DOUBLE code simulations of emissivities of fast neutrals for different plasma observation view-lines of neutral particle analyzers on the COMPASS tokamak

K Mitosinkova\textsuperscript{1,2,4}, M Tomes\textsuperscript{1,2}, J Stockel\textsuperscript{1}, J Varju\textsuperscript{1} and M Stano\textsuperscript{3}

\textsuperscript{1}Institute of Plasma Physics of the CAS, Prague, Czech Republic
\textsuperscript{2}Faculty of Mathematics and Physics, Charles University, Prague, Czech Republic
\textsuperscript{3}Faculty of Mathematics, Physics and Informatics, Comenius University, Bratislava, Slovakia

Email: mitosinkova@ipp.cas.cz

Abstract. Neutral particle analyzers (NPA) measure line-integrated energy spectra of fast neutral atoms escaping the tokamak plasma, which are a product of charge-exchange (CX) collisions of plasma ions with background neutrals. They can observe variations in the ion temperature $T_i$ of non-thermal fast ions created by additional plasma heating. However, the plasma column which a fast atom has to pass through must be sufficiently short in comparison with the fast atom’s mean-free-path. Tokamak COMPASS is currently equipped with one NPA installed at a tangential mid-plane port. This orientation is optimal for observing non-thermal fast ions. However, in this configuration the signal at energies useful for $T_i$ derivation is lost in noise due to the too long fast atoms’ trajectories. Thus, a second NPA is planned to be connected for the purpose of measuring $T_i$. We analyzed different possible view-lines (perpendicular mid-plane, tangential mid-plane, and top view) for the second NPA using the DOUBLE Monte-Carlo code and compared the results with the performance of the present NPA with tangential orientation. The DOUBLE code provides fast-atoms’ emissivity functions along the NPA view-line. The position of the median of these emissivity functions is related to the location from where the measured signal originates. Further, we compared the difference between the real central $T_i$ used as a DOUBLE code input and the $T_{i,CX}$ derived from the exponential decay of simulated energy spectra. The advantages and disadvantages of each NPA location are discussed.

1. Introduction

The neutral particle analyzer (NPA) is a diagnostic tool measuring the energy spectra of fast neutral atoms escaping the plasma [1]. The COMPASS tokamak ($R = 0.56$ m, $a = 0.23$ m, $B_t = 0.9 - 2.1$ T, $I_p$ up to 400 kA, line-integrated $n_e = 2 - 10 \times 10^{19}$ m\(^{-3}\)) [2] is equipped with one ACORD-24 NPA, which has 12 channels for hydrogen atoms (0.25 – 70 keV) and another 12 channels for deuterium (0.3 – 50 keV) and is installed at a mid-plane tangential port [3]. In the near future, a second, ACORD-5, NPA with 5 channels for detection of neutrals will be installed on the COMPASS tokamak. Although this NPA does not distinguish between different atomic masses, it can operate in a

\textsuperscript{4}To whom any correspondence should be addressed.
sweeping mode, which allows one to measure several times as many points of an energy spectrum as the currently mounted detectors. It is possible to connect it at a perpendicular mid-plane port or on the top of the tokamak vessel with a view-line through the plasma center.

The fast neutral atoms escaping the plasma are formed by charge-exchange (CX) collisions between ions and electron donors. The latter are mostly neutral particles propagating from the edge towards the plasma center and undergoing multi-step CX collisions. Using the DOUBLE Monte-Carlo code [4, 5], developed in the Ioffe Institute, St Petersburg, we explored the influence of the plasma density $n_e \ (2 - 10 \times 10^{19} \text{ m}^{-3})$, the fast neutral atoms energy $E_{FA} \ (300 - 10 \ 000 \ \text{keV})$ and the NPA view-line (tangential mid-plane, perpendicular mid-plane, and top center view) on the fast atoms emissivity profiles. The different view-lines are illustrated in figure 1.

The data acquired by ACORD-24 are often processed assuming that the energetic fluxes measured originate from a region where the ion distribution is Maxwellian, i.e., can be characterized by one ion temperature [2]. This assumption allows one to calculate $T_{iCX}$ from the slope of the linear part of the measured energy spectra when plotted in logarithmic scale. However, this assumption is usually not satisfied, as the fast atoms’ region of origin has different ion temperatures. Figure 2 shows an example of a time-averaged signal measured by ACORD-24 during L-mode discharges with different $n_e$, but otherwise comparable.

![Figure 1. The different NPA view-lines. Left-hand side diagram – top-view; right-hand side diagram – chamber cross-section.](image1)

![Figure 2. Time-averaged energy spectra measured during L-mode discharges for different electron densities $n_e$. The noise level is estimated to 1 count/ms.](image2)
The deviation from exponential decay at high energies is due to the poor signal-to-noise ratio. In the case of the lowest \( n_c \), the data measured becomes commensurate with the noise level at the energy of about 3 keV; for the highest \( n_c \) this critical energy is shifted close to 2 keV. This means that in the case of tangential NPA orientation, useful signal can be obtained up to energies 2 – 3 keV only; however, as it is shown in the next section, the fluxes detected do not originate from the central plasma region. The situation can be improved by using a different NPA orientation. The distance between the plasma center and the NPA port is almost 0.4 m for a tangential view. For a perpendicular view at mid-plane, it is only 0.23 m. Thus, the signal from the plasma central part would be improved because of the shorter distance traversed by the fast neutrals.

A more detailed analysis of the spectra measured can be carried out by utilizing the DOUBLE Monte-Carlo code, as it simulates the energy spectra measured based on the plasma parameters provided, namely \( n_c \), the \( T_c \) and \( T_i \) profiles, the magnetic field \( B \) map, the plasma rotation \( v_{rot} \), the effective plasma charge \( Z_{eff} \), the NPA orientation and the COMPASS vessel geometry. All inputs, except the \( T_i \) profile, can be derived from other diagnostic techniques. The \( T_i \) profile can be varied iteratively until the simulated and measured energy spectra of the escaping neutral atoms become sufficiently similar.

In this study, the DOUBLE inputs were fixed for the purpose of comparing the NPA performance for different view-lines at standard COMPASS L-mode discharges parameters \( (B_0 = 1.15 \, \text{T}, \, I_p = 180 \, \text{kA}, \, \text{elongation} \, 1.8, \, T_{ib} = 530 \, \text{eV}, \, T_{edge} = 30 \, \text{eV}, \, n_{neutals\,\,edge} = 10^{16} \, \text{m}^{-3}, \, Z_{eff} = 1.55, \, v_{rot} = 0 \, \text{m/s}) \). The edge neutral density, \( Z_{eff} \) and \( v_{rot} \) were not measured during this series of discharges, but were estimated for the purpose of the simulations. The \( n_c \) and \( T_c \) profiles were varied. Examples of \( n_c \) and \( T_c \) profiles used in the simulations are compared with real measured data obtained by Thomson-scattering (TS) \([6]\) in figure 3. The \( T_i \) profile used is also presented. The value of \( T_{ib} \) in this profile is based on the exponential decay of the energy spectra measured by the NPA in the same series of discharges as the TS data.

![Figure 3](image)

**Figure 3.** Example of \( n_c \) (left) and \( T_c \) (right) profiles used as input to DOUBLE. The measured data are presented by symbols; the data were obtained from several similar discharges for each \( n_c \). The solid lines represent the \( n_c \) and \( T_c \) profiles calculated using formulas based on data fitting, with the central electron density \( n_{c0} \) as input parameter. The input \( T_i \) profile is represented by a dashed line.

The curves were calculated using formulas with one varying parameter, namely, \( n_{c0} \) (central electron density) derived by fitting real plasma discharge profiles that have different requested \( n_c \) only. The \( T_c \) profiles are, naturally, different for different \( n_c \). The colored region delineates the region of \( T_i \) where it is not lower than 80% of \( T_{ib} \) and is referred to as the central plasma part further in the text.

2. **Emissivity function of the detected fast neutral atoms**

The fast neutrals flux detected is the integral of the emissivity along the NPA view line. The emissivity is influenced by the interplay of the probability of formation of fast neutrals and the
probability of their re-ionization (attenuation of the fast neutrals flux) along the view-line. The formation of fast neutrals strongly depends on the CX cross-section, on the fast neutral energy $E_{FA}$, and on the local ion distribution function represented by the ion temperature profile and the donor density, i.e. the penetration depth of neutrals coming from the plasma edge. The re-ionization of fast neutrals depends mostly on $n_e$ and $E_{FA}$. Examples of emissivity calculated by DOUBLE for different view-lines, central plasma densities $n_{e0}$ and $E_{FA}$ are shown in figure 4. The symbols represent the borders between quartiles (25% of the signal entering the NPA originates in one quartile of its emissivity function); i.e. the middle symbols represent also the position of the median.

![Figure 4](image1.png)

**Figure 4.** Emissivity for different central plasma densities $n_{e0}$ $[10^{19} \text{ m}^{-3}]$, energies $E_{FA}$ and view-lines remapped as a function of the minor plasma radius $r$. The location of the quartiles borders is highlighted by symbols. The colored area delineates the central plasma part.

The fluxes of less energetic fast atoms originate from closer to the edge due to the higher probability of their re-ionization, which prevents them from escaping the central plasma. For higher $E_{FA}$ values, the signal originates mostly from the central part due to the longer mean-free-path of the fast atoms, and also due to the $T_i$ drop towards the plasma edge, i.e. the lower high-energy ions population in the edge region. The reduction in the emissivity and the shift towards the edge as $n_{e0}$ increases are also caused by the shortening of the escaping fast atoms’ mean-free-path.

For higher $n_{e0}$ values, the central plasma part cannot be observed in tangential view; e.g., for $E_{FA} = 1 \text{ keV}$ and $n_{e0} = 10^{20} \text{ m}^{-3}$, all quartile borders are out of the central region (as defined in figure 3), while the case of $n_{e0} = 4.5 \times 10^{19} \text{ m}^{-3}$ is not much better. On the other hand, the perpendicular view allows observation of the central region in most of cases; only for the highest $n_{e0}$ and the lowest $E_{FA}$ are all emissivity quartile borders out of the central region.

![Figure 5](image2.png)

**Figure 5.** Dependence of the median radial position $r_{med}$ of the emissivity function on the central plasma density $n_{e0}$ and the fast neutrals energy $E_{FA}$ for different NPA view-lines. The low-field side plasma center border $r = 6.7 \text{ cm}$ is denoted by a black line.
The variation of the median radial position $r_{\text{med}}$ (the border between the second and third quartiles) of the fast neutral emissivity function with $n_{e0}$ and $E_{i0}$ is shown in figure 5 for different view-lines.

The median position $r_{\text{med}}$ moves deeper into the plasma as $E_{i0}$ increases and $n_{e0}$ decreases. In the perpendicular view case, the neutrals still originating from the plasma center are detected above $E_{i0} \approx 1.5$ keV at the highest $n_{e0}$. This is much better than the tangential view case, where at the highest $n_{e0}$ $r_{\text{med}}$ crosses the plasma center border at $E_{i0}$ above 2 keV. When we compare it with actually measured data (figure 2), the signal at higher $n_e$ that is not buried under the noise does not in fact originate from the central region in the tangential view case, i.e. it is then impossible to determine the central ion temperature $T_{i0}$. In the perpendicular view case, the emissivity is higher (figure 4); therefore, the neutrals originate from the plasma center even for the highest $n_{e0}$.

3. Determination of the central ion temperature

As was mentioned in section 1, there exists a simple method of estimating $T_{i0}$ directly from measured data using the exponential decay of the energy spectra $T_{icx}$. Since one run of the DOUBLE code, which is normally used in an iterative loop for $T_i$ profile derivation from measured data, takes about five minutes, we employed it to analyze $T_{i0}$. Figure 6 shows $T_{icx}$ thus derived using energy spectra simulated by DOUBLE. We also performed exponential decay fits for several different $E_{i0}$ regions.

![Figure 6. Central ion temperature $T_{icx}$ derived from simulated energy spectra using its exponential decay in different energy regions (2-5 keV, 1-2.5 keV and 0.3-2.5 keV) and for different NPA view-lines.](image)

The deviation from the preselected $T_{i0}$, used as a DOUBLE code input, assumes its lowest value in perpendicular view. The $T_{icx}$ derived is independent of $n_{e0}$ if one uses the 2-5 keV range for its evaluation in perpendicular and top views. Because the emissivity in the case of perpendicular view is higher (figure 4), there is also a possibility to use a higher $E_{i0}$ range for $T_{icx}$ derivation than in the existing case of tangential view.

4. Conclusions

The analysis of different NPA views using the DOUBLE code with standard L-mode COMPASS parameters as input shows that:

Tangential view cannot be used for observation of the central plasma region at higher $n_e$ ($> 6 \times 10^{19}$ m$^{-3}$), because the fast neutral atoms useful for determining $T_i$ can only escape the central plasma and reach the NPA for the lowest $n_e$. If the energy spectra measured by the NPA are evaluated by a simple $T_{icx}$ analysis, the deviation from the real $T_{i0}$ is at least +15/-17%, depending on $n_{e0}$.

The top view emissivity has similar or lower values as in tangential view, i.e. the signal intensity will be similar or lower. However, a larger part of the signal originates from the plasma center than in tangential view. $T_{icx}$ derived from exponential decay is not sensitive to $n_e$ if derived in the $E_{i0}$ range of 2 - 5 keV. This view-line provides better results than the tangential view;
Perpendicular view is the best of all tested possibilities. The escaping neutral atoms fluxes originate from the central plasma region with sufficient fast atom energies. Therefore, data acquired by an NPA installed with this view will be useful for measurements of $T_\parallel$ and $T_{\text{iCX}}$ derived from energy spectra in the range of 2-5 keV using the simple method that is independent of $n_e$; also, the systematic error (offset) is then the lowest, namely, $\sim 35$ eV, i.e. $\sim 7\%$. Further, even when $T_{\text{iCX}}$ is derived from the lower energy range, the deviation from $T_\parallel$ is still under 10\%.

In summary, the second NPA (ACORD-5) should be tested in perpendicular view, where the escaping fast neutrals flux originates from the central plasma part; i.e., the NPA would be able to measure $T_\parallel$ in this region. There would also be possibility to complement the signal acquired by the second NPA with the data from the present one, which is oriented tangentially and observes a region closer to the edge. By combining these two NPA orientations, fast neutrals fluxes would be measured originating from a wide range of plasma radii.

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