Performance of a directly water-cooled silicon crystal for
use in high-power synchrotron radiation applications †

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Results of measurements made using the Multipole Wiggler at
Beamline 16 of Photon Factory are reported. Double crystal
rocking curves, Si(111) and Si(333) topographs, and thermal
maps of the cooled crystal surface were measured at total
incident power levels up to 1600 W and power densities up to
0.7 W/mm², for two different crystal designs. Significant
crystal deformation occurred in the form of surface
curvature for both designs. Finite element calculations
provided a preview of the experimental results and proved
very valuable in interpretation of the measurements.

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INTRODUCTION

The performance of crystal monochromators may be degraded by thermal distortion induced through irradiation by synchrotron radiation. To avoid this degradation, a number of different crystal cooling schemes have been developed¹⁻¹¹. The most common method actually used is to mount the crystal on a water-cooled metal base plate, often using some material between the crystal and the base plate to improve the thermal contact. However, such a scheme may not be effective enough for the heat loads produced in high power and insertion device beamlines. One dramatic example of this is reported by Smither et al. in these proceedings¹. The output flux from a double crystal monochromator saturated at only 14% of the typical filling current of the storage ring, i.e. at higher stored currents, thermal distortion of the crystal increased while the output from the monochromator did not increase, but stayed constant. The onset of this saturation was at a power density of only 0.2W/mm^2 , which is quite comparable to that produced at a typical unfocused bending magnet source. This value should be compared with the power densities summarized in Table I for various present and future x-ray insertion devices. These values are for an unfocused and unfiltered primary synchrotron radiation beam, which is incident on the crystal at a 20° Bragg angle. While it is true that some relief can be obtained through the use of filters, such techniques are only effective for wiggler sources. For undulator sources, conventional filters will often attenuate the desired

radiation as well. Therefore, it is important to develop new cooling techniques for perfect crystal diffraction optics.

Here, we examine a new scheme for cooling Si perfect crystal diffraction optics. The remainder of the paper is organized as follows: A basic description of the cooling scheme is presented, followed by an outline of the experimental facilities and methods. Results are then presented, with interpretation, followed by a discussion section, and a conclusion.

BASIC DESCRIPTION OF THE COOLING SCHEME

The cooling technique developed for these tests is described with the aid of Figure 1. The crystal is a thick Si(111) block, with semi-circular channels cut into the backside through which water is circulated. The crystal (Figure 1,A) is mounted to a manifold (Figure 1,F) with retaining clamps (Figure 1,E), while an elastomer "O"-ring (Figure 1,D) provides a seal between the water channels (Figure 1,C) and the main monochromator environment. The synchrotron radiation beam (Figure 1,B) is incident in a direction parallel to the planes of the coolant channels and Si fins in the crystal. Crescent-shaped inserts, not shown in Figure 1, are installed in the channels to eliminate variation in the hydraulic cross section along the channels and to match the hydraulic cross section to the capacity of the cooling system.

The performance of this design depends critically on a number of mechanical dimensions. One is the minimum Si thickness between the diffracting surface and the top of the water channel. As this thickness is reduced, the temperature drop between the diffracting surface and the water channel is reduced, but lateral heat flow between the channel and fins is reduced as well, and the crystal deformation due to the differential pressure between the coolant and the main monochromator environment is increased. The individual widths of the cooling channels and Si fins, and the geometry of the crescent inserts influence the effectiveness and uniformity of the cooling, and should be matched to the parameters of the cooling system. The overall thickness of the crystal, from diffracting surface to the coolant manifold, influences the degree of "bowing" in the crystal. This is the bending which can occur when a temperature gradient exists through the thickness of the crystal. A thicker crystal can better resist bowing for a given temperature gradient.

Two different crystals were used for the tests, and are designated crystal "A" and crystal "B". Some of the dimensions discussed above are summarized for them in Table II.

EXPERIMENT

The tests were performed at Beamline 16 of Photon Factory, between June 23 and July 25, 1988. Electron beams

were stored for operations through July 11, while positron beams were stored thereafter. Storage ring parameters for both forms of operation are summarized in Table III.

Beamline 16 receives synchrotron radiation from the Multipole Wiggler/Undulator¹². A summary of some relevant parameters for this insertion device is given in Table IV. The X-ray branch of Beamline 16¹³ is comprised of 1) an upstream aperture, filters, and windows, 2) a double crystal monochromator, and 3) an experimental hutch. Water-cooled four-jaw slit assemblies are located just upstream of the monochromator and just upstream of the hutch. The fixed horizontal aperture, 56mm wide, at 13.8 m from the source, limits the horizontal fan of radiation to 4.06 mrad. Filtering of the primary synchrotron radiation spectrum is accomplished by 0.78 mm of C (of density 0.93 g/cm³) and two 0.2 mm thick Be windows, all located between 18 and 19 meters from the source. The beamline downstream of the second Be window is evacuated using turbo pumps, and the monochromator typically operated in the low 10⁻⁵ Torr range. The double crystal monochromator, located 25.5 m from the source, was equipped with stepping-motor-driven correction stages for essentially all desired motions. Of relevance here, fine tuning of the second crystal Bragg angle was accomplished by stepping motor, with a resolution of 10 motor steps per arc-second rotation. For all tests reported here, the monochromator was operated using Si (111) crystals at the Ni K absorption edge, 8.333 keV.

An infrared (IR) TV camera, sensitive in the wavelength range from 3.0 μm to 5.4 μm , was mounted on the monochromator and viewed the first crystal through a sapphire window at an angle of approximately 15° to the first crystal surface normal.

A chromel-alumel thermocouple was attached to the upstream edge of the crystal using Ag paste.

In the hutch, 34 m from the source, two air-filled ion chambers were used to detect the output synchrotron radiation beam. The ion chambers were positioned in tandem, with a 150 mm long chamber upstream and a 300 mm long chamber downstream. A 1.5 mm thick Al plate was placed between the two chambers so that the downstream chamber was only sensitive to higher harmonics diffracted by the Si(111) crystal.

Control of all monochromator motions and collection of detector data were coordinated through a personal-computer-based data acquisition and analysis system.

The power incident on the crystals was determined from results of separate calorimeter measurements. The results are summarized in Table V.

Cooling water for the test crystals was supplied by a closed-circuit chiller, with a cooling capacity of 10 kW. The total flow capacity was in excess of 25 l/min. The output water pressure was monitored at the pump output, upstream of a filter. Water temperature could be regulated between 15°C and 30°C with a variation of 0.3°C . The tests were performed with the water temperature regulated at 23°C .

Most of the measurements were made during special operations beam time, in which we could specify the stored current in the ring. For such beam time, we set the wiggler gap to its minimum, 19 mm, (see Table IV), and varied the power on the first crystal by specifying the stored current (see Table V). Up to three different measurements were taken at each specified ring current. The primary measurement was of double-crystal rocking curves. Si(111) rocking curves at 8.333 keV, and higher harmonic rocking curves, could be measured. The first allowed harmonic is Si(333) at 25.0 keV so we presume that Si(333) will be dominant in the signal detected in the second ion chamber. For all of these rocking curve measurements, the output photon beam was trimmed using vertical and horizontal slits upstream of the hutch, so as to just fit through the 10 mm V by 50 mm H opening of the ion chambers (0.3 mrad V by 1.5 mrad H at 34 m from the source). X-ray topographs were the second kind of measurement performed. Si(111) and Si(333) topographs were taken. The final measurement taken at each current was a thermal map of the crystal surface using the IR TV camera.

Before the experiments were undertaken at Photon Factory, finite element analyses were carried out to determine the temperature and deformation fields in the crystal. The purpose of these analyses was not only to correlate the experimental and analytical results, but also to study the crystal behavior in regions where experimental data cannot be obtained. A general purpose finite element

program, ANSYS¹⁴, was used for both the thermal and the stress-deformation analyses. The program has comprehensive 3-D analysis capabilities required for the present application.

The crystal geometry used in the finite element model was essentially the same as that of crystal "A" except that the minimum Si thickness at the top of the channels was 0.5 mm. This thickness was under consideration for a new crystal at the time the analysis was carried out. The 5 mm wide channels were envisioned to have inserts which would reduce the effective channel area to 34 mm² and the hydraulic diameter to 3 mm. Based on a water flow of 8 l/min, one can readily calculate¹⁵ the relevant flow parameters: Reynolds number $Re = 960$ (i.e., laminar flow), Nusselt number $Nu = 13$, and the film coefficient for the convective heat transfer $h_f = 0.27$ watts/cm² °C.

In order to model the crystal with sufficient detail, three elements along the channel width and two elements along the fin width were used. Taking advantage of the two-fold symmetry, only a quarter of the crystal was modeled using 2940 elements and 4378 nodes. A beam power of 1.5 kw was applied on the top surface nodes using a Gaussian distribution along the beam direction. A normal pressure of 330 kPa was applied at the nodes on the interior surface of the crystal. Nodes on the outside perimeter and up to a height of 10 mm were restrained to represent the boundary conditions of the side clamps (see Figure 1, E). Material properties of silicon used in the model were: thermal

conductivity, $k = 168$ watts/m °C, elastic modulus, $E = 158$ GPa, and coefficient of thermal expansion $\alpha = 2.5 \times 10^{-6}$ °C⁻¹. The results are discussed within the following section.

RESULTS AND INTERPRETATION

Figures 2, 3, and 4 present the rocking curves taken during the special operations time. In Figure 2, note the asymmetry of the curves at higher stored current, and that the curve width always exceeds the theoretical value. Also, note the systematic shift of the peak position with stored current. The same basic features appear in Figures 3 and 4 for crystal "B". Note, however, that the peak asymmetry is not as great in Figure 3 for crystal "B" as in Figure 2 for crystal "A". In Figure 4, note that the widths of the Si(333) curves far exceed that of the theory.

The rocking curve peak heights are plotted in Figure 5 as a function of the stored ring current, however, the peak heights have been divided by the stored current itself and normalized to 1.0 for 1.0 mA stored current. Consider that if the cooled crystal performed ideally, such a plot would be a straight line of value 1.0 for all stored currents. The deviation from such a line indicates a loss in output flux due to the crystal deformation.

We begin interpretation of the data with Figure 6, which presents a collection and correlation of several types of data, both for crystal "A" and crystal "B". The uppermost panels (a and e) represent cross sections through

the centers of the crystals, essentially perpendicular to the incident beam direction. The panels below these, (b and f), are portions from the thermal map displays. They include the two dimensional (2D) thermal image of the crystal surface, and thermal cross sections through the 2D image along the two crossed center lines. The periodicity of the fins and channels can be seen in the thermal maps, though perhaps with some difficulty in the reproduced figure for crystal "B". In both cases, the channel is hotter, by as much as 25°C for crystal "A", but only by about 1°C for crystal "B".

These results are predicted by the finite element calculation, which models a variant of crystal "A". The observed temperature difference is in good agreement with the calculated results.

The origin of the temperature difference between fin and channel in the test crystals is the poor convection heat transfer coefficient between the Si and the water, relative to the thermal conductivity of Si. Under such conditions, the overall temperature drop occurs almost entirely in the boundary layer between the water and the Si, not through conduction in the Si. As a result, while the fin is able to make effective use of a relatively large cooled surface area, by virtue of the Si thermal conductivity, the cooled area available to the thin section of the channel is quite restricted. If the convection heat transfer coefficient could be increased enough, however, the situation would reverse, and the channels would be cooler than the fins.

The overall temperature drop would then occur primarily in the Si by conduction, and the thin section of the channel forms only a small thermal conduction resistance to the fluid interface, whereas the average distance between the fin and the fluid interface is larger, and forms a greater thermal resistance.

The Si(111) topographs in Figure 6 appear as panels c and g. For crystal "A", a "ball"-and-"stick" pattern appears, while for crystal "B" an essentially structure-less image results, as would be expected in the ideal case. We determined, using the IR TV camera, the upstream four-jaw slits, and a phosphor screen in the hutch, that the fins produce the "balls" in the topograph for crystal "A" while the channels are responsible for the "stick" portions of the image. This is reflected in Figure 6 by the alignment of the topographs with the thermal map and crystal cross section, panels b and a.

The "ball" portion of the topograph is produced by a portion of the output x-ray beam with a relatively large vertical extent, while the beam which produces the "stick" is smaller in vertical extent. This difference is due to a difference in the radius of curvature of the cooled crystal surface over the fins relative to the channels.

The finite element calculations predict that such radii of curvature will accompany the temperature differences already mentioned. The sign of the difference predicted between the radius of curvature of the fin and the channel is correct to produce the observed effect. Figure 7 shows

the predicted deformations for the variant of crystal "A" along the central fin and along its nearest channel, while Figure 8 shows the deformations across the fins and channels along the vertical center of the incident beam (the parameters used are quoted in the figure caption). The upper curves in both figures are the deformations due to the incident synchrotron radiation beam, i.e. "thermal deformations"; the lower curves are pressure deformations, (due to coolant pressure and atmospheric pressure). It is apparent from the figures that the surface of the crystal has become convex, and, specifically from Figure 7, that at the center of the crystal (X-coordinate = 0) the radius of curvature along the fin (dotted line) is larger than that along the channel (solid line). The larger radius of curvature along the fin implies that the output beam from the fin will be larger in vertical extent, which it is.

The Si(333) topographs (Figure 6 d and h) yield an experimental measurement of the surface radius of curvature. The image presented in panel d confirms the finite element predictions. Experimentally, when the output beam from the monochromator was filtered in the hutch with a 1.5 mm Al plate, and this beam then used to expose a piece of photographic film, a thin horizontal line generally resulted. If the second crystal in the monochromator were stepped through an array of uniformly-spaced angular positions and a multiple-exposure film produced, a family of horizontal lines resulted. The vertical displacement of

adjacent lines (Δy) can be related to the radius of curvature of the first crystal (R) by

$$R = \frac{\Delta y}{\Delta \theta_2 \sin \theta_B} , \quad (1)$$

where $\Delta \theta_2$ is the angular step taken by the second crystal and θ_B is the Bragg angle. Qualitatively, the radius of curvature can be discerned from the spacings of the lines on the Si(333) topographs, as long as the topographs are taken with a constant angular step, $\Delta \theta_2$. If the lines are closer together, the radius of curvature is smaller. Note how the line spacing in Figure 6 panel d is clearly larger in the "ball" region, which confirms that the radius of curvature is larger over the fin.

Now let us specifically consider crystal "B". By reducing the widths of the channels and the fins (see also Table II), we hoped to improve the cooling efficiency. This in fact occurred, since when both crystal "A" and crystal "B" were operated under very comparable situations (stored current = 200 mA, water flow rate = 23 l/min), the peak temperature on crystal "A" was 42°C while that of crystal "B" was 34°C. The temperature difference between channels and fins was also reduced, as already indicated above.

However, the crystal surface is still curved, as can be seen from Figure 6, panel h, although the radius of

curvature appears more uniform across the crystal surface. This radius of curvature was calculated using results from 7 Si(333) topographs and equation (1) above. The results are presented as Figure 9. The radius of curvature decreases as the square root of the stored current. We have no explanation for this square root dependence at present.

The crystal radius of curvature results can explain the change in rocking curve width with stored current. A summary of rocking curve width data, taken from the curves presented as Figures 2, 3, and 4 is presented as Figure 10. Note that in the ideal case, the Si(111) curves should have a full-width-at-half-maximum (fwhm) of about 10 arc-seconds, while that for Si(333) should be less than one arc-second. Note also that the two curves for crystal "B" are essentially parallel; the Si(111) and Si(333) rocking curve widths have the same sort of dependence on stored current. The curve for crystal "A", however, is not the same. The basic trend is the same, but as a fingerprint, it is clearly different from crystal "B". The curve labeled "simple model" is calculated as follows: Consider the second crystal in the monochromator as an angle selector. The first crystal is curved (average radius R), so the second crystal should find diffracted x-rays it can pass to the output over a range of angles roughly equal to the range of angles which the incident beam size (W) subtends on the crystal surface, i.e.

$$\text{Rocking Curve fwhm} \approx \frac{W}{R} = \frac{d}{\gamma \sin \theta_B} \cdot \frac{1}{R}$$

where "W" is the length illuminated on the cooled crystal along the beam direction and "d" is the source-to-crystal separation (25.5 m), " γ " is the particle energy divided by the particle rest-mass energy (4892), and " θ_B " is the Bragg angle (13.7°). The "simple model" curve was obtained by plotting W/R, where R is the average R taken from the Si(333) topograph data (not the minimum R from Figure 9).

In a qualitative way, the decreasing radius of curvature with stored current explains the Si(111) rocking curve peak heights presented in Figure 5. As the radius of curvature of the cooled crystal decreases with increasing incident power, the diffracted x-ray beam covers an ever increasing range of angles and wavelengths. The second crystal always selects a fixed wavelength bandpass and angle bandpass, so the output peak flux decreases as the second crystal bandpass selects a fixed width of an ever decreasing flux density.

DISCUSSION

It is clear from our experience with crystal "A" and crystal "B" that for a given cooling system, i.e. available pumping power and cooling capacity, an optimum overall geometry (see Table II) probably exists. Crystal "B" is closer to the optimum than crystal "A", in terms of the fin

and channel dimensions; but due to its decreased overall thickness (~20 mm vs. 30 mm), bowing is likely to be a greater problem. (Of the deformation illustrated in Figure 7, 60% is due to bowing.) Gaining the ability to calculate the optimum geometry for a given cooling system would be a significant accomplishment.

On a more general level, the cooling scheme investigated here is influenced by two measurable quantities; pressure and temperature. The differential pressure between the monochromator environment and the coolant in the crystal results in the kind of distortion presented in Figures 7 and 8. Although pressure deformations were not specifically investigated for crystal "A", in crystal "B" at 1 mA of stored current and maximum differential pressure (~23 l/min water flow and a total differential pressure of 340 kPa), the measured radius of curvature was 550 m, while with the minimum differential pressure (water flow off, differential pressure of 100 kPa), the radius was still 1200 m. Increasing the overall crystal thickness, which also increases the difficulty of fabricating the channels, should reduce this effect.

Temperature is influential in several ways. Temperature gradients are the primary problem. If the gradients are large enough, the stresses built up through local dilation of the material can directly affect the dynamical diffraction of x-rays. At a lower level, they produce bending and bowing. If the stresses are even lower, such that bending is unimportant, the variation of

temperature in the crystal can still give rise to a curved crystal surface, purely through dilation, i.e. the product of the local temperature and the thermal expansion coefficient.

The reduction of thermal gradients, therefore, can be beneficial. The approach most often taken is simply to reduce the gradient as much as possible by supplying the most effective uniform cooling possible. Along these lines, the use of liquid Ga cooling with the present geometry may be effective. The convection heat transfer coefficient for laminar flow of liquid Ga is over 40 times that of water, but when an optimized cooling geometry is employed for each fluid, the difference is really only a factor of two.¹⁶

The elimination of thermal gradients may be a more effective approach to crystal cooling. One scheme would be to match the application of cooling to the incident power profile, with the aim of creating a uniform, though perhaps elevated, surface temperature. The present design, with cooling channels which closely approach the diffracting surface only near the vertical center of the incident synchrotron radiation beam, is one step in that direction. However, the temperature profiles measured with the IR TV camera show no dramatic equalization effect. This is related to our small convective heat transfer coefficient; the temperature drop across the Si is small relative to that at the boundary layer, so the surface temperature simply reflects the local power density. If the heat transfer coefficient were raised to a point where the conduction drop

in the Si became dominant, the temperature equalization effect should appear. A second scheme would be to add external heat to equalize the input power density over the surface.

A different general attack on the problem is that proposed by Bilderback⁷. Thermal gradients are of no consequence if the thermal expansion coefficient can be reduced to zero. This is not as outlandish as it might seem, because for Si, a zero-crossing for the thermal expansion coefficient occurs at about 125 K, which is above the boiling point of liquid nitrogen. Nevertheless, an economical cryogenic system capable of removing kilowatts of heat at such temperatures is yet another question.

CONCLUSION

We have presented a description, together with performance data, for a directly-cooled Si crystal geometry intended for high-power synchrotron radiation applications. In its present form, objectionable deformation of the crystal occurs well before the maximum available power loading is applied. A surface radius of curvature, resulting from thermal gradients and from the differential pressure between the coolant and the monochromator environment, appears responsible for several major features of the experimental data. An optimized geometry, or the use of other coolants, may still offer some improvement.

Finite element calculations, performed together with the experimental work, have proved very valuable, both as a preview of what the experiments might show, and as a resource in the examination of questions beyond the reach of experiment. Such calculations are now clearly capable of evaluating major characteristics of a crystal-cooling scheme, such as that investigated here, in place of experiment.

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Figure Captions

- Fig. 1 Schematic drawing of the crystal cooling scheme. A, machined Si block; B, incident synchrotron radiation beam; C, water passages; D, "O"-ring seal groove; E, crystal clamp block; F, coolant manifold.
- Fig. 2 Si(111) rocking curves from crystal "A".
Water pressure = 350 kPa.
- Fig. 3 Si(111) rocking curves from crystal "B".
Water pressure = 240 kPa.
- Fig. 4 Si(333) rocking curves from crystal "B".
Water pressure = 240 kPa.
- Fig. 5 Normalized rocking curve peak height/stored current vs stored current. For an undeformed crystal, the ordinate would be 1.0 for all stored currents. The deviation seen above about 10 mA is a loss of output flux due to significant crystal deformation.
- Fig. 6 A collection and correlation of data for crystal "A" and crystal "B". The upper panels (a and e) represent cross sections through the crystals.

Panels b and f present a portion of the thermal map displays; the two dimensional thermal image of the crystal surface and thermal cross sections along the two crossed center lines. Panels c and g are Si(111) topographs while panels d and h are Si(333) topographs. The black lines which extend from panel to panel indicate the fin and channel dimensions in the magnification appropriate for each panel. Note the appearance of the fin and channel periodicity in both thermal maps. The channels are hotter in both cases. For crystal "A", the periodicity also appears in the Si(111) topograph, as a "ball" and "stick" pattern. The "balls" are associated with the fins in the crystal. The pattern is due to a periodic change in the surface radius of curvature, as seen in the Si(333) topograph (d). For crystal "A", i ring = 298 ma, water flow rate = 10 l/min, water pressure = 350 kPa, and each of the four divisions in the thermal cross sections represents 18.3°C. For crystal "B", i ring = 296 mA, water flow = 24 l/min, water pressure = 230 kPa, 7°C per division in the thermal cross sections.

Fig. 7 Calculated deformations of the diffracting surface, parallel to the centermost fins and channels, for a variant of crystal "A". Upper curves are thermal deformations; lower curves are pressure deformations. Incident power = 1.5 kW, water flow rate = 8 l/min, total differential pressure = 330 kPa. The crystal dimensions used are the same as those for crystal "A" in Table II, except the minimum Si thickness is 0.5 mm.

Fig. 8 Calculated deformations of the diffracting surface across the fins and channels, along the vertical center of the incident synchrotron radiation beam, for a variant of crystal "A". Parameters are the same as in Figure 7.

Fig. 9 Variation of the radius of curvature of crystal "B" as a function of the stored ring current. We have no explanation at present for the square-root-of-stored-current dependence.

Fig. 10 Variation of the rocking curve width with stored ring current. The "simple model" curve is a plot of the angle subtended by the illuminated distance along the fins and channels on the curved crystal surface.

Table I. Surface power densities generated by present and future insertion device

DEVICE	λ_0 (cm)	$K_{\max}$	N	E (GeV)	I_{ring} (mA)	d (m)	P_{dave}^a (W/mm ²)
PF Multipole Wiggler	12.0	16.8	26	2.5	350	25.5	3.6
NSLS Hybrid Wiggler	12.0	12.3	15	2.5	250	16.0	2.8
CHESS Wiggler	34.0	49.5	3	5.4	70	14.5	5.9
SSRL 54 Pole Wiggler	7.0	10.7	27	3.0	100	22.8	3.1
PEP Undulator	7.7	1.59	26	15.0	30	56.0	12.3
ESRF Undulator	5.0	2.10	40	6.0	100	30.0	11.5
APS Undulator "A"	3.3	2.37	156	7.0	100	30.0	142

^a Incident Bragg angle of 20° is assumed

Table II. Dimensions of crystals tested

		Crystal "A"	Crystal "B"
Minimum Si thickness	(mm)	1.0	1.5
Fin width	(mm)	2.5	1.3
Channel width	(mm)	5.0	0.8
Diameter of channel saw	(mm)	101.6	100.0
Number of channels		14	30
Overall crystal thickness	(mm)	30.0	21.7

Table III. Photon Factory operating parameters

Stored Particles	electrons	positrons
Particle Energy (GeV)	2.5	2.5
Maximum Stored Current (mA)	300	250
Lifetime at Maximum Current (hr)	>24	>24

Table IV. Beamline 16 Multipole Wiggler/Undulator parameters

Period (cm)	12.0
Number of Periods	26
Minimum Gap (mm)	19
Peak Magnetic Field ^a (Tesla)	1.47
Critical Energy ^a (keV)	6.11
Full Horizontal Opening Angle ^a (mrad)	6.7
Maximum Radiated Power ^b (kW)	8.01

^a At minimum gap.

^b At minimum gap, and a stored current of 300 mA.

Table V. Incident power on the test crystals

Wiggler gap (mm)	19.0
Critical energy (keV)	6.11
Incremental incident power (W/mA)	5.3
Maximum incident power ^a (W)	1600
Incremental Power Density (mW/mm ² mA)	2.3
Maximum Power Density ^a (W/mm ²)	0.70

^a for a stored current of 300 mA

Fig. 1. T. Overlaid and (V-4)

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Fig. 2. T. Overduin et al (V-4)

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Fig. 3 T. Oversluizen et al (V-4)

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Fig. 4 T. Overschueren et al (V-4)

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CRYSTAL "A"

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CRYSTAL "B"

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DEFORMATIONS - CRYSTAL A

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Fig 8

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Fig. 9 T. Oversluizen et al. (V-4)

A line graph showing the relationship between rocking curve width (fwhm in arc-seconds) on the y-axis and stored current (mA) on the x-axis. The y-axis ranges from 0 to 25 with major ticks every 5 units. The x-axis is logarithmic, ranging from 1 to 300 with major ticks at 1, 2, 5, 10, 20, 50, 100, 200, and 300. Five data series are plotted:

- design "a" (111)**: Represented by squares. It starts at approximately 17.5 arc-seconds for 4 mA and increases to about 23.5 arc-seconds at 200 mA.
- design "b" (111)**: Represented by solid circles. It starts at approximately 11.5 arc-seconds for 1 mA and increases to about 24.5 arc-seconds at 200 mA.
- design "b" (333)**: Represented by solid triangles. It starts at approximately 8 arc-seconds for 1 mA and increases to about 19.5 arc-seconds at 200 mA.
- simple model**: Represented by 'x' marks. It starts at approximately 6.5 arc-seconds for 1 mA and increases to about 15.5 arc-seconds at 200 mA.
- design "b" (333)**: Represented by open triangles. It starts at approximately 8 arc-seconds for 1 mA and increases to about 15.5 arc-seconds at 200 mA.

All curves show an upward trend, indicating that the rocking curve width increases with stored current. The curves for design "b" (111) and design "b" (333) are very close to each other, as are the curves for design "b" (333) and the simple model.

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