International Journal Of Engineering Research And Development
e- ISSN: 2278-067X, p-ISSN: 2278-800X, www.ijerd.com
Volume 16, Issue 10 (October 2020), PP. 20-28

Development of Cost Effective Lab Scale 6 Tesla Superconducting Magnet

V.Ravindra[1], Uttam Bhunia[2], P.N. Vishwakarma[3],V V Rao[1], S.K. Sarangi[4]
[1]*Indian Institute of Technology, Kharagpur, India*
[2] *VECC, Kolkata, India*
[3] *National Institute of Technology, Rourkela, India*
[4] *CV Raman Global University, Bhubaneswar, India*

***Abstract**: Research in the area of developing low cost superconducting magnets is rapidly increasing to meet the demand in the areas of clean energy production, compact electrical machines and high field facilities for characterization of advanced materials. Keeping in view of these facts, a lab scale cost effective superconducting magnet system (6 Tesla) is designed and developed in house using Nb- Ti wire (0.43 mm nominal diameter, Cu: SC Ratio of 2:1). This paper describes astep by step procedure of former making, coil winding and testing procedure. Training of the superconducting magnet by repeated quenching is also described in this paper. Further, the axial variation of the magnetic field in the 1" bore confirms a uniform zone (±1%) in the central region over a length of 4 cm. The current to field ratio measured experimentally tallies with the theoretical calculation.*

Date of Submission: 08-11-2020 Date of Acceptance: 23-11-2020

I. INTRODUCTION

It is now a standard practice to usecompact superconducting magnets (SC Magnets) in scientific research, involvinglarge magnetic fields (> 5 Tesla) [**1**]. They are used in a wide range of experimental work including magneto-optics, Mossbauer effect, nuclear magnetic resonance, magnetic characterization of solids and high resolution lenses for electron microscopy. Further, SC magnets of medium size are routinely used in hospitals for magnetic resonance imaging (MRI).

The overall cost of keeping the superconductor cool in an SC magnet is smaller compared tothe cost of operating normal copper based electromagnets, which dissipate heat and have high power requirement for their operation [**2**]. Hence, SC magnets are used in high energy physics where beams of protons and other particles are accelerated to almost the speed of light and made to collide with each producing newfundamental particles. It is expected that this research will answer basic questions about structure of matter such as those about the origin of the mass of particles that make up the Universe.

Superconducting magnets are also important in future power generation based on magneto hydro dynamics (MHD) and controlled nuclear fusion. Levitating trains are also being built based on superconducting magnets mounted on the trains.

The recent discovery of high Tc superconductors cooled by liquid nitrogen has further increased the public awareness about the importance of superconducting magnetic devices for electrical power sector [**3**]. These devices include Superconducting Magnetic Energy Storage (SMES) for power system stabilization [**4**], Superconducting generators coupled to wind energy turbines [**5**] and Superconducting field coils in compact electrical motors [**6**] for ship propulsion.

From the above discussion, it is very clear that researchers have to concentrate in developing both LTS and HTS superconducting magnets in a cost effective manner to compete with equivalent copper based electromagnets. In the present work, an attempt is made to make an inexpensive LTS based lab scale superconducting magnet using cheaper materials (commonly available in market) and simple procedures (without requiring complicated equipment), to take care of the commercial constraints faced in modern technologies. Based on this experience, we also propose to develop scaled- up versions of LTS/HTS based superconducting magnets with low budget to meet their increasing commercial demand in future.

II. DEVELOPMENT OF LAB SCALE SC MAGNET

This section gives a step by step procedure in developing anin-house LTS based superconducting solenoidal magnet, to be made available for laboratory research at a low price. It is worth mentioning here that the present procedure is useful for any educational/R&D institute to develop their own cost effective SC magnet.

Figure 1 shows the photograph of the inexpensive NbTi based SC magnet developed in house, whose specifications are given in table 1.

Fig 1: Photograph of lab scale LTS-SC magnet along with support structure to be cooled in a cryostat

Bore diameter of the magnet	15 mm
Former material	Aluminum (Al)
End flange Diameter/thickness	60mm / 10 mm
Length of the Coil	140mm
No of Layers	26
No of Turns per Layer	234
Total No of Turns	6161
SC Wire used	NbTI (multi filamentary)
Length of Wire	0.7 Km
Type of insulation	Fibre glass cloth
Insulation thickness	0.1mm (Applied after every four layers)

Table 1: Specifications of in-house developed LTS-SC magnet

2.1 Design Considerations

Design of a lab scale superconducting solenoidal magnet (cylindrical symmetry) starts with selecting the experimental space (the bore dia (2R) and axial length of uniform field zone (ΔZ)). In the present case we have taken both 2R and ΔZ as 2.54 cm (1 inch). For attaininguniform field, we need to wind the superconducting solenoid on a non-magnetic former with an overall axial length (l), several times more than diameter. In our case keeping in mind the cryostatic requirements, we have taken the total length of the magnet (l) as 14 cm. Having chosen the magnet dimensions, we now need to choose the superconducting wire with necessary diameter (d) and length (L).

While diameter (d) of the wire fixes the number of turns per layer, the overall length of the wire(L) is selected to fix the number of layers. Obviously the total turns (N) is given by ‘number of turns per layer multiplied by number of layers’. The purchase requirement of the total length of SC wire is approximately given by total number of turns multiplied by the perimeter of average turn ($\pi * d_{avg}$). The d_{avg} is taken as average of inner diameter and outer diameter of the SC coil.

After deciding the coil geometry and the wire specifications, we need to wind the solenoid on a non-magnetic former (in our case Aluminum) following some established procedures with necessary pre-tension and inter layer insulation.

Superconducting magnets are required to withstand huge electromagnetic stresses under current excitation. Fig 2 shows the distribution of electromagnetic forces in a typical lab scale solenoid of finite length along with field profiles.

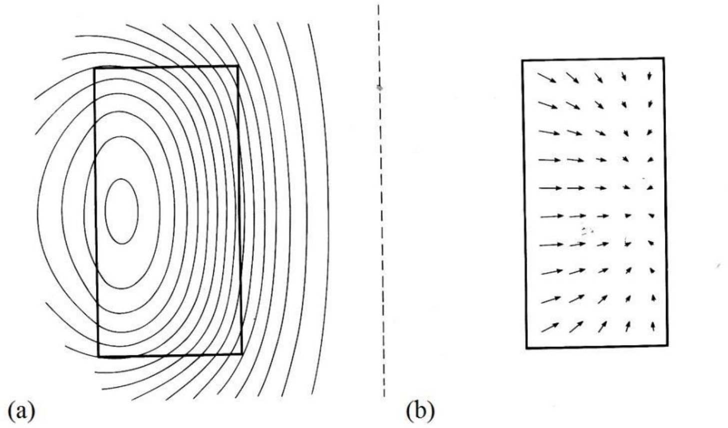

Fig 2: (a) Field profile and (b) Electromagnetic force pattern in a lab scale superconducting solenoid [1]

Considering cylindrical coordinate system (as the solenoid is of cylindrical shape), the current (I) is in 'ϴ' direction, magnetic fields (B) are in axial (central field at midpoint) as well as radial (at the ends of the coil). Hence, the resultant electromagnetic stresses (cross product of B & I) are distributed in radially outward(at central zone) and axially compressive (at the ends of magnet coil) as shown in fig 2.

Similarly, while designing the ampere turns (product of turns and operating current) and working volume of uniform central field (proportional to bore diameter and uniform field length), we need to consider the thermal margin ($T_c(B)-T_{op}$) available to absorb the released thermal energy during magnet-quench without permanent damage to the SC coil. In addition, the cryostatic safety aspects (i.e. sudden high pressure developed by LHe evaporation during quench) should also be considered while designing the magnet.

Superconducting magnets are mostly air-core type to produce very high fields (in our case 6 Tesla). This is due to the fact that the iron-core gets saturated anyway at high fields (more than 1 Tesla) and hence will not serve the purpose of enhancing the flux density.

The magnetic fields at the central point of the air-core superconducting magnets can be estimated from the equation given below.

$$B = \frac{\mu_0 NI}{h}$$

where $\mu_0 = 4\pi \times 10^{-7}$is the permeability of free space in T-m/A, N is the total number of turns, I is the current passed in Amperes and h is the length of the SC coil in 'm'.

In our case N=6161 turns, I=49.6 A and h=0.11m and hence the calculated central field is B=3.491T at 49.6 Amp. This value is in agreement with the experimental value measured at the central point of the SC magnet (3.506T). This close agreement shows that the in-house developed cost effective superconducting magnet is successfully operated up to 6 Tesla field without any degradation.

2.2 Selection of the Former for SC magnet

As the SC magnet is operated at cryogenic temperatures (4.2 K in our case), the properties of the materials differ drastically from that at room temperature. Hence, the material selection for the former becomes very crucial with respect to its physical properties such as thermal expansion, specific heat and density.In the present case, Aluminum is used as former material. The reasons behind this selection are: low cost, easy to machine, light weight, low specific heat, high thermal conductivity, sufficient mechanical strength to withstand large electromagnetic stresses at high operating currents and magnetic fields. Figure 3 shows the 3-D view of the base aluminum former before the NbTi coil is wound on it.

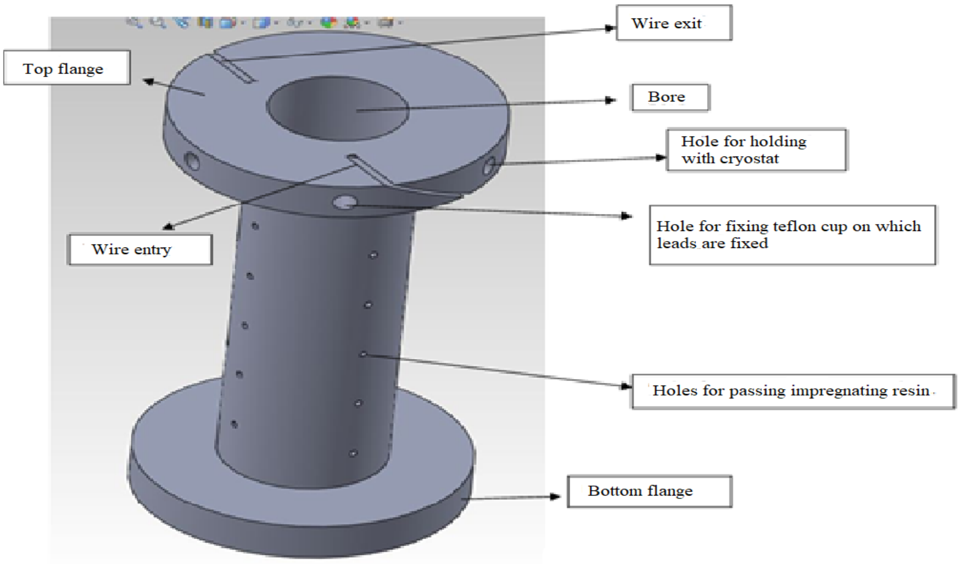

Fig 3: 3-D view of Aluminum former

After machining the former to the required dimensions, its surface is smoothened by sand paper. Sufficient care is taken to remove all the metal particles which are likely to punch holes through the insulation of the wire during SC coil winding and may cause short-circuit. Six holes (diameter 10mm each) are drilled at six symmetrical locations on the side of top flange of the former (Refer Fig 3).Of the six holes, three holes are used to fix the magnet to the three supporting rods (stainless steel) for locating the magnet in liquid helium (LHe) cryostat. Remaining three holes with electrically insulating sleeves are used to fix an insulating Teflon cup on top of the magnet. This insulating cup is required to support the electrical lead connections. Several small holes of 2 mm diameter are also drilled along the length of the former. These holes allow the LHe coolant to touch the inner windings of the coil.

2.2 Coil Winding / Insulation Procedures

The former along with the interior surfaces of its top and bottom flanges (towards the SC coil) is covered with nomex paper with the help of Elmo Luft 1A-Golden fast drying insulating varnish manufactured by Elantas Beck India Ltd. This is done to electrically insulate the former from the SC winding.Now with the help of same adhesive, fiber glass cloth is wrapped on top of this to get a smooth and uniform base for winding (Figure 4). The fiber glass cloth is basically a class F (155^0 C) insulation [**7**].

Fig 4: Fibre glass cloth being wound on the former attached to the winding machine

Fig 5Nb-Ti superconducting wire is being passed through sleeves in a slot on top flange.

A slot-cut is made on the top flange of former for taking out the free ends of Nb-Ti superconductingwire (Figure 5**)**. To prevent the wires from being scratched and also to provide electrical insulation, thesuperconducting wire is passed through fiber glass sleeves, right from the exit from the winding upto the electrical connections. Approximately, 50 cm of SC wire is kept free on both ends for electrical connections.

Now, the first layer of Nb-Ti wire is wound slowly and uniformly on a table-top winding machine after proper adjustment of former and winding-tension to avoid jumping or wobbling during winding.Adhesive is applied on the winding, on completion of first layer. Then, the second layer is laid followed by third, fourth etc.After every four layers, fiber glass cloth is wrapped on the winding with the same adhesive. This is done to provide strength to the superconducting winding to withstand the huge electromagnetic hoop-stress during current excitation. Any small amount of movement in magnet may quench the whole magnet. In this way superconducting winding is done for 26 layers, with 234 turns (on average) on each layer. Figure 6 shows the SC magnet after final layer winding. After the completion of the last layer, the winding is wrapped nicely with fiber glass cloth with sufficient adhesive (Figure 7). The outgoing-lead is then carefully taken through another slot on top flange using the same procedure adopted earlier. The whole winding is left for drying under normal conditions for one week (Figure 8).

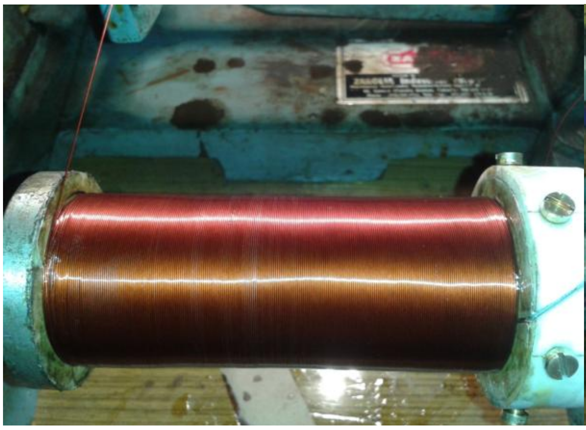

Fig 6 Final layer ofsuperconducting winding, without fibre glass cloth

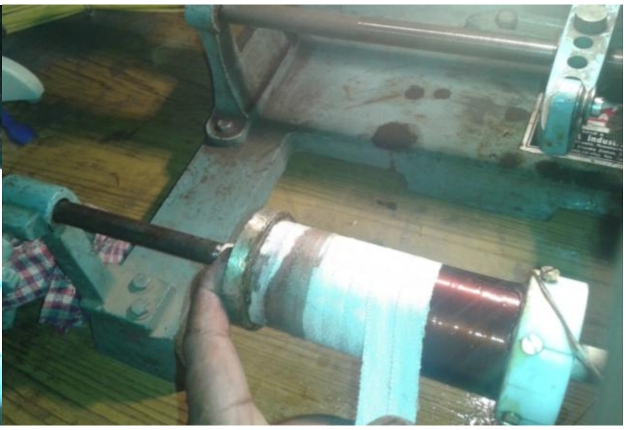

Fig 7 Fibre glass cloth being wound with adhesive on top of the final super conducting coil layer

Fig 8 CompletedSuperconducting magnet left for drying of adhesive

Fig 9 Racquet thread being wound on top of the fibre glass cloth wrapping for reinforcement

Once the adhesive is dried, the winding is covered tightly (external wrapping) with a badminton racquet string (Figure 9). This serves the dual purpose of giving the aesthetic look as well as providing mechanical strength to the SC winding. During coil energization, the developed electromagnetic hoop-stress is compensated by this external wrapping force, so that SC wire motion is avoided.

2.3 Current Lead Connections

Two square pieces of PCB Board (1 inch by 1 inch) are stuck to the top flange of the former with adhesive, keeping the copper portion on top side and Bakelite portion to the bottom side so that it is insulated from the former.The copper sides are tinned with lead-tin solder.The in and out leads of the coil are carefully soldered to these contact pads after removing insulation for some length, taking care of the insulation to the former. For this, the unsoldered end leads are kept inside of insulating sleeves that are stuck to the former with minimum stress.

Two conducting flexible copper strips are then used to connect these end points to the vapour cooled OFHC (oxygen free high conductivity) current leads supported from the top flange of the cryostat with insulating spacers. The SC wire of the two leads are run parallel to the braids for some length so that current does not flow through the braids in the portions dipped in helium, thereby avoiding joule heating nearer to the SC coil.

III. Testing of the Prototype Super Conducting Magnet

Testing of the in-house developed superconducting solenoidal magnet involves:

(a) Cooling of S.C magnet while monitoring R-T curve to confirmonset of superconductivity.

(b) Testing of SC coil for producing large magnetic fields (∼6 Tesla) by passing high currents at very low voltages.

(c) Testing the health of the coil after repeated quenching of the SC coil.

3.1 Cooling of Magnet & R-T Monitoring

Figure 10 shows the wheel-mounted double walled cryostat along with in-house developed SC magnet and its support structure. The vacuum jacket of the cryostat is evacuated to high vacuum (~10^{-5}mbar) using turbo molecular pumpand sealed by closing the vacuum valve. The liquid helium reservoir contains the provision for superconducting magnet, liquid Helium transfer inlet, liquid Helium level measurement, current leads to the magnet and probe for field measurement. The magnet is supported from the top flange using three stainless steel tubes to reduce conduction heat transfer (because of low thermal conductivity of steel with high tensile strength). The rods also support the radiation baffles arranged in the vapor space of the liquid helium reservoir. To reduce the cost, the radiation baffles are made of commercially available stainless steel plates with low emissivity. The top flange has got the necessary ports for helium recovery, liquid helium transfer lines, end connections of vapor cooled current leads (OFHC) and electrical feed-through for connecting the field probe and temperature sensor. The end connections of current leads are connected to power supply using a pair of good quality / high current copper cables. Care is taken to avoid any loose connection, which may produce large lethal voltages during charging / discharging of SC coil with ~1 henry inductance.

Fig 10: Magnet suspended from top flange by supporting rods shown along with the cryostat for testing.

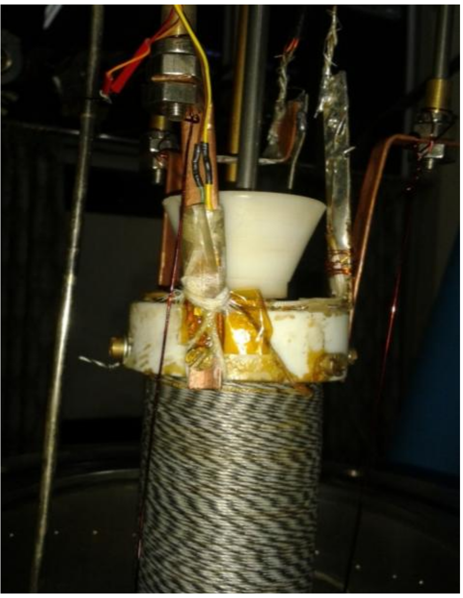

Fig 11: SC Magnet with current leads and sensors (temperature and field)

The cool down characteristic of super conducting magnet assembly is carefully monitored using a calibrated diode temperature sensor mounted at the top-edge of magnet (Figure 11). The support structure containing magnet is slowly inserted in the cryostat with the help of chain & pulley arrangement (Figure 12).

Fig 12 Magnet being inserted inside the cryostat, with the help of chain and pulley arrangement

Fig 13: Pre cooling of cryostat using liquid nitrogen

Cryostat and transfer lines are initially evacuated to 10^{-5} Torr using a turbo-molecular pumping station. This level of vacuum further improves at liquid Helium temperature during the experiment due to cryo pumping.

Before cooling the magnet to liquid Helium temperature, it is pre-cooled to 77 K temperature by liquid nitrogen (Fig 13). This minimizes the consumption of liquid Helium (LHe) required to further cool the magnet from 77K to 4.2K and for sufficient collection of LHe in the cryostat. Before transfer of LHe, the leftover liquid nitrogen employed for pre cooling must be boiled off from the liquid helium container. After all the liquid nitrogen is removed, the container is purged with Helium gas. The purging is necessary to avoid solidification of LN_2 if any present during cool down to 4.2 K with liquid Helium.

After ensuring the intact vacuum and pre-cooling of magnet to 77K, liquid Helium transfer line is inserted slowly into liquid Helium storage Dewar and magnet cryostat, keeping the venting (recovery) valves of the both closed. Due to self-pressurization of Helium Dewar from the evaporated liquid Helium (due to heat leak during insertion of transfer line), both cryostat and storage dewar attain a positive pressure. Now, if we open the vent of cryostat only, liquid Helium gets transferred from storage dewar to the cryostat, slowly cooling the magnet. After some time when the self-pressure comes down relatively, helium gas is used to pressurize the storage dewar for further transfer of LHe. At this stage, we also monitor the temperature and resistance of the superconducting magnet coil. The coil temperature slowly falls and after sufficient time when liquid Helium starts getting collected the magnet reaches a constant temperature of 4.2K. The transfer of liquid Helium is terminated after collecting liquid Helium to sufficient safe level (monitored by liquid Helium level detector) above the SC magnet.

While cooling to 4.2 K, the R-T curve shows a steady fall in resistance, finally reaching to zero resistance indicating that the magnet is in super conducting state. Sudden sharp transition could not be seen (normally observed in short sample) since the coil is made of long NbTi wire (approx 700m) with most of it in interior layers of SC coil covered by insulation and hence slowly cooled by conduction. This way, even after liquid helium is collected, different inner portions of the coil are cooled to superconducting state at different times. The coil is maintained in superconducting state by maintaining sufficient liquid helium above the coil. After attaining thermal equilibrium, the coil is tested for superconductivity by observing negligible voltage (measured by nano voltmeter) even with few amperes of current flowing. At this stage further experiments are carried out for magnetic field production (up to 6 T) using DC currents at low voltages up-to critical current (92 Amp at self-field) of SC coil.

3.2 Charging of SC Magnet and Measurement of Magnetic Field

After cool down of magnet to its superconducting state, it is tested for high current charging leading to generation of high magnetic fields. With the help of a commercially available power supply (Oxford

Instruments, Mercury iPS), different D.C. currents are passed in steps (up to quench) and the corresponding magnetic fields produced are measured using a Hall probe as shown in Figure 14. Figure 15 shows the axial field variation along the length of the magnet showing a field homogeneity over a length of approximately 4 cm in the middle.

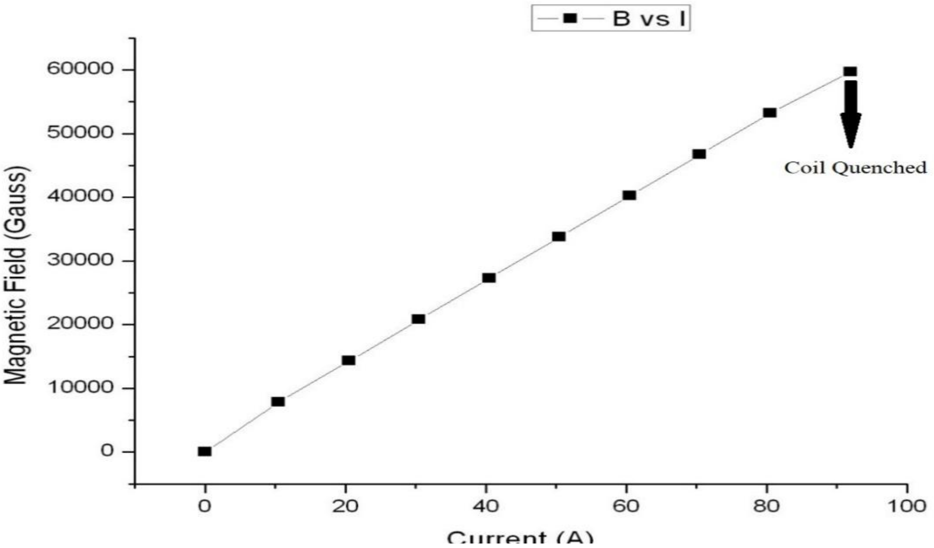

Fig 14 Current vs Central Field in thesuperconducting magnet till quench

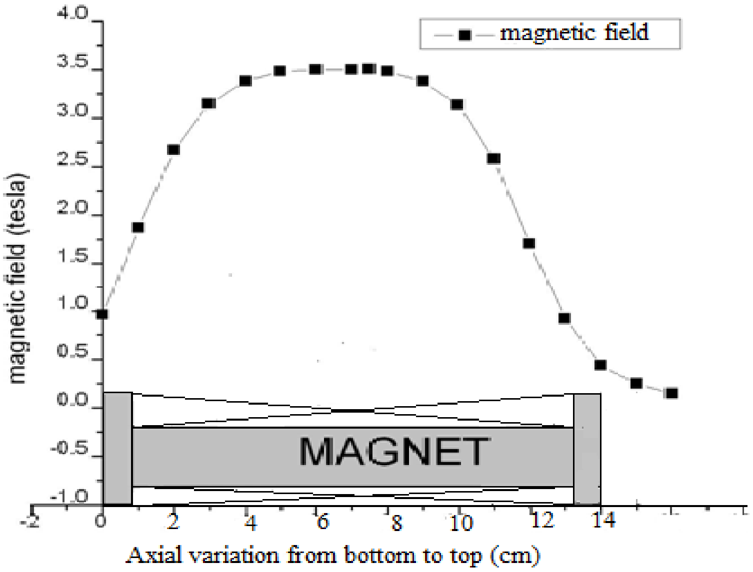

Fig 15 Field homogeneity ofsuperconductingmagnet at an operating current of 49.6 Amp

3.3Quench Test of The SC Coil

Usually the superconducting magnets are trainedby repeated/ controlled quenching of the magnet. Keeping this in mind, the present magnet is quenched by passing currents higher than the critical currents (at the corresponding generated fields). During quenching, a sudden vigorous boil off of helium is observed, due to transition from superconducting state to dissipative normal state of magnet. Precautions are taken to immediately reduce the current in order to safeguard the magnet and cryostat. After the quenching test, sufficient liquid helium is again transferred into the cryostat up to the safe level (higher than the magnet level), by monitoring the liquid helium level indicator. At this stage, the coil is again tested for high field production by passing various currents to ensure that the SC coil is not damaged. The current to field ratio obtained in this post quench test is in agreement with that of the virgin test (i.e before quenching). This way the SC magnet is trained by repeated quenching, taking all the safety precautions for coil and cryostat.

IV. CONCLUSIONS

A small prototype superconducting magnet (Bore dia= 15mm, Flange dia=60mm, length=140mm) using Nb-Ti superconducting wire was wound on an Aluminum former, with intermediate interlayer insulations and external wrapping.The magnet is supported by a suitable support structure with the necessary instrumentation for the monitoring of magnet temperature, liquid Helium level and the magnetic field produced.

The magnet is tested for superconductivity at Liquid Helium temperatures and the field to current ratio measured was in good agreement with calculated value. Thus the in house developed cost effective built superconducting magnet is successfully tested for high field production (up to 6T) giving confidence to produce larger SC magnets. The B-I curve of the SC magnet is linear with a constant ratio of 0.07T/A. The magnet is also tested for its safe recovery after quenching.

REFERENCES

[1]. M.N. Wilson Superconducting Magnets, Oxford University Press 83 ISBN 0-019-854805-2
[2]. R.G. Sharma, Superconductivity: Basics and Applications to Magnets (Springer, New York, 2015)
[3]. “Fundamental Elements of Applied Superconductivity in Electrical Engineering”, Yinshun Wang, Wiley Press, 2013.
[4]. “Design and Development of High Temperature Superconducting Magnetic Energy Storage for Power Applications- A Review”, Poulomi Mukherjee and V. V. Rao, Physica C: Superconductivity and its applications, Volume 563, August 2019, pp. 67–73.
[5]. “10 MW Class Superconductor Wind Turbine Generators”, by Gregory Snitchler, Bruce Gamble, Christopher King, and Peter Winn, IEEE Transactions on Applied Superconductivity, Vol. 21, No. 3, June 2011.
[6]. “Development and Testing of a 1G based High Temperature Superconducting (HTS) Double Pancake Coil for HTS Synchronous machines”, V A S Muralidhar Bathula, U K Chowdhury and V. V. Rao, Physica C: Superconductivity and its applications, Volume 562, March 2019, pp. 36–41.
[7]. www.snehamtapes.com/tapes_electrical.html

V.Ravindra, et. al. “Development of Cost Effective Lab Scale 6 Tesla Superconducting Magnet." *International Journal of Engineering Research And Development*, vol. 16(10), 2020, pp 20-28.