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Thermal loading considerations for synchrotron radiation mirrors

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Abstract

Grazing incidence mirrors used to focus synchrotron radiation beams through small distant apertures have severe optical requirements. The surface distortion due to heat loading of the first mirror in a bending magnet beam line is of particular concern when a large fraction of the incident beam is absorbed. In this paper we discuss mirror design considerations involved in minimizing the thermal/mechanical loading on vertically deflecting first surface mirrors required for SPEAR synchrotron radiation beam lines. Topics include selection of mirror material and cooling method, the choice of SiC for the substrate, optimization of the thickness, and the design of the mirror holder and cooling mechanism. Results obtained using two-dimensional, finite-element thermal/mechanical distortion analysis are presented for the case of a 6° grazing incidence SiC mirror absorbing up to 260 W at Beam Line VIII on the SPEAR ring. Test descriptions and results are given for the material used to thermally couple this SiC mirror to a water-cooled block. The interface material is limited to applications for which the equivalent normal heat load is less than 20 W/cm^2 .

Introduction

In the course of designing x-ray beam lines to meet the needs of our National Laboratory/University of California Participating Research Team at the Stanford Synchrotron Radiation Laboratory/SLAC SPEAR ring, we have considered in detail the effects of thermal loading on the optical elements. In this paper we concentrate on the primary focusing mirrors required for two Beam Line-VIII bending magnet lines. These vertically deflecting mirrors, designated MO and MO', are at grazing angles of 6° and 2.5° , respectively, and hence absorb most of the incident radiation. The total heat dissipated by each of these mirrors is not nearly as great as will be required by the first mirrors in the wiggler beam lines to be developed later. The distortion of each bending magnet beam line mirror is of concern because most of the heat deposition is in a relatively narrow band in the center of the mirror. Of the two mirrors, the effect of the thermal loading on the 2.5° grazing incidence mirror is less because the total power and power density are lower, however, since this mirror is a toroid focusing both tangentially (in the vertical) and sagittally (in the horizontal) on the monochromator slits, the surface slope distortion tolerances are more critical. In contrast the 6° grazing incidence cylindrical mirror only focuses sagittally. Thus the slope tolerances along the long axis are not quite as critical.

In this paper we discuss mirror design considerations involved in minimizing the effects of thermal distortion. These include the selection of mirror material and cooling method, optimization of the thickness, and the design of the mirror holder and cooling mechanism. The two-dimensional finite-element analysis of the 6° cylindrical mirror will be featured along with specific tests of the chosen cooling interface material.

The design to be discussed is limited by the interface material to applications such as bending magnet beam lines for which the normal equivalent heat load is less than 20 W/cm^2 . The methods chosen may not be directly applicable to the first mirrors that will be required for our wiggler beam lines. For example, the horizontally deflecting primary mirror for the wiggler soft x-ray branch absorbs up to 2 kW of power. In this case carefully considered direct water cooling methods must be employed.^{1,2} (See Ref. 1 for a design description of this direct-cooled, horizontally deflecting, 2.8° flat wiggler mirror.) The collimating mirror needed for our wiggler hard x-ray branch is an intermediate case. Since the required grazing angle is less than 0.3° necessitating a very long mirror, the wiggler thermal load is spread over a much larger area. In addition, most of the wiggler spectrum is reflected, therefore the method developed to limit distortion of the bending magnet mirrors may be suitable if applied over a much greater length.

Mirror material selection process

Substrate materials considered for first surface synchrotron radiation mirrors include aluminum, OFHC copper, SiC, and fused silica. Their thermal properties are summarized in Table 1. In their wiggler mirror analysis, DiCennaro et al.³ have shown that the slope distortion varies nearly inversely with the deformation figure of merit that we define as k/α and that the surface temperature varies inversely with thermal conductivity. In addition, the maximum thermal stress was shown to vary nearly inversely with the thermal stress figure of merit $k(1 - \nu)/E\alpha$. Fused silica, although potentially yielding the best surface finish, is unacceptable for high grazing angles because of its poor figure of merit for thermal distortion and low thermal conductivity. Although OFHC copper is clearly superior to aluminum, both metals have thermal properties adequate for many bending magnet beam line applications. They can be diamond-turned, electroless-nickel plated, and polished to better than $10 \text{ \AA}$ rms. Difficulties due to long order roughness for existing electroless-nickel plated mirrors still remain however.³ Furthermore, there is a degree of risk in using soft copper due to spontaneous mechanical distortion after machining, polishing, or even accidental mishandling. For high peak power applications requiring internal cooling channels and a brazed assembly, an alloy of copper (C15715) has been chosen for development by DiCennaro et al. at Lawrence Berkeley Laboratory.⁴ Preliminary efforts to diamond turn this alloy have not been successful.⁴

In comparison to metal mirrors, SiC with a better figure of merit for thermal distortion, is the material of choice when evaluated in terms of cost and technical risk, including polishability, and substrate stability under mechanical, thermal, and radiation loads.^{5,7} Other factors that led to our choice of SiC as the substrate material are its high stiffness, low internal thermal stress, high yield strength, high relative hardness, UHV compatibility, recoatability, and adequate thermal conductivity. Acid removal of carbonaceous buildup without the need for repolishing is a major advantage. Moreover, the very hard SiC chemical vapor deposition (CVD) coated surface is much more resistant to surface damage resulting from inadvertent mechanical abuse during the routine cleaning and handling procedure.⁸ Note also that a very thick CVD layer decreases the thermal distortion up to a factor of 2.

Table 1. Comparison of Material Properties and Figures of Merit

Properties	CVD-SiC	α -Sintered	Aluminum	OFHC Copper	Fused Silica
Thermal Conductivity, k (W/cm/K)	2.00	1.26	1.66	3.94	0.015
Thermal Expansion Coeff, α (10^{-6} per K)	2.90	4.02	23.7	17.0	0.55
Elastic Modulus, E (10^4 psi)	65.0	59.0	10.0	17.0	10.5
Poisson Ratio, ν	0.142 ^a	0.142	0.330	0.337	0.165
Figures of Merit					
Deformation $10^4 k/\alpha$	68.9	31.3	7.0	23.2	2.7
Stress 1 $10^{-3} k/E\alpha$	10.6	5.3	7.0	13.6	2.5
Stress 2 $10^{-3} k(1 - \nu)/E\alpha$	9.1	4.6	4.7	9.0	2.1

^a α -Sintered SiC value used.

CVD-coated SiC can be polished reliably to less than 8 Å rms on relatively large mirrors. These super finishes are necessary for high reflectivity with low scattering. Two very high quality CVD-coated SiC MO mirrors were recently received from the supplier.⁹ Surface finish was sampled using a Wyko profilometer yielding average values of 2.1 ± 0.5 and 2.5 ± 0.7 Å rms, respectively, prior to the platinum coating and less than 5 Å rms afterwards. The figure accuracy also exceeded our specifications and was estimated from interferometry data to be between $\lambda/2$ and $\lambda/4$.

Silicon carbide's high stiffness, yield strength, and hardness enabled us to consider a nontraditional mirror holder/cooling block design. This involves mechanically loading the mirror such that when the nominal thermal load is superimposed onto the mirror, the mirror will return to its unstressed position. This enables 75% of the mirror to be within 2 arc-sec slope error for at nominal operating conditions compared to 3.5 arc-sec over most of the mirror for the unconstrained case.

Mirror description

Table 2 summarizes parameters of two vertically deflecting first surface SiC mirrors, MO and MO', required for our VUV and soft x-ray bending magnet beam lines, respectively. Each of the Pt-coated, CVD-coated, α -sintered, SiC mirrors is required to focus a beam through a small distant aperture. Since vertical aperture dimensions are tighter and more critical than that of the horizontal, mirror tolerances both in form and surface finish along the long mirror axis (beam direction) are most critical in both cases. The MO mirror's optical width is 106 mm. The overall base material width is 130 mm, including two square 10-by-10-mm side rails along the length of the mirror to accommodate the clamping springs of the mirror holder/chill block assembly.

Table 2. Silicon Carbide Mirror Parameters

Mirror Designation	MO	MO'
Type	Cylindrical	Toroidal
Focus	Sagittal	Sagittal/Tangential
Maximum Power	263 W	110 W
Grazing Angle	6°	25°
Size L, W, T	300 by 110 by 35 mm ³	380 by 100 by 45 mm ³
Radius of Curvature		
R1—Transverse	929.2 mm	419.0 mm
R2—Along Beam	Infinity	114.57 m
Optical Form Tolerance	$\lambda/2$ @ 6328 Å	$\lambda/4$ @ 6328 Å
Surface Finish	2.5 ± 0.7 Å rms ^a (measured)	<5 Å rms max

^a <5 Å rms after Pt coating.

Mirror surface distortion—two-dimensional analysis

It is important to understand the magnitude of the thermal distortions induced in the optical surface of the grazing incidence mirrors, and if possible, to keep distortions within allowable limits. A parameter study using known material properties in a two-dimensional computational analysis was used to investigate this problem. Table 3 summarizes the thermal input parameters used for the 6° MO mirror.

Table 3. Two-Dimensional Thermal Analysis Input Parameters for a 6° SiC Mirror 8.5 m from SPEAR Bending Magnet

Type	Nominal Operation (3.00 GeV, 100 mA)	Maximum Operation (3.75 GeV, 100 mA)
Power Flux (W/mr)	9	22
Total Power (W)	110	260
Gaussian FWHM (mm) (Normal to Mirror)	27	23
Normal Incident Equivalent Power (W/cm ²)	3.9	11.4

Figure 1. Thermal SiC synchrotron radiation mirror distortion and corresponding slope β vs distance along the long axis calculated using two-dimensional finite-element analysis. The 300-mm-long and 35-mm-thick, vertically deflecting mirror at 6° grazing incidence is 8.5 m from a SPEAR bending magnet source. SPEAR is at 3.0 GeV, 100 mA. The mirror is unconstrained. (a) Two-dimensional results showing CVD-SiC distortion magnified 20 000 times. (b) Corresponding slope for CVD-SiC. (c) Two-dimensional results showing α -sintered SiC distortion. (d) Corresponding slope for α -sintered SiC.

The synchrotron radiation power distribution from a bending magnet is uniform horizontally and Gaussian vertically centered on the electron orbital plane. The thermal input to a vertically deflecting mirror, therefore, is uniform across the mirror face (short axis) and is nonuniform along the long mirror axis with a Gaussian distribution symmetric about the center. For the case of interest, the SPEAR vertical divergence at 3 GeV is only 0.34 mrad FWHM, hence the projected FWHM of the Gaussian thermal deposition normal to the mirror surface is only 27 mm for a 6° grazing incidence mirror at 8.5 m. Across the face the heat input is slightly curved due to the mirror's cylindrical curvature, but can be considered flat for our analysis. A two-dimensional mesh from front to back and along the long axis of the mirror was created to analyze the magnitude and shape of the thermal distortion as a function of cooling method and material thickness. The mesh was zoned finest in the area where distortion was expected to be most predominant. The following cooling options were modeled:

- (1) Radiative cooling only to the surrounding vacuum tank enclosure.
- (2) Conductive cooling of the entire bottom surface.
- (3) Conductive cooling of the middle of the bottom surface directly below the central thermal loading.

For the radiative case, the bottom and ends were modeled with an emissivity of 0.9, a value suggested by the manufacturer. The platinum-coated mirror surface was modeled with a conservatively low emissivity of 0.02. A measured value of 0.18 has been obtained for a platinum sample finished to 40 Å rms.¹⁰ Lower emissivity values are expected in our case, since the surface roughness is below 5 Å rms.

Shown magnified 20,000 times in Figure 1, the calculated distortion is a simple elevation localized in the central portion. Initial calculations used to determine the mirror thickness and cooling method were done by approximating the Gaussian input with a uniform heat input of equivalent magnitude. Figure 2 shows calculated surface distortion amplitude vs distance along an unconstrained mirror for the flat and for the Gaussian heat input. Although the width of the peak is different, the maximum amplitude of the distortion is the same for either heat input model over the rest of the mirror. Since the results differ only in the width of the peak, our conclusions regarding cooling method and thickness are considered valid.

To determine the optimal design thickness for the SiC mirror, the mirror distortion was calculated for several mirror thicknesses assuming an unconstrained boundary with the entire bottom surface cooled. As shown in Figure 3, the results indicate that 35 mm is a good choice.

To model conductive cooling, nodes of the mesh model were set at a constant value of 27°C for the entire bottom in one case and for the central 18 mm in another. The results are shown in Table 4. The maximum angular distortion of approximately 4.3 arc-sec was observed for both conductive cooling methods. A slightly higher value of 5.3 arc-sec coupled with an unacceptably high peak temperature of 385°C was obtained for the case featuring radiative cooling only. Note that the method of cooling did not significantly affect the magnitude of the thermal distortion on the mirror surface, but did affect the final peak temperature. Conductive cooling was therefore chosen to limit the mirror surface temperature and to reduce distortions of the entire assembly, particularly at the mirror/holder interface, arising from differences in thermal expansion.

Figure 2. Calculated slope β vs distance along the long axis for a CVD-SiC mirror for two heat input models, Gaussian and flat. The entire mirror bottom is cooled. Mirror is unconstrained. SPEAR is at 3.75 GeV, 100 mA.

Figure 3. Calculated maximum slope β vs mirror thickness for an unconstrained CVD-SiC mirror with flat heat input and the entire bottom mirror surface cooled. SPEAR is at 3.75 GeV, 100 mA.

Table 4. Comparisons of Cooling Methods for CVD-SiC

Method	Maximum Temperature (C°)	Maximum Angle (arc-sec)
Radiative	385	5.3
Full Bottom Conduction	36	4.3
Central Bottom Conduction (1.8 cm)	42	4.3

It is not easy to design interfaces requiring heat conduction in UHV. In order to conduct heat with adequate efficiency across mechanical joints, contact pressures well above 1000 psi^{11,12} are needed. The proposed solution utilizing commercially available silver-plated, beryllium-copper finger stock was considered. "Multilam" (manufacturer's tradename) normally a high current electrical conductor, was chosen because of the high moment generated by its individual fingers (10 per inch length) and its relatively short heat transfer length. In addition, this material has a very small contact spot size (high stress contact area) making it ideal for this application.

Interface material thermal test

An experiment was performed to determine the thermal transfer characteristics of the proposed finger stock material. A schematic of the test setup and a photograph are shown in Figure 4 (a) and (b), respectively. Data were taken with the Multilam finger stock compressed by 0.018 in. and repeated with the Multilam removed. Figure 4(c) shows the results. The difference in the two plotted curves represents the heat transferred solely via the Multilam. The value for $h_c A_c$, convection coefficient times contact area, was measured to be 0.0394 W/°C per cm (0.190 Btu/hr/°F per in.) of length of material. This yields an average rise of 44°C (79°F) across the interface for a total heat input of 260 W, the maximum operating condition.

Interface material mechanical test

To determine the Multilam's spring stiffness, a compressive load test was performed. The measured load deflection curve had little hysteresis and was very linear giving the resulting spring constant of 1078 lb/in. For the chosen deflection of 0.018 in., the resulting load of 19.4 lb is required per inch of length of Multilam. This corresponds to a total load of 441 kg (971 lb) for 127 cm (50 in.) of material (ten 12.7-cm-length strips) for the final MO mirror holder design.

Two-dimensional analysis combining thermal/mechanical effects

By utilizing the mechanical load imposed by the Multilam, it is possible to partly compensate for the thermal distortions in the mirror. The mechanical moment induced by the mirror holder side rail springs and the Multilam produces a slight concave profile along the long mirror axis. A two-dimensional finite-element analysis based on this concept was used for optimization. The results suggest, as shown in Figure 5, that the mirror profile can be kept flat within 2 arc-sec over 75% of the total mirror surface at nominal 3 GeV beam operation. For the parasitic running mode where the thermal load is small, the mirror distortion is very close to that of the purely mechanical spring loading case. At maximum beam operating conditions the thermal distortion tends to dominate as expected.

MO mirror holder/chill block design

An assembly drawing for the resulting mirror holder along with an exploded isometric drawing of the water flow cooling block is shown in Figure 6. A photograph of the assembled holder plus alignment mirror is shown in Figure 7. The design features a copper/stainless steel, vacuum-brazed cooling-block assembly. Water flows through passages machined directly in the copper mirror base mounting plate. The Multilam is held in 20° beveled grooves across the copper plate's upper surface. The mirror is pressed against the Multilam via the side loading plates. These are designed with very stiff flat stainless steel fingers that force the mirror against the Multilam, maintaining the desired Multilam compression. The upper stiff spring of the side rails serves as the datum for mirror positioning. The twelve 5/16-18 UNC (united national course) loading screws have been precision machined along with mating washers to guarantee that this desired compression is maintained. An internally formed bellows, used for a vacuum barrier, allows the necessary movement of the chill block in the Multilam spring loading operation. Within the copper/stainless brazed assembly an internal chamber vented to the atmosphere protects the vacuum chamber from water pressure joint failure. Finally, the upstream mirror mask is supported on the water-cooled copper plate and protects the mirror from accidental normal incidence beam impingement.

Summary

Because it provides relatively low thermal distortions, SiC is a good substrate material for first surface mirrors required for moderate incident power densities such as synchrotron radiation bending magnet lines. Our two-dimensional finite-element analysis results indicate that for the case of an unconstrained grazing incidence mirror absorbing up to 11 W/cm² from a SPEAR bending magnet, increasing the mirror thickness above 35 mm does not significantly affect the slope distortion along the long axis. Calculations indicated that the method of cooling (radiative only vs conductive) does not significantly affect the magnitude of the mirror thermal distortion. However, radiative cooling only yields unacceptably high surface temperatures. Conductive cooling a portion of the bottom surface was therefore chosen to limit the surface temperature and to reduce distortions of the entire mirror/holder assembly. Although we haven't yet exploited it, thermal distortions can be reduced by as much as a factor of 2 by increasing the CVD-SiC layer thickness deposited on the sintered SiC.

A commercially available silver-plated, beryllium-copper finger stock was chosen as the material used to thermally couple the SiC mirror to a brazed copper-stainless steel chill block. The spring stiffness and thermal transfer characteristics of the material were tested.

Figure 4. Multilam interface material contact conductance test. (a) Test schematic showing thermocouple (TC) locations. Heat flux $\dot{Q}_{out}$ was measured using H_2O flow rate and temperature difference (TC8-TC6). (b) Photograph of test setup. (c) Heat flux per unit temperature difference across Multilam vs heat flux transferred. The value derived for the contact heat conductance times area $h_c A_c$ was $0.0394 \text{ W/}^\circ\text{C/cm}$ (or $0.190 \text{ Btu/hr } ^\circ\text{F/in.}$).

Figure 5. Thermal/mechanical α -sintered SiC synchrotron radiation mirror distortion (magnified 20,000 X) and corresponding slope β vs distance along the long axis calculated using two-dimensional finite-element analysis. The 300-mm-long and 35-mm-thick, vertically deflecting mirror at 6° grazing incidence is 8.5 m from a SPEAR bending magnet source. (a) Low-power case, mechanical loading only; (b) 3 GeV, 100 mA, 3.94 W/cm²; (c) 3.75 GeV, 100 mA, 11.4 W/cm². Mechanical loading is applied by stiff-spring side-loading plates that press the mirror against the Multilam mounted on the water-cooled copper base.

Figure 6. Mirror holder assembly (a) side view, (b) center sectional view, and (c) exploded view showing water passages in copper cooling plate directly below SiC mirror.

The material is suitable for applications with power densities less than 20 W/cm^2 . The mirror holder-chill block assembly was designed to produce a slight concave profile along the long mirror axis, thus partly compensating for the effect of thermal distortions and keeping the mirror flat to within 2 arc-sec over 75% of the total mirror surface at nominal 3 GeV SPEAR operation. By increasing the mechanical loading, it is possible to reduce the average thermal distortion even further at 3 GeV. In doing so, however, the mechanical distortion at low power starts to become unacceptable.

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Figure 7. Photograph of assembled mirror holder. The SiC mirror has been replaced with an aluminum alignment mirror mockup.

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