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The SMC (Short Model Coil) dipole: An R&D program for Nb_3Sn accelerator magnets

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Abstract

The Short Model Coil (SMC) assembly has been designed, as test bench for short racetrack coils wound with Nb_3Sn cable. The mechanical structure comprises an iron yoke surrounded by a 20 mm thick aluminium alloy shell, and includes four loading pads that transmit the required pre-compression from the outer shell into the two coils. The outer shell is pre-tensioned with mechanical keys that are inserted with the help of pressurized bladders and two 30 mm diameter aluminium alloy rods provide the axial loading to the coil ends. The outer shell, the axial rods, and the coils are instrumented with strain gauges, which allow precise monitoring of the loading conditions during the assembly and at cryogenic temperature during the magnet test. Two SMC assemblies have been completed and cold tested in the frame of a European collaboration between CEA (FR), CERN and STFC (UK) and with the technical support from LBNL (US). This paper describes the main features of the SMC assembly, the experience from the dummy assemblies, the fabrication of the coils, and discusses the test results of the cold tests showing a peak field of 12.5 T at 1.9 K after training.

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Index Terms— **Magnet, Superconducting magnet, Dipole, Nb_3Sn, NED, EuCARD.**

I. INTRODUCTION

THE SHORT MODEL COIL (SMC) project started in 2007 within the context of the Next European Dipole (NED-1.5) Joint Research Activity. SMC is a CERN-CEA-RAL-LBNL collaborative program part of the FP7 European project EUCARD [1], aimed at designing, manufacturing and testing Nb_3Sn racetrack subscale coils in a dipole configuration in order to reach 12 T on the conductor [2]. It takes over most of the features of the Subscale Dipole (SD01) assembly [3]. An adapted support structure is used to perform training studies on different types of cables while investigating the pre-stress influence on coil behaviour. Variable pre-stresses can be applied on the coil pack in the three directions to explore the mechanical stress limit [4], [5].

The SMC consists of two double pancake racetrack coils mounted in a shell-based structure using bladders and keys [6]. The assembly with the first two coils, called SMC1, was tested in October 2010, using a 1.25 mm diameter Internal Tin strand in a 14 strand cable. The fabrication of these coils was still on a steep learning curve and they reached 40% of the short sample current at 4.2 K. The construction of SMC2 was abandoned because the scheduled specific ceramic insulation was proven to be too brittle to support the expected level of compressive stresses. A new set of coils for SMC3, using a Powder-In-Tube (PIT) conductor, has been ramped up to 95% of the short sample current at 4.2 K, and to a maximum magnetic field on the coil of 12.5 T at 1.9 K.

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II. SMC3 COMPONENTS AND ASSEMBLY

A. Mechanical structure components

The mechanical structure, shown in Fig.1, consists of a yoke composed of two halves surrounded by an Al alloy cylinder.

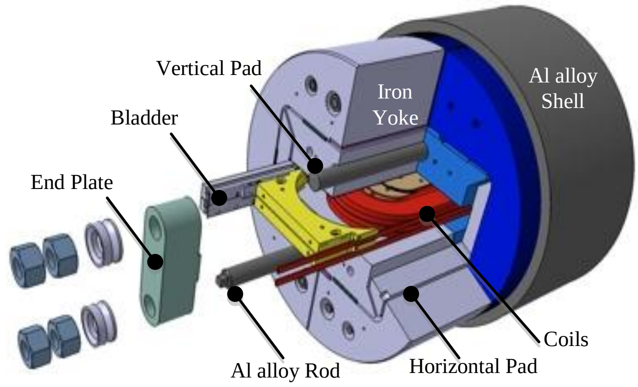

Fig. 1. SMC structure and main magnet components

The central part of the yoke is made of 18 LHC-type iron lamination sheets of 5.8-mm-thickness while its ends are made of stainless steel, in order to contribute to bring the peak magnetic field position in the coils straight section. Each of the two half yoke stacks are pre-assembled, aligned and compressed by a dedicated pin system. The assembled parts are machined to guarantee a surface finish of 0.02 mm. A 20 mm thick AW 2219-T851 aluminium cylindrical shell surrounds the iron yoke and provides after cooling, by differential thermal contraction, the required pre-load to the coils, to maintain a stable structure up to 13 T field. The two coils are mounted in a bolted steel structure composed of two horizontal and two vertical pads, to obtain a “coil pack”. The vertical pads are also composed of two steel parts and an iron core while the horizontal ones are made of monolithic 304L steel. Two 7075-T651, 30 mm diameter aluminium alloy rods provide the longitudinal compression to the coils. The rods can be pre-stressed at room temperature by a hydraulic piston.

The bladders used for the assembly of the magnet are made of two 0.3 mm-thick rectangular stainless steel sheets laser welded all around together. A junction block allows the water injection on one side of each bladder. The water feed tube is TIG welded to the junction box. Slip-shims mounted with the bladders, are used to compensate the gap between the yoke and the coil pack. These shims protect the bladders from surface irregularities on the yoke halves and allow pulling the bladders out of the structure after the loading operation. Temporarily, iron keys are used to keep the yoke halves in position while the coil pack is placed into the iron yoke aperture. In order to pre-load the coils at room temperature, steel keys and shims are inserted inside the gaps opened by the bladders, inflated by a dedicated hydraulic pump unit. The detailed design with a mechanical analysis is described in [9].

B. Cable

The cable used in the SMC3 is a Rutherford type cable with a rectangular cross-section made of 14 strands of 1.25 mm diameter. The Nb_3Sn strand, having 288 filaments to get 50 μm diameter filaments, was developed in the frame of the Next European Dipole (NED) program by SMI using the PIT process [7] and was manufactured by Bruker-EAS. The SMC cable is fabricated with a width of 10 mm, a thickness of 2.2 mm and a twist pitch of 60 mm, to provide mechanical stability for coil winding while having a small overall compaction of ≈82%. The heat treatment schedule with 100 hours at 650 ^{o}C provides fair Residual Resistive Ratio (RRR) values on the cable (between 70 to 80) and gives at 4.2 K a critical current of 15400 A at 12 T and of 18 500 A at 11 T. The values of the cable critical current were determined from the critical current measurements performed on five extracted strands. These values correspond at 12 T to a critical current density of 2400 A/mm^2 in the non-copper part.

C. Coils

The coils have been designed to get the magnetic peak field in the coil straight section [4]. Two spacers reduce by 0.5 T the magnetic field on the coil ends. The central posts, spacers and end-shoes were machined using a Ti-6Al-4V titanium alloy. A 0.2 mm thick skin of ceramic 989F applied with a brush and a S2 glass tape 416D locally wrapped around the cable with 50% overlap, reinforce the electrical insulation on the layer jump groove. The Nb_3Sn cable insulated with a sleeve of FII-282, is wound using a winding tension of 200 N for the first turns and progressively reduced to a tension of 100 N. After winding of the first layer, a 0.3 mm thick mica sheet is placed between the two layers to ensure the electrical insulation between them. The coil is then mounted in a stainless steel reaction mould designed with a larger cavity than the final theoretical size of the coil. The mould cavity is larger by 4% in the transversal direction and 2% in vertical and longitudinal direction to allow the conductor expansion during the heat treatment made in a vacuum furnace.

For the impregnation of the coils a mould with identical dimensions as the reaction mould is used. The impregnation is made in a vacuum tank using a mix of Epoxy resin type MY 750 and polyetheramine hardener Jeffamine D-400®[1].

D. Magnet instrumentation

The SMC magnet is equipped with strain gauges to monitor the mechanical strain of the structure and of the coils. Each coil has eight measuring points equipped with two-measuring-grids strain gauges. Four cavities are machined on each side of the central post of the coil to prevent gauges damages during loading. A groove, spark eroded on two sides of each cavity containing a strain gauge, allows the measurement in one main direction and minimizes the influence of the perpendicular strain. Connecting two grids of the same gauge in half-bridge configuration allows compensating external perturbations such as the temperature or magnetic field on the measurements. Cabling the half-bridges using five wires twisted by pairs for powering, compensates the length of the cables and the capacitive effect between them.

The rods are equipped with four strain gauges connected in full-bridge configuration. The full bridge configuration permits to compensate the external environmental perturbations and to measure directly the traction/compression stress without other effects like torsion or bending. The shell has six measuring points. The strain in two principal directions: longitudinal and azimuthal, is measured at each point. The points are equipped with two, double measuring-grid strain gauges. One gauge is active and the second one is used as thermal compensation. The MGC Plus[2] data acquisition system, with Canhead® modules are used to record the data. The apparent strain and change of the gauge factor at cryogenic temperature were taken into account.

The coils are equipped with one Hall probe, two spot heaters and eight voltage-taps for quench signal records per coil face. The Hall probes are placed in the central post. One spot heater is placed in the high field and one on the low field region of the coils. Voltage taps are placed such as to allow recording the signals of the first turn of each layer of each coil, the layer jump, a high and a low field region multi turn segments.

E. Magnet instrumentation wiring

Dedicated printed circuits called “traces”, inspired from those used in the magnets built recently within the LARP collaboration, have been developed at CERN [8]. The traces are made of 25 μm stainless steel strips, glued and pressed on top of a 25 μm Kapton® sheet of type LS 110[3] coated with 25 μm glue. The stainless steel sheet is then coated by metallization with a 20 μm layer of copper. The circuit is printed and engraved. The copper layer is removed on the spot-heaters surface by a chemical attack. Four strain gauges, one Hall probe, two spot-heaters and eight voltage taps can be connected to each trace.

F. Magnet assembly

The magnet is composed of two double pancake coils externally spliced in series. The coils are insulated from the pads by using cured epoxy on glass-fabric substrate, EPGC 203 sheets and mounted in the steel load pads cavity. Twenty bolts hold the “coil pack” that it can be inserted into the iron yoke.

The shell is positioned vertically on top of a support structure to perform the assembly of the magnet. The yoke is put inside the shell and is temporarily shimmed to allow the coil pack insertion and centring. Four lateral bladders are slid with the slip-shims in the cavity between the yoke and the coil pad. By monitoring the shell strains, the bladders are gradually pressurized up to 142 bar, with successive pump and purge operations, forcing the yoke against the shell

[1] Trademark of Huntsman Corporation

[2] Trademark of HBM

[3] Trademark of DuPont

inner diameter surface until reaching the target shell strain of ± 500 µm/m [9]. The gain on the pre-load of the coils is obtained by increasing the size of the interference keys. The stretching of the shell provides the compressive force to pre-load the coil pack.

The lower vertical compression is obtained by using two bladders pushing in the vertical direction.

After the loading of the coil pack, the longitudinal pre-load of the coil at room temperature is obtained by pre-stressing the rods with a hydraulic piston. For SMC3 the rods were loaded to the minimum pre-stress.

When the structure reaches its final configuration (Fig. 2.), the bladders are deflated and pulled out. The coils are connected electrically in series by soldering. For this operation a dedicated copper piece equipped with a 250 W electrical heater as a mould was developed. The mould, after soldering, remains around the splice as a thermal and mechanic stabilizer.

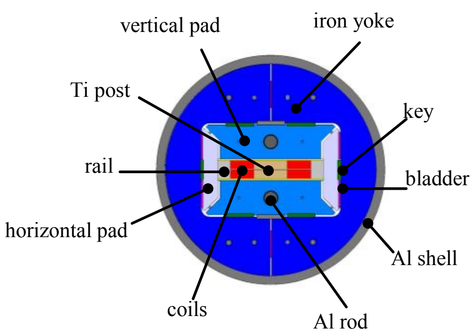

Fig. 2. Cross section of the SMC

III. Cold Powering Test and Test Results

SMC3 was tested at CERN, in the new vertical test facility in the building called SM18, during the summer 2011. The cold powering test includes, apart of the training test, the measurements of the RRR, the splice resistance, the inductance of the coils, and the mechanical behaviour of the structure and its influence on the coils during cool-down, warm-up and powering. Test has been performed at 4.2 K and at 1.9 K with variable current ramp rates.

A. Quench detection and magnet protection

The quench detection is based on several voltage signal records. The trigger level for the quench detection and protection was fixed at 100 mV with a checking time windows of 10 ms. The voltage signals used for the security matrix are differential signals that compares the two coils or the two layers of the same coil, making the detection and protection system redundant.

The magnet is protected with the help of an external dump resistor of 40 mΩ leading to a maximum of 560 V tension at 14 kA and 45 ms decay time of the current. This protection system is capable to extract approximately half of the energy of the magnet. Miits values between 4 and 6 MA^2s were calculated for quenches recorded between 11.4 kA and 14 kA and a temperature of 75 K was deducted, from the voltage measurements of the quench signals, as hot spot temperature.

B. Residual Resistive Ratio (RRR)

The RRR measurements were performed during the cool-down and during the warm-up while the magnet was powered with 2 A. Thanks to a controlled and slow cool down process the two measurements are consistent and comparable with the measurements performed on the extracted strands of the same cable. The RRR value is calculated to be equal to 75. The RRR for these measurements was defined as the ratio between the resistance of the copper matrix of the cable at room temperature (295 K in this particular case) and the same resistance during the plateau, just before the transition from normal to superconducting stage, around 20 K.

C. Inductance measurements

During a ramping with 10 A/s up to 10 kA, the voltage of the magnet and both coils separately were measured with the goal to deduce their inductance. The results of 1.8 mH for each coil are consistent with the simulations made with “ROXIE” [10].

D. Splice resistance measurements

Two double layer coils, wound with one single cable compose SMC3. On each side of the coil, the Nb_3Sn cable is prolonged through a splice, with Nb-Ti cable. The Nb-Ti cable is used for the series connection between coils and to the current leads. The splices were measured at cold, during a powering plateau of 10 minutes once at 5 kA and once at 10 kA. None of them showed resistance higher than 1 nΩ.

E. Training of the magnet

The training of the magnet was started at 4.2 K and continued at 1.9 K. The very first quench in the magnet occurred at 11.41 kA, corresponding to 81.4% of the short sample value at 4.2 K and 10.4 T. In total 52 quenches were recorded which allows us to identify a training phase and two plateaux: one at 95% of the load line at 4.2 K and one at 92% at 1.9 K equivalent to a field of 12.5 T on the conductor (see Fig. 3).

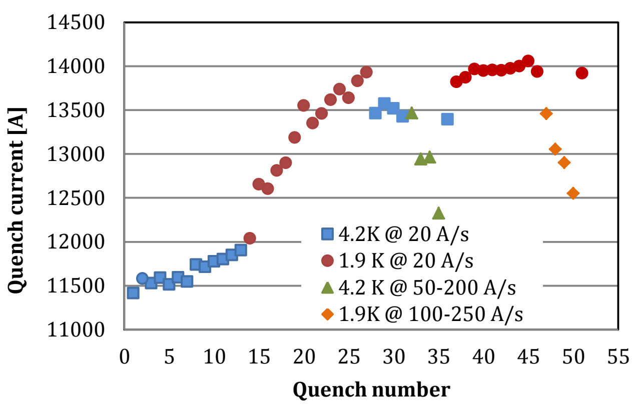

Fig. 3. Training history of SMC3

While the training was performed with 10 A/s or with 20 A/s ramp rate, several quenches were recorded after a powering with faster ramp rates between 50-250 A/s at 4.2 K and 1.9 K.

F. Quench location

75% of the quenches were localized with the help of the voltage taps in the high-field zone on the straight part of the magnet in coil 1. 73% of those quenches occurred on the same side of the layer 1, in the first turn in contact with the central post, between Vtap 72 and 102.

The training started on one side of this portion of cable and travelled with the consecutive quenches towards the other side. Plateau quenches occurred both at 4.2 K and

1.9 K at the middle of this portion of cable at the point of the maximum field in the coil 1 as shown in Fig. 4.

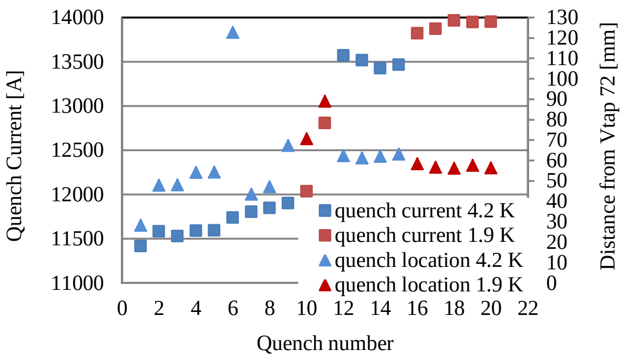

Fig. 4. Location of quenches detected between Vtap 72 and 102, during training of SMC3.

Quench propagation velocity, varying from 10 m/s for the lower current quenches and up to 21 m/s for the plateau quenches, was calculated with the Time of Flight method.

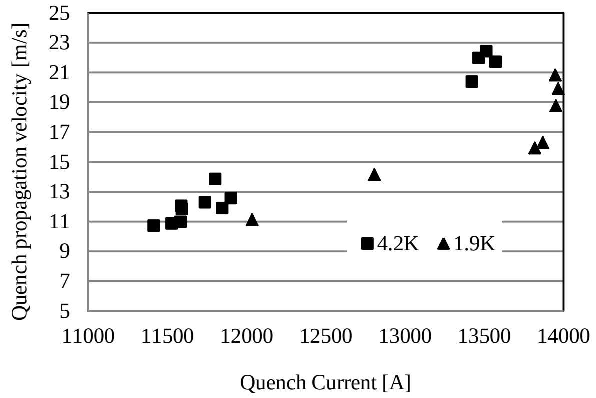

Fig. 5. Quenches propagation velocity calculated for quenches detected between Vtap 72 and 102, during training of SMC3.

None of the quenches occurred in the splices and less than 10% of the quenches were localized in one of the two layer jumps. In coil 2, that has showed an excellent behaviour, only one quench was recorded at 4.2 K and three quenches at 1.9 K before reaching to the plateau.

G. Strain measurements and training

Strain gauge measurements were recorded during cool-down, warm-up and during each ramp to a quench. Both coil 1 and 2 were symmetrically pre-stressed during the assembly with approximately 38 MPa, the goal being to obtain at cold 115 MPa on the peak magnetic field zone located in the straight parts of the coils. The symmetry was broken at cold when coil 1 showed lower pre-stress than coil 2. From quench number 16 on, coil 1 showed a discharge at 11 kA as illustrated in the Fig. 6. For the rest of the training the discharge was observed regularly by both upper and lower layer strain gauges of coil1. The discharge occurred at lower and lower current level, such that in case of 1.9 K plateau quenches at 14 kA, the discharge was observed already at 8 kA. Coil 2 does not show any discharge during these tests.

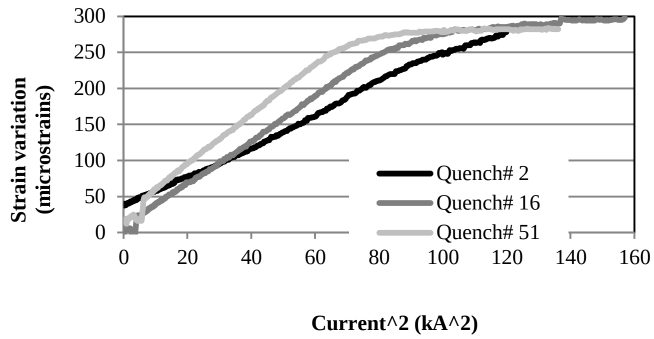

Fig. 6. Strain measurements variation on coil 1 during ramping to quenches nr. 1, 16 and 51. The strain gauges had an offset when starting to ramp.

IV. Conclusions

The goal of the project, to build a device for testing Nb_3Sn coils and to study their behaviour under variable stress conditions, has been achieved: the magnet trained by quenching in the high field zone located in the straight part, where the maximum stress is seen by the coils after cool-down. The construction of the SMC3 magnet has been a good occasion to study the Nb_3Sn magnet technology and to check the different materials and techniques to build high field magnets. Its excellent performance is remarkable not only by the very high field: 12.5 T achieved after the training, but also due to the first quench level, at 82 % of the 4.2 K short sample limit, the good performance of all splices and layer jumps which are the most critical parts of the coils.

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