A reflectometer for at-wavelength characterization of XUV-reflection gratings

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ABSTRACT

Within our technology center for production of highly efficient precision gratings a versatile 4-circle UHV-reflectometer for synchrotron radiation based at-wavelength characterization has been fabricated. The main feature is the possibility to incorporate real live-sized gratings. The samples are adjustable within six degrees of freedom by a novel UHV-tripod system, and the reflectivity can be measured at all incidence angles for both s- and p-polarization geometry. The reflectometer has been setup in a clean room hutch and it is coupled permanently to the optics beamline PM-1 for the UV and XUV range with the polarization adjustable to either linear or elliptical. The setup will be open to users by the end of 2014.

Keywords: XUV-radiation, reflectometer, at-wavelength metrology, synchrotron radiation, polarization, reflection gratings

1. INTRODUCTION

At-wavelength metrology is a powerful and indispensable tool for the development, characterisation and final control of XUV-optical elements [1 - 4]. Since the optical constants of the coating materials involved depend on wavelength, information on reflectivity or diffraction efficiency at a certain wavelength can be obtained only by this method and cannot be deduced from any other diagnostics results. Thus this method is complementary to ex-situ profilometry methods delivering information about figure and finish (slope and roughness) of optical elements [5, 6], or Cu K-α diffractometry which in the case of multilayers delivers information on interfacial roughness and layer quality.

The Helmholtz-Zentrum Berlin operates a grating technology project for the fabrication of high-precision laminar and blazed gratings [7]. Within this project we have designed and fabricated a versatile UHV-reflectometer described briefly previously [8] for the at-wavelength characterisation of the in-house produced gratings, i.e. the determination of the diffraction efficiency in the wavelength range of interest which is the ultimate test before delivery.

This reflectometer complements the metrology instrumentation at BESSY-II: the existing reflectometer [9, 10] at the old / previous optics beamline [10] and the polarimeter / ellipsometer chamber [11] for polarisation studies on magnetic or non-magnetic samples [12].

The main feature of the reflectometer is the possibility to incorporate *real* gratings with dimensions up to 360 mm length 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 -90° and +90° incidence angle for both s- and p-polarisation geometry which requires an azimuthal rotation of the sample around the beam direction. A variety of detectors with a high dynamic range of magnitude is available. The reflectometer is located in a moderate clean-room hutch at the experimental floor of BESSY-II and is permanently attached to the Optics Beamline PM-1 which is described elsewhere in these proceedings [13]. It is based on an old SX700-Plane Grating Monochromator (PGM) [14, 15] operated in collimated light which has been setup at a BESSY-II bending magnet. It operates in the UV, EUV and soft x-ray range and the beam polarisation is adjustable to either linear or elliptical. This beamline replaces the existing optics beamline PM-4 [10] at which the beamtime had to be shared with another experiment.

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In this report we give information about the technical/optical and engineering features and first commissioning results of the reflectometer. It has been completely designed in house and was constructed and assembled outside. The reflectometer setup as a fixed (and only) end station at the Optics Beamline guarantees a short-term access for rapid quality control of optical elements and for scientific reflectometry projects. It will go into operation by the end of 2014 and will be available for external users.

2. OPTICS BEAMLINE

The new beamline PM-1 adds another attractive XUV experimental station to the portfolio of approximately 25 PGM beamlines at BESSY-II [16] 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 [14, 15]. Table 1 lists the main parameters of source and beamline.

Figure 1 shows the optical layout of the beamline. The bending magnet radiation is vertically collimated by the toroidal mirror M1 and horizontally focused at the sample in a 3:2 demagnification. The SX700 monochromator (Plane Mirror (PM) and Plane Grating (PG)) is operated in collimated light to have maximum flexibility in operating modus (spectral purity, high resolution, high flux). The cylindrical mirror M3 focusses the dispersed radiation vertically onto the exit slit (SL). The toroidal mirror M4 refocuses the beam onto the sample position in a nearly 1:1 magnification. All optical elements are coated with gold. Focus size will be approximately 0.2 x 0.3 mm FWHM (v x h) for standard beamline settings.

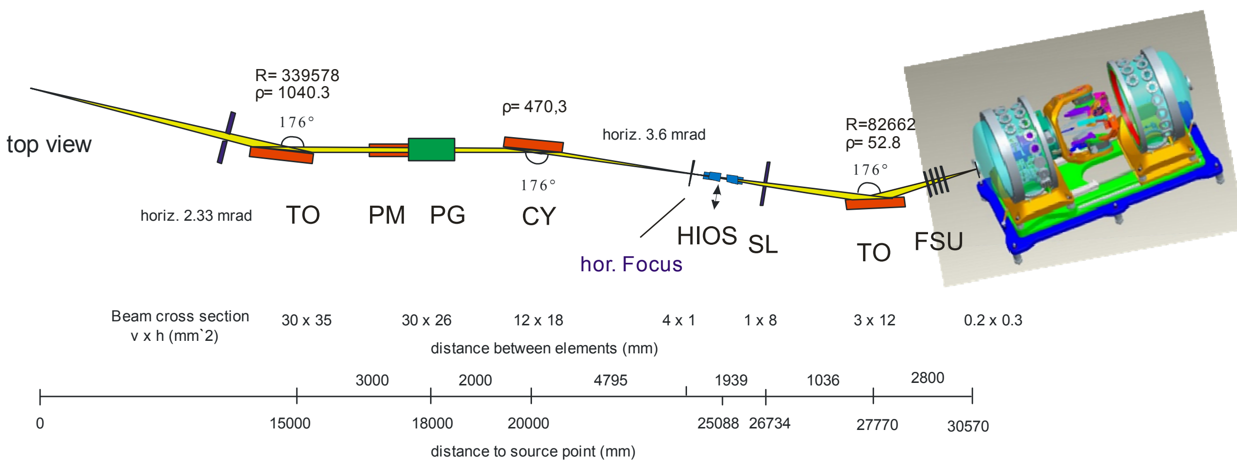

Figure 1. Schematic diagram of the optics beamline PM-1 and the reflectometer end station

Table 1. Parameters of BESSY-II dipole source DIP 1.1 and the optics beamline PM-1

Source	Dipole BESSY II Dip 1.1
e-beam size, σ	47 µm x 96 µm (v. x h.)
e-beam divergence, σ'	20 µrad (v.)
Beamline acceptance	0.5 mrad x 2.33 mrad (v x h)
Monochromator	SX700 – Plane Grating Monochromator (PGM) in collimated light, variable c_{ff}
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 (600 l/mm) G2 (1200 l/mm)
Beamline length	30.57 m
Resolution	3000 @ 400 eV @ c_{ff}=2.25 @ 0.1 mm exit slit
Polarisation	Linear / elliptical (off-plane dipole radiation)
Focus size	0.2 mm x 0.3 mm (v x h) FWHM
Divergence at sample	0.3 mrad x 3.5 mrad (v x h) FWHM
Flux at sample	10^{10}-10^{11} s^{-1} / 100 mA
High order suppression	Filters, 4-mirror system
Straylight suppression	Slits, pinholes

3. REFLECTOMETER

The reflectometer has been specified to complement the features of the existing reflectometer and polarimeter: measurement flexibility on realistic large-scale samples together with polarization sensitive reflectometry, i.e. option for measurement of both Rs and Rp components.

The project management was based on the following principles:

- Optical specification, technical design and construction drawings made in-house
- Order and construction of individual packages at companies site
- Assembly of all individual packages at main contractors site
- Develop control software in-house using LABVIEW
- Data acquisition and control of beamline and reflectometer by SPEC program using EPICS-variables for motors and detectors

Figure 2 shows the complete reflectometer assembly in its UHV-chamber. The individual work packages will be explained in detail in the following subsections.

- Vacuum chamber and stand
- UHV-Optical Bench
- Tripod
- Load-lock
- Control (Labview, SPEC)

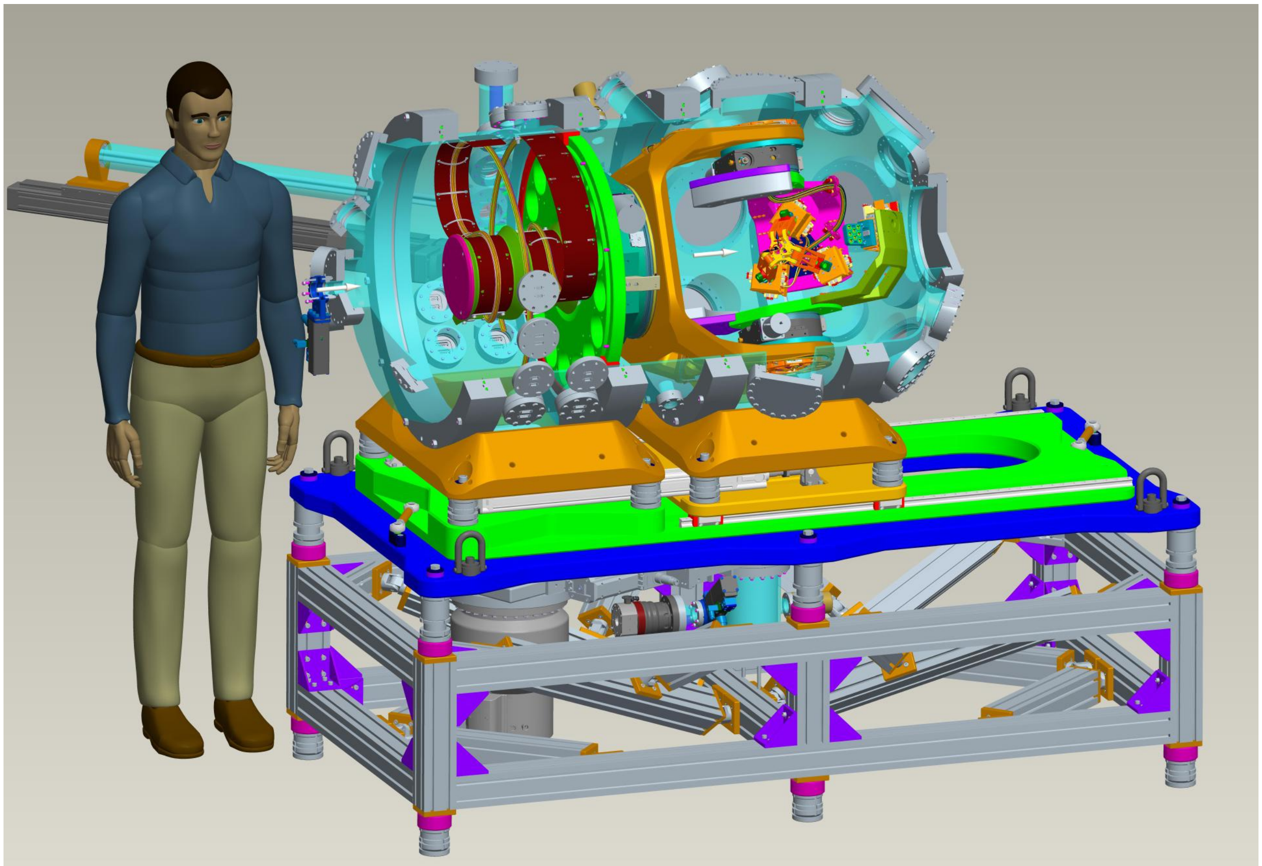

Figure 2. Schematic diagram of the reflectometer. Synchrotron light comes from the left side.

3.1 Vacuum chamber and stand

The UHV-reflectometer chamber is a 1 m long stainless steel tube of 0.8 m diameter and two half domes on both sides. The tube is split into two halves for easy access and maintenance, which are connected by differentially pumped double O-ring sealed flanges. The downstream half of the vessel stands on a rail system and is longitudinally moved by a pneumatic drive. The base plate glides on a coated Al-plate for easy 2 D adjustment and the whole assembly with a weight of 2.1 tons is transported on air cushions. The chamber is pumped by a 2000 l/s turbo molecular pump reaching a base pressure of $<5x10^{-9}$ mbar. To speed up pump down time to not more than two to three hours a liquid nitrogen cold trap and a Titanium sublimation pump can be activated additionally.

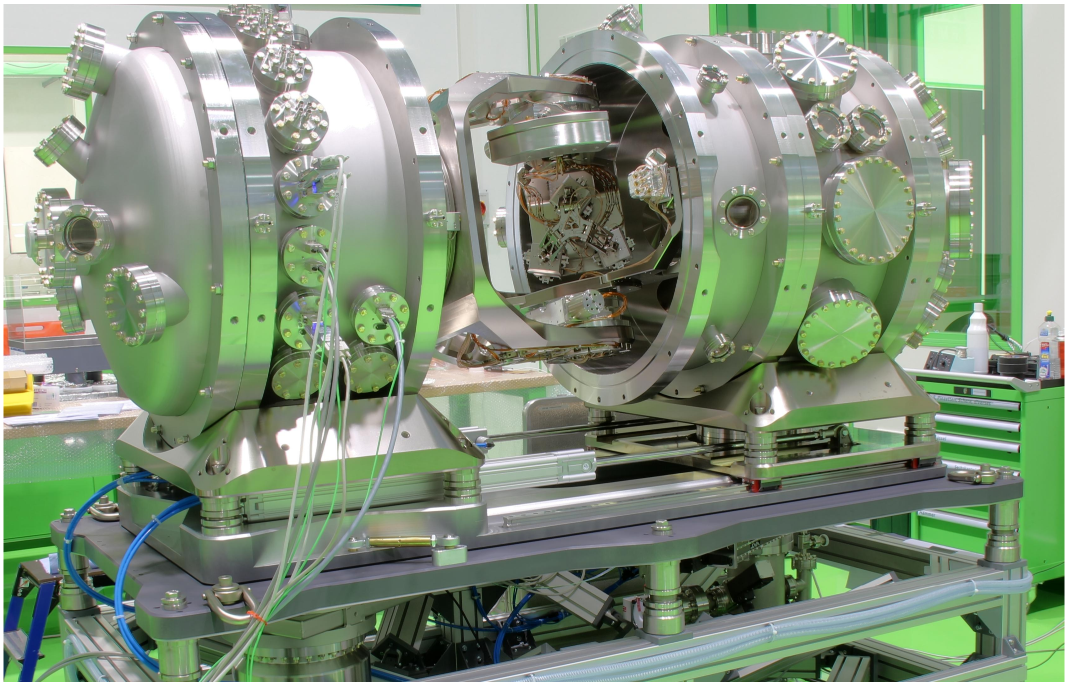

Figure 3. The reflectometer vacuum chamber opened to show the UHV-optical bench. The light comes from the left side.

3.2 UHV-optical bench

The optical specification for the functionality of the reflectometer comprised the following items:

- Azimuthal angular range β 0° – 360º
- Incidence angular range θ -90° – +90°
- Detector in-plane range 2θ -180°– 180°
- Detector off-plane range χ -4° – 4°
- Full flexibility in sample positioning
- Option for a variety of detectors with and without angular resolution and high dynamic range: GaAs-Photodiodes, Channeltron,…
- Option for sample current measurement (sample electrically insulated)
- Load-lock for samples of size up to 50 x 50 x 10 mm^3

This resulted in an UHV-optical bench design which is shown schematically in Figure 4. A large stainless steel base plate of 700 mm diameter (green) rigidly attached to the chamber wall holds a large goniometer (Huber model 430) for the azimuthal rotation. This goniometer holds a precisely manufactured and robust U-shaped base plate (total weight 52 kg), onto which two smaller goniometers (Huber model 411) are mounted opposite to each other and perpendicular to the large goniometer. They are pre-aligned on a common rotation axis for the sample stage and the detector arm, respectively. The goniometers realize three circles, and the detector arm holds a translation stage for off-plane detector movement to approximate the fourth circle of the reflectometer. Thus together with the six axes of the tripod sample alignment stage we have realised a four circle – 6 axes UHV-diffractometer. All motorized rotations and translations are controlled by rotational or linear encoders (Renishaw tonic) and two stage limit switches. A patent has been granted for a new wiring arrangement of a simple and compact two-stage limit switch requiring only two cables instead of four [17]. All 272 shielded capton-insulated wires for the motors, limit switches, and encoders of the ten axes and of the detectors are fed axially through the large goniometer and are guided on a special UHV-energy chain to hinder / prevent twisting during rotation of β by 360°.

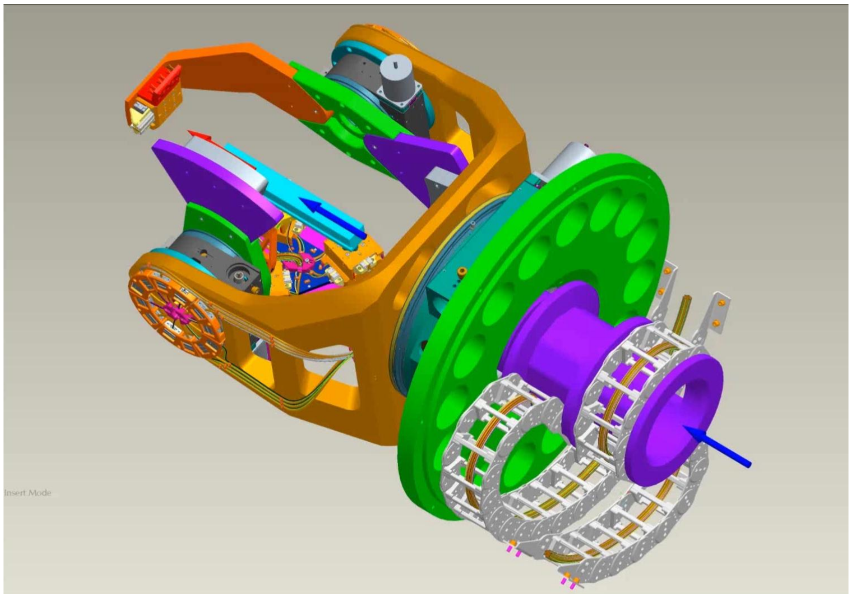

Figure 4. The UHV-optical bench showing the three goniometer circles for azimuth, θ and 2θ rotation. The light comes from the right side (blue arrow). The sample is shown in light blue, and the energy chain in light gray for the cable guidance.

3.3 Tripod

The specification for the sample base plate is as follows:

- Maximum sample weight 4 kg
- Maximum sample dimension 360 x 60 x 60 mm^3
- Sample adjustment in six degrees of freedom
- Sample surface scan of 15 x 15 mm

From this specification a tripod design was developed in our institute which is shown schematically in Figure 5. It is a compact UHV-compatible design of 200 mm by 200 mm footprint. The tripod unit allows adjustment of the sample base plate in six degrees of freedom: translations Tx, Ty and Tz and rotations Rx, Ry and Rz. Cross slides, a combination of two perpendicularly arranged saddle slides, are activated by six piezo-ceramic motors (Nanomotion) with a resolution of 100 nm). Three aluminum legs, which are connected by flexural pivots on one side and by cardan joints on the other side support the sample base plate. All translational motions are controlled by linear encoders (Renishaw) and by two-stage limit switches. Closed loop motion is computerized by a LABVIEW program, and access from the data acquisition program to Cartesian coordinates is via EPICS variables.

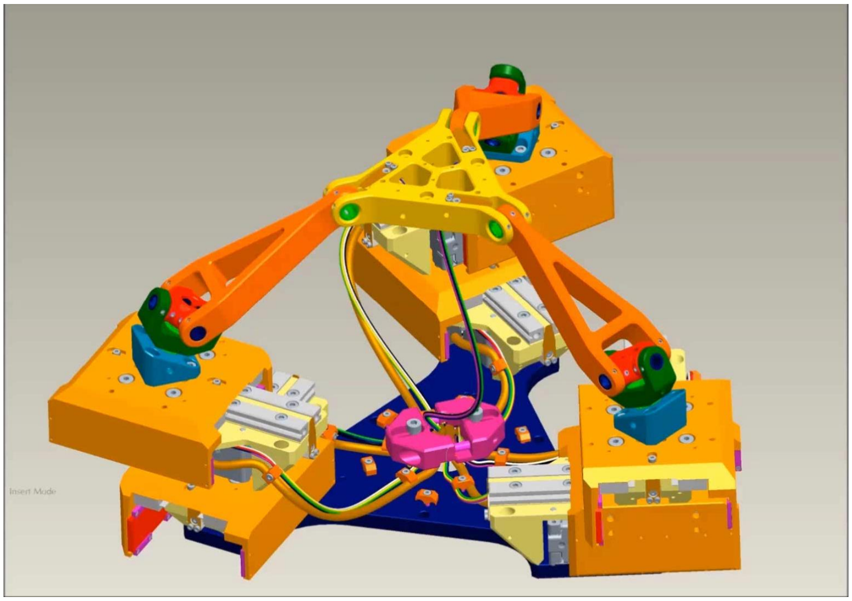

Figure 5. The tripod unit for sample adjustment in six degrees of freedom.

The available sample scan range as function of the tripod position is shown in Figure 6. Plotted is the x- and y-translation range (surface scan) as function of the sample height (z-position) for negative (left) and positive z-position with respect to the middle position at z = 0. At maximum or minimum sample height, the translational range in x- and y-direction goes to zero. The translational data were calculated under the assumption of maintaining a rotational freeedom of +/- 1° for Rx and Ry, and +/- 5° for Rz.

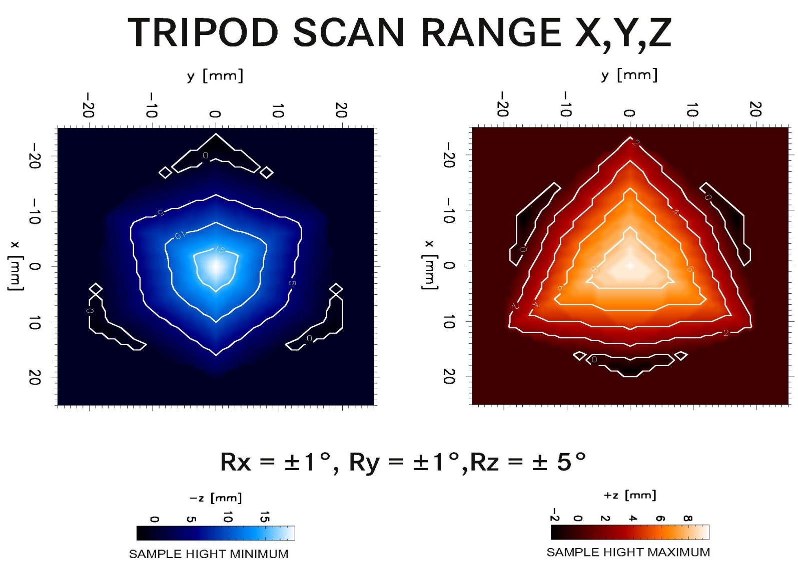

Figure 6. The tripod unit scan range in x and y-direction as function of sample height for a fixed rotational range of Rx, Ry and Rz as indicated.

3.4 Load-lock

The reflectometer will incorporate a magazine for up to 10 samples in a separate small vacuum chamber attached to the main chamber, and a load-lock for rapid sample transfer and change. This will be provided for small and thin samples up to a size of 50 mm x 50 mm x 10 mm only. The sample transfer will be done by a motorized linear translation with automatic magnetic fixing and unfixing of the samples which are in a standardized frame. This novel technique requiring one linear translation only has recently been patented [18]. Larger samples need to be changed by venting and opening of the vacuum chamber and placing them manually onto the tripod base plate.

3.5 Control

The instrument together with the beamline is operated with SPEC-program (trade name by Certified Scientific Software Corp.). This allows for 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 program can be operated by user friendly macros and is fully remotely controlable. All motors of the beamline and the reflectometer are accessible through the computer network via EPICS variables. The flowchart of the control is displayed in figure 7. The beamline control is based on a VME-crate with MAXv motor controllers and IK320 interface for the encoders (Heidenhain) of the SX700 monochromator. The reflectometer control uses Labview program with controllers and drivers for the piezo-motors (Nanomotion) of the tripod and stepping motors (Phytron) for the goniometers. The Cartesian coordinates of the tripod and the goniometer angles are provided as EPICS-variables for the SPEC data acquisition program.

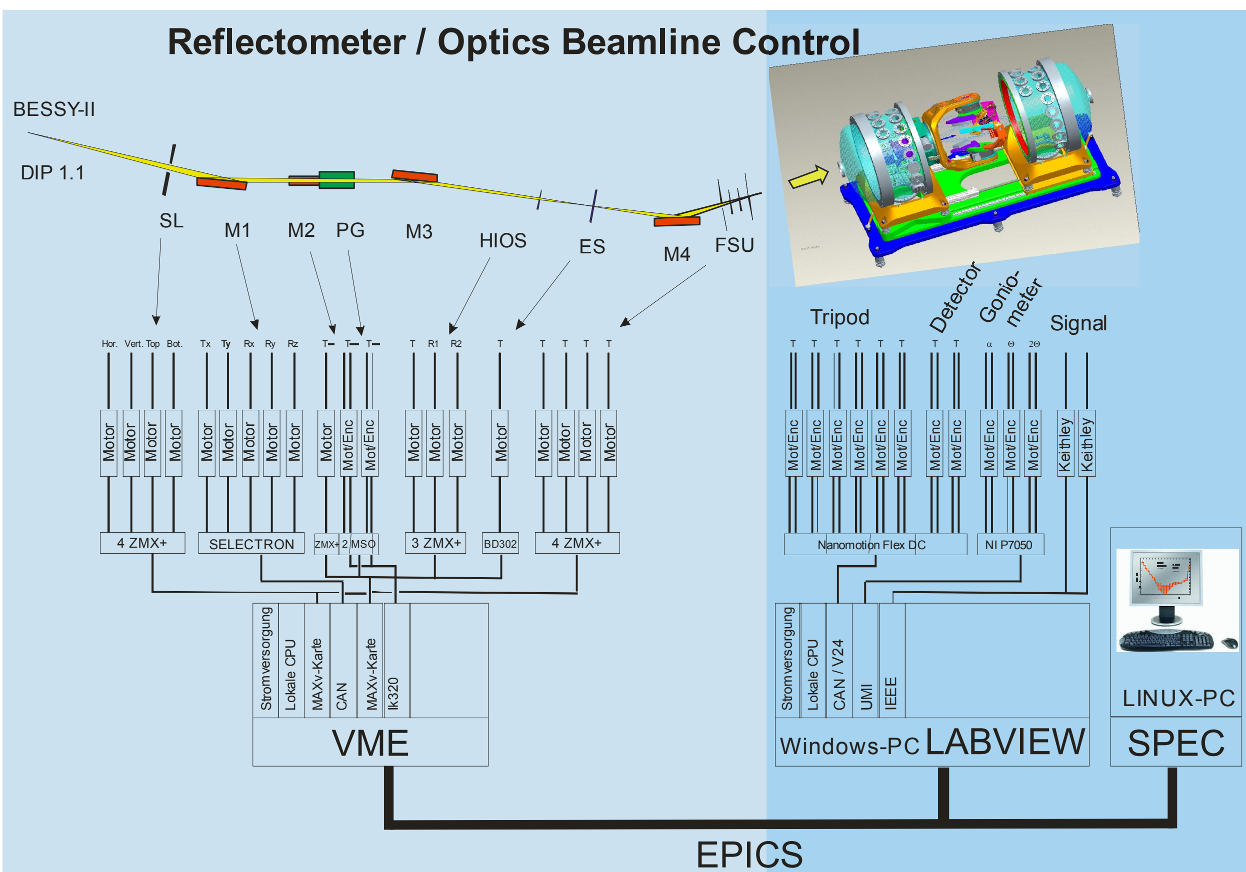

Figure 7. Flow chart of the beamline and reflectometer control.

4. PERFORMANCE OF TRIPOD

A key element of the reflectometer is the positioning device for the samples to be investigated. The sample sizes vary from small wafer test pieces less than 10 mm in size up to large-scale mirrors or gratings up to 360 mm length and 4 kg weight. Thus a precise alignment of the sample surface onto the beam spot and into the rotation axes of the β-,θ- and 2θ-goniometers is of utmost importance. Therefore the positioning capabilities and accuracy of the tripod have been measured before with use of two electronic autocollimators, oriented perpendicular to each other and looking onto two mirrors, which were and aligned perpendicular to each other and fixed onto the tripod base plate. In this way all rotational degrees of freedom of the mirrors could be detected simultaneously: Rx, Ry and Rz. The tripod was scanned in all three directions Tx, Ty and Tz to cover the total scan volume, and the cross talk to the rotational angles Rx, Ry and Rz was recorded. The figure 8 shows a summary of the measurements. The colour-code refers to the quadratic sum of all rotations (sqrt(Rx^2+Ry^2+Rz^2). Figure 8a gives the open loop rotation of the tripod mirrors which is in the range of up to 500 arcsec during translation. When a correction matrix is applied which takes into account the experimental results of figure 8a, the cross-talk is reduced to less than 10 arcsec (figure 8b). When the autocollimator signal is used as a feedback to the positioning device (closed loop operation) the cross-talk is further reduced to less than 0.5 arcsec. This value is limited by the stop-criterium for the feedback loop operation and not by the positioning accuracy of the device. Thus this precision can be further increased, if required.

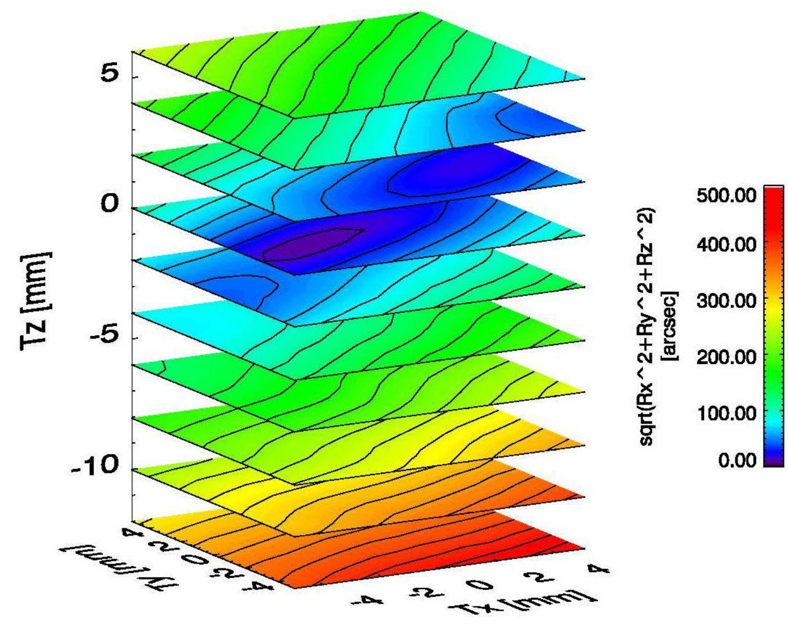

Figure 8a. Cross talk of tripod in open loop operation

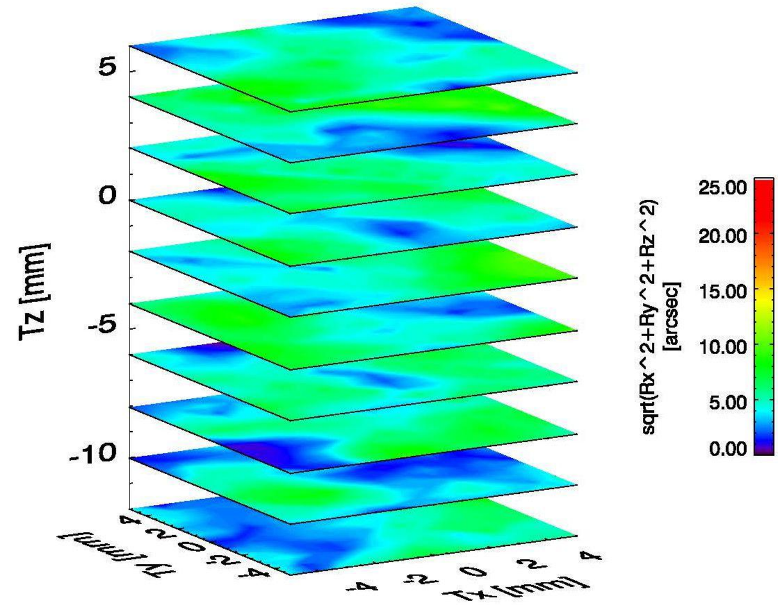

Figure 8b. Cross talk of tripod in a corrected open loop operation

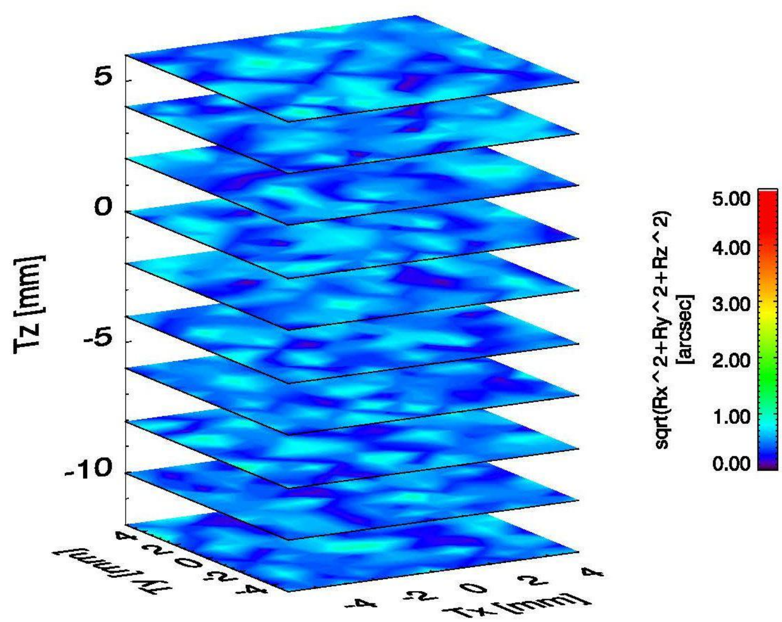

Figure 8c. Cross talk of tripod in closed loop operation

5. OUTLOOK

The HZB grating fabrication facility is now well established. It was shown that the gratings have better performance than previous ones produced commercially with respect to blaze angle homogeneity, roughness, efficiency and stray light [19]. The versatile 4-circle UHV-reflectometer described here is an essential tool for the final control of the gratings before delivery. It is located in a clean room hutch as permanent end station at the BESSY-II optics beamline for UV, EUV and XUV radiation and it is a fundamental and indispensable infrastructure tool for the development and at-wavelength characterization of optical elements. It will establish another standard for At-Wavelength Metrology in XUV with the rare feature of polarization sensitive measurements in s- and p-polarisation geometry on large samples. It will be available by the end of 2014 and is open to outside users.

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