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A Review of Nb_3Sn Dipole Magnets: Mechanical Design and Fabrication

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Nb_3Sn dipole magnets reviewed were fabricated by the following Labs:

Lawrence Berkeley National Laboratory
CERN – ELIN
Brookhaven National Laboratory
University of Twente

Design and Fabrication of the Nb_3Sn Dipole Magnets by LBNL

Papers

- Design of the Nb_3Sn Dipole D20, D. Dell' Orco, R. Scanlan and C.E. Taylor, *IEEE Trans. on Applied Superconductivity*, Vol 3, No.1, 1993.
- Fabrication and Component Testing Results for a Nb_3Sn Dipole Magnet, D. Dell' Orco, et al, *IEEE Trans. on Applied Superconductivity*, Vol 5, No.2, 1995.
- A 50 mm Bore Superconductor Dipole with a Unique Iron Yoke Structure, D. Dell 'Orco et al., *LBL Technical Report*, SU-MAG 375; LBL 32071.

Design Goals

To design a magnet with a short sample field of 13 T, 50 mm bore diameter, 50 mm maximum winding thickness and 9 mm collar thickness.

The key issues in the magnet design are cable design, cable insulation, Nb_3Sn heat treatment, end spacer, wedge material, joint or splice design, coil impregnation, pole design and yoke assembly.

(1) Cable Design

Two sources of conductor, TWAC and IGC both based on the internal tin approach were considered. TWAC: high volume fraction of Sn with a Nb diffusion barrier to produce high Jc. IGC: low Cu to non-Cu ratio, moderately high volume fraction of Nb and Sn and Ta diffusion barrier.

Cables showed substantial degradation while keystoning; micrographs from keystoned cables showed severe deformation of the filament bundles on the narrow edge of the keystoned cables. Final cable design had no keystone angle to avoid degradation. IGC conductor is chosen for inner cable and TWAC conductor for outer cable as TWAC conductor showed some degradation even in rectangular sections of the inner cable.

(2) Cable Insulation and Heat Treatment

Glass-fiber insulation was used. The insulation should withstand the Nb_3Sn reaction heat treatment. Recommended 740 ^{o}C heat treatment could not be implemented as the insulation was extremely fragile. Finally the cables were heat treated at 680 ^{o}C for a week. "Sleeve" was made and then slipped onto the cable which is approximately 500 m long. Ceramic insulation coating was applied on the metal pieces (end-spacers and the wedges) to avoid shorts due to abrasion.

(3) Joint or Splice Design

The splice design is required to attach NbTi cables to Nb_3Sn cables at the coil ends. The following are the steps involved:

- Conductor is formed into the final shape and restrained during reaction by a fixture.
- After reaction, fixture is removed and replaced with a clean high conductivity Cu fixture.
- Nb_3Sn cable, NbTi cable and the Cu pieces are coated with flux; Pb-Sn eutectic solder strips are placed between the each component in the Cu fixture.
- Heat is applied.

This design resulted in a resistance of 0.6 nO or about 0.025 W at 6000 A heating per joint.

(4) Epoxy Impregnation

The epoxy should have low viscosity, long pot life, good thougness and be compatible with glass-fiber reinforcement. The epoxy chosen was CTD-101. The maximum prestress applied should be atleast 100 MPa less than the maximum compressive load the composite stacks could withstand before the epoxy begin to show cracking. Compression tests were preformed to obtain the mechanical properties of both the inner and outer stacks at ambient temperature and at 77K.

(5) Collar and Yoke Assembly Design

Elliptical collar (87.1 x 89.1) with 9 mm thick at the mid-plane is used. Packs of 90 laminations each thick 1.37 mm are used while collaring. Both straight sections and the ends are collared and the prestress due to collars is about 15 MPa.

The yoke assembly consists of two halves of iron yoke separated by the Al bars, ring and collet support system and stainless steel shell. A vertically split yoke (outer radius = 381 mm) with a tapered gap (0.56 – 0.76 mm) was used with a Al spacer of 280 mm long with 025 mm clearance. This clearance allows the compression of the collar and the coils to reach the design prestress after assembly.

For D20, the full prestress for the coils was obtained by welding the stainless steel shell in the press. However for D19, the collets are placed over the yoke and the rings are pressed into place one at a time; the ring and collet system have a taper angle of 20 and an interference of 0.71 mm with the yoke, this drives the collet against the yoke which decreases the gap and compresses the collars and coil. As the gap is decreased, keys in the collar become unloaded and the entire coil is supported by the external rings; collars acts as a spacers. Yoke gap and hence the coil prestress is determined by the size of the

Al spacer. A prestress of 70 MPa on the coils were achieved. The difference in thermal contraction between the iron yoke, ring and the coils keeps the coil prestress almost constant during the cooldown.

A stainless steel was welded around the ring over the length of the magnet to provide the axial stiffness. The ends were preloaded at room temperature with a 27 KN axial compressive load. Axial constraint was accomplished by 150 mm thick stainless steel end plates welded to the shell.

The limiting factor for the short sample still remains the outer layer pole turn.

(6) Mechanical Analysis

ANSYS was used to perform the mechanical analysis. The following are the assumptions adopted in the mechanical analysis:

- Iron yoke has infinite permeability and no saturation
- All materials are homogeneous and linearly isotropic
- Coils have no hysteresis
- No sliding between the coils and the copper wedges
- No friction
- Plane stress analysis is valid

Three dimensional interface elements were used to model the relative sliding and separation of the different materials inside the magnet (between coils and collar, collar and yoke and yoke and Al spacer).

The goal of the mechanical analysis was to design the magnet such that the yoke gap closes during the cooldown and does not open when the Lorentz forces are applied; to minimize the stresses and displacements and to have a minimum residual compression at the poles.

First Nb_3Sn Dipole Magnet by CERN - ELIN

Papers

- Towards a 1m Long High Field Nb_3Sn Dipole Magnet of the ELIN-CERN Collaboration for the LHC-Project, S. Wenger, F. Zerobin and A. Asner, *IEEE Trans. on Magnetics*, Vol 25, No.2, 1989.
- First Nb_3Sn, 1m long Superconducting Dipole Model Magnets for LHC Break the 10T Field Threshold, A. Asner, R. Perin, S. wenger and F. Zerobin

(1) Superconducting + Structural Materials

Inner and outer coils are wound with different Nb_3Sn cables. Unlike LBL dipole, both the cables are keystoned. The insulation material used was the glass and/or mica tapes. The cables are insulated one-sided with 0.14 mm thickness. The wound layers are then reacted in an oven under inert gas at 675 ^{o}C for 144 hrs.

Critical current measurements of the pre-formed and reacted cable samples were measured at FERMILAB. No sample of the test coil cable could be quenched at 10.8 T and a current of 19.7 KA.

Collars were made up of a special aluminum alloy which are surrounded by two vertically split iron halves and finally a outer retaining cylinder which is also made of a special aluminum alloy with high tensile strength.

(2) Mechanical Structure

“Hybrid” mechanical structure in which the coil/collar assembly at room temperature provides only a part of the final coil pre-stress. During cool down, the coil/collar assembly is further compressed due to the shrinkage of the outer aluminum cylinder by closing the vertical gap between the split iron halves. NOTE: the gap has to be carefully designed; need FEM and short sample tests to verify the analysis.

(3) Mechanical Analysis and Short Sample Tests

The mechanical analysis was performed with contact frictional elements and material properties that include thermoelastic, non-linear elastic and orthotropic properties. The azimutal and radial elastic moduli of the Nb_3Sn composite (Nb_3Sn + bronze + copper + insulation + epoxy) was measured and used in the mechanical analysis. This ensures that the coils are not operated in the non-linear regime of the compression Vs deformation curve and that the coils are always kept under compression.

15 cm long short sample tests were performed to verify the mechanical design and analysis. The length is depended on the twist pitch of the cables (= 12 cm). The sample has only straight sections, which are insulted, reacted and impregnated. Coils are placed in Al collars, which are then clamped (with tapered keys, not sure). The whole assembly was then placed between the iron yokes and held together by the outer ring. Strain gauges are mounted on all the active components to obtain the stress-strain behavior which were then compared with the finite element computations.

Different collar and clamping designs were also investigated using the short sample tests at liquid N_2.

(4) Fabrication Issues

The winding machine which consists of mandrel, clamps and compression device should be carefully designed so that shapes will withstand the thermal cycle during the reaction of the cable. This is absolutely necessary as the Nb_3Sn cables of the bronze matrix type must be rigidly supported during the whole process of winding and reaction.

Internal coil splice design was used. The splice was performed after the reaction process. The joints were tested separately for contact resistance.

Collars are compressed on to the coils and then clamped. The collar/coil assembly is placed into the laminated iron halves. Rigid end-plates for the retention of the axial forces are tightened. Finally the outer cylinder made of aluminum alloy is shrink fitted.
CAUTION: for the outer aluminum cylinder, the stresses remain well under the break down values of the aluminum alloy even under accidental conditions.

11.5 T Nb_3Sn Dipole Magnet by Univ. of Twente

Papers

- An Experimental 11.5 T Nb_3Sn LHC type of Dipole Magnet, A. den Ouden, S. Wessel, E. Krooshoop, R. Dubbeldam and H.H.J. ten Kate, *IEEE Trans. on Magnetics*, Vol 30, No.4, 1994.
- Quench characteristics of the 11 T Nb_3Sn model dipole magnet MSUT, A. den Ouden et al.

(1) Conductor Design

Conductor design optimization was performed to obtain the position and tilt of the pole plan, number of layers, effective insulation thickness, cable dimensions.

Degradation due to cabling was measured: 20% degradation for inner cable and 25 % for outer cable. A short impregnated sample of the outer cable loaded with a transverse pressure of 150 MPa shows a reversible degradation of 5-8%. Incomplete impregnation of the sample or the absence of the filler material (e.g., glass fibers) can lead to a much larger degradation of 10-15% which is only partly reversible.

(2) Coil Supporting System

Ring shaped shrink fitted aluminum collaring system: controlled room temperature prestress and increased bending stiffness

Separate stainless steel pole inserts. Alignment of the poles w.r.t the coils is achieved by inserting a copper piece between pole insert and the first winding of the outer layer.

Yoke has a vertical split which will stay open during all stages. The interference between yoke and collars is explicitly defined by an arc shaped zone at the inner radius of the yoke plates.

End-plates are not connected to the outer stainless steel cylinder. Eight 20 mm thick pulling rods going through holes in the yoke take care of the adjustable axial support.

All surfaces where elements can or will slide, low friction phosphor-bronze sheets covered with MoS powder are introduced.

(3) Cable Insulation and Heat Treatment

First attempt: glass/mica tape wrapped around the cable with 50% overlap. This led to low shear strength and very low thermal conduction in the windings due to insufficient impregnation of mica layers under pressure

Second attempt: single sheet of the glass/mica tape parallel with the cable + wrap S2 glass without overlap. This wrapping will hold glass/mica in position, improves epoxy impregnation, enhances shear strength and increases the effective thermal conductivity of the insulation layer by a factor of 2 at 4.5 K. The glass tape is heat treated in air at 300 ^{o}C before use.

Reaction was done at 680 ^{o}C in vacuum. Most of the binder material from the glass/mica tape evaporates at 300 ^{o}C.

(4) Splice Design

First turn of the outer layer is placed in the pole plane of the inner layer over a length of 3 twist pitches.

After heat treating the inner and outer coils separately, the coils are stacked with a connection piece (Cu plate) wrapped with reacted Nb_3Sn wires. The connection piece and both the coil terminals are soldered simultaneously with Ag/Sn.

(5) Epoxy Impregnation

- G10 end-pieces and temporary pole inserts are installed
- Steel foils of 0.05 mm covered with a non-adhesive layer is placed between coils and supporting elements to form vacuum enclosure.
- CIBY GEIGY MY740/HY906/DY062 epoxy with pot life of 6 hrs at 55 ^{o}C was used.
- After impregnation final stainless steel pole inserts are mounted equipped with shims.

(6) Coil Assembly and Collaring

Compressive stress in the coils at all stages can be achieved if the Young’s modulus of the coils is around 15-20 GPa. Note that the effective E of the impregnated coils is about 2-5 GPa. Hence 0.5 mm tangential oversized poles are pressed to their final dimensions which results in the coil Young’s modulus of about 18 GPa.

Stacked collar laminations are heated up to 200 ^{o}C which creates 0.3 mm radial mounting space for coils that are inserted in 10 sec. Collar shrinks 0.8 mm into the coils which leads to 65 MPa of prestress.

A Nb_3Sn High Field Dipole by BNL

Paper

- A Nb_3Sn High Field Dipole, R. McClusky, K.E. Robins and W.B. Sampson, *IEEE Trans. on Magnetics*, Vol 27, No. 2, 1991.

(1) Coil Winding

Four layer design with bore size of 80 mm. Note that the inner and outer coils are made of different cables. Only the inner coils are fabricated using “wind and react” technology. A ribbon made from S-glass, 10 mm wide and 0.1 mm thick was used to insulate the inner coils with 50% overlap. The outer coils are insulated with conventional Kapton and B-stage epoxy-fiberglass insulation. The outer cable was reacted before winding with MOBILE 1 synthetic oil (used to reduce sintering). Due to a larger bore diameter, it was possible to wind the outer coil after cable reaction.

Heat Treatment: All the coils were reacted at low pressure in argon atmosphere (10^{-3} mm Hg) in four stages → 200 hrs at 220 ^{o}C, 48 hrs at 340 ^{o}C, 24 hrs at 580 ^{o}C and 150 hrs at 650 ^{o}C. The inner coils were reacted in a special fixture which maintains the shape during heat treatment.

(2) Magnet Construction Details

The upper and lower inner coils are clamped on a stainless steel bore tube by 25 mm thick aluminum rings spaced at 50 mm intervals.

The space between the clamps was then wound with Kevlar epoxy to apply prestress to the coils. Clamps were removed after curing and the epoxy fiber glass bands are ground to fit the inner diameter of the outer coils. Epoxy applies the azimuthal force to each layer of the conductors and the yoke prevents the coils from distortion during excitation.

(3) Post-mortem Analysis

Inner-windings had moved away from the pole pieces leaving a gap of almost 2 mm. The possible reason could be low prestress. Note that the assembly was NOT EPOXY IMPREGNATED. It is believed that epoxy impregnation might prevent the gross motions of the coil.