THERMAL MODEL AND ASSOCIATED NOVEL APPROACH FOR SYNCHROTRON RADIATION LINER WITH END COOLING*

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Abstract

An end conductive cooling approach has been developed to reduce the radial space budget of a synchrotron radiation liner to permit the maximum possible liner tube inner diameter (ID). A thermal model has also been developed to analyze the thermal performance of such liners. This approach is found to be acceptable for a liner in a 5 m long quadrupole magnet and 3 m long spool piece, but not for a longer 15 m dipole. The heat transfer and temperature distribution were calculated respectively along the axis of two different liner model: 20K and 80K liner with different thicknesses (0.5 - 2 mm) of liner tubes and different emissivities (0.05 - 0.3) of liner surface for a variety of magnets. The thermal model is also applied to the case of an 80K liner connected directly to a 4K beam position monitor (BPM). In order to utilize the end cooling, a good thermal joint and a compact heat exchanger are designed.

I. INTRODUCTION

A uniform and maximum possible liner inner diameter (ID) is needed due to: (1) particle beam commissioning, (2) particle beam dynamic stability,and (3) safety margin of impedance. However, the maximum liner ID is constrained by: (1) the available magnet beam tube inner diameter (ID), and (2) the minimum liner radial space. Using regular cooling, the minimum liner radial space is 6 mm and using end conducting cooling, the radial space needs to be 3.5 mm. The 80K synchrotron radiation liner prototype was designed to be tested at the SSCL Accelerator System String Test (ASST) facility. In the case of the 80K ASST liner, the 25.3 mm design was chosen for the maximum liner ID.

Since the magnet quench induced Lorentz pressure on a CQM liner is much smaller than that on a CDM liner, the pure copper tube was chosen for the CQM liner material. The RRR and thickness of the copper tube must be of sufficient value due to both requirements (1) resistance wall: conductivity $\times$ Thickness > $2\times10^5\ \Omega^{-1}$ and (2) conducting heat transfer requirement. However, the RRR and thickness shall not be too larger in order to reduce the Lorentz pressure. This paper will focus on a thermal model used to predict the thermal performance of an end cooling liner for different cases.

II. THERMAL MODEL FOR END CONDUCTIVE COOLING

An end conductive cooling approach for the Spool Piece and CQM is shown in Figure 1. The 80K GHe flows through a compact heat exchanger located at each end of the liner tube outside of the CQM cold mass. The rest of the liner tube is refrigerated by thermal conduction. A compact heat exchanger & a good thermal conducting joint is designed to utilize the end cooling approach and to assure an easy assembly.

A thermal model to analyse the end conductive cooling was developed by Q.S.Shu and K.Yu [1][2], assuming: Q_S synchrotron radiation, 0.14 W/m; Q_L (heat leak through support)/2L; Q_r (heat leak by radiation)/2L; L half length of the CQM or Spool Piece; A the cross section area of the liner tuber; $\lambda(T)$ the heat conductivity; $\lambda(80)_{Cu}\approx 5.50$ W/(cm.K); $\lambda(80)_{snl\ stl} \approx 0.045$ W/(cm.K); $\varepsilon_1,\varepsilon_2$ the emissivity.

$$Qr = \sigma A(T_1^4-T_2^4)\varepsilon_1\varepsilon_2/(\varepsilon_1+\varepsilon_2-\varepsilon_1\varepsilon_2)$$

$$dQ_c = (Q_s- Q_L-Q_r)dX$$

if $q=(Q_s-Q_L-Q_r)$

$$Qx = -\lambda(T)AdT/dX$$

and $Q_{x+dx}= -\lambda(T)Ad[T+(dT/dX)dX]/dX$

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$$=-\lambda(T)A[dT/dX+(d^2T/dX^2)dX]$$

We know $Q_{x+dx}=dQ_c+Q_x$

$$d^2T/dX^2 = -q/[\lambda(T)A]$$

$$T(X)=-\{q/[2\lambda(T)A]\}X^2 + C_1X + C_2$$

boundary conditions:

$$T(X)\perp_{x=L} = 80\text{ K};\ T(X)\perp_{x=L}= 80\text{ K}$$

we have,

$$T(X) = -\{q/[2\lambda(T)A]\}X^2 + \{q/[2\lambda(T)A]\}L^2 + 80 \qquad (1)$$

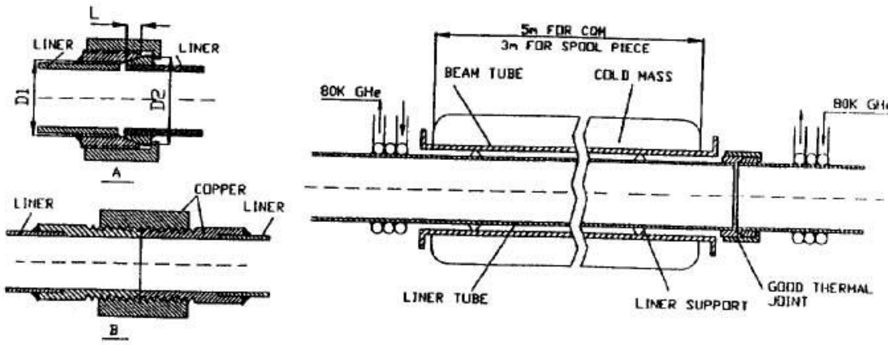

Figure 1. A schematic drawing of a liner with the end conducting cooling.

Using the model: l)The temperature distribution along the liners as functions both of the emissivities and of the tube thicknesses were calculated. 2) The maximum $\triangle T$ could be less than 5K for Spool Piece liner, and 10K for CQM. 3) A temperature difference between the Spool Piece pipe ends and the middle of the liner is 2K when copper layer of 2 mm is used and 10K with copper layer of 0.5 mm was used. 4) For CQM $\triangle T$ of 6K is obtained when copper layer of 2 mm, and 26K when copper of 0.5mm. 5) The correction of the effect of the magnetic field on copper thermal conductivity is considered. Figures 2, 3, and 4 show some of the calculated results.

III. THERMAL MODEL FOR 80K LINER WITH A 4K BPM

If a 4K BPM is used, the 80K liner end conductive cooling becomes more complicated. As shown in Figure 5. To reduce the heat leak through the copper liner tube from 80K to 4K BPM, a 10 - 20 cm long piece of stainless steel tube is insert between the BPM and copper liner tube. The synchrotron radiation, the heat leak from liner to BPM, the heat leak from liner to 4K beam tube and the heat exchange between the liner and the 80K GHe must meet the law of conservation of energy .

First, we calculate a temperature distribution along the S. S Liner tube;

when $0 \leqslant X \leqslant L$, we have,

$$T_S(X) = -qX^2/(2\lambda_s A_s) + S_1X + S_2 \qquad (2)$$

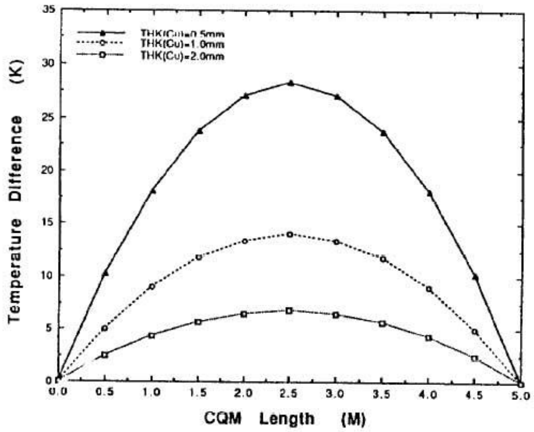

Figure 2. Temperature distribution of 80K liners as function of liner tube thicknesses.

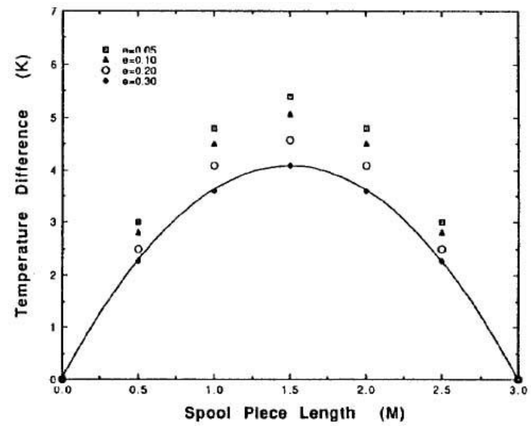

Figure 3. Temperature distribution of 80K liners as function of liner surface emissivities.

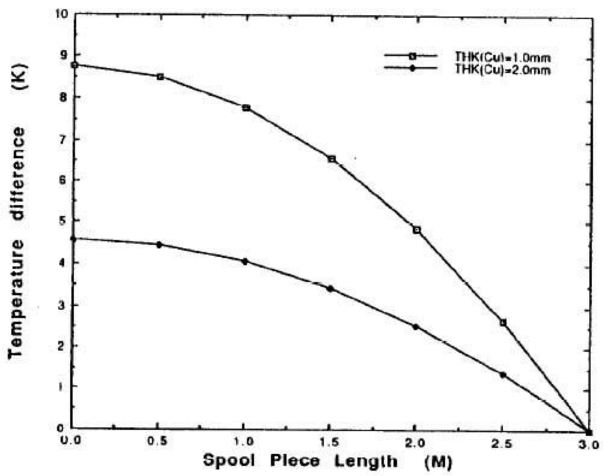

Figure 4. Temperature distribution of 20K liners with one end cooling only.

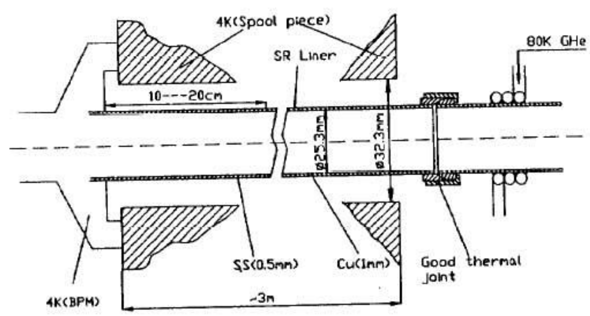

Figure 5. A schematic drawing of an 80K liner with a 4K BPM

The temperature distribution along the copper tube shall satisfy Eq.(3) if $L \leqslant X \leqslant L_0$

$$T_C(X) = -qX^2/(2\lambda_c A_c) + C_1 X + C_2 \qquad (3)$$

Eq. (2) & (3) must meet the following boundary conditions:

$T_s(0) = 4$

$T_c(L_0) = 80$

$\lambda_C A_c\{\partial T_c(X)/\partial X\}|_{X=L} = \lambda_s A_s\{\partial T_s(X)/\partial X\}|_{X=L}$

$T_s(L) = T_c(L)$

The C_1, C_2, S_1 and S_2 can be determined:

$S_2 = 4$

$S_1 = [\lambda_c A_c/(\lambda_s A_s)]\,[80+qL_0^2/(2\lambda_c A_c) - qL^2/(2\lambda_c A_c)+qL^2/(2\lambda_s A_s)-4] / [\lambda_c A_c L/(\lambda_s A_s)-L+L_o]$

$C_1 = [80+qL_o^2/(2\lambda_c A_c) - qL^2/(2\lambda_c A_c)+qL^2/(2\lambda_s A_s)-4] / [\lambda_c A_c L/(\lambda_s A_s)-L+L_o]$

$C_2 = 80+qL_o^2/(2\lambda_c A_c)-L_o\{[80+qL_0^2/(2\lambda_c A_c) - qL^2/(2\lambda_c A_c) +qL^2/(2\lambda_s A_s)-4] / \{\lambda_c A_c L/(\lambda_s A_s) - L+L_o]\}$

Using Eq. (2) and (3) the temperature distribution can be calculated & shown in Figure 6.

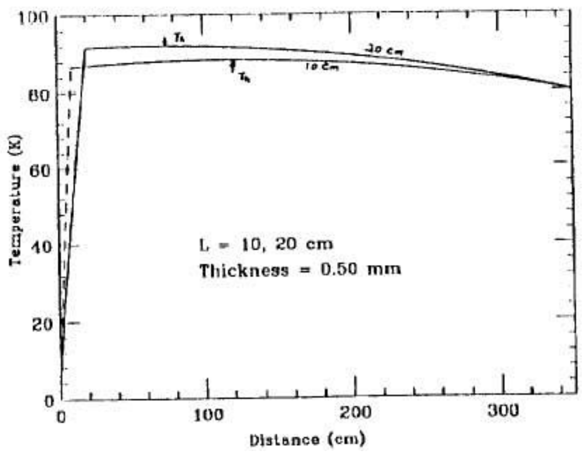

Figure 6. Temperature distribution along an 80K liner with a 4K BPM.

IV. GOOD THERMAL CONDUCTING JOINT

A good thermal conducting joint concept, as shown figure 1, was proposed by Q.S. Shu & K. Yu. The joint makes liner assembly easier. Assume synchrotron radiation of a quadrupole to be 1 W. The heat transferred at each liner end is 0.5 W. If the pressure on the Cu-Cu machined contact is 7 MPa, thermal conductance of the contact (at temperature range 5—25K) is h(T) = 0.13T (W/cm^2. K). The temperature across the joint $\triangle T$(at 80K) $\leqslant$ 1K.

V. COMPACT HEAT EXCHANGER

To make end cooling work, a compact heat exchanger with a length of less than 5 cm was developed. The total heat to be transferred by the heat exchanger is Q=2 W. Design parameter used were: copper cooling tube ID=0.25 cm, mass flow rate of the 80K GHe, dM/dt = 0.25 g / sec. The temperature increase of GHe is $\triangle T$. R_c= GD/η = 31812, $P_r = \eta C_p/\lambda$ =0.357, $h = 0.023\ C_p\ G^{0.8}\ \eta^{0.2} / (\ P_r^{0.6}\ D_e^{0.2}\ )$ = 0.0345. If three turns are used, L = 28.75 cm, $\triangle T$< 1K.

ACKNOWLEDGEMENTS

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REFERENCES

[1] Q. S. Shu, Status Report on the ASST Liner System Design, SSCL-N-805, November, 1993.
[2] 80K ASST liner Design Report, prepared by Q.S.Shu (in preparations)