

## Liquid nitrogen cooled monochromators for wigglers

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Much attention has been paid to finding solutions for cooling monochromators exposed to the high power density x-ray beams from undulators. Two very promising technologies are liquid-nitrogen-cooled Si and water-cooled diamond crystals because of their increased thermal conductivity and reduced coefficient of thermal expansion as compared to room-temperature silicon. Recent results obtained on a focused wiggler beam at the European Synchrotron Radiation Facility (ESRF) have shown that these two techniques should handle undulator beams from the third generation sources, such as the Advanced Photon Source (APS). A cryogenically cooled, thin diffracting element Si monochromator was tested to an absorbed power of 154 W with an incident peak power density of  $420 \text{ W/mm}^2$ . In these experiments no thermal broadening of the rocking curve at the 1 arc second level was detected [1].

Previously, a thin, water-cooled diamond crystal platelet had also been tested on the same beamline. In the diamond experiment, the incident power density was  $3.5 \text{ kW/mm}^2$ , however, the absorbed power was only about 10 W due to the low absorption coefficient of diamond. Again, no thermal broadening was detectable [2].

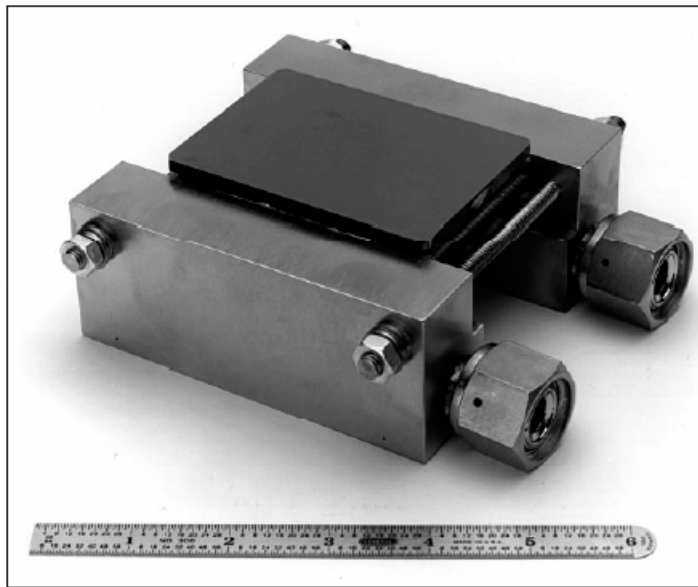
With the cooling of undulator optics reasonably well in hand, we at the APS have been looking at the problem of crystal cooling for wiggler beams. Wigglers are characterized by moderate power densities, but very large total powers compared to undulators. For example, at closed gap operation (2.1 cm) the standard APS wiggler produces 7.4 kW of total power and the peak heat flux is about  $80 \text{ W/mm}^2$  at normal incidence 30 m from the source. For comparison, the central cone of radiation from APS undulator A delivers about 750 W with a peak

power density of  $150 \text{ W/mm}^2$  at closed gap. Following on the success of liquid nitrogen cooled Si monochromators with undulators, we are exploring the use of cryogenic monochromators for wigglers.

Recently, an experiment was performed at the F2 Station at CHESS to evaluate the performance of cryogenically cooled Si monochromators under relatively low power densities (on the order of  $14 \text{ W/mm}^2$ ) but with a total incident power approaching 2 kW. The principal concern in handling high total absorbed power is the ability to remove the power while remaining below the critical heat flux at the crystal-coolant interface. So-called nucleate boiling is very effective, from a heat transfer point of view, for removal of large amounts of heat. However, when the critical heat flux is reached, nucleate boiling transitions to film boiling, where a thin insulating layer of gas is generated between

the optic and the coolant reducing the heat transfer capability of the system, causing a large temperature rise in the optic. Because of this possibility and potential vibrations induced by the boiling coolant, it is generally desirable to maintain the coolant in single phase.

One method of increasing the heat removing capacity of the crystal while maintaining single phase flow is to use enhanced heat transfer channels. Summarized here are the results of testing of such a crystal; in this case, the enhancement was attained by bonding porous Cu mesh inserts in the cooling channels. To our knowledge, this is the first time such tests have been made using high power synchrotron radiation beams.



(Figure 1) Photograph of unenhanced monochromator crystal and coolant manifold.

### The Crystals and the Cryogenic Cooling System

A photograph of the crystal is shown in Fig. 1. Seven 6.4 mm diameter coolant channels, spaced 9.5 mm on-center, were core-drilled along the beam direction into a rectangular block of (111) oriented silicon. The dimensions of the crystal are 86 x 60 x 25 mm<sup>3</sup>. The diffracting surface of the silicon was 12 mm from the top of channels. Two such crystals were fabricated. In one, the coolant channels were left as drilled, and in the second a copper mesh was bonded into the coolant channels using a thermally conductive paste. Indium O-rings were used to make a vacuum-tight seal between the crystal and the liquid nitrogen manifold. The Cu mesh enhances the heat transfer coefficient by increasing the turbulent mixing, and the Cu wires act as pin fins increasing the heat transfer area. Bonding the mesh in the channel increases the conduction of heat from the wall into the coolant. Enhancements of 5-10 have been reported when water is used as the coolant. An enhancement of the heat transfer coefficient of 8-9 was calculated for these crystals using liquid nitrogen as the coolant for the various flow velocities. However, boiling in the meshed crystal should be avoided due to the large pressure drop and vapor blockage.

A closed-loop, liquid nitrogen pumping system was used to cool the monochromator. This system is an integral unit composed of a Barber-Nichols Inc. (Denver, CO, USA) centrifugal pump and a vacuum-jacketed heat exchanger. The pump head is submerged in a pool of pressurized liquid nitrogen. Liquid nitrogen in the closed-loop is pumped into the monochromator vacuum chamber, through the crystal, and is returned to the pumping system. It then passes through a coiled heat exchanger, which is submerged in an open-loop bath of liquid nitrogen at atmospheric pressure. The liquid in the open-loop boils off, removing the heat from the optic-loop, and is vented. The optic-loop nitrogen then returns to the suction side of the pump. The liquid nitrogen level in open-loop of the heat exchanger is maintained automatically using an external storage dewar.

### Monochromator Performance

The cryogenically cooled test optic was housed in a vacuum tank located approximately 26.5 meters from the source. The F2 station takes about half of the horizontal extent of the beam from a 24-pole, permanent-magnet wiggler with a critical energy  $E_c$  of 22 keV. A total of 0.08 inches of Be (four vacuum windows) and 0.010 inches of graphite was between the source and the test optic. Given these parameters, the calculated (vertically integrated) incident power is 21.125 W/mA when the horizontal slits are fully open giving a beam width of about 45 mm at the crystal. Under these conditions, we measured approximately 18.4 W/mA with a Cu calorimeter. All of the experiments described below were made with the vertical slits completely open.

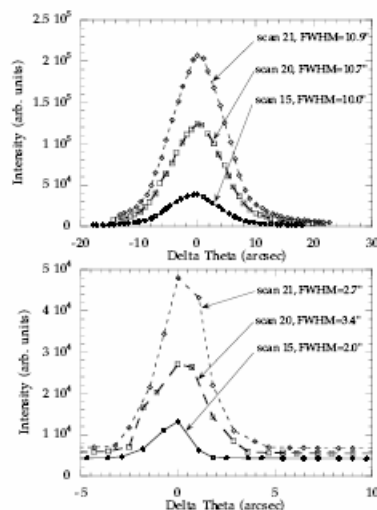
Double-crystal rocking curves were recorded for each cooled crystal by setting them at a Bragg angle of 14.3° to diffract 8 keV x-rays for the Si (111) planes and rotating a second Si(111) analyzer crystal. The power load on the cooled crystal was adjusted by varying the horizontal beam size using a set of slits. The combination of Bragg angle and the thickness of the crystal used in this experiment resulted in more than 80% of the incident power being absorbed in the volume of the crystal between the diffracting surface and the coolant channels.

All data was collected with two ion chambers in the diffracted beam. By placing 0.125 inches of aluminum between the two chambers, rocking curves at 8 keV from the (111) planes and at 24 keV from the (333) planes were collected simultaneously in the first and second detectors, respectively.

Figures 2a and 2b show selected rocking curve scans produced with the unenhanced crystal for Si(111) at 8 keV and Si(333) at 24 keV, respectively. Scan 15 was recorded at a current of 114.5 mA, but with beam width on the crystal of only 4-5 mm, while scan 20 was recorded at 108.7 mA and a beam width of approximately 13 mm. Scan 21 was recorded at 105 mA and a horizontal beamsize of 20-21 mm. Calorimetry taken at the last experimental condition showed an incident power on the crystal of 600 W. The total power does not scale linearly with horizontal beam size since the power distribution for the wiggler is parabolic in the plane of the orbit. The liquid nitrogen flow rates for scans 15, 20, and 21 were 9.4, 10.4, and 10.4 l/min, respectively. The 8 keV rocking curve widths (FWHM) were 10.0, 10.7, and 10.9 arc secs, respectively, which are in close agreement with the self-convoluted Darwin-width of 10.2 arc secs. The third order rocking curves at 24 keV were 2.0, 3.4, and 2.7, respectively. The calculated value is 0.62 arc secs. The difference is due to the residual strains in the crystal from fabrication and/or mounting. Nonetheless, less than 1 arc sec of broadening of the rocking curves was observed up to incident powers of 600 W.

Figures 3a and 3b show a selection of the rocking curves collected with the porous-media-enhanced crystal. Scan 32 was made with a horizontal beam width of about 5 mm and scan 36 with a horizontal beamsize of about 10 mm. The rocking curve widths for 8 keV and 24 keV were 9.8 and 10.0 arc secs, and 2.3 and 2.0 arc secs, respectively. Scans 41 and 44 were taken with the same horizontal beam size of

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(Figure 2) a) (top) Rocking curves of unenhanced crystal for Si(111) at 8 keV and, b) (bottom) Si(333) at 24 keV. Horizontal beam size for the scans: scan 15: 5 mm, scan 20: 13 mm, and scan 21: 20 mm. Scan 21 had a measured incident power of 600 W. The peak intensities are arbitrarily set at a delta theta of zero arc secs.