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An elegant method to estimate helium-like ion densities from visible and VUV plasma spectroscopy

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Abstract. A method is presented to estimate the densities of He-like carbon and oxygen ions from the observation of the Li-like $3p \rightarrow 3s$ transitions in the visible and the $3p \rightarrow 2s$ transitions in the vacuum ultraviolet. The method is based on a zero-dimensional model for plasmas with short particle confinement times. General coefficients for this study are derived and evaluated numerically. The method is applied to Extrap-T1 reversed field pinch data.

1. Introduction

A standard task of plasma spectroscopy is to determine absolute concentrations of impurities. Already at modest temperature, around 100 eV, this requires instrumentation over a wide wavelength range. Resonance lines for ionization stages of light impurities up to Li-like ones are in the vacuum ultraviolet (VUV) wavelength region, and for He-like and H-like species they are in the soft x-ray region. Visible spectroscopy, on the other hand, is easy to calibrate and can be performed in air. The light can be transported by optical fibres from the experiment to the spectroscopic equipment.

As long as species up to Li-like ones are studied, visible and VUV lines can be found to characterize the ions. In this paper we present a simple method, applicable to plasmas with large particle fluxes and short confinement times, that can be used to estimate He-like ion densities from a zero-dimensional model. This model should be applicable in particular to small and medium size reversed field pinch (RFP) experiments (Bodin 1990).

It can be shown that transport processes under the constraint of ambipolarity are characterized by mass and charge independent diffusion coefficients (Fussmann *et al* 1991). If we assume that the particle confinement time as a result of these transport processes is the same for all ion species, the particle confinement time can be obtained from the intensity of $H\alpha$ (Johnson and Hinnov 1973).

The method and the conditions under which it may be used are outlined in section 2. In section 3 general results for carbon and oxygen are presented. Finally, the method is applied to Extrap-T1 RFP discharges.

2. Method

In a zero-dimensional model, the time development of the He-like ion density can be written as

$$\frac{dn_{\text{He}}}{dt} = -\frac{n_{\text{He}}}{\tau_p} + n_{\text{Li}}n_e S_{\text{Li} \rightarrow \text{He}}(T_e, n_e) - n_{\text{He}}n_e S_{\text{He} \rightarrow \text{H}}(T_e, n_e) - n_{\text{He}}n_e \alpha_{\text{He} \rightarrow \text{Li}}(T_e, n_e) + n_{\text{H}} n_e \alpha_{\text{H} \rightarrow \text{He}}(T_e, n_e). \quad (1)$$

Here, n_e , n_{Li} , n_{He} , and n_{H} are the number densities of electrons, and of Li-, He- and H-like ions of the studied species, τ_p is the particle confinement time and $S(T_e, n_e)$ and $\alpha(T_e, n_e)$ are the collisional dielectronic rate coefficients for ionization and recombination (Summers 1974) as a function of electron temperature, T_e , and electron density, n_e .

The ionization potential for He-like ions is much higher than for Li-like ions. Therefore, in general, $S_{\text{He} \rightarrow \text{H}}(T_e, n_e) \ll S_{\text{Li} \rightarrow \text{He}}(T_e, n_e)$. Also at sufficiently high temperatures $\alpha_{\text{He} \rightarrow \text{Li}}(T_e, n_e) \ll S_{\text{Li} \rightarrow \text{He}}(T_e, n_e)$. Thus, we may simplify equation (1) to

$$\frac{dn_{\text{He}}}{dt} \approx -\frac{n_{\text{He}}}{\tau_p} + n_{\text{Li}}n_e S_{\text{Li} \rightarrow \text{He}}(T_e, n_e). \quad (2)$$

A similar simplification cannot be made for other ionization stages of carbon and oxygen, since the ionization potential for adjacent ionization stages is normally comparable. It is only because of the closed-shell properties of He-like ions that equation (2) can be used.

From equation (2), we obtain in equilibrium

$$\frac{n_{\text{He}}}{n_{\text{Li}}} = \tau_p n_e S_{\text{Li} \rightarrow \text{He}}(T_e, n_e) \quad (3)$$

which should be compared to the well known result that follows from a balance between ionization and recombination

$$\frac{n_{\text{He}}}{n_{\text{Li}}} = \frac{S_{\text{Li} \rightarrow \text{He}}(T_e, n_e)}{\alpha_{\text{He} \rightarrow \text{Li}}(T_e, n_e)}. \quad (4)$$

As a result, the ratio between the fractional abundances of He-like and Li-like ions is reduced by a factor $\tau_p n_e \alpha_{\text{He} \rightarrow \text{Li}}(T_e, n_e)$. The equilibrium charge state distribution is not reached due to the transient ionization (Carolan and Piotrowicz 1983).

In figures 1 and 2 the characteristic times for further ionization, $1/(n_e S_{\text{He} \rightarrow \text{H}})$, and for recombination, $1/(n_e \alpha_{\text{He} \rightarrow \text{Li}})$, are plotted. The rate coefficients were taken from Arnaud and Rothenflug (1985) corrected for multistep processes using the results of Summers (1974). For given density and temperature we can determine the largest particle confinement time that justifies the simplification made in equation (2) using these figures. A particle confinement time comparable with $1/(n_e S_{\text{He} \rightarrow \text{H}})$ may still be acceptable. In this case, we shall obtain the sum of He-like and H-like ion densities from this analysis.

In order to estimate the abundance of He-like ions from equation (3) we have to know n_e , T_e , n_{Li} and τ_p . If we assume that the particle confinement time is the same for all plasma species, the particle confinement time can be obtained from the intensity of $\text{H}\alpha$ (Johnson and Hinno 1973) according to

$$\tau_p = \frac{\int n_p dV}{\int \Gamma_{\text{H}} d\sigma} \approx \frac{n_p V}{\Gamma_{\text{H}} A}. \quad (5)$$

Here n_p is the number density of protons, V is the total plasma volume and A the total plasma surface. The flux of hydrogen atoms, Γ_{H} , per unit area and time can be measured by observation of $\text{H}\alpha$ (in $\text{photon cm}^{-2} \text{ sr}^{-1} \text{ s}^{-1}$)

$$\Gamma_{\text{H}} = 4\pi(S/X)_{\text{H}} I_{\text{H}\alpha} \quad (6)$$

Figure 1. Contours of the characteristic time for further ionization, $1/(n_e S_{\text{He} \rightarrow \text{H}})$, for carbon (top) and oxygen (bottom) in seconds.

Figure 2. Contours of the characteristic time for recombination, $1/(n_e \alpha_{\text{Li} \rightarrow \text{He}})$, for carbon (top) and oxygen (bottom) in seconds.

Here $(S/X)_\text{H}$ is the dimensionless number of ionizations per photon and $I_{\text{H}\alpha}$ is the radiance of $\text{H}\alpha$.

The abundance of Li-like ions may be obtained from visible spectra, namely from the observation of $3p^2P^o \rightarrow 3s^2S$ transitions, or from $3p^2P^o \rightarrow 2s^2S$ lines in the VUV wavelength region.

$$n_{\text{Li}} = \frac{I_{\text{Li}}}{\langle n_e \epsilon_{\text{Li}} \rangle} \approx \frac{I_{\text{Li}}}{(\ell/4\pi) \langle n_e \rangle \epsilon_{\text{Li}}(T_e, n_e)}. \quad (7)$$

Here I_{Li} is the measured radiance of the Li-like multiplet, $\epsilon_{\text{Li}}(T_e, n_e)$ is the rate coefficient for the effective emissivity in photon $\text{cm}^3 \text{s}^{-1}$ of the Li-like multiplet accounting for multistep processes and $\langle \rangle$ represents a line-of-sight average over the plasma column length ℓ .

If we combine equations (3), (5), (6) and (7), assuming $n_p = n_e$ for simplicity, we find that the fraction of He-like ions, $f_{\text{He}} = n_{\text{He}}/n_e$, is independent of the electron density, n_e :

$$f_{\text{He}} = \frac{V}{A\ell} \frac{I_{\text{Li}}}{I_{\text{H}\alpha}} \frac{(S_{\text{Li} \rightarrow \text{He}}/\epsilon_{\text{Li}})}{(S/X)_\text{H}}. \quad (8)$$

The reason for this is that, as $1/\tau_p \gg n_e \alpha_{\text{He} \rightarrow \text{Li}}$, the Li-like ions are, in fact, in a state of influx, and so the concept of ionization per photon, which has already been applied successfully to C^{1+} , C^{2+} , O^{1+} and O^{2+} ions (Behringer *et al* 1989) is extended to Li-like ions. It should be noted that the flux in this context is the flux of Li-like ions by transport. The influx at the plasma boundary is larger, and ions are lost at all previous ionization stages with a rate $\simeq 1/\tau_p$.

The advantage of this formal density independence is that the estimate is not sensitive to errors in the measurement of n_e , which otherwise result in error propagation. However, the dependence on n_e re-enters into equation (8) through the density dependence of the rate coefficients.

3. Theoretical results

A more realistic approach to the estimate of He-like abundances will have to consider the spatial distribution of n_e and T_e , the actual ratio n_p/n_e as well as the proper geometry of the line-of-sight. For this study, the quantity S/ϵ_{Li} is needed separately, which is given in table 1 for carbon and in table 2 for oxygen for the visible transitions $3p^2P^o \rightarrow 3s^2S$. The corresponding quantities for the VUV transitions $3p^2P^o \rightarrow 2s^2S$ can be obtained by multiplication with the branching ratio (Klose and Wiese 1989). The result for the visible transitions is also displayed in figure 3. The excitation rate coefficients for oxygen have been calculated from the cross section results of Zhang *et al* (1990). The data for carbon have been taken from Cochrane and McWhirter (1983). Since the $3p^2P^o$ level is close to the ionization threshold, redistribution processes affect the effective excitation to $3p^2P^o$ and the ionization so that the density dependence of ϵ_{Li} and S are comparable. Thus, the coefficient S/ϵ_{Li} is fairly independent of density.

Table 1. Number of ionizations per photon $S_{Li \rightarrow He}/\epsilon_{Li}$ for carbon for the transition $3p^2P^o \rightarrow 3s^2S$ (5801.3–5812.0 Å). The corresponding quantities for the transition $3p^2P^o \rightarrow 2s^2S$ (312.42–312.46 Å) can be obtained by multiplication with the branching ratio 0.317/44.9 (Klose and Wiese 1989).

T_e (eV)	n_e (cm ⁻³)			
	$\leq 10^{13}$	10^{14}	10^{15}	10^{16}
1.0E+01	6.19E+00	8.36E+00	1.18E+01	1.40E+01
2.0E+01	3.23E+01	3.90E+01	4.77E+01	4.72E+01
3.0E+01	6.05E+01	6.95E+01	8.09E+01	7.58E+01
5.0E+01	1.04E+02	1.15E+02	1.29E+02	1.18E+02
7.0E+01	1.35E+02	1.46E+02	1.61E+02	1.48E+02
1.0E+02	1.67E+02	1.78E+02	1.94E+02	1.81E+02
2.0E+02	2.14E+02	2.24E+02	2.43E+02	2.39E+02
3.0E+02	2.42E+02	2.51E+02	2.71E+02	2.74E+02
5.0E+02	2.75E+02	2.84E+02	3.06E+02	3.19E+02
7.0E+02	2.95E+02	3.03E+02	3.25E+02	3.45E+02
1.0E+03	3.14E+02	3.21E+02	3.42E+02	3.68E+02
2.0E+03	3.39E+02	3.44E+02	3.63E+02	4.00E+02
3.0E+03	3.48E+02	3.51E+02	3.68E+02	4.11E+02
5.0E+03	3.55E+02	3.56E+02	3.71E+02	4.19E+02
7.0E+03	3.56E+02	3.56E+02	3.70E+02	4.19E+02
1.0E+04	3.57E+02	3.56E+02	3.68E+02	4.18E+02
2.0E+04	3.55E+02	3.51E+02	3.60E+02	4.09E+02

The coefficient $(S/X)_H$ is available from Johnson and Hinnov (1973). For illustrative reasons and for simple estimates, we also present the ratio of the two quantities, as given in equation (8). As one can see in figure 4, this quantity depends on electron density. The dependence stems mainly from the well known but often neglected dependence of $(S/X)_H$ on electron density.

4. Application to Extrap-T1 RFP data

We have applied our method to the estimate of He-like oxygen abundances in Extrap-T1 RFP discharges (Brunsell *et al* 1991) from the radiance of $O^{5+} 3p^2P^o \rightarrow 2s^2S$ at 150.1 Å.

Table 2. Number of ionizations per photon $S_{\text{Li} \rightarrow \text{He}}/\epsilon_{\text{Li}}$ for oxygen for the transition $3p^2P^o \rightarrow 3s^2S$ (3811.4–3834.2). The corresponding quantities for the transition $3p^2P^o \rightarrow 2s^2S$ (150.09–150.12 Å) can be obtained by multiplication with the branching ratio 0.510/254 (Klose and Wiese 1989).

T_e (eV)	n_e (cm $^{-3}$)			
	$\leq 10^{13}$	10^{14}	10^{15}	10^{16}
1.0E+01	8.72E-01	9.61E-01	1.07E+00	1.04E+00
2.0E+01	2.00E+01	2.16E+01	2.39E+01	2.25E+01
3.0E+01	6.19E+01	6.56E+01	7.17E+01	6.71E+01
5.0E+01	1.60E+02	1.67E+02	1.80E+02	1.71E+02
7.0E+01	2.45E+02	2.53E+02	2.72E+02	2.66E+02
1.0E+02	3.43E+02	3.53E+02	3.77E+02	3.81E+02
2.0E+02	5.46E+02	5.57E+02	5.90E+02	6.33E+02
3.0E+02	6.64E+02	6.75E+02	7.12E+02	7.84E+02
5.0E+02	7.98E+02	8.09E+02	8.49E+02	9.61E+02
7.0E+02	8.80E+02	8.91E+02	9.32E+02	1.07E+03
1.0E+03	9.70E+02	9.82E+02	1.02E+03	1.18E+03
2.0E+03	1.10E+03	1.12E+03	1.15E+03	1.32E+03
3.0E+03	1.16E+03	1.17E+03	1.20E+03	1.37E+03
5.0E+03	1.22E+03	1.23E+03	1.25E+03	1.41E+03
7.0E+03	1.26E+03	1.26E+03	1.28E+03	1.43E+03
1.0E+04	1.27E+03	1.28E+03	1.29E+03	1.42E+03
2.0E+04	1.30E+03	1.31E+03	1.30E+03	1.41E+03

Figure 3. Number of ionizations per photon $S_{\text{Li} \rightarrow \text{He}}/\epsilon_{\text{Li}}$ for carbon (top, see table 1) and oxygen (bottom, see table 2) for the transition $3p^2P^o \rightarrow 3s^2S$. The full curve is for $n_e = 1.0 \times 10^{14}$ cm $^{-3}$ and the broken curve for $n_e = 1.0 \times 10^{16}$ cm $^{-3}$.

Figure 4. Contours of the ratio of ionizations per photon $S_{\text{Li} \rightarrow \text{He}}/\epsilon_{\text{Li}}$ for carbon (top) and oxygen (bottom) for the transition $3p^2P^o \rightarrow 3s^2S$ to the corresponding quantity of hydrogen H α .

The line average electron density, measured by interferometry, is in the range 5×10^{13} – 5×10^{14} cm $^{-3}$, the electron temperature is ≤ 200 eV and the particle confinement time is 10–60 μ s. According to figures 1 and 2 the method presented in section 2 can be applied,

since $1/(n_e S_{\text{He} \rightarrow \text{H}}) \approx 1$ ms and $1/(n_e \alpha_{\text{He} \rightarrow \text{Li}}) \approx 5$ ms under these conditions. Thus, the loss of He-like oxygen is given by τ_p , and the ratio of the fractional abundances between He-like and Li-like ions will be reduced to less than 1/100, when compared with the result that would follow from a balance between ionization and recombination (see equations (3) and (4)).

Figure 5. Results for Extrap-T1 RFP discharges at 50 kA ($\square$) and at 80 kA ($\bullet$) in deuterium. Each data point in the figures represents the average result from five discharges during the current rise phase (for times before 0.2 ms), and from ten discharges for times after 0.2 ms. Spectra are taken during 35 μ s. A few representative error bars are given to illustrate the averaged time intervals and the shot-to-shot variation. Further error bars are omitted for clarity. Left from top to bottom: toroidal plasma current I_ϕ ; line average electron density n_e ; line average electron temperature T_e from VUV line intensity ratios; particle confinement time τ_p . Right from top to bottom: fraction of oxygen ions O^{4+} and O^{5+} obtained from VUV radiances using a zero-dimensional collisional radiative model; fraction of O^{6+} obtained from the method described in this paper, using the radiance of $3p^2p^0 \rightarrow 2s^2S$; effective ion charge Z_{eff} obtained by summing over individual contributions from all measured ion species of carbon, nitrogen, oxygen and chlorine.

In figure 5 we present toroidal plasma current, I_ϕ , line average electron density, $\langle n_e \rangle$, line average electron temperature, $\langle T_e \rangle$, and particle confinement time, τ_p , together with the results for the oxygen ionization balance as obtained from two series at 50 and 80 kA in deuterium. The electron density is approximately equal for the two series, while the electron temperature reaches 100 eV for the 50 kA series, and 200 eV for the 80 kA series. For the experiments, we use a VUV spectrometer (Fonck *et al* 1982, Brzozowski *et al* 1991) which has been absolutely calibrated using the branching ratio technique (Klose and Wiese 1989). One of the branching ratios that has been used is the $\text{O}^{5+} 3p^2p^0 \rightarrow 2s^2S$ to $\text{O}^{5+} 3p^2p^0 \rightarrow 3s^2S$ line ratio. VUV spectra are taken during 35 μ s and the gate time is varied from shot to shot.

The line average electron temperature is measured using the intensity ratio of $O^{5+} 3p^2P^o \rightarrow 2s^2S$ to $O^{5+} 2p^2P^o \rightarrow 2s^2S$. This electron temperature represents the plasma conditions under which O^{5+} is ionized, which is the relevant temperature for the estimate of O^{6+} abundances. It is interesting to note that the measured temperatures exceed the temperature of maximum fractional abundance for O^{5+} that would be obtained if the ionization balance between O^{5+} and O^{6+} were to be given by ionization and recombination. Due to the transient ionization, this equilibrium charge state distribution is not reached. This fact is exploited by our measurement. In the initial phase of the discharge, when O^{5+} is not observed, we use the line ratios of O^{4+} and O^{3+} for the measurement of the electron temperature.

The line average densities of oxygen ionization stages up to O^{5+} were derived using a zero-dimensional collisional-radiative model. The atomic data for this study have been collected by Lang and Summers. Metastable and ground-state densities are measured separately for O^{2+} , O^{3+} and O^{4+} , and these ion populations are then added to obtain the total density. In the case of O^{4+} , reported in figure 5, we used $O^{4+} 629.73 \text{ \AA}$ and $O^{4+} 758.68\text{--}762.00 \text{ \AA}$ to measure $2s^2^1S$ and $2s2p^3P^o$.

Details of the measurement of the deuterium influx, Γ_D , are given in appendix A. Since the density is, in fact, varying on a time scale comparable with τ_p , we modify equation (5) in order to obtain τ_p according to

$$\tau_p = \langle n_d \rangle / \left(\frac{A}{\gamma V} \Gamma_D - \frac{d\langle n_d \rangle}{dt} \right) \quad (9)$$

where γ is a shape factor obtained from the density profile, which is assumed parabolic, and $\langle n_d \rangle$ is given by equation (11). Since it turns out, that O^{6+} gives a major contribution to the plasma dilution, the calculation has to be repeated several times, until self-consistent results are obtained. Starting with a given deuterium influx and a plasma dilution based upon ions up to O^{5+} , the particle confinement time is used to calculate the fraction of O^{6+} . When this ion density is included, the result for the deuteron density decreases, therefore the resulting τ_p is reduced, the corresponding calculated density of O^{6+} is reduced and *vice versa* in the next iteration step.

In figure 5 we can see the following trends for the oxygen ionization balance. For the 80 kA series, O^{4+} reaches its maximum fraction at around 0.12 ms, and the maximum of O^{5+} is seen around 0.15 ms into the discharge. Then, both directly measured ionization stages return to a lower level, which is approximately constant throughout the discharge. The calculated fraction of O^{6+} rises to an approximately constant level during the first 0.2 ms. For the 50 kA series, a different result is obtained due to the lower electron temperature and particle confinement time. The fraction of O^{4+} and of O^{5+} remains almost constant throughout the discharge. The calculated result for O^{6+} indicates a slow rise, to values around 1%. The ionization balance thus is shifted towards a lower average ion charge in the 50 kA series compared with the 80 kA series. This is consistently observed for the ratio between the directly measured fraction of O^{5+} and O^{4+} and for the ratio between the calculated fraction of O^{6+} and the directly measured fraction of O^{5+} .

Other plasma species such as carbon, nitrogen and chlorine have concentrations typically less than 10% of the oxygen concentration. Since all dominant ion fractions, f_i , are measured for each species i with charge Z_i , we can explicitly calculate the effective ion charge, Z_{eff} , the line average deuteron density, $\langle n_d \rangle$, and the total particle density, $\langle n \rangle$, as

$$Z_{\text{eff}} = 1 + \sum_i f_i Z_i (Z_i - 1) \quad (10)$$

$$\langle n_d \rangle = \langle n_e \rangle - \sum_i f_i \langle n_e \rangle Z_i \quad (11)$$

$$\langle n \rangle = \langle n_e \rangle + \langle n_d \rangle + \sum_i f_i \langle n_e \rangle. \quad (12)$$

The result for Z_{eff} is also shown in figure 5. An alternative method to obtain Z_{eff} by a measurement of the absolute level of the continuum intensity has not been possible, since no sufficiently wide wavelength region free of spectral lines could be found. On the other hand, such a measurement on its own would not be sufficient, since neither $\langle n_d \rangle$ nor $\langle n \rangle$ can be obtained in this way, without further knowledge of the plasma composition. From Z_{eff} and with T_e in eV, we can then calculate the Spitzer resistivity η_S and resistance R_S

$$\eta_S = 3.04 \times 10^{-5} \frac{\ln \Lambda(n_e, T_e, Z_{\text{eff}}) Z_{\text{eff}}}{\gamma_E(Z_{\text{eff}}) T_e^{3/2}} \quad (13)$$

$$R_S = \frac{2R_0}{a^2} f(\Theta) \eta_S \quad (14)$$

where R_0 is the major radius, a is the minor radius, and the factor $f(\Theta)$ considers the helical structure of the parallel current in an RFP (Sprott 1988). The coefficients $\ln \Lambda(n_e, T_e, Z_{\text{eff}})$ and $\gamma_E(Z_{\text{eff}})$ are given by Spitzer (1962). For both the series of discharges presented here, R_S accounts for 50–70% of the total plasma resistance for times before 0.1 ms, and for 20–40% for times after 0.1 ms. The behaviour of the non-Spitzer loop voltage, $I_\phi(R - R_S)$, reflects the activity of the so-called dynamo process that sustains the magnetic field configuration.

For the measurement of the plasma composition, specifically for a calculation of Z_{eff} , n_d and n , it is necessary to measure the density of all ionization stages up to and including O^{6+} under the transient ionization conditions in Extrap-T1. With these densities, Spitzer plasma resistivity, an improved result for the particle confinement time, and an estimate of the total plasma pressure can be obtained. Our method makes these results available to us with visible and VUV spectroscopy alone.

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Appendix A. Measurement of particle influx

The influx of deuterium is obtained from the intensity of $D\alpha$ based on assumptions on the radial profiles of T_e and n_e necessary to obtain the radiance per unit influx. In this model, the radial profile of the electron density is assumed to be parabolic, i.e. $n_e(r) = n_e(0)(1 - (r/a)^2)^{\alpha_n}$ with $\alpha_n = 1.0$, and the electron temperature is assumed almost flat, i.e. $T_e(r) = T_e(0)(1 - (r/a)^2)^{\alpha_T}$, with $\alpha_T = 0.1$. Then, for a given influx Γ_D of

deuterium atoms with velocity v_D , the radial profile of the deuterium atom density $N_n(r)$ in level n can be obtained solving

$$-\frac{1}{r} \frac{\partial}{\partial r} (r \Gamma_D) - S(r) n_e(r) N_1(r) = 0$$

$$\Rightarrow N_1(r) = N_1(a) \left(\frac{a}{r} \right) \exp \left(- \int_r^a \frac{n_e(r) S(r)}{v_D} dr \right) \quad (15)$$

$$\frac{N_n(r)}{N_1(r)} = n^2 \exp \left(- \frac{E_n - E_1}{T_e(r)} \right) r_1(n). \quad (16)$$

Here, S and r_1 are the quantities taken from Johnson and Hinnov (1973), evaluated for the local electron temperature and density. From the profile of $N_3(r)$, we obtain the radiance of $D\alpha$ per unit influx by integration along the line-of-sight. This quantity is found to be mainly dependent on $\langle n_e \rangle$ and weakly dependent on $\langle T_e \rangle$ over the operational regime of Extrap-T1. Since both $\langle n_e \rangle$ and $\langle T_e \rangle$ are measured, we can calculate the deuterium influx from the observed radiance of $D\alpha$ using this quantity. Choosing different profile parameters for density and temperature within reasonable limits, i.e. $0.5 \leq \alpha_n \leq 2.0$ for the density and $0.0 \leq \alpha_T \leq 0.5$ for the temperature, the coefficient changes as much as 20%. The choice of v_D does not affect the result, as long as the assumption behind the solution to equation (15), that the flux of deuterium vanishes for $r = 0$, remains valid. For typical parameters in Extrap-T1, this assumption holds for velocities up to $3 \times 10^4 \text{ m s}^{-1}$, corresponding to a kinetic energy of 10 eV.

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