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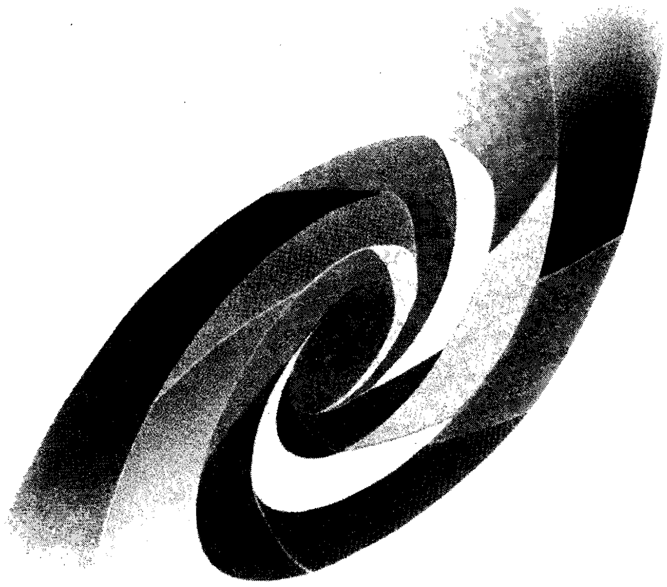

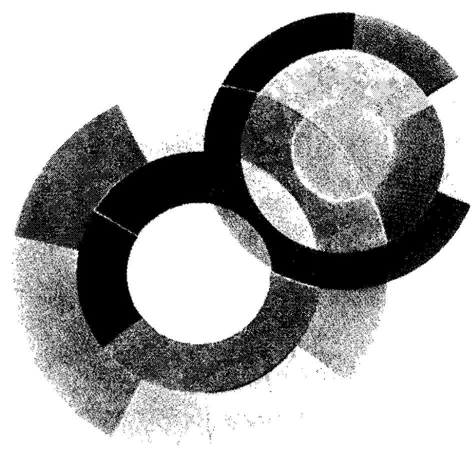

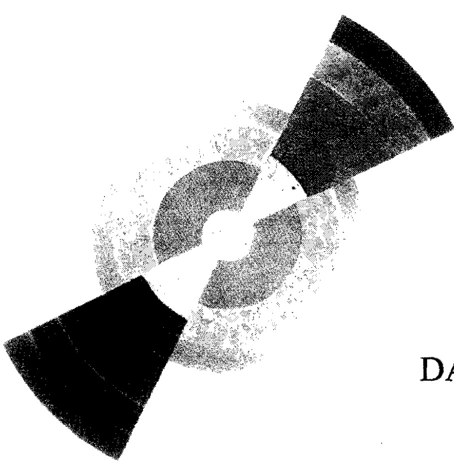

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Development and Manufacturing of a Nb_3Sn Quadrupole Magnet Model at CEA/Saclay for the TESLA Interaction Region

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Abstract—**One possible application of Nb_3Sn, whose superconducting properties far exceed those of NbTi, is the fabrication of short and powerful quadrupole magnets for the Interaction Regions (IR) of large particle accelerators. In some cases, as in the future linear collider TESLA, the quadrupole magnets are inside the detector solenoid and must operate in its background field. This situation gives singular Lorentz force distribution in the ends of the magnet. To learn about Nb_3Sn technology, evaluate fabrication techniques and test the interaction with a solenoidal field, DAPNIA/SACM at CEA/Saclay has started the manufacturing of a 1-m-long, 56-mm-single-aperture quadrupole magnet model. The model relies on the same coil geometry as the LHC arc quadrupole magnets, but has no iron yoke. It will produce a nominal field gradient of 211 T/m at 11,870 A. The coils are wound from Rutherford-type cables insulated with glass fiber tape, before being heat-treated and vacuum-impregnated with epoxy resin. Laminated collars, locked around the coil assembly by means of keys, restrain the Lorentz forces. After a recall of the conceptual design, the paper reviews the progress in the manufacturing and test of the main components as well as in the design and delivery of the main tooling. The first coil is expected to be wound and heat treated during the last quarter of 2003.**

Index Terms—**Superconducting Quadrupole Magnet, Nb_3Sn, Wind & React.**

I. Introduction

THE final focalization of high intensity beams in large particle colliders usually requires sets of strong superconducting dipole and quadrupole magnets, which are located close to the interaction points. As the Interaction Regions (IR's) are very crowded, see for instance the design of the Large Hadron Collider (LHC) Interaction Regions [1], there are definite advantages in increasing the field integral or the focalization power of these magnets to reduce their length and save some space.

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Furthermore, in some accelerator designs, such as in the TeV Superconducting Linear Accelerator (TESLA), under study at DESY, the final focusing quadrupole magnets end up inside the detector magnet, and must sustain a 4 T solenoidal field [2]. The requirement for high field and high field gradient, or the ability to operate in a sizable background field, precludes the use of NbTi. It has long been thought that interaction region magnets could serve as a test bed for Nb_3Sn applications to large particle accelerators. For instance, Twente University in the Netherlands is working since 1998 on a Nb_3Sn model of beam-separation dipole magnet that could advantageously replace the low-field magnets presently considered for the LHC at CERN [3]. Similarly, a collaboration made up of Fermilab, Brookhaven National Laboratory (BNL) and Lawrence Berkeley National Laboratory (LBNL) is promoting a US-LHC Accelerator Research Program (LARP) aimed at upgrading the final-focusing quadrupole magnets of LHC [4]. More recently, a collaboration involving 6 European institutes is pushing forward a proposal to build the Next European Dipole (NED), which targets also LHC IR upgrade [5].

CEA/Saclay has undertaken, since 1996, an R&D program aimed at designing and building a short Nb_3Sn quadrupole magnet model. To save time and money, the model design is based on the design of the quadrupole magnets for the arcs of the Large Hadron Collider (LHC). The 3-m-long, 56-mm-twin-aperture LHC arc quadrupole magnets, relying on NbTi cables and polyimide insulation, have been developed at Saclay for CERN [6] and are now under series production at ACCEL Instrument GmbH [7].

The Nb_3Sn magnet model described here is 1-m-long and has a single-aperture of 56-mm and no iron yoke. It is developed in collaboration with Alstom/MSA which was responsible for producing the conductor.

The four Nb_3Sn coils will be realized following the so called "wind, react and impregnate" technique. The coils will be manufactured separately. They will be wound in the desired saddle-shape, starting from a cable made up of Nb_3Sn precursors and copper stabilizer, and then heat treated at 660°C in an inert gas flow for about 240 hours. After heat treatment, the coils will be vacuum-impregnated with epoxy resin to confer them a rigid shape and facilitate subsequent handling.

II. Final Design Overview

A. Electromagnetic design

The quadrupole magnet model relies on the same coil geometry as the LHC arc quadrupole magnets, but it has no iron yoke. At a nominal current of 11,870 A, the field gradient is 211 T/m. The components of the Lorentz force over a coil octant at 11,870 A are: 400 kN/m (outwardly) along the pole mating planes and 711 kN/m (downwardly) along a perpendicular direction. The high order multipole components are all below 10^{-4} units.

B. Mechanical Design

A cross-sectional view of the quadrupole magnet cold mass is shown in Fig. 1. The two layers of each coil will be wound "in one go" without internal splice. After coil heat treatment and impregnation with epoxy resin, mechanical massaging will be carried out on the whole length of each pole using the coil size measurement machine. This massaging is necessary to reduce the effect of the singularity observed during the initial loading of conductor stacks representative of coil straight section (see section IV). Then, the four coils will be assembled together and covered with quench protection heaters and polyimide ground plane insulation. The coil assembly will be restrained by laminated, 2-mm thick, austenitic steel collars locked by eight, full-length, tapered keys. The 8 keys will be driven into keyways on the collar outer surface by means of a press. As for the LHC arc quadrupole magnets, the collaring will be performed vertically. Finally, the collared-coil assembly will be centered within a precisely-machined steel inertia tube delimiting the region of liquid helium circulation.

The aim of the collaring operation is to apply a large azimuthal pre-compression to the coil by the use of the collar poles. The pre-compression is needed both to compensate the thermal shrinkage differentials during cool-down and to compensate stress redistribution during excitation.

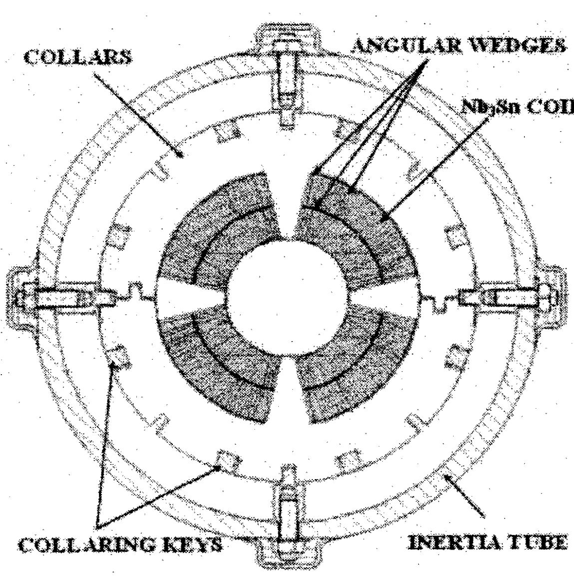

Fig. 1. Cross-sectional view of Nb_3Sn quadrupole magnet model.

The finite element (FE) model of the structure has been developed using the COFAST3D approach [8], which is a module developed specially for the CASTEM software package [9]. COFAST3D is based on a decomposition of the structure into sub-structures for an easier iterative resolution scheme. It shows a great reduction of computing time when complex and multiple contact zones are taken into account, especially in a 3D approach like here.

The FE model is restricted to $1/4^{th}$ of the quadrupole magnet cross section. All successive steps of loading history, from collaring to cool-down and to excitation are described. The thermo-mechanical properties of conductor blocks have been measured on ten-stack samples fabricated following processes similar to those foreseen for coil production [10].

Fig. 2 shows the computed azimuthal stress distribution in the coil at 4.2 K and 11,870 A. All the parts of coil assembly remain in compression and the peak stress on the conductors is always below the critical level of 150 MPa. At the pole area, the minimum stress remains superior to 13 MPa thereby avoiding a separation at the coil/collar pole interface during energization and preventing field quality distortions.

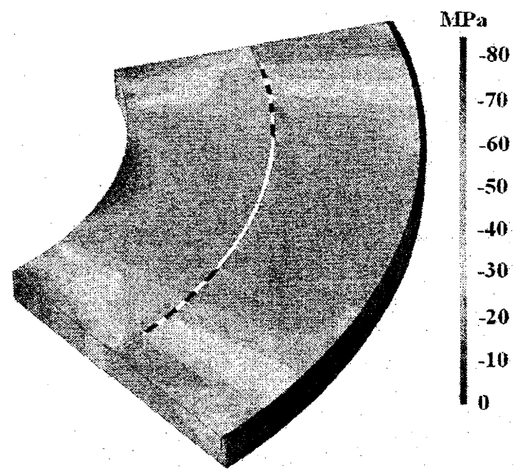

Fig. 2. Azimuthal coil stress distribution at 11,870 A.

III. Cable Development

A. Model Cable Manufacturing

Cable design has been developed in collaboration with Alstom/MSA following closely LHC outer cable specifications. The chosen conductor is a Rutherford-type cable, 15.1-mm wide, 1.48-mm thick (mid-thickness), with a keystone angle of 0.9°. 36 Nb_3Sn strands, with a nominal diameter of 0.825 mm and a copper-to-non-copper ratio of about 1.4 to 1, are arranged in two layers, separated by a 13-mm wide, 25-µm-thick, stainless steel core. Strand design is based on internal-tin process. Each strand is made up of 19 multifilamentary bundles, spaced by 6 CuSn elements and surrounded by a double Nb/Ta diffusion barrier and a copper outer sheath.

The critical current density in the non-copper of the final strand has been measured to be of the order of 1850 A/mm^2 at 4.2 K and 7 T (yielding 765 A/mm^2 at 4.2 K and 12 T). The effective diameter of the filaments after the heat treatment was measured to be ~19 μm [11].

Alstom/MSA has started final strand and cable production. The delivery at Saclay of the final cable is planned for the end of 2003. Critical current measurements will be carried out on virgin and extracted strands.

B. New Cable Development

A new wire and cable development has been initiated in 2002 with Alstom/MSA to boost the critical current density of the wire up to 2000 A/mm^2 at 4.2 K and 12 T. The other parameters are the same as for the model cable. The boost in critical current density is required to meet the performance specifications for the TESLA final focusing quadrupole magnets.

IV. Insulation Development And Tests

A. Insulation Development

Cable insulation for the quadrupole magnet model relies on a mineral fiber tape, double-wrapped around the cable prior to winding. After heat treatment, the tape wrapping is completed by a vacuum impregnation with epoxy resin, enhancing dielectric strength and providing a rigid bonding. The tape ensures a proper spacing between coil turns and prevent resin crack. According to electromagnetic design, the turn-to-turn insulation thickness must be of the order of 220 μm under 80 MPa. This tight dimensional constraint is imposed by the fact that we are re-using the electromagnetic design of the LHC arc quadrupole magnets, that had been optimized for a polyimide insulation.

After an R&D program, based on tensile and dielectric strength measurements, to compare various insulation systems [12], the chosen tape was a 15-mm-wide, 60-μm-thick quartz fiber tape. Quartzel™ fibers with diameters as small as 17 g/km are commercially available but they need to be woven on old wooden looms to limit tension and risk of breakage.

Quartz-fiber-based insulation underwent all tests successfully. Nevertheless, we had some difficulties in realizing cable wrapping. This is due to the fact that the tape sizing must be removed prior to wrapping to prevent subsequent pollution during coil heat treatment. Tape sizing removal is carried out by carbonization in air at 350° C. Without sizing, the tape becomes fragile and cannot be wrapped around the cable using an automatic wrapping machine and only hand-made wrapping turned out to be satisfactory.

Another problem appeared to be the control of tape width. Indeed the reliance on an archaic loom does not allow to perform all the on-line controls that can be performed on more modern machines. The woven tapes exhibited some width irregularities, eventually leading to non-reproducible wrapping or over thicknesses. Further tests varying the tape weaving parameters (number of warp and fill ends) did not lead to better results. This problem could be resolved by modifying or rebuilding the loom - a work well beyond the scope and financial reach of the project.

Keeping in mind our primary goal of developing industrial fabrication processes, we preferred to check other solutions, using thicker glass fiber tapes. 80-μm-thick E-glass fiber tapes and 100-μm-thick S2-glass fiber tapes have been taken into account. As described in the next section, tests on stacks made up of 10 insulated conductors have been carried out to study the influence of tape overlapping (from 20% to 50%) and tape thickness on composite behavior.

B. Ten-stack test results

Two series of stacks of ten insulated cables were manufactured and tested in compression. Cable wrapping was performed in one single layer with an overlap of respectively 20, 33 and 47 % for S-glass fiber tape and 33, 40 and 50% for E-glass fiber tape. The cable stacking was alternated to compensate for the keystone edge. Stack height was controlled during heat treatment and impregnation by means of carefully dimensioned moulds.

Each sample was mounted in a U-shape, stainless-steel holder and was loaded in compression along its transverse direction through a stainless steel upper bar. The stress-strain curve of each sample was monitored for three successive cycles at room temperature. Each stack was tested twice.

Composite behavior, as illustrated in Fig. 3, is similar to that observed on quartz-fiber-based samples [10]. The first loading curve for a virgin stack exhibits a pronounced non-linear behavior, whose average slope is smaller than the slopes of the subsequent loadings. Then, the curve exhibits an hysteresis between loading and unloading, which evolves from cycle to cycle and seems to be more or less stabilized after three loadings. For the second test, the first loading still remains different than the following ones, but in a less dramatic way than for a virgin stack.

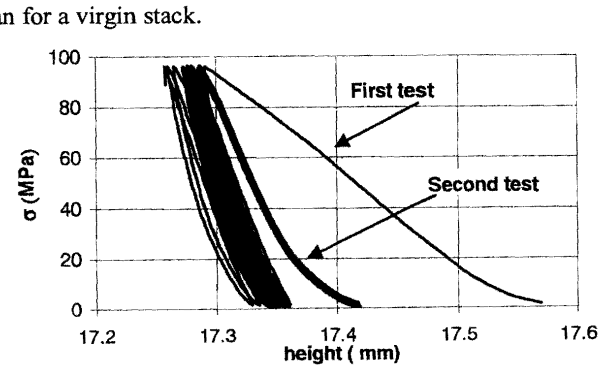

Fig. 3. Compressive test curves for a S2-glass-fiber-based sample.

The strong non-linear behavior of virgin stacks could be explained as a rearrangement of the strands in the cables. Additional tests on ten stacks made up of non insulated cables seem to confirm this hypothesis.

In Fig. 4, ten-stack dimensions under 80 MPa for the first cycle of the second test (corresponding to the collaring process in the "massaged" coil history) are related to initial dimensions (measured with a micrometer after vacuum impregnation, equal to the impregnation mould cavity height). The final dimension of the stack seems to be driven by the initial height of the impregnation mold, more or less independently from overlapping percentage. The fitting curves are a little bit different for the two insulation systems, but show a linear behavior with a slope equals to 1. Based on these tests, the S2 glass system was chosen for cable insulation.

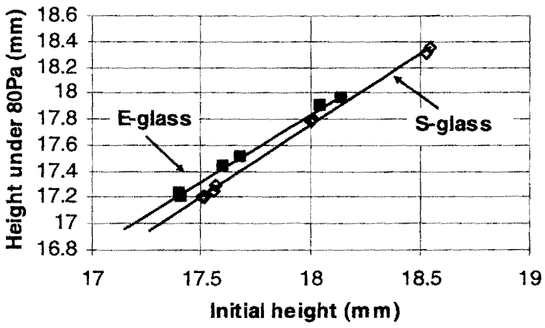

Fig. 4. Final height versus initial height for S2-glass and E-glass based samples. Measured values and fitting curves.

V. Tooling and Components

The detailed design of components and tooling is almost finished. Unlike initially foreseen [13], pole pieces are no more integrated in the impregnated coil. Temporary pole pieces will be used during heat treatment and impregnation, and will subsequently be replaced by collar pole pieces during collaring (as in LHC arc quadrupole magnet assembly process). 0.5-mm-thick, stainless-steel protection sheets will be placed between the coil and the pole pieces to prevent damage of coil insulation.

Coil end spacers (Fig. 5) will be realized in Al–80 wt% Cu alloy, machined using a 5-axis EDM tool and will be insulated from the coil by means of 0.1-mm-thick mica sheets. Turn-to-turn insulation pieces, cut out from 0.1-mm-thick mica sheets, will be added in the coil end regions.

The insulation spacer between coil layers will be made up of a ceramic fiber sheet, 0.5-mm thick, that will be laser-cut to avoid unweaving. Interlayer insulation will be completed by coil vacuum impregnation with epoxy resin.

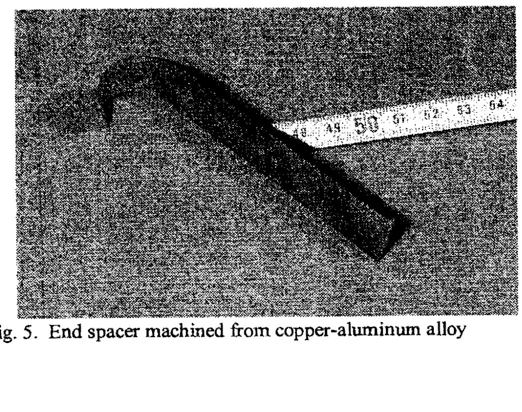

Fig. 5. End spacer machined from copper-aluminum alloy

VI. Manufactory And Tests

Coil winding is expected to start before the end of the year 2003. Two dummy poles (pole 00 and pole 0) will be manufactured (using dummy Nb_3Sn cables), to validate fabrication tools and procedures. Then, five poles will be fabricated from the final cable. After fabrication and mechanical test, the dummy coils will be cut and assembled to validate collaring procedure. Both dummy and model coils will be instrumented with capacitive-stress-gauges. Stress evolution in the coils will be monitored during all steps of magnet fabrication and test. The final coils will also be instrumented with voltage taps.

To evaluate the influence of an external field on the coil ends (as will be the case for the TESLA final-focusing quadrupole magnets), the magnet model will be tested in the aperture of a 2-T, 530-mm inner-bore MRI magnet available at CEA/Saclay. The cold mass is expected to take place in June 2005.

Acknowledgment

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