ANL/UPD/CP-102943

User Program Division
Advanced Photon Source, Argonne National Laboratory
Argonne, IL 60439

Future Metrology Needs for FEL Reflective Optics

Lahsen Assoufid

2000

To be submitted for the SPIE Meeting in San Diego, CA.

---

*This work is supported by the U.S. Department of Energy, Basic Energy Sciences-Materials Sciences, under contract #W-31-109-ENG-38.

9/12/00

Submitted to Conference AM229 at the **SPIE Meeting in San Diego-CA**, July 30-August 4, 2000.

Future Metrology Needs for FEL Reflective Optics

Lahsen Assoufid
Advanced Photon Source
Argonne National Laboratory
9700 South Cass Avenue, Argonne IL 60439

Abstract

An International Workshop on Metrology for X-ray and Neutron Optics has been held March 16-17, 2000, at the Advanced Photon Source, Argonne National Laboratory near Chicago, Illinois (USA). The workshop gathered engineers and scientists from both the U.S. and around the world to evaluate metrology instrumentation and methods used to characterize surface figure and finish for long grazing incidence optics used in beamlines at synchrotron radiation sources. This two-day workshop was motivated by the rapid evolution in the performance of x-ray and neutron sources along with requirements in optics figure and finish. More specifically, the performance of future light sources, such as free-electron laser (FEL)-based x-ray sources, is being pushed to new limits in term of both brilliance and coherence. As a consequence, tolerances on surface figure and finish of the next generation of optics are expected to become tighter. The timing of the workshop provided an excellent opportunity to study the problem, evaluate the state of the art in metrology instrumentation, and stimulate innovation on future metrology instruments and techniques to be used to characterize these optics.

This paper focuses on FEL optics and metrology needs. (A more comprehensive summary of the workshop can be found elsewhere.[1]) The performance and limitations of current metrology instrumentation will be discussed and recommendations from the workshop on future metrology development to meet the FEL challenges will be detailed.

Keywords: Optical metrology, free-electron laser, grazing-incidence mirror, surface figure, surface finish

1. Introduction

Free-electron laser (FEL)-based sources being planned around the world, such as the Linac Coherent Light Source (LCLS) at Stanford (USA) and the TESLA x-ray FEL (Germany), are designed to operate at x-ray wavelengths around 1 Å. These sources, built around linear accelerator technology and long insertion devices, are expected to deliver diffraction-limited x-ray beams with unprecedented intensities, full transverse coherence, and a short pulse length in the femtosecond range (230 fs for LCLS). For example, the peak brilliance of LCLS radiation is expected to be at least ten orders of magnitude higher than the current third-generation sources such as ALS, APS, ESRF, and Spring8, with a transverse coherence length an order of magnitude higher (100 μm vs. 10 μm for the current third-generation synchrotron radiation sources). Preserving the high quality (low emittance, coherence, brilliance, and time structure) of photon beams produced by these FEL sources will put stringent requirements on the quality of their beamline components. In particular, grazing-incidence mirrors, which will be used for power filtering, beam collimation, steering, focusing, and harmonic rejection, will be required to have unprecedented degrees of surface figure and finish. These requirements, along with others related to high-heat load and ultrahigh vacuum, will pose challenges for both fabrication and metrology. The workshop provided an excellent opportunity to study these aspects, evaluate the state of the art in metrology instrumentation, and stimulate innovative ideas on future needs. In this paper the current state of the art in mirror polishing will be discussed. Then specific needs for both mirror and metrology instrumentation requirements will be addressed, and the various issues tackled during the workshop will be described.

2. Current State of the Art in Mirror Polishing

Development of third-generation synchrotron radiation sources such as the Advanced Light Source (ALS), Advanced Photon Source (APS), European Synchrotron Radiation Source in Grenoble-France (ESRF), and Super Photon 8 GeV Ring (SPring8) in Japan has pushed fabrication of x-ray mirrors to unprecedented limits. Successful collaborative efforts between mirror manufactures and synchrotron radiation beamline scientists and engineers has led to the development of reliable sources of adequate mirrors. Specific fabrication tools were created and a specialized metrology tool, the long trace profiler (LTP)[2] was developed to measure surface figure and curvature of long aspheres. Standard commercial instruments had to be adapted to evaluate figure and finish of these optics.

Although the workshop's main focus was metrology instrumentation, various aspects of synchrotron radiation (SR) optics, such as fabrication and material specifications and requirements, were also discussed. The workshop began with a brief review of the history of synchrotron optics and a forward look at optical systems and metrology needs (Malcolm Howells, ALS/LBNL). Howells suggested standardization of optical components as a means to save cost and time in developing new beamlines. Sunil Sinha (APS/ANL) presented the framework for understanding the effects of surface roughness and figure error on mirror performance and coherence preservation. He compared various techniques for evaluating diffuse scatter and speckle, including x-ray bidirectional reflectance distribution function (BRDF), scanning probe microscopes, and optical profilometers.

Currently, a typical grazing-incidence mirror is about 1 meter long for undulator insertion devices (ID) and at least 1 m long for bend magnet beamlines. The most commonly used substrate materials are single-crystal silicon, ultra-low expansion (ULE) glass, Zerodur, Glidcop, SiC, and in some cases float-glass. Si, SiC, and Glicop are very often used for their superior thermal properties at room temperature, where cooling of optics is necessary in order to minimize thermally-induced distortions. Over the last few years, surface roughness of mirrors has decreased from a few Å rms down to the 1-Å rms level, and the slope error has dropped from a few microradians rms down to less than 1 µrad rms depending on the substrate material, shape, and size. However, Even with these advances in mirror fabrication technology, residual imperfections on mirrors (as well as in other optical x-ray SR components) were found to degrade the quality of x-ray beams from third-generation sources.[3-4] For many experiments the irregularity generated by a low level of imperfections in optical components is still acceptable. However, techniques for maintaining x-ray beam quality (emittance and coherence) are still evolving. Therefore, tolerances of optical elements adapting the beam properties to a particular experiment will become more stringent. In particular, beam coherence is important in many experiments, such as microtomography, holography, phase contrast imaging, etc. There is clearly a need to further improve polishing techniques beyond the current state of the art. Fortunately, promising techniques to prepare a new generation of mirrors are being investigated. For example, an ion beam figuring technique has been described as a way to further improve conventionally polished substrates (O. Hignette, ESRF). A 300-mm Si substrate prepared using this method (by ESRF and ZEISS) yielded a surface slope error of 0.1 µrad rms. Perhaps another promising technique to correct surface errors (not discussed at the workshop) is by differential deposition of a thin film on the mirror surface. This concept has been used to produce elliptical K-B microfocusing mirrors from cylindrical substrates.[5]

3. FEL Challenges

Because of the lack of experience with FEL operating in the x-ray regime, no precise requirements for surface figure or finish were presented for beamline optics in these machines. We do know that FEL sources will be characterized by peak brightness ten orders of magnitude higher that the current third-generation sources (John Arthur-LCLS/SLAC). Moreover, FELs will deliver beam that is fully coherent, with a transverse coherence length much larger than that of the current third-generation synchrotron source (hundred of µm vs. 10 µm for current third-generation sources). Therefore, subnanometer roughness levels now achieved over millimeter length scales must be extended over longer lateral scale lengths in order to preserve the intrinsic beam coherence (Sinha). On the other hand, because of high peak power in power density generated by these sources, material with low absorption such Be, C, and diamonds will be used as possible reflecting material. Fortunately these materials are also highly reflective (> 99 % for Be) at very short (1 Å) x-ray wavelengths. Figure 1 compares reflectivity curves of Be, C, Si, and Pt as a function of mirror angle at 1 Å radiation wavelength.

The tighter tolerances on surface figure and finish along with mirror material requirements bring new challenges to both mirror manufacturers and metrologists.

4. Metrology Instrumentation Requirement and Developments

The standard metrology instruments used to inspect synchrotron radiation optical components are a long trace profiler (LTP) for measuring surface slope error and curvature, a figure interferometer, and a roughness-measuring instrument. These are noncontact measuring instruments. The roughness-measuring instrument is generally an interference visible light microscope, but an atomic microscope is a useful as a complementary tool. These instruments, typically housed in a clean room (of Class 10,000 or better) with a well controlled environment, are chosen to cover the wide range of spatial frequencies needed for the complete characterization of an optic. The following section summarizes instrument discussions during the workshop.

4.1. The long trace profiler performance, development, and innovations

The long trace profiler, as developed by Peter Takacs and Shinan Qian (BNL),[1] is so far the only instrument available to the SR community to directly measure with submicroradian accuracy the slope of long, aspherical mirrors used in SR beamlines. Many variations of this instrument have been used around the world. Each LTP is unique in that it is usually upgraded by its owner with customized hardware and measurement techniques for improving accuracy and versatility.[4] The current performance of a commercial standard LTP, the LTP II system, is at the 0.5-µrad rms level (Takacs). Optics with a much lower slope error limit (0.1 µrad) are now in demand, and there is clearly a need to improve the performance level below this limit. However, sources of errors for the current LTPs were identified, and ways to mitigate them along with performance expectations were presented by Takacs, Steve Irick (LBNL), Heiner Lammert (BESSY), and Giovanni Sostero (ELETTRA). As with all ultraprecision measuring machines, the major error source limiting the LTP performance is environmental instability. Temperature control at the ±0.1 °C level is adequate for a 0.5-µrad rms system noise level, but significant improvement in the thermal control of the local environment will be necessary to get down to the 0.1-µrad rms accuracy and repeatability level. The target is an accuracy level on the order of 0.05 µrad, which can be achieved by stabilizing the temperature to within ±0.033 °C (Takacs). The inhomogeneity in the index of refraction of the LTP transmitting optical components (prisms, lenses, etc.) is also a source of error (Heiner Lammert, BESSY II). The error induced by the variation in the index of refraction is particularly important when evaluating curved surfaces with small radii (large test beam deflection angle). Lammert has estimated that the variation in the index of refraction, Δn, of LTP transmission optical elements should not exceed 10^{-8}.

Beside the standard version, several new LTP concepts being currently developed were discussed during this workshop by François Polack (LURE), Ajay K. Saxena (Indian Institut of Astrophysics), Ingolf Weingärtner (PTB), and Shinan Qian (BNL).

4.2. Interferometer performance, limitations, and developments

Commercial interferometers are generally not optimized for evaluation of SR mirrors, and their performance has not reached the fundamental limits yet (Chris Evans, NIST). Environment stability is one of the major limiting factors along with a traceability issue. Another limitation comes from their reliance on a reference mirror for measurements, and they are only suitable for weak aspheres. Weingärtner (PTB) discussed a high-resolution, large-area, curvature-scanning device that can be used for steep aspheres. He also described a method for extracting the shape from the curvature without cumulative errors. In the past, such errors have prevented this otherwise attractive approach from working correctly with large optics. Raymond Mercier (Institut d'Optique, Orsay) developed a figure interferometer to test XUV optics with a noise level to 0.2 nm rms, also much lower than for a standard interferometer. Alain Dubois (Ecole Superieure de Physique et de Chimie Industrielle de Paris, Paris) discussed a roughness instrument built around a Nomarski polarizing differential microscope. The instrument yields a differential roughness profile instead of a topographic profile but requires no reference mirror and has a very low noise level of 5 pm compared to commercial instruments. Standard figure interferometers have a typical aperture of about 150 mm diameter. Therefore, measurements of long grazing-incidence mirrors have to be performed at an angle. Michael Bray (MB Optique) proposed stitching interferometry as an alternative to overcome the aperture limitation. The idea is to use a conventional figure interferometer to make a sufficient number of overlapped submeasurements to cover the entire mirror surface. Then these measurements are stitched together numerically to compose a complete 3-D mirror surface. The algorithm used was impressively successful in view of the many unsuccessful attempts to solve the same problem in the past.

4.3. Other developments

Because evaluation can be done with radiation of the relevant wavelength and within the natural environment of an experiment, synchrotron radiation is obviously the ultimate tool for testing and characterizing an optic. However, because *in situ* metrology requires rather complicated and expensive equipment, it can only be used as a complementary method, not as a tool for inspection of delivered optics. Olivier Hignette (ESRF) used x-ray long trace profilometry to measure mirror slope errors with 50-nrad accuracy, much below the current accuracy of the current LTPs. He also described beamline wavefront analysis and optimization techniques as a means to adjust and tune either individual components or a beamline as whole.

In situ metrology is a valuable tool for monitoring the long-term stability of a beamline optical system. Therefore, it needs to be installed permanently and be quickly deployable.

5. Specifications and Standardization Issues

Experience at SR facilities has shown that the traditional way of specifying an x-ray mirror--which consists of using one value for rms roughness and one value for rms slope error--might be inadequate. An upper bound on the power spectral density function (PSD) would be a better choice (Howells). Performance-related specifications were also suggested (Howells). The idea consists of specifying an optic that will deliver light from a source to a slit (say) by requiring that a certain percentage of photons must be delivered by the optic in a test with the given source/slit geometry.

Other issues discusssed during the workshop included standardization of metrology methods specific to SR mirrors, and standard simulation and tolerancing code. Modeling and simulation usually play a critical role in designing optical components and optimizing optical systems for synchrotron radiation applications, and feedback from optical metrology can be used to render a realistic optical design. Therefore, simulation codes that make use of metrology data as input must be developed. The ray-tracing code SHADOW is widely used in the synchrotron radiation community for simulating a variety of optical systems and is very useful in applying geometrical optics models. In particaular simulation is critical in predicting the performance of optics for the the planed FEL. It is, therefore, desirable to develop a standard wave optics code with user friendly interface, integrate a routine for metrology data input, and develop the capability for optimizing an entire beamline.

6. Conclusions

Thanks to development of third-generation synchrotron radiation sources, the optical quality of grazing-incidence mirrors has dramatically improved over the last decade. However, further improvement in mirror quality is necessary in order to meet future demands from both the current- and next-generation synchrotron light sources. The current interferometer-based instruments have not yet reached their fundamental limits. Environment stability is one of the major limiting factors. The performance of the current LTP can be further improved beyond the existing limit (0.5 µrad) by excellent temperature stability and better optomechanical components. The target is an accuracy level on the order of 0.05 µrad, which can be achieved by stabilizing the temperature to within ± 0.033 °C. Standards in metrology methods are highly desirable, and standards in optical components would save money and time. A standard wave-optics simulation code for designing and predicting the performance of optics and beamlines is needed. Predictions based on optical metrology measurements also need to be implemented. The workshop was successful in addressing the problems faced by metrologists, beamline scientists and engineers, and vendors. A follow-up meeting was suggested, and ESRF was the proposed host in two years time.

7. Acknowledgments

The content of this paper is derived from presentations and discussions during the International Workshop for Metrology X-ray and Neutron Optics held at the Advanced Photon Source, Argonne National Laboratory, Illinois, March 16-17, 2000. I am grateful to the members of the workshop organizing committee (O. Hignette-ESRF, M. Howells-ALS/LBNL, S. Irick-ALS/LBNL, H. Lammert-BESSY II, and P. Takacs-BNL) and the workshop speakers. Also, I would like to address many thanks to D. Mills (UPD/APS Division Director) and A. Macrander for their support, as well as the staff of ANL Conference Services and the APS User Office for their help in the workshop organization. This work is supported by the U.S. Department of Energy, BES-Materials Sciences, under Contract No W-31-109-ENG-38.

8. References

1. L. Assoufid, O. Hignette, M. Howells, H. Lammert, and P. Takacs, "Future Metrology Needs for Synchrotron Radiation Grazing-Incidence Optics," *submitted to Nucl. Instrum. Methods.*
2. P.Z. Takacs and S. Qian, United States Patent 4884697 (1989).
3. A. Snigirev *et al.*, *Nucl. Instrum. Methods* **A370**, 634 (1996).
4. G. Srajer *et al.*, Argonne National Laboratory, private communication.
5. Gene E. Ice *et al.*, Rev. Sci. Instrum. **71** (7), 2635 (2000).

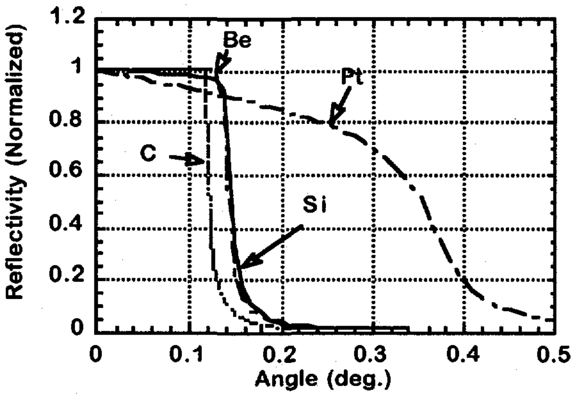

Figure 1: Reflectivity curves of Be, C, Si, and Pt at 1 Å radiation wavelength as a function of mirror angle.