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DEVELOPMENT OF HIGHLY POLISHED, GRAZING INCIDENCE MIRRORS FOR SYNCHROTRON RADIATION BEAM LINES AT SSRL

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Development of highly polished, grazing incidence mirrors for synchrotron radiation beam lines at SSRL

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ABSTRACT

New platinum-coated grazing incidence mirrors with low surface roughnesses have been developed to focus bending magnet radiation from the SSRL/SLAC SPEAR storage ring on the entrance slits of two Beam Line VIII grating monochromators. The first mirror in the toroidal grating monochromator (TGM) branch is a cooled SiC cylinder capable of absorbing synchrotron radiation power levels of up to 260 watts without excessive distortion. This mirror deflects the beam vertically through a 12° angle and focuses it sagitally on the TGM entrance slit plane. The second TGM optical element is a fused-silica spherical mirror with a large radius of curvature that deflects the beam vertically through an additional 12° and focuses it tangentially with 3/1 demagnification. The first mirror in our spherical grating branch is a 5°-vertically deflecting, cooled SiC toroid designed to focus tangentially on the monochromator entrance slits and sagitally on the exit slits. A 4°-deflecting fused silica mirror is used after the exit slits in each beam line to refocus on to the sample. For this application a thin cylinder is bent to approximate an ellipsoid. The mirrors are now installed at SSRL and performance measurements are planned. Qualitatively the focus of the TGM optics at the entrance slit plane appears very good. In this paper we discuss considerations leading to the choice of SiC for each of the two first mirrors. We present highlights of the development of these mirrors with some emphasis on SiC polishing techniques. In addition, the specialized metrology developed to produce the more difficult figure of the toroid will be described. Measured surface roughness and figure results will be presented.

1. INTRODUCTION

Several state-of-the art grazing incidence mirrors have been designed, fabricated to our specifications, and installed in Beam Line VIII at the Stanford Synchrotron Radiation Laboratory, SSRL. As part of the X-ray Calibration and Standards Facility Project, Beam Line VIII consists of two general purpose beam lines branching from the same bending magnet source on the SPEAR storage ring. These synchrotron radiation sources, along with a wiggler hard x-ray line (BL-X) now under construction, have been designed to serve the needs of a participating research team formed by the University of California, and the Lawrence Livermore, Los Alamos, and Sandia National Laboratories. Each of the two bending magnet branches has appropriate prefocusing optics, a grating monochromator with three interchangeable gratings, a refocusing mirror, and a sample chamber all operating in ultra-high vacuum (UHV). The toroidal grating monochromator (TGM) provides continuously tunable radiation in the 8-185 eV range and the spherical grating monochromator (SGM) covers the 60-1100 eV range. The BL-VIII grazing incidence mirrors that are the subject of this paper are all platinum coated and have low surface roughness and figure tolerances required to obtain good x-ray reflectivity without excessive scattering losses. The throughput of our beam lines has been enhanced by the high quality of the mirrors that have been developed.

After an overview of beam line optics, we will discuss our grazing incidence mirror development including some details of mirror selection, fabrication, surface finish, and mirror mount considerations. Table 1 summarizes our grazing incidence mirror parameters. The SiC primary mirrors will be discussed first followed by the fused silica mirrors used down stream. Metrology developed for the SiC toroid will be included.

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Table 1. Summary of Beam Line VIII Grazing Incidence Mirror Parameters.

Mirror Parameter	M0	M0'	M1	M2, M2'
Type	cylinder	toroid	spheroid	bent cylinder
Material	SiC	SiC	fused silica	fused silica
Sagittal focus	0.9/1	0.9/1	negligible	3/1
Tangential focus	none	3/1	3/1	3/1
Maximum power (watts)	260[a]	110[a]	<2	<1
Grazing angle (deg.)	6°	2.5	6	2
Size LxWxT (mm^3)	300x110x35	380x100x45	452x100x45	240x40x4.5
Angular acceptance				
V(mrad) x H(mrad)	3 x 12	1.5 x 5	--	--
Radius of curvature				
R1-transverse	929.2 mm	419.0 mm	63.7 m	52.3 mm
R2-along beam	infinity	114.6 m	63.7 m	43 m to ∞
Optical form tolerance[b]	$<\lambda/4$	$<\lambda/1$	$<\lambda/4$	$<2\lambda$
Surface finish (Å rms)				
Before Pt coating	3 ± 1	<5	<5	<10
After Pt coating[c]	<5	<6	<5	<10
Supplier	Continental	F. Cooke	Zygo	F. Cooke
Holder/mover design	LLNL/SSRL	LLNL/SSRL	LLNL/BNL	SSRL

[a] A cooled mirror holder was required.
[b] At 6328 Å.
[c] Platinum coating (1000-1500Å).

2. SYNCHROTRON RADIATION BEAM LINE OPTICS

Figure 1a shows schematically the x-ray optics arrangement for our 6 m TGM beam line. The monochromator optics from entrance to exit slits are based on proven designs in use at BNL, NSLS.[1] The first mirror in the TGM branch, designated as M0, deflects the beam vertically through a 12° angle and focuses it approximately 1x1 sagitally on the TGM entrance slits, S1. The fused silica spherical mirror M1 then deflects the beam through an additional 12° and focuses it tangentially with 3/1 demagnification on S1. The focusing functions of these two mirrors are almost completely independent since the effect of the large M1 radius on the sagittal focus is negligible. In order to design the TGM beam line optics, we made extensive use of the SHADOW ray tracing code developed by F. Cerrina and coworkers.[2] In particular we optimized the position of M1, the M0 location having been constrained by other alcove requirements. It should be noted that the long distance of the first mirror from the source and alcove wall constraints very significantly influenced our beam line optical design. We confirmed our selection by comparing with many alternatives such as a flat mirror followed by an ellipsoid. Except for the beam's somewhat large horizontal size at S1, the chosen design yields a good match to the grating section. The grating is fully illuminated by a 3 mrad x 12 mrad radiation distribution from the SPEAR source as we intended. The horizontal size will be reduced by the proposed SPEAR emittance upgrade.[3]

Three interchangeable toroidal gratings, mounted in a UHV chamber, are the critical dispersive optical elements in the monochromator.[4] Wavelength is changed by rotating the operating grating. Beam directions in and out of the grating remain fixed. The toroidal grating refocuses the beam both sagitally and tangentially on the exit slit plane. An exit mirror in turn refocuses the beam on the sample with 3/1 demagnification producing spot sizes of less than 0.5 x 2 mm^2. The beam line features a comparatively spacious arrangement of the monochromator and end station on a mezzanine.[5] Moreover, we achieved our design goal of bringing the beam into the sample chamber parallel to the mezzanine floor.

Figure 1b shows the SGM grating branch optical design. Initially intended for our SPEAR bending magnet, the SGM optics arrangement can be used very well as a wiggler side branch.[6] Optics in this branch are much more grazing due to the lower x-ray wavelength range covered (8-220 Å). A toroidal first mirror deflects 5 horizontal mrads from the BL-VIII bending magnet vertically 5° upward. The mirror focuses the beam tangentially (nearly vertically) into a slightly curved horizontal line on the SGM entrance slit plane S1' and sagitally on the exit slits S2' nearly 6 m beyond.

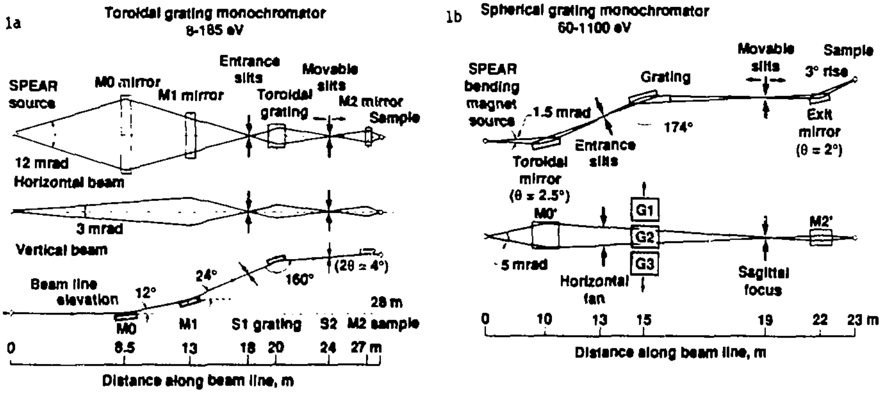

Figure 1. X-ray optical design for Beam Line VIII at SSRL. a. Toroidal grating branch. b. Spherical grating branch.

Using SHADOW[2], M. Rowen compared S1' focal distributions from the toroid and from an alternative prefocusing spherical mirror pair with decoupled sagittal and tangential focusing functions.[7] He assumed nominal SPEAR operation and included mirror reflectivity. He concluded that, compared to the double mirror system, the toroidal mirror delivers about 70 to 75% of the flux to the monochromator at 5-mrad horizontal fan size in spite of the smile shape that the toroid introduces at the S1' tangential focus. Furthermore the toroid performs better than the pair below roughly 3 mrad. It will do well in a wiggler side branch (<2 mrad).[6] A more compelling argument favoring the difficult toroid fabrication is that a second prefocusing mirror extends the beam line beyond the available space.

System optics from the monochromator entrance slits to the exit slits are based on a new design due to H. Hogrefe and M. Howells, LBL.[6] The grating is spherical with a 55 m radius that vertically disperses the beam downward deflecting it through a constant total angle of 6° and focusing it tangentially on the exit slits.[8] Unlike the toroid, the large radius of curvature has almost no effect on the sagittal focus. Thus the beam distribution at S2' is much closer to ideal than in the case of the TGM. The beam is refocused at the center of a UHV target chamber located nominally 3 m from S2' into spot sizes expected to be smaller than 0.5x1 mm^2 at the sample. The refocusing mirror in this branch is very similar to that of the TGM branch except that a vertical deflection upward was chosen to bring the SGM beam closer to the horizon at the target.

In the design of SR beam lines, a dominant consideration is the reflectivity of mirrors as a function of grazing angle. Figure 2 shows ideal platinum reflectivity versus photon energy calculated for the BL-VIII mirrors. The rolloff in reflectivity from two 6° reflections is well suited for the TGM photon energy range. The grazing angle chosen for the SGM range is more of a compromise. The rolloff of the single 2.5° reflection (5° deflection) is not as rapid as we would prefer. On the other hand choosing a larger grazing angle reduces throughput throughout the range of interest. The exit mirror rolloff extends well beyond the end of the monochromator range in both cases.

3. SiC PRIMARY MIRRORS

Fig 3 shows schematically the first mirror, M0, and mirror mount oriented on SPEAR. Optical requirements are severe for such grazing incidence mirrors used to focus SR beams through sub-millimeter apertures at several meters. Thermal distortion is of particular concern when a large fraction of the incident beam is absorbed as is the case for both of our primary mirrors. Power levels up to 260 and 110 watts are incident on M0 and M0', respectively. Due to the low SR vertical divergence, the heat deposition tends to produce significant localized surface slope distortion. As reported previously, we have used finite element analysis to investigate the effects of thermal/mechanical loading on our two primary mirrors.[9] To keep slope distortion within acceptable limits, we studied different

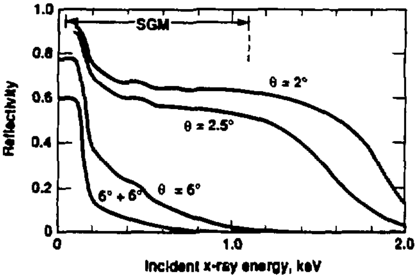

Figure 2. Calculated platinum mirror x-ray reflectivity for each of our BL-VIII mirrors. The effect of two 6° reflections (from M0 and the M1) is also shown.

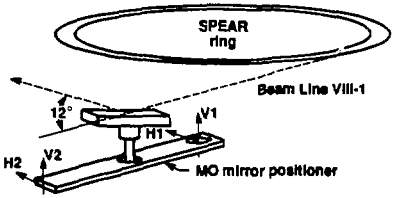

Figure 3. First mirror M0 and its positioner shown schematically on SPEAR storage ring.

mirror substrate materials and cooling methods. Rather than aluminum or OFHC copper coated with electroless Ni, we selected commercially available sintered SiC coated with CVD SiC for polishing since it provides relatively low thermal distortion and avoids certain cost and technical risk factors. (Note that by using thick CVD-SiC, slope distortion can be reduced up to a factor of 2.) The greater resistance to thermal stress provided by copper or its alloys[10] is not required for primary mirrors at grazing angles under 10° on a SPEAR bending magnet.

Our calculations indicated that cooling only by radiation gives unacceptably high surface temperatures. Side cooling is ruled out by the mirror's large width, 110 mm, and by the requirement for passage of radiation very close to M0 on both sides with no clamping allowed at beam level. Finding that distortion is rather insensitive to the method of conductive cooling, we chose to cool a portion of the bottom surface to limit the surface temperature. Since conductive cooling appears adequate, we did not investigate internal cooling designs. Our substrate thickness studies showed that increasing the M0 mirror thickness above 35 mm (giving a length to thickness ratio of 8.6) does not significantly effect the slope distortion. Although the incident power density is about 3 times lower for the 2.5°-grazing primary mirror, the expected thermal distortion using fused silica is still not acceptable, since it is roughly 13 times greater than that of SiC. Due to this, the progress in our SiC polishing technology,[11] and the similarity of mirror dimensions, we opted for obtaining a SiC toroidal mirror and using M0 mirror assembly designs.

The 110x300 mm^2 cylindrical mirror M0 was fabricated by the Continental Optical Co. from an alpha-sintered blank by Sohio Engineered Materials. The essential requirement for good polishing was a uniform CVD-SiC 400-µm layer deposited by the Texas Instruments Co. Final CVD-SiC grinding and polishing processes were aided by a collaborative effort using technology developed at LLNL.[11] Figure 4 shows the finished cylindrical mirror after plating with platinum.

As described in reference 12, the 100x380 mm^2 toroidal mirror was produced by F. Cooke, Inc., from a similar SiC blank and CVD SiC layer. The profile metrology developed for the toroid by one of us, S. F., is discussed later. Final grinding and polishing was done by Cooke Inc., in collaboration with one of us, B. F.

Figure 5 shows the toroidal mirror mounted in its water-cooled holder that we designed. The M0 and M0' mirror holder designs incorporate a new technique for reducing thermal distortion.[9] We applied unequal spring forces distributed along the edges to bend the mirror producing a slight concave profile along its long axis. This profile is preset to partly compensate for bending induce by surface heating from the SPEAR source. For this optimization we used finite element analysis to superimpose slight mechanical preloading forces onto the thermal distortion. Our final iteration for M0 produced a mirror calculated to be within 2 arc-sec. for over 70% of the mirror surface at nominal 3 GeV SPEAR operation.

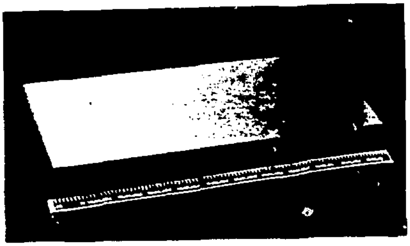

Figure 4. Cylindrical SiC primary mirror M0 produced by the Continental Optical Co.

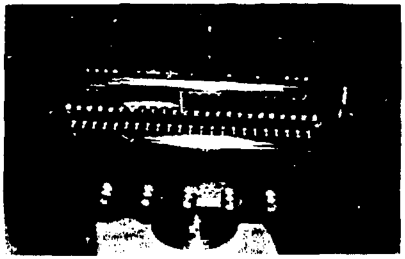

Figure 5. Toroidal SiC mirror M0' produced by F. Cooke, Inc. mounted in its water-cooled holder that we designed.

Our primary mirror cooling design provides very good thermal conductivity from the mirror to a brazed copper-stainless steel cooling block. The UHV requirement led to our use of a commercially available torsional finger stock.[13] This silver-plated beryllium copper material has excellent thermal properties, and its many torsional fingers each apply a relatively high load over a small area thus providing good thermal contact in vacuum. The spring stiffness and thermal transfer characteristics of the material were confirmed by tests. The material is suitable for applications with power densities less than 20 W/cm^2.

A rigid single post containing cooling tubes is bellows-coupled into vacuum to support the mirror. Based on an arrangement developed and in use at SSRL, the mirror alignment assembly provides stable, mechanically-isolated support.[14] Remote vertical and horizontal adjustments are made relative to a fixed external reference surface located below the chamber as shown schematically in Figure 3. The roll axis is accurately preset. Vertical translation allows complete removal of the mirror from the beam. The mover's long base line contributes to a pitch step resolution of about one arc-sec allowing precise beam centering.

Figure 6 shows representative SiC mirror surface roughness results taken from a series of Wyco profilometer measurements by P. Takacs at BNL.[15] The M0 cylinder results indicate that the mirror is one of the best SiC mirrors of its type ever made.[15] The schedule prohibited testing the toroidal mirror before platinum coating. Since the results after coating indicate better than 6 Å rms, we infer a sub-5 Å rms finish for the CVD-SiC surface. It is very encouraging that these results can be obtained for a large mirror with such a difficult profile.

Figure 7 shows the toroidal mirror mounted in the profile test configuration used during the final polishing operation and a schematic drawing of this optical arrangement. The test is based on the fact that the desired toroidal surface is very nearly ellipsoidal. The optical arrangement was devised so that the toroidal mirror images two points, approximately 10 and 5.3 m away respectively, onto each other with almost no aberration.[16] These two points correspond to the foci of the ideal ellipsoid. In the test arrangement, collimated light exits the interferometer and passes through the first negative lens which presents to the toroid a virtual source approximately 10 m away. The toroidal mirror reflects the light to form a real image 5.3 m from its surface. Thus, the light reflected from the mirror is weakly converging towards that remote point. The spherical wave front is then collimated by the second negative lens. This light is reflected upon itself by the plane mirror and passes back through the lens and toroid into the interferometer. The system is double pass, and since we are testing a reflecting surface, the wave front errors are again doubled. The oblique geometry reduces the test sensitivity by the cosine of 86.53°; thus, one fringe in the resulting interferogram, such as that shown in Figure 8, corresponds to a 4-wave error in the toroid. The appropriate test geometry is based on the dependence of the angle of incidence, θ, on the sagittal and tangential radii, R_s and R_t, respectively, given by

$$\cos^2 \theta = R_s/R_t$$

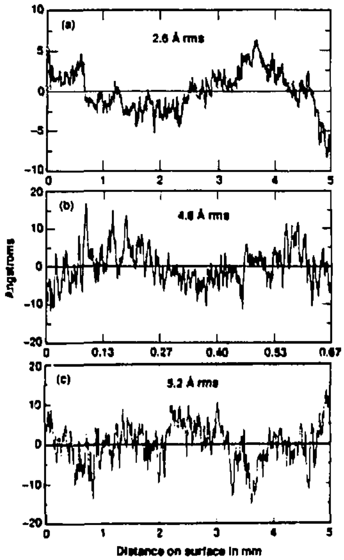

Figure 6. Representative SiC mirror surface roughness measurements made with a Wyko profilometer by Takacs at BNL. a) MO cylinder before Pt coating. b) MO cylinder after Pt coating. c) MO' toroid after Pt coating.

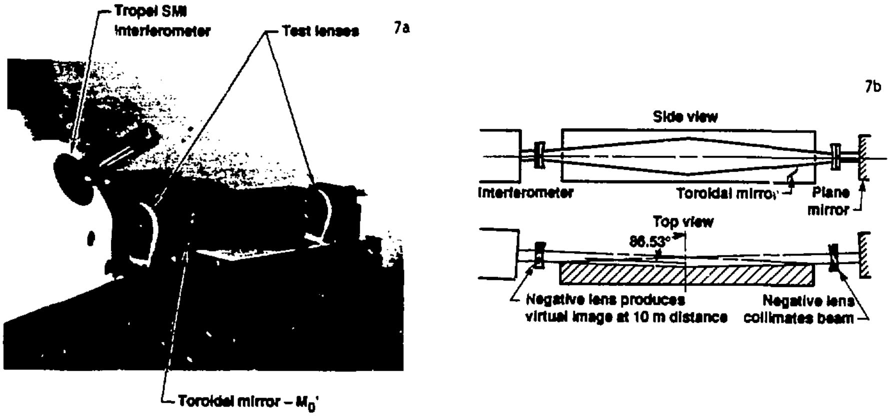

Figure 7. Toroidal mirror profile optical test arrangement. a) toroid mounted in the test setup. b) profile test geometry.

This formula predicts an optimum angle of incidence of 86.569° that is very close to the value 86.534° obtained by optimization using the ACCOS V code (a computer program by Scientific Calculations, Inc., Fishers, N.Y.). This test setup has a residual comatic error of under 1/4 wave which could be eliminated if a cat's-eye retroreflector were used instead of a plane mirror.

The interferogram in Figure 8 was used to evaluate the mirror profile obtained during the final stages of the mirror fabrication. Note that the fringes are compressed along the long axis due to the test obliquity. The interferogram shows that the mirror is suitably concave and free from irregularities. These optical test results are in agreement with physical measurements by F. Cooke.[12]

Figure 8. Toroidal mirror profile interferograms showing concavity and absence of irregularities. See reference 12.

4. FUSED SILICA FOCUSING MIRRORS

4.1 Spherical prefocusing mirror

Figure 9 shows the M1 spherical mirror sized to accept the full beam from M0, as well as the M1 chamber, and mirror alignment mechanism. This design is complicated by the mirror's operating height and angular position, as well as our need for ample clearance below the mirror tank. We considered a bent-flat fused silica mirror designed to approximate a cylinder. This would have required designing a new mirror bender for the elevated location. Therefore we opted for a 452 x 100 mm^2 spherical mirror of 64 m radius fabricated by the Zygo Corp. Fused silica was selected because of the low power levels expected (less than 2 w).

An M1 chamber and support frame was designed that was rigidly attached to the bottom of the 61 cm thick concrete mezzanine floor. A unique 3-point kinematic mirror support was devised based partly on designs in use at BNL, NSLS.[17] For our application the three support and alignment axes are bellows-coupled into vacuum from the top as shown and attached to either side of the mirror base. Flexure pivots eliminate backlash from sliding joints. Modeling results indicated that this system is mechanically very stiff and resistant to vibration. Stepper motor drives on each axis give better than 1 arc-sec resolution in pitch, thus meeting our requirement for precise alignment of the beam on the TGM entrance slits. A commercially available controller was programed to move the 3 axes in order to produce pure pitch, roll, and elevation motions.[18] The large radius spherical mirror is very insensitive to yaw error. We thus eliminated horizontal translation requirements by making the mirror sufficiently wide to handle anticipated beam excursions.

Figure 10 is a photograph of the SPEAR beam focus at the TGM entrance slit plane taken during a recent 3 GeV series after alignment of M0 and M1 mirrors. The aspect ratio and size of the image are reasonable and the beam appears free of scattered components.

4.2 Refocusing mirror

Our refocusing mirror is based on a proven exit mirror design developed at SSRL.[14] This assembly features a kinematically mounted UHV chamber housing a thin cylinder of fused-silica that is bent to simulate an ellipsoid. The mirror bender is supported by three vertically oriented, micrometer driven axes that provide mirror pitch, roll, and height adjustments. Changing the long radius adjusts the vertical focus of the beam at different target locations along the beam line, an advantage for tandem target chambers. The other refocusing mirror that we considered, an ellipsoid, does not have this flexibility, moreover the ellipsoidal profile entails fabrication difficulties. (See reference 19, these proceedings).

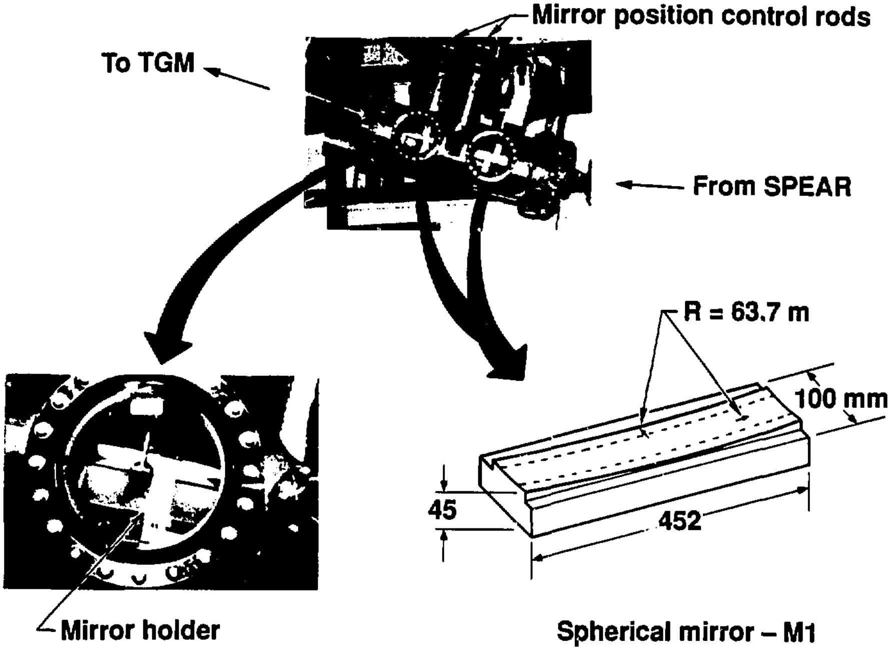

Figure 9. BL-VIII-1 fused silica spherical mirror M1 and its assembly.

Figure 10. BL-VIII-1 beam focused at the TGM entrance slit plane using the prefocusing mirrors M0 and M1.

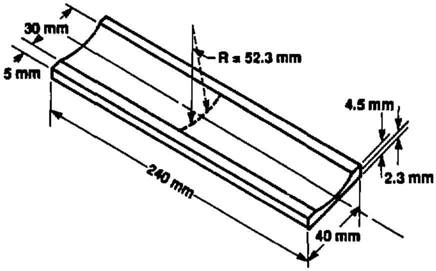

Figure 11. Bent cylindrical fused silica mirror used for refocusing on both BL-VIII branches.

Fabrication of the cylinder is complicated by its thin cross section. Our analysis of bending stresses led to an optimum design of 4.5 mm thickness and a center thickness of 2.3 mm. as shown in Figure 11. This yields a maximum induced tensile bending stress of 2.9 mPa (421 psi) at the bottom surface corresponding to a safety factor of 2.3. Thinner designs have increasingly higher center stresses across the 30-mm mirror width because the mechanical loading points are on the mirror edges.

The key to the mirror fabrication by F. Cooke Inc., was careful selection of stress-free fused silica and skilled grinding and polishing procedures during which the thin mirror blank was coupled to a thick fused silica backing blank. The resulting surface finish was better than 10 Å which is acceptable for our refocusing mirror applications.

5. DISCUSSION AND CONCLUSIONS

Several state-of-the art grazing incidence mirrors have been designed, fabricated to our specifications, and installed in our BL-VIII facility at the Stanford Synchrotron Radiation Laboratory. Major problems for these SR grazing incidence mirrors include beam losses caused by scattering due to surface roughness and figure error. Additional problems for primary mirrors include beam losses due to thermal distortion as well as long term degradation of surfaces caused by thermal cycling and radiation damage. Our use of back conductively cooled SiC provides a good solution for all of these primary mirror problems for bending magnet power levels up to 300 w and 20 w/cm^2 equivalent normal heat load. For our TGM branch first mirror, a uniform CVD-SiC layer deposited on a cylindrically formed, alpha-sintered SiC substrate has been successfully finished to 3 Å rms with the aid of LLNL polishing expertise. A less than 5 Å rms finish has also been obtained on a difficult SiC toroid required for SGM branch prefocusing. The successful toroidal mirror fabrication is due in part to the expertise of the manufacturer and to the development of a profile testing method used during production and discussed herein. For the future, we recommend greatly increasing the CVD-SiC thickness to obtain a factor of 2 decrease in thermal distortion. Furthermore, efforts should be made to decrease the degradation in surface roughness that occurs as a result of the metallic reflective layer deposition.

Our SiC mirror holder-cooler concept is now in use on both branch lines. This involves preloading each mirror along its long axis to partly compensating for the effect of thermal distortions. The remote alignment system, capable of better than 1 arc-sec. resolution in pitch, has been very satisfactory.

Designed to provide the TGM tangential focus, the new 63 m-radius, spherical, fused silica mirror has contributed to enhanced TGM throughput. With its triple axis control providing better than 1 arc-sec. pitch resolution, the LLNL designed, top-mounted, mirror holder/positioner assembly has permitted precise beam centering on the TGM entrance slits. A commercial controller has been programmed to generate pure roll, pitch, and elevation motions. The beam focus and stability at the TGM entrance slits have generally been good throughout our brief experience to date.

From a user standpoint, the TGM refocusing mirror has performed better than we expected. The thin, fused silica cylinder clamped to its SSRL bender/positioner has produced appropriately demagnified, well-defined beam images at the center of the TGM target chamber. The tangential focus is readily controlled and the sagittal focus can be varied by adjusting the mirror's grazing angle. The need for manual micrometer adjustments and lack of decoupled mirror motions is offset by the close proximity of the mirror to the target chamber allowing good visual feedback. No difficulties with bending stresses have been observed. We are looking forward to obtaining operating experience with the refocusing mirror recently installed in the SGM line and, for that matter, our new SR grazing incidence optics in general.

6. ACKNOWLEDGMENTS

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9. F. R. Holdener et al., "Thermal loading considerations for synchrotron mirrors," Proc. SPIE 640-Grazing Incidence Optics, 116-124 (1986).

10. R. DiGennaro, W. R. Edwards, and Egon Hoyer, "Predicting thermal distortion of synchrotron radiation mirrors with finite element analysis," Proc. SPIE 582-International Conference on Insertion Devices for Synchrotron Sources, 273-280 (1985).

11. B. A. Fuchs and N. J. Brown, Lawrence Livermore National Laboratory, Livermore, CA, "Development of polishing methods for chemical vapor deposited silicon carbide mirrors for synchrotron radiation," UCRL-95892 (1987) and B. A. Fuchs, "Removal rates of chemical vapor deposited silicon carbide (CVD SiC)," these proceedings.

12. F. Cooke, S. Fantone, and B. A. Fuchs, "Toroidal mirror of evaporated silicon carbide", Applied Optics 26, 2050-2052 (1987).

13. The silver-plated beryllium copper finger stock, "Multilam" (trade name) is normally used as a high current electrical conductor.

14. These designs were developed by Richard Boyce, Stanford Synchrotron Radiation Laboratory, Stanford, CA, private communication (1985).

15. P. Z. Takacs, Brookhaven National Laboratory, Upton, Long Island, NY, private communication (1986). See also P. Z. Takacs, "Metrology of reflected optics for synchrotron radiation," Nuclear Instrum. and Meth. A246, 227-241 (1986).

16. W. T. Welford, Aberrations of the Symmetrical Optical System (Academic Press, London, 1974), p. 170.

17. Our M1 mirror mount design is based partly on designs by T. Oversluizen, National Synchrotron Light Source, BNL, Upton, Long Island, NY, private communication (1985).

18. A Compumotor model 3000 indexer was programmed to generate pure M1 motions by T. Braun and K. W. Neufeld, private communication, Lawrence Livermore National Laboratory, Livermore, CA (1986). Recent modifications were made by M. B. Schneider, Lawrence Livermore National Laboratory, Livermore, CA, (1987).

19. M. Grindel, "Manufacturing and testing of a grazing incidence mirror," these proceedings.