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Contact-Cooled U-Monochromators for High Heat Load X-ray Beamlines

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ABSTRACT

This paper describes the design, expected performance, and preliminary test results of a contact-cooled monochromator for use on high heat load x-ray beamlines. The monochromator has a cross section in the shape of the letter U.

This monochromator should be suitable for handing heat fluxes up to 5 W/mm^2. As such, *for the present application*, it is compatible with the best internally cooled crystal monochromators.

There are three key features in the design of this monochromator. First, it is contact cooled, thereby eliminating fabrication of cooling channels, bonding, and undesirable strains in the monochromator due to coolant-manifold-to-crystal-interface. Second, by illuminating the entire length of the crystal and extracting the central part of the reflected beam, sharp slope changes in the beam profile and thus slope errors are avoided. Last, by appropriate cooling of the crystal, tangential slope error can be substantially reduced.

Keywords: monochromator, x-ray, thermal management, contact cooled.

1. INTRODUCTION

Modern synchrotron x-ray facilities produce intense broad-band x-ray beams that often need to be monochromatized to illuminate and probe experimental targets.

Single crystals, such as silicon, are often used for monochromatizing x-ray beams. Because these monochromators absorb all but a small bandwidth of the incident radiation, they are thermally deformed. This reduces the system throughput. Development of monochromators that are appropriately designed and cooled to reduce undesirable thermal distortions and provide acceptable performance is an important thermal management issue for developers of high heat load x-ray beamlines.

Many designs and solution approaches have been suggested. Broadly, they rely on (a) reducing the absorbed *heat load* by using upstream apertures, filters, or utilizing thin crystals, etc., (b) reducing the absorbed *heat flux* by using asymmetrically cut or thin crystals, (c) implementing efficient cooling schemes to minimize temperature and temperature gradient in the crystal, and (d) using materials with favorable thermal distortion figure-of-merit, such as silicon at cryogenic temperatures, or diamond at room or lower temperatures.

Depending on the application, the required performance, and the heat load, one or more of these schemes are combined to meet specific needs. No solution fits, is suitable, or economical

for all applications. For the direct undulator A radiation, cryogenic cooling has proved quite successful (Rogers, 1996).

In the present paper, the design of a high heat load monochromator for one of the beamlines at the Advanced Photon Source (APS) Sector 2 (Yun, et al., 1996) is described. The design objective has been a reliable, inexpensive, and simple *water-cooled* monochromator. This monochromator together with an upstream mirror provide a solution to the high heat load x-ray beamline thermal management.

Use of a cooled mirror as a first optical element is not new and its advantages and disadvantages for the present application are described elsewhere (Yun et al., 1992). For the present purpose, the power filtering of mirrors is relevant. An x-ray mirror reflects all energies less than a critical value (determined by the angle of incidence and the surface material), and as such, it acts as a power filter reducing the heat load on downstream components.

2. THERMAL LOAD SPECIFICATION

The radiation source considered here is the x-ray beam from the APS undulator A. With a circulating electron energy of 7 GeV, a beam current of 100 mA, and a 4.5 mm x 4.5 mm aperture at about 30 m from the source, the thermal load at a mirror immediately downstream of the aperture can be evaluated. In the present beamline design, a 1.2-m-long silicon (Si) mirror with three stripes of Rhodium (Rh), Si, and Platinum (Pt) on the reflecting surface intercepts the beam at an angle of 0.3°. This angle is temporary and will shortly be changed to 0.15° permanently.

Incident and reflected power and peak normal incidence heat flux are shown in Fig. 1 for the Platinum-coated stripe (reflecting the most power). As shown, at closed gap, the reflected heat load from the mirror is about one fifth of the incident beam. This illustrates the power filtering capability of the mirror. From Fig. 1, it is evident that the maximum reflected power load is about 400 W and 30 W/mm^2.

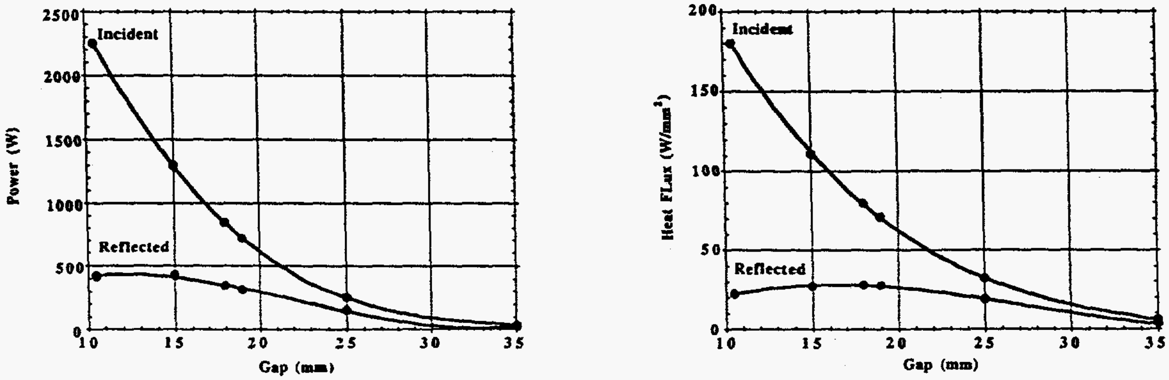

Figure 1. Computed incident and reflected power (left) and peak normal incidence heat flux (right) for a Platinum-coated mirror. The mirror is placed at 30 m from the undulator A and downstream of a 4.5 mm x 4.5 mm aperture. It intercepts the beam at a 0.3° angle.

For a crystal monochromator placed at 60 m from the source, the heat load and *normal* incident heat flux would be 400 W and 8.5 W/mm^2, respectively. If the mirror is placed at 0.15° with respect to the beam, then the corresponding reflected power and normal peak heat flux at the monochromator would be 900 W and 16 W/mm^2, respectively.

3. MONOCHROMATOR DESIGN

Using the mirror as a first optical element and reducing the heat load on downstream components to one fifth allows utilization of a water-cooled monochromator. A simple robust water-cooled silicon monochromator is advantageous in that it does not require internal or cryogenic cooling.

In the design of the present monochromator, which has a U-shaped cross section (thus the name U-monochromator), the aim has been to develop a cooled first crystal such that it (a) is water cooled, (b) is contact cooled, (c) has a 500 W and 5 W/mm^2 rating with rms slope error less than 10 μrad (2 arc seconds) in the central part corresponding to the undulator harmonic cone, (d) is strain-free mountable, (e) is modular/easily replaceable, and (f) is simple, reliable, and inexpensive to make and operate.

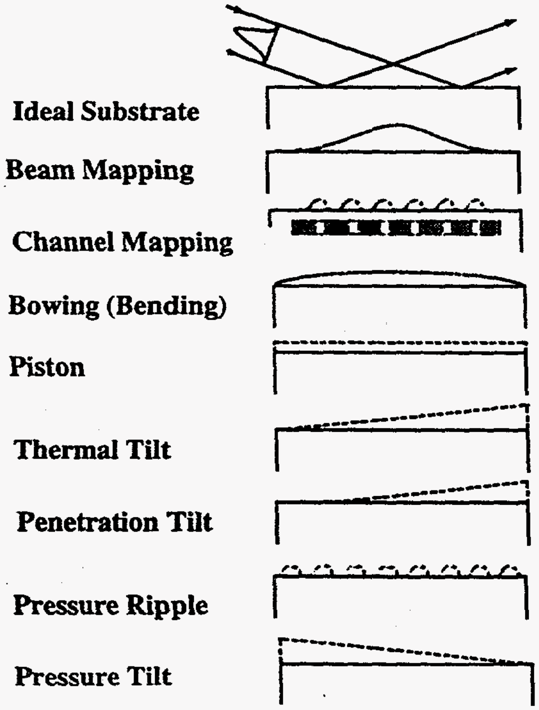

Figure 2. Various components of deformation in a cooled optical substrate subjected to an incident x-ray beam, described in the text.

The design adapted is based on careful consideration of the types of deformations a general cooled substrate, such as a mirror or a monochromator, undergoes when it is subjected to an incident beam. Fig. 2 shows these types. A cooled optical substrate illuminated with a non-uniform incident beam as shown in Fig. 2 will undergo: (1) mapping distortion, which roughly resembles the incident power profile, and is due to the lateral variation of the average in-depth temperature, (2) bowing or bending distortion, which is due to an in-depth gradient of the average lateral temperatures, (3) piston deformation, which is the isotropic growth of the substrate due a net overall temperature rise in the substrate, (4) thermal deformation, which is due to the thermal gradient in the substrate introduced as a result of the warming up of the cooling fluid, if any, as it traverses the substrate, (5) penetration distortion, due to the line-of-sight deposition of x-ray power in non-opaque substrate materials, and (6) pressure-induced distortions, which may be due to pressurized cooling channels, if any, or to the coolant pressure gradient (drop) across the substrate.

For the present application and using a contact-cooling approach, all but mapping and bowing deformations are absent, negligible, or unimportant. The key in the design is thus in dealing with mapping and bowing distortions. We accomplish this as follows.

First, since mapping tangential slope errors are due to heat flux gradient along the length of the substrate, illuminating the entire length is quite helpful. Thus, the substrate length is selected accordingly even if a smaller part of the beam is needed. This is particularly suitable in the case for undulator beams in which the central cone (having a full width much smaller that of the power profile) is often needed. Slits, if necessary, are placed *downstream* of the monochromator to select the desired part of the beam.

Second, the bending of the crystal can be substantially reduced or reversed by a reverse thermal moment, a concept that we have successfully used in the design of high heat load mirrors (Khounsary et al., 1996). Since bowing of the substrate is due to the in-depth temperature gradient of the substrate, cooling the substrate on the back produces the largest slope error. Moving the cooling location towards the reflecting surface, (for example, on the sides on the reflecting surface) reduces the thermal moment with respect to the reflecting surface and thus the bending of the substrates.

In the case of mirrors, two narrow cooling blocks are placed on the two sides flush with the reflecting surface. One can use wider cooling blocks (to reduce the temperature in the mirror) if one could make a U-shaped mirror and cool wide areas on the sides. This is not feasible, however, because it is extremely difficult to polish the reflecting surface of a U-shaped mirror with conventional means.

For the monochromator, a design sketched in Fig. 3 is adapted. This figure shows the reverse thermal moment applied to the monochromator. Cooling is provided through a layer of gallium/indium eutectic (75% Ga, 25% In) in contact with a cooled copper block that also acts as crystal holder shown in Fig. 4. Figure 5 shows a photograph of the U-monochromator in its housing/cooling block ready for installation.

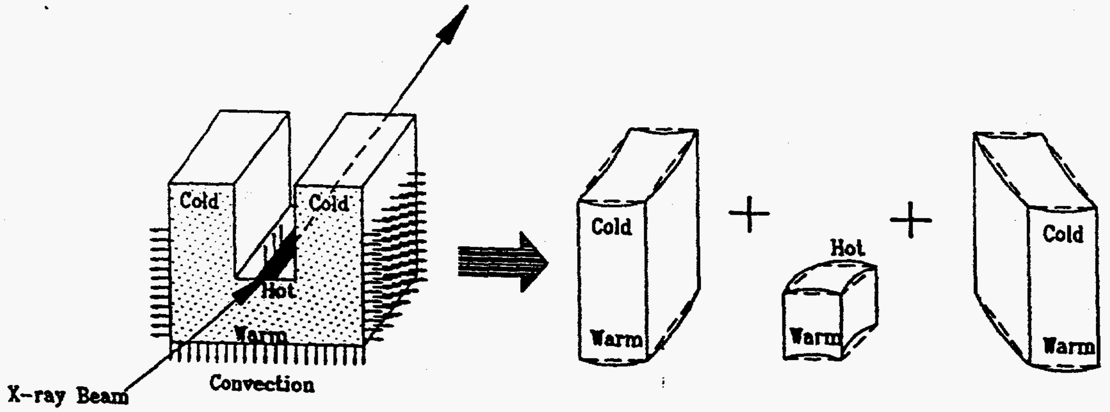

Figure 3. A diagram showing the reverse thermal moment concept as used in the U-monochromator. Cooling on the sides and above the reflecting surface is used to apply a thermal moment to reduce/reverse some of the tangential bending in the substrate.

The exact dimensions of the monochromator are determined by the beam size, incident angle(s), crystal plane orientation, asymmetric cut angle (if any), and through a numerical optimization process. The goal of the optimization can vary but it should aim at minimizing the slope error in the central parts of the monochromator and possibly reducing the maximum temperature and stress in the system.

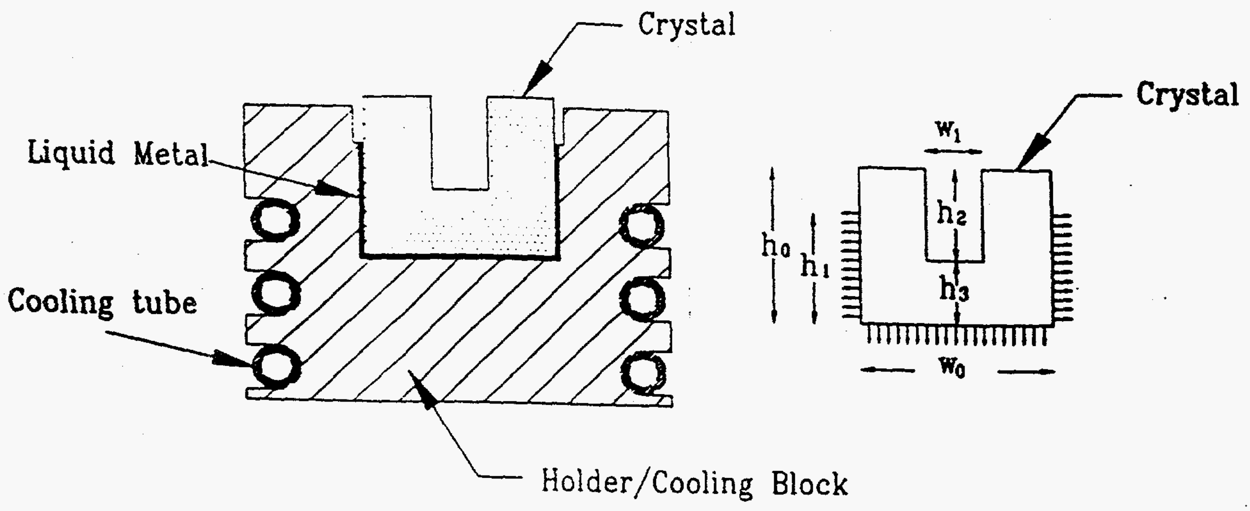

Figure 4. The cross section of the U-monochromator in its holder/cooling block. Geometric nomenclatures are shown. Length of the crystal, L, is perpendicular to the paper. In the present design, $h_0 = 7$ mm; $h_1 = 13$ mm; $h_2 = 10$ mm; $h_3 = 7$ mm; $w_0 = 20$ mm; $w_1 = 6$ mm and $L = 20$ or 30 mm.

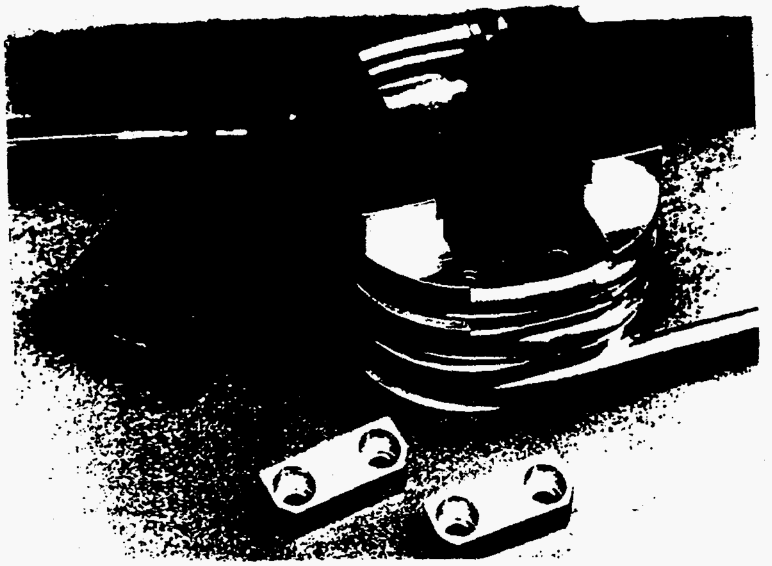

Figure 5. U-monochromator and its housing/cooling block ready for assembly.

Some basic consideration of the critical geometric parameters involved, however, is helpful. The cooling height h_1 (see Fig. 4) is selected such that (a) bending due to cooling on the bottom is reversed and, (b) the maximum temperature is reduced. In fact, progressively increasing the cooling height h_1, (and also h_0) can successively reduce convex bending, flatten the central part of crystal and upon further increase will render the crystal concave (focusing). Focusing in this manner is an interesting concept, which however requires micro-management of the substrate. The bending reversal is more pronounced with thinner (smaller h_3) and longer monochromators.

The length the crystal is selected such that it is always fully illuminated and intercepts a larger beam than the central undulator beam cone. Thus, the central cone radiation is essentially reflected from the central (more flat) part of the crystal.

Other dimensions of the crystal are selected based on thermal mechanical considerations aimed at providing the lowest temperature rise without significantly compromising the slope errors. Typical dimensions used in the present design are listed in the caption to Fig. 4.

Fig. 6 shows the temperature profile in the U-monochromator designed. Due to symmetry, only one quarter of the model is shown. The tangential deformation and slope are shown in Fig. 7. As seen, the peak-to-valley slope error in the central ± 3 mm of the monochromator is only about 9 μrad.

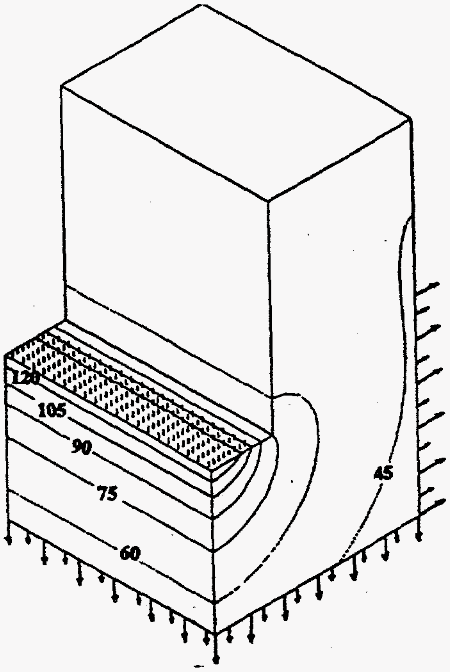

Figure 6. Computed temperature profile in the U-monochromator. Due to symmetry, one quarter of the model is shown. In this case, a uniform heat flux of 5 W/mm^2 over a 20 mm x 4.0 mm area for a total power of 400 W is assumed.

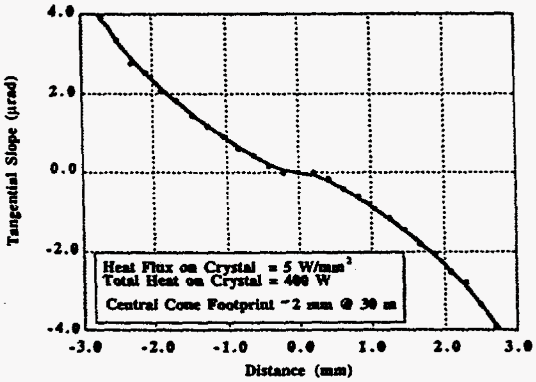

Figure 7. Predicted tangential slope error in the ±3 mm central region of the U-monochromator for a uniform thermal load of 400 W at 5 W/mm^2 over a 20 mm x 4.5 mm area.

4. SOME PRACTICAL CONSIDERATIONS

Since for a given geometry, thermal deformation and the temperature in a U-monochromator vary linearly with heat load, heat-load fluctuations should not pose any particular problem if monochromator performance under the maximum thermal load is acceptable.

However, because the crystal temperature can rise as much as 100°C, it is necessary to heat the second crystal to match the d-spacing of the first crystal; otherwise, upon tuning, the exit beam will be displaced. With 100°C temperature difference between the first and the second silicon crystals, $\Delta d/d = \alpha\Delta T \sim 3 \times 10^{-4}$. The angular shift in the exit beam when crystals are tuned is given by $\Delta\theta = 2(\Delta d/d)\tan\theta$. Here d, θ, and α refer to the d-spacing, the angle of incidence and the coefficient of thermal expansion for silicon. Assuming $\theta = 45°$ and $\Delta T = 100°C$, then and the coefficient of thermal expansion for silicon. Assuming $\theta = 45^\circ$ and $\Delta T = 100^\circ C$, then $\Delta\theta = 600\ \mu rad$. It may then be desirable to heat the second crystal, a process that can be accomplished through a feedback loop.

The limitation of the power load on the crystal in the present design is imposed not by strain but by the allowable stress. Assuming an allowable stress of 10,000 psi (70 MPa), which is a good working number for etched silicon, one can arrive at a maximum allowable temperature gradient on the order of 100°C in the crystal, which is close to the conditions for the monochromator described. Users must make sure the crystal is well etched and evaluate the stress levels prior to fabrication.

The *variation* of the temperature, and thus the d-spacing, across the first crystal surface may also be an issue, more so in the sagittal direction than the tangential. However, in the central parts of the reflected beam, which may be the desired and usable part, temperature gradients should be modest.

The sagittal slope errors in the U-monochromator are rather large (>100 µrad) due to a sharp cut-off in the heat flux in that direction. This deformation is further exacerbated by the unconstrained wings of the U-monochromator. One remedy is to use the central part of the beam in the sagittal direction. Currently, the design of an O-monochromator depicted in Fig. 8 is being considered. The sagittal slope is expected to be lower with correspondingly higher stress in the crystal.

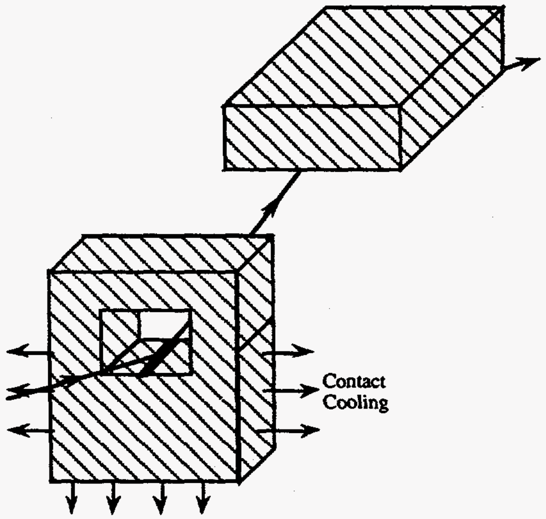

Figure 8. A depiction of an O-monochromator designed to partially suppress unrestrained sagittal slope errors in the U-monochromator.

For cooling the U-monochromator in its holder, a thin layer of liquid metal eutectic is used to enhance heat transfer at the silicon-cooling block interface (Fig. 4). It seems that a clearance of about 50 to 250 µm between the crystal wall and the cooling copper block walls on each side is appropriate. The cooling copper block should be nickel coated to avoid rapid dry out of the liquid metal on copper. The eutectic is applied and worked into the desired surface areas of the crystal and the cooling block so that it wets the surfaces. The crystal is then set in place snugly and without any mechanical strains.

5. PRELIMINARY EXPERIMENTAL RESULTS

Very limited experimental results are available at this time to draw meaningful conclusions and make a comparison between theory and measurements. This task would involve numerical evaluation of the expected performance of the crystal under the prevailing non-uniform heat-flux experimental conditions and accounting for the x-ray filters and windows present. Very preliminary data indicates that for the 20-mm-long monochromator, with a peak heat flux of 3-4 W/mm^2 and a total power of about 120 W, the tangential slope error is about 8 μrad across the central ±3 mm of the crystal. If true, for the *present application* (where only the central part of the beam is needed), this design is on par with the best internally water- or gallium-cooled monochromator designed to date,

Further tests and analyses needed to evaluate the U-monochromator will be carried out and presented in a future report.

6. CONCLUSIONS

Design, analysis, and implementation of a new x-ray monochromator design, which is U-shaped, were described. This monochromator is expected to provide acceptable performance for power loading of up to 5 W/mm^2 and several hundred watts per centimeter linear length. Expected performance and some practical aspects of this monochromator were discussed. The limited experimental data available precludes drawing general conclusions, but it appears that the data are consistent with expectations of a few μrad tangential slope error in the central region of the monochromator for 3-4 W/mm^2 heat flux.

7. ACKNOWLEDGMENTS

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