Chapter 3: Experimental Studies on High Temperature Superconductors & its applications

Chapter 3

In this chapter, the characterization of most commonly used and commercial available high-\(T_c\) 2G YBCO and BSCCO superconducting tapes have been discussed. Additionally, conditions under which they are used in laboratory and in industries have been discussed. The experimental set-up and instruments have also been discussed in details.

3.1 I-V characteristic of high-\(T_c\) samples

I-V characteristics of 2G YBCO and BSCCO virgin high-\(T_c\) tapes at liquid nitrogen temperature of 77 K have been investigated before their applications in various experimental applications. This I-V characteristic curve provides valuable information regarding the critical current \(I_c\) of a tape derived from critical voltage criterion. Based on these parameters, the laboratory experiments have been designed for further specific investigations.

3.1.1 Experimental Set-up

Coated YBCO and BSCCO conductors of overall dimensions 300 \(\times\) 4 \(\times\) 0.2 mm\(^3\) were taken as samples. Three voltage terminals were soldered at the middle portion of the tape at a distance of 5.0 cm, 10.0 cm and 15.0 cm from the central axis. These three voltage terminals were used for the measurement of the critical current \(I_c\) at each subsection as shown in figure 3.1. The sample tape was connected to current leads via flexible copper braids and lugs using high-conductivity silver flux. Additional care was taken so as to keep the contract resistance very low such that the Joule’s heating at the terminal ends is minimized. The sample along with the copper braids and lugs were completely dipped inside a Styrofoam LN\(_2\) bath to avoid evolution of local hot spots. After proper cool down, the experiment is carried out with sweeping of current within the range of 0 \(\leq I \leq 100\) A for YBCO tape and 0 \(\leq I \leq 150\) A for BSCCO tape. The current ramp rate varied from 1.0 A/s to 5.0 A/s in each case.
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Figure 3.1: Soldering of voltage terminals with superconducting tape.

Data acquisition schematic for this experiment is shown in the figure 3.2. For each case of ramp rate, the transport current ‘I’ was driven by unipolar AMI XFR (0-200A, 0-12V) DC power supply. Current ‘I’ was ramped through AMI programmer (Model 430) up to its maximum amplitude and then was ramped down to zero. During the ramp-up and ramp-down phases, the voltage drops at the two voltage tape junctions and transports current were acquired using Keithley Multimeter (Model 2750 Integra Series). The sampling frequency of this Keithley Multimeter was 84 ms per data point. The multimeter was connected to LABVIEW installed PC via GPIB interface. One precision signal conditioning card was used to amplify the voltage signals corresponding to three voltage taps. I-V measurement adopted the standard four probe methods. In this method, current source supplied test current (± I) to the sample through one set of test leads, while the voltage across the sample was measured through a second set of leads, known as sense leads. Although small current may flow across the sense leads, it is generally negligible for practical purposes. Since the voltage drop across the sense leads is negligible, so the
voltage measured by the meter is essentially same as the voltage across the sample. Consequently, the resistance value can be determined much more accurately than with the two probe method.

Several other precautions had also been taken in order to achieve the best possible performance. Usage of silver soldering at input joints, three wire input configurations, shielded twisted cables and shielded enclosures were some of the cares also been taken. Silver solder material was recommended for low-level measurement to reduce thermoelectric emf in input cable. Copper-silver contacts have 3 to 10 time lower thermoelectric coefficients than that of copper lead-tin contacts.

![Diagram of experimental setup](image-url)  
Figure 3.2: Data acquisition schematic for $I_c$ measurement.
3.1.2 Sensors, Instrumentation & Data logging

As shown in the figure 3.2, the input current to the test sample was provided by AMI PS programmer from 10 VDC/200 A power supply, while output voltage across the joints were measured using Keithley multimeter via signal-conditioning cards. The experimental DATA were collected and saved in PC through PXI based DATA acquisition. The main features of these experimental arrangements were detailed below

(a) **10 VDC / 200 A Power supply**

This power supply provides very low noise, precisely regulated and variable DC output. Standard analog programming, standard remote monitoring of output voltage and current, optional isolated programming or readback and optional GPIB programming or RS-232 control are the prime feature of this power supply along with Over voltage protection and thermal shutdown. It is also designed for continuous use in standalone or systems applications. Multiple such units can be connected in parallel or series to provide increased current or voltage. This power supply is typically used to power DC equipment, control magnets or burn in components.

(b) **Model 430 Programmer Integrated Power Supply Systems**

The AMI Model 430 Power Supply Programmer is a sophisticated digital power supply controller that allows an operator to manage a superconducting magnet system with unprecedented accuracy and ease. The Model 430 is designed to control a wide range of single, dual, and four quadrant linear and switching power supplies. The most frequently used functions are accessible via single keystroke or shift plus keystroke. For other functions, a menu driven format guides the user to enter inputs using the push button front panel interface. Some the salient features of this programmer are

- Ultrahigh resolution and accuracy
- Upper current limit and voltage limit settings
- Easy to read digital Vm/Vs (magnet and supply voltage) display meter
- Can automatically determine inductance of load
- Drivers for LabView
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- User-adjustable threshold quench detection with detection I/O
- Automatic ramp down and quench inputs
- Galvanically isolated Program Output signal to prevent ground loops
- Control multiple parallel or series configured supplies
- Programmable piecewise-continuous ramping with 10 current dependent rates

(c) Signal-conditioning (Gain) card

In order to detect few hundreds of nano-volt signals in the cryogenic temperature environment, the signal-conditioning card was used along with multimeter. Out of several options, the signal-conditioning card based on OPA177 was used due to it's ultra-low offset voltage (25 μV max at 25 °C), outstanding thermal drift (0.1 μV/°C max), excellent gain linearity, lower input bias current and lower power dissipation (2 mA supply current max). With a specified gain configuration, the output signal of the card was in the range of few tens of millivolt which could be measured and stored easily. Any further amplification stage or even higher signal gain was avoided in order to preserve very high offset stability and gain accuracy over wide temperature range for continuous time operation. Any stable residual offset could be nullified using onboard offset compensation arrangement. An active two-pole low pass filter to limit the signal bandwidth as well as noise bandwidth followed the precision gain stage.

As the input signals were very slow, almost of DC nature, signal bandwidth was limited to 10 Hz. Due to this configuration, all high frequency noise and all spurious pick-ups were eliminated at the output. Total noise-band was limited to ± 2 mV with shorted input terminals to the ground. Since PCB design played a critical role in terms of layout and component placement to achieve this performance, PCB layout was made in 2 layers with special precaution for input signal guarding, signal ground plane, input signal routing, power supply decoupling etc.. A guarding pattern as shown in figure 3.3 was made in PCB layout to completely surround the high impedance input leads and was connected to a low impedance point which was at the signal input potential. The 8-pin DIP amplifier IC was used as surface mount component to avoid through-hole contacts.
Careful shielding was done on high impedance input leads and large feedback resistors to reduce "hum" pickups in input circuitry. A solid signal ground plane was provided on the component side of the PCB. All unused space on both sides of the PCB was used for ground plane to create lowest impedance path on the PCB. The plane was extended beneath the body of the ICs on both sides of the PCB. The input signal ground return, the load return and the power supply common were connected to same physical point on the plane to avoid ground loops which could cause in-principle unwanted feedback. A close attention was given on power supply bypassing and decoupling. The system power supply was well bypassed with 100 μf electrolytic capacitor at power entry. All power pins of different ICs were decoupled locally using 10 μf tantalum capacitor and 0.1 μf ceramic capacitor. Surface mount capacitors were used for decoupling to minimize routing distance from power pins and terminating ground plane. All signal and power supply paths were routed as short and direct in order to minimize stray capacitance and inductance.

All input and output connections were directly soldered on the PCB to avoid any contact related problems. Complete PCB assembly was shielded in a small Aluminium housing that was kept on signal ground. Input cable shield and output cable
shield were also connected at one end on input signal ground. Signal ground was provided from a signal grounding strip to a ± 15 V power supply common. The physical component layout and PCB of the signal conditioning card was shown in the figure 3.4.

![Figure 3.4: PCB layout of signal conditioning card.](image)

The results of this experiment along with the detailed discussion are elaborated in the section 4.1.
3.2 Critical Current Characteristics of 2G YBCO Tape under Twisting Moment

Commercial grade high temperature, high amperage second generation (2G) YBCO coated conductors fabricated through RABiTS / MOD route are available now-a-days in long length at low cost. They are extensively used in electrical power cable (Rutherford cable) in the form of stacked twisted HTS conductors [3.1-3.3]. Even the proposal of coated conductor in cable-in-conduit conductor (CICC) configuration employs the idea of stacked HTS conductor twisted over different transposition lengths [3.4]. In such applications, individual HTS tapes are subjected to twist induced strain. The strain beyond a certain limit can critically affect the transport property as well as can modify the super-current carrying path in the coated conductor [3.5]. Previous works on the torsional strain dependence of Bi-2223, YBCO coated conductor shows experimental findings on \(I_c\) and \(n\)-value degradation characterization. Finite element analyses along with theoretical co-relation have also been surveyed on torsion experiments of high temperature superconducting tapes [3.6-3.8]. All practical HTS based applications are electrically charged to their respective nominal currents at a certain allowable rate. Often it is observed that the critical current gets affected as a function of the current ramp rate [3.9]. Faster the ramping of current, lesser becomes the critical current for a given field, operating temperature and strain state. In the present study, torsional strain dependence of critical current of coated conductors has been investigated experimentally for different current ramp-rates. Again, the stress magnitude and its distribution along the length of the conductor have been studied analytically as well as supported FEM simulation.

3.2.1 Sample preparations

Second generation (2G) high temperature YBCO coated conductor manufactured by American Superconductor Corporation (AMSC) contains YBCO film deposited on oxide-buffered Ni-W alloy substrate [3.10]. The schematic of the tape used for experiment is shown in the figure 3.5 and its properties are given in the table 3.1.
Table 3.1: Properties of AMSC make YBCO tape.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>YBCO film thickness</td>
<td>0.8 µm</td>
</tr>
<tr>
<td>Substrate thickness</td>
<td>75 µm</td>
</tr>
<tr>
<td>Overall dimensions (2L x 2a x 2b)</td>
<td>300 x 4 x 0.2 mm³</td>
</tr>
<tr>
<td>Young’s modulus (E)</td>
<td>13.33 GPa</td>
</tr>
<tr>
<td>Poisson’s ratio (v)</td>
<td>0.28</td>
</tr>
</tbody>
</table>

The coated YBCO conductor of length 300 mm was clamped tightly to hylum supports which were connected to knob arrangements at the both sides outside the cold bath in order to avoid the sample getting removal from the cold bath every time during the change of its twist angle. Thus, the effect of thermal cycling on the tape was avoided. The knobs could be rotated in either direction to provide prefixed twist induced strain. The sample tape was connected to current leads via flexible copper braids which also got twisted along with the sample tape. Thus, the stress concentration at the edge of the tape was further eliminated using intermediate flexible copper braid between sample tape and current leads. These copper braids were dipped into LN₂ bath to avoid evolution of local hot spots as shown in the figure 3.6. Two voltage terminals with sufficient lengths were soldered at the center of the tape at a distance of 5.0 cm and 10.0 cm from the middle node.
This ensured that during twist of the tape, no additional stress gets developed due to these voltage terminals. These two voltage terminals were used for the measurement of the critical current $I_c$ at each subsection.

![YBCO sample preparedness for twist experiment.](image-url)

**Figure 3.6: YBCO sample preparedness for twist experiment.**

### 3.2.2 Experimental Set-up

The experimental set-up for uniform twisting of the superconducting tape and its DATA acquisition during ramping of current are shown in the figure 3.7. The twist angle ‘$\theta$’ was increased up to $1680^\circ$ with constant rotational angle interval of 30 degree. The experiment was repeated for the current ramp rates of 1.0 A/s to 5.0 A/s for each twisting interval. As discussed earlier, the transport current ‘$I$’ was driven by using unipolar AMI XFR (0-200A, 0-12V) DC power supply and is ramped at a given ramp rate through AMI programmer (Model 430) up to its maximum amplitude. Using this AMI programmer, the current was also ramp-down to zero in similar fashion. During the ramp-up and ramp-down phases, the voltage drops and transport current were acquired in Keithley Multimeter (Model 2750 Integra Series) connected to a LABVIEW installed PC via GPIB interface. Since these current and voltage signals were of very low amplitudes, these signals were...
amplified to measurable level using a precision signal conditioning card. The uniform twisting of the tape at a particular experimental angle is shown the figure 3.8.

Figure 3.7: The experimental set-up for uniform twisting of the superconducting tape and its DATA acquisition during current ramp-up / ramp-down.
3.2.3 Sensors, Instrumentation & Data logging

The instrumentation and DATA logging used here are of similar to those discussed in details in the section 3.1.2.

3.2.4 Strain Characterization

During twisting of the superconducting tape, it was subjected to the linear twisting moment of torsion. It also resulted in the maximum shear stress in the cross-section of the tape. Thus, maximum shear stress \( \tau_{\text{max}} \) developed \([3.11]\) in YBCO tape due to the twisting can be estimated from the expression

\[
\tau_{\text{max}} = \frac{M_t}{8ab^2} \left(3 + 1.83\alpha + 2.66\alpha^2 - 5.41\alpha^3 + 2.73\alpha^4 \right)
\]

where \( \alpha = \frac{b}{a} \) is the aspect ratio of the tape under test, \( M_t \) is the twisting moment, \( 2a \) is the width of the tape and \( 2b \) is the thickness of the tape. The twisting moment along the axis of tape is given by

\[
M_t = GJ \frac{\theta}{2L}
\]

with

\[
G = \frac{E}{2.\left(1+\nu\right)}
\]

Figure 3.8: Image of YBCO tape at an experimental twisting angle of 990°.
being the modulus of rigidity of the composite material and

\[ J = ab^3 \left( \frac{16}{3} - 3.36\alpha \left( 1 - \frac{\alpha^4}{12} \right) \right) \]  

(3.4)

being the polar moment of inertia of the tape section.

Similarly the maximum torsional shear stain \( \varepsilon_t \) [3.12] developed at the midpoint of the width side of the cross-section can be evaluated as

\[ \varepsilon_t = \frac{b\theta}{L} \]  

(3.5)

where 'L' is the length of YBCO tape that is subjected to the entire range of twist angle.

3.2.5 FEM modeling

A detailed analysis based on finite element model has been attempted to corroborate the experimental as well as analytical findings COMSOL software (version 4.1). In the analysis, a 3D beam model has been used to estimate torsional shear stress distribution along the length of the beam and is compared with the analytical solutions.

Model Definition

The geometrical details of the actual tape, table 3.2, have been used in cross-sectional parameters. The beam element in COMSOL multi-physics assumes that all the beam element properties and idealizes the actual tape cross-section into a single line.

Table 3.2: Parameters of YBCO tape considered for FEA analysis.

<table>
<thead>
<tr>
<th>Quantity</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample length</td>
<td>300 mm</td>
</tr>
<tr>
<td>Cross-section area</td>
<td>( 0.8 \times 10^{-6} ) m²</td>
</tr>
<tr>
<td>Moment of inertia in stiff direction</td>
<td>( 1.06 \times 10^{-14} ) m⁴</td>
</tr>
</tbody>
</table>
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<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moment of inertia in weak direction</td>
<td>$3.2 \times 10^{-12}$ m$^4$</td>
</tr>
<tr>
<td>Torsional constant</td>
<td>$1.03 \times 10^{-3}$ m$^4$</td>
</tr>
<tr>
<td>Torsional section modulus</td>
<td>$5.33 \times 10^{-11}$ m$^3$</td>
</tr>
</tbody>
</table>

Material Properties

The other properties of the composite material as given in the table 3.1 and the density of 6000 kg/m$^3$ had been used in analysis.

Boundary Conditions

The mid-node of the beam had been set as fixed constraint and the calculated twisting moments were applied as edge load at the both ends of the beam in opposite directions.

Results of modeling

The torsional shear stress distribution is depicted in the figure 3.9. It shows that the maximum shear stress is concentrated near the fixed node of the beam.

Using equations (3.1) and (3.2), the maximum shear stress and twisting moment for the experimental angles were calculated and shown in the figure 3.13 along with the shear stress obtained using FEA model. The stress as obtained in the simulation is in good agreement with the analytical results of the shear stress for the twist angle per unit length up to 16 (°/cm), for higher twisting moments, a slight deviation in analytical and simulation result has been observed.
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Figure 3.10: Twisting moment and shear stress for different twist angle per unit length.

The results of this experiment along with the detailed discussion are elaborated in the section 4.2.
3.3 Characterization of laboratory scale high-T_c, D-shaped magnet

Superconducting magnets have found broad range of applications in utilities, nuclear fusion devices, accelerators etc. [3.13]. These magnets during their operations are required to be operated in high magnetic fields with steady DC transport currents or with rapidly changing transport currents. Thus, the magnets are subjected to varying electromagnetic forces and thereby necessitating stress / moment reduced configuration in their geometry of constructions backed with rugged mechanical support structures. In fusion reactor applications, the mechanical integrity thus becomes a critical design driver. In order to achieve ‘bending moment free’ configurations in tokamak, D-shaped configurations for toroidal field (TF) magnets are preferred [3.14-3.15]. In such configurations, tensile force is produced in the tangential direction of the winding pack without any bending moment. Further, the magnitude of the tensile strength is uniform along the conductor cross-section. Thus it is considered as optimized the winding configuration for such magnets against the electromagnetic forces. Consequently, additional requirements of mechanical support are greatly reduced.

‘D-shaped Toroidal magnets’ makes it feasible to produce plasma with non-circular cross-section in a tokamak. Such elongated plasmas can carry more plasma current compared to circular toroidal plasma columns. Therefore, elongated and triangular toroidal plasma columns in a tokamak are advantageous in thermo-nuclear reactor. Till date such superconducting magnets have been fabricated from low temperature technical superconductors such as Steady State Superconducting Tokamak (SST-1) in India, EAST Tokamak in China, KSTAR tokamak in Korea, Tore Supra Tokamak in France and so on [3.16-3.19]. However, it is important to characterize such magnets wound from technical high temperature superconductors. In order to demonstrate the various characteristics of a high-T_c based superconducting magnet for such applications, a laboratory scale magnet has been designed, developed and experimentally characterized in this chapter.
3.3.1 D-shaped magnet design parameters

As explained above, in a steady state tokamak devices, the toroidal field (TF) magnets are preferred to be D-shaped [3.20-3.22]. These magnets produce a toroidal DC magnetic field around the torus. The TF magnets suffer a large in-plane forces as a result of the interaction of toroidal field crossed with the current flowing in the magnet winding packs. Additionally, the TF magnets also experience a twisting moment around the mid-plane of the torus. In the tokamak configurations, the toroidal magnets constitute about 75% of the magnets and thus very integral part of magnetic systems in a tokamak.

A typical D-shaped magnet in a scaled-down version has been designed and fabricated using a commercially available BSCCO tape. The details characteristic of this tape is given in the table 3.3 below.

<table>
<thead>
<tr>
<th>Table 3.3: Properties of BSCCO tape used for D-shaped magnet.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tape type</strong></td>
</tr>
<tr>
<td>Tape thickness (mm)</td>
</tr>
<tr>
<td>Tape width (mm)</td>
</tr>
<tr>
<td>Tape matrix material</td>
</tr>
<tr>
<td>Tape laminate</td>
</tr>
<tr>
<td>Manufacturer</td>
</tr>
</tbody>
</table>

This D-shaped magnet is fabricated in double pancake winding configuration based on the FEA analysis such that the self-field on the magnet surface does not exceed 0.1 T. This limitation was as per the manufacturer's recommendation. Beyond this, as per the manufacturer, the degradation in transport property of the tape may start. The critical input parameter for FEA analysis was the maximum allowable current density. This engineering current density for a given magnet is calculated based on the formula \( NI/A \); where 'N' is the number of the turns, 'I' the transport current and 'A' the cross-sectional area of the winding pack. Results from the FEA analysis is shown in figure 3.11. The results indicate that the D-shaped magnet with 15 turns produces a maximum self-field of 0.114 T at the magnet surface.
Figure 3.11: FEA analysis of D-shaped magnet for (a) Induced self-filed profile, (b) line plot of field profile.
3.3.2 Magnet Fabrication

There are two basic methods of magnet winding, (a) layer winding and (b) pancake winding of a superconducting magnet. In layer winding, the conductor is wound around a cylindrical core by placing one turn next to another. This proceeds down the cylindrical surface until a layer is formed covering the core. The second layer is wound on top of the first layer and proceeds up the cylindrical surface until a second layer is formed and so on. This winding is continuous with a transition between two adjacent turns as well as between the last turn of the nth turn with the first turn of the (n+1)th layer. In pancake winding, the conductor is wound about a cylindrical core placing one turn on top of each preceding turn to form a plane of turns perpendicular to the axis of the cylindrical core. However, it suffers from the disadvantage of having one end of the conductor remaining with the innermost layer which is at a high field.

In double-pancake winding, two pancakes are wound for a single piece length. The winding starts from the middle of the length. After completion of first pancake from half of the conductor length, the conductor is wound along the axis at the outermost turn to start the second pancake next to first. For the second pancake, the conductor spirals inwards to the core, one turn nested within another. This method is very useful for winding the superconducting magnets because the conductor joints can be easily formed on the outside of the coil and also the magnet can be manufactured in modular form with several double pancakes being wound at the same time and then can be brought together at final assembly.

A BSSCO high-$T_c$ superconducting tape of 2800 cm long was taken for D-shape magnet fabrication. Since the perimeter for a single wound was 790 mm, each pancake had 15 complete turns excluding the extra straight terminal lengths on both sides. The complete winding was carried out over a non-magnetic SS 304 L D-shaped structure. The 3D model of the magnet is shown in figure 3.12 whereas various other magnet parameters are listed in the table 3.4. A photograph of the wound magnet is shown in figure 3.13.
Figure 3.12: 3D modeling of D-shaped magnet along with its various dimensions.
Table 3.4: Double pancake D-shaped magnet parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coil winding length (mm)</td>
<td>28000</td>
</tr>
<tr>
<td>Coil configuration</td>
<td>Double pancake type</td>
</tr>
<tr>
<td>Conductor’s current density</td>
<td>$62.5 \times 10^6$ A/m²</td>
</tr>
<tr>
<td>Number of turns</td>
<td>15 (clockwise)</td>
</tr>
<tr>
<td>Number of turns</td>
<td>15 (anticlockwise)</td>
</tr>
<tr>
<td>Radii of constructions (mm)</td>
<td>50.44, 73.19, 145.23</td>
</tr>
<tr>
<td>Length of straight section (mm)</td>
<td>176.88</td>
</tr>
<tr>
<td>Height (mm)</td>
<td>280.62</td>
</tr>
<tr>
<td>Inter-turn transition length (mm)</td>
<td>0.2</td>
</tr>
<tr>
<td>Inter double-pancake transition (mm)</td>
<td>70</td>
</tr>
<tr>
<td>Coil inductance (mH)</td>
<td>~ 83 (measured value at 1.0 Hz)</td>
</tr>
<tr>
<td>Insulation type</td>
<td>Dry</td>
</tr>
<tr>
<td>Insulation kind</td>
<td>Kapton</td>
</tr>
</tbody>
</table>

Figure 3.13: Photograph of D-shaped BSCCO magnet wounded on SS 304 L structure.
3.3.3 Experimental Set-up

The experimental setup is shown in figure 3.14. Three voltage terminals were soldered at the middle portion of the tape with width of 5.0 cm, 10.0 cm and 2375.00 cm from the central axis. These three voltage terminals were used for the measurement of the critical current $I_c$ at each subsection. Two straight end terminals of D-shaped magnet were connected to current leads via flexible copper braids and lugs using high-conductivity silver flux so that Joule’s heating at the terminal ends got minimized. For self-field and external field measurements, two numbers of Hall probes (Lakesor and F. W. Bell make) were placed at the mid-plane of magnet straight portion in parallel and perpendicular to the tape surface.

![Diagram of Experimental Set-up](image)

Figure 3.14: Experimental set-up for D-shaped double pancake magnet characterization.
A constantan wire of 0.12 mm diameter was used as a heater and wounded up to 2.0 cm length at the mid-section of the magnet innermost layer. A thin layer of the Apiezon N grease was applied on both sides of the heater for better heat transfer. A power supply with a current limit of 3.0 A and a voltage limit of 30 VDC was used for pulsing to the heater having 65 \( \Omega \) of resistance with maximum power of 585 W. During the quench study, AMI XFR (0-200A, 0-12V) DC power supply for transport current drive operated in constant current mode. Pt-100 temperature sensor was mounted at the innermost layer of the magnet straight portion near to the heater for the temperature measurement. The entire magnet including leads and braids were completely dipped into Styrofoam LN\(_2\) bath to avoid evolution of local hot spots. After proper cool down, the experiment was carried out with passing the current up to 100 A. The current ramp rates of 1.0 A/s to 10.0 A/s were considered for each case i.e. with and without external magnetic field. The low external magnetic field ranging from 0-0.3 T was applied perpendicular to the tape surface with a permanent magnet.

Data acquisition schematic for this experiment is shown in the figure 3.15. For each case of ramp rate, the transport current 'I' was driven by unipolar AMI XFR (0-200A, 0-12V) DC power supply. Current 'I' was ramped through AMI programmer (Model 430) up to its maximum amplitude and then ramped down to zero. During the ramp-up and ramp-down phases, the voltage drops at the junctions and transports current were acquired using Keithley Multimeter (Model 2750 Integra Series). The sampling frequency of this Keithley Multimeter was 84 ms per data point. This multimeter was connected to LABVIEW installed PC via GPIB interface. Also a precision signal conditioning card was used to amplify the voltage signals corresponding to two innermost voltage taps into measurable level. I-V measurement was pursued using standard four probe method. The temperature and the self-field and applied external fields were also acquired during the experiment.
Figure 3.15: Photograph of the experimental set-up for D-shaped magnet characterization along with its DATA acquisition during current ramp-up / ramp-down.

3.3.4 Sensors, Instrumentation & Data logging

The instrumentation and DATA logging used here are of similar to those discussed in details in the section 3.1.2 except Hall probes for magnetic field measurement and temperature sensors for temperature measurement. The main features of the Hall probe and temperature sensor is detailed below
(a) Hall probe

Transverse type magnetic field sensors, based on hall generator principle, were used in the experiment to measure the self and external magnetic fields around the D-shaped magnet. Hall sensor when exposed to magnetic field under the influence of an external driving electric field, generates hall voltage, which is given by

\[ V_h = \gamma \times B \times \sin \theta \]  

(3.7)

where \( V_h \) is the Hall voltage (mv), \( \gamma \) is the magnetic sensitivity (mV/kG) at a given control current, \( B \) is the magnetic field flux density (kG), \( \theta \) is the angle between magnetic flux vector and the plane of hall generator.

The small signal information from each sensor, superimposed with the surrounding noise was extracted using the customized signal conditioning electronics [3.23]. Table 3.5 lists some of the characteristics of the sensors used during the D-shape magnet characterization experiment.

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Make</td>
<td>F W Bell</td>
</tr>
<tr>
<td>Sensor model</td>
<td>BHT-921 (14210)</td>
</tr>
<tr>
<td>Operating temperature range</td>
<td>4 K to 373 K</td>
</tr>
<tr>
<td>Operating characteristic</td>
<td>Linear</td>
</tr>
<tr>
<td>Dynamic signal range</td>
<td>-3.0 T to 3.0 T</td>
</tr>
<tr>
<td>Sensitivity</td>
<td>0.658 mV/kG</td>
</tr>
<tr>
<td>Adhesive for sensor mounting</td>
<td>Kapton tape</td>
</tr>
</tbody>
</table>

The signal conditioning electronics for Hall probe was made from the PCB using a modular design. Hall probe is an active sensor which operates with control current of 100 mA. A combination of 3 terminal regulators LM7809 and LM317 were used to fabricate 100 mA current source daughter cards and was plugged on the main PCB. The hall voltage produced from the sensor is received differentially in the instrumentation.
amplifier followed by the isolation amplifier and filter. Two ±15 V power supply were used for current source and output section respectively. Table 3.6 describes some of the technical parameters of the signal conditioning card for hall probe sensor.

Table 3.6: Parameters of signal conditioning card for Hall probe.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Hall probe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement technique</td>
<td>Differential measurement</td>
</tr>
<tr>
<td>Signal amplification</td>
<td>100</td>
</tr>
<tr>
<td>Signal bandwidth</td>
<td>10 Hz</td>
</tr>
<tr>
<td>Isolation</td>
<td>3.5 kV peak</td>
</tr>
<tr>
<td>Biasing current</td>
<td>100 mA</td>
</tr>
<tr>
<td>Power supply</td>
<td>±15 V Raw, Bias &amp; ±15 V output</td>
</tr>
<tr>
<td>Input connector</td>
<td>4 Pin Lemo</td>
</tr>
</tbody>
</table>

(b) Temperature sensor (Pt100 RTD)

Pt100 RTD is a Resistance Temperature Detector for temperature sensing consisting of deposited film of pure metal, Platinum. The element’s resistance is of 100 ohm at 0°C and increases with temperature in a known and repeatable manner. It exhibit excellent accuracy over a wide temperature range, -200 to 650 °C along with very good stability and repeatability with drift ~ 0.05 °C over a five-year period and < 0.001 °C repeatability error. It produces a more linear curve than thermocouples or thermistors. Also it provides a much larger voltage drop as an output than thermocouples i.e. they are more sensitive. This element is connected in one of the popular three circuit configurations depending on the accuracy requirement. Wiring configurations are 2 wires / 3 wires / 4 wires as shown in figure 3.16.
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a. Two-Wire RTD Configuration

\[ \text{Connection to Terminal Block} \]

b. Three-Wire RTD Configuration

\[ \text{Connection to Terminal Block} \]

c. Four-Wire RTD Configuration

\[ \text{Connection to Terminal Block} \]

Figure 3.16: Wiring configuration for Pt100 RTD temperature sensor.

In a two-wire circuit, a current is passed through the sensor. As the temperature of the sensor increases, the resistance increases. This increase in resistance will be detected by an increase in the voltage \( (V = I \cdot R) \). The actual resistance causing the voltage increase is the total resistance of the sensor and the resistance introduced by the lead wires. As long as the lead wire resistance remains constant, it will not affect the temperature measurement. The wire resistance will change with temperature but if the ambient conditions change, the wire resistance will also change introducing errors. If the...
wire is very long, this source of error could be significant. Two-wire RTDs are typically used only with very short lead wires, or with a 1000 Ω element.

In a three-wire RTD, there are three leads coming from the RTD instead of two. Two leads carry the measuring current while the third acts only as a potential lead. Ideally, the resistances of two leads are perfectly matched and therefore canceled. The resistance in third lead is equal to the resistance of the sensor at a given temperature (usually the midpoint of the temperature range). At this point, no current passes through the center lead. As the temperature of the sensor increases, the resistance of the sensor increases causing the resistance to be out of balance. Current then flows in the center lead and will indicate an offset temperature.

The optimum form of connection for RTDs is a four-wire circuit. It removes the error caused by mismatched resistance of the lead wires. A constant current is passed through the outermost leads while the inner leads measure the voltage drop across the RTD. With a constant current, the voltage is strictly a function of the resistance and a true measurement is achieved. This design is slightly more expensive than two-wire or three-wire configurations, but is the best choice when a high degree of accuracy is required.

For the temperature measurement, the same signal conditioning electronics which was used for Hall probe was also used. Table 3.7 describes some of the technical parameters of the signal conditioning card for temperature probe sensor.

Table 3.7: Parameters of signal conditioning card for temperature sensor.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Hall probe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement technique</td>
<td>Four probe measurement</td>
</tr>
<tr>
<td>Signal amplification</td>
<td>100</td>
</tr>
<tr>
<td>Signal bandwidth</td>
<td>5 Hz / 50 Hz</td>
</tr>
<tr>
<td>Isolation</td>
<td>3.5 kV peak</td>
</tr>
<tr>
<td>Biasing current</td>
<td>10 μA</td>
</tr>
<tr>
<td>Power supply</td>
<td>± 15 V Raw &amp; ± 15 V output</td>
</tr>
<tr>
<td>Input connector</td>
<td>5 Pin Combico</td>
</tr>
</tbody>
</table>
3.3.5 Quench Study of D-shaped magnet

The minimum quench energy (MQE) is defined as the minimum heater energy required for quenching the magnet. In the experiments, the measurement of the MQE is in fact the measurement of the minimum heater pulse voltage $V_{\text{min}}$ that initiates a quench in the magnet. The MQE is then calculated based on the heater pulse voltage, the current flow into the heater or the resistance of the heater, and the temperature profile during the experiment.

After determination of the critical current $I_c$ of the magnet, the transport current $I_t$ was ramped to the desired fraction of the end-to-end $I_c$ using a fixed ramp rate controlled by a ramp generator. $I_t$ was kept less than $I_c$ to ensure a stable equilibrium of the magnet. Once a stable equilibrium at the desired $I_c$ and $T$ was established, the heater was pulsed to induce a local thermal disturbance in the magnet and the magnet voltages as functions of time and location were monitored. Initially, the heat pulse amplitude was low. If the conductor did not quench, the sample was re-cooled to the starting temperature and the experiment was repeated with higher heater pulse amplitude. This procedure was repeated until the magnet voltages increased without recovery, indicating that the magnet got quenched. At this stage, the experiment was discontinued to protect the sample from damage by quickly reducing the transport current to zero. The procedure to measure the MQE is shown in figure 3.17.
The heater energy that quenches the magnet is called the 'quench energy'. Magnet recovers superconductivity with energy lesser than this value. Assuming that the resistance \( R(t) \) of the heater is weakly dependant of the temperature during the heat pulse duration \( t_p \), the minimum quench energy can be calculated from the expression

\[
MQE = \frac{V_{\text{min}}^2}{R t_p}
\]  

(3.8)

where \( V_{\text{min}} \) is the minimum heat pulse voltage that quenches.
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