Thermal diffusion and quench propagation in YBCO pancake coils wound with ZnO and Mylar insulations

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Abstract

The thermal diffusion properties of several different kinds of YBCO (yttrium barium copper oxide) insulations and the quench properties of pancake coils made using these insulations were studied. Insulations investigated include Nomex, Kapton, and Mylar, as well as insulations based on ZnO, Zn₂GeO₄, and ZnO–Cu. Nomex, Kapton, and Mylar, chosen for their availability and ease of use, were obtained as thin ribbons, while the ZnO based insulations were chosen for their high thermal conductivity and were applied by a thin film technique. Initially, short stacks of YBCO conductors with interlayer insulation, epoxy, and a central heater strip were made and later measured as regards their thermal conductivity in liquid nitrogen. Subsequently, three different pancake coils were made. The first two were smaller, each using one meter total of YBCO tape present as four turns around a G-10 former. One of these smaller coils used Mylar insulation co-wound with the YBCO tape, the other used YBCO tape onto which ZnO based insulation had been deposited. One larger coil was made which used 12 total meters of ZnO insulated tape and had 45 turns. Temperature gradients were measured and thermal conductivities were estimated from these coils; the results obtained were compared to those for the short stacks. Quench propagation velocity measurements were performed on the coils (77 K, self-field) by applying a DC current and then using a heater pulse to initiate a quench. Radial NZP (normal zone propagation velocity) values (0.02–1 mm s⁻¹) were two orders of magnitude lower than axial values (∼10–20 mm s⁻¹). Nevertheless, the quenches were generally seen to propagate radially within the coils, in the sense that any given turn in the coil is driven normal by the turn underneath it. This was due to the fact that while the radial NZP is much lower than the NZP along the conductor (∼100 ×) the distance by which the normal zone must expand longitudinally is much larger than the distance by which it must expand radially to reach the same point; in our case this ratio is ∼1600.

(Some figures in this article are in colour only in the electronic version)

1. Introduction

1.1. Background

Most of the quench and overcurrent studies for YBCO coated conductors have been directed towards fault current limiters, or other AC devices, although some initial results related to quenching in strands have been performed [1–5]. Some results on early conductors showed normal zone propagation velocities (NZP) of 2–5 mm s⁻¹ at 80 K and 50–98% of Ic [1], measurements of more recent conductors have typically given 10–20 mm s⁻¹ [2–5]. The measurement processes varied; sometimes they were performed in vacuum, or more frequently under gas cooling. More recently, results for quench measurements of small coils of YBCO are becoming available [6, 7], although much work remains to be done. Of course, as it was for other magnet/conductor systems,
insulation is very important. One of the key issues is that YBCO coated conductors are very thin, and thus in order to have good thermal transport and high engineering critical current density in the winding (which we denote \( J_c \)) a thin and thermally conductive insulation is needed. YBCO coils have typically used a thin film insulation, co-wound with the conductor, such as Nomex, Kapton, or Mylar. However, these insulations are somewhat thicker than would be desired, and can limit \( J_c \) and thermal conduction. Another alternative is the use of a thin sol–gel type insulation, similar to that used for Bi-2212 [8], bearing in mind that those of [8] tend to stick best to Ag surfaces. But presently, researchers looking at YBCO for magnet applications tend to use Mylar or similar insulation—even if noting the need for better thermal conductivity [9].

Below we will investigate both quench propagation in small pancake coils made with coated conductor and the differences seen with different insulations methods. One of the key drivers for this work has been the need to increase the NZP, in order to enhance magnet protection, this is also investigated below.

1.2. Outline

This work focuses on the measurement of thermal gradients and quench propagation in pancake YBCO coils insulated with Mylar and ZnO. There were two motivations for this work. First, we wished to explore quench propagation in YBCO coils. While quenching in BSCCO based coils has been extensively studied, the materials properties and high aspect ratios of coated conductors change quench propagation in interesting ways. Secondly, we wished to investigate the possibility of speeding the quench of YBCO coils by allowing radial transport of the quench zone.

The idea of radial quenching in YBCO coils was suggested by Oberly [10] as a possible way to mitigate problems related to the slow NZP in YBCO conductors. It is well known that the time required for longitudinal quench propagation along YBCO tape at 77 K is roughly three orders of magnitude greater than that of NbTi or Nb3Sn at 4.2 K. The NZP speed for NbTi is some meters per second (m s\(^{-1}\)), while that of YBCO is some few mm s\(^{-1}\) to some tens of mm s\(^{-1}\) [1–5]. This leads to problems in magnet protection [11]. Under static conditions (i.e., without ramping fields or currents) there is a minimum energy required to cause a quench, the minimum quench energy (MQE). At lower perturbation energies the magnet may recover, but once the MQE is reached, it will proceed to a full quench. At this point, the currents are transferred into the surrounding matrix, thereby heating it and causing the quench to propagate. The speed of the propagation depends on a number of factors, including the heat capacity of the conductor, its resistivity in the normal state, and the level of current in the cross section [11]. As this speed slows, the time required to detect the quench increases, and a smaller region must absorb the energy being dumped into the magnet. Ultimately, the power to the magnet must be shut off as soon as possible after the quench, perhaps using quench heaters to drive larger sections normal (although the MQE needed for YBCO is much higher, and may make this scheme more difficult).

For clarity, when discussing the pancake coil measurements and analysis below, we can consider the pancake coil to lie in the \( r-\theta \) plane, axial refers to properties along the \( z \)-axis, azimuthal refers to properties in the \( \theta \) direction, and radial refers to properties in the \( r \)-direction. The longitudinal direction in the tape (i.e., along the direction of the current flow) then corresponds to the azimuthal direction in the coil, and the tape perpendicular direction corresponds to a radial direction in the coil. The tape parallel direction is associated with properties either along the azimuthal–longitudinal direction, or along the axial direction in the coil.

The fact that normal zone velocities vary with direction is well known, harking back to the early days of stability studies on low \( T_c \) conductors [12–14]. Indeed, many of the essential aspects of strand and magnet stability are very similar to those of low \( T_c \) materials [15], and the 3D nature of quench propagation is well understood in principle [11, 15]. However, while truly detailed and 3D models have been developed, usually 1D models dominated by longitudinal normal zone propagation frame the conceptual approach to thinking about quench in magnets. This has also been the starting point for considering quench in YBCO magnets, with the focus on coil-azimuthal propagation of the quench, corresponding to a longitudinal propagation within a tape. At first glance, this makes sense, since the longitudinal propagation in an isolated tape is much faster than the expected radial propagation within a coil—at least in absolute terms. This scenario implicitly assumes that the insulation between adjacent turns will have a lower thermal diffusion constant, causing quench propagation to occur along the length of the tape, even when it is wound into a coil. However, as is especially true for racetrack magnets (but also for solenoids) the distance around the circumference (or path) of the magnet is much longer than the radial turn-to-turn distance given the very thin YBCO conductor. Thus, it was postulated that if the thermal diffusion in the radial direction could be enhanced, the quench could be made to propagate radially within the coil at the same time as it propagated longitudinally along the wire (azimuthally within the coil), thus causing a much larger fraction of the coil to quench in a given time.

In order to increase the thermal conductivity of the winding pack, we investigated the use of thin ZnO based insulations known to be electrically insulating and thermally conductive. A series of ZnO based insulations has been developed at CeramPhysics, and were the basis of the insulating materials used here [16, 17]. The thermal properties of pure- and varistor-grade ZnO were first investigated by Lawless and Gupta [16] in the temperature range of 1.7–25 K. The thermal conductivities of both of these materials were found to be large (~10 W m\(^{-1}\) K\(^{-1}\)) at 25 K. As a result, they were then proposed [16] for use as insulation in HTS coils. The goal was to identify materials that not only provided thinner electrical insulation, but also improved quench protection because of their large thermal conductivity. The thermal conductivities of pure- and varistor-grade ZnO were found to be a nearly constant 62 W m\(^{-1}\) K\(^{-1}\) in the temperature range 60–90 K. As a result, pure ZnO was chosen as the material of interest for further investigation as an insulator for YBCO. It has several desirable properties in addition to its large thermal conductivity: low cost, and ease of application by sputtering.
Of course, because the winding must be epoxy impregnated, the inter-tape regions will contain epoxy as well as insulation, both of which have relatively low thermal conductivity. With Nomex, Kapton, or Mylar, the insulation layer is impermeable to the epoxy. On the other hand, with a ceramic insulation like ZnO, the epoxy may interpenetrate cracks in the relatively thin ZnO layer. Thus in both cases the final thermal properties of the interlayer are some combination of the epoxy and the insulation.

In this paper, we compare thermal conductivity and quench propagation in YBCO pancake coils wound with ZnO based insulations to one wound with Mylar insulation. We first measured the thermal conductivities of model winding stacks: simple stacks of conductors instrumented for temperature and voltage. The thermal gradients in ZnO and doped ZnO insulated YBCO stacks were measured and compared to those in stacks insulated with Nomex, Kapton, and Mylar. The average thermal conductivity of the ZnO insulated stacks were not very different than that of the Nomex, Mylar, and Kapton stacks. After an autopsy of the coils and the stacks measured in this work, it was observed that the coated conductors were thicker on the edges that they were in the middle (apparently due to preferential Cu deposition there) which allowed an epoxy filled gap to form in the coils and the stacks. Thus, it was not possible to reach the high thermal conductivities which were expected with the ZnO based insulations. It is worth noting that the average thermal conductivity of a coil may be ultimately limited by the apparently ubiquitous presence of a thermal interface contact resistances; the true levels which can be reached must be determined by a further set of experiments with uniform thickness conductors. In any case, the results here do point to the need to use uniform thickness coated conductors in order to reach maximum radial thermal conductance. Following these stack measurements, several YBCO pancake coils were made, both with ZnO insulation as well as with Mylar insulation. Thermal gradients were measured in these coils and compared to the tape stack measurement results (similar epoxy interlayers were seen in the ZnO insulated coils). Finally, NZP measurements were made on the coils, and the results for ZnO insulated coils were compared to those for Mylar insulated coils. The ZnO coils were found to have the highest packing density while their thermal conductivities and NZPs were found to be only slightly increased. However, it was found that quenches tended to propagate radially both for the ZnO and also the Mylar insulated coils, due to a large coil perimeter/conductor thickness ratio.

2. Sample preparation and experimental measurements

Two different IBAD-architecture tapes were obtained from Superpower, conductor 1 and conductor 2 (see table 1). Both conductors 1 and 2 were used for short stack measurements (see below), while all of the coils used in this study were wound with conductor 2. Three insulations were available as ribbons; Nomex, Kapton, and Mylar, their thicknesses were 38 μm, 40 μm, and 19 μm, respectively. Short stack samples were used for 1D thermal propagation measurements, while the coils were used for in situ thermal propagation measurements and NZP measurements. All measurements were performed at 77 K in LN2.

2.1. Preparation of short stacks of YBCO and thermal measurements

In preparation for 1D thermal propagation measurement, YBCO tape was cut into segments approximately 4 cm in length. These segments were then stacked and epoxy impregnated using Stycast 1266 epoxy and a wet lay-up technique (the tapes were dipped in epoxy and then assembled). Stycast 1266, a low viscosity, moderately thermally conductive epoxy (as opposed to Stycast blue (2850FT)) was chosen to mimic the CTD 101 (epoxy #101 from Composite Technology Development Co., Lafayette, CO) used for vacuum impregnation of the coils [18, 19], since vacuum impregnation with CTD101 was difficult to achieve for these short samples (the thermocouples were damaged). A pressure of 8.9 MPa was applied during drying to simulate a typical expectation for a magnet winding. A heating strip, which consisted of a meandering twisted pair made from 41.3 Ω m⁻¹ nichrome wire, was placed in the central layer of the stack (figure 1, see (b)–(d)). Either 5 (set 1) or 7 (set 2) layers of YBCO were used on each side of the central heating strip. Thermocouples (E-type) were then distributed throughout the stack. There were two sets of measurements, set 1 included all the ZnO based stacks, set 2 included the Nomex, Kapton, and Mylar based stacks. For set 1, five YBCO strips were used on each side of the heater, and thermocouples T3–T5 were used for the thermal measurements. For set 2, seven strips

| Table 1. Conductor specifications. |
|-------------------------------------|
| Conductor 1 | Conductor 2 |
|-------------|-------------|
| \( I_c \) (A) | Minimum \( I_c \) | 95 | 60 |
| \( w \) (mm) | Conductor width | 4.04 | 4.044 |
| \( w_c \) (mm) | Total conductor edge width \((2d_{cen})\) | 0.04 | 0.044 |
| \( w_{cen} \) (mm) | Conductor central region width | 4 | 4 |
| \( d_{YBCO} \) (μm) | YBCO thickness | 3 | 2 |
| \( d_{y} \) (μm) | Copper stabilizer layer thickness \(^a\) | 40 | 44 |
| \( d_{Ag} \) (μm) | Silver overlayer thickness | 2 | 2 |
| \( d_{sub} \) (μm) | Substrate thickness | 100 | 50 |
| \( d \) (μm) | Total conductor thickness | 145 | 98 |

\(^a\) The tapes are fully enclosed (surrounded) by a \( d_{cu} \) thickness of Cu.
Figure 1. Short stack thermal measurement arrangement, including; (a) short sample block mounted in thermal gradient measurement holder, (b) short sample block, consisting of an epoxied stack of instrumented and insulated YBCO conductor segments, with the schematic positions of thermocouples on different layers shown, (c) in-plane arrangement of nichrome heater wire meander, and (d) expanded view of stack center showing nichrome heater placement in the stack.

Table 2. Coil description.

| Coil name | Tape length (m) | Conductor type | No. turns | Insulation | Coil ID (cm) | Active coil height (mm) | Former height (cm) |
|-----------|----------------|----------------|-----------|------------|--------------|------------------------|-------------------|
| A         | 1              | 2              | 4         | Mylar      | 7.62         | 4                      | 3.5               |
| B         | 1              | 2              | 4         | ZnO        | 7.62         | 4                      | 3.5               |
| C         | 12             | 4              | 45        | ZnO        | 7.62         | 4                      | 3.5               |

of YBCO were used on each side of the heater. Thermocouples were labeled and measured on one side of the heater only; they were denoted T1–T5.

The sample segment was then placed into a block of closed cell styrofoam with a 4 cm × 0.4 cm opening designed to allow thermal diffusion in one dimension only (figure 1(a)). The thermocouple readings were taken using a Keithley Integra series 2700 multimeter set up to read E-type thermocouples. The heating strip was connected in series with an HP 6114A precision power supply and an HP 3457A multimeter/ammeter. The sample edges were sealed to the styrofoam with silicone grease to prevent liquid nitrogen entry and to thus maintain the validity of the 1D approximation.

2.2. Preparation of the coil and instrumentation for coil thermal diffusion and quench measurement

Three YBCO pancake coils, designated A, B, and C, were wound with conductor 2, which was 4 mm wide and surrounded on all sides by a 22 μm thick copper stabilizer. The specified minimum $I_c$ was 60 A at 77 K and self-field. All used G-10 coil formers 3.5 cm high, and with an outer former diameter (coil ID) of 7.62 cm. The YBCO coils were vacuum impregnated using CTD101 epoxy, this is summarized in table 2. During the winding, heater segments, thermocouples, and voltage taps were introduced. For coil A, YBCO tape was co-wound with a 19 μm thick Mylar tape. For coils B and C, the YBCO tape was sputter-coated with 200 nm thick ZnO at the National Renewable Energy Laboratory (NREL). This coating served as the insulation, replacing the Mylar.

In preparation for measurement, the room temperature resistance per unit length of each coil was measured to ensure no turn-to-turn shorting was present. Additionally, $I_c$ (77 K) was measured for each segment of the coils to ensure that the tape was not damaged in coil winding. After this, radial thermal conductivity and quench propagation were measured for each coil while immersed in LN2. Radial thermal gradients were measured by applying a constant power to the heater (no applied current), and then measuring the temperature at various positions in the winding using the embedded E-type thermocouples. Quench propagation was measured by applying a set current (a DC current at some fraction of $I_c$), after which the heater was energized at a set current for a given time. Quench propagation was then monitored by the voltage developed between pairs of taps embedded in the winding. The system for quench propagation measurement consisted of an A/D board whose amplified signal was read by a computer using Labview. There were sixteen input channels, each with a 16 bit resolution on the A/D board, ±5 V full scale. The input amplifiers had a gain that could be varied from 1 to 2000, giving an input resolution of $10 \text{V} / 2000 = 0.005 \text{V}$, or about 80 nV. The response time was limited
S1–S3. Per layer

Delta1

heater at the top of the diagram (above layer 1), and the liquid shown in the inset, which shows one half of the stack with the thermocouples T4–T5. The thermocouples are distributed as heater power in watts. The measurements were performed on between a pair of thermocouples divided by the number of YBCO/insulation layers in (average) value based on the properties of each of the composite elements. This will allow us to; (i) predict the final composite value from that of the constituent elements, or (ii) extract the value of a given element if the average is present, or another part of the composite is limiting the thermal conductivities possible for ZnO based materials are either not present, or another part of the composite is limiting \( \kappa \). The values for \( \kappa \) are average values across the whole stack, rather than specific to the insulation itself. However, it is possible to more closely estimate the actual layer thermal conductance by calculation, as shown below.

3. Thermal propagation measurements on the short stacks

Thermal gradients were measured on six different YBCO short sample stacks forming two sets (three samples each). The first set of samples (S1–S3) had ZnO based insulations, the second set (S4–S6) had Nomex, Kapton, and Mylar insulations. Figure 2 shows the thermal gradients in short sample stacks S1–S3. Per layer \( \Delta T \) (defined as the temperature difference between a pair of thermocouples divided by the number of YBCO/insulation layers in between them) is plotted versus heater power in watts. Measurements were performed on thermocouples T3–T5, with thermocouples placed as shown in inset. Inset shows one half of the stack, with the heater at the top of the diagram (above layer 1), and the liquid nitrogen bath at the bottom (below layer 5). Table 3 lists some of the physical parameters of the stacks.

The experimentally measured thermal conductivities for the YBCO stacks were extracted from the standard equation for heat diffusion, namely

\[ \Delta T = \frac{Q L}{A \kappa} \]  



\( \Delta T \) is the temperature difference (in kelvins), \( Q \) is the heat transported (in watts), \( L \) is the distance (in meters), \( A \) is the area (m²) for heat flow, and \( \kappa \) is the thermal conductivity (W m⁻¹ K⁻¹) of the composite stack. Since in our case, the stack is exposed to the LN₂ on both wide faces, the heat flow in equation (1) goes both ways, and thus the total cooling area is twice the area of the stack face. The appropriate length is 1/2 of the total stack depth. The results (averaged over both T3–T5 and T4–T5) are presented in table 3; note that \( \kappa \) for the Cu doped ZnO is slightly higher than the others.

Figure 3(a), paralleling the data of figure 2, shows the thermal gradients for short sample stacks S4–S6 (Nomex, Kapton, and Mylar). Per layer \( \Delta T \) is again plotted versus heater power in watts. Measurements were performed on thermocouples T2–T5, with thermocouples placed as shown in the inset. The overall thermal conductivities are similar to those of S1–S3, which suggests that the high thermal conductivities possible for ZnO based materials are either not present, or another part of the composite is limiting \( \kappa \). The values for \( \kappa \) are average values across the whole stack, rather than specific to the insulation itself. However, it is possible to more closely estimate the actual layer thermal conductance by calculation, as shown below.

3.1. Estimation of the thermal conductance

The values measured above for \( \kappa \) are composite values. We can use a simple set of calculations to estimate a composite (average) value based on the properties of each of the composite elements. This will allow us to; (i) predict the final composite value from that of the constituent elements, or (ii) extract the value of a given element if the average is measured and all other components are known or estimated. There are two main directions to be considered, along the conductor (or azimuthally within the coil), and perpendicular to the conductor (or radially within the coil).
numbers (see table 4, and [17–23]), and ignoring for now the parameters of which are given in table 4. Then putting in principle anisotropy could easily be accounted for. The measured results for the stacks are similar to this, if somewhat smaller, ranging from 0.7 to 0.9 W m⁻¹ K⁻¹. We have also made an estimate for the stacks with ZnO based insulations, this estimate is 14.9 W m⁻¹ K⁻¹ for conductor 1.

However, if we add in the parallel portion of Cu at the edges, we get (for conductor 2)

\[
\langle \kappa \rangle_{\perp, \text{tape+e}} = 13.1 \text{ W m}^{-1} \text{ K}^{-1} \left( \frac{4000}{4044} \right) + 520 \text{ W m}^{-1} \text{ K}^{-1} \left( \frac{44}{4044} \right) = 18.6 \text{ W m}^{-1} \text{ K}^{-1}
\]

where \( \kappa_{\perp, \text{tape+e}} \) is the tape perpendicular conductivity including the edge effects. These values are listed in table 4, along with similar calculations for conductor type 1.

We can now calculate the case of a winding or stack layer, including the conductor layer, the interlayer (insulation + epoxy), and also the effects of the conductor edges. Approximating the conductor as rectangular, we can see the average layer (conductor layer + interlayer) conductivity as two parallel channels, one through the tape, and one through the tape edges. Each of these components is a series average of conductor layer and interlayer contributions, leading to

\[
\langle \kappa \rangle_{\perp, \text{layer}} = \frac{w_e \kappa_e + w_{\text{cen}} \kappa_{\text{cen}}}{w_e + w_{\text{cen}}} = \frac{1}{w_e + w_{\text{cen}}} \times \left\{ \frac{w_e L_{\text{layer}}}{\kappa_{\text{Cu}}} + \frac{L_{\text{int}}}{\kappa_{\text{int}}} \right\}^{-1}
\]

Here \( \kappa_{\perp, \text{layer}} \) is the average layer thermal conductivity in the tape perpendicular direction, \( w_e \) and \( w_{\text{cen}} \) are the widths of the strand in the edge (Cu only) and central regions, \( \kappa_e \) is associated with the edge regions, and \( \kappa_{\text{cen}} \) the central regions of the layer. The tape thickness is given by \( d \), and the interlayer (inter-tape distance) by \( L_{\text{int}} \), leading to \( L_{\text{layer}} \) as the total layer thickness \( d + L_{\text{int}} \), and \( \kappa_{\text{int}} \) is the average thermal conductivity of the epoxy and the insulation. We can then estimate what the \( \kappa_{\perp, \text{layer}} \) is for stacks or windings with various insulations. The values for stacks using Nomex, Kapton, and Mylar are listed in table 4, assuming for simplicity negligible epoxy thickness, for both conductor 1 and 2. The values for conductor 1 range from 0.46 to 1.57 W m⁻¹ K⁻¹. The measured results for the stacks are similar to this, if somewhat smaller, ranging from 0.7 to 0.9 W m⁻¹ K⁻¹. We have also made an estimate for the stacks with ZnO based insulations, this estimate is 14.9 W m⁻¹ K⁻¹ for conductor 1.
μ in the center of the width of the stacks, and this gap is along the edges of the stack. This allows a gap to exist results in the pressure applied during curing to be transmitted the tapes are then stacked, the stiffness of the Hastelloy strip middle—this is due to extra stabilizer at these edges. When we see the reason for the much lower than expected thermal conductivity of the stacks with ZnO based insulations. The something else is limiting the thermal conductivity. The large deviation with the ZnO system is not, and suggests measurement for the Nomex, Kapton, and Mylar insulations are within the realm of possible error contributions. However, the large deviation with the ZnO system is not, and suggests something else is limiting the thermal conductivity.

An autopsy of stack S3 is shown in figure 3(b). Here we see the reason for the much lower than expected thermal conductivity of the stacks with ZnO based insulations. The YBCO coated conductor is thicker at its edges than it is in the middle—this is due to extra stabilizer at these edges. When the tapes are then stacked, the stiffness of the Hastelloy strip results in the pressure applied during curing to be transmitted along the edges of the stack. This allows a gap to exist in the center of the width of the stacks, and this gap is filled with epoxy. The epoxy present here is about 25 μm thick. This value can be either estimated from the macroscopic measurements made on the stacks (the portion of the half width not taken up by five times the conductor thickness) or directly measured in SEM, where an average value of 25 ± 6 μm was measured. This amount of epoxy dominates the thermal conductivity of the stack. We have re-calculated the expected thermal conductivities of the stacks, based on a 25 μm thick layer of epoxy between the conductors (see table 4), obtaining 1.64 W m⁻¹ K⁻¹, reasonably consistent with the measured values of 0.8–1.4 W m⁻¹ K⁻¹.

Given the epoxy layer present, the results from this work do not explore whether or not the high thermal conductivities promised by ZnO based insulations are actually possible (the results below show a similar epoxy layer in the ZnO insulated coils). However, the results do represent measurements for YBCO stacks made with the given conductor, and point to the need to use flat YBCO coated conductors if we wish to make coils with maximum radial thermal conductivity. However, it is worth noting here that even if we were able to minimize the epoxy layer substantially, reaching all the way to the high values of coil or stack thermal conductivity predicted by a simple calculation may be prevented by other effects. As a possible contributor, we must not forget the influence of the interface on the thermal conductivity, an effect referred to as thermal contact conductance.

A number of things contribute to thermal contact conductance, including both intrinsic physics effects, as well as the partial contact of microscopically rough surfaces, and the presence of native oxides or other contaminants. Taking only the influence of the native Cu oxides themselves, we see that the effects can be substantial. These layers, while even thinner than the ZnO layers (about 4–5 nm [24, 25]) are quite resistive, both electrically [26–28] and thermally. Of course other factors also play a part making a de-convolution of the various effects difficult. Fortunately, some experimental results do exist. A number of studies have looked at heat flow between bulk metallic materials butted directly together, or with various interlayers, and with varying pressures, using thermal measurements performed at low temperatures [29], estimations can also be made from electrical measurements [30]. Based on these measurements, specifically for the case of epoxy interlayers, the thermal interface conductance can vary greatly, from roughly $R_H^{-1} = 10^3$ to $10^5$ W m⁻² K⁻¹, where $R_H$ is

| Component          | Thickness (μm) | (κ) (W m⁻¹ K⁻¹) at 77 K |
|--------------------|---------------|-------------------------|
| Copper stab.       | 40            | 520                     |
| Silver over.       | 2             | 430                     |
| Hast sub.          | 100           | 7.00                    |
| YBCO               | 3             | 8                       |
| Total              | 145           | —                       |

| Insulation material | Thickness (μm) | (κ) (W m⁻¹ K⁻¹) at 77 K |
|---------------------|---------------|-------------------------|
| Nomex               | 38            | 0.1                     |
| Kapton              | 40            | 0.4                     |
| Mylar               | 19            | 0.16                    |
| ZnO                 | ≈0.2          | ≈62                     |
| Stycast 1266        | ≈0.2–0.4      |
| CTD 101             | 0.37          |

| (κ) (W m⁻¹ K⁻¹) | Tape, no edge | Tape, edge |
|----------------|--------------|------------|
| Tape, edge     | 9.84         | —          |
| Stack, Nomex   | 0.46         | 129        |
| Stack, Kapton  | 1.61         | 128        |
| Stack, Mylar   | 1.22         | 144        |
| Stack ZnO     | 14.9         | 163        |
| Stack ZnO + epoxy | 2.07      | 139        |

| Component          | Thickness (μm) | (κ) (W m⁻¹ K⁻¹) at 77 K |
|--------------------|---------------|-------------------------|
| Copper stab.       | 44            | 520                     |
| Silver over.       | 2             | 430                     |
| Hast sub.          | 50            | 7.00                    |
| YBCO               | 2             | 8                       |
| Total              | 98            | —                       |

| Insulation material | Thickness (μm) | (κ) (W m⁻¹ K⁻¹) at 77 K |
|---------------------|---------------|-------------------------|
| Nomex               | 38            | 0.1                     |
| Kapton              | 40            | 0.4                     |
| Mylar               | 19            | 0.16                    |
| ZnO                 | ≈0.2          | ≈62                     |
| Stycast 1266        | ≈0.2–0.4      |
| CTD 101             | 0.37          |

| (κ) (W m⁻¹ K⁻¹) | Tape, no edge | Tape, edge |
|----------------|--------------|------------|
| Tape, edge     | 13.1         | —          |
| Stack, Nomex   | 0.35         | 188        |
| Stack, Kapton  | 1.29         | 185        |
| Stack, Mylar   | 0.93         | 219        |
| Stack ZnO     | 18.6         | 261        |
| Stack ZnO + epoxy | 1.64      | 208        |

* a Value is an estimate based on [18, 19].
* b Assuming zero thickness epoxy.
* c Epoxy layer is 25 μm thick.

Table 4. Thermal conductivities and dimensions.
defined from [29]

\[ \Delta T = Q \left( \frac{L}{A\kappa} + \frac{R_H}{A} \right). \]  

(6)

If we choose \( 10^4 \) W m\(^{-2}\) K\(^{-1}\) as a representative value, and then use the above equations to estimate the thermal conductivity for a Cu interface with no insulation at all (including only the thermal boundary resistance) we can define an effective interface \( \kappa \) by noting that \( \kappa_{\text{eff}} = \frac{L_{\text{eff}}R_H}{A} \), or just directly use equation (6), to obtain an average thermal conductivity of about 1.5 W m\(^{-1}\) K\(^{-1}\). This value is in fact quite similar to the experimental measurements of all samples in this work. It is possible to lump all of these influences together and treat the whole insulation layer as a thermal contact resistance as has been done for Kapton in [31], but it turns out that the results of experimental measurements under various pressure conditions [31] are quite variable. The value is quite uncertain (by an order of magnitude), and thereby cannot really be used to predict what levels of thermal conductivity will ultimately be achievable in coils with thin ZnO layers whose thermal conductivity is optimized by the presence of minimal epoxy. It turns out then, that good estimates of radial (tape perpendicular) thermal conductivities are difficult to make from first principles, and experimental measurements are essential.

**Tape parallel (azimuthal) thermal conductance.** For the tape parallel (azimuthal) thermal conductance the elements must be treated as a parallel conductance. Here we restrict ourselves to heat flow parallel to the tape, and in the direction of current flow within the tape, that is, along the azimuthal direction in a coil. The thermal conductance is then given by

\[ \langle \kappa \rangle_{\text{tape}} = \left( \frac{1}{A_{\text{cond}}} \right) \left( \sum \kappa_i A_i \right) \]

(7)

where \( A_{\text{cond}} \) is the total area of the conductor end on, \( A_i \) is the end area of the \( i \)th component of the conductor, and \( \kappa_i \) is the \( i \)th thermal conductivity. Using the physical dimensions and thermal conductivities in tables 1 and 4, we can find \( \kappa \) to be 163 W m\(^{-1}\) K\(^{-1}\) and 261 W m\(^{-1}\) K\(^{-1}\) for conductors 1 and 2, respectively. We can then use equation (6) to estimate the effective azimuthal conductance for the insulation layer. The average effective thermal conductivity, which is given by

\[ \langle \kappa \rangle_{\text{ins}} = \left( \frac{1}{A_{\text{layer}}} \right) \left( A_{\text{cond}}\kappa_{\text{conf}} + A_{\text{ins}}\kappa_{\text{ins}} \right). \]

(8)

The values \( \kappa_{\text{ins}} \) with Nomex, Kapton, Mylar, and ZnO based insulations are listed in table 4. As a practical matter, the thermal conductivity contribution of the insulation layer to the tape parallel thermal conductance is negligible, and the final layer thermal conductivity is an area normalized \( \kappa_{\text{layer}} \).

**Coil axial thermal conductance.** Now, we must also consider the thermal conductance axially within the coil, which corresponds to heat flow parallel to the wide face of the tape, but perpendicular to the tape winding direction (or current flow direction). The thermal conductance is again a parallel conductance calculation, and gives in fact the same value as the above tape-parallel azimuthal conductance to a very good approximation. This does assume that the coil is wound as a single pancake coil, or a series of pancakes, with negligible thermal barrier between them. If we wish to treat stacked pancake coils with non-negligible thermal barriers, we would need to modify the calculations accordingly, but this is not treated in this work.

4. **Coil measurements**

4.1. **Measurements of coil A (1 m/4 turns, Mylar insulated)**

The second half of this work is concerned with thermal gradients and NZP in small pancake coils. Three coils were wound as described above, and then measured first for thermal gradients under constant heater power, and then subsequently for NZP. For coil A, Mylar insulation was used, and it was co-wound with the YBCO tape. The total tape length was 1 m, leading to a total of four turns. Two heaters were placed in this coil (HT1 and HT2), as shown in figure 4. The primary heater, HT1, was 12.7 cm long with a resistance of 300 Ω, while a backup heater, HT2, was 6.35 cm long, with \( R = 260 \) Ω. Three thermocouples (T1–T3) were used; the radial distance T1–T2 and T2–T3 was 0.22 mm in each case, such that between T1 and T3 the total distance was 0.44 mm. Five voltage taps were also embedded in the coil, with a fixed distance of 14.0 cm between each tap and its neighbor, except for the distance between V5 and V6, which was 12.7 cm. Resistance measurements were made between all sequential pairs of voltage taps at room temperature to check for shorts, none were found. Transport \( I_c \) measurements were also made between all pairs of sequential voltage taps (injecting current at the current leads), and the \( I_c \) values ranged from 49.2 to 69 A. In fact, \( I_c \) was 69 A at the innermost portion of the winding, and ranged from 54 to 49.2 A from V2–V6. As can be seen in table 1, the minimum \( I_c \) for the tape was specified as 60 A, based on measurements made by the supplier on an every-meter basis. While the total length of this tape is about 1 m (about the length of measurement), this result suggests some degradation of \( I_c \) during winding.

4.1.1. **Thermal gradient measurements of coil A (1 m/4 turns, Mylar insulated).** Figure 5(a) shows the temperature versus heater power in W cm\(^{-2}\) at thermocouple positions T1–T3 along the radial direction of coil A at heater powers of 0.752 W (0.148 W cm\(^{-2}\)), 1.69 W (0.322 W cm\(^{-2}\)), and 3 W (0.591 W cm\(^{-2}\)). The coil is immersed in liquid nitrogen (all measurements in this work are performed in liquid nitrogen). No transport current is flowing for the thermal gradient measurements. Here, \( T_p = T_h - T_0 \) (the temperature at a given heater power, \( T_h \), minus the temperature with no applied power, \( T_0 \)). Figure 5(b) shows the temperature gradient radially across coil A for these heater powers. These data can be used to evaluate the radial thermal conductivity of the winding. We might think to apply the equation for heat flow out radially from a hollow cylinder, which in its simplest form can be 1D in the radial direction. For the case of the inner and
Figure 4. (a) Schematic of coil A (1 m, Mylar insulated). Thermocouples are numbered T1-3, and voltage taps V1–V6. Two heater strips are located on the inner surface of the coil, HT1, the primary heater, and HT2, the backup heater, (b) coil A after winding and epoxy impregnation.

outer diameters of the cylinder being very similar (a very thin coil), this collapses to a 1D slab model. For the present case, where we have a heater length \( L_h \), a tape width \( w \), and a coil thickness (radial direction) \( t_c \), this would be expressed, from equation (1), above, as

\[
Q = \frac{\Delta T w L_h \kappa}{t_c}.
\]  

(9)

The epoxy layers above and below the winding are quite thin and contribute negligibly to the radial thermal conductivity (and in any case the thermal conductivity through the winding is much higher). Under a 1D assumption (using equation (9), with the heat propagating across the winding radially) an average thermal conductivity can be obtained for the winding, for coil A this is \( \kappa = 2.93 \text{ W m}^{-1} \text{ K}^{-1} \). Here we have taken \( L_h \) as the length of the heater coil, and have modeled the winding as a 1D slab of length \( L_h \), width \( w \), and thickness \( t_c \). The former is insulating and heat is taken to flow radially outward only. This is higher than the estimation for \( \kappa_{\perp \text{layer}} \) above, at 1.22 W m\(^{-1}\) K\(^{-1}\), as well as higher than the measured values for the stacks, at 0.9 W m\(^{-1}\) K\(^{-1}\). The reason for this disagreement is that the heat flow is not merely 1D. Unlike the short stack measurements, where the short stack measurement apparatus restricted the heat flow to 1D only, these coils can have heat flow radially, azimuthally, and axially. Considering for the moment only radial and axial heat flow, we obtain

\[
Q_{\text{tot}} = Q_{\text{axial}} + Q_{\text{radial}} = \left[ \frac{A_{\text{rad}} \kappa_{\text{rad}}}{t_c} + \frac{A_{\text{ax}} \kappa_{\text{ax}}}{w} \right] \Delta T
\]  

(10)
where \( \kappa_{\text{rad}} \) and \( \kappa_{\text{ax}} \) are the thermal conductivities of the coil in the radial and axial directions. The total heat removal is of course increased by the axial heat flow. In principle a third term for azimuthal heat low should also be included. This term should have an azimuthal thermal conductivity similar to the axial thermal conductivity based on the arguments given above in section 3. However, the prefactor for the axial term, \( A_{\text{ax}}/I \), taking the associated denominator to be the coil perimeter, is an order of magnitude smaller than that for the axial term, so we will ignore the azimuthal term. This is fortunate, since only in this case are the radial and axial heat diffusion easily separable, as in equation (10). This treatment is approximate, but is useful to clarify the reason for the difference in measured thermal conductivities. The above equation (10) can be re-written as

\[
\kappa_{\text{eff}} = \kappa_{\text{rad}} \left[ 1 + \left( \frac{I_c}{w} \right)^2 \frac{\kappa_{\text{ax}}}{\kappa_{\text{rad}}} \right] = \frac{Q_t}{\Delta T w L_h}.
\]

(11)

If we use the estimates from table 4 for the stack (coil) average thermal conductivities for heat propagation either perpendicular and parallel to the tape (conductor 2), as well as the tape thickness and width, specifically for Mylar stacks, we obtain an estimated value for \( \kappa_{\text{eff}} \) of 5 W m\(^{-1}\) K\(^{-1}\), bracketing the experimentally measured value of \( \kappa \) for the coil (2.9 W m\(^{-1}\) K\(^{-1}\)) in between that expected for radial propagation only, and that for the case of radial and axial propagation.

4.1.2. Quench propagation measurements for coil A (1 m/4 turns, Mylar insulated). The first set of quench measurements were performed on coil A. In these measurements, a steady transport current of 34.8 A was applied to the coil, which was 0.7 of the minimum \( I_c \) of the coil (49.2 A). In order to initiate the quench, heater pulses of 0.59 W cm\(^{-2}\) (heat current = 100 mA) were then applied for various times using HT1. Under these conditions, for shorter heater pulse times (5–7 s), only region V1–V2 developed a normal zone. For pulse durations of 8 s or more, a normal zone also appeared in region V3–V4, and at 9 s a normal zone appeared also between V5 and V6. Figure 6 shows this last condition, with a 9 s heat pulse applied. For a 10 s pulse duration, V6–V7 also developed a normal zone. The normal regions appeared in the following order: (1) V1–V2, (2) V3–V4, (3) V5–V6, and finally for a 10 s pulse (V6–V7). The fact that the voltage taps do not quench in a consecutive order (e.g., V2–V3 and V4–V5 are not excited initially) cannot exclude the possibility of normal zone propagation along the tape length and suggests its propagation in a radial direction across the winding. Indeed, although not shown in figure 6, V4–V5 (next) and V2–V3 (last) do eventually quench. A section of V2–V3 does appear over the heater, but it is the smallest region of any voltage tape segment, and it is near one of the edges of the heater, rather than the center. The observation that this segment is the last to quench is again consistent with strong radial propagation. We can expect that the normal zone propagates outward, centered on the axial center of the heater. This is caused primarily by the fact that the distance over which the normal zone needs to propagate radially in order to get to the next turn is quite small because of the thinness of the tape, while an azimuthally (longitudinally) propagating normal zone must travel around the coil’s circumference. Finally, we note that the coil was not damaged during this series of quench experiments; we repeated the measurements with a heat pulse of 99.7 mA for 10 s and obtained results nearly identical with those from the previous runs.

4.2. Measurements of coil B (1 m/4 turns, ZnO insulated) For comparison to coil A, with Mylar insulation, a second coil was wound (coil B), which we expected to insulate with only a thin layer of ZnO applied directly to the tape prior to coil winding. The total tape length was 1 m, and there were four turns in the coil. Again, two heaters were placed in the coil (HT1 and HT2), as shown in figure 7. The main heater, HT1, was 12.7 cm long and had a resistance of 640 \( \Omega \), while the backup heater, HT2, was 6.35 cm long with \( R = 581 \Omega \). Three thermocouples (T1–T3) were used. Seven voltage taps were distributed uniformly in angle (to improve our ability to assess the now-expected radial propagation) as shown in figure 7. Along the radial direction, the voltage taps were typically one turn apart, and within the coil they were arranged to lay at one of three distinct angles. Resistance measurements were made between all sequential pairs of voltage taps at room temperature to check for shorts, none were found. Transport \( I_c \) measurements were also made between all pairs of sequential voltage taps (injecting current at the current leads), and the \( I_c \) was relatively homogeneous with an average \( I_c = 73.8 \pm 5.8\% \).

4.2.1. Thermal gradient measurements of coil B (1 m/4 turns, ZnO insulated). Figure 8(a) shows the temperature profile for coil B, in terms of \( T_p \) versus heater power for several different power inputs. Here, \( T_p = T_h - T_0 \) (the temperature at a given heater power, \( T_h \), minus the temperature with no applied power, \( T_0 \)). Figure 8(b) shows the temperature gradient at two different power levels. We again can use equation (9) to extract \( \kappa \), obtaining \( \kappa = 5.27 \text{ W m}^{-1} \text{ K}^{-1} \). In this case, only...
Figure 7. Schematic of coil B (1 m, ZnO insulation). Thermocouples are numbered T1-3, and voltage taps V1–V7. Two heater strips are located on the inner surface of the coil, HT1, the primary heater, and HT2, the backup heater.

Figure 8. Thermal gradients in coil B (1 m, ZnO insulation); (a) $T_p$ (defined as the temperature at a given heater power, $T_h$, minus the temperature with no applied power, $T_0$) at T1, T2, and T3 versus heater power ($HT1$, $R = 616 \Omega$, $L = 12.7$ cm) in W cm$^{-2}$, (b) Temperature gradient radially across coil B for heater powers of 1.21 W cm$^{-2}$ (solid) and 3.17 W cm$^{-2}$ (dashed).

4.2.2. Quench propagation measurements for coil B (1 m/4 turns, ZnO insulated). Figures 9–11 show the quench propagation through coil B (1 m, ZnO insulation) with increasing energy deposition. First, figure 9 shows a quench propagation measurement where $I = 34.8$ A (1/2 of the minimum $I_c$ of 69.5 A) was supplied to the coil. The heater pulse (starting at 2 s) was 75 mA (giving 680 mW cm$^{-2}$) for 5 s. Normal zones form between V1–V2, V4–V5 and V6–V7. Looking back to figure 7 we can see that these regions of the coil are at the same angular position, but at increasing radial distances. The fixed angle layout of the voltage taps makes the fact that the propagation is dominated at early times by radial

the outer two thermocouple positions were considered. We notice in figure 8 that there is a substantial difference in the gradients between T1 and T2, as compared to T2–T3. This is most likely due to differences in the axial positions (heights) of the thermocouples. Because of the presence of axial thermal conductivity, any axial displacements will introduce errors, since there will be an axial temperature gradient. In any case the value of $\kappa = 5.27$ W m$^{-1}$ K$^{-1}$ is consistent with measurements made on coil C, below. Again using equation (11) and the values of table 4 to make estimates of $\kappa_{eff}$, we obtain 5.5 W m$^{-1}$ K$^{-1}$, relatively consistent with the measured value. These values are significantly larger than the experimental stack measurements of 0.8–1.4 W m$^{-1}$ K$^{-1}$ due to the axial thermal propagation.
It is worth pointing out at this point that many quench propagation measurements were made on the three coils in this paper, and only a summarized and representative set of data is presented here, focusing on the essentials of the results. Partial recovery was often seen for middle-to-longer duration quench runs, followed by complete quench when the experiments ran long enough. However, the exact progressions of the partial recoveries were not usually repeatable. The specific origin of these partial recoveries is unknown, beyond that fact that transient effects, either in heat generation or heat removal must be involved. We speculate that one possible origin may be due to variations in cooling due to convection in the LN$_2$ bath.

Minimal or no boiling of the LN$_2$ was observed to be caused by the application of current to the coil, but significant boiling did occur after the initiation of the quench, due to heat from the heater, as well as the ohmic losses in the normal regions of the strands under quench conditions. Such boiling in LN$_2$ may cause convection in LN$_2$, causing additional cooling at the coil surface and allow for partial recoveries away from the directly heated areas (at longer times the expanding heat zone drives every part of the coil normal). Such effects have been observed in continuous AC loss measurements in our lab, where the conditions are more amenable to direct observation of nitrogen convection; it is not clear if this or some other mechanism is responsible here. Thus, we have focused the results in this paper on quantifying the early times within the quench measurements, and will return to the question of partial recoveries for a later work.

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![Figure 9](image_url) Quench propagation measurement for coil B (1 m, ZnO insulation). In this run, $I = 34.8$ A was supplied to the coil continuously, then at $t = 2$ s, HT1 was excited with 75 mA, giving 680 mW cm$^{-2}$, for 5 s. Normal zones are seen to form between V1–V2, V4–V5 and V6–V7, regions of the coil at the same angular position, but at increasing radial distances. The measurements thus indicate radial heat propagation.

![Figure 10](image_url) A second set of quench propagation measurements for coil B, in this case at a higher heat pulse level. In this run $I = 34.8$ A was supplied to the coil continuously, then at $t = 0$, HT1 was excited with 100 mA, giving 1.21 W cm$^{-2}$, for 2 s. Normal zones are seen to form for V1–V2, V4–V5, V6–V7 and V3–V4. Taps V1–V2, V4–V5 and V6–V7 are positioned at the same azimuthal position as HT1 at increasing radial distances within the winding. The measurements again indicate radial heat propagation.

![Figure 11](image_url) A third set of quench propagation measurements for coil B, in this case at a higher heat pulse level. In this run $I = 34.8$ A was applied to the coil continuously, then at $t = 0$, HT1 was excited with 100 mA, giving 1.21 W cm$^{-2}$, for 160 s. Normal zones are seen to form in the order V1–V2, V4–V5, V6–V7 and V3–V4. Taps V1–V2, V4–V5 and V6–V7 are positioned at the same azimuthal position as HT1 at increasing radial distances within the winding. The measurements again indicate radial heat propagation.
Figure 12. NZP velocities for a series of quench measurements performed on coil B. There are three groups of data, the first set of runs was performed with a DC coil current of 34.7 A and a heater deposition of 3.47 W (680 mW cm$^{-2}$), the second set at $I = 34.7$ A and a heater power of 6.16 W (1.21 W cm$^{-2}$). Within these sets the results for different heater excitation times are shown. The last two columns show data for elevated DC currents in the sample (42.37 A and 54.12 A), applying 6.16 W for 160 s.

Figure 12 shows the NZP radial velocities (NZP$_{ra}$) for a series of quench measurements performed on coil B. In order to calculate the NZP, a normal zone was defined to be associated with the existence of a certain measurable voltage. The level of noise present gave a minimum floor for the voltage criterion of NZ detection; for consistency we chose an electric field as the criterion, specifically 4.73 $\mu$V cm$^{-1}$. The uncertainty in time determination was on a level of 20 ms. In figure 12 there are three groups of data, the first set of runs was performed with a DC coil current of 34.7 A and a heater deposition of 3.47 W (680 mW cm$^{-2}$), the second set at $I = 34.7$ A and a heater power of 6.16 W (1.21 W cm$^{-2}$). Within these sets the results for different heater excitation times are shown. The last two columns show data for elevated DC currents in the sample (42.37 A (61% of $I_{c,\min}$) and 54.12 A (78% of $I_{c,\min}$)), applying 6.16 W for 160 s. Within these groups, three values are provided for each measurement. These three different values correspond to three different places in the coil. The measurements marked as ‘inner region’ were made by measuring the propagation time between tap set V1–V2, and tap sets V4–V5 (see figure 7). The ‘outer region’ values were obtained by measuring the propagation time between taps V4–V5 and taps V6–V7, near the outer perimeter of the coil. To obtain the average, we measured the propagation time from taps V1–V2 to taps V6–V7. We note that the NZP$_{ra}$ was somewhat larger in the inner region of the coil, which might be expected based on its proximity to the heater. Taking the average values as most representative, values of NZP$_{ra}$ were typically in the range $\sim 0.02$–1 mm s$^{-1}$. There was no systematic dependence of NZP$_{ra}$ on heat pulse duration, rather what we see is some level of scatter about a given value. However, NZP$_{ra}$ generally increased with heat pulse power as well as the transport current of the sample.

4.3. Measurement of coil C (12 m/45 turns, ZnO insulated)

Finally, it was of interest to investigate a slightly larger coil (denoted coil C). This coil also used a ZnO insulation. The total tape length was 12 m, leading to a total number turn of 45, see figure 13. The primary heater, HT1 had a resistance of 666 $\Omega$, and a length of 12.7 cm. Five thermocouples (T1–T5) were placed in the angular center of HT1 with 1.53 mm between each of them in the radial direction. Thirty voltage taps were distributed uniformly in angle as shown in figure 13. Along the radial direction, the voltage taps were 10 turns apart, and along the azimuthal direction they were 60° apart. The $I_c$ for this coil varied from 43.4 to 73.7 A. The variation in this case was continuous, with the highest $I_c$ at the outermost regions of the coil, and the lowest $I_c$s at the innermost regions. Given the slowly varying nature of this change, and the increasing number of turns in the winding, this may be due to a field dependence of $I_c$.

4.3.1. Thermal gradient measurements of coil C (12 m/45 turns, ZnO insulated)

Thermal gradients for coil C are shown in figure 14 (again, $T_p = T_h - T_0$). Using again equation (9) and the data in figure 14 we obtained an average thermal conductivity of the winding of coil C as $\langle \kappa \rangle = 4.44$ W m$^{-1}$ K$^{-1}$. Here we took the gradient from the steepest portion of the curve, that between T1–T2, assuming at this low level of excitation the heat is removed (axially, see above) by the T3 layer. The coil is now not as thin as coils A and B, and thus the application of equation (11) is more questionable. However, the obtained value can be compared to the previous coil measurement, coil B, which yielded $\kappa = 5.27$ W m$^{-1}$ K$^{-1}$ as well as to the previously mentioned experimental results on stacks (0.8–1.4 W m$^{-1}$ K$^{-1}$, table 3) and the theoretical estimates (table 4).

4.3.2. Quench propagation measurements for coil C (12 m/45 turns, ZnO insulated)

Figures 15 and 16 shows the quench properties of coil C (12 m/45 turn, ZnO insulation). Due to the limited number of channels on our data acquisition device, we chose to look at the ‘upper’ portion of the coil as shown
Figure 13. (a) Schematic of coil C (45 turn/12 m, ZnO insulation). Thermocouples are numbered T1-6, and voltage taps V1–V30. Two heater strips are located on the inner surface of the coil, HT1, the primary heater, and HT2, the backup heater. (b) Coil C after winding and epoxy impregnation.

Figure 14. Thermal gradients in coil C (45 turn/12 m, ZnO insulation). $T_p$ (defined as the temperature at a given heater power, $T_h$, minus the temperature with no applied power, $T_0$) versus distance through the coil winding for 0.471 W cm$^{-2}$ (solid) and 1.31 W cm$^{-2}$ (dotted).

Figure 15. Quench propagation measurements for coil C (45 turn/12 m, ZnO insulation). In this run, $I = 34.9$ A was applied to the coil continuously, then at $t = 0$, HT1 was excited with 100 mA, giving 1.21 W cm$^{-2}$, for 60 s. The data has been smoothed with a lowpass filter for clarity. A normal zone is shown for V1–V6, normal zones also form for V13–V18 and V10–V11. NZP$_{ra} = 0.33$ mm s$^{-1}$. After this normal zones on taps V19–V24, V25–V30 and V22–V23 start to become visible.

in figure 13 (top); that is voltage taps on the upper portion of this figure were attached to the data acquisition device. Figure 15 shows a quench measurement where $I = 34.9$ A (50% $I_{c,\text{min}}$) was applied to the coil, and HT1 was excited with 100 mA, giving 1.21 W cm$^{-2}$, for 60 s. The data has been smoothed with a lowpass filter for clarity. A normal zone is shown for V1–V6, normal zones also form (in sequence) for V13–V18 and V10–V11, V19–V24, and V25–V30. All of these except V10–V11 are at increasing radial distances above each other and the heater, indicating again radial NZP. This NZP$_{ra} = 0.33$ mm s$^{-1}$. The generation of a normal zone on taps V10–V11 indicates an azimuthal normal zone propagation. Looking at figure 15, we can see that a normal zone is initiated in V10–V11 at about 8 s, while the same is true for V13–V18. Unfortunately, the voltage taps at V7–V12 (at the same radial level of V10-11) were not functioning. However, since the V7–V12 layer is midway between the V13–V18 and the V1–V6 layers, we can estimate that a normal zone appears here at a time midway between that of V13–V18 (8 s) and V1–V6 (immediate). This leads to a propagation time from the center of V7–V12 to the edge of V11–V12 of 4 s. The distance it must travel is 8.7 cm, leading to NZP$_{az} \approx 20$ mm s$^{-1}$, comparable to the 10 mm s$^{-1}$ measured for coil B. These azimuthal values are only approximate, but similar to those seen for stand alone tapes. We note that the voltages on voltage tap sections at larger radial distances (V19–V24, and V25–V30) are developing more slowly than those at smaller radial distances, presumably again due to the axial heat removal, and smaller perturbations at further distances. Similar effects are present in V10–V11.
The radial values are much smaller, figure 16. uncommon for short pulse measurements like those shown in not all of which could be shown here, and recovery was not However, many other measurements were taken on this coil, at longer times so it is not clear if there was a recovery or not.

Table 5. Summary of results.

| Coil/stack | \( \kappa_{\text{eff, meas coil}} \) (W m\(^{-1}\) K\(^{-1}\)) | \( \kappa_{\text{eff, est coil}} \) (W m\(^{-1}\) K\(^{-1}\)) | \( \kappa_{\text{eff, meas stack}} \) (W m\(^{-1}\) K\(^{-1}\)) | \( \kappa_{\text{eff, theor}} \) (W m\(^{-1}\) K\(^{-1}\)) | Radial NZP, \( \text{mm s}^{-1} \) | Azimuthal NZP, \( \text{mm s}^{-1} \) |
|------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-------------------------------------------------|-----------------------------------|-----------------------------------|
| Coil A     | 2.93                                            | 5                                               | 0.9                                             | 0.93                                            | 0.05–0.1                          | —                                 |
| Coil B     | 5.27                                            | 5.5                                             | 0.8–1.4                                        | 1.64                                            | 0.02–1                            | 10                                |
| Coil C     | 4.44                                            | —                                               | 0.8–1.4                                        | 1.642                                           | 0.33                              | 20                                |

Figure 16 shows a quench measurement where \( I = 44.53 \text{ A} \) (64% \( I_{\text{c, min}} \)) was used, and HT1 was excited for 5 s with 100 mA (1.30 W cm\(^{-2}\)). A normal zone forms for V1–V6, normal zones also form for V13–V18, V19–24, and V25–30. We note that the voltage formation in V25–V30 is more rapid than expected; the reason for this is unknown.

Figure 16 shows a quench measurement where \( I = 44.53 \text{ A} \) (64% \( I_{\text{c, min}} \)) was applied to the coil continuously, then at \( t = 0 \text{ s} \), HT1 was excited with 100 mA, giving 1.30 W cm\(^{-2}\), for 5 s. We then follow the progress of the normal zone formation with no heater excitation from \( t = 5 \text{ to } 50 \text{ s} \).

A normal zone is shown for V1–V6, normal zones also form for V13–V18, V19–24, and V25–30. We note that the voltage formation in V25–V30 is more rapid than expected; the reason for this is unknown.

Table 5 shows for a comparison of the results for \( \kappa \) via coil measurement, stack measurement, and calculation, are shown in table 5. The NZP values measured both radially and azimuthally. The azimuthal values, 10–20 mm s\(^{-1}\), are similar to those seen for single coated conductor tapes [1–5]. The radial values are much smaller, \( \sim 0.02–1 \text{ mm s}^{-1} \), reflecting the much lower \( \kappa \) value in that direction.

5. Summary

The thermal diffusivity properties of several different kinds of YBCO insulations and the quench properties of coils made using these insulations were studied, specifically comparing a high thermal conductivity insulation (ZnO) to Nomex, Kapton, and Mylar insulations. One of the goals was to increase the radial speed of propagation for the normal zone, in order to compensate for the relatively low longitudinal NZP for YBCO, thus making the coils easier to quench protect. However, the results for all short sample thermal conductivities were \( \sim 1 \text{ W m}^{-1} \text{ K}^{-1} \).

The lack of distinction for the ZnO based insulations was attributed to the presence of an epoxy layer between the conductors within a gap caused by conductor thickness variations. The measured thermal conductivities for the coils ranged from 2.9 to 5.3 W m\(^{-1}\) K\(^{-1}\); the fact that these were larger than the short stack values was due to the presence of axial as well as radial thermal propagation.

Additionally, quench propagation velocity measurements were performed on three coils (77 K, self-field). Normal zone propagation velocity values were obtained for the coils both in the radial direction and in the azimuthal direction. Radial NZP values (\( \sim 0.02–1 \text{ mm s}^{-1} \)) were two orders of magnitude lower than axial values (\( \sim 10–20 \text{ mm s}^{-1} \)). Nevertheless, the quenches were generally seen to propagate radially within the coils, in the sense that any given turn in the coil is driven normal by the turn underneath it. This initially surprising result is due to the fact that while the radial normal zone propagation velocity (NZP) is much lower than the NZP along the conductor (\( \sim 100 \times \)) the distance the normal zone must expand longitudinally is much larger than that which it must expand radially to reach the same point, in our case this ratio is \( \sim 1600 \).

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