Design of a high–efficiency extreme ultraviolet overview spectrometer system for plasma impurity studies on the stellarator experiment Wendelstein 7-X

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The design for a set of four high-efficiency vacuum ultraviolet/extreme ultraviolet (VUV/XUV) spectrometers has been developed, which shall be used for plasma impurity monitoring and impurity transport studies on the stellarator experiment Wendelstein 7-X (W7-X). The new high-efficiency XUV overview spectrometer (HEXOS) system covers the wavelength range from 2.5 to 160 nm, divided into four subsections with some overlapping, thus achieving a complete coverage of prominent spectral lines from the relevant impurity elements. Taking into account spectrometer geometries and detector geometries, toroidal holographic diffraction gratings are numerically optimized to maximize the total throughput while maintaining good spectral resolution. The performance of the spectrometers is tested and optimized by means of ray tracing calculations. In order to prove the potential for line identification as well as the expected levels of signal intensity and noise figures of the new systems, spectra are simulated using the impurity transport code STRAHL. Under typical plasma conditions on W7-X the new spectrometers will allow clear identification of all relevant impurity elements in the plasma. The large collected photon flux results in a high accuracy for the measured line intensities, even when operating the spectrometers at spectra rates of 1000/s.

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I. INTRODUCTION

The plasma properties in magnetically confined fusion experiments are strongly linked to the content and transport of impurities, which include all elements in the plasma apart from the hydrogen fuel. Impurities are either released to the plasma via the unavoidable plasma–wall contact (Be, B, C, O, Si, metals), or produced by the fusion reaction (He), or added on purpose (He, N, Ne, Ar) in order to modify the plasma radiation properties.\(^1\) Within the hot plasma center, impurities cause an enhanced cooling of the plasma by radiation and a dilution of the hydrogen fuel, both leading to a reduction of the fusion power density. However, within the colder plasma edge region an elevated level of radiation from impurities facilitates the power exhaust from the plasma by distributing the outgoing power fluxes to large wall areas. Furthermore, an enhanced impurity concentration was shown to reduce the level of fluctuations and anomalous transport in the plasma edge region,\(^2\) giving rise to an improvement of the overall plasma confinement.\(^3\) Apart from the physics issues, a detailed knowledge and control of the impurity content in the plasma is important also for the safety of the plasma device with respect to the load on and the lifetime of plasma-facing machine components. Material-related issues as well as the impurity behavior in general, will become even more important for the next-step fusion devices which are presently under planning or construction such as the international thermonuclear experimental reactor (ITER)\(^5\) and Wendelstein 7-X (W7-X),\(^6\) where it is foreseen to increase the discharge duration up to about 30 min, in order to go forward towards the quasicontinuous plasma operation which will be required for a future fusion reactor.

The most fundamental experimental method to monitor the impurity behavior in fusion plasmas is the measurement of their characteristic line radiation by passive spectroscopy.\(^7\) Under the typical plasma conditions in current magnetic fusion experiments with electron densities in the order of \(n_e = 10^{19} - 10^{20} \text{ m}^{-3}\) and electron temperatures in the range of \(T_e = 0.1 - 10 \text{ keV}\), the strongest spectral lines of most of the relevant impurity ions radiate within the vacuum ultraviolet/extreme ultraviolet (VUV/XUV) wavelength range (1–200 nm). The observation of line radiation emitted from the various ionisation stages of impurity ions provides an experimental approach to both the determination of the impurity concentrations as well as insight into particle transport issues. The need for simultaneous monitoring and identification of the variety of relevant particle species demands spectroscopic instrumentation which provides a complete survey of this wavelength region at a good spectral resolution. For studies of the impurity transport by transient impu-
rity injection experiments, the spectrometers should be optimized for high throughput and high detection efficiency in order to provide high time resolution.6

Commonly used VUV/XUV spectrometers operated on magnetic fusion experiments basically consist of the three optical elements: entrance slit, diffraction grating and plane detector, where the reflective grating serves both to diffract the incoming radiation and to image the entrance slit onto the detector.10–14 Over the past 2–3 decades, significant progress has been achieved in the instrumentation, making use of developments in both grating and detector technology. VUV/XUV spectrometers based on traditional Rowland gratings were first constructed, using plane open microchannel plate (MCP) detectors mounted tangential to the Rowland circle.10,12 Then VUV overview spectrometers of the SPRED type (survey poor view extended domain) based on aberration-corrected holographic toroidal gratings11,13 have been developed enabling flat field detection. These instruments provide a high throughput, since geometric light losses by astigmatism are practically avoided. Mechanically ruled aberration-corrected concave gratings were also employed to construct flat-field spectrometers with good spectral resolution in the XUV range,14 but with relatively poor throughput due to the astigmatism introduced by the concave surface. However, in total, only a limited number of different spectrometer concepts has been developed and a consistent and optimized set of efficient VUV/XUV spectrometers suitable for a complete coverage of the wavelength range of interest at a sufficient spectral resolution is presently not available.

In this article, we describe the development of a set of four new VUV/XUV overview spectrometers, which cover the entire wavelength range of 2.5–160 nm, divided into four different subsections with some overlapping. The new high-efficiency XUV overview spectrometer (HEXOS) system shall be installed at one common port of the W7-X experiment to monitor the same plasma volume, to enable making both a quantitative comparison of measured intensities as well as a relative intensity calibration between the neighboring wavelength channels. The optical design of the spectrometers is presented and their expected performance is discussed based on results from plasma impurity modeling.

II. SPECTROMETER DESIGN

The development goal for the set of new VUV/XUV spectrometers presented here is to define the optimum wavelength ranges for the measurement task and to provide an optical design of the individual instruments which is optimized for large throughput in combination with good spectral resolution. The total throughput depends on the grating efficiency, the detector quantum efficiency, the imaging properties of the grating (e.g., geometrical light losses), and on the etendue \( E = \Delta \Omega \times w_S \times h_S \), where \( \Delta \Omega \) denotes the illuminated solid angle of the spectrometer and \( w_S \) and \( h_S \) denote the width and height of the spectrometer entrance slit, respectively. For the development of the new instruments we make use of some techniques which are well established in VUV/XUV spectroscopy; however, several relevant parameters are to be optimized. Based on the geometrical boundary conditions for the spectrometer installation at the plasma experiment W7-X and on the need to obtain efficient instruments with high throughput, we decide to use an optical layout with a single reflective diffraction grating as the only optical element, thus avoiding intensity losses caused by additional mirrors. Using toroidally shaped diffraction gratings, geometrical light losses caused by astigmatism can be practically avoided. The well developed holographic grating recording technique provides a powerful tool to greatly reduce aberrations and to give freedom for detector mountings which are different from Rowland geometry. Laminar (rectangular) groove profiles generated by ion etching processes result in a high efficiency for first order diffraction, strong suppression of higher diffraction orders, and a low straylight background, see, e.g., Ref. 11. These are important features to achieve a good signal to noise ratio in the measured spectra.

The general scheme for the optical setup of the spectrometers is displayed in Fig. 1. Note that in our nomenclature the incidence angle \( \alpha < 0 \), the diffracted light angle \( \beta > 0 \) and \( -\alpha > \beta \), so that the first order grating equation reads \( \sin \alpha + \sin \beta = -G \lambda \), where \( G \) is the groove density and \( \lambda \) the wavelength. In general the designs presented below are non-Rowland designs, because the detector position and the detector angle \( \Phi \) are determined according to the optimization of efficiency and linewidth rather than from \textit{a priori} geometrical constraints.

The successive steps of the design process are: first the definition of the wavelength ranges based on the given measurement tasks; second the definition and optimization of the detector properties; third the choice of the spectrometer geometries based on performance optimization considerations; and finally the development of the appropriate holographic diffraction grating recording optical setup.

A. Wavelength ranges

The definition of wavelength ranges for the new instruments depends on the particle species which are expected to be present in the plasma of W7-X and the spectral position of their most intense resonance lines. The list of materials of interest comprises in the first place carbon and boron, which are the main elements of the main plasma-facing components in the first period of plasma experiments at W7-X, and oxygen, which is ubiquitously present in all vacuum system; furthermore metal species (Fe, Cr, Ni, Cu) which are included in the vacuum vessel and in structural components; high-Z materials (W), which may be used as plasma-facing material in a later phase of the experiments, various elements used in insulators or ceramics (F, Al, Si, Zr); and finally...
several gases or metals, which may be injected for the purpose of radiation cooling or impurity transport studies (He, N, Ne, Ar, Ti). Since it is expected that the total impurity radiation intensity in the plasma is in many cases dominated by the contributions from carbon, we use the spectral position of two important carbon line pairs to define the boundaries for the total wavelength range to be monitored. For the lower edge of the wavelength range, these are the Lyman series transitions of the H-like carbon ions (C vi) radiating at 3.4 and 2.8 nm, respectively, whereas for the upper wavelength edge the Li-like (C iv) line pair at 154/155 nm is used, which is frequently found to be the spectral line with the highest emitted photon flux in magnetically confined fusion plasmas. In order to have these spectral lines located in a sufficient distance from the detector edge, we choose the total wavelength range to be 2.5 nm until 160 nm. This range is further to be divided into four different subsections including some overlapping to avoid problems due to detector edge effects, where the total number of four instruments is defined by both the installation possibilities given at the plasma experiment W7-X and the available budget. The definition of the ranges for the individual instruments is on the one hand based on the location of certain spectral lines within the overlap region to allow for a comparison of the relative efficiencies of the neighboring instruments during operation and on the other hand we take into account the available possibilities for calibration by plasma light sources (see Fig. 2).

The selected wavelength range covers the intense Mg-like, Na-like, Be-like, and Li-like resonance lines of all elements in the periodic table up to at least Mo (Z=42), while the quasicontinua of high-Z metals (Wo, Ta) around 5–6 nm are also accessible. For the test and calibration of spectrometer Nos. 3 and 4, a stationary hollow cathode discharge is foreseen, which provides intense spectral lines in the range of 16–147 nm with tabulated line intensities suitable for absolute calculation. The testing of spectrometer Nos. 1 and 2 will be performed using a pulsed pinch discharge, which is optimized for operation with Xe as working gas in the 13 nm wavelength range, but can be also used with Ar as working gas, exciting intense spectral lines down to wavelengths of 4.9 nm (Ar ix).

B. Detector design

The detailed optical design work for the instruments has to start with the selection of a certain detector scheme, where in particular the size and the relative angles between the detector and the incoming diffracted radiation have an impact on the required length of the instruments and on the design of the gratings. The scientific and technical goals described above demand a robust and reliable detector system which is compatible with a high throughput spectrometer system (large height of both entrance slit and detector) and which allows for a continuous readout of spectra at high time resolution. We decided to use a special design open MCP detector and the fast camera head described in Ref. 17, which is based on a linear array with 1024 pixels of each 25 μm width and 2.5 mm height for light detection. This detector scheme has already been successfully operated attached to the SPRED spectrometer at the medium-sized tokamak experiment TEXTOR. In particular, a nearly noise-free behavior of the detector was observed even in the case when RI mode discharges with high plasma densities and high auxiliary heating power (ion cyclotron resonance heating and deuterium neutral beam injection) were performed. Consequently, no problems are expected in the operation of this detector type at W7-X, since here the expected levels of neutron fluxes and gamma radiation are not too different from the levels observed on TEXTOR. However, in the case of operation at large fusion experiments like JET or ITER with D–T discharges and substantially higher levels of neutron and gamma radiation, a thorough detector shielding or even a placement of the complete spectrometer systems behind the biological shield would be required to keep the detector noise sufficiently low. The image quality MCP (by Burle Industries, Inc.) with extended dynamic range (EDR) property has a diameter of 40 mm, a length to pore size ratio of L/D=60 to provide a sufficiently high total amplification, a pore diameter of 10 μm with a bias angle of δ=8° (i.e., the tilt of the channel axes against the MCP normal), and CsI coating to increase the quantum efficiency in the XUV wavelength range. Compared to the design described in Ref. 17, the MCP detector design is improved to achieve an enhanced output light intensity (linear dynamic range) by using a selected EDR–MCP with very low longitudinal resistance (<8 MΩ), thus allowing for higher output current densities, and by enlarging the voltage between the MCP exit side and the P47 phosphor screen up to 8 kV, thus increasing the photon gain per incoming electron at the screen. This scheme allows the linear array of the camera head directly onto the 40/25 mm fiber taper exit of the MCP detector without the need for an additional first generation light amplifier in between them.

The quantum efficiency of this detector system depends on the one hand on the relative angle ε between the incoming radiation and the orientation of the bias angle δ of the MCP channels, ε=Φ−β+δ (for illustration see Fig. 3), and on the other hand on the photon energy of the incoming radiation.
Both the angular and energy dependence are related to the absorption and grazing reflection behavior of the photons down the MCP channels, where the highest probability for secondary electron release is obtained for the photon being absorbed in the CsI coated part of the channel wall, but not penetrating to deep into the material. Following the experimental results presented in Ref. 19, the angular dependence of the quantum efficiency shows a maximum which shifts towards larger relative angles $\varepsilon$ and broadens when going to lower photon energies. In the case of spectrometers covering a large wavelength range, the optimum value for the angle $\varepsilon$ therefore typically varies by some degrees with the wavelength along the detector surface. This dependence can be taken into account and partly compensated for, when the bias angle of the MCP detector is oriented in the focal plane as shown in Fig. 3 and the MCP angle $\Phi$ is chosen such as to obtain $\varepsilon(\lambda_2) > \varepsilon(\lambda_1) > 0$, making use of the fact that $\beta_2 < \beta_1$. The actual settings used in our design are given in Table I.

C. Spectrometer geometry

The choice of the incidence angle $\alpha$ is strongly related to the achievable total throughput of the spectrometer. In order to obtain instruments with high throughput, the useable solid angle should be maximized, which implies choosing a small absolute value for the incidence angle $|\alpha|$. However, since the decrease of reflectivity of the metallic coating at low wavelengths can only be compensated for by choosing large values of $|\alpha|$, a reasonable compromise has to be found for each of the four instruments, thus trying to obtain a high total throughput which is sufficiently flat over the wavelength range of interest. The actual choice of the incidence angle $\alpha$ is iteratively improved by determining the first order diffraction efficiency, including the reflectivity of the grating coating, by means of electromagnetic calculations (for the results see below).

Finally, the distances between the entrance slit and the grating center $L_A$ and between the grating center and the detector $L_B$ have to be chosen. Once the wavelength range, incidence angle, and detector angle are determined, the minimum possible value for the exit beam length $L_B$ is defined by the fact that the groove density of the grating should be limited to a maximum value of 2000–2500/mm, in order to avoid problems with the grating quality (aberrations correction manufacturing capabilities). Regarding the incidence beam length, a symmetric setup with $L_A = L_B$ is chosen, since in this case the achievable linewidth at a given etendue shows a weak minimum due to toroidal surface imaging properties. The foreseen installation geometry for the four instruments at one common port on W7-X with inner diameter of about 260 mm as well as cost considerations demand a geometrically compact design of the spectrometers. Prior to the installation on W7-X, a detailed testing procedure is scheduled for the new spectrometers on the tokamak experiment TEXTOR, where two ports with inner diameter of 100 mm are available for installation. Therefore we decided on a mechanical arrangement of the new instruments in the form of two double spectrometer systems, each of them containing two complete spectrometers including entrance slits, gratings, and detectors. For reasons of convenience the arm lengths of the two spectrometers included in one double spectrometer system are chosen equal. All geometrical data of the spectrometers are summarized in Table II.

### Table I. Detector angles for the VUV/XUV spectrometers.

<table>
<thead>
<tr>
<th>Spectrometer No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>MCP angle $\Phi$ (degrees)</td>
<td>79.2</td>
<td>71.1</td>
<td>62.7</td>
<td>47.9</td>
</tr>
<tr>
<td>Wavelength range ($\lambda$/nm)</td>
<td>2.5–10.5</td>
<td>9.0–24</td>
<td>20–66</td>
<td>60–160</td>
</tr>
<tr>
<td>Relative incidence angle ($\varepsilon$/degrees)</td>
<td>4.0–9.1</td>
<td>7.0–12.1</td>
<td>9.0–15.5</td>
<td>15.0–21.4</td>
</tr>
</tbody>
</table>

### Table II. Geometrical data of the VUV/XUV spectrometers.

<table>
<thead>
<tr>
<th>Spectrometer No.</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength range ($\lambda$/nm)</td>
<td>2.5–10.5</td>
<td>9.0–24.0</td>
<td>20.0–66.0</td>
<td>60.0–160.0</td>
</tr>
<tr>
<td>Incidence angle $\alpha$ (degrees)</td>
<td>$-86$</td>
<td>$-76$</td>
<td>$-65$</td>
<td>$-45$</td>
</tr>
<tr>
<td>Exit beam angle $\beta$ (degrees)</td>
<td>78.1–83.2</td>
<td>67.0–72.1</td>
<td>55.2–61.7</td>
<td>34.5–40.9</td>
</tr>
<tr>
<td>Incidence arm length $L_A$ (mm)</td>
<td>450</td>
<td>450</td>
<td>350</td>
<td>350</td>
</tr>
<tr>
<td>Exit arm length $L_B$ (mm)</td>
<td>446.9–447.9</td>
<td>448.4–449.5</td>
<td>349.8–352.7</td>
<td>352.2–359.3</td>
</tr>
<tr>
<td>Detector width ($w_G$) (mm)</td>
<td>40</td>
<td>40</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Grating width ($w_G$) (mm)</td>
<td>24</td>
<td>24</td>
<td>30</td>
<td>18</td>
</tr>
<tr>
<td>Grating height ($h_G$) (mm)</td>
<td>4.5</td>
<td>8</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>Entrance slit width ($w_S$) (mm)</td>
<td>0.22</td>
<td>0.12</td>
<td>0.06</td>
<td>0.06</td>
</tr>
<tr>
<td>Entrance slit height ($h_S$) (mm)</td>
<td>3.8</td>
<td>3.8</td>
<td>3.8</td>
<td>3.8</td>
</tr>
</tbody>
</table>

### III. DIFFRACTION GRATING DESIGN

#### A. A priori reduction of open parameters

For the development of aberration-corrected holographic diffraction grating designs, we restrict ourselves to the case of grating recording conditions where the toroidal substrate...
is illuminated by laser light focused through two point-like apertures which are located in the horizontal midplane of the torus. When working optical conditions are fixed, the optical imaging properties of a holographic grating of this type are fully determined by seven parameters, which are the large radius \( R \) and the small radius \( \rho \) of the toroidal substrate, the laser recording wavelength, and the coordinates of the two recording points. The remaining grating design task is to find a set of these seven parameters which provides a minimum width of the spectral lines over the wavelength range of interest at a high overall efficiency and throughput, taking into account, e.g., geometrical light losses. For the solution of this minimization problem in seven dimensions, we choose a practical approach where the number of free parameters is a priori reduced down to three by the considerations presented as follows. Since the wavelength ranges are chosen such as to have the zero order wavelength localized not far away from the detector edge, we define the large radius of the toroidal substrate and the detector position by the condition to have the meridional focus of the zero order radiation located within a plane coinciding with the detector surface, yielding the condition

\[
R = \frac{L_A}{\cos \alpha}.
\]

Second, the small radius is chosen to obtain good focusing in the sagittal direction within the center of the detector, thereby minimizing the geometrical light losses due to astigmatism,

\[
\rho = \left( \frac{\cos \alpha + \cos \beta}{\frac{1}{L_A} + \frac{1}{L_B}} \right),
\]

where the length \( L_B \) and the angle \( \beta \) are the polar coordinates of the detector center. As a third parameter, the laser wavelength used for grating recording is fixed to a value determined by the grating manufacturing process. Finally, one of the polar angles of the two recording points can be eliminated using the grating equation and iteratively determining both the groove density in the center of the grating and the detector position along the detector coordinate such as to get the designed wavelength values imaged to the right and left edge of the detector. The remaining three unknown parameters of the grating have to be determined from the minimization of the linewidth.

**B. Grating optimization procedure**

The numerical optimization of the grating design is performed in terms of geometrical optics. The general techniques to be used for this purpose are well known and will only be briefly explained here (for a detailed treatment see, e.g., Refs. 20 and 21), however, some emphasis will be put on the description of special methods which are applied here. For a given set of the seven gratings parameters, the light path of each incident ray originating from point \( A \) located at the entrance slit area and falling onto the grating at point \( P \) (see Fig. 4) can be determined from Fermat’s principle, i.e., the minimization of the light path function, yielding point \( B \) where the diffracted ray impinges on the detector.

In the work described here, the optical performance of the diffraction grating is analyzed numerically by generating many incident rays for five different wavelengths (typically 50,000 rays each), determining the impinging points on the detector for each of the first order diffracted rays (ray tracing), and finally calculating the mean linewidth from the histogram of the impinging points sorted along the detector coordinate. In this procedure the direction of the incident rays is generated in a random process, assuming an extended homogeneous light source of area \( A_L \) located at some distance \( D \) in front of entrance slit and illuminating the entrance slit with size \( w_S \times h_S \) homogeneously, thus simulating the real conditions under which the spectrometers will be used. Choosing the size of the light source somewhat larger than the maximum solid angle of the instrument as defined by slit size and grating size, the effective etendue \( E_{\text{eff}} \) of the spectrograph is readily determined

\[
E_{\text{eff}} = \frac{A_L}{D^2 w_s h_s T},
\]

where \( T \) denotes the fraction of those emitted rays which hit both the grating within the prescribed width and height as well as the detector within the area that is covered by the sensor of the camera head. Repeating the whole procedure for different settings of the three unknown grating parameters, a set of grating parameters can be determined which provides a minimum linewidth for the given geometry. From the optical imaging linewidth as determined from the histogram of impinging points, the expected instrumental profile detectable by the camera head is calculated by convoluting the histogram with a Gaussian curve of width 0.08 mm (full width half maximum), thus approximating the broadening effects caused by the MCP detector. This detector broadening mainly originates from the proximity focusing of the electrons onto the phosphor screen and from the finite size of both the MCP channels and the fibers in the 40/25 mm fiber taper exit window. A typical example of the spot diagram plots and instrumental profiles is shown in Fig. 5.

As the next step of optimization, numerical grating designs are developed for different settings of the four parameters: \( w_S, h_S, w_G, \) and \( h_G \), and the optimum choice for these parameters is made based on a plot of the linewidth as a function of the effective etendue (see Fig. 6).

Out of the different configurations, one selects the one that provides the smallest linewidth for a predefined value of

![Fig. 4. Spectrometer geometry and light path.](image-url)
the etendue. As a final step in the spectrometer design work, the first order grating efficiency is calculated from electromagnetic theory, taking into account both the reflectivity of the grating surface material as well as the actual shape of the groove profile. In order to obtain high efficiencies in combination with a not too large variation of its absolute values over the wavelength range, we select Au coatings for spectrometer Nos. 1–3, while the diffraction grating for spectrometer No. 4 is to be manufactured from silicon. The resulting efficiency curves are displayed in Figs. 7 and 8. Within the wavelength range of interest, the first order efficiency of the four gratings varies between 5% and 25%. We note at this point that the installation of optional thin film filters is foreseen in the light path for all of the HEXOS spectrometer channels in order to be able to reduce light contributions from unwanted spectral ranges and in particular to reduce the broadband zero-order image scattered light falling onto the detector, if required.

Since all the design steps described above are strongly interrelated, the sequence of design steps was repeated several times in order to iteratively find the best performing solution for the application under discussion. The final optical performance data of the four spectrometers are listed in Table III. In the case of spectrometer No. 1, the detected linewidth (instrumental profile) is determined mainly by the width of the spot diagrams, while for spectrometer No. 4 the detector broadening effects dominate over the width of the spot diagram.

IV. NUMERICAL TEST OF SPECTROMETER PERFORMANCE

The expected performance of the spectrometers can be tested numerically by calculating the intensity of suitable spectral lines for relevant plasma conditions and estimating

FIG. 5. (Color online) Spot diagrams and linewidth for grating No. 1.

FIG. 6. (Color online) Optimization of slit and grating size for grating No. 1.

FIG. 7. First order grating efficiency for gratings Nos. 1 and 2.
the expected signal to be measured by the spectrometers. For the calculation of line intensities we use the impurity transport code STRAHL, which solves the system of continuity equations for the ionization stages of selected impurity species, based on prescribed radial distributions of electron density \(n_e\), electron temperature \(T_e\), radial particle diffusion coefficient \(D\), and radial particle drift velocity \(v\). Atomic data are taken from the ADAS database. Since experimental data from W7-X discharges are not yet available, the simulation is performed for typical plasma conditions at the tokamak TEXTOR, which may serve as a relevant example for the case of W7-X, since both the minor radius as well as the typical heating power density of the two plasma experiments are of similar magnitude. As the input parameters for the calculation, we use smooth electron density and temperature profiles with central values of \(n_e=3.0 \times 10^{19} \, \text{m}^{-3}\) and \(T_e=1.5 \, \text{keV}\), respectively, which are typical for ohmically heated TEXTOR discharges. For the radial transport properties of the impurities, we use the simplified case of an assumed constant radial diffusion coefficient of \(D=1 \, \text{m}^2/\text{s}\), while the radial particle drift velocity is set to \(v=0\). The magnitude of the impurity particle densities and concentrations are chosen in agreement with typical experimental conditions in fusion experiments. Results for the sight-line integrated intensities of four different spectral lines are listed in Table IV. For the evaluation of the number of detected photons, we use the etendue and grating efficiency data from the calculations presented above. Since reported data from the literature for the quantum efficiencies for MCPs with CsI coating in the wavelength range of interest vary strongly, we use a value for the quantum efficiency of 10% which is regarded as a safe estimate in our calculation.

Assuming that the error margins for the measurement of spectral line intensities are determined mainly by the statistics of the number of detected photons, we conclude that the operation of spectrometer Nos. 2–4 at a spectra rate of 1000/s will lead to achievable accuracies in the range of 1%–3%. In order to also obtain measurement accuracies on the order of 3% with spectrometer No. 1, an enhanced integration time of 5 ms per spectrum will be required due to the lower photon flux and the smaller etendue for this system.

V. DISCUSSION AND OUTLOOK

The design of four new high efficiency XUV overview spectrometers (HEXOS) has been developed, which in total cover the wavelength range from 2.5 to 160 nm, divided into four subsections with some overlapping. The HEXOS systems are optimized for high efficiency at a good spectral resolution and a broad wavelength coverage, in order to allow for both a reliable identification of all relevant plasma impurities as well as for operation at high time resolution which is required when performing transient transport studies. Compared to spectrometers commonly used at magnetic fusion experiments, the HEXOS 1 system provides a much larger efficiency, thus allowing for faster measurements, while the HEXOS 2 and HEXOS 3 systems provide overview spectra with improved spectral resolution at a high efficiency. Following the physical design presented here, the mechanical construction of the HEXOS instruments for W7-X is ongoing and an extended period of testing is scheduled at the tokamak TEXTOR, prior to the installation of the completed systems at W7-X. It is expected that the combined use of the four new systems will open new possibilities for the monitoring and investigation of plasma impurity properties in magnetically confined fusion plasmas.

<table>
<thead>
<tr>
<th>TABLE III. Optical data of the VUV/XUV spectrometers.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Spectrometer No.</td>
</tr>
<tr>
<td>Wavelength range (nm)</td>
</tr>
<tr>
<td>Wavelength resolution (from imaging only) (nm)</td>
</tr>
<tr>
<td>Detected linewidth (nm)</td>
</tr>
<tr>
<td>Illuminated solid angle of entrance beam (10^−4 sr)</td>
</tr>
<tr>
<td>Effective etendue 6 (10^−3 mm² sr)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Spectral line</th>
<th>C vi</th>
<th>Fe xxiii</th>
<th>Ar xvi</th>
<th>C iv</th>
</tr>
</thead>
<tbody>
<tr>
<td>Wavelength (nm)</td>
<td>3.37</td>
<td>13.28</td>
<td>35.39</td>
<td>154.82</td>
</tr>
<tr>
<td>Impurity density (10^{17} , \text{m}^{-3})</td>
<td>3.0</td>
<td>0.03</td>
<td>0.3</td>
<td>3.0</td>
</tr>
<tr>
<td>Assumed impurity concentration in plasma center</td>
<td>10^{-2}</td>
<td>10^{-4}</td>
<td>10^{-3}</td>
<td>10^{-2}</td>
</tr>
<tr>
<td>Intensity (W m^{-2})</td>
<td>940</td>
<td>108</td>
<td>540</td>
<td>960</td>
</tr>
<tr>
<td>Spectrometer efficiency</td>
<td>0.07</td>
<td>0.2</td>
<td>0.15</td>
<td>0.2</td>
</tr>
<tr>
<td>Etendue (mm² sr)</td>
<td>3.0 \times 10^{-5}</td>
<td>1.0 \times 10^{-4}</td>
<td>2.0 \times 10^{-4}</td>
<td>2.1 \times 10^{-4}</td>
</tr>
<tr>
<td>Detector efficiency</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.1</td>
</tr>
<tr>
<td>Number of detected photons per ms</td>
<td>267</td>
<td>1156</td>
<td>2.3 \times 10^{4}</td>
<td>2.5 \times 10^{5}</td>
</tr>
</tbody>
</table>
18 NMOS linear array type S3904-F by Hamamatsu (www.hamamatsu.com).
23 H. P. Summers, Atomic Data and Analysis Structure, 2002 (http://adas.phys.strath.ac.uk/)