

# QUALITY CONTROL TECHNIQUES APPLIED TO THE LARGE SCALE PRODUCTION OF SUPERCONDUCTING DIPOLE MAGNETS FOR LHC

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## Abstract

The LHC accelerator, under construction at CERN, is characterized by the use on a large scale of high field superconducting dipoles: the 27-km ring requires 1232 15-m long dipole magnets designed for a peak field of 9 T. The coils are wound with Rutherford-type cable based on copper-stabilized Nb-Ti superconductors and will be operated at 1.9 K in pressurized superfluid helium.

The challenge that had to be faced has been an efficient, cost-effective and reproducible mass production to very tight tolerances: the field quality must be better than  $10^{-4}$  and the geometry of the cold bore tube and magnet controlled to 0.1 mm over the whole length, any deviation being liable to induce delays and significant cost increase. This paper presents the main methods and tools chosen to face successfully this challenge: some methods were foreseen in the technical specification, others were implemented based on the experience gained in several years of fabrication.

## INTRODUCTION

The LHC accelerator, under construction at CERN, is characterized by the use of high technology superconducting dipole magnets. The 27-km ring requires 1232 15-m long dipole magnets providing a peak field of 9 T. The coils are wound with Rutherford-type cable based on copper-stabilized Nb-Ti superconductors. The magnets will be operated at 1.9 K in super-fluid helium.

At the beginning of June 2006, about 90 % of the dipole cold masses have been delivered to CERN.

Stringent requirements were imposed by the inevitable use of the existing infrastructure, mainly the LEP\* underground tunnel. The limited space available for the magnet system and the cryogenic distribution lines pushed the designers to study unusual solutions, the cleverest one being the two-in-one structure. In this case, the two magnet rings in which the particles circulate in opposite direction are housed in a common mechanical structure called the cold mass assembly (see Fig. 1).

The design of the magnet system aiming at producing stronger field to guide particles beam of higher energy of the order of 7 TeV, the necessity to attain higher field quality in order not to perturb the particles beam and both space and budget limitations ended up with a dipole of rather small aperture of 56-mm diameter. The necessity to

guarantee sufficient mechanical aperture for the particles beam led to specify extremely tight geometric tolerances.

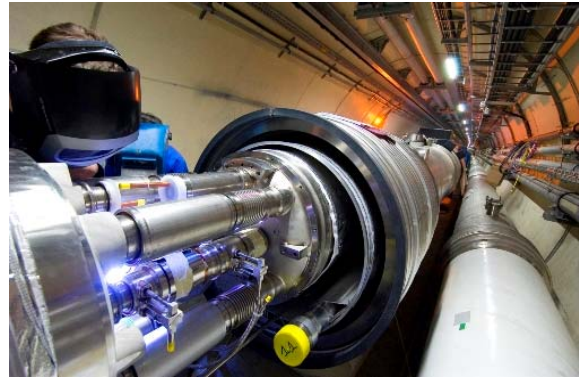


Figure 1: The former LEP tunnel to house the LHC.

## THE CHALLENGE

To assure the production and delivery schedules and on grounds of risk reduction policy, the production of the 1232 dipole magnets needed for LHC was given to 3 manufacturers in 3 different countries. Moreover, to assure an excellent uniformity of the quality of the magnet parts, which is essential for the final quality and performance of the magnet, the procurement of the main components was taken in charge by CERN. Consequently, we ended up with a multitude of contractors, which necessitated the implementation of adequate quality control tools and check points to guarantee the specified requirements.

## THE GEOMETRY

### *The main features*

The magnet is bent to follow the theoretical trajectory of the particles beam. The sagitta of the active part of the cold mass, which has a length of 14.343 m, is 9.14 mm at room temperature. It is obtained by clamping firmly the magnet parts together during the welding of the two half-cylinders so as to induce a hoop-stress of at least 150 MPa. This is necessary to assure the mechanical stability of the coils in all operation conditions.

Stringent tolerances were imposed to the sextupole and combined octupole/decapole spool pieces mounted at the ends of the cold mass to avoid feed-down effects. The position of the end covers and that of the extremity flanges, especially those welded to the end of the cold bore tubes, have to be controlled to within few tenths of millimetre to enable correct alignment and interconnection in the tunnel.

\* The Large Electron Positron (LEP) was the biggest accelerator at CERN. It has been dismantled to provide the necessary space for the LHC machine.

*The measurements tools*

Controlling the cold mass curvature and positioning the critical elements could only be achieved with the guidance of 3D optical measurements. The dimensional measurements are carried out with a laser tracker, the LTD-500<sup>®</sup> of the company Leica Geosystems AG. Special software written in Visual Basic, the DGM [1], used in combination with standard routines and functions of the LTD-500<sup>®</sup> like “Axyz<sup>®</sup>” was developed at CERN to automate the measurements in view of higher reliability and productivity. The software contains modules to perform on-line analysis, i.e. checks and comparison of the measurements results with the specified tolerances. Then, the measurements data are reported in standardized format enabling further treatment and uploading in the CERN database. The reliability of both hardware and software has been excellent.

*The tolerances*

At the beginning of the production, the tolerances were intentionally specified very tight because the details of the machine optics and the requirements for the interconnections were not yet fully clarified. Difficulties were encountered during the pre-series production in order to meet all initial tolerances. However, some properties were better than expected. This left room to relaxation of some tolerances as shown in Table 1.

Table 1: Geometric tolerances in Industry

Parameter	Nominal value	Initial tol., ±	Relaxed tol., ±
Length [mm]	15158	2	2.2
Curvature/Sagitta [mm]	9.14	r 1	h 1.5 v 0.8
End cover position [mm]	0	h/v 0.5	h/v 0.75
End cover angle [mrad]	0	0.4	1
End flange position [mm]	0	r 0.3	r 0.6
End flange angle [mrad]	0	4	5
End tube length [mm]	64	0.3	0.5
Spools pieces [mm]	0	r 0.3	r 0.3

Then, quickly following the pre-series, the geometry results were improved whereas after delivery at CERN and integration in the cryostat, the cold mass geometry was altered because of insufficient intrinsic stability of the cold mass [2]. Attempts to correct the cold mass curvature during the production to fit better the nominal geometry were done but without great success. The key to improve the geometry parameters was in fact the interface of the cold mass with the cryostat, i.e. the cold mass supporting system. Originally, the cold mass was let free in the horizontal plane at the central support whereas finally the cold mass central support was blocked either to the geometry measured in industry or to a statistical adjustment determined for each manufacturer.

Figure 2 shows the position of the end flanges in the horizontal plane after fiducialization at CERN. As of

beginning of 2005, the blocking of the central support has allowed maintaining, after integration in the cryostat, the good positioning of the flange obtained in industry. Although there is a large spread after cryostating, the mean value is perfectly under control, which is important for the beam physics.

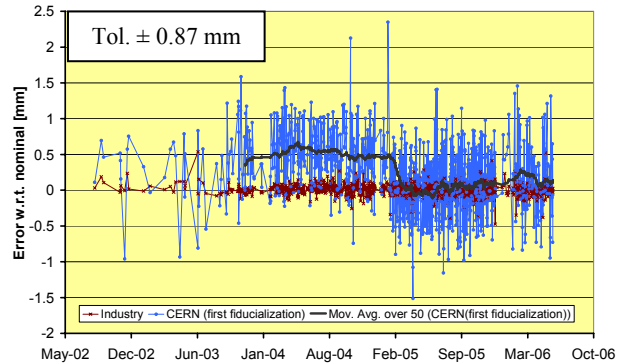


Figure 2: End flanges after fiducialization at CERN.

**THE FIELD QUALITY**

*Regarding the field quality*

The magnetic field in a dipole can be expressed as

$$B_y(x, y) + iB_x(x, y) = 10^{-4} B_1 \sum_{n=1}^{\infty} (b_n + ia_n) \left( \frac{x + iy}{R} \right)^{n-1}$$

where  $(x,y)$  are the transverse coordinates,  $R$  is the reference radius (17 mm for LHC), and  $B_1$  is the dipole field component. The harmonics  $b_3, b_5, b_7 \dots$ , are intrinsic in a coil lay-out that satisfies the up-down and left-right symmetry, i.e. controlled by design, whereas the other harmonic terms result from violation of these symmetries, caused, e.g., by component tolerances or assembly errors. The field harmonics are expressed in units in  $10^{-4}$  with respect to the main field. All field harmonics and the main field are measured at room temperature with a rotating coil of 750 mm length [3] in 20 consecutive positions. Position 1 and 20 cover the ends of the coils, and 2 to 19 the straight part.

These measurements are carried out at the manufacturer’s premises at two different stages of the assembly procedure, after the collaring (collared coil, i.e. the superconducting coils clamped in the collars) and after the welding of the shrinking cylinder (the cold mass, i.e. the collared coil inside the iron yoke and the austenitic stainless steel cylinder). Here we present the results relative to the cold masses. Control limits for field harmonics, the main field and main parameters, as, e.g., the magnetic length, have been established to identify field anomalies during production. For each set of measurements, data are split into average values along the straight part, variation along the straight part, and coil heads. For each subset, the average  $\mu$  and the standard deviation  $\sigma$  of each multipole are evaluated. The control limits are set to  $4\sigma$  since in this way, in the hypothesis of a Gaussian production without any field anomalies, one has only one case out of the control limits over the total

production of 2500 apertures, i.e. one false alarm, on each multipole. We also defined a second range, with a double width of  $8\sigma$ , to point out very strong field anomalies.

### Field quality specifications

The dipole production is steered with respect to beam dynamics requirements [4]. Some of the unwanted harmonics will be compensated by corrector magnets, and the design incorporates budgets for different kind of systematic errors. There are also budgets for random errors. For example, variation in the bending strength, BL, introduces a deviation in the closed orbit trajectory of the beam. This reduces the mechanical aperture available for the circulating beam. Another important source of reducing aperture is the  $\beta$ -beating which is due to perturbation of transversal betatron motion. It is driven by the  $b_2$  harmonic and from feed-down of the  $b_3$  harmonics due to misalignment of magnets in the tunnel. Systematic  $b_3$  errors per sector will be corrected by sextupole correctors but the correctors themselves introduce feed-down errors if misaligned.

### Control of series production

Figure 3 shows the allowed harmonic  $b_3$  as an example [5]. The solid lines are the targets for the systematic value. Firm 1 being recently out of target is partly compensated by firm 2.

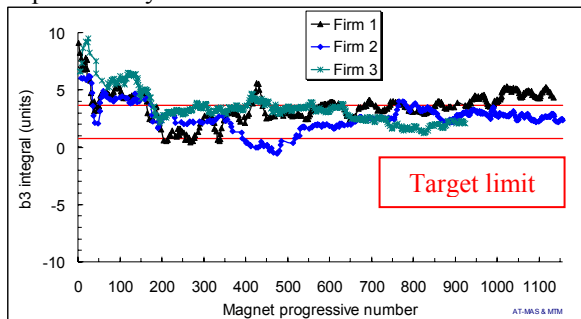


Figure 3:  $b_3$  harmonic at r.t. along the production: moving average for each cold mass assembly.

Figure 4 shows the standard deviation of all harmonics with respect to the field quality targets (solid lines). The harmonic  $b_3$  is globally well inside limit while  $b_5$  is globally slightly higher than the specification (not critical for beam dynamics).

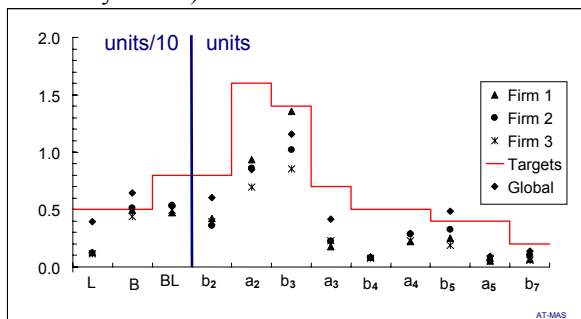


Figure 4: Standard deviation of bending strength and harmonics for 90 % of the production.

The uncertainty of the warm-cold correlation has been added quadratically in order to give the best estimate for cryogenic temperature (1.9 K). All together the situation looks extremely positive.

## CONCLUSIONS

The use of a laser tracker for the 3D measurements and positioning operations turned out to be entirely satisfactory. Although the measuring accuracy of such device depends on the length of the object and on environmental parameters like temperature and air flow, adequate software and redundancy in the measurements allowed attaining a precision of the order of 0.2 mm. This enabled a sufficient knowledge of the cold mass geometry parameters consistent with the machine requirements. Because the contact surface of the cold mass support bases is not sliding smoothly on the cold feet pads as designed, one should rather consider using the very large inertia of the vacuum vessel to block the cold mass.

The equipment for the field quality measurements worked with a good reliability during the series production and the measurement method with rotating coils is sufficiently precise for main field and multipole measurements. The weakest point was the measurement of the main field orientation. Due to the limited strength of the orbit correctors, the main field angle has to be controlled within the tight limits of  $\pm 1$  mrad for each magnet. Since the precise measurement of the field angle in industry was not the goal of the measurement system, the systems operate with a precision only marginally below the requirements.

The different measurements introduced as integral part of the cold mass assembly, magnetic and geometry, have proven to be cost-effective tools to reach our goals.

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