PSFC/JA-09-23

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MIT Plasma Science and Fusion Center

September 22, 2009

Supported in part by a grant from the MIT Energy Initiative.

CURRENT LEAD OPTIMIZATION FOR CRYOGENIC OPERATION AT INTERMEDIATE TEMPERATURES

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Plasma Science and Fusion Center, MIT
Cambridge MA 02139 USA

ABSTRACT

The refrigeration power for large current superconductor systems, such as for electrical power distribution, is dominated by current lead losses. The use of multiple cooling stages between room temperature and ~ 70K is investigated as means to decrease the refrigeration power. We show that it is possible to decrease the electrical power requirements for the refrigerator by about 1/3 through the use of two-stages current leads; this computed power saving is based on a conservative estimate of refrigerator performance. Using data from real systems, that is, higher temperature refrigerators operating at higher fractions of their Carnot efficiencies we believe that the refrigerator electrical power requirement can actually be decreased by 1/2. Means have been investigated to optimize current lead performance at lower than maximum current operation. Adjustment of the cooling power of the intermediate temperature refrigerators achieves limited success in power consumption minimization. Other means to optimize the performance will be described. The implications of intermediate stages for stability of the current leads following a short overcurrent period will be described.

KEYWORDS: current leads; high temperature superconductors; intermediate temperature

INTRODUCTION

Progress in high temperature superconductors has opened up superconducting applications that otherwise have been economically unattractive. [1] One such application is power transmission, where the use of liquid nitrogen coolant substantially simplifies the cryogenic requirements. The US Department of Energy has co-funded three substantial demonstrations of the use of HTS in AC transmission lines. [2]

For transmission applications, the losses in the current leads are small compared with distributed losses along the superconducting line which are dominated by thermal radiation (cryostat losses) and by the AC losses in the cable. Minimization of the current lead losses is not important. In these applications the lines operate at relatively high voltages and relatively low currents, compared with distribution cables. [3, 4, 5, 6]

As an example of a superconducting distribution system, several teams, including ours, have been looking at the possibility of using HTS distribution systems in data servers and supercomputing centers. [7] These centers have large power consumption, usually more than 10 MW, with very high power distribution density. [8] Large cross-section, normal conductors are presently used, with substantial power dissipation even when operated at reduced current densities.

A small program at the Plasma Science and Fusion Center at MIT is looking at the potential of using DC distribution, using HTS cables, in data centers. In this application, the use of relatively low voltages (~ 400 V DC) results in substantial currents to be distributed, on the order of 20 kA. Under these circumstances, current leads represent a substantial and dominant heat input to the cryogenic environment.

Means of optimizing current leads have been discussed in the past, mainly for applications to cryogenic environments around 4 K. Recently, the development of HTS current leads that can transfer currents between 77 K and 4 K have been developed with several companies selling commercial components. There has been little prior development of methods to minimize the heat input to the liquid nitrogen environment, as the requirements are significantly reduced compared with the more severe requirements to 4 K. However, in some potential applications, as in data server or supercomputer centers, means to minimize the cryogenic refrigeration load is desired.

In this paper, the minimization of the refrigeration power for current leads between room temperature (298 K) and 65 K are discussed. The use of multiple intermediate stages is analyzed. This method has proven very useful to minimize the cooling requirements when operating between room temperature and 4 K. [9]

MODEL

The methodology developed by McFee [9] was used in this analysis. McFee's work provides a general methodology to optimize current leads, even with temperature dependent thermal and electrical properties.

The McFee formulism can be reduced to three equations. The minimum energy transmitted from temperature T_H *to* cold temperature T_L is given by

$$\dot{Q}(T) = I\left[2\left(\frac{k}{\sigma}\right)_{ave}\left(T_H - T_L\right)\right]^{1/2} \tag{1}$$

and

$$\left(\frac{k}{\sigma}\right)_{ave} = \frac{1}{T_H - T_L}\int_{T_L}^{T_H}\frac{k(T)}{\sigma(T)}dT \tag{2}$$

where $k(T)$ and $\sigma(T)$ are the temperature dependent thermal and electrical conductivities of the conductor, and I is the design transport current. The ratio of length to cross sectional area of the current lead that results in minimum thermal loss is given by

$$\frac{L}{A} = \frac{1}{I^2}\left[\sigma(T_L)\left[\dot{Q}_L\right]_{\min} - \int_{T_L}^{T_H} \frac{d\sigma(T)}{dT}\dot{Q}(T)\,dT\right] \tag{3}$$

where T_L is the low temperature. Since *Q(T)* is proportional to the current *I* by equation (1), the ratio *IL/A* is independent of current and only depends on the high temperature T_H, the low temperature T_L and the material properties of the current lead.

A case of special interest is the heat (and associated electrical power requirement for the refrigerator) that is transmitted from one temperature to another when a current lead optimized for a given current is operated without current, such as during idle times of a magnet or no power transfer in a distribution or transmission line. Once the optimum *IL/A* is identified for a given temperature difference and material properties, the power transmitted from one temperature to the next when there is no current flowing is determined from

$$\dot{Q}(T_L)/I = \frac{\int_{T_L}^{T_H} K(T)\,dT}{I\,L/A} \tag{4}$$

The calculations in this section assume current lead made from copper with RRR =100. Alternative materials [10] are discussed in the next section.

To determine the electrical power requirement for the refrigerator system, an assumption needs to be made with respect to the efficiency of the refrigerators. In this paper, it is assumed that the refrigerator efficiency is a constant fraction of the Carnot efficiency between room temperature and the operating temperature or the refrigerator. This is a simplifying assumption as the efficiency drops (compared with Carnot) for small capacity units and for lower temperatures. A relatively conservative multiple of 9 (i.e., 11% of Carnot efficiency) is used in Section III for all refrigerators, independent of temperature and capacity. The normalized electric power requirement for an individual refrigerator P_E is thus, $(P_E/I) = 9(Q/I)/\eta_{Carnot}$, where $\eta_{Carnot} = T_L/(T_H - T_L)$ is the Carnot efficiency of the refrigerator operating between upper temperature T_H and lower temperature T_L. The total electrical power is the sum of the electrical power of the individual refrigerators.

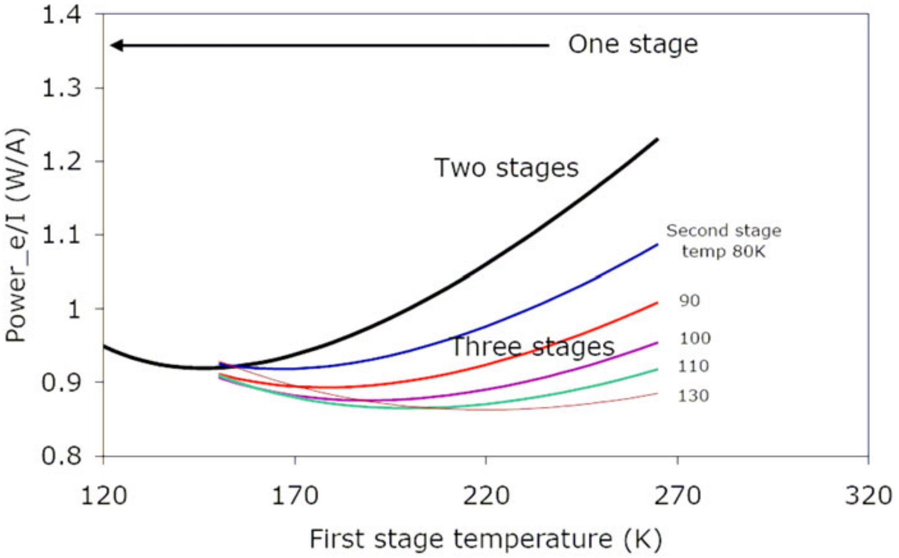

FIGURE 1. Normalized refrigerator system electrical power as a function of the temperature of the intermediate stage for two and three stage refrigeration systems (between 298 K to 65 K)

COPPER LEADS

The electrical power requirement has been calculated for three cases when the leads are manufactured from copper: a single stage current lead (cooling only at the operating cryogenic temperature), one with cooling at an intermediate temperature, and finally one with two intermediate cooling temperatures.

The temperature of operation has been varied in the second and third cases such that the total electrical power of the refrigerators is minimized. The minimization function is the electrical power. Alternatively, the minimization function could be the capital cost of the overall refrigeration system, or the cost of ownership (capital and operating costs).

FIGURE 1 shows the results of the calculations for the single stage, two-stage and three-stage current leads. The calculated normalized electrical power P_E of the refrigerator or refrigerator set, assuming the model described in the previous section, are shown as a function of the lower temperature of the upper stage (first stage), for two-stages and three-stages systems. Also shown in the normalized electrical power for the single stage. For the single stage case, the normalized electrical power is 1.36 W_E/A, (W_E is electrical power in Watts) which decreases to about 0.92 W_E/A for two stages, for a one third reduction of electrical power. The gain of going from two-stages to three-stages is minimal, with an additional electrical power reduction of about 6%.

The case of two-stages has a broad optimum around an intermediate temperature of 145 K. At this intermediate temperature, the normalized thermal input power at the first (145 K) and second (64 K) stages are 0.039 and 0.017 W_T/A, respectively (W_T is thermal power in Watts), with electrical powers of the respective refrigerators of 0.37 and 0. 55 W_E/A.

The corresponding values of *IL/A* at the electrical power minimum are 3.7 MA/m for the single stage case, and for the two stage current lead, *IL/A* ~ 2.83 MA/m for the high temperature side and 1.48 MA/m for the low temperature side.

FIGURE 2 shows the value of *IL/A* required for the single and two stage current leads, as a function of the cold stage temperature. Note that the values of *IL/A* for each stage of the two stage current lead is ~2/3 the same as that of the single stage current lead.

The properties of the optimized current leads, including the thermal loading in the case of no current, are shown in TABLE 1 for both the single and two stage current leads.

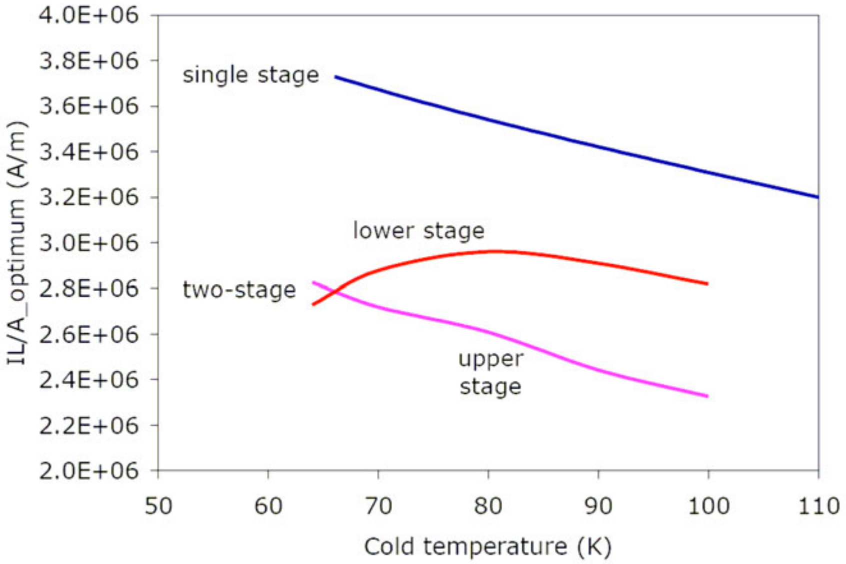

FIGURE 2. Values of *IL/A* for optimized single-stage and two-stage current leads.

TABLE 1. Characteristics of the optimized single and two stages current lead

		Single stage	Two stages	
			Upper stage	Lower Stage
P_e/I	W/A	0.042	0.039	0.017
IL/A	MA/m	3.73	2.83	2.73
$P_e/I_{no\ current}$	W/A	0.027	0.022	0.014

It is interesting to note the thermal power loading at the different temperatures. For the case of two stages, the power loading at the 64 K station and at the intermediate temperature stage is shown in Figure 3 as a function of the intermediate stage temperature. As the temperature of the intermediate stage increases, the individually optimized thermal loading to the upper stage decreases while the thermal loading to the lower stage increases. At the system optimum intermediate temperature (around 145 K as shown in figure 2), the thermal loading to the low temperature is slightly less than half the thermal loading of the intermediate stage. At this optimum, the electrical power of the 64 K temperature refrigerator is, however, about 50% larger than that of the intermediate temperature refrigerator.

TABLE 2 shows the results of the calculations for the two-stage system as a function of the cold temperature. The system performance has been evaluated for cold temperature of 64K, 70K, 80K and 90K. The associated value of the intermediate temperature that minimizes the electrical power consumption of the refrigerator system is shown to increase faster than the cold temperature.

Also shown in TABLE 2 are the system-optimized values of the normalized heat flow when operating at full current and the associated value of *IL/A* of the optimized system. TABLE 2 shows these values for both the upper stage and the lower stage. The impact on the system of operating without current, especially during extended periods, as in cases where a load such as a bank of computers in the data center have been disconnected, as also shown in TABLE 2 for the case of optimized two-stages current lead.

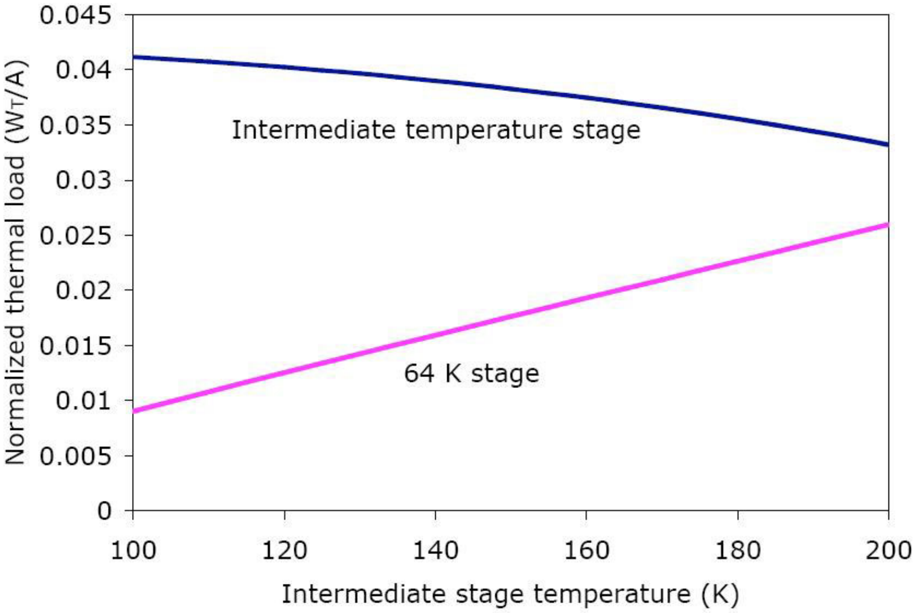

FIGURE 3. Normalized thermal loads at the 64 K and intermediate-stage temperature as a function of the intermediate temperature, for optimal individual leads

TABLE 2. Characteristics of optimized current leads with two stages as a function of the lower temperature

Lower temperature	K	64	70	80	90	100
Intermediate temperature	K	145	155	165	180	190
Upper stage						
$\dot{Q}$	W/A	0.039	0.038	0.037	0.036	0.035
IL/A	MA/m	2.83	2.72	2.61	2.44	2.33
$\dot{Q}_{\text{no current}}$	W/A	0.022	0.021	0.021	0.020	0.019
Lower stage						
$\dot{Q}$	W/A	0.017	0.018	0.020	0.022	0.023
IL/A	MA/m	2.73	2.88	2.96	2.91	2.82
$\dot{Q}_{\text{no current}}$	W/A	0.014	0.014	0.013	0.014	0.014

NON-COPPER CURRENT LEADS

This section discusses the possibility to use alternative materials in current leads.

Using the formalism by McFee, from equation (1) for a given temperature span, the thermal loading is minimized for those materials with the lowest ratio of thermal to electrical conductivities. Figure 5 shows the parameter k/σ as a function of temperature for copper and three aluminum alloys: 1100, 5083 and 6061. [11, 12] It is clear that over the entire span, with the exception of a very small region near 65 K, the use of 1100-series aluminum minimizes the thermal loading, for any temperature span and irrespective of the number of stages.

TABLE 3 shows the results from the optimization of a single stage and two-stage current leads, between 298 K and 65 K. The intermediate temperature of the optimum system has increased to about 150 K. As in the case of copper, the optimum is quite broad.

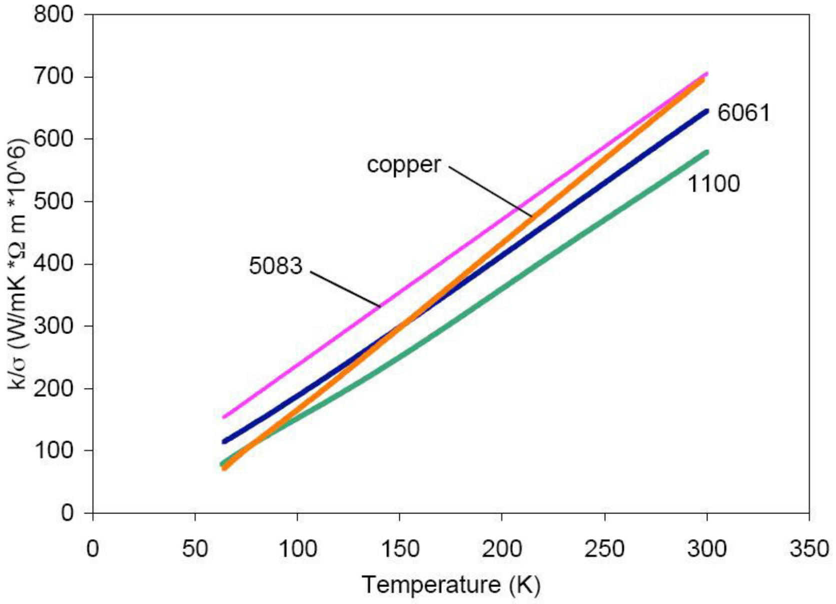

FIGURE 4. Thermal to electrical conductivity ratio for copper and aluminum alloys vs. temperature.

TABLE 3. Optimized current leads with 1100 series aluminum

		Single stage		Two stages	
Intermediate temperature	(K)			150	
				Upper stage	Lower Stage
$\dot{Q}/I$	W/A	0.039		0.035	0.017
IL/A	MA/m	2.18		1.62	1.85
$\dot{Q}/I_{\text{no current}}$	W/A	0.024		0.020	0.011
P_e/I	W/A	1.278		0.867	

REDUCED CURRENT OPERATION

The use of multiple stages increases operational flexibility even after the currents leads have been assembled. In particular it is of interest to determine whether the variable intermediate temperature can be used to improve performance of the current lead when it operates at less the full current.

The case of optimized, full current operation is investigated, with T_h = 298 K, T_c = 64 K, T_i = 145 K and IL/A_h = 2.83 MA/m and IL/A_c = 2.73 MA/m. The results as a function of the intermediate temperature are shown in FIGURE 5. Although the minimum is shallow, it offers the opportunity of matching the required refrigeration to the one needed to minimize ice formation at the hot end.

CONCLUSION

This works summarizes efforts to decrease the refrigerator power requirements for current leads operating between room temperature and near liquid nitrogen temperatures. This work is relevant to systems operating at temperatures around liquid nitrogen, as well as to systems operating at lower temperature that use low-thermal conduction HTS current leads, as the overall electrical power requirement of these current are dominated by the stages between room temperature and around 70K.

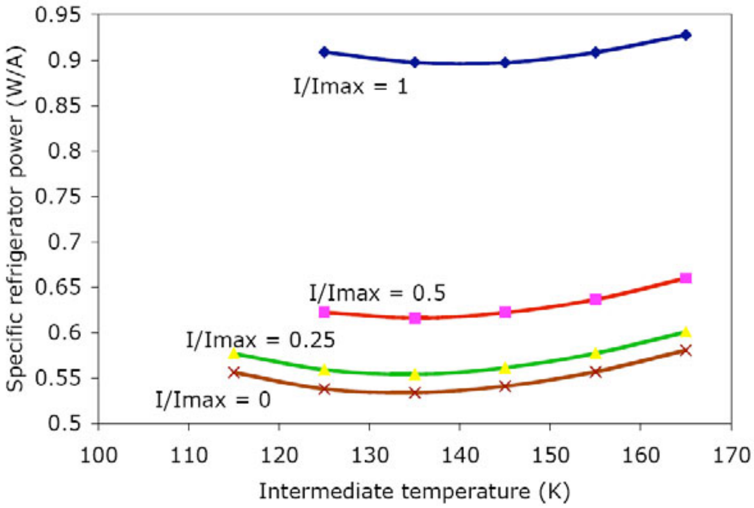

FIGURE 5. Refrigeration power as a function of the intermediate temperature T_i

It is shown that it is possible to decrease the electrical power requirements of the refrigerator by about 1/3 through the use of two-stage current leads, using refrigerator performance that is conservative. With real systems, with higher temperature refrigerators running at higher fractions of their Carnot efficiencies, it is suggested that the refrigerator electrical power requirement of practical systems can be decreased by 1/2.

Not analyzed in this document is the impact of the optimization on capital cost, or, more importantly, on the cost-of-ownership. Only the electrical power requirement was minimized. The higher temperature refrigerators are cheaper that comparable low temperature refrigerators, but the fact that each individual refrigerator of a multi-stage unit has smaller capacity increases the cost per unit.

ACKNOWLEDGEMENTS

This work was carried partly under the auspices of the MIT Energy Initiative Seed Fund Award Number: 015728-007.

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