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Preliminary Thermo-Mechanical Analysis of the Second Phase Photon Shutters for Insertion Device Beamline Ends at the Advanced Photon Source

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Abstract

The photon shutters (PS) on the insertion device front end of the beamlines at the Advanced Photon Source (APS) are designed to fully intercept powerful 7-GeV undulator radiation. Traditional materials (oxygen-free copper and Glidcop) are used in their construction. Initially, the APS proposes to operate the storage ring at 100 mA. In later phases of operation, the APS will operate the storage ring at 300 mA. The heat flux from the undulators is enormous. For example, in the later phase of the project, the first photon shutter (PS1) placed at a distance of 17 m from the Undulator A source will be subjected to 1400 W/mm^2 at normal incidence with a total power of 11.4 kW.

The PS uses an enhanced heat transfer mechanism developed at Argonne National Laboratory, which increases the convective heat transfer coefficient to about $3 \text{ W/cm}^2 \cdot ^\circ\text{C}$ with single phase water as the coolant. To be able to handle the expected three-fold increase in the intense heat flux, some low-Z materials (such as beryllium or graphite), which can absorb the x-rays through their thickness, are now considered as the facing material on the absorber base plate of the PS.

Our analysis of PS1 indicates that the face plate made of either graphite or beryllium retains its integrity in most of the cases. The maximum effective stress of the absorber plate (made of annealed OFHC) exceeds the yield strength (50 MPa) except in the case of an absorber with a 10-mm graphite face plate.

1 Introduction

The photon shutters (PS) [1 and 2] on the insertion device front end [3 and 4] of the beamlines at the Advanced Photon Source (APS) are designed to fully intercept powerful 7-GeV Undulator A [5] radiation. The heat flux from these undulators is enormous. For example, the first photon shutter (PS1), placed at a distance of 16.9 m from the Undulator A source, will be subjected to a peak heat flux of 469 W/mm^2 at normal incidence at 100 mA with a total power of 3.8 kW. In the later phase of the project, the numbers will increase to 1400 W/mm^2 at normal incidence at 300 mA with a total power of 11.4 kW. The PS uses an enhanced heat transfer mechanism developed at Argonne National Laboratory, which increases the convective heat transfer coefficient to about $3 \text{ W/cm}^2 \cdot ^\circ\text{C}$ [6 and 7] with single phase water as the coolant. This enhancement reduces the maximum temperature and the maximum stress in the absorber by about 15 to 30 percent [8] compared to unenhanced, two-dimensional, single-channel absorber geometry (as shown in Fig 1a) with a previously proposed Undulator A [which had a wider x-ray footprint on the face plate because of a larger K (maximum deflection parameter) - 2.5 rather than 2.23 of the current Undulator A]. Such a reduction in maximum temperature is important for a material like OFHC copper (not annealed) because the mechanical strength of this material drops off precipitously

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at operating temperatures above 175°C.

To be able to handle the expected three-fold increase in the intense heat flux during the later phase operations at the APS, some low-Z materials (such as beryllium or graphite), which absorb the x-rays through their thickness, are now considered as the facing material on the absorber plate (which is OFHC). The use of beryllium in conjunction with copper tubing to form beryllium-copper composite components has been previously proposed and studied also [9].

In the ensuing preliminary studies, the maximum temperatures and effective stresses in the design of a PS for the later phase of the APS operations are analyzed. The power distribution, power absorption in semitransparent media, and finite element modeling are also discussed.

2 Power Distribution

The Undulator A power distribution is given as:

$$q \frac{W}{area} = \frac{10.84 \cdot 10^6}{l^2} \cdot B_0[T] \cdot E^4[GeV] \cdot I[A] \cdot N \cdot G(K) f_k(\gamma\theta, \gamma\psi), \quad (1)$$

where

$$f_k(\gamma\theta, \gamma\psi) = \frac{16K}{7\pi G(K)} \int_{-\pi}^{\pi} d\alpha \left(\frac{1}{D^3} - \frac{4(\gamma\theta - K\cos\alpha)^2}{D^5} \right) \sin^2 \alpha, \quad (2)$$

and

$$G(k) = K \frac{K^6 + \frac{24}{7}k^4 + 4K^2 + \frac{16}{7}}{(1 + k^2)^{\frac{7}{2}}}, \quad (3)$$

$$D = 1 + (\gamma\psi)^2 + (\gamma\theta - K\cos\alpha)^2, \quad (4)$$

where

B =	0.8 [T]	maximum magnetic field
E =	7[GeV]	positron beam energy
I =	300[mA]	positron beam current
N =	160	number of periods
K =	2.23	maximum deflection parameter
l		distance from the source
ψ =		vertical angle w.r.t. beam center
θ =		horizontal angle w.r.t. beam center
γ =		1957 E.

The total power can be written as

$$Q_{total}(W) = 0.633 \cdot E^2[GeV] \cdot B_0^2[T] \cdot L \cdot I[A], \quad (5)$$

where

$$L = 2.38 \text{ [m]} \quad \text{device length.}$$

For low-Z materials, the transmitted power can be written as

$$Q_{transmitted}(W) = \int_0^\pi \int_{E_{min}}^{E_{max}} S(E) \cdot \alpha_t(E) \cdot \exp^{-\alpha_t(E) \cdot z} \cdot dE \cdot dz, \quad (6)$$

where

$$\begin{aligned} S(E) &= \text{source spectrum} \\ \alpha_t(E) &= \frac{1}{\text{thickness}} \text{ absorption coefficient (function of thickness and energy).} \end{aligned}$$

For our preliminary analysis, we make the approximation that, for low-Z materials, the absorbed power can be written as

$$q \frac{W}{area} = \frac{10.84 \cdot 10^6}{l^2} \cdot B_0[T] \cdot E^4[GeV] \cdot I[A] \cdot N \cdot G(K) \cdot f_k(\gamma\theta, \gamma\psi) \cdot \int_0^\pi \alpha_t \cdot \exp(-\alpha_t \cdot z) dz, \quad (7)$$

where

$$\alpha_t = \frac{1}{\text{thickness}} \text{ absorption coefficient (function of thickness).}$$

We also assume that the remainder of the heat flux is deposited onto the low-Z material-OFHC interface, the power distribution due to the interfacial heating is in the form of

$$q \frac{W}{area} = \frac{10.84 \cdot 10^6}{l^2} \cdot B_0[T] \cdot E^4[GeV] \cdot I[A] \cdot N \cdot G(K) \cdot f_k(\gamma\theta, \gamma\psi) \cdot \int_0^\pi \exp(-\alpha_t \cdot z) dz. \quad (8)$$

The URGENT [10] program was used to calculate the Undulator A spectrum, and TRANSMIT [11] program were used to calculate the transmitted power. Then, the absorption coefficient was calculated. Table 1 lists the percentage of power transmitted, and the value of α_t for beryllium and graphite.

Table 1. Power Transmitted and Value of α_t

Thickness of Face Plate (mm)	Beryllium		Graphite	
	Power (%) Transmitted	α_t $\frac{1}{\text{mm}} \times 10^{-3}$	Power (%) Transmitted	α_t $\frac{1}{\text{mm}} \times 10^{-3}$
0.1	98	200	90	1000
1	91.3	90	75	300
5	81.3	42	59	100
10	75.6	28	50	65
114	50	6	20	14

3 Finite Element Model

Figure 1b shows the proposed PS1 plate-geometry design for the second phase of operations at the APS. The design consists of a copper base plate and a brazed low-Z face plate. Figure 2 shows the finite element models of various face-plate thicknesses. Figure 3 shows how x-rays travel through low-Z materials. The sizes of the finite element models depend on the thickness of the face plate. For example with a 10-mm face plate, the model in the x direction is about 500 mm long.

The plate geometry is the same as that of the photon shutter designed for the first phase of operation at the APS. It has five center channels with copper mesh brazed inside and two side channels to supply the inlet water. The effective convective heat transfer coefficient is about $3 \text{ W/cm}^2 \cdot ^\circ\text{C}$ [4 and 5], At the two outer supply channels, it is on the order of $1 \text{ W/cm}^2 \cdot ^\circ\text{C}$. The cooling water is at 24°C at the inlet.

Table 2 shows the material properties used in the analyses.

Table 2. Material Properties

			OFHC	Beryllium	Graphite
Conductivity	K	$\frac{W}{\text{cm} \cdot ^\circ\text{C}}$	3.9	2	24 (xy)^* , $.07 \text{ (z)}^*$
Young's Modulus	E	MPa	1.1×10^5	3.2×10^5	$2.8 \times 10^4 \text{ (xy)}^*$, $1.1 \times 10^4 \text{ (z)}^*$
Thermal Exp. Coef.	α_e	$\frac{1}{^\circ\text{C}} \times 10^{-6}$	17.7	12	1 (xy)^* , $26. \text{ (z)}^*$
Poisson Ratio	ν		.343	0.02 – 0.08	0.1 – 0.2
Yield Strength	σ	MPa	50 (Annealed)	206 – 480	NA

* (xy): On xy plane, (z): in z direction (see Fig. 1)

The Glidcop face plate is used to compare the other two materials, beryllium and graphite.

The properties of Glidcop are similar to those of OFHC, except the yield strength of Glidcop is 400 MPa at 650°C, which is much better than that of OFHC.

4 Results and Discussion

4.1 A 3-mm Face Plate

At the 1.5° inclined geometry used and with a 3-mm-thick face plate of a low-Z material, geometry dictates that the x-rays have to travel a theoretical 115 mm before reaching the interface between face plate and base plate. During this travel, about 80% of the total power will be absorbed by a 3-mm graphite face plate, and about 50% of the total power will be absorbed by a 3-mm beryllium face plate.

From Table 1, it can be easily seen that the surface of the face plate will absorb the maximum amount of the power. With increased depth the absorbed power by the face plate decreases. The surface maximum temperature of beryllium is about 39°C, which is low due to the very low absorption coefficient and the inclined geometry, both of which help to dissipate the heat. The stress at the interface is high (322 MPa) due to the slightly different thermo-mechanical properties (i.e., thermal expansion coefficient and Young's modulus) between the two materials. Besides, about 50% of the total power reaches the interface, resulting in local heating, which induces a large thermal gradient at the bonding surface.

Table 3 summarizes these results.

Table 3. PS1 with a 3-mm Face Plate, $h = 3 \frac{W}{\text{cm}^2 \text{ } ^\circ\text{C}}$.

	Beryllium Face Plate	Graphite Face Plate	Glidcop Face Plate
Max. Temperature on Beryllium Surface(°C)	39	116	450
Max. Surface Eff. Stress (MPa) of Face Plate	50	3	679
Max. Temperature on the Bonding Surface(°C)	185	87	262
Max. Eff. Stress (MPa) of OFHC at Interface	322	119	336

Figure 4 shows the temperature contour of 3-mm face plate. The maximum surface temperature of the graphite face plate is higher (about 116°C) due to the higher absorption coefficient of graphite and its very low thermal conductivity ($0.07 \frac{W}{\text{cm } ^\circ\text{K}}$ in the z direction, see Figs. 1 and 3). The heat was spread evenly in the xy plane because the thermal conductivity is high ($24 \frac{W}{\text{cm } ^\circ\text{K}}$) in the xy plane. Note that, at the same x and y coordinate,

the material has very different temperature along the z direction. The maximum interface temperature and effective stress are lower because the Young's modulus of graphite is low, and only 20% of the total power reaches the interface. Figures 5 and 6 show the temperature and effective stress contour of the base plate.

4.2 A 5-mm Face Plate

At the 1.5° inclined geometry used and with a 5-mm-thick face plate of a low-Z material, geometry dictates that the x-rays have to travel 191 mm before reaching the interface. About 85% of the total power will be absorbed by a 5-mm graphite face plate, and about 60% of the total power will be absorbed by a 5-mm beryllium face plate.

Increasing the face plate thickness will decrease the maximum temperature and effective stress at the interface but will increase the maximum surface temperature and effective stress slightly. (Fewer x-rays will reach the interface and the heat deposited on the face plate surface can be diffused by the larger thickness.) For a graphite face plate, the maximum surface temperature increases from 116°C to 129°C if the face plate thickness is increased from 3 mm to 5 mm; this is due to a very small thermal conductivity in the z direction (see Figs. 1 and 3).

Table 4 summarizes the calculated results.

Table 4. PS1 with a 5-mm Face Plate, $h = 3 \frac{W}{\text{cm}^2 \cdot ^\circ\text{C}}$

	Beryllium Face Plate	Graphite Face Plate	Glidcop Face Plate
Max. Temperature on Face Plate(°C)	41	129	460
Max. Surface Eff. Stress (MPa) of Face Plate	55	4	683
Max. Temperature on the Bonding Surface(°C)	152	71	212
Max. Eff. Stress (MPa) of OFHC at Interface	258	89	242

4.3 A 10-mm Face Plate

At the 1.5° inclined geometry used and with a 10-mm-thick face plate of a low-Z material, geometry dictates that the x-rays have to travel 381 mm before reaching the interface. About 91% of the total power will be absorbed by a 10-mm graphite face plate, and about 68% of the total power will be absorbed by a 10-mm beryllium face plate.

The absorber with a 10-mm graphite face plate seems to be the best choice because the maximum temperature (57°C) and the maximum effective stress (52 MPa) at the interface are the lowest, although the face plate has the highest maximum surface temperature (160°C).

Table 5 summarizes these results.

Table 5. PS1 with a 10-mm Face Plate, $h = 3 \frac{W}{\text{cm}^2 \text{ } ^{\circ}\text{C}}$.

	Beryllium Face Plate	Graphite Face Plate	Glidcop Face Plate
Max. Temperature on Face Plate($^{\circ}\text{C}$)	43	160	483
Max. Surface Eff. Stress (MPa) of Face Plate	65	6	689
Max. Temperature on the Bonding Surface($^{\circ}\text{C}$)	127	57	147
Max. Eff. Stress (MPa) of OFHC at Interface	206	52	170

It is obvious that none of the absorbers with a beryllium face plate will survive due to the very high interfacial stresses (from 206 MPa to 322 MPa), which exceed the yield strength (50 MPa) of annealed OFHC. (For annealed metals, it is reasonable to assume identical yield behavior in tension and compression [12].)

4.4 Discussion

All the face plates discussed above will retain their integrity (except Glidcop) because the maximum effective stresses are lower than the yield strengths. The width of the graphite face plate in the y direction plays an important role. If the size is reduced the temperature will rise precipitously. For example, for a 10-mm graphite face plate, if the side width is reduced by 20 mm in the y direction, the temperature rises about 100°C . If the side width of a 10-mm graphite face plate is reduced by 30mm (or a total of 24 mm width in the y direction), the temperature raises about 250° .

The question is then how to ensure that the interfacial stresses are kept within a tolerable range. For example, x-rays can be reduced or intercepted before reaching the interface. Or, increasing the face plate thickness will ensure that fewer x-rays reach the interface.

We studied parametrically the thickness of the face plate (which controls the percentage of x-rays reaching the interface). Resulting interfacial temperature and stress were calculated and shown in Tables 6 and 7.

Table 6. PS1 with Different Thicknesses of Beryllium Face Plates (Different Percentages of Total Power Deposited at the Interface), $h = 3 \frac{W}{cm^2 \text{ } ^\circ C}$

	5%	10%	15%	20%
Max. Temperature on the Bonding Surface($^\circ C$)	40	56	72	88
Max. Eff. Stress (MPa) of OFHC at Interface	32	64	96	129

Table 7. PS1 with Different Thickness of Graphite Face Plate (Different Percentage of Total Power Deposited at the Interface), $h = 3 \frac{W}{cm^2 \text{ } ^\circ C}$

	5%	10%	15%	20%
Max. Temperature on the Bonding Surface($^\circ C$)	45	60	73	87
Max. Stress (MPa) of OFHC at Interface	32	58	89	119

If the total power reaching the interface can be reduced to 8% for a graphite face plate and 6% for a beryllium face plate, the resulting interfacial stresses are within the elastic range of annealed OFHC.

The orthotropic thermal conductivity ($k=24 \frac{W}{cm \text{ } ^\circ C}$ in the xy plane) of graphite resulted in a lower temperature gradient in the xy plane than in the case of beryllium. Although the temperature gradient becomes larger in the z direction ($k=0.07 \frac{W}{cm \text{ } ^\circ C}$ in z direction), the resulting thermal stress is low because Young's modulus is very small in the z direction. With regards to temperature and stress considerations, the design looks good. However, there are a myriad of remaining issues to examine including the radiation damage of graphite, delamination, expansion of graphite with a larger thermal gradient in the z direction (the thermal expansion coefficient in the z direction is $26 \frac{1}{^\circ C} \times 10^{-6}$), et cetera.

The Glidcop face plate always shows failure because the maximum effective stress exceeds its yield strength (about 350 MPa at $400^\circ C$). The difference between the Glidcop and the low-Z material face plates is that x-rays on a Glidcop surface result in surface heating instead of volumetric heating as is the case with beryllium and graphite.

5 Future Work

This work constitutes a mere feasibility study into the use of low-Z materials in the design of PS1 to handle the enormously increased power levels with phase II of the APS project.

Research on low-Z material face-plate designs is continuing. A good candidate material must possess the following properties:

1. low bonding temperatures and stresses
2. low surface temperature
3. radiation hardness
4. thermal expansion match for both face plate and base plate
5. high thermal cycling resistance.

6 Acknowledgments

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References

- [1] Deming Shu, H.L. Nian, Zhibi Wang, J. T. Collins, David G. Ryding, and Tuncer M. Kuzay. The First Photon Shutter Development for APS Insertion Device Beam Line Front Ends. SPIE'92, Technical Conference 1739, High Heat Flux Engineering, July 19-24, 1992, San Diego, CA.
- [2] H.L. Nian, I.C. Albert Sheng and Tuncer M. Kuzay. Thermal Analysis of a Photon Shutter for APS Front Ends, Nucl. Instr. and Meth. A319, 197 (1992).
- [3] Tuncer M. Kuzay. Functional Description of APS Beamline Front Ends Argonne National Laboratory, ANL/APS/TB-5, 1993.
- [4] D. Shu, J. Barraza, T. Sanchez, R. W. Nielsen, J. T. Collins, and T. M. Kuzay. Front End Designs for the 7-GeV Advanced Photon Source. Nucl. Instr. and Meth. A319, 63 (1992).
- [5] B. Lai, A. Khounsary, R. Savoy, L. Moog, and E. Gluskin. Undulator A Characteristics and Specifications, Argonne National Laboratory, ANL/APS/TB-3, 1993.
- [6] Tuncer M. Kuzay, J. T. Collins, A. M. Khounsary, and M. Gilberto. Enhanced Heat Transfer With Wool-Filled Tubes. ASME/JSME 3rd Joint Heat Engineering Conference, Reno, Nevada, March, 1991.
- [7] Tuncer M. Kuzay, J. T. Collins, A. M. Khounsary, and P. J. Vicaro. Experimental and Analytical Studies on Fixed Mask Assembly for APS with Enhanced Cooling. Proc. SPIE 1345, 122 (1990).
- [8] H.L. Nian, Tuncer M. Kuzay and I.C. Albert Sheng. Thermo-Mechanical Optimization of Photon Shutter 1 for APS Front Ends, Argonne National Laboratory, Light Source Note. LS-205, 1992.

- [9] Dennis M. Mills, Donald H. Bilderback, and Boris W. Batterman. Thermal Design of Synchrotron Radiation Exit Ports at CESR. IEEE Trans. on Nucl. Sci., Vol. NS-26, NO. 3, 1979
- [10] R. P. Walker and B. Diviacco. URGENT Proc. 4th Int. Conf. Synchrotron Radiation Instrumentation, Chester, July 1991, Sincrotrone Trieste Report ST/M-91/12.
- [11] B. Lai and F. Cerrina. Shadow: A Synchrotron Radiation Ray Tracing Program, Nucl. Instrum. and Methods. A 246, 337 (1986).
- [12] George E. Dieter *Mechanical Metallurgy*, McGraw-Hill Series in Materials Science and Engineering, 2nd edition, 1976, p 311.

Fig. 1a Simplified Model for Closed Form Approximation

Fig. 1b Proposed PS Plate Geometry

Fig. 2 Finite Element Models with Various Thicknesses of Low-Z Materials

Fig. 3 X-Ray Beam Travels in Low-Z Materials

Fig. 4 Temperature Contour of Face Plate

Fig. 6 Effective Stress Contour of Base Plate

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