



SUPERCONDUCTING CABLE AND MAGNETS FOR THE LARGE HADRON COLLIDER

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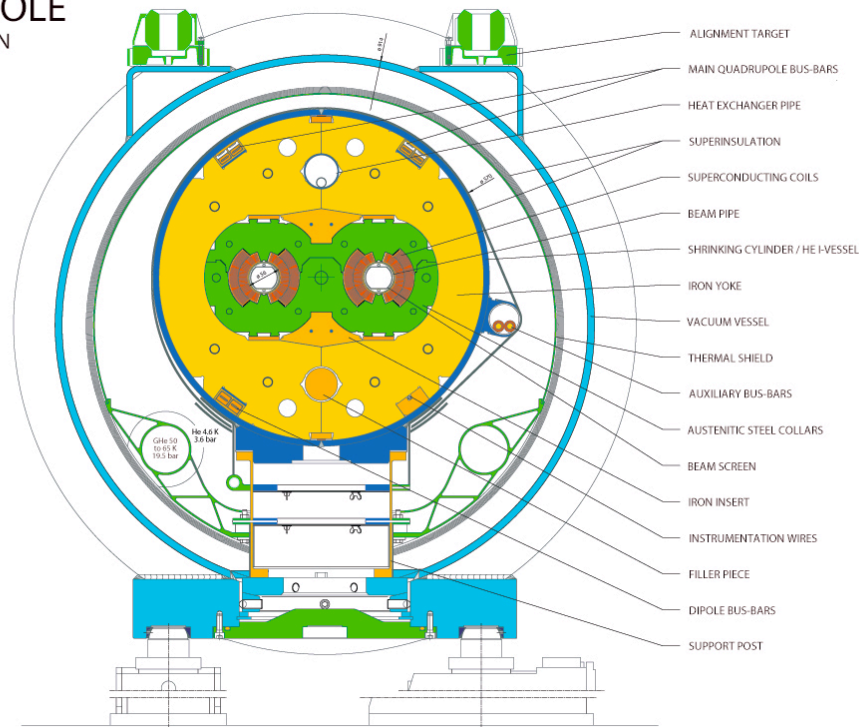
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Abstract. The Large Hadron Collider (LHC) is a high energy, high luminosity particle accelerator under construction at CERN and it will be the largest application of superconductivity. Most of the existing 27 km underground tunnel will be filled with superconducting magnets, mainly 15 m long dipoles and 3 m long quadrupoles. These 1232 dipole and 400 quadrupole magnets as well as many other magnets, are wound with copper stabilized NbTi Rutherford cables and will be operated at 1.9 K by means of pressurized superfluid helium. The operating dipole field is 8.33 T; however the whole system is designed for possible operation up to 9 T. The coils are powered at about 12 kA and about 12 GJ of magnetic energy will be stored in superconducting devices. After a brief review of the main characteristics of the superconductors and of the magnets, the special measures taken to fulfill the mass production with the necessary accuracy are presented. The results on one third of the superconducting cable production and on the first fifty magnets are reported and discussed.

1. Introduction

The LHC [1], is a circular accelerator designed to accelerate two counter-rotating beams of protons from injection energy of 0.54 TeV up to a flat top energy of 7 TeV, at which time the ring is switched from the acceleration mode to the collision mode. The main component of the collider, and by far the most complex and expensive, is the magnetic system which is based on superconducting magnets of various sizes and field strengths. The 1232 main dipole magnets, 15 m long and generating 8.33 T at 1.9 K, are the principal magnetic components and fill 2/3 of the 27 km circumference underground ring [2]. Figure 1 shows the cross section of the dipoles and its main components. Many other superconducting magnets such as the main quadrupoles, insertion quadrupoles, sextupoles, octupoles and a variety of superconducting correctors [3] are needed in the machine. A total of about 8000 superconducting magnets will be installed in the LHC tunnel. All these magnets make use of highly sophisticated, fine filament NbTi superconductor, arranged in Rutherford cable to allow high current with very high packing factor. For the entire LHC machine some 1200 tons of NbTi/Cu conductor are employed and eight companies are engaged in the production of the cable [4]. CERN has worked very closely with each of the cable vendors to ensure the strict uniformity of production that is essential to meet the tight specifications required by the LHC magnets.

LHC DIPOLE CROSS SECTION



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Figure 1 Cross section of straight part of the main dipoles in its cryostat.

The magnets have been designed to operate at about 86% of the critical current on the load line and are slowly ramped from 0.54 T to 8.33 T, making the magnetization of the filaments and the coupling effects in the cable critical to the performance. Furthermore, as the magnets are elements of the optical lattice, the field quality is very demanding and the bending strength of all magnets must be the same in within a few parts in 10^{-4} . This means that poor performance of a dipole cannot be compensated by better performance of another one: the weakest dipole will eventually determine the energy performance of the whole machine and poor field quality of a small family of magnets can spoil the machine luminosity (rate of the useful events at collision).

In total some 12 MJ are stored as magnetic energy (at ultimate field) in the ring and hundreds of high amperage currents leads are needed for the powering. The helium inventory amounts to about 60 tonnes stored in the magnets, 30 tonnes in the feedboxes and the cryogenic line that runs along the magnet in the whole 100 m underground tunnel and about 5 tonnes in the ground plants.

2. Superconducting Cable

The design of accelerator magnets is such that the overall current density, J_{ov} , is by far the dominant factor in attaining peak field. Indeed, referring to Fig. 1, the field generated is proportional to J_{ov} and to the coil thickness. However, coil thickness has to be minimized for reasons of magnetic efficiency and ultimately of cost and feasibility. Coil thickness should not be much larger than the radius of the coil aperture. So very high current density is the key factor for high field, requiring the best superconductor J_c , despite the necessity of fine filaments, and also avoiding diluting the J_c in the final coils: addition of stabilizer, cable degradation, cable voids, insulation, and conductor free space in the

winding, all have to be minimized. To make the best use of the steep increase of J_c vs. field of NbTi, the coils of the main dipoles are graded with use of different cables for the two winding layers, cable 01 and 02, while the main quadrupoles are all wound with cable 02 only, since the gain in grading is less and the choice resulted in a considerable economic advantage.

The main specifications of the LHC superconductors are listed in Table 1. The key element to reach such specification are the use of very high quality primary material (specified by CERN), the use of proper Nb barrier to avoid interface problem caused by the aggressive heat treatment in presence of fine filaments, the follow up supported by the SPC (Statistical Process Control) that enables CERN and the companies to monitor the production and to take corrective action in due time. This means that the quantity of measurements required in the company and at CERN is considerable. For example at CERN in the first half of 2003 some 3000 cold tests were performed.

Table 1. – Characteristics of the cables for the main dipoles and quadrupoles

STRAND	Type 01	Type 02
Diameter (mm)	1.065	0.825
Cu/NbTi ratio	1.6-1.7 ± 0.03	1.9-2.0 ± 0.03
Filament diameter (µm)	7	6
Number of filaments	8800	6425
I _c (A) @1.9 K	515 (±4 %) @ 10 T	380 (±4 %) @ 7 T
J _c (A/mm ²) @1.9 K	1530 @ 10 T	2100 @ 7 T
μ ₀ M (mT) @1.9 K, 0.5 T	30 ±4.5	23 ±4.5
CABLE	Type 01	Type 02
Number of strands	28	36
Width (mm)	15.1	15.1
Mid-thickness (mm) @ MPa	1.900 ±0.006	1.480 ±0.006
Keystone angle (degrees)	1.25 ±0.05	0.90 ±0.05
Cable I _c (A) @ 1.9 K	13750 @ 10T	12960 @ 7T
Maximum I _c cabling degradation	5 %	5%
Interstrand resistance (μΩ)	10-50	20-80

2. 1 Critical current density

The magnet performance, i.e. quench behavior, depends critically on critical current density (J_c). To avoid as much as possible redistribution and other effects that might become critical for the magnet operation, the superconductor J_c must be not only high but also very uniform all along the strand production and among different manufacturers. So tight control limits have been set, imposing not only the minimum value of the specifications (see table 1) but also a maximum deviation of 4% from the running average. The results on the first 3/8 of the production is very satisfactory, a results of many years of R&D carried out in strict contact among CERN and various manufacturers.

The cabling operations introduce some degradation but, for this high quality product it is very well predictable from a limited number of strands extracted from a cables. The good production is demonstrated also by the small value of the degradation, 2-3%, as shown on the production of cable 02 for a whole octant in Fig. 2.

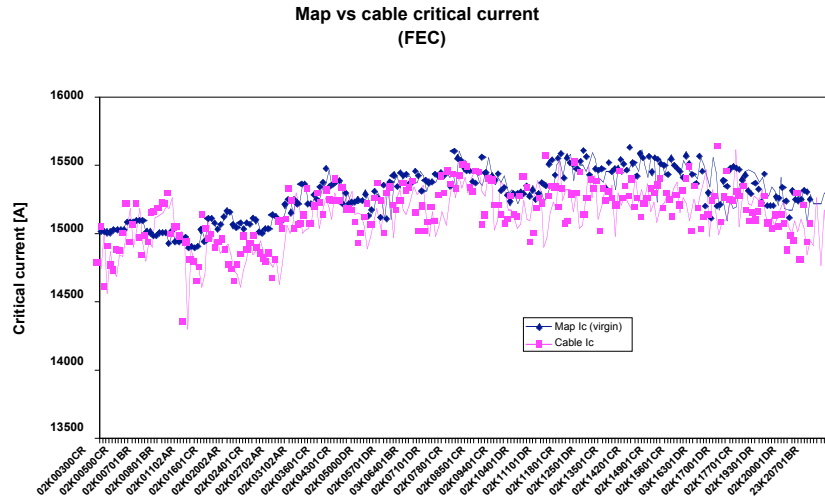


Figure 2 The critical current as predicted by measurements at 6 T and 4.222 K on virgin strands (no degradation accounted), shown by diamonds, compared with the actual measurement on cable (accuracy ± 200 A), squares, for the production for a whole octant of cable 02.

2.2 Magnetization

Due to the importance of field quality at injection ($B_0 = 0.54$ T) and to avoid its disruption by the persistent current, not only the filament size is 6-7 μm , see table 1, but for the first time in a big project severe magnetization limits are part of the specifications, with a prescribed minimum value and strict control limits, as for most of the relevant parameters. Magnetization proved to be the most difficult parameter to be kept under control and some derogations have been granted in order to help starting of the production. Actually by proper mixing of few high magnetization strands in a cable with low magnetization strands we could accept most of the strands outside the control limit. However some billets exceeding acceptable value had to be rejected. Filament distortion is usually the signature of very high magnetization values, see [4], mostly originated by insufficient control of extrusion parameters. It is worth noticing that severe filament distortion usually completely spoils good magnetization while I_c is almost unaffected.

2.3 Stabilizer content and resistivity

The copper fraction must be reduced to a minimum to preserve the current density. In accelerator magnets the superconductor area is between 30 and 40% of the cross section, (see table 1). This implies very high dissipation in the copper following a transition, since J_{Cu} is very near to J_{NbTi} , putting a lot of constraints on magnet protection. In the case of a quench most of the energy is dissipated in the magnet itself and since many magnets are series connected, the resistance of stabilizer must be equal, within severe limits, among cables in the same magnet and among magnets series connected, to avoid voltage unbalance and overheating. This calls for very strict control limits of the stabilizer to superconductor ratio (Cu/NbTi) and of the RRR of the copper. The copper content is carefully monitored during the production process over the entire length of the billet and the the RRR at the end-tail of each billets and on one cable out of four.

2.4 Cables and coupling current control

The strong dissipation following a quench caused by the small amount of stabilizer, as mentioned above, requires that the inductance be as small as possible in order to put the current in the cold diode bypass line. This calls for high amperage transport current, about 12 kA, for the LHC main dipoles and quadrupoles. Rutherford cable, shown in Fig. 3, is the most compact cable with a filling factor of about 90% and with I_c degradation of a few percent. It has a geometry that helps to build accurate windings with very well defined strand position that is essential for field quality and for pre-stress control. However in the ramp from injection to flat top field, the field variation perpendicular to the broad face generates coupling currents that are mainly controlled by the contact resistance, R_c , among strands at the top and bottom faces of the cable. Control of R_c in a practical and inexpensive way has required a considerable amount of R&D and the solution has been an accurate coating ($0.5 \pm 0.1 \mu\text{m}$) of tin-silver alloy on all strands. After cabling, the cables are oxidized through a thermal heat treatment. This enables measured contact resistance to stay in the target range: $15 < R_c < 100 \mu\Omega$. The hard lower limit to avoid adverse effects on the field quality during ramp is $10 \mu\Omega$. The coating method followed by cable oxidation is adequate but it does not guarantee sufficient uniformity among cables of different production lots. Measurable skew harmonics can be generated by differences of 30% in R_c , well within our control limits. To avoid this, the four poles of each magnet are wound with cable of the same manufacturer, of the same tinning bath, of the same cabling batch and of the same heat treatment group, to maximize uniformity in the same magnet. In Fig. 6 the results of contact resistance measurements over much of the delivered inner cable type 01 is shown.

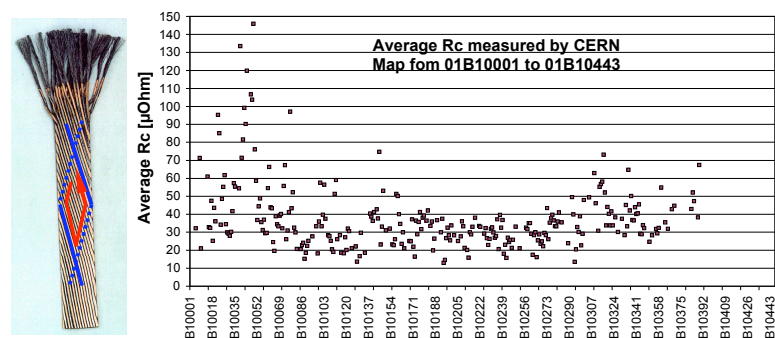


Figure 3 Large face of a Rutherford cable where a path of the main coupling currents are evidenced. Value of the inter-strand for one producer.

The cable QA procedure consists of many other measurements. In addition to R_c , M , I_c , RRR and Cu/NbTi, mechanical and metallurgical properties are checked at least in one out of four cables, i.e. one cable per dipole. Moreover in each of the cabling lines CERN has integrated different measuring devices. The most important is a new system capable of on-line image analysis. It is mainly devoted to detect surface defects and cross-overs. Attempts to automatically detect cold welds by imaging techniques or eddy currents have not been successful. Visual inspection and manual controls are used to ensure that cold welds are not included in the windings. For these reasons CERN has resident inspectors in the two main European cabling facilities.

3. Dipole Magnets

The dipole magnets are designed such that the two apertures are fully coupled mechanically and magnetically, as shown in Fig.1. This design, called a twin dipole [5], imposes some constraints but also allows considerable savings and helps to keep parallelism among the two apertures, an important feature for the collider operation. It is worth mentioning that the magnet will be operated at 8.3 T at 1.9 K, with about 1.5 K of temperature margin (this would scale to about 0.5 K at 4.2 K, where the heat capacity are larger). However the magnet must withstand heating coming from possible beam losses that can consume more than half of this margin. For this reason it is very important that movement and friction, the main sources of quenches, be very small with energy release per event of the order of mJ. The key for good magnet performance, after the proper design of the conductor, is a robust mechanical system and good winding procedures to correctly position the conductors.

3.1 Collared Coils

A schematic of a winding for a dipole and of the electromagnetic forces is shown in Fig. 4. The forces at 8.3 T are very high. These forces are taken by the collars, see Fig. 1, a compact structure, 40 mm thick, of special austenitic steel whose profile is precise with $\pm 30 \mu\text{m}$ over the 15 m length. Furthermore, collars plays a key role in obtaining the requisite field quality by imposing the right shape to the coils. However precise and strong might be the collar structure, the electromagnetic forces act on each single strand of the cable, see Fig.3 and to avoid movement during excitation the winding must be very accurate, avoiding gaps and holes, especially in the saddle shaped ends. The collaring pressure reaches a peak about 150 MPa, under action of the huge collaring press and about half of this pressure remains on the coils after the collars are locked by means of pin rods and the pressure in the press is released.

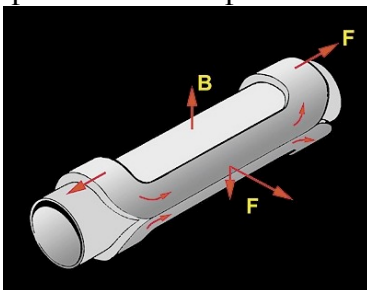


Figure 4 Schematic of dipole with force direction. In the LHC dipoles the horizontal force per unit length of the magnet is about 4 MN/m.

3.2 Cold Mass Assembly

The collared coils are completed with the addition of a low carbon yoke that serves both to return flux and to transmit further compressive pressure from the shrinking cylinders to the collared-coil assembly as shown in Fig. 1. The shrinking cylinder is composed of two half shells welded around the magnet. The whole assembly is further compressed by controlled weld shrinkage. The magnet is designed in such a way that despite the loss of part of the pre-compression during cool down (coils contract more than all other components) sufficient stress remains to balance the electromagnetic forces.

One additional difficulty for the LHC is that the magnet is curved, with a total sagitta over the 15 m length of $9 \pm 1 \text{ mm}$, a tolerance that so far has been most difficult to obtain. This has required both an improvement of the components-assembly-welding technique and a release of the horizontal tolerance to 1.5 mm.

The shrinking cylinder is a critical element in the cold mass construction since it is at the same time both a restraining cylinder, with large circumferential stress and the superfluid helium vessel. For these reasons welding is a critical operation in the construction line and it is carried out on a huge specially designed press with a rather new technique called

STT (surface tension transfer), a low energy process where the parameters are varied and controlled with a time response of milliseconds to cope with variations of the bevel gap and of other parameters.

3.3 Controls and production steering through field quality

A key feature in the procurement of the LHC magnets is the introduction of severe quality assurance (QA) procedures and holding points during the entire manufacturing process, like magnetic measurement on warm coils at a moderate amperage. This is done for all types of LHC magnets immediately after collaring in order to be sure that the field quality is as designed. It also enables us to carry out corrections at an early stage. While the time between the collaring and the testing at CERN of the finished magnet inside the cryostat is about 6 months, warm magnetic measurements can take place the day after collaring. Furthermore, magnetic measurements have proved to be very useful in detecting defects that would have been acceptable for field quality but might have hampered the quench performance. The most important parameters, the integrated field strength for the dipole collared coils is shown for the first octant in Fig. 5.

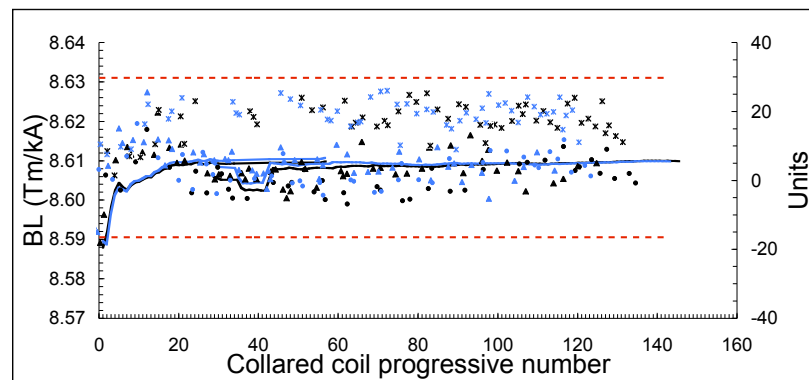


Figure 5 Integrated field strength for the first octant of collared coils.

3.4 String of Magnets, Cryogenics and HTS Current Leads

The LHC is powered by eight sectors, each consisting of 154 dipoles all powered in series, and the same concept applies to all other magnets, although the numbers is less impressive. The energy stored in a sector is 1.5 GJ (at 9 T) and great care must be taken to avoid damaging magnets because of a quench, mainly by spreading quench all over the winding by means of heaters and bypassing the winding through a cold diode.

The thermal load of the magnets has been moderately optimized, and in the final design to save on investment cost there no radiation shield cooled at 5 K between the thermal shield at 60 K and the 1.9 K mass. Each magnet has a thermal load of about 2.6 W at 1.9 K mostly coming from radiation from the thermal shield (Fig.1).

Low pressure 1.9 K HeII is formed inside the heat exchanger tube positioned in the upper yoke (see Fig.1) and by exchange the atmospheric pressure helium of the cold mass is cooled at 1.9 K. In total 8 units capable of 2.4 kW at 1.9 K are installed.

The massive use of low consumption current leads helps in keeping the cryogenic losses at acceptable level: in the LHC this was the best use of an excess of 20-40 K He gas that is ideal to intercept the heat in the junction between the HTS part and the warm end (copper) of the current, reducing by a more than a factor ten the 4.2 K consumption. The 13 kA HTS currents leads, specially designed and developed by CERN, have a consumption at 4.5 K of 1 W [6].

5. Production Status

Today all four main companies (one for quadrupoles and three for dipoles) have entered into full series production, i.e. they have completed the first 7% of production. Actually for collared coils (CC) more than one octant, precisely 165 CC for dipoles and 45 CC for quadrupoles, has been produced and about 90 dipoles Cold Masses (CM) and 7 quadrupoles CM have been delivered to CERN. One octant of complete dipoles is expected to be delivered to CERN by the end of 2003 and the production is scheduled to finish in the second half of 2006.

The results of the cold tests are very positive. So far only a few of the early production magnets have been rejected, mainly due to errors typical of the learning phase of the project. The quench results are summarized in the graph of Fig. 6.

In conclusion, series production of the LHC superconducting magnets is progressing well toward completion and, despite difficulties and budgetary restrictions, the project is well on the track to success. The LHC project will be the world's largest demonstration of the feasibility of superconducting and cryogenic technologies.

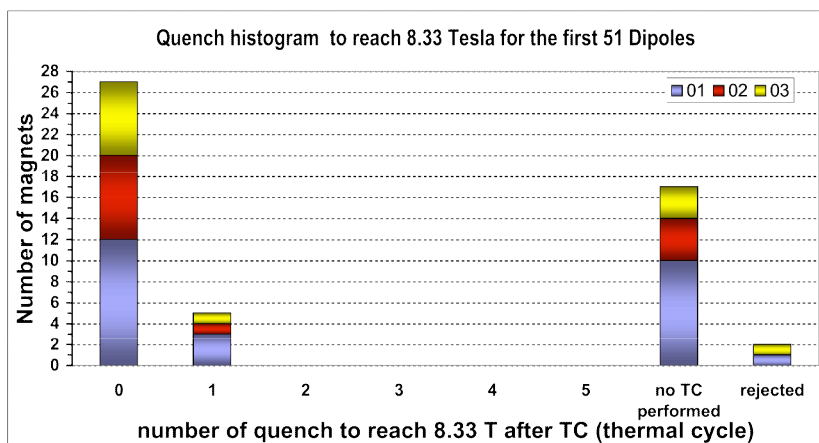


Figure 6 Quench statistics for dipoles (1st, 2nd and 3rd manufacturers). After thermal cycles only 10% still need a quench to reach nominal field (all they are above 8 T). No TC is performed on excellent magnets.

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