Title
Engineering for High Heat Loads on ALS Beamlines

Permalink
https://escholarship.org/uc/item/6x09n92h

Authors
DiGennaro, R.
Swain, T.L.

Publication Date
1989-08-07

LBL-27600

Lawrence Berkeley Laboratory
UNIVERSITY OF CALIFORNIA

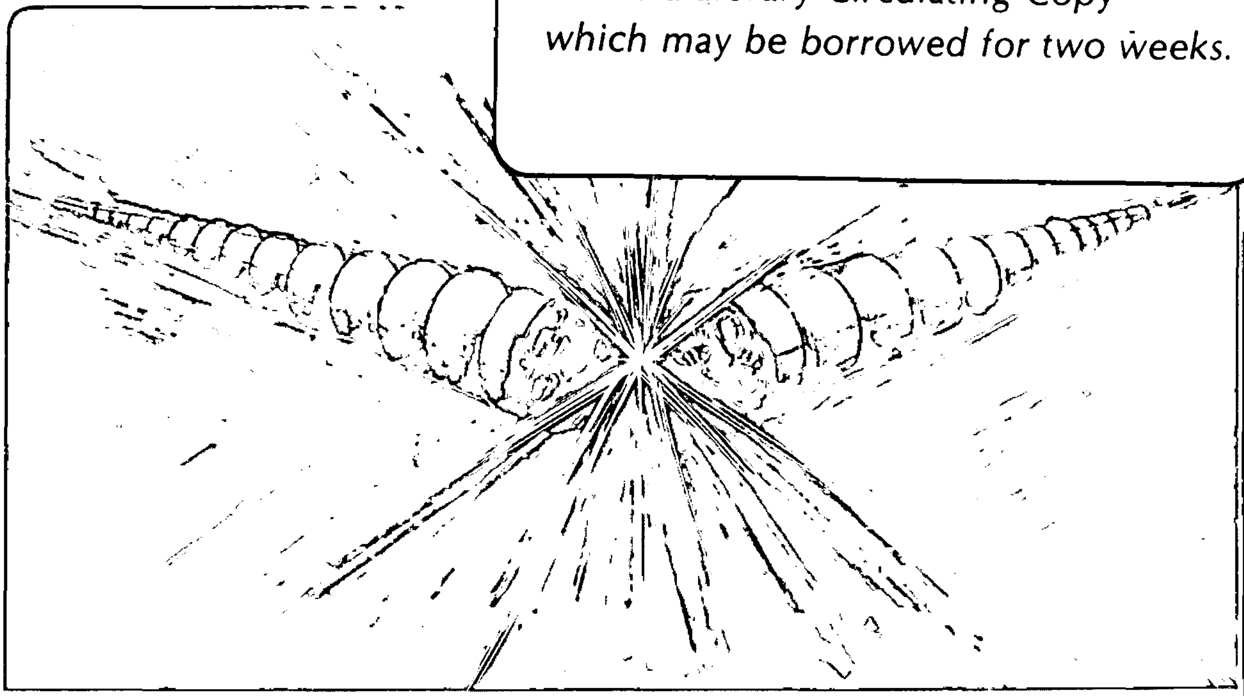
Accelerator & Fusion Research Division

Presented at the 6th National Conference on
Synchrotron Radiation Instrumentation,
Berkeley, CA, August 7–10, 1989, and
to be published in the Proceedings

Engineering for High Heat Loads on ALS Beamlines

R. DiGennaro and T. Swain

August 1989



Prepared for the U.S. Department of Energy under Contract Number DE-AC03-76SF00098.

DISCLAIMER

LBL-27600

Engineering for High Heat Loads on ALS Beamlines

Richard DiGennaro and Thomas Swain

Engineering Division
Lawrence Berkeley Laboratory
University of California
Berkeley, CA 94720

Presented at the
6th National Conference on Synchrotron Radiation Instrumentation
August 7-10, 1989
Berkeley, CA

This work was supported by the Director, Office of Energy Research,
Office of Basic Energy Sciences, Material Sciences Division
of the U. S. Department of Energy under Contract No. DE-AC03-76SF00098.

Abstract

This paper discusses general thermal engineering problems and two specific categories of thermal design issues for high photon flux beam lines at the LBL Advanced Light Source: thermal distortion of optical surfaces and elevated temperatures of thermal absorbers receiving synchrotron radiation. A generic design for water-cooled heat absorbers is described for use with ALS photon shutters, beam defining apertures, and heat absorbing masks. Also, results of in-situ measurements of thermal distortion of a water-cooled mirror in a synchrotron radiation beam line are compared with calculated performance estimates

Introduction

Lawrence Berkeley Laboratory (LBL) and the Center for X-Ray Optics first became involved in the development of synchrotron radiation instrumentation during the design and construction of the LBL-Exxon-SSRL 54-pole wiggler on Beam Lines 6-1 and 6-2. E. Hoyer[1] and R.T. Avery[2] initiated LBL's engineering efforts related to water-cooled masks, graphite filters, beryllium windows, and aperturing devices for the intense beams from insertion device sources, which led to further development and the use of finite element analysis to understand thermal design issues for x-ray optical components subject to high heat loads.[3,4,5] Current efforts are underway to develop the next generation of devices for the Advanced Light Source (ALS) beam lines for wiggler, undulator and bend magnet sources. The primary objective is to develop cost-effective designs for directly cooled mirror and grating substrates, thermal absorbers for beam defining apertures, and other components that are subjected to high heat loads in the ultra-high vacuum (UHV) environment.

Our fundamental design approach for accommodating high heat loads is based on the use of OFHC copper, GlidCop,[6] and stainless steel furnace-brazed assemblies with machined, internal water-cooling channels. There is a strict, standard requirement that all water joints and connections must be isolated from UHV with venting to atmosphere, which imposes an additional constraint on the requirement that bakeable materials and all-metal seals must be used for vacuum hardware.

Elevated Temperature Limits

Two basic design issues tend to dominate the choice of a thermal absorber configuration: elevated temperatures and excessive thermal distortion. In the case of non-optical devices with direct water cooling, like shutters or beam-defining apertures, the elevated temperature at a water channel surface is usually the limiting factor (to avoid nucleate boiling conditions with a reasonable safety margin) which determines allowable incidence angles and cooling channel geometry for continuous exposure to the beam. Materials with high thermal conductivity are preferred in order to enhance heat transfer to the convective cooling surfaces. The use of GlidCop instead of OFHC copper allows design configurations to accept significantly higher thermal stresses; often, allowable thermal loads are bounded by temperature limits rather than by stress limits for yielding or fatigue failure.

In the case of non-water-cooled or indirectly cooled devices for which local heat loads are dissipated by conduction and radiation, surface temperatures in the region of beam impingement usually determine the operating limits. Surface melting conditions, high stresses, or brittle failure due to thermal shock must be avoided during brief or occasional exposure that may be monitored for transient thermal response. Other indirectly cooled devices that might receive continuous beam exposure may be operationally limited by elevated temperatures that accelerate outgassing and vacuum degradation. Since most design configurations must accommodate thermal expansion of mating parts during bakeout, distortions (in non-optical devices) caused by elevated temperatures due to beam impingement are not likely to be a design limit. An exception is in the case of instrumentation that requires a high degree of positional stability, for which direct cooling is usually required.

Thermal Distortion Limits

In the case of optical components that receive high heat loads, thermal distortion of the optical surface and its effect on beam line performance is usually a primary design issue. For directly-cooled optical substrates, distortion due to gross bending of the substrate is often small compared to the surface figure errors due to local differences in thermal expansion caused by temperature gradients near the illuminated area. Surface figure distortion is reduced by the use of materials with a high ratio of thermal conductivity to thermal expansion coefficient (k/α), and by cooling configurations that minimize temperature gradients in the optical substrate. CVD silicon carbide is often preferred as a substrate material for its high k/α ratio ($\sim 31 \times 10^4$ W/cm) and high polishability,[7,8,9,10] but substrate design and optical performance are often limited by difficulties in minimizing the volume of material affected by temperature gradients in the substrate. It is hard to get water cooling close to the illuminated region using a silicon carbide substrate. Our choice of OFHC copper and GlidCop as substrate materials for optical components sacrifices some performance due to a lower k/α ratio ($\sim 23 \times 10^4$ W/cm), but enables the use of common fabrication methods to build machined and brazed substrate assemblies that have internal water-cooling channels very close (3–4 mm) to the illuminated surface. As a result, only a relatively small volume of the substrate is affected by temperature gradients, potentially with an overall reduction of surface figure errors due to thermal distortion. Optical surfaces are plated with electroless nickel which can be polished to a low-scatter finish (less than 10 Å rms roughness) that is generally acceptable for ALS beam line applications.

For indirectly-cooled optical substrates where absorbed heat loads are relatively small and figure error tolerances are moderate, the choice of substrate material is the critical factor for minimizing distortion. CVD silicon carbide is preferred, but low-expansion ceramics and glasses such as fused silica are more readily available and may often be used with acceptable performance.

Front End Thermal Absorbers

The ALS can accommodate up to 11 insertion device and 48 bend magnet beam lines. Although they will have a wide range of spectral and spatial power output characteristics, all will require directly cooled thermal absorbers for the front end photon shutters and for other masks and beam-defining aperture devices. In order to minimize engineering, fabrication, and assembly costs without compromising reliability and safety, we have developed a generic, water-cooled thermal absorber design that can be adapted to many beam line applications with only minor modifications.[11]

The thermal absorber is a brazed assembly of copper and stainless steel with internal, machined channels for water-cooling and vents to atmosphere, as shown in Figure 1. It may be flange-mounted with a hinged or linear-drive mechanism so it can be positionied to intercept the photon beam. The cooling channel configuration is designed for typical beam line applications where heating occurs along a line (as shown) with a horizontal grazing incidence angle. The horizontal incidence orientation is often preferred over vertical incidence primarily for its better thermal performance, allowing larger grazing incidence angles and shorter devices to be used with high heat loads, as described by R.T. Avery.[2] For a given beam incidence angle, heating along a line rather than distributing heat over a larger area results in lower peak surface temperatures because high power densities can be dispersed more effectively by conduction to active convection-cooling surfaces. With area-heating instead of line-heating, the central part of the heat zone becomes a hot spot that determines the allowable thermal and stress limits, and distributed water-cooling channels are less effectively utilized. Nevertheless, the basic thermal absorber design may also be used for vertical grazing incidence angles, such as a vertical beam defining aperture, but the allowable thermal loads may be slightly lower.

Thermal Absorber Design Optimization

The basic design for the thermal absorber assembly is derived from machining and brazing fabrication requirements, as well as from the technologies and experience gained from existing beam line instrumentation at other synchrotron radiation facilities. The water-cooling channel details are optimized to limit temperatures at the convection surfaces and thermal stresses in the material. With the use of higher-strength GlidCop instead of OFHC copper, the maximum allowable thermal loads are determined primarily by allowable water temperature rise rather than by thermal stress limits. Using finite element analysis to evaluate 2-d thermal-stress models for typical beam line applications, we optimized the configuration for the number and shape of the cooling channels, water flow rates and convection heat transfer variables, wall thickness between channels and thickness to the heated surface, etc. An important design trade-off with respect to allowable loads, safety margins and material properties involves minimizing the wall thickness to the heated surface in order to reduce thermal stresses, balanced by the need for a thick enough wall to conduct the heat to a large area for convection cooling to avoid nucleate boiling conditions at the water-cooled surfaces.

Allowable Thermal Loads

The optimized cross-section for our thermal absorber allows thermal loads for line-heating up to 425 W/cm lineal power density, with a maximum temperature rise of 65°C at a convective cooling surface and less than 207 MPa (30,000 psi) maximum thermal stress. For any insertion device or bend magnet beam line thermal absorber, the maximum horizontal grazing incidence angle is determined by the source distance and source power density, and the main absorber parameters that may require customization are the absorber length and mounting angle. For example, one of the most severe applications for this absorber is on the U8 undulator beam line where the primary photon shutter could receive a thermal load of up to 9.6 kW, with 2060 W/mrad peak horizontal lineal power density and must be able to cover a maximum beam opening angle of 19 mrad (including potential steering errors). For a shutter located at 7.5 meters from the source, it requires a pair of thermal absorbers, each with 8.9° horizontal grazing incidence angle and 61 cm (24 in) length. .Water flow rate requirements are modest - with a minimum flow switch setting at 3 m/sec (10 ft/sec). Higher flow rates, up to 6 m/sec (20 ft/sec), improve the safety margins slightly, but for some applications flow-induced vibration could limit the allowable coolant flow rates.

Water-cooled Mirrors

The water-cooled mirror system that we propose to use for ALS beam lines was initially developed for use on SSRL Wiggler Beam Line 6-1 and the NSLS X-1 Undulator Beam Line.[12,13] The BL 6-1 design loads require that the mirror be capable of receiving the maximum beam power of the 27-period wiggler without damage to the optical surface — up to 2.4 kW of absorbed power with a peak power density of 5.2 W/mm^2. The nominal operating conditions are significantly less demanding when the mirror is required to deflect only the outer edge of the wiggler beam to the side branch. For the maximum power conditions, thermal stresses would exceed the yield strength of OFHC copper, a condition which requires the use of GlidCop for its high strength, dimensional stability, excellent thermal conductivity, and ease of fabrication. GlidCop also has a good K/α ratio, and based on finite element analyses, surface figure errors due to thermal distortion are within acceptable limits using a single, lengthwise water-cooling channel near the optical surface. During the development of this mirror for B.L. 6-1, we determined that it would also be suitable for use on the NSLS X-1 beam line in order to meet the stringent surface figure-error tolerances. For this application, a second cooling channel was added to provide an additional clear aperture region on the X-1 mirror for an alternate optical coating, with the assumption that the additional cooling would in no way impair performance, but would, perhaps, reduce slope errors resulting from thermal distortion.

We expect that thermal loads and tolerances for surface figure errors on ALS mirrors will be comparable to the X-1 undulator beam line requirements, and that, in some cases, the effects of sagittal and tangential figure errors on condensing mirror surfaces will have a major limiting effect on photon throughput. The existing mirror system design can be used for alternate mirror sizes without any significant modifications, and the positioning degrees of freedom are consistent with the needs for our proposed beam lines. Since the substrate design was selected initially to accommodate the high thermal loads from the B.L. 6 wiggler, it is likely that some design refinements can improve performance for ALS undulator beam line applications.

Comparison of Mirror Performance with Thermal Distortion Calculations

The installation of our mirror on the NSLS X-1 beam line provides the opportunity for direct comparison of measured mirror thermal distortion with the computed estimates using finite element analysis. Modelling assumptions and approximations that were used for the initial design analyses can be confirmed or challenged to improve our confidence in the predictions for mirror performance. Earlier in-situ measurements of distortion of NSLS mirrors, including the X-1 mirror, were done using a lateral shearing interferometer.[14] However, the absorbed power level at the time was too low to produce any measurable distortion. Recently, we repeated the distortion measurements with a slightly different lateral shearing interferometer arrangement[15] and with higher power conditions.[16] Our results are summarized below.

The X-1 mirror is a flat, horizontally-deflecting mirror that acts as a power filter for downstream optical elements, similar to the function of the SSRL B.L. 6-1 mirror. If we extrapolate the thermal distortion calculations that were done for SSRL heat loads in Figure 2, we expect the maximum sagittal slope error to be approximately 5 μrad for the estimated 0.1 W/mm^2 peak absorbed power density for the operating conditions during our measurements. For our measurements, the interferometer was set up to be sensitive primarily to sagittal slope errors. The change in the interference fringe orientation angle observed when the beam line shutters open and when they are closed gives a measure of the change in radius of curvature of the reflected wavefront. With an assumption that the reflected wavefront from the thermally distorted surface is approximately cylindrical, measured fringe rotation angles of about 4° at 5–10 mm offset from the beam centerline correspond to a wavefront radius of curvature of 1500 meters. Since the mirror radius of curvature is twice the wavefront radius, the measurements indicate a 3 ± 1 μrad sagittal slope error at a 5–10 mm offset on one side of the beam, and roughly half that on the opposite side.

Although our measurements are quite close to the extrapolated calculations and it is encouraging to find that the calculations are conservative, investigation of the discrepancies and possible sources of error are appropriate with regard to implications for ALS mirror and beam line designs. The most obvious difference is the asymetry of the slope errors. The initial calculations were done for a single, centered cooling channel, and the X-1 mirror has one additional side cooling channel for an alternate clear aperture and optical coating. Temperature gradients are more severe in the direction of the side cooling channel, causing larger slope errors on that side (explaining the asymetry), and the overall effect of doubling the cooling surfaces could explain the lower measured value of the slope.

Other, more subtle differences between the calculated and observed values are less evident. The calculations for SSRL are based on an electron beam energy of 3.0 GeV, a 200 mA current, a 27-period wiggler with deflection parameter K equal to 11.5; the mirror is located at 8.7 meters from the source and has a 2.8° grazing incidence angle. The X-1 mirror was operated at 2.5 GeV, 95 mA, and a 35-period undulator with deflection parameter K equal to 2.5; the mirror was at 13.3 meters with a grazing angle of 2.3°, and the vertical beam height was limited to about 2.5 mm at the mirror using an upstream, beam-defining aperture. Consequently, the broad, truncated-Gaussian heat load distribution for the measurements was somewhat different from the narrow full-Gaussian distribution in the analyses, and extrapolations based simply on peak absorbed power density at the beam center may be misleading. Also, the calculations were initially used to estimate a maximum sagittal slope error that occurs near the edge of the illuminated region (for wiggler radiation), whereas the measurements evaluated an average slope at 5–10 mm from center.

Because of the discrepancies between the analytic model and the measurements, additional finite element analyses were done to model more closely the conditions of the experiment, using the actual dimensions and thermal boundary conditions of the mirror substrate. The asymetry in the slope errors due to thermal distortion with two cooling channels is confirmed, but the new estimated average sagittal error is about 8 μrad with a 2.5 mm apertured beam height and 4 μrad with a 1.5 mm height. In those places outside the illuminated region where measurements were made, slope errors show a strong dependence on total power, with variations resulting from modeling different aperture sizes. During our distortion measurements, we neglected to confirm the actual beam height, and it is possible that the mirror was receiving a smaller aperture than 2.5 mm, which would partially explain the discrepancy.

Another variable that could not be confirmed is actual heat load on the mirror. Total absorbed power on the mirror, based on theoretical undulator output and reflectance for beryllium, was calculated to be 53 W for a 2.5 mm aperture or 34 W for a 1.5 mm aperture. Based on the measured water temperature rise of about 0.4°C when the shutter was opened, the absorbed power was about 26 W (with only limited accuracy due to the small temperature change). The effects of variations in water flow rate or film coefficient are small and not likely to be significant for these results.

Although we cannot completely explain the difference between the measured slope errors and the calculated errors, the results indicate that careful modeling of the thermal loads is perhaps the most important variable for accurately predicting thermal distortion of optical surfaces. Our finite element modeling techniques appear to produce slightly conservative estimates of slope errors, a factor that warrants further investigation with regard to design implications for ALS beam line optics.

Future Directions

In summary, LBL has developed detailed designs for water-cooled mirror and diffraction grating substrates to reduce thermal distortion of optical surfaces at the ALS,[17] and we have a conceptual design for a generic thermal absorber for non-optical applications where direct cooling is required. These existing design concepts are likely to be satisfactory for all front end and branch line components that are included in the initial construction of the Advanced Light Source. We expect that some optical performance improvements may be possible with design refinements for specific beam line configurations, and that any design changes will consider tolerance requirements for optical fabrication as well as thermal distortion with respect to overall beam line cost and performance. Two other areas for further development include extension of this fabrication technology for a water-cooled, bendable mirror substrate for use with adaptive optical systems, and design or material changes that reduce the weight of a mirror substrate to allow rapid, closed-loop feedback control for beam steering. A lightweight thermal absorber would also allow rapid closure in conjunction with fast valve systems that detect beam line vacuum systems faults.

Acknowledgements

This work was supported by the Director, Office of Energy Research, Office of Basic Energy Sciences, Material Sciences Division, U.S. Department of Energy under Contract DE-AC03-76SF00098.

We would like to recognize a variety of contributions to these studies from numerous people, including Dave Attwood and the LBL Center for X-Ray Optics, John Chin, Malcolm Howells, Egon Hoyer, William Johnston and the LBL Computing Division (for assistance with video image processing of interference patterns), Kurt Kennedy, Brian Kincaid, Ted Kozman and the LBL Mechanical Engineering Department (for support for the mirror thermal distortion measurements), Ted Lauritzen, Worley Low, Wayne McKinney, John Meneghetti, Alan Paterson, Harvey Rarback, and Peter Takacs.

References

1. E. Hoyer et al., *Nucl. Instrum. Meth.* **208**, pp. 117-125 (1983).

2. R.T. Avery, *Nucl. Instrum. Meth.* **111**, pp. 146-158 (1984).

3. R. DiGennaro et al, *Proceedings of the SPIE* **582**, pp. 273-280 (1985).

4. W.R. Edwards et al, *Proceedings of the SPIE* **582**, pp. 281-290 (1985).

5. R. DiGennaro et al, *Nucl. Instrum. Meth.* **A266**, pp. 498-506 (1988).

6. GlidCop AL-15 (UNS Copper Alloy C15715) is a proprietary alloy by SCM Metal Products, Chemicals Division of SCM Corp., Cleveland, Ohio.

7. V. Rehn and W.J. Choyke, *Nucl. Instrum.* Meth. **177**, pp. 173-178 (1980).

8. P.Z. Takacs et al., *Nucl. Instrum. Meth.* **111**, pp. 133-145 (1984).

9. S.L. Hulbert and S Sharma, *Optical Engineering* Vol. 27 No. 6, pp. 433-439 (1988).

10. F.R. Holdener et al., *Proceedings of the SPIE* **640**, pp. 116-125 (1986).

11. T. Swain, *Thermal Absorber Design for ALS Beam Lines*, Lawrence Berkeley Laboratory note LBID-1524 (1989).

12. R. DiGennaro et al., *Proceedings of the SPIE* **582**, pp. 273-280 (1985).

13. R. DiGennaro et al., *Nucl. Instrum. Meth.* **A266**, pp. 498-506 (1988).

14. Shi-Nan Quian et al, SPIE Electro-Optic Imaging Systems and Devices Symposium, Los Angeles (Jan 11-16, 1987).

15. M.W. Grindel, *Proceedings of the SPIE* **680** (1986).

16. Additional details of the thermal distortion measurements and finite element analyses will be published at a later date.

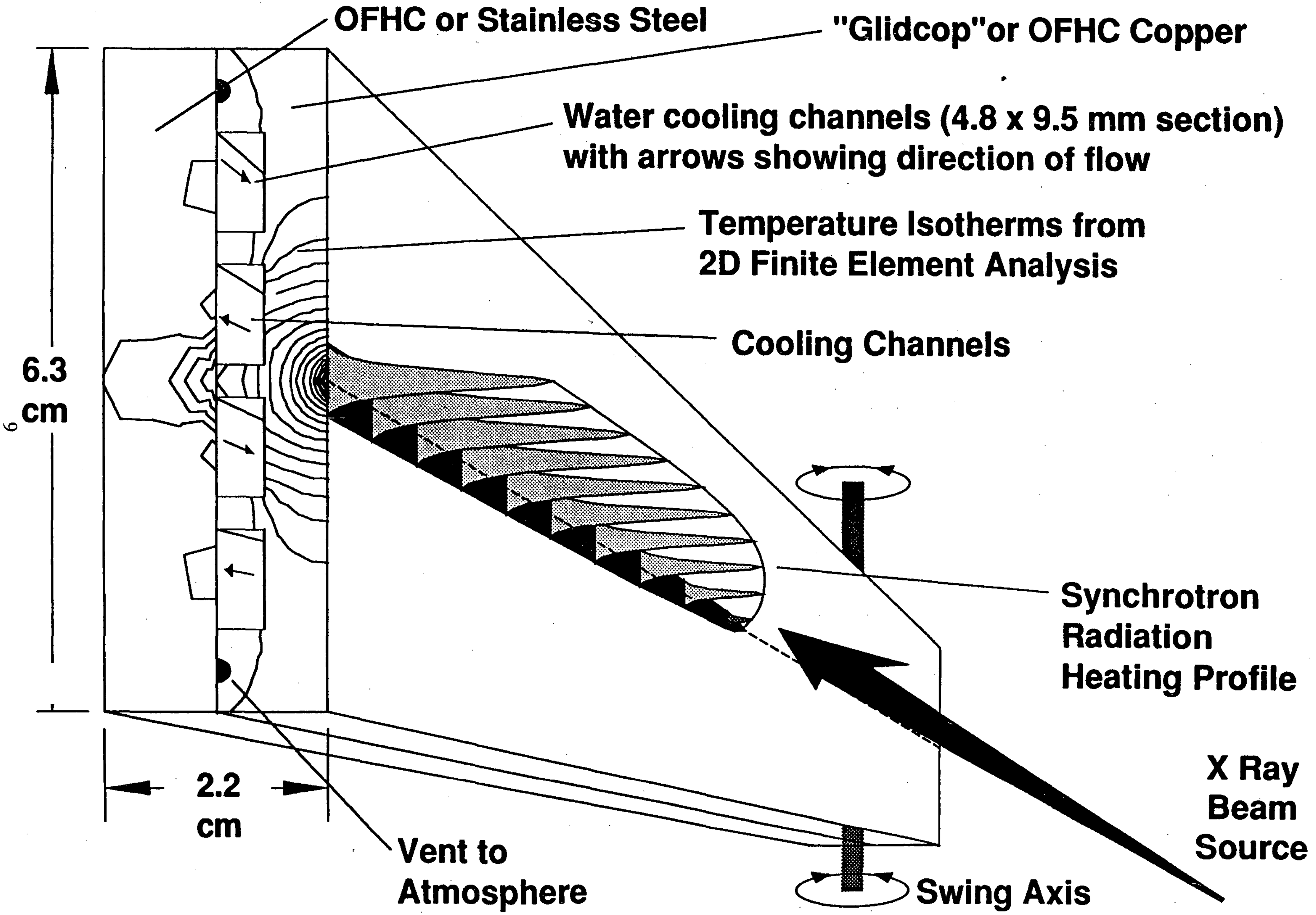
17 See also R. DiGennaro and T. Swain, *X-Ray Optics Design for High Heat Load on ALS Beam Lines,* (these proceedings).

Figure Captions

Figure 1. Generic configuration for a water-cooled thermal absorber for ALS front ends and beam lines. The brazed assembly has 4 parallel water channels to accomodate lengthwise heat loads up to 425 W/cm., being limited by the allowable temperature rise at the cooling channel wall.

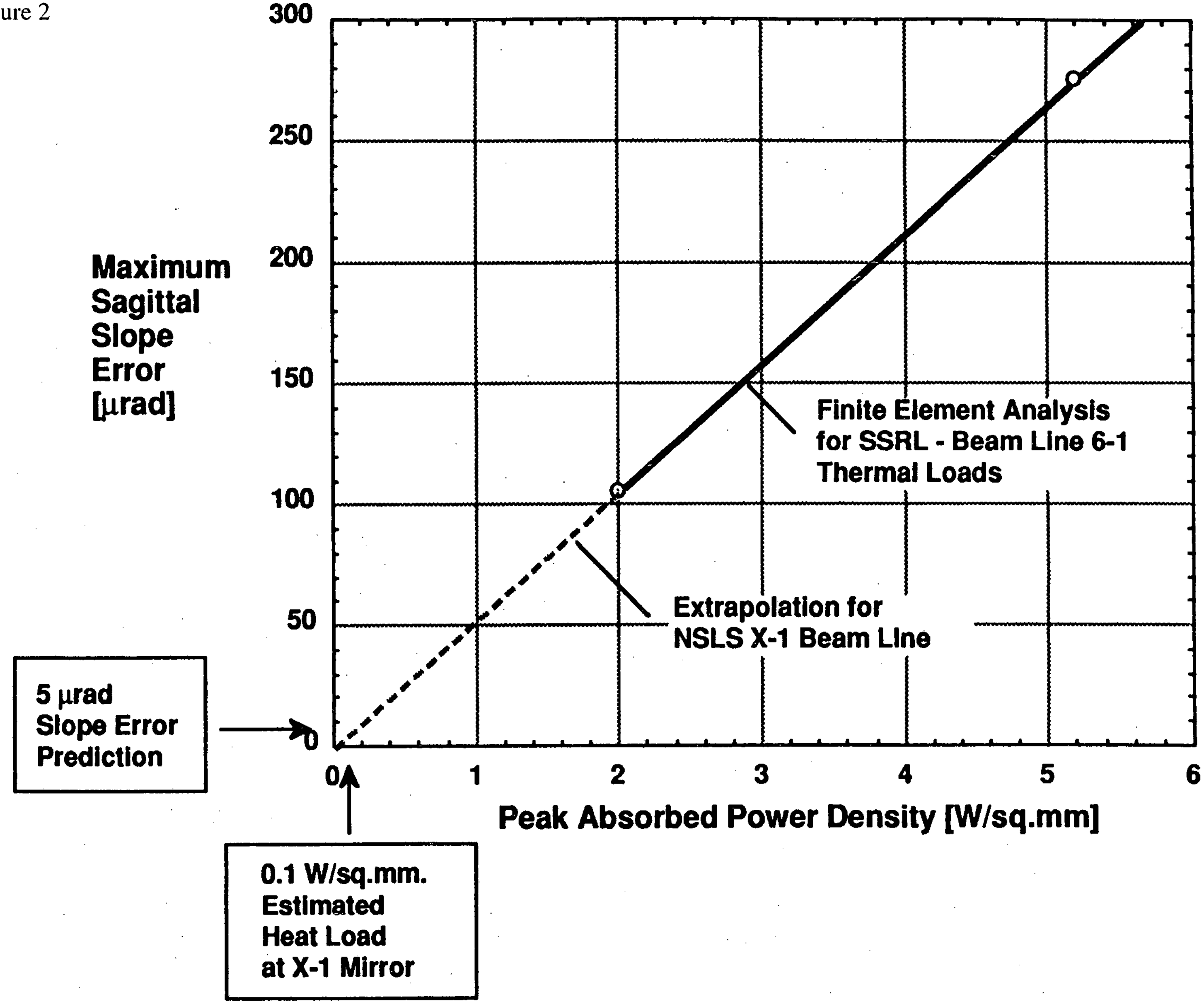
Figure 2. SSRL Beam Line 6-1 M-Zero mirror slope error estimates extrapolated to predict mirror distortion on the NSLS X-1 Beam Line.

Figure 1



OFHC or Stainless Steel
"Glidcop"or OFHC Copper
Water cooling channels (4.8 x 9.5 mm section)
with arrows showing direction of flow
Temperature Isotherms from
2D Finite Element Analysis
Cooling Channels
6.3
cm
Synchrotron
Radiation
Heating Profile
X Ray
Beam
Source
2.2
cm
Vent to
Atmosphere
Swing Axis

Figure 2


Maximum Sagittal Slope Error [µrad]
300
250
200
150
100
50
0
0
1
2
3
4
5
6
Peak Absorbed Power Density [W/sq.mm]
Finite Element Analysis for SSRL - Beam Line 6-1 Thermal Loads
Extrapolation for NSLS X-1 Beam Line
5 µrad Slope Error Prediction
0.1 W/sq.mm. Estimated Heat Load at X-1 Mirror

LAWRENCE BERKELEY LABORATORY
UNIVERSITY OF CALIFORNIA
INFORMATION RESOURCES DEPARTMENT
1 CYCLOTRON ROAD
BERKELEY, CALIFORNIA 94720