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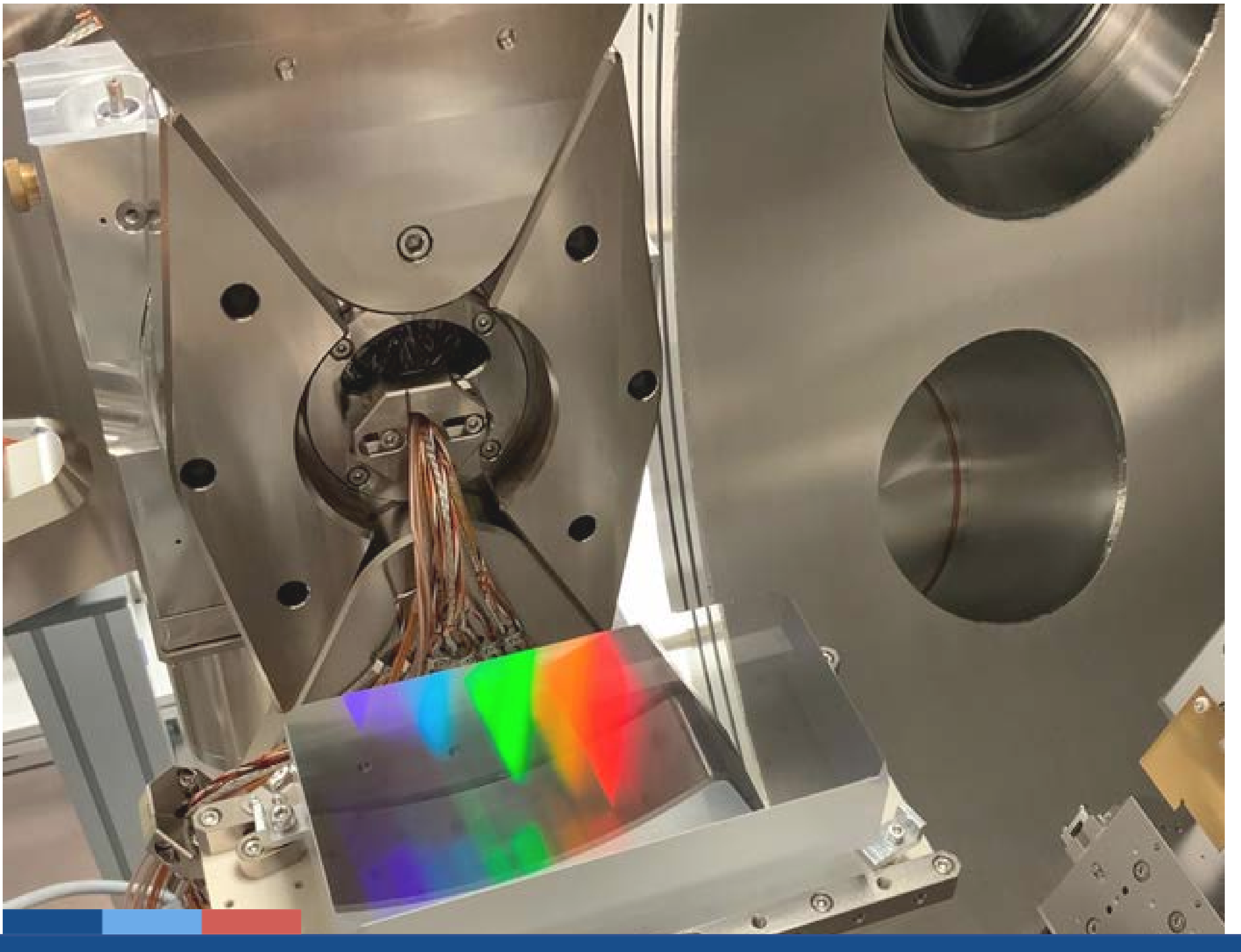

IWXM 2022

7th International Workshop on Metrology for X-ray Optics, Mirror Design and Fabrication

5th-8th April 2022 - Virtual

Book of Abstracts

Oral Presentations

Session 01 | Fabrication and finishing technology for X-ray mirrors

Development of a monolithic Wolter-type mirror for stable hard X-ray focusing

Yasunori Senba[1]*, Hikaru Kishimoto[1], Takahisa Koyama[1], Hirokatsu Yumoto[1], Yoshiki Kohmura[2], Jumpei Yamada[2], Akira Miyake[3], Shunichiro Matsuzaka[3], Toshio Nakano[3], Shota Matsuyama[3], Hiroki Nakamori[3] and Haruhiko Ohashi[1]

[1]Japan Synchrotron Radiation Research Institute, [2]RIKEN SPring-8 Center, [3]JTEC Corporation

*e-mail: *ysenba@spring8.or.jp*

Abstract

Kirkpatrick-Baez (KB) optics is commonly used in synchrotron radiation facilities not only for ultimate nano focusing but also for general blight micro focusing. However, KB optics has large comatic aberration and small tolerance of alignment error. Therefore high accuracy and stability are required for the multi-axis stage with 7 or more axes in the mirror system. We propose a monolithic Wolter-type focusing mirror, which consists of ellipsoid and hyperboloid surfaces on a single substrate. The Wolter-type mirror [1] is roughly satisfying the Abbe sine condition, hence, this optics has a small comatic aberration. Therefore the monolithic Wolter mirror with property of high stability and easy alignment is adequate as a focusing optics. However, it is difficult to fabricate two steep 2D aspherical surfaces with high precision of relative positional relationship between each surface. The soft X-ray monolithic Wolter mirror, whose length is 210mm and glancing angles are 1.2 and 1°, had been developed and installed for micro-ARPES apparatus at BL25SU of SPring-8 [2]. For applying the monolithic Wolter mirror to hard x-ray focusing, a steep shape on a long substrate is required.

In this study, the monolithic Wolter mirror is designed and developed for hard X-ray region up to 12 keV by optimizing glancing angle and length to 5 mrad and 550 mm. Entrance and exit length of the mirror are 50m and 1.6m, which correspond to typical values at standard experimental hutch of SPring-8 and the magnification factor is 1/30. The surface shape is shown in Figure 1. Because tilted ellipsoid and hyperboloid surfaces are fabricated on a substrate, the monolithic Wolter mirror has large sag of above 1.2mm and minimum radius of curvature of 30 mm. The performance tests of the mirror were carried out at BL29XU. Reflected beam image, focusing beam size and reflectivity were evaluated. After figure correction of surfaces, the focusing size of 0.5 um was achieved with source size of 10 um. The mirror has been used in HAXPES apparatus at BL09XU. The focused beam sizes of vertical and horizontal dimensions without source size limitation are 1 and 20 µm, respectively. In addition to the figure error on the surfaces, the reflected beam image and focusing size measured at the beamline will be presented.

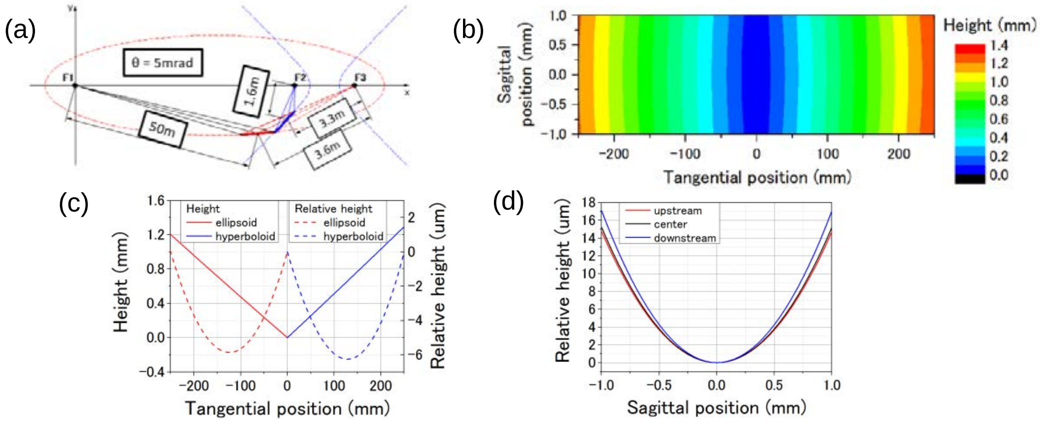

Figure1. Optical layout (a), 2D surface profile (b), line profile in tangential direction (c), and in sagittal direction (d) of the designed monolithic Wolter mirror.

Keywords: hard X-ray, focusing optics, Wolter mirror, monolithic

References:

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Fabrication of XFEL sub-10 nm focusing optics based on advanced Kirkpatrick-Baez mirrors

Jumpei Yamada[1,2], Satoshi Matsuyama[3,2], Takato Inoue[2], Atsuki Ito[2], Taito Osaka[1], Ichiro Inoue[1], Yuichi Inubushi[4], Hirokatsu Yumoto[4,1], Takahisa Koyama[4,1], Haruhiko Ohashi[4,1], Kazuto Yamauchi[2], and Makina Yabashi[1,4]

[1]RIKEN SPring-8 Center, [2]Osaka University, [3]Nagoya University, [4]JASRI

*e-mail: *yamada@spring8.or.jp*

Abstract

The intense X-ray free-electron laser focused to a single-nanometer scale will open up new frontiers in many scientific fields, including X-ray nonlinear optical phenomena [1,2] and single-molecule structural analyses [3]. We have developed an XFEL sub-10 nm focusing system reaching ~10^{22} W/cm^2 intensity at SACLA. For the sub-10 nm focusing optic, an advanced KB (AKB) mirror system based on Wolter-type III geometry [4] has been employed. The AKB with hyperbolic convex and elliptical concave mirrors (Fig. (a)) can satisfy the Abbe's sine condition, which leads to a reduced coma aberration and a high tolerance to the incident angle error. Moreover, the system combining diverging and converging optics can provide a large demagnification factor even with a short source-mirror distance, being compatible with compact XFEL facilities. We have designed and developed the AKB mirror system with numerical apertures of 0.01 and demagnification factors of over 6000, which can attain a 6 (horizontal: H) × 7 (vertical: V) nm focusing spot size at 9.1 keV in SACLA BL3.

One of the challenges for the mirror fabrication was the precise measurements of the surfaces with small radii of curvature of 2~3 m. The required accuracy for such steeply curved mirrors was less than 1 nm PV, which has been difficult to achieve by conventional metrology. We applied an X-ray single-grating interferometer [5] for the in-situ wavefront measurement, complementing the measurement accuracy and spatial frequency of ex-situ stitching interferometers. The former X-ray wavefront measurement was highly advantageous to verify the low-frequency shape errors including primary aberrations, and the latter had sufficient accuracy to determine the high- and middle-frequency shape errors. Then, we could efficiently suppress undesired middle-frequency shape errors in the initial fabrication process, and subsequently, finish the mirrors by wavefront correction using a differential deposition technique [3]. The experimentally obtained X-ray wavefront accuracy was λ/15 rms (Fig. (b)), suggesting nearly diffraction-limited focusing performance under the Maréchal's criterion. Also, ptychographic probe measurements indicated the sub-10 nm focusing capability.

In the presentation, we will discuss the design and fabrication of the mirrors, as well as the results of the focus characterizations, the status of the stability, an alignment procedure of the system.

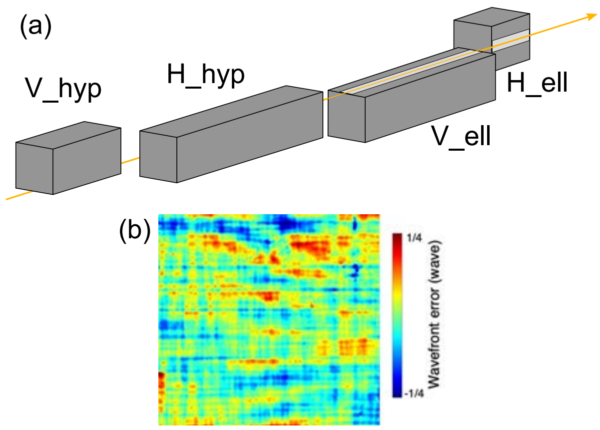

Figure (a) Schematic drawing of the sub-10 nm focusing AKB mirrors. (b) A wavefront errors of the sub-10 nm focused beam, measured at SACLA BL3.

Keywords: XFEL, hard X-ray, nanofocusing mirrors, wavefront measurement

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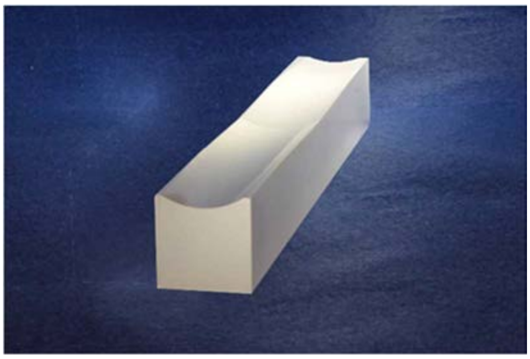
Three-dimensional shape measurement of monolithic Wolter mirror for soft X-ray

Takehiro Kume[1*], Yusuke Matsuzawa[1], Kentaro Hiraguri[1], Yasunori Senba[2], Hirokatsu Yumoto[2], Takahisa Koyama[2], Haruhiko Ohashi[2], Yoko Takeo[2,3], Hidekazu Mimura[3], and Hirokazu Hashizume[1]

[1] Natsume Optical Corp., 1200-29 Kawaji, Iida, Nagano 399-2431, Japan, [2] JASRI, 1-1-1 Kouto, Sayo-cho, Sayo-gun, Hyogo 679-5198, Japan, [3] The Univ. of Tokyo, 7-3-1 Bunkyo-ku, Hongo, Tokyo 113-0033, Japan

*e-mail: takehiro.k@mflens.co.jp

Abstract



Wolter mirrors, which consist of ellipsoidal and hyperboloidal surfaces, are suitable optics for highly efficient sub-micron focusing of soft x-ray. They also roughly satisfy the Abbe sine condition, and consequently accept several hundreds of microradians of alignment errors. The monolithic Wolter mirrors, in particular, have the advantages of cost and convenience because of their requirement of fewer alignment axes. On the other hand, they have a depth of a few millimeters in their tangential profiles, and their radii of curvature in the sagittal direction can be down to a few tens of millimeters. In addition, to accept the incident x-ray distributing in a millimeter-sized area, their angular range in the sagittal direction needs to be several tens of degrees.[1] These geometrical features inhibit applying interferometer-based shape measurement, resulting in difficulty in the mirror fabrication.

A tactile measurement method is a possible solution for evaluating steep shape of soft x-ray mirrors. It does not require a reference surface with a similar shape of samples and has a wide measurable range of depth and angles. Measurement errors depending on the curvature of samples, in principle, does not arize. In this study, we evaluate the shape error of a high-precision monolythic Wolter mirror for soft x-ray by a three-dimentional measurement apparatus with a contact probe. Current status of our fabrication techniques related to soft x-ray mirrors such as electrofroming and high spatial resolution machining is also reported.[2]

Keywords: x-ray mirror, three-dimensional measurement, soft x-ray

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Multilayer focusing mirrors for intense X-rays from SR and XFEL sources

Takahisa Koyama[1,2*], Hirokatsu Yumoto[1,2], Takanori Miura[1], Kensuke Tono[1,2], Makina Yabashi[1,2] and Haruhiko Ohashi[1,2]

[1]Japan Synchrotron Radiation Research Institute, 1-1-1, Kouto, Sayo, Hyogo 679-5198, Japan,
[2]RIKEN SPring-8 Center, 1-1-1 Kouto, Sayo, Hyogo 679-5148, Japan

[*]e-mail: *koyama@spring8.or.jp*

Abstract

Multilayer focusing mirrors enable a larger glancing angle, resulting in a larger acceptance aperture and a shorter focal length than those of total reflection mirrors. Therefore optical systems with a high throughput and a high demagnification ratio can be designed.

One of the key characteristics of the SPring-8 is to provide highly brilliant X-rays in high-energy region. By using a double multilayer monochromator (DMM) with a wide bandwidth, the photon flux can be dramatically increased compared with that of a double crystal monochromator. In addition, a multilayer focusing mirror can enlarge the acceptance aperture when compared with that of a total reflection mirror. We have designed DMM and the multilayer focusing mirrors for BL05XU [1] of SPring-8 for utilizing high-energy high-flux X-rays of 100 keV (Fig.1). The multilayers for the focusing mirrors and DMM were deposited by a coating system developed at SPring-8. DMM has a $[Cr/C]_{150}$ multilayer with a period (d) of 3.33 nm and a glancing angle (θ) of 1.9 mrad. The X-rays from DMM has a photon flux of 3×10^{13} ph/s with a bandwidth of 1%. The focusing mirrors with 200 mm length $[W/C]_{50}$ laterally graded multilayers (d = 3.2-3.8 nm (Mv), d = 3.2-4.2 nm (Mh), θ of center part 1.85 mrad (Mv), 1.77 mrad (Mh)) were arranged in the KB geometry. The focusing beam has a size of 0.26 µm (H) × 0.25 µm (V) with a photon flux of 6×10^{10} ph/s for high resolution mode with a limited aperture of the front end slit (FES). The size is increased to be 5 µm (H) × 0.3 µm (V) with a photon flux of 1×10^{12} ph/s for a high flux mode with FES open.

The multilayer focusing mirrors are also useful for increasing the fluence of X-ray free electron laser (XFEL) pulses. Since XFEL pulses could damage the multilayer coatings, we investigated the damage threshold of the multilayer coatings, and confirmed to have sufficient tolerance. We designed and fabricated multilayer focusing mirrors to focus 4-keV XFEL pulses, and installed them into a coherent diffractive imaging (CDI) system. The focusing mirrors with 80 mm length $[Cr/C]_{30}$ laterally graded multilayers (d = 6.0-7.7 nm (Mh), d = 5.1-8.5 nm (Mv), θ of center part 25 mrad) were polished and deposited. To investigate XFEL irradiation tolerance of the multilayer coatings, test pieces of the Cr/C multilayer were irradiated with various irradiation fluences using a 1 µm XFEL focusing system [2] and a dedicated irradiation chamber [3] at BL3 of SACLA. Measured damage threshold fluences were one order of magnitude higher than unfocused beam fluence at the place of the CDI system. We thus confirmed that the Cr/C multilayer is applicable for focusing mirrors of the SACLA. We evaluated focusing performances of the mirrors at BL2 of SACLA. The focusing beam size of around 100 nm and the intensity of 3×10^{19} W/cm^2 were achieved.

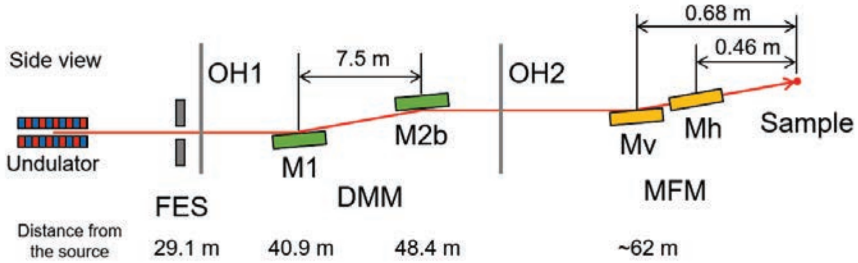

Figure 1. Schematic layout of multilayer focusing system at BL05XU of SPring-8.

Keywords: multilayer focusing mirror, multilayer monochromator, high energy, XFEL, damage threshold

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Preferred presentation format: oral

Development of high-precision X-ray mirrors using deterministic fabrication techniques and stitching interferometry

Qiushi Huang[1]*, Qiaoyu Wu[1], Handan Huang[1], Yunyang Zhang[1], Yingna Shi[1], Shuai Yan[2], Yumei He[2], Jie Wang[2], Zhong Zhang[1], Zhanshan Wang[1]*

[1]*Key Laboratory of Advanced Micro-Structured Materials MOE, Institute of Precision Optical Engineering (IPOE), School of Physics Science and Engineering, Tongji University, Shanghai 200092, China*
[2]*Shanghai Synchrotron Radiation Facility, Shanghai Advanced Research Institute, Chinese Academy of Sciences, Zhangheng Road 239, Pudong District, Shanghai, 201204, China*

huangqs@tongji.edu.cn
wangzs@tongji.edu.cn

Driven by the increasing demand of high-precision X-ray mirrors in synchrotron radiation and free electron lasers both worldwide and in China, deterministic fabrication and stitching interferometry metrology techniques were developed in the Institute of Precision Optical Engineering (IPOE). The stitching interferometry was first developed based on global stitching algorithm which was used on curved mirrors with large radius of curvature (RoC). As demonstrated on a 80mm length spherical mirror with 100m RoC, the repeatability error of multiple stitching measurement results reached 0.3 nm (RMS). The absolute measurement accuracy of the residual figure error of the spherical mirror is less than ±5nm PV as compared to the NOM in Shanghai Synchrotron Radiation Facility (SSRF) [1-2]. For curved mirrors with smaller RoC and larger size, the number of sub-apertures significantly increased, and other profile measurement methods were used to assist and correct the accumulated stitching error. The stitching method was also used to measure long flat mirror. The deterministic fabrication methods developed include profile coating and ion beam figuring. A elliptical cylindrical mirror for KB focusing system was fabricated by using the profile coating technique. Its one-dimensional hight error of the central 50mm area is 1.9 nm RMS and a one-dimensional focus resolution of 207 nm was measured at Shanghai Synchrotron Radiation Facility (SSRF). The ion beam figuring method is used to figure relatively large mirrors, and a first pair of plane mirrors used for bending focusing system has been fabricated. The figure error of the 240 mm long trapezoidal mirror was reduced from 13 nm to 1.6 nm (RMS) by two iterations. The smallest one dimensional slope error is 131 nrad after figuring as measured by NOM. The roughness after both profile coating and ion figuring remained below 0.3 nm RMS. This pair of trapezoidal flat mirrors have been installed and used in the hard X-ray micro-focusing beamline in SSRF. A 500mm length flat mirror was also manufactured and the figure error in the center $485\times10mm^2$ area was improved to around 2nm (RMS).

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Oral Presentations

Session 02 | Metrology challenges for X-ray mirrors I

01 | MooNpics – European metrology collaboration in a large-scale round-robin test | Silja Schmidtchen (Europ. XFEL)

02 | In pursuit of fundamental limits in deflectometric form measurement: Current status and future challenges | Ralf Geckeler (PTB)

03 | Knowing the Limits - Surface Deviation in the Mid-Spatial-Frequency Range by Deflectometric Measurements | Ronald Kometer (Hofbauer Optik Mess- und Prüftechnik)

04 | Optimized design of the ALS LTP-2020 using geometrical and physical optics raytracing | Peter Takacs (SMS)

05 | Binary pseudo-random test standards for characterization of various metrology instruments over high to mid spatial frequencies | Keiko Munechika (HighRI Optics)

MooNpics – European metrology collaboration in a large-scale round-robin test

S. Schmidtchen[1]*, I. Freijo Martin[1], M. Vannoni[1], E. Plönjes[2] and H. Sinn[1]
(on behalf of the MooNpics collaboration)

[1] European XFEL, Holzkoppel 4, 22869 Schenefeld, Germany
[2] Deutsches Elektronen-Synchrotron DESY, Notkestrasse 85, 22607 Hamburg, Germany

*e-mail: silja.schmidtchen@xfel.eu

Abstract

The MooNpics project - Metrology On One-Nanometre-Precise Optics - was started in 2017 as a large-scale approach to improve the European metrology to the single nanometre level. The main goal was to improve the quality and availability of the high-precision X-ray optics required in diffraction limited light sources. 10 European lights sources and two manufacturers of high-precision X-ray mirrors were collaborating in this project. Different work packages were created to focus on the metrology and analysis methods used in the European light sources' metrology labs as well as on software and methods for focal spot reconstruction and fast mirror alignment.

Over four years, a metrology round-robin amongst the participating metrology labs was done with three high-precision X-ray mirrors. Mirrors with very different parameters were chosen to meet the large variety of metrology instruments used in the facilities and to explore different aspects of height and slope error measurements. A 950 mm long plane mirror, a spherical mirror with 9 m radius of curvature and a tangential ellipse with different chirp profiles were used in this experiment.

The large amount of metrology data collected during the round-robin gives a unique chance for cross-calibration of instruments and methods used in the facilities. In addition, it allows us to develop new methods, to create standards and to improve deterministic polishing methods of high-precision X-ray mirrors in close collaboration with our industrial partners. After finalization of the project, a summary of the round-robin realisation is presented here.

Keywords: Metrology, round-robin, X-ray optics

In pursuit of fundamental limits in deflectometric form measurement: Current status and future challenges

Ralf D. Geckeler[1*], Andreas Just[1], Matthias Schumann[1], Michael Krause[1], Ian Lacey[2], and Valeriy V. Yashchuk[2]

[1] Physikalisch-Technische Bundesanstalt, Bundesallee 100, 38116 Braunschweig, Germany, [2]Advanced Light Source, LBNL, 1 Cyclotron Road, Berkeley, CA 94720, USA

*e-mail of corresponding author: ralf.geckeler@ptb.de

Abstract

Over the last two decades, deflectometric profilometry using commercial autocollimators has successfully established itself as the standard in high-precision form measurement of beam-shaping optics for synchrotrons and x-ray free electron lasers [1]. Despite this progress, we are still a long way from reaching the fundamental limits of this measurement technology. This is due to the fact that angle measurement with autocollimators depends on a variety of influencing factors, some of which have so far only been characterized to a limited extent. In addition, methods already developed to compensate for these influences have not yet established themselves in the metrology community.

We present an overview of the known influencing factors that limit deflectometric form measurement. These include the reflectivity and the radius of curvature of the surface under test, the position and shape of the aperture diaphragm, which limits the beam cross-section on the specimen, optical aberrations and adjustment deviations of the opto-mechanical components of the autocollimator, as well as the crosstalk between the autocollimator's measuring axes when both of them are engaged simultaneously. Environmental parameters such as temperature, air pressure and humidity, constitute significant influencing factors [1, 2]. Many of these influences interact with the path length of the autocollimator measuring beam, which returns to the autocollimator after reflection at the specimen surface. This length is subject to major changes with most deflectometers, which scan the test specimen by means of a movable pentaprism. Research on algorithms for determining the shift of the reticle image on the CCD detector of the autocollimator with sub-pixel resolution and accuracy appears to be promising. Advanced optimal measurement strategies for reducing random, drift, and systematic measurement errors using knowledge about their origins and correlation properties have been developed and successfully applied [3]. In this paper, we place particular emphasis on providing a broad overview of the existing strategies for minimising and compensating for systematic measurement errors in autocollimator-based form measurement and on describing their practical implementation. This work was supported in part by the U. S. Department of Energy under contract number DE-AC02-05CH11231.

Keywords: x-ray optics metrology, autocollimator, angle metrology, form measurement, deflectometric profilometry

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Knowing the Limits - Surface Deviation in the Mid-Spatial-Frequency Range by Deflectometric Measurements

R. Kometer[1], E. Hofbauer[1]

[1] HOFBAUER OPTIK Mess- & Prüftechnik, info@hofbauer-optik.de

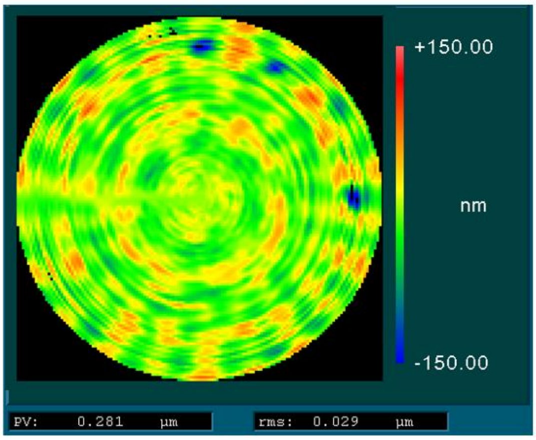
r.kometer@hofbauer-optik.de

ABSTRACT

In the field of precision optics, there is an increasing demand for an accurate characterization on the one hand of form errors (i.e. astigmatism, coma, spherical aberration, …) as well as mid-spatial frequency errors (MSFE) and high-spatial frequency errors (HSFE) – on spherical and aspherical lenses or even freeforms. Deflectometric acquisition of Optical Surfaces (DaOS) using V-SPOT technology has been proven to achieve accurate surface profiles for large quasi-planar optics and for small aspherical optics at moderate cost and low preparation effort [1,2]. In order to extend the resolution limit, the optical and mechanical device has been improved to provide on the one side topography information in the slope domain at high accuracy (< 5 µrad) and an improved lateral resolution (< 0,2 mm) to cover surface profile errors in the mid-spatial-frequency range from 1 to 10 mm^{-1}. The resolution limit of the setup is proofed by measurement of a chirped profile. Within this presentation we are providing the experimental setup and the measurement procedures to achieve production relevant information about the surface quality. Slope deviations of aspheric samples (glass and metal) are analyzed in angular spectral components and the surface profile is compared with interferometric data to proof accuracy and lateral resolution of our device. The figure on the left is showing a reconstructed residual surface profile of the sample under test (aspherical glass optic). In order to focus on the mid-spatial frequency errors (MSFE), the first 36 Zernike orders are subtracted. The profile is clearly revealing a spoke wheel structure, which is typical for remains of the grinding process [3]. The clear appearance of the small marker structures (blue dots) proofs the lateral resolution of the setup. As final conclusion we outlook for further improvements of the proposed device to allow full control of form deviation and mid-spatial frequency errors.

Hofbauer – DaOS – 36 Zernike subtracted

The values are sampled to a [151x151] matrix



Keywords: aspheres, freeforms, shape measurement, Deflectometry, V-Spot, Vignetting Field Stop VFS procedure, MSFE, mid-spatial frequency errors, slope error

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Optimized design of the ALS LTP-2020 using geometrical and physical optics raytracing

Peter Z. Takacs[1*], Ian Lacey[2], and Valeriy V. Yashchuk[2]

[1]Surface Metrology Solutions LLC, 19 S 1st St, Minneapolis, MN 55401 USA, [2]Advanced Light Source, LBNL, 1 Cyclotron Road, Berkeley, CA 94720, USA

*e-mail of corresponding author: takacs.surfmetsoln@gmail.com

Abstract

Early versions of the Long Trace Profiler (LTP), the LTP I and LTP II, developed at Brookhaven National Laboratory were designed without the aid of sophisticated optical design codes. Although the original optical system design is quite simple [1], known error sources, such as ghost ray interference, could not be easily evaluated by pencil and paper methods. We have now developed a complete model of the LTP system using the geometrical and physical optics design capabilities of Zemax OpticStudio™ [2], and have used it to optimize the optical system design and minimize error sources in the new LTP-2020 under development.

The major error sources in the LTP design are wavefront irregularities introduced by glass inhomogeneity and surface roughness, and ghost ray interference caused by multiple reflections between and within optical elements. The use of a polarizing beamsplitter cube in all LTP optical systems requires that the probe and reference beams pass through a significant thickness of glass, with ample opportunity for multiple reflections. The transmitted probe beam wavefront picks up a significant amount of optical path irregularity that distorts the nominal ideal Gaussian image spot and leads to systematic slope errors on the order of a microradian. Requirements for x-ray mirror slope errors are now in the nanoradian range, so such large systematic errors are difficult to correct. The cemented doublet Fourier transform lens, with its 4 surfaces and interior glue layer, introduces additional wavefront error. The new LTP-2020 design eliminates the PBS cube by replacing it with a much thinner wedge plate beamsplitter, WPBS. The return beam reflects off of the back surface of the WPBS and does not pick up any glass thickness error. But this requires that the back surface of the WPBS be super-polished flat. Fortunately, this is not a difficult fabrication problem. The cemented doublet has been replaced by a singlet lens with one mild aspheric surface. The aspheric surface gives a sufficient degree of freedom so that distortion is minimized over the full 20 mrad surface slope angle measurement range, which is twice the range of the old lens. The main issue with the lens is to be able to produce the surface quality sufficient to meet the ~1 nm RMS wavefront irregularity over the 2 mm to 100 micron spatial period bandwidth, to which the image distortion is most sensitive.

Using the non-sequential raytrace design mode of OpticStudio™, we have investigated ghost ray interference from multiple reflections between and within optical elements, in detail. This has allowed us to replace the cube beamsplitter with a thin wedge plate beamsplitter, but with a deliberate misalignment that moves the ghost rays away from the main beam, eliminating the interference problem. The WPBS is designed with a 0.5° wedge angle on a 5 mm thick substrate. It requires two custom coatings: an anti-reflection coating on the front face and a 10,000:1 polarizing coating on the rear face, both optimized for 45° incidence angle. We are in the process of engaging vendors who will sign up to the stringent fabrication requirements of the lens and WPBS and are seeking to establish collaborations with other LTP users interested in improving instrument performance. This work was supported in part by the U. S. Department of Energy under contract number DE-AC02-05CH11231.

Keywords: x-ray optics metrology, profilometry, optical design, geometrical optics, physical optics, Zemax

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[2] OpticStudio is a registered trademark of Zemax, LLC, 10230 NE Points Drive, Suite 500, Kirkland, Washington 98033 USA

Binary pseudo-random test standards for characterization of various metrology instruments over high to mid spatial frequencies

Keiko Munechika*,[a] Stefano Cabrini,[b] Weilun Chao,[c] Raymond Conley,[f] Ian Lacey,[d] Carlos Pina-Hernandez,[a] Simon Rochester,[e] Peter Takacs,[g] and Valeriy V. Yashchuk[d]

[a]HighRI Optics, Inc., 5401 Broadway Terr, St. 304, Oakland, CA 94618, USA;
[b]Molecular Foundry, Lawrence Berkeley National Laboratory, Berkeley, CA, 94720, USA;
[c]Center for X-ray Optics, Lawrence Berkeley National Laboratory, Berkeley, CA, 94720, USA;
[d]Advanced Light Source, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA;
[e]Rochester Scientific, LLC, 2041 Tapscott Avenue, El Cerrito, CA 94530, USA
[f]Advanced Photon Source, Argonne National Laboratory, Lemont, IL 60439, USA
[g]Surface Metrology Solutions, LLC. 19 South First St. UnitB901, Minneapolis, NM 55401, USA

*e-mail of corresponding author: km@highrioptics.com

Abstract

The performance of any metrology tool, and the level of confidence in the data obtained, directly depends on the ability to characterize (calibrate) the tool. The calibration has to enable data processing to mitigate the effects of imperfections of the tool on the results of measurements. Here, we explore technological, metrological, and analytical aspects of the application of a technique for calibrating the instrument transfer function (ITF) of interferometric microscopes. The technique [1], based on test samples structured as one- and two- dimensional (1D and 2D) binary pseudo-random (BPR) sequences and arrays (BPRAs), employs the unique properties of the BPR patterns in the spatial frequency domain. The inherent 1D and 2D power spectral density of the patterns have a deterministic white-noise-like character that allows direct determination of the ITF with uniform sensitivity over the entire spatial frequency range and, in the case of the BPRAs, the entire 2D field-of-view of an instrument. As such, the BPRA samples satisfy the characteristics of a test standard: functionality, ease of specification and fabrication, reproducibility, and low sensitivity to manufacturing error. We discuss the results of the development and application of a series of BPRA test samples with elementary feature sizes in the range from 1.5 nm and up to 15 µm, optimized to cover a broad range of metrology instruments used for inspection of mid to high spatial frequency features. The application examples include electron microscopes [2], x-ray microscopes, interferometric microscopes, and large field-of-view Fizeau Interferometers [3]. The data acquisition and analysis procedures for different applications of the ITF calibration technique developed are also discussed.
This work was supported by the U. S. Department of Energy under contract number DE-AC02-05CH11231 and by the NASA STTR/SBIR program under award number 80NSSC20C0505.

Keywords: x-ray optics metrology, power spectral density, PSD, instrument transfer function, ITF, calibration, test standards, binary pseudo-random, microscopy, interferometry, scatterometry

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Oral Presentations

Session 03 | X-Ray optics for astronomy

01 | Electroformed X-ray Optics for Microscopy and Astronomy | Hidekazu Mimura (Univ. of Tokyo)

02 | BEaTriX, the new X-ray facility for PSF and Effective Area calibration of X-ray optics | Stefano Basso (INAF)

03 | Characterization of silicon pore optics for the ATHENA observatory at the X-ray parallel beam facility XPBF 2.0 | Michael Krumrey (PTB)

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05 | Development in carbon-based coatings for X-ray astronomy | Giacomo Rivolta (INAF)

Electroformed X-ray Optics

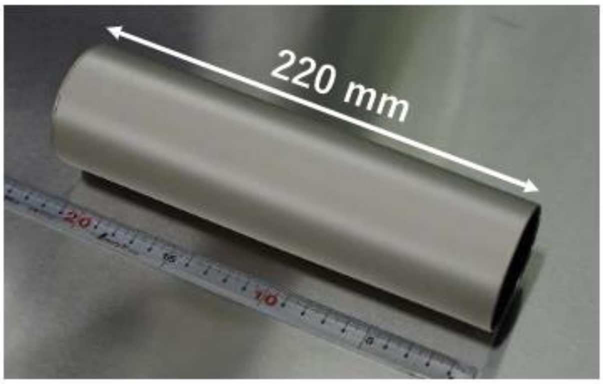
for Microscopy and Astronomy

Hidekazu Mimura[1], Takashi Kimura[1], and Ikuyuki Mitsuishi[2]

1. The University of Tokyo, 7-3-1 Bunkyo-ku, Hongo, Tokyo 113-0033, Japan
2. Nagoya University, Furo-cho, Chikusa-ku, Nagoya, Aichi 464-8602, Japan

*e-mail: mimura@edm.t.u-tokyo.ac.jp

Abstract



We have been developing ellipsoidal mirrors and Wolter mirrors for X-ray focusing and imaging. The mirror fabrication system consists of mandrel fabrication and electroforming processes[1)]. By adopting room temperature electrodeposition conditions, we have succeeded in developing a precise electroforming process[2)]. The fabricated mirrors were installed at SPring-8 and SACLA. As a result, soft x-ray focusing with a size of 200 nm and soft x-ray imaging with a spatial resolution of 200 nm were realized[3)]. These have been used to construct soft X-ray microscopes in both facilities.

The developed manufacturing process has now been applied to Wolter mirrors for X-ray telescopes. The first target is a Wolter mirror to be used for FOXSI, a project to observe the sun. The Wolter mirror has a diameter of 60 mm and a length of 200 mm.

In this presentation, we will report the status of fabrication and application of electroformed X-ray mirrors for use in microscopy and astronomy.

Keywords: electroforming, X-ray mirrors, x-ray microscope, x-ray telescope

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BEaTriX, the new X-ray facility for PSF and Effective Area calibration of X-ray optics

S. Basso[1*], B. Salmaso[1], D. Spiga[1], M. Ghigo[1], G. Vecchi[1], G. Sironi[1], V. Cotroneo[1], G. Pareschi[1], G. Tagliaferri[1], D. Sisana[2], C. Ferrari[3], M. Sanchez del Rio[4], V. Burwitz[5], D.D. Ferreira[6], S. Massahi[6], F. Christensen[6], M. Bavdaz[7], I. Ferreira[7]

[1]INAF Astronomical Observatory Brera, Via E. Bianchi 46, Merate, LC (Italy), [2]Politecnico Milano, Via La Masa 34, Milano (Italy), [3]IMEM-CNR, Parco Area delle Scienze 37/A, Parma (Italy), [4]European Synchrotron Radiation Facility, B.P. 220, Grenoble (France), [5]Max-Planck-Institut f r extraterrestrische Physik, Giessenbachstr, Garching (Germany),[6]DTU-space, Juliane Maries Vej 30, DK-2100 Copenhagen (Denmark), [7]ESTEC, European Space Agency, Keplerlaan 1, 2201 AZ Noordwijk (Netherlands)

*e-mail: stefano.basso@inaf.it

Abstract

BEaTriX (Beam Expander Testing X-ray facility) is the new facility available at the INAF-Osservatorio Astronomico Brera (Merate, Italy) for the calibration of X-ray optics. It is a compact facility (9 x 18 m^2) with a beam line in vacuum (10^{-6} mbar) with a unique optical setup able to create a large (170 × 60 mm^2), uniform, monochromatic and parallel X-ray beam (residual divergence of 1.5 arcsec vertical x 2.5 arcsec horizontal, HEW) at the energy of 4.51 keV. The beam is obtained with an X-ray microfocus source placed in the focus of a paraboloidal mirror, a monochromation stage with 4 symmetrically cut crystals, and an expansion stage where the beam is diffracted and expanded by an asymmetrically-cut crystal. The key axes of all the optical components are motorized for a proper beam alignment. The expanded beam fully illuminates the optics under test, imaging the focused beam at 12 m distance, where a CCD camera is placed on the detector tower and motorized in order to perform intra and extra focal acquisition (0,5m range), as well as scan the normal plane to 1,4m distance. The detector tower can be placed at different positions to test different focal length. A thermal box is also present to radiatively heat the testing optic and check its optical performances under different temperatures.

The facility is now in the commissioning phase and will soon become operative for the X-ray acceptance tests (PSF and Effective Area) of the ATHENA Silicon Pore Optics Mirror Modules (MM).

We will present the facility, the results of the beam characterization obtained via an in-house built Hartmann test, and the plan for the coming future to upgrade the facility with a beam line at 1.49 keV.

Keywords:
BEaTriX, ATHENA, X-ray testing, X-ray microfocus source, beam expander, asymmetric diffraction, crystals

Reference:

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Characterization of silicon pore optics for the ATHENA observatory at the X-ray parallel beam facility XPBF 2.0

M. Krumrey[1]*, E. Handick[1], L. Cibik[1], M. J. Collon[2], G. Vacanti[2], N. M. Barrière[2], E. Hauser[2] and M. Bavdaz[3]

[1] Physikalisch-Technische Bundesanstalt (PTB), Abbestr. 2-12, 10587 Berlin, Germany
[2] cosine measurement systems, Warmonderweg 14, 2171 AH Sassenheim, The Netherlands
[3] European Space Agency, ESTEC, Keplerlaan 1, 2200 AG Noordwijk, The Netherlands

e-mail: michael.krumrey@ptb.de

Abstract

For new astrophysics X-ray observatories like the Advanced Telescope for High ENergy Astrophysics (ATHENA), an envisaged effective area of 1.5 m² at 1 keV requires mirror surfaces of several hundred m². As such an area is not achievable with a single mirror in space, Wolter-I nested X-ray optics based on silicon pore optics (SPO) technology will be utilized [1]. The X-ray Parallel Beam Facility (XPBF 2.0) has been installed in the PTB laboratory at BESSY II to characterize these SPOs [2]. In contrast to the beamline XPBF 1 which provides since 2005 a pencil beam to investigate individual pores of mirror stacks, a multilayer-coated toroidal mirror is used for beam monochromatization at 1 keV and collimation, enabling the use of beam sizes between about 100 µm x 100 µm and 7.5 mm x 7.5 mm while maintaining the beam divergence well below 2 arc sec. Thus, the quality of individual pores as well as the focusing properties of large groups of pores can be investigated. The beamline also features increased travel ranges for the main in-vacuum hexapod to accommodate larger SPOs and an SPO-to-detector-distance of 12 m corresponding to the envisaged focal length of ATHENA. Two electronic autocollimators are used to guaranty a hexapod positioning accuracy of 0.7 arc sec. A movable CCD-based camera system with a vertical travel range of 2 m and a travel range of 1 m in beam direction is used to register the direct and the reflected beam. The positioning of the detector can by verified by a laser tracker.

The beamline has been upgraded recently [3] and is nowadays not only used to characterize mirror stacks, but also to control the focusing properties of mirror modules - consisting of 4 mirror stacks - during the assembly at the beamline. For the mass production of the required 600 mirror modules, two additional beamlines will be installed after the final acceptance of ATHENA following the Mission Adoption Review expected in early 2023.

Figure 1: XPBF 2.0 with the sample chamber in a clean tent and the CCD-based detector on a vertical translation with 2 m travel range (left) and hexapod system to align and assemble 4 mirror stacks to a complete mirror module

Keywords: ATHENA, silicon pore optics (SPO), X-ray astrophysics, X-ray metrology

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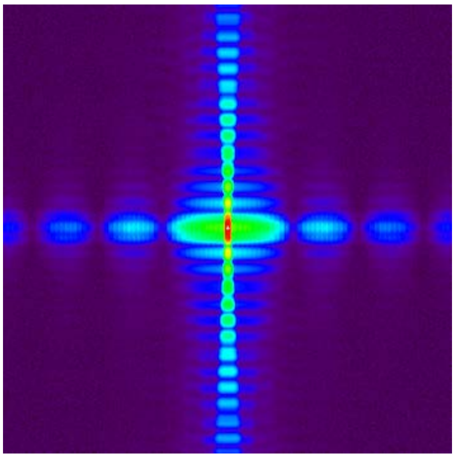
Modelling diffractive effects in Silicon Pore Optics mirror modules for the ATHENA X-ray telescope

Daniele Spiga[1*], G. Sironi[1], D. Della Monica Ferreira[2], A. S Jegers[2], E. Bergbäck Knudsen[2], M. Bavdaz[3], I. Ferreira[3]

[1]INAF-OAB, Via Bianchi 46, 23807 Merate (Italy), [2]DTU-space, J. Maries Vej 30, DK-2100 Copenhagen (Denmark), [3]European Space Agency, Keplerlaan 1, 2201 AZ Noordwijk (Netherlands)

*e-mail: daniele.spiga@inaf.it

Abstract



The modeled focal spot (2 mm x 2 mm area) of an SPO mirror module with pores 2.13 mm x 0.66 mm, at 40 Å wavelength.

Silicon pore optics (SPO) are the technology selected for the assembly of the mirror module of the ATHENA X-ray telescope [1]. An SPO mirror module consists of a double-reflection, quadruple stack of etched and wedged silicon wafers in order to create a stiff and lightweight structure, able to reproduce in each pore the Wolter-I geometry required to image X-rays on the telescope focal plane. Due to the small pore size (a few mm^2), aperture diffraction effects in X-rays are small, but not totally negligible to the angular resolutions at play. In contrast, diffraction effects are the dominant term in the UV light illumination that will be used to co-align the 600 mirror modules of ATHENA to a common focus. For this reason, diffractive effects need to be properly modeled, and this constitutes a specific task of the ESA-led SImPOSIUM (SIlicon Pore Optic SImUlation and Modelling) project [2] being carried out by OAB and DTU. In this context, a specific software tool (SWORDS: SoftWare fOR Diffraction of Silicon pore optics) has been developed to the end of simulating diffraction effects in SPO mirror modules. The software makes use of an FFT-based approach of the phase shifts distribution throughout the mirror module aperture, treating mirror imperfections as distortions of the focused wavefront [3]. This approach also allows the user to effectively predict the effects of various imperfections (figure errors, primary-secondary segment misalignments) in a self-consistent way, in different experimental configurations (X-ray source off-axis or at finite distance), as a fast and reliable alternative to ray-tracing, also at X-ray wavelengths. Finally, since the method assumes spatial coherence of the source, the simulation can also be applied to simulate the illumination of an SPO mirror module in synchrotron light.

Keywords: SWORDS, SImPOSIUM, diffraction, silicon pore optics, wave optics

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Development in carbon-based coatings for X-ray astronomy

Giacomo Rivolta[1,6*], Ricardo Bruni[2], Marta M. Civitani[1], Vincenzo Cotroneo[1], Thorsten Döhring[3], Eugenio Gibertini[4], Luca Magagnin[4], Giovanni Pareschi[1], Suzanne Romaine[2], Leandra Sethares[2], Giorgia Sironi[1], Gianpiero Tagliaferri[1], Giuseppe Valsecchi[5]

[1] INAF-Osservatorio Astronomico di Brera, Via E. Bianchi 46, 23807 Merate, Italy

[2] Center for Astrophysics | Harvard and Smithsonian, 60 Garden St, Cambridge, MA, 02138, USA

[3] TH Aschaffenburg – University of Applied Sciences, Würzburger Str. 45, D-63743 Aschaffenburg, Germany

[4] Politecnico di Milano, Dipartimento di Chimica, Materiali e Ingegneria Chimica "Giulio Natta", via Mancinelli 7, I-20131 Milano, Italy

[5] Media Lario S.r.l., Località Pascolo, I-23842 Bosisio Parini (LC), Italy

[6] Università degli Studi di Milano, Dipartimento di Fisica "Aldo Pontremoli", via G. Celoria 16, 20133 Milano, Italy

[*] e-mail: giacomo.rivolta@studenti.unimi.it

ABSTRACT

Traditional X-ray telescopes employ mirrors made with precious metallic coatings (such as Ir or Au); these materials, however, present absorption edges that limit reflectivity in the band below 4 keV.

Our search for alternative coatings is focused on using carbon-based materials, and, after multiple tries, dopamine turned out to be the most suitable; indeed, when applied on top of traditional high-Z layers, a significant increase in reflectivity in the band below 2-4 keV is expected.

The deposition of such thin layers (about 10 nm) can be challenging and not easily compatible with the conventional processes used for the fabrication of X-ray optics.

In this work, we present results of reflectivity measurements of two types of samples: gold (Au) monolayer and iridium/chromium (Ir/Cr) multilayers; both samples were overcoated with a thin layer of dopamine. The reflectivity measurements show, at the energy accessible in a laboratory environment, an effect of the coating which is in full agreement with the model. A relevant enhancement in the soft X-ray region can be expected on the base of the same model.

These results show that both Au and Ir/Cr are successfully compatible with dopamine and this can be crucial in the development of future telescopes, like ATHENA (ESA), Lynx (NASA) and eXTP (CAS).

Oral Presentations

Session 04 |Metrology challenges for X-ray mirrors II

01| PyXsurf: an open-source library for analysis of surface metrology data | Vincenzo Controneo (INAF)

02 | Study of acquisition strategies for sub-aperture stitching using Fizeau interferometry | Amparo Vivo (ESRF)

03 | Subaperture stitching algorithms for X-ray mirror metrology | Bharrath Reddi Adapa (ESRF)

04 | X-ray demonstration of real-time, sub-nanometre, closed-loop control of a bimorph deformable mirror using in-situ interferometric feedback | Ioana-Theodora Nistea (Diamond Light Source)

05 | The importance of retrace errors for high-quality Fizeau interferometry | Katherine Morrow (STFC)

PyXsurf: an open-source library for analysis of surface metrology data

Vincenzo Cotroneo

INAF-Osservatorio Astronomico di Brera, Via E. Bianchi 46, 23807 Merate, Italy

email: vincenzo.cotroneo@inaf.it

Abstract

Surface metrology data, representing a set of points in the 3D space, are of general interest in almost any field of science and technology and are obtained with a broad range of metrology instruments, operating over different characteristic scales. Despite the common nature of data and operations, data are usually processed using very different tools, mostly depending on each instrument's OEM software or user code available at each facility, with little or no reuse of code and concepts, and little interoperability between different fields or different instruments.

Python is well equipped to manage and visualize 2D data, however it doesn’t natively handle the correspondence between a surface map and its positional coordinates, making some operations non intuitive or quite laborious to perform.

pyXSurf is an open-source, flexible library, written in Python, probably the most widely used language in scientific data analysis, that offers a common framework for simple and complex surface data operations. The features of Python allow an easy integration with the many highly specific analysis and visualization tools available, and the possibility of integration with several flavours of interfaces. The self documentation capabilities of Python also enhance maintainability and allow a soft learning curve.

I will give an overview of the package and present some usage examples from real-life, mainly applications to metrology of astronomical X-ray mirrors.

Study of acquisition strategies for sub-aperture stitching using Fizeau interferometry

***Amparo Vivo*, François Perrin, Bharath Adapa, Raymond Barrett**

ESRF, 71 avenue des Martyrs - CS 40220,38043 Grenoble Cedex, France

Author e-mail: vivo@esrf.fr

Abstract

The use of sub-aperture stitching methods for Fizeau interferometry for measuring the surface topography of X-ray mirrors was implemented at the ESRF optical metrology laboratory in 2015 [1]. Initially applied to plane mirrors up to 1 meter long, the technique using a flat transmission element has been rapidly extended to allow measurements of tangential cylinders, spheres or elliptical mirrors, with radii of curvature varying from tens of kilometres down to few meters. The low emittance Extreme Brilliant Source upgrade of the ESRF [2-3] has required new state of the art mirrors for several beamlines, with peak-to-valley shape errors at the nanometre scale and root mean square (rms) slope errors below 100 nanoradians. This has driven our laboratory to push our existing metrology tools and measurement protocols in order to perform reliable measurements with the required precision. The systematic intercomparison of Fizeau stitching results with LTP and micro-stitching interferometry when possible has been key to achieving such performance.

In this paper, we study the influence on Fizeau stitching results of some acquisition parameters including focus quality, system error file subtraction, pixel size calibration and environmental effects. Measurement results on high quality mirrors will be presented.

Keywords: X-Ray mirrors, interferometry, Fizeau stitching

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Subaperture stitching algorithms for X-ray mirror metrology

BHARATH REDDY ADAPA,* AMPARO VIVO, FRANCOIS PERRIN, AND RAYMOND BARRETT

The European Synchrotron (ESRF), 71 avenue des Martyrs, CS 40220, 38043 Grenoble Cedex 9, France
**bharath-reddy.adapa@esrf.eu*

Abstract: The apertures of X-ray mirrors are often larger than the measurement apertures of common optical metrology instruments. To overcome this limitation, subaperture stitching is an increasingly widely used technique for X-ray mirror metrology. In this approach, the full surface is measured in a series of highly overlapped subapertures which are subsequently recombined to recover the overall surface topography. Although some commercial and some instrument specific user algorithms have been developed, thus far no generic standardized stitching platform allowing their application to various data has been available. We present some of the existing/new stitching algorithms and show our implementations in an open source software platform applicable to data acquired from diverse instruments [1]. The software, PyLOSt (Python Large Optic Stitching), was developed using Python and PyQt. It was later implemented using Orange data-mining framework which provides interactive data analysis with distributed workflow in terms of multiple widgets.

The software also explores issues regarding standardization of data formats, analysis methods as well as data sharing and reproducibility, and provides some solutions. A new dataset format has been developed in our stitching software to represent measurement data. This format extends the widely used python N-dimensional array implementation to include parameters such as measurement data units, pixel size, motor positions for subapertures etc. The stitching algorithms have been implemented in the software and tested using simulated X-ray mirror data for validation. The stitching algorithms have also been intensively tested in comparison to data stitching by commercial software such as MetroPro from Zygo, using the same measurement data. The algorithms have also been rigorously tested and improved with respect to performance of execution time and memory requirements on a Windows 10 computer. Some of these validation tests and performance tests will be presented during the IWXM 2022 workshop.

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Figure 1: Subaperture stitching using pylost (orange) compared to Zygo MetroPro stitching for measurements with a Zygo VeriFIRE Fizeau interferometer on a flat 100 mm mirror manufactured by JTEC. A total of 47 subapertures with a step of 1.4 mm are stitched.

X-ray demonstration of real-time, sub-nanometre, closed-loop control of a bimorph deformable mirror using in-situ interferometric feedback

Ioana-Theodora Nistea[1]*, Simon G. Alcock[1], Vivek. Badami[2], Riccardo Signorato[3], M. Fusco[4], Hongchang Wang[1], and Lingfei Hu[1]

1 Diamond Light Source Ltd, Harwell Science and Innovation Campus, Didcot, OX11 0DE, UK
2 Zygo Corporation, 21 Laurel Brook Road, Middlefield, Connecticut 06455, USA
3 S.RI. TECH s.r.l.s, Viale del Lavoro 42A, 35010 Vigonza, Italy
4 CAEN, S.p.A, via della Vetraia, 11, 55049 Viareggio, Italy

*e-mail: ioana.nistea@diamond.ac.uk

Abstract

Major technological advances at synchrotron and free electron laser facilities, including brighter X-ray sources, faster detectors, and automated sample handling, means there is an increasing demand to tailor the X-ray beam profile, without loss of flux, to match the size and shape of the sample. Alternatively, such X-ray beam changes can be used to probe sub-regions of various sizes and locations on larger samples. For beamlines which routinely measure hundreds, and sometimes thousands, of samples per day, such changes need to be made rapidly and autonomously. Previously [1], we showed that multiple absolute distance sensors of the Zygo ZPS™ interferometric system can simultaneously measure the surface profile of an X-ray mirror with sub-nanometre sensitivity. Data are in excellent agreement with the Diamond-NOM slope profiler in the Optics Metrology Lab at Diamond. A major advantage of the ZPS™ system is its ability to capture the optical surface profile at kHz frequencies, making it an ideal metrology instrument to record dynamic behaviour of active optics. Bimorph piezo-electric deformable mirrors operating in open loop suffer from significant curvature drift when large and frequent changes are made to the optical surface. Such drifts are caused by strain and relaxation of the opto-mechanical holder, photon- or environmentally-induced thermal expansion of components, and piezo-elastic creep of the bimorph actuators.

To overcome these effects, we have developed a closed-loop control system for a bimorph X-ray mirror. Using feedback from the ZPS™ system, the bimorph's surface is measured and adaptively corrected to a user-defined profile with sub-nanometre resolution by iteratively applying voltages at a refresh rate of ~ 0.5 Hz from an HV-ADAPTOS power supply.

We present the first X-ray demonstration of real-time, closed-loop control of a bimorph mirror operating on a synchrotron beamline. After focussing optimization using the X-ray speckle technique [2], we demonstrate that major changes can repeatedly be made to the X-ray beam, without subsequent drift, using closed-loop control of the bimorph. Currently, the closed-loop algorithm measures and corrects the mirror every ~ 2 seconds. With enhanced low-level control there is scope to increase the refresh rate to tens or hundreds of Hz. We expect these innovations will revolutionise how bimorph mirrors are used adaptively to rapidly change, and instantly stabilise, the size and shape of the X-ray beam at free electron laser and synchrotron facilities.

Keywords: adaptive optics, bimorph deformable mirrors, closed loop control, ZPS interferometer

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The importance of retrace errors for high-quality Fizeau interferometry

Katherine Morrow[1*], Murilo Bazan da Silva[2], Simon G. Alcock[2]

[1] ASTeC, STFC Daresbury Laboratory, Daresbury, WA4 4AD, UK.

[2] Diamond Light Source Ltd, Diamond Light Source Ltd, Harwell Science and Innovation Campus, Didcot, OX11 0DE, UK

*katherine.morrow@stfc.ac.uk

Abstract

Preserving the brightness of ultra-low emittance synchrotron and free electron laser sources requires X-ray optics with nanometre-scale height errors. This is a major challenge for optical metrology, making it vitally important to minimize experimental errors to obtain accurate results. In interferometry, retrace error occurs wherever the surface of the test optic is not perfectly matched to the form of the reference optic. The magnitude of retrace increases as the test surface deviates from the shape of the reference optic. When measuring curved mirrors, especially aspherics, a limited choice of reference optic frequently leads to non-null conditions and retrace error. A popular method to overcome this limitation is stitching interferometry, where the optical surface is imaged in numerous, overlapping, sub-aperture regions. Each small, sub-aperture is sequentially nulled relative to the reference optic. This minimizes the amount of deviation from the null condition, and hence reduces the magnitude of retrace error. However, quantifying retrace error is helpful to guide the number and overlap percentage of sub-apertures to suit the curvature of each test mirror.

Based upon a series of automated measurements of a super-flat mirror, with a range of pitch and roll angles, we have developed an empirical model of the retrace error of a Zygo HDX Fizeau interferometer in the Optics Metrology Lab at Diamond Light Source [1]. The retrace error for each measurement was represented using the first 25 Zernike polynomials in the Wyant index. By modelling how the Zernike coefficients change as a function of the position and local angle of each sub-region of the test surface within the Fizeau's field of view, the retrace error can be computed for any optic. The effectiveness of this model was compared with measurements of two, high-grade, X-ray optics: a cylindrical mirror (radius of curvature ~ 115.92 m); and an elliptical mirror with 3-lanes. For each optic, the measured retrace error was approximated as the difference between the full-aperture image (includes retrace) and a stitched version using small sub-apertures (minimal retrace). In both cases, the measured retrace error was in good agreement with the prediction made by the Zernike model.

Simulations showed that the retrace error of even a weakly curved mirror (radius ~ 1 km) was 9 nm peak-to-valley over the 150 mm field of view of the Fizeau. This demonstrates the importance of reducing retrace errors to enable accurate measurement of X-ray mirrors with single-digit nanometre surface errors.

Keywords: Metrology, X-ray optics, Fizeau, retrace error, interferometry

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Oral Presentations

Session 05 |Active and adaptive optics for X-ray applications

01 | Ion beam figuring of synchrotron mirrors at NSLS-II | Tiany Wang (BNL)

02 | Piezo-electric adaptive optics for synchrotron and FEL application | Joern Weber (Carl-Zeiss)

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Ion beam figuring of synchrotron mirrors at NSLS-II

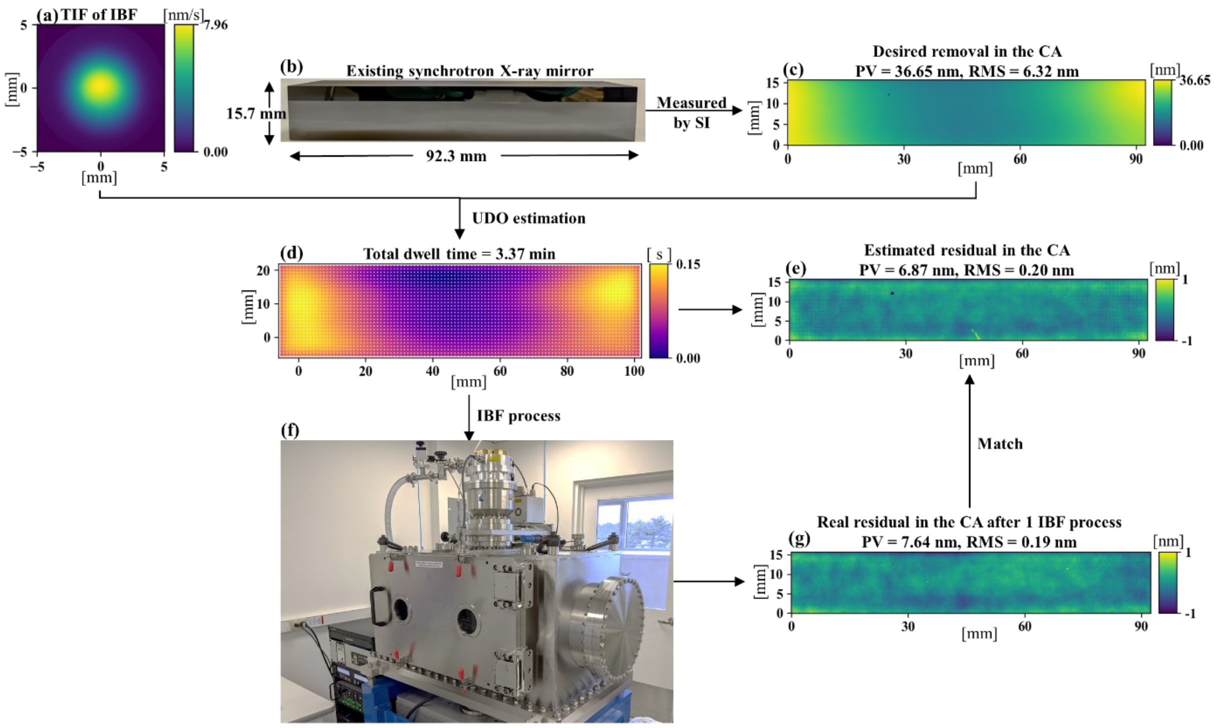
Tianyi Wang[1*], Lei Huang[1], Mourad Idir[1]

[1] National Synchrotron Light Source II (NSLS-II), Brookhaven National Laboratory, Upton, NY 11973, USA

[*]email: tianyi@bnl.gov

Abstract

To meet the ever-increasing performance demands of synchrotron mirrors for beamlines at modern synchrotron radiation and free-electro laser facilities, we have developed an Ion Beam Figuring (IBF) system for synchrotron mirror fabrication and have successfully demonstrated a novel mirror fabrication process with the capability of producing ≤180 mm-length flat and elliptical mirrors. As an example, the figure shows our recent experiment of improving the form of an existing multi-layer mirror to 0.19 nm root mean square [1]. In



this presentation, we will demonstrate the IBF solutions at NSLS-II to obtain this sub-nanometer level result. The roadmap of the IBF development is first briefly reviewed, with the key milestones highlighted. The IBF-specific surfacing methodologies, including dwell time optimization, tool path planning, and metrology are introduced. Finally, our long-term objective and future R&D directions will be shared.

Keywords: ion beam figuring; optical fabrication; surface finishing

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Piezo-electric adaptive optics for synchrotron and FEL application

Authors: J. Weber*(1), H. Enkisch(1), N. Niewrzella(1), K. Hild(1), M. Bayraktar(2), P. Lucke (2), F. Bijkerk (2), C. Schroer(3), E. Plönjes (3), M. Ruiz Lopez(3), K. Tiedtke(3), M. Lyubomirskiy (3)

Affiliations: 1) Carl Zeiss SMT GmbH, Rudolf-Eber-Str. 2, 73447 Oberkochen, Germany
2) Industrial Focus Group XUV Optics, MESA+ Institute of Nanotechnology, University of Twente, Drienerlolaan 5, 7522 NB Enschede, Netherlands
3) DESY, Notkestraße 85, 22607 Hamburg, Germany

*email: joern.weber@zeiss.com

Abstract

With increasing quality and coherence of X-ray photon beams imperfections of the X-ray optical components become limiting for the achievable focus size and quality (Ref1). This calls for better figure correction of the optics making the manufacturing more and more challenging and expensive (Ref2) and potentially preventing or slowing down further progress in the scientific community.

To solve this, Bayraktar et al (Ref3,4) proposed to correct the wavefront by means of adaptive optics making use of piezoelectric layers. Nematollahi et al. (Ref5) for the first time showed a working demonstration device of such an optic. We are presently developing such adaptive optics on a larger scale. Such a mirror could consist of a rigid substrate, the actuation stack (comprising a lower electrode, the piezo-electric layer, and an upper electrode), a buffer layer covering the structures of the actuation stack and providing a smooth surface, and finally the reflective coating (Fig. 1). Ideally, per beamline one adaptive optics will be sufficient, if its position is carefully chosen to have optimum compensation potential. Most effectively a mirror delivering light to several end stations is made adaptive. Depending on the end-station served and on the wavefront errors to be corrected the adaptive mirror can be tuned. This would reduce the total number of adaptive mirrors further. As a result of such an approach the requirements on all other optical elements can potentially be relaxed enabling the re-use of existing components.

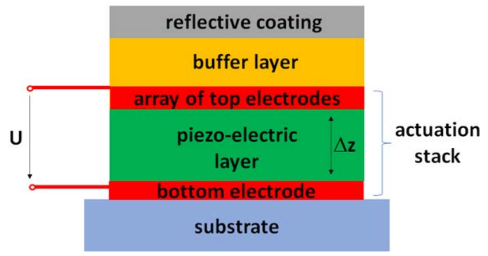

Figure 1: Schematic cross-section of an adaptive optical element

Another benefit of adaptive optics is the possibility to compensate for deformations that depend on the actual thermal load. This way it is possible to keep the focus quality constant for very different use cases, even if changes occur on millisecond time scales.

Finally, adaptive optics enable not only smaller foci but open the field for custom-defined focal shapes like squares, rectangles, rings, and dipoles.

We will report on the status of piezo-adaptive X-ray optics and discuss the above-mentioned applications.

Keywords: figure correction, adaptive optics, thin films

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Construct of long trace profiler for metrology of Adaptive X-Ray Optics at NSRRC

Shang-Wei Lin [1*], Duan-Jen Wang [1], Chih-Yu Hua[1] , Hok-Sum Fung [1], Chao-Chih Chiu [1], Huang-Wen Fu[1], Ming-Ying Hsu [1], Gung-Chian Yin [1]

[1] *National Synchrotron Radiation Research Center, Hsinchu, 30076, Taiwan,*

Email: lin.sw@nsrrc.org.tw

ABSTRACT

A specially designed 25-actuator optical surface bender for the gratings and mirrors is developed and operated at Taiwan Photon Source (TPS) [1]. It is a powerful tool for X-ray optics surface with nano-accuracy to give full play to the excellent performance of the facility. This type of bender has been widely used in current operating beamlines [2,3] and recently constructed beamlines at TPS. These optical elements are VFM, grating, VRFM, and HRFM, respectively. For the installation and testing of these 25-actuator optical surface benders, we have built an additional metrology laboratory at the TPS beamlines zone. the metrology laboratory at NSRRC has been building begin 2021 and a new Long Trace Profiler will be installed in 2022. The accuracy of the instrument is expected to be <0.1μrad rms for components less to 1m in length. We can monitor various effects on optical components such as thermal bump and bending moment, etc. via LTP. Then test adaptive X-ray optics to maximize the performance of adaptive optical elements before installation in beamlines. In this paper, we present some design considerations and the performance of the LTP system.

Keywords: Long trace profiler, Surface profile measurement, Optical metrology, X-ray mirror.

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A design method of X-ray focusing mirrors capable of correcting arbitrary astigmatism

Yoko Takeo[1,2*] and Hidekazu Mimura[3]

[1] The Institute for Solid State Physics, The University of Tokyo, [2] Japan Synchrotron Radiation Research Institute, [3] Department of Precision Engineering, School of Engineering, The University of Tokyo

*e-mail: takeo@issp.u-tokyo.ac.jp

Abstract

The basis for designing a focusing mirror is a conic curve such as an elliptic, parabolic, or hyperbolic function. For instance, the shape of a mirror that focuses a beam from a point to a point is a revolving surface of an elliptic function with two points as foci. In synchrotron radiation facilities, grazing incidence mirrors defined by ellipses or their approximations are used to focus, image, and forms X-ray beams. The beam may diverge from or converge to different points in the vertical and horizontal directions in X-ray beamlines due to the asymmetric nature of sources, the configuration of monochromators, and optical elements with only one-dimensional focusing capability. The asymmetric beam has a wavefront with astigmatism aberration. The conventional choice for eliminating or adding astigmatism is a toroidal mirror[1]. Toroidal mirrors have low focusing performance due to their constant sagittal curvature. Yashchuk et al. proposed a more advanced design for a mirror that focuses the beam collimated in only one dimension to a point[2]. This mirror converts a beam with specific astigmatism to another beam with no astigmatism.

We proposed a design method adaptive for arbitrary astigmatism of entrance and exit beams. As shown in Fig., The entrance and exit focal lengths can be set independently for the sagittal and meridional focusing, respectively. All rays of the entrance beam pass through two orthogonal source lines. Similarly, two orthogonal condensing lines define all rays of the exit beam. A single equation can generate various mirrors by setting four focal lengths appropriately. The condition where one of the two entrance focal lengths is at infinity indicates the entrance beam collimated in one direction. When the reflected beam should converge to a point, the two exit focal lengths are equal. The optical simulations suggested that the mirrors focus rays tightly to the single-nanometer scale. The proposed method would expand the design possibility of synchrotron radiation beamlines.

Keywords: Mirror design, X-ray beam shaping, Optical simulation, Astigmatism correction

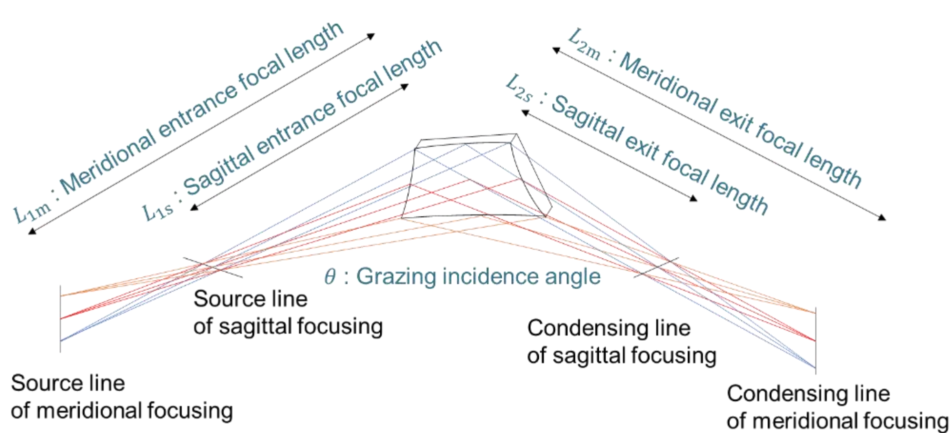

Fig. Schematic of focusing mirror for elliptically diverging and converging beams

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Oral Presentations

Session 06 |Optics at new storage ring and free-electron laser sources

01 | On the inspection of optics for the MAX IV synchrotron radiation facility – experiences and conclusions | Frank Siewert (HZB)

02 | Metrology for “hybrid” reflection zone plates on spherical substrates | Alexei Erko (IAP)

03 | Accounting for Spatial Frequency Distribution in X-ray Mirror Surface Specifications | Francois Polack (Soleil)

04 | Design, specification, optical metrology and commissioning of a pre- KB mirror for zoom-tomography | Bernd Meyer (LNLS)

05 | The Advanced Photon Source New Slope Measuring System: Upgrades, Performance, and Results of Mirror Measurements | Lahsen Assoufid (APS)

On the inspection of optics for the MAX IV synchrotron radiation facility – experiences and conclusions

F. Siewert[1*], J. Buchheim[1], G. Gwalt[1], A. Sokolov[1], S. Lemke[1], J. Knedel[1], S. Alimov[1], T. Seliger[1], O. Kutz[1], Y. Cerenius[2], F. Hennies[2], L. Pickworth[2], A. Lassesson[2], K. Chernenko[2], T. Ursby[2], U. Johansson[2], P. Sondhauss[2], K. Klementiev[2], A. Preobrajenski[2], M. Agåker[2,3] and R. Sankari[2,4]

[1]Helmholtz Zentrum Berlin, Albert-Einstein-Str. 15, 12489 Berlin, Germany, [2]MAX IV Laboratory, Lund University, PO Box 118, SE-22100 Lund, Sweden, [3]Department of Physics and Astronomy, Uppsala Universitet, Box 516, 75120 Uppsala, Sweden, [4]Computational Physics Laboratory, Tampere University, PO Box 692, FI-33014 Tampere, Finland

*e-mail: *frank.siewert@helmholtz-berlin.de*

Abstract

In this work we report on the experience gained from the inspection of various optical components for the MAX IV synchrotron facility in Lund, Sweden. These optical elements include mirrors of different geometries and diffraction gratings for both beamlines and spectrometers.

Over the last eight years about one hundred optical elements have been measured by means of ex-situ, as well as at-wave-length, metrology. This was critical for the verification of their quality to be compliant with the requirements of the beamlines at the first diffraction limited storage ring MAX IV [1]. Such optics feature a precision of a few nanometers in terms of figure error on a macroscopic length scale, and of sub-nanometers for the micro-roughness [2].

To cover the spatial frequency range spanning from a few nanometers up to the full optical aperture length (in some cases up to a meter in length) these optics have been inspected ex-situ by means of scanning force microscopy (often referred to as AFM), white light interferometry (WLI), and slope-measuring profilometry (SMP) respectively at the BESSY-II Optics Lab in Berlin. Additionally we applied at-wave-length metrology at the BESSY-optics-beamline [3] to characterize the performance of various types of diffraction gratings as well as to test the quality of the coating material. Based on these results we will show the current state of quality for synchrotron optics and discuss critical topics such as the quality and stability of reflection coatings on top of mirrors and gratings.

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Metrology for "hybrid" reflection zone plates on spherical substrates

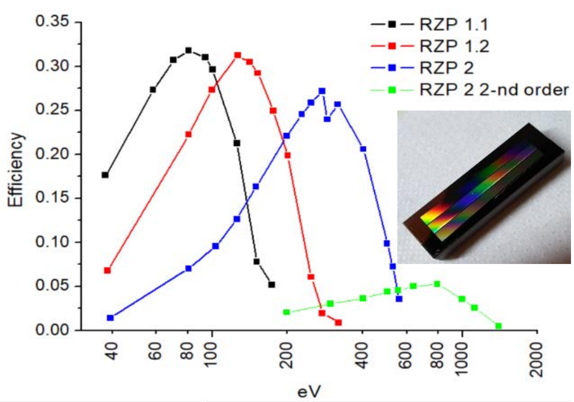
Alexei Erko[1], Christoph Braig[1], Andrey Sokolov[2], Frank Siewert[2], Christian Seifert[1]

[1]Institute of Applied Photonics e. V. (IAP), Rudower Chaussee 29/31, 12489 Berlin, info@iap-adlershof.de
[2]Helmholtz-Zentrum Berlin (HZB), Albert-Einstein-Str. 15, 12489 Berlin, andrey.sokolov@helmholtz-berlin.de

Corresponding author e-mail address: erko@iap-adlershof.de

Abstract

Reflection zone plates (RZPs) have found applications in different fields of soft X-ray instrumentation built at large scale facilities such as synchrotron radiation sources and free-electron lasers [1,2] as well as in the laboratory, using Laser Produced Plasma (LPP) sources or femtosecond pulses from High Harmonic Generators (HHGs) [3]. All these spectrometers and monochromators were based on elliptically shaped RZPs fabricated on planar substrates. Recenly, a new type of RZPs has been developed: the "hybrid" reflection zone plate (HRZP). It is based on the idea of combining an array of RZPs fabricated on the same substrate into one continuous Fresnel structure, providing a highly defined linear focus on the detector. The HRZP allows to minimize the sagittal chromatic aberrations and to enlarge the angular acceptance of the HRZP, due to the reduction of the line density of the grating structure at the sagittal edges. The wide energy range of the HRZP is provided by a spherically curved substrate with an optimized radius of curvature.



For the present experiment, three HRZP structures were used on a highly curved surface with a radius of curvature of 3.8 m and period variations of up to 1000%. This progress was made possible by the development of corresponding software at IAP for the calculation of RZP structures on curved surfaces and the simulation of their optical performance. Finally, the metrology developed in cooperation between IAP e.V. and HZB for at-wavelength reflectometry on curved surfaces allows to determine the diffraction efficiency of the HRZP.

Figure 1. Diffraction efficiency measured at the optics beamline of BESSY II for 3 HRZPs on a spherical substrate with a radius of 3.835 m.

The metrology process for the characterization of HRZPs consists of several steps, including:

- initial characterization of the substrate with optical methods like interferometry and profiling,
- scanning electron (SEM), optical (OM), and atomic force microscopy (AFM) for control of the resist pattern after the lithography process,
- AFM control of the etching depth with sub-nanometer accuracy,
- reflectometry measurements of the HRZP diffraction efficiency,
- resolving power measurements on corresponding instruments or test stations at NOB GmbH and IAP.

In Fig. 1, an example of an HRZP array for applications in an electron probe micro-analyzer (EPMA) is shown. The HRZP array consists of three different HRZPs, to cover the energy range (35 – 850) eV. Each individual HRZP features an optimized depth of the laminar profile, providing maximum efficiency at the designed energy.

This research was partially funded by the Federal Ministry for Economic Affairs and Energy within the project "WDSX" under the grant number ZF 4302304 SY9 for IAP e.V.

Keywords: Reflection zone plates, femtosecond soft X-ray spectroscopy, metrology of X-ray optics

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Accounting for Spatial Frequency Distribution in X-ray Mirror Surface Specifications

François Polack[1*], Uwe Flechsig[2], Guillaume Blanchard[1] and Ray Barrett[3]

[1] Synchrotron Soleil, BP 48 91192 Gif-sur-Yvette, France, [2]PSI, WSLA 124, 5232 Villigen,Switzerland, [3]ESRF, CS 40220, 38043 Grenoble Cedex 9, France

*e-mail: *francois.polack@synchrotron-soleil.fr*

Abstract

Optical surfaces of X-ray mirrors are usually specified by a few statistical parameters such as the peak-to-valley (PV) or root mean square (RMS) amplitude of the figure or slope errors of the real finished surface from an ideal reference,. Such global values become insufficient when local deterministic finishing techniques are applied in manufacturing and surfaces are employed with almost coherent beams, since different spatial distributions of errors may have quite different effects on the reflected beam. High spatial frequency defects can be well represented by their statistical properties and because far-field diffraction effects are described by the Fourrier Transform (FT) of the induced phase defects, FT based noise analysis tools, such as the Power Spectral Density (PSD), are appropriate. The impact of low frequency errors are however highly deterministic and the utility of statistical descriptions is less clear. It is therefore important to understand the relationship between the mathematical description of a surface and measurable physical effect on the reflected beam.

When a collimated light beam is reflected by an imperfect surface, a fraction of the beam intensity is scattered out of the specular direction. It was first shown by Bennett and Porteus [1], that under a Gaussian distribution of phase fluctuation, the total intensity loss termed total integrated scatter (TIS) is simply related to the phase variance σ^2 by $\exp(-\sigma^2)$. The Maréchal criterion is equivalent to a TIS=0.2, and corresponds the relative loss of intensity at the centre of the Point Spread Function (PSF). On the other hand, the PSF broadening with respect to a perfect reflected wavefront is directly related to the variance of the phase gradient, hence of surface slopes, for both coherent and incoherent illumination.

The PSD of a random statistical distribution can be viewed as the contribution to the total variance of a given spatial frequency, and integrals of the PSD as contributions of a frequency range. Integrals of the PSDs or cumulated PSDs are an easy and graphical way of representing the contributions of separate frequency bands to the total scatter and PSF broadening.

We discuss the choice of frequency ranges, and their relative contribution to the total variances, on fractal surface models and on real measured PSDs. The acquisition, and computation procedures (including filtering) applied to achieve stable and reliable values, must also be fully specified as various definitions used in the literature [2]. We conclude by suggesting the addition of new parameters to allow a more pertinent specification of high quality optical surfaces. Target values of these parameters for achieving almost diffraction limited X-ray mirrors are proposed.

Keywords: Optical surface quality, surface specification, figure errors, slope errors, scattering, PSD.

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Design, specification, optical metrology and commissioning of a pre- KB mirror for zoom-tomography

Bernd C. Meyer1*, Yuri R. Tonin[1], Izabela Z. do Lago[1], Julia C. S. Carvalho[1], Regis S. de Oliveira[1] Lucas M. Volpe[1], Gabriel B. Z. L. Moreno[1], Francesco R. Lena[1], Artur C. Pinto[1], Nathaly L. Archilha[1], Gabriel S. R. Costa[1], Lucca B. C. Campoi[1]

[1]Brazilian Synchrotron Light Laboratory (LNLS), Brazilian Center for Research in Energy and Materials (CNPEM), Zip Code 13083-970, Campinas, Sao Paulo, Brazil.

[1]e-mail: bernd.meyer@lnls.br

Abstract

The MOGNO (Micro- and Nanotomography) beamline is designed for zoom-tomography of internal 3D structures of different materials and is operating on a bending magnet source at medium (22 / 39 keV) and high (67.5 keV) energies. MOGNO beamline optic's concept is based on a multilayer-coated Kirkpatrick-Baez (KB) mirror system to focus the beam on both directions. Nanometric focus (120 nm) implies a short working distance, but on the other hand larger beam inhomogeneities out of focus, which contradicts the requirements for zoom-tomography. Therefore, a horizontal focusing mirror (M1) is introduced upstream the KB mirror to counterbalance the inhomogeneity caused by the horizontal KB (M2) mirror by matching the acceptance of the M1 and M2 mirrors. This work describes critical aspects of the optical and mechanical design process of the M1 mirror. In order to cope with the lateral stability requirement of 40 nrad RMS, the mirror mechanics design follows an exactly-constraint approach. The M1 mirror has a hybrid fixture concept where intermediary Invar alloy pins are epoxy-glued to the silicon substrate and thereafter clamped to the kinematic mounting frame. This leads to less stresses transferred to the mirror, resulting in lower deformations, lying in the same order as the metrology system accuracy. Stitching Fizeau interferometry is applied to characterize the mirror figure error. The accumulated deformation limit of the M1 mirror is smaller than the sensitivity of the Fizeau interferometer. Measurements indicate no significant deformation larger than possible to measure by the interferometer as predicted by simulations. First commissioning results of the M1 mirror are presented and compared to the design parameters of the beam. The beam caustic was measured by the fluorescence signal obtained scanning a thin gold stripe in horizontal and beam propagation direction. Thus, the horizontal focal position can be exactly aligned (depth of focus is 300 µm), the beam size in focus position can be measured and the homogeneity out of focus can be characterized.

Keywords: stitching interferometry, surface error, deformation

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The Advanced Photon Source New Slope Measuring System: Upgrades, Performance, and Results of Mirror Measurements

Lahsen Assoufid[1*], Jun Qian[1], Max Wyman[1], Raluca Ghilea[1,2], Zhi Qiao[1]

Steven Kearney[1], Curt Preissner[1], Mike Fisher[1], Joseph Sullivan[1], Peter Takacs[1,3]

[1] X-ray Science Division, Argonne National Laboratory, 9700 S Cass Avenue, Lemont, IL 60439, USA, [2]Student, Colgate University, 13 Oak Dr, Hamilton, NY 13346, USA, [3] Surface Metrology Solutions, LLC, 19 South First St. Unit B901, Minneapolis, MN 55401, USA

*assoufid@anl.gov

Abstract

The Advanced Photon Source Upgrade project (APSU) Feature and Enhancement beamlines include 58 state-of-the-art X-ray mirrors and mirror-bender assemblies with a variety of sizes, shapes and surface figure/finish specifications (rms slope and shape error requirements as low as <50 nrad and sub-nanometer respectively). The APSU project requires that these parameters be checked for compliance before installing the mirrors in the host beamlines. During the past two years, the Advanced Photon Source slope measuring profiler, built in 2012, has undergone an extensive upgrade in order to perform these necessary acceptance tests for APSU while meeting future measurement needs. The presentation will begin with a brief overview of APSU mirrors and metrology plan. Then, the new slope measuring system will be presented in detail, along with recent measurements performed on the first series of state-of-the-art large X-ray mirrors received to date.

*Work performed at Argonne was supported by the US Department of Energy, Office of Science, Office of Basic Energy Sciences, under contract No. DE-AC-02-06CH11357.

Oral Presentations

Session 07 | In-situ metrology and wave front measurements

01 | At-wavelength wavefront evaluation of a Schwarzschild objective using a high numerical aperture wavefront sensor | Mabel Ruiz Lopez (DESY)

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At-wavelength wavefront evaluation of a Schwarzschild objective using a high numerical aperture wavefront sensor

Mabel Ruiz-Lopez (1), Masoud Mehrjoo (1), Barbara Keitel (1), Domenico Alj (2,3), Guillaume Dovillaire (4), Philippe Zeitoun (2), Elke Plönjes (1)

[1]Deutsches Elektronen-Synchrotron, 22607 Hamburg, Germany, [2]Laboratoire d'Optique Appliquée, 91761, Palaiseau, France, [3]MAX IV Laboratory, P.O. Box 118, Lund 221 00, Sweden, [4]Imagine Optic, Orsay, 91400, France

Email: mabel.ruiz-lopez@desy.de

Abstract

Hartmann wavefront sensors are well known in the Extreme Ultraviolet (EUV) as a powerful technique to measure wavefront distortions caused by focusing optics. They are often used at FLASH, the Free Electron LAser in Hamburg at DESY, to demonstrate micro-focusing of beamlines with curved optics, i.e., elliptical mirrors, Kirkpatrick Baez optics, etc. Recently we exploited its capabilities for aligning more complex, high numerical aperture optical systems such Schwarzschild objectives [1]. EUV Schwarzschild optics are on-axis reflective objectives made of a large concave mirror with a central aperture and a convex small mirror suspended in a spider mount. Schwarzschild objectives, proposed for EUV lithography as a tool for inspection of the mask and for imaging the integrated circuit patterns, can potentially achieve nanometer resolution when both mirrors are perfectly aligned. Wavefront sensing is particularly useful for characterizing and optimizing such optics. Our Schwarzschild objective allows correcting the mirror position *in-operando* by adjusting piezo motors on the convex mirror. The Schwarzschild objective was illuminated with 13.5 nm radiation from FLASH and at-wavelength wavefront evaluation was demonstrated using an in-vacuum Hartmann wavefront sensor. The wavefront measurements were analyzed using the wavefront sensing package Wasaap (WAvefront Sensor AnAlysis in Python) [2], which has been developed in-house in Python and is publicly available to the scientific community. A combination of the traditional centroid and the Fourier Demodulation methods enables thorough analysis of complex magnified, annular and discrete Hartmann patterns.

Keywords: Extreme Ultraviolet, Hartmann Wavefront Sensor, high numerical aperture, on-line analysis

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X-ray mirrors metrology with Speckle Angular Measurement

Simone Moriconi[1,2]*, Hongchang Wang[1], Murilo Bazan Da Silva[1], Ioana Nistea[1], Simon G. Alcock[1], Matthew Hand[1], Lingfei Hu[1], Alexander Korsunsky[2] and Kawal Sawhney[1]

[1]Diamond Light Source Ltd, Harwell Science and Innovation Campus, Didcot, OX11 0DE, UK

[2]Department of Engineering Science, University of Oxford, Parks Road, Oxford, OX1 3PJ, UK

*email: simone.moriconi@diamond.ac.uk

Abstract

To preserve the exceptional quality of X-ray beams produced by highly coherent and brilliant sources, extreme quality X-ray mirrors are required for free electron laser and synchrotron radiation facilities. Since *in-situ* X-ray metrology is not readily accessible to manufacturers and users of X-ray mirrors, *ex-situ* visible light metrology is essential for efficient and accurate characterization of X-ray mirrors before installation at beamlines. Recently, a laser Speckle Angular Measurement (SAM) metrology instrument has been developed [1]. Here we present an experimental comparison between SAM and two other *ex-situ* metrology instruments used in the Optics Metrology Lab at Diamond: the Diamond-NOM [2] and a Fizeau interferometry stitching system. We compare and contrast the performance of these different and complementary instruments for a range of X-ray mirrors.

Keywords

ex-situ metrology; SAM, speckle angular measurement; laser speckle angular measurement; X-ray mirror metrology; nano-precision metrology, optics, metrology

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High-Precision At-Wavelength Metrology facility for XUV diffractive optics at BESSY-II

Andrey Sokolov[1,*], Frank Eggenstein[1], Peter Bischoff[1], Matthias Mast[1], Yue Yu[1,2], Franz Schäfers[1], Jens Viefhaus[1]

[1] Helmholtz-Zentrum Berlin für Materialien und Energie (BESSY-II), Albert-Einstein-Str. 15, D-12489 Berlin
[2] Key Laboratory of Advanced Micro-Structured Materials MOE, Institute of Precision Optical Engineering,School of Physics Science and Engineering, Tongji University, Shanghai 200092, China

*e-mail: andrey.sokolov@helmholtz-berlin.de

Abstract

The At-Wavelength Metrology facility for sophisticated XUV optics such as diffraction gratings is operating since many years at the BESSY-II storage ring. As the main instrument a versatile 11-axis UHV-reflectometer is permanently connected to the dedicated Optics beamline which has permanent access to the X-ray beam [1,2]. The setup covers the energy ranges of EUV and XUV radiation. High spectral purity of the incident beam is achieved by a set of 12 absorption filters and a High-Order Suppressor System (HiOS) consisting of 4 mirrors which can be inserted into the incident beam under variable angles of incidence without changing the original beam path. It was experimentally tested that this system gives a nearly high-order free beam between 12.5 eV and 1800 eV. A flexible sample support system based on an UHV-tripod gives 6 degrees of freedom for a precise alignment and mapping of the optical elements under test. Optical elements with sizes up to 360 x 60 x 60 mm^3 have been tested, for samples smaller than 60 x 40 x 10 mm^3 a fast in-vacuum transfer load-lock system is available.

In more than seven years of operation, the station was successfully used to perform precise characterization of the efficiency of our in-house produced diffraction gratings [3] as well as to develop novel optical concepts employing e.g. reflection zone plates (RZP), multilayer mirrors, multilayer coated gratings [4], poly-capillary lenses and copy-stamp gratings. Part of the beamtime is dedicated to commercial measurements and to scientific user projects focused on investigation of optical properties as well as internal microstructure and interfaces in (ultra-)thin layered systems. The present status of the metrology station, its upgrade projects and recent challenging results on X-ray optics will be presented.

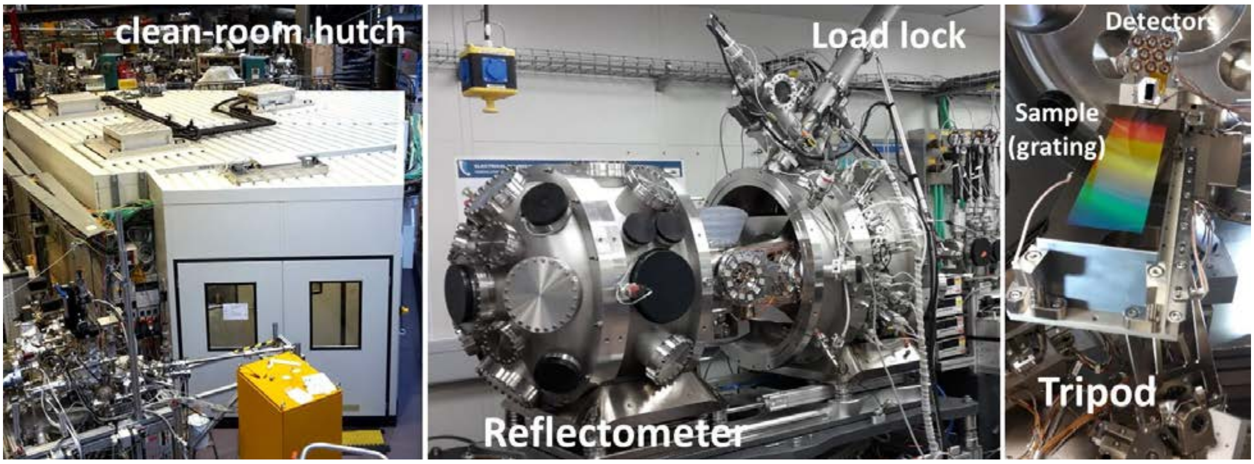

Figure 1: Optics beamline - At-Wavelength Metrology facility.

Keywords: At-Wavelength Metrology, EUV, reflectometry, XRR, XUV diffraction gratings, XUV optics efficiency, reflection spectroscopy

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Optical constants in the EUV regime and the redesign of PTB's soft X-ray beamline at BESSY II

Richard Ciesielski[1], Leonhard Lohr[1] and Victor Soltwisch[1]

[1]Physikalisch-Technische Bundesanstalt, Abbestr. 2-12, 10587 Berlin

e-mail: richard.ciesielski@ptb.de

Abstract

The development of extreme ultraviolet (EUV) lithography for semiconductor technology in the last years caused an increased demand for high-accuracy, at-wavelength metrology [1]. The German national metrology institute, the Physikalisch-Technische Bundesanstalt (PTB), has a long standing expertise in soft X-ray radiometry and scatterometry using synchrotron radiation for metrology applications. We here present measurements of the optical constants of 19 different pure materials and alloys, relevant for EUV lithography masks [2]. Reflectometry measurements of thin film samples and rigorous mathematical modelling of the retrieved data allows to obtain the optical constants of these materials at wavelengths around 13.5nm, which is the central wavelength for current EUV technology.

At a bending magnet of the electron storage ring BESSY II in Berlin we operate a beamline with an SX700-type, grating-based monochromator in the photon energy range from 50 to 1700eV in combination with a lubricant-free reflectometer. Calibrated detectors allow for reference-free measurements that can be carried out in the full range from normal to grazing incidence, which makes it a powerful tool for standard measurements as well as for research projects [3]. After successful 20 years of operation, the beamline is now being redesigned and updated to extend its capabilities and to adapt for future challenges. We discuss the merits and drawbacks of the less common choice of a constant focus factor (cff) below 1 in the plane grating monochromator regarding the achievable energy resolution, spot size, beam divergence and imaging properties.

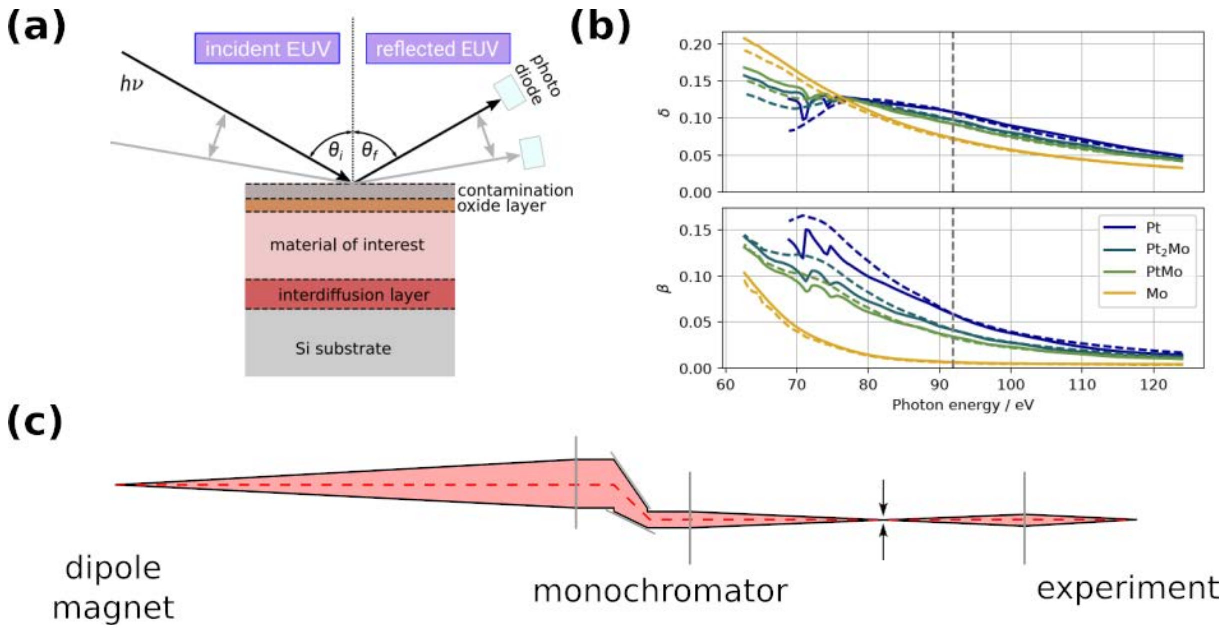

Figure 1(a) Schematic of reflectometry measurements on a thin film stack. (b) Optical constants of alloys of platinum and molybdenum in the EUV range. (b) General layout of the new soft X-ray / EUV beamline.

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Advanced X-ray wavefront sensing technology developments at the Advanced Photon Source

Zhi Qiao*, Xianbo Shi, Luca Rebuffi, Michael J Wojcik, Lahsen Assoufid

Advanced Photon Source, Argonne National Laboratory, Lemont, IL, 60439, U.S.A.

*e-mail of correspondence author: zqiao@anl.gov

Abstract

X-ray wavefront sensing has become crucial for X-ray beam diagnostics and at-wavelength metrology at synchrotron radiation and free-electron laser facilities worldwide. Grating interferometry and speckle-tracking methods are considered the most advanced wavefront sensing technologies, showing complementary advantages in their speed and resolution. This presentation reports on the latest developments on speckle-based wavefront sensing techniques at the Advanced Photon Source, including the coded-mask-based multi-contrast imaging (CMMI) method [1] and the speckle-based phase-contrast imaging neural network. As a result of these enhancements in hardware and software, the new techniques exhibit superior computational efficiency, phase sensitivity, and spatial resolution than traditional methods. We also demonstrate their applications in real-time wavefront sensing, high-resolution at-wavelength metrology, and tomographic phase-contrast imaging [2].

Keywords: wavefront sensing, X-ray optics, speckle tracking

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Oral Presentations

Session 08 | Metrology challenges for X-ray mirrors III

01 | Diamond-VeNOM: a high-speed, double-autocollimator, slope profiler for characterising X-ray mirrors | Simon Alcock (Diamond)

02 | The stitching interferometry instrument of ALBA | Josep Nicolas (ALBA)

03 | Progress report on the development of stitching interferometry instrumentation at SOLEIL | Muriel Thomasset (Soleil)

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05 | The art of high-accuracy ex situ metrology for x-ray optics developed at the Advanced Light Source | Valeriy Yashchuk (LBNL)

Diamond-VeNOM: a high-speed, double-autocollimator, slope profiler for characterising X-ray mirrors

Simon G. Alcock*, Murilo B. da Silva, Ioana-Theodora Nistea, and Emilio Perez-Juarez

Diamond Light Source Ltd, Harwell Science and Innovation Campus, Didcot, OX11 0DE, UK

*e-mail: simon.alcock@diamond.ac.uk

Abstract

We present the Diamond-VeNOM (velocity-NOM): a high-speed slope profiler of X-ray optics.

Since 2007, the Diamond-NOM [1] has played a major role in the Optics Metrology Lab (OML) at Diamond. Metrology feedback has helped to optimally clamp hundreds of X-ray crystals and mirrors into beamline opto-mechanical holders [2]. The Diamond-NOM can demonstrably measure curved mirrors with slope errors < 50 nrad rms. However, multiple scans with the mirror in a range of configurations are needed to reduce the impact of systematic measurement errors. With the necessity to more frequently characterise the highest-grade mirrors for beamline and machine upgrades, the speed of scanning becomes increasingly important.

In the Diamond-VeNOM, a next-generation, Elcomat5000 autocollimator from Möller-Wedel, Germany with a 250 Hz acquisition rate is used in combination with an old Elcomat3000: one to monitor the parasitic angular errors of the air bearing scan stage; the other to directly measure the surface under test (with or without a pentaprism). A new Power PMAC clipper controller enables quicker and more reliable motion control of the scan stage. Based on high-speed feedback from the air bearing's encoders, a PandA I/O box triggers millisecond duration shutters to temporarily block the light from both autocollimators when the stage reaches a series of user-defined positions. This innovation automatically synchronises the position of the motion stage with the output of both autocollimators, reducing the burden of post-processing data alignment. The new controller and software developments enable more flexible coordination of the motion trajectory of the scan stage and acquisition of autocollimator data.

Overall, we demonstrate that the advantage of fly-scanning, combined with the speed enhancement of the new autocollimator, leads to a 20X time efficiency for the Diamond-VeNOM compared to the Diamond-NOM's traditional step-scans, without loss of metrology data quality.

Keywords: Diamond-NOM, slope profilometry, autocollimator, X-ray mirrors

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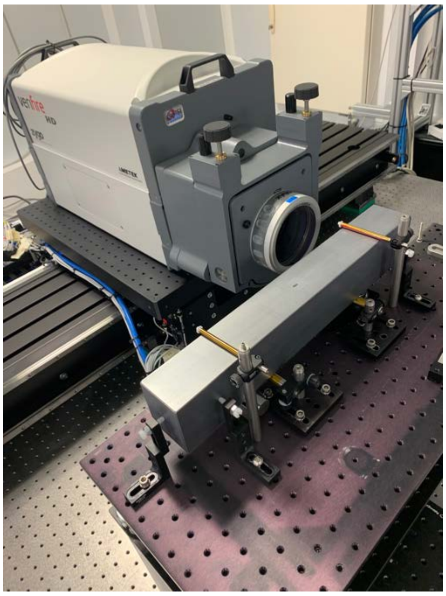
The stitching interferometry instrument of ALBA

Josep Nicolas*, Albert Van Eeckhout, Igors Sics, Llibert Ribó, Carles Colldelram

ALBA Light Source Facility, Carrer de la Llum 2-26, Cerdanyola del Vallès, 08290 Barcelona, Spain
[2]ALS Berkeley CA, USA

**e-mail: josep.nicolas@cells.es*

Abstract



We present the stitching interferometry system of the ALBA optics laboratory. We describe the main features of its setup, its measurement routines, and the reconstruction algorithms used with it. We also discuss the first commissioning results. The instrument is composed by a 100 mm aperture Zygo Verifire HD Fizeau interferometer, which is the main sensor of the system. It is mounted on top of a scanning and positioning stage with four degrees of freedom: Horizontal displacement, with a range of 1500 mm; vertical displacement, with a range of 20 mm; and yaw and roll rotations (>1 deg range each). The positioning system is designed and built in-house, and has been optimized for high vibrational stability, keeping a minimum height of the optical axis of the interferometer with respect to the optical bench. All motion axes have absolute encoders, and work in close loop. All three orientation angles of the interferometer platform are monitored by an external autocollimator and two high resolution inclinometers.

The system allows measuring long x-ray optics in face-side orientation. The solution we have chosen scans the interferometer and keeps fixed the optical element under test. This is very convenient when measuring bender systems, connected to their cables, or to their cooling circuits. By moving the Fizeau and not the optics under test, one assures that the load on the stage, and therefore its vibration behavior, is always the same. The motion stage is integrated into the Tango control system of the laboratory, while the communication with the interferometer, is done via a Python socket listener running at the interferometer control computer. The stitching applications are run in a matlab environment, and allow for a rapid configuration using a GUI, or by a command-line functions, for easy scripting.

The stitching acquisition routine applies un-even spacing between sub-aperture acquisitions, in order to avoid periodic errors in the reconstruction. Before each sub-aperture acquisition, the Fizeau is automatically oriented to minimize the number of fringes in its field of view, in order to minimize retracing errors. The resulting orientation is measured by means of an autocollimator, looking at the interferometer platform, and by two inclinometers, that measure the relative roll between the optical bench, and the interferometer stage. The Fizeau platform allows displacements also in the vertical orientation, since these are required to measure and compensate sagittal errors of the measurement.

The sub-aperture data, is reconstructed using in-house developed error suppression algorithms, that allow effectively removing reference flat errors, guidance errors, and allow using the trajectory data to solve the ambiguities on curvature.

Keywords: Optics, Metrology, Stitching, Interferometry, X-ray.

Progress report on the development of stitching interferometry instrumentation at SOLEIL

M. Thomasset[1], S. Brochet[1], D. Dennetiere[1], G. Cauchon[1], B. Capitanio[1]

F. Polack[1], G. Blanchard[1]

[1] Synchrotron SOLEIL, l'Orme des Merisiers, Saint Aubin, 91192 Gif sur Yvette, France

muriel.thomasset@synchrotron-soleil.fr

Optical metrology controls implemented in synchrotrons facilities have been long relying mostly on 1D profilometry (LTP, NOM). Indeed, this technique makes it possible to avoid the use of a reference mirror and enables to measure any type of profile with the same sampling frequency for mirrors up to 1 m length. Then, 1D stitching methods were developed [1], first to measure curved mirrors but, but also to eliminate the systematic errors of the instrument from the results by exploiting the redundancy of overlapping measurements.

With the upgrade of 3rd generation synchrotron machines which provide close to diffraction limited photon sources, wavefront preserving optics will be quite generally looked for, leading to specify mirror surfaces below 1 nm PV on the whole clear aperture. The polishing manufacturing processes are now commonly relying on local touch-up techniques, such as ion beam figuring or fluid jet polishing, which allow reducing the height errors in the nm range with a tool size of a few mm radius. The isolated uncorrelated line profiles given by profilometers show their limits and mapping techniques, such as interferometry, are also required. In order to achieve sub-nanometer resolutions on the clear aperture of synchrotron optics, often exceeding 500 x 20 mm^2, stitching procedures are requested.

As early as 2010, SOLEIL undertook the construction of a Michelson type interferometer called MINT [2] (Michelson Interferometry for Nanoscale Topography) with a sampling frequency of 20 µm and a measuring field of 12 X 10 mm allowing the measurement of mirrors up to 300 mm long. The first results in 2012 showed an excellent agreement with LTP measurements to the exception of the curvature terms which is still an issue of stitching.

In 2019, SOLEIL purchased a commercial interferometer with a 100 mm pupil, i.e., a sampling frequency of 90 µm (30 and 10 µm accessible using afocal optics). This instrument was mounted on an hexapod in 2021. An optical table with integrated translation completes the system and will allow mirror characterization over lengths of up to 1.5 m. This system called TITAN (Tracking Interferometry for Topography At Nanoscale) is complementary to the MINT and the LTP and due to an overlap of their sampling frequencies, will allow cross-analysis of measurements. Stitching 2D algorithms, which are actively developed and widely shared in the community, e.g., in the PyLost sofware [3], are increasingly reliable. And the exploitation of the full redundancy of the whole measured data, as in 1D stitching, is an achievable prospect for near future. Profilometry will also guarantee the validation of the reconstruction of the curvature of the mirrors. Mirrors available with the MoonPics and other forthcoming European projects are excellent test-objects to check and improve this metrology.

Keywords: Profilometry, 2D optics metrology, interferometry, stitching, cross-measurement

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Recent development on optical metrology at NSLS-II

Lei Huang, Tianyi Wang, Kashmira Nakhoda, and Mourad Idir

National Synchrotron Light Source II, Brookhaven National Laboratory, Upton, NY 11973, USA

e-mail: lhuang@bnl.gov

Abstract

Following the development of the synchrotron radiation and free-electron laser facility, the requirement on state-of-the-art X-ray mirrors gets higher to maintain the incoming perfect beam and focus it at the diffraction limit for beamline experiments.

The optical metrology needs to be able to characterize these high-quality X-ray optics. The specific optical metrology is getting more challenging not only from the measurement repeatability and the measurement accuracy, but also from the required measuring range in terms of total slope range, the radius of curvature, and the physical length of the mirror.

In this work, we would like to present our research and development efforts for X-ray mirror metrology both for the day-to-day X-ray characterization necessary to meet the stringent requirement for the NSLS-II beamlines' mirrors and for the figure errors as metrology feedback to the X-ray mirror polishing using ion beam figuring recently developed at the NSLS-II Optics and Metrology Laboratory.

To continue improving the optical metrology capabilities, some potential future research and development will be addressed as well.

Keywords: X-ray optics, optical metrology, and X-ray mirror characterization

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The art of high-accuracy ex situ metrology for x-ray optics developed at the Advanced Light Source

Valeriy V. Yashchuk

Advanced Light Source, LBNL, 1 Cyclotron Road, Berkeley, CA 94720, USA

*e-mail of corresponding author: vvyashchuk@lbl.gov

Abstract

The thorough realisation of the advantages of the new generation x-ray light sources, Diffraction Limited Storage Rings (DLSRs) and Free Electron Lasers (FELs), requires high-performing, near-perfect, x-ray optics, capable of delivering light to experiments without significant degradation of brightness and coherence. Consequently, the stringent requirements of beamline optics drive the state of the art in ex situ optical metrology, used for quality assessment, mounting refinement, beamline performance optimization of pre-shaped optics, as well as for the shape adjustment and actuation mechanism calibration of bendable optics. The refined metrology data are also vital for fabrication specification of x-ray optics in terms of desired system performance, avoiding costly over- and performance-degrading under- specification. Increasingly stringent requirements on optical elements have led to significant dedicated metrology efforts among the optics teams at practically all x-ray facilities around the world.

Here, we present an overview and discuss the results of the ongoing efforts at the Advanced Light Source (ALS) X-Rays Optics Laboratory (XROL) [1] to bring the x-ray optics and ex situ metrology to the state-of-the-art level, in support of advanced instrumentation at the ALS and for the ALS-Upgrade (ALS-U) project [2]. Our major research accomplishments, which would be impossible without highly productive and enjoyable collaborations with many outstanding colleagues around the world, has resulted in the creation of a laboratory infrastructure (including a class-200 clean-room XROL facility with improved environmental conditions and a set of original and upgraded commercial high-performance metrology instruments) and a closed loop system of methods, techniques, devices, and software for high accuracy data acquisition, processing, reconstruction, modelling, forecasting and simulation for improvements in high accuracy X-ray optics metrology and in the optimization of beamline performance. The infrastructure, the developed methods and techniques, and the many highly productive collaborations, discussed and illustrated in this work with numerous examples of the XROL measurements with state-of-the-art x-ray optics, all together constitute a foundation of the art of high-accuracy metrology for x-ray optics and optical systems at the ALS.

The challenges of x-ray optics and ex situ metrology we address are shared, and we anticipate that the results of our work presented here will be helpful for further development of the Art of High-Accuracy Metrology for X-Ray Optics and continued advances of the Art over time. This work was supported in part by the U. S. Department of Energy under contract number DE-AC02-05CH11231, DOE BES STTR Programs under Award No. DE-SC0011352, NASA SBIR/ STTR Program, project No. 15-1 S2.04-9193 and contract No. 80NSSC20C0505.

Keywords: x-ray optics metrology, measurement errors, instrumental transfer function, ITF, calibration, modelling, x-ray optics, beamline performance optimization, optics specification

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Posters

Poster Sessions 01 / 03

P01 Round-robin comparison and repolishing of a 3-lane ellipse X-ray mirror from the MooNpics collaboration between European light sources and X-ray optic manufacturers, Simon Alcock (Diamond Light Source)

P02 Mechanical bending of high performance x-ray mirrors, Konstantin Andrianov (Axilon)

P06 Active optics systems at the ALBA beamlines, Nahikari González (ALBA)

P08 The TPS 34 Metrology Laboratory and Bendable Mirror Measurement Long Trace Profiler Test, Ming-Ying Hsu (NSRRC)

P12 Development of an advanced LTP at the ALS: Operation and data acquisition with a two-carriage gantry system, Ian Lacey (LBNL, Advanced Light Source)

Posters

Poster Sessions 01 / 03

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Round-robin comparison and repolishing of a 3-lane ellipse X-ray mirror from the MooNpics collaboration between European light sources and X-ray optic manufacturers

Simon G. Alcock*, Ioana-Theodora Nistea, and Murilo B. da Silva
(on behalf of the MooNpics collaboration)

Diamond Light Source Ltd, Harwell Science and Innovation Campus, Didcot, OX11 0DE, UK

*e-mail: simon.alcock@diamond.ac.uk

Abstract

We present a round-robin metrology comparison of a 3-lane, tangential ellipse, X-ray mirror, as part of the MooNpics CALIPSOplus project ("Metrology On One-Nanometer-Precise Optics"). MooNpics is a collaboration between European vendors of X-ray mirrors and metrology labs at free electron laser and synchrotron light sources. The goal is to improve metrology capabilities to create enhanced quality X-ray mirrors [1]. This project includes a wide range of metrology instruments, which are broadly representative of usage within the optical testing community, including: slope profilometers, Fizeau- and micro-interferometers, wavefront sensors, and X-ray techniques.

Aside from the ellipse lane, the other two lanes have parabolic arcs [2] superimposed upon the ellipse profile. These arcs provide well defined patterns for measurement. A series of fiducial marks were added to the optic: these proved to be highly beneficial for alignment of measurement and analysis regions. We compare the low- and mid-spatial frequency surface errors of the mirror, and comment on trends observed by different categories of metrology instruments. The round-robin exercise helped to refine "best practice" metrology procedures for transportation, mounting, and testing of X-ray mirrors. It also highlighted systematic measurement issues with several instruments. Once identified, such problems can be investigated and corrected, leading to improved measurement reproducibility and confidence within the community.

For consistency, all data were analysed using Diamond's standard algorithms. However, in future, the unprocessed datasets could be shared within the community to benchmark different analysis techniques, including Fourier filtering and ellipse fitting. The goal is community-wide standardisation of data formatting and analysis techniques. Ideally, with everyone contributing and using the same freely available, open-source software, such as the PyLOSt stitching software [3] developed as part of the MooNpics collaboration.

Based on metrology data provided by the collaboration, ion beam figuring (IBF) was performed at Carl Zeiss SMT, Germany. We show that IBF successfully improved all aspects of the mirror, including: correcting the ellipse parameters; reducing high- and mid-frequency spatial polishing errors; and improving the shape of the parabolic arcs.

Keywords: Metrology of X-ray mirrors; MooNpics collaboration; slope profilometry; interferometry

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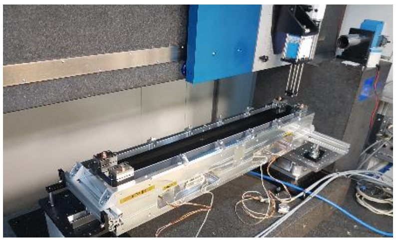
Mechanical bending of high performance x-ray mirrors

Andrianov K[1*], Wiesemann U[1], Schacht A[1], Waterstradt T[1], Diete W[1]

[1]Axilon AG, info@axilon.com

*e-mail: konstantin.andrianov@axilon.de

Abstract



Next generation light sources and ongoing updates challenge the optical components and the whole manufacturing chain beginning with the polishing process and the metrology tools and techniques which are needed for quality validation of the optical components. One critical optical component is the x-ray mirror which often needs to be actively bent during operation without or with an absolute minimum degradation on the optical performance. Therefore not only the mirror substrate itself needs to be of highest performance – mirror substrates with slope errors bellow 100nrad RMS and height error specification in the nm range are available – also the mechanical components which are used to support, position and shape the mirror have to be able to maintain this performance. We present our two moment mechanical mirror bender system which demonstrate the possibility of shaping high performance mirrors proving minimum influence of the bender by preserving slope and height values of the unbent and relaxed mirror substrates. We present first measurement results of x-ray mirrors bent to an elliptical shape. The presented results were collected with a KB system designed for the GM-CA mission at the APS Sector 23. Two metrology campaigns where carried out with the vertically deflecting and horizontally deflecting bender in there operating orientation. These measurements were carried out at the metrology labs at ALBA as well as at the APS. The trapezoidal shaped mirror substrates where manufactured by Jtec Corporation. The system is designed to be used in absolute dry UHV environments, all mechanical components are lubricant free which eliminates the possible contamination of the optical surface. The basic design can be easily adapted for different working orientations, mirror shapes and sizes. For upwards and downwards deflecting systems spring actuated gravity sag compensators are used which allow an extremely precise compensation of the gravity sag.

Active optics systems at the ALBA beamlines

Nahikari González[1]*, Alejandro Crisol[1], Joaquín B. González[2], Carles Colldelram[1], Josep Nicolas[1]

[1]ALBA Light Source Facility, Carrer de la Llum 2-26, Cerdanyola del Vallès, 08290 Barcelona, Spain
[2]MAX IV Laboratory, Lund University, PO Box 118, SE-22100 Lund, Sweden

**e-mail: nahikari.gonzalez@cells.es*

Abstract

We present the latest results of the active high-order correction mirror bender system developed at our facility. The system is our standard focusing optical element, and several units have been installed at newly-constructed beamlines. Some of them are already in operation, and future beamlines foresee this optical element, too.
The device is an elliptical mirror bender, with independent motorized actuators at both ends of the mirror. The system allows adding manual or motorized actuators at any position along the mirror, to provide high-order correction of wavefront distortions.
The simplest version of the system is just the main frame and the bending actuators. It has been designed to minimize the total length of the system (only 20 mm longer than the mirror), maximizing the stiffness of the box, while providing space around the mirror (for correctors and cooling), and a mass center close to the mirror substrate, for good stability in any orientation of the mirror. The mechanics can easily adapt to different lengths, and sections of the mirror substrate. The bender has enough dynamic range to obtain curvatures as low as 56 m starting from flat, which makes it usable for microfocus applications.
The bender frame allows including a number of point-force actuators, which can be motorized for adaptative correction at the beamline, or can be manually adjusted at the lab. We use motorized actuators to correct high order wavefront errors only measurable at the beamline under operation. This is, for instance, the case of thermal distortions or wavefront aberrations caused by other beamline components. The actuators use a combination of elastic and magnetic forces to introduce sub-nanometer resolution deformations of the substrate. The combination of forces is engineered to provide high stability against mechanical drifts, and against changes of curvature configuration of the mirror.
The manually operated version of the actuators is the unexpensive solution we use almost exclusively to improve the figure of the mirror, by reducing the residual low frequency errors left by the polishing. We do not use actuators to correct gravity sag or high order ellipse terms, since we engineer the width of the mirror substrate to obtain the exact ellipse under the gravity orientation foreseen for the system. This is more accurate, as the force is continuously distributed, and is inherently more stable. This approach is validated by several systems, of different sizes, thicknesses and orientations, including the extreme case of a 12 mm-thick, 600 mm-long, facing-down mirror for which high order ellipse terms are equivalent to 2.3 μrad rms, and that is bent to nominal with a bending accuracy below 40 nrad rms.
When required, the system includes also a water cooling circuit for the mirror. The cooling scheme we use is based on a thin GaIn pellicle as the contact between the mirror side faces and the cooling circuit itself. This cooling scheme avoids hardly predictable mirror deformations introduced by traditional side cooling, and avoids also the use of liquid Galinstan, which, in addition to the risk of contamination accidents, limits the working orientation of the mirrors.
Tests at the laboratory show that the system provides reproducibility and stability in the order of $\Delta R/R<10^{-5}$ as well as resolutions well below that value, without parasitic deformations of the substrate. Correctors allow removing surface errors with sub-nanometer resolution and reproducibility. Commissioning results at the beamline, show that the systems reliably meet their nominal performances also in actual operation conditions.

Keywords: Adaptive Optics, X-rays, Beamlines, Mirrors.

The TPS 34 Metrology Laboratory and Bendable Mirror Measurement Long Trace Profiler Test

Ming-Ying Hsu, Hok-Sum Fung, Shang-Wei Lin, Huang-Wen Fu,
Gung-Chian Yin, Yu-Shan Huang

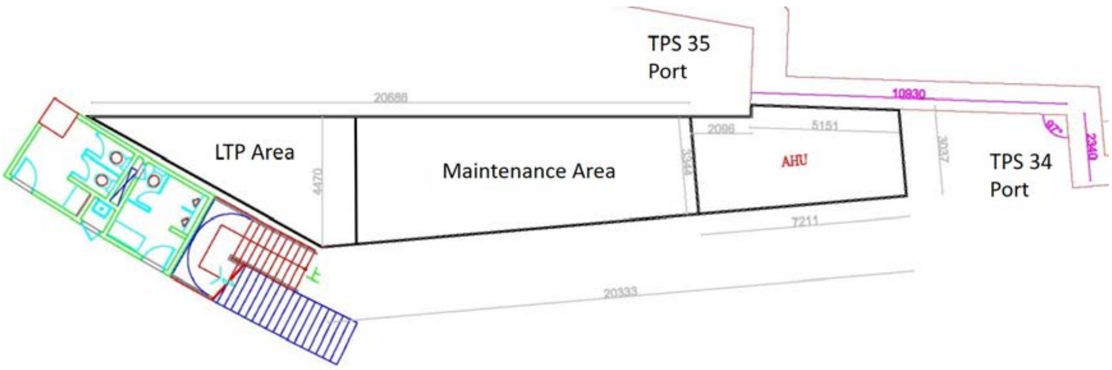
National Synchrotron Radiation Research Center, 101 Hsin-Ann Road, Hsinchu Science Park, Hsinchu 30076, Taiwan, R.O.C

Abstract

The TPS phase III project will have nine beamline construction simultaneously. The mirrors for the beamline are needed to make acceptance test, and the soft X-ray beamline bendable mirror system is required to assemble and test. After the TPS Phase-III beamline construction is finished, the TPS mirrors and vacuum chamber repair and maintenance are essential. Therefore, the TPS 34 is a 10,000 class clean room with a temperature a 25 ± 0.5 °C, and the cleanroom area is 68 m^2.

The LTP local area is designed with extra HEPA to achieve high-level (class 10) cleanness for the mirror measurement. The TPS 34 metrology laboratory construction will finish in 2021 January; the new LTP system is also soon moving in and tested.

Keyword: Cleanroom, LTP, TPS



Development of an advanced LTP at the ALS: Operation and data acquisition with a two-carriage gantry system

I. Lacey[1*], K. Anderson[1], J. Dickert[1], B. Nelson[2], P. Z. Takacs[3], and V. V. Yashchuk[1]

[1] Advanced Light Source, LBNL, 1 Cyclotron Road, Berkeley, CA 94720, USA,
[2] Meadows Manufacturing, 545 Parrott Street, San Jose, CA 95112, USA,
[3] Surface Metrology Solutions LLC, 19 S 1st St, Minneapolis, MN 55401 USA

*e-mail of corresponding author: ilacey@lbl.gov

Abstract

High precision surface slope deflectometry using Long Trace Profiler (LTP) type instruments of various configurations has become a standard component of the ex situ metrology of high quality x-ray optics for grazing angle applications at third and fourth generation synchrotrons, as well as at modern Diffraction Limited Storage Ring (DSLR) and Free Electron Laser (FEL) facilities. The architecture of such LTP systems is based on a pencil beam interferometer (PBI) for a probe sensor, typically mounted on the moving gantry, thus requiring monitoring of the gantry wobble; alternatively, a scanning pentaprism is used with a stationary sensor [1].

Here we present a two-air-bearing-carriage system on a common ceramic support beam designed to adapt both traditional modes of LTP operation, with movable and stationary optical sensors, in the new LTP-2020 [2] under development at the Advanced Light Source (ALS) X-Ray Optics Laboratory (XROL). Two-carriage gantry system design approach has been used, for example, in the Extended Shear Angle Difference (ESAD) deflectometers [3], based on a commercial electronic autocollimator with LED light source, developed at the Physikalisch-Technische Bundesanstalt (PTB).

Unlike the two-carriage shearing ESAD system mostly used for high-precision characterization of flat mirrors in face-up orientation, we aspire to preserve the major advantage of the current ALS LTP-II by designing the LTP-2020 gantry system with a capability of raising and lowering the ceramic beam with the carriages and sensors. This design allows characterization of unmounted optical substrates, and is easily reconfigurable for measurements with multi-element optical systems and large mirror assemblies, such as x-ray bendable mirrors, be they with face-up, side-facing, or even face-down orientation. We discuss the modular design of the LTP-2020 gantry system and different optical sensors [2] mounted to the separate carriages that allows application of sophisticated data acquisition algorithms for ensuring high-accuracy metrology with aspherical x-ray mirrors and variable-line-spacing (VLS) diffraction gratings. Additionally, the two-carriage two-optical-sensor LTP-2020 allows an effective in-house round-robin to obtain high-confidence metrology data via cross-comparison metrology with uncorrelated systematic errors, for a single alignment of the surface under test.

We are in the process of engaging vendors who will sign up to the stringent fabrication requirements of the LTP-2020 sensor optical elements of an original design [2] and are seeking to establish collaborations with other LTP users interested in improving instrument performance. This work was supported in part by the U. S. Department of Energy under contract number DE-AC02-05CH11231.

Keywords: x-ray optics metrology, autocollimator, long trace profiler, angle metrology, deflectometric profilometry, optical design

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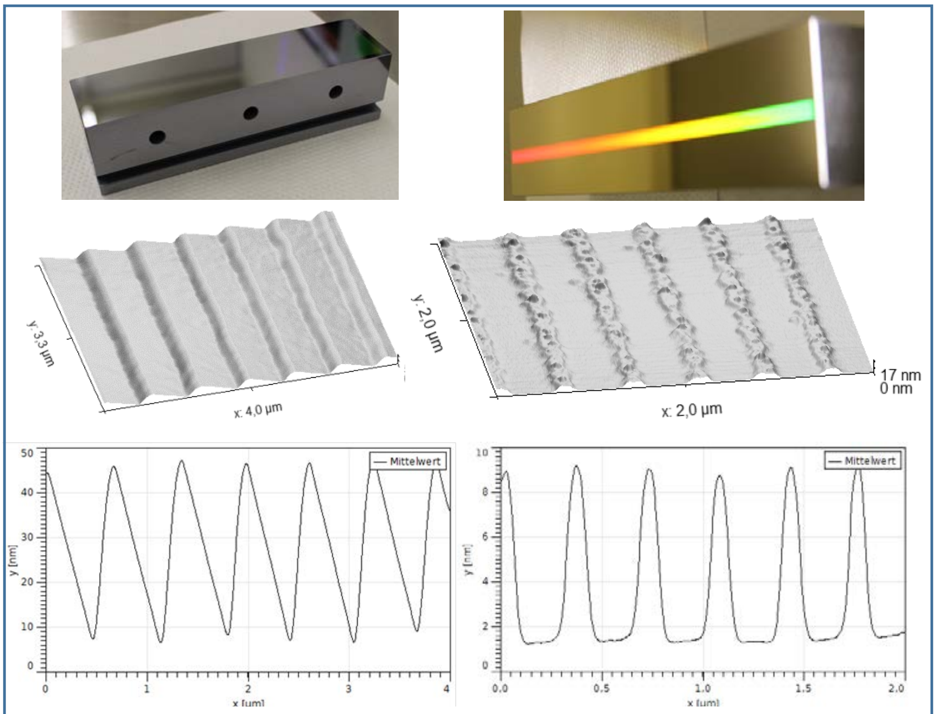
Update on the grating manufacturing at HZB: high line density blazed and long aperture laminar gratings

Stephanie Lemke[1]*, Svyatoslav Alimov[1], Jeniffa Knedel[1], Oliver Kutz[1], Tino Seliger[1]
[1] Helmholtz-Zentrum Berlin für Materialien und Energie, BESSY-II, Albert-Einstein-Str. 15, 12489 Berlin, Germany
*e-mail: stephanie.lemke@helmholtz-berlin.de

Abstract

Helmholtz-Zentrum Berlin (HZB) has manufactured over 100 synchrotron gratings since 2011, with more than 25 installed in HZB beamlines and instruments. The gratings have constant (CLS) or varying (VLS) line spacing profiles with line densities (LD) ranging from 50 to 4000 L/mm on plane, spherical, cylindrical and toroidal surfaces. R&D to extend our capabilities, especially into tender X-ray region [1], are ongoing.



Photo, 3D AFM image, 2D average profile of a 1600 L/mm blaze grating after ion etching (left) and a 3000 L/mm laminar grating (right).

We present exemplary results of the past two years: we manufactured a 2400 L/mm CLS grating with 0.8° blaze and 176.9° apex angle, which represents the maximum LD for our blazed gratings. While this LD remains very challenging regarding ruling periphery conditions (temperature, vibration, diamond wear etc.), with more than ten 2400 L/mm gratings we gathered lots of experience with respect to LD and profile uniformity as well as its metrology. Another challenge was a 1600 L/mm CLS grating with 5.5° blaze angle, which is our new highest realized blaze angle in silicon.

To overcome the limited length of about 150 mm for blaze gratings work on the ruling engine GTM24 is an ongoing process [2]. First ruling results at 600 L/mm to be inspected at wavelength are expected in 2022. However, processes were already tested using laminar gratings on large substrates. We manufactured a 150 L/mm VLS grating, the length of the optical area was >295 mm. The etch depth variation was $2\sigma = 0.6$ nm. Such gratings are of special interest for FEL beamlines. For spectrometers in soft X-ray region high line densities on large areas are of much interest. We manufactured a 3000 L/mm VLS grating with ≥210 mm x ≥44 mm on a spherical substrate. The etch depth variation with $2\sigma = 0.3$ nm for 6.5 nm average depth was at the limit of measurement accuracy for our Nanosurf NaniteAFM.

Keywords: grating, variable line density, blaze, laminar, FEL

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Measurement of the first pair of high accuracy K-B mirrors of HEPS by FSP

Ming Li[12*], Changrui Zhang[1], Rongli Cui[1], Fugui Yang[1], Dongni Zhang[1,2], Fang Liu[1,2], Fan Li[1], Junliang Yang[1], Congcong Li[1], Jun Han[1,2]

[1] *High Energy Photon Source, Institute of High Energy Physics*
[2] *University of Chinese Academy of Sciences*

*lim@ihep.ac.cn

Abstract

The first phase of construction of China's first fourth-generation synchrotron radiation source, the High Energy Photon Source (HEPS), will be completed by the end of 2025, and 15 high-performance beam-lines will be completed by then. These beam lines will feature 33 high-precision X-ray mirrors with surface slope and shape accuracy requirements as high as 50nrad and 0.35nm, including elliptical figure mirrors, Advanced K-B mirrors, toroidal mirrors, bent mirrors and so on. So far, our first pair of high-precision elliptical K-B mirrors have been measured on the Flag-type Surface Profiler (FSP). This presentation will introduce the measurement results of the K-B mirrors and the analysis. We can see the mirror shape error, ellipse fitting parameters and instrument error in detail.

*Work performed at IHEP was supported by the project of X-ray Mirror Innovation Cross Team, Chinese Academy of Sciences, JCTD-2020-02.

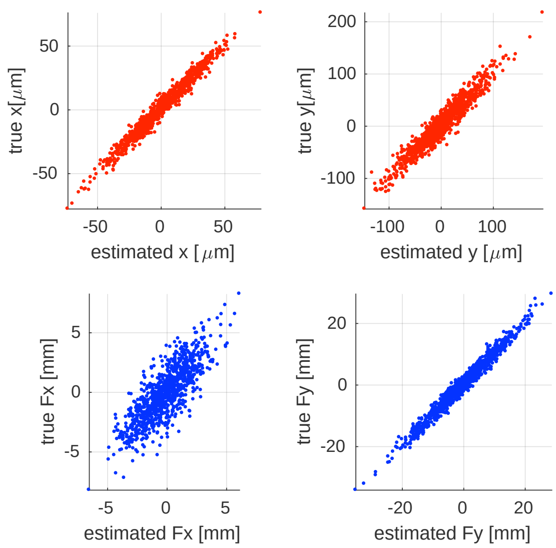
Strategies for focus and position stability based on the beamline error response matrix

Josep Nicolas*, Damià Garriga, Nahikari González, Judit Juanhuix

ALBA Light Source Facility, Carrer de la Llum 2-26, Cerdanyola del Vallès, 08290 Barcelona, Spain

**e-mail: josep.nicolas@cells.es*

Abstract



In this work, we describe the strategy to stabilize the beam at the sample position of a microfocus macromolecular crystallography beamline (BL06-XAIRA). This beamline achieves a spot size on sample of 1x1 μm^2, and therefore requires the position and focus to be stable well within the micron, also during acquisition. As in many other beamlines, the sample environment does not leave room for an x-ray beam position monitor (xBPM) close enough to the sample. That means, that angular drifts of the beam, not measurable by the xBPM, may lead to differences between the xBPM signal and the actual position of the beam, making it useless for such a small focus beamline. These angular drifts are caused by the positioning errors of all the optical elements upstream the beamline, up to and including the source.

We propose a method to evaluate the impact of these errors at the same time that allows studying more complex detection configurations, like combining several xBPMs, or other physically measurable signals.

The method is based on the Error Response Matrix (ERM) of the beamline. This is the matrix that gives the linear approximation to the dependence of the positions of the beam at the sample plane, xBPM plane, etc., as a function of all the possible misalignments of the optical elements of the beamline. The matrix is obtained by a Monte Carlo simulation. It consists on running multiple iterations of the beamline raytracing adding random errors to the position and angles of all the optical elements, and recording the corresponding positions at the different planes of interest. The resulting data is then used to run multivariable linear regression that gives the matrix elements of the ERM.

Once the matrix is obtained, one can use it to determine the dependence between the xBPM readout position and the true position on sample, as well the probability of the residual error. In the case of BL06-XAIRA, this error is 4 μm in horizontal, and 14 μm in vertical, too large for a 1x1μm^2 spot.

The method also allows including additional xBPMs to the evaluation of the spot position, and provides the coefficients of the corresponding formula. It can incorporate also other measurable variables, for instance some position parameter of the optical elements. In the case of XAIRA, adding a second xBPM is not enough, but adding an accurate measurement of the pitch angle of the focusing mirrors (assuming we use a distance measuring interferometer) allows determining the position of the spot on sample from indirect measurements, with an error below 0.12 μm (H) and 0.09 μm (V).

Keywords: Optics, Metrology, Stitching, Interferometry, X-ray.

References:

A Fizeau interferometry stitching system to characterize X-ray mirrors with sub-nanometre errors

Murilo B. da Silva*, Simon. G. Alcock, Ioana-Theodora Nistea, Francis Bailey, and Kawal Sawhney

Diamond Light Source Ltd, Harwell Science and Innovation Campus, Didcot, OX11 0DE, UK

*e-mail: murilo.bazan-da-silva@diamond.ac.uk

Abstract

We present an adaptable, Fizeau interferometer stitching system [1] designed to characterize the surface profile of the most challenging X-ray optics for synchrotron and free electron laser sources. The Fizeau stitching system, developed in the Optics Metrology Lab [2] at Diamond Light Source, is advantageous for two reasons: it significantly extends the optical length and curvature range which can be measured by the interferometer; and the stitched result has enhanced accuracy due to a large redundancy of data and suppression of systematic errors.

A Zygo Verifire HDX Fizeau interferometer with a 150 mm diameter output laser beam is mounted on an adjustable support platform. Finite element analysis guided the design of the support platform to minimise the transmission of vibrations between the optical table and the interferometer. A stack of motorised stages provides 4-degrees of translation and rotation to move and orient the surface under test relative to the Fizeau interferometer's beam. Controls software was developed in-house to synchronise Fizeau acquisition with coordinated motion of the mirror under test. Overlapping sub-aperture Fizeau images are combined using the PyLOSt stitching software [3] produced by the MooNpics collaboration [4]. Python scripts automate the processing of pre- and post-stitched interferometer images.

After careful minimisation of the Fizeau's systematic errors, several challenging optics were investigated to quantify the system performance. Nanometre-level agreement was obtained with the Diamond-NOM slope profiler and a Bruker GTX stitching micro-interferometer. Any individual HDX scan, relative to the average of the ensemble, has an average slope error repeatability of < 15 nanoradians rms. Compared to measurements by the Diamond-NOM, a reproducibility of < 25 nrad rms was achieved for an elliptically curved mirror. This provides confidence that the HDX can reliably measure X-ray mirrors with slope errors < 50 nrad rms. Finally, we demonstrate that this new system can provide high-quality metrology inputs for deterministic ion beam figuring to iteratively improve the slope error of an X-ray optic to < 100 nrad rms, and ultimately to extend beyond the current state-of-the-art.

Keywords: Fizeau interferometry, sub-aperture stitching, metrology system development

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Specifications of beamline optics towards next generation light sources - contamination free and figure errors of under 50 pm

H. Ohashi[1,2*], H. Yumoto[1,2], T. Koyama[1,2], Y. Senba[1,2], H. Yamazaki[1,2]

1 Japan Synchrotron Radiation Research Institute, 2 RIKEN SPring-8 Center

*e-mail: hohashi@spring8.or.jp

Abstract

Next generation light sources can generate x-rays with high brilliant and high degree of transverse coherent, which expands the applicable targets on various applications such as diffraction coherent imaging and ptychography. The key issues of the beamline optics are to preserve coherence. We investigate the sources which disturb coherence to improve uniformity of beam image.

Various surface contaminations on silicon crystals and mirrors result in non-uniformity of x-ray beam. It is important to handle the optical elements in clean environment, which are few sticky chemicals and less-particles of over several-tens-microns size, as well as to install the optics in an ultra-high vacuum [1]. Speckle from a vacuum window of Beryllium also is conspicuously observed on the beam image depending on the distance between window and sample. Since control of the purity and defects in Be foil is difficult, we should design a vacuum system of beamline to reduce the number as much as possible.

Advances in the technologies on surface-polish and metrology have fulfilled to adequate quality to total reflection x-ray mirrors for completely spatial coherent light sources such as XFELs. High-precise x-ray mirrors with figure errors of 1 nm or less are widely used in x-ray beamlines as a diffraction-limited focusing optics and higher order suppressing mirrors. In particular, figure errors in the mid-spatial-frequency (MSF) range directly cause fringes on an x-ray image. For example, the intensity fluctuation on a reflected image from two sets of plane mirrors with figure errors of 0.2 nm in MSF was observed +/- 6%. It was improved to +/- 3% after the surface was re-polished to the errors of 0.1 nm or less in MSF. In the case of the substrate for a 100 keV multi-layer monochromator to provide high-energy and extremely high-flux beam [2,3], ultra-fine surface with less than 50 pm in MSF is estimated to improve the beam uniformity.

In this paper, we report on the present status of uniformity in beam image affected by plane mirrors and vacuum windows, which are also indispensable for next-generation light sources. We are in the early days of diffraction-limited light sources and discuss specifications of beamline optics for the coming light source recognizing some of key issues already revealed at SPring-8.

Keywords: x-ray mirror, high-energy high-flux, multilayer monochromator, Be window, speckle, contamination

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PZT bimorph mirror to reduce the "Junction effect"

Yoshio Ichii[1], Akira Miyake[1], Shinya Aono[1], Shinsaku Shiroma[1], Hiroki Nakamori[1], Masahiko Kanaoka[1], Hiromi Okada[1], Takato Inoue[2,3], Satoshi Matsuyama[2,3], and Kazuto Yamauchi[3]

1. JTEC Corporation, 2-5-38, Saito-Yamabuki, Ibaraki, Osaka, JAPAN
2. Nagoya University, Furo-cho, Chikusa-ku, Nagoya, Japan
3. Osaka University, 2-1, Yamadaoka, Suita, Osaka, Japan

Email: yoshio.ichii@j-tec.co.jp

Abstract

PZT (lead zirconate titanate) bimorph mirrors have been widely used in X-ray regimes [1-3]. However, when the mirror length is long over 160 mm, the entire optical area cannot be covered by a single PZT bar tangentially because there is a limit to the fabrication size of a single PZT bar plate. Therefore, a gap is inevitably existing between the PZT bar plates at the case such as 400 mm long. The cross-sectional second-order moment of this gap area differs from that of the PZT bonded area, resulting in an undulation when bending by applying voltage (the junction effect). In this study, we developed a PZT bimorph mirror that does not undulate when bent. At the structure where the separated PZTs according to channel number and bonded to the top and bottom surfaces of the mirror, the junction effect due to gap was reduced by keeping a certain distance from the edge of the PZT to the effective area, in which level can be acceptable for coherent beamlines.

Keywords:
Xray Mirror, Bimorph, Adaptive, PZT

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Reflection Zone Plates on Curved Substrates

Jürgen Probst[1], Heike Löchel[1], Anke Teichert[1], Julia Braenzel[2], Holger Stiel[2], Thomas Krist[1], Alexei Erko[3]

[1]NOB Nano Optics Berlin GmbH, Krumme Straße 64, 10627 Berlin, Germany
[2]Max Born Institute, Max-Born-Straße 2A, 12489 Berlin, Germany
[3]Institute of Applied Photonics (IAP) e. V., Rudower Chaussee 29/32, 12489 Berlin, Germany

e-mail address: *info@nanooptics-berlin.com*

Abstract

Two major steps in the development of reflection zone plates (RZP) were accomplished in the last years: they were built on curved substrates and their structure was improved. Thus, a new generation of highly efficient diffractive optical elements is now available: hybrid reflection zone plates on spherical substrates (HRZP).

In comparison to the "conventional" elliptical RZP with a point focus, the HRZP produces a straight, two-dimensional (2-D) line segment focus. The 2-D diffractive structure of the HRZP allows for a relaxed line density at the sagittal edge of the RZP and thus, the aperture of the HRZP is no longer strictly limited. A spherical surface allows to build flat-field spectrometers with a broad energy range for different applications in soft X-ray spectroscopy [1-2].

In this poster, we present results from the first experimental investigations of RZP and HRZP, which were realized on spherical substrates with radii of 55 m, 29 m and 3.8 m.

For the first time, we used elliptical RZPs on spherical substrates to construct a high-resolution fluorescence spectrometer, as described in [1]. Here, the RZP was fabricated on a spherical substrate with a radius of 29 m and covered the photon energy range of (150 – 750) eV with a spectral resolving power $E/\Delta E > 2000$.

Also, for the first time an HRZP was tested at the Max Born Institute (MBI) in the spectrometer at a laser produced plasma (LPP) source [2]. It had a radius of 55 m and covered an energy range of (150 – 1300) eV with a spectral resolving power of up to $E/\Delta E = 1000$.

Finally, an HRZP was tested in a wavelength dispersive x-ray spectrometer WDSX, which can be used at electron microscopes. It had a radius of 3.8 m and covered an energy range of (35 – 850) eV with a spectral resolving power at the Fermi edge of Al at 72 eV of $\Delta E = 0.3$ eV.

This research was funded by the Berlin Program "ProFiT" in the project "MOSFER" with grant numbers 10168769 for IAP, 10168775 for NOB and 10168892 for MBI, co-funded by the European Regional Development Fund (ERDF).

Keywords: Reflection zone plates, curved substrates, soft x-ray spectroscopy.

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Optical metrology for full characterization of mirror benders

Igors Sics*, Jordi Prat, Marta Llonch, Jon Ladrera, Josep Nicolas

ALBA Light Source Facility, Carrer de la Llum 2-26, Cerdanyola del Vallès, 08290 Barcelona, Spain

**e-mail: igors.sics@cells.es*

Abstract

In the last years, our metrology laboratory has qualified and calibrated more than 50 mirror benders, with different designs, lengths, and specification levels. In this work we present the usual test procedures and describe the analysis tools we use to provide a complete characterization of the mirror bender behavior. Most of these tests are not standard, and have been developed to determine particular aspects of the bending system.

In the general case, the goal of a metrology job is threefold: First, one does measurements to do the fine tuning of the bender, for instance to adjust twist, gravity sag compensation or bending range. Then, one tests that the bender and optics system meets its contractual specification requirements, like repeatability, stability, resolution, or slope error at the nominal figure. These tests often reveal features of the mirror bender, that are not strictly specification parameters, but provide information about the mechanical behavior of the system. This is, for instance the case of the stability of variations of the gravity sag compensation, the changing parasitic roll and pitch, or the crosstalk between the two bending actuators. Finally, one important goal of the metrology campaign is to provide a calibration of the bender. This is, to provide the final user with equations and parameters that allow operating the bender at the beamline. The difficulty here is to describe the bender in a useful way for the final user, more interested in the spot size and figure, than in the response of the bender to each actuator.

The basic instrument we use for this characterization is the ALBA-NOM, but it is not the only one. The stitching interferometry platform is tremendously useful during the adjustment of the twist, as well as to check the symmetry of local deformations at the mirror clamps, even to determine the nature of some 4^{th} order, polynomial errors. For the rest of the tests, one-dimensional profiles are sufficient, and the NOM provides them with higher accuracy in much shorter time than the interferometer.

In order to determine the contribution of the bender to the observed mirror profiles, we often use a deformation model of the mirror, based on the elastic beam theory. This allows, for instance determining the forces required at each gravity sag compensation spring, or what are the motor positions required to obtain the nominal ellipse. The elastic beam theory is also used to analyze the contribution of the bender to the repeatability, or stability errors, and allows understanding deviations from the expected behavior when they occur.

Keywords: Optics, Metrology, Active Optics, x-Rays

Development and the optimization of X-ray optics-on-chip for nano-focusing synchrotron beamlines

H. van der Velde[1], M. Lyubomirskiy[2], F. Seiboth[2], W.T.E. van den Beld[1], M.D. Ackermann[1], C.G. Schroer[2] and I.A. Makhotkin[1]

1. Industrial Focus Group XUV Optics, MESA+ Institute for Nanotechnology, University of Twente, Enschede, The Netherlands
2. CXNS – Centre for X-ray and Nano Science, Deutsches Elektronen-Synchrotron DESY, Notkestraße 85, 22607 Hamburg, Germany

e-mail: h.vandervelde@utwente.nl

Abstract

Modern synchrotron radiation sources such as MAX IV, ESRF, and the developing project of PETRA IV are based on diffraction-limited storage rings capable of generating ultra-high brilliance X-ray beams. Because of the very small sizes of the X-ray source, such beams can potentially be focused down to nm-size beams using special X-ray optics.

Si nano-focusing lenses (NFLs) are currently one of the most used concepts of refractive X-ray lenses capable of focusing of X-ray to sub 100 nm beam sizes. The NFLs are fabricated through reactive ion etching of Si. A typical focusing lens consists of an array of identically shaped lenses. The quality of the focused spot is directly dependent on the accuracy with which the designed array of lenses can be transferred into Si wafer. To create an aberration-free wavefront of a focused beam the lenses should have perpendicular sidewalls with minimal sidewall roughness over the total depth of ~50 um. A discrepancy between the designed and manufactured structures should be as small as 100nm. We have optimized the Si etching process to fulfill these criteria. The first batch of Si lenses was already characterized at beamline P06 on Petra III synchrotron.

The next step in developing X-ray optics is replacing Si with more thermally and radiation stable material. We have made the first attempt to manufacture SiC NFLs. We will present an optimization of clean-room etching processes for making Si and SiC NFLS at our MESA+ cleanroom.

Keywords: Nano-Focusing lenses, Silicon, Silicon Carbide

Recent progress on the focusing long trace profiler at HEPS/BSRF

Ming Wu, Fugui Yang*, Quan Cai, Ming Li, Weifan Sheng
Beijing Synchrotron Radiation Facility, Institute of High Energy Physics, Chinese Academy of Sciences, 19B Yuquan Road, Shijingshan, Beijing, China 100049
*Email: yangfg@ihep.ac.cn

Deflectometric profiler based on f-θ principle such as long trace profiler(LTP) and NOM have been widely used in X-ray optics surface metrology. Considering the sampling spot on the surface under test, those profilers so far perform well on profile metrology for error at spatial frequency lower than $1mm^{-1}$. But it is very difficult to recover sub-millimeter profile information. In 2019, a new LTP which uses sub-millimeter focused light spot to scan the sample has been proposed and tested. In this paper, we report on a specifically designed profiler system with high-accuracy long-trace platform carrying the focus-type optical head. This paper includes a review of several numerical simulations and practically experiments performed on Focusing LTP(FLTP). Spatial frequency response calibration simulation with chirped sample shows the advantage in spatial resolution. Defocus test corroborates the ability to adjust spatial resolution. The test on curved mirror proves its capability of highly curved mirror measurement.

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Optical coherence tomography using extreme ultraviolet source as a tool for metrology of multilayer optics

Antony Jose Arikkatt*, Przemysław Wachulak, Andrzej Bartnik, Henryk Fiedorowicz

Institute of Optoelectronics, Military University of Technology, 00-908 Warsaw, Poland

*email: antony.arikkatt@wat.edu.pl

Abstract

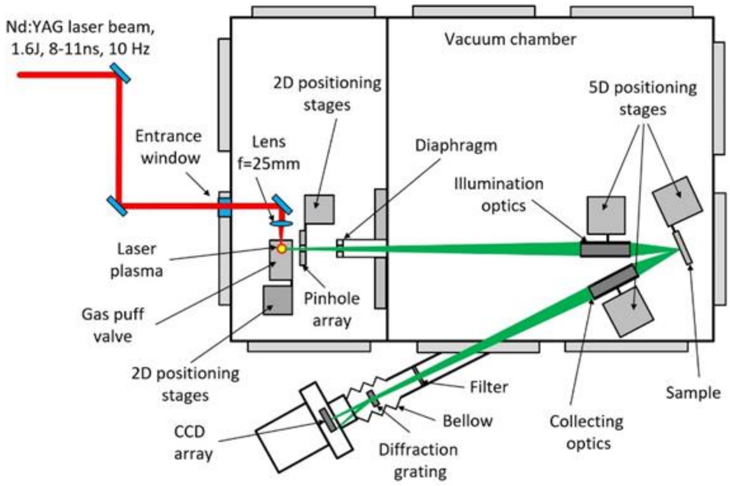

Figure 1. Schematics of experimental set up for XCT system

Optical coherence tomography (OCT) is a well-established interferometric imaging technique providing high resolution cross-sectional views of objects. The axial resolution of OCT is limited to about 1 µm when using infrared and optical wavelengths. The obvious way to improve resolution is to use short wavelength sources. Optical coherence tomography using broad bandwidth extreme ultraviolet (EUV) and soft X-rays (SXR) has been recently proposed [1,2]. This OCT variant, referred to as X-ray coherent tomography (XCT), allows the reduction of axial resolution from micrometers to a few nanometers. The XCT imaging with axial resolution better than 8 nm was demonstrated using extreme ultraviolet and soft X-rays from a synchrotron [1]. Tomographic imaging with an axial resolution of about 22 nm has been recently demonstrated using extreme ultraviolet from a laser-driven light source based on high-order harmonic generation (HHG) [2]. A depth profile of multilayer optics with 2 nm axial resolution was measured using a compact laser plasma light source based on a gas puff target [3]. This shows the potential of this new imaging technique for use in metrology of multilayer X-ray optics.

Here we present a newly developed XCT system based on laser produced plasma EUV source and EUV focusing optics equipped with 2D scanning of the sample. Scheme of the system is shown in Figure 1. A nano second laser pulse with an energy of 900 mJ is used to produce a broadband EUV radiation from a Kr:Xe plasma . The system characteristics and the XCT measurements of a fabricated multilayer structure are presented. We also present postprocessing techniques to improve the quality of the reconstructed 3D image of the multilayer sample.

Keywords: multilayer optics, metrology, extreme ultraviolet

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Coherence diagnostics for synchrotron beamlines using the Fourier-analysis method: Enabling systematic time-resolved 2D spatial-coherence studies

K. Bagschik[1*], M. Schneider[2], J. Wagner[3], R. Buss[3,5], M. Riepp[1], A. Philipi-Kobs[1], L. Müller[1,6], W. Roseker[1], F. Trinter[1,7], M. Hoesch[1], F. Scholz[1], J. Seltmann[1], J. Buck[1], J. Viefhaus[8], S. Eisebitt[2], G. Grübel[1,5], H. P. Oepen[3,5], R. Frömter[3,4]

[1] DESY kai.bagschik@desy.de, matthias.riepp@desy.de, andre.kobs@desy.de, leonard.mueller@desy.de, wojciech.roseker@desy.de, moritz.hoesch@desy.de, frank.Scholz@desy.de, joern.seltmann@desy.de, jens.buck@desy.de, gerhard.gruebel@desy.de, [2] MBI Berlin, mschneid@mbi-berlin.de, eisebitt@mbi-berlin.de, [3] CHyN Hamburg, Jochen.Wagner@inficon.com, ralph.buss@physik.uni-hamburg.de, oepen@physnet.uni-hamburg.de, [4] JGU Mainz, rfroemte@uni-mainz.de, [5] CUI Hamburg, [6] Universität Hamburg, [7] FHI Berlin, florian.trinter@desy.de, [8] HZB Berlin, jens.viefhaus@helmholtz-berlin.de

*e-mail: kai.bagschik@desy.de

Abstract

The spatial-coherence properties of X-ray radiation at synchrotron beamlines are playing a decisive role for the performance of coherence-based experiments and ideal focusing capabilities. Tools for beam-coherence diagnostics are essential in this context, not only for the preparation and operation of these experiments but also in order to identify sources of spatial-coherence degradation within beamlines. There is a growing demand for spatial-coherence measurements at synchrotron beamlines, not least because of present and future upgrades of synchrotron facilities to diffraction-limited storage rings.

The Fourier-analysis method is based on small-angle scattering from an object with controlled spatial randomness. It is able to perform systematic and time-resolved two-dimensional spatial-coherence measurements at synchrotron beamlines, such as the soft X-ray beamline P04 at PETRA III. Due to the simple and fast analysis, systematic coherence studies for various beamline settings and photon energies can be carried out in a short time [1]. The time-resolved aspect means that the spatial-coherence properties can be studied on time scales comparable to beamline optics vibrations. For this purpose, the Fourier-analysis method with an integrated curved-grating beam monitor is used [2,3]. The direct and simultaneous monitoring of the photon beam not only circumvents the otherwise necessary separate determination of the illuminating intensity distribution required for the Fourier-analysis method, but also allows direct access to temporal changes in the size, shape, and position of the photon beam at the sample position.

Keywords: Coherence, Synchrotron Radiation, Diagnostics

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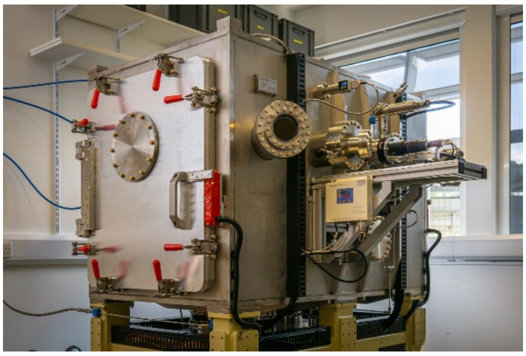
Ion Beam Figuring (IBF) of X-ray mirrors at Diamond Light Source

Matthew Hand*, Simone Moriconi, Hongchang Wang, Simon Alcock, Murilo Bazan Da Silva and Kawal Sawhney

Diamond Light Source, Harwell Science & Innovation Campus, Didcot, OX11 0DE, UK

e-mail: matthew.hand@diamond.ac.uk

Abstract



The quality of synchrotron X-ray mirrors is often a limiting factor in the performance of many beamlines. Deterministic ion beam figuring (IBF), based on metrology feedback, is commonly used to manufacture high-quality mirrors with slope errors of << 500 nanoradians. At Diamond Light Source, an in-house IBF system has been developed [1] that incorporates a laser speckle angular measurement (SAM) instrument [2] to reduce the time required for each IBF iteration. This on-board metrology system enables fast, in-situ measurements of the optical surface before and after each figuring run to better characterize and more quickly guide the IBF removal process. Comparisons between ex-situ metrology (interferometry and profilometry) and the on-board SAM system have confirmed that the surface profile of test mirrors is considerably improved by IBF processing that utilizes these in-situ measurements. Such fast correction of mirror surface errors will open new routes for the development of next-generation super-polished X-ray mirrors. Additionally, with the forthcoming Diamond-II [3] storage ring upgrade, there is scope for the IBF system to refurbish and improve existing mirrors with a fast turnaround time.

Keywords: ion beam figuring, optical metrology, X-ray optics, synchrotron radiation

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Recent developments and applications of X-ray speckle-based techniques at the Diamond Light Source

Lingfei Hu[1*], Hongchang Wang[1], John Sutter[1], Oliver Fox[1] and Kawal Sawhney[1]

[1] Diamond Light Source Ltd., Harwell Science and Innovation Campus, Didcot, Oxfordshire OX11 0DE, United Kingdom

*e-mail: lingfei.hu@diamond.ac.uk

Abstract

Over the last decade, X-ray speckle-based techniques have been successfully demonstrated for both in-situ at wavelength metrology and advanced X-ray imaging at the Diamond Light Source (DLS) [1, 2]. Three types of speckle-based techniques will be introduced in this talk. Firstly, a self-reference X-ray speckle scanning technique has been developed to measure the spatial variation of the curvature of a wavefront. Wave optics theory predicts a direct relationship between the curvature of the wavefront and the intensity distribution of an image taken in the far-field, and this has been confirmed experimentally [3]. The wavefront of the incident beam is typically entangled with the measured wavefront from a test optic. To overcome this issue, a two-dimensional absolute measurement of the wavefront can make use of the reference beam to eliminate the influence of the incident beam. Plane mirrors have been measured using this method and allow the correction of any roll angle misalignment. Finally, fast wavefront sensing using a novel Alternating Speckle Tracking (AST) method has been demonstrated. This technique requires a simple setup to make temporally-resolved measurements. The AST method has been used to monitor the dynamic behaviour of a bimorph mirror. The time resolution is limited by the hardware capabilities of the B16 Test Beamline at the DLS. These three examples demonstrate that X-ray speckle-based techniques can be valuable tools for the rapid alignment and optimisation of optics and samples on synchrotron and free-electron laser beamlines.

Keywords: X-ray optics, speckle-based technique, in-situ metrology, wavefront measurement

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The challenge of precise grating characterization using AFMs at HZB

Jeniffa Knedel[1]*, Svyatoslav Alimov[1], Oliver Kutz[1], Stephanie Lemke[1], Tino Seliger[1], Andrey Solokov[1]

[1] Helmholtz-Zentrum Berlin für Materialien und Energie, BESSY-II, Albert-Einstein-Str. 15, 12489 Berlin, Germany

*e-mail: j.knedel@helmholtz-berlin.de

Abstract

The gratings group at Helmholtz-Zentrum Berlin (HZB) uses AFMs to precisely characterize the grating profiles. Currently, we run two Nanosurf NaniteAFM systems and one Nanosurf FlexAFM [1, 2] both of which are used during the grating manufacturing process. Although using this measurement technique seems to be straightforward for our purpose, we face a variety of challenges. These include calibration accuracy, nonlinearities of scanners and angle deviations observed at small transverse measurement fields.

Since the blaze angle is of large importance, both the lateral direction and height calibration of the AFM must be accurately set in order to ensure the blaze angle is determined correctly. For grating line densities of 500 to 2400 lines/mm at a typical blaze angle of 1° one has to characterize structure heights in the range of 35 nm down to below 10 nm. Possible scanner nonlinearities motivate the need for calibration standards designated for these height ranges. Commercially available calibration probes usually have large tolerances especially in height direction. Given the data in [3], typical errors for a 20 nm height standard are about ± 1.5 nm, transferring into an error on the blaze angle of about ± 7.5%. Taking lateral tolerances of approximately ± 1.5% into account, this limits the accuracy of the blaze angle to below 10%. In turn, this motivates us to manufacture and characterize our own better-known standard gratings covering suitable z- ranges down to 10 nm. Our primary calibration standard is characterized to have a height of (9.5 ± 0.2) nm by at-wavelength reflectometry at HZB. Considering this improved height tolerance only, we were able to reduce the blaze angle uncertainty to around ± 2% compared to the ± 7.5% mentioned before for the commercial standard.

The challenges we faced in production and especially in verification of our AFM standards by reflectometry measurements and simulations are summarized in this work. Furthermore, our AFM calibration procedures and the remaining uncertainties on the blaze angle are outlined, taking into account our experiences with scanner nonlinearities.

Keywords: grating, blaze, AFM, measurement, calibration, nonlinearities

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Wavefront measurements for high heat road optics by using Talbot interferometer with calibrated gratings

Takahisa Koyama[1,2*], Takamitsu Saito[1], Satsuki Shimizu[1], Yasuhiro Shimizu[1], Hikaru Kishimoto[1], Hirokatsu Yumoto[1,2], Yasunori Senba[1,2], Hiroshi Yamazaki[1,2], Jumpei Yamada[2], Yoshiki Kohmura[2] and Haruhiko Ohashi[1,2]

[1]Japan Synchrotron Radiation Research Institute, 1-1-1, Kouto, Sayo, Hyogo 679-5198, Japan,
[2]RIKEN SPring-8 Center, 1-1-1 Kouto, Sayo, Hyogo 679-5148, Japan

[*]e-mail: *koyama@spring8.or.jp*

Abstract

Distortion of beamline optics such as crystals of monochromator and mirrors due to heat load, figure error, and clamping appears as low-order errors of wavefront distortion, resulting in shift of light source position. This affects the focusing optics to shift the focal point and/or degrade the focus size. This effect is observed to vary the wavefront radius of curvature (ROC), which can be measured by using wavefront measurement techniques such as Talbot interferometer [1,2].

There are two types of Talbot interferometers, one with single grating and the other with double grating. The single grating interferometer is often used to measure the wavefront of a divergent beam from a focal point formed by focusing optics. In the case of measurement of unfocused beam (near parallel beam), a self-image formed by the phase grating G1 is comparable to the grating structure, thus a high-resolution imaging detector is required. By arranging the second grating (absorption grating G2) at the position of the Talbot distance, moire fringes can be formed and easily observed. The double grating Talbot interferometer can be used to estimate the deviation of the light source position on the wavefront of the beam, however, an error in the grating period appears as an error at this deviation.

In this study, we precisely measured the deviation of the grating periods p_1 and p_2 of the two gratings of G1 and G2 by using a quasi-parallel beam generated in a 1 km beamline, BL29XU-L of SPring-8. The source position was determined by placing a virtual light source far away from an observed point. The virtual light source was formed by a TC slit placed at 50 m from the undulator light source. The X-ray beam was observed at 938 m from the virtual light source. The double grating Talbot interferometer was constructed in front of the imaging detector. The experimental condition, for example, was as follows: Si phase grating G1 and Au absorption grating G2 were used; specified grating periods p_1, p_2 = 4.8 µm; The 1st order Talbot distance was 115 mm at X-ray energy of 12.4 keV. In the case of these gratings, measured wavefront ROCs were 1003 m and 768 m when using grating set A and B calculated using specified grating period, respectively. These values were calibrated to 938 m. The differences between p_1 and p_2 were 10 ppm and 30 ppm of grating set A and B, respectively. Using these results, we have been measuring the heat load tolerance of various beamline monochromators and focusing beams.

Keywords: Talbot interferometer, grating interferometer, wavefront measurement

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A hybrid measurement scheme for nanometrology using soft X-rays

Leonhard Lohr[1*], Richard Ciesielski[1], Analía Fernández Herrero[2], Andreas Fischer[1], Alexander Grothe[1], Frank Scholze[1], and Victor Soltwisch[1]

[1] Physikalisch-Technische Bundesanstalt (PTB), Abbestraße 2-12, 10587 Berlin, Germany, [2] Helmholtz-Zentrum Berlin für Materialien und Energie (HZB), Albert-Einstein-Straße 15, 12489 Berlin, Germany

*e-mail: *leonhard.lohr@ptb.de*

Abstract

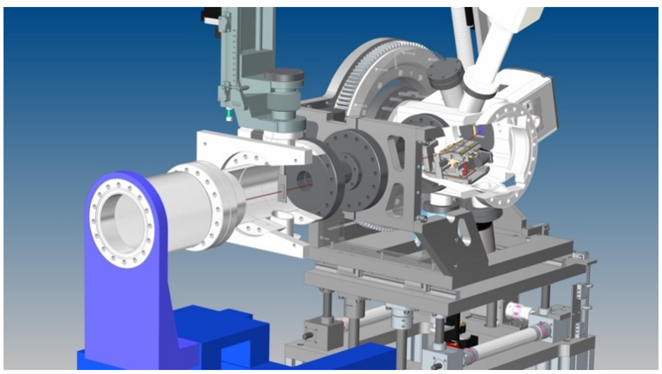

Figure 1: Small angle soft X-ray scattering and fluorescence chamber at relaxed position where the angle of incidence of the beam (red line) is 15 degrees.

Modern technological products, such as advanced integrated electronic circuits, work with ever smaller and more complex three-dimensional nanostructured semiconductor surfaces. Such devices need to work with ever tighter tolerances on their geometry. Therefore, advanced metrology is an important enabler for the technological development. Especially, optical metrology is an all-rounder in this field. Linear gratings with small spacing and high aspect ratio are prototypes for the metrology challenges in semiconductor production. Methods such as small angle X-ray scattering or X-ray fluorescence under grazing incidence are used to determine geometrical dimensions and the shape of metrology test structures with uncertainties in the sub-nm range [1, 2]. But, also measuring nanostructured surfaces on small test patterns on dies from semiconductor fabs is an important metrology challenge. By using these methods, the photon beam spot size is too large for sufficient accurate measurements achieved with advanced optical metrology.

We present a setup, mounted on the SXUV-beamline at PTB's laboratory at the electron storage ring BESSY II in Berlin. The design of this setup is based on previous proof-of-principle experiments for angle resolved scatterometry [3]. The setup works with synchrotron radiation in an ultra-high vacuum without lubricants. Its small and compact design enables detection of scattered monochromatic soft X-rays under angles of incidence up to 30 degrees. The large angle reduces the photon beam spot size. An area detector covers diffraction patterns like them from scattered hard X-rays under grazing incidence. Depending on the incident photon energy, fluorescence from the comparably small, excited regions of the sample can be measured simultaneously with a silicon drift detector.

We present first measurement results from small test patterns which are located by imaging the surface using a wide photon beam.

Keywords: extreme ultraviolet, soft X-ray scattering, soft X-ray fluorescence, photon beam spot size

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Single-shot wavefront characterisation employing ptychography at X-ray free-electron lasers

Masoud Mehrjoo[1], Konstantin Kharitonov[1], Mabel Ruiz-Lopez[1], Barbara Keitel[1], Svea Kreis[1], Martin Seyrich[1], Elke Plönjes[1].

1 Deutsches Elektronen-Synchrotron (DESY), Notkestr. 85, 22607, Hamburg, Germany.

*e-mail: masoud.mehrjoo@desy.de

Single-shot characterisation of X-ray free-electron laser (FEL) pulses is of vital importance to control experiments. We report on ptychographical wavefront imaging of soft X-ray pulses, focused by a pair of Kirkpatrick–Baez mirrors. We developed a ptychography algorithm based on automatic differentiation, which is a modern computational technique adopted from deep learning and mainly used to solve optimisation problems. The proposed ptychography [1] routine can reconstruct the main coherent modes of the FEL pulses together with unique modal weights for each shot. Shot-to-shot fluctuations of the light pulses and partial spatial coherence can be numerically integrated into the proposed routine as optimisable parameters. This unique feature is solely achievable by utilizing automatic differentiation.

Keywords: Single-shot characterisation, ptychography, free-electron lasers, automatic differentiation

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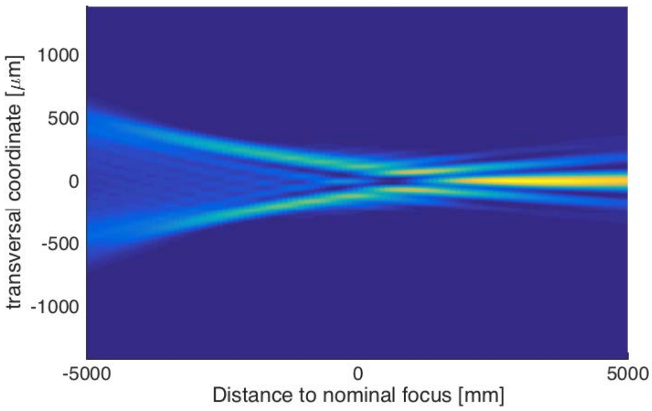
WOW, a quick wavefront propagation simulation tool for beamline design and specification

Josep Nicolas*[1], Daniele Cocco[2]

[1]ALBA Light Source Facility, Carrer de la Llum 2-26, Cerdanyola del Vallès, 08290 Barcelona, Spain
[2]ALS, 1 Cyclotron Rd, Lawrence Berkeley National Laboratory, Berkeley, CA 94720-8229, USA

*e-mail: josep.nicolas@cells.es

Abstract



We present WOW (Wave Optics Workshop), a wavefront propagation code specifically designed as a tool for beamline design and specification. The code, written in Matlab, consists on a series of functions, data structures, and methods that allows for quick and accurate calculation of the propagation of a coherent wave along a multi-element optical system.
The basic element of the code is the Fresnel-Kirchhoff diffraction formula, which allows obtaining the amplitude propagation between any two points of space through an arbitrary surface. Although the equation is exact for arbitrary surfaces (within the scalar theory) and it does not require any projection on any coordinate transformation, it still requires heavy computing, as it involves looping over 6 variables, corresponding to the two dimensions of the two continuation planes, and a double integral over the optical surface. In order to achieve workable computation speed, it is necessary to reduce the dimensionality of the problem.
In the first place, WOW calculates only the meridional plane of the problem, as other codes do. This is a limitation considered acceptable, since most optical systems in DLSRs and FELs use only meridional curvature. The absence of sagittal focusing allows separating the calculations of the vertical and horizontal planes, therefore reducing the dimensionality of the problem from 6 to 3.
On the second place, WOW does not use arbitrary continuation planes between the different optical elements of the beamline, but only in the vicinity of the conjugate planes of the source. This is a unique feature of WOW, which has several advantages. On the one hand, at these planes the beam size is small. The small beam size allows limiting the maximum angular frequency that is calculated, and this limits the required number of samples over the mirror surface that need to be calculated for the integral to converge. On the other hand, at conjugate planes, one can assume translation invariance coordinate transformations between planes. This means that one can calculate the point spread function (PSF) of a single point and then perform the convolution with the amplitude distribution at the object plane. These assumptions allow reducing the dimensionality of the problem to 2, at the same time that minimizes the number of required samples on the mirror. This allows for most typical propagations to be computed in a matter of few seconds.
None of the assumptions of WOW implies any approximation or limitation on the surface or on the distance between optical elements, and therefore it provides an accurate calculation for arbitrary surface errors, independently of the nominal figure, and independently of the magnification of the system.
The speed and accuracy of the code, makes of WOW a very useful tool for beamline design. It is especially useful to integrate wavefront propagation calculations in optimization loops, where many iterations are typically needed. There are many other situations where multiple propagation computations are useful. For instance, exploring the beam near the focus plane (see figure), or calculating the spectral resolution of a grating monochromator, by propagating a range of wavelengths to the exit slit plane. In summary, WOW provides the optical designer the tools to have quick answers when exploring different concepts of the optical system, for better understanding of it, and for a more efficient problem solution.

Keywords: Optics, Wavefront propagation, Simulation, X-ray, Beamlines.

Latest results of pure ellipsoidal surfaces figure

Iulian Preda,
Crystopt-X®, 261 35 – Landskrona Sweden

Abstract

A severe improvement of the beam transport elements – x-ray optics - is imposed by the fourth generation, diffraction limited synchrotron radiation sources. Now, a need for simultaneous focusing in both, horizontal and vertical plane using higher than ever precision optics became stringent.

Successive iterations of surface finishing and figuring results are presented here together with the evolution of surface quality of an ellipsoidal element with optical surface of 20x260 mm and of about 9 to 1 focusing ratio.

Super-resolution image reconstruction for surface metrology of x-ray optics

Simon Rochester,[1*] Keiko Munechika,[2] Ian Lacey,[3] Peter Z. Takacs,[4] and Valeriy V. Yashchuk[3]

[1]Rochester Scientific, LLC, 2041 Tapscott Ave., El Cerrito, CA 94530, USA
[2]HighRI Optics, Inc., 5401 Broadway Terr., St. 304, Oakland, CA 94618, USA
[3]Advanced Light Source, Lawrence Berkeley National Laboratory, Berkeley, CA 94720, USA
[4]Surface Metrology Solutions LLC, 19 S 1st St., Minneapolis, MN 55401 USA

*e-mail of corresponding author: simon@rochesterscientific.com

Abstract

We present experimental, analytical, and numerical methods developed for reconstruction of two-dimensional surface-height profiles of x-ray optics to recover information at spatial frequencies beyond the nominal resolution of the measuring instrument. Image degradation due to the nonideal instrument response is deconvolved using the measured instrument transfer function (ITF).

We measure the ITF using a recently developed technique based on test standards patterned with a binary pseudo-random array (BPRA; see Refs. [1,2] and references within). These are effectively “white-noise” surface topographies, which would result in a flat spatial-frequency response when measured by an ideal instrument. When measured by the metrology tool in question, the observed deviation from a flat response constitutes a measurement of the ITF.

We have developed an algorithm for the deconvolution procedure and implemented it in user-friendly software, generalizing earlier software for reconstruction of one-dimensional surface slope metrology [3]. This is a true image restoration (as opposed to a subjective image enhancement) method, as the height topography deconvolution is based on high-confidence information on the ITF, experimentally determined in the dedicated calibration tests with the BPRA standards and modeled and parametrized using the developed software. We demonstrate the high efficacy of the deconvolution procedure and software using surface height measurements with an interferometric microscope.

This work was supported by the NASA STTR/SBIR program under award number 80NSSC20C0505 and by the U.S. Department of Energy under contract number DE-AC02-05CH11231.

Keywords: x-ray optics metrology, power spectral density, PSD, instrument transfer function, ITF, calibration, test standards, binary pseudo-random, microscopy, interferometry

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Design, fabrication, and testing of 2-mm-long X-ray mirrors for soft-X-ray nanofocusing

Takenori Shimamura[1,2], **Yoko Takeo**[2,3], **Takashi Kimura**[3], **Yasunori Senba**[2], **Hikaru Kishimoto**[2], **Haruhiko Ohashi**[2], **and Hidekazu Mimura**[1]

[1] Department of Precision Engineering, School of Engineering, The University of Tokyo,
[2] Japan Synchrotron Radiation Research Institute (JASRI), [3] The Institute for Solid State Physics, The University of Tokyo

*e-mail: shimamura@edm.t.u-tokyo.ac.jp

Abstract

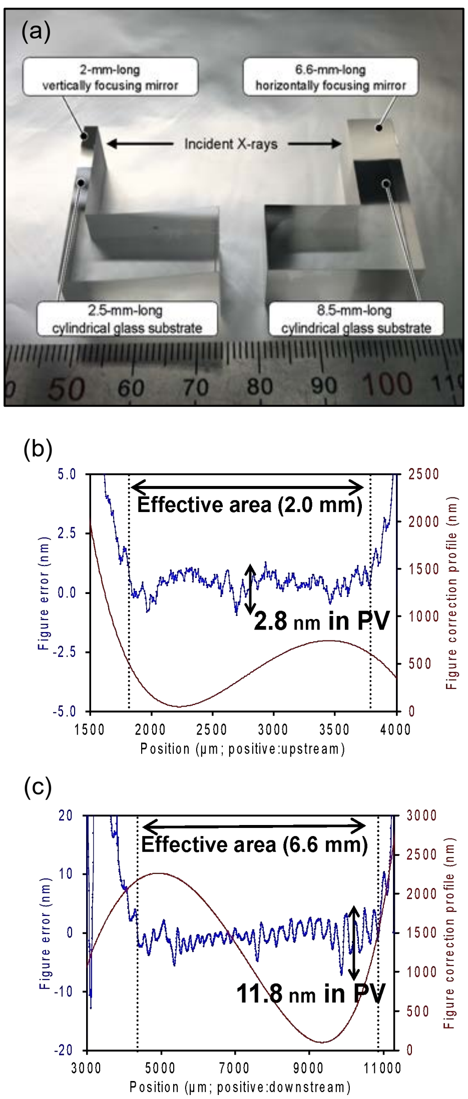

Fig. (a) Image and figure profiles of (b) 2- and (c) 6.6-mm-long mirrors.

Backgrounds:
The Kirkpatrick-Baez mirror is a reflective optic commonly used to focus hard X-rays. This type of focusing device offers a relatively long working distance above 20 mm, while its focusing size record has recently reached 5.8 nm with an X-ray free-electron laser at a photon energy of 9.1 keV[1]. However, considering a larger demagnification and numerical aperture as well as the effects of slope errors on the focus, short-focal-length mirrors are also advantageous to X-ray nanoprobes. In this study, to achieve an extremely short focal length, the mirror length is reduced to 2 mm. Likewise, the focal length is designed to be 2 mm long.

Methods:
This 2-mm-long mirror is paired with the 6.6-mm-long one, and both are designed to have a grazing angle of 25 mrad[2]. This novel design leads to a strongly curved elliptical surface with radii of curvature of 150 and 620 mm for the 2- and 6.6-mm-long mirrors, respectively. To fabricate these steep and free-form surfaces, this research employed a differential deposition process[3] with a DC magnetron sputter system and a scanning white-light interferometer (Zygo 700S). The cylindrical glass substrates were sliced into the L shape, and the threefold differential deposition was performed on the shorter cylindrical area, as shown in Fig. (a). The differential deposition adopted unique strategies from the viewpoints of sputtering and metrology. A double-stencil method and a simple and reference-free stitching method successfully produced precise surfaces.

Results:
Fig. (b) and (c) show the figure profiles and figure correction profile at the middle of the 2- and 6.6-mm-long mirrors, respectively. The figure errors of the mirrors achieved less than 0.5% of the maximum film thickness. The figure errors were 2.8 and 11.8 nm in peak-to-valley (PV) for the 2- and 6.6-mm-long mirrors, respectively, and these values are sufficiently negligible to focus 1-keV soft X-rays into a spot size of 50 nm in an X-ray experiment. The aspect ratio in this differential deposition process was 1000 to 1, 50 times higher than that in previous approaches. AFM observation revealed that this differential deposition process suppressed the severe deterioration in the surface roughness caused by thick layers.

Keywords: Kirkpatrick-Baez mirrors, ultrashort mirrors, strongly curved X-ray mirrors, differential deposition, scanning white-light interferometer, sputtering, double-stencil method

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Automated Design and Optimization of Transfocators

Peter Sondhauss[1]

[1]University of Lund, MAX IV, Lund, Sweden

peter.sondhauss@maxiv.lu.se

Abstract

The design of a transfocator for compound refractive lenses (CRL) depends, apart from imaging geometry and wavelength range, critically on beam profile. As the beam profiles from synchrotron light sources are rarely Gaussian and above that change considerably after passing through each lens element, the design process usually involves ray-tracing. Additionally, for each wavelength, lens element configuration (types and numbers) and the transfocator position in the beam have to be calculated. Very often, this is done externally, i.e. using spread sheets, online calculators [1] or analytic expressions [2].

Ray-tracing of more conventional X-ray optics has become not only more comfortable but also more powerful by automation routines such as auto-focusing or auto-tuning of angles and distances [3]. Auto-focusing for example allows to (automatically) compensate for the deformation of upstream optical components under heat load. In the real world this is achieved on the side, when the optics are aligned. The extension of these automation routines to transfocators is subject of the presented work.

Transfocators are unique, as they consist of a large and varying number of optical elements. Therefore, just determining the configuration for obtaining focus at a given position is not straight forward. Thin lens approximation does not apply for the system of lens elements as a whole, as the distances between the elements are too large. On the other hand, the inverse process, i.e. the calculation of overall focal length and principal points for a given configuration of lens elements is straight forward. The ray transfer matrix method can be used. Hence, the way to go is to calculate the focal spot positions for all configurations and to pick the configuration with focus closest to the given position. Any mismatch to the given position can be compensated for by moving the transfocator along the beam by a calculable amount. Subsequent ray-tracing provides throughput and allows optimization of the lens element type.

Keywords: X-ray optical design, simulation, ray-tracing, compound refractive lens, transfocator

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Preparation and characterization of Mo/B_4C bi- and multilayer mirrors

Michael Störmer[1*] **and Fabian Wilde**[1]

[1] Institute of Materials Research, Helmholtz-Zentrum Geesthacht, Max-Planck-Strasse 1, D-21502 Geesthacht, Germany,

*e-mail: *michael.stoermer@hereon.de*

Abstract

At current free-electron lasers (FEL) and synchroton sources, relatively long x-ray mirrors up to 1.5 m are employed for beam transport and guidance. At the Helmholtz-Zentrum Hereon we are able to fabricate a broad variety of coatings such as single, double and multiple layers with various layer thicknesses [1, 2]. Currently, bilayers of Mo/B4C were prepared with extreme tight specifications for FEL applications. Some Mo/B4C multilayers with different d-spacings and up to 400 pairs were synthesized. The aim is to fabricate two identical multilayer x-ray mirrors for tomography applications generating a high photon flux with a relatively narrow energy bandwidth in an energy range about 20 keV. The multilayers will be used for nano tomography experiments at our PETRA III beamline P05 [3]. Selected layers were characterized and analyzed by x-rays. The experimental results are discussed with respect to their applications, and furthermore, long-term stability was investigated.

Keywords: x-ray mirrors, magnetron sputtering, thin films, free-electron laser, x-ray tomography

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In-situ measurement of thermal deformations of mirrors under undulator radiation using Fizeau interferometer

Hirokatsu Yumoto[1,2*], Takahisa Koyama[1,2], Hiroshi Yamazaki[1,2], Yasunori Senba[1,2], Koji Tsubota[1], Masayuki Tanaka[1], Hikaru Kishimoto[1], Shunji Goto[1,2], Makina Yabashi[1,2], Haruhiko Ohashi[1,2]

1 Japan Synchrotron Radiation Research Institute, 1-1-1, Kouto, Sayo, Hyogo 679-5198 Japan.

2 RIKEN SPring-8 Center, 1-1-1 Kouto, Sayo, Hyogo 679-5148 Japan.

*e-mail: yumoto@spring8.or.jp

Abstract

X-ray optical components for next generation high-energy high-flux beamlines were developed at the R&D-ID beamline BL05XU of SPring-8. To provide high-flux beams with ~1% monochromaticity, total reflection mirrors to reject higher order harmonics and a double multilayer monochromator (DMM) have been installed as key optical components. We constructed a test bench in optics hutches to evaluate qualities of the optical components under a high heat load condition from an undulator source up to ~300 W [1]. With the total reflection mirrors at an x-ray energy of 4.5 keV, we measured a high flux beam at 1×10^{15} photons/s with an energy bandwidth of 1.4%. With DMMs at an x-ray energy of 30 (100) keV, we obtained a high flux beam of 1×10^{15} (3×10^{13}) photons/s with an energy bandwidth of 1.5% (1.0%).

Thermal deformations of these mirror optics operated under high heat load conditions must be minimized with an appropriate mirror cooling system. For downstream optics such as micro-/nano-focusing mirrors, it is critically important to avoid wavefront degradations of a reflected x-ray beam. We conducted in-situ observations of mirror surfaces under undulator radiation with a Fizeau interferometer to evaluate two-dimensional thermal deformations. Observation results can be utilized to reliable predictions based on theoretical calculations. The Fizeau interferometer was used to measure surface profiles of a mirror set in a vacuum chamber through a sapphire window. We observed a thermal deformation showing a concave curve with a height of ~60 nm per 80 mm in the longitudinal direction (X-ray beam direction) at an absorbed power of < ~230 W. In this measurement, the mirror with a glancing angle of 1.9 mrad was cooled with a liquid nitrogen cooling system. We confirmed that a thermal deformation of the DMM was effectively suppressed to provide the 100-keV beam at a normal heat load condition with an absorbed power of < ~40 W.

In this presentation, I will overview the current state of the development.

Keywords: in-situ metrology, thermal deformation, high heat load mirror, high-energy high-flux beamline, double multilayer monochromator (DMM).

Reference:

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