

Lead Article

J. Synchrotron Rad. (2000). 7, 53–60

The historical development of cryogenically cooled monochromators for third-generation synchrotron radiation sources

Donald H. Bilderback,^{a*} Andreas K. Freund,^b Gordon S. Knapp^c and Dennis M. Mills^d

^aCornell High Energy Synchrotron Source and School of Applied and Engineering Physics, 281 Wilson Laboratory, Cornell University, Ithaca, NY 14853, USA, ^bEuropean Synchrotron Radiation Facility, BP 220, F-38043 Grenoble CEDEX, France, ^cMaterials Science Division, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439, USA, and ^dAdvanced Photon Source, Argonne National Laboratory, 9700 South Cass Avenue, Argonne, IL 60439, USA. E-mail: dhb2@cornell.edu

(Received 8 September 1999; accepted 13 January 2000)

In the period of the late-1980s, before the construction of multi-GeV third-generation storage rings with their intense insertion-device sources, the perceived number one problem for X-ray instrumentation was proper cooling of the first optical element in the beamline. This article, first given as an acceptance speech for the Compton Award ceremony at the Advanced Photon Source, presents a somewhat historical and anecdotal overview of how cryogenically cooled monochromator optics have been developed to provide a monochromator cooling solution adequate for today's power levels. A series of workshops and international collaborations were the key components for the progress and final success of this development.

Keywords: monochromators; cryogenic cooling; X-ray optics; undulators; liquid nitrogen; crystals; Compton.

1. Introduction

The 1998 *Advanced Photon Source Arthur H. Compton Award* which recognizes an important technical or scientific accomplishment at, or beneficial to, the APS was given to Donald H. Bilderback (DHB) of CHESS, Andreas K. Freund (AKF) of ESRF, Gordon S. Knapp (GSK) and

Donald Bilderback is the Associate Director of the Cornell High Energy Synchrotron Source and an Associate Adjunct Professor of Applied and Engineering Physics.

Andreas Freund is Staff Scientist and Head of the Optics Group at the European Synchrotron Radiation Facility.

Gordon S. Knapp was the Deputy Director of Basic Energy Sciences Synchrotron Center Collaborative Access Team (BESSRC CAT) at the Advanced Photon Source during the period described in this paper.

Dennis Mills is a Senior Scientist, Group Leader for the X-ray Optics Group, and Director of the Synchrotron Radiation Instrumentation Collaborative Access Team (SRI CAT) of the Advanced Photon Source.

Dennis M. Mills (DMM) both of APS 'for their innovation and leadership in developing cryogenically cooled X-ray optics suitable for handling the high power density of undulator X-ray beams, thus allowing users to perform scientific research at the third-generation synchrotron facilities' (award citation). The award ceremony took place at the Ninth Users Meeting for the APS (Fig. 1) on 13 October 1998. It is obvious that the achievement honored by this prize was the result of both the ingenuity and hard work of many more scientists and engineers. It was also the fruit of international communication and collaboration between experts in the synchrotron radiation community. The aim of the present article is twofold. First, we want to forward the recognition to our collaborators, to thank them for their devoted efforts and to invite them to join us in this celebration. Second, we feel that the history of cryogenic cooling of monochromators for synchrotron radiation deserves to be traced, last but not least because it is a nice example of a good balance between competition and collaboration in the field of X-ray instrumentation.

2. Hot X-rays and cool optics

Most hard X-ray beamlines at synchrotron radiation facilities require a monochromator to select a particular X-ray

energy. This job must be performed without degrading the quality of the beam that is characterized by the emittance, *i.e.* the product of source size and beam divergence, and by the brilliance, *i.e.* the number of photons per unit emittance, time and spectral bandwidth. Highly perfect single crystals, usually made of silicon or germanium (a gift from nature and the semiconductor industry), are adequate because their X-ray reflection properties expressed in terms of their angular acceptance, the so-called Darwin width, is of the order of the beam divergence, a few arcseconds (Matsushita & Hashizume, 1983). Silicon and germanium are resistant to radiation but must be cooled to withstand the heat load when exposed to the intense synchrotron beams. While such monochromators, simply cooled by water, had become a common instrument at first- and second-generation sources, they posed a unique new challenge a few years ago when it was planned to insert them into the unprecedented high power density beams expected from third-generation sources. Mirrors could be used upstream to decrease the heat load by approximately a factor of two, but the remaining power would still be high enough to represent a serious problem for the monochromator.

Fig. 2 illustrates the nature of the problem to be solved if efficient use of the source radiation is to be made (Smither, 1989). In a typical double-crystal monochromator the first crystal selects the desired X-ray energy, while the second crystal redirects the beam parallel to the incident beam. The first crystal absorbs most of the high incident power contained in the beam emanating from the X-ray undulators or wigglers. Whereas cooling can be made efficient enough to prevent melting, the main difficulty arises from the thermal distortions generated by the temperature gradients in the first monochromator crystal. As a consequence, the highly collimated incident X-ray beam will diverge after reflection such that different energies will be associated with different directions and the second crystal

can no longer simultaneously diffract all the X-rays reflected by the first crystal. The net effect is that the transmission of the double-crystal device will be reduced by one or two orders of magnitude, spoiling the brilliance of the X-ray beam and directing a beam much weaker than expected to the experiment. Clearly, there is no sense in building brighter sources if the brilliance cannot be preserved by the optics!

Thus the challenge in the mid- and late-1980s was to find an engineering pathway to a solution capable of totally preserving the brilliance of the X-ray beams generated by these new sources soon to be constructed. This need was arising at existing synchrotron radiation sources too, where crystals heated by wiggler beams were already severely

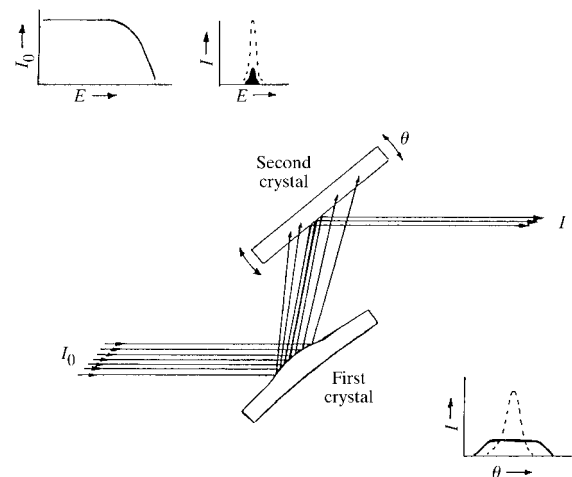


Figure 2

Schematic drawing of the two-crystal monochromator showing the effects of photon beam heating of the first crystal (Smither, 1989). The effect of the thermal bump on the first crystal is to increase the divergence of the X-rays diffracted from the first crystal. The second crystal subsequently does not accept all of the rays simultaneously and overall the two-crystal monochromator throughput is significantly reduced.



Figure 1

Compton Award ceremony. From left to right: Jon Tischler representing the APS Users Organization, Donald H. Bilderback, Andreas K. Freund, Gordon S. Knapp, Dennis M. Mills, award recipients, and David Moncton representing the APS.

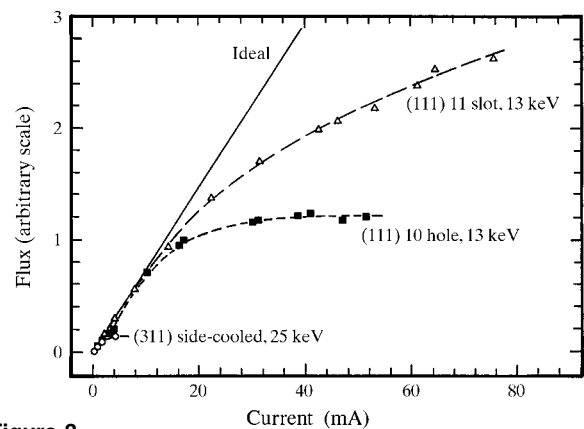


Figure 3

Observed output of a gallium-cooled silicon double-crystal monochromator as a function of electron beam current at CHESS. The deviation of the experimental data from the ideal slope occurred at a power density of 3 W mm^{-2} (Bilderback *et al.*, 1989) and is an indication that the crystal is thermally distorted.

Table 1

Comparison of heat flux levels associated with various physical processes† including insertion devices (IDs).

Process	Approximate heat flux (W mm^{-2})
Fission reactor cores	1–2
Interior of rocket nozzle	10
Commercial plasma jet	20
Sun's surface	60
Fusion reactor components	0.05–80
Meteor entry into atmosphere	100–500
IDs on third-generation sources	25–>300

† Adapted from R. D. Boyd, C. P. C. Wong & Y. S. Cha, Sandia Report SAND84-0159, January 1985.

distorted and even shattered at high power levels. At that time the indirect side-cooling geometry was replaced by direct internal cooling and water was replaced by liquid gallium. Finite-element analysis was extensively used to predict thermal deformation. Although the efficiency was improved, it still appeared to be insufficient. An example is given in Fig. 3 showing the deviation of the intensity transmitted through a double-crystal monochromator from a straight line expected for ideal optics with increasing electron beam current and therefore increasing heat flux on the first crystal that was directly cooled with gallium.

The problem worsened as the *power density* incident upon the optics increased, since both source size and beam divergence decreased with steadily improving machine performance. Table 1 gives a useful scale of comparison of the heat flux in normal incidence on X-ray optics, compared with other known physical processes. One can easily see that power densities from undulator insertion devices (IDs) at third-generation sources can far exceed those of the surface of the sun or of electron-beam welders.

All these experiences obviously led to fears that optical components might not even survive in the much more intense X-ray beams expected from the third-generation sources. In a figurative sense, the feeling many of us had was expressed by a knight in armor facing the mythical fire-breathing dragon. The knight knows full well that his protection will go only so far, and he wonders if he can really survive in the end! As optical designers, we too have wondered whether *any* solution would be good enough and whether our optics could stand up to the 'hot breath' of the X-ray beam. At that time the construction of the ESRF had already been started and the decision to build the APS had been determined, so a solution *had* to be found, and soon.

The following is a brief summary of the engineering and fabrication issues that had to be overcome to solve the thermal problems associated with high-power undulator and wiggler beams. In many ways we can only review a small portion of the crystal cooling activities that have taken place and that were presented and discussed at many meetings and workshops. We apologize in advance to our colleagues who have been working in this and related areas and who are not mentioned here, as we focus our overview

Table 2

There are many possible choices of materials, coolants, methods, project goals *etc.* that each must be carefully balanced in the context of the entire monochromator development process.

Materials	Silicon, germanium, diamond
Material properties	Diffraction, mechanical and thermal
Coolants	Water, liquid metal (gallium), cryogenic (LN_2 , propane <i>etc.</i>)
Coolant properties	Heat capacity, density, heat-transfer coefficient, boiling temperature, operating range
Crystal geometry	Thick or thin Bragg (reflection) or Laue (transmission) Long or short heat-flow path Side or internal cooling Normal, asymmetric or inclined geometry Adaptive or passive bending Heat exchanger type – drilled holes, pin-post, rectangular slots <i>etc.</i>
Project issues	Strain and bonding of crystal to coolant system Complexity <i>versus</i> performance Cost of engineering and testing Vacuum compatibility Annual operational costs

to those developments that were relevant to the development of cryogenic cooling. Also, the list of references is necessarily incomplete. Not only do we wish to describe the technical developments, but we also wish to mention briefly some of the key meetings and group interactions that occurred. Without a large group of dedicated individuals working at times separately and other times together, we would probably not now be reaping the rich harvest of scientific results that we currently experience as a result of cryogenically cooled optical components. For recent overviews of diffraction physics see Authier & Malgrange (1998), and of X-ray optics for synchrotron radiation see Hart & Berman (1998), and references therein.

3. Engineering issues and developmental milestones

Table 2 outlines the various topics that had to be addressed in the design and fabrication of the optics. For instance, there were many different materials to consider, each with its own set of properties. There were also many different types of coolants available and a variety of possible cooling geometries. If it seems confusing to make a choice among all the different combinations of materials, coolants and geometries, that is because it is! This is perhaps one of the reasons why progress in high heat-load optical components has taken so long, since it typically takes months to years to take an idea from concept to test, then additional time to further refine the design, and more time to integrate those component revisions into the final device, such as a double-crystal monochromator.

All of these different aspects of the project require optimization, and developing the better-cooled monochromator is much like developing a faster racing car. It is not sufficient to develop only an engine with high horsepower, or a sleek chassis with a good suspension, or a tire

with great tread life and a good grip on the road. All of these ingredients must be carefully integrated in a balanced way to make a racing car with the best possible performance. So it is with the monochromator designs. The material properties, coolant and heat exchanger combination must be appropriately ‘tuned’ to work well together to yield superior performance.

The history of the cryogenic monochromator can be divided into roughly three parts: (i) ideas followed by detailed estimates, (ii) feasibility experiments and (iii) integration into X-ray beamlines.

3.1. Ideas followed by detailed estimates (1985–1989)

Many innovative monochromator developments had taken place up until 1985, but it was realized that most of those designs would be inadequate for the third-generation sources, such as the ESRF and the APS. In retrospect, the solution to the cooling problem took a very positive turn with a paper given at the Synchrotron Radiation Instrumentation (SRI) conference held at Stanford University in the summer of 1985 (Bilderback, 1986). It was proposed to take advantage of the particular thermal properties of materials such as silicon (and other diamond-like III–V and II–VI semiconductors), where the coefficient of thermal expansion passes through zero at ~ 125 K (Fig. 4, for Si) and the thermal conductivity is greatly enhanced at cryogenic temperatures (Fig. 5). Both of these property changes are favorable for optics under high heat loads and represent a true gift of nature to the engineer. Victor Rehn independently had the same idea of using the improved material properties at low temperature and proposed making cryogenically cooled X-ray mirrors. His ideas were presented several months later, again at a meeting at Stanford on high-heat loading issues (Rehn, 1985). One sentence from Rehn’s paper was insightful, not only for mirrors but for future monochromators as well: ‘The combination of high thermal conductivity and zero thermal expansion coefficient make such mirrors extremely attractive, but the difficulties of operating mirrors at cryogenic

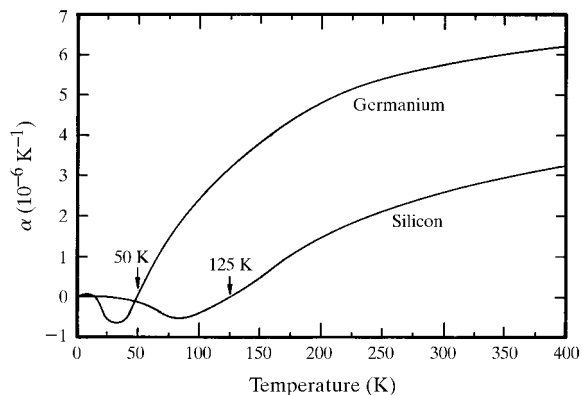


Figure 4 Thermal expansion coefficient of silicon and germanium. For silicon, the thermal expansion coefficient has a zero crossing at ~ 125 K.

temperatures in storage-ring vacuum should not be underestimated’. Rehn’s prediction has been borne out in the challenge of the design and operation of the devices.

In this period, many other approaches to mitigate thermal distortions, such as the use of liquid gallium, adaptive bending of heat-strained optics, micro-channel, pin-post and jet cooling, thin crystals, inclined geometries *etc.*, were being discussed and some of them are still pursued today. This was also a very exciting period in X-ray optics development because of the many formal and informal workshops and meetings, often satellite meetings of national or international SRI meetings, where people met and freely shared their insights and latest test results. Not only were ideas exchanged, but also individuals built relationships that would become useful for future collaborations. One of the first such meetings took place at the invitation of the ESRF when about 25 individuals went to Grenoble in September 1987 (Fig. 6) to help solve the ESRF optics problems as the ESRF would be the first third-generation source to experience the strongly increased brilliance. It was at this workshop that a variety of cooling ideas were discussed including estimates of increased performance of cryogenically cooled optics (Pattison, 1988). This international meeting and the friendships that were built laid a strong foundation for the events to follow in later years.

It is interesting to note that there was also one negative result reported during this period in July 1988. That report stated that cryo-cooling would not be feasible in the geometry where the heat conduction paths were short, only

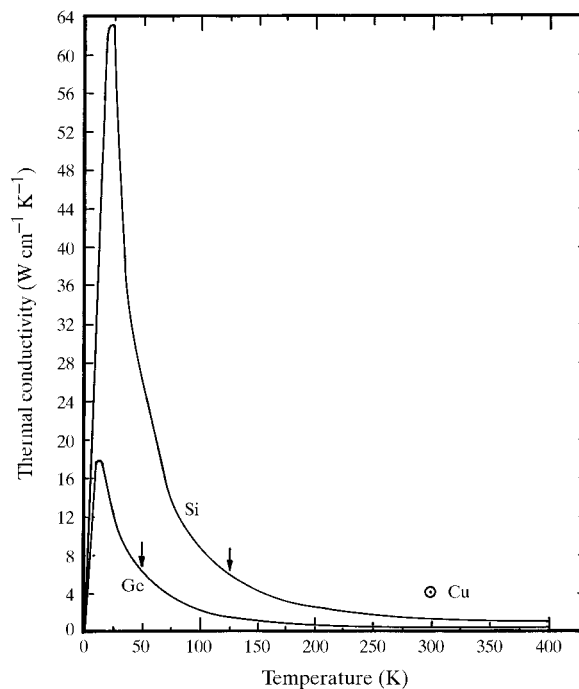


Figure 5 Thermal conductivity of silicon and germanium as a function of temperature. For comparison, the circle indicates the conductivity of copper at room temperature.

a millimeter or so long in the silicon crystal. Fortunately this result did not dampen the enthusiasm of the cooling community for trying the cryogenic possibility. The solution to the problem of low heat transfer capability of liquid nitrogen, the coolant finally chosen, was simply the use of longer conduction paths and larger heat-exchange interfaces! This period of estimates and model calculations for cryogenic cooling and of reports on the performances of other techniques culminated in a workshop hosted by the APS in August 1989 with almost 100 participants from all over the world.

3.2. Feasibility studies (1990–1992)

In this relatively short period, two key experiments were undertaken at two operating laboratories, HASYLAB and NSLS, that could provide assistance for a new third-generation source about to turn on.

Stefan Joksch of HASYLAB and a group from the ESRF including Gérard Marot, Michael Krisch and AKF used an optical interferometer designed and built at HASYLAB for high heat-load tests that had enough sensitivity to measure the thermally induced distortions of a crystal illuminated by a wiggler source (Joksch *et al.*, 1991). They were able to observe that the undesired bending of a germanium single crystal from a 100 W X-ray beam was reduced by a factor of 15 when the crystal was cooled from room temperature to 173 K. This was the first really promising result of low-temperature cooling, but at a heat flux level still much below that of the ESRF undulator and wiggler beams. During the following months a complete liquid-nitrogen cooling loop was set up in the basement of a building at the ESRF where Gérard Marot and Michel Rossat tested cryogenic components such as valves, flowmeters and pumps, and worked on various problems such as the link between the cooling pipes and

the silicon crystal, bonding of silicon to invar, avoiding mounting strains *etc.* At the same time, Lin Zhang refined his finite-element calculations.

The second test experiment took place at the NSLS at the invitation of Jerry Hastings. Following a preparatory meeting at Brookhaven in September 1990, both side-cooled and internally cooled silicon crystals were carefully prepared at the ESRF and mounted on a flange that was then shipped to Brookhaven. A group that included AKF, Gérard Marot, Michel Rossat, Lin Zhang and Eric Ziegler from the ESRF, Stefan Joksch from HASYLAB and Hiroshi Kawata from the Photon Factory traveled to Brookhaven in February 1991 benefiting from almost empty airplanes but suffering two hours of search by the security because of the Gulf War. A vacuum cross with entrance and exit beryllium windows was provided by the NSLS and mounted on the test stand on the wiggler beamlines X17 and X25. The experiments were prepared and carried out with the efficient help of Lonny Berman, Dean Chapman, Mike Iarocci and technical staff.

These experiments were crucial because they were performed under conditions comparable with the ESRF undulators: a mirror-focused 75 W intense wiggler beam generated a heat flux of 150 W mm^{-2} on the silicon crystal. The double-crystal (333) reflection that was studied at 18 keV had a theoretical perfect crystal rocking-curve width of about 1 arcsec. It was exciting to watch how, during cooling down, the almost 60 arcsec-wide rocking curves at room temperature (Fig. 7) gradually narrowed to 1 arcsec at 372 K (Freund, 1992; Marot *et al.*, 1992), following exactly the ratio of thermal expansion divided by thermal conductivity to which the thermal slope error is proportional (Fig. 8)! At the same time the output peak intensity went up by a factor of 50, as expected. It is interesting to note that multilayers coated on silicon



Figure 6

Participants at the ESRF Optics Workshop, 21–23 September 1987. From left to right, standing: W. Graeff, J. Schneider, B. Dorner, B. Buras, M. Cooper, A. Freund, J. Hastings, P. Suortti, P. Dhez, R. Smither, P. Pattison, D. Bilderback, P. Elleaume, E. Ziegler; sitting: P. Siddons, K. Kohra, H. Tolentino, A. Fontaine, T. Matsushita. Other participants: M. Altarelli, R. D. Deslattes (21 September was his birthday!), R. Haensel, L. Braicovich, A. Magerl, A. Miller, C. Riekel.

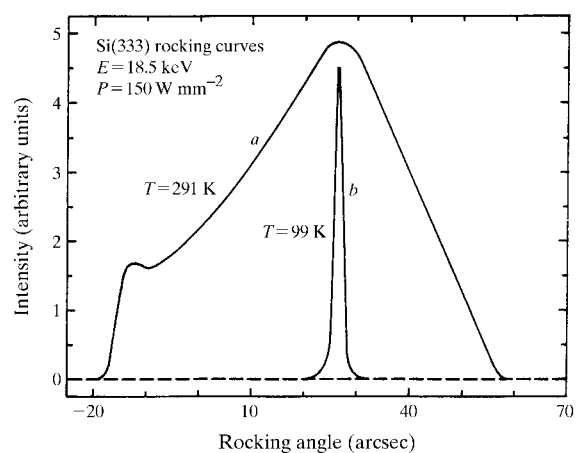


Figure 7

Double-crystal rocking-curve width at 291 K (curve *a*) and 99 K (curve *b*) taken at NSLS X25 wiggler line (Freund, 1992). The rocking curve *b* is considerably narrower than curve *a*. (For better visualization, the two curves have been scaled to keep the peak heights similar; however, the actual unscaled areas under both curves are equal.)

substrates nicely survived cryogenic cooling tests under the same heat-load conditions, whereas a 14 μm thin helium gas-cooled silicon foil shattered in the hot X-ray beam. The results were reported immediately after the experiments during one of the traditional Friday lunch meetings at the NSLS when eating sandwiches and savoring a cake made by Mrs Denis McWhan; a nice combination of X-ray science and American gastronomy. The good results were further presented at an *ad hoc* high heat-load workshop organized by Lonny Berman and held a few days later.

The feasibility of using liquid-nitrogen coolant with silicon optics at an adequate level for strong ESRF beams was thus shown! Cryogenic cooling had just come of age and this demonstration gave great hope that ESRF monochromators could live up to their expectations. AKF still remembers the great relief expressed at a meeting of the ESRF Scientific Advisory Committee chaired by Jens Als-Nielsen when the good news was reported back home.

3.3. Integration into ESRF and APS beamlines (1993–present)

Buoyed with the success at the NSLS, cryogenically cooled versions of silicon optics were built at the ESRF and put into operation after completing the cooling-loop technology with sub-coolers, pumps, special vacuum connections and all those ‘small details’ that needed hard work by Gérard Marot, Michel Rossat and Johan Holmberg. Most of these side-cooled optics were made of very massive blocks of silicon to minimize mounting deformation and featured cooling manifolds that are pressed against the block for contact cooling through indium foils (Fig. 9). At the beginning of 1993 the first cryogenically cooled monochromator went into routine operation (Bösecke & Holmberg, 1993). Later in 1993, the cooling system for supplying liquid-nitrogen flow through the optics was refined so the several cubic meter supply and recovery

tanks that took up so much floor space could be replaced by a central storage tank that supplied liquid nitrogen. That tank now supplies the 12 cryogenically cooled monochromators (on 70% of all the undulator and wiggler beamlines) presently in operation at the ESRF. A crystal directly cooled through holes fabricated in the crystal has since been installed on one beamline using a C-ring to seal the crystal-to-manifold joint, a technique developed at the APS (Rogers, Mills, Fernandez *et al.*, 1996). Besides the liquid-nitrogen cooling, low-temperature helium gas cooling has also been successfully developed and installed at the ESRF.

For the sake of completeness it is interesting to note that at this time another solution to the high heat-load problem was developed in parallel at the ESRF, NSLS and APS: diamond crystals that can operate at room temperature. In fact, the ratio κ/α of diamond at room temperature is close to silicon at 77 K. This technique is attractive because it is very simple. It is presently used for some applications, for example in protein crystallography beamlines that employ transmission optics to feed several stations with one insertion device. This development was reviewed by Freund (1995). Cryogenic cooling of diamond, whose thermal properties improve very much at low temperatures in a fashion similar to that of silicon, was reported by Yamaoka *et al.* (1995).

Now let us turn our attention to the R&D activities at the APS. In place during this period was a multifaceted program that was exploring a variety of approaches for cooling optics, including cryo-coolants. Shawn Rogers was assigned the task of working on the cryo-cooling program at the APS. His finite-element analysis of cryo-cooled silicon indicated that internal cooling would be the best approach for the higher power and power densities expected at the APS as compared with the ESRF. By the mid-1990s he had a cryogenic pump operating and had

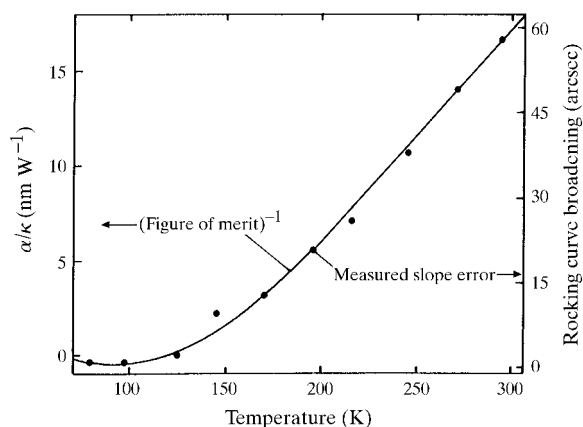


Figure 8

The solid line is the coefficient of thermal expansion (α) divided by the thermal conductivity (κ) plotted as a function of temperature. The circles represent measured rocking-curve broadening and are observed to track the figure-of-merit curve. In both cases the smaller values at low temperature are consistent with improved performance.

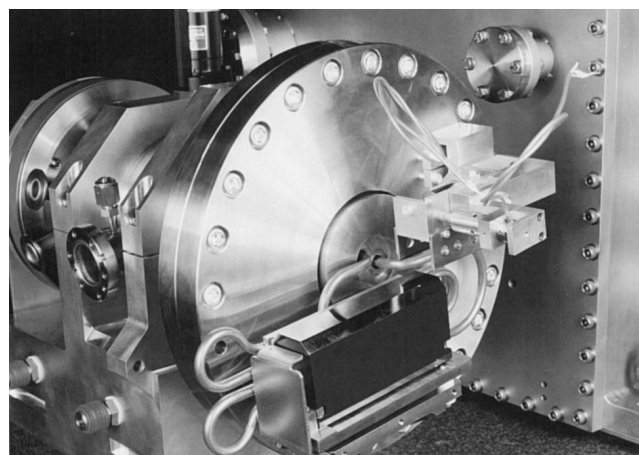


Figure 9

Cryogenically cooled monochromator at the ESRF. A massive silicon crystal, attached to a cooled metal manifold, is mounted on the rotating plate of the double-crystal fixed-exit mechanics built at the ESRF. Photograph courtesy of Fabio Comin.

explored crystal designs that used C-rings for making a vacuum-tight radiation-compatible seal between the silicon crystal and the manifold. Also during this time period, GSK became intrigued with the possibility of cryo-cooling. He read a paper (Yang *et al.*, 1993) outlining a potential design for a cryogenically cooled Laue monochromator. Two things caught his attention: an analytical model describing the temperature distribution in a thin web, and the concept of putting the heat exchanger a large distance away from the heat source. GSK gave an informal talk at the APS outlining his ideas and it was immediately realized that this design was easily adaptable to internal cooling and the C-ring sealing method. DMM's reaction was "Let's go full bore on this."

Shawn Rogers and GSK refined the design to include many internal passages and the C-ring seal to minimize crystal strain (see Fig. 10). This design was presented during a cooling workshop at the APS in July 1994 and the idea of testing it at the ESRF was brought up. The timing was fortuitous since earlier that year (in January) the first tripartite meeting of the APS, ESRF and SPring-8 had been arranged by the managements of the organizations to foster and formalize collaborations between the three facilities. This was the perfect project to collaborate on and, as a result, beam time was granted to test the crystal on a powerful focused-wiggler beam (beamline ID09) at the

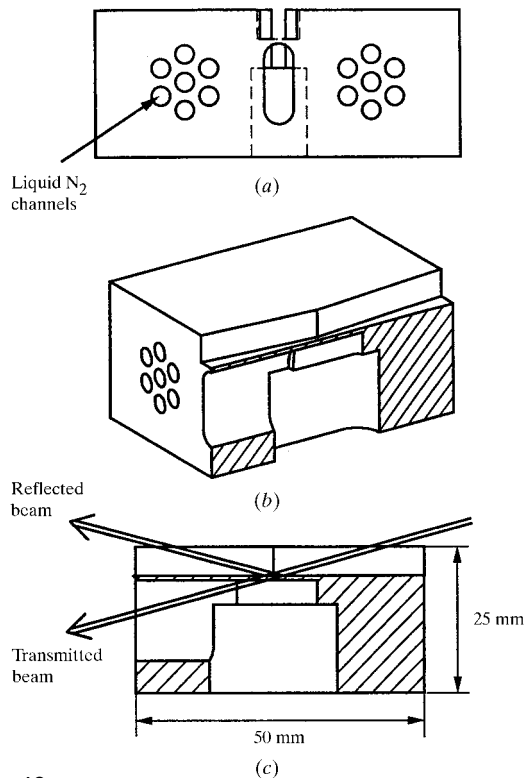


Figure 10
(a) End view, (b) pictorial view and (c) cross sectional view of the APS cryo-cooled crystal tested at the ESRF showing the path of the incident, transmitted and reflected beams. A special C-ring (not shown) forms the seal between the group of seven cooling channels and the coolant distribution manifold.

ESRF. (The experiment was scheduled to commence on 10 November 1994 and a better birthday present for DMM could not have been had!) The results of that first experiment (Rogers *et al.*, 1995) and a second run (Rogers, Mills, Fernandez *et al.*, 1996) can be seen in Fig. 11. Needless to say, it was a huge success. Perhaps even more amazing was that this activity was brought from concept to successful testing in under a year! These tests provided the confidence to pursue development of a very similar crystal design for use at the higher power levels expected at the APS. The first test of this crystal design on an APS undulator beamline under full power (undulator A with a gap of 11 mm and circulating current of 100 mA) was made in March 1996 by Shawn Rogers, Patricia Fernandez, Wah-Keat Lee, Tim Graber and DMM. It proved totally adequate for the APS undulator beam (Rogers, Mills, Lee *et al.*, 1996) and currently 75% of the insertion-device beamlines at the APS (16) are using, or are planning to use, cryogenically cooled silicon optics. It is interesting to note that, as can be seen in Fig. 11, the performance of this crystal was found to be equally good when diffracting from the thin web as from the thick portion of the crystal. In fact, recent designs have disposed of the thin web geometry and replaced it with a much simpler thick crystal geometry, the only consequence being a slightly higher usage of liquid nitrogen. It seems that our initial finite-element analyses were a bit too conservative; but this is why one does experiments!

4. Conclusions and outlook

We have given a brief historical review of the great progress that has been made in the cooling of monochromator optics for today's third-generation sources such as the APS and the ESRF. The successful developments described here have arisen from the ingenuity and hard work of many

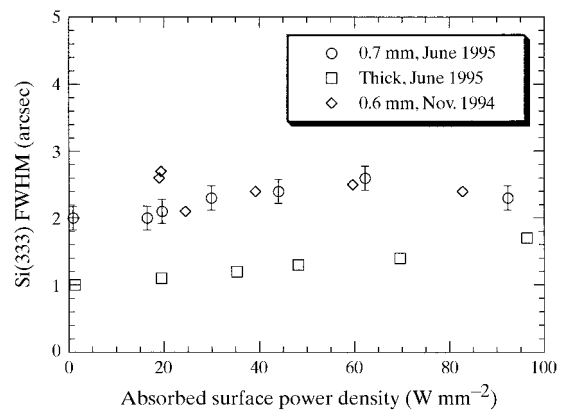


Figure 11
Si(333) double-crystal rocking-curve widths taken at 30 keV as a function of absorbed power on the thin (0.7 mm) and thick (>25 mm) portions of the APS crystal and from the thin part of a previously tested APS crystal (0.6 mm). The rocking-curve widths are independent of the heating load, proving that the crystal is not distorting significantly with absorbed power load.

individuals. Many persons have been involved in the design, testing and fabrication of silicon crystals, the development of cryo-compatible monochromators, and in the design and operation of cryo-pumping systems. To these individuals and the many more who shared in the set-up and experimental testing, we say thank you for the joy we have received from working with you.

Is the development work finished? Not yet! There are refinements that can be added. For high total power, porous media heat exchangers, of the type used in the APS front-end components, might be added, a suggestion originally attributed to Tunch Kuzay. In fact, crystals with these enhanced heat exchangers have already been fabricated at the APS and used to remove 1.8 kW of power from a cryogenically cooled monochromator tested on the CHESS wiggler beamline (Rogers, Mills, Assoufid & Graber, 1996). The whole area of strain-free bonding of silicon is still not fully resolved and the APS has been engaged in a program to develop a silicon-to-silicon bond over the last several years (Graber *et al.*, 1997). The thermal conductivity of germanium and both float-zone and Czochralski grown silicon at low temperature was measured very precisely to feed the finite-element analysis calculations with more accurate data (Freund *et al.*, 1998). These are needed if the critical limit of cryogenic cooling is approached (Zhang, 1993; Rogers, 1997). The possibility of using isotopically enriched silicon can also be explored, because a 60% increase of conductivity is expected with respect to high-purity natural silicon (Capinski *et al.*, 1997).

There are also improvements in accelerator performance and design that will undoubtedly demand further advances in the cooling designs of crystals. In the immediate future, storage rings can be expected to run at higher current (the ESRF is running at twice the original design value), with smaller insertion device gaps (the APS has installed a 5 mm vacuum chamber that permits a magnetic gap of 8.5 mm), and with longer insertion devices (APS has recently installed two undulators in series in sector 1 of the SRI CAT for a total of 5 m and SPring-8 has a 30 m straight section available. Therefore the future safe handling of even higher power densities is very important. On the even longer time scale, perhaps fourth-generation X-ray sources based on free-electron lasers will be our future. Might they be equipped with cryogenically cooled diamond crystals? Perhaps, but right now we can pause for a moment as a community and savor the good news that the monochromator heating problem of today's third-generation rings such as the ESRF and APS has been adequately solved at today's power level. This has come about with genuine international communication and cooperation of many laboratories and their staff. The aim of this and future

development work is and will always be 'allowing users to perform scientific research'.

GSK and DMM were supported by the US Department of Energy, BES-Materials Science, under Contract No. W-31-109-ENG-38. DHB was supported by the US National Science Foundation under Grant DMR-9311772.

References

- Authier, A. & Malgrange, C. (1998). *Acta Cryst.* **A54**, 806–819.
- Bilderback, D. H. (1986). *Nucl. Instrum. Methods*, **246**, 434–436.
- Bilderback, D. H., Henderson, C., White, J., Smither, R. K. & Forster, G. A. (1989). *Rev. Sci. Instrum.* **60**, 1973–1976.
- Bösecke, P. & Holmberg, J. (1993). *ESRF Newsl.* **17**, 10–11.
- Capinski, W. S., Maris, H. J., Bauser, E., Silier, I., Asen-Palmer, M., Ruf, T., Cardona, M. & Gmelin, E. (1997). *Appl. Phys. Lett.* **71**, 2109–2111.
- Freund, A. K. (1992). *Rev. Sci. Instrum.* **63**, 413–418.
- Freund, A. K. (1995). *Opt. Eng.* **34**, 432–440.
- Freund, A. K., Gillet, J.-A. & Zhang, L. (1998). *Proc. SPIE*, **3448**, 362–372.
- Graber, T., Krasnicki, S., Fernandez, P. B., Mills, D. M., Tong, Q.-Y. & Gösele, U. M. (1997). *Proc. SPIE*, **3151**, 54–64.
- Hart, M. & Berman, L. (1998). *Acta Cryst.* **A54**, 850–858.
- Joks, St., Marot, G., Freund, A. & Krisch, M. (1991). *Nucl. Instrum. Methods Phys. Res. A*, **306**, 386–390.
- Marot, G., Rossat, M., Freund, A., Joks, St., Kawata, H., Zhang, L., Ziegler, E., Berman, L. E., Chapman, D., Hastings, J. B. & Iarocci, M. (1992). *Rev. Sci. Instrum.* **63**, 477–480.
- Matsushita, T. & Hashizume, H. (1983). *Handbook on Synchrotron Radiation*, Vol. 1, edited by E. E. Koch, p. 261. Amsterdam: North-Holland.
- Pattison, P. (1988). *Synchrotron Rad. News*, **1**, 10–12.
- Rehn, V. (1985). *Proc. SPIE*, **582**, 238–250.
- Rogers, C. S. (1997). *Proc. SPIE*, **3151**, 201–207.
- Rogers, C. S., Mills, D. M., Assoufid, L. & Graber, T. (1996). *Rev. Sci. Instrum.* **67**, 3350 (Abstract). (Full paper on CD-ROM of 9th National Conference on Synchrotron Radiation Instrumentation.)
- Rogers, C. S., Mills, D. M., Fernandez, P. B., Knapp, G. S., Wulff, M., Hanfland, M., Rossat, M., Freund, A., Marot, G., Holmberg, J. & Yamaoka, H. (1996). *Rev. Sci. Instrum.* **67**, 3350, (Abstract). (Full paper on CD-ROM of 9th National Conference on Synchrotron Radiation Instrumentation.)
- Rogers, C. S., Mills, D. M., Lee, W.-K., Fernandez, P. B. & Graber, T. (1996). *Proc. SPIE*, **2855**, 170–179.
- Rogers, C. S., Mills, D. M., Lee, W.-K., Knapp, G. S., Holmberg, J., Freund, A., Wulff, M., Rossat, M., Hanfland, M. & Yamaoka, H. (1995). *Rev. Sci. Instrum.* **66**, 3494–3499.
- Smither, R. K. (1989). *Workshop on High Heat Load X-ray Optics*, Report ANL/APS/TM-6, p. 101. Argonne National Laboratory, Argonne, IL 60439, USA.
- Yamaoka, H., Freund, A. K., Holmberg, J., Rossat, M., Wulff, M., Hanfland, M., Lee, W.-K. & Mills, D. M. (1995). *Nucl. Instrum. Methods Phys. Res. A*, **364**, 582–584.
- Yang, B. X., Meron, M., Ruan, Y. & Schildkamp, W. (1993). *Proc. SPIE*, **1997**, 302–315.
- Zhang, L. (1993). *Proc. SPIE*, **1997**, 223–235.