DESIGN, DEVELOPMENT AND TESTING OF Nb-Ti SUPERCONDUCTING MAGNET & CREATION OF LIQUID HELIUM TEST FACILITY

A THESIS SUBMITTED IN PARTIAL FULFILLMENT

OF THE REQUIREMENTS FOR THE DEGREE OF

Master of Technology (Res.)

in

Mechanical Engineering

By

VUTUKURU RAVINDRA

Roll No-611ME303

Department of Mechanical Engineering

National institute of Technology

Rourkela

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CERTIFICATE

This is to certify that the work reported in this thesis entitled “**DESIGN, DEVELOPMENT AND TESTING OF Nb-Ti SUPERCONDUCTING MAGNET & CREATION OF LIQUID HELIUM TEST FACILITY**” being submitted by Shri Vutukuru Ravindra (Roll no: 611ME303) for the degree of Master of Technology (By Research) in the Department of Mechanical Engineering, National Institute of Technology, Rourkela has been carried out under our guidance and supervision.

To the best of our knowledge, the matter embodied in the thesis is a bonafide record of work carried out by Shri Vutukuru Ravindra and has not been submitted to any other University / Institute for the award of any Degree or Diploma.

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Place: NIT Rourkela

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ACKNOWLEDGEMENTS

I take immense pleasure in thanking my supervisors Prof.S.K.Sarangi, Director NIT Rourkela and Prof P.N.Vishwakarma for guiding me with encouragement throughout my project period.

I wish to express my deep sense of gratitude to Prof R.K.Sahoo for his encouragement and useful suggestions, which helped me in completing the project work.

I am sincerely thankful to Prof K.P.Maity, Head, Department of Mechanical Engineering and my DSC members (Prof A.K.Panda and Prof S.Panigrahi) for their advice and guidance.

The help from Mr.Uttam Bhunia, Mr.Subimal Saha and Cryogenic facility staff of VECC Kolkata in providing the experimental facilities to test the magnet, is thankfully acknowledged

I wish to express my sincere thanks to Mr.Soumen Kar, Mr. D.Rajasekhar, Mrs Poulomi, Ms. Ipsita Das and Mr Nageswar Rao for their timely help in the conduct of my project work. I would also like to thank Mr Mohan Lal Ghosh, Mr Naren Bisoyi, Mr Somnath Das for their valuable assistance in the project work.

Finally, yet importantly, I would like to express my heartfelt thanks to my beloved parents for their blessings, my friends/colleagues (Ajay Gupta, Sachindra Rout, Pankaj Singh, Balaji Ku. Chowdhary, Achuth Biswal, Jashashree Ray, Kiran Kumar Gurrala, D.Koteshwar Rao, Rajendra Prasad,Kishore Ragi) for their help and wishes for the successful completion of this project.

Any omission in this brief acknowledgement does not mean lack of gratitude.

VUTUTKURU RAVINDRA

ABSTRACT

Research in the area of advanced materials for various applications is the demand of time. Discovery of nano technology, high Tc superconductivity and multi functional materials are just few of them. For proper understanding of the underlying physics, Low temperature investigations on these materials are very much needed. If magnetic field is added to low temperature, sometimes new insights are witnessed e.g., superconductivity, quantum Hall effect etc. Intense efforts are going on around the world to make simple and inexpensive superconducting magnet systems for performing variable temperature experiments on the above materials under high magnetic fields. Keeping in view of these facts, a lab scale mobile superconducting magnet system is designed and developed in house using Nb- Ti wire (0.43 mm nominal diameter, Cu: SC Ratio of 2:1) and tested for production of 6 Tesla field and repeated quenching of the coil. The thesis describes the step-by-step procedure involved in winding and testing of the superconducting magnet. Further, a simple commercially available Liquid Helium transport dewar is suitably modified for magnet insertion with necessary instrumentation for liquid helium transfer port, hall field-probe, LHe level indicator, temperature and field sensors, power supply and vapor cooled current leads etc. The magnet is tested in a commercially available cryostat, available at VECC Kolkata.

In a parallel effort, the present thesis also describes the setting up of Liquid Helium production and magnet testing facility along with necessary vacuum and electrical instrumentation. The out come of the present thesis is expected to accelerate the growth of Cryogenic/Vacuum/Applied Superconductivity research at NIT Rourkela.

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CHAPTER 1

INTRODUCTION AND LITERATURE SURVEY

1.1 INTRODUCTION

The year 2011 saw the completion of 100 years of discovery of superconductivity by Prof H. Kammerlingh Onnes and his students at Leiden University, Holland. Since then, the area of superconductivity has inspired many researchers and technologists for its basic understanding and possibility of technological applications. During several years of research, many unsolved mysteries of superconductivity have been addressed, leading to technological advancements. One such property which has been understood well is the classification into type I and type II superconductors.

1.1.1 Type I and II superconductors

It was observed that the phenomenon of superconductivity is susceptible to the prevailing conditions and ceases to exist beyond a boundary constituted by temperature; magnetic field and current density (**Figure 1.1**). Interestingly these boundaries separating the superconducting and non-superconducting (here onwards called normal) states are sharp for elemental metals whereas the boundaries are broad for alloys & compounds. The superconductors with sharp boundaries are called type I where as those with broad boundaries are called type II superconductors. Type I superconductors seldom find any technological applications, except in understanding of underlying fundamental physics. It is the type II superconductor which is of great many technological applications. Surprisingly the key to that many applications is the boundary region: wider the boundary region, higher the applications. The boundary region is called vortex state or mixed state (see **Figure 1.2**).

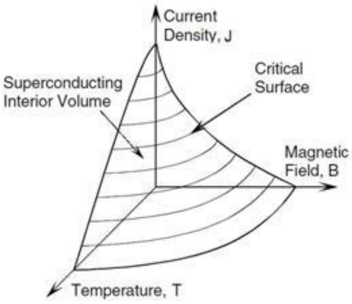

Fig 1.1: Critical surface of a Type II Superconductor (http://www.lhc-closer.es/1/4/8/0)

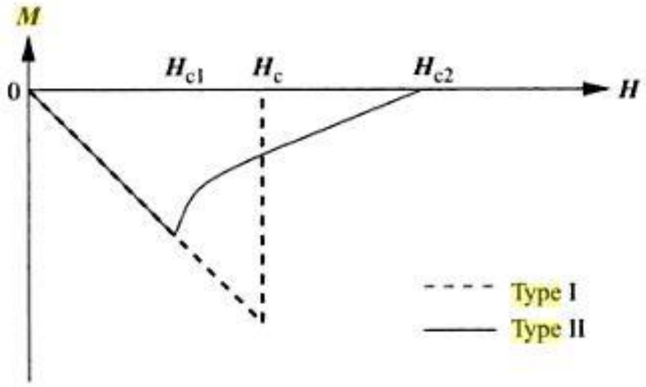

Fig 1.2 Magnetization versus applied magnetic field for type I and type II superconductors

Figure 1.2 shows the phase diagram of superconductors as a function of applied magnetic field. Similar phase diagrams exist in terms of current density and temperature. According to the figure, it is found that in type I superconductors, the internal magnetic field is zero (as expected from the Meissner effect) until a critical magnetic field, H_c, is reached when a sudden transition to the normal state occurs. This results in ~~the~~ penetration of the applied field into the interior. Type II superconductors, on the other hand, respond differently to an applied magnetic field. An increasing field from zero results in two critical fields, H_{c1} and H_{c2}. At H_{c1} the applied field begins to partially penetrate into the interior of the superconductor. The zero resistance state, however is still maintained till H_{c2} is reached, above which the material behaves like a normal conductor. For applied fields between H_{c1} and H_{c2}, the field is able to partially penetrate the superconductor, ~~so~~ the Meissner effect is incomplete, allowing the superconductor to tolerate very high magnetic fields and currents (**Figure 1.3**).

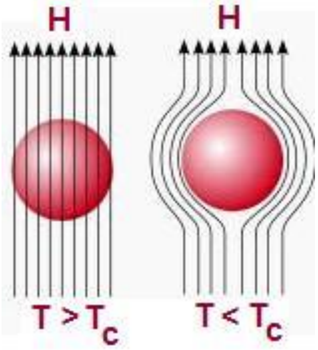

Fig 1.3 Meissner Effect (http://www.lhc-closer.es/1/4/8/0)

Type II superconductors are most technologically useful because the second critical field Hc_2, can be quite high, enabling high field electromagnets to be made out of superconducting wire. Wires made from say niobium-tin (Nb_3Sn) having H_{c2} value as high as 24.5 Tesla are useful in applications requiring high magnetic fields, such as Magnetic Resonance Imaging (MRI) machines. As a comparison, the strongest permanent magnet available today is able to produce a field no more than 1 Tesla.

In a type I superconductor the coherence length ξ, (length over which superconductivity changes) is bigger than the penetration depth λ.

In a type II superconductor the coherence length is shorter than the penetration depth. Then it is energetically favorable for vortices to form.

Coherence length is a measure of the distance within which the superconducting electron concentration cannot change drastically in a spatially-varying magnetic field.

Penetration depth characterizes the distance to which a magnetic field penetrates into a superconductor and becomes equal to **1/e** times that of the magnetic field at the surface of the superconductor

The ratio $\kappa = \lambda/\xi$, where λ is the London penetration depth, is known as the Ginzburg–Landau parameter. Type-I superconductors are those with $0 < \kappa < 1/\sqrt{2}$, and type-II superconductors are those with $\kappa > 1/\sqrt{2}$.

For temperatures T near the superconducting critical temperature T_c, $\xi(T) \propto (1-T/T_c)^{-1}$.

1.1.2 Low Temperature Superconductors (LTS) and High Temperature Superconductors (HTS)

For nearly 4 decades after the discovery of high field superconductors, the LTS materials such as NbTi and Nb3Sn dominated the scene. These materials are cooled by liquid helium, as the maximum Tc_0 (i.e at zero field) technologically useful superconductor is around 15 K. These materials, listed in Table 1.1, are known as Low Temperature Superconductors (LTS). In view of the excessive cost and inconvenience of using liquid helium, the applied superconductivity aspect was very limited, mostly in low temperature physics laboratories and medical domain (MRI).

However after the discovery of superconductivity in La-Sr-Ca-Cu-O at 40K by Bednortz and Muller, the situation rapidly changed. Within few years several useful compounds with Tc_0 above the liquid nitrogen temperature (77K) were discovered. These materials popularly known as High Temperature Superconductors (HTS) are listed in Table 1.2 along with their critical temperature Tc_0. Today the metallurgy of these brittle HTS materials is well developed to realise few kilometers of continuous tape for power and nuclear applications.

ELEMENT/COMPOUND	Tc_0 in K	Hc_0/Hc_2 (at 4.2K)in T	J_{c0} in A/mm^2	λ_0 (nm)	ξ_0 (nm)
Pb	7.19	0.053	$1.2*10^6$	37	83
Sn	3.72	0.031	10^6	34	230
Nb	9.25	0.195	2000	39	38
Nb_3Sn	18.3	24	4700	65	3
Nb_3Ge	23.0	38	200	90	3
Nb_3Ga	20.3	34	280	200	3.5-20
Nb_3Al	19.0	33	1000	210	3.5-20
V_3Ga	15.0	23	10000	90	3
V_3Si	17.1	23	1300	60	3

Table 1.1 List of LTS materials and their respective properties (http://en.wikipedia.org/wiki/List_of_superconductors)

In Table 1.1, the first two materials are Type I superconductors whereas the remaining materials belong to Type II.

COMPOUND	T_{c0} in K	Hc_2 in T	J_c in A/mm^2	λ_0 (nm)	ξ_0 (nm)
$Bi_2Sr_2Ca_2Cu_3O_x$ (BSCCO-2223)	105	150T	10000	210	1.6
$Bi_2Sr_2CaCu_2O_x$ (BSCCO-2212)	80	225T	930	269	1.6
YBCO	90	120T for ⊥ field and 250T for ∥ field	$2*10^5$	λ_{ab}=150nm λ_c=800nm	ξ_{ab}=2nm ξ_c=0.4nm
$HgBa_2Ca_2Cu_3O_8$	133	108T	62	206	1.8

Table 1.2 List of HTS materials and their respective properties (http://en.wikipedia.org/wiki/High temperature_ superconductor)

1.2 LITERATURE SURVEY ON SUPERCONDUCTORS

1.2.1 Applications of superconductors

The first large scale commercial application of superconductivity was in magnetic resonance imaging (MRI). This is a non-intrusive medical diagnostic technique that after substantial computer processing creates a three-dimensional image of say tumors and other abnormalities within the body or the brain. This requires a person to be placed inside a large and uniform electromagnet with a high magnetic field. Although, in principle, normal electromagnets can be used for this purpose, finite electrical resistance of copper wire limits the maximum current to be passed, thereby limiting the magnetic field. Moreover, because of finite resistance, large amount of heat is generated with commensurate cooling requirements. Superconducting magnets on the other hand have almost no power requirements apart from maintaining the cryogenic temperature. Once electrical current flows in the superconducting wire, power supply can be switched off and the current will persist indefinitely as long as the temperature is kept below the transition temperature of the superconductor.

Superconductors can also be used to make devices known as a Superconducting Quantum Interference Devices (SQUID). This is incredibly sensitive to small magnetic fields. It can detect the magnetic fields generated by the heart (10^{-10} Tesla) and even the brain (10^{-13} Tesla). For comparison, the Earth's magnetic field is of the order of 10^{-4} Tesla. As a result, SQUIDs find wide range of applications, including non-intrusive medical diagnostics of the brain.

A Josephson junction (JJ), used in transistors, digital electronics, quantum computing etc consists of a pair superconducting films coupled by a weak link. The weak link can consist of a thin insulating barrier (known as a superconductor–insulator–superconductor junction, or S-I-S), a short section of non-superconducting metal (S-N-S), or a physical constriction that weakens the superconductivity at the point of contact (S-s-S).

The traditional use of superconductors has been in scientific research where high magnetic field electromagnets are required. The cost of keeping the superconductor cool is much smaller than the cost of operating normal electromagnets, which dissipate heat and have high power requirement. One such application of powerful electromagnets is 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 new fundamental 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. Further, superconducting magnets are essential in nuclear fusion systems for huge energy production (details given in next section).

Levitating trains have been built that use powerful electromagnets made from superconductors. Superconducting electromagnets are mounted on the trains, normal electromagnets, on a guideway beneath the train, repel the superconducting electromagnets to levitate the train while propelling it forwards.

Recently, after the high T_c superconductors are made available in long lengths (>100mtrs), electrical engineers are continuously working on using them for power applications such as superconducting cable, motors, fault current limiters (SFCL) and energy storage systems(SMES).

1.2.2 Uses of Superconducting Magnets

1.2.2.1 Research magnets

It is now standard practice to use superconducting magnets to be used in scientific research involving large magnetic fields. They are cheaper to buy, more compact and can produce higher fields. They are used in a wide range of experimental work, including magneto-optics, Mossbauer effect, nuclear magnetic resonance, several areas of solid state physics, and on a prototype basis in high resolution lenses for electron microscopy.

1.2.2.2 High energy physics

Magnetic fields are used extensively in high energy physics research to accelerate, focus, manipulate and analyse the beams of energetic charged particles which are used to investigate the fundamental structure of matter. A large laboratory for such research consumes nearly 100 MW of electrical power, most of which is expended in the production of magnetic fields by means of conventional electromagnets. Superconducting magnets are being used increasingly because they save energy and also because they produce higher fields.

Collisions between particles are often studied by means of large bubble chambers which make the tracks of charged particles visible as a line of tiny bubbles. It is very helpful to know the momentum of each particle, and this may be calculated from the curvature of its track in a magnetic field. Very large magnets are therefore used to produce a field over the whole chamber volume. Nowadays these magnets are almost always superconducting because it has been established quite conclusively that the capital cost of a superconducting magnet is cheaper than a conventional system (when power supplies and cooling water are taken into account). Further, the superconducting magnets are safer and convenient to run, as they are free from Iron and operate at very low voltages.

1.2.2.3 Nuclear Fusion

Very large and powerful superconducting electromagnets are being used in possible future energy sources based on nuclear fusion. When two light nuclei combine to form a heavier nucleus, the process is called nuclear fusion. This results in the release of large amounts of energy without any harmful waste. Two isotopes of hydrogen, deuterium and tritium, will fuse to release energy and helium. Deuterium is available in ordinary water and tritium can be made during the nuclear reactions from another abundantly available element – lithium. For this reason it is called clean nuclear energy. To realise this reaction, the deuterium and tritium gases must be heated to millions of degrees so that they become fully ionized. As a result, they must be confined in space so that they do not escape while being heated. Powerful and large electromagnets made from superconductors are capable of confining these energetic ions. An international fusion energy project, known as the International Thermonuclear Experimental Reactor (ITER) is currently being built in the south of France that will use large superconducting magnets and is due for completion in 2017. It is expected that this will demonstrate energy production using nuclear fusion.

1.2.2.4 Magnetohydrodynamic power generation

Magneto hydrodynamic (MHD) power generation is a technique for the direct conversion of thermal energy to electrical energy. On a much shorter time scale than fusion, it could be making significant savings in the use of fossil fuels by improving the efficiency of electrical power generation. An MHD generator uses the hot combustion gases directly as its working substance, thereby enabling higher conversion efficiency. The gases must first be made electrically conducting by doping them with an easily ionized ‘seed’ material such as potassium. They are then made to flow through a duct in a transverse magnetic field. The usual dynamo effect causes an e.m.f to be induced in this moving gaseous conductor and d.c electric power may be extracted from electrodes lining the duct.

Like the fusion reactor, MHD generators must have superconducting magnets if they have to produce more power than they consume. A dipole winding is used to produce the necessary transverse field- similar to an accelerator magnet but much larger.

1.2.2.5 D.C. motors

Superconducting electric motors can be more efficient, smaller, and much lighter than conventional motors which always use generous quantities of iron in their armature and field cores. The advantages of a superconducting motor are most apparent in the largest sizes, especially where high torque at low speed is required, in marine propulsion or rolling mill drives. Several prototypes of quite substantial size have been built, although non are yet in regular service. In all these prototypes, only the stationary field winding has been made superconducting, with the rotating armature remaining at room temperature. This arrangement avoids not only the problems of a rotating cryostat and the transmission of large torques between room and low temperatures but also the energy dissipation which would be caused by relative motion between superconductor and field. All prototypes so far have used the homopolar principle, which is based on the Faraday disc. A normally conducting disc, placed within the bore of a superconducting solenoid, has current fed into its centre and extracted from its periphery by means of sliding brushes. Under the influence of its radial current and the axial field, the disc rotates. Note that this configuration has the advantage of producting no torque reaction or field fluctuation on the superconducting solenoid. Various elaborations of the basic principle are possible, with multiple or segmented discs or drums.

1.2.2.6 A.C. motors

Unfortunately the dissipation of energy due to flux motion is far too great to permit the use of superconductors in high fields which are oscillating at power frequencies. Ripples of small amplitude, possibly superimposed on a d.c. level, may be tolerated however and thus possibilities exist for using superconductors to produce d.c fields in a.c. machines. The prime contender is the a.c. generator, which normally takes the form of a two- or four-pole d.c. rotor, rotating at synchronous speed within a three phase a.c. stator winding.

Similarly in a.c. motors, only one component may be made superconducting. This time it must be the rotor and the design of a cryostat to rotate at 50-60 Hz with a centrifugal acceleration of some 5000g raises many technical problems. In spite of these difficulties, several prototype machines have been built and most of the world’s generator manufacturers are now carrying out research in this area. It is thought that the superconducting machine should be very competitive at all ratings above about 300MW (**Figure 1.4**).

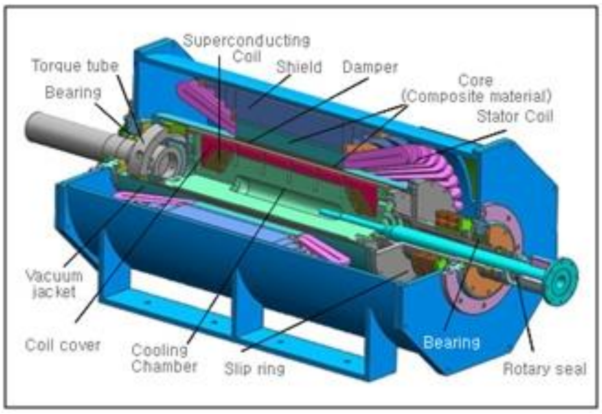

Fig 1.4 Superconducting AC Machine (http://engineering.electrical-equipment.org/electrical-distribution/super-conducting-generators.html)

1.2.2.7 Superconducting Fault Current Limiter

Superconductivity is also used in an ingenious device for the protection of a.c. power systems against damage by accidental short circuits. Known as superconducting fault current limiter(SFCL), it is based on the saturable reactor principle and uses normal room temperature windings to carry the 50-60 Hz line current. These windings are magnetically coupled to soft iron cores which give them a very high self inductance. Also coupled to the iron is a d.c superconducting coil (magnet) which is sufficiently powerful to completely saturate the iron. Under normal operating conditions the self-inductance of the a.c. coils is therefore quite low because the saturated iron has very little effect. If the a.c. current is sufficiently large during fault condition, however it will take the iron out of saturation during those half-cycles in which a.c. and d.c. fields are in opposition to each other. In other words, the self inductance of the a.c. coils will rise automatically to block an incipient high current caused by a short circuit occurring somewhere in the system. Symmetrical blocking of the fault current may be achieved by using a pair of a.c. coils connected in series opposition so that successive half cycles are blocked by alternate coils (**Figure 1.5**).

Fig 1.5: Superconducting Fault Current Limiter

(http://iopscience.iop.org/0953-2048/25/10/105011/article)

1.2.2.8 Energy storage

The energy density of a 10T field is $B^2/2\mu_0 \sim 4 \times 10^7\ Jm^{-3}$, which is considerably higher than capacitor banks, comparable with flywheels, and rather less than batteries. Superconducting magnetic energy storage (SMES) magnets have therefore been proposed for a variety of applications where it is necessary to transfer electrical energy back and forth: the magnets in a pulsed accelerator for example in the pulsed toroidal coils of a tokomak. On a much grander scale, it has even been suggested that very large magnets of roughly 100 m diameter might be used to even out the daily variations in electrical power demand. These magnets would be situated in tunnels deep underground and would use the natural bedrock to support their enormous electromagnetic forces.

Extracting the energy from SMES presents some difficulties. If the load is purely resistive, one may simply open a switch which diverts the magnet current into the resistor, but this process is not well controlled and will not work for inductive loads. A better proposition is to electrically invert the magnet current through a transformer which is coupled to the load. If the load is purely inductive, an energy storage capacitor must be connected in the inverter circuit. It is also possible to use arrays of coils which are allowed to move, thereby changing their mutual inductance and transferring energy from one to the other.

Tripathy S.C. [**1**] has discussed about the design and test results of a 30MJ Superconducting magnetic energy storage device which was built and field tested by the Bonneville Power Administration in USA in 1982 (**Figure 1.6**).

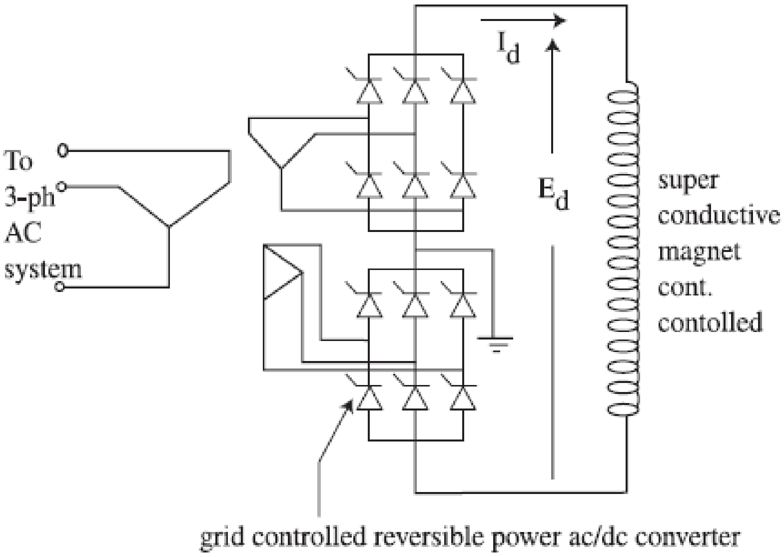

Fig 1.6: Basic circuit elements for SMES unit for power system applications [1]

1.2.2.9 Magnetic separation

All materials become magnetized to some extent when placed in a magnetic field. The magnetization M, defined as magnetic moment per unit volume, will be large in ferromagnetic materials, small in paramagnetic materials, and small and negative in diamagnetic materials. In the presence of a field gradient, these materials will experience a force per unit volume, F= M X gradient|H| which pushes paramagnetics towards the high field and diamagnetics away from it. These forces have long been used in industry to concrete iron ores to separate scrap iron from other materials. In recent years there has been a growing interest in applying similar processes to the separation of finely divided and weakly magnetic materials. To produce the maximum force, gradient |H| must be as large as possible and so must M be, which, for a given material, means that H must also be large. The highest field gradients have so far been achieved by using magnetized iron in the form of very fine filaments which produce high-field gradients in their immediate vicinity. A bundle of these filaments, i.e. a mass of steel wool, may thus be used as a magnetic filter, trapping all magnetic particles passing through it. To minimize frictional and electrostatic forces, the process is usually carried out wet, i.e. with the particles suspended in slurry. High gradient magnetic separation is already being used to remove iron impurities from china clay, to purify steel mill effluents, and to concentrate low grade iron ore. It seems likely that it will also be used in other processes of mineral extraction, water purification, chemical engineering, and the removal of sulphur from coal. Commercial units to date use conventional copper magnets, but it is already clear that superconducting magnets can offer substantial improvements in separation performance and energy consumption.

1.2.2.10 Magnetic levitation

The idea of floating a vehicle on magnetic fields is not new; it was first demonstrated by Bachelet in 1912 and has been discussed at regular intervals ever since. The advent of superconducting magnets, with their ability to produce high fields cheaply with low energy consumption and small weight penalty, brought a new dimension to the old debate (Rhodes and Mulhall 1981). As a result of this, magnetically levitated transport is now attracting attention in several countries where the wheels are not actually touching the track. The wheels are needed at low speed but not at high speeds, when the vehicle is levitated on a cushion of magnetic field and propelled by a travelling wave of magnetic field. There are no moving parts to wear out or make a noise, the ride is smooth, and high speeds may be reached safely.

1.2.3 Availability of Superconducting Magnets

Superconducting magnets are available at many places in the world, like in the United States at:

- Indiana University
- Sandia Laboratory
- University of Colorado
- Purdue University
- University of California
- NASA-Lewis
- Oak Ridge National laboratory, NRL (Naval Research Laboratory) and
- Carnegie-Mellon University.

In Japan at:

- Tokyo University
- Japanese National Research Institute for Metal.

In Russia at:

  - Lebedev Physical Institute
  - Electronics Institute at Moscow.

In Germany at

- University of Wurzburg.

In England at:

- Clarendon laboratory in Oxford.

In Brazil at:

- University of Sau Paulo

In Poland at:

- International Laboratory of High magnetic fields and low temperatures.

And in India at:

- IUAC, New Delhi
- IIT Kharagpur
- NIT Rourkela
- BARC Mumbai
- VECC Kolkata
- SSPL New Delhi
- NPL New Delhi
- RRCAT Indore
- IPR,Ahmedabad
- IISc, Bangalore
- TIFR, Mumbai

1.2.4 Literature Review on various aspects of Superconducting magnets.

The first superconducting magnet was built by George Yntema in 1954 using niobium wire and he achieved a field of 0.71 T at 4.2 K **[2]**. Though the field achieved was not very high, but this definitely opened a new door of applied superconductivity. Seven years later in 1961, another discovery by Kunzler that superconductivity in Nb_3Sn persists till 88kGauss, indicated a possibility of using this material for generation of fields up to 8.8 Tesla [**3**]. Since then many compounds and alloys of transition metals were tried for high Hc and high Tc, and it was found that Nb-Ti alloys could reach a Hc of 14.5 Tesla [**4**]. Since then, Nb-Ti is available in long length and has been the work force of superconducting magnets.

Recently high Tc superconductors (T_c>77K) are coming slowly to market for possible applications. In spite of intense research in this area the major hurdle for the commercialization of superconducting wires was the brittle nature of these alloys. Due to this, it was very difficult to draw them into long length wires. With the advancement in the technology of powder-in-tube method, making of superconducting wire of several kilometers is no more a difficult task [**5, 6**]. Commercially the superconducting magnets made of these wires are coming up. Still in our country, one has to pay higher amount to purchase superconducting magnet, as none of the companies are of India based. Hence, many Indian researchers have put effort in making superconducting magnets using low T_c Superconductors. R.G.Sharma, who is considered a pioneer of making superconducting magnets in India, has made several Nb-Ti superconducting magnets of various designs and field strength **[7]**. Recently P Khatua et al [**8**] designed and fabricated a 6.5 T superconducting magnet and a magneto transport measurement set-up. The performance of the apparatus is tested over a range of temperatures and fields upto 6.5T. Magneto transport data is also obtained with excellent temperature and field stability. (**Figure 1.7**)

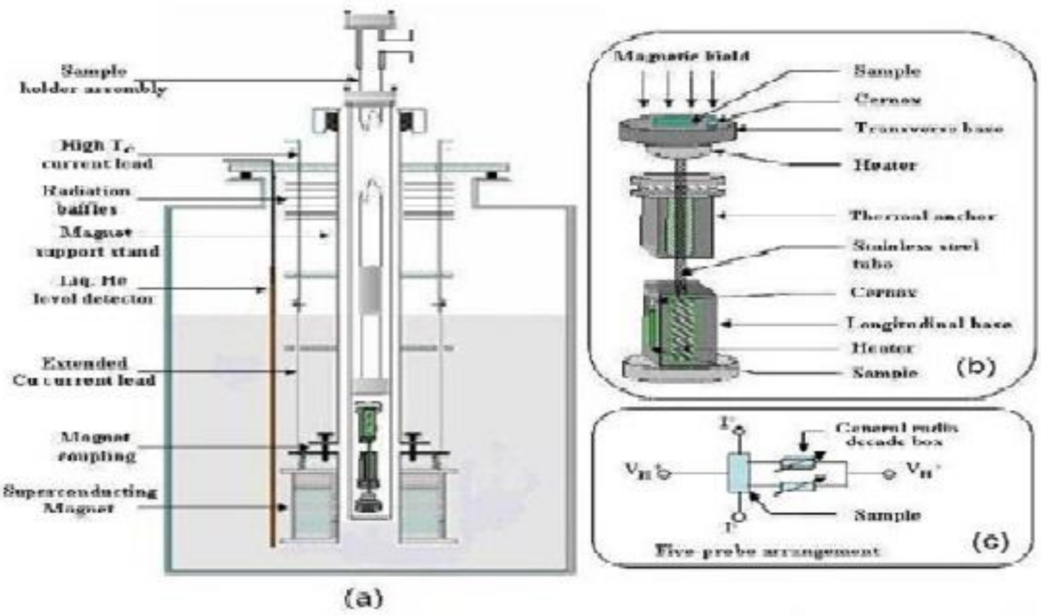

Fig 1.7: Schematic diagram of (a) the magneto-transport setup consisting of a 6.5 T superconducting magnet and a variable temperature sample holder assembly, (b) detailed design of the sample holder for electrical measurements in longitudinal and transverse orientations of the samples with respect to the magnetic field and (c) Five-probe arrangement for Hall effect measurement. **[8]**

Lankai li et al [**9**] have analyzed the effect of pretension, support structure and cool down on mechanical disturbances of superconducting coils. It has been observed that a reasonable pretension increases the stability of a superconducting magnet. M.Z.Guan et al [**10**] have measured the stress and strain on a 5T superconducting magnet during coil excitation. They compared the theoretical and experimental values and found good agreement. One of the biggest challenge in making a large field magnet is the cooling of magnet and immediate dissipation of heat produced during any possible quench. In this direction, large bore superconducting magnet with narrow liquid helium channels are designed, manufactured and tested by Baozhi Zhao et al [**11**]. The magnet reached the designed maximum operating current of 305A through stops at 100A, 150A, 200A, 250A, 280A and 300A (**Figure 1.8**). No quenching is observed during the whole charging process.

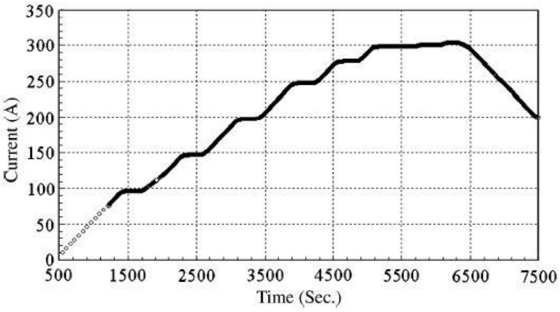

Fig 1.8: Magnet charging process [11]

With time, magnetic field strength of superconducting magnets increased by large amounts leading to storage of large energy in the magnet. But, this also increased the risk of accidents while quenching of magnet and hence protection against quenching became very essential. H.Schultz [**12**] analysed these issues of quench protection and quench simulation in superconducting magnets. Here, the protection is considered as the problem of rapidly detecting an irreversible loss of superconductivity (quench) and converting the magnetic stored energy to thermal energy (dump) without permanent damage (protection) to the s.c. coil. While fabricating superconducting magnets one should consider methods for avoiding all structural and electrical failure mechanisms through proper design, fabrication and operation of a magnet. J.K.Lee et al [**13**] have investigated about the Quench Dynamic characteristics in an epoxy impregnated superconducting magnet. The investigation is done by both experimental methods and simulation methods. The quench is induced by a ring heater located at the inside of the magnet mid plane. Two dimensional quench phenomena can be simulated by calculating longitudinal and transverse propagation velocities using conventional formula. For calculating transverse quench propagation velocity, the resistive voltage components are separated from the simulated voltage tap signals. Y.Iwasa [**14**] has reviewed mechanical disturbances in superconducting magnets. The advances in identifying the disturbances have been discussed. Monitoring the magnet by acoustic emission technique is used to confirm definitely that mechanical disturbances, particularly conductor motion and epoxy fracture are the principal causes for premature quench in high performance magnets. C.Schmidt [**15**] has investigated the stability of superconductors in rapidly changing magnetic fields. In this, a stability model is developed which compares the energy coupled into the conductor by the field pulse with the energy which can be absorbed by the surface near the helium layer due to the transient heat transfer.

Guillaume Donnier- Valentin [**16**] has discussed about various design and theoretical aspects of superconducting magnets. It includes designing of a superconducting magnet with different wires (Nb-Ti, Nb_3Sn, BSSCO, MgB_2 and YbCo), insulations, impregnation process etc.Okada et al [**17**] have examined the effect of mechanical disturbances on stability of impregnated windings. The changes of the macroscopic mechanical properties have been measured in terms of load-displacement curve and the stress analyses are made by finite element method (FEM). It has been confirmed experimentally that the epoxy crackings and bond failures could induce the rigidity degradation and cause heat generation which could lead to a cause the premature quench. Schwartz J [**18**] has discussed about the issue of quench in high temperature superconducting magnets and also suggested potential solutions driven by new technologies such as optical fiber based sensors and thermally conducting electrical insulators.

Tony Tadic et al [**19**], have presented a method for optimal design of superconducting magnet systems for magnetic resonance imaging (MRI). This magnet has been made from MgB_2 high temperature superconducting material that operates in conduction cooled cryogen free environment. Mantone et al [**20**], have patented a method of making insulated superconducting magnet coil using a crepe paper which is wound initially and on which the superconductor is wound. Again on the coil, crepe paper is wrapped which acts as an insulating and friction reducing component. S.Yokoyama et al [**21**], have designed, fabricated and tested a cryogen free conduction cooled NbTi superconducting magnet for X-band Klystron experiments (**Figure 1.9**). The rated field of the magnet is 0.7T and the coil is cooled by a two stage GM cycle refrigerator. The magnet is expected to produce 5T field when operating current of the coil is 100% of the load line at 4.2K.

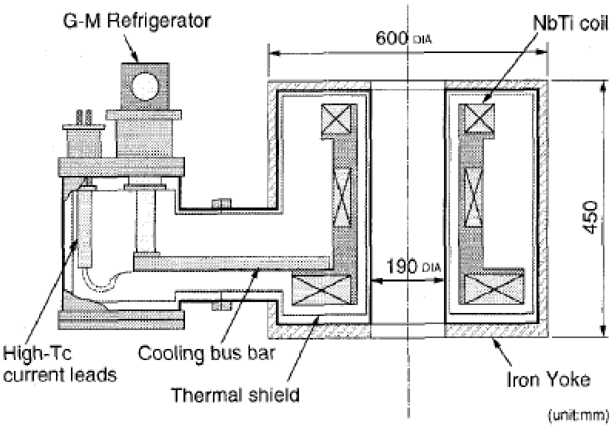

Fig 1.9: Schematic structure of the conduction cooled superconducting magnet for the X-band klystron [21]

Martin N Wilson [**22**] has discussed about the superconducting materials for magnets from three viewpoints: firstly the basic physical properties of the materials themselves, secondly the constraints and preferences imposed by the requirements of magnet building and finally the manufacture of magnet conductors as a commercial product. Choi Y.S. et al [**23**], have designed, fabricated and tested a conduction cooled cryogen free superconducting magnet (**Figure 1.10**) with room temperature bore. The temperature distribution along the conductive link was measured during the cool down process as well as at steady state. It has been observed that an indium sheet between the cold head and cooling plate had a higher effective contact conductance than that of cryogenic grease.

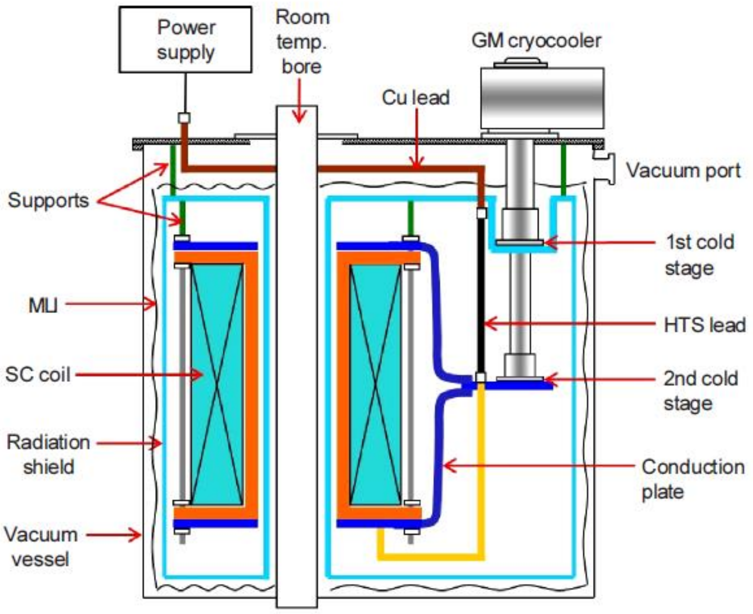

Fig 1.10: Conduction cooled cryogen free superconducting magnet system with room temperature bore [23]

Watazawa K et al [**24**] have designed a mobile cryocooler cooled 6T NbTi superconducting magnet with room temperature bore of 220mm (**Figure 1.11**). A mechanical persistent switch has been used to limit the load from the switch into the 4K GM cryocooler.

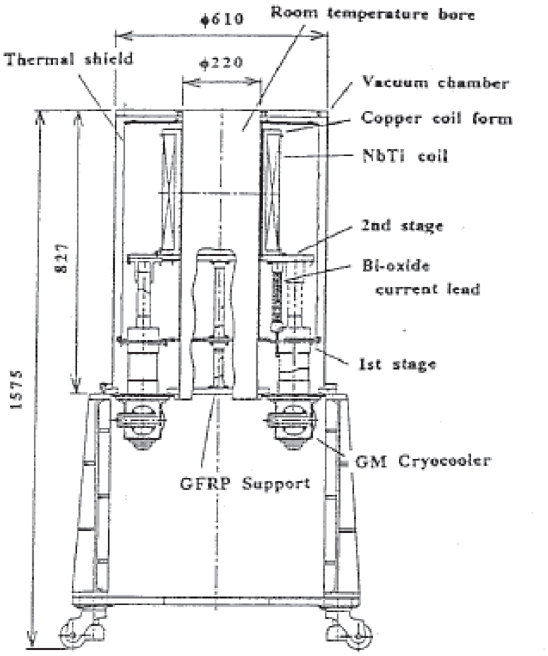

Fig 1.11: Sectional view of the cryocooler cooled 6T NbTi superconducting magnet with room temperature bore of 220 mm [24]

Kozak S et al [**25**] have analyzed a NbTi magnet for an OGMS (Open Gradient Magnetic Separation) separator cooled by commercial SRDK-408 cryocooler (**Figure 1.12**).

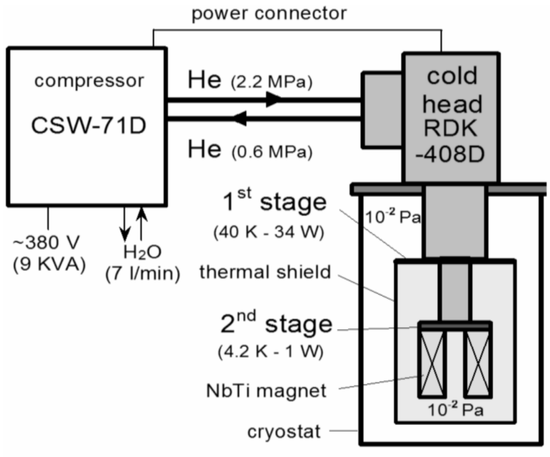

Fig 1.12: The NbTi magnet cooled by a commercial SRDK-408 cryocooler [25]

Nowack Gerd F [**26**] , has designed a novel approach to the superconducting magnet coil systems for high resolution NMR- Spectroscopy. It is found that field homogeneity for different current densities can be achieved by a special winding technique and best results can be found using non-rectangular cross sections.

K Venkataratnam et al [27], have optimized the superconducting magnet coil for a micro SMES unit (**Figure 1.13**). The difference between the design of a solenoid coil made of copper conductor and superconductor to get maximum stored energy is brought out. In case of coils wound with room temperature good conductor, the design is decided by thermal considerations while in superconducting coil it is limited by the critical flux density consideration. With drum type cryostat, the design of the SC coil is further limited by the cost of the cryostat.

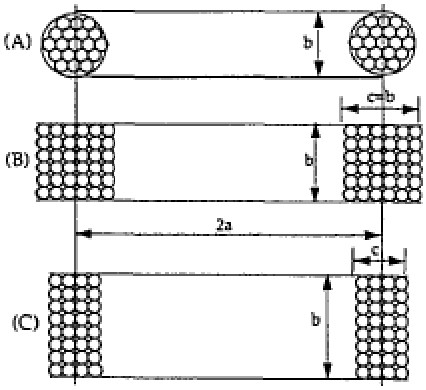

Fig 1.13 various configurations of the coil [27]

Huang Xianrui et al [**28**], have patented a passive quench protection circuit for superconducting magnets. The apparatus includes at least one superconducting coil and a passive quench protection circuit electrically coupled to the coil in parallel (**Figure 1.14**). The circuit includes a heater and current limiter connected in series. The heater is thermally coupled to the coil and the current limiter blocks current through the circuit at a current lower than the critical rating of the heater.

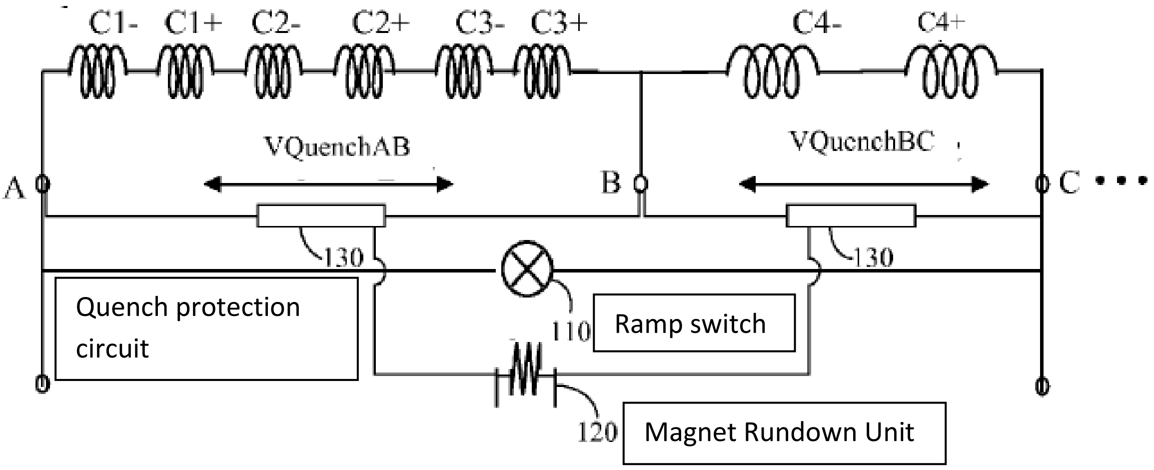

Fig 1.14: Superconducting magnet apparatus [28]

Polak M et al [**29**] , have studied the influence of filament spirality on current-voltage characteristics of twisted multi filamentary NbTi superconductors for high energy magnets. It is found that electric field inhomogeneities along each filament arise as a result of varying the angle between the external magnetic field and filament axis. It is observed that by twisting a multi filamentary NbTi composite superconductor periodic in homogeneities of critical current density are introduced into the filaments (**Figure 1.15**).

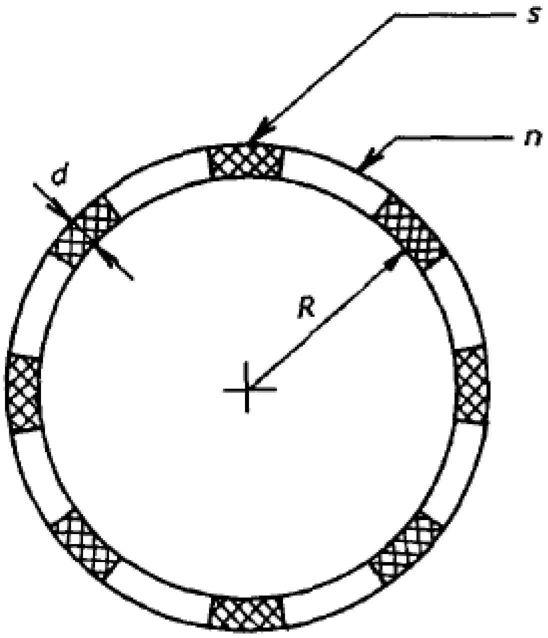

Fig 1.15: Cross section of the model one-layer sample: s, superconductor; n, normal metal [29]

Honghai Song et al [**30**], have discussed about the work done at Super Power in winding, fabrication, engineering design and other considerations of 2G HTS coils.

Fig 1.16: Second generation HTS wire produced by Super Power [30]

The 2G-HTS tape(**Figure 1.16**) is suitable for a wide variety of applications like energy, industrial, science and research, military and defense, transportation, space, healthcare etc.

Karl J Best and Hans hillmann [**31**] have discussed about the magnet construction by wet winding technique with High Tc ceramic material. It is found that in order to reduce magnet training, laboratory scale magnets are usually impregnated either with epoxy resin (which is polymerized during the manufacture of coil) or with some thermoplastic material like oil or paraffin (which is frozen during cool down). All these precautions are taken in order to prevent the movement of windings during energizing the magnet. The same effect can also be obtained by impregnating the coil, layer by layer during the winding operation. The advantage of this wet winding technique is that even special types of filled epoxy resin can be applied with their coefficients of thermal expansion adapted to those of the metallic components of the magnet.

P.Kush et al [**32**] have discussed about the vacuum impregnation facility of superconducting magnets at BARC. The facility can be used for large coil of dimensions of up to 45 cms diagonally and weighing approximately 25 kgs. The curing of the coil can be performed at any temperature up to 200 ^{0}C. It is observed that movement of conductors should be prevented because incorrect positioning of conductors will cause errors in magnetic field and rubbing of conductors against each other, or against other parts of structure, causing frictional heating which may degrade the performance of the superconductors. Arnold J J et al [**33**] have analysed various thermo physical properties of a toughened epoxy for impregnating superconducting magnets. The resins analysed have a low viscosity (< 1 poise), sufficiently long pot life (≥ 6 hrs) and excellent thermal shock resistance (≥ 25 cycles). As epoxy impregnated superconducting coils increase in size, the role of epoxy becomes more critical one.

Ceramic superconductors are strain sensitive and require mechanical support. In large superconducting magnets, stability is achieved with cable-in-conduit conductors (**Figure 1.17**). And therefore the role of epoxy is to transfer both mechanical loads and provide thermal insulation. Pulsed magnets also use epoxy potting compounds for structural integrity and insulation.

Fig 1.17: Section of the CICC conductor [33]

Suzuki T et al [**34**] have discussed about the cryogenic small flaw strength and creep deformation of epoxy resins. Resin cracking, a cause of coil quenching in superconducting magnets, occurs when a resin contains small flaws and sustains high thermal stress. Coil windings impregnated with epoxy resin have a rigid structure and thus prevent friction and plastic deformation. The mold resin, on the other hand has larger thermal expansion than that of the conductor. This difference causes tensile thermal stress in the resin during cooling from the mold temperature to the operating temperature. When the operating magnetic force increases the stress in the resin and causes a resin fracture, releasing elastic energy in the form of heat, which may cause coil quenching.

C H Joshi and Y Iwasa [**35**] have simulated the current decay and terminal voltages in adiabatic superconducting magnets through a computer program. In this program, the winding of each section is assumed to be a closed packed hexagonal arrangement of wire impregnated with epoxy resin. The program predicts the current, terminal voltages and temperature distribution for each section of the coil. The normal zone is assumed to originate at the high-field region of the winding and to grow radially and axially by heat conduction through the epoxy and insulation. This model has been successfully applied to many solenoids and the predictions and experimental results have been found to be in agreement. The computer simulation is based on a semi-empirical correlation which describes the rate at which a resistive region in the winding grows with time.

Hara N et al [**36**] have estimated the maximum voltages in superconducting magnet systems during a quench. A computer program has been developed for calculation of voltage distribution within superconducting coils during a quench. In the case of a superconducting magnet operated in the persistent mode, it becomes especially important to estimate the voltage distribution in the coil, because the terminal voltage between both ends of the coil is always zero.

Cryogenic Limited UK and American Magnetics [**37, 38**] have supplied hundreds of cryogen free superconducting magnets to researchers around the world (**Figure 1.18**). The benefits of Cryogen free high field magnet systems are: No liquid cryogens required, automated operation, open access software code, ease of use, system standby, system protection, no retractable leads required, turnkey system, proven technology. Cryogen free magnet systems use a closed cycle helium refrigerator to cool the cryogenic assemblies to temperatures close to 4K. In certain configurations the magnet is conductively cooled in a vacuum, whereas some geometries use traditional LHe cooling with a cryocooler to recondense liquid helium: thereby resulting in a zero boil-off system.

Fig 1.18: Cryogen Free Superconducting magnets [37,38]

Anil K Singh et al [**39**] have presented a cost effective technology for experiments of low temperature and high magnetic field measurements based on two stage Gifford- Mcmahon closed cycle cryocoolers. The low temperature high magnetic field facility installed at JNU Delhi, can cool down to 1.6K in temperature and can generate up to 8 tesla magnetic field without any use of liquid cryogen. Leong Ying [**40**] has patented on liquid cryogen free superconducting magnet. Here the superconducting magnet assembly is having two individual magnetic coils contained in separate vacuum jackets with a radiation shield between each magnet and its vacuum jacket. A two stage closed cycle refrigerator is used to cool the magnet , where the second stage is directly coupled with the magnet coil for cooling and the first stage cools an associated radiation shield.

Ziad Melhem [**41**] has summarized the historical development of superconducting magnets at Oxford Instruments (**Figure 1.19**). The first superconducting coil was made by Sir Martin Wood in 1959 and the first dilution refrigerator was made in 1966. Oxford instruments have supplied over 6000+ superconducting magnets all over the world.

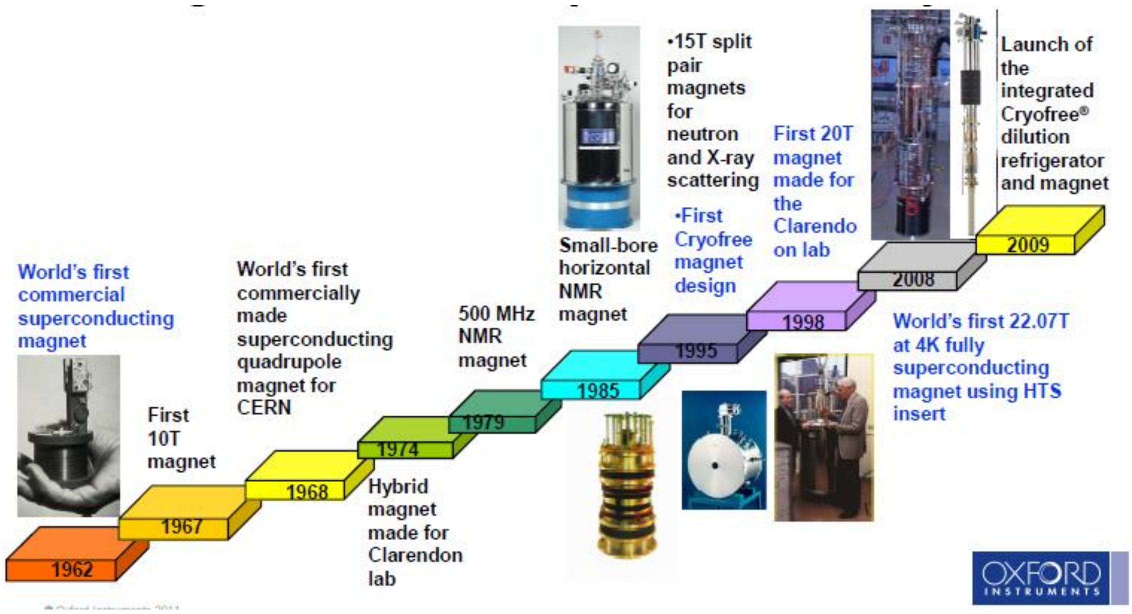

Fig 1.19: Time line of superconducting magnet technology [41]

S Kathiravan and J Kanakaraj [**42**] have reviewed about the potential issues and challenges in MR Imaging. It is observed that the limiting factor in high field MRI is the magnet technology. The challenges for designers has been to increase the field strength achievable with a large bore magnet without sacrificing the spatial homogeneity, temporal stability, patient access and without exorbitantly increasing magnet weight, cost and fringe fields. **Figure 1.20** shows one such MRI system with superconducting magnet.

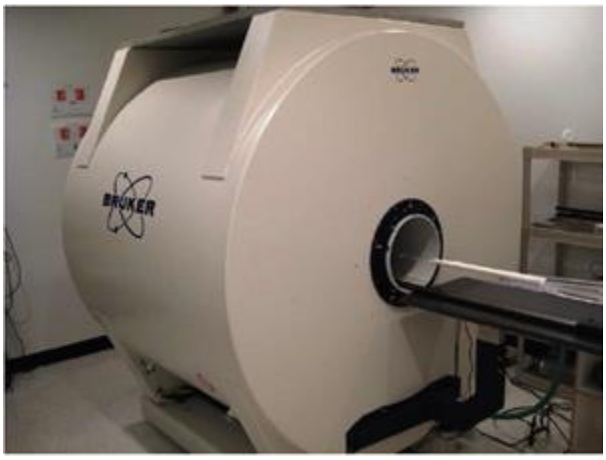

Fig 1.20: 7T Bruker Avance magnet for MRI [42]

J A Taylor et al [**43**] have discussed about the quench protection of a 2 MJ superconducting magnet at the Lawrance Berkeley laboratory, California. The magnet has a conductive bore tube. The methods for quench protection include shifting of main coil current to the conductive bore tube and include (1) allowing the quench to evolve naturally, (2) interrupting the primary circuit while providing a varistor used as a shunt across the coil and (3) turning the entire magnet normal by dumping a short pulse of current from a capacitor bank through the windings. This style of distributed quenching reduces maximum temperature of the hot-spot at quench initiation.

1.3 Motivation behind thesis

Research in the area of advanced materials for various applications is the demand of time. Discovery of nano technology, high Tc superconductivity and multi-functional materials are just few of them. Intense efforts are going on around the world to make simple and inexpensive superconducting magnet systems for performing variable temperature experiments on the above materials under high magnetic fields. Keeping in view of these facts, a lab scale mobile superconducting magnet system is designed and developed in house using Nb- Ti wire (0.43 mm nominal diameter, Cu: SC Ratio of 2:1) and tested for production of 6 Tesla field and repeated quenching of the coil.

1.4 Outline of the thesis

The current thesis consists of five chapters. The significance of the present investigation and literature related to superconducting magnets is described in chapter 1 as introduction and literature review. Design, development and initial testing of prototype superconducting magnet is presented in chapter 2. Testing of the magnet in Liquid helium environment is described in chapter 3. Chapter 4 deals with the setting up of Liquid Helium plant and magnet test facility at NIT Rourkela. Chapter 5 sums up the present work and give the important conclusions and future scope.

CHAPTER 2

DESIGN, DEVELOPMENT & INITIAL TESTING OF A LAB SCALE SUPERCONDUCTING MAGNET

This chapter deals with the step-by-step procedure of developing a lab scale superconducting magnet in-house.

2.1 CONSTRUCTION OF PROTOTYPE SUPERCONDUCTING MAGNET

We have purchased the Nb-Ti wire from Supercon Inc. with the following specifications for solenoidal magnet development.

2.1.1 S.C. Wire specifications

- Wire :Nb-Ti in copper matrix
- Type :MF (Multifilamentary)
- Company Name :Supercon
- Wire Code :54S33
- No. of Filaments :54
- Critical Current :110 Amperes at 5 Tesla ($J_c = 8.37 \text{ X } 10^8$ Amp/m^2) and 23 Amperes at 9 Tesla
- Nominal Dia (inc insulation) :0.430 mm
- Cu / Nb-Ti Ratio :2:1 (approx)
- 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 attaining such uniformity we need to wind the superconducting solenoid with a overall axial length (l), several times more than ΔZ. 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 mandrel 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 X perimeter of average turn (πd_{avg}). The d_{avg} is taken as average of inner diameter and outer diameter of the coil.

- The required central field in the bore (r=0/z=0) can approximately be computed as $\mu_o N*I/l$. Unlike copper wires the SC wires can carry much larger currents to produce very high field. However we need to be careful not to pass currents more than critical current at the working field. In addition an optimum Cu:SC ratio is maintained in multifilamentary superconducting NbTi wire to protect the coil from burning during quench.
- After deciding the coil geometry and the wire specifications, we need to wind the solenoid following some established procedures with necessary pre-tension and inter layer insulation. Finally the magnetic field variations in the SC coil are measured at various currents and at various axial locations to satisfy the requirement with the available current source and cryostat. These design aspects are included in this chapter along with developmental details.

The specifications of the proposed solenoidal superconducting magnets are as follows.

2.1.2 S.C. Magnet Specifications

- Bore dia of the Coil :15mm
- End flange Diameter :60mm
- Length of the Coil :140mm
- No of Layers :26
- No of Turns per Layer :234
- Total No of Turns :-6161
- Length of Wire :0.7 Km
- Type of insulation :fibre glass cloth
- Insulation thickness :0.1mm
  (Applied for every four layers)

2.2 DESIGN OF FORMER

The prototype magnet is a solenoid type magnet where, the superconducting wire (Nb-Ti) is wound over a hollow bobbin shaped former. For a superconducting magnet, the winding is done at room temperature but it operates at liquid helium (LHe) temperature. At LHe temperature (4.2 K), the properties of the material differ drastically from that at room temperature. Hence, the material selection for the former becomes very crucial. One property which is of extreme importance in this context is the thermal expansion of the material. Since, a large volume of the superconducting wire consists of copper; a copper former is an obvious choice to minimize the strain produced (if any) because of the difference in thermal contraction of wire and former. Copper is also chosen for its good thermal conductivity [**44**]. Sometimes stainless steel is also used as former material, for its excellent strength and non-ferromagnetic nature [**45**].

In our case, the former-material is neither of the above two and Aluminum is used as former material. The reasons behind this selection are the following

1. Low cost compared to copper and stainless steel
2. Easy to machine
3. One of the best thermally conducting metals after copper.
4. Light weight
5. The force exerted by the solenoid while charging the magnet is radially outside i.e, the coil tries to unwind itself. Hence strength of former material plays very limited role.
6. The specific heat capacity of Aluminum and copper at liquid helium temperature is comparable: 7mJ.mol^{-1}.K^{-1} and 5.8 mJ.mol^{-1}K^{-1} for Aluminum and Copper respectively.
7. Finally, the weight of the magnet made on Aluminum based former is much light-weight as compared to copper or stainless steel based formers.

Having no prior experience of magnet winding, we decided to go for a small magnet, so that in case it fails, the wastage of superconducting wire will be minimum. **Figure 2.1** shows the mandrel sketch created by solid works model.

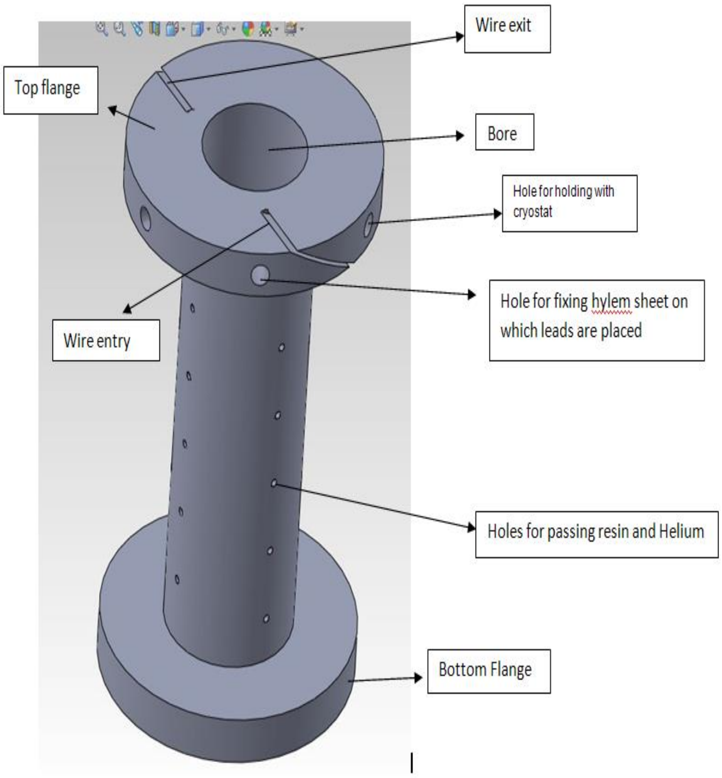

Fig 2.1: Mandrel sketch

After machining the former to the required dimensions, its surface is smoothened by sand paper. Sufficient care is taken to remove all metal particles which are likely to punch hole through the insulation of the wire during 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 2.1) so that the magnet can be attached to the support structure from the cryostat top flange. Of the six holes, three holes are used to fix the magnet to the three supporting rods (stainless steel) of the support structure. Remaining three holes 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 are also drilled along the length of the mandrel of size 2mm diameter. These holes allow the liquid helium coolant to touch the inner windings of the coil. Various stages of former being machined is shown in **figure 2.2**.

Fig 2.2: Various stages of former making (a) starting aluminum rod (b) machining of rod in lathe machine (c) boring of central hole (d) finalizing the former.

2.3 COIL WINDING / INSULATION- STEP BY STEP PROCEDURE

1. In order to get a successful winding of superconducting wire, a rehearsal winding by copper wire of approximately same diameter is done on another former of similar dimension (**figure 2.3**). As the superconducting wire also contains a large amount of copper, the rehearsal winding helped us in estimating various aspects of superconducting winding, such as amount of pretension needed while winding, length of wire needed, and adhesion of wire by an adhesive used, number of turns coming on the solenoid, etc.

Fig 2.3: Rehearsal winding of copper wire on the mandrel

2. First the mandrel along with the interior surfaces of its top and bottom flanges (towards the coil) is covered with nomex paper with the help of Elmo Luft 1A-Golden fast drying insulating varnish by Elantas Beck India Ltd. This is done to electrically insulate the former from the winding.

3. 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 2.4**). The fiber glass cloth is basically class F (155^0 C) insulation **[46]**.

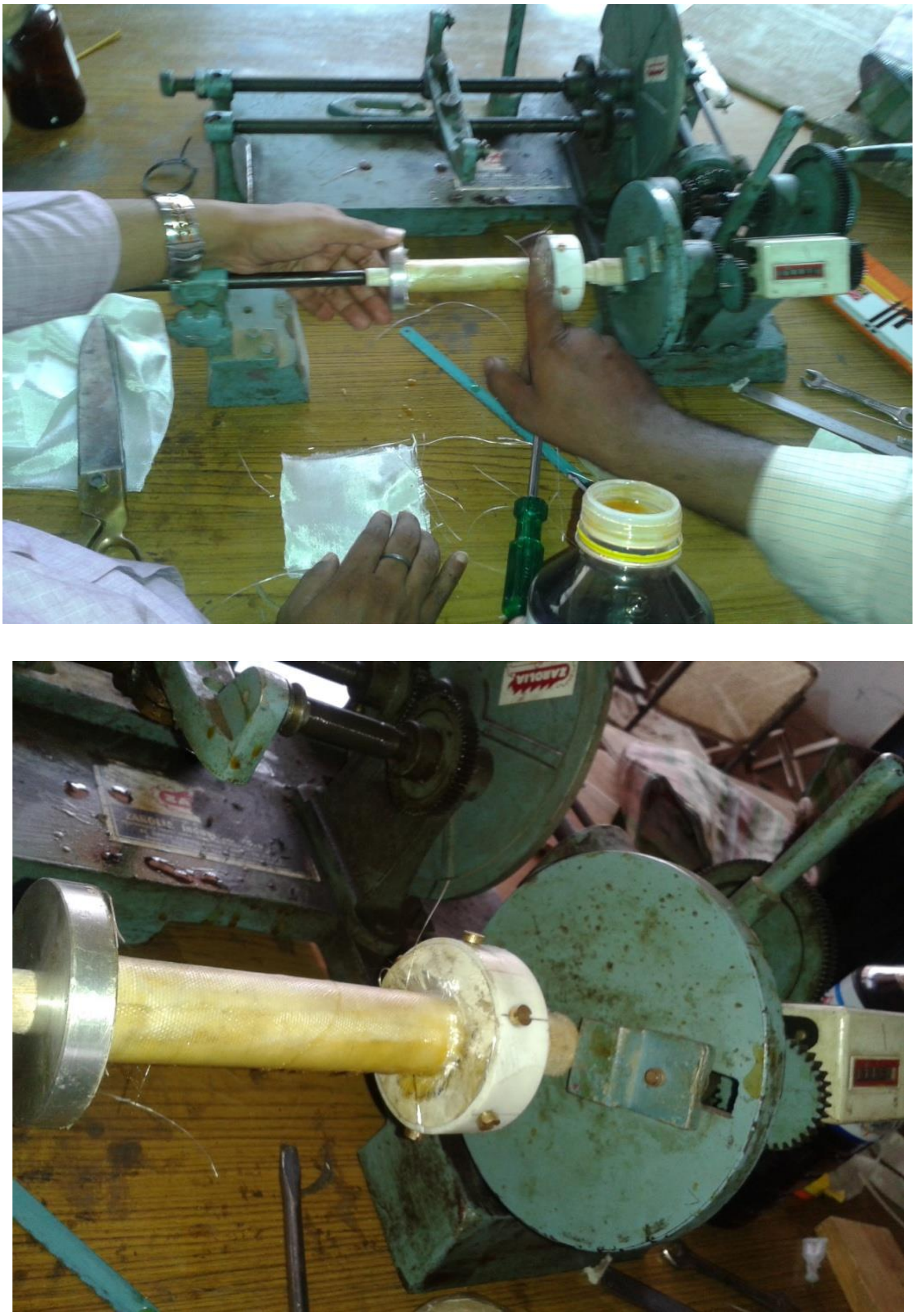

Fig 2.4: Fibre glass cloth being wound on the mandrel for insulation and for providing winding base

4. In our first attempt, the winding process is initiated on a lathe machine. The former is fixed between the chuck and tailstock of lathe machine. In order to provide some

pretension to the copper wire, the wire is passed through a burette clamp fixed on the toolholder of lathe machine. Hence the pretension in the wire is controlled by tightening or loosening the clamp. For proper winding, the wire feeding must move laterally by the amount of thickness of wire for every rotation. We found it difficult to maintain the uniform lateral motion of carriage, as this was done manually by moving the carriage via carriage wheel, even though lathe was running with minimum speed. Very often we faced the problem of wire jumping and hence decided to go for automatic lateral movement. Through internet searching, we came to know that this facility is available in winding machines used for coil winding. A portable semiautomatic winding machine is hired locally and the rehearsal winding of copper wire is successfully completed. This copper based magnet is tested for magnetic field generation at room temperature and liquid nitrogen temperature. Approx 50 Gauss of magnetic field is generated by passing 0.26 amp current at room temperature. Due to lowering of resistance at liquid nitrogen temperature, we could pass 1.26 amp of current for same voltage of 29V (**figure 2.5**).

5. Success of copper wire winding encouraged us to move ahead for the NbTi superconducting wire winding. On another aluminum former, steps 2 and 3 were repeated. The pretension during winding is provided to the wire by passing the wire through the burette clamp fixed between the spool and the former (attached to winding machine).

6. A slot-cut is made on the flange of former for taking out the free end of Nb-Ti superconducting wire (**figure 2.6**). To prevent the wires from being scratched and also to provide electrical insulation, the superconducting wire is passed through fiber glass sleeves, right from the exit from the winding to the electrical connections (**figure 2.7**). Approximately, 50 cm of SC wire is kept free on both ends for electrical connections.

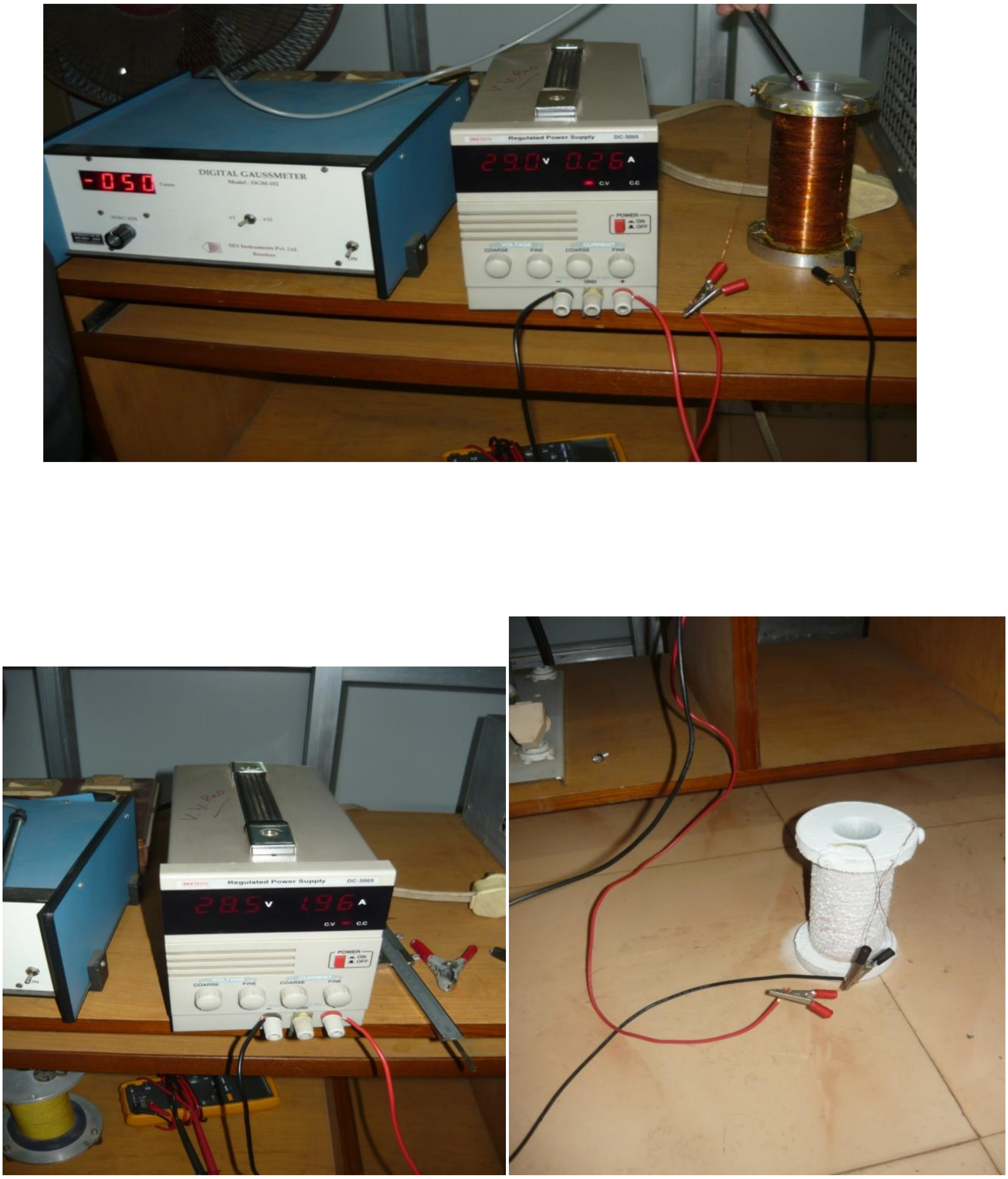

Fig 2.5 Testing of copper wire magnet for magnetic field generation. (Top) At room temperature, 0.26 A current is passed to get 50G magnetic field. (bottom) At 77K, the current could be raised to 1.96A.

Fig 2.6 (top) Slot cut is being made, to take the superconducting wire out. (Below) Complete mandrel with slot

Fig 2.7 Nb-Ti superconducting wire is being passed through sleeves in cut slot.

7. Now, the first layer is wound slowly and uniformly after proper adjustment of former and winding machine to avoid jumping or wobbling during winding.
8. Adhesive is applied on the winding, on completion of first layer. Then, similarly second layer is laid and third, fourth, etc.
9. After every four layers, fiber glass cloth is wrapped on the winding with the same adhesive (**figure 2.8**). This is done to provide strength to the superconducting winding, because while charging, the magnet tries to unwind itself. 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 2.9**). **Figure 2.10** shows the magnet after final winding. After the completion of the last layer, the winding is wrapped nicely with fiber glass cloth with sufficient adhesive (**figure 2.11**). 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 2.12**).

Fig 2.8 Fibre glass cloth wound over the intermediate layers.

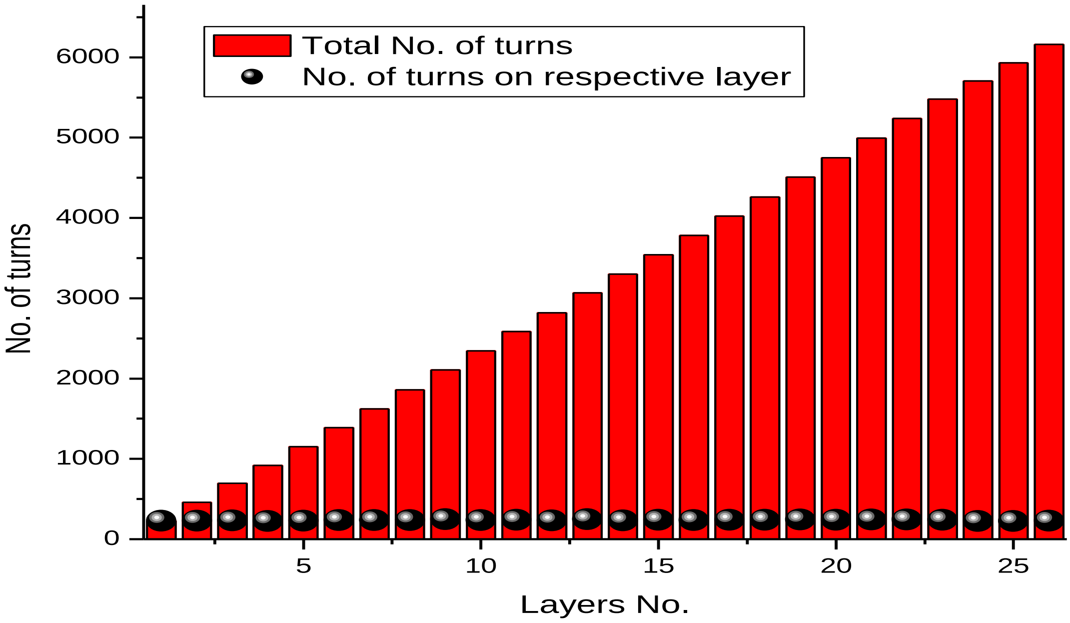

Fig 2.9 Number of turns on respective layers and total no. of turns after each layer.

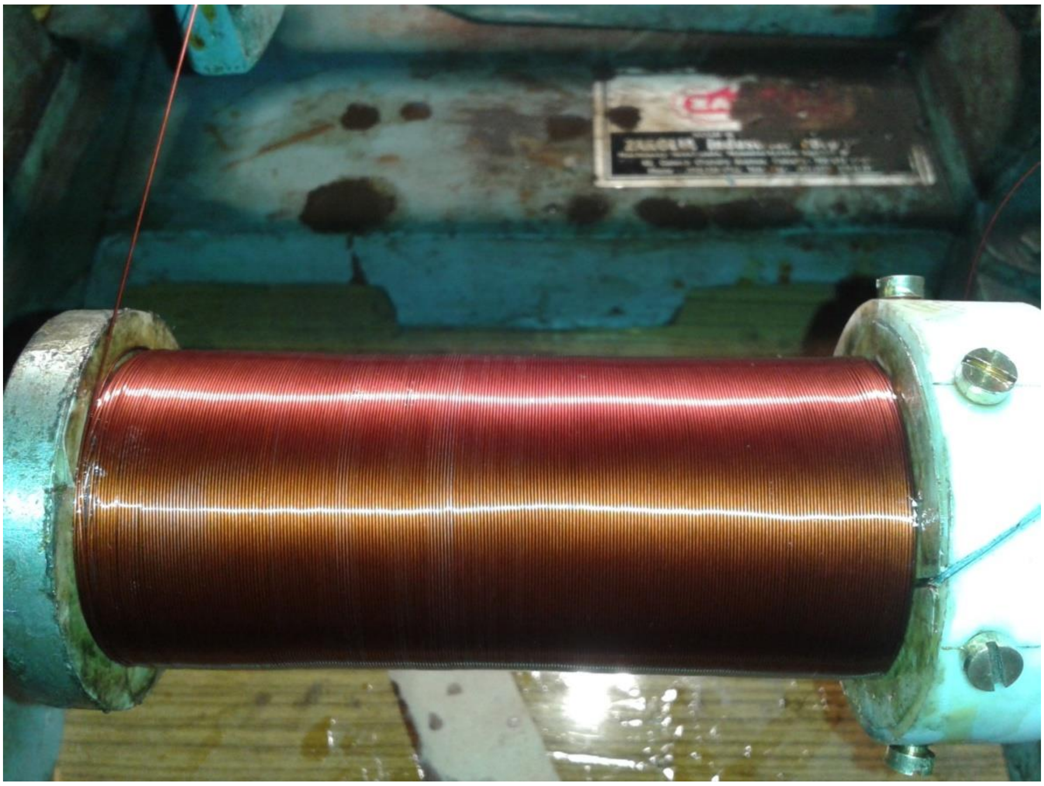

Fig 2.10 Final layer of superconducting winding, without fibre glass cloth

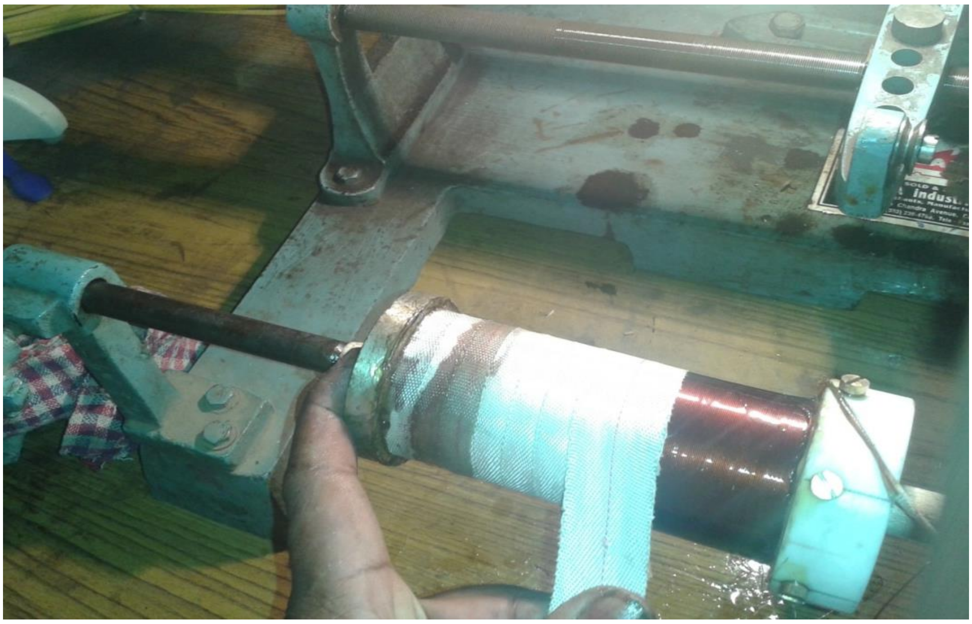

Fig 2.11 Fibre glass cloth being wound on the top of final super conducting layer

Fig 2.12 Fibre glass cloth wrapped superconducting magnet left for drying

10. Once the adhesive is dried, the winding is covered tightly (external wrapping) with badminton racquet string (**figure 2.13**). This serves the dual purpose of giving the aesthetic look as well as providing strength to winding. During coil energisetion, the developed hoop stress is compensated by this external wrapping force, so that SC wire motion is avoided.

Fig 2.13 Racquet thread being wound on top of the fibre glass cloth wrapping.

2.4 END CONNECTIONS

Connecting the coils to the current leads is done by the following manner-

i) Two square pieces of PCB Board (1 inch by 1 inch) are stuck to the top flange of the mandrel with adhesive, keeping the copper portion top side and insulating portion to the bottom side so that it is insulated from the mandrel.

ii) The copper sides are tinned with lead-tin solder.

iii) 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 mandrel. For this the unsoldered end leads are kept inside of insulator sleeves that are stuck to the mandrel with minimum stress.

iv) Two conducting flexible copper strips are then used to connect these end points to the vapour cooled leads of 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 heating nearer to the SC coil.

CHAPTER 3

TESTING OF THE PROTOTYPE SUPER CONDUCTING MAGNET

Testing of the developed Superconducting coil involves:

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

(b) Testing of SC coil for producing large magnetic fields (~5 Tesla) by passing high currents at very low voltages.

(c) Testing the health of the coil after a quench of the coil.

The present chapter describes these experimental procedures and results are given below.

Convincing results obtained from the initial testing of the magnet at liquid nitrogen temperature and low current, encouraged us to test the magnet under extreme conditions i.e., liquid helium temperatures and high current. Hence the superconducting magnet is tested at liquid helium temperature for high magnetic field production. Non-availability of liquid helium at our institute compelled us to take help of other institutions in the testing process. Variable Energy Cyclotron Center (VECC) Kolkata agreed to help us in this regard; hence the testing is done at VECC.

Figure 3.1 shows the schematic drawing of the liquid Helium Cryostat at VECC, used for testing of superconducting magnet. The Dewar used is a double walled super insulated liquid helium container.

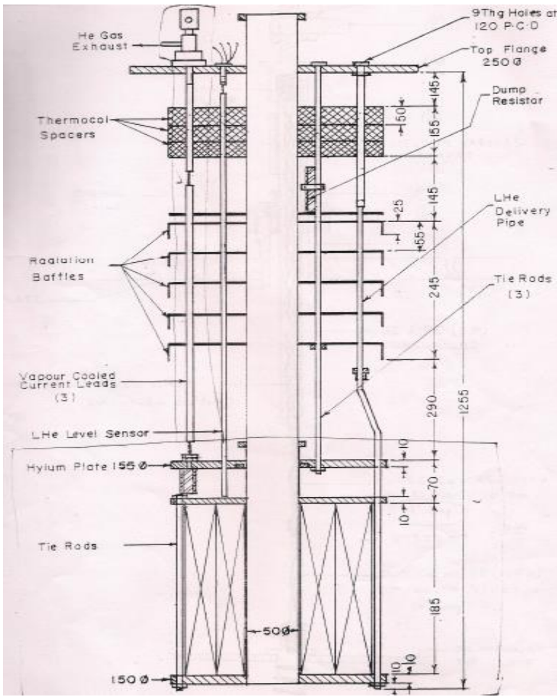

Fig 3.1 Schematic drawing of the liquid helium cryostat

3.1 COOLING OF MAGNET & R-T MONITORING

The vacuum jacket is evacuated to high vacuum (~10^{-5}mbar) using turbo molecular pump (**figure 3.2**) and 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 (**figure 3.3**). 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 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.

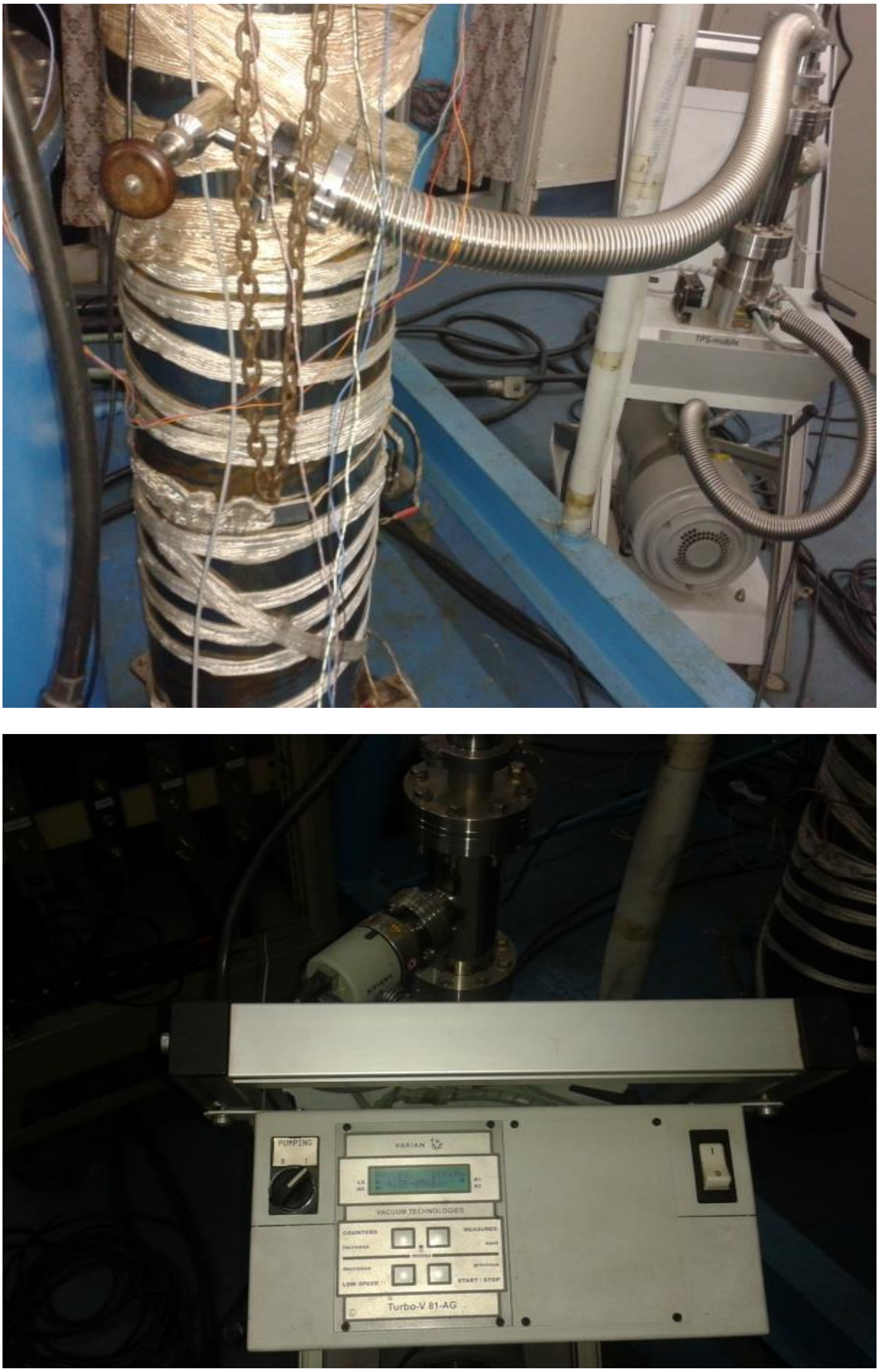

Fig 3.2 (top) Evacuation of cryostat with backing, by turbo molecular pump (bottom) front of vacuum pump

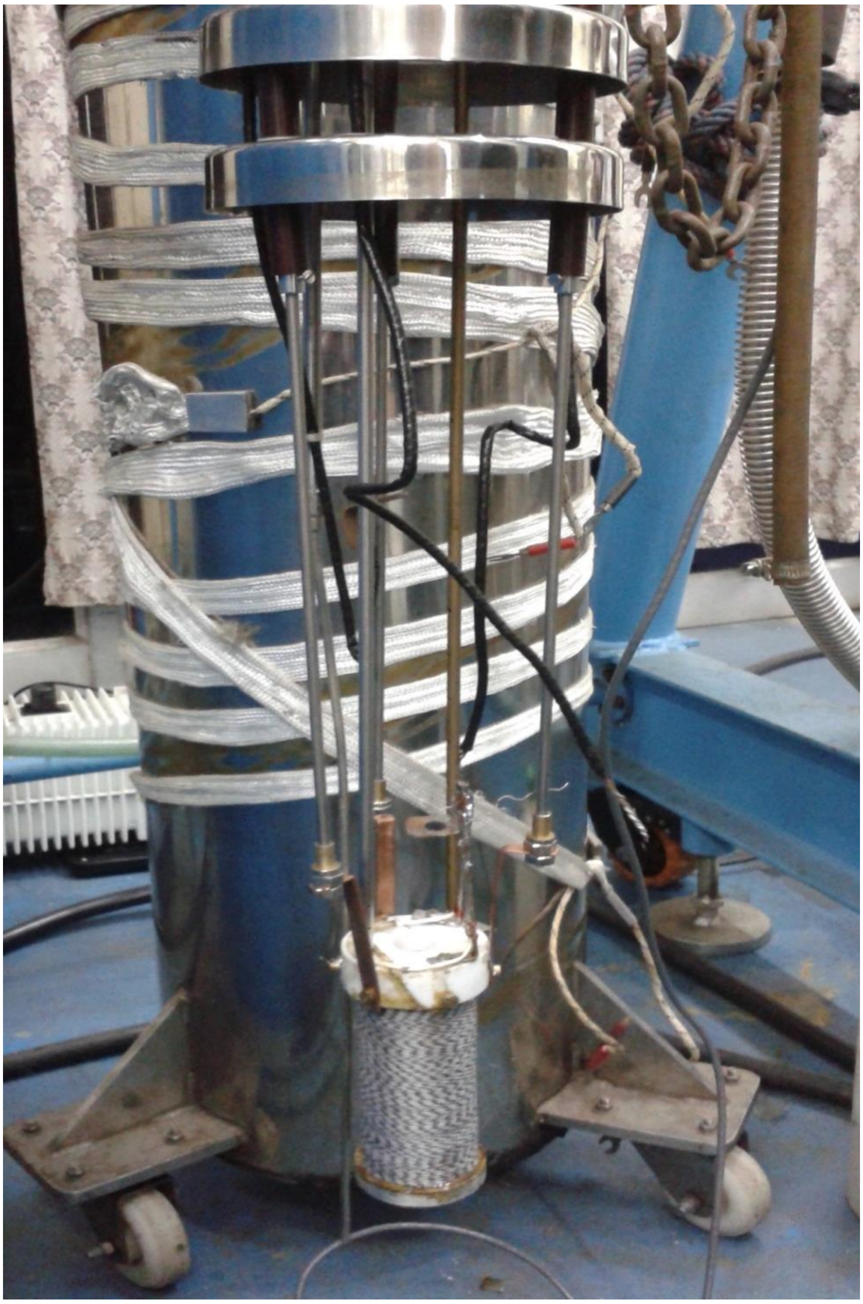

Fig 3.3: Magnet suspended from supporting rods. Behind seen is the cryostat, in which the magnet is inserted for testing.

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 3.4)**. The support structure containing magnet is slowly inserted in the cryostat with the help of chain & pulley arrangement **(figure 3.5)**. The whole assembly is subjected to evacuation via turbo molecular pump.

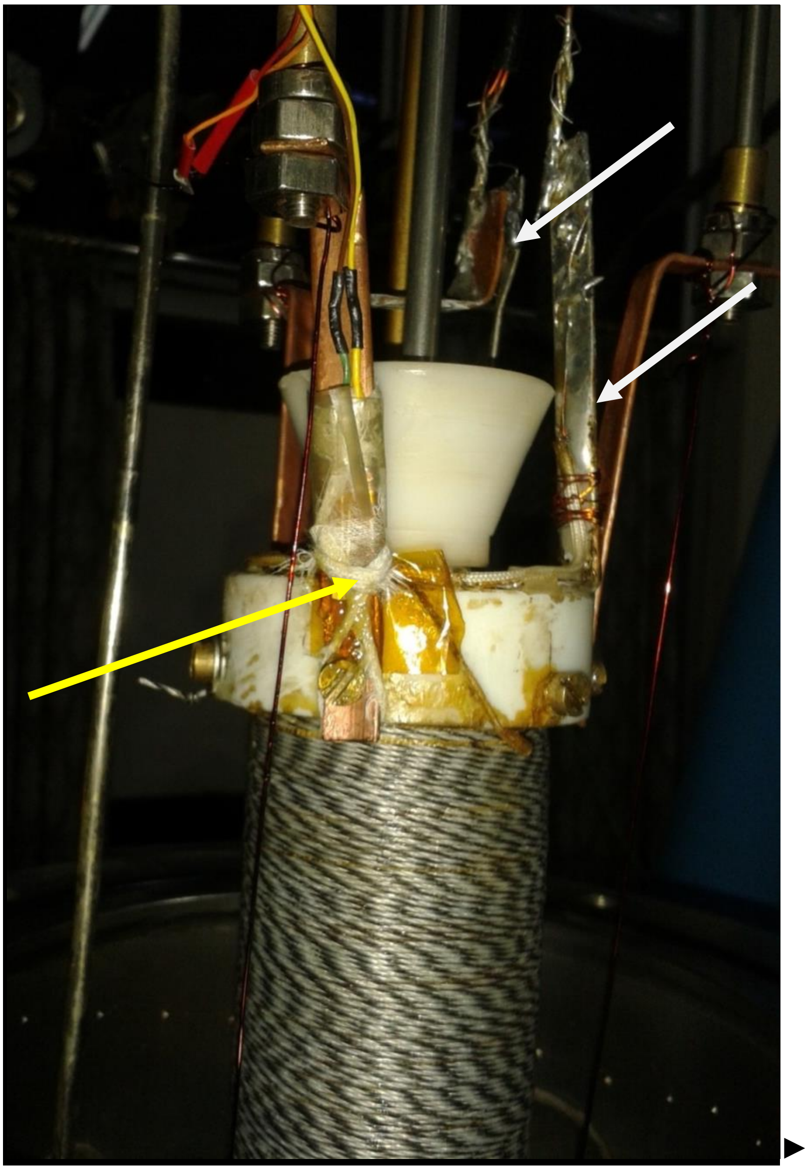

Fig 3.4: Magnet attached to the supporting rods. The arrow (yellow) shows the location of diode temperature sensor. The double arrow (white) shows the electrical leads connected to the magnet.

Fig 3.5 Magnet being inserted inside the cryostat, with the help of chain and pulley arrangement.

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 liquid Nitrogen temperature **(figure 3.6)**. This minimizes evaporation of liquid Helium as now it is required to cool only from 77K to 4.2K and for sufficient collection in the cryostat. Before transfer of liquid Helium, the remaining liquid (gas) nitrogen must be removed from the liquid Helium container. After all the liquid nitrogen is boiled off, the container is purged with Helium gas. The purging is necessary to avoid solidification of LN_2 if any present during cool down with liquid Helium.

Fig 3.6 Pre-cooling of cryostat using liquid nitrogen

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 Dewar attain a positive pressure. Now if we open the vent of cryostat, liquid

Helium gets transferred slowly cooling the magnet **(figure 3.7)**. After some time when the self-pressure comes down relatively, helium gas is used to pressurize the Helium Dewar. 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 magnet.

Fig 3.7 Frosting over the cryostat, while transferring liquid helium to the cryostat

While cooling to 4.2K the R-T curve (**figure 3.8**) 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 covered by insulation and hence cooled by conduction. This way even after liquid helium is collected, different 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. 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 up to 92 Amp at low voltages.

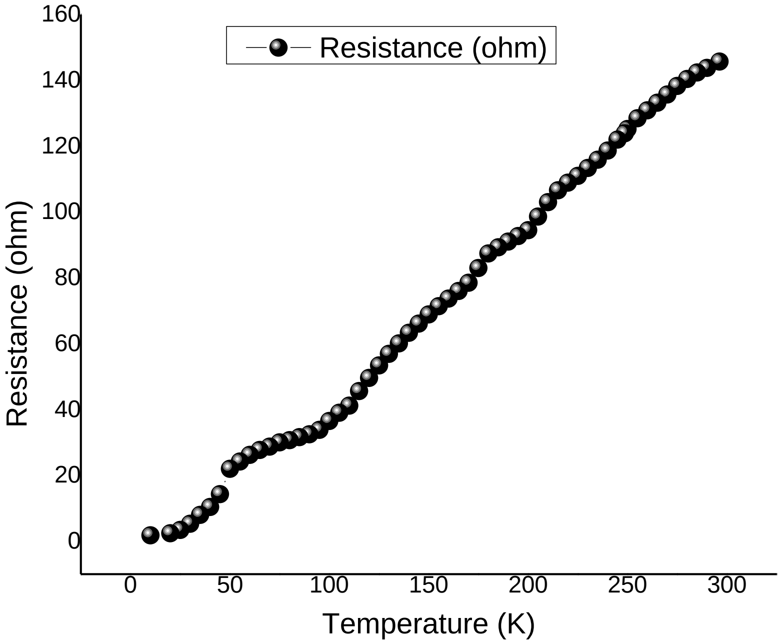

Fig 3.8 Decrease of coil resistance while cooling the magnet coil

3.2 CHARGING OF MAGNET AND MEASUREMENT OF MAGNETIC FIELD

After cool down of magnet to its superconducting state, it is tested for high current conduction 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 and the corresponding magnetic fields produced are measured using Hall probe. The magnetic field values so obtained are shown in **figure 3.9, figure 3.10.** The results are in very good agreement with theoretical values except at low fields where a small deviation is found which may be due to offset and zero errors in the measuring-equipment.

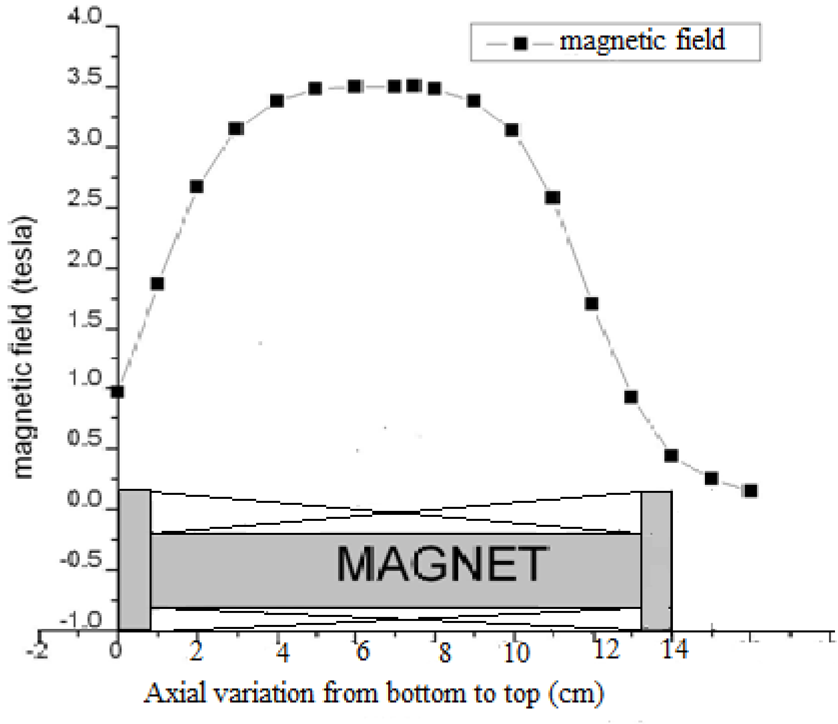

Fig 3.9 Field homogeneity of superconducting magnet. Current passed is 49.6 Amp

Fig 3.10 Assembly of instruments used for testing of superconducting magnet

3.3 QUENCH TEST OF THE SC COIL

Usually the superconducting magnets are trained by 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 normal state of magnet. Precautions are taken to immediately reduce the current in order to safe guard the magnet. After the quenching test , sufficient liquid helium is again transferred into the cryostat up to the safe level (higher than the magnet), 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 quenching (**Figure 3.11**)

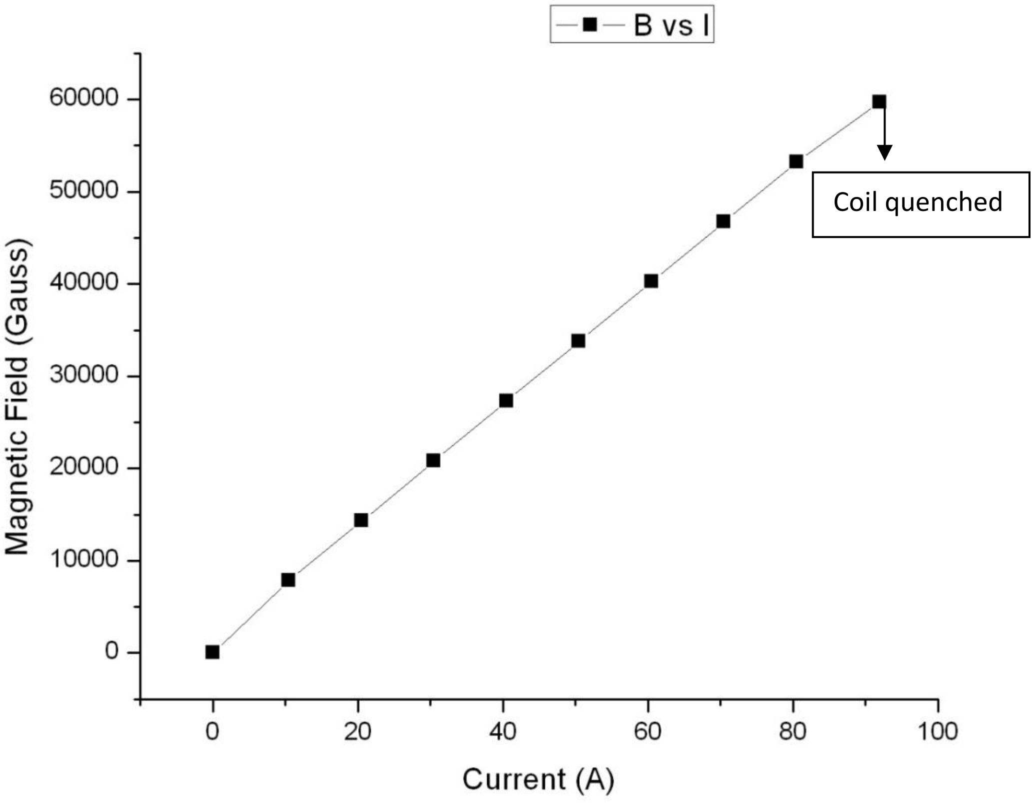

Fig 3.11 Current vs Field variation in the superconducting magnet till quench

3.4 THEORITICAL CALCULATION OF CENTRAL FIELD FOR COMPARISON

The magnetic field at the central point of the coil is calculated by

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

Where $\mu_0 = 4\pi \text{ x } 10^{-7}$ is permeability of free space in T-m/A

N is the total number of turns

I is the current passed in Ampere

h is the length of the coil wound in ‘m’

In our case on calculating with N=6161 turns and I=49.6 A and h=0.11m we get B=3.491T. This value is in agreement with the experimental value measured at the central point of the magnet (3.506T). This close agreement shows that the in-house developed superconducting magnet is successfully operated up to 6 Tesla field.

CHAPTER 4

MAGNET TEST FACILITY AND LIQUID HELIUM PLANT AT NIT ROURKELA

Liquid Helium is used as a coolant for most superconductive windings, even those with critical temperatures far above its boiling point of 4.2 K. This is because the lower the temperature, the better superconductive windings work- the higher the currents and magnetic fields they can stand without returning to their non-superconductive state.

So in this regard, we have developed a test facility consisting of Pulse tube based liquid helium plant, a high current low voltage power supply unit, a super insulated cryostat for housing and testing the magnet and a high linearity hall effect probe for field measurement.

4.1 MAGNET TEST FACILITY AT NIT ROURKELA

Magnet power supply unit

For testing the present magnet, a commercial power supply (Oxford Instruments, Mercury iPS) is procured in the laboratory. It is a high precision, highly stable power supply designed for charging a superconducting magnet in laboratory applications. The supply is capable of sourcing and sinking current and it also accurately controls the slew of the current. The power supply includes a high-power load-resistor to dissipate stored energy from the magnet

Fig 4.1 Mercury iPS power supply unit

Magnetic Field Sensor

For the measurement of magnetic field provided by our superconducting magnet, we have used a high linearity Hall Effect probe (LHP-NA of Arepoc SRO).This probe is supported by a long insert (SS pipe) supported from the top flange. A constant current source is used to pass 50mA through the sensor and the output is measured in a nanovoltmeter. The sensor is having four different colour leads out of which green and black leads are for current and orange and red are for field.

Fig 4.2 Hall Effect probe

PARAMETER	UNIT	VALUE
Magnetic field range	[T]	0-30
Temperature range	[K]	1.5-350
Nominal control current I_n	[mA]	100
Maximum control current	[mA]	150
Sensitivity at I_n	[mV/T]	>10
Linearity error at 300K, B=0-1 T	[%]	<0.2
Linearity error at 77K, B=0-0.2T	[%]	<0.1
Linearity error at 4.2K, B=0-5T	[%]	<1
Mean temp. Coefficient of sensitivity at temp. range 4.2-77K	[K^{-1}]	2.10^{-5}
Mean temp. Coefficient of sensitivity at temp. range 77-300K	[K^{-1}]	3.10^{-5}
Residual voltage	[µV]	<100
Temperature coefficient of residual voltage	[µV/K]	<0.02
Input resistance at 4.2K (in zero field, including leads)	[Ω]	0.9
Input resistance at 77K (in zero field, including leads)	[Ω]	1.1
Input resistance at 300K (in zero field, including leads)	[Ω]	1.5
Output resistance at 4.2K (in zero field, including leads)	[Ω]	1.3
Output resistance at 77K (in zero field, including leads)	[Ω]	1.8
Output resistance at 300K (in zero field, including leads)	[Ω]	3
Quantum oscillation beginning at 4.2K	[T]	>2
Amplitude of quantum oscillations at 4.2K, B=0-5T	[%]	<0.1
Active area	[mm^2]	0.05
Control current leads (green, black)	[mm]	Ø0.1
Hall voltage leads (orange, red)	[mm]	Ø0.08

Liquid Helium Cryostat

The figure (**Figure 4.3**) shows the Liquid helium cryostat suitably modified to house the magnet insert. The cryostat is a super insulated container with necessary relief/vent valves, top flange, couplings for liquid helium transfer line, current leads, hall probe, helium gas recovery port and LHe level indicator. Liquid helium is transferred from the plant dewar to this cryostat through suitable vacuum insulated flexible transfer line (**Figure 4.4**).

Fig 4.3 Liquid helium Cryostat

Fig 4.4 Helium Transfer from plant dewar to test dewar

Figure 4.5 shows the details of the top view of the cryostat flange and magnet with support structure.

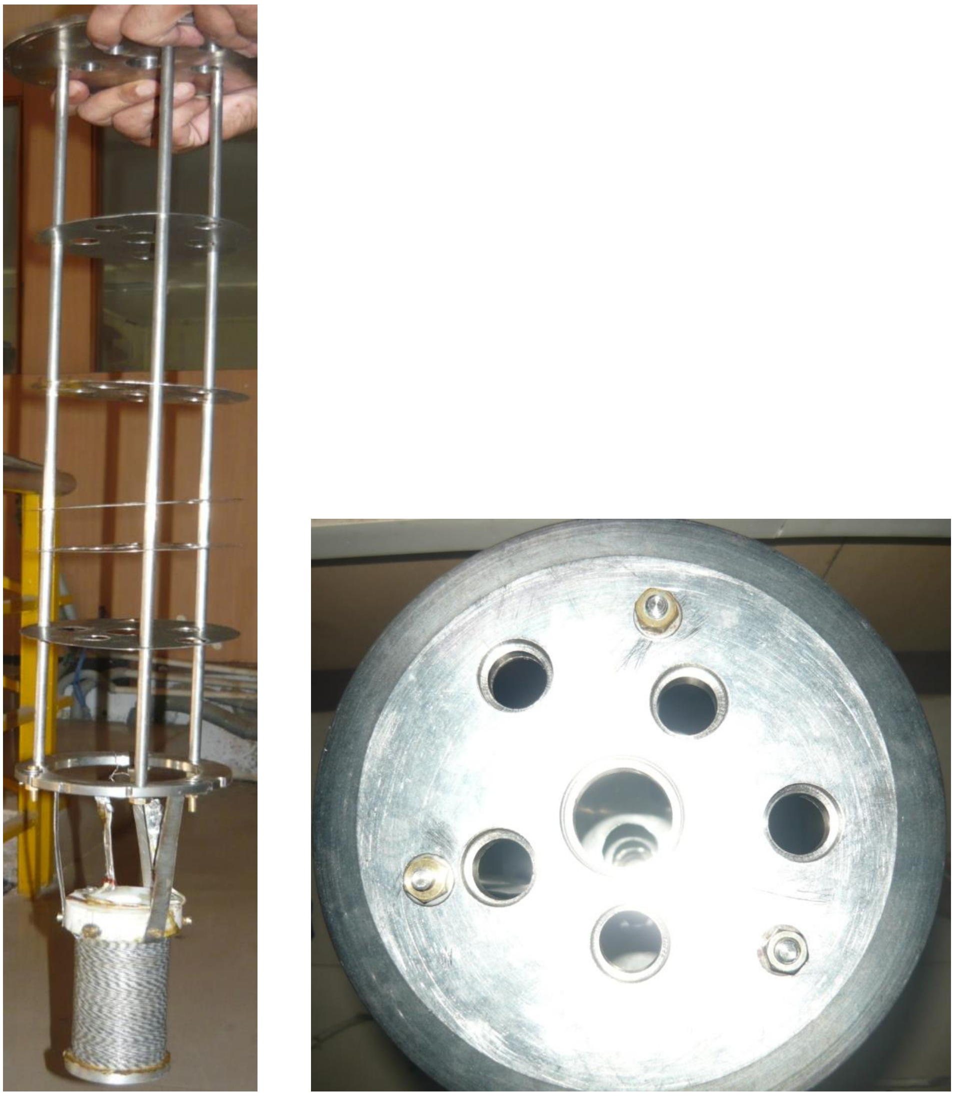

Fig 4.5 (Left) Magnet with support structure (Right) Cryostat Flange

Fig 4.6 LHe Test facility for superconducting magnet testing

Cryomech’s Liquid Helium plant is designed to produce liquid helium from any room temperature helium gas source with a purity of 99%. The liquid helium (LHe) is produced and stored in the system’s dewar. A standard liquid helium plant consists of a pulse tube cryorefrigerator with liquefaction heat exchangers, a liquid helium dewar as well as a liquid helium level sensor and controller.

Room temperature helium gas enters the dewar where it is liquefied and stored. A Cryomech Pulse Tube Cryorefrigerator is used to liquefy the helium. The liquid helium plant is fully automatic and will shut down the cryorefrigerator when the dewar is full. The liquid helium level controller indicates the liquid level in the dewar and will automatically restart the system at a preset low level.

The operation of the Cryomech Cryorefrigerator is based on a closed-loop helium expansion cycle. A complete system consists of two major components: one is the helium compressor package, which compresses refrigerant and removes heat of compression; the other is the cold head, which takes refrigerant through one or more additional expansion cycles to cool it down to cryogenic temperatures. The refrigerant gas used in the Cryomech Cryorefrigerator is 99.999% pure helium. Flexible stainless steel lines called helium flex lines carry compressed helium from the compressor package to the cold head and carry low-pressure helium back.

The compressor package works as follows. An oil-lubricated compressor compresses the pure low-pressure helium that is returned from the cold head. The heat of compression is removed via a heat exchanger, and the oil from the compression process is removed in a series of oil separators and filters. The compressed helium is then fed to the cold head via the high-pressure helium flex line.

In the cold head, adiabatic expansion of the helium and further heat removal allows cooling to cryogenic temperatures. The low-pressure helium then returns to the compressor package via the low-pressure helium flex line.

4.2 FEATURES AND BENEFITS OF CRYOMECH LIQUID HELIUM PLANT

Features

- Easily Installed.
- Fully automatic operation.
- Cryomech Pulse Tube Technology
- Microprocessor controlled helium compressor.

<u>Benefits</u>

- Requires only electrical power and water cooling.
- Does not require full time, trained operator.
- High reliability and long mean time between maintenance.
- Remote operation and monitoring.

Some technical specifications (Weight and dimensions) of the Cryomech Helium Plant shown in **figure 4.7**

PARAMETER	VALUE
System Weight: Dewar Empty Dewar Full	 1020 lb, 463 kg 1061 lb, 481 kg
Dimensions (L* W* H)	53.5*30.5*72 in, 136*77.5*183 cm
Dewar Capacity	40 gal, 150 liters
Maximum Inlet Pressure	110 PSIG, 7.6 bar
Alkalinity	5.8<pH<8.0
Calcium Carbonate	Concentration < 80 PPM

Electrical Specification

PARAMETER	380/415 Volt 50 Hz Model
Nominal Voltage	380/415 VAC
Operating Voltage Range	342-456 VAC
Frequency	50 Hz
Phase	3
Nominal Input Power Maximum: Steady state	 10.8 KW 9.0 KW
Maximum Current	19 A
Dedicated Circuit Breaker	25 A
Mains supply Voltage fluctuations	Up to ± 10 % of the nominal voltage

Operating Parameters

PARAMETER	VALUE
Ambient Temperature Range	45 to 100^0 F, 7 to 38^0 C
System Helium Pressure	17.2±0.34 bar @ 50 Hz, (250± 5 PSIG @50 Hz)
Acceptable location	Indoors only
Maximum altitude for use	6560 Ft, 2000 m
Environment	Pollution Degree 2
Installation	Category II
Maximum relative humidity	80% for T<(88^0F,31^0C). Decreasing linearly to 50% at (104^0F, 40^0C)
Maximum sound level	76 dBA at 1 meter

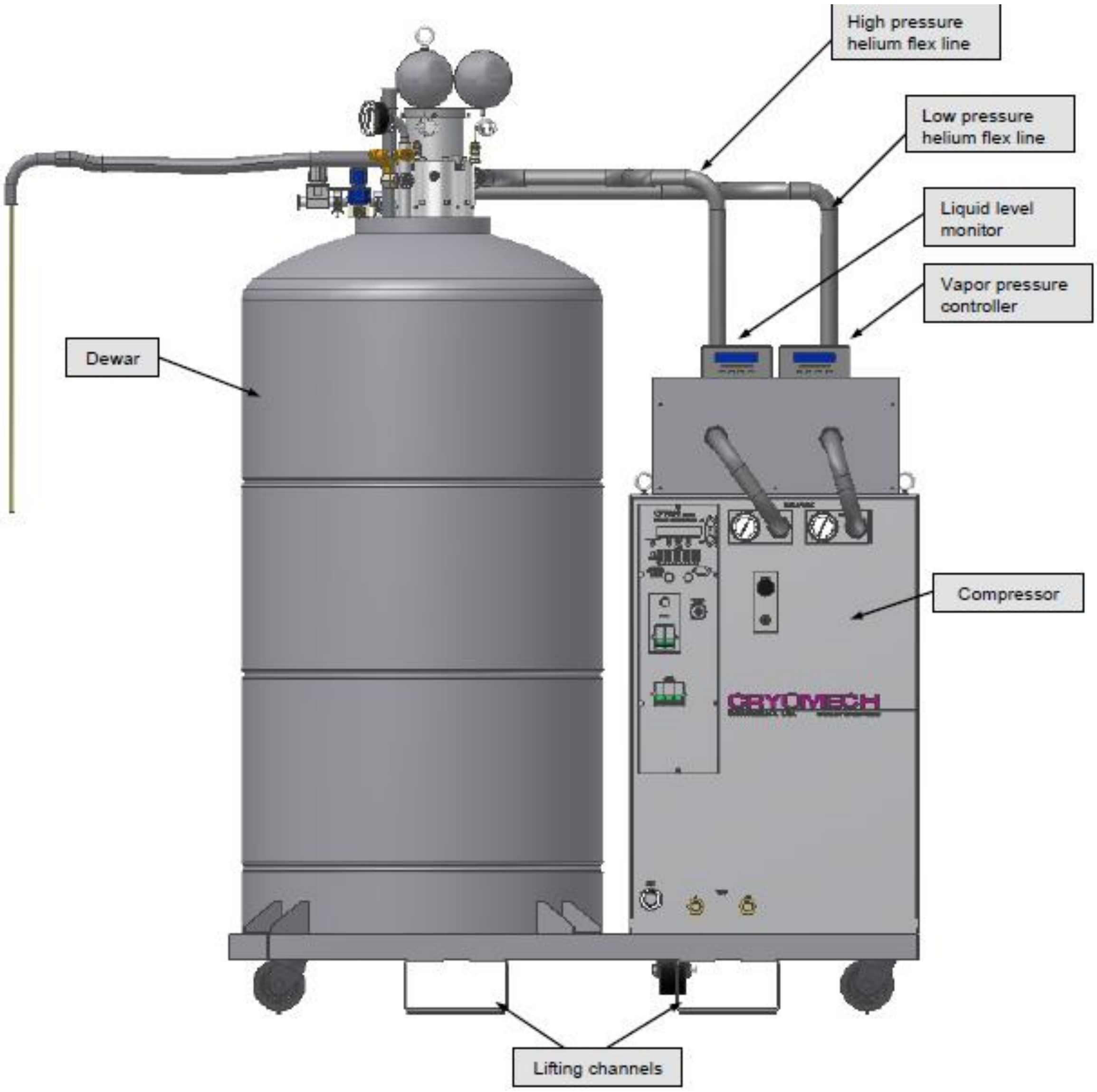

Fig 4.7 LHeP18 plant

CHAPTER 5

SUMMARY AND CONCLUSIONS

SUMMARY

So in this way a small superconducting magnet is designed, fabricated and tested in liquid helium environment for magnetic field generation. Also a test facility is developed in house for future testing of similar magnets with larger sizes and configurations.

CONCLUSIONS

The conclusions, which can be drawn after these exercises, can be summed up as follows:

(i) A small prototype superconducting magnet (Bore dia= 15mm, Flange dia=60mm, length=140mm) using Nb-Ti superconducting wire (nominal dia including insulation = 0.430 mm, No of filament = 54) was wound on an Aluminum mandrel, with intermediate interlayer insulations and external wrapping.

(ii) 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.

(iii) The magnet is tested for superconductivity at Liquid Helium temperatures and the field to current ratio measured was in good agreement with calculated value.

(iv) Thus the in house built superconducting magnet is successfully tested for high field production (up to 6T).

(v) The B-I curve of the SC magnet is linear with a constant ratio of 0.07T/A.

(vi) The magnet is also tested for its safe recovery after quenching.

(vii) Cryogenic test facilities for in-house testing of such magnets are developed at NIT Rourkela along with necessary electrical instrumentation such as power supply and field sensors.

SCOPE OF FUTURE WORK

- Variable temperatures insert to be developed inside the magnet for property measurements at high field and low temperature.
- Electromagnetic stresses to be computed for developing larger magnets.
- Magnet to be re tested using the in house liquid helium test facility.

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