Variable Temperature Total AC Loss and Stability Characterization Facility

Sastry Pamidi, Doan Nguyen, Guomin Zhang, David Knoll, Ulf Trociewitz, and Justin Schwartz, *Fellow, IEEE*

***Abstract*—The design of a versatile ac loss and stability characterization facility for high temperature superconducting materials suitable for variable temperature measurements is described. A non-metallic vessel inside a transverse field double-helix magnet acts as the measurement chamber. A cryocooler cools the samples to a target measurement temperature between 35 and 80 K. The facility is suitable for measurements on samples as long as 15 cm with ac transport current and ac background magnetic field, both at variable frequency. The facility allows for sample rotation to vary its orientation with respect to the magnetic field. Initial temperature measurements showed that the sample could be maintained at uniform temperature to $\pm$0.5 K. AC loss measurements performed on a precursor setup, identical in concept, confirmed the suitability of the double-helix magnet design and cryocooler based cooling arrangement.**

***Index Terms*—AC loss, high-temperature superconductors, stability, superconducting filaments and wires.**

I. Introduction

Large-scale power applications of high temperature superconductors (HTS) are looking more promising with the advances in commercial production of long-length, high-performance $YBa_2Cu_3O_7$ (YBCO) coated conductors [1], [2]. The interest in evaluation of ac losses of YBCO coated conductors has increased in the recent past to generate much needed engineering data [3]–[14]. The topic of quench stability and normal zone propagation is also attracting attention [15], [16]. Reliable data on ac losses and quench stability are essential in designing cryogenic systems and protection mechanisms for superconducting power equipment. Thorough understanding of ac loss and stability mechanisms also helps in the development of YBCO coated conductors with reduced ac loss and increased stability. Both ac losses and stability of HTS materials are functions of temperature, transport current density, background magnetic field, magnetic field orientation with respect to the sample, frequency of transport current and magnetic field, and the phase difference between transport current and magnetic field. There have been several reports on improved measurement techniques for obtaining reliable data on HTS materials. Most reported measurements have been at 77 K in a liquid nitrogen bath [3]–[9] with a few reports of lower temperature measurements [10]–[12]. It is difficult to measure ac loss and stability properties at lower temperatures primarily due to the problems associated in maintaining a uniform temperature while a transport current of hundreds of amperes is injected through the sample. Another difficulty is in providing uniform magnetic field across a reasonable length of the sample; both ac loss and stability measurements demand long sample lengths to ensure reliable data.

Manuscript received August 26, 2006. This work was supported by the Office of Electricity Delivery and Energy Reliability, U.S. Department of Energy, Award DE-FG02-05CH11292.

S. Pamidi, D. Nguyen, G. Zhang and D. Knoll are with the Center for Advanced Power Systems, Florida State University, Tallahassee, FL 32310 USA (e-mail: pamidi@caps.fsu.edu; nguyen@caps.fsu.edu).

U. Trociewitz is with the National High Magnetic Field Laboratory, Florida State University, Tallahassee, FL 32310 USA.

J. Schwartz is with the National High Magnetic Field Laboratory, Department of Mechanical Engineering, Florida State University, Tallahassee, FL 32310 USA.

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TASC.2007.899038

TABLE I
PARAMETER RANGE FOR THE AC LOSS AND STABILITY MEASUREMENT FACILITY

Parameter	Target value
Sample length	Up to 20 cm
Transport current	Up to 650 A, frequency DC - 10 kHz
Background field	0 - 200 mT, frequency DC - 10 kHz
Temperature range	35 – 100 K
Cooling environments	Vacuum, helium gas, or a liquid cryogen
Magnetic field orientation	0 –180°

The focus of HTS research at the Center for Advanced Power Systems (CAPS) has been on the development of a versatile facility for measuring ac loss and stability characteristics at variable temperatures under simultaneous ac transport current and ac background magnetic field. The new feature of the facility is a transverse field helical magnet with a bore diameter large enough to accommodate a cold head of a cryocooler enabling variable temperature measurements in a background ac magnetic field. Two precursor measurement systems have been designed and tested to validate the suitability of the above components. In the first, a smaller magnet with an identical design concept was used for ac loss measurements at 77 K and in the second, a cryocooler based variable temperature measurement setup was adapted for self-field ac loss measurements on YBCO samples in the temperature range of 35–80 K [13], [14], [17]. This paper describes the concept, design, and the main components of the new comprehensive measurement setup as well as results from the two precursor systems.

II. The Design Concept

The target values of the various parameters for the measurement setup are listed in Table I. The concepts are similar to that used by other groups for measurements at 77 K [3]–[12]. The main challenges involved in designing the facility were achieving variable but stable temperatures in the bore of ac magnet and creating a uniform ac magnetic throughout the sample length of 15 cm. The magnet is a layered double helix

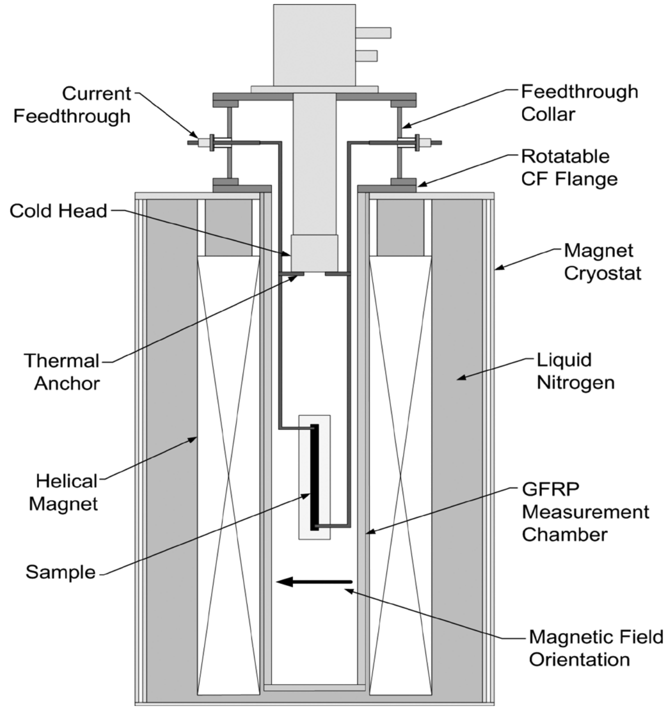

Fig. 1. Schematic of the variable temperature ac loss and stability measurement facility.

winding with a bore diameter of 16.50 cm and a uniform magnetic field up to 200 mT over a length of 20 cm. A Cryomech AL 330 cryocooler with a capacity of 170 W and 40 W at 50 K and 20 K, respectively is used to cool the sample to the required temperature. The measurement chamber consists of a sealed glass fiber reinforced plastic (GFRP) tube. The cold head of the cryocooler sits near the top of the measurement chamber, which extends into the bore of the magnet. Fig. 1 depicts a schematic of the measurement set up with its various components. The following sections describe the details of the critical components of the set up.

A. The Magnet

Fig. 2 depicts a photograph of the magnet used to produce background transverse ac field. The double-helix dipole magnet has two sets of tilted coils, each consisting of three layers. The coils are wound with Litz copper wire. The tilted coils are connected in series in such a way to cancel the axial field component producing a transverse field perpendicular to the axis of the coil. Fig. 3 depicts the concept of double-helix dipole magnet. The magnet produces a highly uniform magnetic field over a region of 20 cm in length as depicted in Fig. 4. The magnetic field values depicted in Fig. 4 are the calculated values. The calculated values were confirmed by measurements with a hall sensor at a few representative current values. The magnet is suspended in a cryostat so that it can be cooled with liquid nitrogen during operation. There is a gap between windings to allow liquid nitrogen flow between layers for efficient cooling. The magnet conductor sits in machined helical groves and is directly exposed to liquid nitrogen without any epoxy or insulation. The field constant is 1.487 mTA^{-1}, requiring 135 A to generate a field of 200 mT. The magnet is powered with a set

Fig. 2. View of double-helix magnet assembly showing the outer helix.

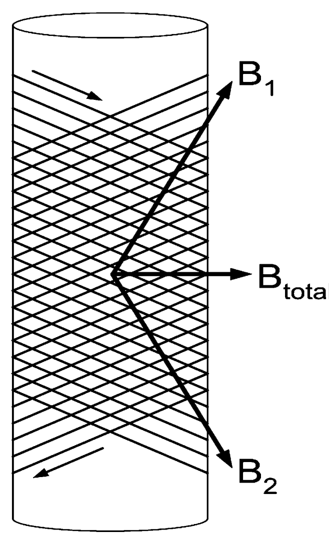

Fig. 3. The concept of the layered double-helix transverse-field magnet shown Figs. 1 and 2.

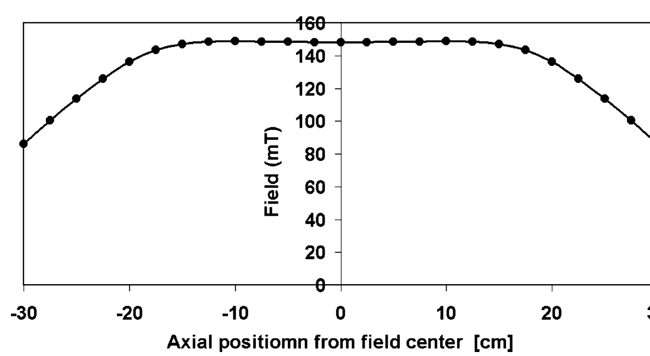

Fig. 4. A plot of magnetic field strength along the length of the magnet showing a 25 cm long uniform field region.

of four AE Techron 7782 amplifiers suitable for variable frequency operation. The magnet has a bore diameter of 16.50 cm to accommodate the 16.25 cm OD, 14.60 cm ID GFRP tube that serves as the measurement chamber.

B. Measurement Chamber

As depicted in Fig. 1, the sample chamber is made up of a thick walled GFRP tube sealed at the bottom. The top of the tube is attached to a rotatable stainless steel CF flange and the flange-tube joint sealed with Stycast. A feed through collar with four KF40 ports rests on the top of the tube flange. The bottom of the collar seals the steel flange that supports the GFRP tube. The top of the collar is sealed with the cold head flange via a CF joint. The collar, the GFRP tube, and the cold head flange assembly together form the vacuum tight measurement chamber. The collar provides access to the current leads, instrumentation wiring, and vacuum ports. The rotatable flange allows for the rotation of the sample to change its relative orientation with respect to the magnetic field. The sample holder is suitable for measurements under vacuum in semi-adiabatic conditions or in helium gas atmosphere to provide better thermal equilibrium. The sample chamber can also be filled with liquid nitrogen or liquid helium to perform experiments in a bath of cryogen.

C. Cold Head and Sample Holder Assembly

The maximum allowed magnetic field around the cold head is 0.5 mT. Hence, the cold head and sample holder assembly was designed to place the cold head just above the top of the magnet and the sample in the center of the magnet. The sample holder is a G10 block suspended from the bottom of the cold head using copper rods that also act as current leads. The G10 block supports a sapphire plate on which the sample sits and the current leads on either end of the sapphire plate. The current leads are thermally anchored to the cold head with a thin sapphire plate acting as an electrical insulator. As shown in Fig. 1, the copper current-lead rods from the cold head anchor points are coplanar with the G10 sample holder as well as the superconducting sample. A resistive heater located between the sapphire plate and the G10 sample holder is used for temperature control.

III. Results and Discussion

The magnet, cryostat, power supplies, cryocooler, measurement chamber, and sample holder were assembled and tested for vacuum integrity and temperature uniformity. The cryostat that houses the magnet was filled with liquid nitrogen. The measurement chamber was pumped to 10^{-5} Torr vacuum. With the cold head operating, the temperature at several positions along the sample holder and current leads was recorded to check for temperature gradients. Fig. 5 depicts temperature traces as a function of time. It took about 4 hours for the sample to reach 35 K. These measurements showed that a uniform temperature could be maintained across a 15 cm long sample with a maximum variation of ±0.5 K.

The suitability of the double-helix magnet design was confirmed through total ac loss measurements at 77 K in a smaller magnet, identical in concept to the magnet described above. Fig. 6 depicts total ac loss at 77 K on an YBCO sample. The details of the measurements at 77 K are reported previously [13], [14].

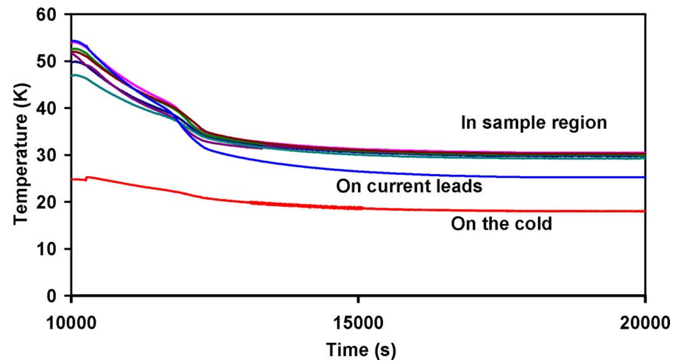

Fig. 5. Temperature recorded on the cold head and several locations of the current leads and sample region.

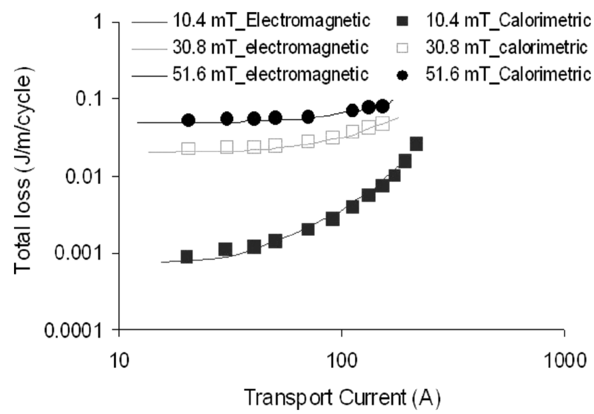

Fig. 6. Total ac loss of a YBCO coated conductor sample, at 77 K, as a function of transport current at different background ac field strengths measured by electromagnetic (lines) and calorimetric method (symbols).

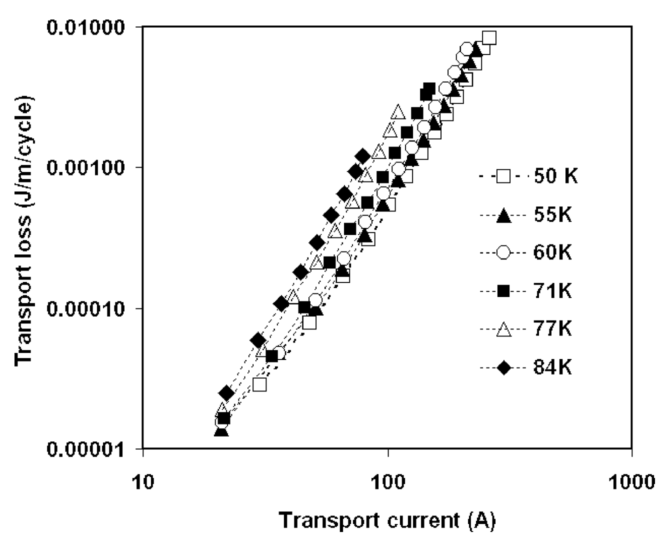

Fig. 7. Self-field loss as a function of transport current at various temperatures between 50 and 84 K for silver sheathed Bi-2223 superconducting tape.

The possibility of obtaining uniform temperature over a 15 cm long sample in 35–80 K range has been confirmed in self-field ac loss measurements and stability/quench propagation measurements using a Cryomech AL330 cryocooler [17]. Uniform temperature within ±0.5 K was maintained throughout the measurement range. Fig. 7 depicts measurements of self-field ac loss on a Bi2223 tape between 50 K and 80 K.

The facility described is also suitable for stability and quench propagation studies on HTS materials under simultaneous ac/dc magnetic field and ac/dc transport current because the experimental requirements are identical to those of ac loss measurements. Stability and quench propagation measurements have been performed by other researchers under dc transport current [18], [19]. The facility reported here would allow for experiments at variable temperatures under ac transport current and ac magnetic field.

IV. Conclusion

A versatile experimental facility was setup to measure ac loss and stability properties of HTS materials at variable temperatures. The setup allows for total ac loss measurements with ac transport current and ac background magnetic field. It is possible to measure samples as long as 15 cm and to vary their orientation with respect to the magnetic field. A novel double-helical magnet with a large bore made it possible to accommodate the cold head to enable measurements between 35 and 100 K. The experimental facility will be used to understand ac loss and stability characteristics and to generate engineering data on YBCO and other HTS materials at wide range of operating parameters.

Acknowledgment

The authors thank the American Superconductor Corporation for providing the superconductor samples used in the study.

References

[1] R. A. Hawsey and D. K. Christen, "Progress in research, development, and pre-commercial deployment of second generation HTS wires in the USA," *Physica C: Supercond.*, in press.

[2] Y. Shiohara, Y. Kitoh, and T. Izumi, "Highlights in R&D for coated conductors in Japan," *Physica C: Supercond.*, in press.

[3] S. P. Ashworth and M. Suenaga, "The calorimetric measurement of losses in HTS tapes due to ac magnetic fields and transport currents," *Physica C*, vol. 315, pp. 79–84, 1999.

[4] S. P. Ashworth and M. Suenaga, "Experimental determination of the losses produced by the interaction of AC magnetic fields and transport currents in HTS tapes," *Physica C: Supercond.*, vol. 329, pp. 149–159, 2000.

[5] J. J. Rabbers, B. ten Haken, and H. H. J. ten Kate, "Advanced ac loss measurement methods for high-temperature superconducting tapes," *Rev. Sci. Instrum.*, vol. 72, pp. 2365–2373, 2001.

[6] N. Amemiya, Z. Jiang, Y. Iijima, K. Kakimoto, and T. Saitoh, "Total AC loss of YBCO coated conductor carrying AC transport current in AC transverse magnetic field with various orientations," *Supercond. Sci. Technol.*, vol. 17, pp. 983–988, 2004.

[7] Z. Jiang and N. Amemiya, "An experimental method for total AC loss measurement of high Tc superconductors," *Supercond. Sci. Technol.*, vol. 17, pp. 371–379, 2004.

[8] R. Grabovickic, J. W. Lue, M. J. Gouge, J. A. Demko, and R. C. Duckworth, *IEEE Trans. Appl. Supercond.*, vol. 13, pp. 1726–1730, 2003.

[9] M. D. Sumption, E. W. Collings, and P. N. Barnes, "AC loss in striped (filamentary) YBCO coated conductors leading to designs for high frequencies and field-sweep amplitudes," *Supercond. Sci. Technol.*, vol. 18, pp. 122–134, 2005.

[10] C. Schmidt, "Temperature dependence of ac-losses in multifilamentary Bi-2223 tapes between 4.2 K and Tc," *Cryogenics*, vol. 44, pp. 187–195, 2004.

[11] M. Majoros, L. Jansak, S. Zannella, F. Curcio, P. La Cascia, V. Ottoboni, C. M. Friend, L. Le Lay, B. A. Glowacki, and A. M. Campbell, "Temperature dependence of transport AC loss in Bi-2223/Ag multifilamentary tapes," *Physica C*, vol. 310, pp. 6–11, 1998.

[12] K. Wakasugi, S. Murase, F. Naito, and S. Shimamoto, "Effects of frequencies and temperatures on self-field loss for Ag/Bi-2223 tapes," *Physica C: Supercond.*, vol. 310, pp. 1209–1212, 2001.

[13] D. N. Nguyen, P. V. P. S. S. Sastry, G. M. Zhang, D. C. Knoll, and J. Schwartz, "AC loss measurement with a phase difference between current and applied magnetic field," *IEEE Trans. Appl. Supercond.*, vol. 15, pp. 2831–2834, 2005.

[14] D. N. Nguyen, P. V. P. S. S. Sastry, D. C. Knoll, G. Zhang, and J. Schwartz, "Experimental and numerical studies of the effect of phase difference between transport current and perpendicular applied magnetic field on total ac loss in Ag-sheathed $(\mathrm{Bi,Pb})_2\mathrm{Sr}_2\mathrm{Ca}_2\mathrm{Cu}_3\mathrm{O}_x$ tape," *J. Appl. Phys.*, vol. 98, pp. 1–6, 2005.

[15] R. C. Duckworth, M. J. Gouge, J. W. Lue, C. L. H. Thieme, and D. T. Verebelyi, "Substrate and stabilization effects on the transport AC losses in YBCO coated conductors," *IEEE Trans. Appl. Supercond.*, vol. 15, pp. 1583–1586, 2005.

[16] X. Wang, A. R. Caruso, M. Breschi, G. Zhang, U. P. Trociewitz, H. W. Weijers, and J. Schwartz, "Normal zone initiation and propagation in Y-Ba-Cu-O coated conductors with Cu stabilizer," *IEEE Trans. Appl. Supercond.*, vol. 15, pp. 2586–2589, 2005.

[17] G. M. Zhang, D. C. Knoll, D. N. Nguyen, P. V. P. S. S. Sastry, U. P. Trociewitz, X. Wang, and J. Schwartz, "Temperature dependence of critical currents and AC losses in $(\mathrm{Bi,Pb})_2\mathrm{Sr}_2\mathrm{Ca}_2\mathrm{Cu}_3\mathrm{O}_x$ and $\mathrm{YBa}_2\mathrm{Cu}_3\mathrm{O}_x$ tapes," unpublished.

[18] R. C. Duckworth, J. W. Lue, D. F. Lee, R. Grabovickic, and M. J. Gouge, "The role of nickel substrates in the quench dynamics of silver coated YBCO tapes," *IEEE Trans. Appl. Supercond.*, vol. 13, pp. 1768–1771, 2003.

[19] H. M. Kim, J. Jankowski, H. Lee, J. Bascunan, S. Fleshler, and Y. Iwasa, "Stability of bare and copper-laminated YBCO samples: Experimental and simulation results," *IEEE Trans. Appl. Supercond.*, vol. 14, pp. 1290–1293, 2004.