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Design of VUV impurity monitors and VUV imaging spectrometers for ITER

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Introduction and Overview. Vacuum ultraviolet (VUV) spectroscopy is a key diagnostic for the identification and monitoring of impurities in fusion plasmas. Using advanced diffraction grating design techniques [1, 2], efficient overview spectrometers with good wavelength resolution can be constructed for any desired wavelength region within the extended VUV wavelength range (about 1 nm to 200 nm). The VUV spectrometer design for ITER can therefore be based on the measurement requirements for ITER and on the wavelength positions of the most important spectral lines for the relevant impurities rather than on the availability of existing grating designs. In this paper we present a new design for six VUV spectrometer channels for the ITER main plasma monitoring VUV system and a spectrometer design of a high-resolution imaging VUV spectrometer for the measurement of the radial profiles of ion temperature and plasma rotation in the plasma edge region.

Measurement tasks for the new spectrometers. According to the approved ITER measurement requirements, the most relevant impurities for ITER are Be, C, Cu and W (from plasma-facing and structural components) as well as Ne, Ar and Kr (seeded impurities), where an accuracy of 10 percent is demanded for the determination of the relative concentration and influx data for these particle species, given at a time resolution of 10 ms. The main task for the VUV monitoring system is to provide these data, based on the measurement of the most intense spectral lines of the respective impurity ions. However, it can be expected that the ITER plasma may additionally contain significant concentrations of He (fusion product), Cr and Ni (structural components), N and O (air components) and even more exotic species such as Al, Si, Zr and Mo (e.g. from diagnostic components or insulators). In the worst case, most or even all of these particle species would be abundant in the ITER plasma and radiate simultaneously. The high number of possible spectral lines requires a VUV instrumentation for ITER which fully covers the relevant wavelength range at a sufficient wavelength resolution, allowing to distinguish between all different impurity species for all possible impurity mixtures in the plasma. Furthermore, a high overall efficiency (throughput) of the instruments is needed to fulfil the requirements for measurement accuracy.

Concept for the new spectrometers. The general design for each of the new VUV spectrometer channels closely follows the HEXOS [1, 2] as well as the earlier SPRED [3, 4] concept, which use 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. Based on a listing of relevant spectral lines [5], a consistent scheme of spectrometer channels is developed, which provides a full coverage of the range 2.3 nm to 160 nm at a good wavelength resolution. The data of these new spectrometers are given in table 1.

Instrument No.	1	2	3	4	5	6
wavelength range / nm	2.3 – 8	7 – 16	14 – 27	24 – 44	39 – 80	70-160
line width / nm	0.02	0.03	0.038	0.058	0.105	0.24
incidence angle α / degrees	-86	-83.5	-70.0	-70.0	-60.0	-50.0
distance slit – grating L_A / mm	800	650	550	500	400	300
mean exit arm length L_B / mm	647	648	650	501	406	307
Etendue / mm^2 sr	1.6e-05	3.0e-05	1.0e-04	1.0e-04	1.0e-04	1.0e-04

Table 1: *Summary of geometric and optical data of the ITER VUV spectrometer channels*

The wavelength ranges were chosen taking into account the position of important spectral lines, and in particular 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 spectrometer channels. 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 a time resolution of 10 ms.

Grating design and optimisation. The groove pattern of the gratings is formed by superposition 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, minimising the line width for a given spectrometer geometry over a given wavelength range. From the spot diagrams obtained by subsequent ray-tracing calculations the figures for line with and etendue (product of entrance slit area and solid angle) of the spectrometer are derived. As an example, the results for the case of spectrometer no. 2 are shown in figure 1.

Test of performance. In order to estimate the expected signal-to-noise ratio of the spectrometers, the intensities of spectral lines from carbon (Z = 6) and nickel (Z = 28) are calculated using the impurity transport code STRAHL [6]. Flat n_e profiles ($n_e \approx 1\times10^{20} m^{-3}$) and peaked T_e profiles (central values of T_e = 25 keV) from ASTRA calculations [7] are used as input data and atomic data for excitation and recombination are taken from ADAS [8]. For simplicity, a constant radial diffusivity of D = 0.1 m^2/s is assumed and the radial drift velocity is set v = 0, leading to a constant impurity density over the minor radius.

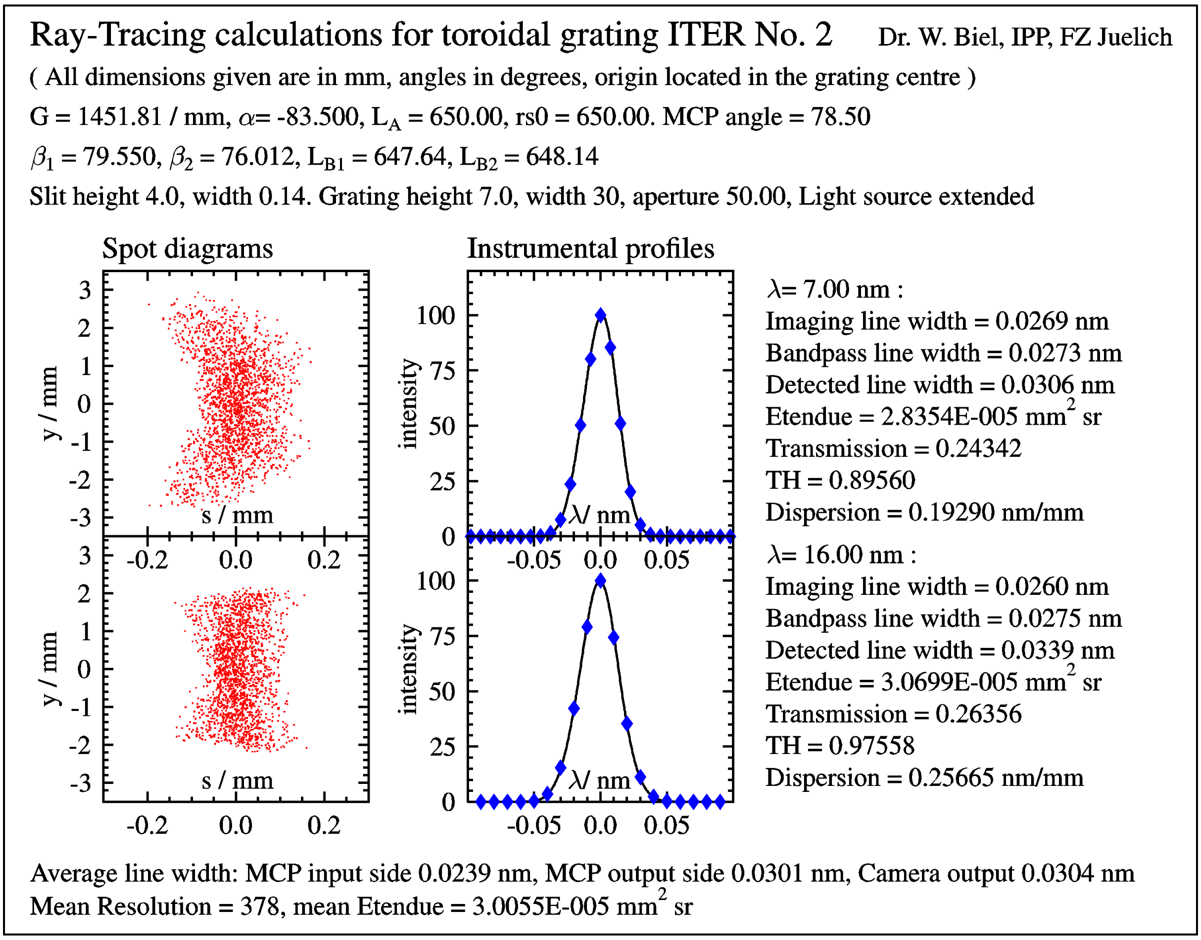

Figure 1: *Ray-Tracing results for ITER spectrometer No. 2*

Intensity estimation for carbon: The most intense spectral line in the VUV range with respect to the photon flux is the Li-like C IV resonance line at 154 nm, for which the STRAHL simulation predicts a sight-line integrated intensity of 2.6 W/m^2 at a carbon density of 10^{16} m^{-3}, which refers to a carbon concentration of 10^{-4}. Taking into account the reflectivity losses at the two imaging mirrors ($R_1 = R_2 = 0.5$) and the spectrometer etendue of 10^{-4} mm^2 steradian valid for spectrometer no. 6 and making conservative assumptions about the grating efficiency ($\eta_G = 0.1$) and the detector quantum efficiency ($\eta_D = 0.1$), this results in a number of about 400 detected photons within the integration time of 10 ms. Assuming that the measurement accuracy is mainly determined by the Poisson statistics of the detected photons, we conclude that the ITER requirements can be fulfilled for carbon.

Intensity estimation for nickel: The most intense VUV line with respect to the photon flux is the Li-like Ni XXVI resonance line at 16.54 nm, for which the STRAHL simulation predicts an intensity of 58 W/m^2 at a nickel concentration of 10^{-5}. Taking into account the efficiency data for spectrometer no. 3, this results in a number of about 1000 detected photons within the integration time of 10 ms. We conclude that the ITER measurement requirements can be fulfilled also for the case of nickel. This statement can be safely transferred to the neighbouring element Cu (Z = 29), which has a similar transition for the Li-like Cu XXVII at 15.36 nm.

Implementation at ITER. The six spectrometer channels are to be mounted behind the bio-shield at the equatorial port no. 11 arranged in two groups, including the channels no. 1-3 and 4-6, respectively. Plasma light is guided to the boxes containing the spectrometers by means of two sets of two toroidal mirrors each, which image a rectangular blanket opening onto the entrance slits of the spectrometers. The arrangement of beam paths and detectors is shown in fig. 2.

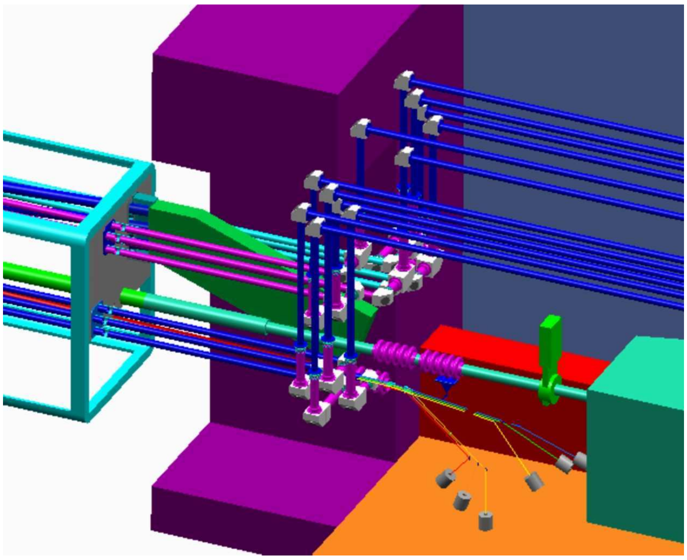

Figure 2: *Arrangement of VUV spectrometer channels*

Imaging spectrometer. The optical design for a high-resolution imaging spectrometer has been developed in order to measure radial profiles of ion temperature T_i and rotation velocity v_i in the wavelength range of 21-26 nm, which includes intense spectral lines from He, Be, C, O, Ar, Cr, Fe, Ni and Cu. The high spectral resolution of $\lambda/\Delta\lambda > 1500$ allows to measure ion temperatures of $T_i > 500$ eV and ion velocities of $v_i > 10$ km/s, while maintaining a high throughput in order to meet the ITER measurement requirements with respect to time resolution and measurement accuracy. Implementation is foreseen in upper port no. 9.

Conclusion: Optical designs of advanced VUV spectrometers for ITER have been developed and tested numerically. The new designs provide a good spectral resolution and a high throughput which are superior to nowadays standard VUV systems, clearly allowing to meet the ITER measurement requirements.

References:

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