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Status of the Construction of the First 15 m long Superconducting Dipole Prototype for the LHC

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Abstract

CERN and INFN are jointly building the first full-size superconducting dipole prototype for the LHC. This magnet, whose construction was launched in spring 1995, is completely manufactured in industry. Its fabrication required the upgrade of the tooling which was used to build three 10-m long prototypes under a previous CERN-INFN Collaboration. The construction is being completed and the cryostated magnet is expected to be at CERN for testing by the end of 1997. In this paper we discuss the results of the measurements carried out at 4.2 K and 2 K to determine the conductor properties (Ic of wires and cables, magnetization), as well as the short sample limit. The main features of the coil construction are presented, together with the results of the main fabrication phases. In particular, the validity of the fabrication techniques is assessed based on the obtained results.

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I. Introduction

An international Collaboration has been set-up between CERN and INFN (the Italian “Istituto Nazionale di Fisica Nucleare”) to jointly finance the fabrication of the first full-length (15 m) LHC dipole prototype aimed to reach the nominal field of 8.3 T, corresponding to the LHC design energy of 7 Tev/beam [1], [2]. The magnet cryostat, as well as the cryostating operations are also covered by this CERN/INFN Collaboration.

The geometry of this magnet (Fig. 1), which magnetical length is 14.2 m at the operating temperature of 1.9 K, is conceptually based on the previous 10 m long prototypes [3]. The main differences are the smaller cable width (15 mm instead of 17 mm), the coil aperture (ø56 mm instead of ø50 mm) and the intra-beam spacing (194 mm instead of 180 mm). Moreover, this magnet is curved.

The prototype is fabricated by the Italian firm Ansaldo under CERN technical responsibility and CERN/INFN global responsibility. CERN is also responsible for the magnet design, as well as of the procurement and supply to Ansaldo of some critical components like fine-blanked collars and yoke laminations, end spacers, shrinking cylinder shells. INFN holds the technical responsibility of the development, fabrication and supply of the superconducting cables.

So far the following main operations have been carried out:

. a dummy pole was built to establish the winding and curing techniques. It was then used as a part of a 4-m-long collaring model, assembled to define the collaring operations.

. the four superconducting poles have been wound, cured and collared.

. the collared coils have been assembled into the iron yokes and the shrinking cylinder shells have been longitudinally welded.

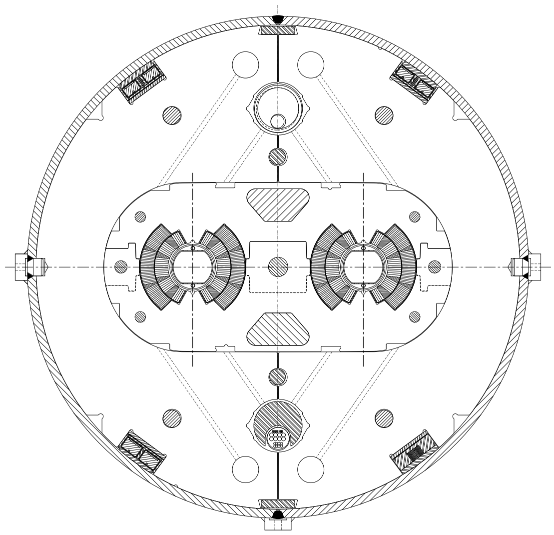

Fig.1. Cross-section of the 15-m dipole prototype.

At present the electrical connections are being made, which will be followed by the mounting of the end covers, by the completion of the cold mass assembly and by the leak/pressure testing. The cold mass is expected to be shipped on beginning November 1997 from Ansaldo to the Italian firm Zanon for the cryostating operations. Shipping to CERN is scheduled by the end of November 1997. Once at CERN the prototype will be prepared for testing, which will be carried out on the new CERN test bench presently under assembly.

In the next paragraphs an overview is given of the main technical aspects linked to the fabrication of this prototype.

II. Tooling

To manufacture this first full-length prototype, some of the heavy tools used for the previous 10-m long dipole magnets fabricated at Ansaldo were extended, starting in Spring 1995. This was the case for the winding machine and for the curing/collaring press. The required modifications, although carried out with accuracy, were not optimal since they were introduced on old Ansaldo tools already adapted in the past to fabricate the 10-m long LHC prototypes.

Other tools have been re-designed and made new. This was the case for the winding mandrels and the curing moulds which were assembled by using very precise fine-blanked laminated parts (precision better than 0.02 mm). This has assured a high functionality and reliability of the tools.

III. Conductor and Cables

The conductor for the dipole consists of two different types of Rutherford cable, one for each layer. The wire was all manufactured by EM, Europa Metalli (I); the cabling was partly done by EM and partly by Brugg Kabel (CH).

The conductor was made according the specification [4], as reported in Table I.

TABLE I
Main Characteristics Of The Conductors

	Cable 1 (inner)	Cable 2 (outer)
Strand diameter (mm)	1.065 ± 0.003	0.825 ± 0.003
Filament diameter (μm)	7	6
Cu/Sc (in volume)	≥ 1.60	≥ 1.90
Strand critical current (A)	≥ 515 at 10 T, 1.9 K (532 at 7 T, 4.22 K)	≥ 380 at 9 T, 1.9 K (387 at 6 T, 4.2 K)
No. of strands	28	36
Cable width (mm)	15.0	15.0
Cable mid-thickness (mm)	1.89	1.47
Keystone angle	1.30°	1.00°
Compaction	88%	87%
Cable critical current (A)	13750 at 10 T, 1.9 K	12960 at 9 T, 1.9 K
Cu RRR	≥ 70	≥ 70
Unit length (m)	460	780

Tolerances in size are very stringent, ± 3 μm for the virgin wire and ± 6 μm for the cable thickness. The strands, before cabling, are coated with SnAg(5wt% Ag) and no cold junction was allowed.

The required critical current for the inner cable corresponds to a critical current density J_c in the virgin wire of about 1550 A/mm^2 at 7 T, 4.2 K and a field shift of 2.9 T of the J_c curve at 1.9 T, provided that the cabling degradation is not more than 5%.

For the outer cable a J_c of 2100 A/mm^2 at 6 T and 4.2 K, with a 2.95 T shift and not more than 5% cabling degradation is sufficient to meet the specification.

The NbTi (47 wt% Ti) had a Nb anti-diffusion barrier of about 5% of the superconductor cross section.

The wire manufacturing, about 80 km for the inner strand and 170 km for the outer strand, went very smooth. No breakage at all was detected on the wire for the inner cable while two breakages occurred in the outer cable. This was also due to the moderate cold work chosen by EM for this production (the corresponding ε_F was 3.16 for the inner wire and 3.56 for the outer one).

I_c measurements on wire were performed at 4.2 K for all wires and at 2.17 K on few of them. The further shift toward higher fields at 1.9 K was then evaluated with a linear extrapolation. The I_c computed in this way have been compared with measurements done at CERN [5] directly at 1.9 K: the agreement is good. Systematic comparisons between measurements carried out at LASA, CERN and BNL, indicate that the wire I_c is reliable within 2%. All critical currents are here quoted according to the $\rho_c = 10^{-14}$ $\Omega\cdot$m criterion, taking into account only the superconductor cross section.

The critical current was measured on wires both before and after the last heat treatment (HT) on spool before cabling.

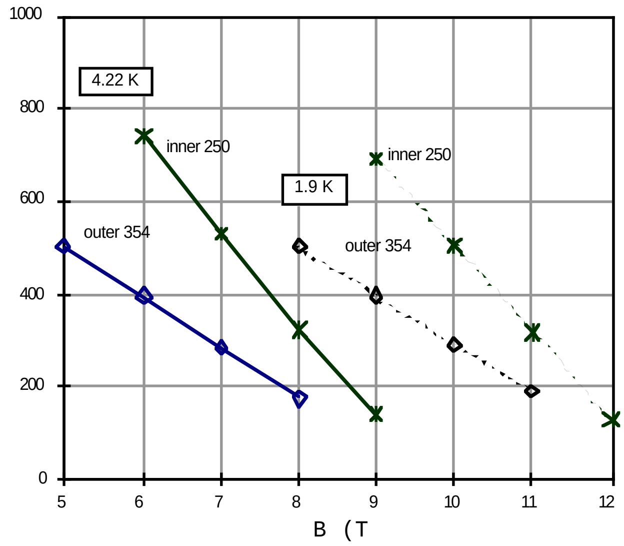

Fig. 2. Critical current vs. applied magnetic field for two wires extracted from cable. The field shift is about 2.85 T for the inner and 3.01 T for the outer one.

The I_c values before this HT were found 3-5% higher than the specifications but reduced more than expected after HT. The shift toward high field at 1.9 K, measured after HT, was 2.5-2.8 T. The shift is larger for the outer wire and smaller for the inner wire, made with a lower value of the residual strain.

The cable current was inferred by measurements on strands extracted from cable, a technique that was already well studied and validated for LHC conductor in a previous job for the first two 10 m long dipoles (having cables 17 mm wide) [6]. Degradation was found negligible, typically 2%, and sometimes even negative. Also the I_c shift was better in extracted strands, 2.85 T for inner and 3 T for outer wire. Clearly this indicates that the cold work induced by cabling was beneficial (this conclusion is not necessarily true for wire fabricated with higher residual strain).

By means of the measurements on identified extracted strands and the cabling map, it was possible to evaluate the cable I_c for each unit: the results are summarised in Table II where identification of cables and coils is also reported (I: inner, E: outer).

From the measured performance, the short sample maximum field of the magnet is about 9.6 T.

TABLE II
Summary Of Cable I_C (at 7.1T for inner cable and 6.9T for outer cable)

Coil # (Ansaldo)	Cable # (EM)	I_c at 4.22 K (kA)	Ic at 1.9 K (kA)
2I	3I	14.17	13.97
4I	5I	14.53	14.31
5I	6I	14.86	14.65
6I	7I	14.86	14.65
2E	3E	14.46	14.49
4E	4E	14.74	14.76
5E	7E	14.44	14.47
6E	8E	14.22	14.24

IV. Coils and Collaring

A. Coil winding and curing

The coils, based on a “5-blocks” configuration, are subdivided in two layers. The cable insulation consists of two layers of polyimide tape (22 mm wide and 25 µm thick), each one 50 % overlapped. A glass-fibre tape (12 mm wide and 120 µm thick) impregnated with B-stage epoxy, is wound around the polyimide insulation, leaving a gap of 2 mm between adjacent turns.

No difficulty of any kind has been observed during coil winding. The pulling force during winding was ~ 400 N for the inner layer and ~ 300 N for the outer one. The force was lowered almost to zero in the coils ends.

A main characteristic of this prototype is that the outer layer is wound on top of the inner layer coil already cured, which hence serves as a winding mandrel. This technique has the major advantage of having the inner layer coil always kept in place, well fixed to its winding mandrel. Moreover, the splice between the two layers is executed before winding the outer layer, thus giving more reliability in terms of manufacturing precision. A dummy pole, consisting of an inner+outer layer coil, was manufactured using Cu cables, in order to establish the winding and curing techniques.

Curing of the coil layers was carried out at a temperature of 145˚C for 1 hour. The average azimuthal stress in the coils during curing was 80 N/mm^2. Because of the adopted winding technique the inner layer coils were submitted twice to this thermal cycle. Considering the low curing temperature, no negative influence is expected for the electro-magnetic behaviour of the cables.

Cooling channels of a new concept, having crossing channels, have been placed in between the two coil layers. The G11 channel foils, 0.5 mm thick, were glued to the inner surface of the outer coil and have the possibility to slide with respect to the outer surface of the inner coil.

To impart the required geometry, as well as to fill the unavoidable voids between conductors, the coils ends are filled with an injection of charged epoxy resin, by using a dedicated tool. The resin system (type Stycast 2850FT) as well as the thermal cycle have been optimised at CERN [7].

B. Coil size

A critical parameter is the uniformity of the coil size at room temperature after collaring, under the nominal stress of:

- 55 N/mm^2 inner layer
- 50 N/mm^2 outer layer

The coil size was measured by pressing each layer separately, by means of a small press having an active length of 300 mm. By displacing this press, 100% of the coil length was measured. The collaring shims have been defined according to these measurements. Electrical checks have regularly been carried out during the pressing cycle (upper pressure 80 N/mm^2). The geometry of the coils under the above-mentioned nominal stresses was very reproducible. An interesting fact is that the profile of all the coils followed the stiffness of the curing/collaring press, with a systematic peak in the region where the continuity of the press is interrupted (this press is the one used in the past for 10-m long magnets, extended to 15 m).

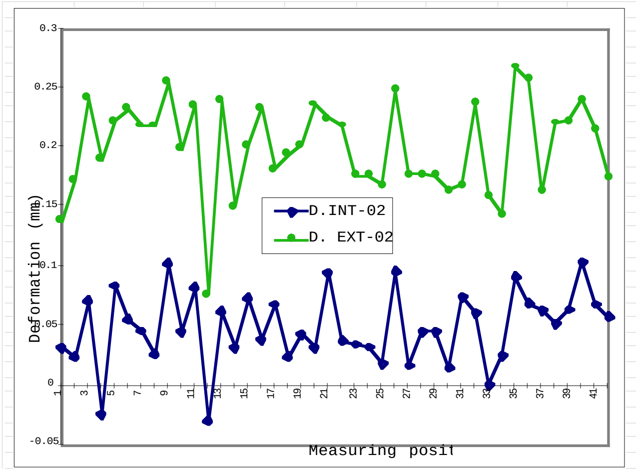

Fig.3. Coil size (pole n.2) as a function of the longitudinal position. The inner layer, lower curve, was measured at an average azimuthal stress of 55 N/mm^2. The outer layer was measured at 50 N/mm^2. The curves represent the average value left/right.

To eliminate this problem a very tight local correction of the shim thickness was carried out, leading to a final precision of the coil size of the order of 100 µm (Fig. 3).

In the coil end regions, special shims were placed in the horizontal plane, between the upper and the lower pole, to account for the change of structural stiffness.

C. Collaring

Preparation to collaring consisted of assembling the poles around a solid collaring mandrel, in placing the ground insulation (six 125 µm thick polyimide foils) and in assembling the collars around the coils. The collars had been pre-assembled in packs 200 mm long.

Collaring was carried out by using the old 970 t/m press which was extended to 15 m. The collaring mandrel was extracted from the coil apertures before pressing and the cold bore tubes were inserted instead. Insertion of the collaring rods (a central rod ø21.95mm and two lateral ones ø14 mm) was carried out in steps, by pressing onto the collars at different transversal positions. Insertion of the rods took place at typical press forces of 450 t/m for the central rod and 600t/m for the lateral rods.

After collaring, the outer profile of the collared coil assembly was measured every 500 mm longitudinally (Fig.5). The deformation of the outer profile of the collars is an indication of the residual state of stress in the coils. By comparing the obtained results with the finite-element calculations [8], the values of stress in the coils are close to the expected ones. The collaring forces and the outer profile of the collars were also in very good agreement with the ones

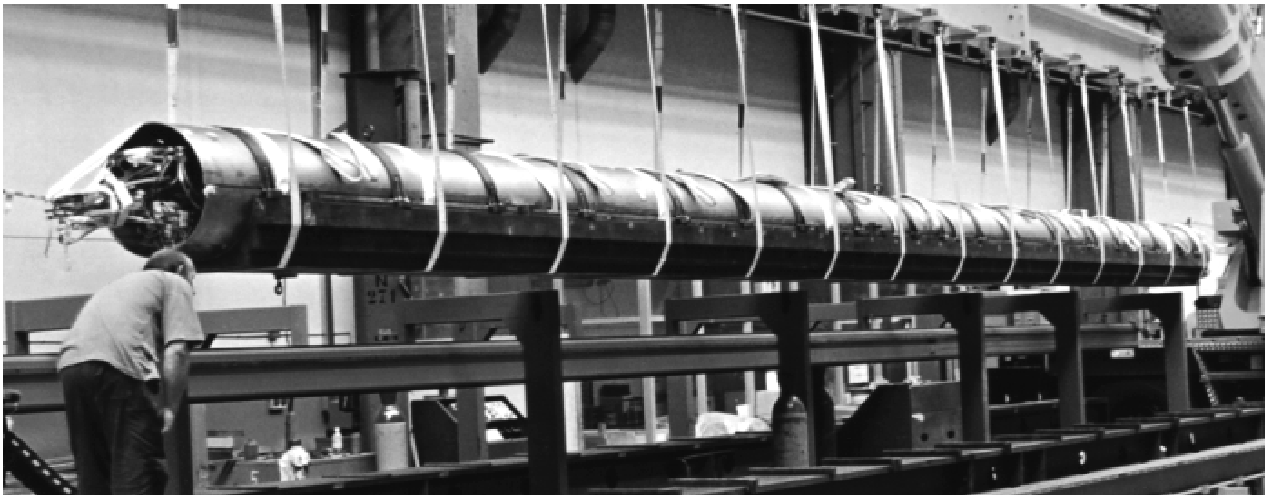

Fig.4. The prototype ready to be displaced onto the welding bench. The cold mass was assembled and aligned straight. Curvature during welding is imparted by shims placed on the welding bench. The metallic belts are still in place (courtesy of Ansaldo).

obtained with a 4-m-long collaring model which was built using the Cu dummy pole. After the usual electrical checks, the collared coils were slowly cooled down to liquid nitrogen temperature. At 77 K, as well as after the collared coils returned to room temperature, the electrical checks were repeated, showing that no electrical degradation had occurred. Repeated geometrical measurements showed that the geometry had practically not changed with the thermal cycle (Fig. 5).

V. Magnet Assembly and Longitudinal Welding

A. Welding models

One of the most critical design and fabrication aspects of the LHC prototypes is the control of the gap size between the two yoke halves after longitudinal welding of the shrinking cylinder. A major difference with respect to the previous 10-m long LHC dipole prototypes fabricated at Ansaldo [9] is that the gap-control-spacers have been suppressed; this requires more attention in controlling the weld shrinkage. Three welding models, about 1 m long, were made with a magnet cross-section identical to the one of the past 10-m long magnets, but without gap-control spacers, to assess the influence of the suppressed elements. Once the yoke laminations and the collars of the new geometry became available, four more models were fabricated to assess the capability to control the gap and to define the developed length of the shrinking cylinder shells. The three last models were also cycled to liquid nitrogen temperature. The thermal cycling showed that no mechanical hysteresis occurred and that once the gap is closed, at a temperature between 100 and 120 K, the possible up/down unbalance in the gap size is practically eliminated thanks to a rotation of the yoke halves. In one of the cooled models, a large unbalance was intentionally introduced which disappeared after having returned to room temperature. The developed length of the half shell that resulted from these tests exactly corresponds to180˚.

B. Collared coils-Yoke-Cylinder assembly

The collared coils were inserted into the yoke without difficulty, despite the small design clearance of few hundredths of a mm. The shrinking cylinder consists of two shells 15 m long, 10 mm thick, made of stainless steel AISI 316LN. The longitudinal chamfer on the shell was precisely machined with a longitudinal straightness better than 0.2 mm. The magnet was assembled straight (Fig.4), and then moved onto the welding bench where shims had been positioned in order to impart a curvature to the assembly. The design central sag for the prototype after welding is ~ 9.7 mm (corresponding to a radius of curvature of 2700 m); considering the expected "spring back" further to welding, the maximum sag on the test bench was set to 15 mm.

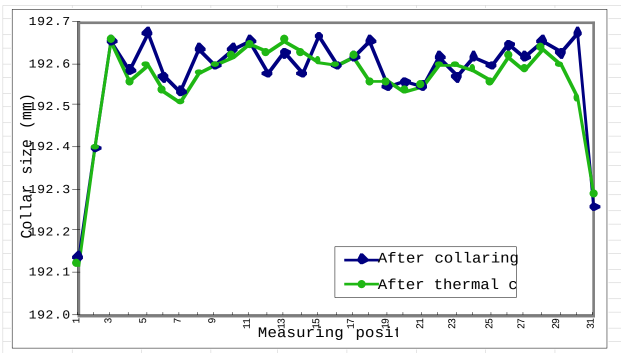

Fig.5. Collar deformation, after collaring, as a function of the longitudinal position. The dimension shown corresponds to the collar size at the vertical axis of the magnet (axis passing through the central collaring rod). The two curves refer to two conditions: after collaring and after a thermal cycle to liquid nitrogen temperature. The values are in good accordance with the finite-element calculations.

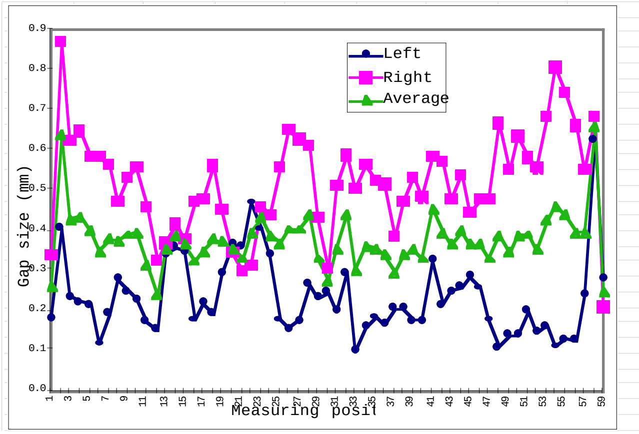

Fig.6. Gap size after welding, as a function of the longitudinal position. The upper and the lower curves show an unbalance up/down. The central curve is the average gap size (average up/down) which shows a very good longitudinal uniformity. The goal for the average gap size was 0.4 mm.

C. Longitudinal Welding

The final alignment up/down of the gap prior to welding was obtained by using 15 m long shims of different thickness, placed between the yoke halves. Metallic belts were tightened to put the two chamfers in contact (Fig. 4). The average overall alignment (unbalance up/down) was ~ 0.1 mm over the whole magnet length. Longitudinal welding of the shells was executed with one manual TIG pass followed by 10 automatic passes. The gap size was constantly monitored by placing probes in between the yoke halves. During welding, probably because of the release of the force exerted by the belts (which had to be taken away just after tack-welding of the cylinder) as well as because of a non-uniform distribution of friction, an up/down unbalance appeared. By properly alternating the weld passes on the two sides, the unbalance was reduced, but still existed at the end of the welding operations (Fig. 6).

However, the obtained average gap (average up/down) resulted close to the objective value (mean value of 0.37 compared to the goal value of 0.4 mm), and showed a good longitudinal distribution. Based on the results of the welding models, it is expected that the up/down unbalance will disappear once the gap gets closed during cool-down. The level of average azimuthal stress in the shrinking cylinder ranges between 200 and 250 N/mm^2, as measured by strain gauges on the cylinder.

VI. Conclusions

Fabrication of the first full-length (15 m) dipole prototype for the LHC is being concluded. The cold mass in its cryostat is scheduled to arrive at CERN by end November 1997. Testing of this magnet will take place on the beginning of year 1998, on the new CERN test bench. The development of this prototype has pointed out the following main aspects:

- The performance of the cables is according to the specifications.
- The technique of winding the coil outer layer on top of the inner layer already cured has been validated.
- Coil winding and curing is well under control.
- The collaring operations on 15 m long coils are mastered.
- The magnet assembly and alignment, including curvature, are well under control.
- A good control of the average yoke gap has been achieved.
- Despite the efforts made, an unbalance up/down of the gap size could not be avoided. However, as proved by welding models this unbalance should disappear at low temperature.

This prototype represents an important step towards the conclusion of the intense R&D phase for the LHC dipole, since for its fabrication full-scale problems had to be tackled and solved. The results of its testing will provide crucial elements in view of the series production of the LHC dipole magnets.

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