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SUPERCONDUCTIVITY: ITS ROLE, ITS SUCCESS AND ITS SETBACK IN THE LARGE HADRON COLLIDER (LHC) OF CERN

Lucio Rossi

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The Large Hadron Collider - LHC, the particle accelerator at CERN, Geneva, is the largest and probably the most complex scientific instrument ever built. Superconductivity plays a key role because the accelerator is based on the reliable operation of almost 10,000 superconducting magnets cooled by 130 tonnes of helium at 1.9 and 4.2 K and containing a total stored magnetic energy of about 15,000 MJ (including detector magnets). The characteristics of the 1200 tonnes of high quality Nb-Ti cables have met the severe requests in terms of critical currents, magnetization and inter-strand resistance; the magnets are built with an unprecedented uniformity, about 0.01% of variation in field quality among the 1232 main dipoles which are 15 m in length and 30 tonnes in weight. The results of this 20 year long enterprise will be discussed together with problems faced during construction and commissioning and their remedies. Particular reference is made to the severe incident which occurred nine days after the spectacular start-up of the machine on 10th September 2008. The status of repair and the plan for the physics program in 2010 are also presented.

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Superconductivity: its role, its success and its setback in the Large Hadron Collider (LHC) of CERN

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1. Introduction

The Large Hadron Collider (LHC) [1,2] is a particle accelerator designed to collide counter-circulating proton beams up to 7 Tev/beam (i.e. 14 TeV centre-of mass-energy) as well as fully stripped heavy ion beams like gold or lead at 2.8 Tev/amu (574 TeV/nucleus). The collider receives particle beams at low energy from its injectors when the field in the main dipoles is 0.54 T. Once the two rings are filled with counter-circulating beams, the field in the main dipoles is increased in 20 minutes up to 8.3 T, meanwhile the RF cavities accelerate each beam up to 7 TeV. LHC is then switched to collision mode, where the beams are tightly focussed by means of special quadrupoles and made to collide almost head-on to produce interesting events. After 2-10 hours of beam collisions, the beam itself is exhausted and is dumped. The dipole magnets are then ramped down to 0.54 T and they stay at flat bottom for some 20-40 minutes. Meanwhile beam injection is repeated before the magnets are ramped up again to 8.3 T for another cycle of high energy collisions. The machine is designed to withstand some 20,000 such cycles in 20 years life time, as well as 20-30 full thermal cycles.

Its twenty year long story from conception to commissioning, passing through the R&D and construction phases, culminated with the spectacular start up of 10th September 2008, an event broadcast worldwide with more than 250 journalists at CERN and a record audience (1st Google UK trends and 3rd in the USA [3]). However, a very severe incident happened on 19th September 2008, causing more than one year of delay to restart the physics program and a minimum 2 years delay to reach the full energy. Although it happened in a relatively low tech system (an interconnection between magnets), the incident has shown faults of design, execution and diagnostics that, even if apparently trivial, are intimately connected with superconductivity and its subtleties.

2. LHC Machine

The main characteristic of the LHC in comparison to previous accelerators is the leap forward in beam energy and beam intensity. The proton beam energy scales as: $E \propto 0.3BR$, where B is the field in the dipole magnets (T), R is the bending radius in the dipole magnets (km) and the particle energy E is in TeV. Superconductivity plays a fundamental role [4] because it allows magnetic fields in excess of 8 tesla to be reached; combined with the 2.804 km curvature radius of the dipoles, this field enables proton beams to reach energies of 7 TeV, almost an order of magnitude larger than previous accelerators. LHC relies on 1734 large magnets, including the accelerator backbone – the 1232 main dipoles (15 m long and 30 tonnes), and 7724 smaller size superconducting corrector magnets. The LHC magnet construction required about 1200 tonnes of superconducting wire; in order to reach the design performance they are (with a few exceptions) cooled at 1.9 K with superfluid helium, with a total helium inventory of some 130 tonnes. In term of superconductors, stored energy and cryogenic system, LHC is by far the largest equipment in the world: actually it is the largest scientific instrument ever built. The machine is complemented by four particle detectors, the devices that detect the particles emerging from the collision points and that are the eyes of the high energy physicists to look for any new phenomena. The two largest of the LHC detectors, called ATLAS [5] and CMS [6], also use giant superconducting magnets to improve sensitivity. These magnets have record characteristics, too: one is the largest size superconducting magnet in the world and the other is the most powerful, in terms of stored energy in a single circuit.

As previously mentioned, the main dipoles constitute the backbone of the machine: their maximum field determines in a direct way the beam energy and they cover 75% of the tunnel length: 65% with dipole magnetic field and 10% with electrical connections of various types. A further 10% of tunnel length is allocated to other types of magnets or magnet-related equipment: quadrupoles, sextupoles, octupoles, corrector magnets (from dipole up to dodecapole order), current feed-through boxes and other cryostat functions. The magnetic system in the LHC therefore covers in total 85% of the 26.7 km long beam path in the tunnel, see Figure 1.

Not only must the magnets reach the maximum possible field, and minimize non field-covered regions: they must also constitute a regular lattice where the performance of each element must be known at the 100 ppm level. A compensation between a low and high performance dipole is not possible: therefore the weakest dipole will eventually determine the energy reach for the LHC.

Figure 1. The superconducting magnets in the LHC tunnel

3. LHC superconductor

Superconducting cables in magnets for accelerators, and in particular for large accelerators where field volume must be a minimum, are designed with three main goals [7,8,9]:

- Maximize the current density in the conductor, since magnet performance strongly depends on it. Lower density cannot be compensated by thicker coils (see section on magnet design).
- Great accuracy of the magnetic field seen by particles, over the full dynamic range from 0.54 to 9 T.
- Uniformity of geometrical, mechanical and electro-magnetic characteristics, throughout the entire production of 1200 tonnes by six different manufacturers.

3.1. Conductor current density

The first goal calls for the highest possible J_c, of course; the performance of the Nb-Ti for accelerators has increased steadily through the years, approaching since sometime what is considered the practical pinning limit of the material. For the LHC the boost was given by cooling down the superconductor to 1.9 K by using superfluid helium [10,11]. In addition the margin to critical current has been reduced and it should be appreciated that the LHC main dipoles work at 86% of the maximum theoretical performance (or quench current) and are designed to operate eventually at 93% of it (“ultimate performance”). This is the reason why uniformity in production is so important: a small deviation of more than 5% from the required J_c performance would adversely affect the operation of the machine.

At the beginning of the project, in the period 1985-90, two routes were pursued [12]: Nb-Ti at 1.9 K and Nb_3Sn at 4.2 K. The current density at that time was not so different in the 8-10 T region, see Figure 2.

A Nb_3Sn, 1 m long, dipole model was successfully built and tested [13]. However, considerations of costs and, especially, of industrial maturity were decisive in the choice in favour of Nb-Ti.

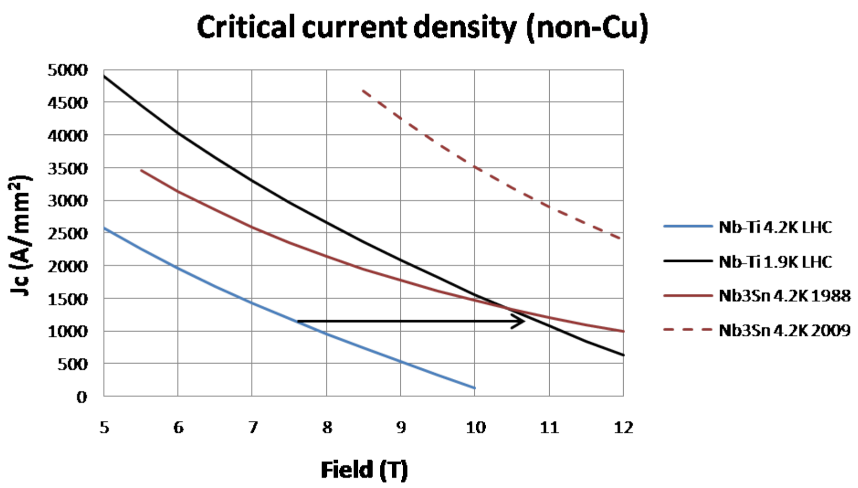

Figure 2. Current density of Nb-Ti and Nb_3Sn at the time of LHC superconductor choice (about 1989). The arrow shows the 3 T shift in Nb-Ti from 4.2 to 1.9 K. For information the recent Nb_3Sn J_c is also reported, however its filament size is much larger.

To avoid diluting too much the superconductor current density, particle accelerator magnet designers act on three parameters:

1st. Reduce the copper content to very low values. A low copper content increases the homogeneity of the Nb-Ti filaments (discussed later) and reduces the cost of conductor manufacture. In practice the copper content (in volume) cannot be reduced below 50-55% for manufacturing reasons; however, considerations of stability and, especially, of protection impose a minimum copper content of more than 60%. The two main strands used for the LHC dipoles and quadrupoles feature 61.5% and 65.% copper content (Cu:Nb-Ti = 1.6 or 1.9).

2nd. Maximise the compaction factor. The conductor is a Rutherford type, i.e. a flat two layer cable first proposed by Rutherford lab and used for the Tevatron magnets (Fermilab, USA). This allows a compaction factor (Area of strand/Area of the envelope of the cable) of around 90%, i.e. only 10% is lost in voids, the minimum to make the cable porous to helium. Rutherford cables are relatively simple and cheap to produce: cabling adds typically only 10% to cost of the strands. However there is always the risk of sharp edge and of current degradation due to strong deformation at the folding at the thin edge of the trapezoid, see Figure 3. The degradation of current density due to cabling is measured by comparing I_c before and after the cabling and for LHC has been negligible. The critical current measured on the entire production of the cable for the dipole inner layer (about 35% of the whole LHC production) is shown in Figure 4 [14].

3rd. Keep the insulation thin: for the LHC dipoles the insulation is only 125 μm thick, made by three polyimide tapes wrapped around the cable.

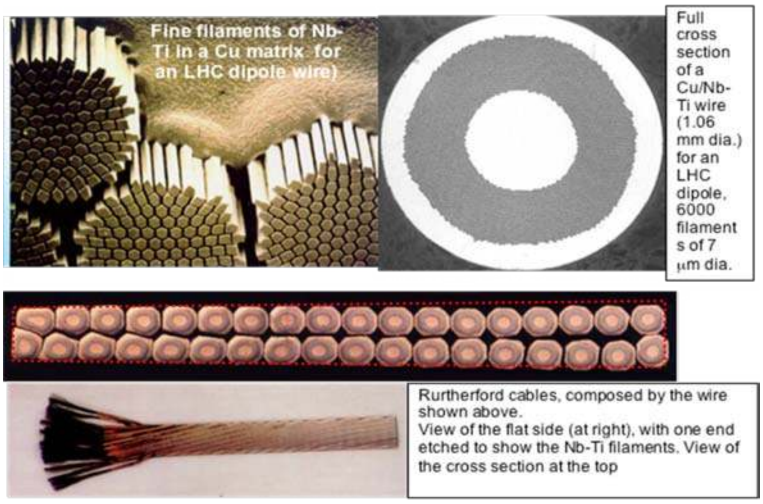

Figure 3. Typical wires and Rutherford cables employed for LHC magnets. The red dashed lines show the trapezoidal shape (keystone) of the cable cross section.

With all these measures the overall current density, i.e., the actual current density over the coil package, is more than 400 A/mm^2 at the operating field of 8.33 T in the magnet bore. Considering that each dipole has 7 Mjoules of stored energy, and that groups of 154 dipoles are powered all in series, this current density constitutes an exceptional challenge for stability and protection.

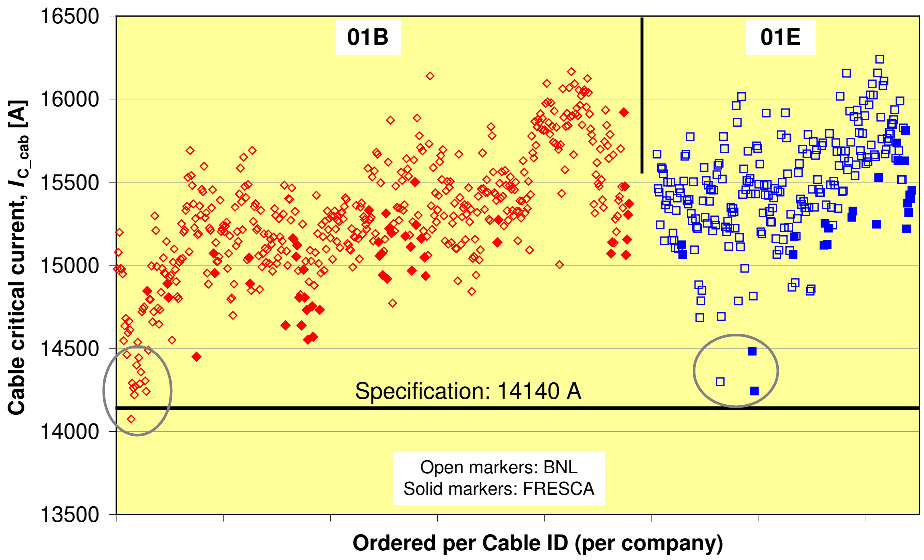

Figure 4. Critical current of the entire production of the largest LHC cable (two manufacturers), compared with specification. Weakest cables are indicated: for most cables the margin is more than 10%. Courtesy of A.Verwej – CERN.

3.2 Magnetic field accuracy

The magnetic field accuracy is affected by the superconductor through three main parameters:

- The geometry of the conductor. The precision of the cable shape is very important as is its uniformity through the production.

- The magnetization due to persistent currents. This very well known phenomenon is critical for LHC and can be detrimental for the machine performance with beam. Magnetization generates spurious fields, especially sextupole components – b_3 – that at low field (when the beam is injected into LHC) must be accurately known and reproducible, to allow correction with small sextupole magnets mounted on each dipole. Magnetization scales as: $M \propto J_c \times D_{eff}$ where D_{eff} is the effective diameter of the superconductor filaments. Since we aim at the highest possible current density, the filament diameter must be minimised. For the LHC the main cables have 7 μm and 6 μm filament diameters, resulting in strands with 6000 to 8000 Nb-Ti filaments. The magnetization properties have been measured on samples from all billets produced for LHC and strict limits were fixed, with a specification of 28 mT of $\mu_0\Delta M$ at 0.5 T. In Figure 5a the results for one cable are reported: it can be noticed that a number of billets (each measurement is a characterization of a billet) showed a magnetization value considerably in excess of the upper limit. However thanks to a good mixing of various strands in a cable, and thanks to the fact that most of the billets were well below the upper limit, the cable magnetization was almost always within specifications, which constitutes a great success of the superconductor manufacturing [15]. This was due to a careful design of the strands, an accurate control of the process and a massive testing campaign. Thorough analysis of jumps in magnetization, totally uncorrelated to other parameters like I_c and the n-value at transition, pointed to severe deformation of the filament (filamentation), see Figure 5b, and their origins were traced back to the hot extrusion process.

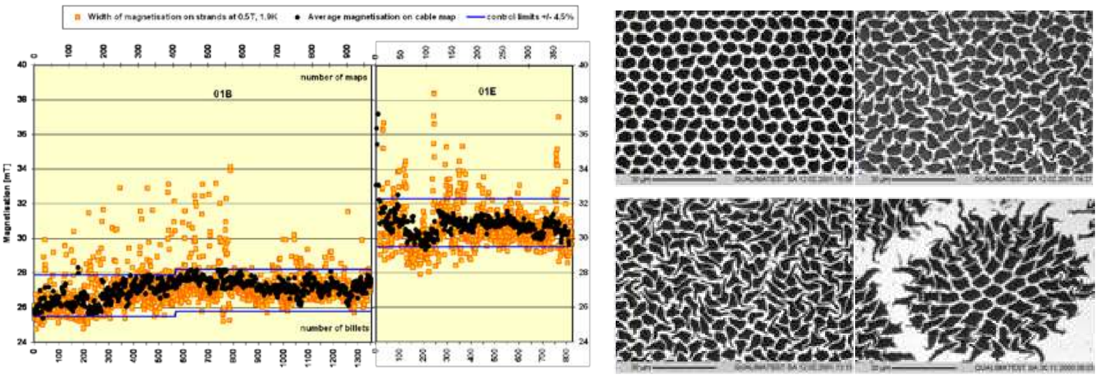

Figure 5. Magnetization measured in strands (orange squares) and the average in the corresponding cable (black circles superimposed), 5.a left; micrographs of cross section of the strands, 5b right, showing good filaments (top left) and cases of deformed filaments: the worst, bottom right, corresponds to $\mu_0\Delta M$ > 35 mT. Courtesy of S. Le Naour – CERN.

- The so-called dynamic properties:
  - *Inter-strand resistance*, i.e., the contact resistance R_c between strands composing the cable. The cable is squeezed in the coils, so the resistance between top and bottom strands in a cable is small, forming circuits with low resistance, see Figure 6a. When ramping up from low field to flat top field a current circulates in each loop generating heat (a negligible effect in LHC at the normal ramp of 7 mT/s) and field distortions. This dynamic effect on field quality may be very detrimental if the resistance of each contact is not above 10-15 μΩ. An R&D effort was therefore launched at the beginning of the project and a relatively simple and effective system was found to control the inter-strand resistance [15]. Wires are hot-dip coated with a thin layer of Sn-Ag (4%) and then, after cabling, the cable is thermally treated in air to form an oxide layer. Other systems, like direct oxidation of copper surface of the strands, were not suitable to obtain good and reliable results. Since a too low resistance has a visible

dynamic effect, the production could be successfully tuned to stay above the minimum limit as shown in Figure 6b.

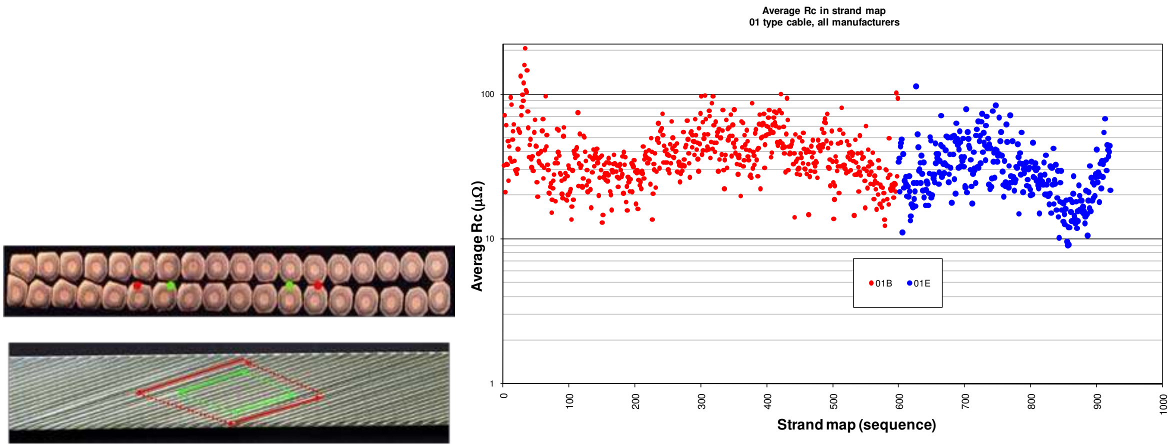

Figure 6. LHC Rutherford cable showing the path of induced current along strands and crossing points between upper and lower cable layer, 6a, left. The graphs on the right show the measurements on the production of inner cable of LHC (two producers), 6b, right. For inner cable the target was R_c > 10 µΩ. Courtesy of D. Richter – CERN.

- The second important dynamic effect is the so called snapback, a strange phenomenon that may plague accelerator magnets (or indeed any superconducting magnet needing precise field at low current after a cycle at high current). During the flat bottom at 0.54 T, the persistent currents slowly decay and so does magnetization, generating a decay in the sextupole components, b3, of the field. This decay is slow and the change of b3 can be easily dynamically compensated by varying the strength of the sextupole corrector magnets. However, once beam injection is finished and the field starts ramping up to follow the beam energy increase, the magnetization value "snaps back" to its previous value before the decay. The jump in b3 is considerable in amplitude and, since it happens in a span of a few amperes, compensating it is not easy. The amplitude of the jump varies with the cable and is impossible to predict for each type of cable – the mean value and its variance had to be carefully evaluated from a limited set of magnet measurements in order to set up a pre-programmed b3 correction by dedicated sextupole families. For the LHC a scaling law capable of describing the snapback behaviour has been successfully worked out [16], as shown in Figure 7.

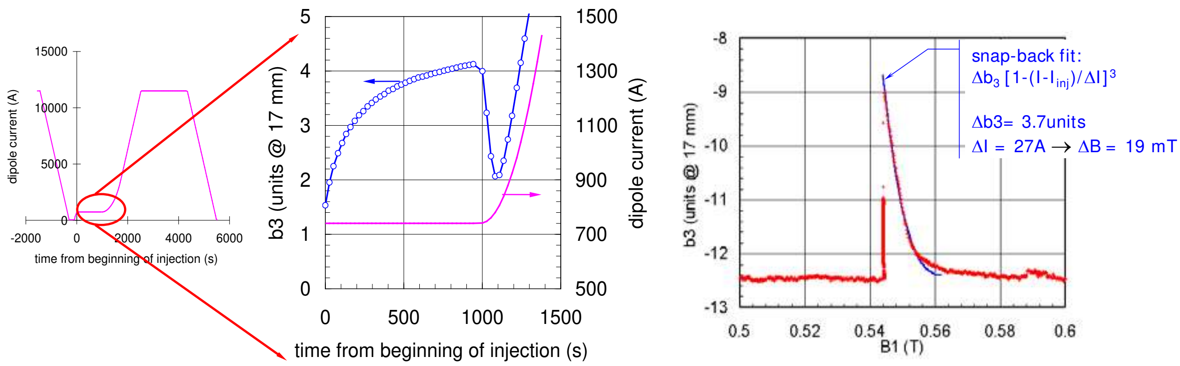

Figure 7. Illustration of snapback: the cycle of LHC requires a flat bottom of about 1000 s at about 730 A (or 0.54 T), see left graph. During the flat bottom the magnetization decays causing the

sextupole components, b3, to change by 3 units (from 1.2 to 4.2) at constant main field, see central graph. When current starts ramping up, b3 snaps back suddenly from 4.2 to 2 (Δb3 = 2.2 units in absolute value). In the plot at the right the same is illustrated vs. dipole field rather than time and the scaling law fit is shown. In this last graph the snap back value is more larger, 3.7 units. Courtesy of L. Bottura – CERN.

3.3 Uniformity of mass production

The previous two subsections of this section on the superconductor, reported on scientific and technical problems. Once these technical problems were solved, which, especially for R_c, happened at the very end of the pre-production phase, the problem appeared of how to guarantee a uniformity in quality all along the mass production of some 1200 tonnes of cables from six different manufacturers. The main steps taken to ensure production uniformity were:

- The companies, or at least a number of them, were kept working with LHC cable target parameters for at least 10 years before the mass production started. Early orders were placed in the late 1980s, while large orders were placed in 1998/99 and mass production started in 2001. Good and long collaboration of companies with CERN, with mutual trust, made this project viable and was a key to success.
- Adoption of SPC (Statistic Process Control). The main parameters governing the production quality were kept continuously under control and had to stay inside control limits (stricter than the specifications). A reaction was requested whenever there was a drift toward the control limits, which required an up to date database correlated with all process settings and a good reactivity, i.e., a prompt analysis of the sources of the deviation with consequent corrective actions.
- Rigorous protocol of measurements in each industry, agreed between each partner and CERN:
    - Each company had a system for characterization of wire production, for example: geometrical size, critical current at 4.2 K (continuously calibrated with the CERN facility), continuous evaluation of tin coating through coulometry (set up by CERN), etc...
    - Each centre for cabling used a system to measure online cable thickness and keystone angle (provided by CERN and set up by LBNL in the frame of the USA contribution to LHC) as well as a cable inspection system (CIS) capable to detect cable imperfections like cross-over or spots of tin through continuous image recording and analysis. This CIS equipment was developed by a small European company in collaboration with CERN.
- Large infrastructure set up at CERN to carry out all types of measurements:
    - All type of room temperature measurements on strands, from dimensions to Cu:Nb-Ti, through precise tin coating thickness on samples based on AAS, Atomic Absorption Spectroscopy, which served as calibration of the continuous measurement in industry. This was essential to determine the correct temperature-time curve of the thermal treatment to reach the desired value of the R_c, see above, [17,18].
    - Check of all characteristics of cable at room temperature, including dimension and visual inspection on a whole piece length. At the production peak we had four spooling lines for cable at CERN. Actually 25% of all cables (i.e. almost 2000 km) was thoroughly inspected at CERN.
    - Cryogenic measurements on wire of: RRR [19], I_c [20], Magnetization [21], R_c [18]. Measurements were at 1.9 K, except for I_c that, in order to allow a continuous cross check with measurements in Industry, was measured also at 4.2 K. I_c measurements were carried out both on virgin strands (to approve the

production of a billet) and on strands extracted from cables, to assess the degradation due to cabling, which in practice was very small but was always a potential risk.

- Measurements on cables at 4.2 K and 1.9 K on a few selected samples, mainly to correlate I_c performance between 4.2 K and 1.9 K and to study special cases or special topics like thermal stability. Some 150 such tests were carried out in the FRESCA facility, capable of 30 kA in a 10 T - 80 mm bore, at 1.9 or 4.2 K [14]. In addition, a massive campaign of 2000 measurements of cable I_c at 4.2 K was provided by BNL in the frame of the USA contribution to LHC, which allowed to test on average 2 unit lengths out of the 8 needed for winding a dipole [14].
- Cable magnetization was measured to verify the final results of the sorting scheme that allowed meeting the tight specification, see previous section.

One of the main factors of risk during production was strand breakage. In order to produce the superconductor at the specified cost and in the scheduled time, the number of breaks had to be a minimum (0-5 per billet, according to different manufacturing processes), not an easy task with wires of 6000-8000 filaments at the 6-7 μm level. Good cleaning and measures to avoid contamination were the critical factors to keep breakage at an acceptable level, which sounds simple but was difficult to maintain on such a large scale production,

The problem of breakage as well as technical problems like proper setting of the tinning or of cabling parameters, were the main bottlenecks for cable production. For almost two years the cable delivery was on the critical path of the project; however, from 2002 the production took off, and from then on it was never again a critical issue. The success of the cable delivery is summarized in the graph of Figure 8.

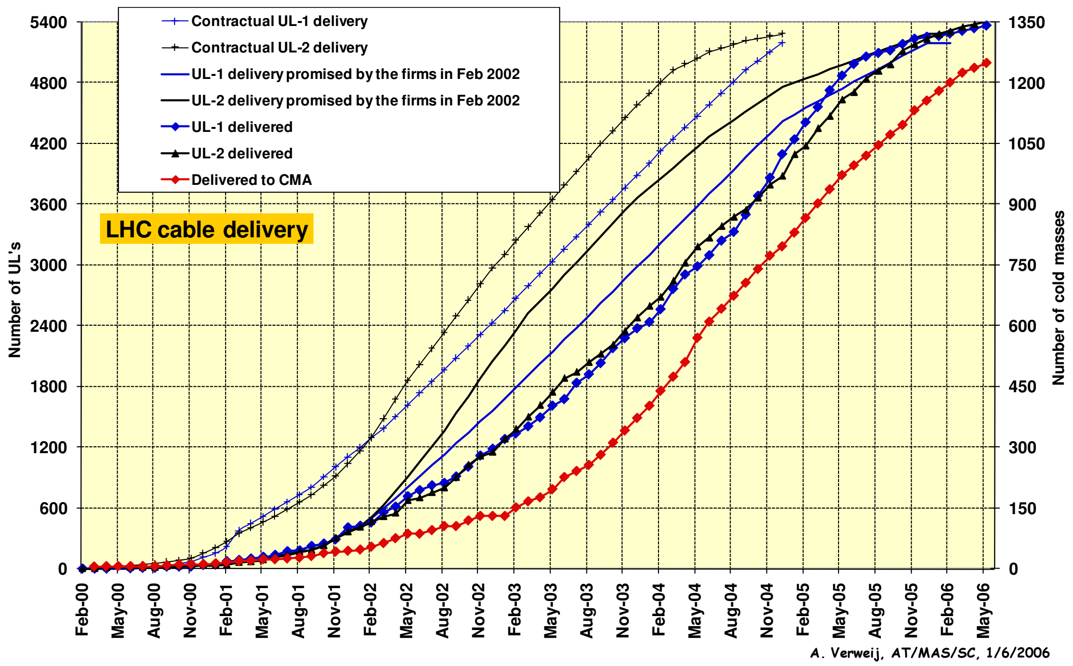

Figure 8. Delivery of the LHC main superconducting cable unit lengths (UL1 = cable for dipole inner layer; UL2 = outer layer). The most important feature is that from the beginning of 2002 the cable delivery was in advance of the needs of magnet companies (CMA - Cold Mass Assembler - in the graph).

4. LHC magnets

4.1. Design concepts

The design of LHC magnets has been technically investigated and discussed in the past, see e.g. [22-27]. Here we will limit our exposition to the most important concepts governing the design and having a basic influence on the superconductivity part and on performance.

As mentioned, the most important type of magnet in the accelerator is the dipole, which produces a uniform transverse (to beam direction) field. The field is created by coils that present a distribution with maximum current at the mid-plane and zero at the pole, called cosϑ current distribution. The coil shape is illustrated in Figure 9. The field given by such a distribution is: $B \propto ½ J\, d$, where d is the coil thickness and J its current density. One should remark that this is exactly half of the field of a solenoid with the same basic parameter, $J\, d$. So clearly in a dipole configuration it is more difficult to reach high field than in a circular coil. Another consideration is more related to the structure of the magnet. As can be seen in Figure 9, the electromagnetic forces are transverse to the coils, i.e., there is no internal stress that can compensate the forces. This requires that forces are fully supported by an external structure, which enhances considerably the difficulty when the level of current density and field is so high. Putting together the two above considerations in a practical way, see Figure 9, one can see that a dipole for an accelerator is a crust of coil where one or two layers of conductor is disposed to approximate a cosϑ distribution and is held by a system of collars tightly surrounding the coils and locked by rods or keys.

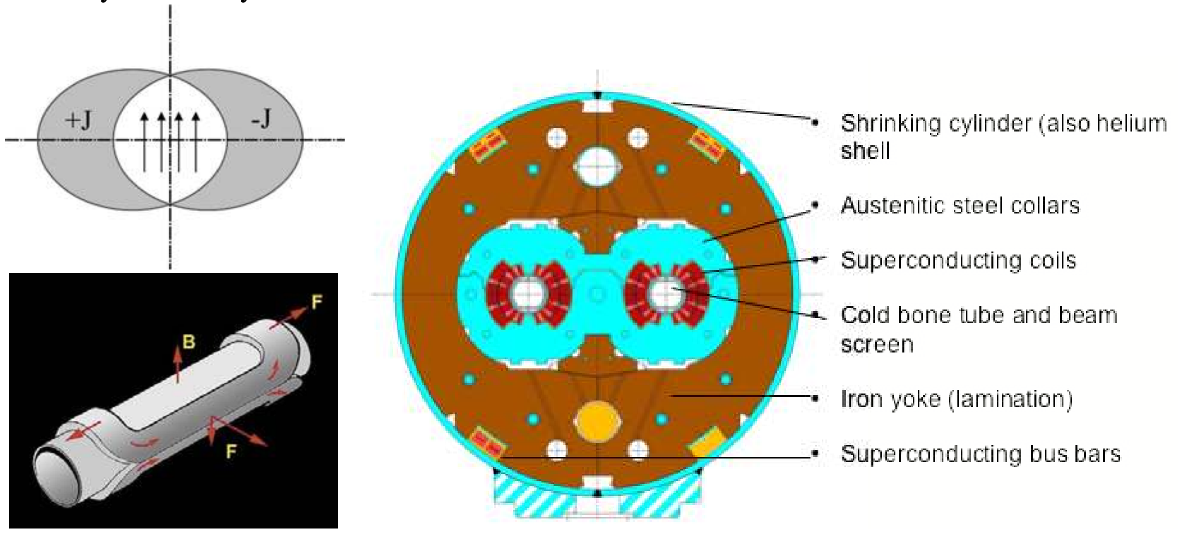

Figure 9. Sketch of an ideal dipole, cross section and coil shape,left; Cross section of the LHC dipole with its main components, right.

The LHC tunnel was inherited from the LEP (Large Electron-Positron collider, [28]) and is not large enough to accommodate two magnets side-to-side to guide the two particle beams. For LHC, the two magnets - each one with its own coil - are lodged in the same iron yoke. This is the basic “two-in-one” concept. This structure is also called “twin” if the coils, as in the LHC dipole, are fully coupled both mechanically and magnetically, as is clear from Figure 9. Initially devised as a way to have a compact system, the “two-in-one” and its extreme “twin” version have been a real challenge because the design is more difficult and more sensitive to mistakes and tolerances. However, it has also contributed to a reduction of the cost with respect to a scheme with two separate magnets, for example the SCC design. We have evaluated the savings at about 15-20% of the cryo-magnet system, or about 10% of the total project cost, which was a key point at the time of approval in 1994-96. In Figure 10 a 3-D sketch of the LHC dipole in its cryostat is shown.

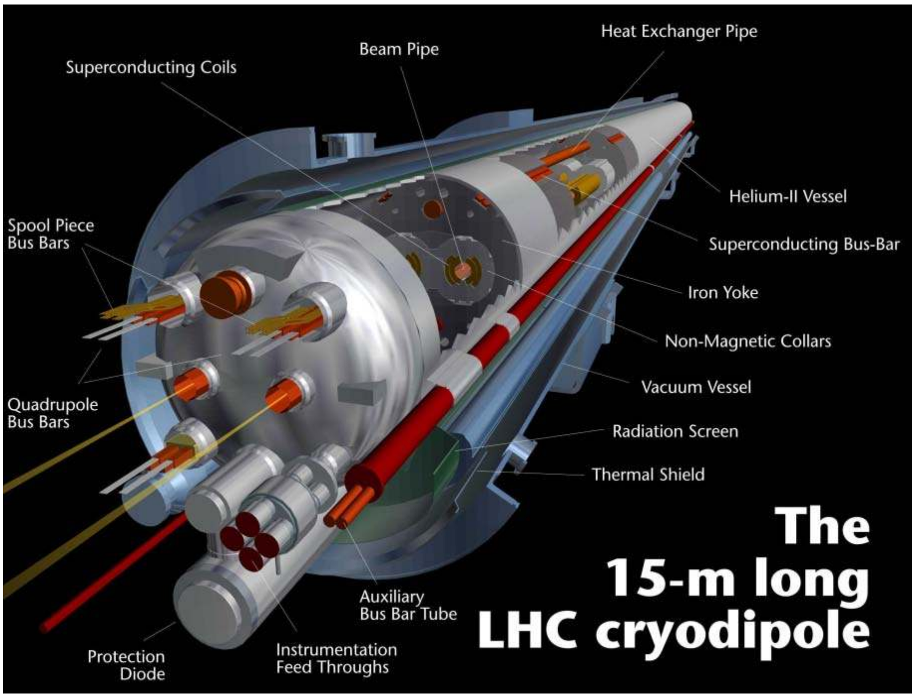

Figure 10. Schematic view of an LHC dipole with the main components indicated

LHC magnets are the last product of a 30 year rush toward high field. As mentioned previously, the current density is the basic property for dipoles (and even more for quadrupoles). Indeed, as shown in Figure 11, any further increase in the dipole field of the LHC, with the same operative working point of 86% of the maximum theoretical current, would have required a very wide coil with an inefficient use of the superconductor [29].

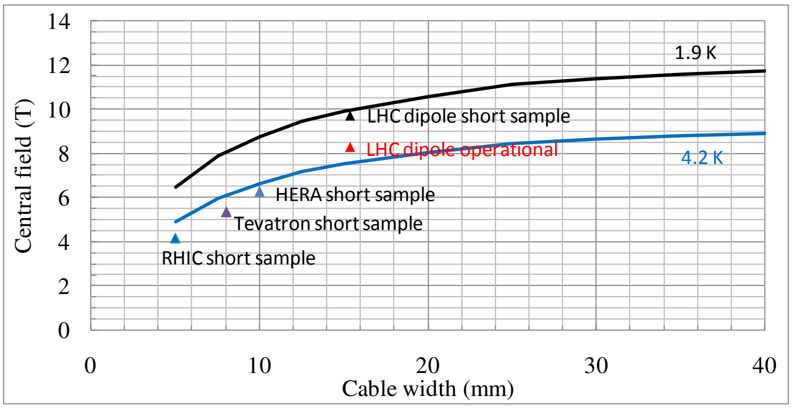

Figure 11. Theoretical scaling law for dipoles based on Nb-Ti superconductor and cosϑ design, with LHC and previous accelerator projects indicated. Courtesy of E. Todesco – CERN.

4.2. Construction

From the point of view of superconductivity the LHC magnet construction has to assure the design prestress with the conductors as near as possible to the ideal position in order to have the minimum perturbation and to avoid premature quenches. Since the field quality at collision energy is dominated by the geometry of the conductor, perfect positioning of the conductor is also a strong requirement from field quality. The main manufacturing steps can be summarized as:

a) Conductor insulation; three polyimide layers were applied, for a total thickness of 120 μm. The outer layer has an additional 5 μm layer of polyimide glue that, once cured at around 180 °C, provides some extra rigidity to the coil assembly.
b) Coil winding; conductors are wound in layers and each layer, being dry, must be accurately supported along its 15 m length.
c) Coil curing, to cure the polyimide resin. This operation is done under high pressure in order to give the coils their basic shape and to position the conductors as near as possible to their ideal position.
d) Coil assembly; pole assembly is done by electrically connecting with an inner splice an inner and an outer coil layer; then four poles are assembled, two by two, in double aperture magnets. At this stage the quench heaters to protect the magnet are mounted between coils and collars.
e) Collaring of the double aperture magnet; this is also a critical operation because the conductors take the position and pre-stress that will determine their performance.
f) The collared coil is then assembled inside the yoke, with the bus bars, and all is welded into the shrinking cylinder under high pre-stress provided by precise presses. The welding operation, as well as the set up of suitable tooling, has been a key operation of the whole process.
g) Completion of the extremities; by mounting the corrector magnets, bellows, and by executing the electrical connection among coils or to the bus bar and to the by-pass diode, a key element for protection.
h) Measurement and alignment of the inside of the magnet apertures; this is done using a suitably developed system and fixation of the cold supports.
i) Closing of the end covers; the covers are welded in place in order to form the superfluid helium vessel, leaving a few entrances, all provided with bellows, for electrical bus bars, for helium and for the two beam vacuum tubes.

The quality of all the main steps has been characterized by measurements, tests and controls. The most innovative was the introduction of magnetic measurements as a cornerstone of the QA test plan[30]. They have allowed detecting at very early stage a difference between design and results in some basic harmonics and we could intervene to correct the coil layout by modifying the conductor spacing at the level of 100 μm. Though small, these changes (at two different times) will be essential for good performance of the accelerator. In Figure 12 the harmonic b3 (sextupole) of the LHC dipole measured at room temperature in the factories [31] is shown with the time of intervention indicated.

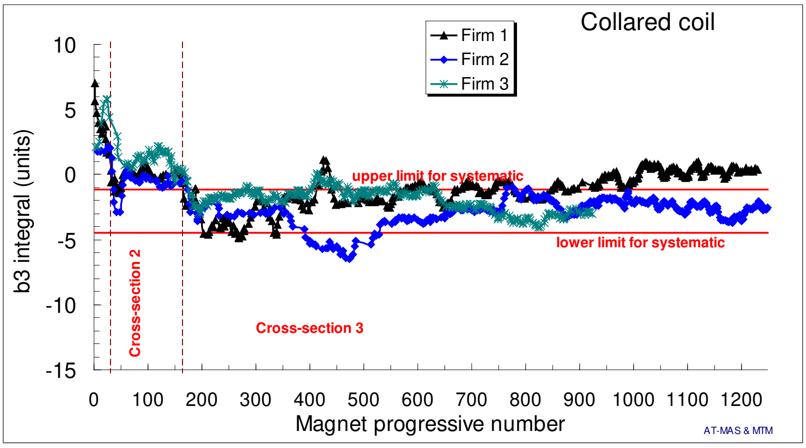

Figure 12. Sextupole components of LHC main dipoles as measured at room temperature (I=8 A) in industry during construction. The two interventions for changing the cross section are indicated by vertical dashed lines. Courtesy of E. Todesco – CERN.

The construction of the LHC magnets has been described in previous papers [32-35], here it is worth to recall that the three manufacturers: Alstom MSA-Jeumont Framatome (Fr) consortium, Ansaldo ASG (It), Babcock Noell (De), have produced magnets according to CERN's detailed design, which allowed small differences in the manufacturing technology. The main components were all procured centrally by CERN and the main tooling (with the exception of the winding machine and curing press) were procured or designed by CERN. Despite this effort of uniformization, small differences in magnet performance are visible among magnets from different manufacturers, both in quench and in field quality. However, all firms were able to provide the magnets within specification and within time (November 2006), with one manufacturer delivering one year in advance, a success that at the beginning was not all granted and constitutes, with the cable production, the best story of the LHC construction [4]. The same is true for the quadrupole production (almost all granted to Accel, De) [32,36,37] as well as for the other large magnets and for most of the large variety of 7700 corrector magnets [38].

4.3. Performance: quench and stability

The margin to critical current is not very high in the LHC magnets and in the dipoles in particular. HeII, with a thermal conductivity 10,000 higher than copper at low temperature, is a very good coolant. However, the high current density and the tiny amount of copper imply that when a perturbation drives a resistive transition, the generated power is large and cannot be easily evacuated. Stability studies, [39,40] established that the quench energy for LHC has two regimes, see Figure 13:

- At $I/I_c < 0.65$ the cable behaves collectively, i.e., there is time for current transfer from the quenched strands to nearby superconducting strands and, due to thermal diffusion and heat transfer, the quenched strand recovers. In this region the minimum quench energy (MQE) is around 1 mJ;
- For I/I_c above 0.8 the MQE is 10 μJ, i.e. a drop of two orders of magnitude, indicating a regime where each strand behaves individually. 10 μJ is the adiabatic stability of the single wire which seems very small compared to the 1.5 K of temperature margin, but one has to consider that, given the small quantity of copper and high J_{copper} at quench of about 1000 A/mm^2 and because of the extremely small heat capacity at 1.9K, the stability margin is really very small.

LHC dipoles work at $I/I_c = 0.6$ at nominal 8.3 T central field (86% of quench current on the load line) and at $I/I_c = 0.75$ at so called ultimate central field of 9 T (93% of quench current on the load line). It is not surprising that, despite the strong prestress, LHC dipoles are not very stable and that training is frequently needed to pass nominal field and that a long training is needed for ultimate operation.

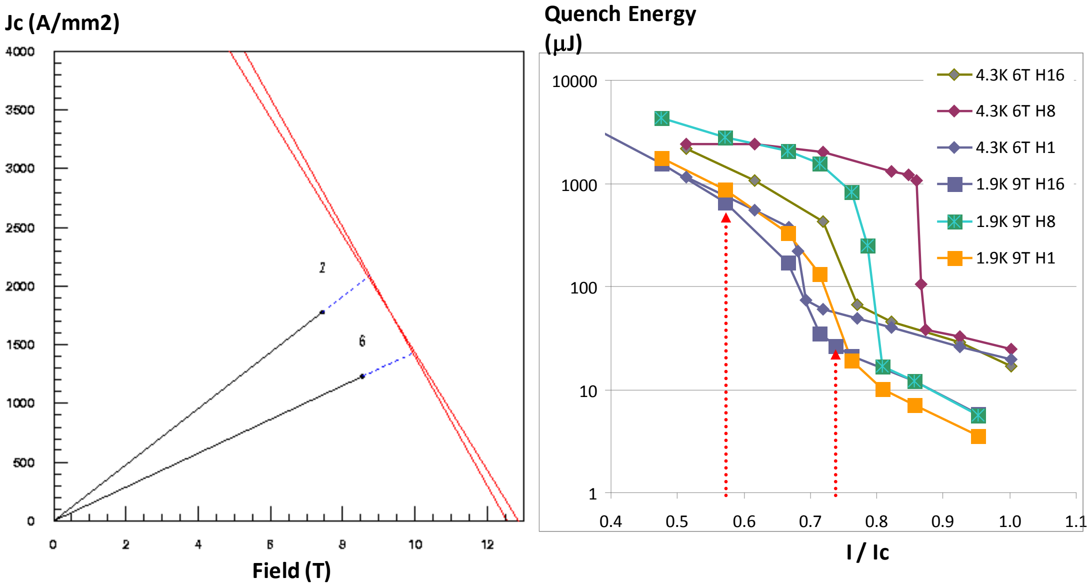

Figure 13. Load line of the LHC dipoles (left) and stability measurements (right). The most important are the large squares (1.9 K), namely H1 and H16, near the edge of the cable. Vertical arrows indicate operational point at nominal (8.3 T) and ultimate field (9 T). Courtesy of A. Verwej and G. Willering – CERN.

All LHC magnets have been cold tested, which has allowed their mechanical and electrical integrity and their quench performance to be assessed. The training behaviour of all LHC dipoles is illustrated in Figure 14, from which one can see that the 1232 dipoles required on average 1 quench/magnet to pass 8.3 T. The quench tests (carried out directly at 1.9 K without precursor test at 4.2 K) are important not only to assess if a magnet reaches and passes the nominal operating field but also to train the magnet in a way that once it is installed in the tunnel it should not require much retraining. Because of the small stability margin the memory between thermal cycles is far from being assured, so the strategy was to push all magnets to the ultimate field of 9 T in the first training curve and submit to a thermal cycle and retraining curve only the weak magnets (defined as the ones that needed more than 9 quenches to reach 9 T). Actually, after some initial delay, the delivery of the magnet production ramped up so fast that the test rate could not follow. The magnet test sequence was then redefined and as a consequence the majority of the magnets were tested only up to nominal 8.4 T or to 8.6 T.

For the limited number of magnets that have been submitted to a thermal cycle, either for checking or because they were the weakest, the number of quenches per magnet to reach the nominal field at second thermal cycle dropped, as expected, to 0.1-0.15, indicating that memory was important to improve the quench performance.

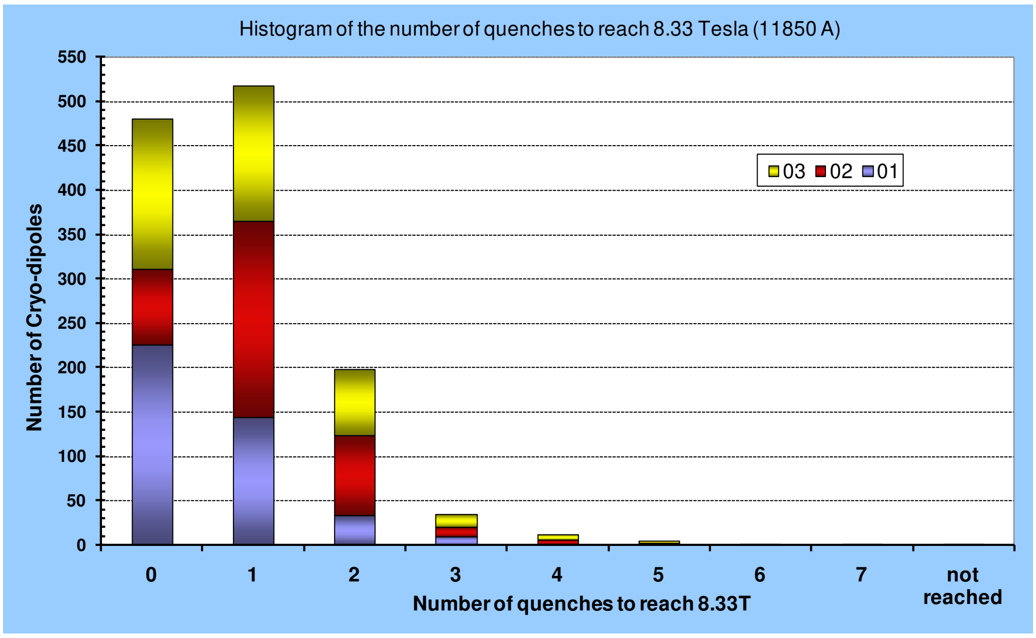

Figure 14. Quench performance to reach nominal field at first test. The different colours represent the three "families" of magnets, i.e. magnets from the different manufacturers. Courtesy of M. Pojer and A. Siemko – CERN.

During commissioning in summer 2008 we found that in the tunnel a family of installed dipoles presented a loss of memory higher than expected. In Figure 15, the forecast of quenches in the tunnel at LHC commissioning (based on the acceptance cold test) is reported for all three families of dipoles: the spread of the curves indicate the uncertainty in the analysis [41]. Markers show quenches actually experienced during the commissioning campaign before start up. For reasons we will explain later (symmetric quench) the dipole current in most sectors was limited to 6.5 T. Only the sector 5-6 was pushed up to 7.9 T. This sector contains a predominance of firm #3 magnets and for them the accentuated loss of memory was recorded. It can be seen that the "firm 3 HC" curve with cross markers stays well below the corresponding forecast from acceptance cold test. For the moment we do not understand the reason for this unexpected behaviour.

This effect, if confirmed, will probably require some 4 months of training campaign of the whole LHC to reach 8.3 T, corresponding to the full 7 TeV energy. However it will be very fast to reach the energy domain of 6.5-6.8 TeV per beam. Since for a hadron collider the discovery potential is a very smooth function of the beam energy, this is not a big issue.

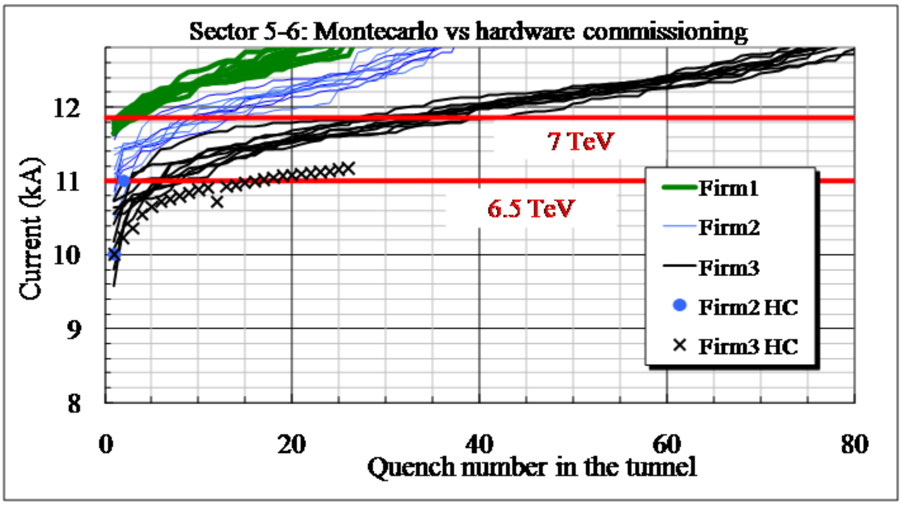

Figure 15. Forecast of quench performance of LHC magnets in the sector 5-6 (1/8 of the machine) inferred by acceptance test on surface, solid curves; actual performance during Hardware Commissioning (HC) of sector 5-6 (black cross or blue dot markers). Courtesy of E. Todesco, CERN.

4.4. Performance: magnetic field quality

As previously mentioned, the geometric part of the field quality was carefully controlled during coil manufacturing. The accuracy of the measurements and of the field model [42] has been demonstrated by the very smooth transfer of the beam in the beam commissioning on 10th September 2008 [43]. The "ease" of the first injection and of circulating beam has also demonstrated the control of magnetization with a remarkable accuracy, a success which must be credited to the very good work in superconductivity of the scientists and industry involved.

The two main areas that still need to be demonstrated in the accelerator with respect to the use of superconductivity are: i) the dynamic effects, i.e., snap back, harmonic variation during ramp and main field and harmonic reproducibility from cycle-to-cycle, and ii) the long term accuracy and stability of the higher order harmonics, i.e. over hours of continuous beam collision, which is critical for reaching the desired luminosity.

5. Installation and Commissioning

The start of installation was strongly delayed by a technical problem with the installation of the cryogenic line in the ring (called QRL); the first sector was made available for magnet installation 18 months later than the scheduled date. The big effort on the cryogenic line absorbed resources from the rest of CERN and deflected attention from some other, subsequently critical, issues such as the preparation of interconnection work.

The IC work was finished for the arc in November 2007, i.e one year after the magnet delivery. It went extremely well despite the great pressure to complete the activity: the leak rate in the 40,000 TIG welds was around 0.4% and out of the 10,000 13 kA Sn-Ag solder joints only 0.1% had to be re-done [44]. The electrical QA also intercepted 0.1% defects in the 55,000 ultrasonic welds on the 600 A bus bars of corrector magnets. However, one of the main QA equipment for checking the quality of the 13 kA splice, based on ultrasonic inspection, was not fully operational until almost the end of the work: only the last sector was inspected with good coverage (80%), with one defective solder joint found and repaired [45]. In view of the subsequent events, this lapse had a big impact.

The sequence of the Hardware Commissioning (HWC) of the magnet system in the tunnel with all ancillary equipment, like cryogenics, power supplies, etc., is quite complex given the number of circuits and powering operations. HWC was strongly delayed in its start by the late availability of both the QRL and the electrical distribution feed boxes. Despite this, in a very short 12 month period, almost all 11,000 circuits were commissioned [46].

An important problem appeared during commissioning of the triplet quadrupole magnets. During the pressure test up to 25 bar there was buckling of the heat exchanger tubes already at 7 bar; this fault was fixed on all triplet magnets. Then at 13 bar a more severe incident occurred, with a large movement due to a design weakness of the longitudinal support. This required a thorough analysis to prevent a future similar incident and a consolidation campaign on all inner triplet magnets in the LHC

The success of the first commissioning with beam on the 10th of September 2008 demonstrated the very good field quality and geometry of the magnets, their precise alignment and very good stability, the accuracy of the power supply and the successful operation of the highly complex 1.9 K cryogenic system. The thermal performance of the magnet cryostats was even better than specified.

Other problems were found but were left to be fixed after the first run, the main being:

- *Symmetric quenches.* The QDS (Quench Detection System) was working only on the differential voltage between the apertures of the same dipole magnet, however it was found that a quench in a dipole could trigger a perfectly symmetric quench in both apertures of adjacent dipoles at 7.5 kA, taking about 650 ms instead of 50 ms to be detected by the QDS. This led to a requirement to limit the powering current to 8.6 kA; meanwhile a new QDS, able to detect such an event, was designed.
- Some magnets showed a *different inductive voltage between the two apertures*. This generated false quench signals during fast discharge. This was temporarily fixed, for the magnets concerned, by increasing the QDS voltage threshold from 100 to 300 mV. We are examining if this can be explained in terms of different inter-strand currents among cables.
- A serious fault (lack of support against electromechanical forces) in the assembly of the 13 kA bus bar inside *empty cryostats* was identified and had to be fixed.

During HWC in 2008 there was not enough time to attend to these and other problems before beam commissioning. They have all been cured this year in parallel with the extensive repair following the sector 3-4 incident (see next section), except for the 6 kA joints and a few empty cryostats, which are less urgent and will be repaired after the 2010 run.

6. Incident in sector 3-4

6.1. Protection Scheme

Before discussing the incident it is necessary to recall the protection scheme [47]. A simplified version is shown in Figure 16; the 154 dipoles in a sector are all powered in series, with one power supply and a dumping resistor in parallel to all circuits, split into two resistors to lower the voltage-to-ground. When a quench is detected on a magnet the dump is activated through a switch. Given the inductance and resistance (determined by the current and maximum voltage) the 1/e discharge time is 104 s, which is far too long for the magnet to survive. Each magnet therefore has a cold by-pass diode and heaters on the coils. As soon as a quench is detected the heaters are fired and the coils are quenched in less than 50 ms. The subsequent sudden voltage rise opens the diodes and the current in the quenched coils decays to almost zero in less than 1 s; meanwhile the whole line (all other magnets and the bus bars by-passing the quenched coils) is still carrying the full current. The bus bars, on which the diode is inserted, bypass electrically the whole magnet but serves also as a connection between adjacent magnets. So during a magnet quench the bus bars carry the global circuit current, decaying with a time constant of 104 s, at the interconnections and in the quenched magnet(s). Of course the bus bar is designed with a copper cross section which is sufficient to safely carry the current during discharge without damage even if its superconductor is driven in normal state.

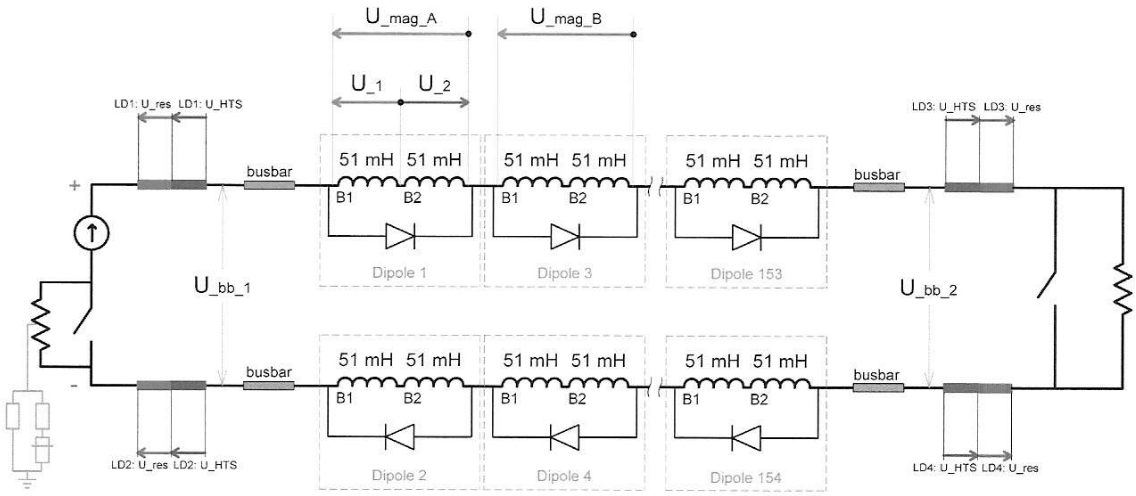

Figure 16. Protection scheme of the LHC magnets during operation (all series connected). The magnets are bypassed, in case of voltage rise, by the diode-bus bar system.

6.2. Incident

On 19th September 2008 during a HWC current ramp to 9.3 kA (about 6.5 T field) of the main dipoles in sector 3-4, an electrical fault occurred in a connection between adjacent magnets. This was the very last ramp before definitive commissioning of the whole machine for operation at 8.6 kA, corresponding to 5 TeV energy.

A sudden increase of the voltage in the main dipole circuit was observed such that the power supply could not deliver the required current and a fast de-ramp with energy discharge on the dumping system was initiated. The discharge was faster than the nominal 104 s time constant and very soon the circuit was divided in two branches, clearly indicating the presence of a short circuit. Many magnets quenched and eventually helium was released into the tunnel and general power was lost in sector 3-4.

At the first inspection in the tunnel, many magnets around the two where the defect originated were found to have been displaced with the interconnection bellows heavily damaged, see Figure 17. In the damaged zone (D-zone), primarily defined where the insulation vacuum was lost and about 750 m in length spanning from magnet Q19 to magnet Q33, considerable damage had occurred. There were deformation of connections, electrical faults (all but the first induced by mechanical displacement), perforation of the helium vessel, local destruction of the beam tube with heavy pollution by debris from the electric arc and from fragments of multi-layer insulation (MLI), breakage or damage of cold support posts, breaches in the interconnection bellows and damage of the warm support jack sustaining the magnets, and cracks in the tunnel floor. The pollution of the beam tubes was much more extensive than the D-zone, spanning the full 3 km-long arc. The report of a task force set up by CERN to analyze the incident and propose possible remedies is available in [48].

Figure 17. Pictures of the damaged zone after the incident. Left: close-up the interconnection where the first arc occurred, with vaporized cryogenic and vacuum pipes and soot deposited everywhere. Right: an interconnection between dipole (blue) and quadrupole (white) with interconnection bellow heavily deformed by displacement of the quadrupole against the dipole. Centre: the same interconnection after removal of the bellows.

6.3. Cause and analysis

The dipole circuit interconnection had a defective joint between superconducting cables. A schematic of the 13 kA interconnection is shown in Figure 18. The technology is soft soldering based on tin-silver alloy, used both to splice the superconducting cable and to connect the copper stabilizer to the cable joint and to the stabilizing copper of the bus bar. When finished the connection looks like a continuation of the bus bars that run along the whole length of the magnet system.

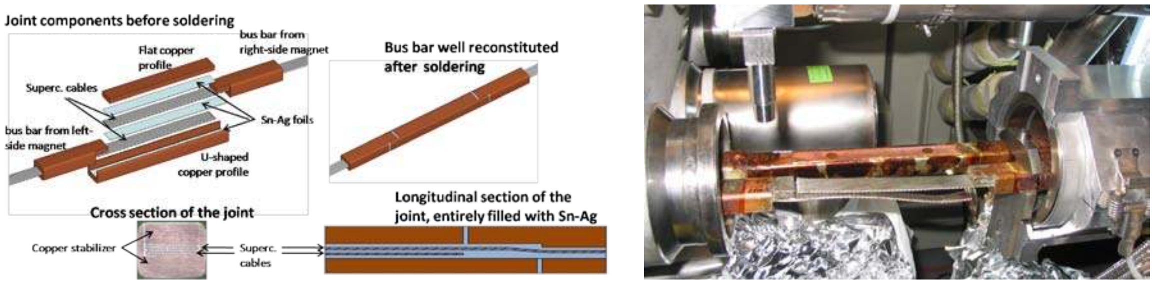

Figure 18. Sketch of the interconnection where the different components are shown, left. A real interconnection under formation, right: there is always a bus bar pair in an interconnection. As-yet unconnected cables are seen in the foreground.

The splice between superconducting cables is specified to have a resistance below 0.6 nΩ at 1.9 K and the actual results on samples during production showed an average of 0.2 nΩ with a variance of less than 0.1 nΩ. The resistance of the splice that failed was later evaluated to be around 220 nΩ.

The fault was not intercepted by the bus bar quench detection system because it was not sensitive enough to detect the ~ 2 mV voltage of the resistive zone; its sensitivity was in fact 300 mV with a 1 V intervention threshold.

It was subsequently found that, during the plateau of current at 7 kA done the previous day, magnet temperature sensors had indicated a small but very clear 40 mK increase above 1.9 K - a clear sign of the existence of an abnormal dissipation of 10.7 ± 2.1 W, corresponding to a resistance of 180-260 nΩ

[48]. We learnt, only a posteriori, that we can use this "micro-calorimetric" technique to detect these type of faults.

A thermo-electrical model was able to simulate a thermal runaway of the normal conducting zone in the splice at 8.7 kA, by making the hypothesis of a resistance of 220 nΩ and no contact between cable and copper stabilizer at the joint and also of a longitudinal gap in the stabilizer, see Figure 19. This discontinuity is very important as it impedes current sharing among cable and stabilizer. The time constant of the current decay in the bus bar is 104 s: while the stabilizer in the bus bar is designed to cope with the heating generated by the current, the copper of the SC cable is sized to withstand in resistive state a discharge time of 1 s, (what we have in a single magnet). If the above mentioned conditions are present together, the joint cannot sustain the discharge and melts away.

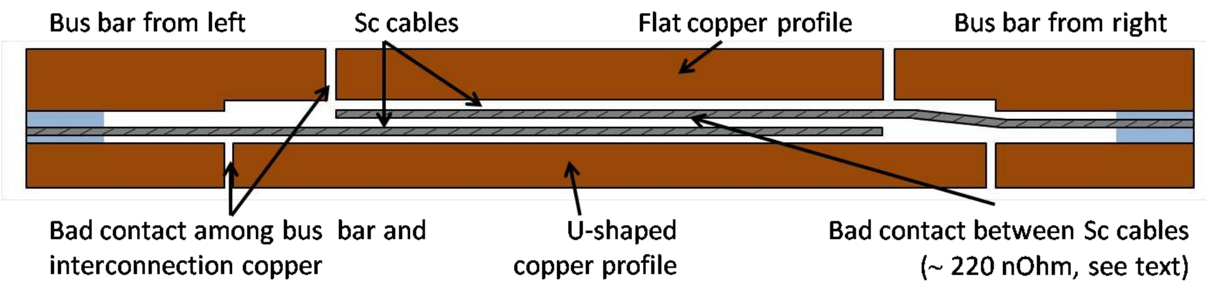

Figure 19. Scheme of the defective joint assumed to have caused the incident.

6.4. Collateral damage
Bad as it was, the incident would "only" have severely damaged two magnets (and polluted a fraction of the beam tube in the sector) if heavy collateral damage would not also have occurred. The 275 MJ power dissipated in the electric arc was sufficient to vaporize the two beam vacuum tubes and to destroy the cryogenic envelope of the line enclosing the faulty connection, which resulted in a massive inlet of liquid helium into the cryogenic insulation vacuum envelope. The helium flooded into the insulation vacuum envelope at an average rate of 13 kg/s with a peak of 20 kg/s, which is a value ten times higher than the one considered as the maximum credible incident (MCI) for the sizing of the pressure relief valves of the vacuum vessel. In addition the helium was violently heated by the power of the arc (2-6 MW). As a result the pressure rose suddenly to 8 bar, well beyond the 1.5 bar absolute for which the system was designed, causing a 56 tonne longitudinal force to build up on the insulation vacuum barriers housed in the quadrupole cryostats. Three quadrupole cryostats equipped with vacuum barriers broke their external supporting jack fixations to the tunnel floor and moved up to 500 mm, see Figure 17, pulling or pushing the adjacent dipoles (30 tonnes each) out of position one by one in a kind of domino-effect. These large movements destroyed or heavily deformed interconnections and pulled apart some other bus bars, generating secondary arcs, which in turn contributed to further helium discharge inside the insulating vacuum vessel and in the beam tube, increasing the pollution. The 8 bar pressure and the push-pull movement severely damaged the large bellows providing the vacuum enclosure around the interconnection and helium was eventually discharged into the tunnel.
The damage was therefore more widespread than had been expected for this type of incident. In summary [49]:

- 53 magnets, 39 dipoles and 14 quadrupoles, were removed from the tunnel: 30 dipoles and 7 quadrupoles were damaged or suspected to be damaged and replaced by spares, while 16 magnets (9 dipoles and 7 quadrupoles) were re-used after minor intervention.
- 9 interconnections suffered strong damage due to electrical arcs.
- 26 magnets were displaced longitudinally.

- Of the 600 MJ of stored energy, about 30% was discharged in the dump resistor, 24% was dissipated as heat inside the quenched magnets (eventually 104 of the 154 series connected dipoles did quench) and 46% was lost in arcs and electrical faults (i.e. sufficient energy to melt 375 kg of copper).
- 6 tonnes of helium were lost in the tunnel, and eventually to the atmosphere, out of the initial inventory of 15 tonnes for the sector.
- The two beam vacuum tubes were polluted with MLI for the 2.8 km length of the arc; a little less than 1 km was contaminated by soot, coming from molten copper and insulation.

6.5. Remedies and mitigation measures

The above-mentioned task force [48] proposed a number of remedies, mitigation measures and points to study to improve safety and reliability. The following recommendations have been already implemented to reduce the risk of such an incident and, in case, to limit collateral damage:

- Implementation of a new QDS on the bus bars and interconnection line, with a sensitivity threshold of 0.3 mV in the ramp. In steady state the new system can detect a bad splice with R > 1-2 nΩ, well below the runaway threshold, now estimated to be around 50 nΩ. The new QDS will also detect symmetric quenches. The present magnet QDS will be used in such a way as to also detect bad splices inside magnets: it has already been found that three magnets (two installed and 1 in reserve) have defective internal splices of 100, 50 and 25 nΩ. As we could only test half of the machine we might detect more cases when the LHC is cooled down. Internal splices, however, are covered by the QDS and protected by the bypass diode.
- The cryostats of the dipoles that were warmed up (half the LHC) have been equipped with new 200 mm relief ports for evacuation of helium. This should keep the pressure well below the design value of 1.5 bar absolute even in case of a helium loss rate of 40 kg/s, twice that of the incident in 3-4 and taken now as the new MCI. The half of the LHC that was kept cold could not be equipped with such new ports; however, some existing ports on the quadrupoles have been equipped with additional low pressure relief devices. This measure will keep the pressure below 3 bar in case of a MCI. This mitigation measure, together with better fixing to the tunnel floor of all 100 quadrupole cryostats with vacuum barrier, would enable, as far as the pressure rise is concerned, to run the accelerator at 5 TeV.

6.6. Lesson drawn from the incident: weakness of stability at interconnection

The above described measures do not fully protect against the fact that the splice between superconducting cables may be good but the surrounding copper stabilizer may not be in contact with the cable, as shown in Figure 20. Actually, if the stabilizer is in good contact with the superconducting cable but just has a small – a few mm – longitudinal gap there is no danger: in case of quench of the joint the current has to pass through the copper of the superconducting cable, however the small generated heat is easily evacuated to helium or to the bus bar through solid conduction. On the contrary, when this gap is coupled with a lack of tin-silver, i.e., the cable at the splice-to-bus bar transition is not in good contact with the stabilizing copper for a certain length, the situation can diverge. The current has to flow through the cable for the whole length where the cable is isolated and the heat may become too large to be evacuated without a large temperature rise and a thermal runaway may initiate, rapidly reaching the melting point in a few seconds.

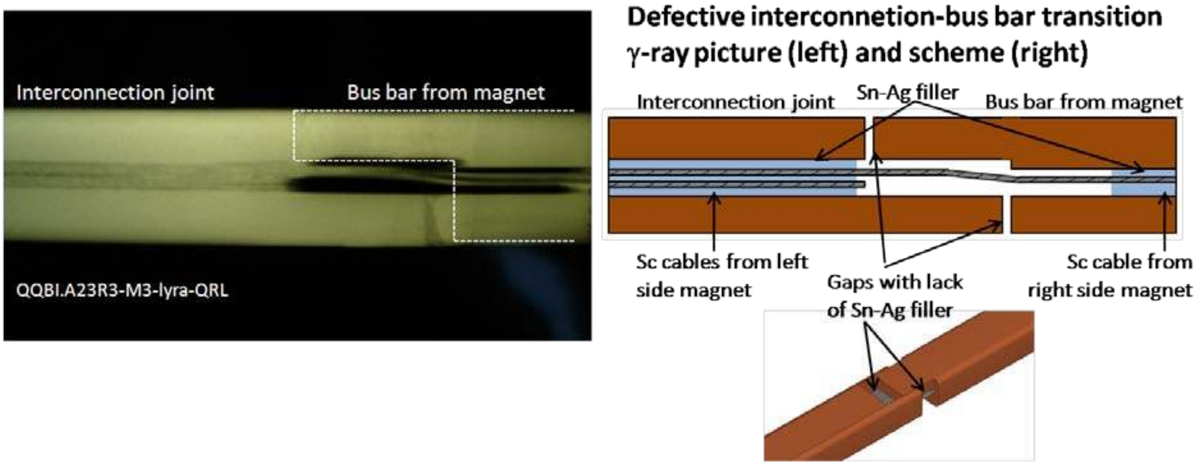

Figure 20. Defective interconnection (with SC cable detached from stabilizer). In the gamma-ray photo the two vertical gaps appear filled with solder: however, electrical measurement and visual inspection show they are actually open, like in scheme at the right, so there is no continuity in the stabilizer and current has to flow in the isolated cable.

The danger of the lack of stabilizer continuity was not immediately realized after the incident. The incident was triggered by a bad splice (i.e. bad SC-to-SC joint) generating internal heat; in the next run we will be able to detect bad splices with the new QDS and we are protected against this failure. However, an interconnection joint can be quenched by external heating, for example by warm helium coming from a nearby quenching magnet. In such a case the lack of stabilizer continuity could cause a bus bar thermal runaway and is a more subtle enemy than a bad splice, since it is more difficult to detect. A diagnostic method was implemented: by measuring a bus bar in its resistive state over a minimum length (2 or 3 magnets, i.e. 30 or 45 m) one can infer if there is a zone or zones where the cable is not in contact with the stabilizer in conjunction with a gap in the stabilizer itself. Unfortunately we could measure only in the four sectors that were warmed up. The four cold sectors had to be measured at 80 K with much less accuracy; as a result one of these sectors was warmed up in order to check a possible bad joint. In the four sectors where we had time to measure and repair, all bad joints where the defect was longer than 20-25 mm were fixed. However, in a fifth sector that was warmed up, only 3 joints were repaired, leaving behind defects of almost 40 mm. In the three sectors which were not warmed up, due to uncertainty in the cold measurements, we cannot exclude one, or more, 70 mm long defect.

Of course such potential length of defect limits the maximum safe current for powering the magnets with no risk of thermal runaway in the joints. Different studies have been made, based on different models, in order to evaluate which is the critical defect length. An experiment performed with a cable insulated from the bus bar stabilizing copper for 50 mm was performed to tune the input parameters for simulations. Based on these studies [50] it was decided to limit field of the magnets to 4.5 T, to allow collisions at half energy of 3.5 TeV. Only after a few months will the accelerator energy be raised, in the 4-5 TeV range (corresponding to a dipole field of 5 to 6 T). However, to exploit the full potential of the accelerator by pushing the magnets to 8.3 T, we need to fix all bad interconnections with the cable detached from the stabilizer copper. This will be a long campaign and time will be allocated for such a job only after the machine has generated enough results and data to satisfy the high energy physicists.

7. Conclusions

LHC is the largest scientific instrument ever built and it relies heavily on superconductivity. The very good design and manufacture of the 1200 tonnes of top quality superconducting cable and of the 1700 large superconducting magnets has allowed a timely start-up of the machine. The high quality of the magnets, all individually tested at above nominal field of 8.3 T, was a key ingredient in the spectacular success of the first beam on 10th of September 2008. Unfortunately, a fault in an electrical connection between magnets has caused a delay of more than one year, in order to repair the 750 m long damaged zone and carry out the necessary consolidation measures on the whole ring to assure electrical and mechanical protection of the magnets. The analysis of the incident revealed that the fault, apparently trivial, stems from a design and manufacturing weakness of the joints of the bus bar at magnet interconnections as well as inadequate methods of QA during construction and commissioning. In addition to the "trivial" mistake of a bad splice, a more subtle defect, related to a lack of continuity in the copper stabilizer, is now evident and is worrying since it is diffused around the machine. The incident also revealed lack of adequate risk analysis (maximum MCI) and of understanding all consequences, as well as an incomplete global magnet circuit protection analysis and an inadequate detection of a dangerous situations. The lack of a global integration approach with thorough examination of the fault tree is one of the main lessons to draw. To avoid such a problem experts of superconductivity and experts of system integration should work in closer collaboration all along the project.

It will still take a couple of years before the machine is fully fixed and capable of delivering 7 TeV beams, i.e., 8.3 T in the magnets. Meanwhile, other required consolidation, revealed during hardware commissioning, like symmetric quench detection and empty cryostats, has been carried out. The next run will be limited to 3.5 TeV, because full mechanical consolidation could not be completed without warming up the entire machine. Once the defective bus bar connections are fixed and the mechanical consolidation is complete, the machine can operate, as far as the magnet system is concerned, at up to 7 TeV, provided the necessary time of about 4 months is allocated to train all the magnets. Operation at up to 6.5 TeV should be possible with virtually no need for additional training quenches.

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