PERFORMANCE OF THE LHC MAGNET SYSTEM

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Abstract

The LHC magnet system, essentially composed of superconducting magnets operating at 1.9 K, has been largely commissioned in 2007-08. Before the serious incident of 19th September 2008, the magnet system was commissioned up to 7 kA (4 TeV proton beam energy); six (out of eight) sectors were commissioned up to 5.5 TeV and one up to 6.6 TeV. For more than one week, both beams have been injected, circulated and captured in the RF bucket, thus assessing the optics at injection energy. The incident in sector 3-4, originated by a serious defect of a high-current joint between magnets with large collateral damage, has changed the plans: 53 magnets in the damaged zone have been substituted or repaired meanwhile a campaign of consolidation is under way to allow safe restart of the accelerator in fall 2009.

All these points and other issues presented and discussed, with emphasis on the incident in sector 3-4.

INTRODUCTION

The LHC magnet system is composed by some 10,000 superconducting magnets of various size and energy and by 154 resistive magnets. The complete system is described elsewhere [1] and we refer to Table 1 for a comprehensive list of the superconducting magnets.

Table 1: LHC Superconducting Magnets

Type	No.of units	Aper-tures	Function
MB	1232	2	Main dipoles
MQ	392	2	Arc quadrupoles
MBX/MBR	16	1	Separation & recombination dipoles
MSCB	376	2	Combined chromaticity & closed orbit correctors
MCS	2464	1	Sextupole correctors for persistent currents at injection
MCDO	1232	1	Octupole/decapole correctors for persistent currents at injection
MO	336	1	Landau damping octupoles
MQT/MQTL	248	1	Tuning quadrupoles
MCB	190	1	Orbit correction dipoles
MQM	86	2	Dispersion suppressor & matching section quadrupoles
MQY	24	2	Enlarged-aperture quadrupoles in insertions
MQX	32	1	Low-beta insertion quadrupoles

It is noteworthy that two important choices serve to characterize the LHC magnet system:

- The nominal field in the main dipoles, 8.3 tesla, is much higher than that of previous superconducting accelerators, (where the field is between 3 to 5 tesla). This required the use of superfluid helium, at 1.9 K, to boost the performance of the superconductors.
- The adoption of the so-called “Two-in-One” concept, where two magnets around the beam tubes are located in the same cold mass. For the dipoles the “Twin” design was chosen, where the two magnets are magnetically and mechanically coupled.

DESIGN AND CONSTRUCTION

The design and construction of the magnet systems has been reported in previous papers [2-4]. Here we recall the major steps in the construction of the magnet system:

1. Production of the superconducting cables: from 1999 to 2005
2. Production of the main magnets: from 2000 to November 2006
3. End of cold test: March 2007
4. Preparation and installation of magnets in the tunnel: from March 2005 to March 2007
5. Interconnection and associated works: from July 2005 to October 2007
6. Commissioning of the magnet system: from May 2007 to September 2008

The actual times employed for construction, assembly in the cryostats, preparation and installation of the main dipoles, are summarized in “Dashboard” format in Fig. 1.

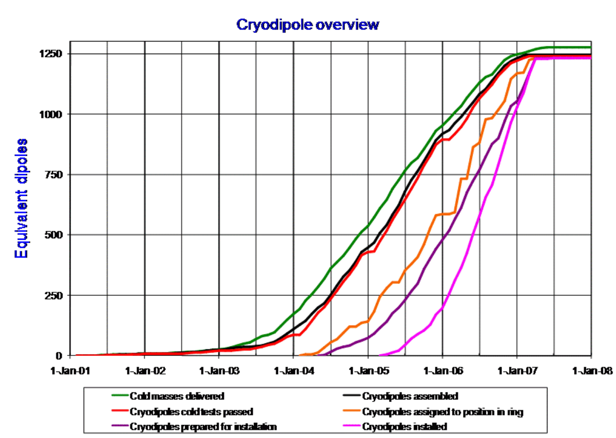

Figure 1: Dashboard for the of LHC dipoles.

The test and measurement activity did not follow the ramp up in dipole production in 2003/04, so a review was held at the end of 2003 to consider how to speed up. The modified cold testing procedures entailed the following:

- Reducing magnetic measurement down to 10-15% of the total number. The uniformity of cable production (important for dynamic and persistent current effects) and the good correlation cold-to-warm for geometric effect (in industry all magnets were measured warm) enabled this reduction without hampering the knowledge of the magnetic field.

- Reducing the acceptance test in term of quench behaviour: magnet were no longer systematically pushed to 9 T, but accepted with 2 quenches to go above 8.4 T (8.3 being the nominal value) in 2004, which was modified to 3 quenches to get above 8.6 T from 2005 on.
- Skipping some electrical measurements like splices that are inside the magnets. In reality this was not clear at the time but was revealed after the incident of 19 September 2008. Splices were found to be always very good at beginning of production, below sensitivity threshold with one doubtful exception (duly returned to the manufacturer for repair). The internal splices are covered by the QDS (quench detection system), so probably it was not considered to be a risk. This later turned out to be not the case.

These new procedures helped to catch up with the delay in cold testing. The quench performance of the main dipoles was very good, with only 12% of dipoles requiring to be tested with a thermal cycle: based on this a maximum number of 200 quenches were estimated to be necessary in the machine to enable 7 TeV operation [5].

In total 24 main dipoles were returned to the manufactures for repair: 12 for electrical faults (mainly quench heater problems); 10 for quench performance; one for mechanical reasons; one for a bad SC cable. In 2004 it was decided to manufacture 30 additional spare dipoles and in total we had 44 dipoles in reserve, 3.6% of the total installed number (the available dipoles at the moment of the incident were 40). The same percentage or more of reserve units was retained for the other magnets, with a few exceptions (MQ: 13 cold masses not "cryostated"). The assembly of magnets in their cryostats as well as cold test and preparation was entirely carried out at CERN in a factory-style activity involving more than 250 people between CERN personnel, associates and external contractors [6-9].

INSTALLATION AND INTERCONNECTIONS

Installation

The start of installation was strongly delayed by a technical problem with the installation of the cryogenic line (QRL), since the magnets can be installed only after complete installation of the QRL in a sector. While the installation of the QRL in the eighth and last LHC sector was delayed by about 10 months, the first sector was made available for magnet transport only 18 months later than the scheduled date. This provided more time for the other systems - including the magnet system. However, the big effort on the cryogenic line did absorb resources and attention from the rest of CERN and deflected attention from some other critical issues, such as the preparation of interconnection work. Moreover, the delay in the start of the magnet installation called for a huge installation rate, peaking at more than 100 large magnets per months (against a nominal of 50), forcing to increase the corresponding rate of magnet preparation, which in turn required a increased technical and logistic effort. The industry-supplied cold mass is itself the most complicated component, but many difficult operations had also to be carried at CERN in order to convert the bare cold masses into complete cryo-magnets ready to be installed. The long delay of the magnet installation due to the QRL problem was such that at a certain point about 1000 large magnets had to be stored outside, many of them for a period of 1-2 years (in the worst case 1200 days).

Interconnections

The interconnection (IC) work and results have been described in several papers [10-12]. Here we wish to recall that the IC is a very complex operation with many steps that have to be sequential over various unit lengths (magnetic cells, cryogenic subsector and vacuum subsector: each one with different length). The main technologies, all automatic, are i) the soft soldering employed to connect the high current (6-13 kA) superconducting cables in the magnet bus bars; ii) ultrasonic welding to connect with neither solder nor flux the small (600 A) superconducting cables of the corrector magnets; the TIG welding of austenitic steel of the various connections and bellows for the vacuum, bus bars and cryogenic lines.

As in the case of magnet preparation and installation, the IC work had to speed up to recover part of the initial delay. At the peak more than 100 persons employed by the main contractor were executing series work in the tunnel, complemented by about 20 persons from CERN for special actions, and about another 120 persons from CERN and collaborating Institutes to carry out various checks and tests foreseen in the QA plan. At the peak, we worked in parallel in six of the total of eight sectors of the LHC, covering a length of more than 20 km. The last IC in the arc was made in November 2007; a few ICs in the interaction region (IR) were finished in April 2008, because of delays due to having to solve problems with the inner triplet quadrupole systems (buckling of the heat exchanger tubes and, later, also of the longitudinal support during pressure test).

The IC work went extremely well despite the great pressure to get it done: the leak rate in the TIG welds was around 0.4% and the number of soldering joints that had to be re-done was at the 0.1% level. The electric QA intercepted also 0.1% defective ultrasonic welds of the 600 A bus bars. However, one of the main QA pieces of equipment for checking the quality of the 13 kA splice, based on ultrasonic inspection, was not really 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.

MAGNET COMMISSIONING

General hardware commissioning (HWC) of the magnet system and the machine is covered by other papers [13-18]. The sequence is quite complex given the number of circuits and complexity of powering operations. It is recalled that HWC was also strongly delayed in its start by the late availability of QRL and of the electrical distribution feed boxes. Despite this, in a very short time, basically one year, almost all 11,000 circuits were commissioned. The success of the first beams day, 10th of September 2008, demonstrated the very good field quality and geometry of the magnets [19], 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.

Problems and Repair or Consolidation Required

A lot of small but annoying problems had to be fixed but were left for after the 2008 run. The main problems concerning the magnet behaviour were:

- Symmetric quenches. The QDS was working only on differential voltage between the apertures of the same dipole magnet. In practice it was found that a quench in a dipole could trigger, perfectly symmetric quenches in adjacent dipoles at 7.5 kA, taking about 650 ms instead of 50 ms to be revealed. This led to a requirement to limit the powering current to 8.6 kA before a new layer of QDS, able to detect such an event, was installed.
- We had magnets that 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.
- Some splices in the 6 kA line are made in hairpin or "praying hands" topology. These joints will likely suffer from fatigue effect after a few thousand cycles. The joints will be fixed later.
- Almost all singly powered magnet circuits were plagued by problems with the helium level gauges.
- A serious fault (lack of support against e.m. forces) in the assembly of the 13 kA bus bar inside the empty cryostats has to be fixed.

During HWC there was not time to attend to these problems before beam commissioning. They are being cured in parallel with the extensive repair following the incident (see next section), except for the 6 kA joints that are less urgent and will be repaired after the 2010 run.

Quench training

Some types of magnets lost, partially or totally, the "memory" of the training done during acceptance testing at the surface. In particular the main dipoles, that in number and energy largely dominate the LHC hardware, were trained to high field in one sector only, up to 6.6 TeV (or 7.9 tesla). By extrapolation from results of this sector to the entire machine we now estimate that a total of 800÷1000 quenches will be needed to enable the machine to run at 7 TeV, requiring from 2 to 4 months. At this moment we don't know which parameter is generating this loss of memory, which seems to be more important for the dipoles from one of the three companies that produced them.. One possible explanation is the – unplanned – storage in the open air, for up to 3 years, which may have led to loss of pre-stress in the SC coils. As mentioned this behaviour is not limited to the main dipoles: some quadrupole and other dipole types apparently show the same phenomenon. Operation at 6.5 TeV will require some 85 quenches of the main dipoles, which represents about 2 weeks of work.

INCIDENT IN SECTOR 3-4

Event

On 19th September 2008 during a current ramp to 9.3 kA (5.5 TeV proton energy) of the main dipoles in sector 3-4, an electrical fault occurred in a connection between adjacent magnets. This was the last ramp before definitive commissioning of the whole machine for operation at 8.6 kA, corresponding to an energy of 5 TeV.

What was observed was a sudden increase of the voltage in the main dipole circuit 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, normally exponential with a time constant of 104s, was erratically faster indicating an abnormal loss of energy; soon after the start of discharge, the circuit was divided in two branches, clearly indicating the presence of a short circuit. Many magnets quenched and eventually helium was filling the tunnel and general power was lost in the sector 3-4 itself.

At the first inspection in the tunnel, many magnets, around the two where the defect originated, were found displaced and the interconnection bellows heavily damaged. 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 mechanical damage had occurred in the magnet connections, electrical faults (all induced by mechanical displacement, except the first), perforation of the helium vessel, local destruction of 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, breach in the interconnection bellows and damage of the warm support jack sustaining the magnets, and cracks of the tunnel floor. The pollution of the beam tubes was much more extended than the D-zone, spanning along the whole arc. The report of a task force, chaired by Ph. Lebrun (CERN), set up to analyze the incident and propose possible remedies, is available in [20].

Cause and Analysis

The dipole circuit interconnection had a defective joint between superconducting cables. A schematic of the 13 kA interconnection is shown in Fig. 2. 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 perfect reconstitution of the bus bars system that run along the whole length of the magnet system.

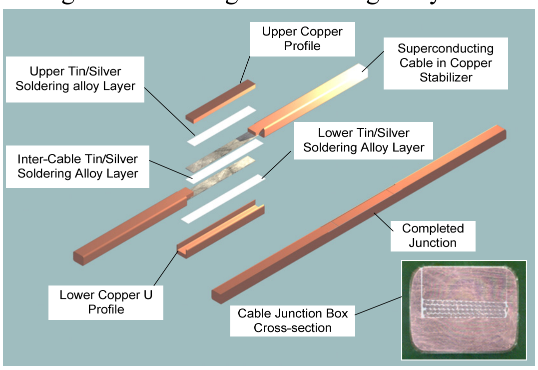

Figure 2: Schematic of a 13 kA connection.

The splice between superconducting cables is specified to be below 0.6 nΩ and the actual results on sample witness showed an average of 0.2 nΩ with a variance of less than 0.1 Ω. The one that failed was later evaluated to be around 220 nΩ. Unfortunately the quench detection system of the bus bar was not sensitive enough to detect the ~ 2 mV voltage of the resistive zone, its protection being ensured for the entire length of the bus and correspondingly set to a 1 V threshold.

It was found that data of temperature sensors placed in the magnet indicated, during the plateau of current at 7 kA done in the previous days, a small but very clear temperature gradient with a difference of up to 40 mK - a clear sign of the existence of an abnormal dissipation of 10.7 ± 2.1 W, corresponding to a resistance of 180÷260 nΩ. A thermo-electrical model was then able to simulate a thermal runaway of the normal zone in the splice at 8.7 kA, by making the hypothesis of a resistance of 220 nΩ and no contact between cable and stabilizer at the joint and also of a longitudinal gap in the stabilizer. 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 copper of the 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.

A longitudinal gap, either total or partial, were reported to be not infrequent in the interconnection works, so a very bad splice is likely to be without protection.

Collateral Damages

Bad as it was the incident would have heavily damaged two magnets "only" (and polluted a large fraction of the beam tube) if heavy collateral damage would not have occurred. The power dissipated in the electric arc was sufficient to destroy the cryogenic envelope of the line enclosing the faulty connection with massive inlet of liquid helium into the vacuum envelope; the two beam vacuum tubes were also vaporized. The helium flooded into the vacuum enveloped 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 for the sizing of the 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 longitudinal force to build up on the insulation vacuum barriers housed in the quadrupoles cryostats. Three of these units broke their external supporting jack fixations to ground and moved up to 500 mm, pulling or pushing the adjacent dipoles (30 tonnes each) that were moved one by one in a kind of domino-effect. These large movements destroyed or heavily deformed both interconnections and bus bars, generating secondary arcs, which in turn contributed to further helium discharge inside the vacuum vessel and in the beam tube, increasing the pollution. The 8 bar pressure and the push-pull movement severely damaged the large bellow providing the vacuum enclosure around the interconnection and helium was discharged into the tunnel.

As a summary we can state that:

- 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 (9 dipoles and 7 quadrupoles) were re-used after minor or no intervention. Some of these 16 units were removed as a precaution, being near to damaged material..
- 9 interconnections suffered damage. due to arcs.
- 26 magnets were displaced longitudinally (either the whole cryostat, together with the cold mass inside, or the cold mass with respect to the cryostat)
- 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 the various 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 of length of the arc; a little less than 1 km also contained debris coming from molten copper and insulation and, required strong cleaning.

Remedies or Mitigation Measures

The remedies taken have been:

- Implementation of a new QDS on the bus bars and interconnection line, with a sensitivity threshold of 0.3 mV. In steady state, a 10 μV sensitivity level is possible, enabling to detect a bad splice with R > 10 nΩ, well below the runaway threshold, now estimated to be beyond 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 been found that three magnets, (two in the LHC and 1 in reserve), have defective internal splices of 100, 50 and 25 nΩ. In the first and third cases, it was confirmed on opening that such a high value of splice resistance is due to absence of solder. As we could only test half of the machine we can expect to detect more cases when the LHC is cooled down. Internal splices are covered by the QDS and protected by the bypass diode.

- The cryostats of the dipoles that were warmed up (half LHC) have been equipped with new 200 mm ports for evacuation of helium. This should keep the pressure well below 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 new maximum credible incident (MCI). The half LHC that has remained cold cannot yet be equipped with such new ports, but 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.
- As it is not possible to fully implement the remedies in half of the accelerator, we will run at up to 4 TeV per beam (slightly below 7 kA) for a certain period, and then possibly push the machine up to a maximum of 5 TeV (8.6 kA in the dipoles), in order to minimize damage in case of faults. Another mitigation measure is to reinforce the anchoring to ground by a factor 2 in all SSS with vacuum barrier: this should guarantee no movement of the SSS cryostats even at 3 bar absolute of pressure (making the reasonable hypothesis – to be tested – that the support posts withstand twice their nominal load).

CONCLUSIONS

The complex magnet system of LHC has been completed and 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 made necessary a stop that will last 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. Meanwhile, other required consolidation, revealed during hardware commissioning, is being carried out. The next run will be limited to 4 to 5 TeV, because full mechanical consolidation cannot be completed without warming up the entire machine. Once this is done, the machine can operate, as concerns the magnet system, at up to 7 TeV, provided the necessary time of 3-4 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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