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Preliminary research on Soldered Stack ReBCO Cable

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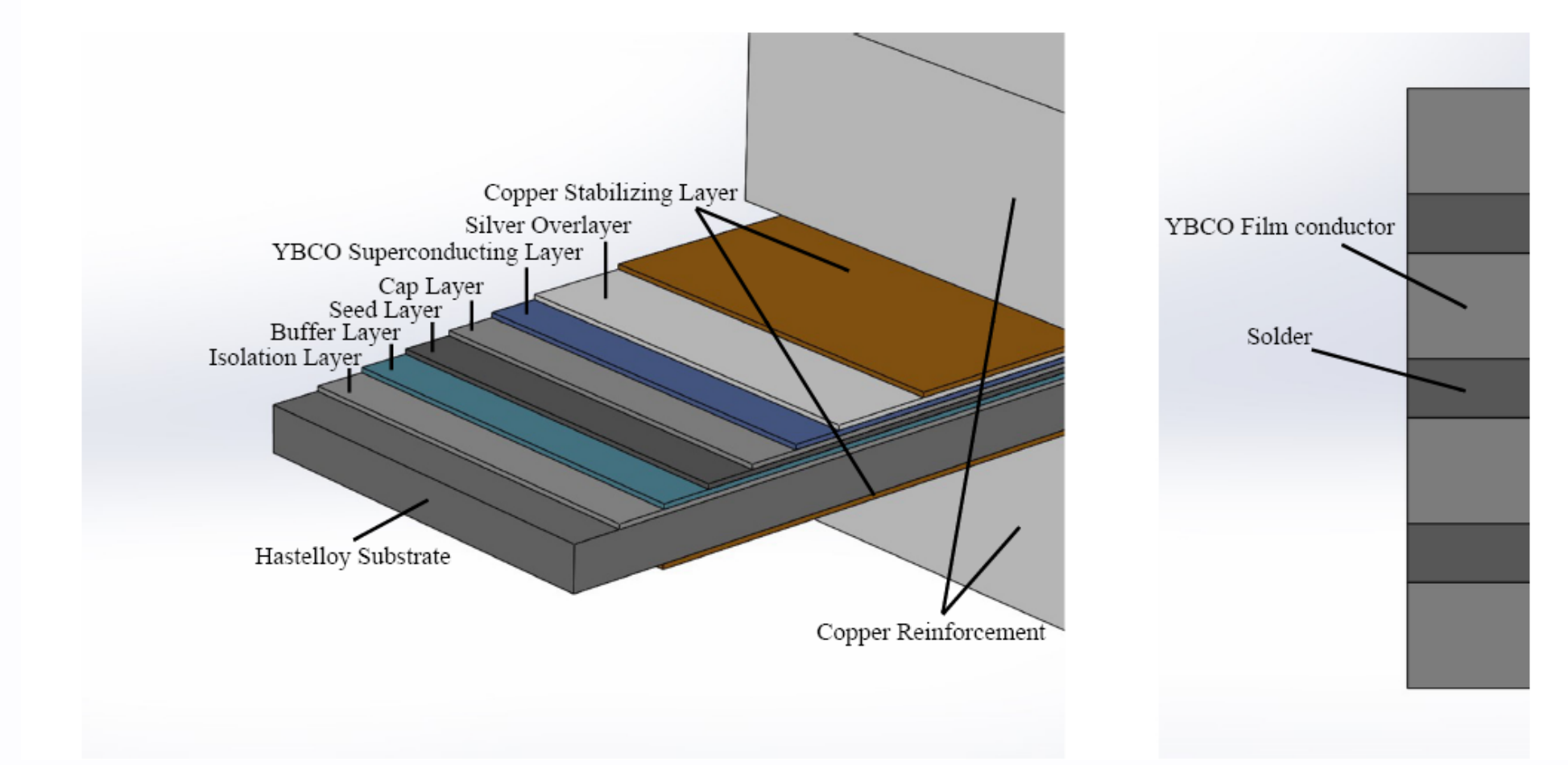
Introduction

ReBCO is the second generation of high temperature superconducting (HTS) materials with potential for high-field applications and low mass quality applications. The fabrication process and performance of superconducting cables are a key issue for superconducting magnets operating at high-field or large sizes. This study describes a process of a soldered stacked conductor using a 4 mm wide ReBCO tape with copper stabilizing layer. The development of this kind of conductor is the preliminary research for more complicated cable modus, such as twisted stacked conductors and aluminum stabilized superconducting cables. The electrical of the ReBCO soldered stacked conductor samples, including critical current were tested and discussed. In the future work, the development route of aluminum-stablized superconducting cables for large-aperture magnet applications is stated.



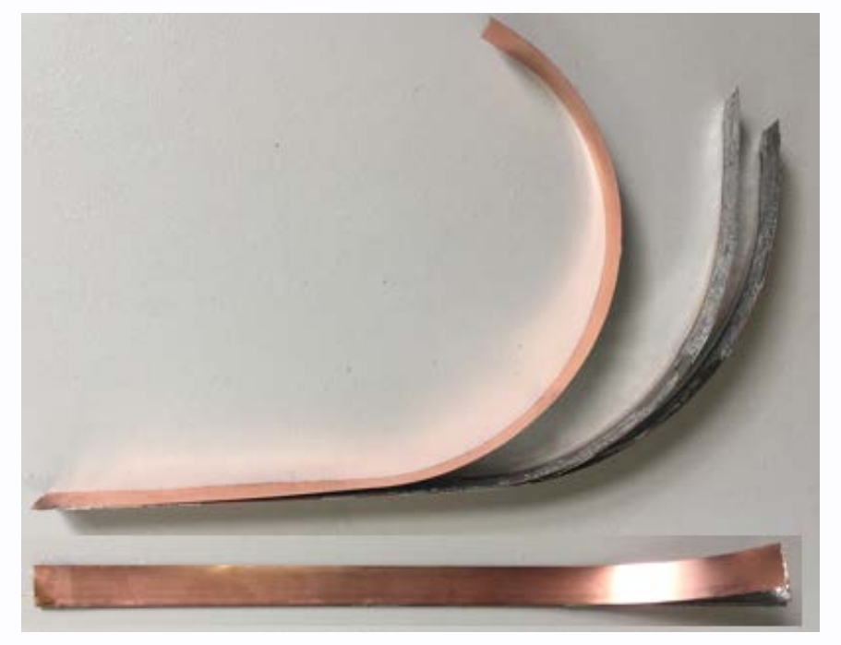
Stack and HTS Cable

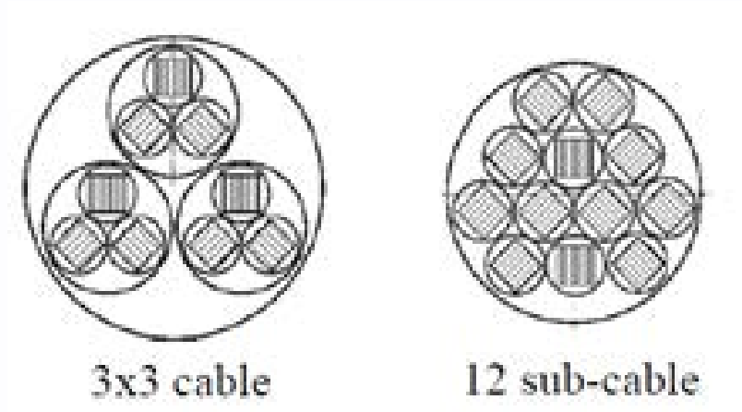
ReBCO materials are used in a variety of different high temperature superconducting applications. Solder stacked conductors can be used to pursue high current applications while effectively reducing AC loss, simplifying processing flow, and improving conductor stability. Some soldering or non-soldering methods for stacking, twisting, and assembling HTS tapes are developed: rebel cable, 3S wire, TSTC cable, etc. The fabrication and test results of a YBCO soldered stacked conductor are described to achieving lower heat leakage current lead applications, or as a basic component of a more complex form of HTS cable. The critical current and n-value of the YBCO soldered stacked conductor were tested at 77K, self-field, and compared with the self-field simulation results and the test results of single YBCO film conductor under magnetic field to discuss the influence of different factors on the conductor performance. For the purpose of current lead application, the thermal conductivity of YBCO soldered stacked conductors at 4K was tested by experimental platform based on GM cryocooler to discuss the thermal load of such conductors.

Twisted stacked Tape by MIT

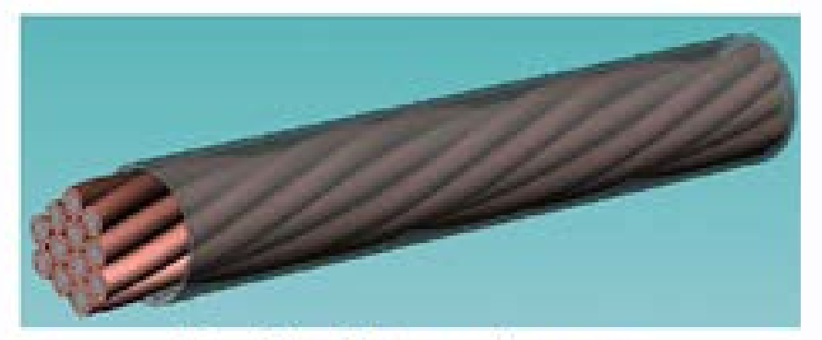
CORC® by ACT

Roebel cable by KIT





3x3 cable 12 sub-cable



12 sub-cable conductor

Fabrication of YBCO soldered stacked conductor

The fabrication of YBCO soldered stacked conductors is a vacuum soldering process. The formation of oxides between layers and the thickness of the conductors are minimized by using a vacuum furnace and solder containing no flux such as rosin. We use high temperature resistant silicone rubber cushions to give proper pressure on the material surface to ensure the flatness and consistency of the conductor.

We tried three common solders, including Sn63Pb37, SnAgCu, and Sn42Bi58. We found that Sn42Bi58 has poor solderability in the absence of flux, and the other two kinds solder have better performance. The electrical properties test is based on the Sn63Pb37 soldered samples. We also used a 10mm wide film conductor to prepare a sample for more convenient measurement of the thermal conductivity.

Table 1. Specifications of YBCO film conductors with copper stabilizing layer provided by SSTC

Item	Unit	Value
Width	mm	4
Entire thickness	μm	65
Thickness of copper stabilizing layer	μm	6
Average critical current @77K	A	150
Unevenness of critical current	%	±15

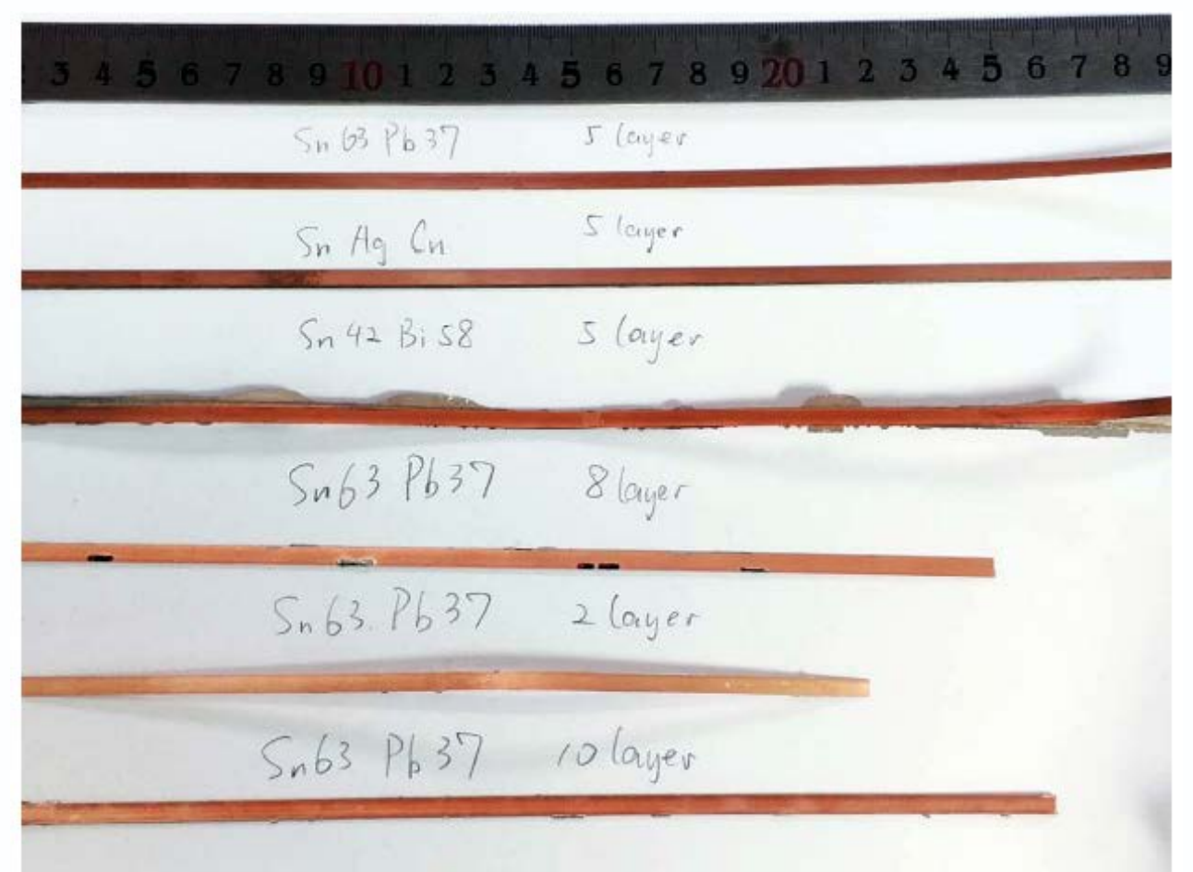


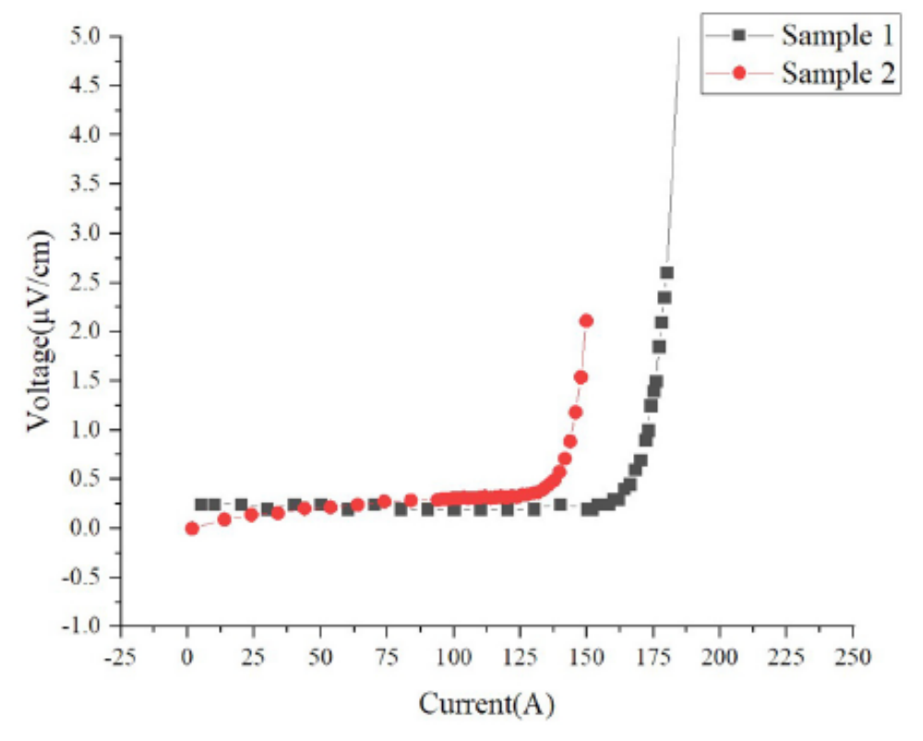
Table 2. Thickness of YBCO soldered stacked conductor samples

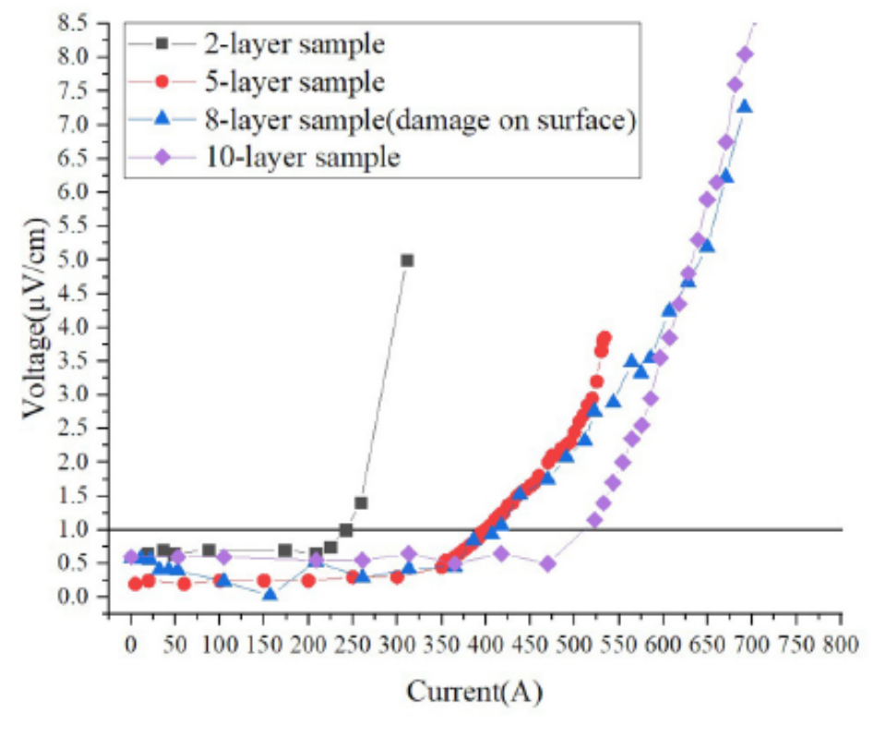
Solder	Layer	Average(μm)	Maximum(μm)	Minimum(μm)
Sn63Pb37	5	377.4	395	359
SnAgCu	5	754.4	781	720
Sn42Bi58	5	340.8	366	332
Sn63Pb37	2	131.8	135	130
Sn63Pb37	8	610.6	642	549
Sn63Pb37	10	699.8	731	675

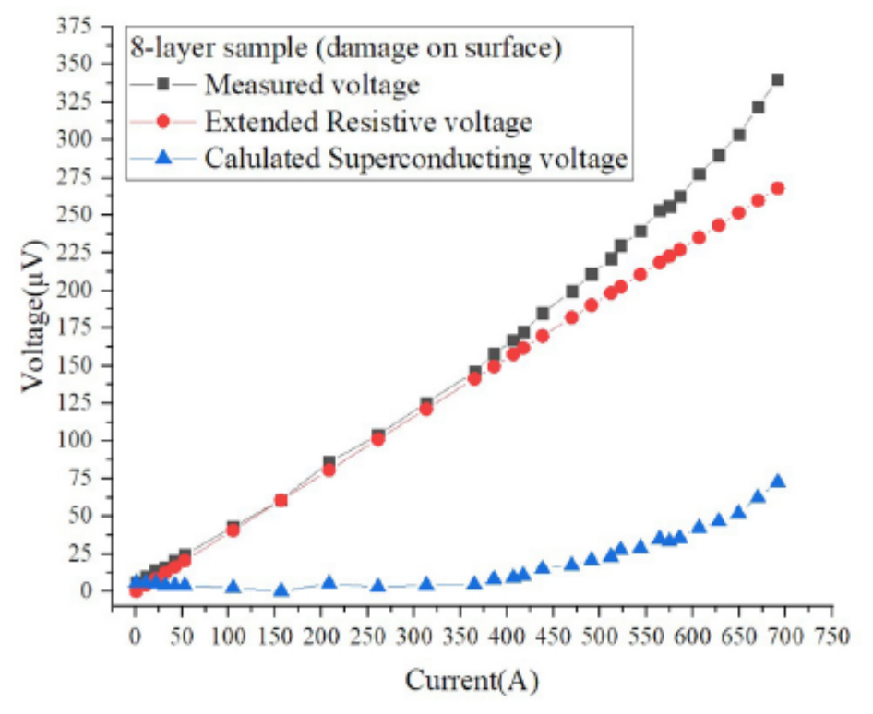
Electrical properties test and discussion

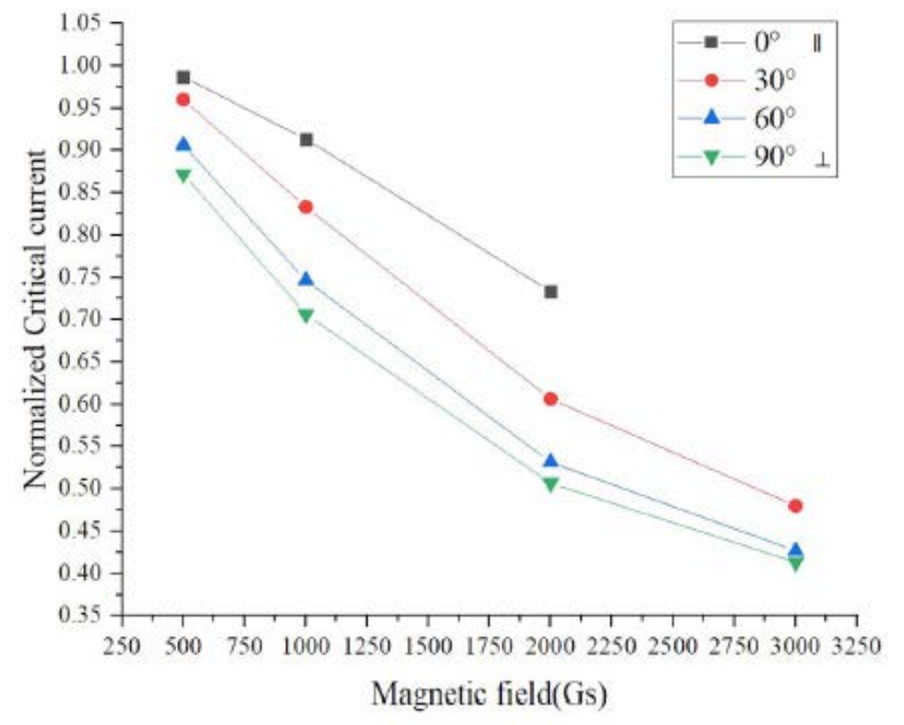
From the test results of these four samples, it can be found that the n-value of the YBCO soldered stacked conductor is lower than that of the single film conductor, which makes the quenching process of the conductor slower, that is, the conductor has better stability. Including the 8-layer sample with damage, showed resistivity at the beginning of the test, but still operate a high current steadily. This is due to the solder between the layers acts as a stabilizer and ensures a more uniform current distribution. A low n-value means that the conductor still has a relatively stable performance when it exceeds the critical current. The critical current of each layer in the YBCO soldered stacked conductor is reduced compared to the critical current of a single film conductor. In the samples of 2, 5 and 10 layers, the critical current of each layer is equivalent to 81.7%, 53.5%, 38.3% of the single film conductor. The degradation after fabrication is obvious, and we consider that the main reason of this degradation is the influence of self-field.

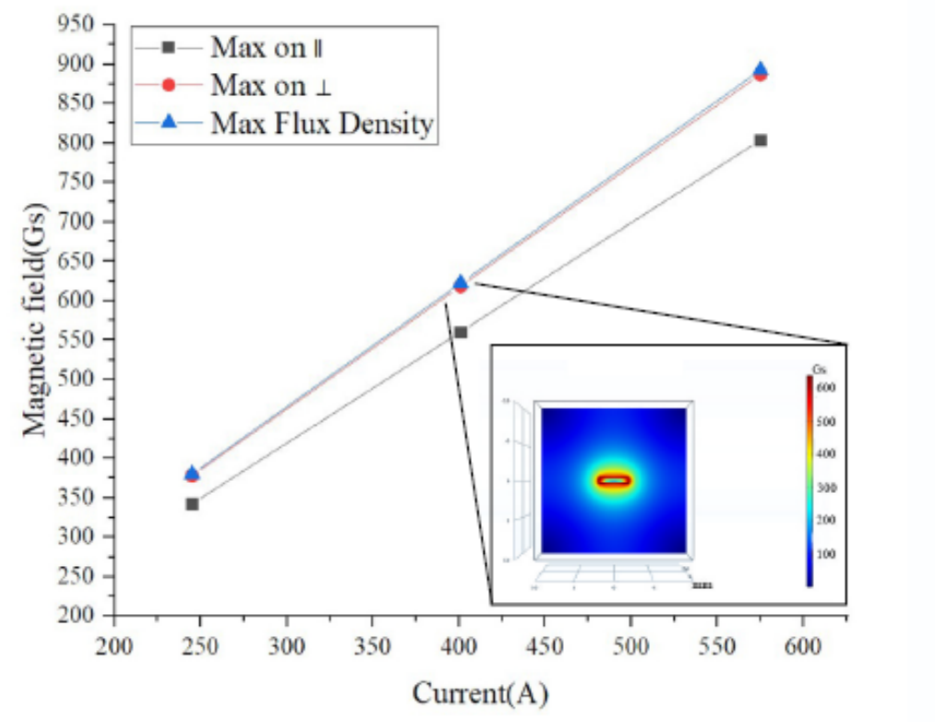
The superconductor is most sensitive to the magnetic field in the vertical direction. Under the vertical field of 3000 Gs, the normalized critical current is 0.41. The self-field of YBCO soldered stacked conductors under different currents is calculated by finite element method. For example, when a conductor operates a 401A current, which represents the critical current of a 5-layer YBCO soldered stacked conductor, the maximum value of the self-field on the cross section is 620.86 Gs, and the maximum value of the vertical field is 617.06 Gs.
We have verified that a single film conductor has substantially no degradation in electrical performance after suffering a high temperature of about 200 ° C equivalent to the soldering process. Therefore, the influence of the fabrication on the conductor can be estimated to be small. Considering the effect on the conductor of a vertical magnetic field of equal strength, the normalized critical current of each layer of the 2, 5, and 10 layers YBCO soldered stacked conductors is 0.90, 0.83, 0.74, and the actual normalized current is 0.817, 0.535, 0.383. The direction of the self-field of the superconductor can be very complicated, and the strong self-field may have a greater influence on the performance of the superconductor than the magnetic field in a single direction.











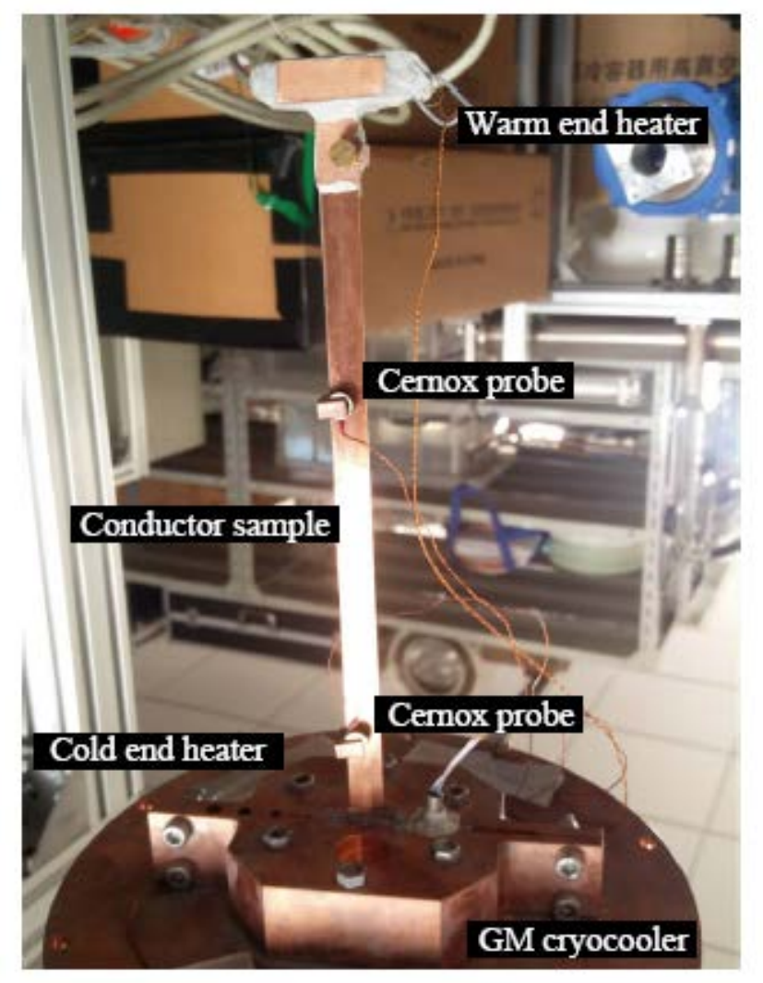
Thermal conductivity test at 4K

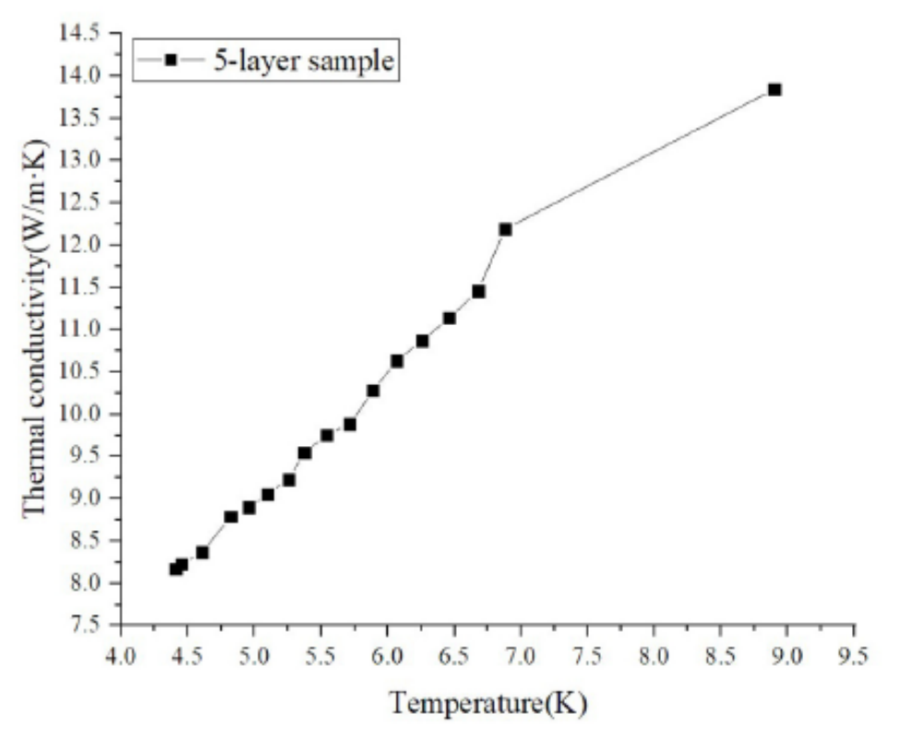
The purpose is for current lead applications, and the axial thermal conductivity of YBCO soldered stacked conductors is tested by experimental platform based on a GM cryocooler. Figure 8 shows the experiment. The measurement is based on the one-dimensional Fourier heat transfer law:

$$Q = \frac{\lambda \cdot A \cdot \Delta T}{l}$$

Two basic steps in the experiment:
A. Control the power of the aluminum oxide heater chip installed at the cold end. After a period, the system reaches thermal equilibrium and measure the background temperature difference due to structural leakage.
B. Control the power of the heater chip installed at the warm end. After a period, the system reaches the heat equilibrium again, and the test temperature difference and the corresponding heater chip power are measured.
In this way, the difference between the measured temperature difference and the natural temperature difference is the true temperature difference between the two test points generated by the power of the warm end heater. When the geometry of the sample is known, the thermal conductivity of the sample along the axial direction can be calculated. Figure 9 shows the thermal conductivity test results for this sample.
The measured thermal conductivity is 8.22 W/m·K @ 4.5K. According to the structure of the YBCO soldered stacked conductor, we fit the thermal conductivity of the sample from the test results:

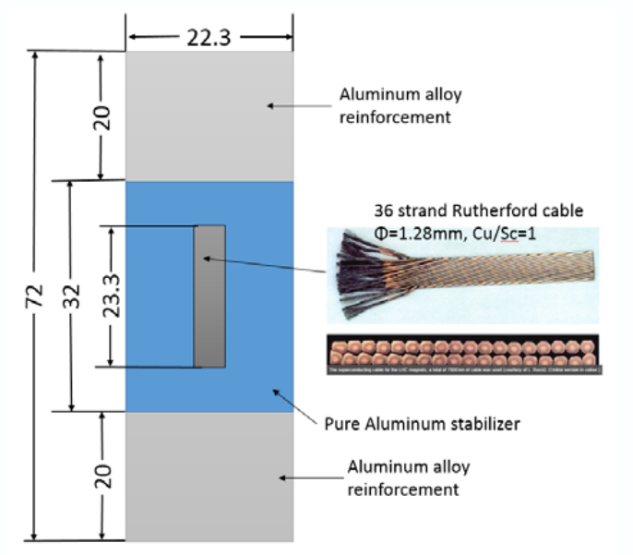
$$\lambda = 2.15142 + 1.38596T - 0.00213T^2$$

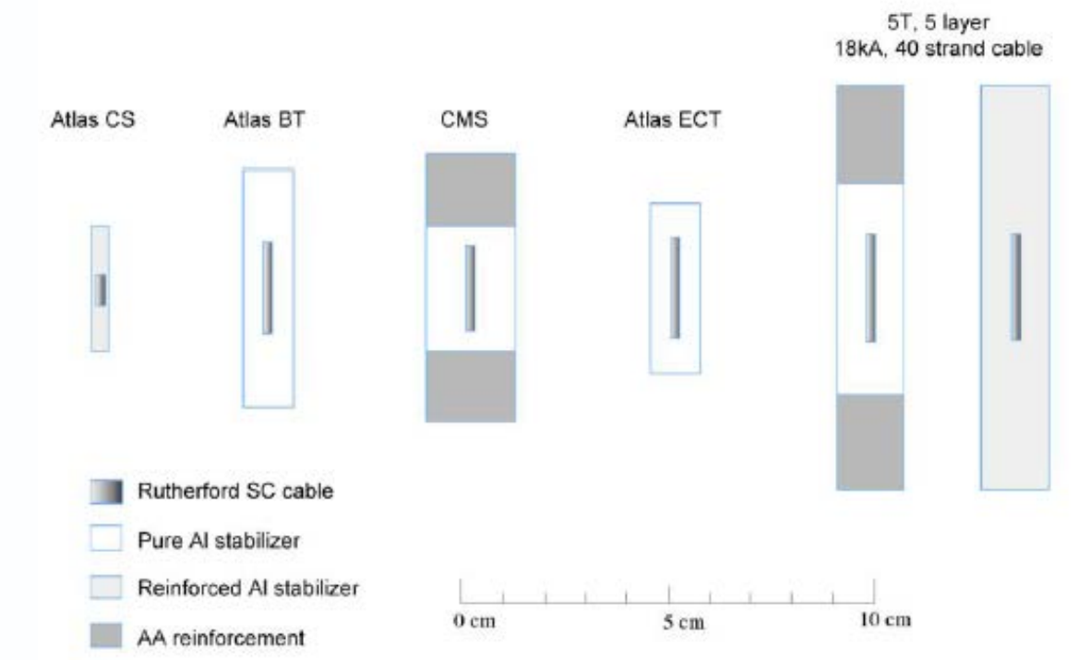


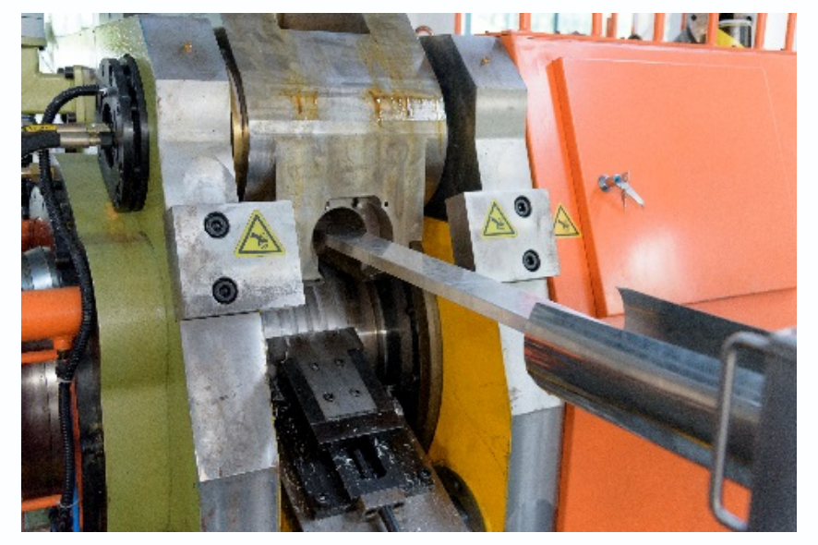


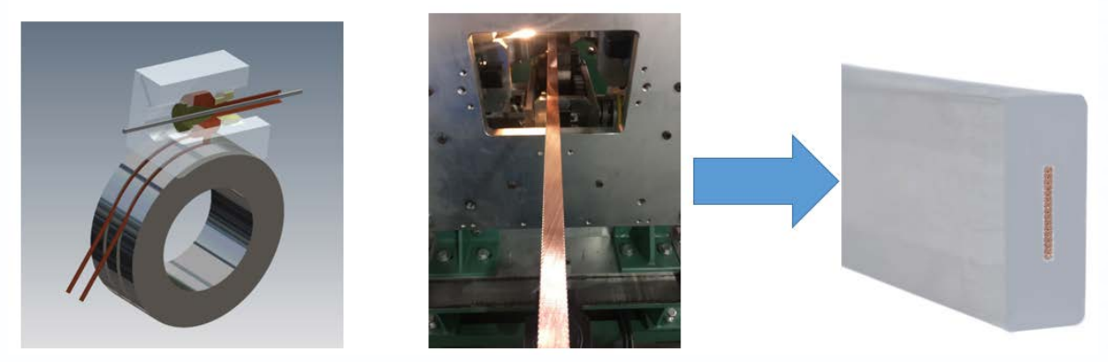
Future Research Towards Aluminum-stabilized HTS Cable

High temperature superconductivity is one of the important trends in the development of superconducting magnets. However, the immature cable form and processing technology restrict the application of high temperature superconducting materials on large magnets. The aluminum-stabilized Rutherford cable is the most widely used form of NbTi material on large detector magnets. Compared to NbTi materials, ReBCO materials have lower material quality, lower requirements for low temperature systems, and thinner coil sizes. Aluminum-stabilized high-temperature superconducting cables are still in the blank. The main functions of aluminum stabilizers are: quench shunting, self-supporting structure. Low temperature superconductors have large-aperture magnets using aluminum-stabilized cables, and no research has been done on high-temperature superconductivity.

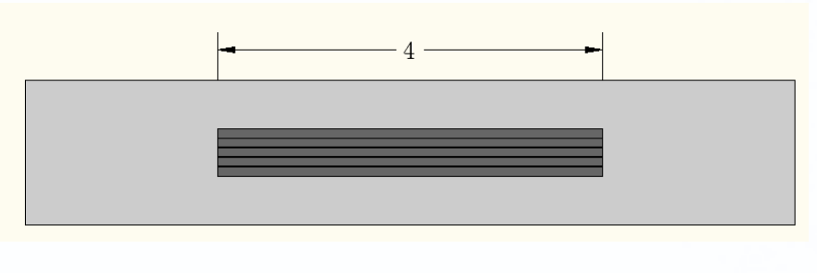


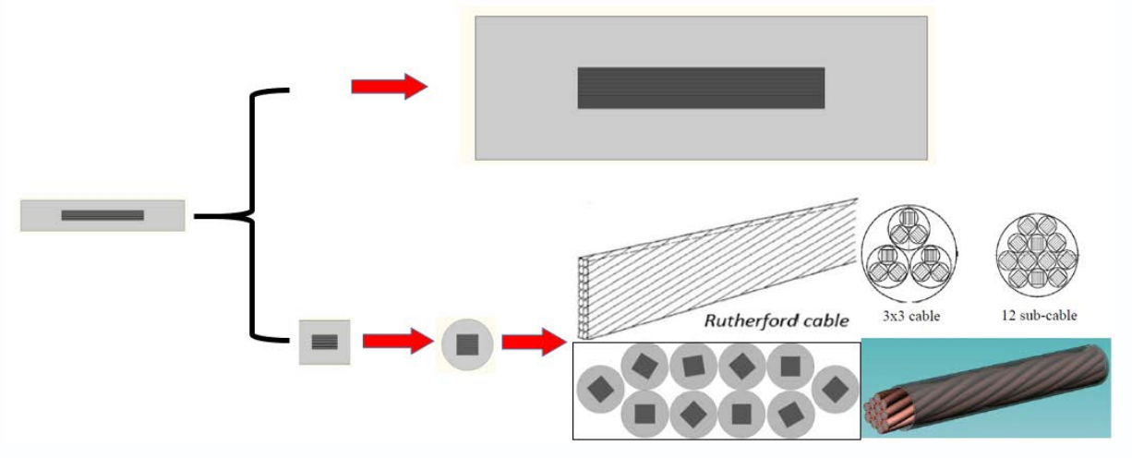


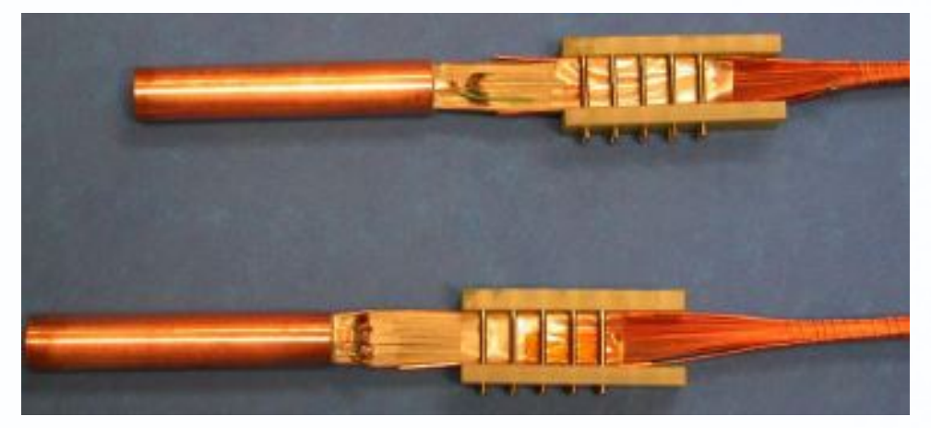




The future research goal is low-quality aluminum-stabilized HTS stacked cable, and provides an important reference for the development of large-scale HTS Stacked cable and the subsequent development of HTS Rutherford cable and CICC conductor. Through the research of this subject, it is hoped to obtain a 100-meter-long low-quality aluminum-stabilized HTS stacked cable, and with this cable to wind a coil module at a large inner diameter.







HTS Cable and Future Collider

Since the discovery of the Higgs particle, accurate measurement of it has become the main scientific goal of the next generation of colliders. IHEP, CAS proposed in September 2012 to build a Circular Electron Positron Collider (CEPC) and timely transform it into a Super Proton-proton Collider (SppC).

For the Innovative Detector for Electron-positron Accelerator (IDEA) part of the detector superconducting magnet, the inner diameter of the coil is 4 meters, the length is 6 meters, and the central magnetic field is 2T. Since the superconducting coil is inside the calorimeter, the quality requirements of the coil, the skeleton and cryogenic vessels are relatively high. Compared with the LTS solution, IHEP has proposed HTS scheme to replace the LTS Rutherford cable with a HTS stacked cable.