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INFORMAL REPORT

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Heat Transfer with a Split Water Channel*

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In a previous note¹ the heat transfer problem associated with the incidence of synchrotron radiation upon a vacuum chamber wall cooled by a single water channel was studied. This problem is illustrated in Fig. 1. Power is supplied to the wall at P watts per azimuthal centimeter. The vertical height of the ribbon of radiation is d, the thickness of the chamber wall is L, and the height of the water channel is H. A numerical solution to the potential problem was found¹ using the two-dimensional magnet program POISSON. Analytically, we found that for $H = \infty$ and $L \gg d$, the temperature difference ΔT between the point B and the water is

$$\Delta T = \frac{P}{\pi k} \left[\ln \frac{6.9L}{d} + f \left(\frac{k}{hL} \right) \right], \quad (1)$$

where k is the conductivity of the wall [watts/cm-°C], h is the film coefficient [watts/cm² - °C], and

$$f(\lambda) = \int_0^{\infty} \frac{dz}{\cosh^2 z} \frac{\lambda}{1 + \lambda z \tanh z}. \quad (2)$$

The function f was numerically evaluated and graphed in ref. 1.

Here, we extend our calculations to consider the case of a split water channel (Fig. 2). We have used POISSON to solve the potential problem for the following choice of parameters,

$$L_1 = 0.236 \text{ cm}, L_2 = 0.475 \text{ cm}, W = 0.635 \quad (3)$$

$$d = 0.033 \text{ cm}, P = 41.4 \text{ watts/cm}, k = 3.3 \text{ watts/cm} \cdot ^\circ\text{C} \quad (4)$$

We plot the isotherms in the chamber wall for a film coefficient $h = \infty$ (Fig. 3) and for a film coefficient $h = 3 \text{ watts/cm}^2 \cdot ^\circ\text{C}$ (Fig. 4). Good agreement with the numerical calculation is obtained by modifying Eq. (1) by replacing L by L_{eff} , i.e.

$$\Delta T = \frac{P}{\pi k} \left[\ln \frac{6.9 L_{\text{eff}}}{d} + f \left(\frac{k}{h L_{\text{eff}}} \right) \right], \quad (5a)$$

where

$$L_{\text{eff}} = \left(L_1^2 + L_2^2 \right)^{\frac{1}{2}}. \quad (5b)$$

We find

$$h = \infty, \Delta T = 18.8^\circ\text{C} \text{ (numerical) and } 18.6^\circ\text{C} \text{ (Eq. 5),}$$

$$h = 3, \Delta T = 24.1^\circ\text{C} \text{ (numerical) and } 25.2^\circ\text{C} \text{ (Eq. 5).}$$

Eq. (5) is physically reasonable and in agreement with our numerical calculations, so we shall use it in what follows. At present we have not derived Eq. (5) analytically.

The beam power in the synchrotron radiation has been considered by G. K. Green.² He showed that a wall at a distance D along the tangent to the orbit, which makes an angle α with the tangent, intercepts power per unit length

$$P = 14.09 E^4 I \sin \alpha / \rho D, \text{ (per unit of } D), \quad (6)$$

where E is the electron energy in GeV, I is the electron current in ma, and ρ is the dipole bending radius in meters. The vertical height of the radiation beam at incidence is

$$d = 2D/\gamma, \quad (7)$$

where $\gamma = 1957E$. For a circular wall at radius R concentric with the electron beam, $D = (R^2 - \rho^2)^{1/2}$, and $\sin \alpha = D/R$, so

$$P = 14.09 E^4 I / \rho R, \text{ (per unit of } R). \quad (8)$$

VUV RING

$$E = 0.7\text{GeV}, I = 1000\text{ma}, \rho = 1.91\text{m}, \gamma = 1370$$

For a circular wall of radius $R = 1.95\text{m}$, $D = 39.3\text{cm}$, hence

$$P = 9.1 \text{ watts/cm},$$

$$d = 0.057\text{cm}.$$

Taking L_1 and L_2 as given in (3),

$$k = 2 \text{ watts/cm} - ^\circ\text{C}, \text{ (aluminum)} \quad (9a)$$

$$h = 1.5 \text{ watts/cm}^2 - ^\circ\text{C}, \quad (9b)$$

we use Eq. (5) to obtain

$$\Delta T = 8.2^\circ\text{C},$$

which is characteristic of the general run of the vacuum chamber in a dipole. At the corner of a beam port, where radiation is taken out of the ring to the experimental area, there is normal incidence ($\sin \alpha = 1$), so Eq. (6) yields

$$P = 45 \text{ watts/cm},$$

and Eq. (5) implies

$$\Delta T = 41^\circ\text{C}.$$

Therefore, the beam ports in the VUV ring produce no difficult heat transfer problems. In fact, the actual temperature difference at a corner will be smaller

then 41°C , because there will be normal incidence only over a small azimuthal region, so the three-dimensional heat flow will lead to a lower temperature difference.³

X-RAY RING

$$E = 2.5\text{GeV}, I = 500\text{ma}, \rho = 6.84\text{m}, \gamma = 4892.$$

For a circular wall of radius $R = 6.88\text{m}$, $D = 74.1\text{cm}$, hence

$$P = 58.5 \text{ watts/cm}$$

$$d = 0.030\text{cm}.$$

Taking L_1 and L_2 as given in (3), and k and h as given in (9), we find

$$\Delta T = 58.7^{\circ}\text{C}.$$

At a point of normal incidence, simple scaling implies

$$P = 543 \text{ watts/cm},$$

$$\Delta T = 545^{\circ}\text{C}.$$

Even though the actual temperature difference will be less than this due to the three-dimensional nature of the flow³, it is still much too large to be acceptable for an aluminum chamber.

If we consider the wall to be copper rather than aluminum we are helped in two ways. Copper has a higher heat conductivity than aluminum, and it can tolerate higher temperatures. If we take

$$k = 3.3 \text{ watts/cm} - ^{\circ}\text{C}, (\text{copper})$$

$$h = 3 \text{ watts/cm}^2 - ^{\circ}\text{C},$$

we find

$$\Delta T = 320^{\circ}\text{C}.$$

We can also estimate the temperature drop across the film. From ref. 1 we expect the maximum heat flux incident upon the water to be watts/cm^2 ,

$$Q = \frac{P}{2L_{\text{eff}}} \left(1 - g \frac{k}{hL_{\text{eff}}} \right),$$

where

$$g(\lambda) = \frac{2}{\pi} \int_0^{\infty} \frac{dz}{\cosh^2 z} \frac{\lambda z \sinh z}{1 + \lambda z \tanh z}.$$

The function g is numerically evaluated and graphed in ref. 1. In the case we are discussing, we find

$$Q = 256 \text{ watts/cm}^2,$$

leading to a temperature drop across the film of

$$(\Delta T)_{\text{film}} = Q/h = 85^\circ\text{C}.$$

This would result in boiling of the water, which we wish to avoid.

The dimensions presented in this note are only intended to be taken as a guide. The chamber can be easily designed so that

$$L_{\text{eff}} = 0.7 \text{ cm}.$$

Also, it is possible to move the point of normal incidence further from the source, for example we could achieve

$$D = 95 \text{ cm}.$$

Then

$$P = 424 \text{ watts/cm},$$

$$d = 0.038 \text{ cm},$$

corresponding to

$$\Delta T = 242^\circ\text{C},$$

and

$$(\Delta T)_{\text{film}} = 55^{\circ}\text{C}.$$

We feel confident that by optimizing the dimensions, we can avoid boiling of the water. Our conclusion is that a copper chamber is a viable solution to the heat transfer problem at a beam port.

References

1. S. Krinsky - "Heat Transfer in the Vacuum Chamber Wall."
NSLS Technical Note 2 (BNL 23749).
2. G. K. Green - "Beam Power in the Synchrotron Radiation."
NSLS Technical Note 3 (BNL 23745).
3. S. Krinsky - "Heat Transfer at a Beam Port Corner."
NSLS Technical Note 7 (BNL 23748).

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Figure 1a.

Figure 1b.

Figure 2a.

Figure 2b.

Figure 3

(h=100)

0.9

0.8

0.7

0.6

0.5

0.4

0.3

0.2

0.1

0.05

0.1 0.2 0.3 0.4 0.5 0.6 0.7