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Thermal Design and Test of 4kA Current Lead based on Stacked YBCO Conductor

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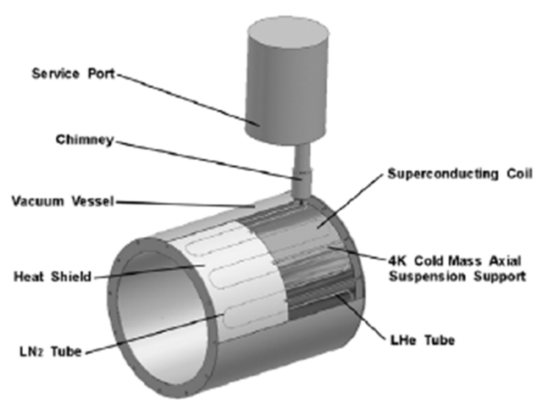
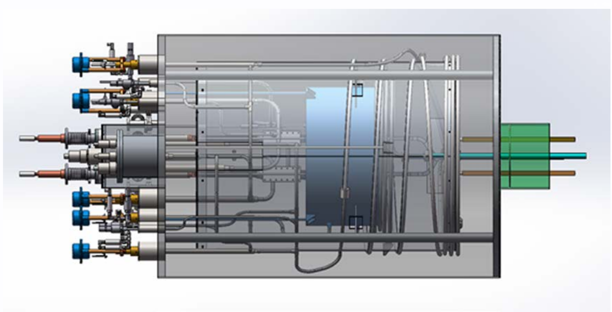
Introduction

For the Beijing Spectrometer III (BESIII) superconducting solenoid magnet (SSM) backup valve box upgrade project, two 4kA HTS current leads were designed, manufactured and tested. The baseline design of the current leads adopted a stacked YBCO conductor solution to achieve a lower thermal load at 4K, improve the stability of the magnet. Owing to the adoption of YBCO conductor, the heat leakage was effectively controlled. The joint component connected the LTS cable adopted a conduction-cooled design, which avoided complicated liquid helium piping and made the entire current lead structure simpler. The development of a novel soldered stacked YBCO conductor is also described. Their thermal conductivity and electrical properties tests, and experimental results of the entire current lead are discussed.



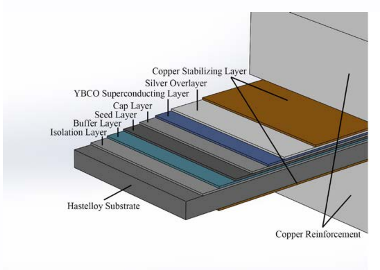


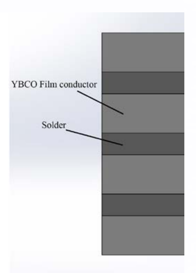
HTS Section Design

BSCCO materials for current lead application are typically packaged in a silver-gold package. Compared to YBCO film conductors, the thickness, cost and thermal conductivity of BSCCO materials are higher, resulting in greater low temperature thermal load and increased cost of use of BSCCO current leads. The entire HTS section consists nine 300 mm length soldered stacked YBCO conductors. Each of the stacked conductors was formed by 10 layers of YBCO film conductor using a vacuum soldering with SnPb6337 as solder. Soldered conductor has an average thickness of 0.72 mm. The conductors also require a second vacuum soldering with SnBi4258 as solder, fixed to stainless-steel shunt and copper support.

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

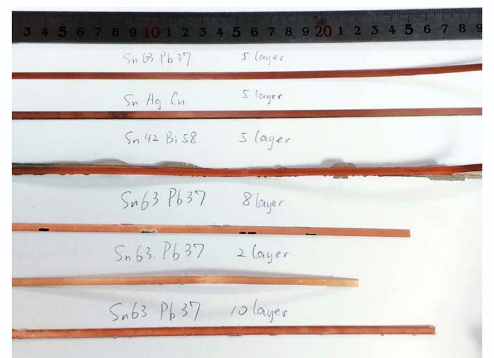


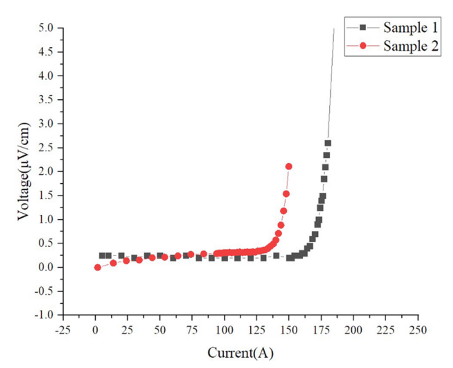


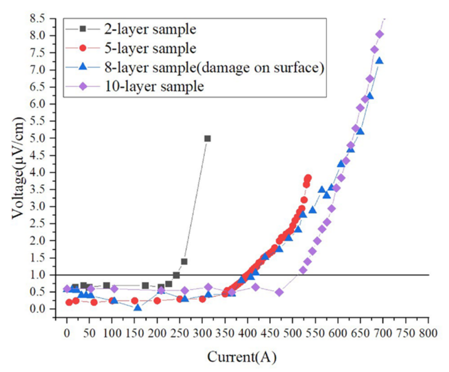
Test of Soldered Stacked YBCO Conductor

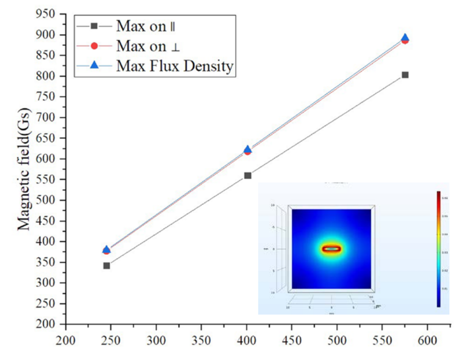
Electrical Properties:

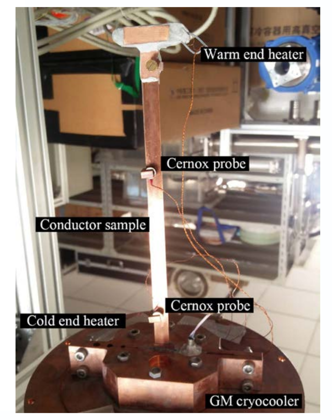
For the electrical properties test of stacked conductor, the four-lead method was applied. At liquid nitrogen temperature, 77K, we tested the stacked conductor samples prepared by SnPb6337 solder, the number of layers was 2, 5 and 10 respectively.

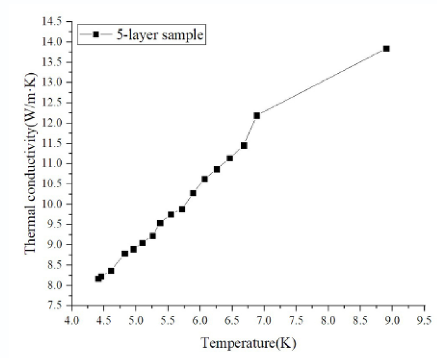












Thermal Conductivity:

The purpose is for current lead applications, the axial thermal conductivity of soldered stacked YBCO conductors is tested by experimental platform based on a GM cryocooler. Fig.5a shows the experiment. The measurement is based on the one-dimensional Fourier heat transfer law:

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

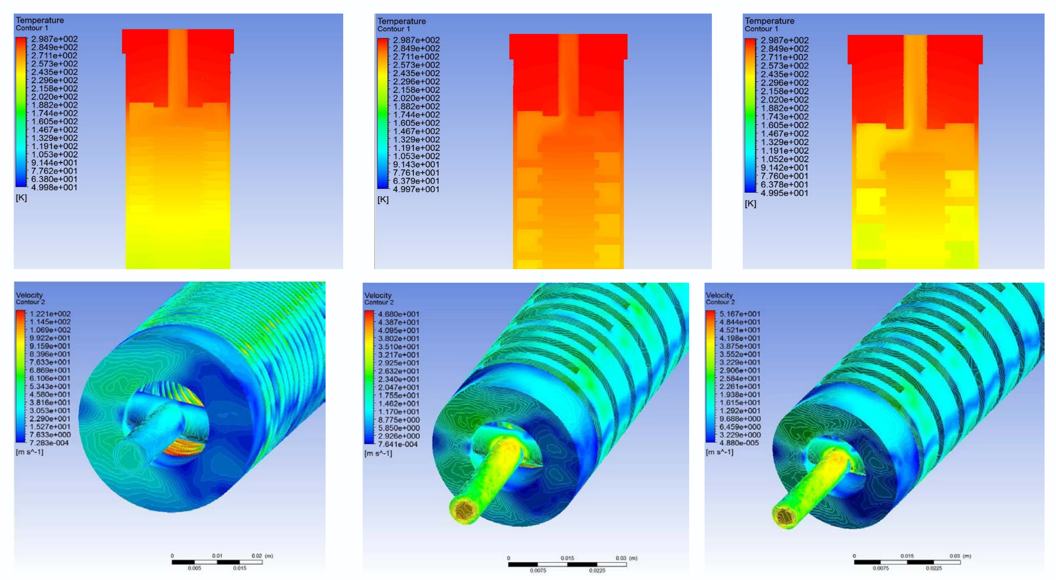
For general current lead designs, the HTS component operates in the 4K-77K temperature range and the resistive heat exchanger section is cooled by nitrogen or helium gas. The application of YBCO materials can significantly reduce the 4K thermal load of the current leads compared to BSCCO materials.

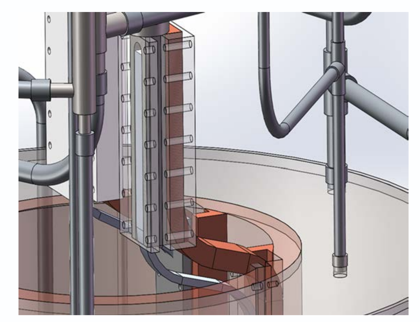
Fin Resistive Heat Exchanger Design

A multi-physics coupling finite element analysis is applied to compare two schemes, the 1 mm fin spacing and the 3 mm fin spacing, and to determine the reasonable range of current lead helium flow rate. The 1mm fin spacing scheme was abandoned since the helium pressure drop was too large to meet the requirements of the cryogenic system. For 3mm fin spacing scheme, when the helium flow rate is in the range of 0.28 g/s to 0.34 g/s, both the helium gas outlet temperature and the helium gas pressure drop are acceptable, which does not cause severe overcooling and meets the requirements of cryogenic system. At the same time, it is also ensured that the top surface temperature of the HTS section does not exceed the design reference temperature, that is, the liquid nitrogen temperature.

Results of FEM Analysis of Fin Resistive Heat Exchanger

Schemes	1mm Fin Spacing	3mm Fin Spacing	3mm Fin Spacing
Helium Flow Rate	0.2876g/s	0.2876g/s	0.3355g/s
HEX Bottom Temp	63.28K	75.02K	66.82K
HTS Top Temp	61.75K	71.63K	64.51K
Helium Outlet Temp	281.1K	286.6K	270.7K
Helium Heat Absorption	345.61W	353.84W	385.03W
Joule Heat	228.83W	283.17W	221.61W
Average Temp of HEX	136.18K	160.79K	135.12K
Inlet Velocity	6m/s	6m/s	7m/s
Outlet Velocity	33.37m/s	33.99m/s	37.41m/s
Outlet Temp	281.1K	286.6K	270.7K
Max Velocity	122.1m/s	46.8m/s	51.67m/s
Pressure Drop	184076.85Pa(1.84bar)	6601.69Pa(0.07bar)	7126.57Pa(0.07bar)



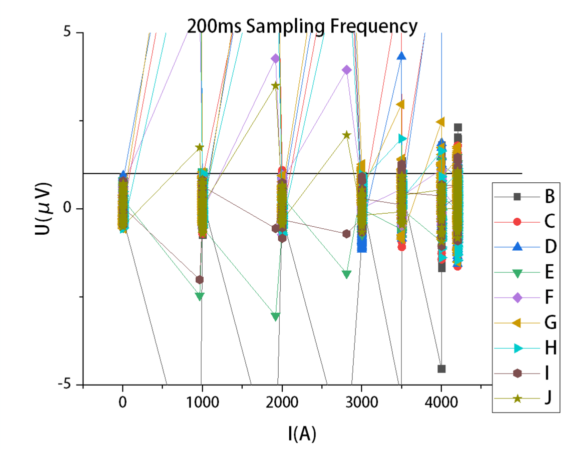


Low Temperature Connecting Section Design

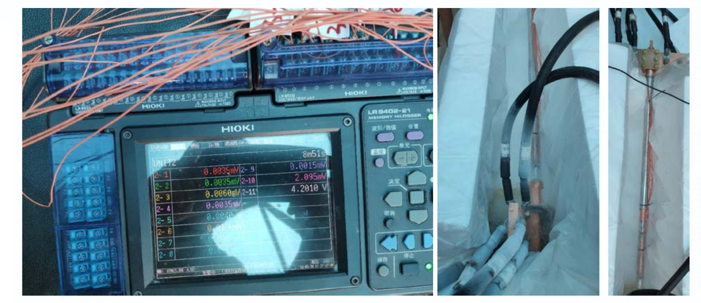
The low temperature connecting section connects LTS cable below the HTS section. Because the superconducting joint technology of YBCO conductor and NbTi cable is not mature yet, and the current lead size is relatively compact, copper support is used to construct the low temperature connecting section under the premise of Joule heat and structural heat leakage. This section is soldered with YBCO conductors and crimped with aluminum-stabilized NbTi Rutherford cables. Due to the application of YBCO materials, the 4K thermal load of a single current lead is lower than 2W, which allows the bottom part of the current lead to be cooled by OFHC belt connected to the inner wall of the liquid helium Dewar. The insulating material between the current lead and the OFHC belt is made of aluminum-nitride film, and the design of the OFHC belt is determined by finite element analysis to ensure that the maximum temperature of the superconducting cable does not exceed 5.5K.

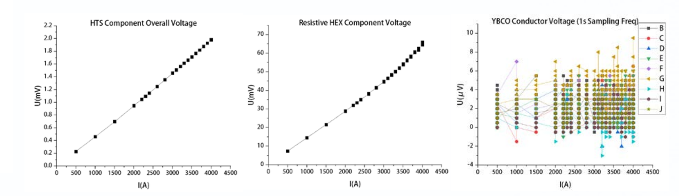
Liquid Nitrogen Immersion Test Results

In the liquid nitrogen immersion test, the operating current reached 4200A, and the voltage monitoring tap installed in the HTS section showed no quenching of all YBCO conductors. As shown in fig.11, the voltage of each YBCO stacked conductor does not exceed the quench criterion, that is, 1uV/cm, and the relationship between the total voltage of the HTS section and the operating current is always linear, that is, the voltage of the copper support and the joint. No shunting occurs on the stainless-steel shunt. From this result, we can also know that the joint resistance between YBCO conductors and the copper support is lower than 2.5E-7 Ω in the liquid nitrogen state.



YBCO Conductor Voltage: NO Quench @4200A





Valve Box Test Environment Under Construction

The newly designed valve box simplifies the liquid helium piping system compared to the existing one, resulting in a reduction in the number of bimetal joints in order to improve the system vacuum that deteriorates these years. In addition, the newly designed binary current lead and liquid helium Dewar will improve the thermal load of 4K and the temperature of the magnet cable in the valve box, improving the stability and safety of the entire system. The binary YBCO current lead is shorted through a length of aluminum stabilized NbTi Rutherford cable to complete the offline test. The purpose of the offline test is to set up a test environment similar to the actual operation of the magnet system to test the binary YBCO current leads.