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COUPLER AND SIMILARITIES TO
SUPERCONDUCTING MAGNET CURRENT LEADS

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Author(s):

Joseph A. Waynert, ESA-EPE
F. Coyne Prenger, ESA-EPE
Dave E. Daney, ESA-EPE

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Thermal Analysis of the APT Power Coupler and Similarities to Superconducting Magnet Current Leads

Joseph A. Waynert, Dave E. Daney, and F. Coyne Prenger
Los Alamos National Laboratory, Los Alamos, NM

Abstract—A detailed thermal analysis has been performed of the 210 kW, 700 MHz RF power coupler (PC) which transfers microwave energy from high power klystrons to the superconducting (SC) resonant cavities for the acceleration of protons. The work is part of the design for Accelerator Production of Tritium funded by the US Department of Energy. The PC is a co-axial design with the RF power transmitted in the annular region between two concentric cylinders. The PC provides a thermal connection from room temperature to superconducting niobium operating at 2.15 K. Heat transfer mechanisms considered are conduction, infra-red radiation, RF joule heating in normal and superconducting materials, and, forced and natural convection cooling. The objective of the thermal analysis is to minimize the required refrigeration power subject to manufacturability and reliability concerns. The problem is reminiscent of the optimization of superconducting magnet leads. The similarities and differences in the results between SC leads and PCs are discussed as well as the critical parameters in the PC optimization.

I. INTRODUCTION

Power couplers (PCs) used in superconducting (SC) accelerators are similar to SC current leads in that they both represent a connection from a power source to a low temperature, SC device [1]. Radio frequency (RF) PCs energize SC cavities which establish RF electric fields to accelerate ionized particles. The PCs used in the Accelerator Production of Tritium (APT) program are somewhat like a high temperature superconducting (HTS) hybrid lead. An HTS hybrid lead is typically thermally anchored at liquid helium temperature at the cold end, and has another thermal intercept at a temperature below its critical temperature. A normal conducting stage provides the connection to room temperature.

Co-axial PCs are common, and represent the design baseline for APT. Fig. 1 shows a typical co-axial PC. The main components are: the inner conductor, which operates near room temperature; outer conductor, which connects room temperature to near liquid helium (LHe) temperature; and possible thermal intercepts to reduce the heat load to LHe. The outer conductor transitions to niobium near its connection to the beam tube to reduce RF losses.

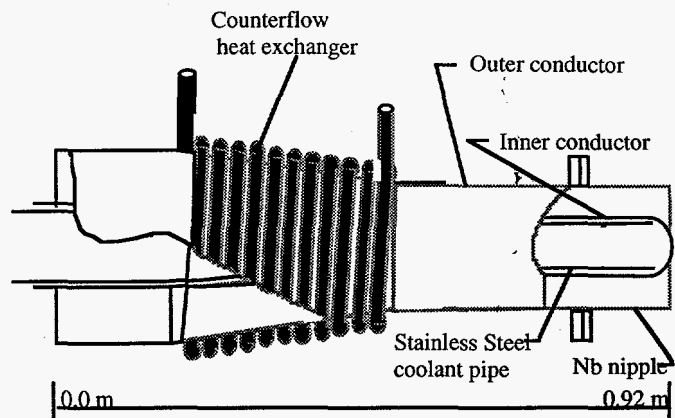


Fig. 1 Schematic of the PC with a simple illustration of a counterflow heat exchanger on the outer conductor.

Similar to SC lead design, we want to minimize the total refrigeration input power required to compensate for the heat leaks.

II. DESCRIPTION OF THERMAL MODEL

Fig. 1 shows a cut-away view of the PC as modeled, with, for illustration only, a counterflow heat exchanger for cooling of the outer conductor. The total length of the PC is about 1006 mm.

The outer conductor is 2.4 mm thickness stainless steel (SS) with a 15 μm copper plating, residual resistivity ratio RRR=50, on the inside diameter (ID). The outer conductor is 152.4 mm ID at the 300 K end and tapers to 100 mm ID at the 2.15 K end. About 120 mm from the beam tube (cold) end, the outer conductor mates with a niobium nipple with RRR=40. The inner conductor is copper, RRR=50, with a wall thickness of 1.5 mm and tapers from 66.7 mm OD to 43.5 mm. Within the inner conductor is another concentric SS tube, which provides coolant for the inner conductor. Helium gas enters the ID of the SS tube from the left of Fig. 1, passes to the right end of the PC, and returns through a 3.2 mm radial gap between the stainless and copper tubes.

The inner and outer conductors are joined by a 1.27 mm thick copper plate at the furthest most position to the left of Fig. 1. This plate is an electrical shorting plate of the RF quarter-wave stub.

The thermal model is axisymmetric, one-dimensional, and uses a finite difference approximation. There are over 200 nodes. Temperature dependent properties are used for: thermal conductivities of the SS, copper, and niobium; RF resistivity

in copper (RRR=2, for 750 MHz) and niobium[2]; and specific heat and enthalpy of the helium coolant. Infra-red radiation heating is calculated assuming gray body, diffuse scattering with the emissivity of all materials being 0.3. Copper can have emissivity values from less than 0.05 to 0.9 depending on the condition of the surface. The value of 0.3 is considered conservative for the 40 year life of the accelerator.

III. RESULTS

The analysis naturally divides into separate consideration of the inner and outer conductors. This paper focuses on the superconducting and cryogenic aspects of the PC, i.e., the outer conductor. The reader is referred to [3] for a detailed discussion of the results on the inner conductor.

A. Resistive Stage

The resistive stage of the PC differs from a classical (dc or low frequency ac) current lead in that most of its cross-sectional thickness is mechanical structure which carries no current. The thermal performance of the PC is consequently degraded because this extra material conducts heat to the cold end, but does not contribute to the current carrying capacity. In fact, a thermally ideal PC would have a copper wall with a thickness of less than one skin depth, and no supporting structure.

We can compare the performance the PC with a classical conduction cooled current lead by comparing the heat conduction equations for the two cases. For a classical current lead, the one-dimensional, steady state heat conduction equation is

$$\frac{d}{dx} \left(kA \frac{dT}{dx} \right) = -\rho \frac{I^2}{A} \quad (1)$$

which, for constant cross-sectional area, A and constant thermal conductivity, k, becomes

$$\frac{d^2T}{dx^2} = -\frac{I^2\rho}{kA^2} \quad (2)$$

Here T is temperature, I current, ρ electrical resistivity and x, axial position.

For the RF case, the heat generation per unit volume of the outer conductor is

$$q_v = \frac{I^2 R_s}{(\pi D)^2 t} \quad (3)$$

which gives

$$\frac{d^2T}{dx^2} = -\frac{I^2 t R_s}{kA^2} \quad (4)$$

for the heat conduction equation. Here, t is the total wall thickness and R_s is the surface resistance in ohms/square, and

D, the tube diameter. Note that (2) and (4) are equivalent for $\rho = t R_s$.

The optimum (minimum) heat leak per unit current, Q/I can be evaluated [4] by writing equations in terms of Q. For the RF case, Fourier's equation is

$$\frac{dT}{dx} = -\frac{Q}{kA} \quad (5)$$

and the change in heat conducted with length due to heating is

$$dQ = \frac{I^2 R_s}{\pi D} dx \quad (6)$$

Combining (5) and (6) and integrating, gives

$$\left(\frac{Q}{I} \right)_{\min} = \sqrt{L'_0 (T_1^2 - T_2^2)^{1/2}} \quad (7)$$

for the minimum value of the heat leak per unit current, which occurs at $Q_{x=0}=0$ ($dT/dx = 0$ at $x=0$). In the above, L'_0 is a pseudo-Lorentz number that is given by

$$L'_0 = \frac{\bar{k} R_s t}{T} \quad (8)$$

where \bar{k} is the average thermal conductivity at position, x of the copper-stainless steel composite wall. The same result as (8), with the Lorentz number L_0 replacing L'_0 was obtained by Odenov [5].

For our PC, we calculate an average value of L'_0 of $11.6 \times 10^{-7} \text{ A}^2\Omega^2/\text{K}^2$ for the temperature range 300 K to 35 K. This value of L'_0 compares to $2.45 \times 10^{-8} \text{ A}^2\Omega^2/\text{K}^2$ for a classical metal and about $2.1 \times 10^{-8} \text{ A}^2\Omega^2/\text{K}^2$ for copper (RRR=100) over the same temperature range. Thus, we calculate, from (7), for an rms current of 65 A (for our 210 kW PC), a heat leak of 23 W to a 35 K thermal intercept, compared to a heat leak of 3.1 W for a classical conduction-cooled current lead with the same current.

As discussed above, the large difference in the heat leaks is due to the necessary SS structure of the PC. The analytically evaluated heat leak of 23 W compares to a value of 23.2 W determined from the one-dimensional finite difference model - a better agreement than might be expected. The agreement seems especially good considering that L'_0 is relatively constant down to 100 K, but increases rapidly at lower temperatures because R_s becomes constant, mainly due to the anomalous skin effect. Thus, (7) becomes increasingly suspect at low temperatures.

Another insight on PC performance to be gained from (7) is the dependence of the heat leak on the low end temperature

T_2 . For T_2 lower than about 100 K, the heat leak at T_2 is nearly constant. This conclusion is verified by our finite difference results.

B. Superconducting Stage

The contribution to the room temperature, T_h , refrigeration input power, P_i , is dominated by heat loads, Q_i , at temperature, T_i as given in eqt. 1

$$P_i = \left(\frac{T_h}{T_i} - 1 \right) \frac{Q_i}{\epsilon_i} \quad (9)$$

where ϵ_i is the refrigeration cycle efficiency relative to Carnot. Factors, sometimes quoted as the ratio, P/Q , yield 770 W/W at 2.15 K; 108 W/W at 9 K, and 17 W/W at 50 K, using efficiencies of 0.18, 0.3 and 0.3 respectively, and show the importance of reducing the low temperature heat loads.

One critical factor in reducing the 2.15 K heat load is to maintain the Nb superconducting. This reduces the RF heat load generated in the Nb by a factor of two or more. Maintaining the warm-end temperature of the Nb at the SS/Nb interface below the superconducting critical temperature (T_c) of Nb, 9.2 K, is not sufficient to guarantee the Nb is SC along its entire length; there may be a standing normal zone, SNZ.

To investigate the existence of the SNZ, we begin with the one-dimensional heat diffusion equation with generation and, for simplicity, constant material properties. Heat transfer is by conduction or radiation (with the inner conductor). Heat generation is from RF joule heating and infra-red radiation exchange, mainly with the inner conductor. For simplicity, we assume the Nb, of length L , is divided into two regions, one with a resistive normal zone with $T > T_c$, and one SC, with $T < T_c$. Equations (10) and (11) show the results of integrating the diffusion equation in the two regions:

$$\theta_1(\xi_1) = \frac{q_1}{2\beta_1} (\xi_1^2 - \xi_1), \quad (10)$$

$$\theta_2(\xi_2) = \frac{q_2}{2\beta_2} (\xi_2^2 - \xi_2) + \xi_2 \quad (11)$$

where

$$\xi_1 = \frac{x}{L_1}, \quad \xi_2 = \frac{x - L_1}{L_2} \quad (12)$$

and

$$\beta_i = \frac{k_i A (T_2 - T_3)}{L_i^2}, \quad \theta_i = \frac{T_i - T(\xi_i)}{T_2 - T_3} \quad (13)$$

and q_i (k_i) is the heat generated per unit length (effective thermal conductivity) in region i ; L_1 is the length of the SNZ; $L = L_1 + L_2$ is the total length; A is the cross-sectional

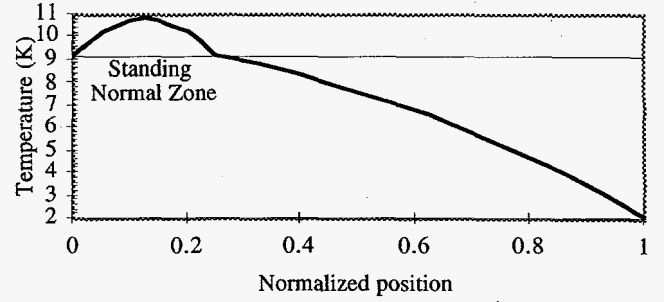


Fig. 2 A representative temperature profile showing a standing normal zone. The horizontal line is at the critical temperature of niobium.

area for conduction; and T_1 , T_2 , and T_3 are the temperatures at normalized positions $\xi_i=0, 1$ and $\xi_2=1$ respectively. In both (10) and (11), ξ varies from 0 to 1. Note that q_1 is from infra-red radiation, mainly from the inner conductor, and q_2 is radiation plus RF joule heating. Fig. 2 shows a representative temperature profile as a function of the normalized position variable, $\xi=x/L$ based on (10) and (11). There is a discontinuity in the slope at the interface of regions 1 and 2 because k_1 , which is the average k between about 11 K and 9.2 K, is about 2.5 times k_2 , which is the average from 2 K to 9.2 K, in this example.

At the interface between regions 1 and 2, the heat fluxes must be equal, i.e. the heating equals the cooling, which results in the constraint,

$$\eta \xi = \frac{2\beta}{q_2(1-\xi)} - (1-\xi) \quad (14)$$

where

$$\eta = \frac{q_1}{q_2}, \quad \xi = \frac{L_1}{L}, \quad \text{and} \quad \beta = \frac{k_2 A (T_2 - T_3)}{L^2} \quad (15)$$

Fig. 3 shows the heating, left hand side of (14), and cooling, right hand side of (14), characteristics graphically. Notice that, depending on q_2 , β , and η , there may be no SNZ, one allowed SNZ, or two, based on the number of intersections of the heating curve, d with cooling curves a , b , or c respectively.

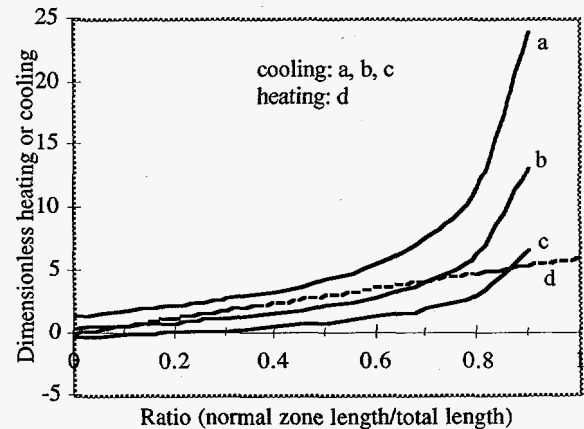


Fig. 3. Representative heating and cooling curves as a functions of $\xi = L_1/L$, ratio of the length of region 1 (potential SNZ) to the total length.

In the case of the two intersections, curve b, the smaller SNZ is not stable. A small perturbation could cause the zone to expand slightly, and the excess heating would drive the resistive portion to the larger SNZ, or a perturbation could cause the zone to shrink slightly, in which case, the excess cooling would cause the zone to disappear.

In general, we are interested in designing a PC that will not have SNZs. The power rating and electromagnetic performance of the PC, along with the RRR of the niobium, will determine the RF heating contribution to q_2 . The infrared radiation contribution to q_1 and q_2 can be calculated by sophisticated computer codes or estimated from first principles. Then $\eta = q_1/q_2$ can be determined. We define a new term

$$R = \frac{2\beta}{q_2} \quad (16)$$

R is the design parameter which allows us to avoid SNZs. R depends on β , which can be adjusted mainly through the choice of Nb nipple length, L , or cross-sectional area, A .

The rules for avoiding SNZs are found by finding the regions for which there are no solutions for ξ in (14), the heat balance equation. To avoid SNZs:

$$\text{if } \eta \leq 2 \text{ make } R > 1; \quad (17a)$$

$$\text{if } \eta > 2 \text{ make } R > \frac{\eta^2}{4(\eta - 1)}. \quad (17b)$$

Now that we are able to avoid SNZs, the discussion turns to other factors controlling the 2.15 K heat leak. With no SNZ present, the temperature distribution throughout the Nb is described by (11), with $L_1=0$, $L_2=L$, and $T_2=T_1=T_c$. Equation (11) can be recast by calculating the heat transferred, Q_3 , at the low temperature, T_3 ,

$$Q_3 = \beta L + \frac{q_2 L}{2} \quad (18)$$

Q_3 is the heat load at 2.15 K, in our case. Because β has a $1/L^2$ dependence, there is an optimum length L to minimize Q_3 , assuming $(T_2 - T_3)$ is fixed. The value of L may be chosen for other reasons though, such as to eliminate SNZs or, for mechanical or manufacturing reasons. Thus, if L is fixed, the heat load can only be reduced by lowering T_2 , decreasing A , decreasing k by choosing a lower RRR Nb, or reducing q_2 . The value of q_2 can be reduced by lowering the emissivity of the materials or lowering the inner conductor temperature. In a typical situation, with geometry, emissivities and inner conductor temperature established, Q_3 is determined only by T_2 , the temperature at the SS/Nb interface.

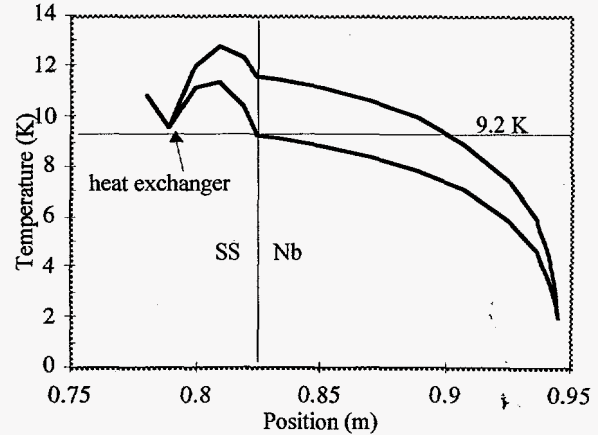


Fig. 4. Two possible temperature profiles exist in the niobium nipple if the heat exchanger is too far from the SS/Nb interface. For the example shown, the heat exchanger is 0.04 m from the interface.

The value of T_2 is usually established by some type of thermal intercept or heat exchanger placed near the SS/Nb interface. The heat exchanger needs to be as close as possible to the interface to stabilize the high temperature end of the Nb. A space of 0.04 m was initially selected to allow room for the flange connecting the resistive portion of the outer conductor to the Nb nipple. Fig. 3 shows the finite difference results. There are two possible steady state solutions; one has a normal zone in the Nb with correspondingly higher heat loads. As seen from the gradient at the SS/Nb interface, the SS is passing an additional gradient heat load to the Nb which is deposited at 2.15 K. To avoid the normal zone, and minimize the heat passed from the resistive portion of the outer conductor, the heat exchanger should be incorporated into the connecting flange itself.

IV. SUMMARY

At first glance, an RF power coupler might not seem very similar to a cryogenic current lead, and depending on your opinion after reading this article, you may still feel that way. The resistive portion of the outer conductor of the PC, appears to be a poorly-designed classical conduction-cooled current lead, because of the need for the SS to support the copper film. The SC portion of the PC has many issues similar to HTC and conventional SC leads.

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