High efficiency XUV Overview Spectrometer HEXOS: Construction and laboratory testing

W. Biel and A. Greiche

Institut für Plasmaphysik, Forschungszentrum Jülich GmbH, EURATOM Association,

Trilateral Euregio Cluster, D-52425 Jülich, Germany, www.fz-juelich.de/ipp

R. Burhenn

Max-Planck-Institut für Plasmaphysik, EURATOM Association, D-17491 Greifswald,

Germany

E. Jourdain and D. Lepere

Jobin-Yvon SAS, F-91165 Longjumeau, France

Abstract

The new High Efficiency XUV Overview Spectrometer system HEXOS has been developed to study impurity concentrations and impurity transport properties in the plasma of the stellarator W7-X. The HEXOS system consists of four different grating based spectrometers, which provide large etendue and good spectral resolution over a broad wavelength range (2.5 nm – 160 nm, divided into four subsections with some overlapping). The mechanical arrangement as two double spectrometers allows for a compact installation geometry on W7-X. Laboratory testing, wavelength and intensity calibration have been performed using a DC hollow cathode discharge (24 nm – 150 nm) and a pinch discharge (2.5 nm – 30 nm).

PACS Numbers: 52.70.-m, 07.60Rd, 52.25.Vy, 52.55.Fa, 52.55Hc

I. INTRODUCTION

The monitoring of plasma impurities in magnetically confined fusion plasmas is frequently performed using broadband spectrometers in the vacuum ultraviolet (VUV) and extreme ultraviolet (XUV) wavelength range[1-5]. However, over the past decades only a limited number of spectrometer concepts have been developed and applied for the diagnostics of magnetic fusion plasmas. Commonly applied spectrometer types on fusion experiments either monitor a limited wavelength range which may be fixed[3] or variable[4,5], or provide an overview over a wider spectral range with only coarse resolution[6,7].

The new HEXOS spectrometer system has been developed as a coherent scheme of four different VUV/XUV spectrometer channels which monitor the wavelength range from 2.5 nm to 160 nm, divided into four different subsections with some overlapping. The design goal was to achieve a full permanent coverage of the wavelength range of interest for the monitoring of impurity ions in magnetic fusion plasmas, while on the same time providing good wavelength resolution and high efficiency, allowing for operation at high time resolution (1000 spectra per second) with good signal-to-noise ratio. The optical layout and the design technique for the development of the holographic toroidal diffraction gratings as well as the detector scheme (open MCP detector with fast camera head based on a linear array) have been described earlier[8,9]. In this paper we focus on the mechanical setup and the alignment procedure of the HEXOS system and we present the first measured spectra from laboratory plasma light sources.

II. HEXOS SETUP

The HEXOS spectrometers use a flat-field arrangement with holographic reflective diffraction gratings on toroidal substrates as the only optical elements. For the four different wavelength ranges of the HEXOS channels, different angles of incidence and grating coatings are used to achieve optimum grating efficiencies for the respective wavelength ranges. The angular orientation of the open MCP detectors is chosen such as to ensure maximum quantum efficiencies for the different spectrometer channels. The general spectrometer layout is shown in figure 1 and the relevant data of the four HEXOS channels are listed in table 1 (for more details see ref. 9).

For the design of the mechanical setup of the HEXOS system the following boundary conditions were important. First, all four HEXOS spectrometer channels are to be installed at one common beam-line at W7-X with inner diameter 26 cm, monitoring the same plasma volume in the so called triangular plasma plane with an almost horizontal sightline. This called for a compact spectrometer geometry which allows mounting all four spectrometer channels in short distance to each other. Second, a testing period of the HEXOS spectrometers is foreseen at the TEXTOR tokamak, where two different beam-lines with only 10 cm inner diameter are available. This required an arrangement compatible with installation at two different locations. Finally, the mechanical setup should allow for an independent geometrical alignment of the optical spectrometer elements including the entrance slit, light flux limiting baffles, diffraction grating and MCP detector while facilitating the alignment procedure by providing an optical plane of reference. To comply with these requirements, an arrangement of the four HEXOS channels in two different double spectrometers was chosen, where a robust spectrometer ground plate (Aluminum, thickness 50 mm) serves as both optical plane of reference and sole carrying structure. Each double spectrometer includes two entrance slits which are 60 mm apart from each other, two different holographic diffraction gratings mounted into kinematic grating holders (adjustable in three translational and three rotational axes) and two open MCP detectors, which are adjustable in three translational axes and one rotational axis (around the vertical axis) to optimize the focal plane. The entrance slit chamber, (which is adjustable in two translational axes within the plane of dispersion), the spectrometer chamber and the two MCP detector support stages are mounted onto the ground plate and mechanically decoupled from each other by flexible bellows. Finally, a two-stage differential pumping scheme with oil-free turbo molecular pumps (pumping speed 400 l/s each) and small pumping apertures located nearby the entrance slits is employed to maintain a pressure below 10^{-6} mbar in the spectrometer chamber even during plasma operation at high pressures (10^{-3} mbar).

Figure 2 shows a photo from the setup of the HEXOS no. 1 and no. 2 double spectrometer, installed onto a mechanical stand for laboratory testing, with the spectrometer chamber and detectors on the right side, turbo pumps installed from the top side and a laboratory light source attached via a flexible bellows on the left side. The design of the HEXOS no. 3 and no. 4 double spectrometer is similar, but with shorter arm lengths (distances slit-grating and grating-detector) and with different incidence and exit beam angles as compared to HEXOS no. 1 and no. 2.

III. ALIGNMENT AND TESTING PROCEDURE

The geometrical pre-alignment of the HEXOS spectrometers was performed by using a laser beam together with a set of precision apertures mounted on the optical plane of reference which were designed to define the nominal light paths for incident beam and the zero order diffracted beams. All optical elements (entrance slit, baffles and gratings) were set precisely (accuracy < 0.5 mm) to their nominal position (nominal height 105 mm above the ground plate) and the incidence angle of the gratings was set precisely to its nominal value (accuracy about 0.1 degrees). The zero order image of the entrance slit was focused onto a screen located at the nominal focal position and the position and shape of the slit image were monitored to adjust the grating tilt. Following this geometrical pre-alignment of the HEXOS channels, two different laboratory light sources were used to test and further optimize the alignment status, to perform the wavelength calibration and to analyze the spectrometer performance (instrumental width, second order diffraction efficiency). Specifically, a pulsed hollow cathode triggered pinch discharge[10] was used as a light source for the HEXOS no. 1 and no. 2 channels. Operating this XUV light source with an internal capacitance of 44 nF, a continuous charging current of 4 mA and a breakdown voltage of 12 kV (defined by adjusting the gas flow in the discharge chamber), plasma pulses are generated with a repetition rate of 6 to 8 per second and an energy of about 3 J each. The orientation of the axis of the cylindrical plasma of this XUV lamp head is identical with those of the spectrometer's optical axis such that the plasma spark appears as a point-like light source with a diameter < 0.5 mm. For the testing of the HEXOS no. 3 and no. 4 channels, a DC high current hollow cathode discharge[11,12] is used. This VUV light source has been calibrated absolutely as a secondary standard against synchrotron radiation and therefore it can be used for both wavelength calibration and intensity calibration[11,12].

Each of the light sources is installed onto a mechanical slide (2 axes translation and 1 axis rotation) and connected to the entrance flange of one of the HEXOS double spectrometers via a flexible bellow (see figure 2). Moving the light source horizontally and vertically, the effect of an extended light source can be simulated, which was utilized to measure the size and optimize the direction of the acceptance angles of the spectrometer channels. The adjustment of the MCP detector to the focal plane was checked and further optimized by monitoring the spectral line positions while moving the light source within the plane of dispersion. Dismounting the camera heads from the MCP detectors, the shape of the light pattern from the individual spectral lines (first order slit images) was observed at the exit of the fiber taper. High resolution photos were taken using a digital camera with an almost distortion-free macro objective, allowing to analyze in detail the tilt of the individual slit images as well as the tilt of the entire spectrum. These light patterns were modeled using a ray-tracing program[9] to predict the necessary re-adjustment steps for the gratings. After a single step of re-adjustment, an almost perfect orientation and shape of the first order spectrum was obtained, meaning that the remaining tilt was only a small fraction of one degree with a negligible effect on the expected line width of the spectrometer. As an example, figure 3 shows the photo from the spectrum of a Nitrogen XUV discharge recorded with the HEXOS no. 2 spectrometer. All intense lines can be attributed to N V (Li-like) transitions in the range between 16 nm and 21 nm.

IV. RESULTS FROM LABORATORY TESTING

After finalizing the alignment procedure, spectra were recorded with all spectrometer channels in order to determine the instrumental widths for the case of small etendue (point-like light source, entrance slit width 30 μm and height 3.8 mm) as well as the second order diffraction efficiencies. Figure 4 shows HEXOS 1 spectra from the pulsed XUV discharge operated with Nitrogen and Argon. Several intense transitions from highly ionized states are visible in first and second diffraction order. The Ne-like Ar IX doublet at 4.9 nm (line separation $\Delta\lambda = 0.045$ nm) can be clearly separated in first order, while the He-like N VI components at 2.9 nm (line separation $\Delta\lambda = 0.03$ nm) can only be separated in second diffraction order.

The HEXOS 4 spectra from the DC hollow cathode discharge operated in Neon and Argon are shown in figure 5. Several transitions from low ionization stages are visible in first and second diffraction order. The measured instrumental width is about 0.25 nm, so that the Ne I doublet at 74 nm ($\Delta\lambda = 0.78$ nm) can be clearly separated in first order.

The instrumental widths of the HEXOS spectrometers achieved during laboratory testing with minimum entrance slit width (30 μm) and illumination at small etendue are summarized in table 2 (row no. 2). These experimental data were compared with ray-tracing calculations[9] in order to determine the spatial resolution of the detector system (MCP with camera). Using this value for the detector resolution as input parameter for ray-tracing calculations, the expected line width for the case of operation at full etendue (conditions at W7-X) is predicted, see table 2 (row no. 3).

The ratio between the second order and first order diffraction efficiencies can be derived from the measured laboratory spectra, in particular for a few intense spectral lines which are located near the lower wavelength limit of the respective HEXOS channels. The experimental data for the most prominent spectral lines are summarized in table 3. The values for HEXOS 1 and HEXOS 3 are in agreement with expectations from electromagnetic grating efficiency calculations, while the experimental data for HEXOS 2 and HEXOS 4 are a factor 2-3 larger than predicted from efficiency calculations. This discrepancy could not be explained so far and further investigations are ongoing.

In summary, the HEXOS spectrometer system construction has been finalized and the alignment and testing procedure in the laboratory has been completed successfully. The design values for the HEXOS performance in terms of broad wavelength coverage while maintaining good spectral resolution at high etendue with high time resolution have been reached and the spectrometer system is now ready for use, setting a new standard for VUV/XUV spectroscopy on magnetic fusion experiments as compared to earlier VUV/XUV spectrometer concepts.

The next steps for the development of the HEXOS spectrometer system are foreseen as follows. First, an absolute calibration will be performed, based on the tabulated intensities of the DC hollow cathode discharge[11,12] as well as on branching ratio data. Second, a full remote control system (SIMATIC) will be implemented, including the operation of the vacuum system, detectors, stepper motor control for entrance slits and filters as well as the temperature stabilization for the spectrometer ground plates. Third, a test period of the HEXOS system of about 3 years duration is scheduled at the tokamak TEXTOR, which will be used to test and further develop the technical operation of the system and to explore the physics possibilities in terms of line identification, impurity transport studies and plasma physics. The ultimate goal is to have the HEXOS system well developed and ready for use for the analysis of plasma impurity densities and impurity transport properties on the new stellarator W7-X as soon as this new fusion experiment will start operation.

V. REFERENCES

[1]Isler R. C., Nucl. Fusion **24**, 1599 (1984)

[2]Behringer K. H. et al., Nucl. Fusion **26**, 751 (1986)

[3]Kita T., Harada T. Nakano N. and Kuroda H., Appl. Opt. **22,** 512 (1983)

[4]Hodge W. L., Stratton B. C. and Moos H. W., Rev. Sci. Instrum. **55**, 16 (1984)

[5]Schwob, J. L., Wouters A. W., Suckewer S. and Finkenthal M. Rev. Sci. Instrum. **58**, 1601 (1987)

[6]Fonck R. J., Ramsey A. T. and Yelle R. V., Applied Optics **21**, 2115 (1982)

[7]Stratton B. C., Fonck R. J., Ida K. Jaehnig K. P. and Ramsey A. T., Rev. Sci. Instrum. **57**, 2043 (1986)

[8]Biel W., Bertschinger G. and the TEXTOR team, Rev. Sci. Instrum. **75**, 2471 (2004)

[9]Biel W., Bertschinger G., Burhenn R., König R. and Jourdain E., Rev. Sci. Instrum. **75**, 3268 (2004)

[10]Bergmann K. et al., Appl. Opt. **38**, 5413 (1999)

[11]Danzmann K., Günther M., Fischer J., Kock M. and Kühne M., Appl. Opt. **27**, 4947 (1988)

[12]Hollandt J., Kühne M. and Wende B., Appl. Opt. **33**, 68 (1994)

Tables:

Spectrometer	**HEXOS 1**	**HEXOS 2**	**HEXOS 3**	**HEXOS 4**
Wavelength range / nm	2.5 – 10.5	9.0 – 24.0	20.0 – 66.0	60.0 – 160.0
Incidence angle α / degrees	-86	-76	-65	-45
Exit beam angle β / degrees	78.1 – 83.2	67.0 – 72.1	55.2 – 61.7	34.5- 40.9
Incidence arm length LA / mm	450	450	350	350
Exit arm length LB / mm	446.9 – 447.9	448.4 – 449.5	349.8 – 352.7	352.2 – 359.3
Detector angle Φ / degrees	79.2	71.1	62.7	47.9

Table 1: Geometrical and optical design data of the HEXOS spectrometers

Spectrometer	HEXOS 1	HEXOS 2	HEXOS 3	HEXOS 4
Achieved instrumental width during laboratory testing (point-like light source, slit 30 μm) / nm	0.025	0.050	0.12	0.25
Spectrometer etendue for conditions on W7-X / 10^{-10} m^2 steradian	0.3	1.0	2.0	2.0
Expected instrumental width for conditions on W7-X (illumination of full etendue) / nm	0.036	0.058	0.15	0.30

Table 2: Performance summary of the HEXOS spectrometer channels

Spectrometer	HEXOS 1	HEXOS 2	HEXOS 3	HEXOS 4
$2^{nd}/1^{st}$ order diffraction efficiency (wavelength)	0.14 (2.9 nm) 0.08 (4.9 nm)	0.24 (11.5 nm)	0.04 (30.4 nm)	0.13 (74 nm)

Table 3: Ratio between measured second order and first order diffraction efficiencies of the HEXOS spectrometer channels

Figure Captions:

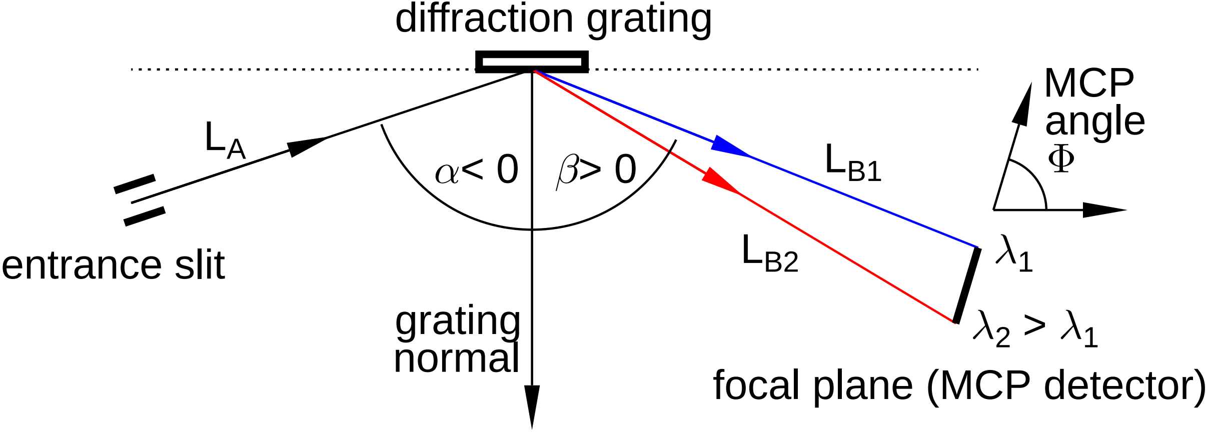
Figure 1: Scheme of the optical layout of the HEXOS spectrometers

Figure 2: Photo from the HEXOS no. 1 and no. 2 double spectrometer setup

Figure 3: Photo from the spectrum of a Nitrogen XUV discharge recorded with the HEXOS no. 2 spectrometer (colors inverted)

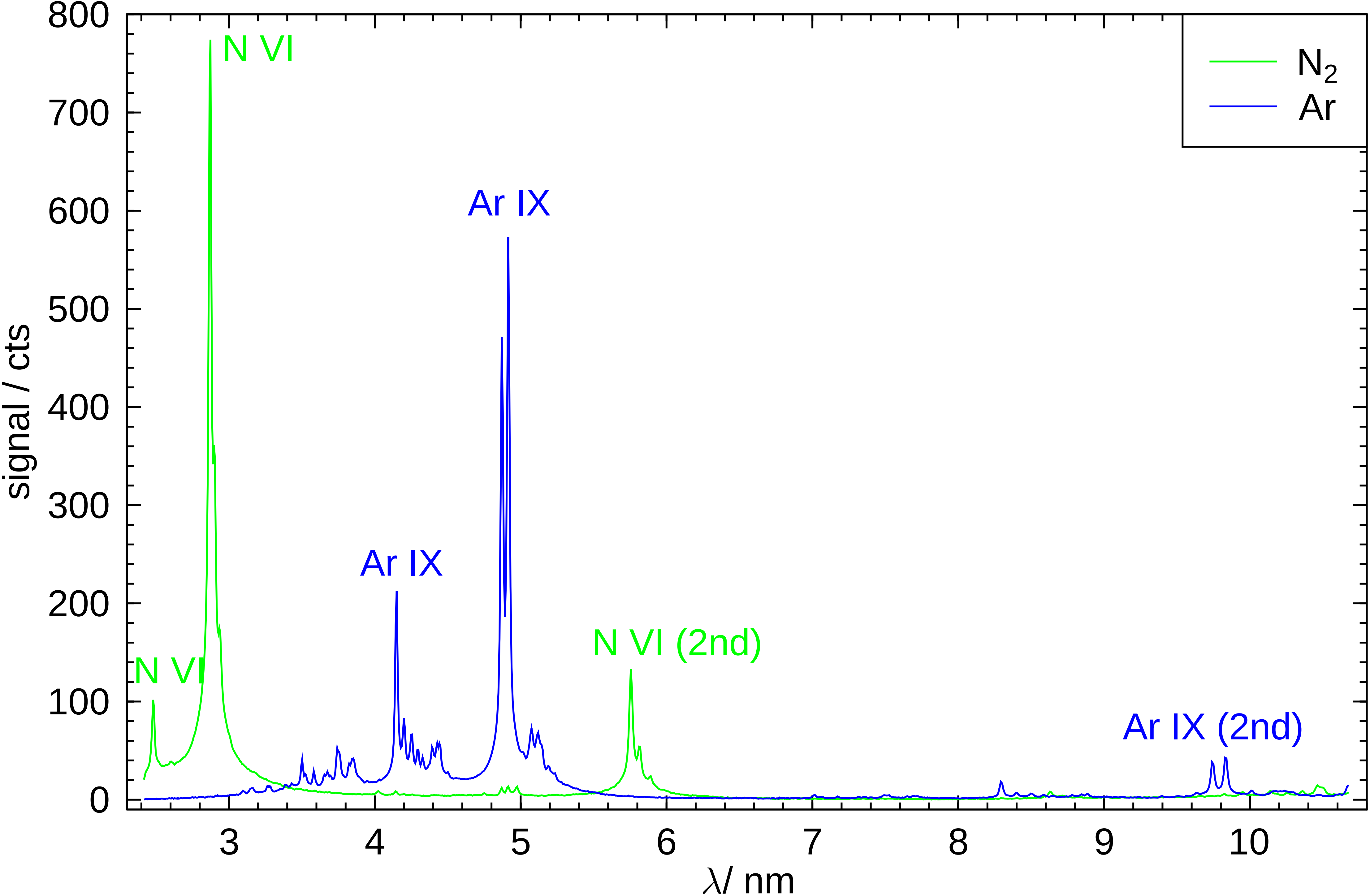
Figure 4: HEXOS 1 spectra from Argon and Nitrogen discharges

Figure 5: HEXOS 4 spectra from Argon and Neon discharges

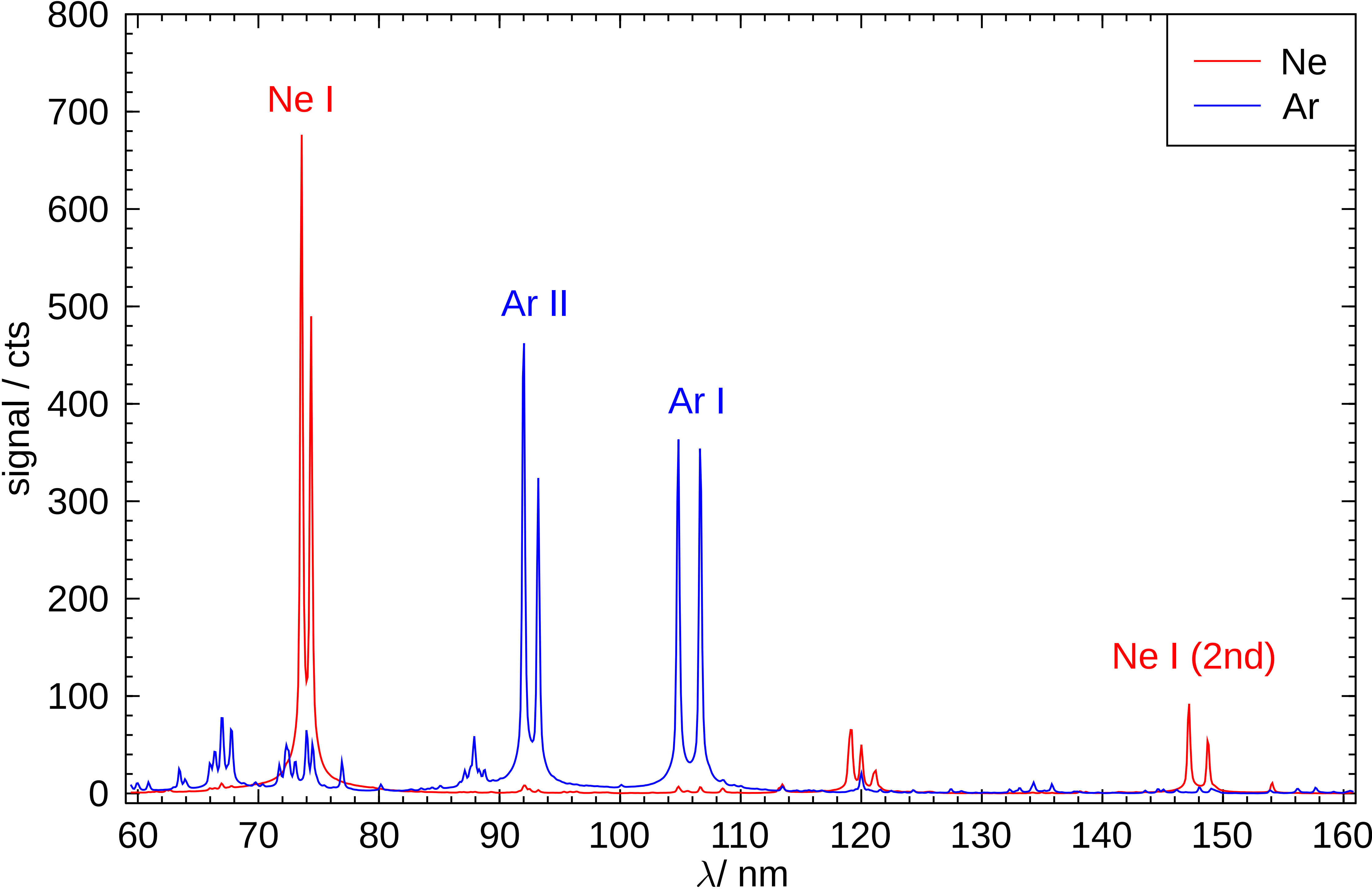


diffraction grating
L_A
entrance slit
$\alpha < 0$
$\beta > 0$
grating normal
L_{B1}
L_{B2}
MCP angle Φ
λ_1
$\lambda_2 > \lambda_1$
focal plane (MCP detector)


Turbo pumps
Light source
Entrance slit chamber
Grating chamber
Detectors



N VI
N VI
Ar IX
Ar IX
N VI (2nd)
Ar IX (2nd)
N2
Ar
signal / cts
λ/ nm
0
100
200
300
400
500
600
700
800
3
4
5
6
7
8
9
10



Ne I
Ar II
Ar I
Ne I (2nd)
Ne
Ar
signal / cts
λ/ nm