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A reflectometer for at-wavelength characterisation of gratings

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ABSTRACT

The design for an UHV-reflectometer for XUV-radiation is presented, which is dedicated to at-wavelength characterisation on high precision gratings. At-Wavelength Metrology is a powerful and necessary characterisation tool for the development and characterisation of optical elements. Since the optical constants of the coating materials involved are dependent on wavelength, information on e.g. reflectivity can only be obtained at-wavelength and cannot be provided by ex-situ methods.

In our institute a technology centre for production and characterisation of highly efficient precision gratings is established. Within this project a reflectometer for at-wavelength characterisation of the fabricated blazed gratings is developed and manufactured. This reflectometer complements the SXR-metrology instrumentation at BESSY-II: the existing reflectometer and the polarimeter/ellipsometer chamber for polarisation studies on magneto-optical samples or non-magnetic multilayers.

The main feature of the reflectometer is the possibility to incorporate *real* gratings with a length up to 600 mm, adjustable in six degrees of freedom by a custom designed tripod system. The reflectivity is measured between -180° and $+180^{\circ}$ incidence angle for both s- and p-polarisation geometry. A variety of detectors with a high dynamic range is accessible.

The reflectometer is coupled permanently to the new optics beamline on a BESSY-II bending magnet operating in the UV, EUV and soft x-ray range with the polarisation adjustable to either linear or elliptical. The station will be available by the end of 2013.

1. Introduction

The Institute of Nanometre Optics and Technology (INT) of Helmholtz–Zentrum Berlin (HZB) which operates the BESSY-II storage ring facility establishes a technology centre for production and characterisation of highly efficient precision gratings [1]. This project combines our long time expertise with a comfortable infrastructure in the field of design, development, characterisation and application of high quality optics. They are used for optical systems and synchrotron radiation beamlines from IR to hard x-rays. In this technology centre diffraction gratings for synchrotron radiation are developed and produced by various methods. Highest grating efficiency is obtained by blazed grating which has a saw-tooth profile. The required precision of the saw-tooth profile in the nanometre range at blaze angles down to 0.1° is technologically challenging. The R&D activities of the grating projects are focused on achieving four goals:

- conceptual design and development of a ruling machine;
- fabrication of blazed gratings by chemical etching of asymmetrically cut Si crystals;
- development and construction of an ion etching machine; and
- development and construction of a reflectometer for at-wavelength characterisation of the gratings at a dedicated optics beamline for XUV-radiation.

At the time of writing some gratings have been fabricated successfully by various techniques.

Not only the gratings are produced in-house, but also fully characterised before delivery by ex-situ and in-situ methods. All grating production steps are supervised by ex-situ metrology comprising the Nanometre Optics Slope Measuring Machine (NOM) [2], Atomic Force Microscopy (AFM) and White Light Interferometry (WLI) for controlling of figure and finish (slope and roughness) and for determining the grating structure and blaze angle homogeneity.

The ultimate test is the determination of the diffraction efficiency of the finished grating in the wavelength range of interest: at-wavelength metrology.

At-wavelength metrology is an essential characterisation tool for the development and characterisation of XUV-optical elements [3–6]. Since the optical constants of the coating materials involved are dependent on wavelength, information on reflectivity at a certain wavelength can be obtained only by this method and cannot be deduced from any other diagnostics results. Thus this method is

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complementary to the above mentioned ex-situ profilometry methods, or Cu-Kα diffractometry which delivers information on interfacial roughness and quality of the reflecting layers.

Within our grating technology project a reflectometer for at-wavelength characterisation of the fabricated blazed gratings is developed and fabricated. This chamber complements the metrology instrumentation at BESSY-II: the existing reflectometer [7,8] at the optics beamline [9] and the polarimeter/ellipsometer chamber [10,11] for polarisation studies on magnetic or non-magnetic samples.

The main new feature is the possibility to incorporate real gratings with dimensions up to $300 \times 60 \times 60$ mm^3 into the UHV-chamber. The samples are adjustable within six degrees of freedom by a newly designed compact tripod system. The reflectivity can be measured between -180° and $+180^\circ$ incidence angle for both s- and p-polarisation geometry. A variety of detectors with a high dynamic range of at least 10 orders of magnitude is available.

A new Optics Beamline based on an SX700-Plane Grating Monochromator (PGM) [12,13] in collimated light operation is being setup on a BESSY-II bending magnet. It operates in the UV, EUV and soft x-ray range and with the beam polarisation adjustable to either linear or elliptical. This beamline will replace the existing optics beamline at which the beamtime has to be shared with another experiment.

In this report we give information about the optics beamline and on the technical/engineering features of the reflectometer. It is completely designed in-house and will be constructed and assembled outside. The reflectometer will be attached permanently to the Optics Beamline as a fixed (and the only) end station to guarantee a short-term access for rapid quality contol of optical elements. It will go into operation by the end of 2013 and will be available for outside users.

2. Technical description of the reflectometer and the optics beamline

2.1. Present status of at-wavelength metrology at BESSY-II

Our Institute for Nanometre Optics has a long time expertise in the design, development, manufacture, characterisation and application of high quality optics to be used for optical systems and synchrotron radiation beamlines from IR to hard x-rays at the BESSY-II storage ring. Some of them have a cutting edge performance in terms of resolving power [14], photon flux, polarisation steering capabilities [15,16] and/or small spot size. Key infrastructure on the theoretical side is the in-house developed raytracing code RAY [17] and the reflectivity programme REFLEC [18]; and on the experimental side the at-wavelength metrology with the existing reflectometer [7,8], which is coupled permanently to the optics beamline [9], and the polarimeter [10], which can be coupled to (elliptically polarising) undulator beamlines at request.

Table 1 lists the main features of the at-wavelength metrology infrastructure. The existing reflectometer is a compact 3-axis UHV-version for reflectivity measurements in s-polarisation geometry (Rs) as function of incidence angle and photon energy. The sample size is limited to a length of 120 mm. It is used for routine checks of multilayer-optical elements, gratings, crystals as well as for basic investigations of compound materials [19,20]. Since it is permanently coupled to the existing optics beamline short-term access is possible. Beamtime has to be shared, however, with another experimental station (SURICAT) for photoelectron spectroscopy (PES) studies.

The polarimeter [10] is a versatile multipurpose 8-axes UHV-instrument to be used as a conventional reflectometer [21,22] (for reflection or transmission samples), as polarimeter [23,24] (with both a retarder and an analyzer element) or as an ellipsometer [25,26] to characterise the phase change Δ on transmission or reflection. Only small test samples are possible. It is used for development of polarising optical elements, for routine checks of the complete polarisation state of elliptical undulator beamlines [16,24], as well as for magneto-optical investigations [27], since both samples can be magnetised in-situ.

The new reflectometer is a combined upgrade of both existing instruments. The versatility of the polarimeter is to be combined with realistic sample sizes. It allows measurements on real optical elements up to 300 mm and 4 kg mass in both s- and p-polarised geometries. This sample size together with the full flexibility in azimuthal orientation determines the dimension of the new chamber, which is considerably larger than the old instrument.

2.2. The new optics beamline

The new beamline adds another attractive XUV experimental station to the portfolio of approximately 25 PGM beamlines at BESSY-II [14] and will replace the existing optics beamline, where the operation of the existing reflectometer has to be shared with a second experimental station, which does not allow an independent operation. The new beamline is available at low cost due to use of an existing front end, mirror chambers and an SX700 monochromator of BESSY-I [12]. Table 2 lists the main parameters of source and beamline.

Fig. 1 shows the optical layout of the beamline. The bending magnet radiation is vertically collimated by the toroidal mirror TO (M1) and horizontally focused in a 3:2 demagnification.

Table 1
Overview of the BESSY-II experimental stations for in-situ SXR-metrology: reflectometry, polarimetry, ellipsometry. (Rs, are the reflectivity components measured in s- and p-polarisation geometry, Ts, Tp are the transmission components measured in s- and p-polarisation geometries, Δ is the relative phase retardance between the p- and s-polarisation components ($\delta p - \delta s$) on reflection/transmission).

	Old reflectometer	Polarimeter/ellipsometer	New reflectometer
Measurements	Rs	Rs, Rp, Ts, Tp, Δ	Rs, Rp, Ts, Tp
Sample size	130 mm × 40 mm	40 mm × 40 mm	300 mm × 60 mm
Sample mass	0.5 kg	0.1 kg	4 kg
Sample adjust	No	No	x, y, z, Rx, Ry, Rz
Sample type	Reflection	Reflection, transmission	Reflection
Sample Azimuth	0°	0–360°	0–360°
Theta	−90–90°	0–360°	−180–+180°
Detector Twotheta	0–180°	0–180°	−180–+180°
Detector Phi	−20–+20°	−20–+20°	−5–+5°
Chamber size	0.8 m × 0.6 m∅	1 m × 0.6 m∅	1.5 m × 0.8 m∅
Weight	500 kg	800 kg	1500 kg
Load-lock	No	Yes (magazine for 10 samples)	Yes (f. samples < 50 mm)
Permanent access	Yes	No	Yes

The SX700 monochromator (Plane Mirror (PM) and Plane Grating (PG)) is operated in collimated light to have maximum flexibility in operating modi (spectral purity, high resolution, or high flux). The cylindrical mirror CY (M3) focusses the dispersed radiation onto the exit slit (SL). The toroidal mirror TO (M4) refocusses the beam onto the sample position in a nearly 1:1 magnification. All optical elements are coated with gold. Focus size will be $0.2 \times 0.3\ \mathrm{mm}^2$.

2.3. The reflectometer

The reflectometer has been specified to complement the features of the existing reflectometer and polarimeter: to have measurement flexibility on real samples. Incorporation of large samples together with polarisation sensitive reflectometry had to be realized. The project management was decided as follows:

- specification, design and technical drawings made in-house,
- construction of individual work packages separated by order,
- mounting and setup of all parts at the main contractor's site, and
- developing control software in-house.

Table 2
Parameters of BESSY-II dipole source DIP 1.1 and the new optics beamline.

Source	Dipole BESSY II Dip 1.1
e-Beam size	40 μm × 65 μm (v × h)
e-Beam divergence	20 μrad (v.)
Beamline acceptance	0.5 mrad × 2.33 mrad (v × h)
Monochromator	SX700-Plane Grating Monochromator (PGM) in collimated light, variable cff
Energy range	10–2000 eV
Beamline optical elements	M1 (Toroidal mirror TO, v-coll., h-foc.)
	M2 (plane mirror PM)
	G (plane grating PG, v-disp.)
	M3 (Cylindrical mirror CY, v-foc.)
	M4 (Toroidal mirror TO, v-, h-refoc.)
Gratings	G1 (1200 l/mm)
	G2 (600 l/mm)
Beamline length	30.27 m
Resolution	10.000@400 eV
Polarisation	Linear/elliptical (off-plane dipole rad.)
Focus size	0.2 mrad × 0.3 mm (v × h)
Divergence at sample	0.3 mrad × 3.5 mrad (v × h)
Flux at sample	10^{10}–10^{11} s^{-1}/100 mA

Fig. 2 shows the complete reflectometer assembly in it's UHV-chamber. The individual work packages will be explained in detail in the following sections.

2.3.1. Incident beam diagnostic

The diagnostic section for the incident beam (Io-section) is located between the refocussing mirror and the reflectometer chamber. It will be equipped with diagnostic tools, all of which are removeable from the beam path (not shown in Fig. 2): an ionisation chamber for energy calibration and to determine the resolving power, a variable-angle three-mirror high-order suppressor for the UV-range, a set of filters for high order suppression, pinholes of different sizes to further collimate the beam and to reduce straylight, and destructive (photodiode) and non-destructive (metal foils) intensity monitors.

2.3.2. Sample adjustment stage (tripod)

Fig. 3 shows the sample adjustment stage, which is a tripod unit developed in-house. It is a compact UHV-compatible design of 200 mm × 200 mm footprint. The tripod unit allows adjustment of the sample base plate in six degrees of freedom: translations in x, y and z and rotations Rx, Ry and Rz. Cross slides, a combination of two perpendicularly arranged saddle slideways, move the base plate, mounted on three aluminium milled legs which are connected by flexural pivots on one side and by cardan shafts on the other side. Closed loop motion is computerised by a

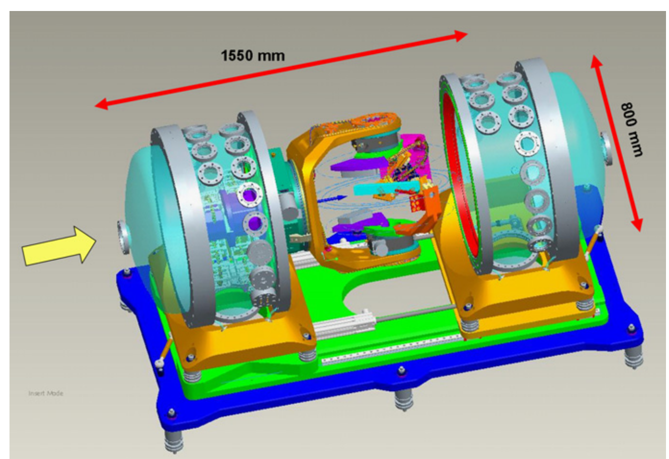

Fig. 2. Schematic setup of the new reflectometer.

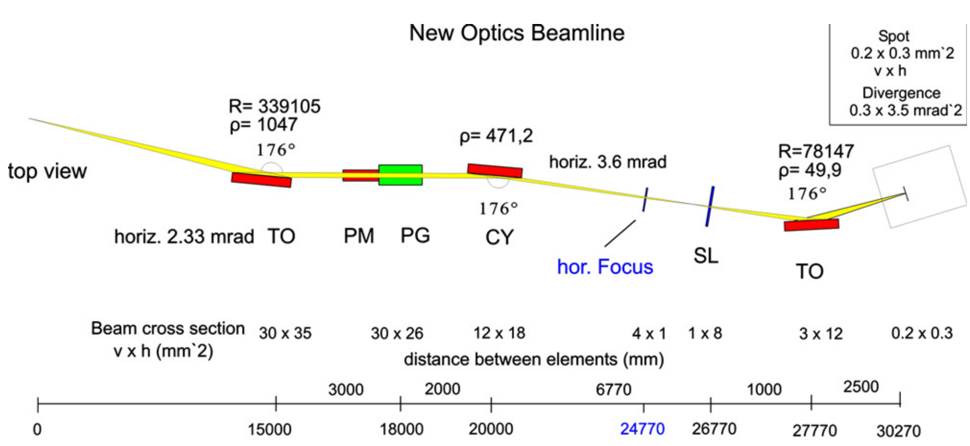

Fig. 1. Schematic layout of the new optics beamline at BESSY-II Dipol 1.1.

LABVIEW programme, and access to Cartesian coordinates is via EPICS variables.

The available sample scan range as function of the tripod position is shown in Fig. 4. Plotted is the x- and y- translation ranges as function of the sample height (z-position) for positive (left) and negative z-position w.r.t. the middle position at $z=0$. At maximum or minimum sample height, the translational range in the x-, and y-directions goes to zero. The translation is calculated maintaining a rotation of $\pm 1^\circ$ for Rx and Ry, and $\pm 5^\circ$ for Rz.

2.3.3. Detector arm

The detector arm is equipped with a variety of detectors to have maximum flexibility in dynamic range, energy response and angular resolution. Photodiodes as well as pulse counting detectors for scattering measurements are provisioned. Positioning of the respective detector into the light path is done via a translation by a saddle slideway (Fig. 5). A Schneeberger recirculating system guides the linear movement of the slides. The slide is driven by a Nanomotion piezomotor, controlled with a Renishaw encoder.

The rotation axes for the detector arm two-theta and the sample axes theta are assembled face to face on two HUBER 411 goniometers (Fig. 6). The detector arm can be shifted perpendicular to the reflection plane with a saddle slideway.

2.3.4. Optical bench

The UHV-optical bench (Fig. 7) consists of two rotary stages for the sample incidence angle and for the detector arm. A HUBER 430 goniometer allows azimuthal rotation in the range of $\pm 180^\circ$ around the synchrotron light beam. This allows measurements in s- and p-polarisation geometries. An aluminium plate with a diameter of 720 mm ensures an accurate positioning of the rotation arms in the vacuum chamber. Approximately 200 cables for motors, limit switches, readouts and detectors are routed inside vacuum by use of energy chains.

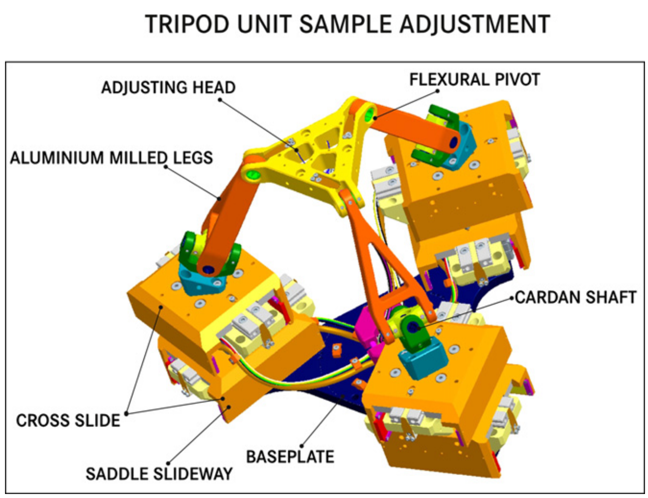

Fig. 3. The tripod unit for sample adjustment in six degrees of freedom.

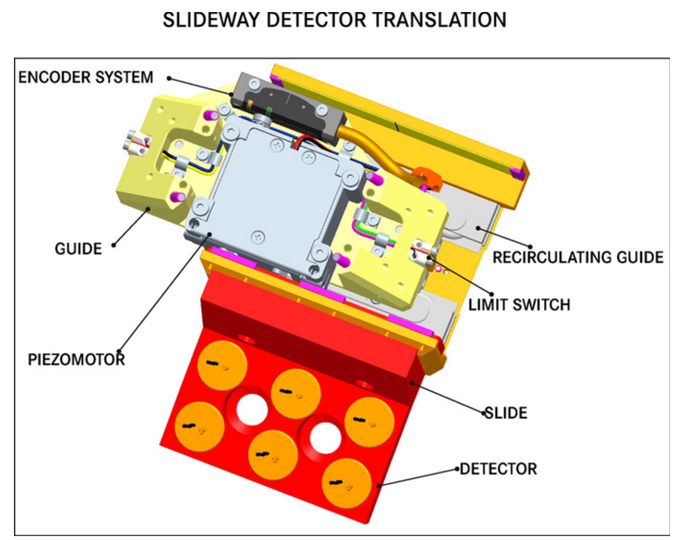

Fig. 5. The detector arm translation stage.

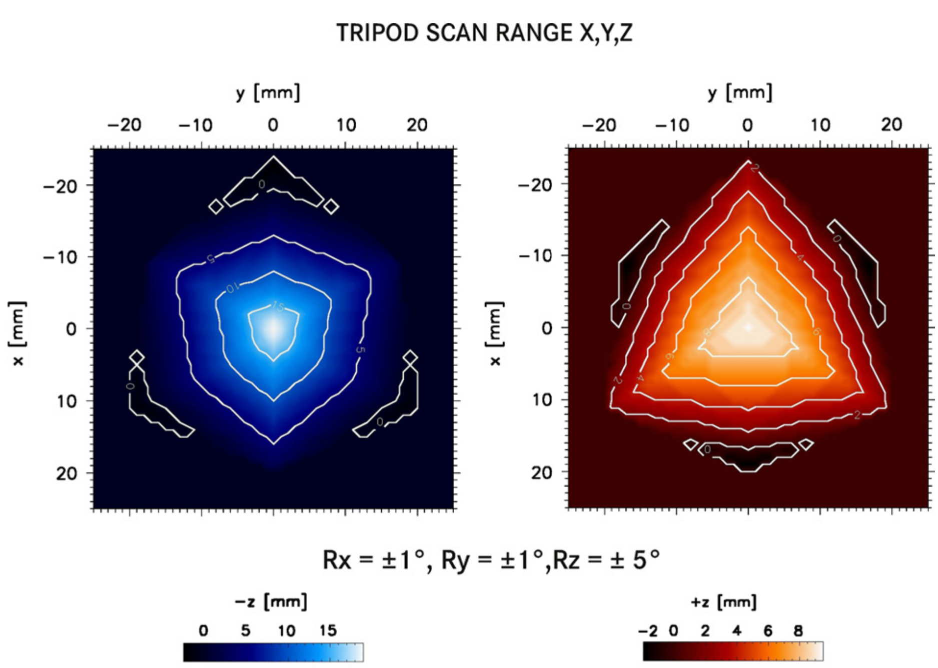

Fig. 4. The tripod unit scan range in the x- and y-directions as function of sample height for a fixed rotational range of Rx, Ry and Rz as indicated.

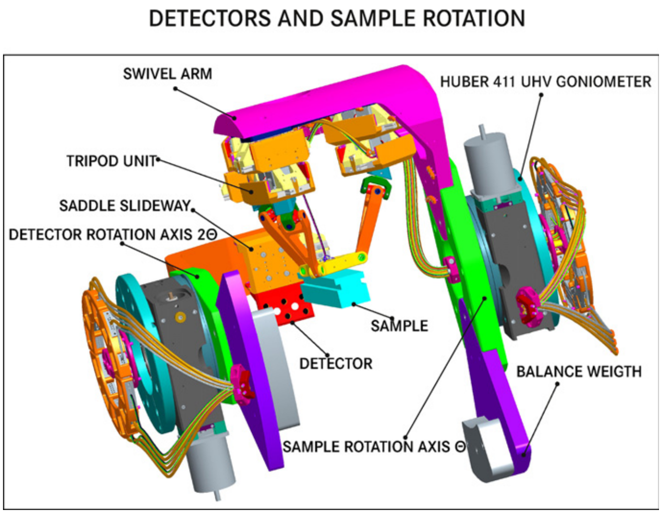

Fig. 6. Sample and detector rotation.

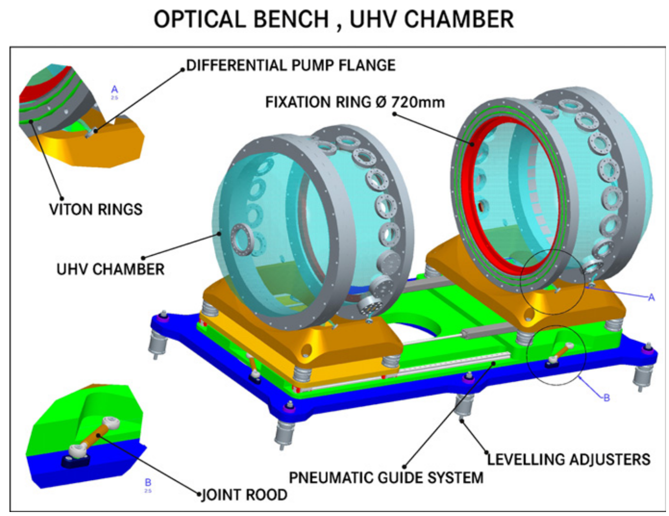

Fig. 8. The UHV-chamber for the reflectometer with the adjustable stand.

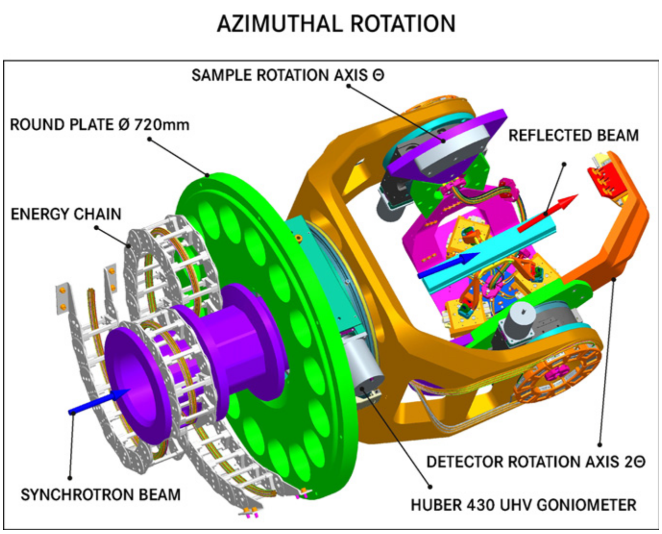

Fig. 7. Sample azimuthal rotation.

2.3.5. *Vacuum chamber*

The UHV-chamber tube (Fig. 8) with a diameter of 800 mm has two large flanges which are sealed by two differentially pumped viton rings. The chamber is opened by a pneumatic guide system which moves one of the two end domes. The chamber can be adjusted in six degrees of freedom by leveling adjusters and three joint rods. A turbopump with 2000 l/min and a cryopump will provide a vacuum of 10^{-9} mbar.

2.3.6. *Load-lock*

A load-lock for rapid sample change (not shown in Fig. 2) is provided for small and thin samples up to a size of 50 mm $\times$ 50 mm only. Larger samples need to be changed by venting the vacuum chamber and moving one of the half domes.

2.3.7. *Control*

The instrument together with the beamline is operated with SPEC programme (trade name by Certified Scientific Software Corporation). This allows full flexibility of positioning and calibrating all motors individually and performing measuring scans as function of all involved motors or a combination of motors. The SPEC programme can be operated by user friendly macros and is fully remote controllable.

3. Conclusion

The UHV-reflectometer as a permanent end station at the BESSY-II optics beamline for UV, EUV and XUV is a fundamental and indispensable infrastructure for the development and at-wavelength characterisation of optical elements, in particular the high precision blazed gratings, manufactured in-house. It will establish another standard for At-Wavelength Metrology in XUV with the unique selling proposition of enabling polarisation sensitive measurements in s- and p-polarisation geometry. It will be available by the end of 2013 and is open to outside users.

Acknowledgement

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