Fabrication and Test of a Nb_3Sn Model Magnet With Ceramic Insulation for the Next Generation Undulator of the LHC

N. Elias, B. Bordini, N. Dalexandro, C. Giloux, M. Karppinen, and R. Maccaferri

***Abstract*—The future run of the Large Hadron Collider with lead ions will require important modifications in the synchrotron radiation profile monitor system, which at present comprises two superconducting undulators wound from Nb-Ti conductor, delivering 5 T in a 60 mm gap, and with a period of 280 mm. Whilst the gap and the nominal field of the future undulators will remain the same, the period shall be 140 mm, which translates to a peak field of over 8 T in the coils and hence requires the use of Nb_3Sn technology. In this paper the electromagnetic design of the undulator is summarized. We describe the fabrication of a race-track coil wound with a 0.8 mm diameter Nb_3Sn strand with ceramic insulation. Finally, the results of successful tests made at 4.3 K and 1.9 K in a mirror configuration are presented. 10 T at 4.3 K and 11.5 T at 1.9 K were measured in the yoke gap, thus validating this concept for the future undulator.**

***Index Terms*— Nb_3Sn, superconducting magnets, undulators synchrotron radiation.**

I. Introduction

IN the Large Hadron Collider (LHC) [1], synchrotron light monitors are used for the measurement of the beam profile. These non-intercepting devices have the advantage of measuring both the transversal and longitudinal beam profile as well as the angular spread. The present LHC configuration for proton beams up to 7 TeV, uses two superconducting undulators wound with Nb-Ti conductor, providing 5 T in a 60 mm gap and a period of 280 mm [2]. For the planned runs with lead ions, the emitted radiation produced by the present undulator cannot be efficiently detected for all beam energies due to its shift to the far infrared of the electromagnetic spectrum [3].

To overcome this constraint, a new undulator is required, having the same gap and nominal field, but a versatile operation with either a 280 mm period or a 140 mm period. The proposed configuration for such undulator results in fields higher than 8 T in the coils, which leads to the choice of Nb_3Sn technology. This paper presents the feasibility study of a model magnet wound with Nb_3Sn conductor with ceramic wet lay-up S-glass braid insulation on a machinable glass ceramics (Macor) support, and reports on the results of the successful tests.

Manuscript received October 18, 2009. First published March 25, 2010; current version published May 28, 2010.

The authors are with the European Organization for Nuclear Research (CERN), 1211 Geneva 23, Switzerland (e-mail: nuno.elias@cern.ch; mikko.karppinen@cern.ch; remo.macaferri@cern.ch).

Color versions of one or more of the figures in this paper are available online at http://ieeexplore.ieee.org.

Digital Object Identifier 10.1109/TASC.2010.2043829

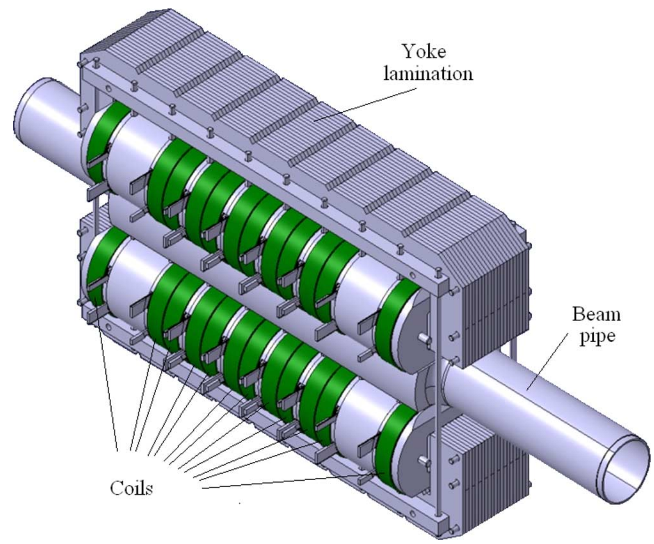

Fig. 1. Conceptual design view of the proposed undulator assembly. The magnet coils are placed vertically on top and bottom of the beam pipe. The iron yoke laminations surround the assembly to guide the magnetic flux in the outer region.

II. Magnetic Design

In the future LHC upgrade with lead ion beams, a versatile undulator configuration is required, which will allow the possibility to change between an undulator period of 280 mm to a shorter period of 140 mm, providing a field of either 5 T or 3 T in the 60 mm vertical gap.

Unlike the present configuration, where the magnet coils are placed parallel to the beam axis, we propose a different approach by positioning the coils perpendicularly as shown in Fig. 1. The change in the undulator period is obtained by powering different sets of coils which results in the desired pattern for the magnetic flux.

The main advantage of this design is that, contrary to what is presented in [4], only one coil type is required. Moreover, the minimum strand bending radius in the coil is independent from the undulator period and can, therefore, be maintained well above the recommended value for the Nb_3Sn strand (>10 mm).

The magnetic flux distribution was derived for the proposed configuration based on computer simulations and it is shown in Fig. 2.

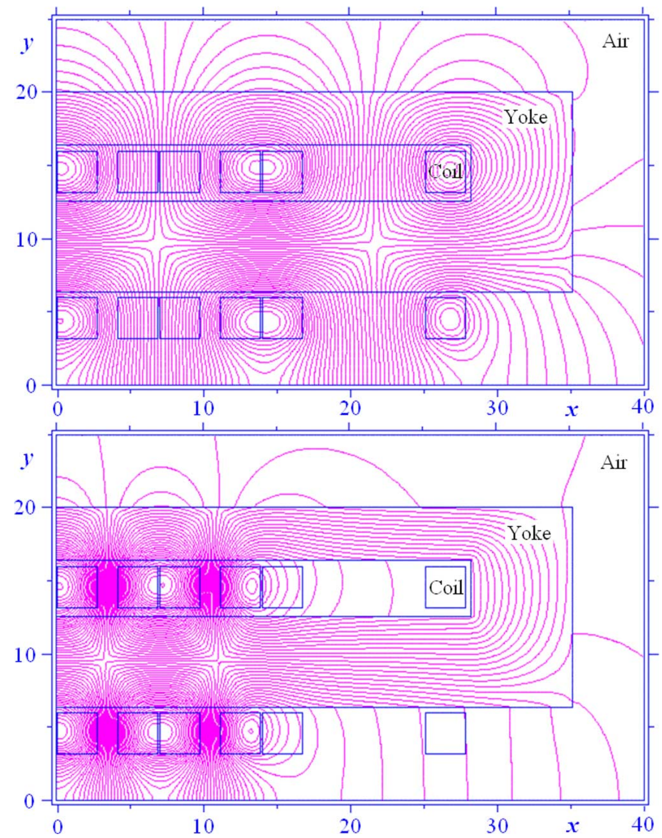

Fig. 2. Simulation of the undulator model made in Poisson [5]. Both configurations are shown, 280 mm period (top) and 140 mm period (bottom). The geometry is simplified to 1/4 of the full undulator, with symmetry planes on the x and y axis. The x axis represents the beam axis. Dimensions are in cm.

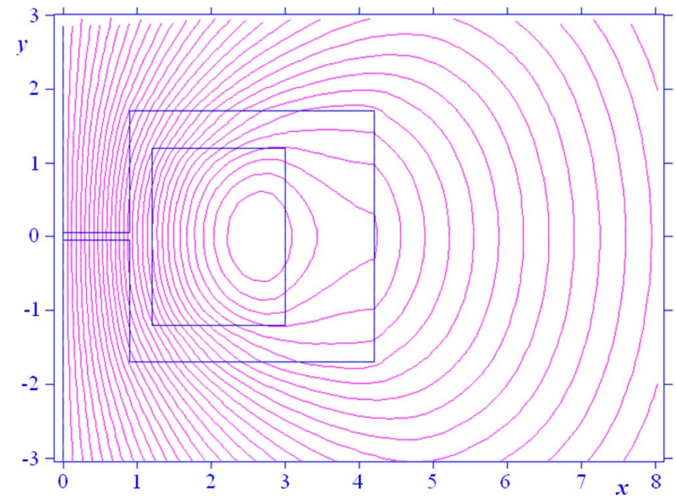

Fig. 3. Model magnet poisson simulation. Detail of the magnetic flux around the coil and central yoke pole, with symmetry plane in y axis. Dimensions are in cm.

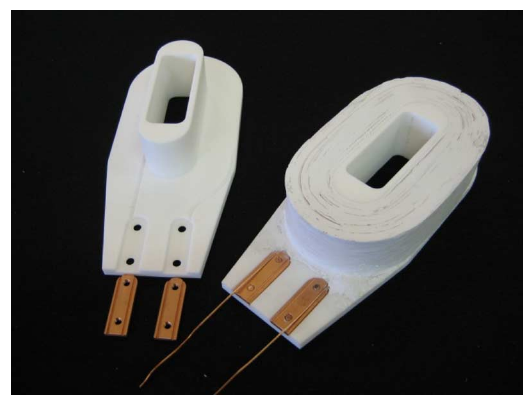

Fig. 4. Magnet ceramics support and final wounded coil with wet ceramics adhesive.

In the case of the shorter period configuration, although the magnetic field in the gap remains low (3 T), the maximum field in the coil is relatively large (~8 T), for which the use of Nb_3Sn becomes mandatory.

To assess the feasibility of such magnet, we studied a model magnet with similar dimensions to the required coils, such that identical conditions, constraints and fabrication challenges can be addressed.

The model magnet is mounted in a mirror configuration in an iron yoke. The yoke pole has an air gap of 1 mm which is used to place the Hall probes for magnetic measurements. The region around the coil is occupied by the support structure which was modeled as air.

In such an arrangement the maximum field occurs in the yoke gap, close to the vertical symmetry plane. When the field in the yoke gap is 10 T, the maximum field in the coil is 8 T. Fig. 3 illustrates the magnetic flux in the model magnet.

III. Model Magnet Description

A. Magnet Support

A single magnet support structure was preferred for minimizing the manipulations with the Nb_3Sn coil, which becomes brittle after heat treatment.

Due to the large temperature range extending from the heat treatment temperature down to the magnet operating temperature, mechanical stresses can arise from the thermal expansion mismatch between the reacted coil and the support structure. Therefore choosing the material correctly is of significant importance for minimizing these effects.

The coil support is made in machinable glass ceramics (Macor) with low thermal expansion coefficient ($\sim 8 \times 10^{-6}$ K^{-1} at room temperature). It has reasonable mechanical strength (compressive strength of 340 MPa) and it can produce complex designs with a good geometrical accuracy. Two copper terminals were embedded and glued to the support structure. After the required heat treatment, the coil terminals were tin soldered onto the copper terminals.

B. Coil Winding

The model coil was wound with a 0.8 mm diameter Rod-Restack-Process (RRP) Nb_3Sn strand produced by Oxford Instruments Superconducting Technology. The strand was provided with a wrapped S-glass braid. Tests results made at CERN with a similar strand can be found in [6]. The expected critical current in mirror configuration, based on the short sample measurements is ~840 A at 4.3 K and ~930 A at 1.8 K.

The coil was wound in a dedicated machine applying a constant tensile force of 50 N to the strand. As the strand is laid onto

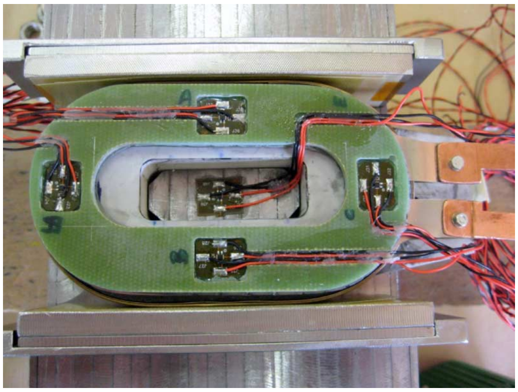

Fig. 5. Top view of the assembly. One central hall probe measures the magnetic flux in the yoke gap; four additional probes complete the magnetic flux map. Lateral vertically positioned tapers, constrain the coil movement against the yoke. The connections for the energy extraction resistor are also visible.

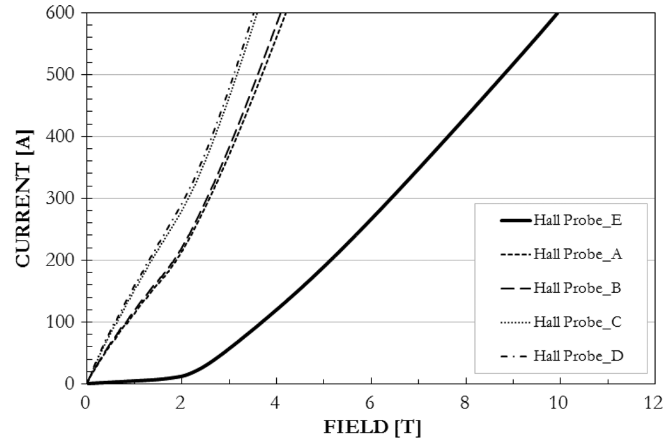

Fig. 6. Load line during current ramp-up. Hall probe 'E' is inserted in the yoke gap. Probes 'A' and 'B' are placed in the straight section, and 'C' and 'D' in the round end of the coil. The effects of the iron saturation can be clearly seen.

the coil support, a fine layer of wet ceramic adhesive (based on alumina) is applied directly onto the S-glass braid of the strand. The applied ceramic adhesive cures at room temperature, providing together with the S-glass braid a good inter turn electrical insulation while preventing the strand from motion. Once a full layer has been laid, additional ceramic adhesive is applied to fill all inter-strand gaps, providing a good geometry correction and replenish of voids on the layer jump region.

In the transition region between the curved sections and the straight section of the coil, the strand tends to adopt a naturally curved position. To correct this effect, once a layer was complete, and whilst the ceramic adhesive cured, lateral compression was applied in the straight section to bring the strands to the correct position. At the end of the complete winding of the coil and curing of the ceramic adhesive, the strand tension was released, and the strand was positioned on the copper terminals.

C. Coil Reaction

To react the coil and to ensure a high Residual Resistivity Ratio (RRR) of the stabilizing copper without suppressing the critical current density at high fields, the wound coil and support structure were heat treated under vacuum according to the sequence: (a) increase the temperature to 205 $^\circ\mathrm{C}$ at 25 $^\circ\mathrm{C/h}$ and hold at 205 $^\circ\mathrm{C}$ for 72 h; (b) increase the temperature to 400 $^\circ\mathrm{C}$ at 50 $^\circ\mathrm{C/h}$ and hold 400 $^\circ\mathrm{C}$ for 48 h; (c) increase the temperature to 695 $^\circ\mathrm{C}$ at 50 $^\circ\mathrm{C/h}$ and hold 695 $^\circ\mathrm{C}$ for 17 h; d) decrease the temperature to room temperature at 50 $^\circ\mathrm{C/h}$. A strand witness sample was reacted in the same furnace as the coil, the measurement showed an adequate RRR higher than 300.

D. Assembly for Test Setup

After the heat treatment the coil was fitted in a mold and coated under pressure with Stycast in order to correct the geometry. A beryllium-copper (Be-Cu) wire of 1 mm diameter was wound around the coil with a tensile force of 80 N for 22 turns, this provides the pre-stress to compensate for the magnetic forces.

A 0.4 mm thick Macor plate was glued to the top surface of the coil, granting a good parallelism with the base of the support structure. On top of this plate, a stainless steel strip acting as an energy extraction resistor for the quench protection was connected in parallel with the coil. A 'fishbone' spacer made of fiber glass to improve the cooling was placed between the final extra layer of fiber glass, where grooves for the Hall probes and wiring were pre-machined.

An array consisting of five Hall probes positioned at different locations was used to map the magnetic flux distribution. One of these was inserted in the yoke gap, where the flux is expected to be maximal, two other were placed on the straight section of the racetrack coil and the remaining two on top of the rounded ends. The coil assembly was positioned in the half yoke construction as shown in Fig. 5.

Tapered shims were positioned vertically on the straight section to give additional lateral support preventing the coil from moving and offering alignment relative to the yoke. The prestress given at room temperature was such that contact was provided when cold. Finally, the second yoke half was lowered into the assembly and tightening rods closed the structure.

For diagnostics and quench protection purposes, two sets of voltage taps were soldered to the interconnection points of the current leads.

IV. Magnet Tests

The model magnet was tested in September 2008 in a vertical cryostat, initially maintained at a temperature of 4.3 K and later at 1.9 K. In the first cold run at 4.3 K, the magnet reached a maximum current of 599 A, corresponding to a measured magnetic flux density in the yoke gap of 10 T.

During this run, the magnet was first powered using a 2 kA power supply. This configuration showed instabilities in the current supply leading to premature power aborts. To overcome this constraint, the setup was changed to a more stable 600 A power supply, resulting in quench training up to the limit of the power supply. Afterwards the setup was changed back to the 2 kA configuration, but the previously mentioned instabilities did not allow further improvements in the magnet performance.

The load line during current ramp-up is presented in Fig. 6 with the measurements from the different Hall probes. The results agree with the magnetic model at the various locations,

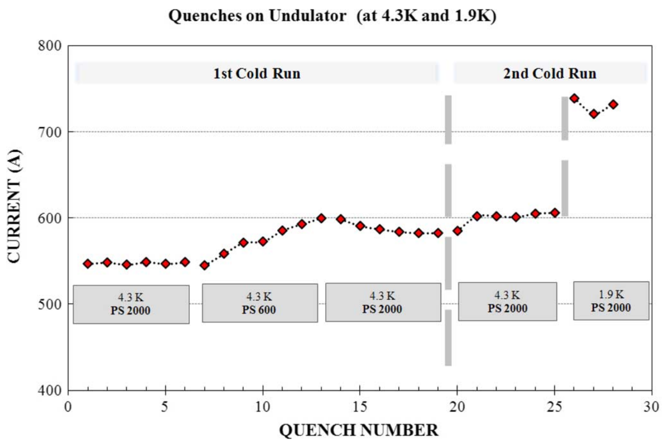

Fig. 7. Summary of the quenches performed in the two runs. In the first run at 4.3 K the magnet achieved a limit of 599 A. In the second run after modifications of the coil support, a limit of 606 A was achieved, corresponding to 10 T in the yoke gap. After further cooling to 1.9 K, the maximum attained current was 739 A corresponding to a magnetic flux density of 11.5 T.

with an estimated maximum magnetic flux density in the coil of 8 T.

At the end of the first cold run the magnet was warmed up and the pre-stress on the coils was readjusted to a higher value. The Be-Cu wire was removed and replaced by a stainless steel hoop. Moreover, the lateral pre-stress was increased by $\sim$10 MPa with additional shims.

At the second cold run initially at 4.3 K, the performance of the magnet slightly improved, allowing a ramp-up to 606 A with the 2 kA power supply. The coil was then cooled down to 1.9 K in a superfluid helium bath. As expected the performance of the superconductor increased, allowing the magnet to reach 739 A, corresponding to 11.5 T in the yoke gap and 9.2 T in the coil. For both cold runs the performance of the magnet reach about 75% of the short sample limit.

Only three quenches occurred at 1.9 K before the appearance of an electrical fault located in the inner strand segment of the transition between the curved and straight section of the coil. In Fig. 7 we summarize the test results for both cold runs.

V. Conclusions

A model magnet corresponding to the undulator upgrade of the LHC synchrotron radiation profile monitors with lead ions has been designed, built and tested.

The undulator design for versatile operation at either at 280 mm or 140 mm period resulted in the vertical positioning of the coils unlike the present undulator. In this configuration a large magnetic flux density occurs in the coil, thus requiring the use of a superconductor with higher performance, such as Nb_3Sn. The magnet was built using a Nb_3Sn RRP strand wound on a ceramics support with wet ceramics adhesive to provide electrical insulation and to avoid inter-strand motion.

During the development of the model magnet we introduced innovative winding techniques, which can become an important asset for future use. The coil was cured following an established protocol and subject to two test runs. The magnet tests showed a good agreement with our magnetic design and resulted in a maximum achieved field in the yoke gap of 10 T at 4.3 K and 11.5 T at 1.9 K, corresponding to 8 T and 9.2 T in coil respectively.

These results serve to validate the feasibility of the applied methods and give confidence for the production of the first undulator prototype.

References

[1] R. Jung, P. Komorowski, L. Ponce, and D. Tommasini, "The LHC 450 GeV to 7 TeV synchrotron radiation profile monitor using a superconducting undulator," in *AIP Proc.*, May 2002, vol. 648, CERN-SL-2002-015BI.

[2] R. Maccaferri, S. Bettoni, D. Tommasini, and W. Venturini Delsolaro, "Manufacture and test of the prototype 5 T superconducting undulator for the LHC synchrotron radiation profile monitor," *IEEE Trans. Applied Superconductivity*, vol. 16, no. 2, June 2006.

[3] R. Jung, Monitoring Lead Ion Beams in the LHC Using a Short Period SC Undulator and the BSRT *CERN Technical Note*, EDMS No. 653588, September 2005.

[4] S. Bettoni, Electromagnetic Design of a Nb_3Sn Superconducting Undulator for the LHC Beam Diagnostics *CERN Technical Note*, EDMS No. 734091, May 2006.

[5] K. Halbach and R. F. Holsinger, "SUPERFISH—A computer program for evaluation of RF cavities with cylindrical symmetry," *Particle Accelerators*, vol. 7, pp. 213–222, 1976.

[6] B. Bordini, R. Maccaferri, L. Rossi, and D. Tommasini, "Manufacture and test of a small ceramic-insulated Nb_3Sn split solenoid," in *EPAC Proceedings*, June 2008.