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EXPLORATORY HEAT TRANSFER STUDIES ON CRITICAL
ELEMENTS OF A PROPOSED 6 GeV SYNCHROTRON*

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Abstract

Certain types of insertion devices for angiography, can produce extraordinarily large heat fluxes on critical components of a synchrotron beam line and its optics. The shutters, beam splitters, filters, and the first-stage monochromators all are subjected to large fluxes of radiation. The cooling requirements of such beam line components are approached in a comprehensive manner to identify the governing parameters from first principles. Analytical techniques have been used to study various methods of handling the heat loads using both liquid metal and water coolants for various potential heated geometries. It is found that when properly designed, liquid metal cooling can be much more efficient. In addition, composites and low Z surfaces have been considered. Also investigated are the heat transfer problems of the optical stages and rotating monochromators.

Introduction

A limiting factor in the design of high-power synchrotron radiation devices is the severe cooling requirements and consequent structural problems imposed on the beam line components. Conceptual design studies on a proposed 6 GeV synchrotron indicate that heat loads on certain elements may be as large as 1 kW/mm^2 . Flux levels of this magnitude are very high for conventional cooling methods and engineering materials. Complicated engineering methods and materials and/or non-conventional cooling methods may therefore have to be utilized in the design of the beam line structures.

Sharma and Ulc¹ propose to use water cooled heavy copper surfaces exposed to the beam at or below 6° grazing angles for their NSLS super-conducting Wiggler Beam. This design allows transient operation of the beam at full power, but severe limitations are imposed on the system operation regarding beam stability and tolerable angular oscillations ($\pm 1.5 \text{ mrad}$). The Wiggler exit part (crotch piece) and the beam splitter elements are the critical pieces.

Mills et al.,² proposed to use a composite beryllium heat diffuser brazed to a water-cooled copper cylinder for the exit-line crotch of the Cornell 8 GeV CESR unit. For this application the computed power density is 0.740 kW/mm^2 . An analysis supported by a reduced power electron beam experiment implied that this composite structure would be able to sustain the heat load imposed on the crotch piece.

In another study, an aluminum model crotch piece that was vigorously water-cooled and subjected to sweeping electron beam radiation showed surface melting at 0.230 kW/mm^2 power density³ in studies supporting a SSRL Wiggler Beam design.

Studies involving cooling of the beam line optics under flux levels in excess of 0.5 kW/mm^2 are very scarce in the open literature. However, the two cases cited above show that a design that is complex or incorporates the selected optical advantages of composite materials (low Z beryllium fused to high Z copper backings) can support higher loads. One aim of our research is to pursue these matters further.

The most critical element of a beam line, the first monochromator, is difficult to cool since it is subjected to the maximum intensity of the beam, and its mechanical and thermal stability must be controlled to a very high degree (angular errors of parts in 10^5 would make a monochromator useless). One method of greatly increasing the heat-load-handling capabilities of any material is to move or spin the material such that the heat load spreads over a large area. Of course, spinning a single crystal monochromator in such a way so that there is practically no variation of the angle of planes of crystals is a formidable engineering task, and one in which we are currently engaged. The rotation method, which has been used to increase the heat-load-handling capabilities of rotating x-ray anodes, has been extensively studied. One of the earliest studies of the rotating anode case was by Muller.^{4,5,6} His work was followed by DuMond et al.⁷ and Oosterkamp.⁸

Muller derived closed form approximate solutions to both stationary and spinning circular anodes and calculated the theoretical load limits. For the spinning target, a periodically heated focal point is assumed. DuMond et al.,⁷ advanced Muller's analysis to a continuously operated spinning target where periodic reheating of every point in the path of the focal spot is allowed so that a steady state of thermal oscillations is established. This treatment results in much better estimates of the thermal loads carried by

a spinning target. Oosterkamp⁸ on the other hand, analyzed extensively both stationary and rotating x-ray anodes under continuous load and with and without water cooling. However, his limited cooled rotating anode solution comes from ad hoc considerations rather than from the first principles on which his stationary anode solution is based.

The above discussed analyses were one-dimensional approximations of problems that are multidimensional. The state-of-the-art review of the targets summarized here reveals that there is no comprehensive solution to a rotating target with cooling and under continuous thermal load. Therefore, the other aim of the present study has been to treat such a rotating target case with cooling and composite materials and in multiple dimensions.

In summary, this study has two aims:

To further study cooling of beam line optics under flux levels $>0.5 \text{ kW/mm}^2$ using designs that are complex or incorporate the advantages of composite material, and

To study the response of a rotating target that uses composite materials, with cooling and in multiple dimensions.

Analysis

The fundamental problem in synchrotron beam line component cooling is indicated schematically in Fig. 1. A plate of thickness d is heated from one side with synchrotron radiation and cooled from the other side by a coolant with a surface heat transfer coefficient h and bulk temperature T_c . The heating can be in the form of a pure surface heat flux q'' or part surface flux q'' and part an internal heat generation u''' , depending on the Z value for the wall material used. For lower Z value materials, such as Be, the heating is purely in u''' form (internal heat generation). But for high Z materials such as copper, stainless steel, or titanium, the total heat flux is absorbed almost entirely at the surface and, therefore, heating is in purely q'' form. The distinction between the high Z and low Z value materials that can be used for the wall is a significant consideration, as will be shown. Volumetric heating with u''' causes specifically lower surface temperatures and generally lower wall temperatures, whereas q'' type heating causes the highest surface temperatures. Because the beam line components are usually housed in an ultra-high vacuum (UHV) environment, the lower surface temperatures are beneficial in terms of metal stripping and sputtering considerations, as well as desirable for structural integrity and the mitigation of localized optical distortions.

Under steady-state conditions the cooling of a wall with thermophysical properties k , ρ , and c (thermal conductivity, density, and specific heat) is controlled by the Biot modulus ($Bi = h d/k$). The cooling of the wall can be controlled by conduction ($Bi < 0.1$) or by convection ($Bi > 0.1$). The former is called thin-wall approximation, and the latter is called thick-wall approximation. Considering two representative wall thicknesses—one 2.5 mm - 0.1 in., and the other 25 mm - 1.0 in.—one can construct a table (see Table 1) using water or liquid-metal coolant for various wall materials. For water, the surface heat transfer coefficient h is $O(10^3)$, whereas for most liquid metals, h is $O(10^4)$.

Table 1. Typical Biot Modulus Values for Walls Cooled by Water and by Liquid Metal

Material	d = 2.5 mm		d = 25 mm	
	Water	Liquid Metal	Water	Liquid Metal
Cu type, $k \sim O(240)$	0.04	0.4	0.4	4.0
Be, TA, BeO, Mo, Al, Ha25 type, $k \sim O(100)$	0.08	0.8	0.8	8.0
Ti, SS type, $k \sim O(10)$	0.8	8.0	8.0	80.

Fig. 1. Fundamental Problem of Synchrotron Beam Line Optics Cooling

A review of Table 1 shows that for most synchrotron wall cases the cooling is convection-controlled. With water as the coolant, the conduction-controlled cases belong to only very highly conductive wall materials (the first two groups of materials in Table 1) and only with wall thicknesses of 2.5 mm or less. A copper wall with water as the coolant becomes, again, convection-controlled whenever the wall thickness exceeds 6 mm (~1/4 in.). Due to the structural integrity considerations the copper conduits used in synchrotron beam line elements are usually thicker than 12.5 mm (1/2 in.). Therefore, the cases highlighted in Table 1 are not

feasible from an engineering standpoint. From the information provided in Table 1 for both water and liquid-metal cooling, any enhancement in the heat transfer coefficient h is beneficial, other factors remaining the same.

Liquid metals, with their superior heat transfer coefficients, are potentially better coolants for beam line optics. However, along with the beneficial effects of improved heat transfer, one also has to consider other aspects such as cost, safety, material compatibility, low vapor pressure, and non-freezing at room temperatures in deciding to use liquid metals as coolants. NaK, a sodium-potassium mixture, gallium, or gallium-indium are potential candidate coolants. An analysis using NaK as a coolant as opposed to water presented here as a case study.

Composite Structures

The use of composite structures in x-ray anode technology to obtain better heat sink capacity under transient conditions is well known. For example, tungsten-clad copper blocks are widely used as targets. The optimization parameter in selecting a two-layer composite structure is given by:⁹

$$n = \frac{\rho_2 c_2 d_2}{\rho_1 c_1 d_1} > 1.0, \text{ heat sink ratio.} \quad (1)$$

The greater the heat sink ratio than unity, the greater the heat sink capacity of the composite under transient conditions.

In the steady-state case, a two-layer plate can be optimized with respect to choice materials and thickness to accommodate higher values of heat input, $q''/\bar{d}$, than is possible by using separate equivalent weights of either material. These results are generally achieved if an outer layer of high-melting-temperature material is backed by a material of higher conductivity and lower melting point. The critical parameter is given by:⁹

$$m = \sqrt{\frac{\rho_2 c_2 k_2}{\rho_1 c_1 k_1}} > 1.0, \text{ interface temperature ratio.} \quad (2)$$

Parameters n and m in proper combination assure obtaining the maximum allowable heated surface and interface temperatures for a given application. Beryllium oxide over beryllium, tungsten over copper or aluminum, and molybdenum over copper are examples of such choices where m and the melting temperature ratios typically are on the order of 2 or better.

Our interest is not so much in selecting composite wall materials for a better heat sink effect, but rather in selecting composites with special optical quality to effect lower surface temperatures on synchrotron heatings. This matter is dealt with next.

Partially Transparent Wall Materials

If a cooled wall of thickness d is exposed to monochromator radiation q'' , and if the wall material is partially transparent to radiation the heat flux at depth x is given by the well known relationship:

$$q_x = q'' e^{-\mu x}, \quad (3)$$

where μ is the mass absorption coefficient.

For a single wall material cooled on the back by a fluid at temperature T_∞ , the 1-D temperature solution in the solid is given by:

$$\frac{k}{q'' d} (T_x - T_\infty) = \frac{1}{\mu d} [e^{-\mu d} e^{-\mu x}] + (1 - \frac{x}{d}) + \frac{1}{Bi} (1 - e^{-\mu d}). \quad (4)$$

The maximum temperature, which is at the surface ($x = 0$), is given by:

$$\frac{k}{q'' d} (T_s - T_\infty)_t = \frac{1}{\mu d} e^{-\mu d} + 1 + \frac{1}{Bi} (1 - e^{-\mu d}). \quad (5)$$

If the solid is not at all transparent to the oncoming radiation (high Z solids), the surface temperature becomes

$$\frac{k}{q'' d} (T_s - T_\infty)_s = 1 + \frac{1}{Bi}. \quad (6)$$

Note that the resulting maximum surface temperature from Eq. 5 will always be less than the one from Eq. 6 as long as

$$(\frac{1}{\mu d} - \frac{1}{Bi}) e^{-\mu d} < 0, \quad (7)$$

or that

$$\frac{1}{\mu d} < \frac{1}{Bi}, \quad (8)$$

or, equivalently

$$\frac{h}{k} < \mu \quad (9)$$

is satisfied.

For the cooled wall temperature with nontransparent solid,

$$\frac{k}{q''d} (T_w - T_\infty)_s = \frac{1}{Bi} . \quad (10)$$

For a transparent solid,

$$\frac{k}{q''d} (T_w - T_\infty)_t = \frac{1}{Bi} (1 - e^{-\mu d}) . \quad (11)$$

According to Eqs. 10 and 11 the cooled wall temperature for the transparent solid will always be lower than the nontransparent solid. This is a direct result of the fact that part of the energy from the radiation reaches all the way to the coolant.

If the wall is exposed to white radiation, as would be the case for a Wiggler insertion device, the mass absorption coefficient μ is a function of the spectral energy, E , of the synchrotron radiation, i.e., $\mu(E)$ and the analysis becomes more complicated.

For the synchrotron radiation resulting from a proposed 6 GeV synchrotron Wiggler with a critical energy E_c and total power P_0 , the power absorbed at a depth x can be calculated with sufficient accuracy for our purposes by the following double integral:

$$\frac{P(x, E)}{P_0} = \left(1 - \frac{2}{E_c} \int_x \int_E E \mu(E) \rho e^{-\mu(E) \rho x} dE dx \right) . \quad (12)$$

This is done to calculate the incident power density P at depth x of a solid of $\mu(E)$ and density ρ subject to a total surface power density of $P_0 = 1 \text{ kW/mm}^2$ and E_c of 31 KeV. The integration of Eq. 12 was carried out using Simpson's technique and the tabular data¹⁰ for the mass absorption coefficient in Eq. 9. The results of the double integration in Eq. 12 are given in Table 2 for beryllium (be), silicon (Si), and aluminum (Al).

Tables 2 shows that Be is a very transparent material that allows absorbs the incident radiation to penetrate to a depth of >40 mm. Therefore, Be would be a good material to use by itself or as a top-layer metal in a composite structure to absorb the applied power in depth. For Al and Si, results show that at a depth of about 3 mm nearly all the incident power is absorbed. Actual depths are much shallower if the synchrotron beam impinges on a beam line surface a shallow angle.

Table 2. Focal Total Power Density Levels in Beryllium, Silicon, and Aluminum Slabs Under Normal Incidence (Eq. 12)

x (mm)	$P_x = \alpha P_0$	x (mm)	$P_x = \alpha P_0$	x (mm)	$P_x = \alpha P_0$
Beryllium		Silicon		Aluminum	
0.4	0.950	0.2	0.49	0.2	0.56
0.6	0.941	0.4	0.40	0.4	0.47
0.8	0.924	0.6	0.32	0.6	0.39
1.0	0.916	0.8	0.26	0.8	0.34
2.0	0.857	1.0	0.21	1.0	0.29
4.0	0.767	2.0	0.06	2.0	0.13
6.0	0.693	2.7	0.00	3.0	0.04
8.0	0.629			3.4	0.02
10.	0.573				
20.	0.371				
30.	0.248				
40.	0.170				

Beam Line Optics - Horizontal Absorber

With the background provided in the preceding sections the first problem to be solved is that of a water-cooled horizontal copper absorber conduit in the beam line that is subject to grazing-angle synchrotron radiation. This problem has been tackled previously by Sharma and Ulc.¹¹ The problem is re-treated here to

*We use these parameters for a proposed 6 GeV Wiggler since these figures would be roughly appropriate for an anglography beam line. This application represents a difficult cooling problem for the proposed 6 GeV machine.

ensure that the solution techniques used in this study compare well with the previous work.

The absorber conduit is a heavy copper duct—16 mm (5/8 in.) thick by 43 mm (1-3/4 in.) wide with a 10 mm (3/8 in.) dia water channel through its center. A maximum power density of 1.0 kW/mm^2 at 6° horizontal angle to the beam is assumed. The water velocity is 6 m/s (20 f/s), requiring water flow of L/s (7 gal/min). A 3-D finite-element solution was carried out using the segmental module shown in Fig. 2. The 7.5 cm (3 in.) basic module was stacked 10 times to represent the 76 cm long (30 in.) absorber. The exit conditions calculated from the imposed initial conditions become input to the next modular length of the absorber until all 10 modules have thus been analyzed. Each module comprises 162 nodes—two in the axial (flow) direction, nine in the lateral direction, and nine in the vertical direction. The beam impinges the absorber centrally and symmetrically. Therefore, only half the absorber is represented by the nodular module using axial symmetry. The beam is represented in three segments approximating a Gaussian power distribution [1].

Figure 3 represents the axial temperature profiles for the surface, the cooled wall, and the coolant water at 0.5 kW/mm^2 and 1.0 kW/mm^2 total power density levels. The beam power is assumed to be purely a surface flux inasmuch as copper is a high Z metal. The highest temperature occurs at the surface and the lowest at the water-cooled interface. The water is assumed to enter the channel at a temperature of 26.7°C .

Fig. 2. Analytical Modeling of Absorber Plate Segment with a Coolant Channel

Fig. 3. Axial Temperature Profiles for a Solid Copper Absorber Plate. Left ordinate at 1 kW/mm^2 power level and right ordinate at 0.5 kW/mm^2 power level.

18 kW), the highest temperature is experienced at the end of the absorber channel which, is about 82°C (solid symbols in Fig. 3 and the right ordinate). The water bulk temperature rise is about 9.2°C, where the highest cooled-wall temperature becomes 61°C.

At 1.0 kW/mm² power density level (total power is 36 kW), the same temperatures are 226°C, 18.8°C, and 154°C, respectively (open symbols in Fig. 3 and the left ordinate). Results indicate that unless pressurized, the water will boil. However, the maximum attained absorber surface temperature is still much below the melting temperature of the copper. Therefore, the constraint to the design is not so much the peak copper temperature but the low boiling temperature of the coolant water. It is for this reason that alternative coolants should be searched for, unless the system can be pressurized or is designed for a boiling water heat transfer.

The results for 0.5 kW/mm² power density levels compare very well with those obtained by Sharma and Uic¹ in a similar, but 2-D, analysis of the absorber channel.

Rotating Targets/Monochromators

The configuration of the rotating target considered is shown in Fig. 4. In conventional x-ray work, the rotating targets are usually manufactured out of copper or tungsten-clad copper. The beam hits the target on the front and the back of the target is cooled by water. Cooling is generally quite vigorous. Typical target sizes are about 100-150 mm in diameter and 3 mm thick. In our study, a 62.5 mm radius target is considered. Both a stationary and a fast rotating target are analyzed with a 3-D model.

With current technology it is not unusual to have targets rotating at speeds exceeding 6000 rpm. At such fast rotational speeds the focal spot for the beam comes around very fast, before has a chance to cool down. Therefore, at fast spin rates the heat load from the beam is smeared uniformly over the area swept by the focal spot. This fact was used to advantage in the early target technology, as it was established that rotating targets would sustain much higher heat loads than stationary targets. In Figs. 5 and 6 the radial and axial temperature profiles for a water-cooled copper target are shown. In the analysis the heat load is gradually increased to the 1 kW/mm² level until steady-state solution is obtained at each power step. The focal area is a 6 mm square. Due to symmetry, only half the target is modeled (for a fast spinning target a wedge model will suffice).

In Figs. 5 and 6 the left ordinate is for a fast-spinning target; the right ordinate is for the stationary target.

Fig. 4. Rotating Target Analytical Model

Fig. 5. Radial Temperature Profiles in a Circular Target. Left ordinate is for a spinning target model; right ordinate is for a stationary model.

Fig. 6. Axial Temperature Profiles in a Circular Target. Left ordinate is for a fast-spinning target model; right ordinate is for a stationary model.

For a fast-spinning copper target, power levels up to 1 kW/mm^2 are accommodated, with the highest temperature attained (at the surface) at about 450°C (below half the melting point of copper).

For a stationary target at power levels of 0.30 kW/mm^2 , surface damage occurs due to partial melting of the copper material.

The radial temperature plots indicate strong localization of the temperature profile despite the high conductivity of copper. The prominent heat transfer direction is axial toward the cooled surface, justifying the approximation of 1-D heat transfer analysis employed in the earlier investigations.⁶⁻⁸

Various other exploratory metallic combinations also were tried as target materials. For example, a tungsten-clad stationary copper target (tungsten thickness $\sim 0.15 \text{ mm}$) with water cooling was found to tolerate heat loads up to 0.5 kW/mm^2 level without structural damage. A fast-spinning tungsten-clad copper target with liquid metal type coolant can tolerate heat loads up to 1.75 kW/mm^2 level without structural damage.

A silicon-crystal-clad copper target (0.25 mm Si , absorbing power within 0.15 mm depth), liquid-metal-cooled and fast-spinning, can sustain beam loading of 1.75 kW/mm^2 without structural damage. The maximum surface temperature in steady state is about 837°C with copper temperatures not exceeding 337°C anywhere. However, the surface temperature attained is much too high to be of practical usage in the beam line. At 0.5 kW/mm^2 loads, such a target will attain a peak silicon temperature of 230°C and a peak copper temperature of 124°C .

These exploratory studies in targets envelope the heat transfer limits in the fast-rotating and stationary cases. Rotational cases between these two cases fall within these limits. The analytical modeling of slower rotating target is a more complex problem; however, it might not be warranted in light of the fact that the operational limits can be established with the analytically more convenient cases of stationary and fast-spinning models.

Pure Beryllium Absorber with Normal Incidence

The last case in our exploratory studies involves a pure beryllium absorber subject to normal incidence of the beam line radiation. Figure 7 depicts the 3-D model used in the analysis. This model and the results should be compared with a Be-Cu composite.²

The total heat load Q is 36 kW , falling on a focal spot $6 \times 6 \text{ mm}^2$. Due to azimuthal symmetry, again only the half model is used. In Fig. 6, $A = 75 \text{ mm}$ (3 in.), $B = 18 \text{ mm}$ (0.75 in.) and $C = 42 \text{ mm}$ (1.750 in.). The coolant channel is a 10 mm dia ($3/8 \text{ in.}$) hole with a water flow velocity of 6 m/s (20 f/s).

The incident normal radiation penetrates the beryllium block and is absorbed by the calculated amounts presented for beryllium in Table 2. The balance of the penetrating radiation is assumed to be totally absorbed by the water.

Summary

The purpose of this analysis was to find out the power density limit of a machinable low Z engineering material under very high flux and subject to conventional cooling. The analytical results indicate that at about 0.2 kW/mm^2 load, the surface temperature will exceed 800°C . However, both in the y and z directions (Fig. 7) the temperature gradients are gradually varying. Severe temperature gradients are, however, setup in the axial direction (x in Fig. 7). The latter can be alleviated by changing the incidence angle of the beam from 90° to more moderate but non-grazing angles.

A solid beryllium absorber subject to inclined beams merits further investigation. Also, Be-Cu composite structures appear to have desirable characteristics at high heat mass. These subjects will be investigated further in future studies.

Fig. 7. Analytical Model for a Solid Beryllium Absorber Plate with Coolant Channel under Normal Incidence of the Wiggler Beam.

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