AC LOSS MEASUREMENTS ON MULTIFILAMENTARY BSCCO 2223 HIGH-TEMPERATURE SUPERCONDUCTORS

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ABSTRACT

A calorimetric method for measuring AC loss in long lengths of high temperature superconductor (HTS) at 77 K has been developed. Complementary systems with resolution down to 1 mW/cc have been installed at Oak Ridge National Laboratory (ORNL) and American Superconductor Corporation (ASC) and give consistent results, confirming the reliability of the technique. AC excitation fields up to 0.25 T and at 5 to 60 Hz are supplied by a multifilament BSCCO solenoid which has been in operation for over a year; this is the world's first HTS magnet system that performs a useful technical function in a cost-competitive manner. Results are presented on 85 filament BSCCO composite conductors showing dependence suggesting hysteretic losses.

INTRODUCTION

Numerous applications of HTS such as power transmission lines, motors, transformers, power electronics, and current limiters require operation of the superconductor in AC fields and the transport of AC current. The net efficiency of the devices and hence their economic attractiveness, depend on the AC loss characteristics of the HTS conductor. Consequently, efforts are underway to develop HTS conductors and devices with reduced AC losses.[1,2] Part of this program is (1) the development of reliable techniques for measuring losses under conditions representative of those used in utility applications and (2) the development of theory to understand those losses. A cooperative program in this area has been in place between ORNL and ASC for several years and has led to the development of complementary loss instrumentation at the two institutions and the fabrication of conductors specifically designed to facilitate the understanding of loss mechanisms in HTS conductors.

While alternative transport or susceptibility AC loss measurements have special problems, especially in HTS tape configurations[3], the calorimetric method provides, in principle, unambiguous results for the true loss. We describe here a sensitive semi-adiabatic calorimetry loss measurement technique which can be used to investigate the field and frequency domains of commercial interest at temperatures from 4.2 K to 77 K. In addition we present initial data from a series of samples which have been designed and fabricated to facilitate understanding of losses in multifilament HTS materials.

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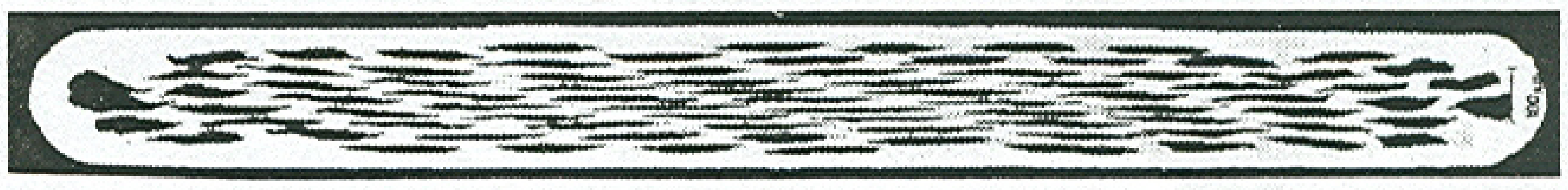

Figure 1. Cross section of 0.25 x 0.025 cm 85 filament conductor.

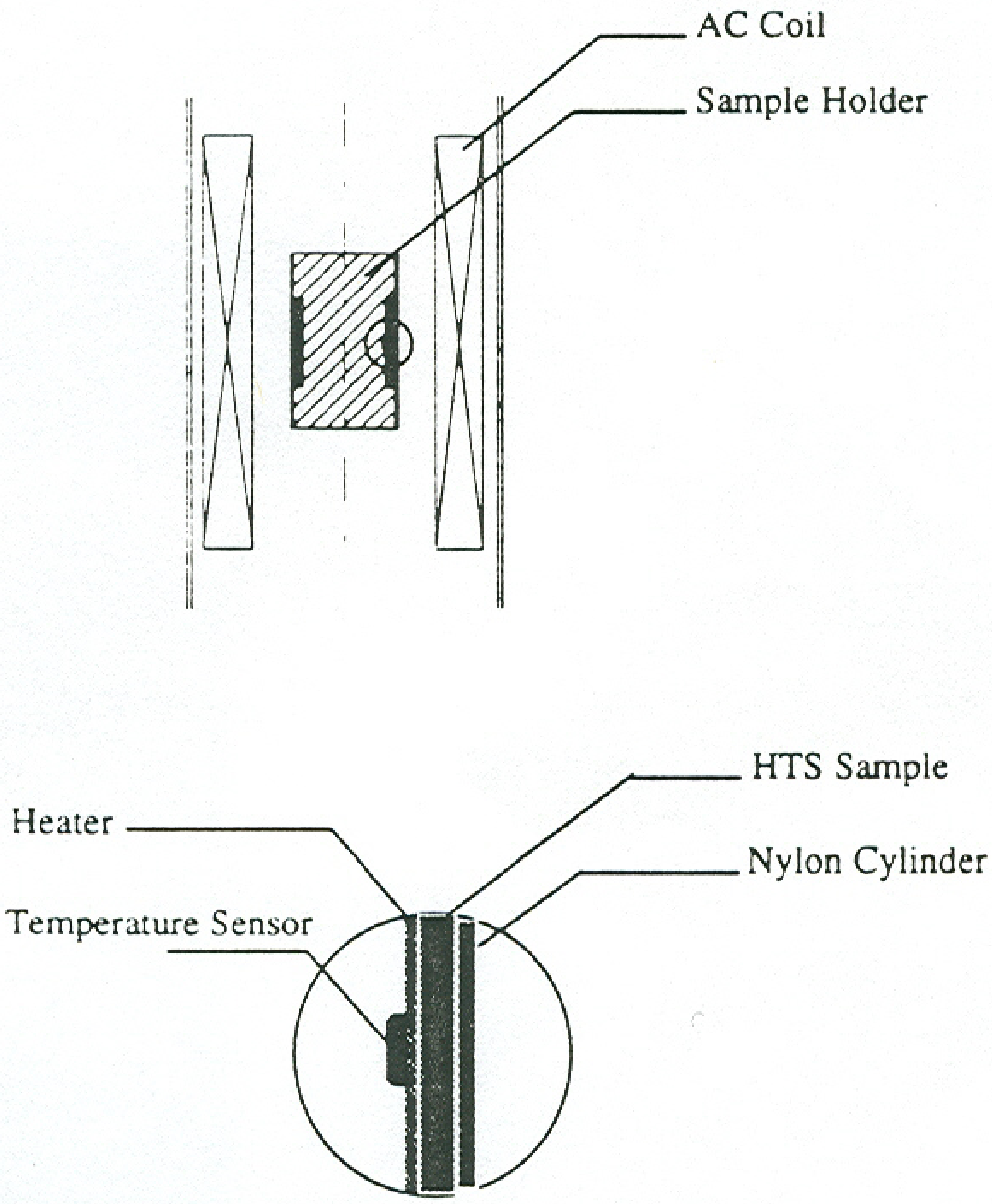

Figure 2. The schematic diagram illustrating the method for measurement of AC loss in HTS sample.

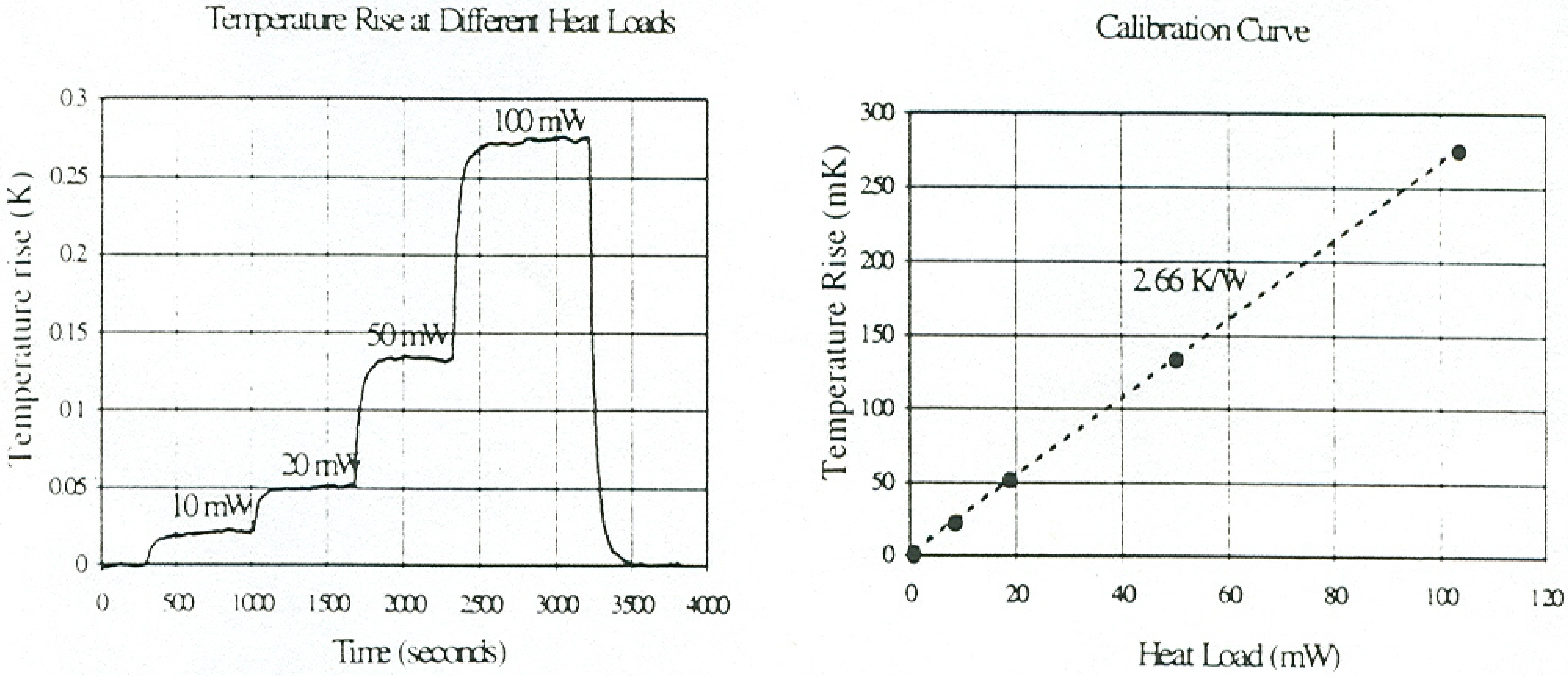

Figure 3. The system is calibrated for each sample by measuring the temperature rise due to power applied via the heater.

Table 1. Performance of AC Loss Systems at ORNL and ASC

	ORNL	ASC
Frequency Range	40-500 Hz	5-50 Hz
Parallel field	0.1T	0.25T
Perpendicular Field		0.05 T
Resolution at 77 K	2 mW/cm^3	1 mW/cm^3

EXPERIMENTAL: HTS SAMPLES AND AC LOSS APPARATUS

Meter-long samples of composite multifilamentary BSCCO-2223 wire were studied. An ASC production 85 filament conductor with an I_c of 31.3 A at 77 K was made. Its transverse cross-section shown in Figure 1.[4] The filaments are untwisted (further results on twisted structures will be presented in a future report). The silver sheath was 25 microns thick on the top and bottom of the tape.

The experimental apparatus for AC loss measurements at ORNL and ASC are based on a calorimetric test method used earlier by Schmidt[5]. In this method the HTS sample is exposed to an alternating field of a certain frequency and amplitude produced by an AC coil. A sensitive temperature sensor mounted close to the sample measures the temperature rise due to losses. The AC losses are estimated by measuring the energy needed to achieve the same temperature rise (as in AC field) using a DC heater placed adjacent to the sample.

Figure 2 shows a schematic of the experimental set-up at ASC. The ORNL apparatus has an identical sample holder with a copper driving coil outside the cryostat. The temperature sensor is placed in a small hole drilled in a cylindrical G-10 sample holder. A heater is wound on the sample holder. The meter-long HTS wire sample is wound on top of heater, typically as a three-layer solenoidal coil with open ends. The sample holder can accommodate samples up to 3 cc in total wire volume. A nylon cylinder covers the sample. Thermal grease is applied to the cylinder walls to prevent the entrance of vapor/liquid into the sample area. The assembly shown in Figure

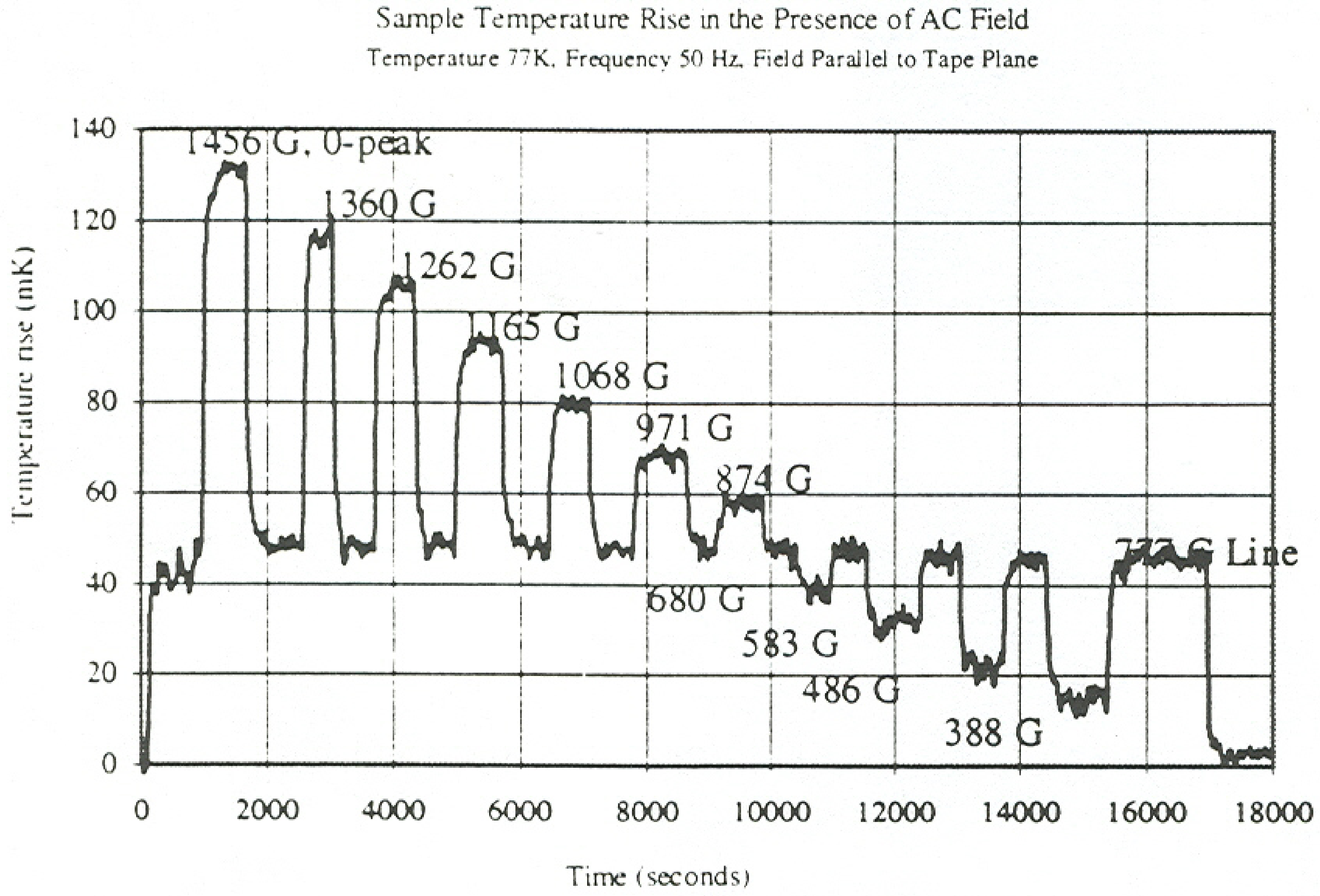

Figure 4. Sample temperature rise in the presence of an AC field. Base temperature: 77K, frequency: 50 Hz, field parallel to tape plane.

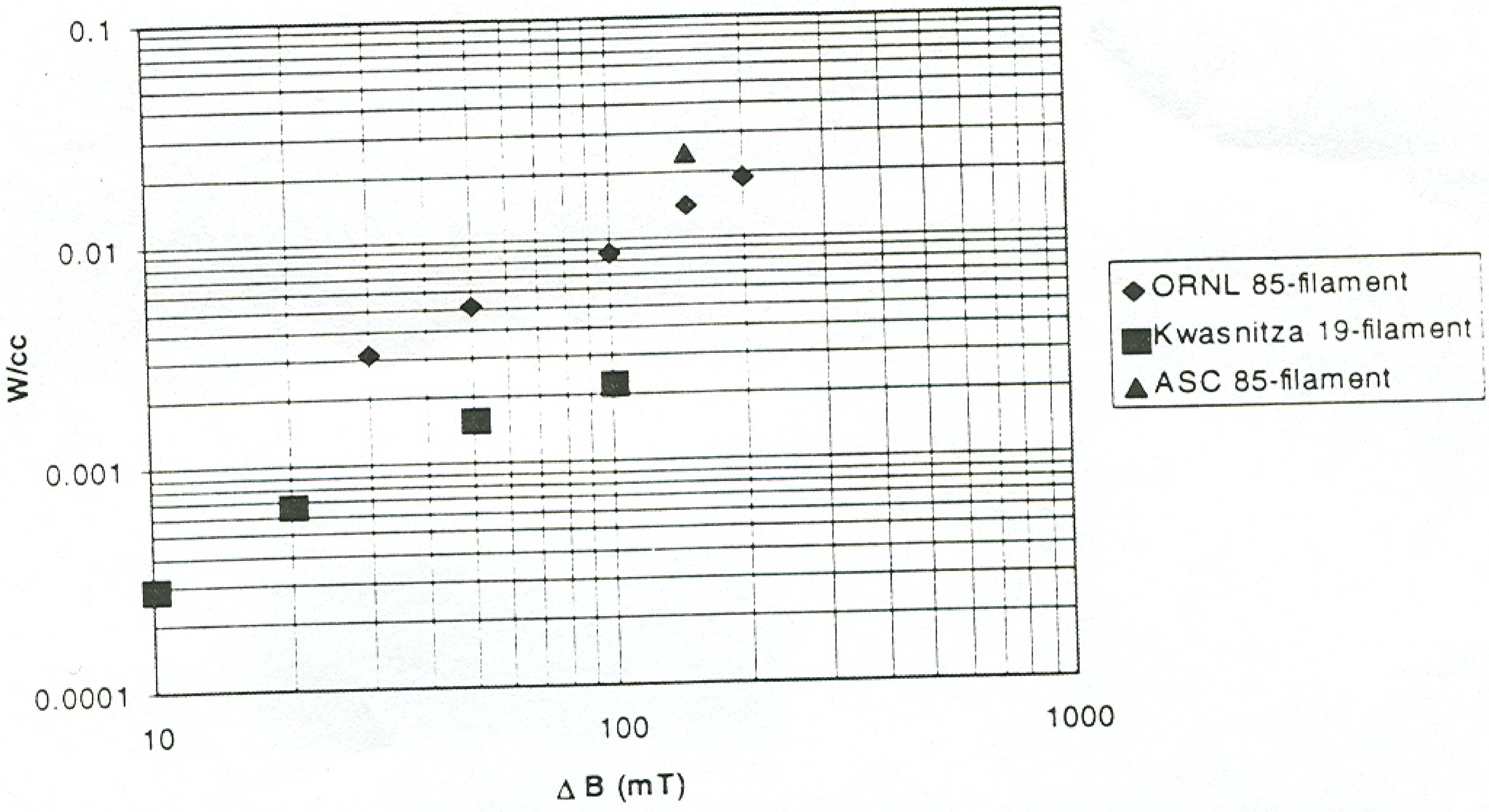

Figure 5. AC loss with magnetic field applied parallel to the wide face conductor at 45 Hz.

2 is placed in a cryogenic environment (liquid or gas). When the AC coil (or ohmic heater) is energized, the sample temperature increases until thermal equilibrium is reached. The total temperature increase depends on the losses. The time taken to reach thermal equilibrium depends on the specific heat of the sample and the holder and thermal conductivity of nylon cylinder. The apparatus has been designed to achieve a suitable compromise between absolute resolution and experiment duration. Sensor temperature in the presence of AC field is recorded while stepping the amplitude of the applied sinusoidal field between the measurement value and a reference value, as shown in Fig. 3. This allows for correction of any long term drifts in the ambient temperature in the vicinity of the sample. The system is calibrated similarly by stepping the heater current, as shown in Fig. 4. The performance is summarized in Table 1. Due to lower specific

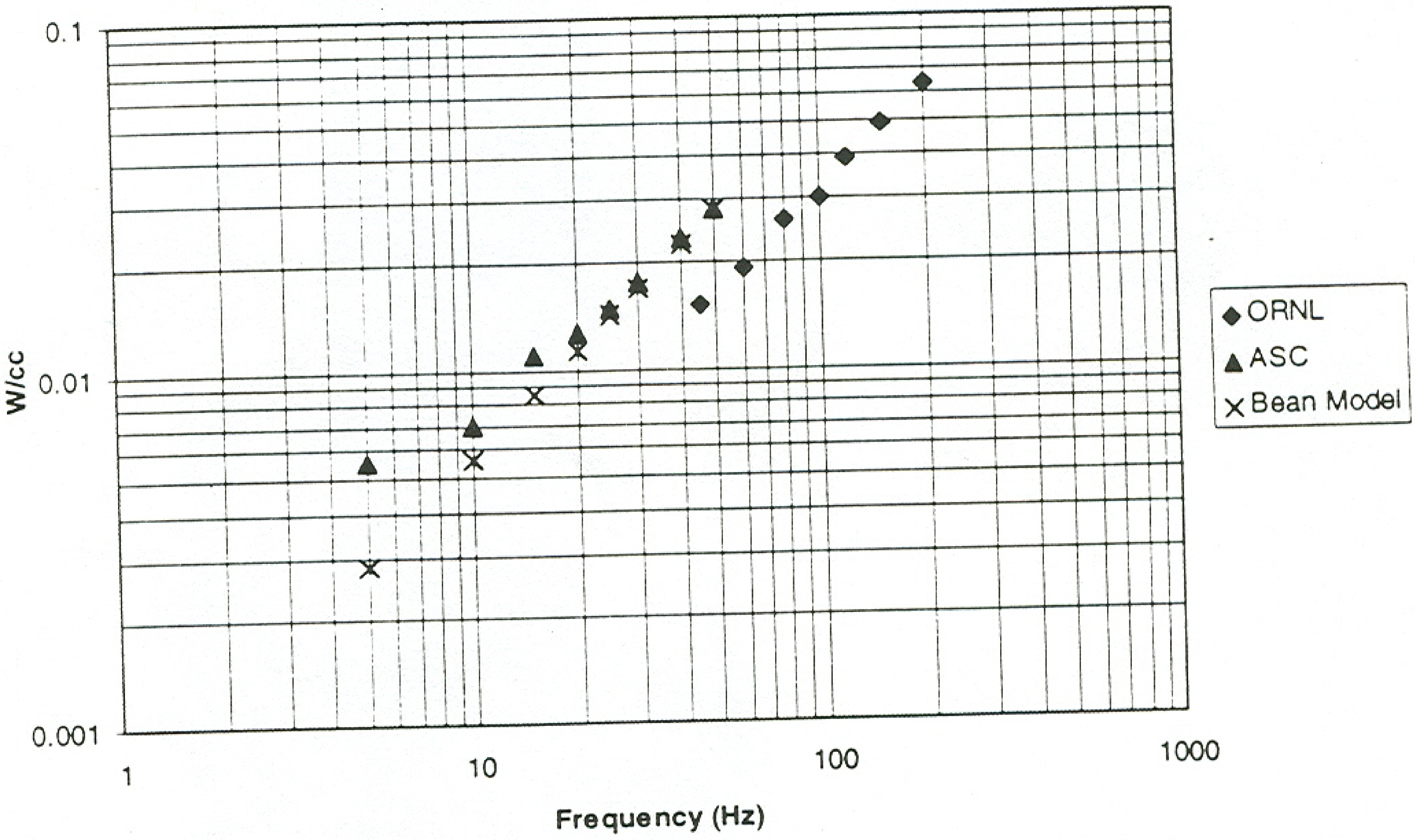

Figure 6. AC loss with magnetic field applied parallel to the wide face of a 85-filament conductor at ΔB=150 mT.

heat of sample holder and higher sensitivity of temperature sensor, measurements made at lower temperatures are more sensitive. At 4.2 K the measurement resolution is estimated to be close to 1 μW/cc.

A special feature of the ASC system is the AC field coil, composed of a stack of 16 double pancakes of ASC pilot production HTS conductor[4], with inner and outer diameters of 5 and 7.4 cm respectively. The stack is 9.2 cm high. It has an inductance, when connected in series, of 65 mH and 9516 A-turns at 1 microvolt/cm at 77 K. For axial fields (parallel to the sample tape plane), the pancakes are all driven in series. For perpendicular fields, the bottom 8 pancakes are wired to flow current opposite to the direction of the top 8 pancakes in an "anti-Helmholtz" configuration. Perpendicular field in this case varies over the sample by about 35%; the maximum field is reported in the data below. Use of HTS coils lowers the losses and consequently the power requirements significantly, as compared to copper, and their use substantially improves the stability and energy resolution of the system. To our knowledge, this coil represents the world's first practical operating HTS magnet system, in contrast to the many demonstration magnets described heretofore. This system has been in operation over a year period with excellent reliability.

Data on the 85 filament untwisted sample from the ORNL and ASC systems are presented in Figs. 5 and 6 for the parallel field configuration. The data are approximately linear in both field and frequency in the regime studied. The ASC results for the 85 filament conductor are generally a factor of 1.5 above the ORNL data. We consider this a good starting point, demonstrating the consistency of the technique. The results can also be compared to an extrapolation of data from Kwasnitsa and Clerc[6], who used a magnetic measurement technique. Their data for a 19 filament sample of roughly 55% the engineering current density is about a factor of 4 lower than the ORNL data when scaling linearly to a 45 Hz power loss. A one-to-one comparison of the two techniques using the same sample is required before concluding which technique is more accurate.

DISCUSSION

We recognize at the outset that much more data needs to be collected to get a more representative picture of the behavior of different wire samples. However, the data of Fig. 5-6 can be very simply explained in terms of the fully penetrated Bean model for hysteretic losses.

Estimates of the sheath eddy current losses indicate that these losses should be negligible. Eddy current coupling losses are expected in an untwisted multifilamentary conductor because of loops of induced current traveling along the superconducting filaments and closing through the normal metal matrix at the ends of the sample, but these losses are also expected to be only a small fraction of the total loss because they are concentrated only at the open ends of the wire. However, these coupling currents have the effect of coupling the filaments together and making them behave much as a single large monofilament, thus increasing the hysteretic losses. The hysteretic losses can be estimated by treating the sample as shown schematically as in Figure 7. The "monofilament" consists of that portion of the conductor containing the filaments. The monofilament thickness is d-2v and the width is w-2v and the monofilament critical current is

$$J_c = I_c/(d-2v)(w-2v).$$

From the Bean model[7] the flux front during each cycle reaches the center of the sample at a peak-to-peak penetration field $B_p = \mu_o J_c\,(d-2v)$ for the case of field parallel to the wide face. In our case this comes out to 16 mT, which is below the experimental range in Fig. 6. Above full penetration, $(B_m > B_p)$ the hysteresis loss per unit volume is

$$P = \frac{f}{2\mu_o}\left(B_m B_p - \frac{2}{3}B_p^2\right)$$

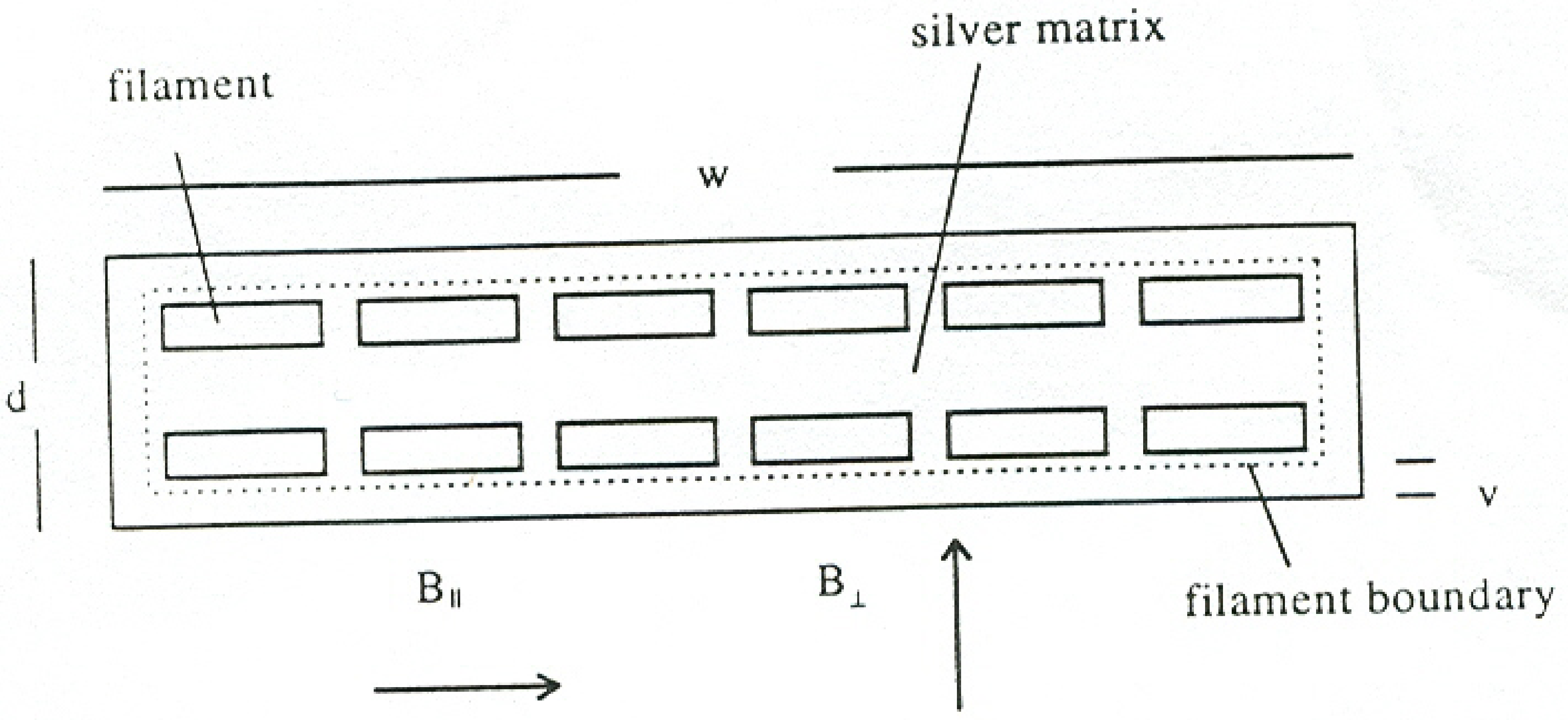

Figure 7. Schematic of a high temperature superconducting composite.

The predictions are compared to experiment in Figure 6. The prediction lies within about 50% of experiment.

CONCLUSIONS

Semi-adiabatic calorimetry has been shown to be an effective method for measuring HTS AC losses in regions of field, frequency, and temperature relevant to commercial applications. Good correlation has been obtained between measurements at ORNL and at ASC on identical samples. The loss behavior of untwisted aspected samples in fields parallel to the wide face of the conductor are in reasonable agreement with the predictions of the Bean model. This AC loss apparatus is the first production HTS system and it has been operating with a high duty cycle for over a year.

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