Thermo-Mechanical Analysis of Fixed Mask 1 for the Advanced Photon Source Insertion Device Front Ends

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Abstract

The first fixed mask (FM1) is one of the critical elements on the insertion device front ends of the beamlines at the Advanced Photon Source (APS) now under construction at Argonne National Laboratory (ANL). The heat flux from the APS undulators is enormous. For example, FM1 placed at a distance of 16 m from the Undulator A source will be subjected to 519 W/mm^2 at normal incidence with a total power of 3.8 kW.

Due to a high localized thermal gradient on this component, inclined geometry (1.5°) is used in the design to spread the footprint of the x-ray beam. A box-cone-shape geometry was designed due to the limited space available in the front end. The box shape is a highly constrained geometry, which induces larger stress levels than would occur in a plate or a tube. In order to handle the expected higher stress and the stress concentration at the corners, a single Glidcop block (rather than copper) was used in the construction.

The FM1 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.

We simulated the location of the x-ray beam in several places to cover the worst possible case. The maximum temperature (about 180°C) occurs when the beam hits the center of horizontal surface. The maximum effective stress (about 313 MPa) occurs when the x-ray beam hits about the corners.

1 Introduction

The first fixed mask 1 (FM1) [1 and 2] is one of the critical elements on the insertion device front end [3 and 4] of the beamlines at the 7-GeV Advanced Photon Source (APS). The front-end design includes a pair of fixed masks (FM) and another pair of photon shutters (PS) [5 and 6]. The FMs contain the x-ray beam, whereas the PSs fully intercept it. However, both components are designed to withstand the x-ray beam coming off the powerful Undulator A [7]. The heat flux from the undulators is enormous. For example, FM1 placed

at a distance of 16 m from the Undulator A source will be subjected to 519 W/mm^2 at normal incidence with a total power of 3.8 kW.

A box-cone-shape geometry (Fig. 1) was designed for the fixed mask due to the limited space available in the front end. The box-cone-shape is a highly constrained geometry, which induces larger stress levels than would occur in a plate or a tube. In order to handle the expected higher stress and stress concentration at the corners, a single Glidcop block was used in the construction.

The FM1 uses an enhanced heat transfer mechanism developed at Argonne National Laboratory, which increases the convective heat transfer coefficient to about $3 \text{ W/cm}^2 \cdot ^\circ\text{C}$ [1 and 8] with single-phase water as the coolant. This enhancement reduces the maximum temperature and the maximum stress in the absorber by about 15 to 25 percent [2] compared to unenhanced, two-dimensional, single-channel absorber geometry 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].

In this paper, the maximum temperatures and effective stresses on a FM are analyzed. The power distribution and finite element modeling are also discussed.

2 Power Distribution

The Undulator A power distribution is given as:

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

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
$I =$	100[mA]	positron beam current
$N =$	160	number of periods
$K =$	2.23	maximum deflection parameter
l		distance from the source
$\psi =$		vertical angle w.r.t. beam center
$\theta =$		horizontal angle w.r.t. beam center
$\gamma =$		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

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

Figure 2 shows the power distribution on a FM at 16 m with normal incidence. The incident angle is about 1.5° at both vertical and horizontal surfaces as shown in Fig. 1.

3 Finite Element Model

The ANSYS program for finite element analysis was used. Several three-dimensional models were created to ensure that the worst possible case was considered. Due to the box-cone-shape geometry, the stress concentration at the four corners is a concern. We have two options to obtain more accurate results in region of the corners:

1. analyze the entire model with greater mesh refinement, or
2. generate an independent, more finely meshed model of the only region of interest and analyze it.

Obviously, option 1 can be time consuming. Option 2 is a submodeling technique, which is also known as a cut-boundary displacement method or a specified boundary displacement method. Displacements on the cut boundary of the coarse model are specified

as the boundary conditions for the submodel.

Figure 3 shows the 3-D ANSYS finite element model for the vertical missteering case. Only one quarter of the FM1 was modeled due to symmetry of the boundary conditions. The model has a fine mesh at both the center of vertical surface and one corner (without the submodeling technique). Figure 4 shows the 3-D ANSYS finite element model for the case in which the x-ray beam impinging at or near one corner.

The effective convective heat transfer coefficient is assumed to be $3 \text{ W/cm}^2 \cdot ^\circ\text{C}$ [1 and 8] at all water channels.

Table 1 shows the material properties used in the analyses.

Table 1. Material Properties

			Glidcop
Conductivity	K	$\frac{W}{cm \cdot ^\circ K}$	3.65
Young's Modulus	E	MPa	1.3×10^5
Thermal Exp. Coef.	α_e	$\frac{1}{^\circ C} \times 10^{-6}$	16.6
Poisson Ratio	ν		.326
Yield Strength	σ_y	MPa	350 MPa at 200°C

4 Results and Discussion

The following discussion is based on a full x-ray beam hitting different locations on the fixed mask (as shown in Fig. 5) with $h=3 \text{ W/cm}^2 \cdot ^\circ\text{C}$. The radius at the four corners has to be 2 mm or larger, or the resulting effective stress at the corners will exceed the yield strength of Glidcop material. The following discussion is based on the model with a 2-mm radius at the corners.

The highest maximum temperature (180°C) occurs when the beam missteers vertically and impings location "1" as shown in Fig. 5. The lowest maximum temperature and stress occur when the beam missteers horizontally at location "2" (as shown in Fig. 5). The highest maximum effective stress (313 MPa) occurs at location "8" when the x-ray beam hits at or near the corners.

4.1 Vertical Missteering

The vertical missteering resulting in the highest temperature field occurs when the beam center at location “1” in Fig. 5. The maximum temperature is about 180°C , and the maximum effective stress is about 273 MPa (as shown in Fig. 6).

In this case, we spread the x-ray beam footprint in the vertical surface (as shown in Figs. 1 and 2), which is not as effective as when spread in the horizontal surface. The line power density in the horizontal surface is larger than that in the vertical surface (the power envelop is heavier in horizontal surface than in vertical surface). When the x-ray beam center hits at location “3” (Fig. 5), the maximum temperature is about 6°C lower than that at location “1”, because the fin helps to dissipate the heat.

4.2 Horizontal Missteering

The horizontal missteering resulting in the lowest temperature and stress field occurs when the beam center is at location “2” in Fig. 5.

4.3 Missteering with Vertical and Horizontal Angle

We will only discuss the vertical surface and the fillet surface because the x-ray beam impinging the horizontal surface results in a lower temperature gradient.

The incident angle is about the same (1.5°) as that in the case of vertical missteering and horizontal missteering. But the power distribution and footprint are more complicated.

We simulated the x-ray beam hitting many locations around one corner to cover the possible worst case. We studied ten cases with the x-ray beam center located in ten different positions (from “3” to “12”) as shown in Fig. 5. As the x-ray beam center moves from location “4” toward “12”, the maximum temperature decreases. When the x-ray beam center is located at location “6”, the maximum temperature is about 169°C . The maximum temperature decreases to 154°C at location “8”; it is about 140°C at location “10”; and it is about 122°C at location “11”; and it is only 110°C at location “12”. The maximum temperature decreases from location “4” through location “12” for the following reasons.

1. There is more material at the corners help to dissipate the heat.

2. The footprint of x-ray beam in the horizontal direction was spread as the x-ray beam hit the fillets, which means the line power density was reduced at any given cross section.

The highest maximum effective stress was found to be about 313 MPa (as shown in Fig. 7) when the x-ray beam center is located at position “8” (Fig. 5), with a maximum temperature of 154°C. Figure 8 shows the effective stress contour when the x-ray beam center is located at “10” in Fig. 5.

Tables 2 and 3 summarize the results from ANSYS calculations.

Table 2. Maximum Surface Temperature and Maximum Effective Stress (assuming $h=3W/cm^2 \cdot ^\circ C$).

Location	1	2	3	4	5	6	7	8	9	10	12
$T_{max}(^\circ C)$	180	106	174	176	173	170	168	154	143	139	109
σ_{eff} (MPa)	273	164	280	303	298	295	290	313	300	294	211

Table 3. Maximum Surface Temperature and Maximum Effective Stress (assuming $h=2W/cm^2 \cdot ^\circ C$).

Location	1	2	3	4	5	6	7	8	9	10	12
$T_{max}(^\circ C)$	187	112	179	181	191	176	173	161	150	146	113
σ_{eff} (MPa)	280	170	285	309	302	299	294	325	312	305	218

Current design using the Glidcop material has a safety factor of 1.25.

5 Acknowledgments

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Table Captions

Table 1: Material Properties

Table 2: Maximum Surface Temperature and Maximum Effective Stress (assuming $h=3W/cm^2 \cdot ^\circ C$).

Table 3: Maximum Surface Temperature and Maximum Effective Stress (assuming $h=2W/cm^2 \cdot ^\circ C$).

Figure Captions

Figure 1: Fixed Mask Geometry Used for Finite Element Model.

Figure 2: The Power Distribution of UA at 16 m, Normal Incidence.

Figure 3: Finite Element Model for Vertical Missteering Case.

Figure 4: Finite Element Model for Missteering Around the Corners.

Figure 5: Location of Various X-Ray Beam Centers Used for Analysis.

Figure 6: Effective Stress Contour for Vertical Missteering Case.

Figure 7: Effective Stress Contour for Missteering at Location "8".

Figure 8: Effective Stress Contour for Missteering at Location "10".

Fig. 1 Fixed Mask Geometry used for Finite Element Model

ANSYS 5.0
AUG 31 1993
16:29:42
PLOT NO. 1
ELEMENTS
TYPE NUM

FM1_UA
DIST=16 m
Inc. Ang 1.5
Max q=13.4 W/mm²
h=3W/(cm² C)
Vertical Misteering

ELEMENTS
TYPE NUM

XV =-1.75
YV =-0.6
ZV =-1
DIST=62.435
XF =50
YF =20.322
ZF =-14.301
A-ZS=90
PRECISE HIDDEN

ELEMENTS
TYPE NUM

XV =-0.75
YV =-0.6
ZV =-1

ANSYS 5.0
SEP 8 1993
16:19:43
PLOT NO. 1
ELEMENTS
TYPE NUM

XV =-1
DIST=44.488
XF =70
YF =-0.07325
ZF =-14.374
PRECISE HIDDEN

ELEMENTS
TYPE NUM

X-Ray Beam
Locations from
"5" to "11"
as Shown
in Fig 5
1.5 Inc. Ang.
4500 elements
6000 nodes

ELEMENTS
TYPE NUM

NIAN
Fig. 4

Fig. 5 Locations of Various X-Ray Beam Centers Used for Analysis

ANSYS 5.0
 AUG 20 1993
 09:34:12
 PLOT NO. 1
 NODAL SOLUTION
 STEP=1
 SUB =1
 TIME=1
 SEQV (AVG)
 DMX =0.015359
 SMN =1.113
 SMX =273.305
 SMXB=273.984

1.113
31.356
61.6
91.844
122.087
152.331
182.574
212.818
243.062
273.305

FM1, UA
 Normal Case

Eff. Stress (MPa)
 $h=3W/(cm^2 C)$
 Dist 16 m
 1.5 Deg.
 Q= 3.8 kW
 NIAN

Fig. 6

ANSYS 5.0
 SEP 10 1993
 10:00:00
 PLOT NO. 1
 NODAL SOLUTION
 STEP=1
 SUB =1
 TIME=1
 SEQV (AVG)
 DMX =0.035673
 SMN =0.654734
 SMX =285.711
 SMXB=312.835
 0.654734
 32.087
 63.79
 95.493
 127.196
 158.899
 190.602
 222.305
 254.008
 285.711

FM1, UA
 Misteering
 Location "8"
 Eff. Stress (MPa)
 $h=3W/(cm^2 C)$
 Dist 16 m
 1.5 Deg.
 Q= 3.8 kW
 NIAN

Fig. 7

ANSYS 5.0
 SEP 10 1993
 10:22:45
 PLOT NO. 2
 NODAL SOLUTION
 STEP=4
 SUB =1
 TIME=4
 SEQV (AVG)
 DMX =0.034656
 SMN =0.62314
 SMX =267.83
 SMXB=294.666
 0.62314
 30.086
 59.804
 89.522
 119.24
 148.958
 178.676
 208.394
 238.112
 267.83

FM1, UA
 Misteering
 Location "10"
 Eff. Stress (MPa)
 $h=3W/(cm^2 C)$
 Dist 16 m
 1.5 Deg.
 Q= 3.8 kW
 NIAN

Fig 8

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