THE LHC SUPERCONDUCTING MAGNETS

L. Rossi, Accelerator Technology Division, CERN, Geneva, Switzerland

Abstract

The Large Hadron Collider (LHC) is under construction at CERN. Most of its 27 km underground tunnel will be filled with superconducting magnets, mainly 15 m long dipoles and 3 m long quadrupoles. The 1232 main dipole and 392 main quadrupole magnets, are complemented by a number of insertion quadrupole magnets: including 86 MQM (matching), 26 MQY (wide aperture) and 32 low-beta quadrupoles (the latter built by KEK and Fermilab). The about 6000 superconducting corrector magnets, many of them individually powered, are also very critical for the functioning of the accelerator. Using copper stabilized NbTi Rutherford cables or single strands, these superconducting magnets will operate in superfluid helium at 1.9 K. The paper reviews the main characteristics of these magnets and addresses the critical points of the design with respect to their use in such a complicated accelerator like LHC. Then the status of the production of the superconducting cable and of the magnets is given, with particular emphasis given to the QA/QC procedures taken to ensure the industrial production according to the tight requirements, and the results on the first 30 main dipoles is presented. Finally, the plan put in place to meet the LHC schedule is 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 ong 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. This means that the 27 km tunnel, made available by the decommissioning of LEP in 2001, will be filled with about 19 km of cryodipoles and 2.5 km of short straight sections (SSS) that accommodate main sextupoles and corrector magnets in the same cold mass of the MQ. The dipoles are optical elements of the machine and they 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 otherwise the weakest dipole will eventually determine the energy performance of the whole machine.

In total 1232 main dipoles (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. The MB cross section 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 interaction regions (IR) are equipped with 32 single bore, large aperture (70 mm), 5 m-long superconducting quadrupoles and with 20 special dipoles for beam separation. The low beta quadrupoles and the beam separation dipoles are being built by USA National laboratories and by KEK-J, and production is proceeding very satisfactorily. However they will not be discussed in this paper.

For the LHC more than 6000 superconducting corrector magnets are foreseen. All are powered in series by octant or in smaller series, with exception of the orbit correctors, to have the maximum flexibility. They also are a considerable challenge in the Project.

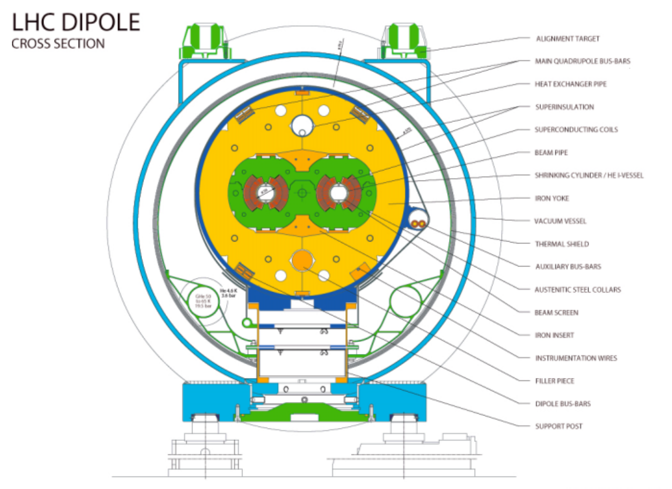

Fig. 1. Cross section of the LHC Main Dipole in its cryostat.

MAGNET DESIGN

Main Dipoles

The design of the LHC MBs has gone through about 10 years of evolution with three generations of design [2] [3]. All main magnets work in superfluid helium (a fundamental choice done as early as 1989 to allow to go beyond 8 T with a sufficient stability margin). The magnets are designed for a nominal operation current of about 11600 A for a central field of 8.33 T, with possibility to reach 9 T (ultimate field). The basic design characteristics of the present third and final generation are:

1) Coil Layout

Coils are wound from NbTi Rutherford cables whose characteristics can be found in [4]. The layout is based on six-conductor blocks arranged in two nested layers. The six-block arrangement is more stable and leaves more room for minor optimizations.

2) Collars

They are of the twin type, i.e. unique collar for the two apertures. They are obtained by fine blanking according to a shape that results in the desired coil cavity geometry under stress and cold conditions. For this reason the collars are slightly elliptical (ε = 0.1 mm) when punched. The choice of stainless steel, introduced relatively late in the Project after a long period when an aluminum alloy was preferred, is not strictly necessary to reach the design field but allows a more comfortable margin in the construction and assembly tolerances. This partly compensates for the higher cost of austenitic steel with respect to aluminum alloy. Also, thanks to its higher rigidity, the use of austenitic steel helps to limit conductor movements, an important issue in magnets where field accuracy is required at 1 cm from the conductor. The severe tolerance on collars (±25 micron) are respected in production with a reasonable margin, although we have to check carefully that jumps due to tool sharpering or replacement are controlled.

3) Coils Characteristics

The coils are composed of poles of two layers each. The need to avoid sorting that would certainly slow the production, or make it more complicated, requires that each pole, and even each layer, 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 main harmonics, sextupole and decapole 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 reason 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 single coil shim adaptation for reasons of time and cost and to control components dimensions and process characteristics vs. time.

4) Cold Mass Assembly

The collared coil assembly is surrounded by the magnetic circuit contained by a shrinking cylinder, see 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 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.

It is of some interest to note that near the magnet ends, for 370 mm, the laminations are composed of an outer shell of low carbon steel, like the magnet straight part, and with an inner shell, 20 mm thick, of special non magnetic stainless steel whose mechanical properties, namely the thermal contraction, have been selected in order to match exactly that of the iron. These nested laminations, are designed to lower the peak field on the coil end (always a quench risk region) while preserving the maximum magnetic length and improving the quadrupole due to aperture coupling at the end.

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.)

Main Quadrupoles

In order to save money and complexity over the whole project, the coil is not graded, and the same cable, identical to the one used for the outer layer of the MBs, is employed to wind both layers of the quadrupoles. This means that the magnetic design is not fully optimized but allows the use of real double pancake techniques, avoiding the splice between layers in the high field region. Nominal gradient is 223 T/m, and 241 T/m at ultimate machine performance (9 T dipole field) when the peak field in the coils reaches 7.5 T. It is worth noticing that although the peak field is somehow reduced in the MQs with respect to the MBs, the field quality is not. Due to a decision to eliminate the dodecapole (first allowed harmonic in quadrupoles) corrector magnets in the machine, the field quality of all quadrupoles must be excellent.

Each coil aperture is independently collared in a four-fold symmetric vertical press, with strong non-magnetic austenitic steel single collars, 27 mm thick. The two apertures are then assembled in a laminated yoke with a central iron arm that decouples the two apertures. Each coil-collar assembly is not supported by the yoke (self supporting collars), that is coupled to the coils only by 3.5 m long centering and antitorsion keys. As it is well known for quadrupoles the alignment is a critical issue. It is obtained by fitting with dowels the yoke into a very precise (better than 100 μm straightness) 5.3 m long inertia tube. The same inertia tube is used also to ensure the proper alignment for other magnets, like sextupoles, octupoles and corrector magnets, forming the so called straight sections. Keeping the tolerances on this assembly will be one of the major challenges in the MQ construction.

A detailed review of the MQ design together with the results on the prototyping phase is reported in, [6]. The MQ is a collaboration among CERN and CEA-Saclay who took care of the design, prototyping and is involved in the follow-up.

Insertion Magnets

For dispersion suppression a certain number of standard MQ, will be inserted in special cold masses, and special quadrupoles, MQM, are employed. MQM has been specially designed to provide almost the same gradient, in the same aperture as the one of the MQ, with 5 kA only. Since each of them, and each aperture, is independently powered, high current would have implied too large power dissipation at 1.9 K. In addition they come in a variety of lengths, the longest being L_m =4.8 m. They have self-supporting collars and the yoke is enclosed by a shrinking cylinder to provide rigidity and a rather low pre-stress.

The MQY, whose design stems out from the first LHC design for an IR quadrupoles, has the difficult task to accommodate larger bore quadrupole (70 mm) while keeping the inter-beam distance of 194.3 mm. The necessity of independent powering and single cryogenic feed for each of them has been satisfied with a design that requires special grading of the cables and maximization of the overall current density (fully keystoned cable). Because of the advanced design they can deliver a nominal G = 160 T/m at about 3.6 kA at 4.5 K, such making possible individual cooling circuit.

A cross section of the MQY [7]. cold mass is shown in Fig.2.

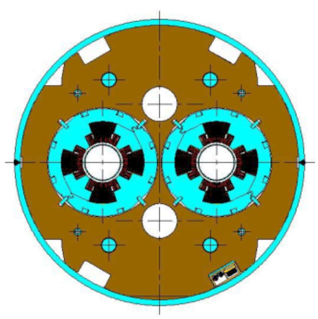

Fig. 2. Cross section of a MQY, with its very thin iron among the apertures

Correctors Magnets

Here the variety is such that a detailed description is left to a specialized paper.[8]. As spool pieces on all the main dipoles we have sextupole correctors (one per channel, electrically independent to allow different current) and octupole and decapole correctors on half of the dipoles, only. Most of the approximately 1000 orbit correctors, are put in the same assembly of the main sextupoles and mounted in the inertia tube of the MQ. The same accommodation has been found for the main octupoles and the tuning quadrupoles, all placed in the SSS together with MQ.

For most of these magnets the special counter winding technique has been applied, with formation of small cable in situ by joining a number of standard strands with wet winding technique, to have a relatively high current at low cost.

Among them, particularly challenging is the long tuning quadrupole, MQTL, that have to operate at 130 T/m, has fully impregnated coils, hot shrink fitted with a cyilinder, and whose coil length is almost 1.5 m.

PROCUREMENTS POLICY AND PRODUCTION STATUS

Main Dipoles and Main Quadrupoles

Three companies, involved since the beginning in the R&D, the French consortium Alstom MSA – Jeumont Industries, Ansaldo Superconduttori (Italy) and Babcok Noell Nuclear (Germany), were each assigned a pre-series contract for dipole cold masses (3×30 dipoles) in autumn 1999 and the final contract (series) for further 3×386 dipoles in spring 2002, for a total contract value exceeding M€ 300.

For the MQs the strategy was different. Given the size, full-length prototyping was developed in the laboratory (CEA-CERN). Then the tender among all European magnet manufacturers for the total quantity of 400 MQ was assigned in 1999 to Accel (Germany).

CERN Supplied Components

As part of a cost saving strategy and in order to keep under control the characteristics of the magnet components having some impact on the final quality and on the schedule, all main components are supplied by CERN to the magnet manufacturers.

This strategy implies that CERN becomes a supplier of its suppliers with an intricate share of responsibility that makes CERN fully responsible for the magnet performance, except in case of negligence or clear fault of the dipole manufacturer. This requires a complex strategy of component procurement and storage. Logistics is certainly one major challenge in this magnet production, together with handling of traceability and non-conformity, all done through an “ad hoc” system called MTF and suitable database.

CERN Supplied Large Tooling

Most of the large tooling, such as the machine for coil measuring and the large presses used for coil collaring and for cold mass welding were specified and procured directly by CERN. In particular the construction and the commissioning of the welding presses were very complicated, These presses have to assure the delivery of a compressive force, to align laminations and to stress the skin, while maintaining the alignment of the 15 m long cold mass according to a shape that, once the shells are welded, should ensure the right curvature. They are equipped with automatic synchronous (both sides) welding equipment, capable of carrying out the welds of the 10 mm thick 316 LN half-shells in a single working shift. The weld must guarantee good quality and a regular pre-stress of about 150 ± 30 MPa and, of course, be leak tight to about 10^{-11}mbar l s^{-1}. The root pass is welded by STT, a rather new process with speed of 70 mm/minute, that has the main advantage of being able to tolerate gap variation of almost ± 1 mm. The equipment for SST and MIG is the same, with an obvious advantage (MIG is a necessary choice for the filling passes.

Finally, as part of the large tooling it is worth mentioning among others the Laser Tracker that is fundamental to measure the curvature, planarity, twist, and inter-aperture distance of the magnets, all along the 15 m long narrow Cold Bore Tube (CBT), with the requested 0.1 mm precision. It is also essential to measure the position (and actually to facilitate in the positioning during their assembly), of the all "3-D" components, i.e. at the magnet extremities. As previously said there are elements that need to be positioned and welded at ± 0.3 mm distance from the ideal line that is defined by the center of the CBT. Although difficult to operate in an industrial environment that looks for quality but also time schedule, the Laser Tracker is proving to be essential, without which the required geometry and alignment of these magnets cannot be guaranteed.

For MB the companies have almost all tooling installed and qualified and they have 60-70% of the personnel required for full rate production, about 35 MB/months in total, to be reached in June 2004. One year of delay has been accumulated in the pre-series phase, and integrated in the main contract signature. To date all companies have almost finished the pre-series magnets and are already winding and collaring for the series. The main problem we are currently working on is the quality of the welding, since repair can be accepted for only a very limited number of magnets, in order to avoid cost and delays. Furthermore the non perfect operation of the welding is probably one of the sources of the too large variability of the magnet curvature: an attempt to cure it with a re-shaping did not give good results and the baseline to obtain good shape directly from the press is pursued. The contract calls for a termination in summer 2006 with very little margin over the installation schedule and today we have 2-3 months of delay.

For the MQ all the tooling is ready and personnel has been hired and trained. Some six months delays has been built up due to longer time to prepare the new workshop, to revamp the CEA tooling, to install and qualify properly the new tooling and to start production of some critical element (like end spacers). Then a major delay in the delivery of a CERN component, namely the MSCB magnet that is needed to complete all MQ cold masses, has impeded the ramp of the production as foreseen, although the company continued to advance in the bare MQ (i.e. up to yoking) productions. However the problem has now been solved, and production is foreseen to be completed well in 2005.

Insertion Magnets

For these magnets the design and then the tendering was finished somehow later than the main magnets. In 2000-2001 all contract were placed (Tesla engineering, GB, for MQM and Accel, D, for MQY) with a strategy that is more oriented to a turn-key product of the bare magnet (i.e. until yoke) with cables, insulation, shells and few other components supplied by CERN. Then the bare magnets will be completed as cold masses at CERN in the factory that was set up for dipole prototyping.

For the MQM the first two magnet prototypes have been delivered by Industry (and very successfully tested). The manufacturer has finished installing all necessary tooling for series production and to hire and train almost all the staff. As soon as the cable production becomes continuous, the company can increase its production to the rate of 4 MQM/month, that will allow the work to finish in 2005.

The situation of the MQY is different. Here the limited number and the fact that they are built in the same factory as the MQ, allow some synergy and movement of personnel among the projects according to needs and schedule requirements. The first prototype is expected at CERN by Summer 2003 and the whole production to be finished by Spring 2006.

Corrector Magnets

Given the large number of contracts, the production status varies very much. Some contracts, such as MCS, the sextupole spool pieces for the dipoles run very well, while others like the decapole-dodecapole spool piece was consistently delayed, although the need of this magnet on 50% of the dipoles only has reduced the impact on dipole production.

The critical one for the main magnets is the MSCB that is slowing down the production of MQ, as previously noted, but other correctors magnets, such as the tuning quadrupoles MQT are near to enter into the critical path.

However now all companies are in production and strategies to catch up (or to avoid further) delays are under discussion.

Production Steering: Magnetic Field

Magnetic field measurements have been introduced in all companies. Measurements are done both after coil collaring and after Cold Mass assembly, at room temperature and therefore reduced current, or as single modules in case of correctors. For corrector magnets, measurements are required at 4.2 K in the companies.

Through these measurements done on collared coils, and thanks to the fact that there is a very good correlation between warm and cold measurements, we can keep under controls the harmonics. Today for the dipoles, the delay between winding and collared measurements is less than 2 months, while the elapsed time from winding to cold test results at CERN is typically 8-10 months. Just recently two further corrective actions for MBs have been decided: i) A change in magnetic length, making it shorter in one company and longer in the other two, to compensate a difference in field strength ii) An increase of the mid-plane gap of about 100 microns, to lower the main harmonics (b_3, b_5 and b_7) by suitable amounts.

It is worth emphasising that magnetic measurements are a mean to intercept minor or serious assembly errors, as already happened two times [9].

PRE-SERIES DIPOLE RESULTS AND DELIVERY

Quench results are very encouraging. The dipole magnets, that were plagued for long time in the R&D phase by long training, are now well qualified for nominal operation and very few have difficulties reaching the ultimate field (9 T). Especially the memory (second thermal cycle) is excellent as shown by the graph of Fig. 3. The weak point of the cold test is the electrical robustness: so far we had approximately 10% of the pre-series magnets that had electrical non-conformities of various types, although only two fatal. Still this is certainly a point that calls for improvement of the cleaning and better QA in the manufacturers premises, since the test procedure foreseen by the QA plan is already as severe as possible.

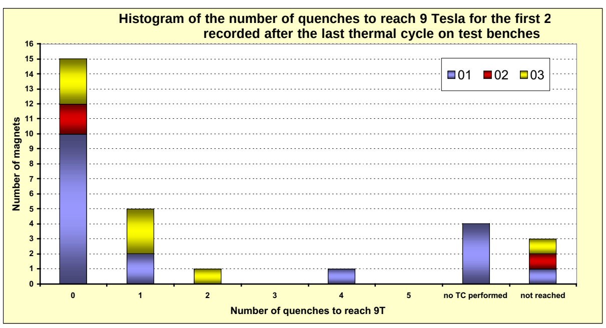

Fig. 3 Number of quench for each of the 29 dipoles tested so far, after first thermal cycles to reach ultimate field of 9 T.

As for delivery, the dipoles provide the 'clock' to the entire project, so their schedule is very critical. The end of all three contracts is foreseen today by June 2006. The actual situation is depicted in Fig. 4, where both the pre-series and series contracts (the sum of the three manufacturers), is compared with actual delivery. To day we are missing some 60 cold masses to be perfectly on time, i.e. approximately 2 months when the foreseen maximum rate of 30-35 CM/months will be attained, in second half of 2004. This is the critical point, indeed: if the extrapolation from the 8 CM/month we have got in March-April (a rate that suffers by the necessary intervention on the welding press) to a number which is four times is correct. All indications coming from the companies are positive, in all single area the stated rate has been actually obtained, although not contemporarily, except in the area of welding repair, that have to be near zero. In Fig. 4 the rate of collared coils (60% of the production time and more delicate than CM assembly, in principle), that shows good progress. Even better is pole production that recently has attained the very comfortable rate of 15 equivalent dipoles. Finally very encouraging is the production of cable for main dipoles and quadrupoles, including cabling, whose initial delays have been so much spoken about. Actually today we have produced already the largest quantity of Sc cable for a single project and have delivered one octant to dipole manufacturers. Thanks to the effort of the CERN team and the commitments of the companies, we have today at CERN more than one octant as strategic stock.

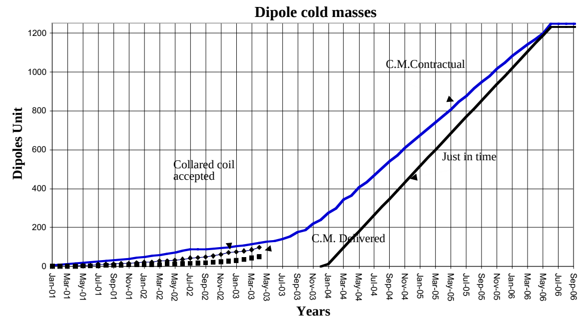

Fig. 4 Delivery of main dipoles (CM, squares), of Collared coils (CC, diamond), contract profiles and just-on-time curves

ACKNOWLEDGEMENT

The author is indebted to many colleagues of the CERN AT division and in particular to: A. Ijspeert, P. Lienard, R. Ostoijc, P. Pugnat, D. Richter.

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