Superconductive coil characterization for next dipoles and quadrupoles generation

Abstract

The LHC is the most sophisticated scientific machine ever built as a device that allows the scientists to explore the universe and its origin. Scientists from all over the world are working to upgrade the LHC to open the door for new physics. HL-LHC (high luminosity LHC) project is the core project at CERN which was approved in 2013 by CERN’s council. In order to increase the integrated luminosity up to 3000 fb^{-1} within this decade. To do so it is crucial to design cutting edge superconducting magnets that can elevate the magnetic field up to 20T, which is Nb_3Sn. However this material is brittle when it functions as superconductor, which makes it hard to be used as a cold magnet. So in this report the fabrication of 10 stacks of Nb_3Sn superconducting multifilament wires was investigated as well as primary test using experimental setup and creating material model for Nb_3Sn with the finite element analysis [ANSYS] is carried out. [1]

Keywords

Nb_3Sn, LHC, HL-LHC, Quadrupole, FEM, Superconducting Magnets, Elastic Modulus.

1. Introduction

The main components of the LHC are the magnets and cryogenics. In addition to other important components that are out of the scope of this report.

1.1. Magnets state-of-the-art

The LHC has 6628 superconducting magnets, in addition to 1232 main dipoles and 300 main quadrupoles. There is also correcting magnets such as sextupoles and octupoles (2464, 8) respectively along 27 km long tunnel. [2]

The dipole magnets are used to bend the beam through homogenous magnetic field. And the quadrupoles magnets are used to focus the beam in one direction and to defocus in the other direction. Usually they are configured in spaced focusing and defocusing cells.

1.2. Superconductivity

The key part which is common between all dipoles and quadrupoles is the coil’s superconducting material. Currently NbTi is used and it has up to 9 T practical operating magnetic field. [3] However for High Luminosity upgrade (HL-LHC) and Future Circular Collider (FCC) projects, the beam has to acquire very high energies of 14TeV [4], and 100 TeV [5] respectively. Which is not achievable by NbTi since the maximum practical operating field for NbTi is 9 T [3], so the magnetic material has to be changed to Nb_3Sn which can push the limits to 20 T magnetic fields with 16 T tested pilot magnets. [6]
In fact, Nb\textsubscript{3}Sn was discovered in 1954 by Matthias et al. [7] But it wasn’t used due to its brittleness, and the coil manufacturing process by that time wasn’t successful. [8]

1.3. Superconducting materials fabrication

Contrary to NbTi which ductile material that is easy to be extruded and rolled up, Nb\textsubscript{3}Sn is very brittle and relatively harder to be manufactured. So another novel way is investigated to fabricate Nb\textsubscript{3}Sn coils for future LHC upgrade.

1.3.1. Niobium titanium wires fabrication (NbTi)

The main NbTi dipole cables can withstand up to 11850\textsuperscript{A} with 8.3 T magnetic field with stored energy of 11 GJ in total at 1.9 K that is obtained by using superfluid helium. [9] The dipole magnets at CERN designed to produce 8.4 T at 1.9K provided by superfluid helium. NbTi is prepared using double stacking process for multifilament, and the main steps starts with cleaning the sample using an acid, assembling the multifilament, which is sent for welding. Afterwards, isostatic pressing is applied on the multifilament, and is send for extrusion, bench drawing, and bull block drawing respectively. The oven is used after that as heat treatment process and again drawing process followed by final drawing after twisting. [10]

1.3.2. Niobium tin (Nb\textsubscript{3}Sn) wires fabrication

Niobium tin is a good candidate for magnetic fields of 10-21 T when cooled to 1.9K [10]. However Nb\textsubscript{3}Sn materials are harder to be manufactured using the same process as that for NbTi, because this material is brittle. The filaments includes tin powder to make it easier to handle, and the process for which these multifilament are manufactured called Powder in Tube (PIT) process, which is done by external supplier, yet the process of making Rutherford cables is done at CERN where the filaments of 0.05 mm diameter are subdivided, twisted together, embedded in copper matrix, and wrapped with fiberglass for insulation purposes. Rutherford cables have trapezoidal cross section for the coil configuration. The wires are stacked in multi strand cable to get the advantage of reducing the length of the piece, and to reduce the number of turns also they are twisted to reduce the coupling currents, and to give rise to higher mechanical stability. Afterwards further heat treatment is described in the following section.

Figure 3 Machine at CERN for making Rutherford cables (Left) & Wire schematic (Right)

2. Nb\textsubscript{3}Sn properties

Scanning through the literature for Nb\textsubscript{3}Sn properties leads to variety of values for elastic modulus and thermal contraction coefficient. The graphs below show the values for elastic modulus and thermal contraction coefficients in 3 direction at room temperature and cryogenic temperature for each direction measured. Available coil properties measures highly dispersed data. Elastic modulus takes values within a range of (15-60) GPa and the thermal contraction within (2-4) mm/m range. [11] [12] [13] [14] [15] This discrepancy occurs due to the anisotropic behaviour of the composite material, and as Chichili et al. [16] indicated that the Poisson ratio differs in each direction as shown in figure (5).

Figure 4 elastic modulus and thermal contraction coefficient values in literature

Figure 5 Poisson ratio values shows that the material is anisotropic [16]
Moreover, these values vary depending on the preparation process of the coil as well as the compression test devices’ accuracy. And since there is no information about these parameters it’s important to carry out the test under defined conditions. Numerical simulations have been carried out before to simulate the behaviour of Nb₃Sn, but there is huge mismatch in elastic modulus values between the experimental data and the numerical results. Which rise the importance of studying the material model that can best fit Nb₃Sn material behaviour using finite element analysis [ANSYS] which is discussed in the Results section.

3. Nb₃Sn coil characterization

The study of the mechanical properties must be carried out on representative samples of the coil. The mechanical characterization has to be performed on 10-stack prepared with the same coil fabrication stages, which is the curing, reaction, and impregnation.

Prior to the preparation, two different moulds have been specifically designed to perform curing/reaction and impregnation. For the curing/reaction moulds, the width and thickness of the bare cable, thickness of the fiberglass, the cable expansion during reaction (width 1.2%, thickness 4.5%), and the mica layers thickness to prevent the sample-mould gluing are all considered. However the impregnation moulds was designed based on the final shape of the 10 stacks, and without considering the mica’s thickness which must be removed prior to the impregnation phase.

3.1. Preparation of 10 stacks

To start with cleaning the 5 moulds with acetone, then to cut the cable (MQXF RRP - 106) to 170 mm long stacks and cut the mica (0.25 mm thickness) into 2 values (10 pieces of 19.15 mm width) and (10 pieces of 18.85 mm width).

3.1.1. Curing

The binder was prepared as following using mass factions of 20 g of part 1, 21 g of part 2, and 2.8 g of part 3 CTD-1202 ceramic matrix.

Afterwards the binder was put by a brush over the cables with the following mass for each mould. Mould 1 has 5.7 g of the binder mixture, Mould 2 has 5.4 g, Mould 3 has 5.8 g, Mould 4 has 5.8 g, and Mould 5 has 5.7 g. It is important to be as accurate as possible while putting the binder so as to have homogenous and equal amount of binder in 5 different samples. Around 40 min later, the penetration of the binder is checked by opening one side and observing the colour change in the
3.1.2. Reaction

Reaction is done to create the superconductive alloy. Copper, tin, and niobium are heated in a cycle in argon atmospheric oven.

The cycle is: 72 hr 210 C, 48 hr 400 C, 50 hr 640 C – ramp 25 deg/h until 210 then 50 deg/h.

Followed by gradual natural convection cooling down. The duration of this process is around three weeks.

3.1.3. Impregnation

After reaction, the 10-stack is vacuum impregnated with epoxy resin. Finally, the 10-stack is cut in 20 mm length pieces in an aluminium mould.

3.2. Preliminary compression test

A preliminary compression test has been carried out in the EN/MME mechanical laboratory with 1MPa/s stress controlled test in the azimuthal direction. And the stroke was measured by average value of three LVDT sensors placed as in picture 14.

The pre-load was set to 5 MPa and to three cycling loops at 50, 100 and 150 MPa.

4. Results and discussion

4.1. Experimental results

The following graph of stress versus strain graph was obtained from the preliminary compression test at room temperature. This result was obtained based on previous 10 stacks which are manufactured by the same procedure described earlier.

The first phase is dominated by the behaviour of the epoxy resin. It represents the weakest part of the sample and cracks propagate during the test, and in the second part of the test the Nb3Sn resistance becomes predominant and its elastic modulus can be measured during the unloading phase. The elastics modulus measured differs with respect to what is found in the literature.

4.2. Numerical results

A material model (implemented in ANSYS) is created to reproduce the experimental curve, taking into account the orthotropic nature of the material.

4.2.1. Facts

The compression test software is considering the cross sectional area to be constant (19.02*19.37 mm²) however in reality during the compression this cross sectional area is
variable and changes with respect to the applied force. So small decrease in the stress is expected due to the increase in the area. This effect is considered and simulated by ANSYS.

Finally, the displacement sensors are placed far from the sample and the displacement value recorded is an average value of the three sensor readings which is considered an error in the measurement. Also the platform’s displacement was included in the average value of the displacement, however considered as negligible error.

### 4.2.2. Assumptions

The simulation assumes homogenous distribution of Nb3Sn material only throughout the geometry. Other materials such as the resin, copper matrix, and fiberglass are not considered in the simulation for simplicity. Also the unloading assumed to be elastic.

### 4.2.3. Numerical approach

The material was created with isotropic elastic modulus of 26.6 GPa and Poisson ratio of 0.27. 0.45 Poisson value [18] was also used, in the simulation however the relative difference is 1E-4 % in the deformation output. So 0.27 was considered in the simulation, since this values differs in the literature.

Multilinear isotropic hardening was used as the material model. The plastic strain values were calculated based on the difference between the total and the elastic strains. The software is capable of generating the total deformation automatically. The geometry is simple cube of Nb3Sn with size of 19.09*19.37*19.92 mm³

The mesh size is 10 mm to have homogenous values per each step of the stress with hex dominant method. The geometry was supported by zero displacement only in the y direction and tabulated force acting in negative y direction.

The analysis setting is set to 6 steps with 25 sub steps. Large deflection is set to ON and nonlinear effect is YES. The force input cycle is: 0 N to -18421N to 0N to -36842N to 0N to -55263N to 0N. These values corresponds to 50, 100, 150 MPa respectively. The output is the directional deformation in y axis, which is converted to strain, and the stress vs. strain curve fitting is obtained. The numerical results as expected is slightly lower than the experimental one and that’s because ANSYS is considering the change in the cross sectional area throughout the cyclic profile. However ANSYS didn’t accept having a material model called hyperelastic response function in parallel with the plastic multilinear hardening model. I recommend further investigation on relating these 2 models since the response function gave exact fit for the unloading part.

![Figure 16 Geometry with Force acting in negative y direction](image)

![Figure 17 Engineering data Stress vs. Plastic strain input values](image)

![Figure 18 Stress (MPa) vs. Strain output values](image)

### Conclusion

Nb₃Sn superconducting alloy is necessary to reach high magnetic fields for the next dipoles and quadrupoles generation. It needs particular fabrication process due its brittleness. Numerical analysis shows promising results for the Nb₃Sn material model that can approximate the experimental curve for future tests.

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Bibliography


international cryogenic materials conference, Ohio, 1954.


