TECHNICAL NOTE

Basic design and test results of High Temperature Superconductor insert coil for high-field hybrid magnet

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In view of the development and demonstration of high field (~ 12 T), a hybrid magnet consisting of the main outer Low Temperature Superconductor coil made from NbTi and High Temperature Superconductor (HTS) insert is developed using commercially available Bi2223/Ag tape. The performance tests were carried out both at 77 and 4.2 K. The HTS-based current lead for the HTS insert is developed and tested considering the diameter of the existing port in the cryostat. Prior to coil manufacturing several measurements were performed on HTS tape under various conditions. Here we describe the design, construction and test results of HTS insert coil.

The significant progress of High Temperature Superconductor (HTS) performance finds practical applications in different fields. Various HTS-based magnet systems have been designed and fabricated worldwide. HTS offers advantages over Low Temperature Superconductor (LTS) at high magnetic field and opens a new frontier for high-field applications[1]. A hybrid magnet consisting of an outer LTS magnet and an inner HTS insert coil was designed and the test was carried out (see Figure 1). The outer magnet was made of stable NbTi conductor constructed for 0.6 MJ SMES system[2]. The combined magnet system was designed to produce about 12 T of magnetic field. As part of the work, HTS-based current lead was designed, developed and fabricated for the insert coil. Different studies were carried out to obtain engineering data which were not readily available for use in the design work. The quench detection circuit was developed for the insert coil. The objective of the programme was to develop a state-of-the-art HTS coil technology aimed specifically for magnets for energy storage and beam line[3,4]. The development of high-field insert is expected to pave the way for high-field NMR magnets and other applications. Furthermore, studies on high-field inserts and the development of advanced high-field system to evaluate them are becoming increasingly important. Here we describe the design, construction and test results of HTS insert coil.

Design and fabrication

The HTS insert was used to create hybrid magnet design, in which the main coil is made from NbTi to produce primary field. The HTS conductors, which have a weak dependence of critical currents against magnetic field were placed inside the primary LTS coil at liquid helium temperature. The clear bore of the outer LTS magnet restricted the windings volume of the insert, while the critical current density in high fields limits the operating current density. The two magnetic coils were powered separately, which made it possible to measure their performance independently.

Evaluation of HTS tape

The current–voltage characteristics of the HTS tape used for HTS insert coil were measured to obtain the basic data for use in the design. Initially all the measurements were carried out in liquid nitrogen temperature. A critical current I_c and an n value were obtained by the measured current–voltage characteristics of the HTS tape, where I_c was 1 μV/cm (ref. 5). A power law, $V \sim I^n$ was fitted to the resistive transition region to obtain the n

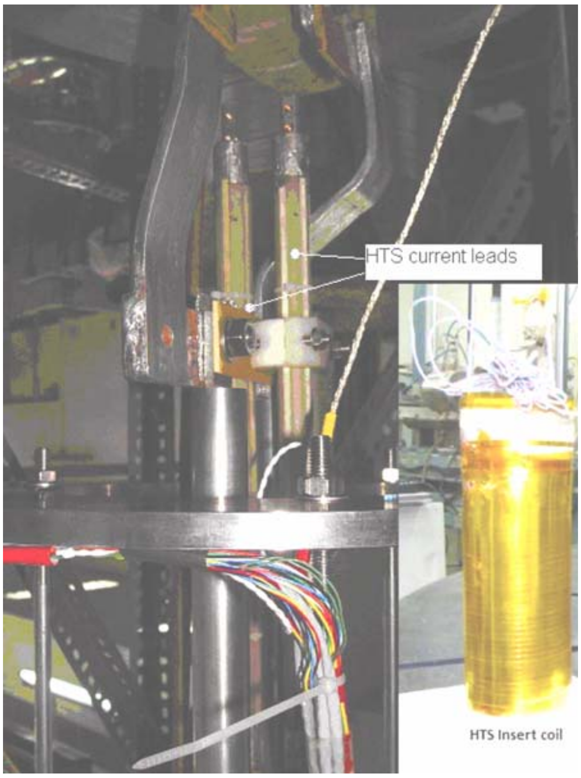

Figure 1. High Temperature Superconductor (HTS) insert coil and the full assembly ready for the test at 4.2 K.

value. The critical current data under tensile stress and different bend diameters were not available. So the measurement was carried out for HTS tape under different tensile loads and bending diameters. Figure 2 shows the degradation of critical current due to 15 kgf of tensile load under bend condition with bend diameter of 60 mm. Several HTS–HTS joints were made and measured in liquid nitrogen temperature using normal lead–tin solder under controlled temperature. The joints were made to ensure minimum electrical resistance and can hold 10 kgf of tensile force without any degradation.

Magnet insert. The insert coil was wound on a stainless steel bobbin of height 330 mm consisting of about 3200 turns. The coil was designed in a solenoid fashion with three co-axial coils having different heights. Each turn was insulated from the adjacent turns by means of a polyamide film of thickness 12.5 μm. Two layers of kapton insulation were wrapped around the bobbin before winding. The ends of the insert coil were connected with the cold end of HTS current lead via Cu strips cladded with NbTi. Two semicircular G10 blocks were used to fill the step regions and tightened with bolt against the surface of the coil. As the available continuous length of the HTS tape was 500 m, there was one HTS to HTS joint and G10 spacer was provided to the adjacent layer for passage to liquid helium. A CERNOX temperature sensor was also mounted near the joint. All three sections of insert coil were provided with a set of voltage taps across each of them. The total length of the HTS tape used for winding was about 950 m. The outer diameter of the insert was 120 mm in order to place it inside the bore of the primary LTS coil. The design specifications of the coil are shown in Table 1.

(i) *Coil shape:* The critical current of HTS conductors has a strong dependence on the radial component of the magnetic field. So the critical current of the coil primarily depends on the value of radial magnetic field in the coil winding section. The magnetic fields of the solenoid coil have significant radial components at the coil ends. Therefore, the size and shape of the magnet needs to be optimized to reduce the radial magnetic field[6,7]. This problem has infinite solutions and some initial constraints were considered to reach a feasible solution. Some of these constraints arose from the coil geometries and conductor properties. The critical bending diameter of the HTS tape and bore diameter of the LTS coil limited the size of the coil. The insert was designed using finite element software ANSYS™ and its in-built optimization routine was used to get the optimum geometry. The optimization strategy aims to minimize the conductor length (or volume), which basically optimizes the magnet cost. The effective I_c of the insert coil was determined by estimating the maximum radial field in the coils ~ 1.2 T under operating temperature of 4.2 K (Figure 3). Thus operating current of 300 A was taken considering safety margin of 20%. The value of radial magnetic field at coil ends of the proposed step-shaped configuration was smaller and was about 70% of the optimized normal solenoid.

(ii) *Coil forces:* In the stage of magnet design, stress distribution inside the coil at different conditions was calculated, to know the limiting values of loading, bending and twisting to avoid degradation of critical current. The limits for the stress and axial stress induced by Lorentz forces are determined by the critical tensile strength of the HTS tape at operating temperature and current. Experimental studies were carried out to obtain critical current degradation, if any, due to externally applied tension. Stress distribution inside the coil was calculated using ANSYS™ during cool-down and energization. In addition, the electromagnetic interaction between the insert and the outer magnet was taken care in the design. The insert coil was installed to adjust its centre to that of the outer magnet as precisely as possible to avoid axial force f_z, which is proportional to the displacement but works to adjust the magnet centre. Electromagnetic force f_r, along the radial direction caused by displacement along the radial direction is also proportional to displacement, but it works to expand the displacement. The insert was supported by three rods from the bottom, designed to absorb this interaction force with some allowable displacement. When the magnetic field centre of a HTS insert was shifted, it experienced f_z = 17 kgf/mm and f_r = 20 kgf/mm

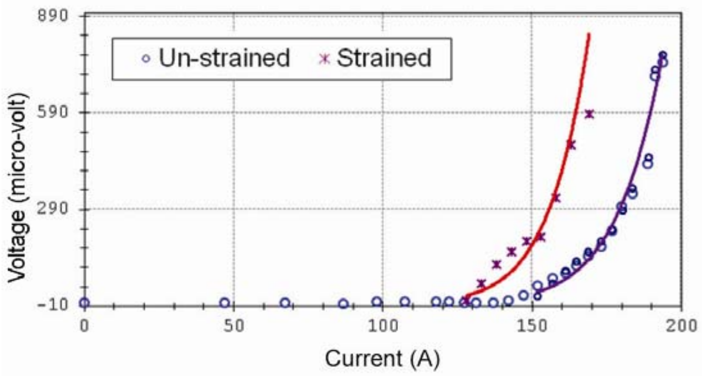

Figure 2. Degradation of critical current measured at 77 K due to tensile loading.

Table 1. Design specifications of the coil

Parameter	Value
Winding type	Step solenoid
No. of co-axial coils	3
Inner diameter (mm)	60
Outer diameter (mm)	120
Maximum height (mm)	320
Magnetic field (Tesla)	~ 6
Total field (T) with both coils on	~ 12
Maximum radial field inside HTS (T)	~ 1.2
Maximum current (A)	300
Operating temperature (K)	4.2
Critical current margin (%)	> 20

respectively, for axial and radial displacements of 1 mm.

(iii) *Magnet quench:* Both the outer magnet and insert coil were provided with quench protection system and dump resistance separately. The inductive current and voltage in the insert coil were estimated for sudden decrease and increase of current in the outer coil. The outer magnet was designed to have a sufficient margin against quench of the insert coil. For quench detection, voltage taps to divide the magnet into two sections were placed at the position where inductance of each section is equal. A dedicated quench-detection circuit was developed in-house based on differential voltage and was successfully tested and used for the HTS insert coil. A computer program for the transition process during quench of HTS coil to normal state was developed and detailed analysis carried out for the insert coil. It was shown that a passive protection scheme is not possible and protection should have external dump resistance. Hence maximum temperature rise was calculated during quench of the insert coil for different values of dump resistance and its value of 300 m-ohm was fixed. Studies were also carried out to account for possible scenarios that may eventually occur after the quench-like rise of cryostat pressure, voltage rise and helium boil-off rate.

Current lead

A HTS-based current lead was designed and fabricated for the insert coil to reduce heat loss from the current leads. It was designed for 500 A of current and consists of vapour-cooled resistive part at the top and HTS at the bottom. Details of the specifications are given in Table 2. Composite HTS tape consisting of Bi2223 filaments embedded into AgAu alloy matrix was used for HTS lead. In the present case, current lead was designed considering the diameter of the existing port in the cryostat. It had a lug at the room temperature end to connect to power supply and sockets for the helium gas cooling the resistive part. Sufficient safety margins were provided against possible troubles like quenching of HTS and accidental stoppage of cooling gas. The resistive section of the current lead consists of 20 numbers copper filaments of 0.9 mm diametre enclosed in stainless steel tube 750 mm in length, cooled by helium gas with $T \sim 10$–20 K. Detailed calculation showed that optimum helium gas flow rate was about 28 mg/sec for 500 A current and requires a small pressure head (~ 1.0 mbar) to maintain the gas flow. The HTS part of the current lead consisted of five HTS tapes (4.4 mm wide and 0.24 mm thick) embedded into the grooves on the outer surface of the G10 tube, which has a diameter of 20 mm. End connections of HTS part were made from copper. At the upper end, a groove was made in the protruding part of the copper (~ 5 cm) for placing the copper wires of the resistive part. The lower end was soft-soldered with copper-cladded NbTi wires. The HTS part was designed to carry 500 A current under applied radial field of 0.2 T and could sustain about ~ 70 K temperature at the warm end with marginal increase of heat load to liquid helium. Maximum radial and axial magnetic fields around the HTS part of the current lead were calculated to be 0.11 T and 0.5 T respectively. Additional design considerations was taken to take care of quench in case of increase of warm-end temperature due to interruption of helium gas flow and current overloading. The HTS part of the current lead was provided with voltage taps for continuous monitoring and connected with quench detection circuit.

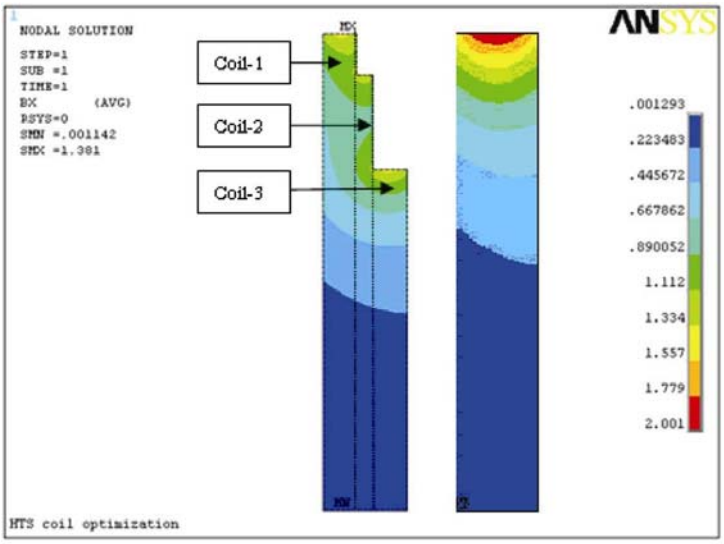

Figure 3. Reduction of radial component of magnetic field at the coil ends using three coils of different axial heights.

Table 2. Details of current lead specifications

Parameter	Value
Resistive section	
Cu wire diameter (mm)	0.9
No. of Cu wires	20
SS tube diameter (mm)	9
Packing density (%)	30
Length (mm)	750
HTS section	
Materials	BSCCO
Matrix material	Ag–Au 5.4 wt%
Critical current @77K, SF	100 A
Cross-section (mm^2)	4.0×0.24
Length (mm)	300
Support material	Nema G-10

Test set-up

The magnet system was placed inside the top access Standard Magnet Dewar (SMD) purchased from Oxford Instruments. This is a liquid nitrogen shielded Dewar having ~ 500 mm bore at the top. Its top plate, magnet support, current leads, helium gas recovery with pressure relief and rupture disc and different feed through ports were designed and fabricated to meet our requirements. A provision was made to initially fill the liquid from the bottom and to top up from above its surface subsequently. To minimize the radiation heat flow down the neck of the cryostat, five thin and polished stainless steel radiation shields were used in the top plate flanges. Several temperature sensors were mounted inside the cryostat attached with both the outer LTS magnet coil and inner HTS insert to monitor the temperature during cool-down and the magnet quench. Liquid helium level was monitored using a level sensor fitted with the cryostat. Voltage taps were provided across the different sections of the coils and measured through Keithely voltmeters. Temperature sensors were attached with the warm ends of HTS leads along with the voltage taps to monitor voltages across them. Quench detection circuit was provided for each coil separately, which has a provision to change and set detection threshold and validation window. Data were continuously monitored and recorded in the computer. A ferromagnetic shielding was provided outside the cryostat to limit the fringe magnetic field to less than 100 G.

Results and discussion

The current–voltage characteristics of HTS tape were measured under different tensile loads at 77 K temperature (Figure 2). The tape was wound over G10 cylindrical block of diameter 60 mm under tension and measured using four-wire method. Some of the samples were tested after releasing the tension and found to be degraded. The joint resistance between HTS–HTS tapes was measured at 77 K with different lapping lengths using normal lead–tin solder and compared with measurements at 4.2 K. There was not much change of joint resistance with operation temperature. One of the termination joints in the innermost coil-1, was found to be very high (~ 400 μΩ), which rises its voltage and temperature rapidly beyond ~ 120 A, as shown in Figure 4. This high resistance produced very large Joules heating, which lead to repetitive quenching at about 160 A current. Unlike coil-1, the resistance of the other two coils was within 100 nΩ, as measured during the test at 4.2 K.

A pair of current leads was installed vertically through the top flange of the cryostat in order to investigate current transport property and heat in leak. Its lower end was connected to a short HTS sample via stabilized NbTi cable. Temperature sensors and voltage taps were attached to each current lead. The temperature, cooling helium gas flow rate and current were monitored and measured during continuous operation. Voltage across the resistive part was monitored and compared with the calculation for flow rate of 14 mg/sec and cold-end temperature of 20 K, as shown in Figure 5. Moreover, it was observed that the HTS part of one of the leads was quenched (Figure 6) during the first test with continuous rise of voltage possibly due to loose contact/opening of the joints between HTS tape and Cu terminal. Consequently, the temperature rose at the warm and cold ends and was about 130 and 28 K respectively, at ~ 300 A current. After proper tightening and re-soldering of the joints, current lead was again re-energized along with the HTS insert coil. This time no abnormal voltage rise was observed, (Figure 6, second test).

Prior to testing the HTS insert coil at 4.2 K, it was tested at 77 K by immersing in liquid nitrogen bath. The quench detection circuit was also connected during energization to avoid any damages to the coil. The coil carried up to 12 A in a thermally stable condition and quenched repeatedly at ~ 16 A with rise of voltage in coil-1. Current above 15 A generated a level of heating in the coil that exceeded the 77 K surface cooling available, leading to an unstable temperature and voltage rise in the coil. Coil voltage was

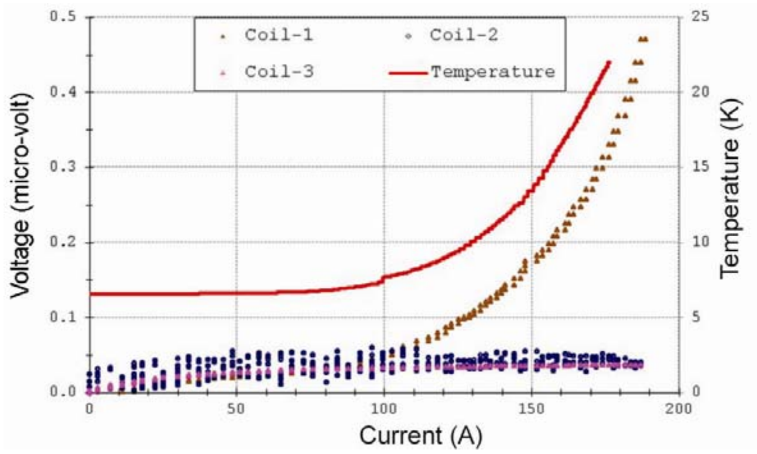

Figure 4. Voltage across the three coils during current ramping along with temperature rise.

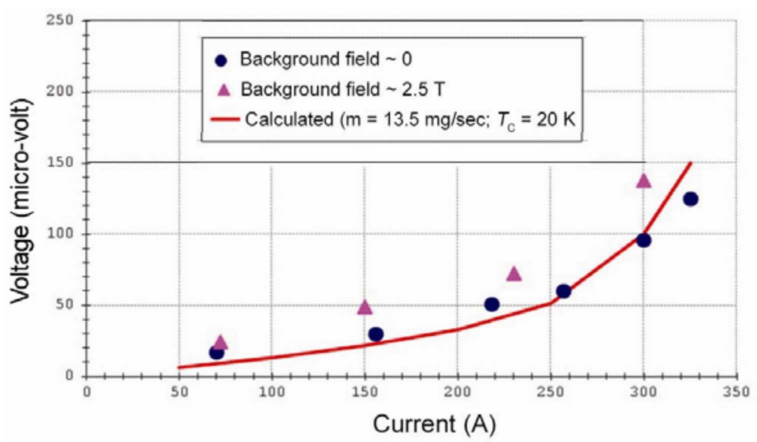

Figure 5. Voltage across resistive part of current lead during current ramping.

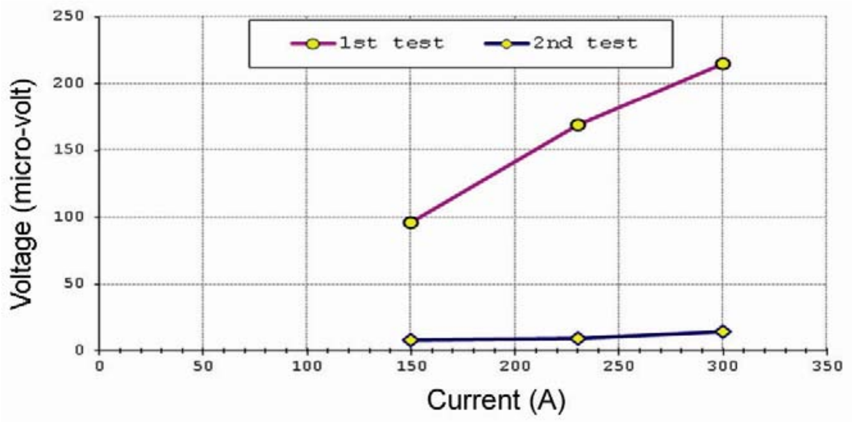

Figure 6. Voltage across the HTS part of current lead showing resistive during the first test.

measured transiently up to 30 A of current and generated about 4.5 kG of magnetic field at the centre. The whole assembly were cooled down to 4.2 K and voltage–current characteristics across the three coils were measured at 4.2 K (Figure 4, coils 1–3). It is evident from the plot that the voltage and temperature rise rapidly in coil-1 and quench the insert. The joule heating due to joint at the end terminal was excessive, leading to quenching of coil-1. The maximum stable current was about 120 A and excess of this led to transient (runway) temperature rise in the coil (Figure 4) and activation of dump circuit. Teslameter and Hall probe were used for measurement of magnetic field at the centre of the magnet and produced about 9 T by exciting both outer LTS and inner HTS insert coil before the HTS coil was quenched.

Conclusion

The HTS-based current lead was designed and tested successfully. Low-resistance solder splicing of HTS tapes to form a continuous winding has been developed. The detailed design studies were carried out for the development of HTS magnet insert and HTS coil as a whole. We have kept different provisions open keeping in mind the future development of HTS magnet. Several shortcomings of the HTS tape were observed during fabrication of the insert coil. The winding process is a delicate one requiring controlled tension to avoid overstraining of the HTS tape. During winding some degradation of critical current was observed due to tension as the HTS tape was released and rewound, especially at smaller radius. It was observed that the HTS coil was able to operate at currents which were significantly higher than that which corresponds to an appearance of the normal zone in the coil. Though we could not reach to the design field level as one of the joints resulted excessive heating and quenching of the magnet insert, the test results and analysis provided a high level of confidence and experience for future development of HTS coil.

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