High Heat Load Synchrotron Optics.*

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ABSTRACT

Third generation synchrotron radiation sources currently being constructed worldwide will produce x-ray beams of unparalleled power and power density. These high heat fluxes coupled with the stringent dimensional requirements of the x-ray optical components pose a prodigious challenge to designers of x-ray optical elements, specifically x-ray mirrors and crystal monochromators. Although certain established techniques for the cooling of high heat flux components can be directly applied to this problem, the thermal management of high heat load x-ray optical components has several unusual aspects that may ultimately lead to unique solutions. This manuscript attempts to summarize the various approaches currently being applied to this undertaking and to point out the areas of research that require further development.

1. Introduction

Synchrotron radiation, that is radiation produced by accelerating charged particles, has had enormous consequences on those research programs that require the use of x-rays. The use of synchrotron radiation has had an impact on an impressively wide range of disciplines including physics, chemistry, biology, materials science, and medicine (1). The x-ray brilliance (number of photons per unit time per unit energy bandwidth per unit area per unit solid angle) of currently operating storage ring sources is already many orders magnitude greater than that from the Cornell 300 MeV synchrotron, where the first condensed matter experiments were performed using synchrotron radiation in the 1950s. This growth of x-ray beam brilliance is due to the progression of improved and optimized sources. First generation sources, accelerators built for high energy physics experiments and used parasitically for synchrotron radiation applications, soon gave way to second generation sources, accelerators optimized (through a reduced particle beam source size and divergence) for the production of radiation from the bending magnets that maintain the accelerating particles in (roughly circular) closed orbits. The family of third generation sources currently under construction worldwide will soon be producing even more brilliant beams from insertion devices. Insertion devices are periodic magnetic structures that cause the circulating charged particles to undergo a sinusoidal trajectory and produce a much more intense beam of radiation than that from bending magnets (2). However, along with an increase in beam brilliance comes an increase in thermal load on the x-ray optical components that intercept the beam. Thermal distortions due to the heating of the optical components can cause a degradation of the beam brilliance delivered to the experimenter's sample. Hence, one of the major challenges to designers of x-ray optical components for third generation synchrotron sources is the problem of effective thermal management.

Because the radiated power generated from synchrotron sources is proportional to the fourth power of the accelerating particles' energy, the problem of high heat loads is especially troublesome for the high energy storage rings such as the 6 GeV European Synchrotron Radiation Source (ESRF) in Grenoble, France, the 7 GeV Advanced Photon Source (APS) at Argonne National Laboratory, Argonne, Illinois, and the 8 GeV SPring-8 in Harima, Japan (3) currently under construction. When coupled with state-of-the-art insertion devices, the x-ray power levels produced at these facilities can be in

excess of 10 kwatts. Even more daunting to designers of the optical components is the unprecedented power densities generated when the particle beams of small source dimensions and divergences pass through special insertion devices called undulators. Because the undulators in these storage rings produce highly collimated x-ray beams, x-ray heat fluxes in excess of 300 watts/mm² at 30 meters from the source (a typical source-to-monochromator distance) will have to be effectively dealt with in the near future (4). (See Figures 1 and 2, which show the power density profile and spectral output, respectively, for Undulator A at the Advanced Photon Source.)

Figure 1 Angular distribution of the power generated from Undulator A (3.3 cm period, 5.0 meters long) on the Advanced Photon Source operating at 7 GeV and 100 ma. Angular dimensions (psi and theta corresponding to the vertical and horizontal opening angles, respectively) are measured in units of $1/\gamma$, where γ is the ratio of the total energy of the accelerated particle to its rest mass. For the APS, $1/\gamma$ equals 73×10^{-6} .

Figure 2 X-ray beam brilliance (on axis, i.e., $\psi=\theta=0$) as a function of energy for Undulator A (1.15 cm gap, $K=2.1$) on the Advanced Photon Source operating at 7 GeV and 100 ma.

2. High Heat Load X-ray Optical Components

Before mentioning some of the approaches that are being explored to abate the effects of thermal distortions on x-ray optical components, it is useful to briefly review two commonly used first optical components, that is those components that will experience the full power of the incident beam. In nearly all hard x-ray ($E_{x-ray} > 4$ keV) beamlines, the first optical component will be either an x-ray mirror or a single crystal monochromator. (Detailed descriptions of these components can be found in Reference 5.)

Because the index of refraction for x-rays in matter is less than unity, total external reflection mirrors can be employed as optical components in this wavelength regime. X-ray mirrors are commonly used for focusing and/or spectral modification. Typical angles of incidence for mirrors (the angle between the incoming beam and the surface of the mirror) are in the range of several milliradians. Due to the small source sizes at third generation sources, the slope error or figure tolerance required to preserve the beam brilliance must be kept to a minimum, typically 1-2 microradians. This slope error requirement also sets the scale for the thermal distortions that can be tolerated in these mirrors. Although the low glancing angle of incidence affords a considerable reduction in the heat flux on the surface of the mirror, maintaining the required figure tolerance is still a considerable challenge.

Perfect single crystals are almost always used to monochromatize the incident polychromatic x-ray beam. The beam is monochromatized through the action of Bragg scattering from the atomic planes within the crystal, namely $\lambda = 2d \sin \theta$, where λ is the diffracted wavelength, d the atomic crystal plane

spacing, and Θ the angle between the incoming beam and the atomic planes. For the (111) set of planes in silicon, incidence angles of 5° to 30° correspond to the energy range of 23 to 4 keV. The angular range of reflection (the Darwin width) for a given wavelength is typically several microradians. For the case of single crystal monochromators, the angular extent of the Darwin width sets the scale for the allowable thermal bowing of the atomic planes. (Note that, for the case of x-ray diffraction, it is the deviation from flatness of the atomic planes that is critical and not the distortion of the surface as is the case in total external reflection mirrors. Surface distortion may be different than the atomic plane distortion if the surface is not parallel to the planes.) Silicon is the universal choice for single crystal monochromators because large perfect crystals can be easily (and inexpensively) obtained. Fortunately for x-ray optical designers, the mechanical and the thermal properties of single crystal silicon are very favorable, with values of $2.3 \times 10^{-6} / ^\circ\text{C}$ and $1.2 \text{ W/cm}\cdot^\circ\text{C}$ for the coefficient of thermal expansion and thermal conductivity, respectively, at room temperature. Nonetheless, because of the higher angle of incidence for crystals as compared to that for total external reflection mirrors, the power densities on the surface of the crystal are considerably higher.

One may ask what is the criterion or measure of performance for these two x-ray optical components. For total external reflection mirrors, the answer is that the thermal distortion in the surface of the mirror should be less than that which would dilute the beam brilliance by some fixed value, say 10%, as determined by the beamline designer. There now exist x-ray ray-tracing programs with sufficient sophistication to calculate the performance of the mirror when figure errors in the mirror surface are introduced. A similar criterion can be applied to perfect crystal monochromators. Modeling calculations for thermally distorted crystal monochromators can also be made, albeit with considerably more effort because the deviation from flatness of the atomic planes is of interest, not the surface figure. However, the final performance of any device will ultimately have to be determined experimentally when fully illuminated by the high power x-ray beam.

3. Approaches to Solutions of the High Heat Load Problem

The level of concern in the synchrotron radiation community over the the problems of high heat load x-ray optics is manifested by the fact that four international workshops have been held over the last five years to bring together the experts working in this field (6). As the power and power densities from insertion devices have increased, so has the sophistication of the engineering approaches required to alleviate the thermal distortion problem. Initially, cooling was performed simply by having the optical component in contact with a cooled substrate. To decrease the thermal contact resistance between the optic and the substrate, liquid gallium (or a gallium/indium mixture) was sometimes employed. However, for the higher power sources, this technique has proven to be inadequate and direct cooling of the optical component by flowing water and, later, liquid gallium through it, was explored. But what really spurred developmental efforts was the potential power loading problems from third generation synchrotron sources. The combined challenge of even greater heat loads and simultaneously more stringent performance requirements of the optics has motivated a variety of innovative approaches to this problem. Needless to say, some have been more successful than others. Since the purpose of this paper is not intended to be a critical review of the various techniques that have been utilized to solve the problem but rather an overview of the field, technical details and the success of the various approaches will not be presented here. (The interested reader can find these details in numerous articles in Reference 2 and in papers in these proceedings.) A list of the major areas of active research addressing the high heat load problem in x-ray optical components can be found in Table I.

4. Outstanding Problems

Advancements in the area of improved heat exchangers have been steadily progressing in all fields that deal with high heat fluxes. However, it is doubtful that further significant increases will be made. Exploring various coolant fluids (water, liquid metals, etc.) may also lead to incremental advances. But even if advances are made on the heat exchanger and coolant fronts, one eventually is limited in the reduction of thermal distortion by the physical properties (thermal conductivity and coefficient of thermal expansion) of the material(s) from which the component is fabricated. An interesting approach that has been suggested to modify the material properties (at least of silicon) is through the use of cryogenic fluids as coolants. Silicon has the interesting property that its thermal conductivity increases while the coefficient of thermal expansion decreases as the temperature is reduced from room temperature. In fact, the coefficient of thermal expansion for silicon is zero at 125°K. These facts make cryogenic cooling a very attractive alternative to room temperature cooling, even though the complexity of a cryogenic system required to handle these levels of total power and heat fluxes is considerable. The area of cryogenic cooling of x-ray optical components is currently an active area of research at several institutions. Two other promising areas for x-ray optical components yet to be fully explored are adaptive optics and the use of synthetically grown diamonds. As mentioned above, even with the best room temperature cooling approaches now available, the residual thermal distortions resulting from x-ray beams from third generation sources may be larger than can be tolerated. Adaptive optical components may provide a solution to this dilemma. Diamond, with its superior thermal and mechanical properties, has the potential to be an excellent replacement for silicon. Currently, single crystal diamonds cannot be grown with the perfection and size that are required for many synchrotron radiation monochromator applications, but the technology of growing diamond crystals is rapidly evolving.

Perhaps one of the most difficult areas of development of high heat load x-ray optics is in the fabrication process. This is particularly true when dealing with perfect single crystal optical components. X-ray diffraction is very sensitive to strains in perfect crystals, and strains, in general, reduce the x-ray reflectivity of the crystal. Therefore, all fabrication processes, such as polishing and bonding for instance, must retain the strain-free nature of the crystalline lattice. Attachment of the supply and return coolant lines must be done with extreme care to avoid straining the crystal, especially when the attachment is directly to the silicon. This problem is exacerbated when using cryogenic coolants since differential thermal expansions between the crystal and its mount can be a source of stain in the crystal. Even if diamond crystals can be grown to the appropriate size and perfection in the future, bonding and fabrication issues will still be an area for research and development.

A final issue that must be addressed for the successful operation of an x-ray optical system is that of vibrations and stability. Flow-induced vibrations must be kept to a minimum if the x-ray beam brilliance is to be preserved by the optical component. Vibrational amplitudes should be a small fraction of the tolerable thermal distortions. This could potentially be a problem for fluid-cooled components that require high velocity fluid flow rates. Care should be taken in the integration of the optical component to its holder and/or drive mechanism and the design of the manifolding system that supplies the coolant to and from the pump.

5. Summary

Although the total power and heat fluxes of the x-ray beams that will be generated by insertion devices on third generation synchrotron sources will present a formidable engineering design challenge, it will not be an insurmountable one. The possibility of heat fluxes of several hundred

watts/mm² brings to mind the heat fluxes produced by electron-beam or laser-beam welders in which materials melt under such flux densities. However, it is our goal not only to keep components solid, but to do so with minimal thermal distortions under the application of heat fluxes of similar magnitude. It is important to remember that certain parameters of the problems with high flux x-ray beams are qualitatively different from those with high flux beams of particles or visible light. Fortunately, some of these differences can be taken advantage of in designing high heat load x-ray optics. In the case of total reflection mirrors, for instance, a significant fraction of the total incident power will be reflected by the mirror, reducing the actual absorbed power in the mirror. Unfortunately, the same cannot be said for single crystals monochromators, which only diffract a very narrow bandwidth (typically several eV) of the incident polychromatic beam that spans over several hundred keV. However, because these devices typically operate with a Bragg angle of 5°-30°, some spreading of the beam, and, therefore, a reduction in surface power density is achieved. X-rays also have a greater penetrating power than electrons of the same wavelength. Thus, although an electron beam with a given heat flux may melt a material, an x-ray beam with the same heat flux may not, because the power deposited *per unit volume* will be appreciably less than in the case of the electron beam. The fact that the mechanism for producing the diffracted beam is not the material interface, as it is for mirrors, but Bragg scattering from atomic planes within the crystal allows one to have an additional degree of freedom in designing crystal optical components, namely, the position of the surface relative to the planes. Judicious selection of the location of the surface relative to the atomic planes can result in a reduction in the specific surface loading via spreading of the beam across a large surface area while still satisfying the geometrical conditions for Bragg diffraction. Equally important to reducing the heat flux in the surface is the concept of thermal management. X-ray optical components are typically much more sensitive to thermal gradients and distortions in the plane defined by the incident and reflected (diffracted) beam than in other directions. By carefully configuring the shape of the optical component and the shape and location of the coolant channels, heat flow and, to some extent, distortion can be minimized. Such techniques provide the basis for the belief that x-ray beams from the third generation sources can be delivered to the experimenter with minimal loss of beam brilliance and that the lack of adequate high heat load x-ray optics will not be the reason that even more brilliant sources of x-rays will not be conceived and designed in the future.

6. Acknowledgements

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7. References

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Table I

**Approaches Under Consideration for Mitigation
of Thermal Distortions**

<u>Technique</u>	<u>Consequence</u>
Geometrical approaches (crystals)	thin crystals to minimize absorbed heat (442)* optimized shape of crystal and coolant channel asymmetric and inclined crystals (459,461)
Liquid gallium cooling (crystals)	improved heat transfer over water cooling (485)
Jet cooling with water (crystals)	local improvement of heat transfer to coolant (437)
Adaptive optics (mirrors & crystals)	remove or alleviate thermal distortion of component through thermal or mechanical bending (423,489)
Cryogenic cooling (silicon crystals)	exploit increased thermal conductivity and the zero crossing in coefficient of thermal expansion at 125°K (468,477)
Enhanced heat exchangers (crystals & mirrors)	microchannels, pin-post, pin-fin, hex, etc., patterns (433)
Substituting silicon with diamond (crystals)	superior thermal and mechanical properties of diamond as compared with silicon

* The numbers shown in parenthesis are page numbers from the proceedings of the most recent International Conference on Synchrotron Radiation Instrumentation held in Chester, England July 15-19, 1991 where results with these techniques were reported. The proceedings were published in Rev. Sci. Inst. 63(1), 1992. Papers dealing with many of listed topics can be found in these proceedings.

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