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High Heat Load X-ray Optics Research and Development.*

Wah-Keat Lee and Dennis M. Mills
Experimental Facilities Division
Advanced Photon Source
Argonne National Laboratory
Argonne IL 60439

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**High Heat Load X-ray Optics Research and Development
at the
Advanced Photon Source - An Overview**

Wah-Keat Lee and Dennis M. Mills
Advanced Photon Source
Argonne National Laboratory
9700 S. Cass Avenue
Argonne, IL 60439

Abstract

Insertion devices at third generation synchrotron radiation sources such as the APS are capable of producing x-ray beams with total power in excess of 7 kilowatts or power densities of 150 watts/mm^2 at a typical location of the optical components. Optical elements subjected to these types of heat fluxes will suffer considerably unless carefully designed to withstand these unprecedented power loadings. At the Advanced Photon Source (APS), we have an aggressive R&D program aimed at investigating possible methods to mitigate thermal distortions. The approaches being studied include, improved heat exchangers, use of liquid gallium and liquid nitrogen as coolants, novel crystal geometries, power filtering, and replacement of silicon with diamond for crystal monochromators. This paper will provide an overview of the high heat load x-ray optics program at the APS.

Introduction

One of the major challenges at third generation synchrotron sources such as the Advanced Photon Source (APS), the European Synchrotron Radiation Facility (ESRF) or SPring-8 is the problem of thermal management in the x-ray optical components. At the APS operating at 7 GeV and 100 ma, 2.4-meter wigglers will produce over 7 kW of total power while undulators, with less total power, will generate x-ray beams with power densities approaching 150 W/mm^2 at 30 m from the source. Without innovative cooling techniques, the thermal distortions on the optical components will dilute the beam brilliance and reduce the beam throughput or, in the worst case, permanently damage the optical component.

Table I shows the total power and power density of the various radiation sources at the APS. It is clear that when considering optics cooling systems for the APS insertion device beams, the system must be capable of dissipating heat in excess of several kilowatts. Depending on the coolant used, this in itself may be a challenge. On the other hand, regardless of the cooling scheme, silicon or germanium will not be able to withstand absorbed power densities of 150 W/mm^2 and still maintain the perfection required in an x-ray optic. The thermal gradients involved would severely distort the crystal. Therefore, it will be necessary to either reduce the power density on the surface of the crystal or to reduce the actual amount of power that is absorbed.

At the APS, there is an aggressive research and development program aimed at investigating a variety of possible solutions to mitigate thermal distortions of x-ray optical components. Because of the varied nature of the experiments expected to be performed at these new third generation sources, the most effective approach for reducing thermal distortion for one experimenter may not be optimal for another. As such, we are exploring several approaches including the use of liquid metal cooling, cryogenic cooling, novel diffraction geometries, substitution of silicon with diamond, enhanced heat exchangers, and the use of mirrors and pinholes as power filters. In parallel, computer modelling is used to optimize and predict the performances of some of these approaches. The testing of possible solutions to the high heat load problem is itself a difficulty because there currently exists no x-ray sources that have both the total power and power densities expected at the APS. Hence we are also engaged in a program to develop x-ray sources whose power and power densities approximate those expected from the APS so that the approaches we are developing can be tested and improved upon before the APS is completed. This paper will provide an overview of the high heat load x-ray crystal optics program at the APS and present results from recent experiments.

Heat Exchanger Design

Prior to the development of these potent insertion devices, most synchrotron x-ray optical components were cooled indirectly with water. In this scheme, the optical component is in thermal contact (either mechanically or via indium-gallium eutectic) to a cooled block, usually copper. However, it soon became clear that such methods are insufficient [1,2]. At the APS, we have designed and tested silicon monochromators with various cooling channels cut into the silicon itself. These include core-drilled holes of various sizes for the coolant to flow through to more complicated slotted crystals. Recently, we have procured a silicon monochromator that has a 'pin-post cell' design heat exchanger [3]. In addition to being a more efficient heat exchanger, the pin-post cell design also has a smaller pressure drop across the crystal. Tests of this pin-post monochromator are currently underway at CHESS.

Liquid Gallium Pump

Currently, the most commonly used coolant for synchrotron radiation optical components is water. However, good thermal conductivity and thermal capacity, together with a low melting point and high boiling point make liquid gallium an attractive alternative to water as a coolant. (Table II compares some of the thermal properties of water with liquid gallium.) In addition,

gallium is relatively safe to work with and compatible with UHV systems because of its extremely low vapor pressure at room temperature. Argonne National Laboratory has been at the forefront in the development of compact liquid gallium pumps for use with synchrotron radiation optics. There are currently two versions of the pump; an AC-powered pump and a DC-powered pump. The AC pump has been operational since 1990, while the DC pump has been operational since 1992. Details of the pump design can be found in the reference 4. The use of liquid gallium as a coolant greatly enhances the performance of silicon monochromators. In addition, due to its increased heat transfer capability, a smaller flow velocity is required to achieve the same amount of heat transfer as compared with water. This in turn can reduce flow-induced vibrations in the crystal.

Inclined Crystal Geometry

As mentioned above, in order for the optical component to simply survive power densities in excess of 100 W/mm^2 , it is necessary to reduce the surface power density on the crystal. An elegant approach to the reduction of thermal distortions in crystals caused by undulator beams is through the use of an "inclined crystal" geometry which has been pioneered by the APS [5,6]. In this geometry, the beam footprint on the crystal is increased by a factor of $1/\cos\beta$, where β is the so called inclination angle (see Figure 1). While the idea of spreading the footprint of the beam is not new (asymmetric crystals, for instance, do the same thing), the inclined crystal has the advantage of being a symmetric reflection. That is, the asymmetry parameter b , ($= \mathbf{k}_{\text{in}} \cdot \mathbf{n} / \mathbf{k}_{\text{out}} \cdot \mathbf{n}$) is -1, where $\mathbf{k}_{\text{in}}$ and $\mathbf{k}_{\text{out}}$ are the incident and diffracted wavevectors, respectively, and $\mathbf{n}$ is the inward-pointing surface normal. The inclined crystal therefore does not have the problem of a limited tunability range as do asymmetric crystals. With the exception of a few small differences, the inclined crystal behaves like a conventional flat crystal. In addition, if the crystal is cooled from behind (the most likely cooling scenario), the thermal gradient is not in the plane of diffraction, as it would be in a similarly cooled flat crystal, but is rather oriented at an angle of β from the diffraction plane. Orienting the gradient in this direction should considerably reduce the effect of the thermal differences on the diffraction performance of the crystal.

The APS has conducted several very successful tests of the inclined crystal geometry. Figure 2 shows the essential results of the inclined crystal geometry from the CHESS/APS undulator run in 1990 [7]. The CHESS/APS undulator installed at CHESS is capable of delivering 380 W of total power and power densities of 40 W/mm^2 at the location of the monochromator (18 m from the source) at 100 mA and 5.43 GeV operation. Figure 3 shows the experimental setup for these high heat load experiments. The crystal used had cooling slots cut into the back side of the face plate. The face plate was then bonded with Die-Attach paste (Johnson Matthey JM4613 AuSub) to another piece of silicon. The whole silicon assembly then is attached to a stainless steel manifold with O-rings providing the coolant seal. For the CHESS experiments, the same crystal was used in both the flat and inclined geometries with identical coolant flow rates of liquid gallium. The crystal was cooled with liquid gallium. In the inclined geometry, the (1,1,-1) planes were used by placing the crystal on a 70.5° incline, resulting in a reduction of the power density on the surface of the crystal by a factor of three. Thus, a direct comparison between the flat and inclined geometries is possible. As can be seen in figure 2, the measured intensity leveled off at about 25 mA ring current in the flat geometry. In the inclined case, the measured intensity starts to deviate from the theoretical value at about 75 mA, as would be expected simply by the scaling of the surface power densities, even though the intensity is still increasing up to 100 mA. The advantage of the inclined crystal geometry is clear.

To further test the inclined crystal geometry, we have performed high heat load experiments at the X-25 focused wiggler beamline at the NSLS [8]. The experimental setup was similar to that used at CHESS, as shown in figure 3. The amount of power incident on the crystal is about 50 W at 192 mA ring current, and the power density is about 120 W/mm^2 . At

the time these experiments were performed, this was the highest power density x-ray beamline available anywhere in the world. For this test, we fabricated a 85° inclination Si(111) slotted crystal. At this inclination, the beam spreads out on the crystal surface $11.5 (1/\cos 85^\circ)$ times more than in the flat geometry. The crystal was held at $\theta = 23.3^\circ$ (5 keV) and cooled with liquid gallium. Figure 4 shows some of the results of this experiment. In the "cold" beam measurement, aluminium filters, which absorb about 95% of the power, were placed upstream of the crystal. In the "hot" beam measurement, the filters were moved between the two ion chambers. Thus, the back ion chamber, I1, which measures the 15 keV third harmonic reflection from Si(333), measures the same photons in both cases. As can be seen in figure 4, there is no observable broadening of the rocking curves in the hot beam. The offset in the rocking curves is 0.9 arc seconds, which is the resolution of the monochromator and is probably due to mechanical backlash. Figures 5 and 6 show the beam footprints on the first crystal in the flat and inclined cases, taken with an IR camera. In the flat case, at 156 mA ring current, the temperature rise on the surface was 56°C above the nominal silicon temperature. In the inclined case, at the same ring current, the temperature rise was only 2.7°C above the nominal silicon temperature.

The results of these experiments are very encouraging. Although we have yet to test the inclined crystal at the power and power density levels of APS Undulator A, computer simulations (see later section) have shown that, with an appropriate inclination angle and reasonable length crystals, the thermal distortions on the crystals would be minimal. Thus, it appears that the inclined crystal (slotted or pin-post cell) with liquid gallium cooling is a possible solution to the APS undulator heat load problem.

Cryogenic Cooling

The advantages of using cryogenically cooled crystals for synchrotron radiation was pointed out by Bilderback in 1986 [9], although the concept of cryogenically cooled laser optical components had been considered a number of years earlier [10]. It is fortuitous that the crystal most often used as the material for x-ray monochromators, silicon, also has a thermal expansion coefficient that has a zero crossing at about 125 K. In addition, the thermal conductivity of silicon increases as the temperature is reduced. These facts make cryogenically cooled silicon particularly attractive for low-distortion optical components. The APS has embarked on a program in liquid-nitrogen cooling of x-ray monochromators [11]. Central to this program is the development of a liquid-nitrogen pumping system, a prototype of which was delivered to the APS in August 1993. The pumping system is a two-loop design: a closed optic loop and an open-loop heat exchanger. The pump can deliver 0-10 gpm, with independent control of the liquid nitrogen pressure up to 150 psi. The open-loop heat exchanger is sized to remove up to 5 kW of power. The option to remove up to 10 kW of power is available. Concurrently, we have begun to look into the design and fabrication aspects of a crystal monochromator that are specific to cryogenic temperatures. Liquid nitrogen has relatively poor thermal transport properties and low critical heat flux. Thus, in order to prevent local boiling, it is desirable to enhance the heat transfer. Several methods are being investigated, including microchannels, jet impingement, and porous matrices. In this effort, a crucial challenge is that of fabrication. The problem of maintaining a strain-free crystal after fabrication and mounting at cryogenic temperatures is indeed nontrivial. We will discuss the general difficulties of crystal fabrication in a later section.

Diamond

The recent advances in diamond fabrication technology have spurred interest in the use of diamonds for synchrotron applications. It is interesting to note that diamond at room temperature has same value for "figure of merit" (thermal conductivity/coefficient of thermal expansion) as does silicon at cryogenic temperatures. Table III shows some of the thermal and mechanical properties of diamond. Clearly, if sufficiently large and reasonably good quality diamonds are available, they would make excellent high heat load x-ray monochromators. From a diffraction

point of view, diamond (111) behaves more or less like silicon (220) reflection as far as the Bragg angle and Darwin width goes. At the APS, we have begun to look for sources of large (approx 1 cm x 1 cm), good quality diamonds. At present, we have two synthetically grown type-Ib diamonds from Sumitomo. They are about 5 mm x 5 mm x 0.3 mm thick and were grown in the (100) direction. Initial rocking curve measurements with MoK α radiation show that, over the entire size of the crystal, the double crystal rocking curve widths are under 10 arc seconds. Because the natural Darwin width of diamond (400) at MoK α is 0.68 arc seconds, most of the measured width comes from the mosaicity of the crystal [12]. Depending on the uniformity of the mosaic distribution, this crystal imperfection may in fact be desirable because the typical undulator central cone radiation opening angle is about 10 arc seconds. We hope to test these crystals under the application of a high heat load x-ray beam at the upcoming CHESS/ANL undulator run scheduled for the fall of 1993. Continuing efforts are underway to look for possible sources of large sized and good quality diamonds to use as monochromators.

Variable Asymmetric Crystal

Although the inclined crystal geometry appears very promising for the undulator heat load problem, it is not well suited to wiggler radiation due to the larger horizontal extent of the wiggler beam. The length required of an inclined crystal that could handle the beam from the planned wiggler at the APS would be impractical. Currently, the APS is looking into two related schemes for dealing with the wiggler heat load problem. The first is a conventional asymmetric crystal. Because the use of asymmetric crystals is well known, it shall not be described here. An interesting variation of the asymmetric crystal (and the inclined crystal) is the so-called variable asymmetric crystal [13]. This scheme requires all 3 degrees of rotation of the crystal (see figure 7). Energy tuning is done by the conventional θ rotation. The rotation about the reciprocal lattice vector allows the incident angle to be varied continuously (going from conventional asymmetric geometry to the inclined geometry). In addition, the rotation about the incoming beam allows for the use of reasonably sized crystals (or alternatively, allows the footprint of the beam to be more or less square in shape as opposed to an elongated trapezoid). However, there are several disadvantages. First of all, the rotation about the beam axis means that the diffraction no longer takes place in the vertical plane. Because the on-axis radiation from the synchrotron is mostly horizontally polarized, a small amount of throughput is lost. Another concern is that the increased number of degrees of freedom means that the alignment of the second crystal relative to the first is more complicated. There is also some beam motion associated with some of these rotations. On the other hand, depending on the experiment, such a monochromator may be suitable in cases where energy tuning is not required on a frequent basis.

Adaptive Optics

It may be that despite efforts to cool the x-ray optic, residual thermal strains will remain. Several methods of adaptive and active optics have been suggested and tried by the synchrotron community. These include bending the first crystal via pressure, mechanical, or thermal means to counter the thermally induced bowing [14-16]. The APS, in collaboration with the University of Missouri, has a program in which the second crystal in a double crystal monochromator is spherically bent to match the residual strain of the first (heat load) crystal. Based on the assumption of a spherical distortion on the first crystal, calculations have shown that, depending on the radii of the first crystal distortion, appropriately bending the second crystal may increase the flux through the monochromator by an order of magnitude. In addition, the beam divergence caused by the first crystal distortion is partially corrected by the bent second crystal. This idea has been tested with neutrons, and plans for synchrotron tests are underway.

Power Filtering

The discussion until now has centered around developing single crystal optical components, that is monochromators, that can function efficiently under these high power loads. However, it is clear that one way to reduce the power and power densities on the crystals is through the use of power filtering. When dealing with undulator beams, spatial filtering, that is using pinholes or slits, can be an effective way of reducing the total power onto the crystal while maintaining the flux of the desired photons. This is due to the fact that the spectral distribution of the beam is not the same as the total power distribution. Calculations indicate that the 3.8 kW of power from the APS Undulator A can be reduced to under one kilowatt while keeping over 98% of the photons in the odd harmonics. Unfortunately, this technique does not reduce the power density on the crystal, which in many cases is the major contributor to thermal distortions. A very attractive approach to reducing the total power and power density seen by the crystal, that works with varying degrees of success for both the undulator and wiggler, is through the use of mirrors as power filters. This technique is particularly effective when working at low energies (4-8 keV) on the undulator where a small magnet gap (and hence high power generation) is required to produce photons of these energies in the first harmonic. For instance, if a mirror is placed before the monochromator and set at an angle corresponding to a cut-off energy of 10 keV, a fivefold reduction of total power and nearly an order of magnitude reduction of power density is achieved when the undulator is operated at closed gap corresponding to a first harmonic energy of 4.2 keV [17]. This technique, of course, required cooled mirrors. However, many of the same approaches used to effectively cool crystals can be directly transferred to cooled mirror technologies. In addition, because the mirrors typically operate at a few milliradians rather than a few degrees, the surface power loading of the mirrors is less than that of crystals. One then only has to be concerned about the hardness of mirror coatings under these high power and radiation fluences. The APS is currently having several mirrors fabricated to explore these cooling and coating lifetime issues.

Fabrication Issues for Perfect Single Crystal Optical Components

One of the major technological challenges in developing x-ray optical components capable of effectively handling the high heat loads is that of fabrication. For cooled crystal monochromators, strain-free bonding of silicon crystals remains an ongoing area of development. Bonding is necessary because most cooling channels are cut into the back of the face plate (diffraction surface) and then bonded to a coolant distribution piece. The bond must not only be mechanically strong while not straining the crystal but must also be resistant to very high levels of radiation and be compatible with the particular coolant being used. While several possibilities for bonding silicon to silicon have surfaced, including the use of Die-Attach paste and the use of "frit-glass," none of these methods, as yet, produce strain-free bonds at the arc second level. Furthermore, the long-term effect of the harsh environment (radiation, liquid gallium, or cryogenic temperatures) on these materials is as yet unknown. A promising new approach is direct silicon-silicon bonding. In this method, very clean and flat pieces of silicon are placed in contact and heated. The resulting bond strength between the crystals can be higher than the tensile strength of natural silicon, with the exact strength highly dependent on the bonding cycle. While the chemistry of the bond is not yet totally understood, it has been suggested that an oxide layer forms between the surfaces and that it is responsible for the bond. The APS has been collaborating with outside institutions (Duke University and the University of Illinois at Chicago) to pursue the possibility of using direct bonding for the fabrication of high heat load silicon monochromators. Aside from the challenges of silicon-silicon bonding, there is another difficult technical hurdle to overcome: that is, metal-silicon bonding. Regardless of the actual cooled x-ray optic, be it a monochromator or a mirror, at some point there needs to be a metal-to-silicon (or some other optical material) connection. Conventional seals using O-rings are not desirable due to radiation damage to the O-rings. Indium or copper seals, although perhaps acceptable for water and liquid-nitrogen cooled optics, are not compatible with liquid gallium. The APS has recently procured a totally manifolded silicon monochromator from Rockwell Power Systems. The monochromator features a pin-post cell heat exchanger design in which the

silicon pieces are "frit-glass" bonded together. In addition, the silicon pieces are also "frit-glass" bonded to a Fe-30%Ni alloy (a type of Inconel). This particular alloy was chosen because of the good match in thermal expansion with the silicon and the frit-glass. Initial examination at room temperature shows that the strain incurred during the complete fabrication process is less than 2 arc seconds over a one-square-centimeter area.

Computer Simulations

Computer simulations can provide useful information regarding the performance of x-ray optical components under thermal loading. In particular, they can provide guidelines for optimal cooling channel/heat exchanger design. At the APS, analytical computations and computer modeling using finite element analysis (FEA) have been performed on various cooling channel geometries, flat and inclined diffraction geometries, and water versus liquid gallium cooling [18,19]. To complete the analysis of the x-ray diffraction performance of thermally distorted crystals, computer simulations have been performed on diffraction properties of the thermally deformed crystals using a simple curved crystal approach [20] and a more sophisticated 8x8 matrix method [21]. In general, the calculations agree with the experiments to within 15%. Figure 8 shows the measured and calculated rocking curve of Si(111) at 5 keV in a flat geometry, taken at CHESS with 60 mA ring current. The agreement is quite good. Intensive computer simulation has been performed to predict the performance of the inclined crystal in the APS undulator beam. The FEA results predict less than a 2 arc second broadening of the Darwin curve in a 85° inclined Si(111) crystal set for 4.2 keV. This energy was chosen because it is the first harmonic of the APS undulator at a closed gap of 11.5 mm (maximum power and power density). The cooling geometry in this simulation is with liquid gallium flowing at 50°C, 10 mm below the diffraction surface. This is a very conservative cooling geometry. Our current cooling channels, either slotted crystal or the pin-post cell design, should provide much better heat transfer. Thus, even with such conservative cooling assumptions, the thermal distortions predicted for the crystal are small.

In addition to the simulations of the thermal response of the crystals under high heat loads, calculations have been made using the 8x8 matrix (Takagi-Taupin) method and forth-order dispersion surfaces technique to confirm that, aside from some very small and subtle differences, the inclined crystal does indeed behave like a flat crystal [22]. Figure 9 shows the results of such a simulation for both the flat and inclined crystals at 5 keV and a 85° inclination angle for Si(111). We have also recently incorporated the inclined crystal geometry into the ray-tracing simulation program SHADOW [23]. Although the inclined crystal geometry behaves essentially like a flat crystal, there are some subtle differences; some are purely geometric, while others are the result of dynamical diffraction. For instance, the beam coming out of an inclined double crystal monochromator is slightly displaced from the conventional flat geometry. In addition, there is a small out-of-plane component. Although small, these differences may be important for some beamline designs. Details of these subtle differences can be found in references [22,23].

Alternate Heat Load Sources

There are currently no synchrotron facilities in the U.S. where high heat load optical components may be tested simultaneously at the power and power density levels approaching that of APS insertion devices. While the X-25 focused wiggler at the NSLS delivers power densities in excess of 100 W/mm², the total power is only about 100W. Similarly, while the CHESS wiggler delivers to the F-2 station total power of nearly 2 kW at 100 ma, the power density is only about 15 W/mm² at the station location. Clearly, alternate sources are needed to test the x-ray optical components designed for the APS insertion devices. The APS, in collaboration with CHESS, is building a focusing mirror to be installed on the CHESS A2 wiggler line. At the experimental location 8 m downstream from the mirror at the focus, a total power of 700-800 W and power densities exceeding 300 W/mm² will be available. The mirror is expected to be installed in the winter of 1993. The APS has also been looking into the possibility

of using high powered lasers as heat sources. Recent tests have shown that by appropriately choosing the resistivity of the silicon, it is possible to couple about 50% of the total power from a 6.7 kW CO₂ ($\lambda = 10.6 \mu\text{m}$) laser into the silicon crystal. Furthermore, the laser power absorption profile within the silicon is comparable to the power absorption profile due to the APS undulator.

Summary

In summary, while the heat load problems of the APS are enormous, considerable progress has been achieved in the past few years. However, two key points need to be stressed. One is that it is not simply a matter of heat removal, but rather a problem of thermal management, that is minimizing thermal gradients and/or orienting those gradients in such a way as to reduce the effect of those gradients on the performance of the optical element. The second point is that, as was mentioned above, one solution will not solve everyone's high heat load problems. The appropriate approach for a particular experiment will depend strongly on the desired energy range, the type of insertion device, whether mirrors can be placed before the monochromator, et cetera. Only after careful consideration of both these points will effective thermal distortion abatement be attained.

It is important to keep in mind that the heat loads shown in Table I are for 2.5-m-long insertion devices and a 100 mA ring current. The APS has the capability of having 5-m-long insertion devices and a storage ring current of 300 mA. This results in a 6-fold increase to the heat load! Thus, it is evident that synchrotron heat load problems are yet to be fully solved and a continuing aggressive research and development program will be required. The continuing success of this effort depends heavily on innovative ideas from the synchrotron scientific community and technological advances in industry.

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Figures

1. Inclined crystal geometry. For a square cross sectional incoming beam, the footprint on the crystal surface (shaded black) is trapezoidal. Notice that the surface normal, $\mathbf{n}$, is not parallel to the reciprocal lattice vector $\mathbf{H}$.
2. Diffracted beam intensity as a function of the ring current for crystals is the flat and inclined geometries. Both sets of data were taken on the same crystal. The inclined data was taken by tilting the crystal 70.5° and reflecting from the (1,1,-1) planes. The straight line shows a least squares fit to the inclined case data for currents ≤ 50 mA.
3. Experimental setup for high heat load tests at the synchrotron. For the CHESS run, the source is the ANL/CHESS undulator, while for the BNL run the source is the focused wiggler beam at X25. Rocking curves are obtained by rocking the second crystal.
4. "Cool" and "hot" beam 15keV Si(333) rocking curves obtained at 192 mA ring current with the X25 focused wiggler beam at the NSLS. The crystal was set at $\theta = 23.3^\circ$ (5 keV, Si(111)). In the cool-beam measurement, the aluminium filter was set upstream of the monochromator, while in the hot-beam measurement, the aluminium filter was set in between the two ion chambers downstream of the monochromator (see figure 3). The offset observed between the two rocking curves is one motor step and is probably due to mechanical backlash. In both cases, the crystals were cooled by liquid gallium flowing at 2 gpm.
5. Beam footprint on the surface of the crystal in the flat geometry (NSLS experiment). The picture shown is that from an infrared camera. The maximum temperature under the beam footprint is about 56°C above the nominal silicon temperature. The crystal size is 4 inches in diameter.
6. Beam footprint on the surface of the crystal in the inclined geometry (NSLS experiment). The maximum temperature under the footprint is about 2.7°C above the nominal silicon temperature. The squarish image indicates the cooled area (where the cooling slots are). The two lighter rectangles within the cooled area are the liquid gallium input and output distribution manifolds.
7. Variable asymmetric crystal rotations. R1: Conventional θ rotation, changes energy. R2: Rotation about the reciprocal lattice vector. Changes the incidence angle (changes the amount of beam spreading). R3: Rotation about the incoming beam. Changes the footprint shape. The sketch drawn here depicts $R2 = 0^\circ$, $R3 = 0^\circ$, which is identical to the inclined geometry. If $R2 = 90^\circ$ and $R3 = 0^\circ$, it would be the conventional asymmetric geometry.
8. Theoretical (undistorted), measured, and calculated (finite element analysis) rocking curves of Si(111) at 5 keV in the flat geometry for the CHESS undulator with 60 mA ring current. As can be seen, the agreement is quite good.
9. Simulations of Si(111) 5 keV rocking curves for flat and 85° inclined crystals using the 8x8 matrix method. As one can see, there is practically no difference between the two curves.

Table I: Power and Power Densities at the APS

	Bending Magnet ¹	Wiggler A ²	Undulator A ³
Total Power ⁴	0.4 kW	7.4 kW	3.8 kW
Power Density ⁵	0.7 W/mm ²	80 W/mm ²	150 W/mm ²

Notes:

1. Assuming 4.5 mrad of horizontal acceptance.
2. 8.5 cm period, 28 periods, 2.4 m long, B = 1.0 T.
3. 3.3 cm period, 72 periods, 2.4 m long, B = 0.7 T.
4. Assuming 100 mA ring current at 7 GeV, windowless operation.
5. Peak power density at 30 m from the source (typical location of first optical element), windowless operation.

Table II: Some Physical Properties of Gallium in Comparison to Water

	Gallium at 303° K	H ₂ O at 300° K
Boiling point (°K)	2676	373
Vapor pressure (mm Hg)	10 ⁻¹⁰	31.8
Thermal Conductivity (W/m-°C)	28.1	0.61
Specific heat (kJ/kg-°K)	0.37	4.18

Table III : Some Physical Properties of Diamond in Comparison to Silicon^[18]

	Diamond (RT)	Silicon (RT)	Silicon(78 °K)
Atomic number, Z	6	14	
Density (g/cm ³)	3.516	2.330	
Thermal conductivity (W/cm-K)	21	1.25	14
Thermal expansion coeff. (K ⁻¹ x 10 ⁻⁶)	0.8	2.33	-0.5
Specific heat (J/kg- K)	520	750	
Thermal diffusivity (cm ² /s)	11.5	0.72	
Young's modulus (GPa)	1050	167	
Poissons ratio	0.1 - 0.29	0.3	
Melting point (°C)	4300	1420	
Tensile strength (GPa)	> 3	NA	
Yield strength (MPa)	NA	1240 - 2060	
Lattice spacing (Å)	3.5670	5.4305	

Figure 1

Figure 2

Figure 3

High heat load experimental set-up at CHESS/BNL

Side View:

Figure 4

Figure 7

Figure 8

Measured, calculated and perfect theoretical rocking curves for 5 keV Si(111) at 60 mA CHESS current

Figure 9

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