Design, analyses, fabrication and characterization of Nb$_3$Sn coil in 1 W pulse tube cryocooler

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Abstract. A laboratory scale Nb$_3$Sn coil is designed, analysed, fabricated and characterized in 1 W pulse tube cryocooler in solid nitrogen cooling mode and in conduction cooling mode. The magnetic field profile in axial and radial direction, Lorentz force component across the winding volume in operational condition are estimated in COMSOL. The coil is designed for 1.5 T at 100 A. It is fabricated in wind and react method. Before winding, the insulated Nb$_3$Sn strand is wound on a copper mandrel which is thermally anchored with the 2$^{nd}$ stage of the cold head unit via a 10 mm thick copper ‘Z’ shaped plate The temperature distribution in 2$^{nd}$ cold stage, copper z plate and coil is monitored in both solid nitrogen cooling and conduction cooling mode. In solid nitrogen cooling mode, the quench of the coil occurs at 150 A for 0.01 A/s current ramp rate. The magnetic field at the centre of the coil bore is measured using transverse Hall sensor. The measured magnetic field value is compared with the analytical field value and they are found to be deviating ~5% in magnitude. Again the coil is tested in conduction cooling mode maintaining the same current ramp rate and it is observed that the coil gets quenched at 70 A at temperature ~ 10K.

1. Introduction

Now a days the conduction cooled “dry” superconducting magnets are gaining popularity over the liquid cryogen cooled “wet” magnet due to the scarcity and elevating price of liquid Helium. Thus the cryocooler cooled dry magnets are being commercialized for SMES, MRI, NMR and several other applications [1],[2]. One of the main advantages of the liquid Helium cooled magnet system is that large reservoir of heat capacity of liquid helium which effectively allows the magnet to be thermally stable as well as accommodates other heat load acting on the whole system and also the heat generated during the quench condition keeping the magnet safe. Recently, experimentations on increasing the heat capacity of the cold body in cryocooled system are going on using solid cryogen exploiting the cooling power of cryocooler [3],[4],[5]. In the present work, a small laboratory scale Nb$_3$Sn based coil is designed, analyzed, fabricated and tested in both solid nitrogen (SN$_2$) and conduction cooling mode at temperature 9-10 K. Nb$_3$Sn is preferred over NbTi due to its higher temperature margin and also at temperature ~10K, the Sumitomo made pulse tube cryocooler accommodates more than 20 W of heat load when the 1$^{st}$ cold stage temperature is 40 K. The coil is made in wind and react method. It is first tested in solid nitrogen cooling mode. The critical current of the coil is observed to be 150 A at ~9K. The magnetic field of the coil is measured at the centre of the coil bore and compared with the analytically estimated field value. Unfortunately the coil gets quenched at only 70 A in conduction mode.
cooling mode. The degradation in critical current in conduction cooling mode may be originating due to handing issue of strain sensitive heat treated Nb$_3$Sn strand.

2. Strand Configuration

The Nb$_3$Sn strand is processed via Bronze route. The average diameter of the strand with glass fibre insulation is ~1.2 mm. The details of the strand configuration are listed in table 1. The cross-sectional view of the strand at 199 x and 1kx magnifications are shown in figure 1(a) and 1(b).

Table 1. Details of strand configuration.

| Parameter                        | Specification |
|----------------------------------|---------------|
| Average Diameter                 | 1mm           |
| No. of Niobium Filaments         | 14000 (approx.) |
| Filament Diameter                | 2.246 µm      |
| Average thickness of Tantalum bar | 16.7µm        |
| Cu: Superconductor               | 1:0.523       |
| Cu: Non-superconductor           | 1:0.8366      |

Figure 1. Cross-sectional view of Nb$_3$Sn strand at magnification (a) 199 x and at (b) 1000x.

3. Magnet Design and analyses details

The coil is designed for 1.5 T of central field at 100 A current. The inner diameter of the copper mandrel upon which the strand is wound is 38 mm and the outer diameter of the winding is 89 mm. The copper mandrel has a centre copper plate of 3 mm thickness parallel to the top and bottom flange of the copper bobbin. The centre plate of the bobbin is made to facilitate cooling in the middle section of the winding pack in conduction cooling mode. The coil parameters are listed in table 2.

Table 2. Magnet Parameters.

| Parameter     | Specification |
|---------------|---------------|
| Inner diameter| 38 mm         |
| Outer diameter| 89 mm         |
| Parameter                  | Value                  |
|---------------------------|------------------------|
| Winding height            | 71 mm                  |
| Designed Field value      | 1.5T at 100 A          |
| Total no. of turns        | 1120                   |
| No. of layers             | 20                     |
| No. of turns/layer        | 56                     |
| Total conductor length    | 172 m                  |
| Winding method            | Wind and react         |
| Operating temperature     | 9-10 K                 |
| Inductance                | 55.25 mH               |
| Stored energy             | ~276 J                 |

### 3.1 Finite element analyses

Three dimensional magnetic field profile of the coil has been estimated using COMSOL (version 5.2) considering symmetric half volume of the coil. This symmetric half volume is modeled inside a large air sphere which acts as infinite boundary. The coil geometry along with the air sphere is shown in figure 2.

#### 3.1.1. Boundary Conditions

Ampere's law is preserved in all domains. The coil is excited with transport current of 100 A driven in the toroidal direction. The coil electrical conductivity is assumed to be $3 \times 10^{10}$ S/m. The whole geometry is meshed with 5128472 no. of tetrahedral domain elements. The average quality of the elements in the geometry is 0.745 and the mesh volume is 0.2617 m³ as per COMSOL mesh statistics. The meshed geometry is shown in figure 3. The problem was computed with linear stationary solver. The volumetric magnetic flux density, axial and radial field distribution as a function of height and width of the coil is represented in figure 4, figure 5(a) and 5(b) respectively. The axial field distribution is non-symmetric as the coil geometry is non-symmetric across the middle section of the coil.

![Figure 2. Coil inside air sphere.](image1)

![Figure 3. Meshed geometry.](image2)

![Figure 4. Magnetic flux density.](image3)
During charging of the coil, the winding pack is invariably subjected to a hoop force resulting from the interaction of the transport current with that of the self field. The volumetric force component along the height and width of the winding pack are estimated. The maximum outward volumetric force along the coil width and height are estimated to be $1 \times 10^8 \text{ N/m}^3$ and $3 \times 10^7 \text{ N/m}^3$ respectively as shown in figure 6(a) and 6(b) respectively. The impregnated insulation is expected to withstand this volumetric force during operation.

**Figure 5.** (a) Axial and (b) radial variation of magnetic field.

**Figure 6.** Lorentz force contribution along (a) width and (b) height of winding pack.

4. Magnet Winding, reaction heat treatment and impregnation

Wind and react method is adopted for fabrication of the coil. The insulated strand is wound over a copper mandrel of 38 mm inner diameter using a solenoid winding machine maintaining a constant winding tension. The drawing of the coil former is shown in figure 7. The length of the strand at the terminals was kept sufficiently long (~0.5 m) to connect them with cryostat current lead and also to accommodate thermal stress in operational condition. The total length of the conductor consumed in 1120 turn of winding is ~172 meters. After winding, the coil is placed inside a furnace where the reaction heat treatment of the coil is carried out in Argon atmosphere at 650°C for 100 hrs.

After heat treatment, the coil is taken for vacuum pressure impregnation. The coil is impregnated using cyanate ester based resin. The coil is placed inside a SS vacuum chamber which acts as mould for impregnation. The vacuum chamber is baked up to 170°C temperature. Then the chamber is evacuated to $10^{-3}$ mbar. Before transferring the resin to the mould, the resin is degassed at temperature ~100°C. Then the resin is transferred to the mould maintaining 2 bar pressure. Then the coil is left for impregnation for 1 hour at 110°C and at 2 bar pressure. After impregnation, particular curing cycle is followed. In the cycle, the mould is heated from 110°C to 150°C at 1°C/min heating rate, then temperature is maintained at 150°C for 4 hours, then again heated from 150°C to 180°C at 1°C/min heating rate and finally holding temperature at 180°C for 2 hours. The images of the coil after heat
treatment and after impregnation are shown in figure 8 and 9 respectively. The coil is released from the mould after completion of curing.

![Coil Former](image1)

**Figure 7.** Coil Former.

![Coil after winding](image2)

**Figure 8.** Coil after winding.

![Coil after impregnation](image3)

**Figure 9.** Coil after impregnation.

5. **Experimental arrangement**

I-V characterization of the coil is carried out both in solid nitrogen cooling as well as in conduction cooling mode maintaining 0.1 μV/cm criteria. The advantage of solid nitrogen cooling over dry magnet is that the solid nitrogen has better heat capacity per unit volume at 4K (0.031 J/cm³)[5] compared to copper which acts as thermal reservoir in case of conduction cooling. Thus the temperature gradient across the winding of the coil is less in solid nitrogen cooling. This allows the coil to be operated at higher current density compared to conduction cooled dry magnet.

The heat treated coil is placed inside the a copper chamber equipped with current lead assembly, instrumentation feedthrough, vacuum port with pumping provision and liquid nitrogen inlet and outlet port. The whole copper can is thermally anchored with the second cold stage of the cryocooler via a cooper ‘z’ shaped plate. The image of the solid nitrogen cooling set up, coil mounting schematic and the position of the temperature sensors are shown in figure 10,11 and 12 respectively.

![SN2 test set up](image4)

**Figure 10.** SN₂ test set up.

![Coil mounting schematic](image5)

**Figure 11.** Coil mounting schematic.

![Temperature sensor mounting location](image6)

**Figure 12.** Temperature sensor mounting location.

After characterizing the coil in SN₂ cooling mode, the coil is impregnated and taken for conduction cooling. The coil was self-impregnated with SN₂ earlier. The coil is thermally anchored with the copper base plate by mechanically bolting the coil bottom flange of 8 mm thickness and also using Apiezon N grease to reduce contact impedance between the mating surfaces.
A two stage pulse tube cryocooler by Sumitomo Heavy Industries with cooling power 1 W at 4K and 40 W at 45 K is employed to cool the sample. The radiation shield is thermally connected with the first cold stage of the cold head unit. The sample was connected to power supply via a binary current lead comprising optimized copper current lead from room temperature to ~40 K and a stack of high temperature superconducting tapes (DI-BSCCO) from 40 K to sample temperature.

I-V characterization of the coil at self–field are carried out using standard four probe method. The pair of current lead was connected to two unipolar AMI XFR (0-200A, 0-12V) DC power supply connected in parallel. The power supply was connected to AMI programmer (model No. 430) to control the ramp up and ramp down rate of the transport current. Temperature was measured using calibrated carbon ceramic sensor (CCS). The temperature of the sensors was monitored using Lakeshore temperature monitor (model 218). The voltage across the sample is measured by Keithley multimeter (Model 2750). All the temperature and voltage data were acquired in LABVIEW platform installed in a PC via PXI based acquisition system. The PXI system was interfaced with a PC via fiber optic link. The sampling frequency of the data acquisition system was kept 1 Hz and all the voltage, current and temperature data were synchronized to same time scale.

6. Results and discussion

I-V characterization of the coil is carried out at ~9 K in SN$_2$ cooling mode. The coil is charged maintaining 0.01A/s current ramp rate. It is observed that the voltage is gradually increasing with current though the temperature of the magnet surface remains fairly constant during coil charging. I-V plot of the coil is shown in figure 12 (a) in SN$_2$ cooling condition. The coil gets quench at 150 A when the temperature increases very fast within 1 A increment of current. The same coil after impregnation is characterized in conduction cooling mode. The temperature of the magnet is maintained at ~10K. The coil is quenched at current 70 A for the same current ramp rate as shown in figure 12 (b).

![Figure 12. I-V plot of coil in (a) SN$_2$ cooling mode and (b) conduction cooling mode.](image-url)

The early quench of the coil may be due to degradation of heat treated strand at the terminals of the winding. The temperature of the coil as a function of current in both cases are shown in figure 13(a) and 13 (b).
The magnetic field at the centre of the bore is measured in SN\textsubscript{2} cooling mode as a function of transport current using InAs Hall generator. The measured magnetic field at current 100 A is \(\sim 1.4\) T whereas the estimated magnetic field at the centre of the bore is \(\sim 1.47\) T. This error (~5\%) between the estimated and measured magnetic field values lies in the mounting inaccuracy of the sensor. The magnetic field vs current plot is shown in Figure 14.

7. Summary
A small laboratory based Nb\textsubscript{3}Sn coil is designed and FEM analyses are carried out for volumetric magnetic flux density, axial and radial distribution of magnetic field and volumetric Lorentz force contribution across the width and height of the winding pack. The coil is fabricated in wind and react mode. After fabrication, the coil is characterized both in SN\textsubscript{2} and conduction cooling mode. The coil is quenched at 150 A in SN\textsubscript{2} cooling and at 70 A in conduction cooling mode. It is suspected that the early quench of the coil in conduction cooling mode may be due to the handling issues of the coil.
terminals during releasing the coil from impregnation mould. The measured magnetic field at the centre of the coil bore at 100 A is observed to be within 5% of deviation from the analytical value. It is planned that a coil with similar configuration yet larger dimensions would be used as background magnet for characterization of short superconducting sample in cryocooler.

References
[1] Korpela A, Lehtonen J, Mikkonen R and Perälä R 2003 *Supercond. Sci. Tech* **16** 11
[2] Kim H S, Kovacs C, Rindfleisch M, Yue J, Doll D, Tomsic M, Sumption M D and Collings E W 2016 *IEEE Trans. Appl. Superconduct.* **26** 4
[3] Haid B, Lee H, Iwasa Y, Oh S S, Ha H S, Kwon Y K and Ryu K S 2001 *IEEE Trans. Appl. Superconduct.* **11** 2244
[4] Iwasa Y, Bascuñán J, Hahn S and Park D K 2012 *Physics Procedia* **36** 1348
[5] Bascuñán J, Hahn S, Ahn M and Iwasa Y 2010 *AIP Conf. Proc.* **1218** 523