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Small layer-wound ReBCO solenoids
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Abstract
The development of the next generation of high field superconducting magnet systems demands studies of new technological approach for its internal sections. Several small HTS solenoids (21 mm inner diameter, 32 layers) were fabricated by layer-winding technique from SuperPower type SCS-4050 ReBCO wire insulated by polyimide wrapping. Different designs of external and internal joints also were also tested. The highest field generated by HTS coil was 2.4 T in a 10 T background field (total field was 12.4 T) at 4.2 K and achieved current density in the coil was 498 A/mm². The results will be used in development of HTS inner sections for 25 T superconducting magnet.

Keywords: Coated conductor; Layer-wound solenoid; High magnetic field; Winding technique

1. Introduction
There is strong interest in the application of ReBCO coated conductors for high field superconducting magnets due its high critical current density and mechanical strength. There is particular interest at the Kurchatov Institute for enhancement of LTS superconducting magnets by replacement of its internal Nb3Sn sections by ReBCO based ones. The near goal is upgrade of our compact 17.7 T superconducting magnet with 39 mm cold bore [1] up to 25 T. The development of ReBCO magnet technology is still in the early stages, and there are no standard methods for ReBCO coil fabrication existed. Therefore, the 25 T magnet project was included a ReBCO layer-winding technology development, searching for new insulation methods and quench protection study. The fabrication and testing of small ReBCO coils, is the first step leading to future high field and very high field superconducting magnets.

2. Layer-wound ReBCO coils
Four small solenoidal ReBCO test coils were wound from insulated conductor supplied by SuperPower Inc. type SCS-4050-i-AP. The HTS conductor had a 50 μm hastelloy substrate and 25 μm copper stabilizer on each side. The SCS-4050-i-AP conductor was insulated by 25 μm polyimide tape wrapping with 50% overlap. The maximum conductor width and thickness were 4.10 mm and 0.20 mm, respectively.

All small ReBCO coils were identical by geometry, their parameters are listed in Table I. In the ReBCO test coil #1 HTS layer was facing outward, other three coils were wound by reversed conductor position. The winding tension was about 30-50 N and was provided by electromechanical brake. The ReBCO test coil #2 was impregnated by silicone grease. Other test coils were not impregnated. The silicone grease was chosen due to its good wetting properties. Impregnation process was quite similar to usual coated conductor wax impregnation technique [2].
Table 1. Specifications of ReBCO test coils

| Parameter                  | Value |
|----------------------------|-------|
| Inner diameter (mm)        | 24    |
| Outer diameter (mm)        | 37.1  |
| Height (mm)                | 25.2  |
| Number of layers           | 32    |
| Number of turns            | 160   |
| Conductor length (m)       | 15.4  |
| Inductance (μH)            | 494   |

Joints between conductors inside winding are inevitable during fabricating of relatively large superconducting magnets. In order to investigate the properties of such joints, the ReBCO test coil #3 was wound with interconnection between conductors at the tenth layer of winding (see joint schematic drawing at Fig. 1).

Due to compact coil design reasons, the ReBCO test coils #1 and #3 were manufactured with 90° angle joints between conductor and bus-bar (single SCS-4050-i-AP tape without isolation and copper bar soldered together). Test coils #2 and #4 were fabricated without intermediate HTS connector, conductors were soldered directly to the copper cylindrical contacts (see Fig. 2).

3. Experimental results

During the tests each ReBCO coil was instrumented with voltage taps and Hall sensor in the centre. Two additional voltage taps were installed at joints of test coil #3. Voltages and signal from Hall sensor were recorded simultaneously via Agilent 34970A DAQ system. Transport current was provided by VCH-300 and TDK-Lambda GEN-1000 power sources.

All ReBCO coils were preliminary tested at 77K before LHe measurements. I-V curves for not impregnated test coil #1, #3 and #4 are presented at Fig. 3a. During LN2 tests the maximum magnetic field at a winding was estimated as 0.2-0.24 T.
Each ReBCO coil was subjected to extensive thermal cycling, after 10 cycles from 77K to room temperature there was no any degradation of superconductor critical properties observed. After LN2 tests the voltage-current dependence for coil #3 was processed numerically by joint voltages subtraction from overall voltage.

I-V curves for silicone grease impregnated coil #2 were measured after each thermal cycle, see Fig. 3b. Silicone grease impregnated coil #2 was degraded, but much slowly compare to epoxy impregnated ReBCO coil insulated by polyimide tape [3]. Coil #2 was fabricated from conductor with better critical properties, so its critical current is higher than for other coils despite of degradation.

The joint resistances were measured also for test coil #3. For interconnection between conductors the resistance at 77K was 3.3 μOhm, or 1.65 μOhm per joint, or 330 - 460 nOhm/cm. Measured in LN2 resistance of angle joints between conductor and HTS bus-bar was 1.7 μOhm, or 270 nOhm/cm.

After LN2 tests ReBCO coils #1, #3 and #4 were operated at 4.2 K in an external magnetic field of 10 T generated by LTS solenoid. The test coils #1 was charged at a rates of 0.5 A/s up to the 300 A, after that charging rate was decreased to 0.15 A/s. After charging to 400 A and held at target current for 250 s, coil was discharged fast (200 ms) without quench. Transport current, Hall sensor voltage and potential at the coil were recorded (see Fig 4). Maximum estimated magnetic field in centre of the coil was 12 T. After discharge test coil #1 was charged again at constant rate 0.5 A, and at 327 A current coil was quenched and burned. Active voltage drop at the test coil #1 was not exceeded measurement error in 200 μV during both charges. Test coil was unwound and inspected, one local burned place was found.

The test coil #3 was charged at constant rate 0.5 A, and at 327 A current coil was quenched and burned at the joint between conductors. Time dependencies for current and magnetic field are shown at Fig. 5. Active voltage larger than 200 μV not detected again.
Maximum voltage at the coil was limited to 200 mV and power supply was programmed for switch off in case of quench. Sensitivity of voltage measurement was also increased. The test coils #4 was charged at 0.5 A/s ramp rate to the 200 A, after that charging rate was decreased down to 0.25 A/s and 0.2 A/s, at 483 A coil quenched (see Fig. 6). Maximum estimated magnetic field in centre of the coil was 12.4 T. Active voltage larger than 100 μV was not detected. After quench coil #4 was not burned completely, but HTS conductor was damaged in point and lost superconductivity permanently.

4. Conclusion

Four ReBCO test coils were fabricated by the layer-winding technology. In the 10 T external magnetic field generated by LTS magnet were reached 483 A quench current (engineering current density 498 A/mm²) and 2.4 T magnetic field. The calculated by free coil model electromagnetic stresses in ReBCO test coils not exceeded 220 MPa. Improvements in the isolation technology of coated conductors, a methods for avoid quenching and protection of REBCO coils are required.

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