EUROPEAN ORGANIZATION FOR NUCLEAR RESEARCH
European Laboratory for Particle Physics

Large Hadron Collider Project

LHC Project Report 894

Manufacture and Test of the Prototype 5 T Superconducting Undulator for the LHC Synchrotron Radiation Profile Monitor

R. Maccaferri, S. Bettoni, D. Tommasini, W. Venturini Delsolaro

Abstract

A superconducting undulator wound with Nb-Ti based conductor, will be used in the LHC as a key part of the synchrotron radiation profile monitor system. Two undulators are needed, one per each circulating beam, providing 5 T in a 60 mm bore over two periods of 280 mm each. A full scale prototype has been designed and successfully tested in the end of 2004. In this paper, the electromagnetic and the mechanical design of the undulator are summarized. The fabrication of the prototype is described and the successful cold test results, both power test and magnetic flux density measurements, are reported.

CERN, Accelerator Technology Department, Geneva, Switzerland

Presented at the 19th International Conference on Magnet Technology (MT19)
18-23 September 2005, Genova, Italy

CERN
CH - 1211 Geneva 23
Switzerland

Geneva, 19 May 2006

Manufacture and Test of the Prototype 5T Superconducting Undulator for the LHC Synchrotron Radiation Profile Monitor

R. Maccaferri, S. Bettoni, D. Tommasini, W. Venturini Delsolaro

***Abstract*—A superconducting undulator wound with Nb-Ti based conductor, will be used in the LHC as a key part of the synchrotron radiation profile monitor system. Two undulators are needed, one per each circulating beam, providing 5 T in a 60 mm bore over two periods of 280 mm each. A full scale prototype has been designed and successfully tested in the end of 2004. In this paper, the electromagnetic and the mechanical design of the undulator are summarized. The fabrication of the prototype is described and the successful cold test results, both power test and magnetic flux density measurements, are reported.**

***Index Terms*—Synchrotron radiation, superconducting magnets, undulators.**

I. INTRODUCTION

IN THE LHC [1], synchrotron light monitors are the only non-intercepting devices able to produce 2-dimensional beam images down to single turn measurements, giving not only the beam size along any axis but also any beam tilt or coupling. The difficulty with proton beams in the LHC is to provide enough photons in the sensitivity region of the imaging detectors over the whole beam energy range and to extract the light out of the magnet chain. Whereas there is no problem to produce light with the fringe and bulk fields of normal bending magnets above 2 TeV, a dedicated undulator has to be introduced for beam energies from 450 GeV to 2 TeV. To cover the full energy range, the emission spectrum has to be kept wide, which implies a small number of periods, two in our case. To provide sufficient photons, the magnetic field has to be as high as possible. To perform single turn measurements down to a single bunch, a design magnetic flux density of 5 T has been taken, which imposes the use of a superconducting magnet. The period length has been fixed at 280 mm and the pole gap to 60 mm to cope with the LHC vertical acceptance in the undulators insertion region. As the half period length is only about twice the pole gap, the peak magnetic flux density at the pole-tip is much higher than the magnetic flux density on the beam axis (B_{GAP}): to provide 5 T to the beam 7.1 T have to be produced at the pole-tip. The magnet has been designed with highly saturated ferromagnetic poles, which limit the peak flux density (B_{COIL}) on the coil to about 6 T.

II. ELECTROMAGNETIC DESIGN

A. The parameters and the constraints

The design has been improved starting from the one presented in [3] and the main parameters are reported in Table 1.

TABLE I
UNDULATOR MAIN PARAMETERS

Item	
Period length	280 mm
Number of periods	2
Iron yoke length	704 mm
Pole gap	60 mm
Operating current	450 A
Coil cross section	35 mm x 44 mm
Bare cable size	0.67 mm x 1.53 mm
Insulated cable size	0.97 mm x 1.65 mm
Cu/Sc ratio	1.63
Operating temperature	4.2 K

The overall magnet dimensions fit in a helium vessel able to be housed in a standard LHC dipole cryostat. The fringe field seen by the other beam, circulating at 420 mm from the axis of the undulator, is kept as low as possible (<20 mT).

B. The model

Each of the two 280 mm period superconducting undulators is composed of eight NbTi coils inserted in two iron yokes (Fig.1). The distance between two adjacent coils is 5 mm which is the minimum necessary for the insulation and for the copper-beryllium retaining hoops. The distance between the conductors and the iron is minimized to 6 mm in

---

Manuscript received September 20, 2005.

R. Maccaferri is with the European Center for Nuclear Research (CERN) 1217 Geneva 23 Switzerland (0041-22-7673587; fax: 0041-22-7676300; e-mail:Remo.Maccaferri@cern.ch). AT dept.

S. Bettoni is with the University of Milan and CERN. 1217 Geneva 23 Switzerland (e-mail: Simona.Bettoni@cern.ch).

D. Tommasini is with the European Center for Nuclear Research (CERN) 1217 Geneva 23 Switzerland (e-mail: Davide.Tommasini@cern.ch). AT dept.

W. Venturini Delsolaro is with the European Center for Nuclear Research (CERN) 1217Geneva 23 Switzerland (e-mail: Walter.Venturini@cern.ch). AT dept.

order to benefit from the field increase due to the iron resulting in a maximum B_{GAP}/B_{COIL} ratio of 0.87 and a 30% margin to quench on the load line.

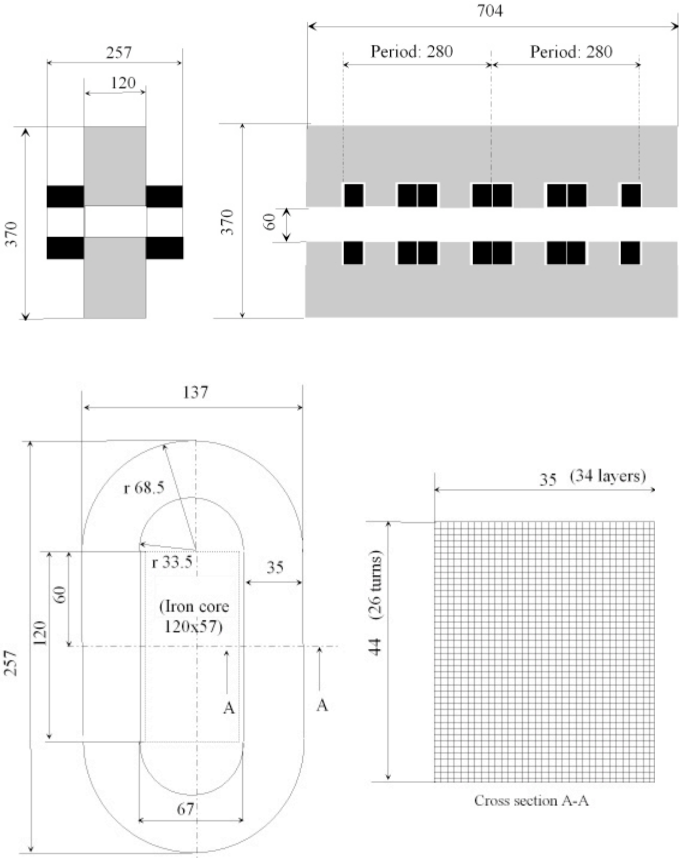

Fig. 1. Undulator layout and coil details. Dimensions are in mm.

C. 2D and 3D calculation

In Fig. 2 the 2D model solved by Poisson is presented.

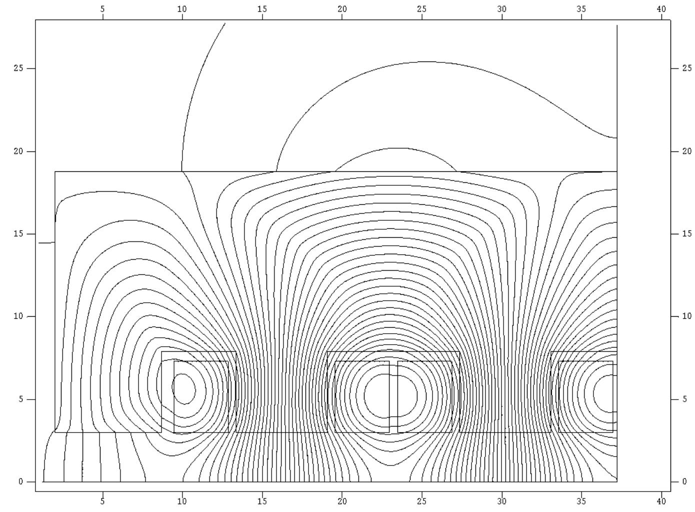

Fig. 2. Poisson undulator model. For reasons of symmetry only ¼ of the complete undulator is simulated. Dimensions are in cm.

This design allows to produce magnetic flux density peaks of 4.85T and 5.31T on the beam axis, with a current of 450A as shown in Fig. 3.

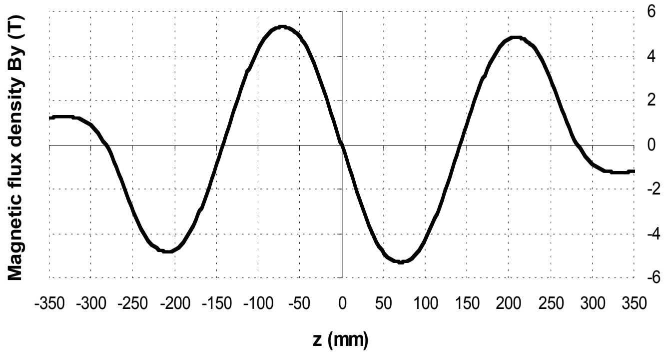

Fig. 3. Two periods magnetic flux density By simulated by Poisson.

The B_{GAP}/B_{COIL} ratio varies from 0.85 for the less intense peak to 0.87 for the maximum one.
The symmetry of the design guarantees that the integral of B along z is zero. To calculate the transversal field uniformity and the fringe field seen by the second LHC beam, a 3D simulation has been done by Tosca©: the relevant results are plotted in Fig.4. The beam aperture in the horizontal plane is 50 mm and for this range the variation is less than 2.4 % which is inside the specifications. The fringe field seen by the second beam is less than 18.3 mT.

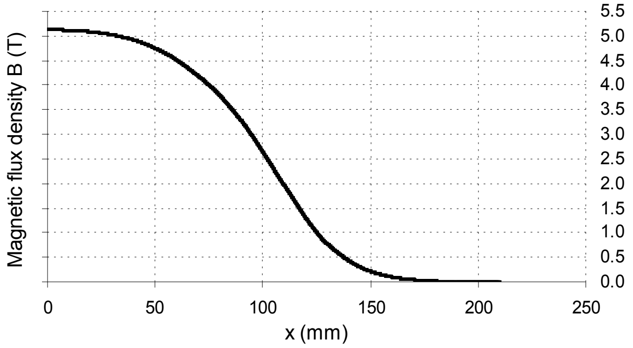

Fig. 4. Magnetic flux density of the By (vertical) component in the transverse direction on the mid-plane.

III. MECHANICAL DESIGN

A. Undulator Manufacture

A first half-period prototype design reported in [4] was tested in 2004 with acceptable results. After that we tested a new one which gives better performance. The main change with respect to the previous design is in the horizontal coil retaining structure: the new one consists in a copper-beryllium ring shrunk around the coil, Fig. 5.

The coils are of racetrack type. They have 34 layers for a total of 884 turns and are wound by using an automatic winding machine which can control the wire tension, the rotating speed and the wire torsion.

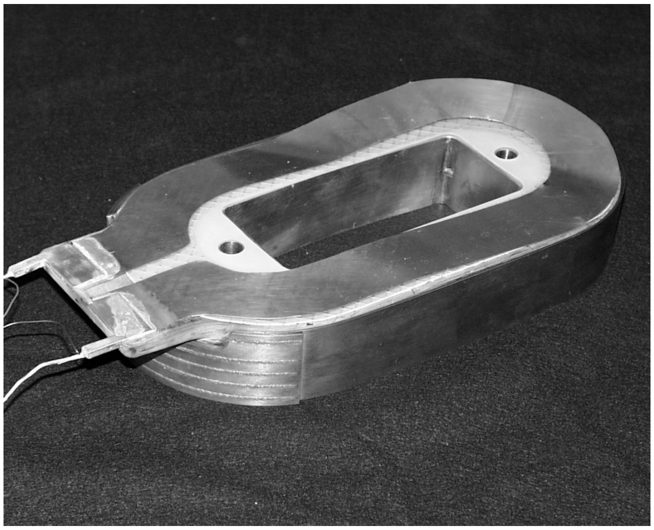

Fig. 5. Single coil assembly with copper-beryllium ring and the flat energy extraction resistor on the top.

Each coil has a stainless steel core covered by a layer of glass-fiber spacers acting as ground insulation and helium ventilation. The coil is impregnated during the winding by wetting the wire with an epoxy resin. After a first curing at 100 ºC the coil is fitted in a mold and coated under pressure with Stycast® to fit dimensions. After a new curing cycle at 120 ºC, the coil is cooled in a nitrogen bath while a 2 mm thick copper beryllium hoop, shaped like the coil perimeter, is heated at 300 ºC.

The temperature differential enables the hoop to be fitted by shrinking, around the coil (Fig. 5). The hoop perimeter is calculated in order to exert a pre-stress on the coil heads of about 1.8 MPa at room temperature, increasing to 2.5 MPa at 4.5 K.

Fig. 6. Undulator full scale prototype assembly: two yoke, eight coils.

The coils are finally mounted in the yokes with no space between them except for the external ones which are copper-beryllium tie bolts. In such way a lateral pre-stress of 6 MPa compressed laterally by a mobile spacer pulled by two long is applied at room temperature and increased to 10 MPa at 4.5 K.

The flat faces of the coils are compressed by two thick stainless-steel plates. The pressure is obtained also in this case with copper-beryllium tie bolts. This retaining structure has permitted to reach the ultimate current value of 500 A with less than 4 quenches per coil. Compared with the previous version (25 quenches per coil) the improvement is considerable. This solution has been adopted for the final version of the undulators.

B. Quench protection issues

The magnet is self-protected against the quenches by 150 mΩ energy extraction resistors directly connected in parallel with each coil. These resistors are in contact with the flat faces of the coils (Fig. 5). During the extraction energy transient they act like coil heaters and spread the quench in the whole magnet. Moreover, as the copper-beryllium hoop is a close turn traversed by the flux produced by the coil, a part of the stored energy is dissipated in it during current decay. In addition to the coil heater a standard external energy extraction system consisting in a 800 mΩ resistor will extract about 50% of the total stored energy in case of quench. The computed hot spot temperature in the quenched coil is 80 K.

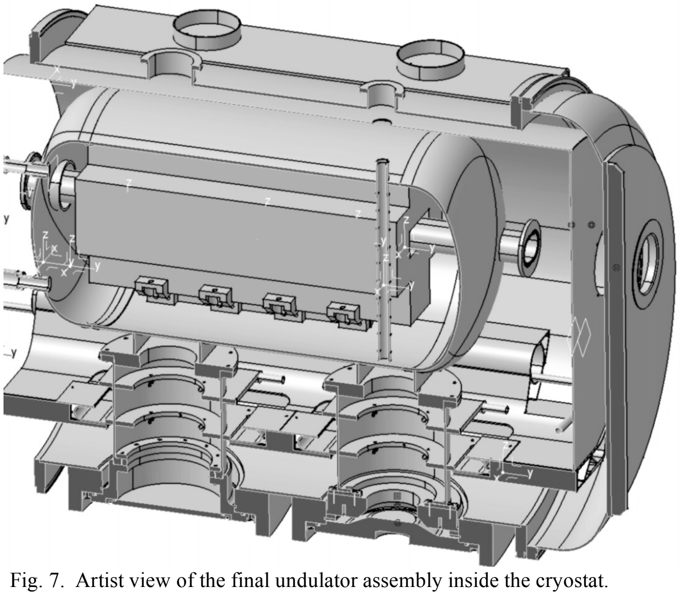

Fig. 7. Artist view of the final undulator assembly inside the cryostat.

IV. COLD TESTS OF FULL SCALE UNDULATORS

Two complete magnets have been tested. The first one, assembled with seven coils previously trained in a half-period structure and one never trained, was tested in November 2004. The training curve is shown in Fig. 8. The already trained coils kept their memory, whereas the new one needed 22 quenches before reaching the nominal current.

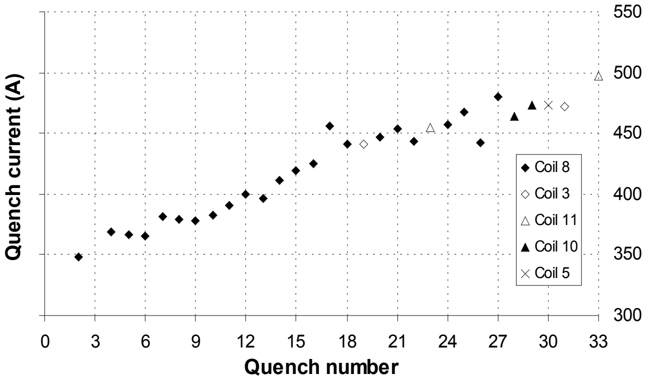

Fig. 8. Training curve of the first undulator assembly at 4.4 K: all quenches between 2 and 18 occurred in coil 8, the only one not previously trained.

The second magnet was assembled with eight new coils never trained and tested in August 2005. The quench performance of this prototype was largely dominated by one single faulty coil (coil 15), as is highlighted in Fig. 9. Above 400 A coil 19 also showed a weakness. This test has been stopped due to the failure of an extraction resistor at 486 A. The defective coils will be replaced by a new one and tested again before the final installation in March 2006.

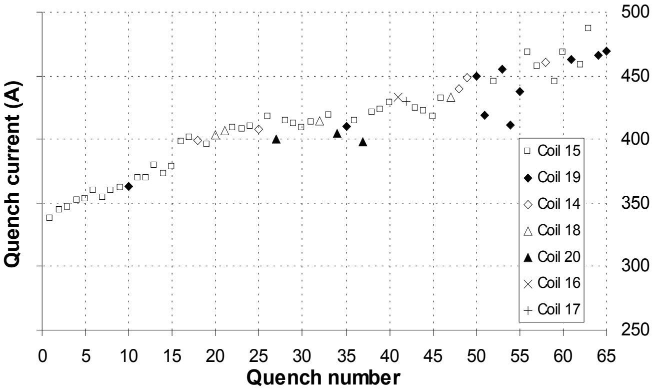

Fig. 9. Training curve of the second undulator assembly at 4.4 K: all coils were at their first training.

V. MAGNETIC FLUX DENSITY MAP MEASUREMENT

A. *Measurement setup*

A matrix of Hall probes disposed over a rectangular area of 360 mm x 50 mm was inserted in the pole gap on the mid-plane, the probes were arranged in 5 rows of 16 probes each one. Only 8 probes were calibrated at cold: the relevant results were used to compute the coefficients of the whole array. Considering the spread inside the group of 8, we can estimate the accuracy of the whole array to be about 2-3%.

The array covered one undulator period, and allowed to build 2D maps of the vertical component of the magnetic flux density with 1 Hz acquisition frequency.

B. *Results*

The magnetic flux density of the vertical component By measured at 4.4 K and 450 A is compared with the model simulations in Fig. 10 and Fig. 11. The agreement is in the order of 5% for the amplitude.

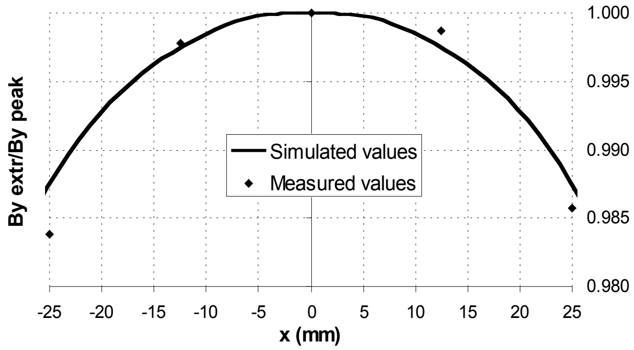

Fig. 10. Normalized magnetic flux density of the vertical component along the transversal axis (calculated and measured).

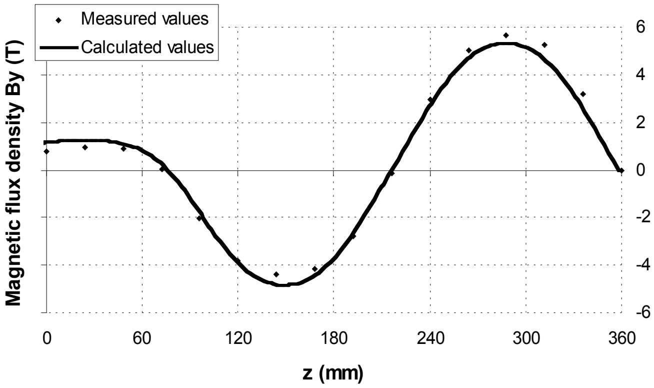

Fig. 11. Calculated versus measured values along the longitudinal axis (computed and measured).

VI. CONCLUSION

Both prototypes fulfill the original specifications given in [3]. During the development we have learned and introduced some innovative features in the winding techniques, the curing processes, the clamping structures and the quench protection. We are now ready to assemble the two undulators that will be installed in the LHC in March 2006.

ACKNOWLEDGMENT

We would like to thank Roland Jung for his continuous support to this project, Hans Kummer and Bruno Meunier for their enthusiasm and competence in the hardware assembly and the team of the CERN vertical test facility for preparing and executing the cold tests and the magnetic measurements.

REFERENCES

[1] R. Jung, P. Komorowski, L. Ponce, D. Tommasini., “The LHC 450 GeV to 7 TeV synchrotron radiation profile monitor using a superconducting undulator”, AIP Proc. 648, 2002 and CERN-SL-2002-015BI, May 2002.
[2] P. Komorowski, “Electromagnetic design study of the 5 T superconducting undulator for the proton synchrotron light source and LHC beam diagnostics”, CERN Technical Note 2002-01: 2002.
[3] D. Tommasini, “Preliminary conceptual design of the 5 T superconducting undulators for the LHC synchrotron radiation profile monitor”, LHC Project Note 299, CERN Geneva : 2002.
[4] R. Maccaferri, M. Facchini, R. Jung, D. Tommasini, W. Venturini Delsolaro, “The 5 T superconducting undulator for the LHC synchrotron radiation profile monitor”, EPAC 2004 Proc. pp. 1630–1632.