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LHC: Experience from the 2008 start-up, preparation and outlook toward 2009 Commissioning

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Summary. — The LHC Collider start-up was successfully achieved on the 10 September 2008. This date is a milestone marking a long path started fourteen years ago with the LHC approval in December 1994. But other milestones are now expected. In fact, after about 10 days of operation, the LHC was subjected to a major stop caused by a faulty interconnection on the magnets interconnections. The fault caused severe collateral damages. This paper shortly recalls some of the achievements of the 10 September start-up and focalizes on: the incident of the 19th of September; its causes and the collateral damages; status of reparation; overlook on the modification made on the Accelerator to limit the repetition of such type of accident and finally looking toward the 2009 Commissioning.

PACS `29.20.-c` – Accelerators.

1. – LHC Commissioning in 2008

After an intense phase of Machine Commissioning (without beam) all along 2008 with test and qualification for the start-up with beam of all magnetic circuits (see fig. 1), the date of 10 September 2008 marked the first complete injection tests and the start of the Beam Commissioning Phase of the LHC. Despite the fact that the commissioning with beam was curtailed 9 days after by the incident in Sector 3-4, these first days of LHC operation had remarkable results.

The injection tests of both proton beams (on the full circumference of the LHC) were rapidly and successfully achieved on the 10 September morning. Such rapid injection test achievement seems to be an outstanding result in the history of commissioning of particle physics accelerator and is directly linked to several factors, among them we could mention:

– Excellent performance of all the key elements of the LHC complex (for example, performance and quality of the Arc main magnets, of all the ancillary circuits, of the beam instrumentation and of the data acquisition chain).

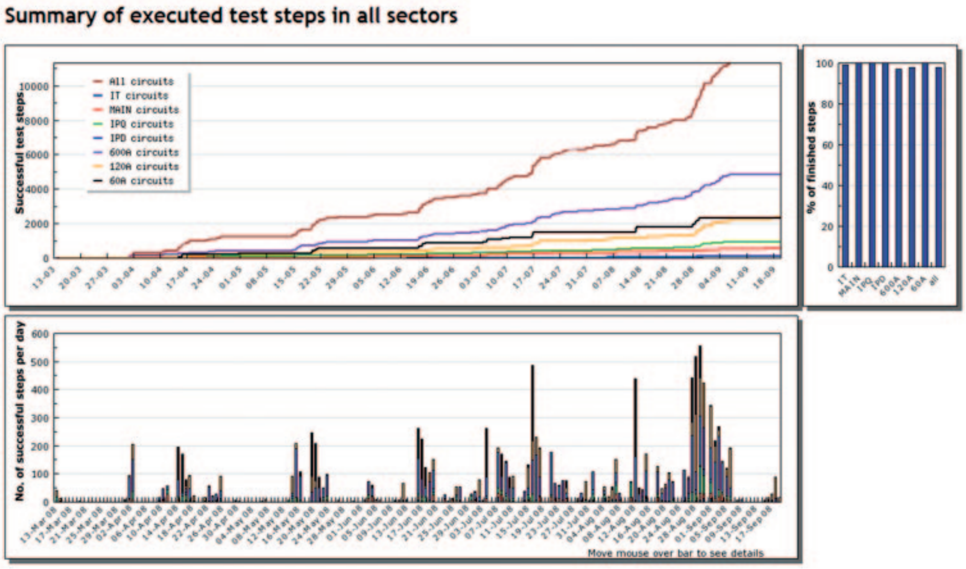

Fig. 1. – LHC Machine Commissioning during 2008: 11122 tests steps completed and successfully achieved (for a total of 11321 to be finally executed).

– Readiness and deployment of all necessary software and controls necessary for a successful start-up of the beam activities (including a robust and complete magnet model based on processing and analysis of measurement data).

– Preparation time dedicated by all the involved Teams to check all the indispensable and "sensible" aspects for a successful start-up of the beam activities (*e.g.*, beam operation requirements, measurements, software, controls).

– Highly motivated and organized Teams in the CERN Control Center dealing with the LHC Machine Commissioning (without beams) all along 2008.

In the 8 days following the start-up, a remarkable amount of work on all the systems was performed: including beam instrumentation (all types), beam dump system, RF and beam control loops, polarity checks of correctors and quadrupoles, beam measurements like aperture scans, beta beating measurement and coupling analysis.

Details on Commissioning and start-up results of LHC can be found in refs. [1-3].

2. – Incident of 19 September 2008

Immediately after the incident a deep investigation program started under the direction of a task force mandated to establish the failure sequence, to analyze and explain the sequence of events and to eventually recommend preventive and corrective actions to avoid a further incident of the same type.

It was finally established that the initial fault developed in a Superconducting (SC) cables splice interconnection on the main dipoles electrical circuit (a series of 154 magnets) where both the longitudinal continuity of the copper (Cu) stabilizer and the bonding between the SC cables to the stabilizer were not correctly executed (see fig. 2).

A study on how the energy stored in the magnets (at the moment of the fault the dipoles circuit was powered at 8714 A) was discharged showed that almost half of the

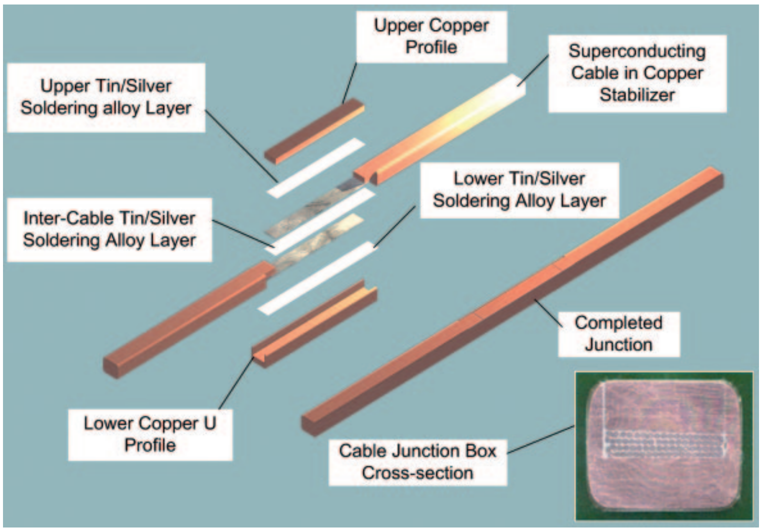

Fig. 2. – The layout of SC cables interconnection splice on the main dipole circuits.

600 MJ stored energy was dissipated through electrical arcs which punctured the helium vessel (see fig. 3).

This caused a massive helium discharge from the cold mass into the insulation vacuum with a flow that was calculated reached a peak of about 20 kg/s. Such a value is well above the design value of 2 kg/s for which two DN90 relief devices were installed on each insulation vacuum subsector. Consequently, the pressure rise was responsible for big axial forces on SSS vacuum barrier, which displaced the cold masses and caused the majority of the collateral damages (see fig. 4).

Secondary arcs were also created in other different locations. Wide regions of the beam vacuum were contaminated with debris of Multi Layer Insulation sheets (MLI) or soot.

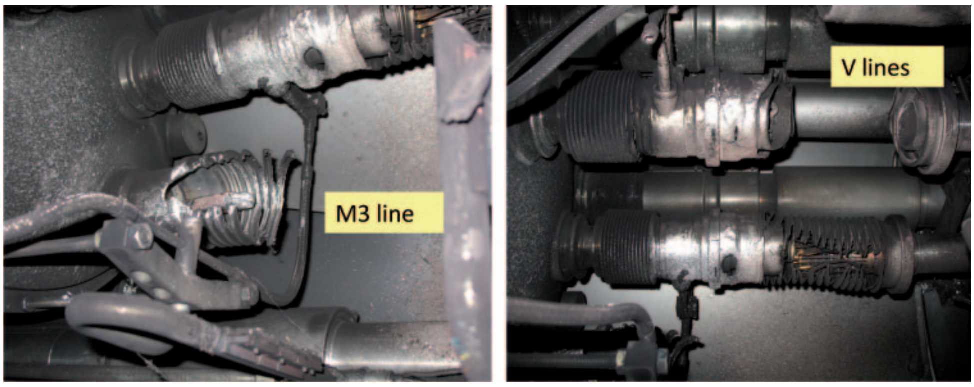

Fig. 3. – The region of primary fault with destruction of the bus-bar and beam vacuum lines and bellows.

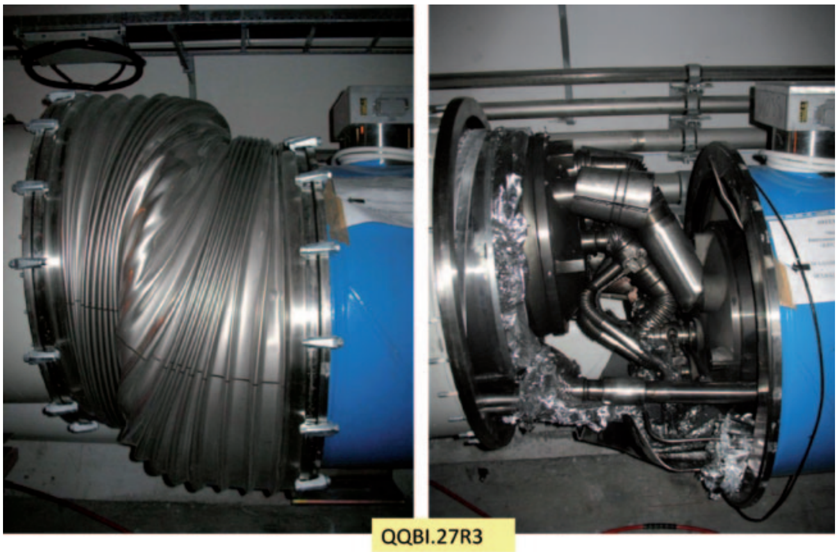

Fig. 4. – Collateral damages: the most extensive damaged zone due to magnets movement.

In conclusion, magnets and other equipment along a zone of about 700 m (about 3% of the entire LHC) had to be removed from the Tunnel and needed to be repaired or replaced. The mentioned pollution of the beam vacuum due to soot and MLI debris were extending beyond the zone where magnets were removed, this because the beam vacuum is not sub-sectorialized inside each LHC Sector.

3. – Reparation

The incident in Sector 3-4 has seriously affected 37 main LHC magnets: 30 main cryo-dipoles and 7 SSS (cryo-assemblies where main quadrupoles are assembled together with other 2 types of corrector magnets). But in order to safely identifying and limiting the incident affected zone, a total of 53 magnets (39 cryo-dipoles and 14 SSS) were removed from the Tunnel, and 9 dipoles and 7 SSS were fully inspected and re-tested at nominal cryogenic condition and then re-installed because found fully operational. The reserve of spare main magnets (some 40 cryo-dipoles and 14 SSS) was sufficient to replace all the damaged main dipoles. Situation was less straightforward for SSS due to the many variants of SSS present in the LHC. In four cases we were obliged to install SSS slightly different in terms of correction magnets. This has modified the layout of 2 correction circuits of the Sector (octupoles and skew quadrupoles circuits), but no major impact on beam operation is expected. For the preparation and test of the spares magnets, a quick restart of all the facilities, requiring an impressive logistics effort was achieved. Magnets left in the Tunnel or re-installed were carefully inspected (visual, electrical, functional, geometrical checks, plus cold test for all the re-installed magnets). Activities to re-build a stock of spare magnets with the repair of the damaged magnets will start as soon as possible in compatibility with resources actually still occupied in the Tunnel.

In practice, reinstallation of the first magnets in the damaged zone started in parallel with the removal of damaged magnets. The last magnet was lowered down in the Tunnel on 30 April 2009. The following activity of magnets interconnection is also a complex chain of operations. In fact the interconnection work requires a minimum chain of adjacent magnets and their alignment to advance in an efficient way. Quality Control issues are here particularly important, both in order to reproduce past quality in the new conditions, and of course to improve on critical aspects. All repairs in Sector 3-4 have been completed and the Sector has been finally closed on the 23rd of June 2009.

4. – Modifications

The task force formulated recommendations on two lines: the first one aim at the prevention of initial fault and the second ones aim at the mitigation of consequences. Proposed actions are concerning, hardware upgrades, improvements of test procedures as well as personnel access rules. Many of these modifications are under implementation during the present shut-down, others will be implemented during the next Commissioning, operation of the Collider and future shut-downs.

The principal modification toward prevention of faults is the upgrade of the Quench Protection System (QPS).

Decision for such upgrade has been triggered by two independent events for which two new additional protection systems have been developed and are under implementation. The first event was a secondary, thermally activated quench, symmetric between the two apertures of a dipole magnet that was not detected for more than half a second. The detection signal that triggers the quench system is based on a difference between the voltage readout signals of the two apertures of a magnet. In the case of this symmetric quench observed in the tunnel, both voltages increased over 4 V while the difference signal stayed well under the voltage threshold (100 mV). To avoid this rare but possible scenario, the new Symmetric Quench QPS system will compare the absolute voltage across any magnet with neighboring magnets. The threshold for this new system will be $300\,\mu$V. Four adjacent magnets will protect each other and whenever the quench heaters of three of the magnets in a subset have been triggered, the fourth magnet will also be triggered. The Symmetric Quench QPS system will be redundant and independent of the original quench protection system for the dipole magnets.

The second event was the Sector 3-4 incident itself where a bus-bar quench was detected but at a threshold that we know now to be much too high. The previous bus-bars detection system was limited by the fact to be a "global" system, monitoring the whole dipole circuit (154 dipole magnet in series). The new system is based on a "local" detection of excessive voltage for each bus-bar segments of the circuit and is implemented with a threshold of $300\,\mu$V and with an integration time of 10 s. Available voltage taps in the magnet circuit (used up to now only for diagnostics) will be wired to the QPS system board cards. This system is based on the design utilized for the protection of High Temperature Superconductor (HTS) Current Leads of the LHC that has shown to work very good. The expected sensitivity (in steady state) will be of $10\,\mu$V, enabling to detect bad splice with $R > 10\,\text{n}\Omega$, well below the runaway threshold, now estimated to be beyond $50\,\text{n}\Omega$. From the logistic aspects, the new QPS systems require pulling 240 km of cables in the LHC Tunnel. Additional crates and power supplies will be housed in the existing racks located under the mid-cell dipoles. These systems will be implemented in the arc dipoles and quadrupole circuits. Regular scans of the circuits will be planned to monitor the splices status and their eventual evolution.

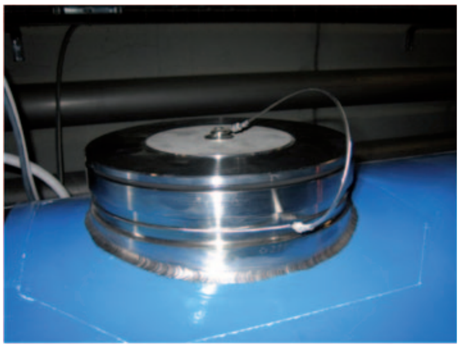

Fig. 5. – The DN200 extra relief valve to be added to all dipoles of the LHC.

The principal two modifications towards mitigation of consequences for an eventual incident are presented below:

a) Following the observed displacements of the magnets the pressure build-up in the insulation vacuum has been reviewed. Currently three spring loaded DN90 devices are located in each SSS (100 m apart). The vacuum vessel and vacuum barrier were designed to withstand the internal pressure under 1.5 bars, corresponding to a maximum helium release inside the vacuum vessel of a mass flow of 2 kg/s. During the incident the internal pressure, estimated from the external bellows deformation, reached 7 bars and an equivalent peak mass flow of about 20 kg/s. It is so clear that the existing pressure relief devices are not sufficient. The most accepted Maximum Credible Incident (MCI) scenario contemplates now damaging of the three main bus bar lines which will rapidly empty the cold mass circuit. This will release the helium at a rate of 40 kg/s. This value of the mass flow was used to recalculate the pressure build-up in the insulation vacuum. Several solutions were studied, the retained one consists in adding extra relief devices DN200 in each dipole (see fig. 5) and to replace fix clamped flanges by spring loaded clamps one DN100 ports on the SSS. The equivalent safety valve cross-section is in this case increased by a factor 33 and the pressure build-up will be reduced below the design values for the vacuum barrier and the floor fixation. Drilling the holes in the dipole cryostat can only be made in warm sectors. This solution is now completely implemented on four Sectors (with a total of 672 DN200 valves installed), for the other 4 Sectors a temporary solution is in place, it consists in preparing other existing ports on the SSS as potential burst-disks in case of overpressure.

b) According to the specification already mentioned in previous paragraphs, the cryomagnets floor supports are designed to withstand a pressure of 1.5 bar in the vacuum barrier which translates to 120 kN in the supporting system. Tests performed in 2003 showed that the failure limit for exceptional conditions occurred at about 150 kN. It is however known that during the incident in sector 3-4 the pressure exceeded 1.5 bar and that some supports did not resist the longitudinal load. After some analysis and iteration, the solution shown in fig. 6 was retained. The reinforcement system has to be installed on the present jacks and has to allow the access to them for future alignment. Installation is now ongoing on all SSS with vacuum barrier. The reinforced floor supports are now designed to resist to forces appearing on the vacuum barrier for an internal pressure of 240 kN (3 bars) compatible with the maximum pressure estimated from a MCI. More details on LHC main magnets systems performances and about the incident reconstruction are assessed and analysis by the task force can be found in refs. [4] and [5].

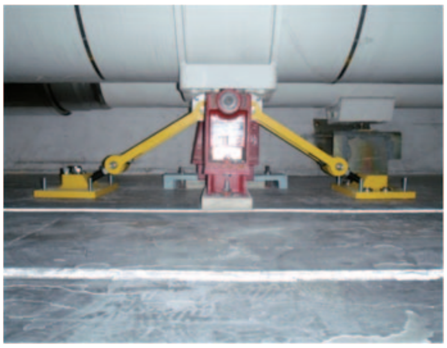

Fig. 6. – (Colour on-line) The reinforcement (yellow parts) on the floor supports of the SSS with vacuum barrier.

5. – Toward the new Commissioning

As already mentioned all repairs in Sector 3-4 have been completed and the Sector has been closed on the 23rd of June 2009. In parallel the new Commissioning of the LHC is started in June in Sector 2-3 and will go on all the summer as the other Sectors will be cooled down at 1.9 K and the modifications still ongoing (new QPS System) completed. The operation with beam is expected for the end of October 2009. Sensitivity studies, analysis and simulation work on the eventual impact on the LHC of non-conform interconnections (for example, by Cu stabilizer discontinuities in the splices) are considerably advanced with respect to one year ago and work on this front is still ongoing. For this and for other reasons (*e.g.*, the complete installation of the DN200 extra pressure relief valves to be done at next shut-down), the beam energy for the next LHC run will be probably limited to a value $\leq 5\,\text{TeV}$ (exact value still under discussion) and only increased after the shut-down 2009-2010.

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