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Future Metrology Needs for Synchrotron Radiation Mirrors

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Abstract

An international workshop on metrology for X-ray and neutron optics, the first of its kind, was held March 16-17, 2000, at the Advanced Photon Source at Argonne National Laboratory. Engineers and scientists from around the world met to evaluate current metrology instrumentation and methods used to characterize the surface figure and finish of long, grazing-incidence optics used in synchrotron radiation beamlines, and to consider future needs for synchrotron, FEL, and neutron sources.

Keywords: Optical metrology, synchrotron radiation, grazing-incidence mirrors, surface figure, surface finish

General requirements for X-ray and neutron beam mirrors

Current (third generation) synchrotron radiation sources are optimized for insertion devices which deliver photon beams with high brightness and coherence. Full exploitation of these features and preservation of brightness of the X-rays required grazing-incidence mirrors typically with lengths of over 1 m, surface figure error below 3 µrad rms, and surface roughness less than 3 Å rms. These requirements, along with others for high heat loading and ultra high vacuum materials, increased demands on mirror vendors. This in turn resulted in collaboration[1] between synchrotron engineers and mirror vendors which successfully led to the development of adequate quality mirrors. Specific fabrication tools and methods had to be developed, a long trace profiler (LTP) was developed[2] to measure surface figure and curvature of long aspheres, and standard commercial instruments had to be adapted to evaluate figure and finish of these optics.

Even so, mirrors were found to produce high-contrast streaks[4] and speckle structure in reflected X-ray beams. For many experiments the irregularity generated by a low level of imperfections in optical components is still acceptable. However, with increasing quality of synchrotron radiation (SR) sources, tolerances of optical elements adapting the beam properties to a particular experiment become more stringent. In addition, beam coherence is important in many experiments, such as microtomography, holography, and phase contrast imaging. The best figure errors obtained to date are 0.5 µrad rms on a 1 m long flat mirror and 0.8 µrad rms on a 1m long cylinder. There is clearly a need to further improve polishing techniques beyond the current state-of-the-art. The workshop, therefore, provided an excellent opportunity to evaluate current metrology capability and stimulate innovation on future instruments and techniques. A summary [3] of the workshop has been distributed to workshop participants.

The metrology workshop began with a brief review of the history of synchrotron optics and a forward look at metrology needs (M. Howells, ALS). Howells also suggested standardization of optical components. S. Sinha (APS/ANL) presented models for surface roughness. He compared various techniques for evaluating diffuse scatter and speckle, including X-ray BRDF, AFM, STM and optical profilometers.

Because of the nature of free electron laser (FEL) beams (high electron density and femtosecond pulses with high peak power) and a lack of experience in FELs operating in the usual X-ray regime, no precise quantities for surface figure or finish were presented. However, the transverse coherence length for FELs is much larger than that of third generation synchrotrons, and one must achieve the same level of roughness over length scales equal to the projected coherence length of the mirror surface (S. Sinha).

Surface roughness requirements for neutron beam mirrors are similar to those of X-ray optics. However, because of the lower brightness of neutron sources, slope errors can be much greater. Therefore, commercial roughness measuring instruments may be used to characterize neutron guides and supermirrors at the SNS (F. Klose). Float glass is the material of choice because it is inexpensive, readily available, and has a roughness often below 3 Å rms.

Interferometer limitations and metrology development

Standard figure interferometers (typically a Fizeau type) are based on phase-shifting interferometry. Standard instruments are not necessarily optimized for SR mirror measurements. Some of the limiting factors for the current figure interferometers are aperture, dynamic range, knowledge of reference front, resolution, and noise. C. Evans (NIST) pointed out that the phase shifting diffraction approach, where diffraction by a λ-size aperture generates a perfect spherical wavefront over a specified numerical aperture, offers a better approach to interferometry. This removes limitations of conventional interferometry (a reference surface and other optics are eliminated) while retaining positive aspects including phase shifting and standard algorithms for data analysis. In addition, evaluation of Atomic Force Microscopes were given by T. Vorburger (NIST) and L. Assoufid (APS).

The long trace profiler

The LTP, originally developed[2] by P. Takacs et al., is so far the only instrument available to the SR community to directly measure the slope of long, aspherical mirrors used in SR beamlines with submicroradian accuracy. The LTP is unique in that it is usually upgraded by the owner with the latest hardware and measurement techniques for improving accuracy and versatility[6]. Many variations of long profilers were proposed by F. Polack (LURE), A.K. Saxena (IIA), I. Weingärtner (PTB), and S. Qian (BNL). D. Cocco (ELLETRA) and A. Rommeveaux (ESRF) presented applications for the LTP.

The current performance of a standard LTP system is at the 0.5 µrad rms level (Takacs, BNL). 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. Sources of errors, ways to mitigate them, and performance expectations were presented by Takacs, S. Irick (LBNL), H. Lammert (BESSY), and G. Sostero (ELETTRA).

Other developments

Synchrotron radiation is the ultimate tool for testing and characterizing optics, since evaluation of the qualities of an optic can be done at the radiation wavelength that is relevant to the particular experiment. O. Hignette (ESRF) presented his work on an X-ray *in situ* metrology method and on beamline wavefront optimization and analysis. He performed X-ray long trace profilometry with 25 nrad precision and 50 nrad accuracy.

A. Dubois (ESPCI) presented a new type of roughness instrument that has noise as low as 5 pm rms, much lower than that of existing commercial instruments, with very little sensitivity to environmental conditions. The system was built around a Nomarski polarizing differential microscope. This shot noise limited instrument yields a differential roughness profile, not a topographic profile, but requires no reference mirror. R. Mercier (Institut d'Optique, Orsay) developed an interferometer to test XUV optics with noise level to 0.2 nm rms. M. Bray (MB Optique) proposed stitching interferometry for characterizing SR optics, and C. Evans (NIST) described stitching interferometry that was used to measure LIGO mirrors of about 250 mm diameter using a standard 150 mm aperture interferometer with an uncertainty of ±1 nm rms.

Specifications and standardization

Figure and finish requirements for SR mirrors is traditionally specified with two single-number parameters: the rms surface roughness and rms slope errors values. However, experience at SR facilities showed that specifying a mirror using these two values is in most cases inadequate. M. Howells suggested that an upper bound on the power density function (PSD) would be a better way of specifying the quality of an optic, and customers who can calculate PSDs should supply them to their vendors so the vendor builds knowledge of what PSDs to expect. Another is the use of performance-related specifications, i.e., performance based on percentage of beam transmitted through a pinhole of given size, or the knife-edge test. Hignette proposed Marehcal's criterion as a way of specifying optics for coherent beams. For grazing incidence mirrors, the equivalent tolerance would be $\lambda/(28 \sin \theta)$, where θ is the grazing incidence angle. For a typical hard X-ray mirror operating at a grazing incidence angle on the order of 3 mrad with a radiation wavelength of 1 Å, one obtains a maximum tolerable deviation of 0.12 nm rms.

Simulation Codes

Because modeling and simulation usually play a critical role in designing optical components and optimizing optical systems for synchrotron radiation applications, optical metrology must 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. Although there are several codes developed for physical optics models (e.g., Kim, Bahrdt[7], Nugent), none are universal and widespread. It is desirable to develop a standard user interface (perhaps integrated into XOP), integrate a routine for metrology data input, and develop the capability for optimizing an entire beamline. A standard code is also needed for acquiring and analyzing LTP data.

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