Development of a Nb_3Sn Quadrupole Magnet Model

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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 crowded interaction regions of large particle accelerators. To learn about Nb_3Sn technology and to evaluate fabrication techniques, DAPNIA/STCM at CEA/Saclay has undertaken an R&D program aimed at designing and building 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 is expected to produce a nominal field gradient of 211 T/m at 11,870 A. The coils are wound from Rutherford-type cables insulated with quartz fiber tapes, before being heat-treated and vacuum-impregnated with epoxy resin. Laminated, austenitic collars, locked around the coil assembly by means of keys restrain the Lorentz forces. After reviewing the conceptual design of the magnet model, we report on the cable and cable insulation development programs and we present the results of NbTi-Nb_3Sn cable splice tests.**

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

I. Introduction

The final focalization of beams usually requires sets of superconducting dipole and quadrupole magnets, which are localized close to the interaction points. As the interaction regions are very crowded, there are some advantages in increasing the field integral or the focalization power of these magnets to reduce their length and save some space. Furthermore, in some accelerator designs, such as in the present design of the Tera Electron volts Superconducting Linear Accelerator (TESLA), the final focusing quadrupole magnets end up inside the detector magnet, and must sustain a 4 T axial field [1]. The requirements for high field and high field gradient or the ability to operate in a sizable background field precludes the use of NbTi, but such interaction region magnets could serve as a test bed for Nb_3Sn application to large particle accelerators.

Nb_3Sn is an intermetallic compound from the A15 crystallographic family whose critical temperature and upper critical field are about twice those of NbTi. However, once reacted, it becomes fragile and its superconducting properties are strain-dependent. Several techniques have been developed to allow the fabrication of multifilamentary composite wires. The wires are made up of Nb_3Sn precursors and copper stabilizer, and can be cabled and wound, but the formation of the Nb_3Sn compound always requires a high-temperature heat treatment (up to 700 °C) for a long time (up to 300 hours) on the final product. The realization of the heat treatment and the difficulty of manipulating reacted Nb_3Sn wires and cables have so far limited their use. Nevertheless, over the last five years, two successful dipole magnet models, having reached maximum fields of 11 and 13.5 T, have raised new hopes about the feasibility of Nb_3Sn magnets [2,3].

To prepare future high-field applications and revive Nb_3Sn technology, DAPNIA/STCM at CEA/Saclay has undertaken an R&D program aimed at designing and building a short 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) developed by DAPNIA/STCM for CERN [4]. The 3-m-long, 56-mm-twin-aperture LHC arc quadrupole magnets rely on NbTi cables and are operated at 1.9 K. Their nominal field gradient is 223 T/m at 11870 A. Up to now, two full-length prototypes have been cold tested, and they both exhibited suitable quench performance [5]. The Nb_3Sn magnet model described in this paper is 1 m long and has a single aperture of 56 mm. It relies on a cable developed in collaboration with Alstom/MSA [6].

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II. Design Overview

A. Electromagnetic Design

The quadrupole magnet model relies on the same four-coil and the same conductor geometries as the LHC arc quadrupole magnets, but it has no iron yoke. In this design, the quadrupole field gradient, g, can be estimated as a function of supplied current, I, using

$$g = 17.775\ 10^{-3}\ I \quad , \tag{1}$$

while the peak field on the magnet coil, B_p, is given by

$$B_p = 0.544\ 10^{-3}\ I \quad . \tag{2}$$

For a cable critical current of 12,000 A at 4.2 K and 7 T (see section on cable development), one can expect a short sample current limit of the order of 12,500 A at 4.2 K, corresponding to a maximum field gradient of 222 T/m.

This value is very close to the operating field gradient of the LHC arc quadrupole magnets.

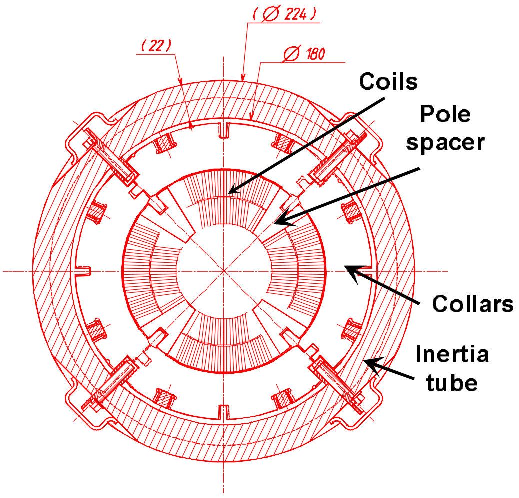

Fig. 1. Cross-sectional view of quadrupole magnet model.

Furthermore, the Lorentz force components over a coil octant at 11,870 A (design current of LHC arc quadrupole magnets) are: 400 kN/m (outwardly) along the mating plane and 711 kN/m (downwardly) along a perpendicular direction.

B. Mechanical Design and Assembly

A cross-sectional view of the quadrupole magnet model is shown in Fig. 1.

The magnet coils are produced according to the “wind, react & impregnate” technique. They are made up of two layers, wound atop of each other from the same cable (without internal splice). The winding of the two layers is performed in one go around a precisely machined spacer, made up of Al–80 wt% Cu alloy and mounted on top of an arch-shaped mandrel. Unlike what is done for NbTi coils, the spacer is left in place and becomes the feature that sets pole angles. After winding completion, the coils are heat-treated and vacuum-impregnated with resin, before being assembled together and covered with ground plane insulation.

As for the LHC arc quadrupole magnets, the coil assembly is restrained by laminated, austenitic collars [7]. The collar laminations are 2 mm thick and extend over a 180° angle. They are stacked up by pairs, made up of two coplanar laminations, and the pairs are rotated by 90° from layer to layer to maintain a four-fold symmetry. Furthermore, the laminations are outfitted with tapered fingers, which go into matching grooves on the outer surface of the pole spacers.

The collars are locked around the coil assembly by eight, full-length, tapered keys. The keys are driven into keyways on the collar outer surface by means of a press. The collaring operation also serves to apply a large pre-compression to the coil assembly, whose outer radius is about 0.3 mm larger than the collar inner radius. The pre-compression is needed to compensate for thermal shrinkage differentials during cooldown and for stress redistribution during excitation.

Finally, the collared-coil assembly is mounted within a thick, steel inertia tube, which provides longitudinal rigidity and alignment in both transversal and longitudinal directions. Also, the tube delimits the region of liquid helium circulation.

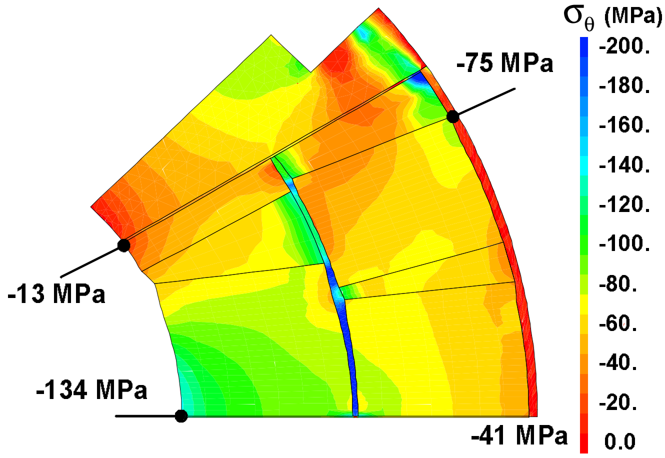

Fig. 2. Azimuthal coil stress distribution at 11,870 A.

A detailed finite element model of the structure has been developed using the CASTEM software package [8,9]. The model describes the successive steps of loading history, from collaring to cooldown and to excitation. It requires suitable values of Young’s moduli and integrated thermal expansion coefficients. The thermo-mechanical properties of conductor blocks have been measured on ten-stack samples fabricated following processes similar to those foreseen for coil production. The results of these measurements are described elsewhere [10].

As illustrated in Fig. 2, the present design allows to maintain all parts of coil assembly in compression at nominal current, while limiting the peak stress on the conductors to less than 150 MPa at all time [9]. Studies are still underway to lower this value.

C. Quench Protection Studies

The magnet model is protected actively by sets of quench heaters localized on the outer surface of each octant. A finite element model, using again CASTEM, has been developed to compute hot spot temperature in case of a quench. The heaters are made up of 11-mm-wide, 30-µm-thick steel tapes sandwiched between two polyimide foils. They are positioned inside the ground plane insulation leaving only one 125-µm-thick polyimide foil between the steel tape and the coil assembly. Each heater covers four outer layer turns and delivers a maximum power of 21 kW with an 11 ms time constant. The results presented here correspond to a pessimistic 1 to 1 copper-to-non-copper ratio.

Under nominal operating conditions, the hot spot temperature is 60 K when the 1.9-mH magnet model is discharged over a 40-mΩ external resistor. It increases to 140 K when the external resistor is omitted. Doubling arbitrarily the delay between heater firing and outer coil quenching, so as to simulate degraded thermal contacts on all heaters, raises the hot spot temperature to 210 K (assuming again no external resistor). If the heaters are not fired at all, the maximum temperature reaches 275 K. Hence, the magnet model protection does not appear to be a critical issue.

III. Cable Development

The flat, two-layer, slightly keystoned, Rutherford-type cable is developed in collaboration with Alstom/MSA. Its specifications are inspired from those of the LHC quadrupole cable [11]. It has 36 strands, a 15.1-mm width, a 1.48-mm mid-thickness, and a 0.9° keystone angle. The transposition pitch length is 100 mm. The critical current is required to be greater than 12,000 A at 4.2 K and 7 T, with a RRR above 100 at 0 T.

An R&D program has been carried out to determine the best configuration in terms of interstrand resistances [12,13]. The chosen design, presented in Fig. 3, incorporates a 13-mm-wide, 25-µm-thick core, made of annealed 316L stainless steel. The core has been shown to ensure a suitable level of crossover resistances (between strands of the two layers), to limit undesirable interstand coupling currents, while maintaining low values of adjacent resistances, to favor current redistribution among same-layer strands. In addition, the core may avoid stress concentration inside the cable.

The strand specifications are inspired from ITER HP2 specifications [14]. The strand layout, shown in Fig. 3, has been developed by Alstom/MSA according to the internal-tin process [15]. The nominal diameter is 0.825 mm, with a copper-to-superconductor ratio of 1.4 to 1. The critical current in the non-copper has been measured to be of the order of 1850 A/mm^2 at 4.2 K and 7 T (yielding 750 A/mm^2 at 4.2 K and 12 T). Furthermore, the effective filament diameter has been estimated to be 19.0 µm (corresponding to hysteresis losses of about 450 mJ/cm^3 in the non-copper for a ± 3 T trapezoidal cycle). The nominal heat treatment is: ramp at 6 °C per hour up to 660 °C, followed by a plateau at 660 °C for 240 hours in a flow of pure argon gas.

Alstom/MSA is now ready to produce 5 x 60-m unit lengths of cable. Critical current measurements on the final cable have yet to be performed. However, to evaluate cabling degradation, measurements were carried out on extracted strands [16]. The irreversible degradation is expected to be less than 10% at 4.2 K and 7 T.

IV. Insulation Development

The cable insulation relies on a mineral fiber tape that is wrapped around the cable prior to winding. The tape ensures a proper spacing between coil turns (for field quality and to limit the risks of turn-to-turn shorts) and serves as crack arrester. Also, it must sustain the heat treatment at 660 °C. After winding and heat treatment, the coil is transferred into a precisely machined mold and is vacuum-impregnated with resin. The impregnation confers a rigid shape to the coil and allows a tight control of its dimensions, while enhancing the dielectric strength of the turn-to-turn insulation.

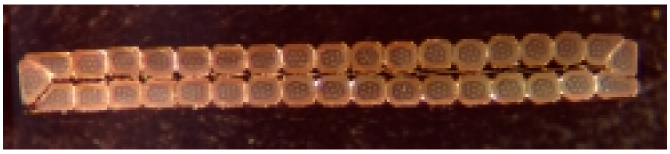

Fig. 3. Nb_3Sn Rutherford-type cable with a 25-µm-thick stainless steel core.

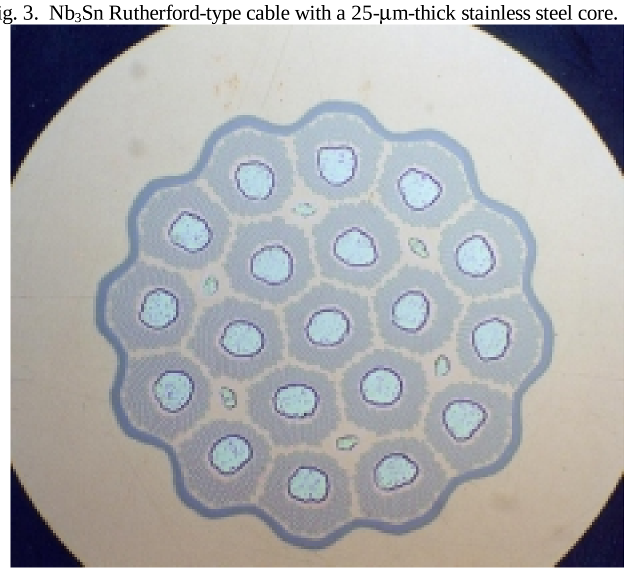

Fig. 4. Internal-tin strand layout developed by Alstom/MSA.

In the case of our quadrupole magnet model, the turn-to-turn insulation thickness must be of the order of 220 µm under 70 MPa. This constraint comes from the existing electromagnetic design that was developed for a NbTi cable insulated with polyimide tapes. (Also, it is always desirable to maximize the overall current density.) An R&D program, based on tensile and dielectric strength measurements, has been carried out to evaluate various insulation systems [17].

The chosen system relies on a 15-mm-wide, 60-µm-thick quartz fiber tape that is double-wrapped around the cable without overlap. Quartz fibers have a good behavior at high temperatures (up to at least 1000 °C) and can be found in small diameters (down to 17 g/km or tex). We use commercially available Quartzel™ fibers [18], but the tape weaving is done on an old wooden loom to limit breakage.

Prior to wrapping, the tape is subjected to an overnight heat treatment at 350 °C in air to remove all organic binders. This operation is needed to prevent the formation of electrically conducting carbon residues during the final heat treatment at 660 °C. However, it renders the tape fragile and easy to tear off by friction.

The resin used for vacuum impregnation is of epoxy type and is provided by Alstom/MSA. The applied curing cycle is: 12 hours at 95 °C followed by 48 hours at 110 °C.

It has been verified on ten-stack samples, made up of insulated conductors that were heat-treated and vacuum-impregnated as for coil production, that the stack height could be controlled within reasonable limits.

V. NbTi-Nb_3Sn Cable Splice Tests

The four coils, which are manufactured separately, must be connected electrically in series and joined to the external current leads. In the case of LHC arc quadrupole magnets, and as illustrated in Fig. 5, the inter-pole connections are realized in so-called *splice-plates* attached to one magnet end. In each of the plates, the conductors assume a circular trajectory and the trajectory orientations are alternated from plate to plate to compensate for solenoidal field effects.