temperatures, and E_c is the critical energy above which the slowing down from plasma electrons is more important than the energy diffusion from collisions with the plasma ions. For neutral beam heated discharges on ASDEX Upgrade and energies slightly above the neutral beam injection energy, we have $E/E_c < 1$. Above the injection energy, the inverse slope of the ion distribution function called the *effective temperature* T_{eff} is thus a weighted sum of the electron and ion temperatures, and T_i can be obtained from measurements of T_e and T_{eff}.

In this work we have tested the validity of the T_{eff} approach in ASDEX Upgrade discharges using the orbit-following Monte Carlo code ASCOT [3]. We have constructed a realistic model for the NPA at ASDEX Upgrade, taking into account the horizontal and vertical viewing angles and the viewing cone aperture size. Modelling the beam ions, we obtain the ion distribution at and above the beam energy. Central ion temperatures obtained from the test ion velocity distribution are compared to the temperatures obtained from both the experimental and simulated charge-exchange (CX) signals.

Simulations. The ASCOT code follows the guiding centre trajectories of test particles in real tokamak magnetic geometry. Test particle collisions with the stationary background plasma are simulated using binomially distributed Monte Carlo operators

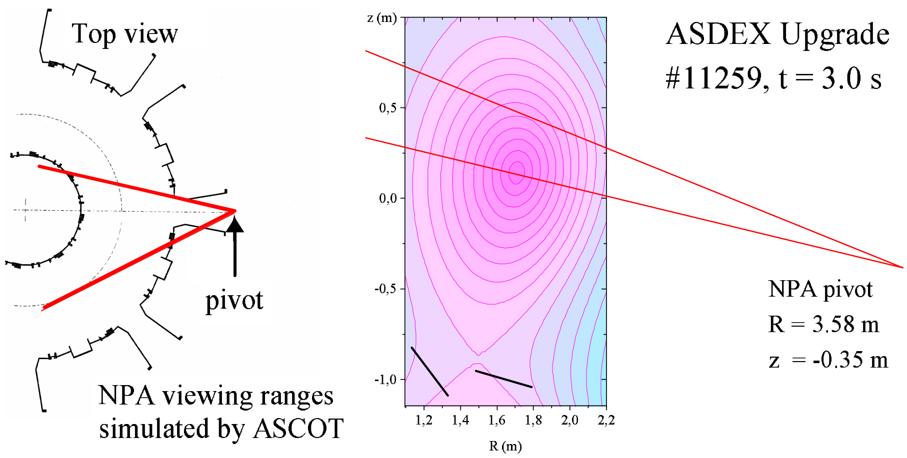

Figure 1: *NPA horizontal and vertical viewing ranges used in the simulations. Horizontal angles (β_h) of $+10°\ldots-25°$ and vertical angles (α_v) of $+14.6°\ldots+23.6°$ were used.*

derived from the Fokker-Planck equation. A hydrogen plasma was assumed, and the magnetic background as well as n- and T-profiles from ASDEX Upgrade discharge #11259 at t = 3.0 s were used. A total of 160000 hydrogen ions were initialised in 20 radial slots, ranging from the plasma centre to the separatrix, with 40 keV energy, realistic beam shape and pitch values corresponding to a $+15°$ injection angle (counterclockwise when viewed from above). The particles were weighted according to the local NBI ion deposition (1/s) obtained from the FAFNER code.

The NPA sightlines were defined as realistically as possible, taking into account the correct shape of the viewing cone. 20 lines-of-sight were implemented in the simulation, corresponding to different vertical and horizontal orientations of the detector. With respect to the temperature measurement, the significant quantity is the closest distance r_{min} of the line-of-sight to the magnetic axis. The horizontal and vertical sightline ranges are shown in Fig. 1. For each line-of-sight there were 8-10 energy channels (from 32 or 42 keV up to 82 keV in 5 keV increments). Since the simulations were made in axisymmetric background (without magnetic field ripple), the toroidal location of the NPA could be omitted in order to improve statistics and CPU efficiency.

The test particles were followed until they reached local thermal energy or hit the vessel wall or divertor. At each time step, the pitch, location and energy of the test particle were checked to see if the particle would, after being neutralized, hit the detector in the energy range of one of the energy channels. When these conditions were satisfied, the CX signal from the test particle was recorded taking into account signal damping due to re-ionisation along the line-of-sight. The neutral density profile obtained from the EIRENE code was used to calculate the re-ionisation probability.

Results. Figure 2 shows $(1/\sqrt{E})\ dn/dE$ in arbitrary units (ln scale). Above the neutral beam injection energy the inverse slopes thus give the effective temperature T_{eff}. The distribution was evaluated in 10 different radial slots, reflecting the local

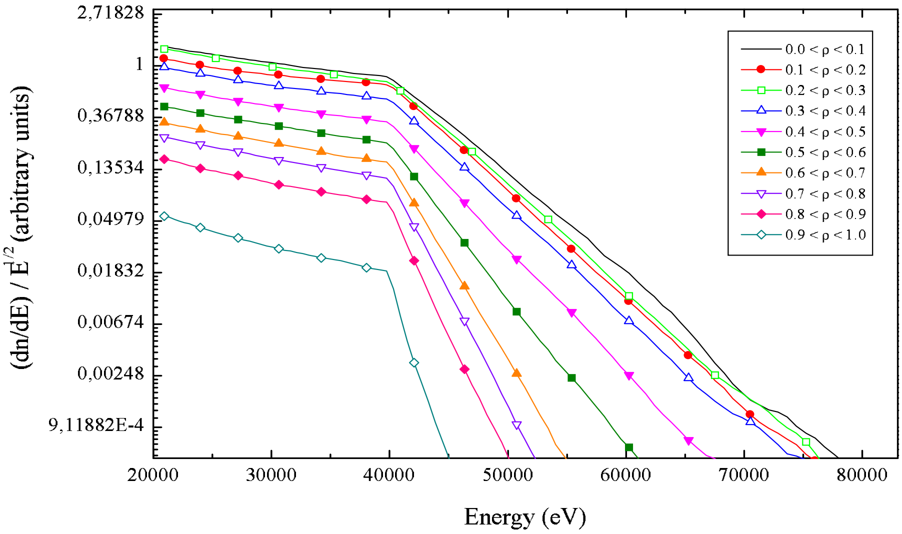

Figure 2: *The test ion distribution* $(dn/dE)/\sqrt{E}$ *in 10 radial slots.*

bulk temperature in each slot. Indeed, the slopes are observed to steepen as one moves outward in radius, implying a diminishing temperature.

Figure 3 shows the CX signal obtained from the simulation using different detector orientations. In Fig. 3(a), the magnitude of the CX signal along a sightline passing close to the magnetic axis ($\alpha_v = +16.1°$, $\beta_h = +3.0°$) is displayed for the 8 energy channels. Clearly the signal comes predominantly from the central region and, thus, the diagnostic should give reasonably reliable data on central ion temperature. Figure 3(b) shows the CX signal as a function of energy for six sightlines. The NPA signals have well-defined slopes, and in the central region they are in good agreement with those shown in Fig. 2, as well as with experimental neutral flux measurements (see Fahrbach *et al*, EPS 2000).

It was observed that with sightlines nearly perpendicular to the plasma, the central

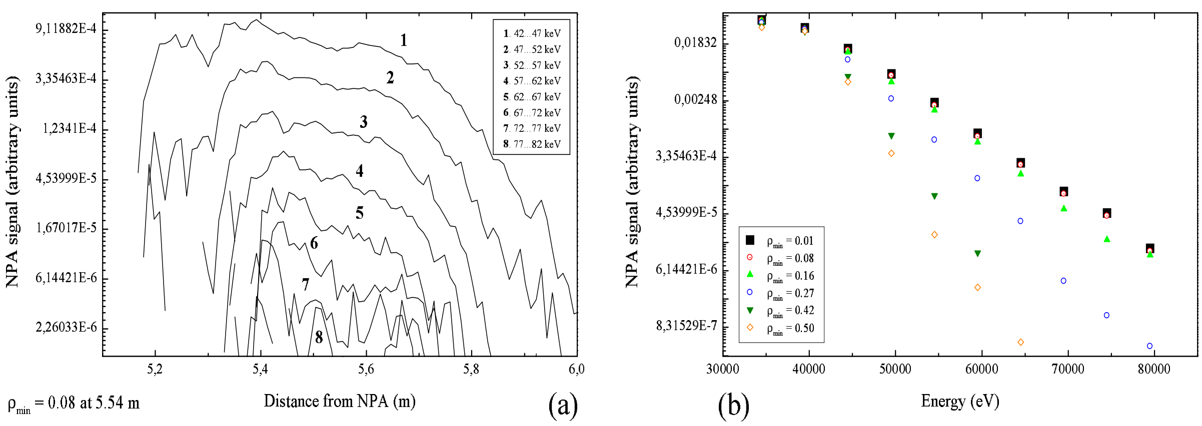

Figure 3: *(a) The CX signal distribution along a sightline with* $\rho_{min} = 0.08$. *(b) The CX signal as a function of energy obtained with six vertically different sightlines at* $\beta_h = +3°$ *(in ln scale).*

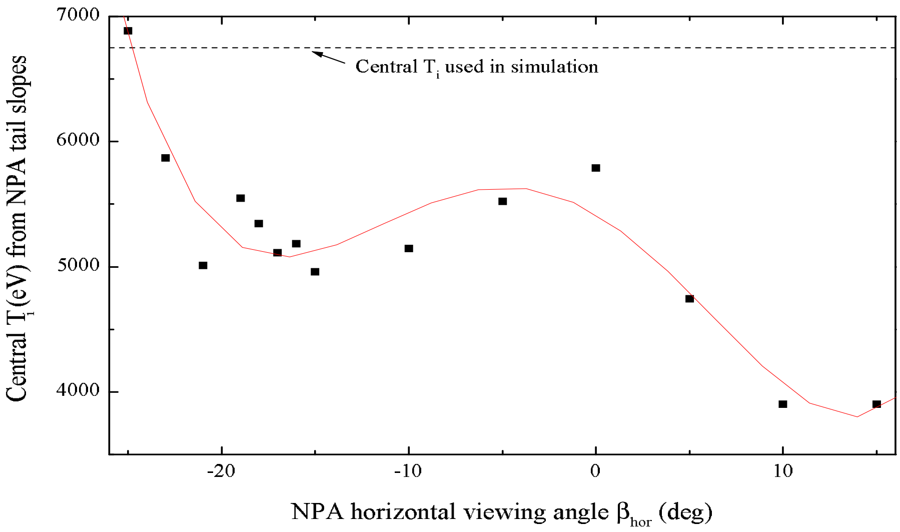

Figure 4: *Central ion temperature obtained from the NPA signal slopes as a function of the horizontal viewing angle* β_h.

ion temperatures obtained by solving T_i from Eq. 1 were 10%–20% lower than what was used in the simulation. The slopes of the CX signals were found to be affected by the NPA's horizontal viewing angle. This effect has also been seen experimentally.

Figure 4 shows the central ion temperature obtained from the NPA signal slope as a function of horizontal viewing angle β_h. When the detector is turned to the toroidal direction where it looks at the beam ion pitch region, the observed slopes get flatter, indicating a higher temperature. The effect is caused by the anisotropy of the beam particle velocity distribution.

Conclusions. The validity of the method of determining the central ion temperature from NPA measurements of the high-energy ion distribution tail slopes has been studied in ASDEX Upgrade. Detailed 5D orbit-following simulations in real ASDEX Upgrade geometry were performed using realistic NBI and NPA models. A good agreement with experimentally measured CX flux was achieved. The obtained central ion temperature values were found to be affected by the horizontal viewing angle of the NPA. The anisotropy of the beam ion velocity distribution causes the observed signal slopes to vary with the pitch range seen by the detector.

With careful selection of the NPA viewing angles, the central ion temperature can be resolved to within 10% accuracy. The determination of the optimal achievable NPA viewing angles on ASDEX Upgrade is left for future work.

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