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Thermal Management of Next-Generation Contact-Cooled Synchrotron X-Ray Mirrors

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ABSTRACT

In the past decade, several third-generation synchrotron x-ray sources have been constructed and commissioned around the world. Many of the major problems in the development and design of the optical components capable of handling the extremely high heat loads of the generated x-ray beams have been resolved. It is expected, however, that in the next few years even more powerful x-ray beams will be produced at these facilities, for example, by increasing the particle beam current. In this paper, the design of a next generation of synchrotron x-ray mirrors is discussed. I show that the design of contact—cooled mirrors capable of handing x-ray beam heat fluxes in excess of 500 W/mm^2—or more than three times the present level-is well within reach, and the limiting factor is the thermal stress rather then thermally induced slope error.

Keywords: mirror, x-ray, optics, cooling, optimization, contact-cooled, design, synchrotron, high heat flux, thermal management.

1. INTRODUCTION

The first optical element on most third-generation synchrotron x-ray beamlines is a single-crystal monochromator, a multilayer monochromator, or a mirror. Mirror and multilayers, henceforth collectively referred to as mirrors, intercept the beam at grazing angles and are made of polished substrates. The x-ray beam produced by an insertion device may be passed through one or more slits or apertures to select the central part of the beam where spectral harmonics having extremely high brilliance are present. This procedure reduces the detrimental thermal load on the optical element making thermal management of optics easier without sacrificing desirable photons.

Because mirrors intercept x-ray beams at grazing incident, the beam footprint stretches over the length of the mirror with a corresponding reduction in the incident heat flux. As an example, the undulator A used on most of the Advanced Photon Source (APS) beamlines provides a beam with an on-axis normal-incidence peak heat flux of 160 W/mm^2 at 30 meters from the source (where the first optics often resides). An undulator gap of 10.5 mm and an electron beam current of 100 mA are assumed. With a mirror intercepting this beam at 0.15° (as in APS sector 2), the peak heat flux on the mirror is about 0.4 W/mm^2. This expansion of the beam and, additionally, the beam's relative horizontal uniformity (along the length of a horizontally deflecting mirror) have made external cooling in the form of an optimal contact-cooling (OCC) technique possible (Khounsary and Yun, 1996).

The present paper reports on the investigation of the design of a new mirror concept using the OCC technique capable of handling x-ray beams with much higher thermal loads.

The impetus for generating more powerful x-ray beams—as always—is to deliver a higher photon count at the sample being investigated. It is interesting to note that, although the x-ray beam generated by a typical undulator at high-energy-third generation synchrotron sources can have several kilowatts of thermal load, only a very small fraction of it—within a narrow bandwidth-is used at a time (as low as a few parts per million).

In the coming years, and consistent with the past trends, one can expect the power of generated x-ray beams to increase substantially. This increase can result from (a) longer or in-tandem insertion devices, (b) smaller undulator gaps (with increasing magnetic field and thus beam power), (c) higher storage ring current, or (d) increased storage ring energy. The thermal load of an x-ray beam increases linearly in (a) and (c), exponentially in (b), and quadraticly in (d).

At the APS, options (a), (b), and (c) are being explored. Undulators have been operated at gaps as small as 8.5 mm, or beam current as high as 160 mA (temporarily) has been reached (Emery, 1999), or two undulators in tandem have been put into service. In fact, some of the high heat load optics development involving single-crystal monochromators has been carried out at the APS sector 1 with two undulators in tandem to simulate 200-mA particle beam current conditions (Lee et al. 1999).

Following a brief discussion of x-ray mirrors, an existing OCC mirror, and x-ray thermal loads in the next section, the design of a new mirror for operation at higher heat loads will be discussed. The most demanding thermal condition that can be envisioned in the foreseeable future at the APS will be considered for the design of a next-generation mirror design.

2. X-RAY MIRRORS

Mirrors used at synchrotron x-ray facilities are either cooled or not cooled. Typically, when a monochromatic beam strikes a mirror, the heat load is small (< 1 W) and no cooling is necessary. When a white or a broad-spectrum synchrotron x-ray beam impinges on a mirror, the heat load can be high and the mirror must be cooled to preserve its integrity and figure.

Mirrors can be internally or externally cooled. The APS has designed and built both kinds (Khounsary, et al.; 1998, Tonnessen et al., 1996). There are advantages and disadvantages to each design approach as described elsewhere (Khounsary et al., 1998). Although there are instances for which an internally cooled mirror may be an appropriate choice, the contact-cooled design is overall simpler and satisfies the stringent surface figure requirements for use on APS undulator beamlines.

Owing to the small grazing angles of incidence and a beam power profile that may be substantially uniform in the central region of the x-ray beams, it is possible to use the OCC technique to remove the incident heat and maintain the mirror figure exceptionally well. This is particularly true for horizontally deflecting mirrors, because, due to large deflection parameters (especially as close undulator gaps where thermal load is also higher), the beam power profiles are more uniform in the horizontal than in the vertical direction. As discussed elsewhere (Khounsary and Yun, 1996), an incident beam introduces thermal distortions in the substrate, with bending and mapping as two of the major components. Bending refers to the deformation of the mirror because a warmer temperature due to the beam on the mirror surface causes a convex mirror shape. Mapping deformation, on the other hand, refers to deformation resulting from variation of the temperature across the beam footprint on the surface of the mirror caused by the spatial variations in the beam power profile. The OCC method suppresses mirror bending but cannot totally eliminate the mapping error. Thus the OCC method is particularly suitable for beams with a slowly varying power profile distribution along the mirror length. This condition, to some extent, can always be satisfied, primarily due to the grazing incident angle involved in x-ray reflection.

The 1.2-m-long M1 mirror at the APS sector 2 beamlines is one of the mirrors built on this principle, and it has been in operation for the past three years (Khounsary et al., 1998). Its specifications are given in Table 1. Details on the construction and performance of this mirror are given in the above reference. For practical reasons, the design studies for new mirrors are carried out in the context of an upgrade for this mirror, although the results are applicable to other similar mirrors on high heat load beamlines.

Table 1: Specifications of the M1-Prime Mirror at the APS.

Substrate	Silicon
Incidence angle	0.15°
Orientation	Horizontally Deflecting
Energy	Up to 35 keV (Rh and Pt coatings)
Dimensions (L x W x D)	1200 mm x 100 mm x 95 mm
Clear aperture (L x W)	1160 mm x 70 mm
rms surface roughness	< 4Å
rms slope errors	≤ 4 μrad (Tangential) ≤ 20 μrad (Sagittal)

3. THERMAL LOAD

The incident beam on the existing M1 mirror is from undulator A (UA) or from the intermediate- energy undulator, IEU, having a 5.5-cm period, as detailed in Table 2. The storage ring current is 100 mA.

As indicated, there are at least four parameters that can be changed to increase x-ray beam strength and thus the thermal load. Because storage ring energy is not likely to change, we concentrate on the increased thermal load on the mirror resulting from changes in the undulator gap, the storage beam current, or undulator length (or tandem undulators). Longer or tandem undulators increase the power additively, having an effect similar to that of increased beam current. In Figure 1, variation of the x-ray beam thermal load from the APS UA with storage ring current and undulator gap is depicted. The solid line indicates the present operational range, while dashed lines show extrapolation for possible future trends.

For the purpose of next-generation mirror design, a power load corresponding to 300-mA beam current at an undulator gap of 10.5 mm is considered (as the extreme data point in Figure 1). Table 3 provides a summary of the source and the thermal load for this configuration. This is fairly substantial thermal load and is unlikely to be reached in the immediate future because of many obstacles unrelated to optics. A successful mirror design for this lofty level of thermal load will remove one of the obstacles in the evolution of x-ray beams. On-axis power profiles of the beam at 300-mA ring current and 10.5-mm undulator gap are given in Figure 2.

Table 2: Source parameters and x-ray beam thermal loads of two APS undulators.

Parameters	**Source**	
	3.3-cm Undulator (UA)	5.5-cm Undulator (IEU)
Period (cm)	3.3	5.5
Deflection parameter at 10.5-mm gap	2.76	6.57
Number of periods	72	43
Total beam power (kW)	5.9	12
Peak power density (kW/mrad^2)	162	143
Normal incident heat flux at mirror, 30 m from source (W/mm^2)	180	159
Power through (h x v) apertures (kW):		
4.5 mm x 4.5 mm fixed aperture	2.2	2.0
4.5 mm x 3.14 mm adjustable aperture (incident on mirror)	1.6	1.4
Peak incident heat flux on the mirror surface (W/mm^2)	0.47	0.42
Average incident heat flux on the mirror surface (W/mm^2)	0.30	0.26

Table 3: Source and thermal load used for the next-generation mirror design.

Parameter	**Value**
Undulator	APS Undulator A
Storage ring energy (GeV)	7
Storage ring current (mA)	300
Undulator gap (mm)	10.5
Undulator A period (mm)	33
Number of periods	72
Device length (m)	2.4
Deflection parameter	2.76
Total beam power (kW)	17.7
Peak power density (W/mr^2)	490
Peak normal incidence heat flux on a mirror @30 m (W/mm^2)	540
Power through a 4.5 mm x 3.14 mm (h x v) aperture striking mirror (kW)	3.8
Peak incident heat flux on a mirror surface @30 m @ 0.15° (W/mm^2)	1.4
Average incident heat flux on the mirror surface (W/mm^2)	0.9

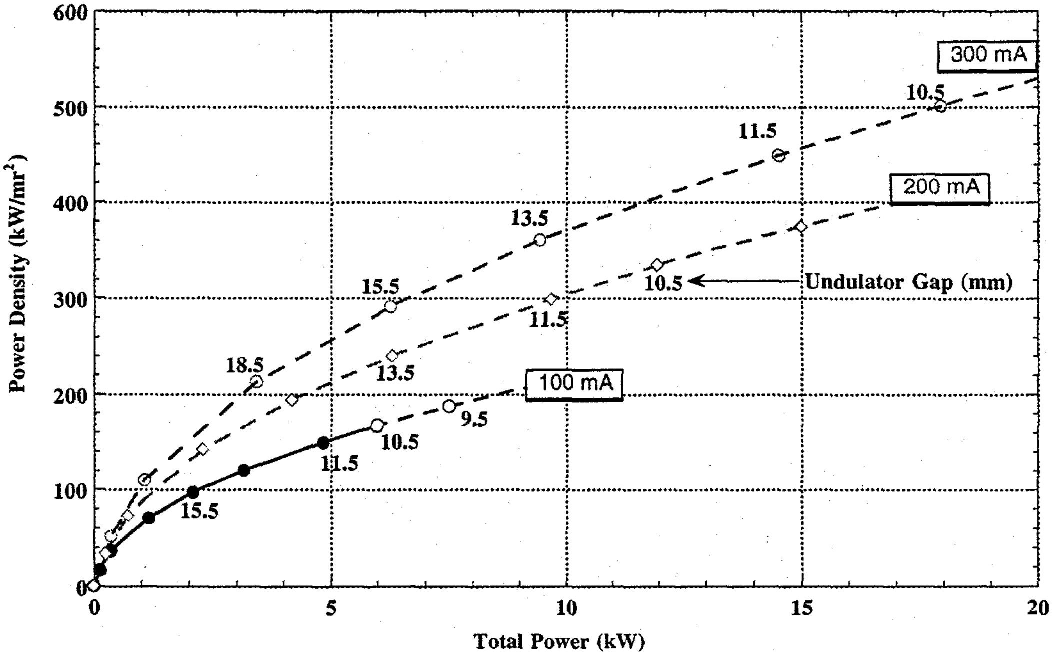

Figure 1: Calculated thermal load of the x-ray beam from APS undulator A at various device gaps and electron beam currents. Presently, closed gap operation is carried out at a gap of 10.5-11.5 mm with a maximum beam current of 100 mA. Solid and dashed lines represent the present and possible future operating ranges, respectively.

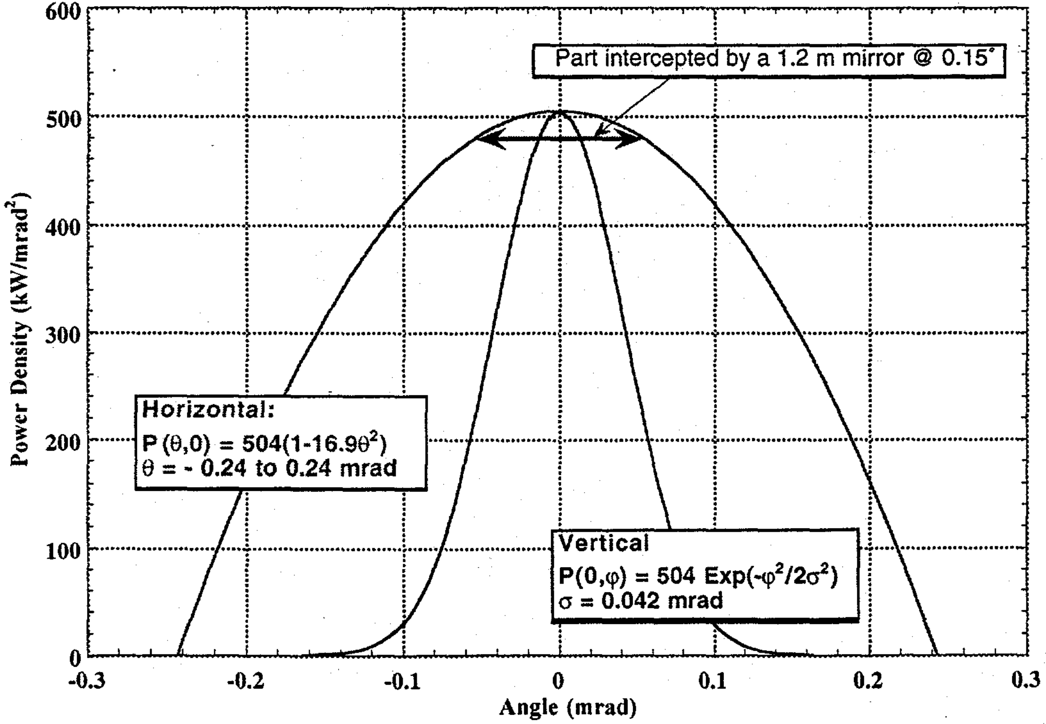

Figure 2: Best curve-fit through the calculated on-axis vertical and horizontal profiles of the APS undulator A at 10.5-mm gap and 300-mA ring current. A 3.1-mm horizontal segment of the beam intercepted by the 1.2-m-long horizontally deflecting mirror is also shown. Up to a 4.5-mm vertical segment of the beam may strike the mirror.

4. MIRROR ACCEPTANCE CRITERIA

The main acceptance criteria for a cooled mirror are based on (a) a manageable temperature, (b) a safe level of thermal stress, and (c) a modest user-defined tangential slope error limit. Sagittal slope errors are not relevant because of the small grazing angles. Other issues, such as vacuum compatibility, low vibration, etc., are relevant but not particular to the present design.

While there is no hard limit on the mirror temperature, it is prudent to keep the mirror temperature at a modest value. A high mirror temperature prolongs the mirror thermal time constant, adversely affects silicon properties, and may result in a gradual heat transfer from the mirror to its support structure, if not well insulated and shielded. The latter can lead to time-dependent mirror displacements due to heating up of the other components. For these reasons and somewhat arbitrarily, we limit the maximum temperature rise to 60°C, or to 85°C when the coolant is at 25°C.

Because silicon is a brittle material, its maximum tensile stress should be kept well below its tensile strength for a good margin of safety. Tensile strength in silicon varies greatly depending on the presence of cracks and microcracks on the surface. A well-etched piece can show a tensile strength in excess of 70 MPa (10,000 psi). Ordinarily, a safety factor of 4 [to keep the stress below 17MPa (2500 psi)] would give a comfortable margin. However, because the maximum tensile stress in contact-cooled mirrors occurs at the cooling interface where Ga/In will be in contact with silicon for a prolonged period of time, a smaller tensile strength, 7 MPa (1000 psi), is used. This gives a margin of safety of 10. Another reason for choosing this low allowable stress level is the stress concentration in the corners of the notches. Machining 1-mm-diamter corners in the notches will lead to tensile stress levels about half the maximum in the mirror, and as such, will have a very comfortable margin of safety of about 20. In any case, the inside of the notches must be fully etched to remove sub-surface damages.

The limit on the tangential slope error is imposed to prevent significant angular spreading of the well-collimated x-ray beam from a third-generation source. This is set at 3 μrad for this mirror. Large sagittal slope errors can be tolerated due to small grazing angles.

5. EXISTING MIRROR DESIGN

The first step in addressing the need for future mirrors is to determine the potential of the existing mirror for higher heat load applications. This can establish the upper limit on the thermal load that the present mirror can handle while providing acceptable thermal, mechanical, and optical performance. With the recognition of this capability, one can proceed to develop new mirror designs suitable for higher heat load beams.

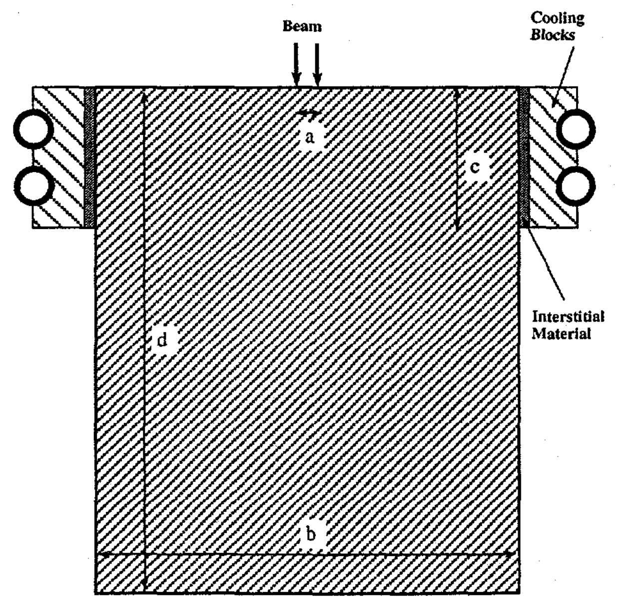

Figure 3: A cross-sectional view of the present M1 contact-cooled mirror with two copper cooling blocks.

The present mirror is a simple polished block of silicon sandwiched between two cooling plates as shown in Figure 3. The dimensions (see also Table 1) are b = 100, c = 15 mm, and d = 95 mm. Incident beam height, a, can vary from a fraction of a millimeter to a maximum of 4.5 mm, while the beam width (3.14 mm) is sufficient to cover the *entire* mirror length (to prevent sharp thermal load variations leading to tangential slope errors in that direction). Currently, indium is used between the copper cooling blocks and the silicon to reduce thermal contact resistance and to enhance heat transfer across the Si-Cu interface. It should be noted that, to a first approximation, if a mirror is uniformly heated along its length, the thermal contact resistance only affects the mirror's overall temperature and not the temperature gradients and thus the tangential slope error in it. Nonlinear material properties and the longitudinally nonuniform x-ray beam power profile, however, will somewhat couple the heat transfer coefficient (which includes contact resistance) with mirror tangential slope error.

The performance of this mirror with 100-mA beam current has been theoretically (Khounsary and Yun, 1996) and experimentally (Khounsary et al., 1998) established. Temperature, tensile and compressive stresses, and the slope error for this mirror at 100-mA beam current are calculated and given in Table 4 (Case A). For the calculations in Table 4, a 1.2 m x 0.1 m x 0.1 m mirror is assumed, and temperature-dependent silicon properties are used. The heat transfer coefficient values applied at the mirror surface are 2350 and 35,000 W/m^2-K for indium and the In/Ga eutectic interface, respectively (Asano et al., 1992, Khounsary et al., 1998).

As seen in Table 4, Case B.1, at 300-mA ring current, the present mirror with indium interface will reach a temperature of over 150°C, and an rms slope error of 14 μrad. Temperature, tensile stress, and slope errors are all outside their respective limits and remain so even if the beam height is reduced to 1.8 mm (Cases C.2 and D.1). If In is replaced with Ga/In, the temperature and stress in the mirror are reduced and are within the acceptable range, but the slope error is still in excess of 3 μrad (Cases B.2, C.2, and D.2). Therefore the data indicate that the present mirror cannot handle 300-mA ring current even if the interstitial material is Ga/In eutectic because the slope errors are too large. In addition, no margin of error is built into these computational results, although a 20-40% margin can be expected due to a number of assumptions made. What can be safely said is that the present mirror with an In interface is not appropriate for higher currents unless beam height is reduced accordingly. Replacing In with Ga/In can allow the existing mirror to operate at about 150 mA if the beam height is reduced from 4.5 mm to 3 mm, or at 200 mA if the latter is reduced to about 1.8 mm. Therefore, a new mirror design that overcomes the higher thermal load barrier in terms of the resulting slope errors is being investigated.

Table 4: Temperature, stress, and tangential slope error in OCC x-ray mirrors. The incident beam is from an APS UA beam at 10.5-mm gap and at beam currents of 100 and 300 mA.

Case	**Beam Current (mA)**	**Beam Footprint Height (mm)**	**Incident Power (kW)**	**Interstitial Material/ Geometry**	**Temperature (°C)**		**Maximum Stress (MPa)**		**90% Slope Error (μrad)**	
					Min.	**Max.**	**Tensile**	**Compr.**	**Max.**	**rms**
A	100	4.5	1.7	In	44	61	2	5	5	3
B.1	300	4.5	5.0	In	82	154	11	31	25	14
B.2				In/Ga	28	83	7	21	16	9
B.3				In/Ga + Notch	28	84	7	21	<3	< 1
C.1	300	3.0	4.2	In	72	131	9	25	17	10
C.2				In/Ga	28	74	6	17	13	7
C.3				In/Ga + Notch	27	73	6	17	< 1	< 0.5
D.1	300	1.8	2.9	In	58	97	5	16	10	6
D.2				In/Ga	27	60	4	12	8	4
D.3				In/Ga + Notch	27	60	4	12	< 0.5	< 0.5

6. NEXT-GENERATION OPTIMAL CONTACT-COOLED MIRROR DESIGN

In a previous publication (Khounsary and Yun, 1996), a detailed explanation of how contact-cooled mirrors can handle the very high thermal loads of undulator beams without appreciable tangential slope error was provided. In the OCC technique, a cooling scheme is used that consists of two optimally sized cooling blocks positioned on the sides of the mirror and flush with the reflecting surface. The incident beam, upon striking, deforms the mirror into a convex shape. But within a few minutes, a certain thermal profile is established across the mirror cross section that counteracts the convex deformation, making the mirror almost flat across its length. This process is entirely due to thermal moments.

The present mirror, when used with a Ga/In eutectic instead of In, is only in violation of the slope error limits. Thus, the question arises as to whether a simple modification of this mirror, in the form of managing the afore-mentioned thermal moments, can lead to a viable design option. The advantages, of course are numerous, for there will be few to no changes in mirror chamber, cooling method, mirror support, etc.

A careful study of the thermal moment across the mirror cross section led to the idea of making small notches along the mirror sides too somewhat confine the cooled areas of the mirror and enhance the counteracting thermal moments mentioned to earlier. A cross section of this mirror is shown in Figure 4. The analyses were performed using finite element method and the detailed modeling and associated issues are not discussed here for brevity.

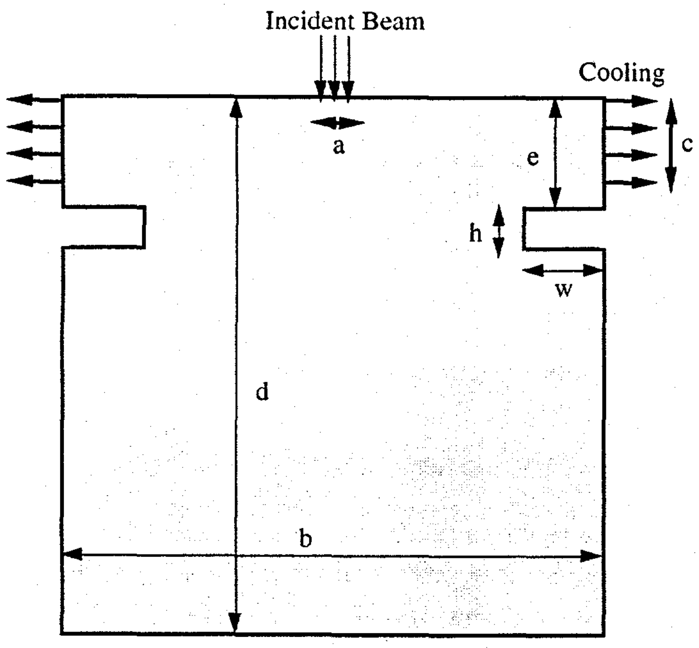

Figure 4: The cross section of the new mirror design that shows the small notches on the sides of the mirror along the mirror length.

The notches confine the colder portion of the mirror as far from the mirror neutral plane (the plane roughly half way down from the reflecting surface and parallel to it). This is a means, in effect, to enhance and adjust a counteracting thermal moment to bend back and reverse the bending produced by the incident beam in the mirror.

Mirror width, b, mirror length, and the beam height, a, are specified by the user, while other dimensions in Figure 4 are selected through an analytical design optimization process to meet the desired temperature, stress, and slope constraints. A range of solutions exists, and one is selected based on a combination of practical and competitive considerations. Note that in general, c≠e.

For the x-ray beam from undulator A at a 10.5-mm gap, two of the possible solutions are shown in Figures 5a-b, where the tangential slope errors are plotted. In Figure 5a, a 15-mm-wide area on each side of the mirror is cooled and the optimal depth of the notch is in the 6-7 mm-range. Note that a small change in the notch depth, from 6 mm to 7 mm will change the mirror shape from convex to concave, however, modestly.

If the cooling width is increased to 20 mm, as shown in Figure 5b, the effective "thermal lever arm" produced in the cooled area of the mirror to counteract the thermal moment produced by the incident beam is shortened (closer to mirror neutral plane). This means that the counteraction is not as effective, and the mirror will remain convex unless the notches are made deeper to further isolate the cold region and increase the counteracting thermal moment. As seen, an 8-mm-deep notch has the mirror only slightly convex while a 9-mm-deep notch will render the mirror concave, but only slightly.

7. DISCUSSION

The new "notched" mirror design, which in principle, is similar to the earlier design and based on a "balance thermal moment" can handle an x-ray beam from the APS undulator A at a closed gap of 10.5 mm and with ring currents of 300 mA or more, depending the beam footprint height. The maximum possible beam height expected on this mirror at the APS sector 2 beamline is 4.5 mm, and this condition is used as the worse case scenario in the design. In fact, the full width at zero height (FWZH) of the UA beam at its lowest harmonic energy (2860 eV) is about 1.8 mm at the mirror in the vertical direction. Thus allowing for margin of a millimeter orbital misalignment and a 3-mm-high aperture opening (and thus beam height) seems quite adequate. However, remember that sector 2 has also another undulator in tandem with UA, and it is used to generate lower energy photons, as low as 500 eV at a closed gap of 10.5 mm. This undulator has a peak heat flux similar to that of UA but a larger horizontal footprint due to its larger deflection parameter of 5.7 (cf. UA's 2.8). At 500 eV, the central cone of radiation from this undulator is wider than UA's, with a vertical FWZH of 100 μrad. This translates to a beam footprint of about 3.0 mm at the mirror, making a slit opening of about 4 mm desirable. This consideration, the fact the vertical opening of the fixed aperture upstream of the mirror is 4.5 mm and the desire to design for the worst possible condition, has led us to use a maximum opening of 4.5 mm. Performance with smaller openings using an adjustable slit downstream of the fixed aperture is given for comparison. As expected, and shown in Table 4, the beam height is a significant parameter in mirror performance as it determines the thermal load.

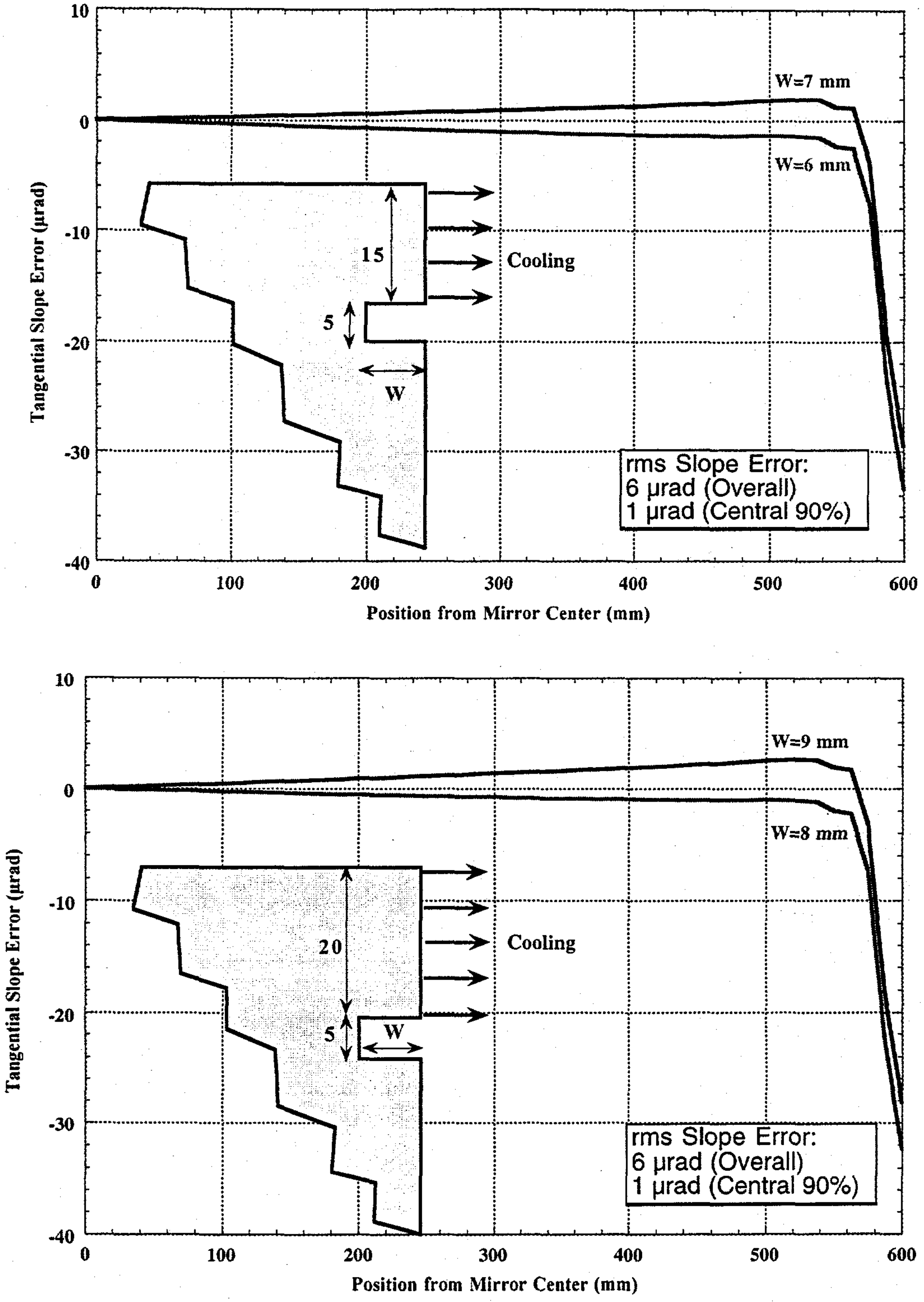

Figure 5-a (top) and 5-b (bottom): Two design configurations of the "notched" mirror showing critical dimensions. The thermally induced tangential slope errors along half the mirror length are shown. APS undulator A beam at 10.5-mm gap and 300-mA beam current. The incident power is 5 kW. Insets show diagrams of the notched portion of the mirror.

In order to put this point into perspective and also to summarize other results, Figure 6 plots the ring current and beam height on the mirror. The curves compare the present mirror with In, or with Ga/In, or with the notch. The allowed region is the segment of the plot below the curve for each mirror. The limitations, as can be deduced from Table 4, are due to slope error for the present mirror (with In or Ga/In) and tensile stress in the case of the notched mirror.

What Figure 6 shows is that even the existing mirror can accept slightly higher ring currents if the beam height on the mirror is substantially reduced. For example, the present mirror can take on 300-mA ring current if beam height is under 1.1 mm. The gain in replacing In with Ga/In as the interface material is a substantial reduction in temperature and stress, and a shorter time constant for the mirror (from about 15 minutes to less than 5).

The fact that the curve representing the existing mirror design does not show substantial gain if Ga/In is used as the interface material instead of In is due to the insensitivity of distortion to the heat transfer coefficient and thus thermal resistance at the Cu-Si interface. The effect is a second-order one and is due to the improved thermal and mechanical properties of silicon at lower temperature resulting from using Ga/In.

Implicit in all the calculations here is a number of conservative assumptions. These include no filter or window upstream of the mirror, all the incident beam is absorbed by the mirror, Compton scattering is ignored, reflection does not adversely change the beam power profile on the mirror, silicon is treated as an isotropic material, etc. It is thus prudent to assume, as indicated earlier, an error margin of 20-40%.

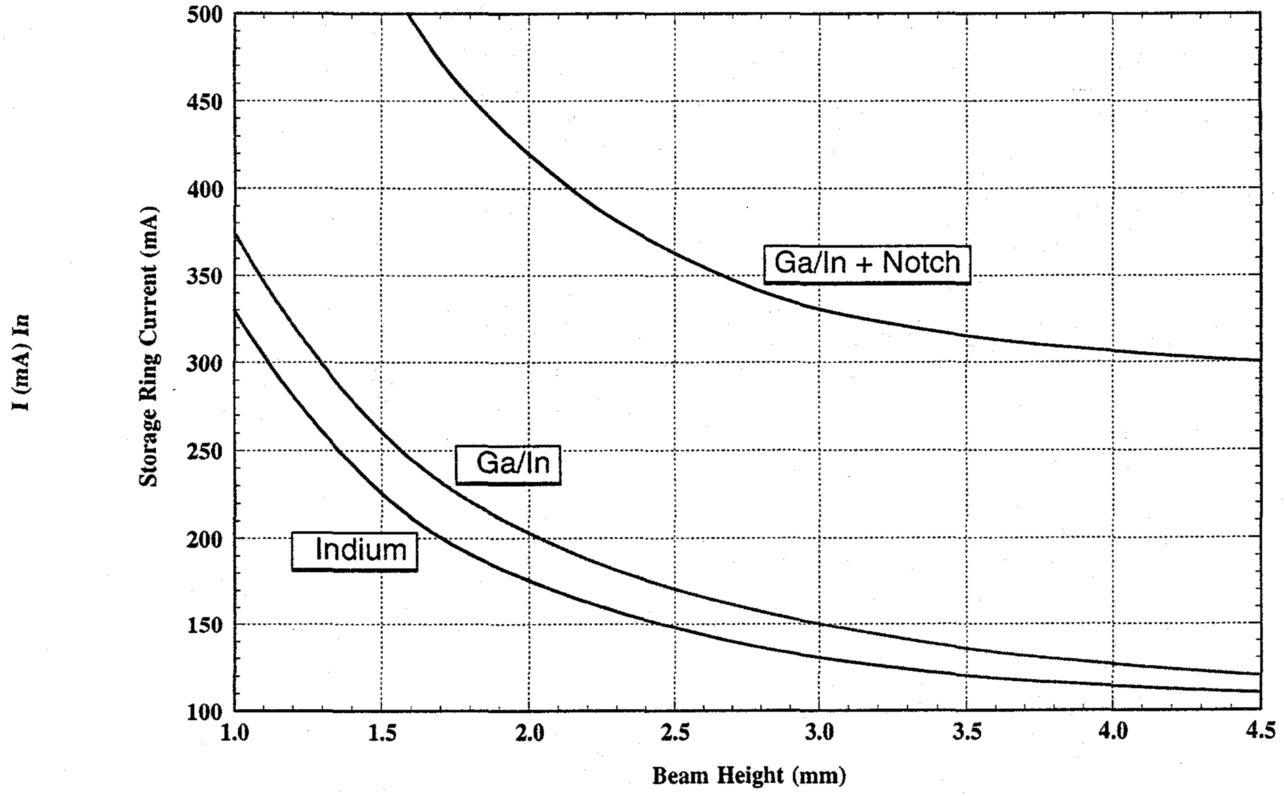

Figure 6: Upper bounds on the combination of the storage ring current and x-ray beam height (at mirror location) to meet temperature, stress, and slope error constraints. The x-ray beam is from the APS undulator A at a 10.5-mm gap. Limitations on the present mirror design (with In or Ga/In interface) as well as the new mirror design are shown.

Regarding the suitably of this type of mirror for general x-ray beamlines, one needs to recognize that such use is generally limited to the following conditions:

It can be shown, but is not reported here, that moving the beam away from the center of the mirror (for example, to reflect the beam off a different coating on the mirror surface) will not affect mirror performance as long as the beam is not too close (< 20 mm) to the cooling pads. The mirror is expected meet the required performance criteria of the incident beam from either undulator at larger than a 10.5-mm gap. One can roughly estimate performance by taking into account the total beam power in a given situation and interpolating the data in Table 4 and Figure 6. Performance is expected to be better for any incident beam having lower power/or and heat flux, *provided* that the beam is not significantly nonuniform in along the mirror length. The analysis has to be repeated for specific cases that significantly differ from the present beam/mirror conditions.

- beam illuminating the entire length of the mirror,
- a relatively uniform absorbed thermal load along the length of the mirror,
- short time constants (to reach mechanical equilibrium) not required,
- small angles of incidence (<5°)
- mirror shape flat with radii less than 1 m

These conditions are not too stringent and can be relaxed if the thermal load is small or if larger thermal slope errors can be tolerated. In other instances, an internally cooled mirror may be appropriate, but such mirrors can be complex both in fabrication and in maintenance and operation.

8. CONCLUSIONS

The design of a new optimally contact-cooled mirror suitable for future x-ray synchrotron beams with much higher thermal loads was described, and its performance under various heat loads simulated by a combination of storage ring current and the incident beam footprint size was discussed. Comparison of this mirror with an existing mirror was made showing that the new design can easily handle APS undulator A power at closed gap even for hypothetical storage ring current in excess of 300 mA with remarkably small tangential slope errors (< 1 μrad). Thus, this mirror can handle beams, for example, generated by two undulators in tandem, or undulators with gaps closer than 10.5 mm, striking at an angle larger than 0.15°, and of course higher storage ring currents.

The principle behind this next-generation mirror is a balancing of the thermal moments in the mirror. This is accomplished simply by judiciously making cuts in the sides along the length of the mirror to efficiently produce a counter moment to flatten a mirror that would otherwise be bent into a convex shape by the thermal load of an incident x-ray beam. The fabrication of the proposed mirror is rather simple and should provide a low-maintenance, robust, and highly reliable mirror for the near future.

It is constructive to reflect on the progress that has been made in the past decade in the area of high heat load optics. A decade ago it was thought that high heat load optics would be the bottleneck and the limiting factor in exploiting the potential of the third-generation synchrotron x-ray beams. Thanks to the tremendous developments in this area at various synchrotron facilities in Europe, Japan, the U.S., and elsewhere, and fruitful collaborations with a number of industrial partners, these problems have largely been solved; the investigation of optical elements for even higher powers is in progress. In the next few years, the storage ring and front-end components —RF fingers, masks, windows, filters, shutters and optics not cooling, may prove to be the limiting factors to higher beam powers. Given the perceived reliability and robustness of the proposed mirror, it may not be inconceivable to explore the possibility of incorporating such mirrors in the front end as a combined optical/thermal management tool.

9. ACKNOWLEGEMENTS

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