CRYOGENICALLY COOLED MONOCHROMATORS FOR THE ADVANCED PHOTON SOURCE

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The use of cryogenically cooled monochromators looks to be a very promising possibility for the Advanced Photon Source. This position has recently been bolstered by several experiments performed on beamlines at the ESRF and CHESS. At the ESRF, several crystal geometries have been tested that were designed for high power densities (>150 W/mm²) and moderate total absorbed powers (<200 W). These geometries have proven to be very successful at handling these power parameters with measured strains on the arc-second level. The experiments performed at CHESS were focused on high total power (>1000 W) but moderate power densities. As with the previously mentioned experiments, the crystals designed for this application performed superbly with no measurable broadening of the rocking curves on the arc-second level. These experiments will be summarized, and, based on these results, the performance of cryogenic monochromators for the APS will be assessed.

1. INTRODUCTION

In the span of only 10 years, the application of cryogenic cooling for high-heat-load silicon monochromators went from a novel concept, with its actual usefulness and practicality highly questionable, to the point where liquid-nitrogen-cooled crystals are now in routine operation on insertion device beamlines the European Synchrotron Radiation Source (ESRF).¹ ² Even with the highly successful programs that had been developed at the ESRF, it was clear that the higher power and power densities that would have to be contended with from the Advanced Photon Source (APS) insertion devices would require further developments.³ (See Figure 1 for plots of the power and power density for two standard APS insertion devices.) One of the advancements felt to be critical was the development of internal cooling of the cryogenic crystals rather than contact cooling. A significant breakthrough that lead to the practicality of this development was a crystal-to-manifold indium o-ring seal that is compatible simultaneously with vacuum, low temperatures, and high levels of radiation. Over the last year, several highly successful and consequential experimental studies were completed by the APS staff and their collaborators on both high power density and high total power synchrotron radiation beams using crystals internally cooled with liquid nitrogen.

Presented here is a summary of the results of those experiments. Based on these results, projections on the performance of cryogenically cooled silicon crystals of similar design on the undulator and wiggler beams at the Advanced Photon Source will be assessed.

II. UNDULATOR BEAM APPLICATIONS

The two most significant test results of cryogenically cooled silicon monochromators are those collected at the APS Undulator A and APS Wiggler A insertion devices. Power and power density are plotted as a function of the deflection parameter, K, for undulator A and wiggler A. More details concerning insertion device characteristics and specifications can be found in reference 9 (wiggler) and reference 11 (undulator).

Figure 1. The power and power density (at 30 m from the source) is plotted as a function of the deflection parameter, K, for undulator A (top) and wiggler A (bottom). More details concerning insertion device characteristics and specifications can be found in reference 9 (wiggler) and reference 11 (undulator).
focused wiggler on BL3 at the ESRF.\textsuperscript{4,5} These experiments, performed in collaboration with scientists from Argonne, the ESRF, and SPring-8, have demonstrated that cryogenically the absorbed power cooled silicon crystals, of the appropriate design, can maintain a high level of performance even at power densities greater than 500 W/mm\textsuperscript{2}. Figure 2 shows a picture of one of the crystals tested.

The concept behind the design of these crystals is to have a thin web monochromating crystal supported on either side by a massive heat sink. The thin web permits a significant amount of the incident beam to pass through the monochromator, while the close proximity of the large heat sinks facilitates good heat removal from the thin portion of the monochromator. This concept is realized in practice by fabricating the thin web/heat sink assembly from a monolith of silicon. The thin web is recessed into the top of the silicon block to allow the heat to flow in a 2π solid angle once it is out of the web (rather than one half of that if the thin web were to be on the top surface). A disadvantage of this design is that it restricts the maximum horizontal width of the incident beam that can be accepted by the crystal.

A brief summary of the experimental conditions under which those experiments were performed is given in Table I below. Rocking curves from the 30 keV photons diffracted by the (333) planes in silicon were used to monitor the thermally induced strains. In all of the experiments, the rocking curve widths were less than 3 arc seconds approaching one arc second when using the thick portion of the crystal. (See explanation of “thick” portion in Table I.) The calculated FWHM of the rocking curve for Si (111) 30 keV is 0.5 arc seconds, the excess width is due to primarily to mounting strains. No systematic broadening of the rocking curve greater than one arc second was observed in any of the measurements. Details of these experiments can be found in references 4 and 5.

The crystals tested were designed to accept a horizontal beam size of 2.5 mm or less. (The vertical extent of the beam is not a limited by this particular crystal design; however the vertical extent of the beam does affect the total power deposited). Analytical calculations indicated that the width of the horizontal beam acceptance is a critical parameter in the design of the crystal\textsuperscript{6} and so this width will be kept fixed in an extrapolation for the use on APS undulators. Figure 3 shows the calculated horizontal and vertical extent of beams from an APS undulator at several energies and harmonics. Calculations included the effect of beam emittance. A horizontal acceptance of 2.4 mm and vertical acceptance of 1.2 mm, 30 meters from the source, corresponds to at least a 75% acceptance of all the flux in the central cone of the first or third harmonic. Figure 4 shows the absorbed power and absorbed surface power density as a function of energy for various silicon crystal thicknesses for a beam of this size. Comparing Table I with the curves of Figure 4b, one sees that power densities considerably higher than that expected at the APS have already been handled with observed thermal strains less than 1-2 arc second. Absorbed power levels are comparable to what is expected in the case of the first harmonic if a thin web of 0.6 mm is used. (A web thickness of 0.7 mm was used in the ESRF experiments.) When operating on the third harmonic, the absorbed power increases as compared to the first harmonic curves due to the shallower Bragg angle associated with these higher energies, while the absorbed power density for the third harmonic is decreased over the case for the first harmonic. Although this additional power should not be a major problem, it is relatively easy to reduce the absorbed power by inserting filters into the beam. For instance, a 0.5 mm thick carbon filter will reduce the flux at 12 keV by only 30% but reduces

![Fig. 2. Photograph of the cryogenic, thin Si monochromator showing its Invar coolant manifold assembly and six-point kinematic base plate.](image)

*Table I Summary of Experimental Parameters*

<table>
<thead>
<tr>
<th>Run Date</th>
<th>Incident Power Density (W/mm\textsuperscript{2})</th>
<th>FWHM Beam Size (x x h mm)</th>
<th>Absorbed Power (W)*</th>
<th>Abs. Surface Power Density (W/mm\textsuperscript{2})</th>
</tr>
</thead>
<tbody>
<tr>
<td>11/94</td>
<td>455</td>
<td>0.2 x 1.8</td>
<td>154</td>
<td>83</td>
</tr>
<tr>
<td>6/95</td>
<td>521</td>
<td>0.3 x 1.2</td>
<td>167</td>
<td>92</td>
</tr>
<tr>
<td>6/95**</td>
<td>493</td>
<td>0.3 x 1.2</td>
<td>174</td>
<td>96</td>
</tr>
</tbody>
</table>

*In the experiments performed at the ESRF, a focusing mirror preceded the test monochromator. This mirror removed all high energy x-rays and therefore almost all (i.e. 90%) of the power incident on the monochromator was absorbed in the thin web.

** Data collected on the “thick” portion of the crystal, i.e. from a part of the groove from which the underside was not machined away to allow passage of the beam through the crystal assembly.
Figure 3. Fraction of total flux transmitted from APS undulator A at several energies and harmonics as a function of the vertical slit size (top) and the horizontal slit size (bottom). Plots are calculated for a distance of 30 meters from the source.

The absorbed power to levels comparable to that encountered in the first harmonic case. Removing power has the added advantage of reducing liquid nitrogen use in the (secondary) open-loop side of the pumping system. If the power absorbed can be kept to 150 watts, the liquid nitrogen burn-off required to remove this heat is only 81 liters/day. Cool-down and transfer losses will, of course, increase this number.

III. WIGGLER BEAM APPLICATIONS

The experiment most amenable to extrapolation to the APS wigglers is one performed several months ago on the F2 wigglers beamline at CHESS. In these experiments, we were able to handle a total of about 1800 W at a crystal surface power density of about 5 W/mm² with less than one arc second of thermally induced strain. This crystal, shown in Figure 5, had a copper mesh brazed to the inside of the coolant channels to augment the heat transfer capability of the crystal over that of a smooth bore channel. Care must be taken when removal of high levels of power is required, or boiling can occur in the coolant. A small amount of boiling is advantageous from a heat-transfer point of view (so long as vibrations are minimized), however as the coolant wall temperature increases, a potential critical heat flux situation can arise where heat transfer to the coolant is significantly reduced due to the generation of a thin gas layer between the coolant wall and the liquid coolant. In our experiments at CHESS, indications of boiling at a total power of slightly larger than 1800 watts were observed with a coolant pressure.
of about 50 psia. Our finite element calculations indicate that boiling can be suppressed up to a total absorbed power value of about 2500 W if the system pressure is increased to 113 psia, where the boiling temperature of liquid nitrogen rises to 100 °K. But for the comparisons described in this paper, the total absorbed power will be limited to 1800 watts or less. To explore the use of cryogenically cooled crystals for the wiggler, two energy regimes will be considered; a high energy regime (E>50 keV) and a low energy (E<50 keV) regime.

A. High energy monochromators

It will be assumed that in this case: (1) the wiggler gap will remain closed at 21 mm, and (2) that a wiggler window assembly consisting of a 0.6 mm carbon filter and two 0.25 mm Be windows will be the standard beamline configuration. Also, it is assumed that filters are acceptable to remove low energy photons so long as the loss of flux at high energies is "reasonable." For this discussion, an 18 mm C filter will be inserted into the beam upstream of the monochromator crystal. (Note that carbon may not be the optimal filter material for reducing power at low energies while maintaining a high throughput at short wavelengths - see reference 8 for comparisons of several filter materials.) Calculations indicate that, under these conditions, the full beam incident power is reduced to approximately 2000 watts and the power density to 32 W/mm2, while flux loss at 50 keV and above is maintained at less than 50%. The full horizontal extent of the beam (35 mm) and the total incident power (2000 W) are similar in magnitude to those used in the CHESS experiments. Even at the relatively low energy of 30 keV, the spreading of the normal incidence power density is about 15 when a silicon (111) reflection in the Bragg geometry is used, putting the surface power density at about 2 W/mm2, considerably less than that encountered at CHESS. Therefore, our current copper-mesh-enhanced crystal design should be fully adequate up to energies where crystal length becomes a problem (typically 60 keV<E<100 keV or so for Si (111) when diffracting in the vertical direction). In fact the surface power density is low enough that other cooling approaches should seriously be considered in these situations.

At higher energies, a more advantageous geometry is the Laue arrangement, where the angle of incidence is near 90° with respect to the crystal surface. This geometry naturally facilitates the use of thin crystals for reduction of absorbed power. However, the crystals must be thick enough so that a fully developed Laue diffracted beam can be attained, typically less than a millimeter range for silicon at energies of 100 keV and greater. One approach we are exploring for beam with cross sections of about 2 mm vertical and 5 mm horizontal is a design similar to that for the undulator beam but, in this case, rotated such that the diffraction is in the horizontal plane. Again, cryogenics may not be required if appropriate power filtering is used.

B. Low energy monochromators

Clearly, since the power density of the wiggler is approximately half that of the undulator at closed gap, simply by limiting the wiggler beam size to 2.4 mm x 1.2 mm (and hence incident to about 230 W - see Figure 6) one could directly apply the thin-crystal approach that has been developed for undulator radiation. Unfortunately, this approach is not photon efficient because the wiggler beam extends to over 35 mm in the horizontal at 30 meters from the source point. The flux remaining at 16 keV would be less than 2% of the total flux available (see ref. 9 for curves of spectral flux as a function of horizontal and vertical acceptances). Given that we would like to accept a larger portion of the horizontal fan of the wiggler radiation, what are the options to do this while staying near the limits of the CHESS experiments, namely, absorbed power of less than 2000 W?

For low energies, power reduction can realized in two ways with the APS wiggler: 1) maintaining the gap of 21 mm, which corresponds to a critical energy of 32.6 keV and limiting the horizontal aperture to about 7 mm (at 30 m from the source) or 2) opening the magnet gap. Unlike the undulator, in which there is a specific magnet gap (and hence radiated power and power density) for a given x-ray energy of interest, a variety of gaps can be used with the wiggler to generate photons at a given energy, although not all gaps may be optimal. Since the user has control of the wiggler gap, a situation not usually encountered at existing synchrotron radiation facilities, it is an additional variable to consider. Hence the combination of variation in both gap and acceptance make this problem difficult to parameterize. For those experiments in which wiggler brilliance comes into play, operating the wiggler at lower critical energies may be the best option since the energy of the maximum brilliance corresponds approximately to the critical energy value9 and
the intensity of higher harmonic photons can be suppressed relative to the fundamental photon flux. The penalty for a smaller $K$ value is a loss in angle-integrated flux when compared to the closed gap, $K = 7.9$, case. Taking a concrete example, let's look at the case with $K = 3.9$; $E_c = 16$ keV, $P_T = 1782$ watts, and $P_d = 40$ W/mm$^2$. In this case, the total power is comparable to that encountered at CHESS. (Note that, when the C filter and Be windows are included in the calculation, the total power drops to about 1.1 kW. Even at this power level, liquid nitrogen consumption would be at the prodigious rate of about 600 liters per day therefore all attempts should be made to reduce the absorbed power in the optical component.) If a silicon (111) monochromator is set to diffract at 16 keV, the corresponding surface power density would be $[40.6 \text{ W/mm}^2 \times \sin (7.1^\circ)]$ or 5 W/mm$^2$, again a value comparable to that encountered at CHESS. Therefore this case is one that our existing mesh-enhanced cryogenic crystals should be able to deal with. Whether it could handle the same situation at 8 keV, where the power density would double but the total power remain the same, will have to be determined experimentally.

**SUMMARY**

Our experimental results need be extrapolated only slightly to go from the test conditions at the focused wiggler beamline at the ESRF to the undulator beam at the APS. These extrapolations indicate that cryogenically cooled crystals of a design similar to those tested should perform satisfactorily with a 2.5 meter long undulator A at the APS under 7 GeV and 100 mA operation. In fact, power densities in excess of those expected for 300 mA operation have been successfully demonstrated but not with the expected absorbed power. If this conclusion is accurate, it bodes well for experimenters at the APS, since an overwhelming majority of the insertion devices to be initially installed will be undulator A type devices.

Notwithstanding the good performance we have achieved with this design of cryogenically cooled crystal, there are still several areas that deserve further study. One is regarding the crystal geometry, namely, whether the groove can be widened to accept 3.5 mm of beam horizontally. This would permit over 95% of the central cone flux to be used. Connected somewhat with the previous point, it is of interest to see how much absorbed power can be tolerated before thermal strains lead to serious degradation of monochromator performance. Although tied intimately to the details of the manifolding and monochromator design, investigations into possible flow-induced vibrations are called for. Tests should also be made with thick crystals to see if in fact the thin web is the source of the excellent observed performance or whether it is simply the enhanced thermal and mechanical properties of silicon at cryogenic temperatures that are responsible for the improvements that are observed over room temperature silicon. And without question, further work should be pursued into developing mounting schemes than reduce the existing small residual strain (about 2 arc seconds) to even lower levels. Strains of 1-2 arc seconds will have a minimal effect on the flux output (recall that the FWHM for the Si (111) rocking curve at 8 keV is 10 arc seconds) but will have a larger effect on the beam brilliance.

Note that if larger horizontal extents are required but, due to thermal considerations, increasing the width of the web is not possible, diffracting in the horizontal plane might provide a solution. Because of the naturally smaller vertical beam extent, this would allow for a narrower channel while still accepting the entire extent of the beam. Horizontal diffraction may have another advantage in that because the vertical phase space is considerably smaller than the horizontal phase space and small distortions in the plane of the diffraction may result in relatively less dilution of the horizontal phase space (and hence beam brilliance) than in the vertical. (This is the same logic behind the reason that the high-heat-load mirrors on the
Sector 2 beamlines reflect in the horizontal rather than the vertical.\textsuperscript{10} The primary penalty for horizontal diffraction is intensity losses due to polarization and a larger energy spread as compared to vertical diffraction.

The extrapolation from our experimental results to the APS wiggler is not so straight-forward as the undulator case due to the large number of experimental conditions (width of beam required, flux vs. brilliance requirements, high or low energy applications, etc.) that are possible. The application of cryogenic cooling to high energy monochromators, whether in the Bragg or Laue geometries, is certainly feasible based on our experimental results since total power levels can be reduced significantly through the use of appropriate filters. In fact, one should look carefully to see if cryogenic cooling is required at all in these situations.

In cases where the wiggler beam is to be used for low energy applications, the situation is more complex. At this time, we do not have a single design for a cryogenically cooled crystal that will function with the full horizontal acceptance of the wiggler beam at any gap and Bragg angle. However, we do believe there are workable solutions based on cryogenically cooled silicon crystals that can be successfully applied to a subset of these conditions, such as the scenario outlined in the previous section. Because there seems to be at present no "universal" design applicable to all experimental conditions for the wiggler beam, experimenters will have to determine which parameters are more important (brilliance, total flux, energy range, horizontal/vertical acceptance, etc.), and optimize a design around those parameters. Needless to say, it is our goal to extend the performance limits we currently have (maximum acceptable power density and absorbed power) once the APS is operating routinely and the wiggler beam is available.

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