Thermal Analysis of the Beam Missteering in APS Storage Ring*

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Abstract

Several bending magnet beam missteering cases have been investigated for the 7-GeV storage ring of the Advanced Photon Source (APS). One of the critical missteering events is presented in this paper. Finite element analyses are performed to solve for both temperature and stress fields. Thermally induced deflections are determined by utilizing beam bending theory. A safe current limit is established for the storage ring chambers.

I. INTRODUCTION

As shown in Fig. 1, a typical sector of the APS storage ring contains three straight sections (sections 1, 3, 5 and 6) and two curved sections (sections 2 and 4). The cross-section geometry of the aluminum storage ring extrusion is shown in Fig. 2. The x-rays are generated in the bending magnet chamber as positrons travel along the curved chamber. A significant missteering of the x-ray fan will subject the curved chamber to local heating which may result in an unacceptably large temperature rise, thermal deflections, and stresses.

As shown in Fig. 2, the chamber extrusion contains three 0.5 inch water channels for both chamber bakeout and cooling. During normal operation, water flows 2 ~3 GPM at 25 °C through the three channels. The corresponding Reynolds number is 16,500. By employing the Colburn equation

$$h\left[\frac{W}{m^2\ {}^\circ C}\right] = (2.26 + 0.028\ T_\infty)\ \frac{\dot{Q}^{0.8}\left[\frac{m^3}{hr}\right]}{D^{1.8}[m]}$$

the equilibrium water convection coefficient is found to be $0.4\ \frac{W}{cm^2\ {}^\circ C}$; where T_∞, $\dot{Q}$ and D are water temperature, flow rate, and channel diameter, respectively.

For most missteering cases the bending magnet fan hits the chamber at a shallow grazing angle. The power is, therefore, widely spread out along the beam direction. A two-dimensional analysis is then sufficient to predict the temperature gradients. The stress induced by thermal gradients can be decomposed into two parts: (1) stress generated by the two-dimensional inhomogeneous temperature field under plane strain conditions, and (2) bending stresses due to thermally induced chamber deflections. Chamber deflections are calculated by imposing the averaged temperature and bending moment changes due to temperature gradients. Details of this analysis procedure can be found in text books, e.g., Boley and Weiner [1].

II. BENDING MAGNET MISSTEERINGS

Ideally the bending magnet x-ray fan will be in the middle of the 10 mm vertical aperture of the photon channel (see Fig. 2). Because of the accidental beam missteerings, however, the x-ray fan can hit the positron beam chamber or the photon channel. Several possible cases of beam missteerings are identified in Table 1. The most critical case is when the positron beam is vertically offset by 5 mm, and the x-ray fan hits its own positron chamber in a region just before the entrance to the photon channel. From the geometry of the curved chamber, a source distance of 1.8 meters and an incident angle of 47 mrad are obtained for this case. A beam power of 2.24 $\frac{W}{mm}$ is deposited on the surface along the z direction.

Assuming the upper and bottom halves of the positron chamber are composed of flat plates of same thicknesses, this heat transfer problem can be solved by a simplified one-dimensional analysis. Let L_1 and L_2 represent the distances of the two waters channels from the beam interception point, and q represent the linear power density of the intercepted beam. The maximum temperature rise is then given by

$$\Delta T_{max} = T_{max} - T_\infty = \frac{q'}{\frac{1}{\frac{1}{ht}+\frac{L_1}{Kt}} + \frac{1}{\frac{1}{ht}+\frac{L_2}{Kt}}}$$

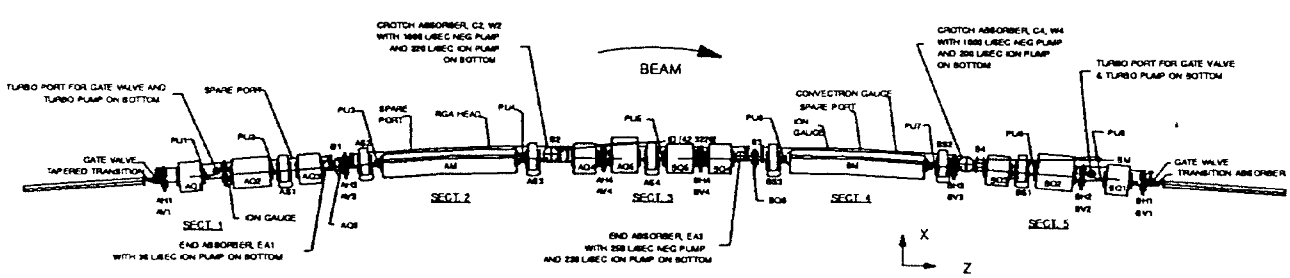

Figure 1. Storage Ring Sector

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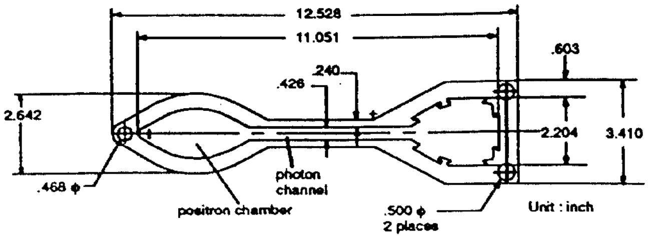

Figure 2. Storage Ring Extrusion

where K and t represent conductivity and thickness of the chamber, respectively. Substituting $L_1(=96.5\text{ mm})$, $L_2(=229\text{ mm})$, $K\left(=0.16\frac{W}{mm\ {}^{\circ}C}\right)$, $h\left(=0.4\frac{W}{cm^2\ {}^{\circ}C}\right)$, $t(=12.7\text{ mm})$ and $q'\left(=2.24\frac{W}{mm}\right)$, the maximum temperature rise $T_{max}-T_{\infty}$ is found to be 100 °C, which is in fair agreement with the maximum temperature rise (110 °C) obtained by a detailed two-dimensional finite element analysis shown in Fig. 3.

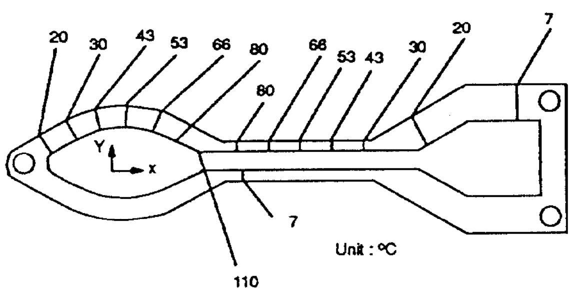

Figure 3. Temperature Rise due to Beam Missteering (Case 2)

When the Gaussian beam size is relatively small, a closed form stress analysis developed by Sheng and Howell [2] can be used. This analysis shows that the maximum stress is practically equal to the off-plane stress (σ_{zz}), and can be obtained by the simple formula:

$$\sigma_{zz}=-\alpha E\Delta T_{max}$$

where α and E represent thermal expansion and Young's modulus, respectively. For 6063 –T5 aluminum, they are 2.25×10^{-5} $\frac{1}{{}^{\circ}C}$ and 1.1×10^{7} Psi, respectively, and the maximum off-plane stress becomes –27 Ksi. Figure 4 shows off-plane compressive

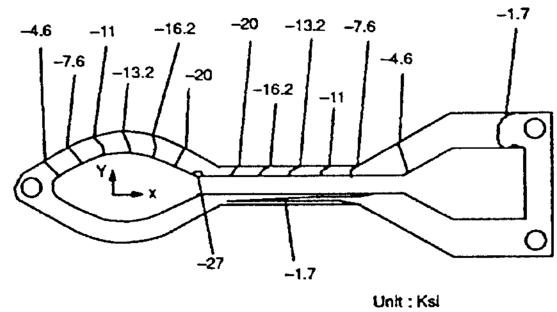

Figure 4. Plane Strain Off–Plane Stress due to Temperature Rise

stress contours. The maximum stress agrees closely with the calculation shown above. Since the entire section behaves like a beam subjected to line heating, the actual maximum stress along the chamber will be lower than that calculated in the two-dimensional model. This is because the chamber at both ends is flexible in the longitudinal direction and releases thermal stresses as it deforms. The procedure for calculating the actual

Table 1
Case Studies of Beam Missteering

No.	Vacuum System Location Being Heated	Source	Distance to Source	Missteering Angle/offset	Current (mA)	Results (maximum): Temperature (0°C ambient)	Stress*	Displacements: X Direction	Y Direction
1	Photon Channel, S2	M2 Bending Magnet (Upstream Sector)	18.6 m (731 in)	.54 mR/5 mm .27 mR/O	300	5°C	1,231 Psi		
2	Positron Chamber S2 or S4	M1 or M2 Bending Magnet	1.8 m (70.87 in)	0/5 mm+	100	110°C (1.1°C/mA)	20,000 Psi (200 Psi/mA)	0.066 in (6.6e–04 in/mA)	0.145 in (1.45e–03 in/mA)
3	Photon Channel S2 or S4	M1 or M2 Bending Magnet	3.6 m (141.73 in)	4.0 mR/9 mm	300	1.4°C (0.05°C/mA)			
4	Back Wall of S4 No additional cooling	M1 Bending Magnet	10.0 m (393.70 in)	None	300	76°C (0.25°C/mA)	18,688 Psi (62.3 Psi/mA)	0.0037 in (1.23e–05 in/mA)	0.0018 in (6.0e–06 in/mA)
5	Positron Chamber S2	M2 Bending Magnet (Upstream Sector)	15.9 m (627.24 in)	.6 mR/5 mm	300	47°C (0.16°C/mA)	5,200 Psi (17.3 Psi/mA)	0.056 in (1.9e–04 in/mA)	0.038 in (1.3e–04 in/mA)
6	Commissioning S6	M2 Bending Magnet	5.3 m (207.3 in)	0/5 mm	300	20°C (0.1°C/mA)	3,566 Psi (16.32 Psi/mA)	0.0183 in (6.1e–05 in/mA)	0.0185 in (6.2e–05 in/mA)

* Resultant bending stress.

maximum chamber stresses and deformations is summarized as follows :

(1) By using the temperature field shown in Fig. 4, across the chamber extrusion one can determine the averaged axial force P and in-plane bending moments M_x, M_y due to temperature gradients,

$$P = \int_A \alpha ET(x^*, y^*)dA,$$
$$M_x = \int_A \alpha ET(x^*, y^*)y^*dA,$$
$$M_y = \int_A \alpha ET(x^*, y^*)x^*dA,$$

where A is the cross sectional area, and x^*, y^* are the plane coordinates with respect to the centroid point of the extrusion.

(2) Generate a three-dimensional finite element beam model and place P, M_x, and M_y on the starting and ending points of the beam heating area. The opposite signs are chosen such that the resultant forces and moments are self balanced. Calculate the chamber deflections and axial force P′ and bending moments M'_x, M'_y.

(3) Determine the moments of inertia I_{xx} and I_{yy}, the resulting bending stresses obtained by reducing the off-plane compressive stress σ_{zz} with axial stresses generated by $\frac{P'}{A}$, $\frac{M'_x y^*}{I_{xx}}$, and $\frac{M'_y x^*}{I_{yy}}$. (Note that A = 12.97 in^2, I_{xx} = 11.6 in^4, and I_{yy} = 220 in^4 for the current chamber design.)

The maximum thermal stress in this case is calculated to be 20 Ksi, which is almost 7 Ksi lower than the value obtained under plane strain assumptions. Since this stress is compressive and lower than the yield stress (25 Ksi at 150 °C), as well as confined in a localized region, it is considered to be within the allowable stress limits.

III. CONCLUSIONS

Several beam missteering cases for the APS storage ring chamber were modeled to determine the temperature, deformations, and stress fields. Analysis results indicate that the chambers are passively save (i.e., they require no active interlock for protection) for beam currents up to 100 mA.

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