SBIR PHASE I REPORT

Insulation and Heat Treatment of Bi-2212 Wires for Wind-and-React Coils

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Introduction

Higher Field Magnets demand higher field materials such as Bi-2212 round superconducting wire. The Bi-2212 wire manufacture process depends on the coil fabrication method and wire insulation material. Considering the wind-and-react method, the coil must unifirmly heated to the melt temperature and uniformly cooled to the solidification temperature. During heat treat cycle for tightly wound coils, the leakage melt from conductor can chemically react with insulation on the conductor and creat short turns in the coils. In this research project, conductor, insulation, and coils are made to systemically study the suitable insulation materials, coil fabrication method, and heat treatment cycles.

In this phase I study, 800 meters Bi-2212 wire with 3 different insulation materials have been produced. Best insulation material has been identified after testing six small (0.5" dia.) coils for insulation integrity and critical current at 4.2 K. Four larger coils (2" dia) have been also made with Bi-2212 wrapped with best insulation and with different heattreatment cycle. These coils were tested for Ic in a 6T background field and at 4.2 K. The test result shows that Ic from 4 coils are very close to short samples (1 meter) result. It demonstrates that HTS coils can be made with Bi-2212 wire with best insulation consistently.

Evaluation of Insulation

As planned we have made a total of six small coils (0.5" dia.) for wire insulation evaluation. Two small coils with each of the three types of insulation were made. Out of

these three types of insulation, two of them were yarn braided around the wire made of alumina based fiber and the other one made of quartz based fiber. The third one was dip-coated with Zirconia (ZrO_2) powder (see Fig. 1).

Fig. 1, 0.5" dia.x3"L. coils after winding.
1. Dip-coating Zirconia powder
2. Alumina based fiber 3. Quartz based fiber

Each coil had 28m in wire length and was wound into five layers, then heat-treated and tested its resistance. Most important, we looked for the compatibility between the insulation and the wire.

After coils heat-treatment, we have observed that insulation of the coil #1 (wire that was dip-coated Zirconia), was falling off very easy (flaking off) causing the wire to get exposed and not getting insulated properly (#1 in Fig. 2). In fact the coil shorted to coil form and had internal shorted when measured with a LCR meter.

The quartz based yarn insulation (#3 coil in Fig. 2) was braided around the wire and heat-treated, but the filaments are very brittle. This causes breaks in some of the filaments during the braiding even using thinner yarn.

The alumina based yarn insulation (#2 coil in Fig. 2) was also braided and heat-treated. This insulation is more flexible than the Quartzel and showed a good insulation material. There were no shorts in the small coils made of alumina and quartz fiber measured with a LCR meter.

Fig. 2, Coil Insulation after heat-treatment

1. Dip-coating Zirconia insulation
   Flaking off
2. Alumina based fiber insulation
   No reaction with the wire
3. Quartz based fiber insulation
   No reaction with the wire

Small Coil Critical Current Test

A couple of good insulated small coils were chosen for critical current test at self field in liquid helium. Fig. 3 shows the coil lead terminals and voltage taps arrangement before connecting onto test header for test in liquid helium.

Fig. 3, Small coil (1/2”) preparation for critical current test in liquid helium

Fig. 4 shows the Ic result of small coil made of wire with quartz braid insulation. The voltage is measured across the lead terminals instead of the coil itself. The base line slope is due to the resistance in lead terminal. This particular coil did not have the voltage tap across coil section. The voltage taps are only across the lead terminals only unfortunately.

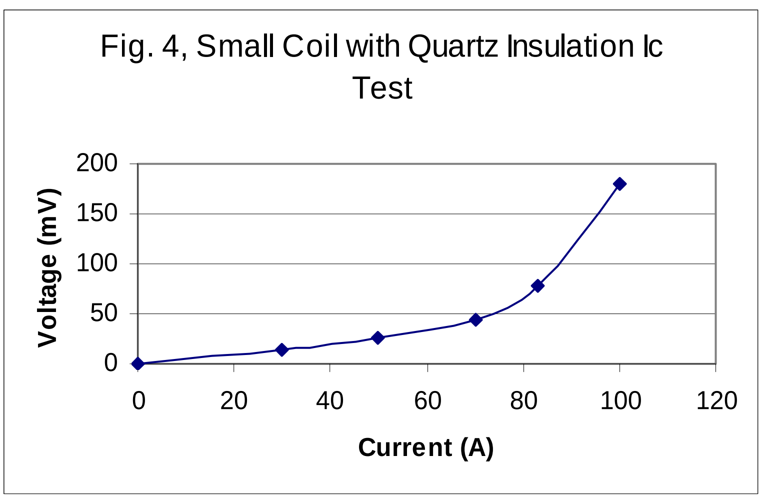
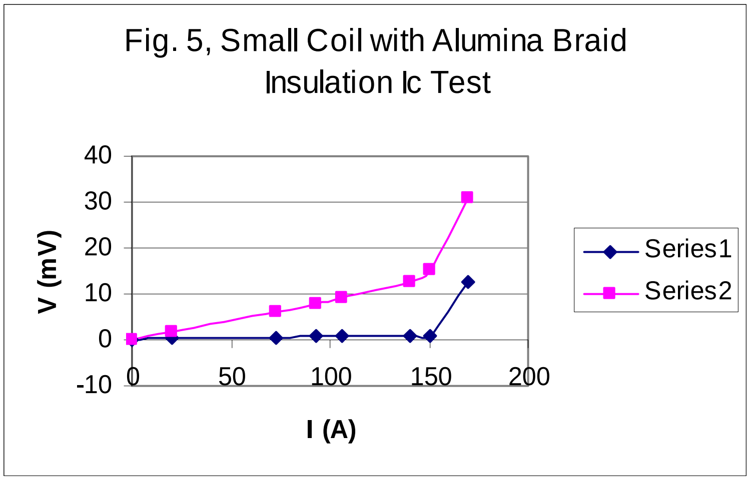


Fig. 5 is the Ic result of the small coil made of wire insulated with alumina based fiber braid insulation. The voltage in series 1 is measured across the coil winding only while voltage in series 2 is measured across the coil winding and leads. The series 1 trace does not exhibit any sign of resistance until transition, showing true superconducting state in the coil.



The critical current of alumina insulated coil is ~ 150A and this value is significantly higher than 80A in the quartz insulated coil. Based upon this observation and the fact that alumina yarn is much more friendly for braiding operation, we have chosen alumina yarn braid insulation for fabrication of 4 of 2 inch diameter coils

2” Dia. Coil Fabrication

From the results of the small (0.5” dia.) coils evaluation, it is clear that the alumina based fiber braid was the best choice for further investigation for coil fabrication. Using the alumina based fiber braid, we have fabricated basically four identical lager (2” ID.x3”L) coils as shown in Table 1 which summarizes the coils parameters. All four coils had about 440 turns and 8 layers. The winding was very smooth with no apparent problem on insulation.

Table 1, Coil Winding Parameters

	Coil-1	Coil-2	Coil-3	Coil-4
ID [mm]	52.8	52.9	52.9	53.0
OD [mm]	71.9	71.7	71.6	72.0
n# layers	8	8	8	8
n# turns (total)	448	444	433	444
Wire length (m)	87.9	87.0	84.8	87.3

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Fig. 6 is a photo for the four coils after winding is done and before heat treatment.

After winding, the coils were delivered to OST for heat treatment.

Fig. 6, Four Finished Coils after Winding and before Heat-treament

When the load inside the furnace is large, it is likely to have a gradient in temperature profile of the load. It is critical to have all Bi-2212 precursor melted in a short time to insure a uniform and excellent superconducting phase. For this reason we used four different heat-treatment cycle with small variation of temperature and time: Coil-1 with Tmelt/10min, Coil-2 with Tmelt/60min, Coil-3 with Tmelt+2°C/60min and Coil-4 with Tmelt-2°C/60min.

During the heat-treatment of the coils, a standard ITER barrel sample with 1m long wire was also heat-treated for the performance comparison between the coils and long samples.

The coils were vacuum-pressure impregnated (VPI) with epoxy after heat treatment to reinforce the coil winding. After VPI with epoxy, the leads wire for current and voltage taps were attached and coils were ready to be mounted onto test header for Ic test in a 6T background field. Fig. 7 is photo showing 3 of 4 coils after heat-treatment and epoxy vacuum impregnation and with leads terminals and voltage taps attached.

Fig. 7, Typical Coils after Heat-treatment and Epoxy VPI

Coil Testing

All coils were tested at 6 and 3 Tesla and self-field in liquid helium. Fig. III-8 is a typical set up for coil Ic testing. Inside the coil inner bore, it has a hall sensor for measuring the total central magnetic field. Table 2 and Fig. 9 summarizes test results of the four coils. The critical current is defined as the transition current at electric field of 0.1μV/cm.

It can be seen from the test results that all four coils have similar Ic which are compared well with the ITER barrel samples(1 meter long wire) that were heat-treated at the same time with the coils (see Fig. 9).

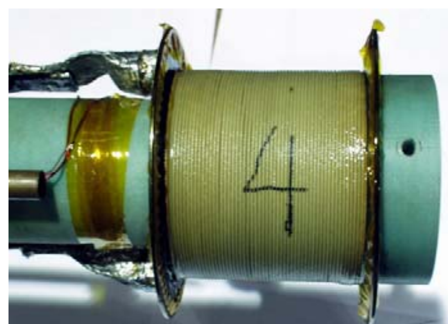

Fig. 8, Sample on the test rig

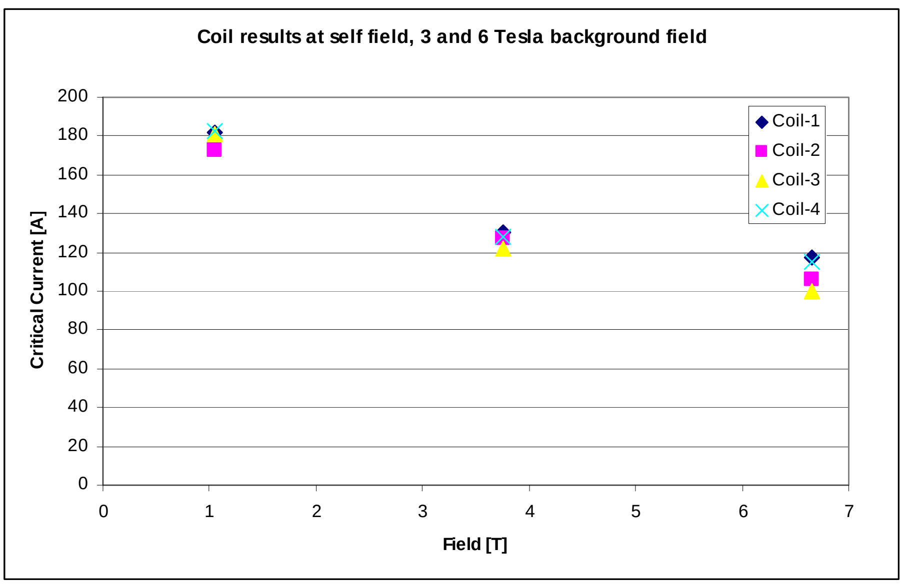

Fig . 9, Critical Current vs. Magnetic Field

Table 2, Coils Test Result Summary

	Field [T]	Ic [A]	Coil Field [T]	Ic [A]	Coil Field [T]	Ic [A]	Coil Field [T]	Ic [A]	Coil Field [T]
	Ic [A] @ SF	182	1.05	172.5	1.00	181.2	1.05	182.7	1.06
Criteria	Ic [A] @ 3T	130	0.75	127.2	0.74	121.8	0.70	128.4	0.74
0.1 uV/cm	Ic [A] @ 6T	117.7	0.68	106.4	0.62	100	0.58	115.3	0.67

The measured self field matches well with the calculated magnetic field for all four coils. Thus it verifies that the coil has no electrically shorted turns in the winding.

Conclusions and Discussions

The goal of this research was to find at least an excellent insulation material suitable for Bi-2212 wire for very high field superconducting magnet application. We have investigated a film coating of Zr oxide by dip-coating and two braid insulations, alumina and quartz fibers. We have found that the Zr oxide film has a tendency of flaking off easily from the surface and developing electrical short between turns and between turns to coil former. Both alumina and quartz fiber braids were adequate for insulation without serious defects, although the quartz fiber braid showed some fray during winding of the coil. Our Ic test results from small (0.5” dia.) coils showed that coil with alumina braids has higher Ic than coil with quartz fiber. Therefore we have chosen alumina base fiber for wire insulation for our 2” dia coil fabrication. Another reason that we have chosen alumina fiber for the insulation system because there was less of fiber damage during the braiding operations compared to the quartz.

We have fabricated and tested four 2 “ dia. coils using 1mm wire insulated with braided alumina fiber and tested in a 6 Tesla background field. They were heat-treated with four different heat-treatment cycles; each coil was heat-treated in separate furnace load. All of them exhibited very similar results and showed no insulation defects in the heat-treatment cycles. There is no degradation in coil Ic when compared with Ic from long (1 meter) sample. We believe that we have identified “electrical insulation material” for B-2212 wire for ultra high field magnet application. This is one major mile stone to build very high field superconducting magnet system for science.

We conclude that the goals have been achieved and we are ready to do further research and development for higher field and larger coils.