Design and fabrication of a high $T_c$ BSCCO based square helmholtz coil

Nayak Pramoda K, Prasad U, Amardas A, Patel D and Pradhan S
Institute for Plasma Research, Bhat, Gandhinagar, Gujarat, India
E-mail: pramoda.srm@gmail.com

Abstract. A square Helmholtz coil has been designed and fabricated using commercial grade HTS BSCCO tape with double pancake configuration. The present work is aimed at generating uniform magnetic field with a square Helmholtz coil pair useful in laboratory applications. It has an advantages over the circular Helmholtz coil which had been fabricated and validated by us earlier in terms of field uniformity. This coil is intended to be used as a background field/magnet for circular Helmholtz coil and possible characterization of High $T_c$ tapes. Design parameters details, magnetic field generated and the fabrication techniques of this square Helmholtz coil have been described in this paper. Measured current voltage (I-V) characteristics following 1.0 $\mu$V/cm criteria and magnetic field profiles of the square Helmholtz coil have been presented in this report in greater detail. From the I-V characteristics, the critical current based on self field dependent of HTS coil is found to be 84 A. The maximum magnetic field is found to be 0.05 T from the magnetic field characteristics.

1. Introduction
Superconducting magnets are useful for generating steady high magnetic fields with excellent stability and homogeneity. The maximum magnetic field generated by the conventional LTS magnet such as NbTi and Nb$_3$Sn have been restricted to approximately 20 T primarily because of the limitations imposed by their upper critical fields. After the discovery of high $T_c$ superconductors such as Ag or Ag alloy sheathed Bi-based HTS tapes [1,2], researchers have renewed interest in developing superconducting magnets having high fields again. The HTS opened the door to realize magnets with fields well above 20 T because of their excellent irreversible fields far over 20 T. Thus, for practical high field requirements, HTS magnets might be a suitable candidate for generating high magnetic field with compact size. The compactness of HTS magnet further adds to the feasible of being used as a cryogen free magnet.

High $T_c$ superconducting tapes are very attractive and potential candidate for high magnetic field and high current application [3, 4]. The magnetic efficiency of the superconductor can be defined from the basic magnetic properties like ac susceptibility, ac loss and field dependent of critical current (Ic). Both ac loss and ac susceptibility of high $T_c$ superconductors are determined using pick-up coil method [5, 6]. In this method, the sample is exposed to external magnetic field either in parallel or perpendicular and the magnetization experienced by the sample is measured. In these measurements, utmost care of the local field variation as well as the field orientation over the entire cross section of the sample is a mandatory. HTS material exhibits very high anisotropy and sensitivity with respect to
field orientation and field gradient [7,8]. Furthermore, noise effect or neighboring interference on the loss signal must be protected or minimized for the shake of the precise measurement. In view of these motivations, we have constructed Helmholtz coil which provides very good homogeneous field and low noise effect especially for the measurement of HTS tapes.

I-V characteristics of superconducting tape gives information about the critical current ($I_c$) of the tape based on critical voltage criterion. The design of SC electromagnet requires the knowledge of critical current ($I_c$) in the coils. For HTS tapes, although the magnetic field dependent critical currents are known, the actual $I_c$ of a specific winding geometric is difficult to predict because of the large field variations across the winding cross section of the tape resulting in a both a gradient of transverse field as well as on the superconductor to normal ‘n’ transition and finally resulting a possible non-homogenous current flow. Thus, it is necessary to characterize the I-V characteristics of a particular winding geometry before designing a HTS coil.

Helmholtz coil configuration is classically used to generate a uniform magnetic filed. This coil consists of a pair of similar coil with equal number of turns and the coils are mounted coaxially at a distance equal to the radius of the coil. When the pair of coils are connected (preferably in series) and the current is passed though them, a high uniform magnetic field gets produced in a considerable volume of space between the two coils. In this configuration, the direction of the field is perpendicular to the plane of the coil.

1.1. Square Helmholtz coil

Helmholtz coil with square winding cross section exhibits better field homogeneity than that with conventional circular winding. On the other hand, square winding is rather difficult to fabricate and requires particular attention to suppress deviation from the design. The vital deviation during winding comes from the corner of the square former. While designing square Helmholtz coil, the corner is made circular with the diameter greater than that of the minimum bending diameter of the winding tape. Therefore, this factor must be taken into consideration while estimating field intensity and field homogeneity in square Helmholtz coil. If each side of the square coil is denoted by 2a, then the axial component (z-axis) of magnetic field, B can be expressed as [9],

$$B = \frac{\mu_0 N I}{4\pi} \left[ \frac{1}{k_1} \left( \frac{2(x+a)}{\sqrt{k_1 + (x+a)^2}} - \frac{2(x-a)}{\sqrt{k_1 + (x-a)^2}} \right) + \frac{1}{k_2} \left( \frac{2(y+a)}{\sqrt{k_2 + (y+a)^2}} - \frac{2(y-a)}{\sqrt{k_2 + (y-a)^2}} \right) \right]$$

Where;

$$k_1 = \frac{\dot{z} + x^2 + (y-a)^2}{(y+a)^2}$$
$$k_2 = \frac{\dot{z} + x^2 + (y-a)^2}{(y+a)^2}$$
$$k_3 = \frac{\dot{z} + x^2 + (x-a)^2}{(x+a)^2}$$
$$k_4 = \frac{\dot{z} + x^2 + (x-a)^2}{(x+a)^2}$$

For, $x = y = z = 0$, the above equation reduces to $B = \frac{\mu_0 I}{\pi a} 2\sqrt{2} N$

In the case of Helmholtz coil, the field point of interests are located in the mid-plane between the two coils. However, the question arises on the uniformity and its extent. In order to determine the uniformity of the magnetic field, we have studied the magnetic field profile the axis of the HTS square Helmholtz coil at different current ranging from 10A to 80A, which is less than the critical current ($I_c$) of the tape as well as that of the coil fabricated.
2. Experimental Details
The square Helmholtz coil consists of two double pancake sub coils, which are fabricated using HTS tape. These tapes are the commercial grade BSCCO tape purchased from American Superconductor Corp. The specification about this tape has been given in table 1. The sub coils are wound over a non-magnetic bobbin made up of commercial grade aluminum. The bobbin is rectangular type with height of 112 mm and length of 73 mm. Two grooves have been made with thickness of 10 mm and a depth of 6 mm each, keeping a distance of 5 mm apart from each side. These grooves are made for winding of the sub coils. At the center of the coil, 90 mm diameter bore is available throughout the length. The corners of the Helmholtz coil are made circular with a diameter of 120 mm, which is greater than the minimum prescribe winding diameter of BSCCO tape.

![Figure 1](image1.png)

**Figure 1.** Schematic diagram of (a) axial cross section and (b) lateral cross sectional view of square Helmholtz coil.

![Figure 2](image2.png)

**Figure 2.** (a) Photograph of the bobbin and (b) assembled coil assembly with stand.
The schematic diagram of the bobbin has been given in figure 1 and shows the axial and lateral cross section of the coil. The above configuration has been optimized from the allowable bending radius of the BSCCO tape, allowable strain on the tape and available single piece length of the BSCCO tape. A maximum field of 0.05 Tesla with field uniformity spread over 53 mm has been possible with this design. In order to produce this magnetic field, the maximum input current was chosen to be 80 A, which is less than that of $I_c$ of the coil geometry of this BSCCO tape. The photograph of the bobbin and assembled coil assembly is given in figure 2 (a) and (b) respectively.

Two BSCCO tapes have been taken for two sub coils each having length of 13 m. The sub coils are fabricated using these tapes wound manually with tight packing in double pancake configuration. In each sub coil, total numbers of turns are 30. The lower to upper double pancake transition is made over typically the length of one of the sides of the sub coil. The specification of the HTS coil is given in table 2. The two sub coil are connected each other in series externally.

| Table 1. Specification of HTS BSCCO tape |
|-----------------------------------------|
| Average width (mm) | 4.26 |
| Average thickness (mm) | 0.28 |
| Minimum 10m $I_c$ (77 K, Self field (1 µv/cm criterion)) | 145A |
| Critical tensile stress | 250 MPa at 95 % $I_c$, Retention (77 K) |
| Critical tensile strain | 0.4 % at 95 % $I_c$, Retention (77 K) |
| Critical bend diameter | 95 % $I_c$, Retention for 38mm dia(RT) |

| Table 2. Specification of HTS Square Helmholtz Coil |
|-----------------------------------------|
| Inner side (mm) | 100 |
| Outer side (mm) | 112 |
| Avg. one side length (mm) | 106 |
| No. of turns in each coil | 30 |
| Separation between the two coils (mm) | 53 |
| Thickness of each coil (mm) | 10 |

| Table 3. Specification of Hall Sensor |
|---------------------------------------|
| Sensor model | HGCA-3020 |
| Sensor type | InAs Hall generator |
| Sensitivity (300 K) | 0.844 mV/kG |
| Sensitivity (80 K) | -0.09% of RT sensitivity |
| Sensitivity (4 K) | -0.70% of RT sensitivity |
| Active Area | 0.030 inch diameter circle |
| Zero field offset voltage | 1.0 µV |

An axial (InAs) hall sensor (model no. 1020D) has been used for measuring the magnetic field. It has the sensitivity of 0.844 mV/kG at room temperature. The specification of the hall sensor is given in table 3. The hall sensor is just mounted on the tip of pospex rod. A stand arrangement with a support has been done in order to hold the hall sensor at the mid plane of the magnet, which is shown in figure 3. For the movement of the hall sensor along the axial direction of the magnet, a micrometer type arrangement has been carried out.
The I-V measurement has been carried out using standard four probe technique at LN$_2$ temperature using a LN$_2$ cryostat. For this purpose, a Styrofoam box of dimension (50 x 40 x 30) cm$^3$ has been used as a LN$_2$ cryostat. The HTS coil with current leads and voltage taps connections were dipped inside this cryostat. The current was supplied by means of AMI precision 100A current source (model no.12100PS) and output voltage was measured using keithley nano voltmeter (model no. 2182A). During magnetic field profile measurement, the current was supplied by the same 100 A current source and the hall voltage was measured using keithley nano voltmeter. The magnetic field was calculated from the measured voltage by taking the sensitivity of the hall sensor at 77 K. The block diagram of the set up is given in figure 4.

3. Results and discussions

The I-V characteristics of the HTS Helmholtz coil has been investigated by taking into account the practical application of the coil. In order to measure the magnetic field profiles of the fabricated hemiholtz coil, it is necessary to know about the critical current (I$_c$) of the coil to charge it below its I$_c$ value. The I-V curves of the double pancake sub coils of HTS coil have been shown in figure 5(a) for sub coil A and in figure 5 (b) for sub coil B respectively. This measurement has been carried out at LN2 temperature (77 K). The voltage drop has been measured independently across each sub coils and have been shown in figure 5 (a) and (b). Each double pancake sub coil is made out of 13m length BSCCO tape. According to 1 µv/cm criterion, the equivalent voltage across each double pancake coil end is 1300 µv. The critical current I$_c$ have been calculated at 1300 µv from I-V curves, which is found to be 84.5 A and 84 A for coils A and B respectively. These I$_c$ values are far less as in comparison with straight BSCCO tape, which is 145 A at 77 K. Such reduction of I$_c$ for the coil geometry has been observed in [10]. With the increase of current, the BSCCO tape of the HTS coil experiences self field which in turn reduces I$_c$. Additionally, the double pancake type of construction as well as the finite inter double pancake transition between the lower half and upper half of the double pancake could possibly add to the degradation of the critical current.
Figure 5. I vs. V of (a) sub coil A and (b) sub coil B at LN2 temperature

The magnetic field profiles have been plotted along the axial direction of the high Tc Helmholtz coil for four different currents i.e. 10A, 30A, 50A and 80A as shown in figure 6. For each current, the hall sensor was moved from one end to another end and vice versa. In the final calculation, the average of the two positions was taken. As described in the experimental section, the magnetic field was calculated from the hall voltage by considering the sensitivity of hall sensor at 77 K. From figure 6, it is observed that the maximum amplitude of magnetic field is increasing linearly with transport current. For all the values of the current, uniform field region is observed within a length of 50 mm with maximum error of around 7 % as mentioned in table 4. The error in the maximum uniform field region is high for I = 80 A due to self field effects. In the present square Helmholtz coil, the magnetic field uniformity is nearly close to the field uniformity of our earlier made circular Helmholtz coil [13] using same superconducting BSCCO tape, which contradicts our objective of fabricating square Helmholtz coil. This is due to the fabricated Helmholtz coil was not made with perfect square corner because of the limitation of the tape which has certain minimum bending radius.

Magnetic field profiles along the axis of the Helmholtz coil with square shape can be calculated analytically using equation 1. However, as a result of limitations on the High Tc tape used, the square shaped Helmholtz Coils had been fabricated with round corners of bending radius 60 mm. The field profile for these as built coils are too complicated to be calculate analytically. Hence, Ansys [11] (version 11), a commercial software based on finite element method has been used for completing the fields. SOLID97 element is used to model the problem as shown in figure 7.
Figure 6. Magnetic field profiles along the axis of the HTS square Helmholtz coil for I = 10 A, 30 A, 50 A and 80 A.

Table 4. Results of the measured magnetic field profiles

| Current (A) | Max. Field (Gauss) | Uniform field Region (mm) with max. error (%) |
|-------------|--------------------|---------------------------------------------|
| 10          | 54                 | 50 (5.17)                                   |
| 30          | 179                | 50 (6.14)                                   |
| 50          | 303                | 50 (5.61)                                   |
| 80          | 473                | 50 (6.76)                                   |

This modelling is based on the magnetic vector potential formulation with the Coulomb gauge. The element is defined by eight nodes and has up to five degrees of freedom per node out of six degrees of freedom. The six degrees of defined freedom are the magnetic vector potential (AX, AY, AZ), the electric scalar potential (VOLT), the electric current (CURR), and the electromotive force (EMF). It is applicable to problems concerning magnetostatics, eddy currents (AC time harmonic and transient analyses); Voltage forced magnetic fields (static, AC time harmonic and transient analyses); and electromagnetic-circuit coupled fields (static, AC time harmonic and transient analyses). The element also has nonlinear magnetic capabilities for modeling B-H curves or permanent magnet demagnetization curves. The centerline field profile calculated by this method is shown in the figure 8, and the in-plane field on mid-axis of one of the coils is shown in the figure 9.
Figure 7. Finite Element Model used to calculate the field profiles.

Figure 8. Magnetic field profile on the centerline of the square Helmholtz coil using ANSYS for applied transport current 80 A.
Figure 9. Magnetic field profile on the plane of one sub coil of the square helmholtz coil using ANSYS for I = 80 A.

The maximum magnetic field at the center of the coil is found to be 382 Gauss from ANSYS analysis for transport current of 80 A. However, the experimentally measured field is 473 Gauss, which is 19 % more than that of calculated value. The error in the magnetic field with respect to the theoretical values calculated using ANSYS along the axis of the square Helmholtz coil has been plotted in figure 10. in normalized scale. This 19 to 20 % error in the magnetic field measurement as observed from figure 10. is may be due to some experimental facts like the improper alignment of the Hall sensors towards magnetic flux lines, loose winding of the HTS tape and due to corner effect etc. As per the specification of the Hall sensor, it is calibrated with field vector 90° to the sensor active area. The magnetic field sensitivity can vary up to maximum 29 % for the angular deviation of 45° from perpendicular direction to the field.

Experimentally, the observed maximum magnetic field along for a transport current of 80 A along the axis of the square Helmholtz coil is found to be 473 Gauss. However, the field on the tape surface is large in comparison to that on the center axis. The observed field on the tape surface is found to be 526 Gauss as seen from figure9. So for the applied current of 80 A, the tape experiences a self field of 526 Gauss. From I-V characteristics of this Helmholtz coil, the critical current is found to be around 84 A at LN2 temperature, which is nearly 40 % less in comparison to the straight tape with \( I_c \) value of 145 A. Such reduction in \( I_c \) value can be understood from the magnetic field dependent \( I_c \) curve of this HTS tape in LN2 temperature. Figure 11. shows the magnetic field dependent \( I_c \) curve of the conductor for field parallel to the tape surface [12] at 77 K. For the applied current of 84 A, the self field generated will be slightly more than 526 Gauss. In the magnetic field dependent \( I_c \) curve, the self field of around 526 Gauss corresponds to current of around 129 A, which should be critical current of the fabricated Helmholtz coil. The measured \( I_c \) of this coil is 84 A which is less from the expected value. This reduction is most likely due to the stress generated on the tape in winding configuration i.e. finite radius bending, inter-double pancake transition and the self field that resulted the degradation of the \( I_c \) value.
Figure 10. plot of (dB/B)% vs. normalized distance along the axis of the square Helmholtz coil.

Figure 11. Magnetic field dependent $I_c$ curve of the tape for field parallel to the tape surface at 77 K.
4. Conclusions

A high temperature superconducting (HTS) square Helmholtz coil has been designed and fabricated by using commercial grade BSCCO tape. The current voltage (I-V) characteristics of this HTS coil has been carried out using standard four probe technique at liquid nitrogen (LN2) temperature. From the I-V characteristics, the critical current based on self field dependent of HTS coil has been calculated and found to be 84 A. Magnetic field profiles have been measured along the axis of this coil using axial (InAs) hall sensor (model no. HGCA-3020). A uniform magnetic field of maximum amplitude of 0.5 KGauss has been obtained for applied current of 80 A at LN2 temperature. The observed field homogeneity is within a length of 53 mm, which is equivalent to the separation between the two coils. The measured field profiles have a very good agreement with that of theoretical values predicated in literature. This coil will be used as magnetizer for the magnetic characterizations like magneto-receptivity, ac susceptibility under DC field etc. of long sample length of size around 50mm length with high aspect ratio. This square Helmholtz coil can provide more field uniformity than that of circular coil provided the fabrication of the coil would have made very close to square shape. However, the winding process is very difficult as compared to circular one. Successive layer of winding is easy to deviate from the right angle towards circular shape at the corners. So high precautions must be taken during winding process of this coil.

References

[1] http://www.amsuper.com/products/htswire/index.cfm
[2] http://www.sei.co.jp/Super/hts-e/index.html
[3] Sato K, Hayashi K, Ohmatsu K, Fujikami J, Saga N, Shibata T and Isojima S, 1997 IEEE Trans. Appl. Supercond. 7 345
[4] Wesche R, Anghel A, Jacob B, Pasztor G, Shindler R and Vecsey G 1999 Cryogenics 39 767
[5] Nayak Pramoda K, Prasad U, Sharma A N, Kedia S, Patel D, Kristi Y, Amin V and Pradhan S 2007 IPR/TR-130/2007
[6] Nayak Pramoda K, Prasad U, Sharma A N, Kedia S, Patel D, Kristi Y, Amin V, Bhavsar V and Pradhan S 2007 IPR/TR-136/2007
[7] Oomen M P 2000 Ph.D thesis 85
[8] Norris W T 1970 J. Phys. D 3 489
[9] Alamgir A K M, Fang J, Gu C and Han Z 2005 Physica C 424 17
[10] Sohn M -H, Kim S, Sim K –D, Min C –H, Lee E -Y, Seong K –C, Kwon Y -K and Kim H –J 2007 Physica C 463-465 1276
[11] http://www.ansys.com
[12] http://www.amsuper.com/html/products/htswire/1gHSP.html
[13] Nayak P K, Prasad U, Sharma A N, Patel D, Kedia S and Pradhan S 2009 Physica C 469 211