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THERMAL STRESS ANALYSIS OF THE SLAC FIXED MASK

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Laboratory

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ABSTRACT

X-ray beams emerging from the new SLAC electron-positron storage ring (PEP) can impinge on the walls of tangential divertor channels. A fixed mask made of OFHC copper is installed in the channel to limit wall heating. The mask is cooled with water flowing axially at 30 °C. Beam strikes on the mask cause highly localized heating in the channel structure. Analyses were completed to determine the temperatures and thermally-induced stresses due to this heating. The current design and operating conditions should result in the entrance to the fixed mask operating at a peak temperature of 105 °C with a peak thermal stress at 26% of yield.

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SLAC MASK/CASE 2/LOWER BEAM STRIKE/TACO3D&GEMINI THERMAL STR
OBLIQUE VIEW OF ISO-CONTOURS

CONTOURS OF EFF. STRESS (V-M) (PA)

MIN= .395E+05 IN ELEMENT 1339

MAX= .675E+08 IN ELEMENT 78

STRESS
CONTOUR VALUES

A= 0.
B= 4.70E+06
C= 8.40E+06
D= 1.20E+07
E= 1.60E+07
F= 2.00E+07
G= 2.40E+07
H= 2.80E+07
I= 3.20E+07
J= 3.60E+07
K= 4.00E+07
L= 4.40E+07
M= 4.80E+07
N= 5.20E+07
O= 5.60E+07
P= 6.00E+07
Q= 6.40E+07
R= 6.80E+07
S= 7.20E+07

Figure 17.

Isobar contour plot of effective stresses
for lower beam strike (case 2)-oblique view

Fixed Mask Thermal-Stress

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SUMMARY

X-ray beams emerging from the undulator of the new SLAC electron-positron storage ring (PEP) can impinge on the uncooled portions of the walls of tangential divertor channels. This causes highly localized heating and thus highly localized thermal stresses in the channel structure. A water cooled mask is fixed in the channel to intercept the portions of the x-ray beams which could strike the channel walls. Shifting the beam orientation can cause a corresponding shift in this locally heated and stressed region.

The resultant temperatures and thermally-induced stresses in the divertor entrance were determined using the LLNL finite element heat transfer computer code TACO3D and the LLNL finite element structural computer code GEMINI. The geometry of the OFHC copper structure is described in Figure 1. Room temperature thermal/mechanical properties are used for the OFHC copper. The centerplane of the 7° ramped surface of the fixed mask absorbs an x-ray beam originating from the undulator. The absorbed x-rays are modeled as a "local surface heat flux". All surfaces are assumed to be adiabatic except the outside surfaces of the walls parallel to the horizontal plane of symmetry. Water flows axially over these outside surfaces at 30°C . All surfaces are assumed to be structurally free (unloaded and able to move in any direction) except the centerplane and the front/rear planes which have zero displacement limits.

The peak temperature in case 1 (upper beam strike) is 104.5°C . The peak temperature in case 2 (lower beam strike) is 101.0°C . For case 1 the peak thermal stress is 70.6 MPa, or about 26% of the yield stress for OFHC. For case 2 the peak thermal stress is 67.5 MPa.

INTRODUCTION

X-ray beams originating in the undulator of the new SLAC electron-positron storage ring (PEP) will overheat uncooled portions of the walls in the ring's tangential side channels. However, these regions are protected from overheating by water-cooled masks fixed inside the channels (Figures 1 and 2). The fixed mask being reviewed in this analysis is made of oxygen-free, high conductivity copper (OFHC).

The beams strike the mask causing highly localized heating. This heating can vary in location because of shifts in the magnetic fields of the undulator. Highly localized heating in a constrained structure will induce large local thermal stresses. Thermal stresses occurring in other components of these channels have been analyzed previously (Reference 1).

Analyses were completed to determine the resultant temperatures and thermally-induced stresses in the fixed mask for two beam strike locations; i.e. near the upper edge of the mask opening and mid-way down the mask's 7° ramp. The temperature distributions are calculated based on a three dimensional, steady state, linear heat transfer analysis using the LLNL finite element computer code, TACO3D. The calculated temperatures were used as input for the three dimensional, steady state, linear stress analyses using the LLNL finite element computer code GEMINI to determine the thermally-induced stresses.

DISCUSSION

Mask Geometry

The fixed mask is a ramped, rectangular structure made from oxygen-free, high conductivity copper (OFHC). In order to keep the number of nodes and elements to a minimum and still obtain acceptable accuracy, the mask was modeled as a quarter symmetry problem (Figure 1) even though the heating caused by the beam would suggest a half symmetry problem. Using a quarter section model is a conservative assumption since the actual temperatures would be slightly lower than those predicted by the half section model. The results indicate that this assumption has a minimal effect on the predicted temperatures. (refer to the Results section of this report.)

All dimensions in the figures are given in millimeters. One ramped inner face inclines at an angle of 7° to the horizontal (yz) plane. The other ramped inner face makes an angle of 10° with the vertical (xz) plane (see Figure 1).

Model Boundary Conditions

The thermal boundary conditions are summarized in Figures 2 and 4. All surfaces are assumed to be adiabatic (no energy flow across the surface) with the exception of the bottom outside surface (not shown in the figure). The effects of thermal radiation heat transfer are neglected. The bottom surface of the quarter section is water-cooled and has 24 channels (for each quarter section) running parallel to the z-axis. Each channel is 6.35 mm high and 1.35 mm wide. Each fin is 6.35 mm high and 1.52 mm wide. The 24 channels are arranged in two groups of twelve with a "spacer fin" 6.35 mm wide between the two groups.

Fixed Mask Thermal-Stress

For easy analysis, the fins were not modeled as discrete elements, but their influence is included by using a higher effective heat transfer coefficient on this surface. The heat transfer coefficient is scaled using a ratio of the actual finned surface area to the corresponding surface area used in the model (i.e. a flat surface in place of the fins). The heat transfer coefficient "amplification factor" resulting from the finned surfaces is 5.55.

The heat transfer coefficient for the flow in the channels was calculated as follows. The water flowing through the channels is at 30 °C and flows at a velocity of 6.1 m/sec. The channel geometry equates to a hydraulic diameter, d , of 2.221×10^{-3} m. For 30 °C water, the Prandtl number, Pr , is 5.49, the kinematic viscosity, ν , is 8.09×10^{-7} m²/sec, and the thermal conductivity, k , is 0.619 W/m °C. At a velocity, V , of 6.1 m/s, the Reynold's Number, Re_d , equals 1.675×10^4 . Using the most popular relation for heat transfer into turbulent flow in a channel,

$$Nu_d = (.023)(Re_d^{0.8})(Pr^{0.4})$$

the Nusselt number, Nu_d , is 108.0. The heat transfer coefficient is defined from the Nusselt number by,

$$h_d = \frac{(Nu_d)k}{d}$$

Thus, h_d is 3.04×10^4 W/m² °C. Applying the heat transfer coefficient "amplification factor" for the finned surfaces, the modified heat transfer coefficient is 1.67×10^5 W/m² °C.

Fixed Mask Thermal-Stress

The structural boundary conditions are also described in Figures 2 and 4. All surfaces are assumed to be free (unloaded and able to move in any direction) with the exception of the symmetry planes and the rear plane. The allowable displacement perpendicular to the symmetry planes is fixed to zero. The node on the corner of the x=0 plane, the rear plane, and the vertical symmetry plane has its allowable "x" displacement set to zero.

There are no pressure loads applied to the convectively cooled walls due to coolant pressure because the hydrostatic pressure (about 200 psi) is significantly lower than the expected thermal stresses (on the order of 10 kpsi to 20 kpsi).

Heat Loads

The depth of penetration of a given energy level of x-ray is inversely proportional to the electron density (which is nearly proportional to the mass density). The penetration depth in a copper slab is very small since it is about 30% of the penetration depth in 6061-T6 aluminum. For this analysis of the copper mask, the heat load from the x-ray beam is modeled as an applied surface heat flux.

The total beam power of 475 watts is assumed to be uniformly distributed over the beam contact area. This area is equal to the width of the beam (approx. 6.5 mm) times the "effective length" of the beam. The effective length, defined as the actual beam height (approx. 1.5 mm) divided by the sine of the horizontal ramp angle (i.e. 7°), is equal to 12.3 mm. The power density (i.e. surface heat flux) is $5.98 \times 10^6 \text{ W/m}^2$. This heat flux provides the heat load boundary condition to the mask model for both beam positions.

Fixed Mask Thermal-Stress

Material Properties

The fixed mask is made of OFHC copper. The analyses used the following room temperature thermal and mechanical properties for this material (References 2 and 3).

Oxygen-free, high conductivity Copper Room Temperature Properties

density	- 8938 kg/m ³
specific heat	- 381 J/kg K
conductivity	- 384.22 W/m K
thermal expansion coefficient	- 17.0×10^{-6} m/m K
elastic modulus	- 1.15×10^5 MPa (17×10^6 psi)
Poisson's ratio	- 0.3
yield strength	- 275 MPa (40×10^3 psi)

The thermal properties of OFHC copper do not change significantly over the expected temperature range 0 °C to 150 °C.

Finite Element Zoning

The SLIC computer code, a 2-D and 3-D finite element mesh generator developed at LLNL, was used to zone the parts for the finite element analyses. Table I gives the number of nodes and elements for each case. Variable spacing between nodes was used to concentrate nodes in areas of high thermal gradients (and, thus high thermal-stress levels). The high gradients were expected near the interfaces between the hot volumes absorbing the x-rays and the unheated adjacent volumes (Figures 3 and 5). The same zoning was used for the TACO3D heat transfer calculations and the GEMINI stress calculations.

RESULTS

Thermal Analyses

A summary of the results of the analyses is documented in Table I and Figures 6 through 11. For case 1 the top of the x-ray beam is level with the top of the ramp. The peak temperature in case 1 is 104.5 °C. It is located on the surface of the ramp at the center of the beam (Figures 6 to 8). For case 2 the center of the beam hits the mask 102.36 mm up the ramp surface from the front edge. The peak temperature in case 2, 101.0 °C, is again located on the ramp surface at the center of the beam (Figures 9 to 11).

Figures 6 through 8 show that the water cooling on the nearby base of the heated quadrant helps restrict the high temperatures to the region near the beam impact locations. This suggests that little of the heat would travel to the unheated quadrant for removal by the coolant flowing over the upper surface.

To check this assumption, a case was run simulating a half section problem. Heat loss through the unheated quarter section was modeled by allowing heat transfer through a thermal resistance attached to the horizontal symmetry plane. The change in maximum temperature from the quarter section model was a fraction of a degree. We felt that this proved that quarter section models give reasonably accurate temperatures and thus, thermal stresses.

Fixed Mask Thermal-Stress

Stress Analyses

For the upper beam strike (case 1), the peak thermal stress is 70.6 MPa (10.4 kpsi). This is about 26% of the yield stress for OFHC (defined at the local element temperature). For the lower beam strike (case 2), the peak thermal stress is 67.5 MPa (9.9 kpsi). This is about 24.5% of the yield stress. The high stresses in both cases are concentrated in a small volume near the beam strike.

Isobar contour plots of the thermally-induced stresses for these two cases are given in Figures 12 to 17 and in the Appendix. The effective stresses are used for comparison with the material's yield stress. The principal stresses (Appendix) are used for defining the direction and type of stress (i.e. tensile or compressive).

CONCLUSIONS

The current design and operating conditions should result in the fixed mask running at a peak temperature of 105 °C with a peak thermal stress of 26% of yield.

REFERENCES

1. Johnson, Gary L., Werner Stein, Stephen C. Lu, and Robert A. Riddle, "SLAC Divertor Channel Entrance Thermal Stress Analysis," LLNL Report UCID - 20498, July 1985.
2. Metals' Handbook, 8th edition and the Structural Alloy Handbook, 1973.
3. Kreith, F., "Principles of Heat Transfer", Intext Educational Publishers, N.Y., N.Y., 1976.

Fixed Mask Thermal-Stress

Table I
Analyses Cases Synopsis

Case No.	Location of Heating	Beam Height/Width (mm)	Number of Nodes	Number of Elements
-------------	------------------------	------------------------------	--------------------	-----------------------

1	upper	1.5/6.5	2139	1584
---	-------	---------	------	------

2	lower	1.5/6.5	1953	1440
---	-------	---------	------	------

Analysis Results Synopsis

Case No.	Maximum Temperature (°C)	Location of Max. T (Node No.)	Maximum Stress (MPa)	Location of Max. Stress (Elem No.)	Maximum Stress* (% of Yield)
-------------	--------------------------------	-------------------------------------	----------------------------	--	------------------------------------

1	104.5	1309	70.6	84	26.0
---	-------	------	------	----	------

2	101.0	844	67.5	78	24.5
---	-------	-----	------	----	------

* Versus tensile yield at the temperature of the maximum stress element.

Figure 1. Schematic of the fixed mask with the characteristic dimensions in mm.

Figure 2. Schematic outline of the modeled part for the upper beam strike location (case 1) including the boundary conditions.

Figure 3. Schematic of the zoning of the modeled part for the upper beam strike location (case 1).

Figure 4. Schematic outline of the modeled part for the lower beam strike location (case 2) including the boundary conditions.

SLAG MASK/CASE 2/LOWER BEAM STRIKE/TACOSD&GEMINI THERMAL STR
ZONING

Figure 5. Schematic of the zoning of the modeled part for the lower beam strike location (case 2).

SLAC MASK/CASE 1/UPPER BEAM STRIKE/TACO3D&GEMINI THERMAL STR
 VIEW PERPENDICULAR TO HORIZONTAL PLANE OF SYMMETRY
 CONTOURS OF TEMPERATURE (DEG. C)

MIN= .300E+02 AT NODE 100
 MAX= .105E+03 AT NODE 1309

TEMPERATURE
 CONTOUR VALUES
 A= 3.00E+01
 B= 3.50E+01
 C= 4.00E+01
 D= 4.50E+01
 E= 5.00E+01
 F= 5.50E+01
 G= 6.00E+01
 H= 6.50E+01
 I= 7.00E+01
 J= 7.50E+01
 K= 8.00E+01
 L= 8.50E+01
 M= 9.00E+01
 N= 9.50E+01
 O= 1.00E+02
 P= 1.05E+02

Figure 6. Isotherm contour plot of surface temperatures for upper beam strike (case 1) from a view perpendicular to horizontal plane of symmetry.

SLAC MASK/CASE 1/UPPER BEAM STRIKE/TACO3D&GEMINI THERMAL STR
 VIEW PERPENDICULAR TO VERTICAL PLANE OF SYMMETRY
 CONTOURS OF TEMPERATURE (DEG. C)
 MIN= .300E+02 AT NODE 100
 MAX= .105E+03 AT NODE 1309

CONTOUR VALUES

A= 3.00E+01
 B= 3.50E+01
 C= 4.00E+01
 D= 4.50E+01
 E= 5.00E+01
 F= 5.50E+01
 G= 6.00E+01
 H= 6.50E+01
 I= 7.00E+01
 J= 7.50E+01
 K= 8.00E+01
 L= 8.50E+01
 M= 9.00E+01
 N= 9.50E+01
 O= 1.00E+02
 P= 1.05E+02

Figure 7. Isotherm contour plot of surface temperatures for upper beam strike (case 1) from a view perpendicular to vertical plane of symmetry.

SLAC MASK/CASE 1/UPPER BEAM STRIKE/TACO3D&GEWINI THERMAL STR
OBLIQUE VIEW OF ISOTHERMS

CONTOURS OF TEMPERATURE (DEG. C)

MIN= .300E+02 AT NODE 100

MAX= .105E+03 AT NODE 1309

TEMPERATURE
CONTOUR VALUES

A= 3.00E+01
B= 3.50E+01
C= 4.00E+01
D= 4.50E+01
E= 5.00E+01
F= 5.50E+01
G= 6.00E+01
H= 6.50E+01
I= 7.00E+01
J= 7.50E+01
K= 8.00E+01
L= 8.50E+01
M= 9.00E+01
N= 9.50E+01
O= 1.00E+02
P= 1.05E+02

Figure 8. Isotherm contour plot of surface temperatures
for upper beam strike (case 1)-oblique view

Figure 9. Isotherm contour plot of surface temperatures for lower beam strike (case 2)-from a view perpendicular to horizontal plane of symmetry.

SLAC MASK/CASE 2/LOWER BEAM STRIKE/TACO3D&GEMINI THERMAL STR
VIEW PERPENDICULAR TO VERTICAL PLANE OF SYMMETRY
CONTOURS OF TEMPERATURE (DEG. C)

MIN= .298E+02 AT NODE 49
MAX= .101E+03 AT NODE 844

TEMPERATURE
CONTOUR VALUES

A= 3.00E+01
B= 3.50E+01
C= 4.00E+01
D= 4.50E+01
E= 5.00E+01
F= 5.50E+01
G= 6.00E+01
H= 6.50E+01
I= 7.00E+01
J= 7.50E+01
K= 8.00E+01
L= 8.50E+01
M= 9.00E+01
N= 9.50E+01
O= 1.00E+02
P= 1.05E+02

Figure 10.

Isotherm contour plot of surface temperatures
for lower beam strike (case 2)-from a view
perpendicular to vertical plane of symmetry.

SLAC MASK/CASE 2/LOWER BEAM STRIKE/TACOSD&GEMINI THERMAL STR
 OBLIQUE VIEW OF ISOTHERMS
 CONTOURS OF TEMPERATURE (DEG. C)
 MIN= .298E+02 AT NODE 49
 MAX= .101E+03 AT NODE 844

TEMPERATURE
 CONTOUR VALUES

A= 3.00E+01
 B= 3.50E+01
 C= 4.0E+01
 D= 4.50E+01
 E= 5.00E+01
 F= 5.50E+01
 G= 6.00E+01
 H= 6.50E+01
 I= 7.00E+01
 J= 7.50E+01
 K= 8.00E+01
 L= 8.50E+01
 M= 9.00E+01
 N= 9.50E+01
 O= 1.00E+02
 P= 1.05E+02

Figure 11. Isotherm contour plot of surface temperatures
 for lower beam strike (case 2)-oblique view

SLAC MASK/CASE 1/UPPER BEAM STRIKE/TACO3D&GEMINI THERMAL STR

VIEW PERPENDICULAR TO HORIZONTAL PLANE OF SYMMETRY

CONTOURS OF EFF. STRESS (V-M) (PA)

MIN= .103E+06 IN ELEMENT 496

MAX= .706E+08 IN ELEMENT 84

STRESS
CONTOUR VALUES

A= 0.
B= 4.00E+06
C= 8.00E+06
D= 1.20E+07
E= 1.60E+07
F= 2.00E+07
G= 2.40E+07
H= 2.80E+07
I= 3.20E+07
J= 3.60E+07
K= 4.00E+07
L= 4.40E+07
M= 4.80E+07
N= 5.20E+07
O= 5.60E+07
P= 6.00E+07
Q= 6.40E+07
R= 6.80E+07
S= 7.20E+07

Figure 12.

Isobar contour plot of effective stresses
for upper beam strike (case 1)-from a view
perpendicular to horizontal plane of symmetry.

SLAC MASK/CASE 1/UPPER BEAM STRIKE/TACO3D&GEMINI THERMAL STR
VIEW PERPENDICULAR TO VERTICAL PLANE OF SYMMETRY
CONTOURS OF EFF. STRESS (V-M) (PA)

MIN= .103E+06 IN ELEMENT 496
MAX= .706E+08 IN ELEMENT 84

STRESS
CONTOUR VALUES

A= 0.
B= 4.00E+06
C= 8.00E+06
D= 1.20E+07
E= 1.60E+07
F= 2.00E+07
G= 2.40E+07
H= 2.80E+07
I= 3.20E+07
J= 3.60E+07
K= 4.00E+07
L= 4.40E+07
M= 4.80E+07
N= 5.20E+07
O= 5.60E+07
P= 6.00E+07
Q= 6.40E+07
R= 6.80E+07
S= 7.20E+07

Figure 13.

Isobar contour plot of effective stresses
for upper beam strike (case 1)-from a view
perpendicular to vertical plane of symmetry.

SLAC MASK/CASE 1/UPPER BEAM STRIKE/TACO30&GEMINI THERMAL STR

OBLIQUE VIEW OF ISO-CONTOURS

CONTOURS OF EFF. STRESS (V-M) (PA)

MIN= .103E+08 IN ELEMENT 496

MAX= .708E+08 IN ELEMENT 84

STRESS
CONTOUR VALUES

A= 0.
B= 4.00E+06
C= 8.00E+06
D= 1.20E+07
E= 1.60E+07
F= 2.00E+07
G= 2.40E+07
H= 2.80E+07
I= 3.20E+07
J= 3.60E+07
K= 4.00E+07
L= 4.40E+07
M= 4.80E+07
N= 5.20E+07
O= 5.60E+07
P= 6.00E+07
Q= 6.40E+07
R= 6.80E+07
S= 7.20E+07

Figure 14.

Iso-bar contour plot of effective stresses
for upper beam strike (case 1)-oblique view

Figure 15.

Isobar contour plot of effective stresses
for lower beam strike (case 2)-from a view
perpendicular to horizontal plane of symmetry.

SLAC MASK/CASE 2/LOWER BEAM STRIKE/TACO3D&GEMINI THERMAL STR
 /VIEW PERPENDICULAR TO VERTICAL PLANE OF SYMMETRY
 CONTOURS OF EFF. STRESS (V-M) (PA)

MIN= 395E+05 IN ELEMENT 1339

MAX= .675E+08 IN ELEMENT 78

STRESS
 CONTOUR VALUES

A= 0.
 B= 4.00E+06
 C= 8.00E+06
 D= 1.20E+07
 E= 1.60E+07
 F= 2.00E+07
 G= 2.40E+07
 H= 2.80E+07
 I= 3.20E+07
 J= 3.60E+07
 K= 4.00E+07
 L= 4.40E+07
 M= 4.80E+07
 N= 5.20E+07
 O= 5.60E+07
 P= 6.00E+07
 Q= 6.40E+07
 R= 6.80E+07
 S= 7.20E+07

Figure 16.

Isobar contour plot of effective stresses
 for lower beam strike (case 2)-from a view
 perpendicular to vertical plane of symmetry.