Review of Scientific Instruments

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Citation: Rev. Sci. Instrum. **83**, 10D519 (2012); doi: 10.1063/1.4732847
View online: http://dx.doi.org/10.1063/1.4732847
View Table of Contents: http://rsi.aip.org/resource/1/RSINAK/v83/i10
Published by the American Institute of Physics.

Method to obtain absolute impurity density profiles combining charge exchange and beam emission spectroscopy without absolute intensity calibration[a)]

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(Presented 7 May 2012; received 7 May 2012; accepted 9 June 2012; published online 20 July 2012)

Investigation of impurity transport properties in tokamak plasmas is essential and a diagnostic that can provide information on the impurity content is required. Combining charge exchange recombination spectroscopy (CXRS) and beam emission spectroscopy (BES), absolute radial profiles of impurity densities can be obtained from the CXRS and BES intensities, electron density and CXRS and BES emission rates, without requiring any absolute calibration of the spectra. The technique is demonstrated here with absolute impurity density radial profiles obtained in TEXTOR plasmas, using a high efficiency charge exchange spectrometer with high etendue, that measures the CXRS and BES spectra along the same lines-of-sight, offering an additional advantage for the determination of absolute impurity densities. © *2012 American Institute of Physics*. [http://dx.doi.org/10.1063/1.4732847]

I. INTRODUCTION

Impurities in fusion plasmas have both beneficial and detrimental effects: on one hand, they contribute to the improvement of confinement and divertor protection by means of radiative edge cooling, on the other hand, impurities in the plasma imply fuel dilution and core radiation losses. In addition, monitoring and removal of the helium "ash," the thermalised fusion product, is a significant issue. The investigation of impurity transport properties is obviously essential and therefore a diagnostic that can provide information on the impurity content is required. Charge exchange recombination spectroscopy (CXRS) is a diagnostic capable of observing plasma impurities and is the only diagnostic that will be able to provide helium "ash" measurements on ITER.[1]

The CXRS measures the light emitted by impurity ions in the plasma after they have undergone a charge exchange process with the neutral atoms from a neutral beam injected in the plasma. The measurement is local, as the active charge exchange signal comes from the location where the neutral beam intersects the lines-of-sight of the spectrometer. The intensity of the light measured is this local emission integrated along the line-of-sight. The emitted light depends on the impurity density n_i and the neutral beam density n_b, as well as the charge exchange emission rates Q_{CX}, which in turn depends on the local plasma and beam parameters (electron temperature T_e, electron density n_e, impurity density n_i, and beam energy E). Consequently, CXRS can provide a measurement of the impurity densities in the plasma,[2] assuming that the neutral beam density is known.

The neutral beam density in the plasma can be derived either from calculations of the neutral beam attenuation in the plasma as: $n_b = n_b(0)\exp(-\int \sigma_{\mathrm{stop}} n_e)$, or from beam emission spectroscopy (BES). The BES measures the light emitted from neutral beam particles after excitation by ion and electron impact. The measured intensity is now dependent on the integral of the neutral beam density along the line-of-sight, the electron density, and the beam emission rates Q_{BES}. The beam emission rates are also dependent on T_e,n_e, n_i, and E. As such, the neutral beam density can be obtained from the BES spectrum.

Combining CXRS and BES, absolute radial profiles of impurity densities can readily be obtained.[3,4] This method is described in detail in Sec. II. A spectrometer designed according to ITER requirements that measures both CXRS and BES is then used to showcase the method. The application of the technique is described in Sec. III and an example of absolute carbon impurity density profiles from a TEXTOR plasma is given. Nevertheless, as discussed in Sec. IV, validation of the technique is required.

II. IMPURITY DENSITY PROFILES COMBINING CXRS AND BES

For positive ion neutral beams, such as the neutral beams at the TEXTOR tokamak, the three beam energy components E, E/2, E/3 have to be taken into account and the CXRS and BES measured light intensities are

$$I_{\mathrm{CX}} \propto \int_{los} n_i \sum_{E=E,E/2,E/3} Q_{\mathrm{CX}}^{E} n_b^{E}\, dl, \tag{1}$$

[a)]Contributed paper, published as part of the Proceedings of the 19th Topical Conference on High-Temperature Plasma Diagnostics, Monterey, California, May 2012.

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$$I_{\mathrm{BES}} \propto n_e Q_{\mathrm{BES}} \int_{los} n_b^E dl. \tag{2}$$

If the same lines-of-sight are used, determination of the intersection integral between the neutral beam and the line-of-sight is not needed and for neutral beam density equal to $n_b^E = f^E \frac{I_{\mathrm{BES}}}{Q_{\mathrm{BES}} n_e}$, the impurity concentration is given by[3]

$$c_i = \frac{n_i}{n_e} = I_{\mathrm{CX}} \sum_{E=E,E/2,E/3} \frac{Q_{\mathrm{BES}}}{Q_{\mathrm{CX}} I_{\mathrm{BES}}}. \tag{3}$$

However, it should be taken into account that the sensitivity of the two detectors measuring the CXRS and BES spectra are not equal. In other words, there are calibration factors that should be included in the above described CXRS and BES intensities, A_{CX} and A_{BES}, respectively. The ratio of these calibration factors can be derived from the spectra, by looking at the bremsstrahlung level at the specific wavelength, performing a cross-calibration of the two detectors[5]

$$\frac{A_{\mathrm{CX}}}{A_{\mathrm{BES}}} = \frac{C_{\mathrm{CX}}}{C_{\mathrm{BES}}} \frac{\lambda_{\mathrm{CX}}}{\lambda_{\mathrm{BES}}}, \tag{4}$$

where C_{CX} and C_{BES} are the continuum level for each of the spectra at the specific wavelength λ_{CX} and λ_{BES}, respectively.

Using this method, no absolute calibration of the detectors is required. All the required information to obtain absolute impurity density profiles can be found in the spectrum itself. It can be argued that even the radial locations of the measurement can be extracted from the BES spectra, by calculating the doppler shift of the first beam energy component in relation to the D_α or a reference line.

A technique like this, apart from reducing any errors due to beam attenuation calculations, provides an additional advantage in reactor or ITER like situations, where access to the instrument and torus hall will not be always possible. In Sec. III, an attempt is made to apply this method in practice.

III. APPLICATION OF THE METHOD ON TEXTOR

A. High etendue spectrometer for ITER core CXRS measurements

An attempt to apply this technique to extract impurity density profiles has been made using a spectrometer designed for core CXRS on ITER,[6] which was installed on the TEXTOR tokamak during the last experimental campaigns.

The spectrometer is a highly efficient optical system with high etendue and high resolution, following the ITER requirements for charge exchange measurements.[7] The light from the tokamak arrives to the spectrometer with a single fiber bundle and is split into three wavelength ranges, allowing simultaneous measurement of carbon, helium, and hydrogen spectra on three different detectors. Consequently, the impurity spectrum, namely, carbon or helium, and the beam emission spectrum are measured on exactly the same lines-of-sight. The spectrometer is looking at neutral beam 2 on TEXTOR and an illustration of the observation geometry and the lines-of-sight can be seen in Fig. 1. The high etendue of the system would also allow for fast measurements (down to a few milliseconds, depending on the readout time of the detectors), making the spectrometer suitable for impurity transport studies.

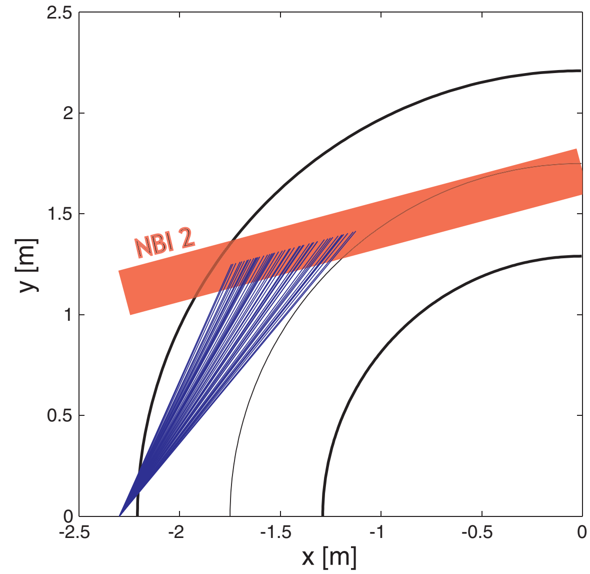

FIG. 1. A top view illustration of the lines-of-sight of the spectrometer on neutral beam 2 on TEXTOR (major radius 1.75 m, minor radius 0.46 m).

B. Carbon density profiles from a TEXTOR discharge

The charge exchange spectrum of the CVI emission (n $= 8 \rightarrow 7$, at 529 nm) and the BES spectrum from a TEXTOR discharge ($I_p = 400$ kA, $B_t = 2.6$ T) are fitted to obtain the measured light intensity, in order to obtain absolute density profiles of C^{6+}. The relatively calibrated intensities for discharge 115155 at 2.06 s are shown in Fig. 2. At this time

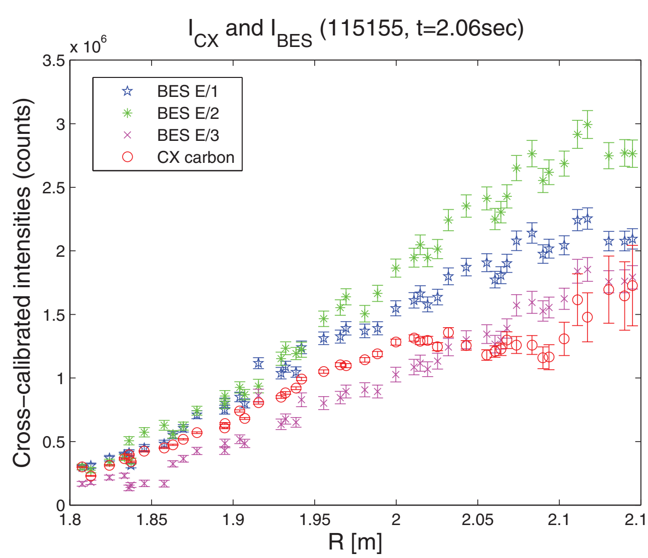

FIG. 2. The CX intensity from the carbon spectrum for TEXTOR discharge 115155 and the intensities of the three beam energy components from the BES spectrum. The data are already cross-calibrated at this point (the carbon CX intensity is multiplied with $A_{\mathrm{BES}}/A_{\mathrm{CX}}$). The error bars correspond to the errors in the fit.

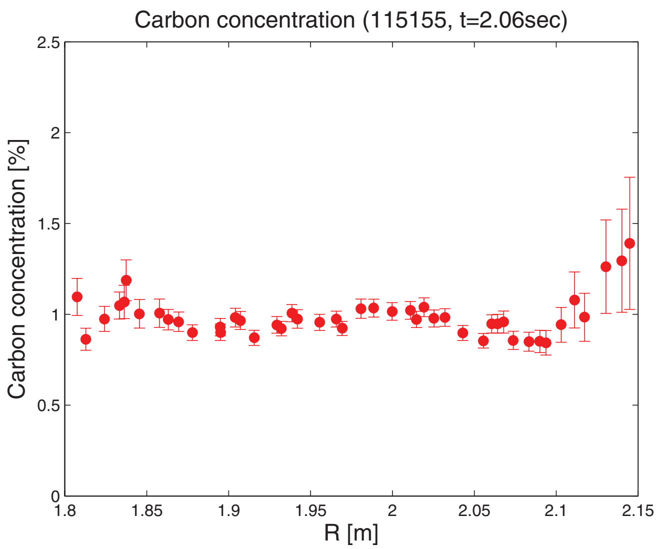

FIG. 3. The C^{6+} concentration for TEXTOR discharge 115155 at t = 2.06 s derived from the cross-calibrated CXRS and BES spectra. The vertical error bars come from the fitting of the spectra.

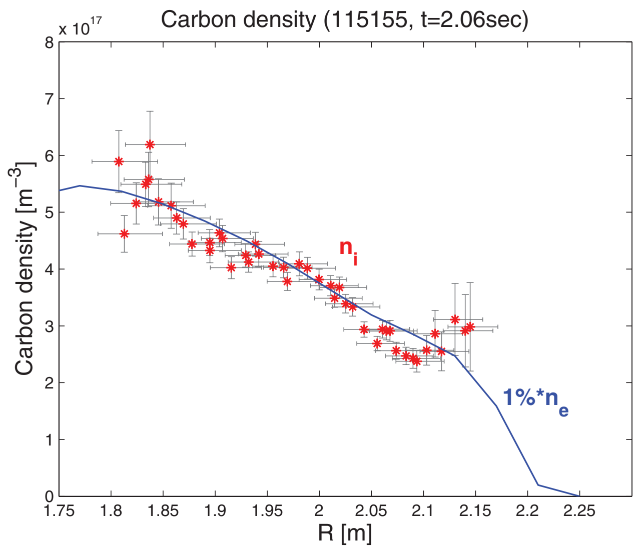

FIG. 4. The carbon (C^{6+}) absolute density profile is plotted together with the electron density profile (multiplied by 1%) for comparison. The uncertainty in the radial location in the plasma is also indicated.

point only NBI 2 (hydrogen), the neutral beam which the CX spectrometer is operated on, is switched on at 50 kV voltage.

Subsequently, the charge exchange and beam emission rates are calculated for the local plasma parameters and the neutral beam energy. A value of 1.9 is assumed for Z_{eff}. As the accuracy of the atomic data is crucial for this technique, the updated ADAS (Atomic Data and Analysis Structure[8]) atomic data for the neutral beam emission rates are used.[9] The excited beam neutrals are also taken into account.

The bremsstrahlung level from the fitted spectra is extracted in order to perform a cross-calibration of the BES and CXRS spectra, as described in Sec. II. The resulting C^{6+} concentration profiles are shown in Fig. 3. The carbon concentration is about 1% for this example. In Fig. 4, the carbon density is compared to the electron density, plotted here in scale. Very good agreement in profile shape is observed.

The vertical error bars in Figs. 3 and 4 are from the fit, while the horizontal error bars indicate the error in the determination of the radial location in the plasma where the lines-of-sight intersect the neutral beam. The uncertainty in the intersection point is about 3–6 cm, which is reasonable taking into account that the neutral beam has a FWHM of about 18 cm.

IV. DISCUSSION

In Sec. III, an absolute density profile of carbon (C^{6+}) has been shown and compared with the electron density for a TEXTOR discharge. The values obtained are still to be checked, for example, against measurements of Z_{eff}, which have not been available.

Regarding the method itself, it should be noted that the cross-calibration of the BES and CXRS spectra in order to achieve accurate results, implies that there should be a line free wavelength range in the measured spectra. The situation becomes even more difficult when the continuum level is very close to the noise level.

The method is shown to be useful and applicable to extract absolute density profiles of impurities in tokamak plasmas, with minimum calibration requirements, however, validation of the method is required where the impurity density profiles should be checked against other diagnostic measurements.

ACKNOWLEDGMENTS

This work, supported by the European Communities under the contract of Association between EURATOM-FOM, was carried out within the framework of the European Fusion Program. The views and opinions expressed herein do not necessarily reflect those of the European Commission. We acknowledge the TEXTOR team.

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