Experiment Setup for Calorimetric Measurements of Losses in HTS Coils Due to AC Current and External Magnetic Fields

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***Abstract*—We present a design and details of construction of two calorimetric systems that allow us to measure the total loss in high temperature superconducting coils or linear samples carrying alternating current while exposed to a strong alternating magnetic field. This measurement technique is based on the boil-off of liquid nitrogen. The first system is designed to measure ac losses in superconducting coils in self-field generated by AC transport current. The second system contains a permanent magnet rotor and simulates the environment of an electric motor or generator. The sensitivity of the system is such that it can measure low losses from a few milliwatts to several hundred milliwatts, in either a static or dynamic magnetic field.**

***Index Terms*—AC losses, calorimetric measurement, magnetic field.**

I. Introduction

As $YBa_2Cu_3O_{7-x}$ (YBCO) coated conductors can now be made in substantial lengths [1], they have become of interest for use in various devices, including field windings in motors and generators [2], transformers [3], and superconductor magnet energy storage devices [4], in addition to the power transmission cables [5], which was the initial goal in their early development. A critical characteristic of wires and cables for many of these applications is their AC losses. The need to measure these losses in device relevant environments have led to the development of several techniques. Some infer the losses through electromagnetic measurements [6], [7], others use calorimetric methods based on the measurement of the temperature increase of the sample [8], [9] or the rate of cryogen boil-off [10]. All these methods have their strengths and weaknesses and for particular experimental conditions some are more suitable than others.

In this paper we briefly describe two systems developed for measurements of the total AC losses in HTS samples and coils. The first system was developed as a sensitive Liquid Nitrogen (LN_2) boil off calorimeter which allows us to measure the self-field losses caused by a transport AC current. A coil is placed in liquid nitrogen and the losses caused by ac current are determined from the total amount of evaporated nitrogen. The specific feature of our approach is that the AC current is turned on for a short period of time (a few minutes), so that over this "active" period the steady state boiling regime is not achieved and the temperature of the coil is not raised significantly.

The second system, a larger machine, designed with a long term prospective to serve as a test bed for the novel types of superconducting wires and coil concepts for many years to come. This machine consists of an eight-pole rotating magnet and the position of the test coil or a straight sample is similar to that they would have in the armature winding of a motor or generator. In the previous experiments on ac losses where the time-varying magnetic field was generated by a solenoid, the maximum sweep rate Bf did not exceed 15–20 T/s [11]–[16]. At the early stage of this project we have come to conclusion that the effort to build a new machine can be justified only if its potential exceeds by at least an order of magnitude the parameters that had been achieved previously. Also, the generators currently used on airborne platforms operate at a frequency of 400 Hz. This was an additional consideration influencing the design parameters. The ac losses in this system are also measured by a sensitive boil-off calorimeter.

II. Self-Field System

The self-field system shown in Fig. 1 uses an outer cryostat consisting of a Liquid Helium (LHe) Dewar with a LN_2 thermal radiation shield. The removable sample chamber was fabricated from a G-10 fiberglass tube bonded to an aluminum flange to fit the 12.7 cm diameter opening for the original LTS magnet. In this flange LN_2 fill and vent ports, a sampling port, and the 7.6 cm diameter opening for power leads cooling section were cut.

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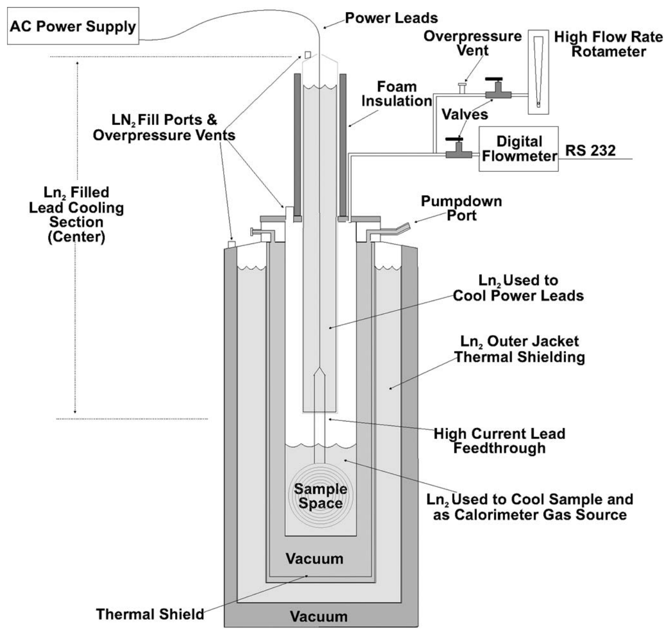

Fig. 1. Vertical cross-section of self field cryogenic calorimeter.

The current leads were two 75 cm lengths of 6 gauge copper braid passing through a 1 m vertical length of 7.5 cm OD PVC pipe filled with LN_2 for heat removal, feeding a 10 cm diameter by 13 cm tall sample space.

Altogether this makes a series of five concentric cylindrical enclosures that include the lead cooling section, the sample chamber surrounded by high vacuum insulation, the LN_2 thermal radiation shield and the outer aluminized Mylar wrapped evacuated insulation space as shown in Fig. 1.

An important feature of this design that sets it apart from many other cryogenic calorimeters, e. g. [10], [17], [18], is that the sample chamber and the current leads cooling section do not share the same pool of LN_2, and the sample chamber is sealed from the environment and from the current leads cooling section. This reduces the base flow of evaporation and the magnitude of its variations.

A. Protocol of Operation and Experiments

The flow rate was calibrated using resistance heaters. A thin film heater of 50 Ω resistance was sandwiched between two aluminum plates in order to increase the surface area to approximately that of the tested HTS coil and avoid the film boiling. It was placed in close proximity to the tested HTS coil.

Since the coil is usually enclosed in an epoxy shell it was virtually impossible to obtain adequately reliable data by waiting until the outflow of evaporated nitrogen stabilizes because of the very long time constant of the protected sample. Moreover, at sufficiently high current the coil may quench before the steady state boiling is established. Over a period of many minutes, in spite of the reductions in background flow, there was still a somewhat unpredictable drift in this flow, and therefore the baseline offset, that prevented achieving the desired measurement resolution. The base background flow for the self field calorimeter was typically in the 2.5 sccm (standard cubic centimeter per minute) to 10 sccm range, representing

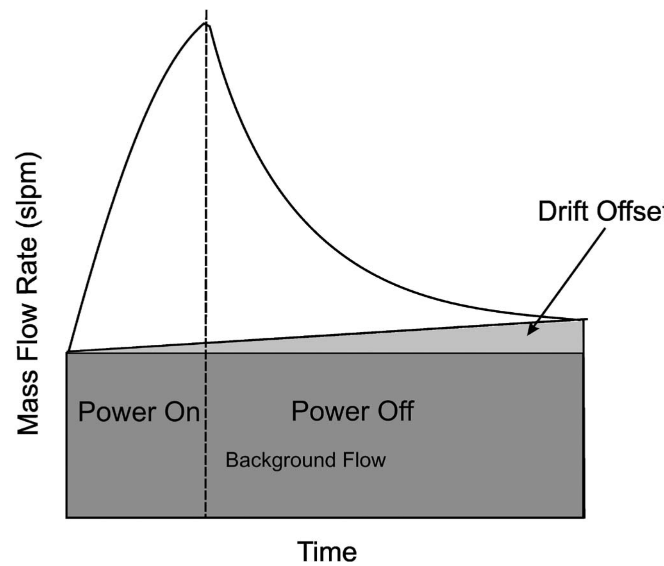

Fig. 2. Time dependence of the mass flow signal.

about 0.009 watts to 0.037 watts. Here we take that the heat of evaporation of one standard cubic centimeter of Nitrogen is 0.225 J. The drift offset range stretched from 0 to 2 times the initial background.

In order to overcome these problems we have used a measurement protocol illustrated in Fig. 2. The current through the coil that generates losses was turned on for about three minutes. Over this period of time the outflow of gas increases. When the current is turned off, the mass flow gradually decreases reaching the background level. Thus, knowing the total amount of evaporated nitrogen above the background level, and correcting for background flow drift, we can calculate the total excess of energy deposited into the pool of LN_2 by the coil. Dividing this energy by the time the current was running, we obtain the power loss. Our estimates based on heat capacity of the coil, and data from the instrumented heater, indicate that the maximum temperature rise inside the coil during this time, with corresponding losses under 1 watt, was of the order of 1 K or less. The calibration heater temperature rose less than 2 millikelvin in this range.

The ohmic power loss in the current contacts was determined by running through the coil dc current equal to the RMS of the alternating current. This amount was subtracted from the total loss.

We also have found by trial an alternative way of determining losses. In experiments with the heater, the rate of increase of the outflow of gas (the initial slope in Fig. 2) was directly proportional to the power deposited through the heater within an uncertainty factor of 2%. This allows us to determine the power loss by using the gas flow data accumulated within first 90 s. The advantage of this method is that there is no need to account for changes in the background rate over the period of 10–20 minutes, which is a characteristic time constant of this apparatus, Fig. 2.

The accuracy of the aforementioned methods of determining ac loss in an HTS was verified by carrying out the measurements on a coil that was previously used to determine the ac loss by electromagnetic measurements [7]. We were satisfied

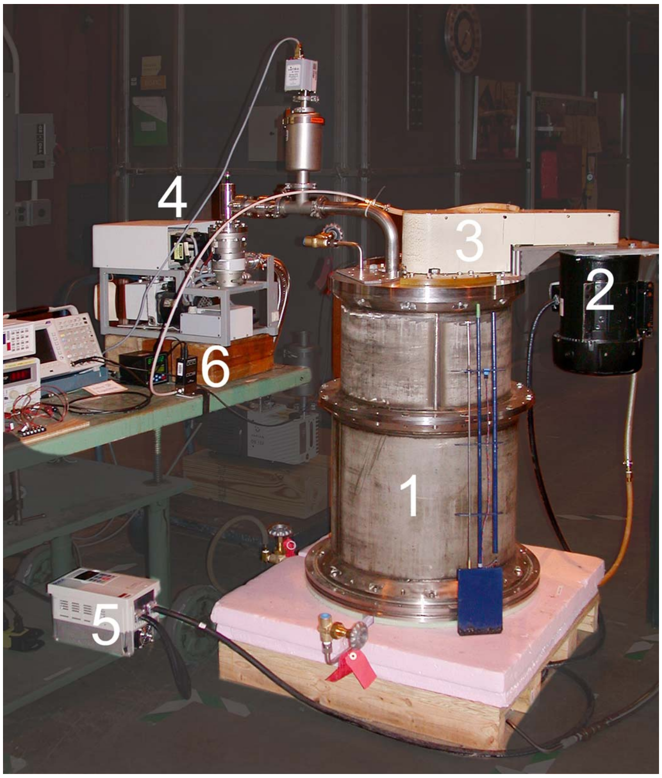

Fig. 3. Photograph of assembled system showing the evacuated main vessel containing the magnet rotor (1). Also shown is the drive motor (2), drive belt (3), vacuum pump (4), drive motor control, and (5) flow meter (6).

that the results obtained by calorimetric methods were in good agreement with these results.

III. Rotating Magnets (SAM) Machine

The second system, shown in Fig. 3, for measuring ac losses contains an eight-pole permanent magnet rotor. The sample, such as an experimental coil is placed in the position equivalent to that of an armature coil in a generator or motor.

The colloquial name of this machine (SAM)—"spin-around-magnets" is also a homage to the eponymous Uncle that sparingly, but patiently had funded this project over the years.

Fig. 4 shows schematically the structure of the machine. The central shaft carries the rotating NdFeB magnet Hallbach array (30 cm OD), surrounded by 3.8 cm annular space (the place where armature windings would be in a generator or motor). This gap from which air is evacuated contains the LN_2 chambers in which a cryostat sample holder (shown at the bottom of Fig. 4) can be inserted.

As in the first machine described above there are two pools of LN_2. The gap between the rotor and the back iron cylinder currently contains one (with the possibility to place several) sample chambers filled with LN_2. Inside this sample chamber we place a sample holder containing an experimental coil or linear sample. This sample holder is also filled with LN_2 whose evaporation provides us with the measure of AC losses. The size and shape of the LN_2 chamber and sample holder can accommodate a variety of different small coils and linear tapes. This assembly is surrounded by the laminated back iron and the outer shell that seals the vacuum. Maintaining about 10^{-5} Torr vacuum inside the machine minimizes the heat leaks into the cryostat holder containing samples. A ferrofluid sealed rotating vacuum feed-through allows us to connect the rotating magnet to the drive motor while maintaining the entire interior of the system evacuated. Nitrogen gas evaporated from the sample chamber is released in the environment. Nitrogen evaporated from the sample holder passes through the flow meter.

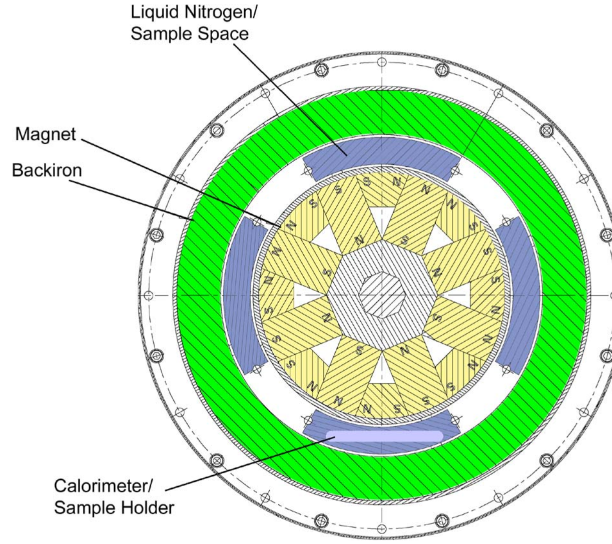

Fig. 4. Horizontal cross-section of the rotating magnets machine. The entire interior is evacuated. Shown are eight-pole rotor assembly (maintained at room temperature), four LN_2-filled chambers inside the vacuum gap, and a sample holder inside one of the chambers containing a test coil also immersed in LN_2. Currently only one chamber is in use. Also shown are the laminated back iron and the outer shell.

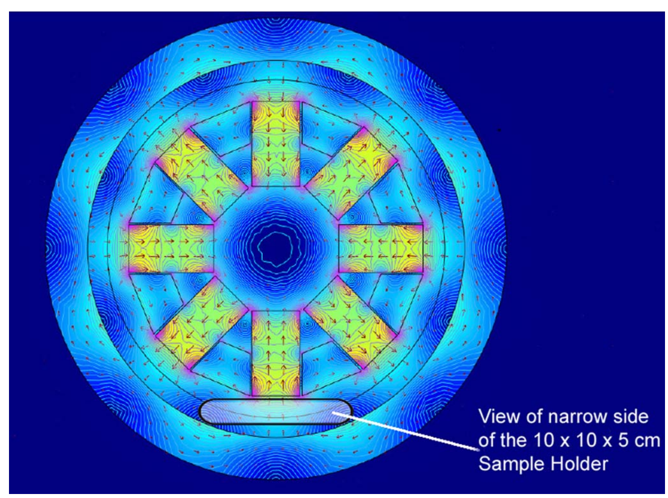

Fig. 5. Horizontal cross-section color map of the field strength pattern inside the machine. The arrows indicate magnetic field lines. The maximum radial field in the gap is close to 0.5 Tesla.

The spatial profile of the magnetic field strength in the vacuum gap of the fully assembled system was mapped while the magnets were rotating using a 1 cm diameter, ten turn copper wire coil. The measured values of the field correlated well with the finite elements calculations shown in Fig. 5. The maximum radial component of the magnetic field in the sample holder is 0.5 T as measured with a Lakeshore model 450 Gaussmeter.

Fig. 6 shows the time dependence of the radial component of the magnetic field in the center of the sample chamber. The

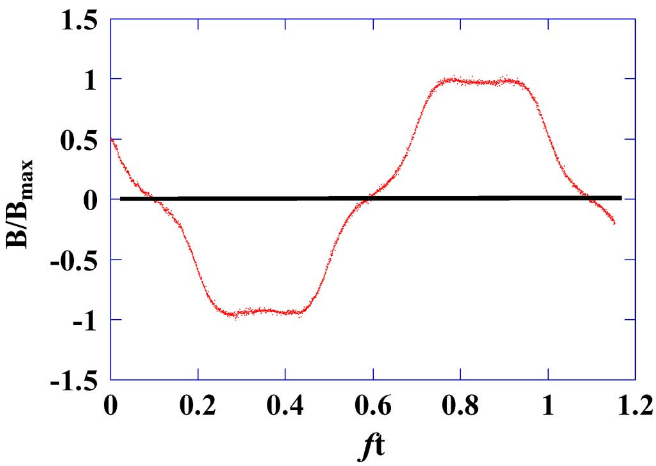

Fig. 6. Time dependence of the magnetic field at a given point inside the sample chamber. Approximately one cycle is shown. The field is normalized to its maximum value at a given point. Time is measured in the units of a period of one cycle. Here f is the frequency of alternating magnetic field.

flat top shape is characteristic of most rotating machines and indicates the presence of high frequency harmonics.

An important attribute of a successful test bed is its suitability for development—a capability for modification or adaptation to new types of tests and requirements, without necessitation of extensive redesign of fundamental components. This machine was built with the goal to closely simulate the stator environment in a motor or generator. The rotor was designed for maximum speed of 6000 rpm, which the eight-pole rotor translates into 400 Hz frequency of the magnetic field (a typical frequency of aircraft based generators).

At the maximum rotation speed this would expose the sample located in this area to 200 T/s sweep rate, which is about an order of magnitude greater than the maximum sweep that has ever been achieved in ac solenoids that were used for testing the ac losses in superconductors. At such sweep rate most currently manufactured superconducting wires, such as low-T_c Nb-Ti or Nb-Sn wires, YBCO coated conductors, or MnB_2 wires would likely quench. As we mentioned before, this machine was built with a long term prospective and with understanding that eventually a more ac tolerant superconductors and novel designs of the coils will be developed and needed to be tested. It should be noted that the machine has not yet been run at the maximum speed. It has been tested so far only at 900–1200 rpm (60–80 Hz).

Operation and Experiments

The first sample holder for this machine was constructed to hold 10 cm long sections of HTS tape or a coil, up to 10 cm in diameter, made out of 4 mm wide conductor. This sample holder has a sealed volume $10 \times 10 \times 0.5$ cm^3 with a valved fill for calibration. To determine the boil off rates resulted from ac losses we have used $10 \times 0.5 \times 0.05$ cm^3 copper strip that generates eddy current losses in rotating field. The copper strip was used to develop the operating procedure and to carry out the reproducibility tests and calibration. Fig. 7 shows a representative example of the changes in flow rate from the sample holder containing the copper strip in response to changing rotation speed of the rotor. The initial speed is 600 rpm, which corresponds to the field variation frequency 40 Hz. The rotation speed was reduced over time in steps of 15 rpm (1 Hz) and the outflow decreased in corresponding steps.

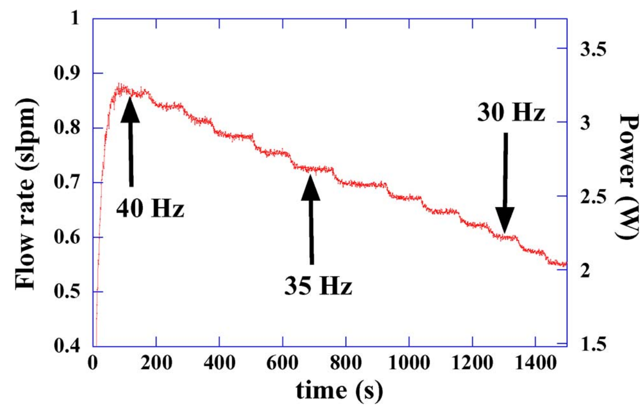

Fig. 7. Flow rate in standard liters per minute due to eddy current losses in a copper strip. The scale on the right shows the power loss that corresponds to the respective flow rate $(1 \text{ slpm} = 3.75 \text{ W})$. The rotation frequency of the rotor decreases in steps. The arrows show the frequency of field variation at a given moment.

IV. Conclusion

Two AC loss measurement systems were designed, built and initially tested. The first system allows us to measure the self-field ac losses in coils due to an applied alternating current. This system has a resolution of about 10 mW and a minimum detectable power loss of 20 mW.

The second system (SAM machine) determines ac losses in the presence of rotating magnetic field with the sweep rate, as currently tested, up to 30–40 T/s, and with the potential to reach 150–200 T/s with the maximum frequency of the rotating field up to 400 Hz. Initial calibration and test results are described.

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