Effect of Collisional Quenching on the Measurement of Ion Species Ratios in Neutral Beam Injectors

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In positive ion based Neutral Beam Injectors (NBI), generally corona model is used in analyzing the Doppler shifted spectroscopy diagnostics data for estimating the ion species mix in the ion-source, ion and beam species fractions in extracted beam and power fractions injected into Tokomak. At the beam energies 10-60 keV/amu, the non-radiative processes such as collisional quenching of the excited neutrals affect these estimations when background pressure is ≥ 1 mTorr. We present here a modified corona model that takes into account the effect due to collisional quenching. We describe the application of the present model to a typical Doppler shifted spectral data obtained in SST-1-NBI injector.

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1. Inroduction

Heating of magnetically confined plasmas by injecting energetic neutrals is demonstrated as one of the most powerful and effective heating mechanisms in all fusion experiments [1]. For most of the fusion experiments till date, positive ion based neutral beam injectors are employed and energies up to 120 keV of Deuterium were successfully injected into Tokomaks [1–6]. During the production of high power neutral beams and their injection into Tokomak plasma, it is necessary to characterize the beam by determining the beam parameters such as ion species mix of the ion source, neutral beam fractions and beam divergence of the extracted beam. An accurate measurement of the above mentioned parameters is also mandatory, since they are important input parameters for the beam aided diagnostics such as Beam Emission Spectroscopy and Charge Exchange Recombination Spectroscopy [2]. Most of these beam parameters are measured using the Doppler shift spectroscopy (DSS) diagnostics as it allows fast, non-intrusive, reliable online measurements of species ratios and beam divergence.

Hence, it has become an indispensable diagnostic tool for all existing neutral beam injectors [3–7]. In past, there were different models formulated to obtain ion species fractions from the DSS observations.

In this framework, it is assumed that the de-excitation is only due to spontaneous radiative decay; in other words, the role of non radiative processes such as the collisional destruction of excited beam species is neglected. The above assumption is valid only under the condition that the rate of radiative decay is much larger than the rate of de-excitation by non-radiative collisions.

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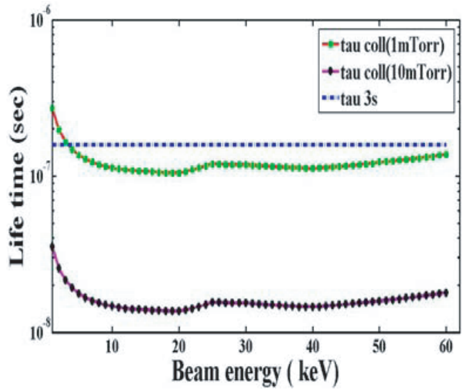

Fig. 1 Comparison of the radiative life time τ_{3s} and life time for collisional quenching calculated at pressures: 1 mTorr and 10 mTorr for the energy range 10 keV-60 keV. Collisional destruction cross-section is taken from Ref [10].

We, therefore, undertook a study to compare the radiative life times of $n = 3$ states with the time scales of non-radiative collisions. In Fig. 1, the radiative life time of 3s is compared with the time scale of the non-radiative process for two different background gas densities (residual pressures). From the Fig. 1, it can be seen that the time scales of non radiative processes become comparable with the radiative life time for the transition 3s-2p for the background pressures of ∼ 1 mTorr and become faster with further increase of pressure. Here, it is also important to realize that these non-radiative processes cause collisional quenching of the excited atoms and thus decrease the observed intensities of the DSS peaks. So, it becomes important to consider such a process when the DSS observations are made at locations where the background pressures are of

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the order of ~ 1 mTorr. But the existing models do not account this effect in their analysis for estimating the species fractions and ion species mix. The aim of the present paper is twofold: 1) to suitably modify the analysis based on the corona model by including the contribution due to non-radiative processes. 2) to examine the results of revised model in improving the accuracies of the estimations of the species mix and species fractions.

2. Emission Model for Species Ratios

In this section, we present a revised theoretical model for computing the species ratios. The excited state $n = 3$ is populated either by state selective electron capture or excitation during dissociative electron capture in case of H_2^+ and H_3^+ states ($n \geq 4$) as the contribution due to cascading need not be considered [8]. Accordingly, the depopulating terms are now the spontaneous radiative decay and the collisional destruction by non-radiative processes. Using this we can write, the excited neutral density per unit length of length of the beam as,

$$\frac{\mathrm{d}N^*_{\mathrm{x,l}}(\varepsilon)}{\mathrm{d}x} = N_{\mathrm{g}} \sum_{\mathrm{k}} N^{\mathrm{k}}_{\mathrm{i,x}}(\varepsilon')\,\sigma^{\mathrm{k}}_{\mathrm{i,l}}(\varepsilon') - \frac{N^*_{\mathrm{x,l}}(\varepsilon) \sum_{n=1}^{2} \sum_{\mathrm{l'}} A_{3,\mathrm{l}\to \mathrm{n,l'}}}{v(\varepsilon')} - N_{\mathrm{g}} N^*_{\mathrm{x,l}}(\varepsilon)\,\sigma^{\mathrm{coll}}(\varepsilon). \quad (1)$$

Where, l = 3s, 3p, 3d for $n = 3$; l' = 2s, 2p for $n = 2$ and l' = 1s for $n = 1$, Eq. (1) can be solved for obtaining $N^*_{\mathrm{x,l}}(\varepsilon)$ at any location x. $N^{\mathrm{k}}_{\mathrm{i,x}}(\varepsilon')$ are the beam fractions at energy ε'. $\sigma(\varepsilon')$ is excitation cross sections to $n = 3$ at energy ε' and $A_{3\to 2}$ are transition probability of radiative decay. If we assume a spatially invariant species density, which is usually valid for the observations made at the end of the neutralizer or at locations downstream from the neutralizer, the observed intensity can now be expressed in its simplified form as,

$$I_{\mathrm{l}}(\varepsilon) = N_{\mathrm{g}} \sum_{\mathrm{k}} N^{\mathrm{k}}_{\mathrm{i}}(\varepsilon')\,\sigma^{\mathrm{k}}_{\mathrm{i,l}}(\varepsilon') \frac{A_{3,\mathrm{l}\to 2,\mathrm{l'}}}{\left[\lambda^{1}_{\mathrm{rad}}(\varepsilon') + \lambda^{1}_{\mathrm{coll}}(\varepsilon)\right]}. \quad (2)$$

In Eq. (2), λ_{rad} is the e-folding distance over which the excited atom in a particular sublevel: l travels before it spontaneously emits an H-alpha photon. λ_{coll} is the collisional mean free path for a non radiative de-excitation. The excited neutrals formed in 3p and 3d states will decay radiatively before they get collisionally-quenched hence only those neutrals which are formed in 3s state will get effected by the collisional quenching owing to their longer radiative life times. Using Eq. (2), the ratio of the intensities of these Doppler shifted spectral lines can be expressed in terms of the ratios of ion species as shown below in Eq. (3) and Eq. (4),

$$\frac{N_2^+(E)}{N_1^+(E)} = C_2^{\mathrm{coll}} \frac{I_{\mathrm{obs}}(E/2)}{I_{\mathrm{obs}}(E)}, \quad (3)$$

$$\frac{N_3^+(E)}{N_1^+(E)} = C_3^{\mathrm{coll}} \frac{I_{\mathrm{obs}}(E/3)}{I_{\mathrm{obs}}(E)}. \quad (4)$$

These factors C_2^{coll} and C_3^{coll} contain the neutralization, excitation cross sections,collisional destruction cross sections and transition probabilities for spontaneous emission. Hence, they depend on the energy of the extracted species and target thickness of the neutralizer. The expression for these factors in the present model are different from the factor obtained using coronal model [3, 4]. The analytical expressions for these factors are supplemented in Appendix.

3. Discussion

It is important to study the behavior of the modified correction factors C_2^{coll} and C_3^{coll} as a function of background density and energy and compare the same with C_2 and C_3 of corona model. The excitation cross section is taken from Williams et al [9, 10]. The collision destruction cross sections are taken from Geddes et al [11]. In Fig. 2, the variation of correction factors obtained in corona and present model are compared in the energy range of 20-60 KeV at a target thickness of 5×10^{15} molecules/cm^2. In Fig. 3, the dependency of C_3 and C_3^{coll} on target thickness is compared at different energies for emphasizing the role of the background density. The factors C_2 and C_3 in corona model become independent of target thickness when the target thickness is $\geq 1 \times 10^{16}$ molecules/cm^2 [5], which is not true in case of the modified factors: C_2^{coll} and C_3^{coll}. They decrease monotonously up to target thickness of 3×10^{16} molecule/cm^2 after which they decrease slowly. This behavior is same at any extracted energy. For thin targets i.e., $\sim 1 \times 10^{16}$ molecules/cm^2, the differences between C_2^{coll} and C_2 and similarly difference between C_3^{coll} and C_3 is substantially large. The difference is in between 10-16 % depending on the energy range. In Fig. 4, we compared the behavior of the factors C_2^{coll} with C_2 at very large target

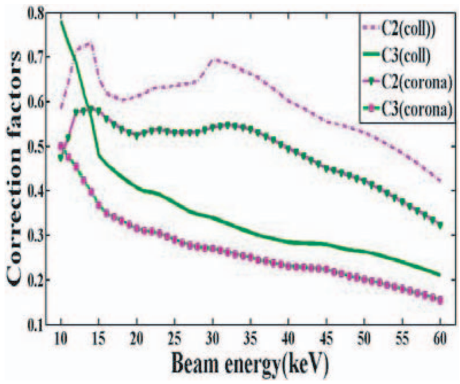

Fig. 2 Variation of intensity correction factors with energy at a fixed target thickness of 5×10^{15} molecules/cm^2.

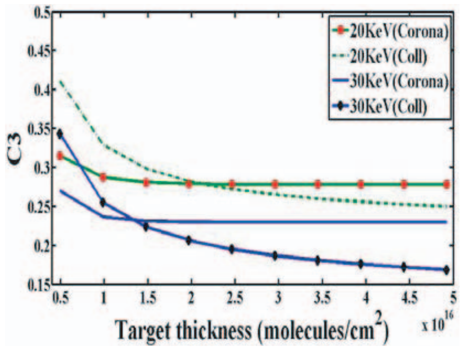

Fig. 3 The variation of $C_3^{\rm coll}$ and C_3 with the target thickness is compared at two different energies 30 keV and 50 keV.

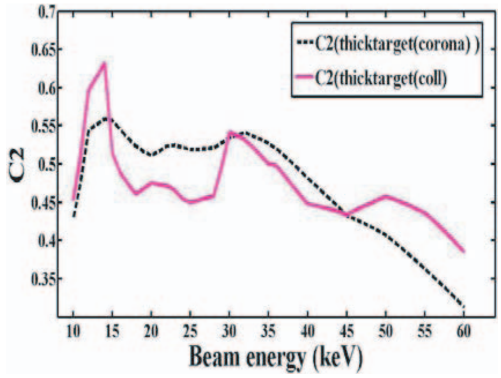

Fig. 4 Comparision of C_2 and $C_2^{\rm coll}$ at large values of target thickness (3×10^{16} cm^2) in the energy range 10 keV-60 keV.

thickness. Here, we point out such a large thick target corresponds to a very large back ground density so there is a complete quenching of 3s states. However, such a large target thickness is never used in neutral beam injectors.

We have recently obtained results of the DSS diagnostics for a positive ion based neutral beam injector in which hydrogen beams of energies up to 25 keV are extracted using a multi-cusp ion source [7]. For the present experiment, the source was operated at $\sim 5 \times 10^{-3}$ Torr which corresponds to a target thickness of 5×10^{15} molecules/cm^2 in the neutralizer and back ground pressure of ~ 1 mTorr in the viewing location. A typical DSS spectrum for a 20 keV hydrogen neutral beam is shown in Fig. 5. From the observed intensities, the ion species fractions, species distribution of the beam and ion species mix in the source are estimated using present model and coronal model. In Fig. 6, the species mix obtained using corona and present model were plotted at the target thickness of 5×10^{15} molecules/cm^2. As shown in the figures, there is a substantial difference of ~ 10 % observed in proton fraction deduced from both the models. It is found out that corona model overestimates the amount of ion species fraction H^+ in the ion species mix and the full energy component H(E) in the beam species distribution. It may be interesting to explore the role of collisional quenching on the species

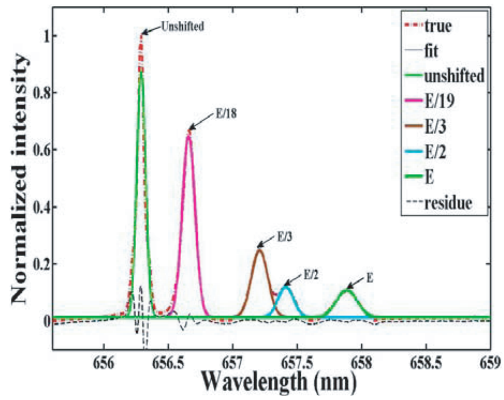

Fig. 5 The experimentally observed Doppler shifted spectrum of the 20 keV extracted beam. Each observed peak is fits well to a single Gaussian and annotated according to their energy groups.

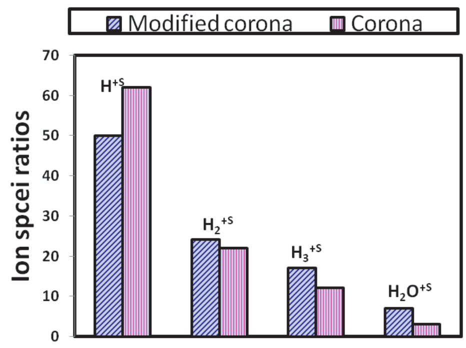

Fig. 6 The measured ion species ratios in a multi cusp ion source operated at a source pressure of 5×10^{-3} mTorr and an arc power of 32 kW. The superscript S stands for source in this figure. The species mix obtained using corona and present model are compared. A large difference in the values for the proton fraction is evident.

measurements by conducting experiments simultaneously at intermediate locations where the validity of the corona model is questionable and then compare with the measurements done at other locations where the residual pressures can differ by at least two orders.

It is to be noted that according to our model predictions, the effect due to collisional destruction appears to cause a systematic correction (always lying on positive side of the derived values from coronal model) at the operating pressures of all neutral beams (1-3 mTorr) and such correction is required so as to obtain an accurate estimation of the mean value of the ion specie fractions from DSS.

4. Summary

We have investigated the effect of the non-radiative processes on the measured intensities of the Doppler shifted H-alpha spectral lines. We have described a revised theoretical model by including collisional de-excitation for steady state conditions. We find that these collisions substantially affect the measurements when the extracted energies are in the range of 10 keV-60 keV and for the background pressures of ≥ 1 mTorr at the observation location. We have compared and discussed the results obtained using the present model and corona model. For our experimental observations with the energy: 20 keV, the full energy component is largely affected by the collisional quenching and showed a difference ∼ 10 % in the values obtained by both the models. We, therefore, propose that the present model can be used to improve the accuracies in the estimation of species ratios in the source and neutral beam fractions of the beam.

Appendix: Expressions for C_2^{coll} and C_3^{coll}

The expressions for C_2^{coll} and C_3^{coll} are given in equation (A.1) and equation (A.2),

$$
\begin{aligned}
C_2^{\mathrm{coll}} &= \frac{\sum_{\mathrm{k}} F_1^{\mathrm{k}}(E)\left[\sigma_{1,3\,\mathrm{s}}^{\mathrm{k}}(E)\, v_{\mathrm{eff}}(E) + 0.118\sigma_{1,3\mathrm{p}}^{\mathrm{k}}(E)\, v(E) + \sigma_{1,3\mathrm{d}}^{\mathrm{k}}(E)\, v(E)\right]}{\sum_{\mathrm{k}} F_2^{\mathrm{k}}(E/2)\left[\sigma_{2,3\,\mathrm{s}}^{\mathrm{k}}(E/2)\, v_{\mathrm{eff}}^2(E/2) + 0.118\sigma_{2,3\mathrm{p}}^{\mathrm{k}}(E/2)\, v(E/2) + \sigma_{2,3\mathrm{d}}^{\mathrm{k}}(E/2)\, v(E/2)\right]} \\
&\quad + F_2^{\mathrm{j}}(E)\left[\sigma_{2,3\,\mathrm{s}}^{\mathrm{j}}(E)\, v_{\mathrm{eff}}^2(E) + 0.118\sigma_{2,3\mathrm{p}}^{\mathrm{j}}(E)\, v(E) + \sigma_{2,3\mathrm{d}}^{\mathrm{j}}(E)\, v(E)\right], \qquad \text{(A.1)} \\
C_3^{\mathrm{coll}} &= \frac{\sum_{\mathrm{k}} F_1^{\mathrm{k}}(E/3)\left[\sigma_{1,3\,\mathrm{s}}^{\mathrm{k}}(E/3)\, v_{\mathrm{eff}}^3(E/3) + 0.118\sigma_{1,3\mathrm{p}}^{\mathrm{k}}(E/3)\, v(E/3) + \sigma_{1,3\mathrm{d}}^{\mathrm{k}}(E/3)\, v(E/3)\right]}{\sum_{\mathrm{k}} F_3^{\mathrm{k}}(E/3)\left[\sigma_{3,3\,\mathrm{s}}^{\mathrm{k}}(E/3)\, v_{\mathrm{eff}}^3(E/3) + 0.118\sigma_{3,3\mathrm{p}}^{\mathrm{k}}(E/3)\, v(E/3) + \sigma_{3,3\mathrm{d}}^{\mathrm{k}}(E/3)\, v(E/3)\right]} \\
&\quad + F_3^{\mathrm{j}}(2E/3)\left[\sigma_{3,3\,\mathrm{s}}^{\mathrm{j}}(2E/3)\, v_{\mathrm{eff}}^3(2E/3) + 0.118\sigma_{3,3\mathrm{p}}^{\mathrm{j}}(2E/3)\, v(2E/3) + \sigma_{3,3\mathrm{d}}^{\mathrm{j}}(2E/3)\, v(2E/3)\right] \\
&\quad + F_3^3(E)\left[\sigma_{3,3\,\mathrm{s}}^3(E)\, v_{\mathrm{eff}}^3(E) + 0.118\sigma_{3,3\mathrm{p}}^3(E)\, v(E) + \sigma_{3,3\mathrm{d}}^3(E)\, v(E)\right]. \qquad \text{(A.2)}
\end{aligned}
$$

$F_1^{\mathrm{k}}(E)$ is the beam fraction in a charge state k originated from the parent extracted ion i. This is obtained by using the formulation given Berkener *et al.* [11]. $v_{\mathrm{eff}}(E)$ is the effective velocity which takes into account the collisional quenching effect. The expression for $v_{\mathrm{eff}}(\varepsilon')$ is given below in equation (A.3),

$$
v_{\mathrm{eff}}^2(\varepsilon') = \frac{A_{3,\mathrm{l}\to 2,\mathrm{l}'}}{\left[\lambda_{\mathrm{rad}}^{\mathrm{l}}(\varepsilon') + \lambda_{\mathrm{coll}}^{\mathrm{l}}(\varepsilon)\right]}. \qquad \text{(A.3)}
$$

When the parent ion is H_2^+ then index j becomes H_2^+ and H_2 similarly when the parent ion is H_3^+ then index j becomes H_2^+, H_2 and H_3^+.

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