

A Tear-Drop Bifilar Sample Holder for Full Excitation and Stability Studies of HTS Cables at 4.2 K Using a Superconducting Transformer

C. Kovacs, M. D. Sumption, E. Barzi, A. V. Zlobin, and M. Majoros

Abstract—HTS cables proposed for next-generation main, hybrid, and insert magnets will have very high I_c (>10 kA) at 14 T and above. Determining the quench, current-sharing, and other properties of these cables will require measurement systems which will likely incorporate a superconducting transformer (SCT). The utilization of high-field persistent mode solenoids will make size and cost less prohibitive, allowing a higher frequency of measurements within a larger number of research facilities. Additionally, a system designed for use with solenoids will allow for experiments at higher maximum fields than that achievable using dipoles and split coils. Proposed in this document is a bifilar sample probe which fits within a 77 mm bore solenoid capable of measuring up to 6 mm outer diameter conductor-on-round-core (CORC) REBCO cables or wires up to 20 kA in transverse fields at 12 T and 4.2 K. Splices and mechanical considerations will be discussed.

Index Terms—High Temperature Superconductor, HTS cables, REBCO, Conductor on Round Core, Superconducting Transformer, Stability, Current-Sharing.

I. INTRODUCTION

HIGH ENERGY physics, high luminosity physics, and user facilities are demanding higher field persistent magnets for exploring new realms in particle physics, material-science, and medical research. These high fields will preclude the use of low-temperature superconductor (LTS) options and to reach persistent magnets above 20 T only two conductors are currently mature, Bismuth Strontium Calcium Copper Oxide (BSCCO) 2212 wires and tapes and Rare Earth Barium Copper Oxide (REBCO) coated conductors [1]. Both of these Cuprate multi-perovskite high temperature superconductor (HTS) options have a very high upper critical

field (B_{C2}) above 100 T and HTS cables have engineering current densities which may reach J_c (10 T, 4.2 K) greater than 800 A/mm² [2]. HTS conductors are ideal for inserts in hybrid LTS/HTS magnets, the HTS insert taking advantage of a high B_{C2} in the high field region.

Knowledge of material properties such as critical current density (J_c), irreversibility field, minimum quench energy, minimum quench power, interconductor contact resistance (ICR), and normal-zone propagation velocity is critical for magnet design. These properties are highly dependent on the structure and processing of HTS cables, and cannot always be approximated with data from single conductors because of differences in self fields, strains, damage induced by processing, and thermal and current sharing. Different cable designs have already been constructed using HTS conductors [3], but with very high critical currents, I_c , accompanied with a high B_{C2} make it difficult to experimentally determine the aforementioned cable properties at conditions relevant for high field applications.

It is possible to circumvent cable testing and measure sub-scale coils to qualify cable properties and magnet performance, but these experiments: 1) use longer conductor lengths and more cryogenics; 2) limit instrumentation and sample preparation options; 3) have higher stored energies, increasing the risk of conductor damage during quench studies; 4) introduce additional variables in a material system that is already hard to quantify. Additionally, when a sub-scale magnet experiment fails, it is at a larger cost.

The main demands of measuring these HTS cables are: 1) low resistance terminals; 2) mechanical support against large Lorentz forces; 3) limited sample space in compact high field magnet bores; 4) maximum injectable sample current. Some cable testing facilities that have the capability to measure HTS cables fully excited and at high fields (> 10 T) are listed below.

A. EDIPO/SULTAN, Paul Scherrer Institute

A 100 kA superconducting transformer (SCT) is able to examine large cross section cable in conduit conductors (CICC) within a long length homogenous field region of 400 mm with applied fields of 10.8 T (SULTAN) and *initially* 12.5 T (EDIPO). The samples are typically straight “hair-pin”

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bifilar samples and the magnets are split-coil (SULTAN) and dipole (EDIPO) [4].

B. Facility for the Acceptance tests of Superconducting Cables, FRESCA and FRESCA II, CERN

The Fresca I facility houses a 10 T dipole and a 32 kA DC power supply or a 40 kA SCT. FRESCA II has a higher field dipole, up to 13.3 T and is in line to receive HTS insert magnets. Both FRESCA and FRESCA II can measure over long sample homogenous field lengths of about 600 mm and typically examine straight “hair-pin” bifilar samples [5,6].

C. High Current Superconductivity Lab, University of Twente

The University of Twente has multiple probes for measuring fully excited cables under applied fields, stresses, and strains. Conductor on round core, CORC, HTS wires have been measured using a 40 kA superconducting transformer and 10.5 T solenoid with the sample spiral wound onto the holder [7]. Previous measurements have used a U-shape holder for measuring Roebel HTS cables [8].

D. Advanced Conductor Technologies, University of Colorado

CORC cable and wires have been spiral wound onto a holder and measured using a 16.5 kA DC power supply and 12 T solenoid [9].

E. Applied Superconductivity Center, NHMFL Florida State University

There are many magnets to choose from, but two that have been used are a 200 mm bore resistive magnet solenoid capable of 20 T and a 12 T split magnet with a 150 mm vertical bore and 30 mm x 70 mm access port. Sample current is injected using a 20 kA DC power supply [10,11]. The 20 T resistive magnet has since been disassembled and components used for the 32 mm bore 41.5 T resistive solenoid.

F. FBI facility, Karlsruhe Institute of Technology

A 12 T split coil can handle straight samples through a 80 mm x 40 mm cross section. The sample has a homogenous field length of 70 mm. Sample current is injected using a 10 kA DC power supply [12].

G. Applied Physics and Superconducting Technology Division, Fermilab.

The Teslatron II, 14 T at 4.2 K and 16 T at 1.9 K solenoid with a 77 mm bore, can measure samples up to ~30 kA using a SCT [13]. One of the sample holders previously used at Fermilab for measuring LTS Rutherford cables with this system is a spiral bifilar; this design maximizes sample length within the solenoid and reduces large integrated body loads on the sample holder due to Lorentz forces. The local Lorentz forces on this sample holder do require an outer Al tube to confine the sample into a channel.

There are two possible sample configurations within the bifilar spiral sample holder, stacked or neighboring. In the case of larger diameter round cables and wires, the stacked

configuration would introduce a much greater length differential and reduced inner radius. The length differential is due to the inner spiral having a smaller bending radius; this differential is important to consider because it would produce hundreds of Newtons per Centimeter forces. In the case of a neighboring configuration, only one leg of the bifilar sample would be pressing into the sample holder due to applied fields, introducing larger forces that need to be handled by an outer structure.

H. Proposed: Tear-Drop Bifilar Sample Holder, Fermilab

There currently does not exist a non-solenoid superconducting magnet capable of measurements at fields greater than 15 T, those relevant for next-generation magnets. A cable sample holder which accommodates transverse field measurements in a solenoid bore is desired because solenoids are capable of delivering the highest fields of different magnet designs due to reduced maximum field and mechanical forces on the winding. The scope of this design is creating a measurement facility capable of measuring properties of fully-excited cables with I_c greater than 20 kA under relevant magnetic fields expected in next generation high-field accelerator magnets.

II. EXPERIMENTAL DESIGN

The principle behind a tear-drop shape bifilar sample holder is a measurement capability within a high field superconducting solenoid with the largest bending radius of the sample achievable. By maximizing bending radius for a given sample, experiments at the maximum fields and minimum risk of sample degradation are possible.

The tear-drop shaped sample holder proposed accommodates the Fermilab 30 kA SCT and Teslatron II measurement station. The samples which will be measured initially are CORC wires with properties shown in Table I and described in [2,14]. Also shown is the I_c of these samples assuming they were assembled with newer thick-film coated conductors [15].

TABLE I
CORC SAMPLE PROPERTIES

	CORC S1	CORC S2
Wire diameter with core (mm)	3.09	3.63
Diameter of Cu core (mm)	2.34	2.56
Number of Tapes (#)	16	29
Tape width (mm)	2	2
Cu thickness (μm)	5	5
Substrate thickness (μm)	30	30
Cross sectional area (mm^2)	7.5	10.35
Percentage of Cu Area (%)	62	55
Twist pitch (mm)	<10 mm	<10 mm
I_c at 77 K, $E_c = 1 \mu\text{V}/\text{cm}$ (A)	748	1659
I_c at 4.2 K and 10 T (A)	~1250	3970
I_c at 4.2 K and 10 T expected with thick-film tapes (A)	~4800	~8700

CORC wires have already been measured by forming over a 30 mm bending radius [2] and have had terminals of varying design [14,16,17]. Coefficient of thermal expansion (*CTE*) matched epoxy impregnation will be required for high field, high I_c measurements [2,18,19]. Epoxy impregnation will occur after the sample is mounted, and the terminals are soldered, in a separate epoxy mold fixture.

Because future HTS samples may have larger dimensions and higher I_c , COMSOL Multiphysics 5.3.0.223 simulations examined a 5 mm diameter sample with I_c of 20 kA at 12 T. The design of the tear-drop bifilar sample holder is shown in Fig. 1 with components incrementally removed for easier viewing. Additionally, the epoxy and stainless steel jacket are transparent and hidden respectively in the Fig. 1 to view the CORC bifilar sample.

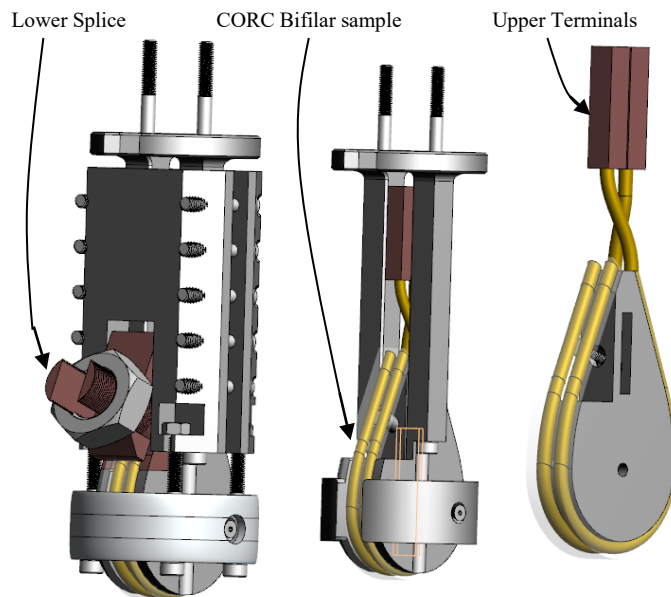


Fig. 1. Tear-drop shaped bifilar sample holder for use with Fermilab's SCT. From left to right is the sample holder with incrementally removed components to make viewing more accessible. The lower terminal will be trimmed down after soldering, removing the compression hexagonal nut from the split-bolt splice. The stainless steel jacket is hidden and the epoxy is transparent in this figure.

A. Simulations of Splices and Terminals for CORC wire

Due to a low inductance, high ICR , and low ramp-rate during measurements and operation the current distribution in CORC cables is mostly determined by inhomogeneity in contact resistances at the point of current injection within terminals [16]. Due to the high resistance of the Hastelloy substrates and ceramic buffer layers, and particularly thin Cu stabilizer of these samples, it will be important to keep the REBCO layered side in close contact with high residual resistivity ratio (RRR) Cu and/or solder to minimize terminal resistances. The total secondary-sample loop resistance for the SCT measurement system should be kept below 2 nOhm to allow stable current measurements at high currents for approximately a minute [20]. For all simulations the CORC conductor was considered a homogenous material with

mechanical properties similar to Copper and very low electrical resistivity ($1 \text{ f}\Omega\cdot\text{cm}$).

The lower bifilar splice terminal proposed in this design is a “praying-hands” joint within a split-bolt splice (SBS) with a “trimmed CORC and staged casing” (TCSC) [17]; the upper terminals are both rectangular prism TCSC terminals. Due to magnetoresistance degradation in Cu conductivity, in the “Electric Currents” and “Heat Transfer in Solids” coupled Multiphysics simulations for splices it was assumed that the final RRR (4.2/273 K) of the Cu was 20 [21]. Both the lower and upper terminals are shown in Fig. 2 and Fig. 3 respectively. Solder interfaces were 0.2 mm thick and the solder at 4.2 K was assumed to have 1/3 of the resistance of Cu at room temperature. The initial temperature was 4.2 K and all external surfaces were fixed at 4.2 K. The mesh size for the splice simulations was 4.5 mm to 0.1 mm with a maximum growth rate of 1.35 and curvature factor of 0.4.

The resistance of all of the splices in the secondary sample estimated from simulations was 13 n Ω , too high at the moment and improvement of the splices is required. Both of these terminals are at least three twist pitches long, allowing room for the trimmed CORC region and homogenous current injection.

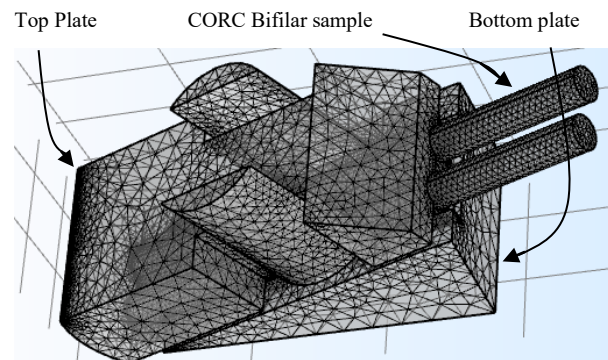


Fig. 2. Lower SBS “praying-hands” bifilar splice joint with two TCSC internal terminals. This terminal will be bolted to the sample holder. Shown is the top plate which is compressed into the bottom plate with a bolt during soldering. Also shown is two CORC wires exiting the SBS at the bottom right.

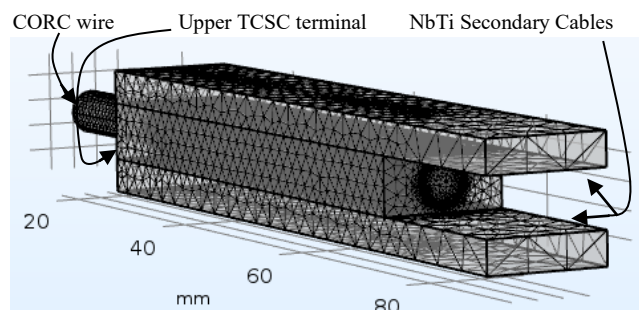


Fig. 3. One of the upper TCSC terminals from the CORC sample to Rutherford cable secondary. Two ~ 10 mm width NbTi Rutherford cables will be used to handle the high currents required in the compact volume below the SCT and above the high field region. The CORC sample is shown entering the TCSC terminal from the left and the Rutherford cables extend from the TCSC sides on the right.

B. Simulations of Tear-Drop Bifilar Sample Holder

For determining local stresses and strains due to Lorentz forces, the Multiphysics simulation coupled “Electric Currents”, “Magnetic Fields”, and “Solid Mechanics” in the elastic regime. The inner most surface in Fig. 4, those surfaces bonded to the bulk stainless steel inner tear drop shape shown in Fig. 3, were fixed in position. The mesh for this simulation was 140 mm to 0.2 mm, growth rate 1.7, and curvature factor of 0.4. The maximum mesh size was large because the simulation was bounded by an outer physical solenoid to generate the magnetic field.

The innermost minimum bending radius is 32.5 mm for a 5 mm diameter CORC sample. Due to a bifilar sample, the total expected body load from simulations was only 40 N. While it is true that hair-pin bifilar samples measured in dipoles and split-coils are able to have similar total body loads, it is more difficult to achieve total body load cancelation within a solenoid. As a comparison, if the tear-drop bifilar holder sample was in a stacked configuration, a significant improvement over a simple U-shape non-bifilar, a total body load over 1000 N would be pressing the sample holder into the magnet. Similar loads would be expected for non-bifilar spiral shaped samples measured in solenoids, due to the requirement of an axial asymmetric high current carrying return path bend perpendicular to the magnetic field in the high field region. If the spiral holder extends outside of the high-field region, preventing the bend return path from causing large body loads, then a similarly large and more complicated load will be introduced from the transverse stray field components from the solenoid on the spiral.

After initial simulations, it was found that local strains experienced in the sample epoxy composite for a sample current of 20 kA at 12 T applied field would greatly exceed the maximum tensile strains capable of a CTE matched epoxy. If cracks develop in the epoxy, it is likely the sample would be degraded or destroyed and the magnet system may become damaged. Because of these reasons, a 1 mm thick stainless steel jacket was required to reduce tensile stresses on the epoxy by keeping materials in the jacket in compression. The sample without and with a stainless steel jacket is shown in Fig. 4. This jacket would be added after instrumentation and epoxy impregnation and the thin conformed jacket would be bonded to the stainless steel sample holder using a Techsonic (Columbus, Ohio) US-935S servo ultrasonic spot welding system. This metal bonding technique can quickly create strong lap joint bonds with minimal heat generation in an open atmosphere [22].

As expected, for 20 kA the self-field contributes strongly to the total field of the bifilar sample; at the bottom of the tear-drop is a ± 1 T range change in the magnetic field magnitude, see Fig. 5. However, due to a 2.5 mm gap between the bifilar sample legs, the maximum field reduction located between the legs is about 0.5 T and the maximum field increase on the outer faces of the bifilar sample is about 0.2 T.

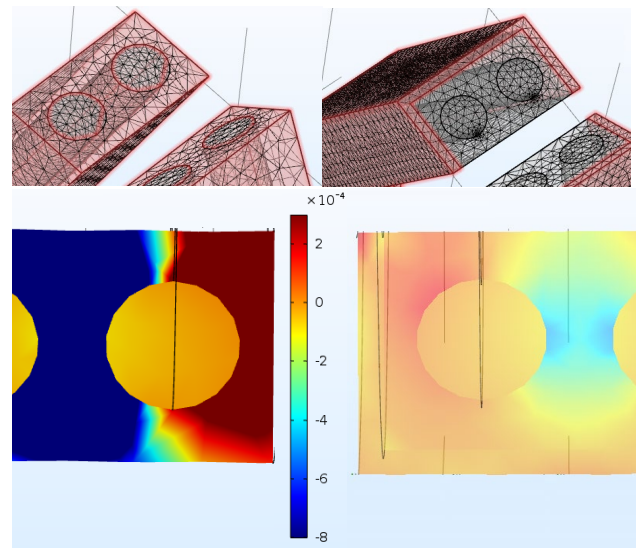


Fig. 4. CTE matched epoxy impregnated CORC bifilar sample with (top right) and without (top left) a 1 mm thick stainless steel jacket. Volumetric strain of sample at bottom of tear-drop for 20 kA and 12 T applied magnetic field for sample with (bottom right) and without (bottom left) jacket. Volumetric strain color scale is 3 to -8×10^{-3} .

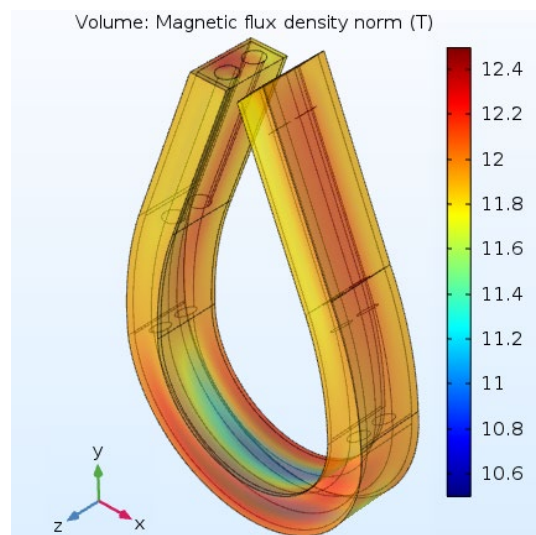


Fig. 5. Magnetic field magnitude of 5 mm diameter CORC bifilar sample at 20 kA and 12 T. There is a 2.5 mm gap between the legs.

CONCLUSIONS

A new bifilar sample holder has been designed in the Multiphysics platform COMSOL. In a bifilar sample arrangement it was possible to reduce total integrated body loads on the sample to only 40 N. Due to very large local tensile stresses in the epoxy impregnated sample, a stainless steel jacket was introduced to keep the epoxy-sample composite under compression. This sample holder has been designed for use with a Fermilab 30 kA superconducting transformer and high field solenoid. This sample holder will allow high critical current, high temperature superconducting cable measurements under controlled magnet relevant conditions.

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