Design of VUV/XUV Spectrometers for Impurity Studies on W7-X

W. Biel, G. Bertschinger, R. Burhenn* and R. König*

Institut für Plasmaphysik, Forschungszentrum Jülich GmbH, EURATOM Association, Trilateral Euregio Cluster, D-52425 Jülich, Germany
*Max-Planck-Institut für Plasmaphysik, EURATOM Association, D-17491 Greifswald, Germany

Introduction and Overview. The content and transport of impurities is a key issue for the performance and optimisation of fusion plasmas, in particular with respect to confinement and stationarity. Impurities are either released to the plasma via the plasma-wall contact (Be, B, C, O, Si, metals), or produced by the fusion reaction (He ash) or added artificially (He, N, Ne, Ar) to modify the plasma radiation properties (radiation cooling). The most fundamental experimental access to identify impurity species is the measurement of their characteristic line radiation by passive spectroscopy. In case of medium-sized fusion experiments like W7-X, the strongest spectral lines of most of the relevant impurity ions are located in the VUV/XUV wavelength range, which can dominate the total radiation power losses of the plasma. Simultaneous monitoring and identification of all of the most relevant species requires a spectroscopic instrumentation which provides a complete coverage of this wavelength region at a sufficient wavelength resolution. For studies of the impurity transport by impurity injection experiments, the spectrometers should be optimised for high efficiency in order to provide high time resolution. Following these requirements, a set of four new VUV/XUV overview spectrometers is developed for W7-X, which shall cover the entire wavelength range of 2.5-160 nm, divided into four different subsections with some overlapping. In this paper, the design of these spectrometers is presented and their expected performance is discussed.

Concept for the new spectrometers. The optical design for the new VUV/XUV overview spectrometers closely follows the SPRED concept [1], which uses a holographic diffraction grating on a toroidally shaped substrate with laminar groove profiles as the only optical element and an open MCP detector in a flat-field geometry. Within this approved design so far 3 different diffraction gratings were available which could be used in the same spectrometer configuration under a grazing incidence angle of about 20 degrees, covering the nominal wavelength ranges of about 10-33 nm, 10-110 nm and 10-160 nm, respectively, with moderate wavelength resolution ($\lambda/\Delta\lambda = 30 \dots 300$). A major drawback of this original SPRED configuration is the limitation of both resolution and efficiency at small wavelengths, which for instance leads to problems in the identification of medium-Z impurities above iron ($Z = 26$) based on their strong Be-like resonance lines ($\lambda = 13.28$ nm for iron). The new concept presented here consists of four different overview spectrometers which

shall be installed at W7-X observing the same plasma volume in the triangular plane. The data of these new spectrometers are given in table 1.
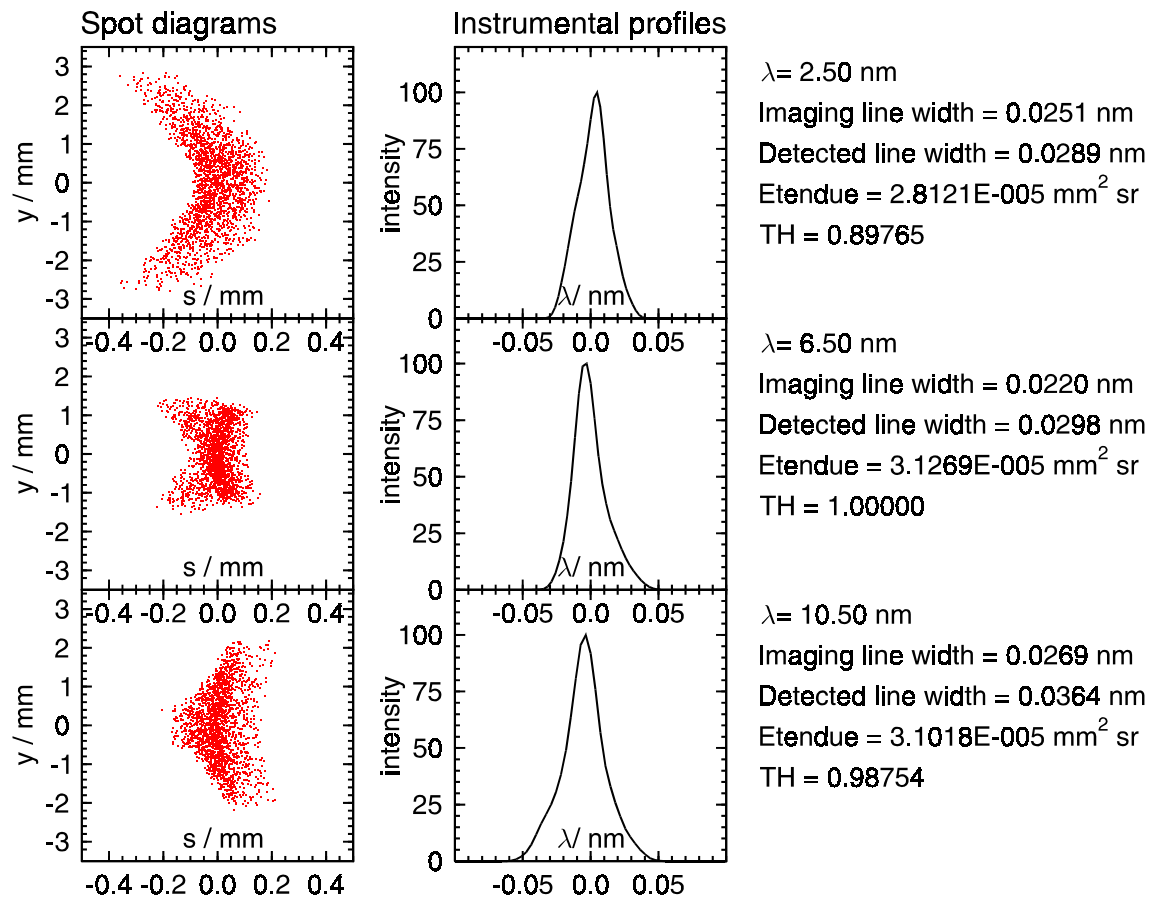
	Flat-field grazing incidence	SPRED ch. 1	SPRED ch. 2	Seya-Namioka
Groove density	1724 l/mm	1915 l/mm	1279 l/mm	1586 l/mm
Incidence angle	86°	76°	65°	39.2°
Wavelength range	2.5 - 10.5 nm	9 – 24 nm	20 – 66 nm	60 – 160 nm
Line width	0.032 nm	0.05 nm	0.13 nm	0.28 nm
Etendue	0.3×10^{-4} mm^2 sr	0.9×10^{-4} mm^2 sr	1.9×10^{-4} mm^2 sr	5.7×10^{-4} mm^2 sr

Table 1: Data of the new spectrometers

The wavelength ranges were chosen to take into account the position of important spectral lines as well as techniques for absolute calibration using secondary standard sources and branching ratio methods. The position and size of the overlap regions is chosen to contain at least one important spectral line, providing a convenient possibility for relative intensity calibration between neighbouring spectrometers, while keeping enough room for slight modifications of the wavelength ranges due to alignment effects and detector edge effects. The permanent monitoring of the entire range of 2.5-160 nm ensures a reliable detection of the most intense resonance lines of practically all of the first 30 elements in the periodical table. In particular, the important Li-like, Be-like, Na-like and Mg-like states are accessible. The incidence angles for all spectrometers are chosen to ensure a high efficiency (throughput) for each instrument, allowing for a good photon statistics when operating the detectors at high time resolution. Compared to commercially available solutions, the etendue and/or wavelength resolution of these new instruments, as determined by ray tracing (see below), are improved by typical factors of 2-5.

Grating design and optimisation. The groove pattern of the gratings is formed by super-position of laser light from two point-like light sources. The full set of 7 holographic recording parameters (radii of the toroidal substrate, laser wavelength and coordinates of the recording light sources) of the new diffraction gratings is determined in a numerical optimisation procedure. In this process the line width is minimised for a given spectrometer geometry over a given wavelength range, see e.g. [2], which leads to a groove pattern with varying groove density and curved grooves on the toroidal substrate. The shape of the slit images in first diffraction order is determined by a subsequent ray-tracing calculation. From the resulting spot diagrams the figures for line with and etendue (product of entrance slit area and solid angle) of the spectrometer are numerically derived. As an example, the results for the case of spectrometer no. 1 are shown in figure 1.

R = 6451.0 mm, ρ = 51.8 mm, G = 1724 / mm, α= -86.00^o, L$_A$ = 450.00 mm
β_1 = 83.34^o, β_2 = 78.37^o, L$_{B1}$ = 451.95 mm, L$_{B2}$ = 458.32 mm
Slit height 2.5 mm, width 0.14 mm. Grating height 8 mm, width 32 mm

λ= 2.50 nm
Imaging line width = 0.0251 nm
Detected line width = 0.0289 nm
Etendue = 2.8121E-005 mm^2 sr
TH = 0.89765

λ= 6.50 nm
Imaging line width = 0.0220 nm
Detected line width = 0.0298 nm
Etendue = 3.1269E-005 mm^2 sr
TH = 1.00000

λ= 10.50 nm
Imaging line width = 0.0269 nm
Detected line width = 0.0364 nm
Etendue = 3.1018E-005 mm^2 sr
TH = 0.98754

Mean imaging line width = 0.0243 nm, mean detected line width = 0.0315 nm
Mean Etendue = 3.0544E-005 mm^2 sr

Figure 1: *Ray-Tracing results for W7-X spectrometer No. 1*

Simulation of spectra. In order to analyse the expected performance of the spectrometers with respect to line position, separation and identification, simulated spectra are created using the STRAHL code [3]. In these simulations a constant impurity density is assumed (constant particle influx and pumping rate, constant diffusion coefficient D = 1 m^2/s, radial drift velocity v = 0). For the input data electron density and temperature, we use smooth profiles with central values of $n_e = 3 \times 10^{19}$m^{-3} and T$_e$ = 1.5 keV. Atomic data are taken from ADAS. Since photon emissivity coefficients (PEC data) due to charge-exchange excitation are available only for carbon, all simulations are based only on rates for excitation and recombination. The simulation yields the intensity of the most prominent spectral lines for important elements between boron (Z = 5) and nickel (Z = 28). For the efficiency of both grating and detector we assume figures of 0.1 each. A superposition of simulated spectra for spectrometer no. 2 is shown in fig. 2. The central concentrations of the various species are assumed, according to typical experimental spectra measured at TEXTOR.
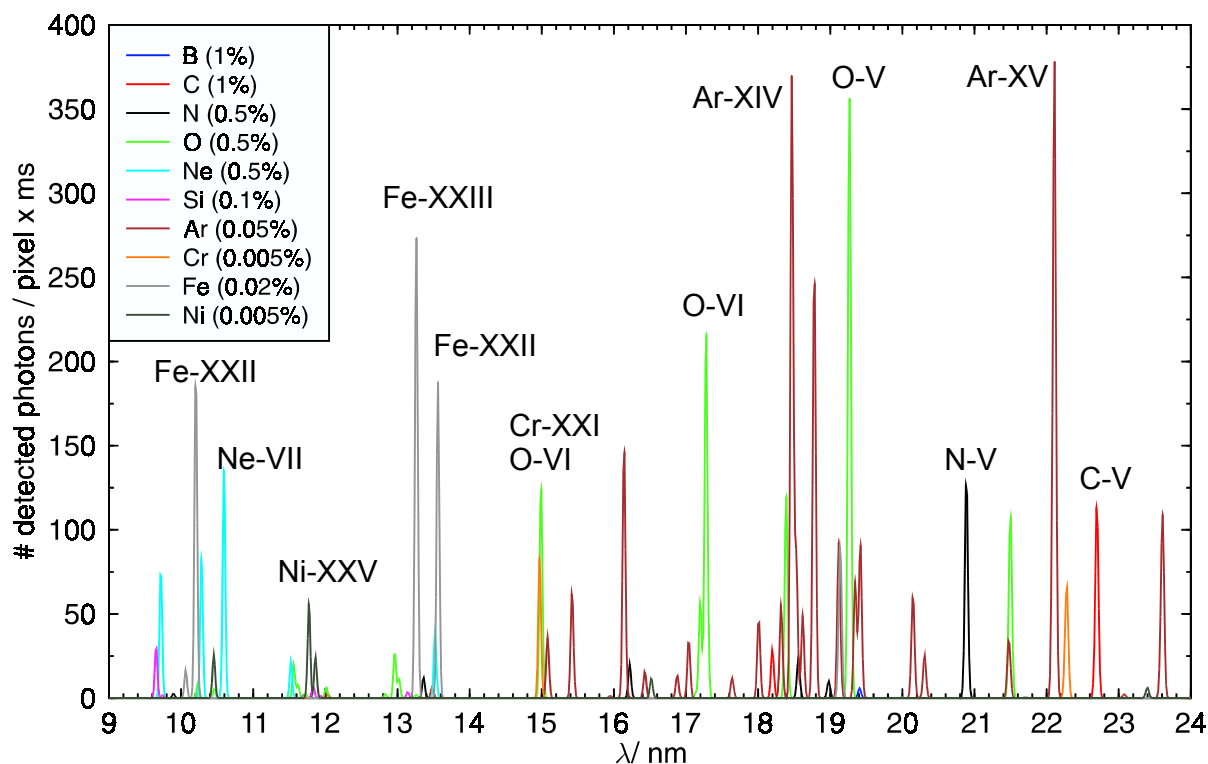
Figure 2: *Simulated VUV spectrum for W7-X spectrometer No. 2*

The simulated spectrum shows, that many prominent resonance lines from different species and ionization stages can be clearly detected and separated. Analysing the set of simulated spectra for all of the spectrometers, we conclude that under most conditions a reliable identification of all of the first 30 elements in the plasma is possible, provided that their concentrations in the plasma are significant and that the number of different elements in the plasma is limited.

The achievable signal-to-noise ratio of the spectrometers may be discussed for the example of the Be-like resonance line of Fe-XXIII at $\lambda = 13.28$ nm, measured by spectrometer no. 2. For the conditions given above and a line width of about 3 pixels, a number of 800 photons per millisecond may be detected. We conclude that this spectrometer can be operated at spectra rates of 1000/second or higher with good accuracy. Due to the smaller etendue and the smaller photon fluxes at lower wavelengths, we find that a reasonable spectra rate for spectrometer no. 1 may be around 100/second.

References:

[1]:   Fonck R. J. et al., Appl. Opt. 21, 2115 (1982)

[2]:   Samson L. A. R and Ederer D. L., Vacuum Ultraviolet Spectroscopy Vol 2, Academic Press, 1998

[3]:   Behringer K, Rep. JET-R(87)08, JET Joint Undertaking, 1987

E-Mail: w.biel@fz-juelich.de