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OPTIMIZATION OF HIGH-TEMPERATURE SUPERCONDUCTOR CURRENT LEADS*

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Abstract—Methods to improve the performance of high-temperature superconducting current leads are analyzed. Designs are considered that are inherently safe from burnup, even if the lead enters the normal state. The effect of a tapered lead that takes advantage of the increase in critical current density with decreasing temperature will decrease helium boiloff by about a factor of two for an area ratio of four. A new concept, in which Ag powder is distributed in increasing concentration from the cold end to the hot end of the lead in sintered YBCO, is shown to have comparable performance to that of leads made with Ag-alloy sheaths. Performance of the best inherently safe designs is about one order of magnitude better than that of optimized nonsuperconducting leads. BSCCO leads with Ag-alloy sheaths show improved performance for Au fractions up to about 3%, after which increases in Au fraction yield negligible performance improvement.

I. INTRODUCTION

Current leads using high-temperature superconductors (HTSs) to deliver power to devices operating at liquid helium temperature have the potential to reduce refrigeration requirements to values significantly below those achievable with conventional leads [1]. In the HTS part of the lead bulk YBCO [2]-[4], bulk YBCO/Ag [2], [5], [6], bulk BSCCO [7], [8], and powder-in-tube (PIT) BSCCO with a Ag-alloy sheath [9]-[13] have been considered.

In this paper HTS lead designs are considered that are inherently safe from burnup, even if the lead enters the normal state. Under this constraint, HTS leads may be optimized for each material considered. Results are presented for sintered YBCO, sintered BSCCO, and PIT BSCCO that uses several compositions of Ag-alloy sheaths. We investigate the effect of a variable cross-sectional area along the lead length. We also investigate a concept, in which Ag powder is distributed in increasing concentration from the cold end to the hot end of the lead in sintered YBCO.

II. VARIABLE CROSS-SECTIONAL AREA

Because critical current density increases as temperature decreases and heat flow at the cold end is mainly dependent on conduction, it is plausible to consider a variable cross-sectional lead in which the area of the HTS is smaller at the cold end than at the warm end. We assume the area varies linearly as

$$A(x)/A_C = 1 + (A_H/A_C - 1)x/L, \quad (1)$$

where A is area, x is distance along the lead, H denotes warm end, C denotes cold end, and L is the lead length.

For a conduction-cooled lead, there is the boiloff helium vapor is not used to help cool the lead. In the superconducting state, there is no Joule heating so the governing equation is

$$d/dx[k(x,T)A(x)dT/dx] = 0, \quad (2)$$

where k is thermal conductivity and T is temperature. The heat flow Q along the lead is the same at both the hot and cold end, so that

$$Q_C = Q_H = mC_L = k(x,T)A(x)dT/dx, \quad (3)$$

where m is the helium boiloff rate and C_L is the latent heat of evaporation.

If thermal conductivity is only temperature dependent, Eq. (3) is separable and is solved to yield

$$m = (1/C_L) \left[\int_{T_C}^{T_H} k(T) dT \right] \left[\int_0^L dx / A(x) \right]. \quad (4)$$

If we define parameter α by

$$1/\alpha = \int_0^1 A_C / A(x) d(x/L). \quad (5)$$

then Eq. (4) becomes

$$m = \alpha A_C / (LC_L) \int_{T_C}^{T_H} k(T) dT \quad (6)$$

If the cross-sectional area varies as in Eq. (1), then

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$$\alpha = (A_H/A_C - 1)/\ln(A_H/A_C) \quad (7)$$

For a fixed L and A_H , it is useful to compare the helium boiloff as a function of the area ratio. This is shown in Fig. 1. The results indicate that an increase in A_H/A_C to a value of 4 reduces the boiloff to half that of a uniform area, and increases in the area ratio beyond this value only slightly decrease the boiloff rate.

Fig. 1. Geometric boiloff factor $\alpha A_C/A_H$ as a function of area ratio A_H/A_C .

III. VARIABLE SILVER CONCENTRATION

We have shown previously [9] for PIT HTS leads with Ag-alloy sheaths that a temperature dependence of thermal conductivity such that the conductivity is low at low temperatures and high at high temperatures has advantage in lead protection. With such a profile, the lead can be designed to yield less boiloff without danger of burnout. Here we extend the analysis to a HTS lead made from a composite of YBCO and Ag for which the concentration of Ag varies linearly from 0.1 at the hot end to zero at the cold end. Compared to a lead made from YBCO, the graded Ag/YBCO lead has the same thermal conductivity at low temperature but a significantly higher thermal conductivity at high temperature.

A composite HTS of YBCO and Ag has thermal conductivity depending on temperature and Ag concentration according to

$$k(T) = k_Y(T)(1-\phi) + k_S(T)\phi, \quad (8)$$

where k is thermal conductivity, T is temperature, ϕ is the fractional concentration of Ag, Y denotes YBCO and S denotes Ag. We consider a linear variation of ϕ

$$\phi(x) = \phi_C + (\phi_H - \phi_C)x/L. \quad (9)$$

and in this paper limit the discussion to $\phi_C = 0$ and $\phi_H = 0.1$.

We compare the graded Ag/YBCO lead to two cases that are already known [9]: (a) pure YBCO lead with no sheath, and (b) YBCO with 10%Ag/palladium alloy sheath. The graded Ag/YBCO lead is denoted by (c). While the thermal conductivities in cases (a) and (b) are only temperature dependent, the thermal conductivity in case (c) is both temperature and space dependent.

The HTS lead is a bistable system that can be either in the superconducting state or in the normal state. The most optimistic situation is a vapor-cooled HTS state in which the helium boiloff is lowest. When the HTS lead converts to the normal state, there is an optimum shape factor corresponding to a minimum boiloff rate. The lead can operate safely at a shape factor slightly higher than the optimum, but eventually at a sufficiently large shape factor the temperature of the lead exceeds its burnout temperature [9]. The most pessimistic design then considers the conduction-cooled normal state, for which there is no vapor cooling.

For lead performance in the conduction-cooled normal state, we must solve the energy balance equation

$$d/dx[k(x,T)A(x)dT/dx] + \rho(x,T)J(x)^2A(x) = 0, \quad (10)$$

where ρ is the electrical resistivity, and J is the current density. By transforming $k(x,T)A(x)dT/dx = Q$, Eq. (10) becomes

$$QdQ/dT + BTI^2 = 0, \quad (11)$$

where B is a constant from the Widemann-Franz law $pk = BT$, and I is the current. By integrating, the heat flow equation becomes

$$[k(x,T)A(x)dT/dx]^2 = I^2[(mC_L/T)^2 - B(T^2 - T_C^2)], \quad (12)$$

For the vapor cooled superconducting state, we assume perfect heat transfer between the lead and vapor and must solve

$$d/dx[k(x,T)A(x)dT/dx] - m[d/dx(c_g T)] = 0, \quad (13)$$

where c_g is the specific heat of the helium gas.

In this work we solve the governing equations by a numerical shooting method [14]. We assume the cold- and hot-end temperatures are fixed at $T_C = 4.2$ K and $T_H = 77$ K, respectively. We first assume a value for m and integrate from $x = 0$ to L for the temperature distribution by the Runge-Kutta method. We then check to see if the temperature at $x = L$ equals T_H . If the equality is not satisfied, we change m and iterate.

Figure 2 shows the helium boiloff rate versus shape factor for three different operating conditions. For the conduction-cooled normal steady-state, there is a minimum boiloff rate corresponding to the optimal shape factor. The right end of the solid line corresponds to the burnout point at which some part of the lead reaches a temperature of 300 K.

For shape factor values below the optimum, it is almost the same as for the normal state. However, for larger shape factors than the optimum, the difference of helium boiloff rates between normal and superconducting states becomes larger. For the vapor-cooled superconducting steady state, the helium boiloff rate is the smallest among the three operating conditions. For shape factors corresponding to the burnout point, the boiloff in the conduction-cooled superconducting state is 0.17, 0.06, and 0.07 mg/sA for cases (a)-(c), respectively. This compares with the 0.51 mg/sA for the theoretical best of an optimized normal lead. Of interest, the graded Ag/YBCO performance is almost as good as that of the lead sheathed with Ag alloy. The vapor-cooled state has a similar relationship between the cases with a boiloff of 0.023, 0.008, and 0.009 mg/sA.

Fig. 2. Steady-state helium boiloff m per ampere of current I versus shape factor JL for three types of HTS leads: (a) YBCO, (b) YBCO with Ag/10% Palladium sheath, (c) Ag/YBCO with graded Ag. The dashed lines are for the conduction-cooled superconducting state. The solid lines are for the conduction-cooled normal state. The dotted lines are for the vapor-cooled superconducting state.

IV. COMPOSITION OF SILVER SHEATH

Substantial interest has been recently shown [9]-[13] in PIT HTS leads with Ag-alloy sheaths. By increasing the concentration of Au with the Ag, the thermal conductivity of the alloy can be reduced [10], making for a smaller shape factor, i.e., a shorter lead, assuming that critical current density does not change. The concern with PIT BSCCO is that only elements such as Au do not react with the HTS, and these alloying elements are significantly more expensive than the Ag. To determine the cost performance of these leads, it is necessary to estimate their performance as a function of alloy content. Figure 3 shows the helium boiloff rate versus shape factor for four different BSCCO lead designs. Thermophysical parameters for the sheaths are taken from [10].

Fig. 3. Steady-state helium boiloff m per ampere of current I versus shape factor JL for four types of BSCCO leads for the conduction-cooled normal state: (d) bulk BSCCO, (e) BSCCO with Ag/1%Au sheath, (f) BSCCO with Ag/2.9%Au sheath, and (g) BSCCO with Ag/11%Au sheath.

When the JL shape factor at burnout is chosen and the helium boiloff rate calculated for the conduction-cooled superconducting state, the results are: (d) 0.09 mg/sA for the bulk BSCCO, (e) 0.08 mg/sA for the BSCCO with Ag/1%Au sheath, (f) 0.06 mg/sA for the BSCCO with Ag/2.9%Au sheath, and (g) 0.06 mg/sA for the BSCCO with Ag/11%Au sheath. A similar ratio of relative boiloffs is expected in the vapor-cooled superconducting state. From these results it appears that the Ag-alloy sheathed leads offer performance improvement over the bulk BSCCO. Increasing the Au content improves lead performance, but after about 2.9%, the increase in performance is negligible. With a higher Au fraction, the shape factor is smaller, i.e., the lead can be made shorter, but the increase in Au content increases the cost of the lead.

V. CONCLUSIONS

HTS leads with a tapered geometry can take advantage of the temperature dependence of the critical current density. Leads with an area ratio of about 4 and a constant area ratio taper along the lead reduce the heat leakage at 4 K to half that of a constant area lead.

A new concept, in which Ag powder is distributed in increasing concentration from the cold end to the hot end of the lead in sintered YBCO, is shown to have comparable performance to the PIT leads. Performance of the best inherently safe designs is about one order of magnitude better than that of optimized nonsuperconducting leads.

For Ag-alloy BSCCO leads with a shape factor set at the burnout condition in the normal state, increasing the Au content of the alloy decreases the helium boiloff rate in the superconducting state. Increase in Au fraction beyond about 3% shows negligible improvement.

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