Thermal conductance at millikelvin temperatures of woven ribbon cable with phosphor-bronze clad superconducting wires

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Woven Nomex® ribbon cables made up with superconducting niobium titanium wire are used at millikelvin temperatures in many large cryogenic instruments. It is important to know how much heat in transmitted down such cables. However, the conductivity of the materials used is not well known. Another problem is that the wires are normally clad with alloys which exhibit some magnetism. This is a potential problem for instruments employing superconducting detectors. A safe non-magnetic alternative to the usual materials is phosphor-bronze clad niobium-titanium wiring. However, there is little experience with such wires. We have therefore measured the conductance of a ribbon cable made up with these wires. The measured values are in good agreement with our predictions, suggesting that the values we have used to model the cable are sufficiently accurate, and could therefore be used to predict the performance of ribbon cables using other cladding materials, so long as the conductivity of the cladding is reasonably well known. As part of our analysis, we consider the likely variation in thermal conductivity values for C51000 phosphor bronze caused by legitimate variations in composition.

Keywords: Superconducting cables (A); Thermal conductivity (C); Instrumentation (D); SQUID systems (F)

1 Introduction

Woven ribbon cables [1] are used at millikelvin temperatures in many large cryogenic instruments. Heat transmitted down the cables is often minimised by using niobium-titanium (NbTi) wire, which is superconducting at temperatures below 10 K. It is practically impossible to solder to NbTi, and thus the wire is generally clad with an alloy which is more amenable to soldering. This alloy is commonly constantan or a similar copper nickel alloy. However, such alloys are somewhat magnetic, and there is the potential for them to cause magnetic interference with SQUIDs where these are used in readout circuitry. Niobium titanium wire is available with copper cladding. Copper is non-magnetic, but it has a high thermal conductivity and must be removed over some part of the wire length. This is possible but not easy to achieve with woven ribbon cables. An alternative non-magnetic, but low conductivity, cladding material is phosphor bronze.

While phosphor bronze is a reasonably common material for cryogenic wiring, the use of phosphor bronze *cladding* on superconducting wire is not usual, and we are unaware of any information on the performance of such cables. Furthermore, the thermal conductivity of the niobium-titanium and the weave material is not well known. We present thermal conductance measurements of a ribbon cable made up in this way, intended for use in the SCUBA-2 astronomical instrument [2] at temperatures below 1 K. While we have not measured the conductivity of the components of the wire individually, the measurements should be of some use in predicting the conductance of similar cables using more common cladding materials since even this is not well known.

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2 Sample

The sample measured was produced by Tekdata[1], and consisted of 40 wires (made up in twisted pairs) each consisting of a 64 μm diameter niobium titanium (NbTi) core with a 10 μm thick phosphor bronze cladding. The phosphor bronze is alloy UNS C51000 (also known as CDA 510), with nominal composition of 4.2 – 5.8% tin and 0.03 – 0.35% phosphorus by weight, the remainder being copper along with trace impurities. The ribbon cable is woven from Nomex®; there are 39 warp (i.e. parallel to the wires) threads of 0.226 mm diameter, and six smaller (0.143 mm diameter) threads, three on each side of the ribbon; the general configuration is shown in Fig. 1. The sample measured was approximately 100 mm long.

We are not aware of any measurements on the thermal conductivity of Nomex in this temperature range.

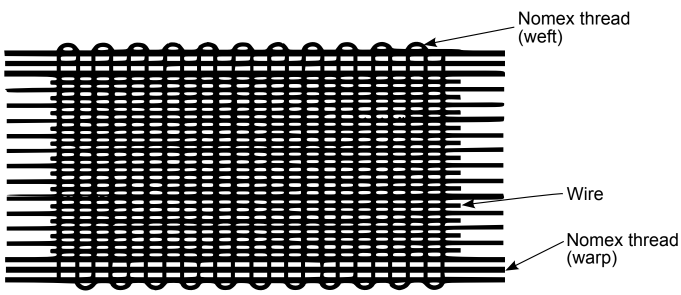

Figure 1: Schematic of the layout of the ribbon cable (the actual number of wires and threads is more than shown)

[1] Tekdata Interconnections Limited, Innovation House, The Glades, Festival Way, Etruria, Stoke-on-Trent, Staffordshire, ST1 5SQ, UK

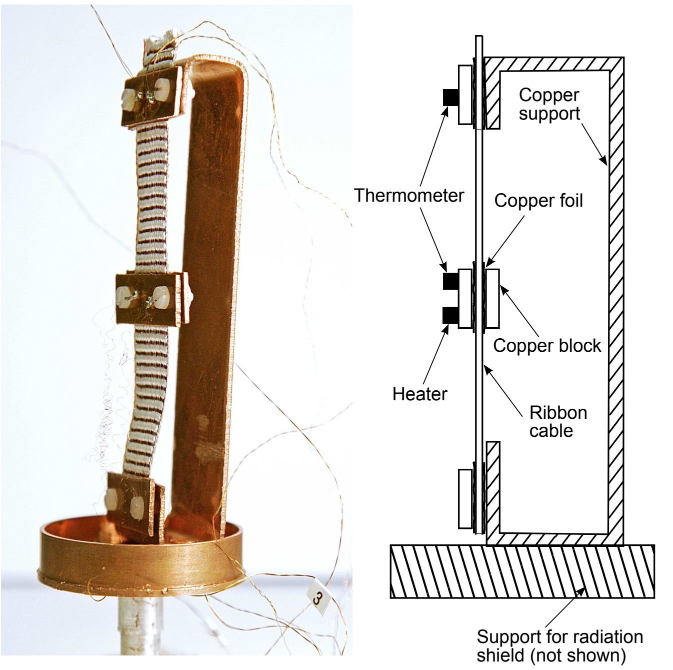

Figure 2: Photograph (left) and schematic drawing (right) of the experimental configuration

3 Measurements

It is difficult to measure the thermal conductance of a single length of a non rigid good insulator, since mechanical support is required and the conductance of this support will be measured in parallel with the sample. We therefore supported the wire at the ends and applied heat in the centre, thus measuring the conductance from the centre to each end in parallel. The experimental configuration is modified from a design we have successfully previously used to measure the conductance of Kevlar® at millikelvin temperatures [3]. The layout is shown in Fig. 2. The ribbon cable was supported at both ends by a copper mount; one end of this was mounted onto a copper block attached to the mixing chamber of a dilution refrigerator. A radiation shield at mixing chamber temperature surrounded the sample. Thermal contact was made to the ribbon cable at both ends by sandwiching it between the mount and a copper block; 50 μm thick copper foil was wrapped around the cable to improve thermal contact. The copper block was bolted to the mount using nylon screws; these have significantly greater thermal contraction than copper, and thus the contact improves upon cooling. At the centre, the cable was sandwiched between two more copper blocks arranged in a similar manner. The centre copper block carried a NiCr heater and a thermometer, and the outer block carried a thermometer. The thermometers were both RuO_2 devices; the calibration method has been described previously [4]. The two lengths of cable across which the measurements were made were both 30 ± 0.1 mm.

To make measurements, the mixing chamber was held at a constant temperature and the equilibrium temperature of the centre copper block measured as a function of applied heater power. Measurements were made at two mixing chamber temperatures (100 and 200 mK); the two measurements were in good agreement with each other.

There are three main contributions to the relative error in the conductance G(T):

– 1) The power supplied to the sample: we estimate that the relative error is of the order of about 0.1%;
– 2) The measurement of the geometry of the wires; this is estimated to be about 4%;
– 3) The uncertainty in the temperature due to the accuracy of the thermometers. A conservative value is 1%.

Taking into account these contributions, the relative error in conductance is about 5%.

4 Results and analysis

The results are shown in Fig. 3. The conductance was obtained by differentiating the applied power as a function of heater block temperature; the conductance for a unit length of the ribbon cable is shown in Fig. 4. This can be represented by the expression

$$G = 3.11 \times 10^{-8} T^{1.19}, \qquad (1)$$

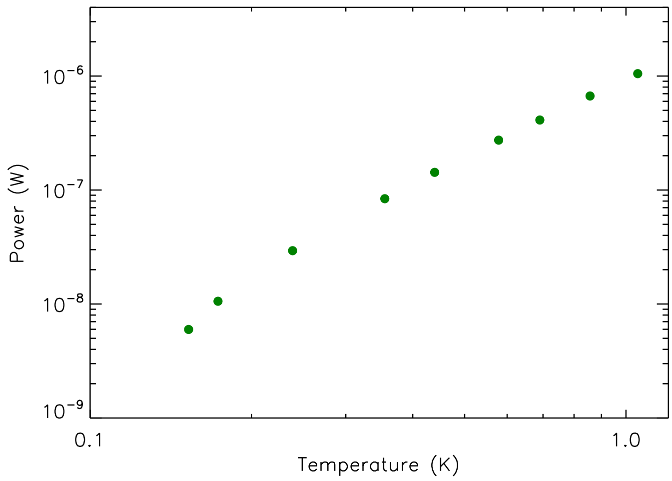

Figure 3: Measured power dissipated in the heater as a function of the temperature measured at the centre block.

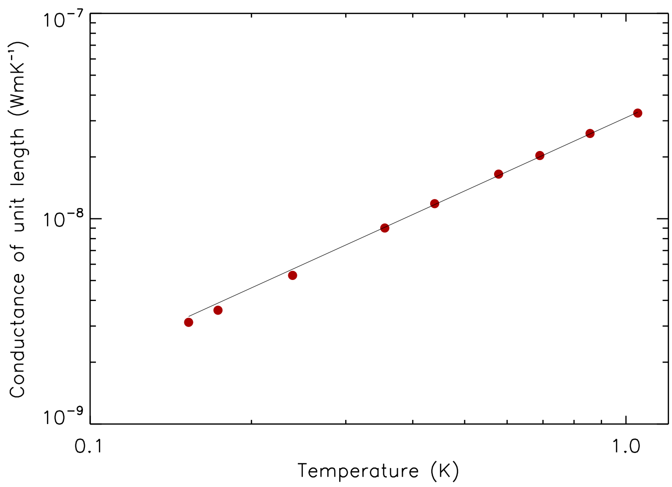

Figure 4: Conductance for a unit (1 m) length of ribbon cable, obtained by differentiating the data shown in Fig. 3. The line shows a power-law fit to the data.

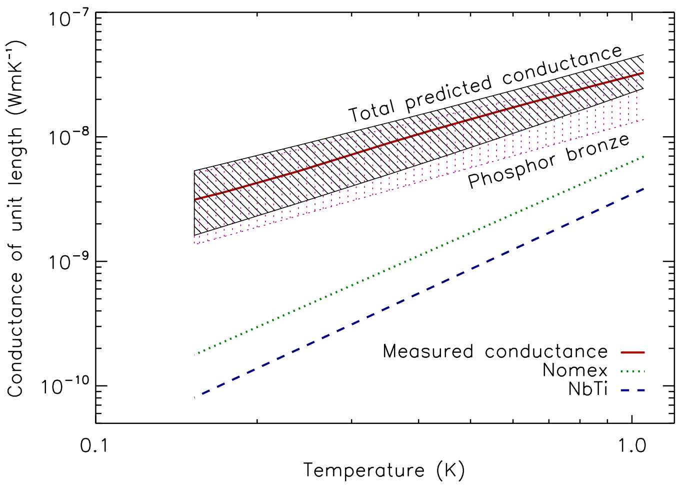

Figure 5: Predicted conductance for a unit length of the ribbon cable and its constituents. The conductance of the Nomex and niobium titanium are shown as single lines (dotted and dashed respectively), while the phosphor bronze conductance is shown as a possible range of values corresponding to variation between different samples of the same material (dotted vertical hatching). The total predicted conductance therefore also consists of a range of values (diagonally hatched area). The measured conductance (converted to a value for unit length of wire) is also shown (thick solid line).

where T is temperature; this is shown as the solid line in Fig. 4. A possible source of systematic error in the measurements would be a significant thermal resistance between the copper blocks and the ribbon cable. We believe based on previous measurements that the mounting scheme we have used provides a contact resistance which is sufficiently small to be neglected. The results suggest that this is indeed the case; the thermal conductance at such a contact is expected on both theoretical and experimental grounds to have a temperature dependence between T^2 and T^3; the observed overall variation of $T^{1.2}$ suggests that any contact resistance is small.

In Fig. 5, the measured values are compared to values predicted from the composition of the ribbon cable. The thermal conductivity of the various components is taken from various measurements in the literature. Unfortunately, reliable values are not available for any of the components in the cable.

The thermal conductivity of NbTi is not well known, and above the transition temperature there is considerable variation depending on exact composition and heat/mechanical treatment, and possibly also between nominally identical samples. Below the transition temperature there is little data. Furthermore, the thermal conductivity of materials in the superconducting state is not well understood. As a reasonable approximation, we use measured values [5] for a niobium-titanium rod. Measurements on NbTi wire are given in the same paper; the conductance was found to be about half that of the rod. Given the uncertainty for this material, we use the rod values as a conservative value, giving a conductivity of

$$\kappa_{\mathrm{NbTi}} = 0.027(T/\mathrm{K})^2\mathrm{Wm}^{-1}\mathrm{K}^{-1}. \quad (2)$$

We are unaware of any measurements of the thermal conductivity of Nomex at cryogenic temperatures. Nomex is an aramid (aromatic polyamide). Another aramidwhich is commonly used at cryogenic temperatures is Kevlar® and we could therefore use the conductivity of Kevlar as a substitute for the unknown values for Nomex. Our recent measurement of the conductivity at millikelvin temperatures [3] gave the following conductivity:

$$\kappa_{\mathrm{Kevlar}} = 3.8 \times 10^{-3}(T/\mathrm{K})^{1.95}\mathrm{Wm}^{-1}\mathrm{K}^{-1}; \quad (3)$$

earlier measurements over the same temperature range [6] were in good agreement.

However, at room temperature we have measured [7] a conductivity of 4 $\mathrm{Wm}^{-1}\mathrm{K}^{-1}$ for Kevlar; this is much higher than the conductivity of Nomex [8], which is around 0.3 $\mathrm{Wm}^{-1}\mathrm{K}^{-1}$, suggesting that Kevlar may *not* have a similar conductivity to Nomex. Nomex fibre *does* have a similar room temperature conductivity to nylon [8], another polyamide (but not an aramid), and therefore the conductivity of nylon at millikelvin temperatures may be a more suitable substitute. There are various measurements in the literature on the thermal conductivity of nylon below 1 K, most of which are in reasonably good agreement. An upper limit to the various measurements (which is close to the values in the well-known paper by Locatelli et al. [9]) is given by

$$\kappa_{\mathrm{nylon}} = 2.6 \times 10^{-3}(T/\mathrm{K})^{1.75}\mathrm{Wm}^{-1}\mathrm{K}^{-1}; \quad (4)$$

this is slightly lower than the values above for Kevlar at cryogenic temperatures. Since the conductivities of nylon and Kevlar are similar at millikelvin temperatures, it makes little difference which we choose; we have chosen the Kevlar values.

For the alloy of phosphor bronze used (C51000), we are aware of only one set of thermal conductivity measurements at cryogenic temperatures [10][2]. Furthermore, there is known to be considerable variation in conductivity between different samples of this material (even at room temperature), since the permissible ranges in the amount of tin and phosphorus present are quite large. Measurements at room temperature from various sources were considered in Ref. [12] and used to generate an equation for the room temperature conductivity as a function of tin and phosphorus content. For the composition ranges allowed for C51000, this predicts a rather large range (44 – 92 $\mathrm{Wm}^{-1}\mathrm{K}^{-1}$) for room temperature conductivity. The lower limit corresponds to the worst case of maximum phosphorus and tin content and is perhaps unlikely. Measurements are presented in Ref. [13] for the thermal conductivity of phosphor bronzes with a range of compositions from around 15 K to room temperature. The room temperature values are generally around 20% higher than the equation from Ref. [12] would suggest, and in particular show less reduction in conductivity with phosphorus content than seen in the measurements used in Ref. [12]. Generating a new equation for room temperature conductivity by including data from both Refs [12] and [13] gives a room temperature range for C51000 of 57 – 92 $\mathrm{Wm}^{-1}\mathrm{K}^{-1}$; the two samples measured in Ref. [13] with composition within the specifications for C51000 fall into this range. However, to be conservative, for our analysis we have used the first and larger range given above.

Having obtained a range of values at room temperature, we need to convert this to a range at millikelvin temperatures. First we consider the conductivity at 4 K, since this is the lowest tem-

[2] In this paper, good agreement was shown with earlier measurements [11] on an alloy with similar composition to C51000 (the phosphorus content was slightly higher than permitted by the C51000 specifications).

perature that we have data for. The measurements in Ref. [10] were made from 4 K to room temperature; at room temperature they are close to the upper limit. To obtain a lower limit for C51000 at 4 K, we assume that the ratio of conductivities at 4 K for two different samples are the same as at room temperature. While this is in general not true for a metal, it should be a good approximation for such a strongly alloyed material as this. The validity of this approximation is supported by the use of an equation [14] derived to predict the conductivity of pure copper as a function of temperature for different purities. While intended for use only with pure copper, it has been shown to also apply well to dilute copper alloys such as beryllium copper [15], and it also fits the data from Ref. [10] reasonably well.

The next problem is that we do not know the temperature variation below 4 K. Above 4 K, the conductivity varies as $T^{1.2}$. The conductivity of a metal due to electrons is expected to vary linearly with temperature; the fact that the exponent is greater than 1 is believed to be due to a significant contribution from conduction through the lattice. In a metal, lattice conduction is expected to vary below 4 K approximately as T^2, and therefore will become much smaller than the electronic conductivity at millikelvin temperatures. The exponent should therefore be somewhere between 1 and 1.2. We therefore obtained upper and lower limits below 1 K by extrapolating the upper limit at 4 K with an exponent of 1, and the lower limit with an exponent of 1.2, giving values of

$$\kappa_{\mathrm{PhBr,\ upper\ limit}} = 0.36(T/\mathrm{K})\mathrm{Wm}^{-1}\mathrm{K}^{-1} \quad (5)$$

$$\kappa_{\mathrm{PhBr,\ lower\ limit}} = 0.14(T/\mathrm{K})^{1.2}\mathrm{Wm}^{-1}\mathrm{K}^{-1}. \quad (6)$$

It can be seen from Fig. 5 that the measured values for the ribbon cable conductance lie within the range of predicted values. Since the contribution from the phosphor-bronze dominates, the fact that we have represented the Nb-Ti and Nomex components by a single value rather than a range has little effect on the range of values for the total predicted conductance; a difference of a factor of two would have little effect on the overall conductance. Given the large uncertainty in the conductivity of all the components, the agreement may be to some extent fortuitous. However, it suggests that the predictions are reasonably accurate. Therefore it should be possible to predict the performance of ribbon cables using other wire and cladding materials with some confidence. In particular, it suggests that the conductance through the Nomex (a poorly known quantity) is small.

5 Conclusions

We have measured the conductance of a sample of woven Nomex ribbon cable containing phosphor-bronze clad niobium-titanium wire. Such a cable has the advantage that it does not contain any magnetic materials, unlike cables employing the more usual monel or constantan cladding. While the thermal conductivity of the different components of the cable is not well known, we have predicted a range of likely values for the conductance. The measured results lie within this range, suggesting that the values we have chosen are reasonably accurate, and thus can be used to predict the conductance of ribbon cables using other wiring materials.

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