ANL/MSD/CP-93788
CONF-970706--

High Heat Load Crystal Cooling Strategies for an APS Wiggler Beamline

Mark A. Beno, G. S. Knapp, M. Engbretson, G. Jennings, C. A. Kurtz, P. A. Montano, and C. L. Wiley

Materials Science Division and Basic Energy Sciences Synchrotron Radiation Center
Argonne National Laboratory, 9700 S. Cass Avenue, Argonne, IL 60439, USA

Materials Science Division
Argonne National Laboratory
Argonne, IL 60439

July 1997

/jc

Distribution:

1-2. M. J. Masek
3. B. D. Dunlap
4. P. A. Montano
5. F. Y. Fradin
6. R. Gottschall
7. Editorial Office
8. Authors

Submitted as a paper to be presented and to be published in the Proceedings of SPIE's Optical Science, Engineering and Instrumentation '97 meeting, July 27-Aug. 1, 1997 in San Diego, CA

This work is supported by the Division of Materials Sciences, Office of Basic Energy Sciences of DOE, under contract No. W-31-109-ENG-38.

DISCLAIMER

DISCLAIMER

High Heat Load Crystal Cooling Strategies for an APS Wiggler Beamline

M. A. Beno, G. S. Knapp, M. Engbretson, G. Jennings, C. A. Kurtz, P. A. Montano, and C. L. Wiley

Materials Science Division and
Basic Energy Sciences Synchrotron Radiation Center
Argonne National Laboratory, 9700 S. Cass Ave
Argonne, IL 60439, USA

ABSTRACT

High energy wigglers produce extremely high total powers. For example, the insertion device for one beamline of the Basic Energy Sciences Synchrotron Research Center (BESSRC) is an elliptical multipole wiggler (EMPW) which can generate circularly polarized X-rays on axis and produces a total power of ~8 kW. This insertion device will be used to simultaneously provide x-rays to three branch lines, a branch equipped with a normal double crystal monochromator feeding a scattering and spectroscopy station, and two branches with single-bounce horizontally deflecting monochromators for Compton scattering and High Energy Diffraction. The crystal optics for this type of device require substantially different heat load solutions than those used for undulator beamlines. We will discuss how the beam is split and shared among the beamline branch lines and present the crystal cooling strategies employed for both the double crystal monochromator and horizontally deflecting single-bounce monochromators.

Keywords: Synchrotron Radiation, High Heat Load Crystal Optics, Wiggler Radiation

1. INTRODUCTION

Wiggler sources at third generation synchrotrons are capable of providing very large photon fluxes (see Fig. 1), but also produce extremely high incident powers and moderately high power densities. The APS Wiggler A[1], a 56 pole permanent magnet device, 2.4 M in length with a maximum critical energy of 32.6 keV, produces a total power density of 7.4 kW and a peak power density of 81 W/mm^2 at 30m. Compare this to the APS Undulator A which generates a peak power of 3.8 kW producing a power density of ~150 W/mm^2 at 30m. From this comparison it is clear that the first crystal of a double crystal monochromator in a wiggler beamline must be capable of handling higher total powers and comparable power densities to those in an undulator beamline. At the same time the heat management solutions which have been developed for undulators are not generally applicable to wiggler beamlines because of the differences in beam geometry. The Basic Energy Sciences Synchrotron Radiation Center Collaborative Access Team (BESSRC CAT) has one beamline equipped with a special insertion device, an elliptical multipole wiggler[2] (EMPW) which can produce circularly polarized X-rays on axis and has a maximum critical energy of 32.6 keV with a total power of ~8 kW. This device produces a beam with a horizontal divergence of ~ 2 mrad and a vertical divergence of $1/\gamma$ (0.073 mrad at the APS), the APS Wiggler A has a horizontal divergence of ~ 1 mrad. These values give beam dimensions at 30 m of 60 mm x 2 mm for the EMPW and 30 mm x 2 mm for Wiggler A as compared to a beam size of ~1.2 mm x 2.4 mm for Undulator A. The heat management solution of choice for undulator beamlines, thin cryogenically cooled crystals[3], relies on the small dimensions of the undulator beam so that modifications of the cryogenic cooling concept are necessary for wiggler monochromators.

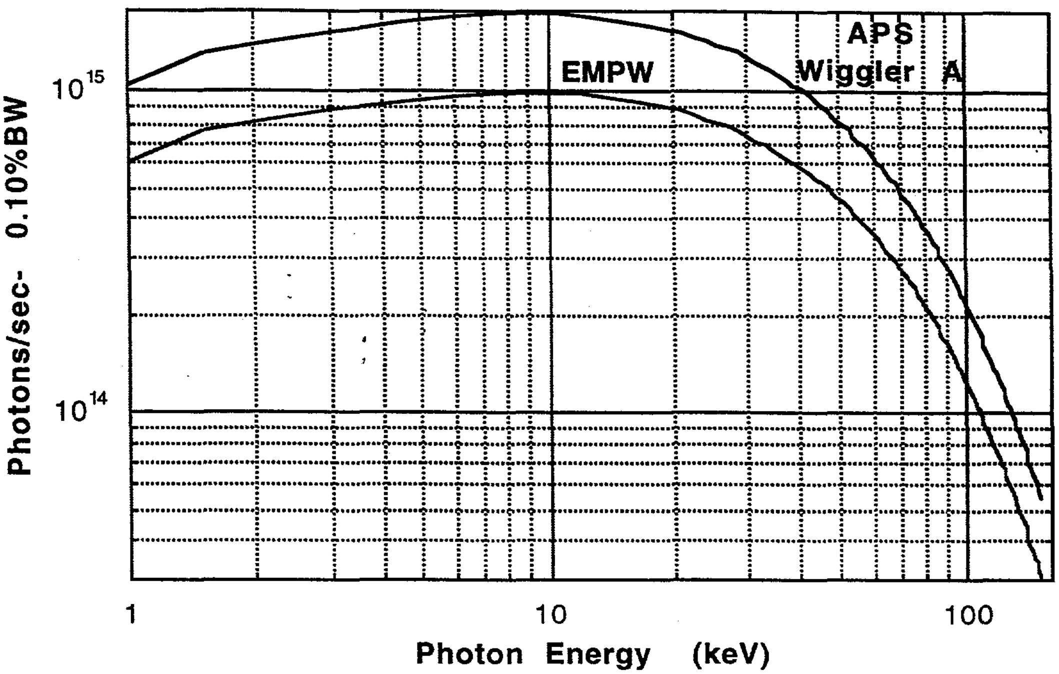


Figure 1. The Spectral Flux from an APS Wiggler A and the BESSRC CAT Elliptical Multipole Wiggler.

Table 1 Parameters for the 11ID Elliptical Multipole Wiggler

Parameter		Value
Period	λ	0.156 m
Number of Periods	N	16
Length	L	2.8 m
Gap	g_y	2.4 cm
On-Axis B-Field	B_y	1 T
	B_x	0.0 - 0.1 T
Critical Energy (max)	E_c	32.6 keV
Deflection Parameter (max)	K_y	14.3
	K_x	1.3
Maximum Angle Deflection	δ_x	1.022 mrad
	δ_y	73 μrad
Total Power	P	7.8 kW
Peak Power Density	dP/dW	41.5 kW/mrad^2
First Optic Distance	Z1	30 m
Beam Width at Z1	DX	60 mm
Power Density at Z1	dP/dA	54 W/mm^2
Beam Height at Z1 (Kx = 0)	DY	2.2 mm (1/γ)
Beam Height at Z1 (Kx = 1.0)	DY2	8 mm

The BESSRC EMPW beamline splits the wiggler beam to provide X-rays to three experimental stations simultaneously. One station is fed by a conventional double crystal fixed offset monochromator[3] where the first crystal is cryogenically cooled. The other two stations receive X-rays from horizontally deflecting single bounce monochromators which are cooled by liquid gallium. In this article we will explain the method by which the wiggler beam is split among these branch lines, and detail the crystal cooling strategy employed for each station.

2. BEAM SPLITTING

The design parameters for the EMPW are given in Table 1[2]. The EMPW produces circularly polarized X-rays on axis. This is accomplished in this insertion device by the use of a permanent magnet structure which can produce a maximum vertical field with $K_y = 14.7$ and electromagnets to provide a horizontal field with K_x max = 1.3. The direction of the circular polarization is then reversed by changing the direction of current flow in the electromagnet, flipping the horizontal field. The last two lines in the table are of particular note. For a normal dipole synchrotron source the X-ray beam in the plane of the ring is linearly polarized while above and below the orbit plane circularly polarized photons are produced. When the horizontal field is applied to the EMPW the beam splits so that linear polarization occurs above and below the orbit plane and circular polarization is observed on-axis. Figures 2a and 2b show calculated[5] vertical and horizontal beam divergences for the parallel and perpendicular components of the beam which result for $K_y = 14$ and $K_x = 1$.

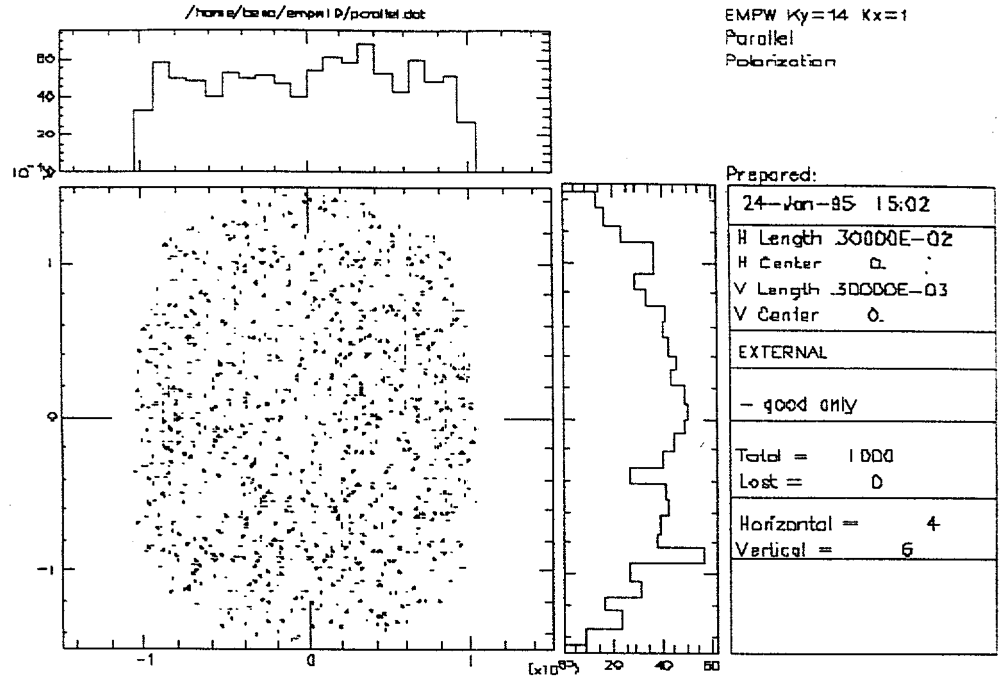
As can be seen from the figures, circular polarization is produced on axis while linearly polarized x-rays are produced above and below the plane of the insertion device. The resultant total vertical beamsize is approximately three times larger thanthat produced without the horizontal field. This large vertical beam allows us to split the EMPW beam in a manner not possible for other wiggler sources.

Figure 3 (a) and (b) show two possible modes of operation for the EMPW beamlines which allow sharing of the beam, the first of these is unique to the EMPW beamline while the latter method can be employed at any high critical energy wiggler. As is shown in figure 2, when a horizontal field is applied to the insertion device the beam expands vertically. In the operating mode shown in fig. 3a, the first monochromator intercepts the linearly polarized beam below the axis, the second monochromator diffracts the on-axis circular polarization and the third monochromator sees only the linear polarization above axis. When circular polarization is required in all the enclosures, or when no horizontal field is applied as is the case for a conventional wiggler, the mode of operation shown in fig. 3b can be used.

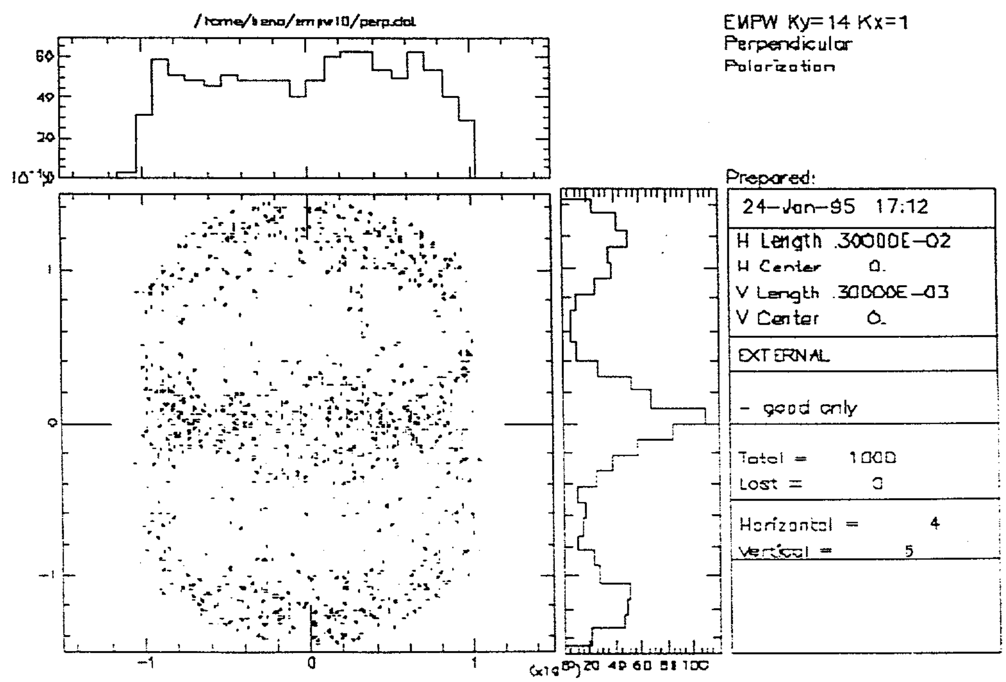
The double crystal monochromator being installed in the EMPW beamline is a Bragg-Bragg, fixed exit, mechanical linkage monochromator design[3] which is capable of scanning operation. This monochromator will use a "thick" cryogenically cooled first crystal. The center of rotation of the crystal is placed at the downstream end of the first crystal. As is illustrated in figure 4, this placement of the center of rotation minimizes the absorption of the first crystal and allows transmission of the high energy beam to subsequent stations (as in mode b of figure 3). This feature is added to the standard monochromator design to keep the path length of the transmitted beams through the first crystal to a minimum. Figure 4 shows the path of the incident beam through the monochromator crystal for 3 different energies.

3. HEAT LOAD CALCULATIONS

Because of the high total power and power density, liquid nitrogen cooling is needed for the first crystal of the standard double crystal monochromator on the EMPW beamline. The two remaining monochromators in the EMPW beamline are horizontally deflecting at relatively low angles (7.5° and 3.8°) so that liquid Ga cooling should be sufficient for the high total power but low power densities on these optics. Table 2 gives the absorbed powers for the optical elements in the beamline. These values were calculated with the PHOTON2 code[6] assuming 500 μm Beryllium and 500 μm Carbon windows upstream of the monochromators (the APS commissioning windows) and for a beam which is 1 mrad. horizontal and $1/\gamma$ (73 μrad) vertical. The two horizontally deflecting monochromators were assumed to be 1 mm thick symmetric Si crystals. The power transmitted through the Be and Carbon windows remaining after slits with a vertical acceptance of 73 μrad is ~2000 W/mrad.



(a)



(b)

Figure 2 Source divergence for EMPW, (a) parallel, (b) perpendicular polarization with $K_y = 14$ and $K_x = 1$.

Table 2 Absorbed Power for EMPW Optics.

Energy 1st Crystal	Crystal	Maximum Path length (mm)	Average Path length (mm)	Absorbed Power (W/100ma)	Power Density ($W/mm^2/100ma$) at 30 m
Mode B (see Fig 3)					
4keV	1st Crystal	4.20	2.01	730	8.9
	Compton Crystal	15.3		739	0.74
	High Energy Crystal	30.2		204	0.10
10 keV	1st Crystal	6.54	3.06	860	4.2
	Compton Crystal	15.3		616	0.61
	High Energy Crystal	30.2		189	0.10
20 keV	1st Crystal	12.55	5.50	1070	2.6
	Compton Crystal	15.3		437	0.44
	High Energy Crystal	30.2		158	0.08
30 keV	1st Crystal	18.69	7.67	1190	1.9
	Compton Crystal	15.3		340	0.34
	High Energy Crystal	30.2		136	0.07
40 keV	1st Crystal	24.86	9.54	1270	1.6
	Compton Crystal	15.3		279	0.28
	High Energy Crystal	30.2		120	0.06
Mode A (see Fig 3)					
4keV	1st Crystal	4.20	2.01	365	4.5
	Compton Crystal	15.3		325	0.32
	High Energy Crystal	30.2		839 Laue 267	0.42 Laue 4.1
10 keV	1st Crystal	6.54	3.06	430	2.1
	Compton Crystal	15.3		325	0.32
	High Energy Crystal	30.2		839 Laue 267	0.42 Laue 4.1
20 keV	1st Crystal	12.55	5.50	535	1.3
	Compton Crystal	15.3		325	0.32
	High Energy Crystal	30.2		839, Laue 267	0.42 Laue 4.1
30 keV	1st Crystal	18.69	7.67	595	1.0
	Compton Crystal	15.3		325	0.32
	High Energy Crystal	30.2		839, Laue 267	0.42 Laue 4.1
40 keV	1st Crystal	24.86	9.54	635	0.8
	Compton Crystal	15.3		325	0.32
	High Energy Crystal	30.2		839 Laue 267	0.42 Laue 4.1

MODE (B) OPERATION

First let us consider the scheme for dividing the wiggler beam depicted in Fig. 3(b), that is, when the wiggler beam successively passes through each of the monochromator crystals. In this case the first crystal of the double crystal monochromator acts as a filter for the subsequent optical elements. As would be expected the maximum absorption occurs at the lowest angle. When the monochromator is tuned for 40 keV operation the heat absorbed by the first crystal is ~1.3 kW with Si 220 crystals. The power density at the first crystal of the double crystal monochromator at this energy is ~ 1.6 W/mm^2.

For a total surface area of the liquid N_2 channels A = 60 cm^2 and Q/A =1.6 W/mm^2, T_E = 88 K and Ts = 105 K for l ~10 mm. These calculations show that the power and power density for high energy (40 keV) operation of the double crystal monochromator are easily handled by a crystal similar in design to that used in the BESSRC undulator beamlines[3]. The other limiting case, i.e. low energy operation of the double crystal monochromator concentrates all the absorbed power in one corner of the crystal. In this case we can assume a cylindrical approximation so that heat absorbed in the corner of the crystal spreads out in π/2. For this geometry, the equation for the peak temperature becomes:

(4) $$T_S = T_K + (T_E - T_K)\exp\left(\frac{2Q}{\pi\Gamma L}\ln\left(\frac{R_2}{R_1}\right)\right)$$

In this equation L is the width of the beam, approximately 40 mm, and the ratio of the distance to the N_2 channels to the part of the crystal illuminated by the incident beam, R2/R1, is approximately 15. With the first crystal at the angle for 4 keV operation, the crystal absorbs ~ 700 W and has a power density of ~9 W/mm^2. In this case the above equation gives a surface temperature of ~130 K well below the 170 K value where distortions of the crystal surface are expected to occur[8]

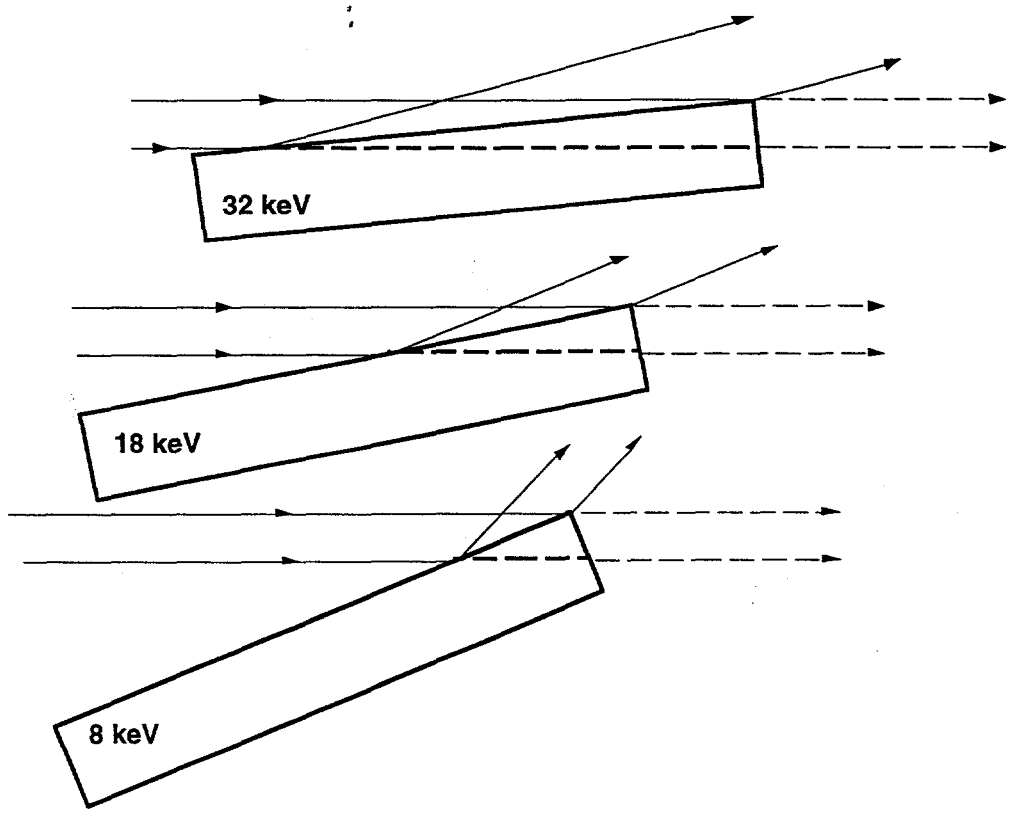


Figure 4 First crystal of the double crystal monochromator on the EMPW beamline at three different energies. The liquid nitrogen cooled Si 220 monolith is mounted so that the top edge of the beam stays at the edge of the monochromator crystal, minimizing the path length of the transmitted beam. This can be done by mounting the first crystal so that the center of rotation is at the top corner of the crystal.

With the EMPW beamline operating in mode **b** the crystal for the Compton branch line has a maximum absorption of ~700 W and the maximum absorption of the monochromator crystal in the High Energy branch line is ~200 W both occurring when the first monochromator is tuned for 4 keV operation. The cooling scheme we have envisioned for these single bounce horizontally deflecting monochromators involves placing the crystal in a water cooled liquid Gallium bath so that the wiggler beam is incident on the Si crystal just over the level of the liquid Gallium (see Figure 5).

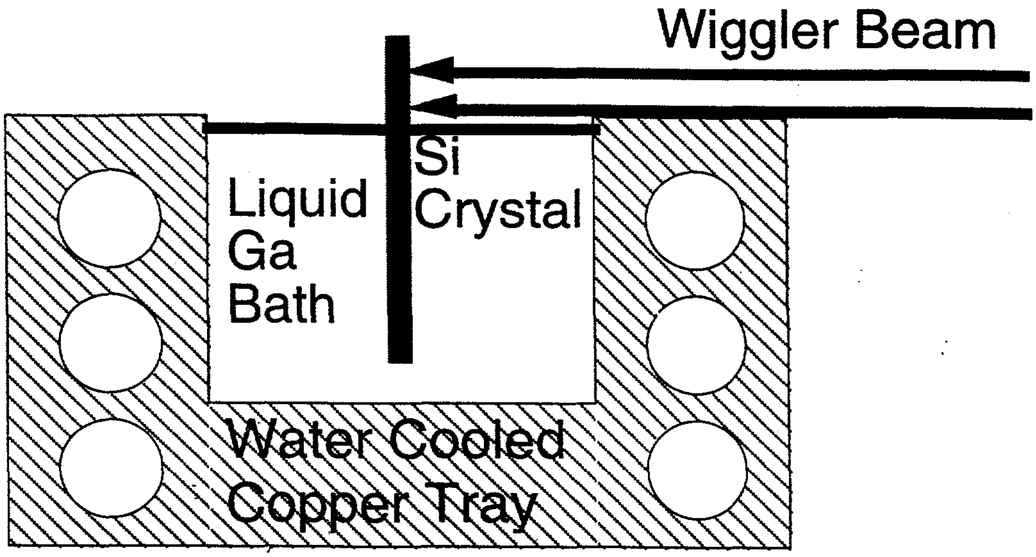


Figure 5. Schematic of the crystal cooling scheme to be employed for the horizontally deflecting Bragg monochromators. The bent Si crystal is cooled by a liquid Gallium bath on the inside of a water cooled copper tray.

Calculations based on a model for one-dimensional heat flow from a uniformly heated region where the x-ray beam is incident into the cooled Ga bath show that the variation in temperature vertically across the beam is less than 2° for the largest heat absorption. This cooling method which allows the Si crystal to be bent to focus the diffracted beam has been successfully employed at an APS bending magnet beamline[9].

MODE (A) OPERATION

If the operating mode depicted in (a) of figure 3 is used substantially different heat loads will be encountered. Exact calculations for this mode of operations are highly dependent on the K_X. value. The calculations presented in Table 2 assume that the applied horizontal field splits the wiggler beam into two beams each with approximately 1/2 the total power of the device. Because the absorbed power and power density is lower for this mode of operation using the same arguments as given above, the powers absorbed by the first crystal of the double crystal monochromator should be easily handled by a bulk cryogenically cooled Si crystal. In this mode of operation, the monochromators for the Compton and High Energy Hutches have very similar incident powers, ~1000 W. However, almost all the incident power will be absorbed in the monochromator crystal for the high energy station while less than half is absorbed by the Compton monochromator. The High Energy monochromator because of the low angle ($\theta = 1.9°$) will absorb approximately 800 W in mode (a) operation and have a power density of ~ 0.8 W/mm^2. The power absorbed by the Compton monochromator will be lower both because of the higher incident angle and because of the lower incident flux of circularly polarized photons. In either case the values are approximately the same as the maximum absorptions discussed above and the gallium-water cooling scheme discussed above will be adequate for these optics.

Another option for the High Energy monochromator is the use of Laue optics. The heat absorbed when the high energy monochromator is used in a Laue mode are also included in Table 2. Using the cooling geometry shown in figure 5, the power density of 4.1 W/mm^2 would produce a ΔT of ~55° across a 2 mm high beam, an unacceptable thermal distortion. Since this optic will be used at ~ 100 keV and above, well above the critical energy of the wiggler, use of filtering of the incident beam can greatly reduce the power incident on the monochromator. Another alternative is cryogenic cooling of the crystal in Laue geometry. This alternative has been shown to be feasible to much higher power densities[7] than those given in table 2.

4. CONCLUSIONS

The heat loads on the three first optical elements given in Table 2 are the determining factors in choosing the cooling strategies for these crystals. The first crystal of the double crystal monochromator has both high total power and a high power density. Liquid N_2 cooling is the most flexible method for cooling this crystal. The crystal used for the Compton station will operate at a fixed angle of $\theta = 3.8°$ and is exposed to moderately high powers and lower power densities. Ga cooling should meet the cooling needs of this optic. Depending on the operating mode, the crystal monochromator for the high energy hutch will have heat loads similar to or higher than those which are observed at the Compton crystal and Ga cooling should be sufficient for this optic used in a Bragg geometry

The calculations given in Table 2 are also applicable to a beamline where an APS Wiggler A is used as the insertion device in mode b . For such a beamline the same total power as generated by the EMPW occurs in 1/2 the horizontal beam width so that absorbed powers and power densities are approximately twice those given in Table 2. Our calculations show that at power levels higher than those given in the table the cooling schemes for the later two crystals produce optics which are not significantly effected by thermal distortions, however the first crystal of the double crystal monochromator will require either enhanced cooling or the restriction of the vertical beam size to produce acceptable performance. particularly for low energy operation.

ACKNOWLEDGMENTS

Work at Argonne National laboratory is sponsored by the US Department of Energy, Office of Basic Energy Sciences, Division of Materials Sciences, under contract W-31-109-ENG-38.

REFERENCES

1. B. Lai, A. Khounsary and E. Gluskin, " Wiggler A Characteristics and Specifications", **ANL/APS/TB-11**, Advanced Photon Source, Argonne National Laboratory, Argonne, IL 60439, 1993.

2. P. A. Montano, G. S. Knapp, G. Jennings, E. Gluskin, E. Trakhtenberg, I. B. Vasserman, P. M. Ivanov, D. Frachon, E. R. Moog, L. R. Turner, G. K. Shenoy, M. J. Bedzyk, M. Ramanathan, M. A. Beno, and P. L. Cowan, "Elliptical multipole wiggler facility at the Advanced Photon Source", *Rev. Sci. Instr.*, **66(2)**,, 1839-1841, 1995.

3. G. S. Knapp, M. A. Beno, C. S. Rogers, C. L. Wiley and P. L. Cowan, "Solution to the high heat loads from undulators at third generation synchrotron sources: Cryogenic thin-crystal monochromators", *Rev. Sci. Instr.*, **65(9)**,, 2792-2797, 1994.

4. M. Ramanathan, M. A. Beno, G. S. Knapp, G. Jennings, P. L. Cowan and P. A. Montano, "Multipurpose monochromator for the Basic Energy Sciences Synchrotron Radiation Center Collaborative Access Team beamlines at the Advanced Photon Source x-ray facility", *Rev. Sci. Instr.*, **66(2)**,, 2191-2193, 1994.

5. C. Welnak, G.J. Chen, and F. Cerrina, "Shadow - A Synchrotron-Radiation and X-Ray Optics Simulation Tool", *Nucl. Instr. and Meth.*, **A347**, 344-347, 1994.

6. D. Chapman, W. Thomlinson . N. Gmur and N. Lazarz "Photon - A Program for Synchrotron Radiation-Dose Calculations", 1987, *Nucl. Instr. and Meth.*, **A266**, 191 1988.

7. B. X. Yang, M. Meron, Y. Ruan, W. Schildkamp, "Performance analysis of cryogenic silicon Laue monochromators at APS undulators", *SPIE* ,**1997**, 302-315, 1993.

8. G.S. Knapp, G. Jennings, and M.A. Beno, "Why cryogenically cooled, thin crystals handle extremely high power densities", *Rev. Sci. Instr.*, **67(9)**, 1996 (CD ROM Issue).

9. S. Brauer, B. Rodricks, and L. Assoufid, M.A. Beno and G.S. Knapp, "Liquid-metal-cooled curved-crystal monochromator for Advanced Photon Source bending-magnet beamline 1-BM", *Rev. Sci. Instr.*, **67(9)**, 1996 (CD ROM Issue).