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ANL/CP--74658

DE92 014863

THERMAL AND STRUCTURAL ANALYSIS OF HIGH PRECISION BEAMLINE POSITION MONITORS FOR SYNCHROTRON X-RAY BEAMS

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ABSTRACT

The photon beam position monitors (PBPM) on the front end of the 7-GeV Advanced Photon Source (APS) synchrotron facility under construction at Argonne National Laboratory (ANL) are precision devices that measure spatial as well as angular positions of the x-ray beams. There exist two such devices on each APS front end, and they are set approximately 4 m apart. The required spatial resolution of these devices is of the order of a few microns; the required angular resolution is less than a micro-radian. These specifications make the material selection, design and stability of the PBPM very challenging tasks. The PBPM blades, which generate the photo-electrons signal from the x-ray beam, are indirectly cooled to prevent overheating by the x-ray beam. Even then, the blade is subject to severe thermal stresses. Prediction of the long-term material and position stability of the PBPM blade requires very careful heat transfer and stress analyses. In this paper, thermal analyses under the prevailing high heat flux from the incident beam and the corresponding stress analyses for various blade configuration are presented. As a result of these analyses, several options in design were developed and compared, including material selection for the blade and its structural detail.

INTRODUCTION

The PBPM on the front end of the 7-GeV APS synchrotron facility are precision devices that measure spatial and angular positions of the x-ray beams [1]. There exist two such devices on each APS front end at approximately 4 m apart [2]. The tight requirements on spatial and angular resolutions make the structural design, and material selection of the PBPM very challenging.

The PBPM is composed of a diamond blade [3] to achieve very good thermal conductance and two copper (Cu) block on each side of the blade. On each side of the blade, there is a layer of 0.5 mm thick oxidized Beryllium (BeO) strip. The BeO layers are used for electrical insulation. The assembly is shown schematically in Fig. 1. On one side, a 10 mm thick Cu block is cooled by water at the opposite surface. On the other side of the diamond blade, a 1.14 mm thick Cu block is clamped down by a group of set screws. These set screws are placed apart judiciously to obtain as uniform as possible an interfacial pressure between the contacting surfaces for good thermal conductance.

In this paper, thermal analyses with different details of modeling of the PBPM under the prevailing high heat flux from an x-ray beam are presented. As a result of these analyses, optimal shapes of the PBPM were investigated and compared, and then material selection as well as structural detail were examined. First, a two-dimensional thermal analysis of PBPM with a constant temperature at the clamped edge of the PBPM was performed. The results were found to be consistent with experimental results. A three-dimensional analysis was then performed to model the PBPM more precisely. Different contact conductance coefficients at the interface of the diamond and the BeO strip were used depending on the interface pressure. A static analysis for this interface pressure was done prior to the thermal analysis to determine the pressure distribution in order to best estimate the contact conductance Fig. 4.

The x-ray source considered for this analysis is the APS Undulator A, which has the highest heat flux of APS devices. The total power of the x-ray beam from this device is 10170 W. The heat flux absorbed by the PBPM at 16 m from the source, shown in Fig. 2, can be approximated by the following expression [4]:

$$F(v, h) = \frac{3P}{4\sqrt{2\pi}\sigma H} e^{-\frac{v^2}{2\sigma^2}} \left(1 - \frac{h^2}{H^2}\right) \qquad (1)$$

where h and v are horizontal and vertical distances measured from the center of the beam, P is the total absorbed power, 2H is the horizontal extent of the beam, and σ is the standard deviation of the vertical Gaussian profile.

Early assessment by analytical and computer solutions confirms that the heat loss through radiation is very small (less than 1%) compared with conduction, and hence is negligible. For an uncoated diamond blade, when the x-ray beam intercepts the diamond blade, the power profile will be absorbed at a very thin layer of the surface. Estimates indicate that the total required diamond thickness for complete absorption of the power is about 10 mm [7]. However, in this study, a metal-coated diamond blade is modeled, and, therefore, surface deposition is assumed regardless of the thickness or kind of metal coating. Depending on the kind and the coating thickness, this assumption yields conservative estimates of maximum temperature.

The analytical study here examines a plausible operational scenario in which x-ray beam missteering occurs, and the PBPM blade is hit directly by the full beam. In normal operating conditions, the PBPM blades are positioned away from the thermally hot central regions of the x-ray beam and are exposed only to the peripheral regions of the beam (soft energies).

NUMERICAL ANALYSIS

Two-dimensional model

The two-dimensional (2-D) analysis assumes that the temperature at the clamped part of the blade remains uniformly constant and the total power is absorbed as surface heat flux.

The diamond blade size of the PBPM design should be as small as possible while keeping the maximum temperature below the tolerance temperature. This implies that the PBPM's shape is optimal when it is designed in such a way that, as the beam moves from the thickest part of the blade toward the tapered end (top to the bottom of the blade), the maximum temperature attained should remain substantially the same for the smallest blade length. A curved shape for the blade will likely be achieved if no constraint is subjected to the shape of the blade during the optimization. However, for linear feedback under normal working conditions, a straight section for working region at the top (between L1 and L2 in Fig. 3) followed by a curved tail (the part between L2 and L) should be used. The working region will be exposed to the peripheral regions of the beam and will send back a signal that is proportional to the position of the beam.

To prevent potential oxidization of the diamond material (a conservative precaution in the UHV environment), it is desirable to keep the maximum temperature of the blade below 600 °C.

For optimization, the maximum temperature is kept below 600 °C as the beam is moved from the top to the bottom of the blade. By doing this, the blade geometry can be optimized by adjusting the dimensions indicated in Fig. 3. These considerations result in the following values for the parameters in Fig. 3: L1=5 mm, L2=45 mm, L=60 mm, H1=12 mm, H2=16 mm, and H=20 mm. The resulting temperatures for different beam locations are presented in Fig. 5.

An examination of Fig. 5 indicates that when the beam moves from the top to the bottom of the blade, the maximum temperature reaches 572 °C. This temperature decreases gradually in the straight section (from L1 to L2), which is designed for a linear signal response to detect the position of the beam. The maximum temperature again rises to 575 °C in the curved part. The curved section is used to reduce the total length of the diamond blade and, hence, the size of the whole PBPM assembly.

Three-dimensional model

The three-dimensional (3-D) analysis models the whole PBPM assembly. For this analysis, the thickness of the diamond blade is taken to be 50 μm. The thinner the blade, the less power is deposited in it, which is advantageous from a cooling point of view. In the ultimate design, a somewhat thicker blade may be used because of the requisite stiffness considerations. A finite element code is used for both the stress and the thermal analyses, in which gap elements were used to model the contact surfaces.

It is a more precise analysis to take into account the contact conductance between different materials and different surfaces in the 3-D model. But it is difficult to estimate the contact conductance between two different materials, since it depends on many variables such as the hardness of the contacting materials, surface finish, contact pressure, etc., [5 and 6]. The most significant variable is the contact pressure.

Since the contact conductance mainly depends on the pressure of the contact surfaces if other factors remain the same, a static stress analysis was carried out to determine a reasonable contact conductance. Because the PBPM utilizes a group of set screws for the blade fastening, the ultimate torque for the set screws was calculated and was then used to obtain the force for input. This value was further checked by some simple in-house tests.

The pressure distribution is shown in Fig. 4. Because the fastened plates are very thin, the high normal pressure is distributed very locally around the set screws. Elsewhere, the pressure is very small. For a conservative but simplified analysis, a 5 ksi pressure is assumed for the contact conductance under the set screws and there is no contact between the screws.

References [5 and 6] contain experimental data on contact conductance for oxygen-free copper and beryllium at different interfacial pressures and under vacuum conditions. However, no data above 1 ksi pressure is given in these references. Therefore, we used the data for 1 ksi in our calculations, again a conservative assumption.

By adjusting the design variables L1 and L2, we tried to keep the maximum temperature below 600 °C when the beam hits anywhere from the top of the blade to the lower part of the blade. The analysis results in the following values for the variables indicated in Fig. 3: L1=3 mm, L2=53 mm, L=70 mm, H1=12 mm, H2=16 mm, H=20 mm. The total length is 70 mm, 10 mm longer than that obtained with the 2-D model. The 3-D model is considered more realistic than the 2-D model because a contact conductance has been modeled rather than the less realistic but simple constant boundary temperature assumption of the 2-D model. The 3-D model results in a longer curved part for the blade in order to achieve a tolerable maximum temperature with beam movement. The curved portion of the blade becomes 17 mm in the 3-D analysis versus 15 mm in the 2-D case. The length of this curved portion also depends on the lowest position that the beam center is allowed to reach before the interlock system engages. Currently, we use a beam position 2 mm above H1 in Fig. 3 as the lowest position of allowed beam missteering before shutdown. The computed temperatures for different beam positions are presented in Fig. 6.

RESULTS

The optimal shape of the diamond blade is investigated by 2-D and 3-D finite element analyses that are intended to help one choose the best blade geometry for thermal performance and design optimization. Both the 2-D and 3-D analyses confirm that the current PBPM design with diamond blades can survive beam missteering when the maximum temperature is kept below 600 °C. A major difference between the 2-D and 3-D analyses is that the maximum temperature is not a function of the blade thickness for the 2-D model, while it is for the 3-D case. In the 3-D model, the maximum temperature varies with blade thickness (which determines the total absorbed power). Calculations confirm that the thinner the blade, the closer are the 3-D and the 2-D results. One obvious reason is that, as the blade becomes thinner, the contact resistance becomes smaller compared with the total resistance. Also, the total power absorbed by the blade is proportional to the thickness of the blade. Because the contact area of the beam remains constant while the blade thickness is varied, the thinner the blade, the lower the temperatures.

A comparative analysis is performed with different contact conductances in the screwed down area to assess the effect of the effective contact conductance on the maximum temperature. When the effective contact coefficient is varied from h=10 $W/cm^2\,^0C$ to 5 $W/cm^2\,^0C$ in the 3-D analysis, calculations show little difference in maximum temperature, which remains constant at about 569 ^0C. When the effective contact coefficient is further reduced to h=2 $W/cm^2\,^0C$, the maximum temperature increases somewhat to 593 ^0C. A value of

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0.5 W/cm^2 ^{0}C gives 700 ^{0}C. The above results show that the relative resistance of the contact surface to the total resistance is very small, and the maximum temperature is not sensitive to the contact pressure within the range of 1 to 10 ksi.

DISCUSSION

The results in this study are from steady-state thermal analyses, which were based on very conservative assumptions. Normally the beam does not remain fixed spatially, and, as the beam moves, the feedback system takes corrective action. In an extreme case of missteering, the feedback system can even shut down the beam. The transient nature of the beam movement should result in lesser thermal effects on the PBPM blades and, hence, added thermal and structural safety. Transient beam analysis will be conducted in future studies. We also plan to test and measure a PBPM on an existing beamline. Those experimental results will be compared with the numerical results.

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Acknowledgement: This work supported by the U. S. Department of Energy, Experimental Facilities, Advanced Photon Source under Contract W-31-109-Eng-38.

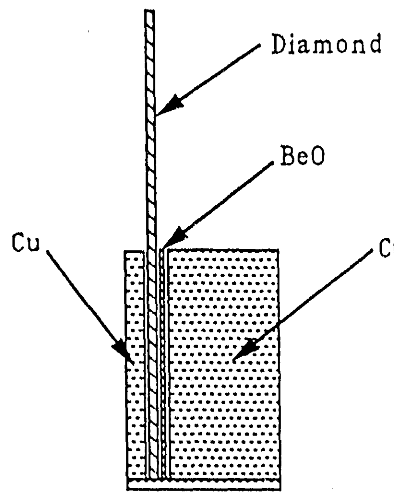

Figure 1. Beam Position Monitor Assembly

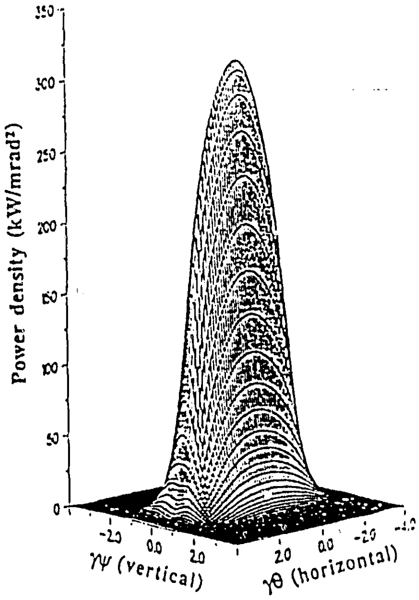

Figure 2. APS insertion device power distribution

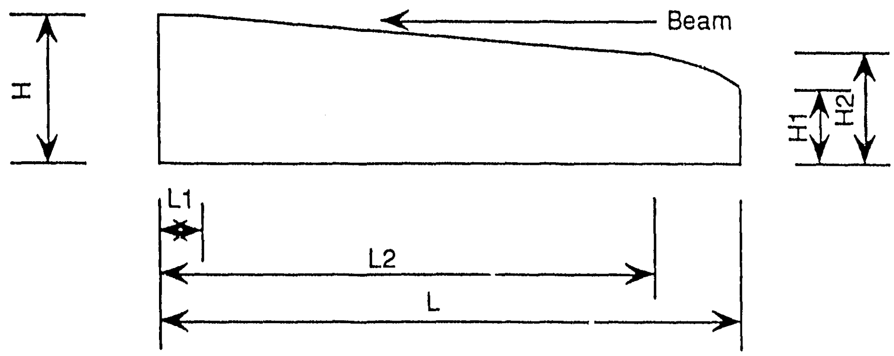

Figure 3. Schematic of the Blade for the Photon Beam Position Monitor

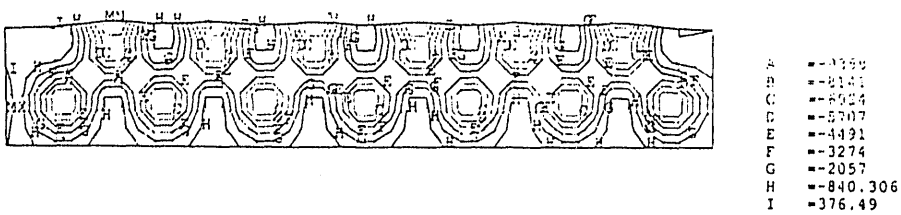

Figure 4. Pressure at the contact surface of diamon and BeO

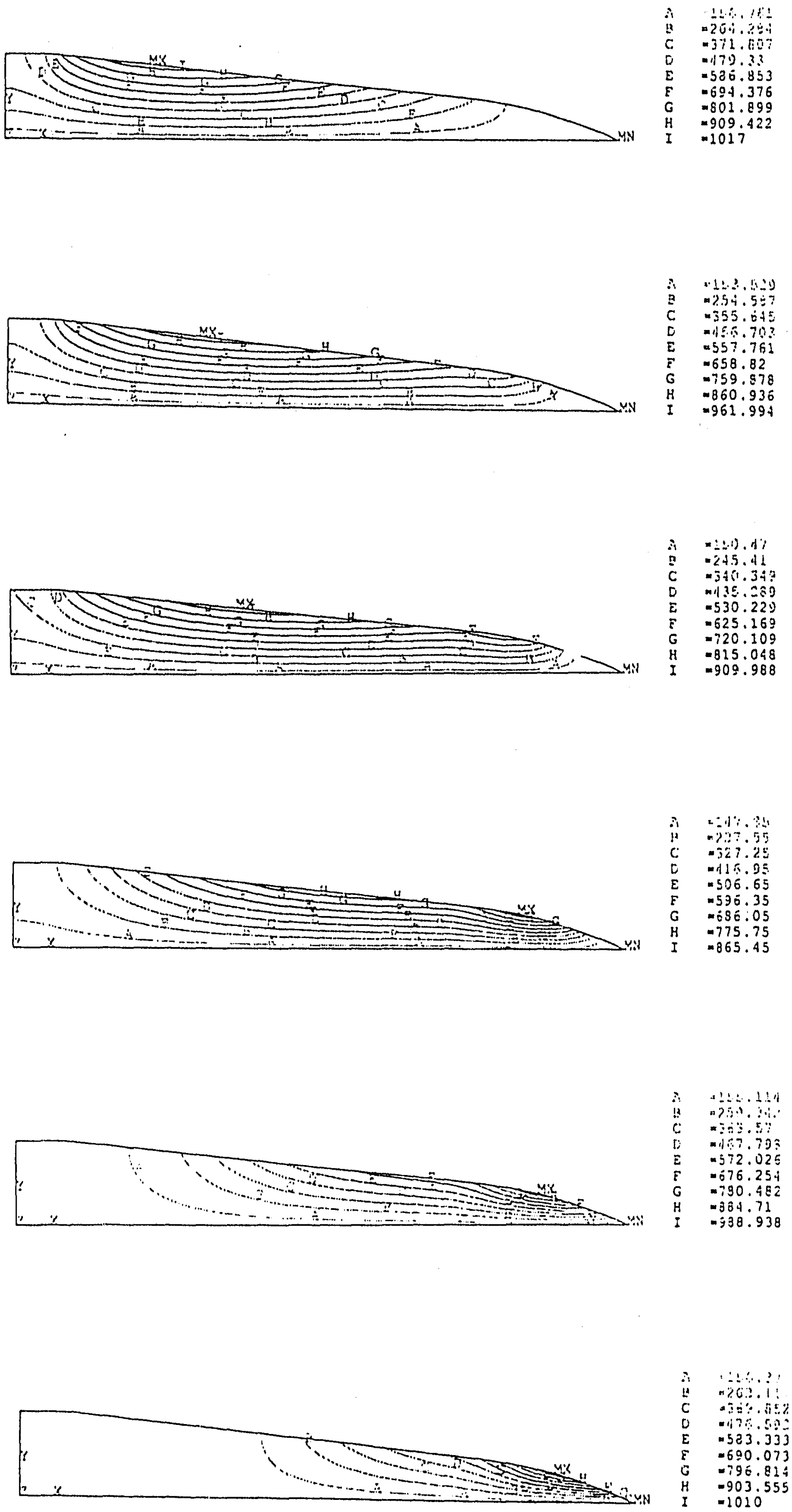

Figure 5. Temperature contours of diamond blade for 2D model

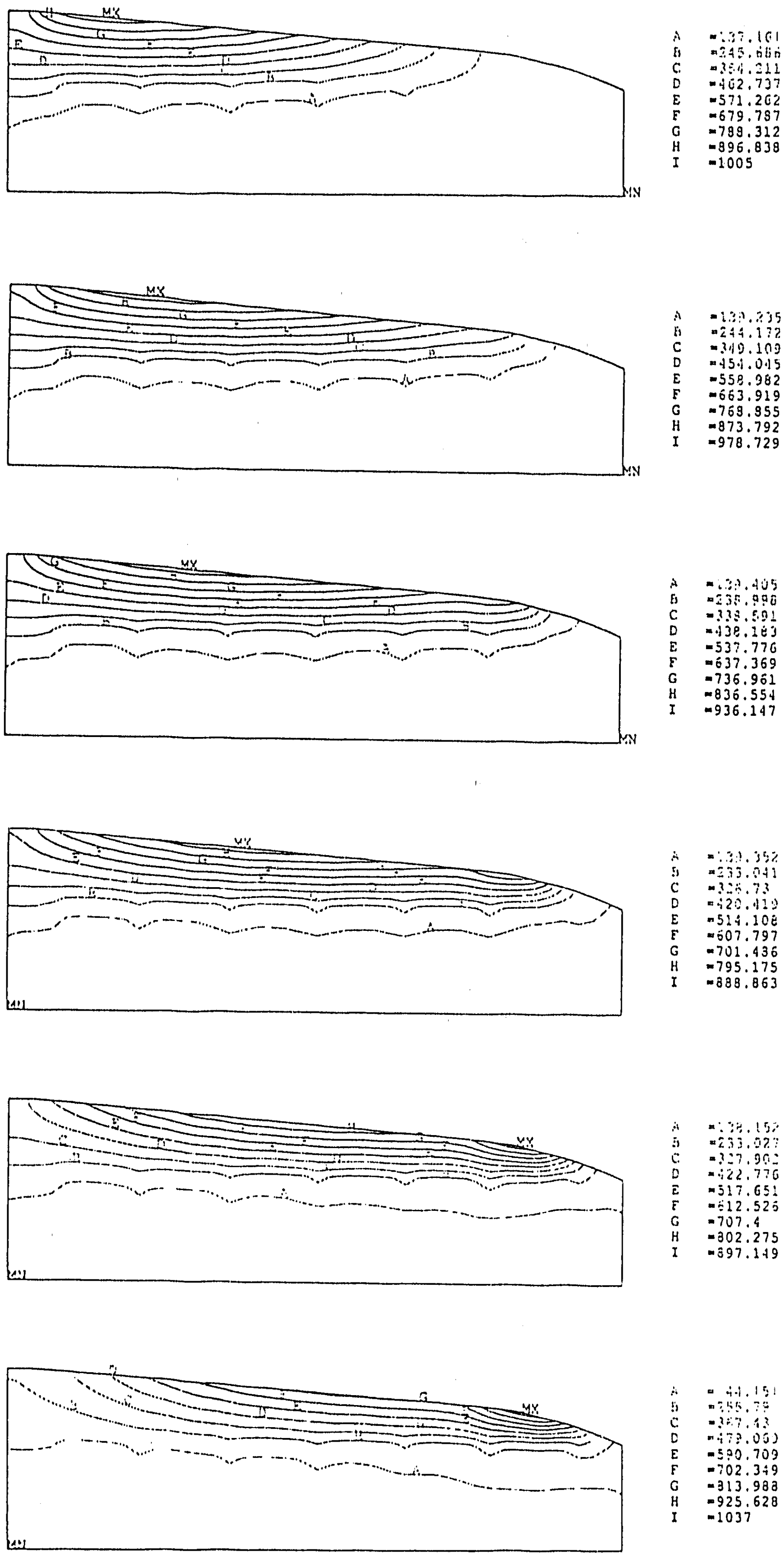

Figure 6. Temperature contours of diamond blade for 3D model

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