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Determination of the AC Losses of Bi-2223 HTS Coils at 77 K at Power Frequencies Using a Mass Boil-Off Calorimetric Technique

Frank Darmann, Shi Dou, and Chris Cook

***Abstract*—A mass boil-off measurement system has been used to accurately measure and characterize the ac loss of high-temperature superconductor (HTS) coils at frequencies between 50 and 200 Hz, and in applied ac fields of up to 0.04 T. The mass boil-off calorimeter incorporated a glass cryostat, a copper field coil, and two mass flow meters. The response of the gas flow to a step change in the applied magnetic field was found to have a time constant of about 600 s. Under suitable experimental conditions, it was possible to measure the ac losses of coils with an accuracy of ± 0.3 W. The ac loss characteristics of an HTS pancake and two HTS solenoid coils are presented and the accuracy of mass flow calorimetry in liquid nitrogen is reported on.**

***Index Terms*—AC loss, boil off, external field, HTS tape, hysteresis loss, transport loss.**

I. Introduction

THE TOTAL ac losses at power frequencies of superconductors in the presence of an ac magnetic field, an ac transport current, a dc background field, and various combinations of these have been measured [1]–[5]. For the most part, however, these losses have been determined on short pieces of tape, and assumptions have been made about how these measurements can predict the ac losses in working devices. Variations in high-temperature superconductor (HTS) tape quality, and parameters such as the critical current, the exponent n value, the overall tape dimensions, the core dimensions, and the filament dimensions and arrangement can affect the way each tape behaves. Damage during coil winding procedures can also affect the ac loss. Hence, the net ac loss of a significant length of tape will be substantially different from that predicted by measurements on a few centimeters of tape. The degree of difference may be used as a benchmark as to the quality of the manufacturing route and the consistency of the physical and electrical properties across a length of tape. In addition, the complexity of interpreting the electrical signals from ac loss measurements for a device has led researchers to pursue other methods of characterizing the ac losses of coils and devices [4], [5].

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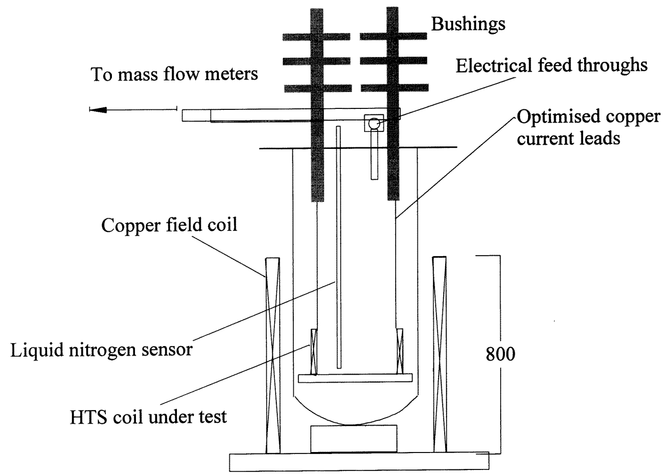

Fig. 1. Overall schematic of the MBC.

A mass boil-off calorimeter (MBC) allows the total loss of an HTS coil or device to be determined in liquid helium or nitrogen. This technique has been used to measure the losses in a superconducting power cable [4]. The apparatus described here includes the possibility of applying both background ac and dc fields, as well as transport ac current over a frequency range of 50–200 Hz.

II. Experimental Setup

Fig. 1 shows a schematic drawing of the MBC apparatus built as part of this work. Metallic components were kept to a minimum in the cryostat design to reduce the influences of stray eddy currents. The thermal heat leak of the current leads was calculated to be 4.5 W. The magnetic field coil was 800-mm long and had a field constant of 1.25 peak mT/A root mean square (rms). The homogeneity of the magnetic field produced by the external field coil was calculated using an FEM software package. Fig. 2 shows the calculated magnetic field components produced within the internal volume of the field coil across a plane perpendicular to the longitudinal axis of the coil, when a 50-A rms excitation current is used. Data across two such planes are shown, one through the center of the field coil and one through a plane 200 mm along the longitudinal axis, which represents a distance of one-quarter of the field coil length. The field was assumed to be symmetrical about the longitudinal axis. The radial component of the magnetic field (which represents the component of field perpendicular to the tape surface within a

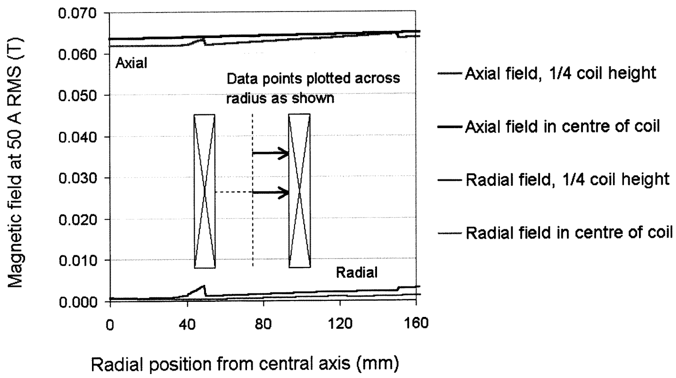

Fig. 2. Calculated axial and radial field components of the field coil across a plane perpendicular to the longitudinal axis of the coil.

coil) was calculated to be less than 4.0×10^{-5} T/A, and the difference between the axial field components (which represents the component of field parallel to the tape surface) was found to be less than 3.9×10^{-5} T/A. Hence, a parallel field may be applied to solenoids with a height of less than 400 mm with a homogeneity of better than 2 mT at a 50-A rms field current.

A 5-V peak square wave signal from a pulsewidth-modulated (PWM) supply was used to control the sinusoidal current output of a lock-in amplifier. This output signal was used as the input to an audio amplifier capable of supplying 220-V ac rms at 50 Hz. The audio amplifier was used to power the transport current through the coils, as the HTS coil inductance was substantially less than that of the field coil. Using this arrangement, a parallel magnetic field and transport current was applied to the HTS coils. In addition, the PWM supply was also used to provide a variable frequency sinusoidal current for both the field coil and HTS coils. This supply included feedback control which kept the rms current to within 0.25 A of the set current. The total harmonic distortion of the current waveform was determined to be less than 0.5% under all load conditions, and was found to be better than 0.05% for the vast majority of the measurement.

Two mass flow meters connected in series were used to determine the flow rate with a full scale (FS) reading of 5 standard liters per minute (SLPM) and 20 SLPM. Note that 1 SLPM $=$ 1 L/min of gas at a temperature of 298 K and pressure of 101 325 Nm^{-2}, and a flow of 1 SLPM of N_2 gas is equivalent to a flow of 0.018667 g/s. A factor of 3.71466 W/SLPM was used to convert the measured boil-off rate of liquid nitrogen to the loss value. The flow meters chosen are designed to accurately measure the mass flow rate of nitrogen over a wide range of temperatures without corrections required. The mass flow meters work by creating a small pressure drop across a unique internal restriction known as a laminar flow element, and measuring differential pressure across it. The Poiseuille equation is used to internally calculate the volumetric flow rate, and internal compensation corrects for differences in temperature such that the indicated flow rate is correct at standard temperature and pressure (STP). The FS readings of the mass flow meters were equivalent to a loss of 18.5 W (5 SLPM) and 74 W (20 SLPM).

The combined pressure drop across the two mass flow meters and pipe work was found experimentally to be less than 1 lb/in^2. This was determined by measuring the pressure of the gas inside the cryostat. This small pressure rise within the cryostat has a negligible effect on the temperature of the boiling liquid nitrogen. The specified pressure drop of the mass flow meters at full flow rate is specified as being 0.5 lb/in^2.

The nitrogen gas at the mass flow meters was found to have a temperature around 300 K. The most likely explanation for this is due to the length of pipework that the gas must traverse before meeting the mass flow meters.

III. Results and Discussion

A. Introduction

The first objective was to determine the heat leak of the silvered glass cryostat using the mass flow meters. The cryostat was operated at a fill level of between 20% and 50% for all experiments. It was found that the background loss at these levels of liquid nitrogen was about 21 W. This value decreased gradually to about 14 W when the cryostat was 40% full. This was a significant loss, and was measured and corrected for before and after each ac loss data point. The magnitude of the loss potentially negates the purpose of having a high resolution flow meter with a small FS so some measurements were taken with only a 20% fill level, at which point the loss of the coil was measured to be very close to the full scale of the 5 SLPM meter. This ensured good accuracy in the data. Experiments with higher losses required a higher fill level so that the measured values were closer to the FS value of the 20 SLPM meter.

The second objective was to measure the effect of stray losses from all the metallic components that could not be replaced with phenolic fabric. The maximum magnetic field was applied to the cryostat with a 70% fill of liquid nitrogen. With no HTS coil in the cryostat, the current leads taken out, and all other metallic components in place, no extra component of loss above the background was detected. Hence, stray losses were neglected for all other experiments in which the current leads were removed.

To measure the effect of the heat leak and resistive loss components of the current leads on the background loss, the leads were short circuited in the cryostat, without the presence of a coil, and the total loss measured across the ac current range of interest. At a constant level of liquid nitrogen, the heat leak into the cryostat owing to the thermal conductivity of the copper will be constant and, therefore, can be neglected. By measuring the total boil-off rate with, and without the current leads, this component of heat leak was found to be about 5 W. The boil-off rates over a 24-h period, taken every 7 s, are shown in Fig. 3.

Fig. 4 shows a closeup of the data taken over a period of 10 min with a typical level of liquid nitrogen, which in this case was 40%. The variations seen are typical of those encountered throughout this study. To determine the uncertainty, it is not necessary to consider the full range of sample results, but rather a suitable band within which the majority of measurements fall. As can be seen, the vast majority of the measurements fall within a band which represents an uncertainty in determining the actual loss of ± 0.1 W, if some of the peaks are neglected. Out of the 87 measurement points shown, 78 of them (or 90%) fall within the band shown, and 9 points (or 10%) fall outside of the band. The uncertainty in the difference between two measurements and,

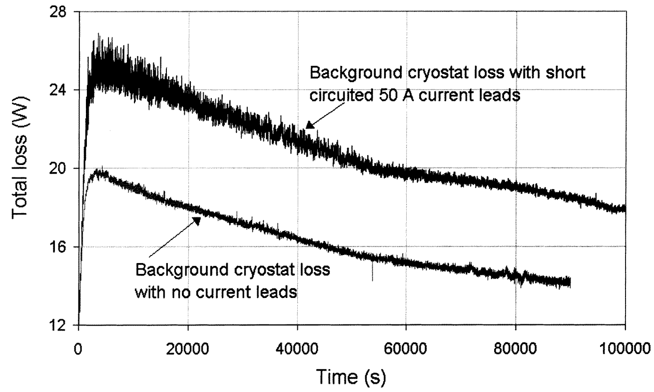

Fig. 3. Heat leak with and without shorted current leads and zero current.

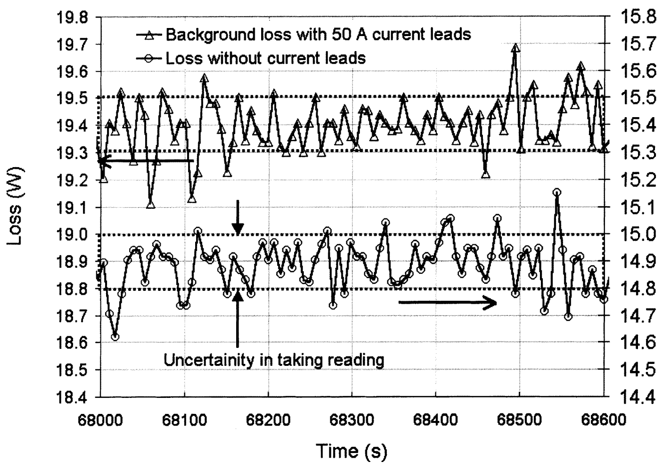

Fig. 4. Closeup of the measured losses of the cryostat with and without current leads inserted. Shown are 87 points collected over a period of 10 min.

therefore, the uncertainty in determining the ac loss of a coil was 0.2 W under these experimental conditions. Hence, the two loss measurements would be read as 19.4±0.1 and 14.1±0.1 W, representing a current lead heat leak of 5.3±0.2 W.

B. Step Response of the System

The system required a significant time to stabilize. Fig. 5 shows a typical equilibrium time for a step change in the copper coil field current. The time constant was approximately 10 min, and each ac loss measurement, therefore, took about 35 min to obtain reliable data. A similar response was also observed after connecting the gas flow pipes from the bushings to the mass flow meters.

During the stabilization period, the relative pressure inside the vessel increased slightly to 1 lb/in^2. The net loss measurement, as indicated on the mass flow meters, was not a true loss value of the HTS coil during the stabilization period, as some of the energy lost by the coil was transferred into the stored energy of the pressurized nitrogen gas in the cryostat, rather than flowing out of the pipe work through the mass flow meters. Therefore, the sum of the energy loss indicated by the mass flow meters and the rate of increase in stored potential energy of the gas equaled the net loss in the system (HTS tape and background). Only after the pressure in the vessel had stabilized and

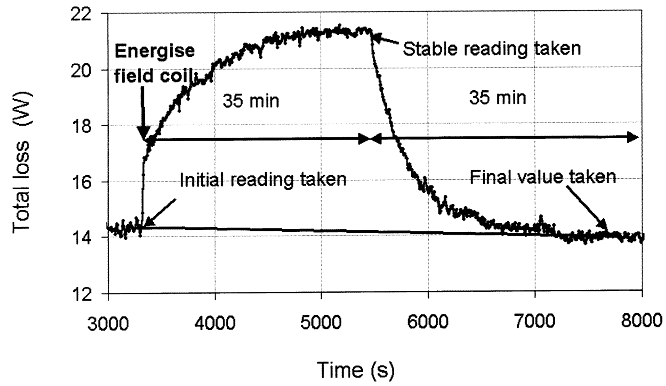

Fig. 5. Typical temporal response of the MBC to a step change in the applied ac magnetic field. In this case, the system was quiescent before turning on the ac magnetic field.

remained constant, did the mass flow readings truly indicate the total losses of the system.

Owing to the long stabilization time required, the level of liquid nitrogen dropped noticeably between the beginning of each test and the end. The background loss, therefore, reduced in this time period, and it was noticed to drop by up to 0.5 W, depending on the level of excitation. For the majority of the experiments, however, the difference in the background boil-off rate between the start and completion of each ac loss measurement point was about 0.0 to 0.2 W. If not allowed for, this feature of the MBC system would introduce a significant error into the calculated ac loss. By using a linear interpolation between the initial and final boil-off rates, a figure for the boil-off rate at the level of liquid nitrogen for which the boiloff reaches stability may be accurately obtained. Usually, the time required for stabilization was the same for the increasing and decreasing parts of the graph, so the average of the boil-off rates before the excitation and after final stabilization was used. For example, the step response in Fig. 5 shows an initial background loss of 14.0±0.1 W and a final background loss of 13.5±0.1 W. The total loss at equilibrium is 21.2±0.1 W. The background boil-off rate at the point of equilibrium would be 13.75±0.2 W and the ac loss of the coil would be recorded as 7.45±0.3 W.

This level of uncertainty was found throughout the range of experiments carried out in this work and error bars included in the graphically presented data all represent an uncertainty of ±0.3 W, when shown.

C. AC Loss of a Solenoid Coil in a Parallel Applied Magnetic Field

A 240-mm-long HTS solenoid coil with composite adhesive insulation and with other details shown in Table I was used to determine the coil losses in response to an applied parallel ac magnetic field. Therefore, the current leads were not inserted into the cryostat. The parallel magnetic field losses were measured using a PWM power supply at 53 Hz and as a check compared to the three-phase, 50-Hz, 20-A variac. The results are shown in Fig. 6, along with lines of slope 3 and slope 1 as a guide to the eye.

The ac loss results obtained on solenoid coil 1 with both the variac and the PWM supply were consistent after allowing for

TABLE I
DETAILS OF SOLENOID COIL 1

Property	Value
HTS Tape thickness	0.30 mm
HTS Tape width	3.5 mm
Tape length	135 m
Ic of coil, 77 K, self field	18 A
Jc of coil, 77 K, self field	$6.1\text{x}10^7$ A/m^2
Layers	3
Turns per layer	60
Total turns	180
Coil height	0.24 m
Coil inner diameter	0.174 m
Coil outer diameter	0.176 m
Penetration field of tape	0.009 T

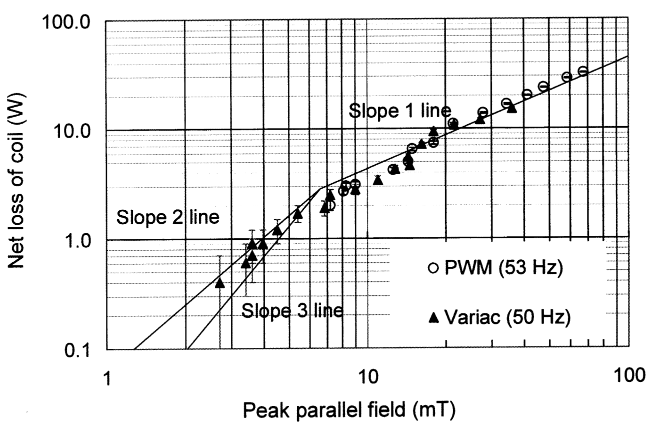

Fig. 6. AC losses of solenoid coil 1 in response to parallel applied magnetic fields where the field coil is powered by a 50-Hz variac operated at line frequency (50 Hz) and a PWM power supply at 53 Hz.

TABLE II
DETAILS OF PANCAKE 1

Property	Value
HTS Tape thickness	0.24 mm
HTS Tape width	3.2 mm
Tape length	40 m
Turns	140
Ic of pancake , 77 K, self field	6.0 A
Ic (0) estimated	10.0 A
Jc (0), 77K	$4.7 \text{ x } 10^7$ A/m^2
Inside diameter	0.025 m
n (77K, self field of pancake)	6.5
Outside diameter	0.118 m

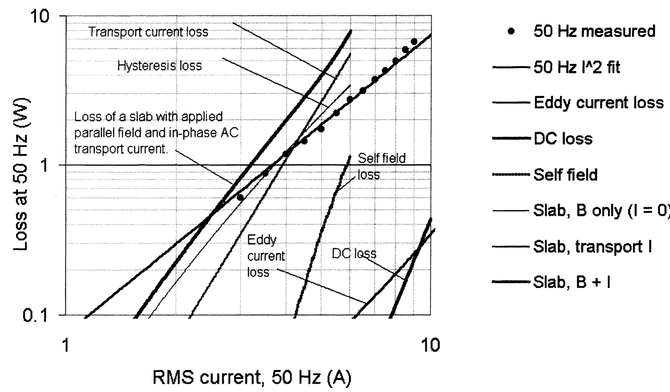

Fig. 7. Measured ac losses of Pancake 1 at 50 Hz and various approximations based on the critical state model of the infinite slab.

the effect of the small difference in frequency. This means that the small harmonic content, present in all PWM devices, did not significantly affect the measured ac loss results.

A thin solenoid in an applied parallel magnetic field can be considered as a long thin slab for the purposes of calculating the ac losses. The field is parallel to each turn of tape, because the field coil is much longer than the HTS solenoid coil. The results at 50 Hz and for applied fields less than 6 mT have a slope of 2, which differs from the characteristic slope 3 derived from the critical state model for an infinite slab [8]. In addition, for fields above 20 mT, the measured loss has a slope-1 characteristic. This indicated that the loss mechanism at 50 Hz was magnetic hysteresis.

It was possible to observe the nature of the boiling liquid nitrogen during the experiments through a purposely included narrow slit in the silvering of the glass cryostat. Boiling was evident on the surface of the coil during the experiments.

D. AC Transport Current Loss in an HTS Pancake Coil

A pancake coil was wound with the dimensions shown in Table II. The ac transport current loss of this coil was characterized with the MBC at a frequency of 50 Hz, as shown in Fig. 7, along with a number of approximations which will be described. In these calculations, the estimated field-free Ic of the tape was used rather than the measured Ic which was significantly less due to the large dc field produced by the pancake [13].

The data in Fig. 7 was fitted to a quadratic of the form shown in (1), where P is the measured ac loss of the coil. Only the ac loss results for which $1.414^* I_{\rm rms} < I_{\rm dc}$ were included for the purposes of finding the parameter A in (1)

$$P = A.I^2 \quad (I_{\rm rms} < I_{\rm dc}, A = 0.071\,75). \tag{1}$$

The self-field losses of Pancake 1 followed a square-law relationship for currents below 7.0 A. The square-law relationship indicates that the ac loss was best described by the relationship developed by Carr for an infinite slab exposed to a field oscillating in-phase with a transport current [10].

There exists a number of analytical equations describing the ac losses of isolated superconductors [8]–[12]. These may be used to approximate the ac losses of a pancake coil by assuming a number of approximations. The magnetic field distribution is required in these calculations. Both the parallel and the perpendicular profiles of the magnetic field across the pancake surface are shown in Fig. 8 as a function of the radial position across the coil.

The Norris equations describing the self field transport ac loss of a tape were used to calculate an initial approximation of the ac losses of the pancake coils [9]. In this approximation, the HTS tape in the pancake coil was assumed to be stretched out in a continuous length and carried an ac transport current with no applied field contribution from the other turns. This calculation represents the lower limit of the losses of the pancake.

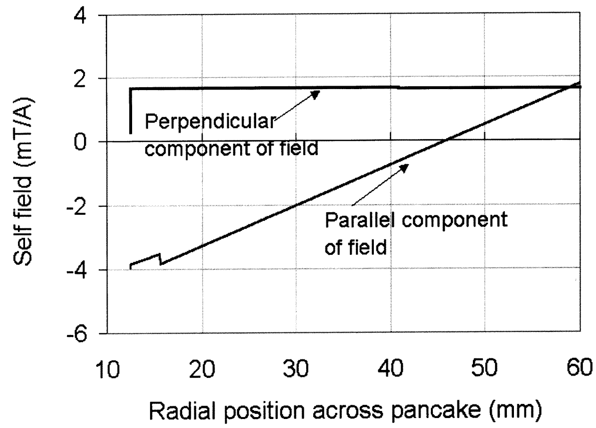

Fig. 8. Components of the magnetic field generated at the surface of the pancake coil.

An approximation to the magnetizing hysteresis loss was obtained by considering the turns of the pancake to be a series of independent straight tapes of appropriate length with each tape exposed to an applied parallel field appropriate with each turn's position within the pancake coil. The Wilson equations describing the loss of an infinite slab in a parallel field with no transport current were used [10].

The total ac loss of the pancake was approximated using the results of Carr, which are appropriate for an infinite slab with an in-phase ac transport current, and an ac parallel magnetic field for ac current amplitudes less than the Ic [11]. Each turn of the pancake was considered independently as an infinite slab with simultaneous transport current and the appropriate applied parallel field consistent with the position in the pancake coil. The transport current loss was also calculated using these equations by assuming that the magnetization loss was independent of the transport current [12].

The measured ac loss at 50 Hz falls between the two extreme approximations of the self-field losses and the infinite slab approximation. However, the slope of the measured loss was clearly less than that of the calculated results. This can be explained by the fact that the approximations all originate from the critical state model, which does not include an n-value in the analytical solutions [8]. It has been shown that a low n-value results in an ac loss profile with a lower slope than that predicted by the critical state model [12].

The measured results are generally lower than those predicted by the Carr model (Slab B + I in Fig. 7). This is due to the fact that the self field amplitudes used in the approximation were calculated at the surface of the pancake and the tape internal field will be lower than this, and will decrease toward the center of the tape, leading to lower actual losses than predicted.

E. AC Losses Due to Transport Current and Applied Fields in an HTS Solenoid Coil

A 296-mm-long, two-layer solenoid coil was wound with a single silver sheathed Bi-2223 tape, using a composite adhesive insulation between turns and between the layers. Other details are shown in Table III. To determine the loss mechanisms, the transport current losses were measured at 55, 110, and 200 Hz, and the applied parallel field losses were measured separately at 55 and 110 Hz. The measured results are shown in Fig. 9. In addition, the dc transport current loss was measured up to 32 A and are included in Fig. 9.

TABLE III
DETAILS OF SOLENOID COIL 2

Property	Value
Half thickness of HTS Tape filamentary zone	0.12 mm
Half thickness of filamentary zone of two coupled tapes	0.24 mm
HTS tape width	3.5 mm
HTS tape length	85 m
Ic of coil , 77 K, self field	16.2 A
Ic (0), 77K, zero field	18.0 A
Jc(0) of coil, 77 K	$7.41x10^7$ A/m^2
n (77 K, self field of coil)	6.0
Resistance (300 K)	3.1 Ohms
Turns	156
Layers	2
Insulation thickness between the two layers	$50x10^{-6}$ m
Inside diameter of coil	0.174 m
Outside diameter of coil not including insulation	0.175 m
Coil height	0.296 m
Tape penetration field	0.011 T

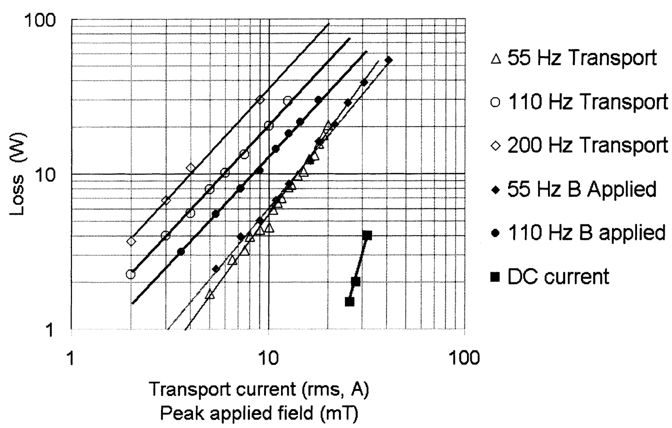

Fig.9. Transport current loss and applied parallel field loss for solenoid 2.

The measured dc transport current loss of solenoid coil 2 was found to be negligible over the range of current considered. The gradient of the dc loss curve at the Ic was determined to be 7 which was consistent with the n-value, 6, of the coil measured in the self field by a four-point technique.

The measured ac loss of solenoid 2 in an applied parallel ac field was found to have a slope of 1.4 in the frequency range 55–110 Hz. In addition, it was found that the measured losses in applied field increased by a factor of two when the frequency of the applied field was doubled from 55 to 110 Hz. This indicated that the coil had an ac loss that increased linearly with frequency and was hysteretic in nature.

The measured transport current losses were found to have a more complex relationship with frequency. They were found to increase by a factor of four when the frequency was doubled from 55 to 110 Hz, indicating that the losses from induced currents dominated the loss at 55 Hz [1]. An increase by a factor of just under two occurred, however, when the transport current frequency was increased from 110 to 200 Hz, indicating that the induced currents had saturated the superconductor, causing further losses to behave more like a penetration type loss mechanism and, therefore, hysteretic-like in nature [10].

IV. Conclusion

The accuracy and range of a liquid nitrogen mass boil-off system was found suitable for characterizing the ac losses of pancakes and solenoids containing as little as 30 m of HTS tape. The best accuracy of the system obtainable was ± 0.3 W for a suitable height of liquid nitrogen, however, uncertainties as high as ± 0.5 W were encountered under certain experimental conditions, and these were avoided as far as possible.

The major advantage of the MBC technique is the ability to measure the ac losses of a coil with an independently applied magnetic field and transport current. This is a difficult task employing purely electrical means. Another advantage is that each loss mechanism is included in the result, so that the losses of real devices are known immediately without having to calculate or estimate them from data taken on short lengths of tape. The variable frequency supply determines whether hysteretic or induced current effects dominated the ac losses of a coil.

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Frank Darmann received honors degrees in physics (specializing in electromagnetics) and electrical engineering specialzing in power engineering and communications) from Monash University, Melbourne, Australia, in 1992 and 1995, respectively, and the Ph.D. degree in electrical engineering (while working at Australian Superconductors, New South Wales, Australia) from University of Wollongong, New South Wales, Australia, in 2002. His engineering honours thesis was on the subject of embedded generation in utilities.

Specializing in high-power superconducting equipment, he has carried out projects for the Ministry of Energy and Utilities, the Electricity Supply Association of Australia, and has built an efficient transformer from high-temperature superconductors. His research interests include saturable fault current limiters for limiting fault currents at substations, high-voltage breakdown of materials in liquid nitrogen, and high-power transformer design for utility applications.

Shi Dou received the D.Sc. degree for his published work on high-temperature superconductivity by University of New South Wales, Kensington, New South Wales, Australia, in 1998.

He is currently the Director of the Institute for Superconducting and Electronic Materials (ISEM), The University of Wollongong, New South Wales, Australia, and an Australian Professorial Research Fellow. His research group consists of more than 50 researchers and students with a world-class laboratory serving ten institutions around Australia. His major contribution to the fields of energy storage and superconductor materials is in the area of materials processing and characterization. Recently, his group has made a breakthrough on the MgB2 using nano-SiC doping to enhnace the critical current density by orders of magnitude. His research work attracted more than 3000 scientific citations. He is the author or coauthor of more than 400 refereed papers and has presented 40 invited talks since 1990. He has been very active in promoting national and interantinal collaborations with more than 40 institutions world wide.

Dr. Dou was elected as a Fellow of the Australian Academy of Technological Science and Engineering in 1994. He was awarded an Australian Professorial Fellowship in 2002, and the Centenary Medal for Service to Australian Socienty in materials science and engineering by the Australian Government in 2003. He has won more than ten academic awards for excellence in research and teaching.

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