Is cold better?-Exploring the feasibility of liquid-helium-cooled optics

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Is colder better?-Exploring the feasibility of liquid-helium-cooled optics

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ABSTRACT

Both simulations and recent experiments conducted at the Advanced Photon Source showed that the performance of liquid-nitrogen-cooled single-silicon crystal monochromators can degrade in a very rapid nonlinear fashion as the power and/or power density is increased. As a further step towards improving the performance of silicon optics, we propose cooling with liquid helium, which dramatically improves the thermal properties of silicon beyond that of liquid nitrogen and brings the performance of single silicon-crystal-based synchrotron radiation optics up to the ultimate limit. The benefits of liquid helium cooling as well as some of the associated technical challenges will be discussed, and results of thermal and structural finite elements simulations comparing the performance of silicon monochromators cooled with liquid nitrogen and helium will be given.

Keywords: Single-silicon crystal monochromators, silicon optics, liquid helium, cryogenic cooling, high heat load, synchrotron radiation.

1. INTRODUCTION

Liquid-nitrogen cooling is now well established as a solution for silicon monochromators used at the third-generation synchrotron radiation sources. At the Advanced Photon Source (APS), a thin-webbed silicon monochromator internally cooled with liquid nitrogen has been developed and has been shown to perform with minimal distortion (less <2 arcsec.) under the high heat load generated by an APS undulator A (UA) operating at 100 mA ring current and 7 GeV energy. However, further testing to an equivalent of 200 mA ring current using two undulators in series revealed that the performance of liquid-nitrogen-cooled monochromators can degrade very rapidly unless the beam size is restricted to that of the central cone of the undulator radiation. This is understandable because thermally induced distortions (which, among others, are responsible for degradation of a monochromator's performance) are proportional to the ratio of the coefficient of linear expansion to the thermal conductivity, \( \alpha/k \), and this ratio varies strongly and in a nonlinear fashion with temperature. The absolute value of the inverse of this ratio, \( k/\alpha \), called the figure of merit and plotted in Figure 1, goes to infinity around 125 K, where the expansion coefficient is zero, but degrades very rapidly as the temperature deviates from it, especially towards a higher temperature. However, silicon properties continue to improve tremendously at temperatures below that of liquid nitrogen. For example, the thermal conductivity is maximum (~51.4 W/cm-K) at 15 K, which is about 34 times that at room temperature and 3.8 times that at liquid-nitrogen temperature (80 K), and the linear expansion coefficient is near zero and is always slightly negative under 25 K. The figure of merit goes again to infinity at around 15 K but remains favorable at temperatures below 20 K. There are three cryogenic fluids within or near this range of temperature: helium, hydrogen and neon. Hydrogen has obviously inherent safety problems. Liquid neon has a much higher critical temperature (44.4 K) and a better thermal conductivity than liquid helium (see Table 1). However, liquid helium is advantageous in term of figure of merit for silicon. Therefore, only liquid helium and liquid nitrogen are compared in this study.

Liquid helium has a gas-liquid phase (He I) transition (for the most abundant isotope, \(^4\)He) at 4.2 K in atmospheric pressures. As the temperature is lowered further, \(^3\)He passes through the so-called lambda point at 2.17 K to become superfluid, a second liquid phase (or He II) of zero entropy, instead of turning into a solid phase. \(^3\)He is very rare component and is very difficult to produce. At low temperature, both

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isotopes remain liquid to absolute zero. Liquid helium does not solidify unless the pressure is in excess of 25 atm. Liquid He II has exceptional transport properties; it has a very low viscosity and a tremendous apparent thermal conductivity compared to liquid He I, 86,500 versus 0.024 W/cm-K at 3.3 K. Because of its remarkable physical properties at low temperature, helium is well studied for a variety of fields, such as low-temperature research and space applications, and has been used for decades for cooling down and as a heat transfer medium in superconducting solenoids and magnets. Therefore, technology for producing, pumping and transferring, and handling of liquid helium is well developed. Moreover, liquid helium has a high specific heat. Therefore, liquid helium looks very promising as a coolant to further enhance the performance of silicon optics for use in high power synchrotron radiation sources. This can be particularly useful in applications where silicon optics with extremely low distortion are required, such as those using optics operating at low grazing incidence angle or for high-energy x-ray monochromators. It may also be useful for asymmetric crystals for preserving x-ray beam coherence properties. The main disadvantage of liquid helium is a much narrower range of liquid temperature (because of a lower heat of vaporization) and its higher cost compared with liquid nitrogen.

This paper explores the feasibility of liquid-helium-cooled optics through a series of finite element analyses (FEA) applied to a silicon monochromator subjected to high heat fluxes generated by x-ray beams from an APS undulator A (UA). The analyses were performed for ring currents from 100 to 200 mA, and the results are compared with those for a liquid-nitrogen-cooled silicon monochromator using the same cooling geometry and heat-load condition. We would like, however, to emphasize that this work was not intended to perform a rigorous study and to answer all of the relevant questions.

### Table 1: Selected properties of helium, neon and nitrogen at their boiling point.

<table>
<thead>
<tr>
<th>Property</th>
<th>Helium</th>
<th>Neon</th>
<th>Nitrogen</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal boiling point, (K)</td>
<td>4.224</td>
<td>27.09</td>
<td>77.347</td>
</tr>
<tr>
<td>Density, (kg/m³)</td>
<td>124.96</td>
<td>120.4</td>
<td>808.9</td>
</tr>
<tr>
<td>Heat of vaporization, (J/kg)</td>
<td>20.73x10³</td>
<td>86.6</td>
<td>198.3x10³</td>
</tr>
<tr>
<td>Specific heat, (J/(kg.K))</td>
<td>4.56x10³</td>
<td>1.84</td>
<td>2.04x10³</td>
</tr>
<tr>
<td>Viscosity, (kg/(m.s))</td>
<td>3.57x10⁸</td>
<td>124.0x10⁸</td>
<td>157.9x10⁸</td>
</tr>
<tr>
<td>Thermal conductivity, [W/(m.K)]</td>
<td>0.0272</td>
<td>0.113</td>
<td>0.1396</td>
</tr>
<tr>
<td>Critical temperature, (K)</td>
<td>5.201</td>
<td>44.4</td>
<td>126.20</td>
</tr>
<tr>
<td>Critical pressure, (Mpa)</td>
<td>0.227</td>
<td>2.71</td>
<td>3.599</td>
</tr>
<tr>
<td>Liquid temperature range, (K)</td>
<td>2.17 – 5.2</td>
<td>27.09 – 44.4</td>
<td>63.4 – 126.1</td>
</tr>
</tbody>
</table>

### 2. FINITE ELEMENT ANALYSIS MODELING

#### 2.1. Monochromator description and cooling geometry

For consistency, the modeled geometry was based on that of a thin-web crystal developed and tested at the APS, although a recent experiment as well as simulations revealed that a thick internally cooled crystal works just as well, if not better. A 3-D diagram of the developed monochromator is shown in Figure 2. It is made from a silicon block, 50 mm long, 85 mm wide, and 35 mm thick with, typically, a (111) orientation. The diffraction part of the crystal consists of a 1-mm-thick and a few-mm-wide thin web machined at the center of the monochromator. The thin web allows for reduction in power absorption, thereby minimizing thermally induced distortions, provided that its width is not too large compared to that of the incident x-ray beam. The crystal is internally cooled through a set of seven 3.2-mm-diameter holes drilled on each side of the diffraction thin web. The crystal is clamped to the cooling manifold and the coolant flows in through one set of holes and returns through the other set.

The purpose of this study was to get qualitative comparative results, and so, to reduce computation time, the following simplifications were made: a) each set of the seven cooling holes is arbitrarily replaced by one single 12.7-mm-diameter hole, to which an equivalent film heat transfer coefficient is ascribed, and b) the grooves and straight cuts (see Figure 2) intended as strain relief from fabrication in the crystal are omitted. The equivalent heat transfer coefficient, $h_e$, is simply equal to the heat transfer coefficient, $h$, obtained for the
seven 3.2-mm-diameter cooling channels multiplied by the ratio of the corresponding cooled area, $A_1$, to the value of the cooled area, $A_2$, corresponding to the single 12.7-mm-diameter hole, i.e.,

$$h_a = h_A \frac{A_1}{A_2} = \frac{\pi x 3.2 \times 7 x L}{\pi x 12.7 x L} = h_1 \times 1.76,$$

(1)

where $L$ is the crystal length. Two-dimensional FEA simulations showed that the simplification applied to the cooling holes has no impact on the temperature profile, and, because the mounting and fabrication strain have not been taken into account in the model, combined with the fact that the cooling holes are located far away from the diffracting area, structural effects are expected to be negligible. Finally, to reduce the crystal temperature to a minimum, the width of the diffracting thin web is made only 1/2 mm larger than that of the impinging x-ray beam, thus leaving only 1/4 mm distance on each side of the beam.

2.2. The heat load

Figure 3 depicts a typical layout of an APS beamline using an undulator A as a source and a monochromator as the first optical element. At 7-GeV ring energy and 100-mA current, an undulator A (2.4 m long with a 3.3-cm period) generates a total power in excess of 5 kW and an angular power density exceeding 154 kW/mrad² at the minimum gap of 10.5 mm. The monochromator is typically located 30 m (30.67 m for the present analyses) from the source and “sees” an incident heat flux of over 171 W/mm². In general, for vacuum requirement reasons, a beryllium window separates the beamline from the ring, but windowless operation is also possible. A pair of vertical and horizontal slits, placed upstream from the monochromator, limits the beam size to the desired acceptance. Since most of the useful photons are emitted within a very narrow cone of the undulator radiation, the slits’ openings are set to the full width at half maximum (FWHM) of this cone, which is approximately 1.5 mm (horizontally) x 0.5 mm (vertically) at the monochromator position. The power absorbed by the monochromator was estimated using XOP, a graphical interface for synchrotron radiation spectral and optics calculations. At 100 mA and with the undulator A gap set to 11 mm, the calculated incident power is reduced to 110 W, and the monochromator absorbs 60 W total power and 80 W/mm² power density. The monochromator intercepts the incident x-ray beam at a Bragg angle $\theta_B=14.3$ degrees (for 8-keV photons), and so, the absorbed surface heat flux is further spread by a factor of $1/\sin \theta_B$ giving a surface heat flux of about 20 W/mm².

Power absorption varies exponentially with crystal depth, and, since the incident x-ray beam contains a considerable number of low-energy photons (UA’s first harmonic occurs at 3.55 keV for 11 mm gap), most of the power absorption (~60%) takes place within the first 1/4 mm of silicon thickness at normal incidence. Note though that assuming that the absorbed power is totally deposited on the monochromator surface for the sake of being on the conservative side is unrealistic and leads to wrong results, because material properties are highly dependent on temperature. So, for the FEA power input, the absorption calculation should be considered as a function of crystal depth by dividing the crystal’s diffracting thin web into several layers (4 layer in this analyses), and one should compute the absorbed power for each layer.

2.3. The heat transfer coefficient

The average heat transfer is generally defined by:

$$h = \frac{q}{T_w - T_f},$$

(2)

where $q$ is the heat flux, $T_w$ is the channel wall temperature, and $T_f$ is the average coolant temperature across the cooling channel. It is typically calculated from an empirical correlation using the Nusselt number

$$h = N_u \frac{k}{D},$$

(3)
where \( \text{Nu} \) is the average Nusselt number, \( k \) is the thermal conductivity of the coolant, and \( D \) is the hydraulic diameter.

In this study, only Helium I cooling was considered. Because of its very low viscosity, liquid helium forced flow becomes turbulent (Reynold’s numbers in the order of \( 10^5 \), much greater than the turbulent regime lower limit of 2000) at very low velocity. So, for a single-phase forced flow regime (i.e., with no boiling), the average Nusselt number is calculated using the so-called Dittus-Boelter correlation

\[
\text{Nu} = 0.023 \text{Re}^{0.8} \text{Pr}^{0.4},
\]

where \( \text{Re} = \frac{\rho \mu V}{\nu} \) is the Reynolds number (\( \mu \) is the dynamic viscosity, \( \rho \) is the density, \( V \) is the coolant velocity inside a cooling channel) and \( \text{Pr} = \frac{C_p \mu}{k} \) is the Prandlt’s number (\( C_p \) is the coolant specific heat).

The heat transfer coefficient used in the FEA analysis was calculated for a flow a rate of 12 l/min. This value corresponds to the limit at which the monochromator conduit system starts to experience flow induced vibrations. Figure 4 compares the calculated heat transfer coefficient of liquid helium and liquid nitrogen as a function of volumetric flow rate for the seven 3.2-mm hole geometry using the properties listed in Table 1.

2.4. The finite element analysis procedure

ANSYS 5.5 code was used to perform the FEA analyses. The monochromator’s geometry was created using solid modeling and meshed with hexahedral volume elements. Fine meshing was applied under the beam footprint area, and, because of symmetry along the beam propagation, only half of the crystal was actually used in the FEA calculations. The total number of elements was over 30,000, which leads to a reasonable compromise between accuracy, memory requirement and computation time.

The monochromator’s performance was evaluated at ring currents of 100, 150, and 200 mA and was assumed to diffract 8-keV photons from (111) atomic planes with the undulator gap set to 11 mm. The 8-keV Bragg reflection and the undulator gap of 11 mm were chosen because they correspond to typical values used for heat-load testing at the APS. Values of the absorbed power and power density by the monochromator are given in Section 2.2 for 100-mA ring current. Both the absorbed power and power density increase linearly with the current. So, for a higher current, values at 100 mA were simply multiplied by the appropriate factor. The heat transfer coefficient calculated for a flow rate of 12 l/min was used (see Figure 4) after correction according to equation (1). The crystal bulk temperature was set to 4 K, and the analyses assume that no radiative heat transfer takes place. Temperature-dependent silicon material properties were assumed, and so nonlinear steady-state thermal and structural analysis procedures were used. Finally, temperature profiles obtained from the thermal analysis were used as input to compute thermally induced distortion in the structural analysis.

3. RESULTS AND DISCUSSION

Results of thermal and structural FEA calculations are summarized in Table 2. The distortions are given in terms of peak-to-valley (P-V) slope error on the crystal surface. These are values obtained on the surface along the beam axis in the tangential direction and within the beam footprint where distortions are maximum.

In general, the performance of a crystal monochromator is evaluated by its ability to diffract incident photons without altering the x-ray beam brilliance. Experimentally, this is indirectly evaluated by simply measuring the monochromator’s throughput by rocking the second (matching) crystal of the monochromator around the Bragg angle and recording the intensity profile at some distance from the monochromator. For a given radiation wavelength and reflection planes, the rocking curve (RC) has an intrinsic width and is typically equal to a few seconds of arc. Any thermal or mounting strain will result in a loss of energy resolution (broadening of the monochromator’s rocking curve) and a loss of beam intensity and hence a loss of beam brilliance, or even a full degradation of the monochromator’s throughput in the
case of severe crystal distortion. In order to preserve the beam brilliance, angular distortion under the beam footprint should be extremely small compared to the full width at half maximum (FWHM) of the monochromator intrinsic angular acceptance (or RC).

From the FEA calculations presented in Table 2 we see that a liquid-helium-cooled monochromator showed negligible distortion (comparison with liquid nitrogen is discussed in Section 4). Although, the minimum crystal temperature shows that the liquid helium is likely to boil (two-phase flow). The wall temperature can be reduced by either increasing the flow rate or by increasing the total cooled area (i.e., the number of channels). Moreover, it is well known that boiling results in improvement of heat transfer. In both cases the crystal temperature will decrease as we will see in the following sections.

Table 2: Finite element thermal and structural results as a function of ring current for a liquid-helium-cooled silicon monochromator under an APS undulator A x-ray beam. (Comparison with liquid nitrogen is discussed in Section 4.) The heat transfer coefficient is calculated for 12 l/min flow rate.

<table>
<thead>
<tr>
<th>Ring Current (mA)</th>
<th>Heat Transfer Coefficient [W/(m².K)]</th>
<th>Tmax (K)</th>
<th>Tmin (K)</th>
<th>Tangl. slope error, P-V (µrad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>Single-phase forced flow</td>
<td>4.078</td>
<td>14.3</td>
<td>5.5</td>
</tr>
<tr>
<td>150</td>
<td>&quot;</td>
<td>4.078</td>
<td>16.7</td>
<td>6.3</td>
</tr>
<tr>
<td>200</td>
<td>&quot;</td>
<td>4.078</td>
<td>19.0</td>
<td>7.2</td>
</tr>
</tbody>
</table>

3.1. Boiling prevention by increasing the cooled area

The 200-mA case is examined. Simulations were performed by increasing the crystal length by a factor of two, which is equivalent to increasing the cooled area or the coefficient of heat transfer by the same factor. As a result (see Table 3), the crystal’s minimum temperature dropped from 7.2 K to 5.4 K, approximately the same value as for the 100-mA case. This temperature is still high, but only marginally higher than the critical temperature of liquid helium. Nevertheless, calorimetric measurements revealed that the computer code used to compute the heat load overestimates the absorbed power and power density by typically 10-20%. The actual crystal temperature should be below that of the gas-phase transition, and so, no boiling is expected to occur.

Table 3: FEA results for single-phase forced liquid helium flow: effect of increasing the total cooled area by doubling the length of the crystal.

<table>
<thead>
<tr>
<th>Ring Current (mA)</th>
<th>Heat Transfer Coefficient [W/(m².K)]</th>
<th>Tmax (K)</th>
<th>Tmin (K)</th>
<th>Tangl. slope error, P-V (µrad)</th>
</tr>
</thead>
<tbody>
<tr>
<td>200</td>
<td>4.078</td>
<td>18.66</td>
<td>5.4</td>
<td>0.037</td>
</tr>
</tbody>
</table>

3.2. Heat transfer in the boiling regime

Boiling occurs whenever there is pressure drop in the system or the coolant is heated above its saturation temperature at the prevailing pressure, and improvement in heat transfer results as long the critical heat flux is not reached. However the mechanism of heat transfer is quite complex and very difficult to accurately evaluate. The heat transfer coefficient depends on various parameters, such as the heat flux, pressure, the mass ratio between the phases involved (vapor and liquid), the mass flow rate, the wall surface material and finish, etc. There are numerous engineering heat transfer correlations to estimate the heat transfer coefficient in the boiling forced flow regime. Most of these use a modified Dittus-Boelter correlation (equation 4) and seem to fit experimental data well. However, the geometry of these experiments is quite different from that of an x-ray monochromator. These experiments were generally performed with a long SS tube immersed in a bath of helium inside of which liquid helium flows. The heat source consists of an electrical heater wound around the test tube over a few centimeters or more. By contrast, an x-rays monochromator has a rather a shorter length and the heat source comes from x-ray absorbed within a very localized volume thorough the crystal thickness. Even so, a correlation was used and showed a gain of a factor of about two in heat transfer as compared with a single-phase flow regime. Obviously, and as expected, the FEA calculations gave similar results as in Table 3.
4. COMPARISON BETWEEN LIQUID-NITROGEN AND LIQUID-HELIUM COOLING

Simulations were performed for a liquid-nitrogen-cooled monochromator using the same cooling geometry and source and beam parameters, and the results are compared with those for the liquid-helium-cooled case. The obtained results are plotted in Figure 5. A number of observations can be made from this plot. The minimum temperature in silicon is far below the critical temperature for liquid nitrogen even at 200 mA. So, no boiling is expected to occur, and the coolant can operate in single-phase flow as long the pressure is maintained below the saturation value. However, liquid-helium cooling gives negligible slope error compared to liquid-nitrogen cooling and is almost zero up 200-mA ring current. The slope error for the liquid nitrogen decreases when the current is beyond 150 mA because the temperature is increasing towards 125 K where the figure of merit is optimum (see Figure 1). For the liquid helium case, on the other hand, the slope error is gradually increasing because the figure of merit is degrading as the temperature increases beyond that of the liquid-helium range. The liquid-nitrogen curve is expected to go through a minimum at higher current (higher absorbed power), but similar effect can be obtained by simply decreasing the cooling efficiency. A series of simulations were performed to verify this tendency by keeping the current at 200 mA and decreasing the heat transfer coefficient. The results are plotted in Figure 6. The slope error curve goes indeed through a minimum but within a very narrow range then worsens very rapidly as the heat transfer coefficient decreases or equivalently as the absorbed power increases. This is not surprising if one looks again at the variation of the figure merit of silicon as a function of temperature (see Figure 1). The figure of merit of silicon has a narrow peak around 125 K (liquid-nitrogen case) but remains always favorable at temperatures below 20 K.

5. CONCLUSIONS

We find that the performance of silicon monochromators under high power loads can be further improved at temperatures much lower than that of liquid-nitrogen which is currently used as a coolant. In particular, the performed analyses showed that a liquid-helium-cooled Si monochromator gave negligible thermally induced distortion compared to one cooled with liquid nitrogen under the high power load generated by x-ray beams from an APS undulator up to 200 mA ring current. Liquid-helium cooling is therefore very promising as a way to further enhance the performance of high-heat-load silicon-based optical components, particularly those used in applications that require very low thermally induced distortions. Applications include high-energy x-ray monochromators and optics working at low grazing incidence angles, such as mirrors, multilayers, and asymmetric crystals for preserving beam coherence properties.

We should emphasize that when using liquid helium as a coolant some considerations have taken into account: a) the cost of liquid helium is higher than that of liquid nitrogen, b) the design of the monochromator tank is more complicated due to radiative heat transfer and the need to seal against helium leaks, and c) excessive boiling of liquid helium may result in unwanted monochromator vibrations. However, these apparent difficulties may not be hard to overcome. Helium has been used in a variety of fields including superconductors (heat transfer medium), space applications, and low temperature research. Therefore, the technological aspects for handling and working with liquid helium are well developed. In particular, boiling can either be avoided by increasing the cooling efficiency (by increasing the number of cooling channels or the coolant mass flow rate) or it can be beneficial as it improves the heat transfer, provided that the system does not operate beyond the critical heat flux.

Finally, liquid helium has obviously a very narrow liquid temperature range (lower heat of vaporization) compared with liquid nitrogen and other cryogenic fluids. As an alternative, liquid neon may be used as it has intermediate properties between liquid helium and liquid nitrogen (No simulations were performed with liquid neon in this study). We would like to emphasize again that this work was not intended to perform a rigorous study; a comprehensive work is needed to compare all of the usable cryogenic fluids.
ACKNOWLEDGMENTS

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12. ANSYS, a general purpose finite element analysis code, Swanson Analysis Systems, Inc., Houston, PA 15342, USA.
Figure 1: Figure of merit, $k/\alpha$, of silicon as a function of temperature. $k$ is thermal conductivity and $\alpha$ is the linear expansion coefficient. Gray areas indicate operation of a silicon crystal at liquid-helium temperature (left) and at liquid-nitrogen temperature (right).

Figure 2: Geometry of the thin-webbed cryogenically cooled silicon crystal developed at the Advanced Photon Source.
Period 3.3 cm
N= 72
Total power>5 kW
@ 100 mA & 7 GeV

Power Density>
151 W/mm²
@ 30 m

Si (111)
double-crystal
monochromator

Undulator A
Be window
2x0.250 mm

White beam
silts

30.67 m

Experiment
station

Figure 3: Typical layout (not to scale) of an insertion device beamline using a monochromator as the first optical element at the Advanced Photon Source (see text for further details).

Figure 4: Heat transfer coefficient as a function of volumetric flow rate for liquid nitrogen and liquid helium.
Figure 5: Comparison between tangential slope error of liquid-nitrogen-cooled and liquid-helium-cooled Si monochromators as a function of absorbed power. The slope errors are peak-to-valley values under the beam footprint on the surface of a silicon monochromator set to diffract 8-keV photons from (111) atomic planes. Corresponding crystal temperatures are given for each calculated slope error point. Note that the lines are a simple guide to the eye.

Figure 6: Calculated surface slope error as a function of heat transfer coefficient (a similar effect will be obtained with the varying the absorbed power) for a liquid-nitrogen-cooled silicon monochromator set to diffract 8-keV radiation from an APS undulator A white x-ray beam at closed gap and at 200-mA ring current. For reference, the crystal's maximum temperature are given for each point. Note that the line is a simple guide to the eye.