Apparatus for Calorimetric Measurements of Losses in MgB$_2$ Superconductors Exposed to Alternating Currents and External Magnetic Fields

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Inexpensive superconducting wires with low AC losses would open up for a large superconductor market in AC electrical power applications. One candidate for this market is the MgB$_2$ conductor. In the development of an AC optimized superconductor, high-quality measurements of the AC losses under application-like conditions must be available. This article describes an apparatus built for this purpose. The measurement method is calorimetric. The temperature increase of the superconductor sample is measured and compared to the temperature increase due to a heater with known heat input. The system is designed for measurements at temperatures down to 20 K, and for magnetic field strengths up to 1 T (peak) combined with transport currents up to several hundred amperes. Results from tests verifying the capabilities of the system are given, as well as from initial AC loss measurements on a tape-shaped MgB$_2$ superconductor.

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1. Introduction

Superconductors have for decades been acknowledged as materials that could introduce major benefits to electric power systems. The possibility to reduce losses and dramatically increase current densities would push the limits of traditional electric power components, such as transformers, cables and motors. However, still the commercial applications are few and the potential of the materials unutilized.

One issue to be solved for a broad use of superconductors in AC applications is the reduction of AC losses. In the late 80s, intensive efforts were put into the reduction of the AC losses in BSSCO/Ag superconductors. The results did not lead to a commercial breakthrough. More recently, the MgB_2 superconductor has been developed into long-length wires. This conductor is inexpensive and more easily manufactured, with prospects of a successful AC loss reduction [1].

AC losses inevitably appear when a superconductor is exposed to an AC magnetic field (externally applied or generated by a transport current), due to the irreversible motion of vortices pushed in and out of the superconductor every half cycle, resulting in hysteresis losses. The AC losses, P_{ac}, are for a given conductor a function of temperature, T, magnetic field, B, transport current, I, and frequency, f,

$$P_{ac} = P_{ac}\,(T,B,I,f). \qquad (1)$$

High quality measurements of AC losses are necessary for the development of good AC superconductors. Two different principles for measuring the losses in superconductors (both used extensively for BSCCO/Ag tapes) dominate in the literature, the electromagnetic [2-3] and the calorimetric [4-6], with good agreement of the results of the two methods [7]. The electromagnetic method is generally faster, and for BSCCO/Ag tapes it requires less thermal considerations as the sample simply can be immersed in liquid nitrogen. On the other hand, the calorimetric method involves less complicated electrical measurements and directly yields the total loss.

For MgB_2 superconductors, measurements of the losses due to AC magnetic fields [8,9] and due to transport currents [9] have been reported. The apparatus presented in this article enables loss measurements in any combination of magnetic fields and transport currents, AC or DC, simulating the likely conditions in AC power components. The measurement system is calorimetric. For measurements in the 20 to 40 K range, in contrast to the case at 77 K, conduction cooling and vacuum need to be introduced and consequently adds no further complication compared to the electromagnetic method. The system's design is based on a previous system for BSCCO/Ag tapes reported in [4] and [10], but aims for the MgB_2 application range. That is, temperatures down to 20 K and magnetic fields up to 1 T (peak) and transport currents of several hundred amperes should be handled.

The principle of the measurement method is explained in section 2, an overview of the system and detailed descriptions of key parts are given in section 3. In section 4 results from system verification measurements and finally initial AC loss measurements on an MgB_2 wire are given.

2. Measurement principle

In the calorimetric method, we measure the temperature increase of the superconducting sample when exposed to an AC magnetic field and/or a transport current. In principle, for an adiabatic system the power loss is given by,

$$P_{ac} = C\, \Delta T_{ac}/\Delta t_{ac} \ , \tag{2}$$

where C is the heat capacity, ΔT_{ac} the temperature increase and, Δt_{ac} the measurement time. However, C is not known and the system is not fully adiabatic. Therefore, the system is calibrated by measuring the temperature increase due to a known heat input in a heater wound together with the sample. The heat capacity is then eliminated from (2) and the power loss is given by,

$$P_{ac} = (\Delta T_{AC}\, \Delta t_{cal}\, /\Delta T_{cal}\, \Delta t_{AC})\, P_{cal} \ , \tag{3}$$

where ΔT_{cal} is the temperature increase during calibration, Δt_{cal} the calibration time, and P_{cal} the power input during calibration. Note that (3) only holds for an adiabatic system. Therefore, the durations, Δt_{ac} and Δt_{cal}, should be kept equal. To account also for the heat transmitted from the sample and the change in heat capacity with temperature, a calibration ratio, r_c, can be introduced,

$$r_c(\Delta t_{cal}\, ,\, T\,) = (\Delta t_{cal}/\Delta T_{cal})\, P_{cal} \ . \tag{4}$$

During calibration, the function $r_c\,(\Delta t_{cal}, T)$ is determined for relevant measurement durations and loss levels, see section 4.

3. Measurement system design

3.1. System overview

Several different aspects need to be considered to realize a measurement system with the desired operating ranges and measurement sensitivity. The low measurement temperature and the high magnetic fields and transport currents involved impose constraints on the design and material choices. The cryostat is built of fibre-glass reinforced epoxy tubes and plates which are glued together. This material is strong, sustains low temperatures, has a thermal contraction comparable to that of metals, and is non-conducting (avoiding induced currents). To allow for sample preparation, the cryostat is divided in a lower and an upper part sealed with an O-ring at ambient temperature. Between the upper and lower cryostat parts, an evacuable space is formed, where a sample holder and the sample is placed and can be cooled down to the desired temperatures by a cooling machine. A set of thermal radiation shields and the use of liquid nitrogen on the outside of parts of the cryostat reduce the thermal load to the cooling machine.

The sample is arranged in a ring enabling magnetic field generation by circular field coils. The sample length is chosen long enough to meet the requirements of minimal bending radius for most samples and to ensure a measurement length with uniform temperature, and it is chosen short enough to enable the generation of a strong magnetic field (low enough inductance in the coils) and for sample preparation practicability.

A cross-section overview of the measurement system is shown in Fig. 1 and a photo of the lower part of the system in Fig. 2. The system is cylindrically symmetric. The sample (1) is placed in the form of a ring, with a diameter of 0.28 m, on top of a sample holder (2), which is in thermal contact with the cold head of a cooling machine (3). These parts are situated in vacuum enclosed by a cryostat (4). The reservoir (5) at the top is filled with liquid nitrogen to limit the heat radiation. At the side (6) and at the bottom (7) radiation shields covered with superinsulation are inserted inside the vacuum to limit the heat radiation in these regions. The latter shield is cooled by liquid nitrogen from outside the cryostat.

For magnetic field generation, copper coils (8) are placed in the liquid nitrogen reservoir on both sides of the sample. Transport currents are injected at the bottom of the cryostat through a copper current feed through (9), cooled by liquid nitrogen on the outside, and then transported via a BSSCO/Ag conductor to a wire cooler (10), where the BSCCO/Ag conductor is soldered to the MgB_2 sample conductor (not part of the 2D figure). Measurement wires are inserted through a separate signal feed through (11).

3.2. Sample arrangement

The sample is glued to the sample holder using Stycast 2850, ensuring good thermal contact. In Fig. 3 arrangements for round and for tape shaped samples are shown. A high-ohmic wire (80 Ω/m) used as heater is wound together with the samples, twisted around the round sample and simply attached to the outside of the tape shaped sample. Similarly a copper wire is wound bifilarly along half of the sample length (to the far side from the point of current injection). The copper wire is used as thermometer (in the 20 - 40 K range the change in resistance is significant for copper) and measures the temperature increase during AC loss measurements and calibration. It is important that the temperature is uniform over the half-turn, and therefore, to control the uniformity, additional shorter copper thermometers are attached at different positions along the sample. The copper thermometers are calibrated in advance with a Cernox temperature sensor.

3.3. Thermal properties close to the sample

The sample holder is made of a 3 mm thick glass-fibre reinforced epoxy tube, with a 0.5 mm thick copper plate (thermally connected to the cold head) glued to the outside, see Fig. 4. The choice of thermal resistance between the sample and the cold head (and consequently in this case the copper plate), is a trade-off between achievable temperature and cool-down time on one side, and measurement sensitivity on the other. A 20 mm space between the copper plate (divided into teeth to avoid large induced currents during AC magnetic field exposure) and the sample results in a thermal resistance of about 30 K/W at 25 K, high enough to see a distinct temperature increase in the sample, and low enough to allow for cooling down within a reasonable time (a few hours).

To enable variation of the sample temperature without introducing large power inputs directly to the sample, a second heater is glued to the top of the sample holder. By adjusting the power dissipated in this wire between 0 and 1 W, sample temperatures in the range 20 to 50 K can be obtained.

3.4. Insulation and cooling system

The sample is placed in vacuum, enclosed by a cryostat, which is built of fibre-glass reinforced epoxy to avoid inducing electrical currents and heat dissipation. A pressure of the order 10^{-2} mbar is obtained with a vacuum pump before turning on the cooling machine, and a pressure below 10^{-3} mbar is obtained when the cold head acts as a cold trap. At this latter pressure, heat is transferred mainly by radiation. At the top of the cryostat, the radiation is limited by filling the reservoir with liquid nitrogen. At the lower side, a radiation shield, covered with superinsulation and thermally anchored to liquid nitrogen on the outside of the cryostat, withdraws heat radiated from the bottom cryostat wall. An additional radiation shield with superinsulation faces the outer cylinder wall to avoid frost on the outside of that wall. The measurement wires (copper thermometers and voltage taps) which enter the vacuum space at room temperature, are first thermally anchored to the lower radiation shield at about 77 K, and then thermally anchored to a wire cooler (not shown in Fig. 1) at about 20 K before entering the sample. With these arrangements, the total thermal load to the cooling machine is only a few watts.

3.5. Magnetizing coils

The magnetic field that the sample is exposed to is generated by passing current in a pair of copper coils concentric with the sample and placed in the liquid nitrogen bath, close to the sample (see Fig. 1). The inner and outer coils are connected in antiparallel, with the main purpose of the inner coil to reduce the inductance of the coil pair. Each coil consists of 44 turns of a 2 mm x 12.5 mm vanish insulated copper strand, filling a coil cross-section area of 25 mm x 50 mm. The magnetic field generated over the sample is 0.62 mT per ampere in the coils. At the sample location, the magnetic field is vertically directed. For round samples the direction of the magnetic field in the plane perpendicular to the current path is unimportant. However, for rectangular or tape-shaped samples one may want to vary the magnetic field direction in this plane. This can be done e.g. by passing currents in only one of the coils and step-wise railing it upwards.

Since the coils are immersed in liquid nitrogen, large currents can be allowed, particularly for short periods of time. At a current of 1.14 kA_{rms} the magnetic field over the sample is 1 T_{peak}. This current, corresponding to a current density of 44 A/mm^2, results in a temperature increase (assuming adiabatic conditions) in the copper coil of about 20 K after 3 s, a time sufficient for making an AC loss measurement.

The resistance of the coils is about 0.01 Ω and the inductance 0.7 mH. At 50 Hz the inductance dominates the impedance (0.2 Ω). To reduce reactive power requirements from the power source, capacitive compensation is used, reducing the impedance of the circuit and enabling experiments to be carried out in a standard laboratory. One should note, though, that when applying a controlled AC voltage to the coils, the circuit should not be fully compensated, as heating of the coils causes their resistance to increase, thereby also changing the current.

3.6. Current injection

When injecting transport current into the sample, the heat transfer through the current leads should be limited. In the system, the current leads consist of three parts. (1) Copper feed-throughs 10 mm x 10 mm, immersed in liquid nitrogen on the outside of the cryostat. (2) BSCCO/Ag conductors

soldered to the copper feed-throughs inside the cryostat. The number of parallel BSSCO/Ag tapes depends on the maximum desired transport current in the sample. The length of the tapes is about 0.5 m (half a turn in the evacuated space below the sample holder). (3) The MgB$_2$ sample wire is soldered to the BSCCO/Ag tape over a length of about 100 mm, and the entire joint is thermally anchored to a copper plate in direct contact with the cold head. The MgB$_2$ sample wire makes a half turn around the sample holder (0.5 m) before entering the top of the sample holder and finally the 0.4 m long measurement area on the opposite side of the sample holder.

It is important that the MgB$_2$ sample wire is at the highest temperature in the section where the AC losses are measured. Otherwise, for transport currents close to the critical current, the wire may go normal. As described in section 3.3, a heater at the top of the sample holder raises the temperature in this area compared to the cold head temperature. Hence, the MgB$_2$ sample wire temperature increases as it enters the top of the sample holder. However, at the half turn (0.4 m) long measuring area on the opposite side, the temperature is practically uniform.

For measurements with transport currents only, the current can be supplied directly from a power source. For combinations of magnetic fields and transport currents, a current transformer is used to keep the magnetic field and sample current in-phase. The magnetic field coils are then connected in series with the primary winding of the transformer, whereas the sample current is fed from the secondary winding. The ratio between magnetic field and transport current is varied by changing the ratio between the turns of the transformer windings.

4. Verification and loss measurements

4.1. System verification and calibration

The basic principle, that losses in the MgB$_2$ sample can be determined from calibration using a heater wound together with the sample, was verified at 42 K (just above the critical temperature of MgB$_2$). The temperature increase was measured first when passing a DC current in the heater, and then when passing a DC current in the MgB$_2$ sample. In both cases the current and the voltage drop was recorded. In Fig. 5 the temperature response is given as function of input power with durations of 5 s and 20 s. The response is virtually independent of whether the heat is generated in the heater or the MgB$_2$ sample.

Calibration is performed to determine the function (4). A typical response of the copper thermometer is shown in Fig. 6. From such a curve, the temperature increase for different durations can be extracted and calibration curves as in Fig 7 can be drawn. When calibration is performed at different temperatures, these curves determine the expression (4).

4.2. Measured AC losses

AC loss measurements have been performed on a tape-shaped multi-filamentary MgB$_2$ superconductor manufactured by Columbus Superconductors. The cross-sectional area of the sample is 0.95 mm x 4.2 mm, of which the MgB$_2$ filaments constitute 18%. Niobium serves as a barrier around each filament and the sheath material is non-magnetic cupronickel (70/30). The self-field critical current is about 260 A at the measurement temperature 33.5 K. The filaments are not twisted.

The measurement results are given in Fig. 8. The frequency is 50 Hz and the magnetic field applied in parallel with the tape face. Losses are measured as function of current with no externally applied field and as function of current combined with a magnetic field of 36 mT_{peak}. In addition losses due to applied field only (up to 100 mT) are shown at the vertical axis. The relatively low magnetic fields used are a consequence of the loss level in the sample (as expected from a broad non-twisted DC wire). The losses of this wire basically follow the same pattern as for non-twisted BSCCO/Ag tapes [11].

5. Conclusions

The presented calorimetric AC loss measurement system gives reliable results and can be a valuable tool in the development of AC optimized MgB_2 superconductors. Benefits of the system is the reliability and the wide range of magnetic fields and transport currents attainable (up to 1 T and several hundreds Amperes) in the 20-40 K temperature range. Furthermore, if and when MgB_2 superconductors with loss levels acceptable for AC applications appear, the system can be used in the design phase of MgB_2 based AC power components.

References

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Figure captions

Fig. 1 Cross-sectional view of the apparatus. The system is cylindrically symmetric around the centre axis.

Fig. 2 Figure of the lower part of the cryostat and the sample holder with the sample.

Fig. 3 Sketch of the sample arrangement with round and tape shaped samples. The heater and the copper thermometer are glued to the sample using Stycast 2850.
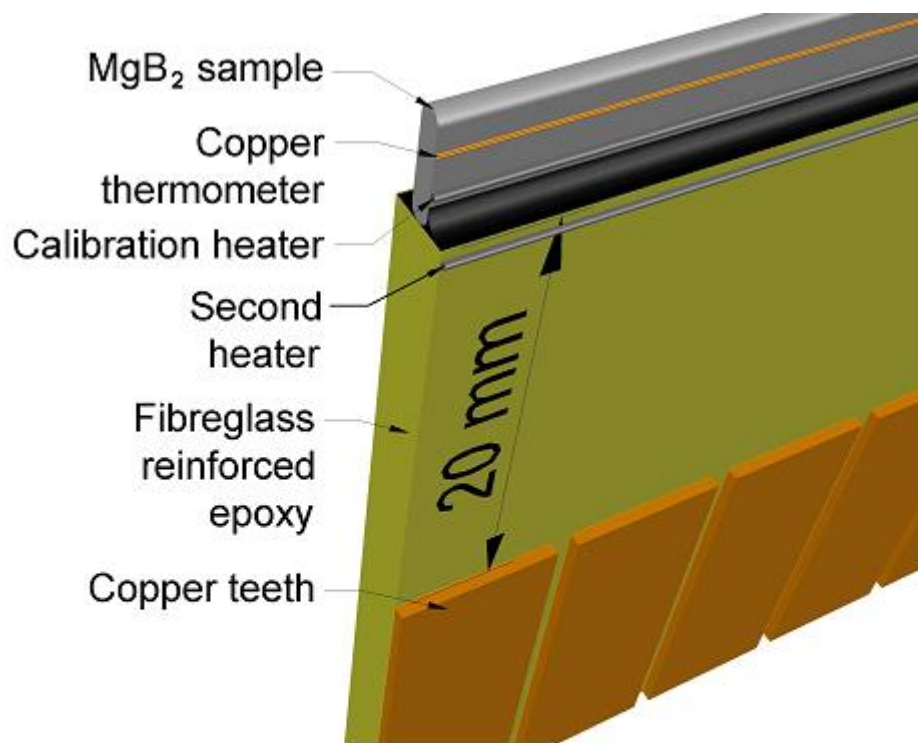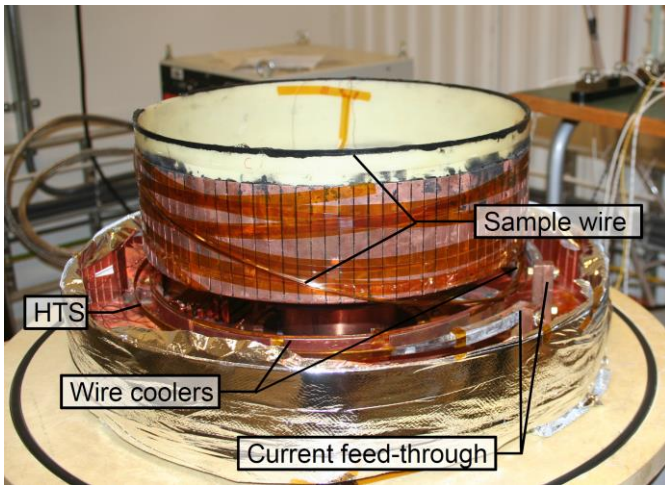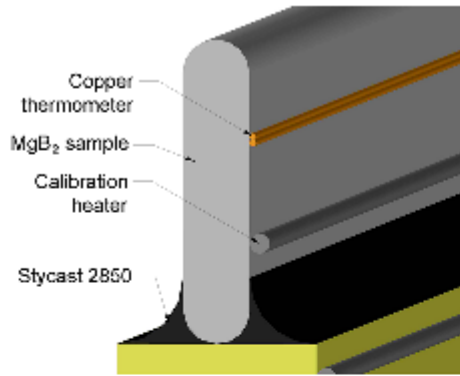
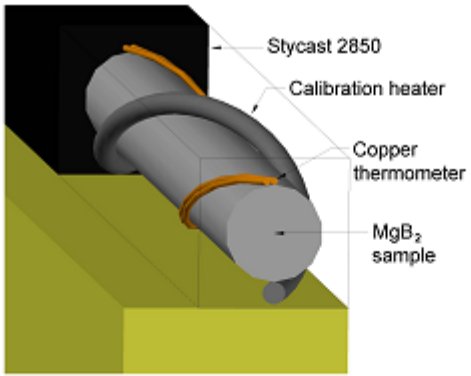**Fig. 4** Top of sample holder.

Fig. 5 Comparison of temperature response at 42 K between power dissipated in the heater and in the MgB_2 sample.
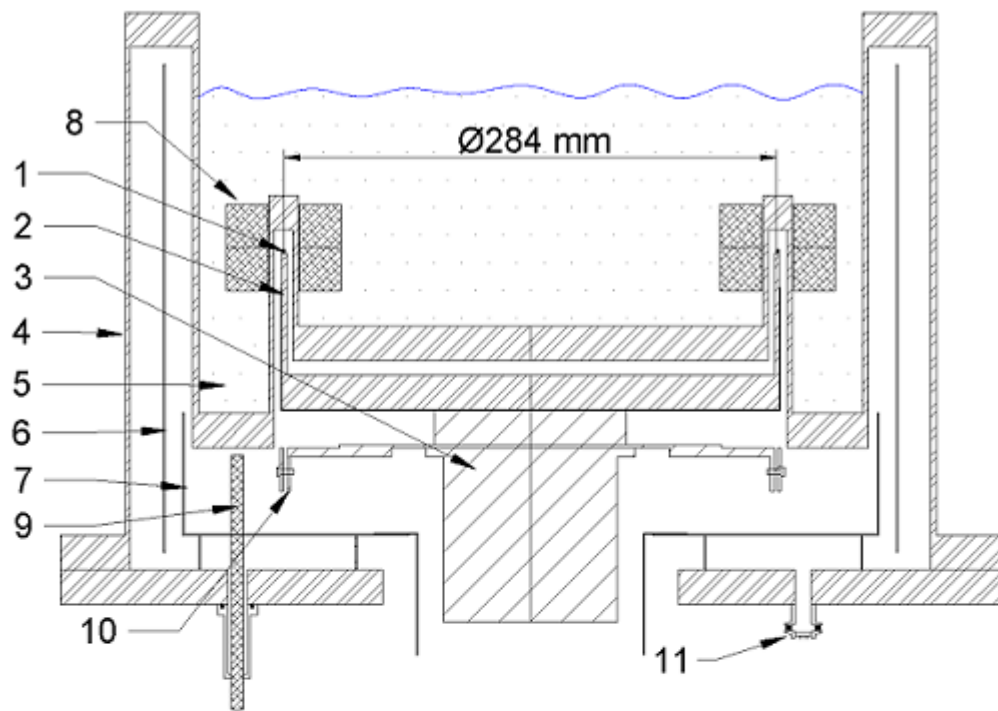
Fig. 6 Response of copper thermometer during calibration at 33.5 K. The pre-performed calibration of the copper thermometer with a cernox thermometer shows that the resistance increase of 0.93 $m\Omega$ corresponds to a temperature increase of 0.53 K.

Fig. 7 Calibration curves for three different temperatures.

Fig. 8 Measured AC losses as function of transport current with no externally applied magnetic field (lower curve) and with an externally applied magnetic field of 36 mT_{peak} (upper curve). At the vertical axis losses with no transport current are given.

MgB$_2$ sample

Copper
thermometer

Calibration heater

Second
heater

Fibreglass
reinforced
epoxy

Copper teeth

20 mm

Ø284 mm

1	Sample
2	Sample holder
3	Cold head
4	Fibre-glass case
5	Liquid nitrogen
6	Radiation shield
7	Radiation shield
8	Magnetization coils
9	Current feed throug
10	Wire cooler
11	Signal feed through