ANH/XFD/CP-99584

Cryogenically Cooled Monochromator Thermal Distortion Predictions*

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October 1999

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JAN 18 2000
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To be published in the Proceedings of the 11th U.S. National Synchrotron Radiation Instrumentation Conference (SRI'99), Stanford, CA, October 13-15, 1999.

*This work is supported by the U.S. Department of Energy, Basic Energy Sciences, Office of Science, under contract #W-31-109-ENG-38.

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Abstract. Silicon crystal monochromators at cryogenic temperatures have been used with great success at third-generation synchrotron radiation sources.^{1,2} At the Advanced Photon Source (APS) the unique characteristics of silicon at liquid nitrogen temperatures (77°K) have been leveraged to significantly reduce the thermally induced distortions on beamline optical components. Finite element simulations of the nonlinear (temperature-dependent material properties) thermal stress problem were performed and compared with the experimental measurements. Several critical finite element modeling considerations are discussed for their role in accurately predicting the highly coupled thermal and structural response of the optical component's surface distortion to the high thermal heat flux. Depending on the estimated convection heat transfer coefficient, the final refined finite element model's predictions correlated well with the experimental measurements.

INTRODUCTION

The thermal distortions of cryogenically cooled silicon crystal monochromators have been measured and characterized for various total incident powers and power densities by the Synchrotron Radiation Instrumentation – Collaborative Access Team, SRI – CAT, at the APS.³ This experimental work has shown that localized distortion in the beam footprint is highly dependent on the characteristics of the beam and the incident angle, e.g., the distribution of the absorbed power as the beam travels through the crystal. To aid in the design of future optical components, a predictive tool/methodology needs to be developed that is able to (i) accurately model the complex/detailed design geometry and (ii) simulate and solve for nonuniform thermal loading and nonlinear material properties. Results from the computer simulations correlated well with the thermal distortions measurements made at the APS.

PROCEDURE

The current APS cryo-cooled silicon monochromator is shown in Figure 1. The depth of the slot is about half of the depth (z-direction) of the crystal. This slot was included to reduce the total absorbed energy of the beam in the monochromator by allowing

more energy to be transmitted. The assumptions for these simulations were as follows: (i) discrete, depth-dependent, volumetric thermal loading; (ii) half-model assumption due to symmetry; (iii) uniform forced convection cooling at the surfaces of the coolant ports; (iv) symmetry boundary conditions at the symmetry plane; and (v) mechanical constraints at seals to allow for expansion or contraction, without rigid body motion.

To reduce the computational time required to solve the full nonlinear thermal-stress problem, a simplified model with a single port was created. A comparison between the detailed 7-port FEA model and the simplified model is given in Figure 2. The peak temperatures within the footprint of the beam between the detailed and simplified models indicated that there is a negligible loss in the accuracy ($< 2\%$).

Zhang⁴ has used a 2-dimensional spatially dependent application of the thermal heat load as an area flux on the surface of the optical component to characterize the thermal distortion in the area of the beam's footprint. This loading assumes that all the energy is absorbed at or very near the surface. A more accurate approach, discussed by Assoufid et al.,⁵ is to consider the loading as discrete, distributed volumetric heat generation loads of the total power absorbed by the silicon crystal as the beam passes through the crystal.

XOP, a computer simulation tool used to predict x-ray beam interaction with various materials and surfaces, was used to determine the amount of absorbed power at different distances below the surface of the silicon crystal. The results from this calculation for APS undulator A at 11mm gap ($k=2.6$) were calculated for normal

FIGURE 1. Silicon monochromator geometry and incident beam ($x=85\text{mm}$, $y=35\text{mm}$, $z=50\text{mm}$)

FIGURE 2. Finite element half-model comparison – front views of the 7-port FEA model and the simplified model

FIGURE 3. Staggered elements simulating the beam's path

incidence at the silicon surface. The predicted distribution of absorbed power revealed that although a large percentage of the total absorbed power occurred in a region near the surface, e.g., at traversed depths less than about 1.0mm, an approximately equal amount is absorbed at traversed depths greater than 1.0mm. A more accurate representation of the thermal loading is achieved by breaking the single uniform surface or volumetric load into multiple discrete volumes that are staggered to simulate the beam's path as it travels through the crystal. XOP was used to determine the normal incident absorbed power in 1.0mm increments along the path of the beam. In the finite element model, this corresponds to the distance from the surface of the crystal along the path of the beam ($\theta=14.3^\circ$, 8keV). The results from the XOP calculation were then used as uniform volumetric thermal loads for each layer of the finite element model. The geometry assumed for the staggered elemental volumes (0.24mm thick) is given in Figure 3.

The forced convection coefficient, h , of the liquid nitrogen for a given flow rate through the actual multiple coolant port design was determined from the relationship

$$h = Nu \frac{k}{D}$$

where Nu is the Nusselt number for simultaneously developing velocity and temperature fields after a square entrance, $k=k(T)$ is the thermal conductivity of liquid nitrogen, and D is the diameter of the port. The correlation for the Nusselt number was determined by Molki et al.⁶ for various entrance configurations. Based on their work and for a flow rate of 7 liters/min., a good estimate of the convection cooling coefficient is $9,000\text{W/m}^2\text{-}^\circ\text{K}$.

RESULTS

The slope error was calculated from the vertical displacements of the nodes along the center of the beam, where the surface distortion is maximum. A family of constant convection coefficient curves, comparing the maximum thermal distortions for a range of absorbed powers, is shown in Figure 4.

A comparison of these analytical results with the experimental results from actual experimental measurements made by Lee et al.³ at the APS is consistent. Several

FIGURE 4. Comparison of thick-section and thin-section thermal distortions

experimental data points have been plotted in Figure 4. Depending on the convection coefficient, the limited experimental data correlates well with the FEA predictions.

ACKNOWLEDGMENTS

This research was supported by the U. S. Department of Energy, BES-Material Science, under Contract No. W-31-109-ENG-38.

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