High-heat-load studies of cryogenically internally cooled silicon double crystal monochromator above and away from cooling channels

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Abstract. High-heat-load studies on Si double crystal monochromator that is internally cooled with liquid nitrogen flow were performed as APS-Upgrade planned to increase ring current to 150 mA. The monochromator consists of two separated Si crystals with diffraction surfaces oriented along (111), diffracting vertically to produce a fixed 35 mm beam offset. Rocking curves were measured for the beam footprint on the first crystal lying both above and away from cooling channels. The beam was produced by two collinear APS undulators type A, each 2.4 m long with 3.3 cm period. Most of the data were obtained for a monochromator set to Bragg diffract at 8 keV for the Si (111) reflection. Through the use of aluminium filters between two sequential ion chambers, we also measured the Si (333) reflection diffracting at 24 keV. We measured the FWHM of rocking curves with either one or both undulators tuned so that the energy of the 1st harmonic matched the Si (111) Bragg energy. Our results show sensitivity to the distance between the beam footprint above and away from cooling channels under high power conditions.

Keywords: High-heat-load optics; X-ray silicon crystal monochromator; X-ray optics; cryogenic cooling.

1. Introduction
It has been shown that at the APS with ~100 mA storage ring current and type A undulators (3.3 cm period), cryogenically cooled silicon monochromators perform well with minimal (< 2 arcsec) thermal distortions [1]. With the APS-upgrade it is planned to increase stored beam current to 150 mA from ~100 mA. Therefore, it is necessary to verify that existing monochromators will continue to perform as desired, or, if need be, to develop a new solutions. We report here on a study to investigate the effect on rocking curves of high heat loads on a cryogenically internally cooled silicon double crystal monochromator both above and away from cooling channels of the first crystal. The internal cooling channels transverse to the beam which is geometry not previously reported for studies done at the APS. The main objective was to obtain data useful for predicting performance at 50% higher ring currents than are available at the present time. The first crystal design included both thick crystal and thin-web sections. Rocking curves for the beam footprint over the thin-web section were found to be broadened compared to the footprint over the adjacent bulk crystal in all cases, and we limit our report here to data obtained only on the bulk part of the crystal. We report rocking curves obtained by

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rotating the second crystal with the beam footprint on the thick part of the first crystal lying both above and away from cooling channels. The two undulators in tandem provided an opportunity to perform high-heat-load optics experiments with a maximum available heat load on the first crystal. Both internally (directly) and side (indirectly) cryogenically cooled silicon crystal studies were conducted at the APS sector 29-ID beamline. In this paper, we are only presenting the results for an internally cooled cryogenic silicon monochromator and only for the case where the beam footprint is on bulk part of crystal.

2. Experimental setup
The high-heat-load (HHL) studies were performed at beamline 29-ID. The experimental setup for the measurements of rocking curves is shown in figure 1. The two collinear undulators were located on the 5 m-long straight section of the APS ring. Collinearity of two undulators was measured to be within 0.2 mm of each other, which demonstrated that two undulators were well aligned. Both undulators were of type A with a 3.3 cm period each 2.4 m long. The minimum undulator gap was 11 mm, which corresponds to a deflection parameter (K_{peak}) of 2.65. A 0.2 mm-thick diamond window was upstream of the white-beam slits and isolated the front-end vacuum from the downstream monochromator. There was a 3 mm (H) x 2 mm (V) mask located upstream of the white-beam slits, which limited the size of the white beam incident on the double crystal monochromator (DCM). The white-beam slits were located at 31 m from the center of the straight section. The distance between the diamond window and the white-beam slits was 1.5 m. The distance between the white-beam slits and the double crystal monochromator (DCM) was 1 m. A 0.25 mm thick Beryllium (Be) exit window was located at a distance of 1.2 m downstream of DCM. The two ion chambers (I0 and I1) were used to measure the FWHM of the rocking curves of Si (111) and Si (333) which was located 2 m from the DCM. The ring current was 102 mA in top-up mode for most of the studies. We used standard ion chambers (Advanced Design Consulting USA) filled with flowing He, with path length of 100mm, plate potential of 300V and 10^5 counts/V gain on the Voltage to Frequency converter.
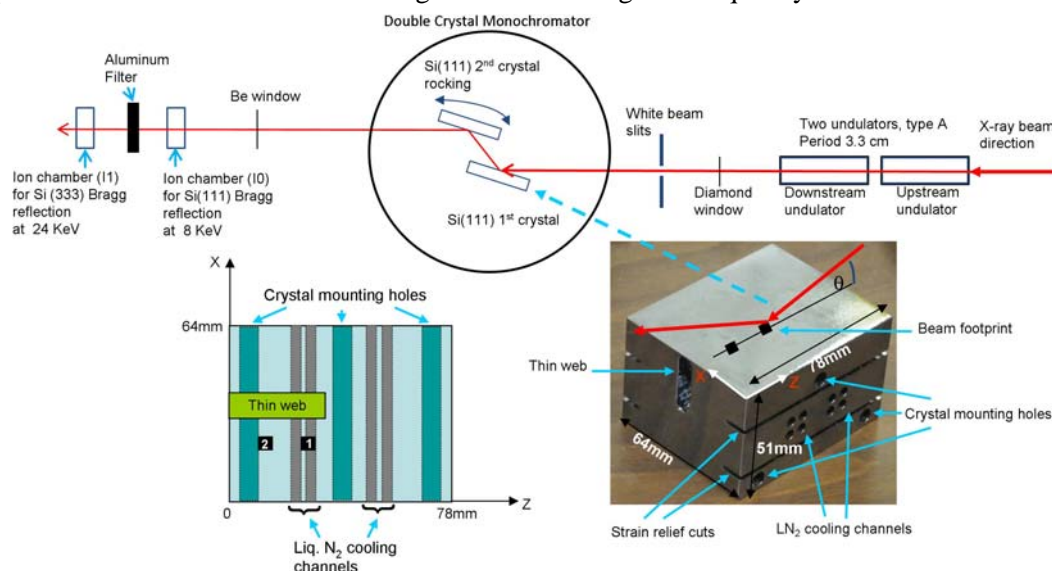

Figure 1: Schematic diagram of the experimental setup at sector 29-ID for HHL studies of the DCM and picture of the first crystal with cooling channels and cross-sectional view of beam footprint on crystal. Beam positions: 1(x,z)=(23,30)mm and 2(x,z)=(23,20)mm.

Measurements were performed with cryogenic silicon crystal as shown in the figure 1. The double silicon crystal monochromator consists of two separated Si crystals with diffraction surface oriented along (111) planes, diffracting vertically to produce a fixed 35 mm beam offset in non-dispersive (+/-) Bragg reflection geometry. The first crystal is internally cooled with liquid nitrogen flowing through

the channels as also shown in the figure 1. The liquid-nitrogen flow rate was 7.1 lit/min and pump pressure was 20 psi. Rocking-curve measurements were performed by rocking the second crystal of the DCM with a piezoelectric actuator. There was also a picomotor that was used to position the center of piezo actuator range. The response of the piezo actuator was non-linear and, consequently, the actual rocking angle needed to be calibrated. The ability to position a rocking curve variously within the range of the piezo actuator by means of the picomotor allowed for precise calibration. The downstream ion chambers I0 and I1 detected the monochromatic beam intensity from the DCM. The monochromator energy was set to 8 keV with a Bragg angle of 14.3°. By using appropriate filters between the ion chambers, I1 detects the higher-energy photons from higher-order reflections Si (333) at 24 keV, as I1 rocking curve is very sensitive to thermal distortions.

3. Results and Discussion

In previous high heat load studies at the APS with Si crystals the cooling channels were oriented so that LN_2 flowed in the direction of the beam with the beam footprint positioned adjacent to, i.e., not directly above the cooling channels [2]. For the crystal that was used for high heat load studies at sector 29-ID APS, the cooling channels were instead oriented for a flow perpendicular to the beam direction. We measured the FWHM of rocking curves with either one or both undulators tuned so that the energy of the 1st harmonic of the undulator matched the Si (111) Bragg energy of the monochromator. We show data taken for the beam footprint lying above the cooling channels and away from the cooling channels in figures 2a and 2b, respectively. Here the estimated uncertainty for the Si (111) FWHM was 0.23 arcsec and for the Si (333) FWHM was 0.03 arcsec. The theoretical FWHM value for Si (111) is 10 arcsec and for Si (333) is 0.60 arcsec. To corroborate that the distortion in the FWHM of the rocking curves is thermal in origin, we performed topography measurements using a rotating anode [3] source with an internally cooled manifold mount in place. Maps of rocking curves [7] FWHM were obtained for the Si (111) reflection with a Si (111) monochromator at 8 keV and the observed difference between FWHM for above and away from cooling channels cases was 0.04 arcsec. We note that the narrowest rocking curves resulted from cooling channels case of figure 2a, and we conclude that the proximity of the beam footprint to the cooling channels is an important parameter for monochromator crystals designed to limit heat load distortion.
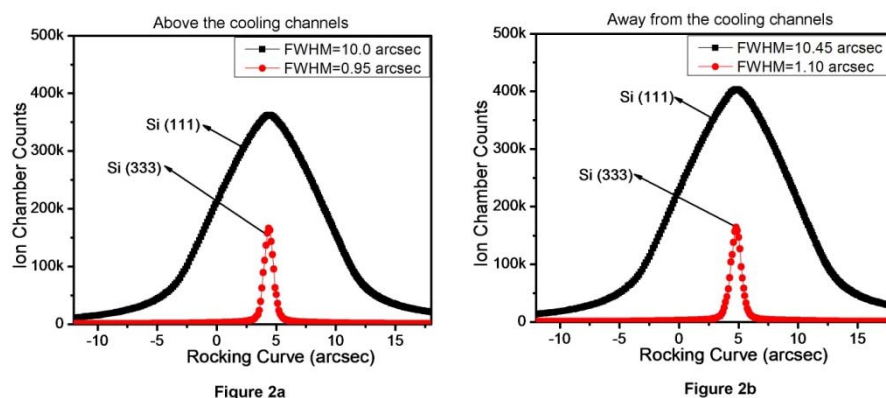

Figure 2: Measurement of rocking curves as a function of the ion chamber counts (counts/sec). Data were taken with two undulators at gap ~18 mm and monochromator energy 8 keV. **2a:** Above the cooling channels of first crystal, **2b:** Away from the cooling channels of first crystal. The ring current was 102 mA. The white-beam slit size was 2 mm (H) x 2 mm (V). The total power load on the crystal was 479 W. Preamp gains for I0 and I1 is 100 nA/V and 2 nA/V. The black square boxes and red circles show the data from I0 and I1, respectively.
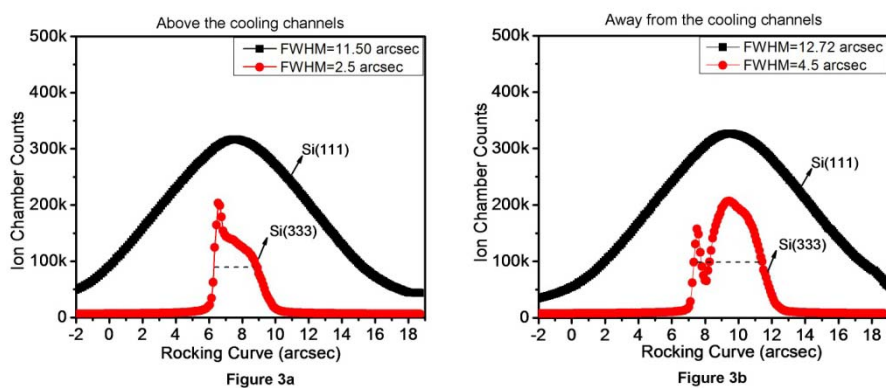
Figure 3: Measurement of rocking curves as a function of the ion chamber counts (counts/sec). Data were taken with two undulators set at gap ~18 mm and monochromator energy 8 keV. **3a:** Above the cooling channels of first crystal, **3b:** Away from the cooling channels of first crystal. The white-beam slit size was 3 mm (H) x 2 mm (V). The total power load on the crystal was 692 W. The dotted line shows the measured FWHM. Preamp gains for I0 and I1 is 200 nA/V and 2 nA/V. The black square boxes and red circles show the data from I0 and I1, respectively.

We performed measurements at various undulator gaps and with various white-beam slit openings ranging from 0.5 mm (H and V) to 3 mm (H) x 2 mm (V) [4]. Here, we are showing the results of 2 mm (H) x 2 mm (V) and 3 mm (H) x 2 mm (V) white-beam slit studies. Figure 2 shows the measured rocking curves results above and away from the cooling channels with a 2×2 mm^2 (H x V) white-beam slit opening. With both undulators set at gap ~18 mm, the total normal power and power density incident on first crystal were 479 W and 30 W/mm^2, respectively. Power calculations were done using the XUS code from the XOP program [5]. Calorimetry was additionally performed; the measured power was 10% less than calculated [6].

The figure 3 shows the FWHM of the rocking curve of Si (111) with 8 keV and Si (333) with 24 keV with a larger slit size of 3 mm (H) x 2 mm (V). Here the distortions and the distortion difference between the two cases are considerably more pronounced. We found that the FWHM of the thermal distortion away from cooling channels was more than the thermal distortion for the case where the footprint lay above the cooling channels.

In conclusion, this paper presents experimental results of rocking curve measurements for the beam footprint located either above or away from the cooling channels with cooling channels for LN$_2$ flowing transverse to the beam direction. We conclude that thermal distortion is less when the beam footprint is closer to the cooling channels.

Acknowledgement

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