Z_{eff} from spectroscopic bremsstrahlung measurements at ASDEX Upgrade and JET

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The effective ionic charge Z_{eff} is a means to assess the impurity content of a fusion plasma. It can be derived from measurements of bremsstrahlung intensity. These have been extended at ASDEX Upgrade by the usage of the sight lines for the charge exchange recombination diagnostic. Together with a previously installed sight line array it is now possible to routinely determine the bremsstrahlung intensity over the whole minor radius purely from spectroscopic measurements. In a tokamak where the plasma facing components are made up of various materials, this is necessary to check if measurements are disturbed by line radiation. The bremsstrahlung background of the respective spectra is determined using Bayesian probability theory, giving consistent and improved error statistics. Using the information for electron temperature and density profiles, the Z_{eff} profile is determined by an integrated method. The same approach to assess the Z_{eff} profile has been demonstrated to be successful also at the JET tokamak.

I. INTRODUCTION

A commonly used quantity in nuclear fusion research characterising the global impurity content is the effective charge state $Z_{\mathrm{eff}} = \sum_i n_i Z_i^2 / \sum_i n_i Z_i$. One method to determine Z_{eff} profiles is to measure the bremsstrahlung of the plasma and to calculate Z_{eff} using independent measurements of electron density n_e and temperature T_e. This approach is used at the tokamak ASDEX Upgrade.

Usually, the measurement of bremsstrahlung is carried out by recording the plasma emission in a certain wavelength range free of line radiation using interference filters and varying types of diodes as detectors. Mostly, a narrow band in the green range of the spectrum is used. The range of up to 5 nm around 537 nm is reported to be line free in several machines (e.g. Ref. 1–3) whereas JET uses a narrow line-free band around 523 nm[4]. At ASDEX Upgrade, the existing filter/detector combinations of the Thomson scattering diagnostic[5] were mainly used for bremsstrahlung measurements, as was previously done at ASDEX[6] and repeated on Frascati Tokamak Upgrade[7]. Although the sensitive Avalanche-diodes used as detectors are very well suited to measure the low intensities of the bremsstrahlung, the interference filters are not optimised for this task. They observe rather broad spectral ranges (up to 80 nm) in the near infrared region. Therefore, the bremsstrahlung signals may be disturbed by line radiation and/or thermal radiation from hot parts of the plasma facing components. To compensate for these disadvantages, the procedure of an integrated method[8], has been extended to incorporate the bremsstrahlung emission measured by the charge exchange recombination spectroscopy (CXRS) diagnostic. Together with a previously installed diagnostic it is now possible to determine the bremsstrahlung emission over the whole minor radius purely from spectrally resolved measurements using spectrometers and CCD cameras.

In Sec. II an overview is given of diagnostic set-ups at ASDEX Upgrade measuring spectrally resolved bremsstrahlung. Sec. III discusses the principle of determining the bremsstrahlung background in these spectra and using this information to deduce Z_{eff} profiles. Sec. IV finally shows an example from JET which demonstrates that this approach to assess Z_{eff} profiles is successful at the JET tokamak, as well.

II. EXPERIMENTAL SET-UP

The measurements of bremsstrahlung intensity at ASDEX Upgrade have been extended by the usage of the sight lines for the CXRS diagnostic[9]. Together with a previously installed sight line array (diagnostic ZEB) it is now possible to routinely determine the bremsstrahlung intensity over the whole minor radius purely from spectroscopic measurements. The sight lines of these diagnostics are shown in Fig. 1, mapped onto a toroidal cross-section.

The 12 sight lines of the diagnostic ZEB view the plasma edge at the outer mid-plane. Focusing the light with a convex mirror onto fibre-guides gives a spatial resolution of 1 cm. The plasma emission is detected using a Czerny-Turner type spectrograph ($f = 0.3$ m) and a 2D back-illuminated frame-transfer CCD-camera (1024 × 1024 pixel). The spectrograph is equipped with two ruled gratings of 1200 rules per mm, blazed at 300 nm and 750 nm respectively in order to cover the complete wavelength range from 300 nm to 1100 nm. In the visible the observed wavelength range at one grating position is up to 30 nm. The minimum cycle time of the camera is mainly determined by the readout time of 45 ms for the current set-up. Mostly, a cycle time of 60 ms is applied, which is a good trade-off with respect to the signal-to-noise ratio in the wavelength range of 532–562 nm which is usually used for Z_{eff} determination.

One sight line array of the CXRS diagnostic is used during this work to cover the whole minor radius in the outer

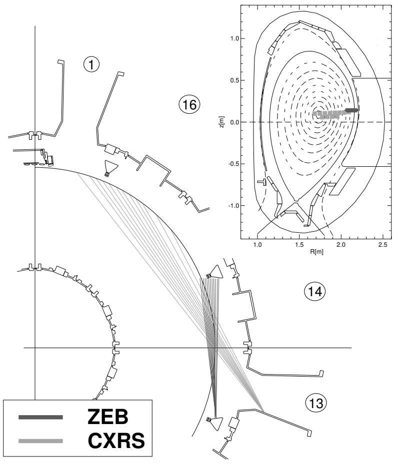

FIG. 1: Sight lines measuring bremsstrahlung intensity spectrally resolved at ASDEX Upgrade

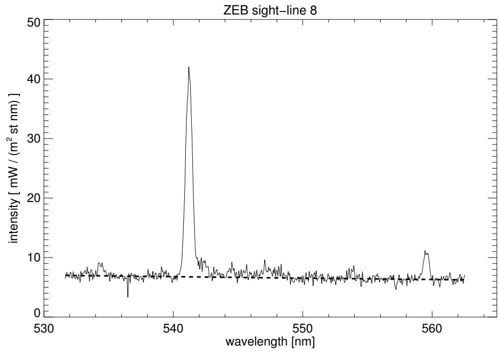

FIG. 2: Fit of the bremsstrahlung background (- - -) to sight line 8 of the ZEB diagnostic in the case of a background plasma with relatively strong spectral lines (#18468, $t = 3.5\,$s).

mid-plane. The array consists of 12 sight lines which are focused onto fibre-guides and detected by a 2D intensified CCD-camera (512×512 pixel) coupled to a 1 m Czerny-Turner type spectrograph with a grating with 2400 rules per mm. For charge exchange measurements of ion temperature and toroidal rotation velocity the C-VI charge exchange line at 529.05 nm ($\Delta n = 8 \rightarrow 7$) is observed in the wavelength range of 526–532 nm.

Both diagnostics are absolutely calibrated. For the intensity calibration we place a calibrated integrating sphere inside the vessel in front of the optics during maintenance periods. Thus all optic components are considered in the same way during calibration as during experimental measurements. In order to further improve the relative channel-to-channel calibration a discharge with a radial sweep of the plasma but otherwise constant parameters is used. The absolute value of the calibration factor is checked during a high-density discharge with known low impurity content.

III. DATA ANALYSIS

The spectra measured by the ZEB and CXRS diagnostics normally show one or several spectral lines. Nonetheless there remain always enough regions of the spectra which exhibit line-free bremsstrahlung background of the plasma. In order to capture the defining characteristics of this background, namely that the background is proportional to $1/\lambda^2$, a Bayesian mixture model as in Ref. 10 is used. An elaborate analysis of the statistical measurement uncertainties allows to separate statistical noise from line emission. This approach provides a natural way to reliably determine the bremsstrahlung emission irrespective of the fraction of line radiation, while including all uncertainties of the measurements. An example for the fit of the bremsstrahlung background to one sight line of diagnostic ZEB is shown in Fig. 2.

The bremsstrahlung emission from several diagnostics at ASDEX Upgrade, including (but not limited to) those measuring spectrally resolved, is inverted to deduce the Z_{eff} profile. In the cold plasma edge line radiation and pseudo-continua from molecular bands dominate the bremsstrahlung background. Therefore, the information from the outermost sight lines of diagnostic ZEB, which usually never touch the separatrix, are used to determine the intensity of a radiative mantle[1]. Its subtraction from the measured intensity of the remaining sight lines, weighted with the path-lengths through the edge region and the widths of the observed wavelength ranges, results in improved deconvolution results.

This approach, explained in detail in Ref. 8, is especially useful in a tokamak where the plasma facing components are made up of various materials (mainly C and W in ASDEX Upgrade) in order to check if measurements are disturbed for various reasons, e.g. due to line radiation. Consistent Z_{eff} values are derived and the limits of validity for each diagnostic involved are clearly identified. An example for Z_{eff} profile deconvolution is shown in the right column of Fig. 3. In this case T_e and n_e profiles are taken from the Thomson scattering diagnostic.

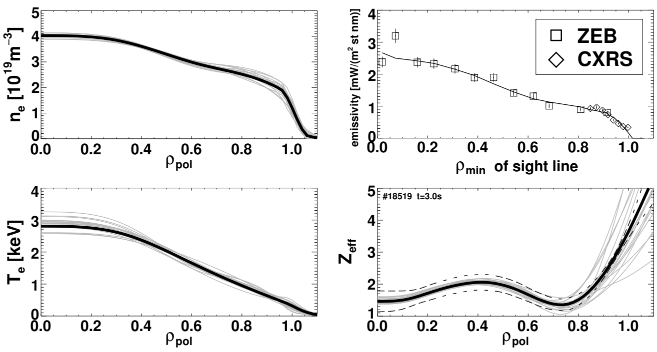

FIG. 3: ASDEX Upgrade discharge #18519, $t = 3.0\,$s. Left column: n_e and T_e profiles (black line: spline fit to raw data, gray lines: Monte Carlo variation of splines). Right column: emissivity per sight line plotted with min. ρ_{pol} of sight line as x-axis, measured (symbols) and reproduced by deconvolution (—), and Z_{eff} profile (—) with confidence band (- - -) corresponding to original spline fits. Z_{eff} profiles in gray correspond to the respective varied T_e and n_e profiles.

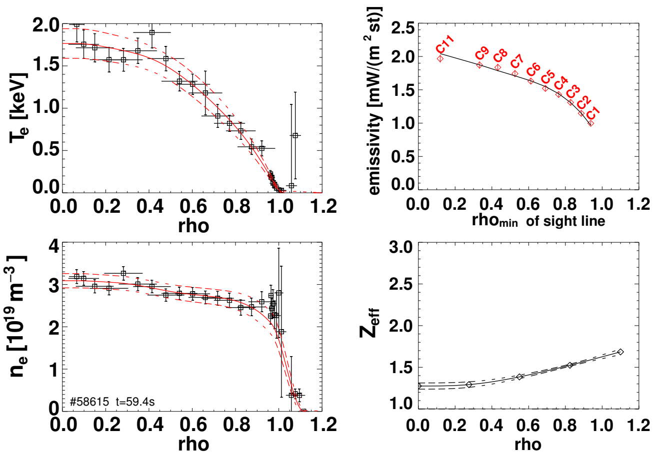

FIG. 4: T_e, n_e, bremsstrahlung emission per sight line and Z_{eff} profiles for JET discharge #58615, $t = 59.365\,\mathrm{s}$.

In the matrix inversion method used for deconvolving Z_{eff} profiles, T_e and n_e are assumed to be known exactly when comparing measured and calculated sight line intensities. Hence, the uncertainties of the T_e and n_e profiles are not reflected in the confidence band of the resulting Z_{eff} profile. The sensitivity of Z_{eff} to the uncertainties in these profiles can be estimated by Monte Carlo variation, using the multi-normal distribution inferred from the variance-covariance matrix of a least squares fit to the T_e and n_e raw data, using an appropriate regression model (left column of Fig. 3: spline fits in black, varied profiles in gray). Significant variation of the resulting Z_{eff} profile (gray profiles in lower left graph of Fig. 3) is seen mainly towards the plasma edge where the uncertainties in the density profiles are largest and also most important due to steep gradients and the strong dependence of Z_{eff} on n_e. In the plasma centre the uncertainty from T_e and n_e variation does not exceed the one from uncertainties in the measurements.

IV. EXPERIMENTAL RESULTS FROM JET

At the JET tokamak there is no dedicated diagnostic to determine Z_{eff} profiles from bremsstrahlung radiation. At present only one vertical and one horizontal sight line of the array described in Ref. 11 are used to determine a line-averaged value from visible bremsstrahlung emission[4]. However, by porting the evaluation procedure used at ASDEX Upgrade it could be demonstrated that the bremsstrahlung emission underlying the spectra of the charge exchange recombination diagnostic at JET may be used to deduce Z_{eff} profiles. In this case the intensity of the bremsstrahlung background is not determined by the Bayesian model but taken directly from the background of the fitted charge exchange lines. T_e and n_e profiles are calculated by fitting a cubic spline to the data from several diagnostics. In case of T_e this is the data from electron cyclotron emission and the one from edge LIDAR Thomson scattering. In case of n_e the spline is fitted to the data of the centre and edge LIDAR Thomson scattering diagnostic. As an example of this approach Fig. 4 shows the spline fits to the raw data (left column) and the resulting Z_{eff} profile (right column). As at ASDEX Upgrade, the main source of uncertainty in the resulting Z_{eff} profile is the accuracy of the n_e profile. Again, for the deconvolution n_e is assumed to be known exactly and the confidence band of Z_{eff} does not reflect this uncertainty.

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