EXPERIENCE WITH LHC MAGNETS FROM PROTOTYPING TO LARGE-SCALE INDUSTRIAL PRODUCTION AND INTEGRATION

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Abstract

The construction of the LHC superconducting magnets is approaching its half way to completion. At the end of 2003, main dipoles cold masses for more than one octant were delivered; meanwhile the winding for the second octant was almost completed. The other large magnets, like the main quadrupoles and the insertion quadrupoles, have entered into series production as well. Providing more than 20 km of superconducting magnets, with the quality required for an accelerator like LHC, is an unprecedented challenge in term of complexity that has required many steps from the construction of 1 meter-long magnets in the laboratory to today's production of more than one 15 meter- long magnet per day in Industry. The work and its organization is made even more complex by the fact that CERN supplies most of the critical components and part of the main tooling to the magnet manufacturers, both for cost reduction and for quality issues. In this paper the critical aspects of the construction will be reviewed and the actual achievements in term of quality and construction time will be compared with the expectations. The main result, the evidence of being able to meet the LHC schedule planned two years ago, as well as the efforts that are still needed to stick to it without loosing in quality will be discussed.

INTRODUCTION

The Large Hadron Collider [1] is designed to accelerate two counter rotating proton beams from injection energy of 0.45 TeV up to a flat top energy of 7 TeV, at which collisions take place for about 10 hours. The main dipole magnets (Main Bends, MBs), fill more than 2/3 of the ring, a 27 km long underground tunnel. The remaining tunnel length is almost all dedicated to beam focusing (Main Quadrupole, MQ) to other beam optics functions (chromaticity control, dispersion suppression, matching sections, etc.) and to the Interaction Regions, IRs. The dipoles must be set to the same field level, or better still, to the same bending strength, BL, to within a few 10^{-4}. The poor performance of one dipole cannot be compensated by better performance of another one: the weakest dipole will eventually determine the energy performance of the whole machine.

In total 1232 main dipoles of which 1104 in the lattice and 128 in the Dispersion Suppression (DS) sections and 392 main quadrupoles (360 in the lattice and 32 in the DS) will be installed.

An artistic sketch of an MB is shown in Fig. 1.

The main magnets are complemented by 86 superconducting quadrupoles used in the matching/DS sections (MQM) and by 26 wide aperture quadrupoles (MQY) that play a fundamental role in the matching sections.

The IR are equipped with 32 single bore, large aperture (70 mm), 5 m-long superconducting quadrupoles MQX and with 20 special dipoles for beam separation. These low beta quadrupoles and the beam separation dipoles are being built by US National laboratories and by KEK-J.

For the LHC main ring more than 7600 superconducting corrector magnets of various types and strength are foreseen. Most are powered in series by octant or in smaller series, except orbit correctors to have the required flexibility. They are integrated inside the cold mass of the large magnets (MB, MQ, MQM, MQY, MQX).

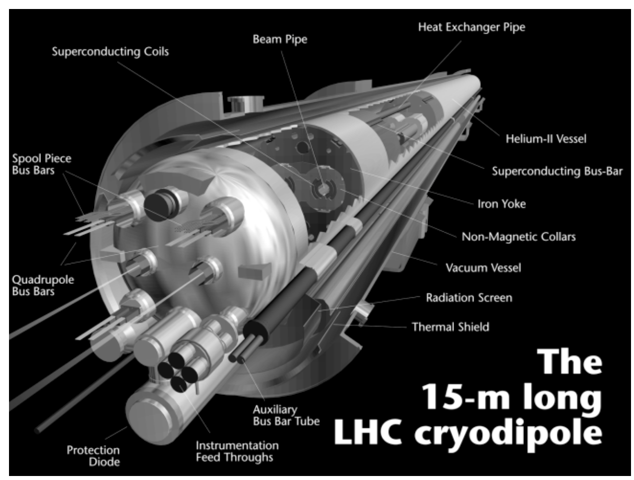

Figure 1: Artistic view of the main dipole in its cryostat.

MAGNET CHARACTERITICS

In this section we'll concentrate on the main dipoles. The other magnets have similar characteristics, see Table I, although the assembly procedures may vary.

The design of the LHC MBs has gone through about 10 years of evolution with three generations of design [2]. All superconducting magnets (except some stand-alone) work in superfluid helium, a fundamental choice done as early as 1989 to allow dipoles to operate beyond 8 T with a sufficient stability margin. Dipoles are designed for a nominal central field of 8.33 T, with possibility to be pushed up to 9 T (ultimate field).

Coil Structure

Coils are wound from two types of NbTi Rutherford cables whose characteristics can be found in [3]. The layout is based on six-conductor blocks arranged in two nested layers. Coils are of the twin type, i.e. unique collar for the two apertures. Collars are obtained by fine blanking according to a shape that results in the desired coil cavity geometry under stress and cold conditions. The choice of stainless steel was introduced relatively late in the Project, after a long period when an aluminium alloy was preferred, and allows a more comfortable margin in the construction and assembly tolerances. This partly compensates for the higher cost of austenitic steel with respect to aluminium alloy.

Table 1: Characteristics of LHC large magnets (7 TeV)

Type-No.	**Coil peak field-Length** (T/m)	**Energy/ Mass** (MJ/kg)	**Current-Temper.** (A/K)
MB-1232	8.57/14.31	6.93/27500	11850/1.9
MQ-392	6.85/3.10	0.79/5000	11870/1.9
MQM-84	6.3/4.8 max	0.62/6000	5390/1.9
MQY-24	6.1/3.4	0.96/4400	3610 /4.5
MQXA-16	8.6/6.37	2.30/9600	7150/1.9
MQXB-16	7.7/5.5	1.36/5700	11950/1.9

Coil Tolerances

Each aperture is composed of two poles, each one formed by two layers. Poles needs to be identical within 100 μm. Indeed a 100 μm variation in the azimuthal coil size corresponds to a variation of about 0.1% of the main field, 3.5 and –0.4 units (10^{-4}) of the sextupole and decapole harmonics, respectively, and to about 12 MPa in azimuthal coil pre-stress. A coil with nominal size and compressive modulus (some 12 MPa at room temperature and 17 MPa at cold) will be submitted to 75 MPa pre-stress. Since the allowed range for coil pre-stress is 60-90 MPa, if the coils differ more than 125 μm from the target they will require a shim thickness different from the nominal size, to the detriment of the field quality. This, together with necessity of top-bottom and left-right symmetry, means that the coils must all be similar, within the quoted figures. The strategy is to avoid as much as possible single coil shim adaptation, and this calls for a strict control of components dimensions and process stability in time (avoiding sorting).

Cold Mass Structure

The collared coil assembly is surrounded by the magnetic circuit contained by a shrinking cylinder, called as Helium vessel in Fig. 1, formed by welding two half-shells made out of 316 LN stainless steel. This provides the necessary rigidity for the whole magnet. The welding forming the shrinking cylinder is critical in order to give the wanted pre-stress and to assure the leak tightness against the superfluid helium. The forces are transmitted by interference among very rigid pieces (collars and yoke). Therefore not only the precision of the single pieces is high but the assembly must also ensure this precision over the 15 m magnet length.

The magnet must be curved, with a sagitta of about 9 mm, corresponding to a radius of curvature of 2812.36 m. This curvature has a tolerance of ± 1 mm, with the exception of the extremities of the magnet where the tolerance is tighter: ±0.3 (systematic) and 0.5 mm r.m.s. in order to keep the corrector magnets centered with respect to the beam tube, to avoid harmonic feed down (detrimental to beam optics).

The overall length of the cold mass (more than 15 m) must be kept within a tolerance of ± 2.2 mm. This figure, which in order to be checked requires a control at ± 5 ºC of the ~28 tonnes cold mass, is very severe and it is actually determined by the rigidity of the bellows in the 400 mm long interconnection zone.

FROM PROTOTYPES TO INDUSTRY

Concerning the main dipoles the project suffered from a change in strategy: at the beginning (1988-1993) due also to constraints caused by decreasing CERN staff in the moment when the LEP commissioning and operation and the LEPII upgrade took place, the R&D and prototyping construction was carried out in Industry.

The first generation of prototypes (at the time 10 m long) ended successfully: the first three dipoles would have been perfectly acceptable for the machine according to the present technical specifications. However the design was changed before they were tested because:

- a few problems encountered on models (actually good but expectations were probably too optimistic);
- increase from 50 to 56 mm of the coil aperture, with consequent chain of changes;
- change of cable width from 17 down to 15 mm; this led to a lower field; increase of magnetic length from 9.2 to 14.3 m, with consequent better filling factor to compensate the lower maximum field;
- change of coil arrangement (from six to five coil blocks per quadrant), and other changes, all triggered by budget restriction.

The necessity to better control the finalization of design and the assembly procedures, suggested to constitute at CERN both a strong shop for short magnet models and a factory (MAF, Magnet Assembly Facility) for full size cold mass assembly of collared coils coming from industry. Companies were kept in the project by means of few orders for collared coils (except the first 15 m long full prototype built by the CERN-INFN collaboration) and new tooling.

This has been a long route, however in this way two goals were reached: a) on the most critical part of the assembly, the collared coils, determining the quench performance and the field quality, the companies kept training, making possible the starting of the industrial production in 2001; b) a better understanding of the cold mass problems (heavily dominated by the increased length and by the curvature control) as well of the procurement strategy.

After a further change of cross section, returning to an improved six coil block layout, and a major change in the 2D mechanics (austenitic steel collars on the place of aluminium ones and change of the collars-yoke interference) a pre-series production of 30 dipoles was assigned to each of the producers at end of 1999. While the plan was to tender for the whole series when 10 complete magnets were fabricated by each vendors, only a few were completed in Spring 2001 when the large tender for the remaining dipoles was launched. It is remarkable that CERN and the companies accepted to sign it at a time when only one Cold Mass Assembler (CMA) was having good results, moreover on a very limited number of dipoles.

Strategy for production and cost containment

The basic idea has been to decouple completely the assembly of the whole magnet cold mass from the procurement of the main components. The most important and most expensive, the superconducting cable, was supposed to be procured by CERN since the very beginning of the project. However at the end almost all important components in the dipole cold mass have been procured by CERN. For some other components, like quench heaters and end spacers, CERN has procured for all pre-series, leaving to the CMA the procurement for the series from the CERN qualified vendors.

To be noticed that in both cases quoted this has generated unexpected problems due to weakening in controls and checks at the procurement site and also due to the difficulty in transferring the experience accumulated in 10 years of R&D: this means that to procure correctly a component, or to make sure it is employed in an adequate way, the initial specification may not be sufficient.

Another part of the strategy for cost containment and for assuring the construction in the requested time frame (5 years of full production) was to keep the three companies involved as from 1995 in business.

Another pillar of this strategy was procurements of the main tooling by CERN, for the following reasons:

- some of the tooling had to be designed by CERN since specification and construction were much interlinked with magnet assembly conception;
- part of the tooling had a long lead time in procuring: waiting the contract adjudications would have caused two years delay on procurement.

However, this means that CERN is supplier of its suppliers and is therefore in an uncomfortable situation.

PROCUREMENT OF COMPONENTS

Today CERN provides 16 finished components to the dipoles CMAs, through 31 industrial contracts or Collaboration Agreements. Most of these contracts serve many types of magnets but some are specific to one cold mass type. In total the number of important CERN contracts to supply components to CMAs is about 50. Some contracts are for raw material (like NbTi ingots, austenitic steel for collars and nested laminations, low carbon steel for yoke lamination) that is needed to feed contracts for finished components; in turn the latters need to serve the CMA contracts in due time.

In two cases, after careful evaluation, we found best to organize fabrication lines at CERN: the Cold Bore Tube insulation and the Heat Exchanger Tube [4]. Both are running very well, demonstrating that for special items big laboratories might be more efficient than industry. Here we will examine a few critical components.

Superconductors

The 400 tonnes of very high quality NbTi (about 40% of the world production for 4 years) needed for the LHC have been fully procured; NbTi is embedded as 6-7 micron filaments in a copper matrix to form the 1200 tonnes of superconducting cable. Today we are at than 65% of production, and we can draw some conclusions:

- the jump from successful prototypes to large production is always very difficult, since quantity by itself generates a new regime, far more complex, that amplifies immediately any latent weak point, not perceived in the prototyping phase;
- the SPC (Statistical Process Control) embedded in the 8 contracts is extremely useful for the company taking it seriously since the very beginning;
- problems are solved by detailed analysis carried out by knowledgeable people, dedicating time and effort without prejudice and by looking first at simple matters.

A good example of the last point is that the most critical issue was the repeated stop in production due to a very high number of wire breakages during cold drawing. After many investigations pointing toward a non-perfect quality of the CERN supplied components (the NbTi ingots) it turned out that metallic inclusions and chips formed all along the whole chain, i.e. cleaning!, were the most important factors causing these breakages.

The delivery of cable is not anymore critical, since autumn 2001. From the point of view of the technical characteristics the superconducting cable is may be the most striking success of the whole project: many parameters of the magnets are not critical because the superconductor meets the specs and it shows a remarkable homogeneity among all seven cable vendors (and four cabling centers). As an example we take the inter-strand resistance, a parameter that controls the induced currents during the ramp up of the magnets. For the LHC, CERN has developed a relatively simple and inexpensive method based on coating of the virgin strands with 0.5 ± 0.1 μm thick Sn-Ag(4%) layer and on a controlled oxidation of the finished cable by means of a thermal treatment in air for few hours at around 200 °C. A thorough work at CERN in strict conjunction with industry allowed to identify the key factors controlling this parameter: the thickness of one of the three different layers of inter-metallic formed at the interface wire-coating. The actions that allowed to transform a laboratory technique in a practical method for production was to calibrate a relatively simple couloscope for measuring the coat thickness versus a precise technique done at CERN (atomic absorption); then for each wire length the coating thickness of few samples are measured by the company;

finally CERN in a very short time, according to a model that is continuously improved with experience, computes and communicates the parameters of the thermal treatment to be applied.
As it can be seen in the plot of conductivity of Fig. 2, the results are very good. The scatter may appear wide but we meet well our actual targets: 10 < Sc < 100 kS. Only the upper limit is actually a "hard" one, determined by field quality at low energy and cable production can be held if it is seriously passed. It is noticeable that corrective actions taken after initial production (drift to 100 kS) have been effective and from then on production stays constant.

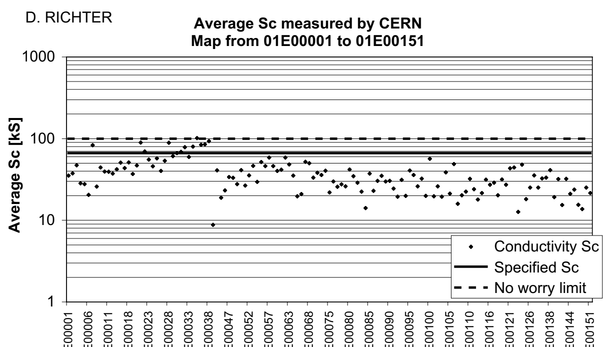

Figure 2: Inter-strand conductivity (Sc) of the production of inner cable for one octant of one manufacturer.

The scatter in Sc is well acceptable magnet-to-magnet: however if we would mix cables of 10 to 100 kS in the same magnet the non-symmetry of the eddy current pattern would generate unacceptable non-allowed harmonics during ramp. So cables are reacted in a batch of four, put in the same box and kept always together, such as to make sure that a batch serves a full magnet. In case of coil impairing (happened so far on few percent of the coils wound so far) we have a scheme to sort the most similar cable in terms of inter-strand resistance (and other criteria, like dimensions) to mitigate the generation of non-allowed harmonics. All these actions necessitate a strong and efficient database to manage communications, approvals, measurements (with different levels of time priority) data exchange, and decision of cable assignment to dipoles. The results is that the effects on field quality of the cable are well inside the assigned budget and that almost all rules of non-mixing have been released.

Punching

As said collars and yoke lamination are obtained by fine blanking, a technology mastered only by a few companies in the world (4-5 in all Europe) that allows fast production on thick sheets with accuracy of 10-50 μm. Here it is worth to underline, as typical example, the action taken on a relatively simple component: the small iron insert with triangular shape that is above the collars in between the two apertures (see Fig. 1). It has a rather important function in the assembly and the 3000 × 2 pieces in each magnets need to be careful aligned. Difficulties of assembly put some doubts on the measurements carried out by the supplier (see left part of the graph of Fig. 3). After careful review of the procedures of measurements we had finally more realistic values, see the central part of the graph. Having secured the measurements, a correction on the tooling was agreed with the company, changing the targets to better fit the need of fast and safe magnet assembly, see right part of the plot of Fig. 3. The extreme accuracy of the measurements, 5 μm, and the reinforced follow up by CERN has positively influenced the attitude of the vendor, resulting in an visible improvement of the achieved tolerances. Again this can be considered an example of problems that appears only in large production and it shows the necessity to integrate the components procurements inside the cold mass process.

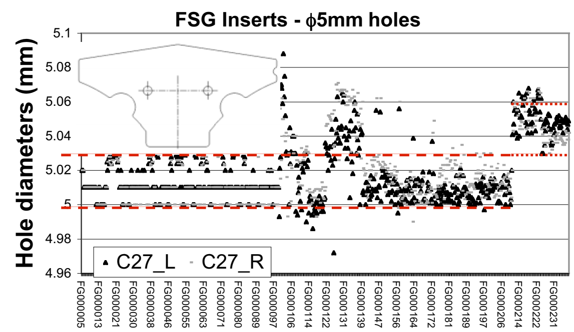

Figure 3: Size of iron insert hole (picture in the graph) vs batch number. Dashed lines represents the allowed bands (old and new).

STATUS OF THE CONSTRUCTION

Coil Size and Shims

The coil size is very good in term of uniformity along the length: after careful intervention at the beginning of the project this parameter is now well within few tens of μm. However the variation of the average size of the coils when analysed in a large production is some 50% larger than the 100 μm target discussed earlier. This might be due to pile up of tolerance of components. However in one company the coil size, after some effort and initial drift and jumps, is within target as shown in Fig. 4. This effect, not clearly identifiable on a set of a few coils, is therefore suspected to be connected most probably to non fully controlled conditions of the curing, a critical process (implying complex tooling, careful assembly, selection of optimum cycle subject to subtle changes, etc.) when run 24 h/day and 6-7 days/week. An effort aimed to improve throughout more recording and control is going on, as well a campaign of cross calibration of the many curing moulds in all companies with instrumented dummy coils.

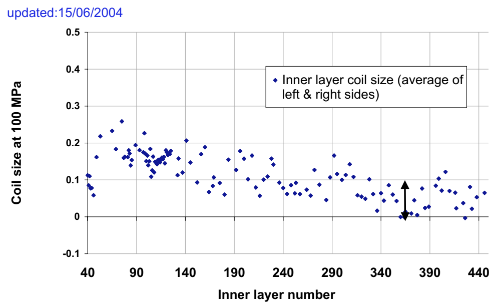

Figure 4: Coils size in mm for one CMA. Arrow indicates the size of the target in uniformity.

Steering Toward Beam Dynamic Targets

Magnetic Measurements are carried out during construction on all LHC magnets at two stages: collared coils and then finished cold mass (or after yoking for quadrupoles). Magnetic measurements are important for controlling construction and singling out manufacturing defects, through a statistical analysis of harmonics followed by an evaluation of the most probable mistakes behind the signals. So far thirteen collared coils were held and eventually de-collared. On eleven we did find the fabrication mistake (of various nature) in the suspected zone. In two recent cases the coils were found more undulated than normal but no precise defect was found.

Magnetic Measurements are necessary also for steering the bending strength and the harmonic content inside the beam dynamic targets. There is an average time delay for a collared coil measured warm in industry and cold measurements at CERN of about 10 months: therefore any change must be determined by warm measurements and corroborated by solid warm-cold correlation. In Fig. 5 the behaviour of the sextupole component of the main dipoles is shown versus the collared coils number: the three families generated by two interventions on the coil cross section (first a change of copper wedges shape after 35 magnets, then an insertion of a midplane shim after 160 magnets, ~1octant) are clearly visible. The result is such that presently the main harmonics, are within target and that the commissioning can count on a solid knowledge of the dipole harmonics.

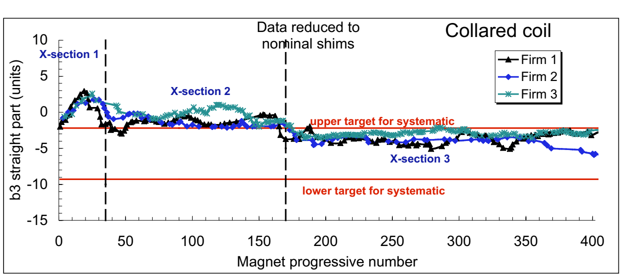

Figure 5: Sextupole components of the main dipoles (collared coils) as measured in industry.

SCHEDULE AND CONCLUSIONS

Today we are receiving between 30 to 35 dipoles per months, which is within the target value. However this exceptional good results is obtained by having a company producing ahead of schedule, one in slight delay and one in strong delay. So all effort in the coming months will be devoted in raising the production in all three company to the desired level (reaching the ceiling of 40 dipole/month) and to examine if the situation requires some reallocation of the magnet share. However the constraints given by certain components may play a crucial role in these decisions. In Fig. 6 the continuous line is the delivery forecast in the last revision of the magnet schedule (May 2003); it is superimposed with the actual delivery, points. This forecast shows today to have been based on a solid ground, so we can expect to have the last dipole delivered by September 2006, as planned. The other magnets are not on the critical path, even if a further delay of the MQ delivery might be critical.

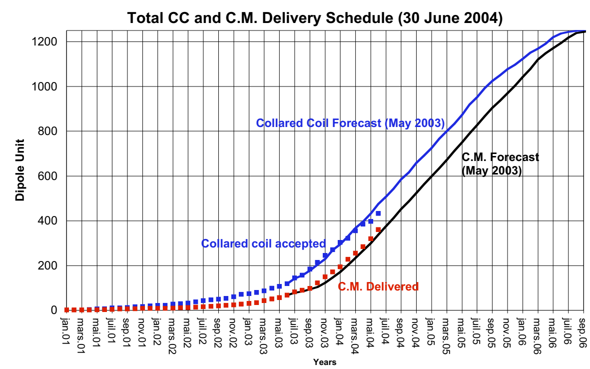

Figure 6: Collared Coils acceptance and Cold Mass delivery for the main dipoles: Continuous lines represent the planning frozen in May 2003 (which has 3 months delays with respect to contracts of March 2002). Markers represent actual achievement.

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