Cryogenic Monochromator as a Solution to Undulator Heat Loads at Third Generation Synchrotron Sources

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Abstract

We have developed a new design for a cryogenically cooled monochromator employing a thin-crystal strategy which is capable of handling the central-cone power of the Advanced Photon Source's Undulator A at closed gap and at the full design current of 300 mA. We have designed and fabricated a Si (111) crystal which has a thin section where the x-rays hit and has internal cooling channels. A invar manifold has also been designed and it will be attached to the Si via In gaskets. We have done detailed modeling, both with approximate analytical and with finite element calculations. The results shown that our design has negligible thermal strain even for closed gap operation.

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INTRODUCTION

In an earlier paper¹ we discussed how a cryogenically cooled, thin crystal can handle the extremely high heat loads generated by the Advanced Photon Source, Undulator A insertion device. In that paper we showed a preliminary design concept and we made temperature rise calculations both by approximate analytical methods, and by finite element calculations. Here, we discuss a new design which we have fabricated and which will be shortly tested at a focused wiggler beamline at CHESS. We have calculated the thermal strain using Finite element methods. Our design was developed by combining two of the successful methods that have been developed to solve the heat load problem; the use of thin crystals and cryogenic cooling. Our method has the advantages that the crystal need not be extremely thin and that the total power loads which the liquid-nitrogen cooling system must handle are greatly reduced as compared to a thick cryogenically cooled crystal.

Undulator A is a 70 period, 2.3 m long insertion device² which produces power densities of 110 W/mm^2 and a total power of 304 Watts in the central cone with 100 mA beam current when the Kincaid parameter, K , is near its maximum value of 2.3. The total angle integrated power is $\sim 4 \text{ kW}$. We consider the case where the monochromator will be located 30 m from the source. A water-cooled aperture will be located upstream to limit the beam flux to 88% of the central cone monochromatic flux in the horizontal direction and 88% in the vertical direction, while excluding most of the unwanted power. This aperture will result in a beam which is 2.4 mm wide and 1.2 mm high. If all the central cone power were to be absorbed in the crystal, the crystal would be subject to unacceptably large thermal gradients as was shown by Zhang³.

The key to the thin crystal approach is that much of the central cone power comes from x-rays which have energies above 20 keV when K is large. Since the absorption coefficient of Si becomes very small at high energies, a reasonably thin crystal will not absorb much of the power in the large K region. By making the crystal thin, the power absorbed can be reduced to 120-130 Watts, producing a temperature rise in the Si strip which does not induce unacceptable strains. Another important factor is that the thermal conductivity of Si at liquid-nitrogen temperatures is so high that the Si can be cooled with the cooling surfaces at some reasonable distance from the thin part of the crystal. This overcomes the fact that the heat transfer coefficient of liquid nitrogen is quite small, hence requiring large surface areas to transfer the heat. It is also important

that thermal conductivity of Si increases by a factor of 9 from room temperature to 80 K, and that the thermal expansion coefficient becomes negative below 125 K. Both these properties are very important to minimize thermal strain.

Figure 1 shows a drawing of the design for the first crystal of a monochromator for undulator A. Two narrow vee shaped channels, with a minimum width of 2.4 mm wide, are machined into opposite sides of a Si block. The thin, center strip of Si which diffracts the incident beam is approximately 15 mm long and 0.6 mm thick (the vee shape is used because in other preliminary tests runs alignment of the crystal direction will be difficult). For clarity in Figures 2b and 2c, we show views of only the Si strip and of one half of the Si crystal block. The crystal strip will be reasonably strain free because of the crystals rectangular shape with slots to let the beam miss the thick sections of the crystal over the range of angles 5° to 32° . Invar blocks are clamped to the ends of the crystal via In gaskets and the liquid nitrogen is pumped through the holes in the Si.

THERMAL AND STRUCTURAL ANALYSIS

A thin, cryogenically cooled monochromator crystal was modeled for use with APS undulator A set to diffract 3.866 keV photons in the first harmonic from the $\langle 111 \rangle$ planes. The crystal was oriented in the Bragg reflection geometry. Due to symmetry, one-half of the crystal was modeled. The diffracting part of the crystal consists of a thin strip 0.6 mm thick and 2.4 mm wide cut into the center of a large Si block. The total absorbed power in the strip was calculated to be 130.1 W for a stored beam current of 100 mA. About 88% of the first harmonic radiation was accepted on the crystal. The beam size at the crystal 30 m from the source at normal incidence was 2.4 mm wide and 1.2 mm in height. The absorbed power was applied as a volumetric heat generation in the thin strip allowing for absorption as a function of depth. Since the x-rays are penetrating the surface at an angle, the temperature distribution and a thermal strain are slightly asymmetric (see below). For modeling purposes the crystal was uniformly cooled from the sides of the Si block. The heat transfer coefficient was $0.6 \text{ W/cm}^2 \text{ K}$ and the bulk liquid temperature was 77 K. This value for the heat transfer coefficient is readily achievable by clamping a cooled copper block to the crystal with an indium interface. Certainly better heat transfer is achievable with direct cooling through channels cut into the silicon itself as in the design shown in figure 1. The temperature profile in the thin strip is shown in Fig. 2.

The peak temperature was 124.8 K. Due to interpolation of the material properties within the finite element program, this temperature is slightly above the zero crossing point of the coefficient of expansion. Consequently, we expect to see a small "thermal bump" under the hottest part of the beam. This temperature field was used to calculate the thermal strain. The vertical displacement and slope of the surface of the thin strip along the central axis is shown in Fig. 3.

For the analysis, the central node on the thin strip was held fixed and a symmetry constraint was placed along the central plane. The rest of the crystal was unconstrained. The figure shows that there is an asymmetry about the central node. This is due to the slight asymmetry in the absorbed power because of the incident Bragg angle of 30.18° causing a twisting moment about the center. This affects the absolute displacement of the crystal surface, but not the slope. A small "thermal bump" is apparent at the center of the crystal. The peak slope is about $5 \mu\text{rad}$. This value is much less than the reflection width of about $79 \mu\text{rad}$.

In our earlier paper we showed that the peak temperature, T_p , at the center of the strip could be calculated from

$$T_p = T_k + (T_0 - T_k) \exp\left[\frac{Qw}{8\Gamma Lt}\right], \quad (6)$$

where T_0 is temperature at the Edge of the strip, Q is the total power absorbed by the strip, L is slightly larger than the length of the beam along the strip, and t is the thickness of the strip and the parameters, T_k and Γ are related to the thermal conductivity of Si, $\kappa(T)$, by the formula

$$\kappa(T) = \frac{\Gamma}{(T - T_K)}$$

where $\Gamma = 446.3 \text{ W/cm}$ and $T_K = 47.4 \text{ K}$. Our solution of the heat flow equation follows the work of Yang *et. al.*⁴. Peak temperatures calculated by these equations agree with the peak temperatures calculated by the finite element analysis for several different power loadings (see table one). By use of these calculations we show in table 1 what would happen at different heat loads and different geometries.

The results shown in this table show that by reducing the width of the channel the peak temperature can be kept below the temperature where the thermal expansion goes positive. Therefore one could actually raise the brilliance of APS by raising the current and still be able to handle a large percentage of the beam.

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Table 1: Key Crystal Temperatures

I (mA)	%cc	w(mm)	TP	TP(FEA)
100	87	2.4	124.0	124.3
100	87	2.4	108.9	110
200	87	2.4	175.3	180
300	57	1.2	123.2	-
300	70	1.56	133.2	-

Here T_p is the peak temperature of the crystal calculated by the analytical formulas. These temperatures are calculated by the analytical equations or by ANSYS (FEA) for a variety of situations for $K=2.3$, ($E=3.866$ KeV). Here I is the current at APS, %cc is the percentage of the central cone flux and w is the width of the strip.

Figure Captions

Figure 1. (a) End view of the crystal .
(b) Perspective view of one half of the crystal.
(c) Side view of one half of crystal

Figure 2. A close up view of one half the proposed crystal with the temperature contours as calculated by an ANSYS calculation.

Figure 3. The vertical displacement and slope of the surface of the thin strip along the central axis

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