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Review of atomic data needs for active charge-exchange spectroscopy on ITER[a)]

O. Marchuk,[1,b)] G. Bertschinger,[1] W. Biel,[1] E. Delabie,[2] M. G. von Hellermann,[2] R. Jaspers,[2] and D. Reiter[1]
[1]*Institut fuer Energieforschung-Plasmaphysik, Forschungszentrum Juelich, 52425 Jülich, Germany and Association EURATOM-FZJ, 52425 Jülich, Germany*
[2]*FOM-Rijnhuizen, Association EURATOM-FOM, P.O. Box 1207, 3430 BE Nieuwegein, The Netherlands*

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The quantitative exploitation of active beam spectra is largely based on an advanced atomic modeling. Under the ITER operating conditions the penetration depth of a diagnostic beam into the plasma core crucially affects the intensities of spectral lines and hence the uncertainties of derived plasma parameters. A critical review of atomic data and an assessment of its error margins are, therefore, urgently needed. The aim of the present work is to verify the existing beam-stopping and beam-emission data for hydrogen beam in fusion plasmas. The agreement between the ADAS database and the present calculations is found to be within 5% for the beam-stopping data in a H-plasma. The calculation of beam attenuation in the presence of He-ash (4%) and Be ions (2%) demonstrates the agreement between the present data and the ADAS database within 10%. Finally, the maximum deviation of 15% is found only for beam-emission data at the electron density of $1\times10^{12}-2\times10^{12}$ cm^{-3}, which is significantly below the ITER density of 10^{14} cm^{-3}. © *2008 American Institute of Physics.* [DOI: 10.1063/1.2965019]

I. INTRODUCTION

The present design of ITER incorporates only a few diagnostic systems capable of providing information on plasma core characteristics such as ion temperature and plasma rotation or density of impurities. So, for example, the He-ash density measurement is required to 10% accuracy at the time resolution of 100 ms and the measurements of ion temperature are required to 5% accuracy within 10 ms.[1] The only diagnostic meeting such challenging needs to the quality of measured plasma parameters is the active charge-exchange spectroscopy. Such quantitative evaluation of charge-exchange spectra can be performed, however, only on a verified set of atomic constants used at the spectra modeling.

The atomic data incorporated in the ADAS database[2] has been extensively used for charge-exchange and XUV diagnostics on fusion devices such as JET,[3] ASDEX,[4] TEXTOR,[5] or TORE SUPRA.[6] The assessment of the quality of these data can be done either on the base of experimental results or by means of independent calculations including multistep processes.[7] So, recently, for example, a seeming inconsistency was pointed out between the ADAS data and calculations[8] for the population density of the excited $n=3$ states. The reason for this discrepancy turned out to be a different set of fundamental data used in calculation. On the other hand, the experiment on Alcator-C Mod pointed out the importance of the charge-exchange capture from the excited $n=3$ states for the boron B^{5+} ions.[9]

The aim of this paper is to verify the quality of beam-stopping cross section (BSCS) and beam-emission cross sections (BECS) for a diagnostic hydrogen beam at ITER conditions. In contrast to all the present devices, less than 2% of the beam penetrates into the plasma core, so that the verification of the atomic data of the beam attenuation becomes the urgent task of the port plug design.

II. OVERVIEW OF DIAGNOSTIC NEEDS

The charge-exchange port plug designed for ITER is demonstrated in Fig. 1. In the present scheme the hydrogen beam with the energy of 100 keV/amu penetrates almost radially into the plasma core with the electron density of about 10^{14} cm^{-3} and the electron and ion temperatures of 20 keV. The distance from the beam entrance point to the plasma core is about 2 m. The input set of atomic data used by the diagnostic includes the BSCS responsible for the neutral beam attenuation in the plasma. The density of neutral beam at the distance x from the entrance can be written as follows:

$$N_b(x) = N_{b0}\exp\left(-\int_0^x \sigma_{\mathrm{BS}}(z)N_e(z)dz\right), \tag{1}$$

where N_{b0} is the neutral beam density at the entrance, N_e is the electron density and $\sigma_{\mathrm{BS}}\equiv\sigma(E_b,N_e,T_e,T_i,\{n_j\})$ is the BSCS. The latter depends on the beam energy E_b, electron density N_e and temperature T_e, and density of ions $\{n_j\}$ with the temperature T_i. The BSCS is determined by excitation/ionization of hydrogen atoms by electrons and ions and by charge-exchange capture by ions.

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[b)]Electronic mail: o.marchuk@fz-juelich.de.

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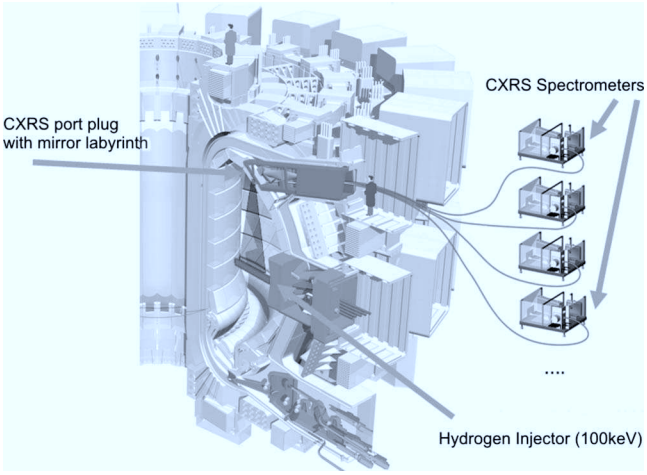


FIG. 1. Overview of the CXRS port plug for ITER (Ref. 10) (based on an ITER drawing).

The second set of data describes the intensity of spectral lines. The intensity of a spectral line I_L due to charge-exchange capture into an excited state of a specific impurity with the density n_Z is determined as follows:

$$I_L(x) = \int_{\text{l.o.s.}} N_b n_Z \langle \sigma_{\text{CX}}(n,n') \cdot u \rangle dl, \tag{2}$$

where the integral is taken along the instrumental line of sight, $\sigma_{\text{CX}}(n,n')$ is the effective cross section of a specific transition between the states n and n', and u is the relative velocity between the neutral beam particle and impurity ion. For example, the He II ($n=4$, $n=3$), Be IV ($n=6$, $n=5$), Ne X ($n=11$, $n=10$), and Ar XVIII ($n=16$, $n=15$) transitions are considered as candidates for the spectrometer design for the ITER. The further technical specification of the design layout can be found, for example in Refs. 10 and 11.

The uncertainties in the cross sections in Eqs. (1) and (2) have different effects. The errors in Eq. (1) propagate along the beam path and consequently the errors of 10% will considerably change the density of neutral particles at the center. Indeed, the e-folding length of the beam at the plasma core is $L_e = 1/N_e/\sigma_{\text{BS}} \approx 0.3-0.5$ m and the errors of 10% in the σ_{BS} will change the neutral density in the core by a factor of 2. In contrast, the signal of a spectral line changes linearly with the uncertainties in the cross sections in Eq. (2). In this paper the comparison of the first set of the cross sections for the hydrogen beam will be performed. The validation of the change-exchange cross sections of impurities is the aim of a future investigation.

III. CALCULATION OF BEAM-STOPPING CROSS SECTIONS

The BSCS, were calculated using the collisional-radiative model for excited states of a hydrogen beam as follows:

$$\frac{\partial N_p}{\partial t} + V_b \frac{\partial N_p}{\partial x} = \sum_{p \neq l} N_l W_{lp} - N_p \left(\sum_{p \neq l} W_{pl} + N_e S_p^i \right), \tag{3}$$

where

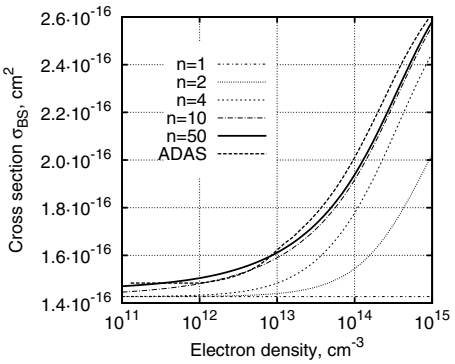


FIG. 2. Steady-state calculations of BSCS for hydrogen plasma. The results are demonstrated for the different number of excited states included in the model. The ADAS data are shown as the dashed line. The beam energy was taken at 100 keV/amu and electron and ion temperatures were taken at 20 keV.

$$W_{lp} = N_e \left(k_{lp}^{ee} + \sum_j c_j k_{lp}^{ie(j)} \right) + A_{lp}, \tag{4}$$

$$S_p^i = k_p^{ei} + \sum_j c_j (k_p^{ii(j)} + k_p^{icx(j)}). \tag{5}$$

Here, N_p is the density of the excited state of hydrogen ($\Sigma_p N_p = N_b$), V_b is the beam velocity, and $c_j = n_j/N_e$ is the abundance of the impurity ion j in plasma. The term W_{lp} describes the contribution from any state l to p and S_p^i is the term responsible for ionization and charge exchange from the state p. The A_{lp} is the radiative rate of the transition from the state l to p, and $k_{pl}^{ee,ie}$ are the excitation ($p<l$) or de-excitation ($l<p$) rates due to electron (ee) or ion collisions (ie). The rates $k_p^{ei,ii}$ are the electron and ion ionization rates, respectively. The ionization of the state p due to charge-exchange process was taken into account with the rate coefficients k_p^{icx}. The cross sections for all collisional processes were taken from Ref. 12 and averaged over the relative velocities of the beam and plasma particles. The radiative rates for $n \leqslant 6$ were taken from the NIST database[13] and hydrogenic approximation was assumed for transitions higher than $n \leqslant 50$.[14]

Using Eqs. (1), (3), and (5) BSCS can be defined using the following expression: $\sigma_{\text{BS}} = \Sigma_p N_p S_p / N_b / V_b$. The BECS

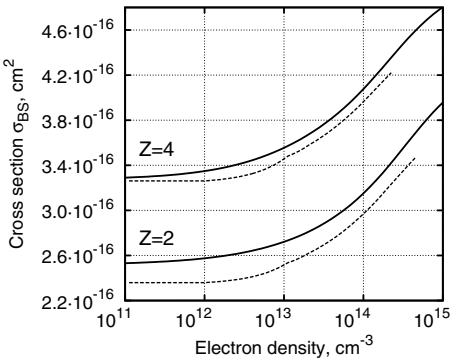


FIG. 3. The BSCS for helium and beryllium plasmas. The number of excited states included in the model is $n=50$. The beam energy was taken at 100 keV/amu, and electron and ion temperatures were taken at 20 keV. The solid lines are based on the present data and the dashed lines are based on the ADAS data.

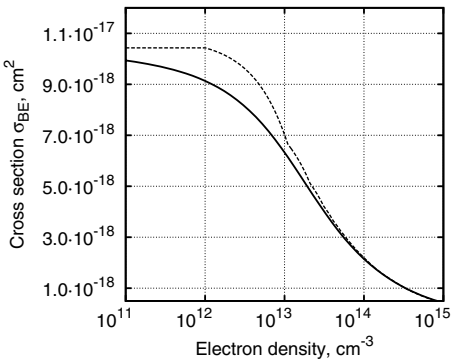


FIG. 4. The beam-emission data for hydrogen plasma. The beam energy was taken at 100 keV/amu, and electron and ion temperatures were taken at 20 keV. The solid line is the present results and the dashed line is the ADAS data.

for the $n=3\rightarrow n=2$ transition, also measured in tokamak plasmas,[3] is determined as $\sigma_{BE}=N_3A_{32}/N_b/V_b$. The BSCS for a hydrogen beam penetrating hydrogen plasma is shown in Fig. 2. The calculations were performed up to $n=50$; however, the results converge within 5% taking only the first $n=10$ states. The agreement with the ADAS data for hydrogen is also obtained within 5%. The results of comparison for the hydrogen beam penetrating in the He- and Be-plasmas are presented in Fig. 3. Here, a deviation of 10% in the cross sections is observed only for the low-density case. The BSCS in a plasma with different impurity concentrations can be calculated using the following relation: $\sigma_{BS}=\Sigma_j c_j\sigma_{BS}^j$, where σ_{BS}^j is the cross section in pure H-, He-, or Be-plasmas.

The results for the beam-emission data in hydrogen plasma are shown in Fig. 4. We note the difference of about 15% observed for the density of $(1-2)\times 10^{13}$ cm^{-3}. Both sets of data are, however, in good agreement with the higher densities relevant to ITER.

IV. CONCLUSIONS

In this paper the beam attenuation atomic data used for the design of active charge-exchange spectroscopy at ITER (Ref. 11) are presented. The difference in the BSCS between the present calculation and the ADAS data was found to be within 7% for plasma parameters expected for the ITER core. This agreement is quite satisfactory. The discrepancy of about 15% for the BECS is found only at low electron densities and hence an additional experimental verification of the beam-emission data is necessary.

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