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**Development and Fabrication of the First 10 m Long Superconducting Dipole
Prototype for the LHC**

E. Acerbi*, M. Bona, D. Leroy, R. Perin, L. Rossi*

Abstract

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Development and Fabrication of the First 10 m Long Superconducting Dipole Prototype for the LHC

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Abstract – A number of 10 m long dipole prototypes for the LHC is being manufactured by European industries, under CERN technical responsibility. This paper resumes the main developments of the design as well as the retained technological solutions for the fabrication of the first 10 m long dipole prototype, manufactured by the Italian firm Ansaldo in the frame of the LHC magnets R&D program.

I. INTRODUCTION

In the frame of the R&D program for the Large Hadron Collider (LHC), CERN has designed dipole magnets in the field range 8-10 T.

The design of such prototypes [1] is the natural evolution from the solution adopted in CERN models [2] and prototype [3] developed so far.

The construction of seven 10 m long prototypes has been commissioned to European firms. Thanks to a collaboration set up between CERN and INFN (the Italian "Istituto Nazionale di Fisica Nucleare"), it was possible for CERN to start the full length dipole development in spring 1990, in advance with respect of its self-financed program. Two of such prototypes [4] were in fact funded by INFN to be developed and built, under CERN technical responsibility, by the Italian firm Ansaldo who will also fabricate a third prototype. INFN also funded the developments of superconducting cables for two dipoles [5], [6] and two 1.8 K cryostats by Italian companies.

The present situation is as follows:

- the first magnet is finished. The cold mass assembly is ready to be shipped to the company (Zanon-I) which has built the cryostat. It is expected that in three months the cryostat will be assembled and the complete dipole sent to CERN for testing;
- the second prototype has been collared. It should be ready for test at CERN in early spring 1994;
- the coils of the third dipole has been already wound and cured. Collaring of this magnet is scheduled in autumn 1993 and shipping to CERN of the complete magnet in its cryostat by mid 1994.

The construction of these prototypes, mainly the first one, required an intense R&D program: several design

Figure 1: up to date cross section of the dipole magnet

and/or fabrication aspects had to be modified during fabrication. A full length dummy coils plus collars assembly was manufactured in order to test the collaring process and to learn how to cope with the strict tolerances required by such a magnet.

The early design improvement and technological development are described in a previous paper [4]. More recent developments as well as the main experimental and fabrication results are now discussed, grouped in three main arguments: coils, collaring and shrinking cylinder welding.

II. COILS

The coils are subdivided into two layers, as shown in the cross section of Fig. 1: for the inner layer a cable composed by $26 \times \phi 1.29$ mm strands was used while for the outer shell 40 strands with $\phi 0.84$ mm were cabled. The cables were not solder impregnated. Both cables were difficult to wind, the inner one because of the high rigidity (which caused problems at the ends where small radii of curvature and twisting are required) and the outer one for a tendency of bulging out when handled. Dummy coils, where solid copper strands were used, were very useful in setting up all the tooling and manufacturing process but

Figure 2: the first 10 m long LHC dipole near completion at Ansaldo.

were not completely representative of the Cu/NbTi cable.

A. Rigidity and Accuracy

In order to obtain a coil geometry as close as possible to the theoretical one, adjustable shims were foreseen in the upper part of the coil arch in between the collar central tooth and the coil block. The equivalent elastic modulus of each coil and each layer was measured along its full length, by compressing with a press at an average stress level of about 80 MPa for the inner layer and 55 MPa for the outer one, with the following results:

- first prototype:

1. $E_{inner} = 31.40$ GPa (max 32.50–min 30.24 GPa)
2. $E_{outer} = 24.85$ GPa (max 28.25–min 22.70 GPa)

- second prototype:

1. $E_{inner} = 32.25$ GPa (max 34.40–min 30.53 GPa)
2. $E_{outer} = 24.55$ GPa (max 24.76–min 24.10 GPa)

The dimensional precision of the coils under compression at the above mentioned stress was about $50\text{ }\mu\text{m}$. It must be said that the intrinsic precision of the modulus measurements depends on friction whose distribution is not perfectly controlled.

B. Coil Ends

As previously mentioned, one of the main problem was the stiffness of the coil ends where different intermediate G11 spacers are placed between groups of coil turns. A technique was developed to mould completely the coil ends, with an injection of a charged epoxy resin (type AV 138) which fills the remaining voids and provides a continuous cable support. Impregnation is made with a tool which imparts with good accuracy the design geometry to the coil ends and leaves a very smooth surface.

With such an impregnation the mechanical stiffness of the coil ends is privileged with respect to the direct cooling. Actually, from the test carried out so far in models, preventing or reducing any possible movements of the conductor, although creating small quasi-adiabatic zones, seems to be the most effective solution to improve the performance of these high field magnets.

III. COLLARING

Shim thicknesses were determined from the elastic modulus measurements. Special shims with channel have been provided to improve the coolant circulation.

After having electrically joined by soldering the inner and outer layer pairs, every pole underwent a further temperature curing. The ground insulation, six $125\text{ }\mu\text{m}$ thick polyimide foils, was placed and the coils were positioned on the collaring mandrel.

Near the coil ends shims were placed on the horizontal plane in between upper and lower poles. In fact this region

proved, in the dummy coil collaring, to be less stiff than the straight part and therefore the shims were added to provide the required compressive stress while ensuring the correct geometry. The coil mandrel was removed after a moderate compression.

Collaring was made by using a 10 MN/m press, [4]. Insertion of the central pinning rod and of the two lateral pinning rods was made by properly pushing at the collars at different positions. Insertion of the nominal diameter rods took place at the following typical press forces per unit length:

Central rod: $F = 6 \text{ MN/m}$; Lateral rods: $F = 10 \text{ MN/m}$

Slightly different compressions were given to the end parts with respect to the straight part thanks to the possibility of load partialisation of the press.

Once the pinning rods inserted and the press load released, the remaining load is indicated by the deformed shape of the collars which was measured every 500 mm, in longitudinal direction. As expected the straight parts resulted more bulged than the end part (last 500 mm). Aside this end effect, the uniformity of the deformed collar shape is within 0.05 mm. In Fig. 3 the average values of the deformation for the main dimensions of the collars are reported (straight part).

By comparing these values with those computed with finite element analysis [1] and taking into account the actual measured tolerances of the collar-coil-rod assembly, the goal of having a remaining stress of at least 80 MPa in the inner layer and 55 MPa in the outer one is achieved. In fact stresses on the first prototype are a bit higher, being actually 85-90 MPa in the inner layer and 55-60 MPa in the outer one.

Figure 3: collar average deformation after collaring.

A. Liquid Nitrogen Cool Down

Once collared the coil-collar assembly was tested for electrical insulation (e.g. ground insulation was checked at 3 kV) and therefore gradually cooled down to liquid nitrogen temperature. Insulation tests were then made and repeated after returning to room temperature. All electrical checks were positive. One, out of 16, quench heater stripe, however showed a weaker insulation with respect to coils. It was decided not to connect it during the magnet test.

IV. SHRINKING CYLINDER AND CONTROL OF THE IRON YOKE GAP

A. New Method of the Shrinking Cylinder Assembly

The shrinking cylinder, made out of stainless steel 316 LN, must have a very precise azimuthal length. For the first prototype the two halves were obtained by cutting a 10 m long tube previously machined in the inside face. The matching took place after definition of dimensions following experimental test on models.

In the original conception the design value of the iron yoke gap was to be obtained by controlling the welding shrinkage without alignment pieces between the yoke halves. Actually this system failed when implemented on models.

A previously abandoned solution was then reexamined and improved. High thermal contraction alignment pieces were then designed to be placed between the yoke halves. These pieces, made of aluminum, are shaped such as to impose the design gap after a weld seam having the theoretical shrinkage. Actually it acts as an important alignment system which can also take part of the loads originated by an excess of shrinkage.

When cooling down the magnet, thanks to the high contraction coefficient, the alignment pieces should either lose contact with the yoke halves with consequent transfer of the whole mating force on the mating faces of the yoke halves, or remain in contact being still slightly compressed, whilst permitting the yoke gap to be closed at low temperature with the required mating force.

B. Welding Models

Three 370 mm long models were made to understand both the suitability of the new solution and to define the welding process also for the quality and safety control.

The models were equipped with strain gauges which measured a stress, averaged on the azimuth, of about 170 MPa after weld shrinkage. No precompression on the half cylinder was necessary during welding. The models were cooled to liquid nitrogen temperature. The stress evolution with temperature was monitored and the kinematics of the parts undergoing relative motion was studied. The results confirmed soundness of the design approach: the gap started closing at about 100 K while the average stress increased to about 270 MPa at 77 K. On returning to room temperature the initial stress level and geometrical conditions were restored.

The yoke lamination were then machined (punched) to house the new alignment pieces and, following the results on models, the sliding foil between yoke and shrinking cylinder was eliminated.

All the above described new features are shown in the magnet cross-section of Fig. 1.

C. Yoke-Cylinder Assembly of the First Dipole

The yoke halves were assembled in a 10 m long stack with a stacking factor higher than 98%. The yoke halves were then assembled around the collars, with a geometrical tolerance of the different parts of only 20-40 μm .

The two cylinder halves of the first dipole were welded manually with a TIG process while automatic welding will

Figure 4: front view of the magnet before closing with end covers.

be used for the second and third dipole. 18 passes were needed, 10 mm being the cylinder thickness. 100% radiographic inspections were made after 1st, 5th and the last pass. The final result was according to the ASME standards, defined by the CERN safety authority as the reference safety code for this case.

The average circumferential stress is about 190 MPa. The mean residual gap between the iron yoke halves is about 0.25 mm, well uniform along the magnet length. The alignment elements are under compression at 60-70 MPa.

V. COMPLETION OF THE MAGNET

After welding of the shrinking cylinder, the magnet "cold mass" was completed for assembling into its cryostat with the following operations:

- the electrical connections between the poles of the beam aperture and between the two apertures were executed by using the same technique of the 1 m long MTA1 models. The main bus bars, as well as the auxiliary bus bars, which are necessary for the first string tests at CERN, were shaped at the magnet ends and connected to the internal coil terminals, see Fig. 4;
- the 11 meter long beam tubes were inserted into the apertures and the two end covers circumferentially welded onto the shrinking cylinder;
- the support feet were welded on the magnet with a positioning tolerance of ± 0.2 mm with respect to the magnetic axes of the apertures.

VI. CONCLUSIONS

The first 10 m long LHC dipole prototype required an intense R&D program and proved to be very useful in transferring the CERN design to the Industry and to transform it into industrial technology. Feed-back from

fabrication technique made the design more suitable for manufacturing environment.

The LHC design has recently evolved toward larger aperture ($\phi 56$ mm instead of $\phi 50$ mm) longer and lower field (8.65 T instead of 9.5 T) dipole magnets. Manufacturing and testing of the present prototypes are providing an indispensable and invaluable experience for the improvement of design details and fabrication method and will indicate the present limit of construction possibilities and performance of high field accelerator magnets.

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VIII. REFERENCES

- [1] M. Bona, D. Perini, "Finite-element structural analysis of the 10 m long dipole prototype magnet for the LHC", *IEEE Trans. Magn.*, vol.28, January 1992, p. 358.
- [2] M. Bona, D. Leroy, R. Perin, B. Szeless, W. Thomi, "Design, Fabrication, Variants and Results of the LHC Twin-Aperture Models", *IEEE Trans. Magn.*, vol.28, January 1992, pag. 338.
- [3] M. Granier et al., "Performance of the twin-aperture dipole for the CERN LHC", CERN/AT-MA/92-04 LHC Note 179, presented at III EPAC, Berlin March 1992.
- [4] E. Acerbi, M. Bona, D. Leroy, R. Perin, L. Rossi "State of the construction of the INFN full length superconducting dipole prototype magnets for the Large Hadron Collider (LHC)", Proc. of III EPAC, Berlin March 1992, pag. 1420.
- [5] E. Acerbi, S. Ceresara, R. Garrè, L. Rossi, G. Volpini "The Italian development of a superconducting cable for the Large Hadron Collider", Proc. of III EPAC, Berlin March 1992, pag. 1417.
- [6] G. Baccaglioni, P. Fabbicatore, R. Garrè, R. Muenich R. Parodi, L. Rossi, G. Volpini, "Critical current measurements of the cable for the superconducting dipole prototype of the LHC", presented at MT-13 Conference, Victoria, B.C., September 1993.