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INTERIM SUMMARY REPORT ON THE ANALYSIS OF THE 19 SEPTEMBER 2008 INCIDENT AT THE LHC

On 19 September 2008, during powering tests of the main dipole circuit in sector 3-4 of the LHC, an electrical fault occurred resulting in mechanical damage and release of helium from the magnet cold mass. Proper safety procedures were in force, safety systems performed as expected, and no one was put at risk. An *ad hoc* task force was set up on 22 September 2008 to investigate the incident, establish the sequence of events, analyse and explain their development in relation with design assumptions and manufacturing and test data, and recommend preventive and corrective actions for further powering of the machine. Today a number of findings have been established, but inspections are not completed and investigations are continuing. Consequently this is an interim summary report of this task force as of 15 October 2008.

Configuration and layout of the LHC in a nutshell

The **arcs** of the LHC, extending over most of the length of each 3.3 km long **sector**, are composed of a periodic lattice of twin-aperture superconducting **dipoles** and **quadrupoles**, installed in a continuous **cryostat**. Corrector magnets, cryogenic and vacuum services, and beam observation instruments are installed next to the quadrupoles in **“Short Straight Sections”**. The elementary **cell** of the lattice, 107 m long, is composed of a horizontally focusing quadrupole, three dipoles, a vertically focusing quadrupole and another three dipoles. In each family, the magnets are electrically powered in series throughout the sector. The magnets, equipped with their helium vessel and end covers, constitute the **“cold mass”**, which in normal operation contains superfluid helium at 1.9 K and 0.13 MPa. The cold masses of neighboring magnets are electrically and hydraulically interconnected. The interconnected cold masses constitute the **helium enclosure**, with a design pressure of 2.0 MPa. The helium enclosure is protected from overpressure by **quench relief valves** set to open at 1.7 MPa, installed every 107 m at the locations of the Short Straight Sections and discharging into the recovery header of the **cryogenic distribution line** running parallel to the magnets along the tunnel. The magnet cold masses are surrounded by a **thermal shield** at around 60 K and enclosed in a **vacuum enclosure** at room temperature, for thermal insulation. The weight of the cold mass is transmitted to the vacuum enclosure via **cold support posts**, made of glass-fiber/epoxy composite to minimize conductive heat in-leaks. The weight is further transmitted from the vacuum enclosure to the tunnel floor by adjustable **support jacks**, anchored in the concrete. The lattice cell corresponds to the extent of the local cooling loops of the cryogenic system, fed from the cryogenic distribution line through a **“jumper” connection** every 107 m at the location of a quadrupole. Two subsequent cells constitute a **vacuum subsector** sharing a common insulation vacuum; the insulation vacuum enclosures of neighboring subsectors are separated by **"vacuum barriers"**. The two **beam pipes** constitute two other separate vacuum systems, extending over the whole length of the continuous cryostat. They can only be segmented by **sector valves** at room temperature outside the arcs, i.e. they extend along the whole length of the continuous cryostat. Thus a loss of tightness of the helium enclosure may result in degradation of the insulation vacuum, normally contained in the 214 m length of one vacuum subsector by the vacuum barriers, or/and of the beam vacuum in each beam pipe, or in both. In case of degraded vacuum, the vacuum enclosure is protected from overpressure by **spring-loaded relief discs** opening at 0.11 MPa to the atmosphere, two of them per vacuum subsector, located on Short Straight Sections.

Incident during powering

The magnet circuits in the seven other sectors of the LHC had been fully commissioned to their nominal currents (corresponding to beam energy of 5.5 TeV) before the first beam injection on 10 September 2008. For the main dipole circuit, this meant a powering in stages up to a current of 9.3 kA. The dipole circuit of sector 3-4, the last one to be commissioned, had only been powered to 7 kA prior to 10 September 2008. After the successful injection and circulation of the first beams at 0.45 TeV, commissioning of this sector up to the 5.5 TeV beam energy level was resumed as planned and according to established procedures.

On 19 September 2008 morning, the current was being ramped up to 9.3 kA in the main dipole circuit at the nominal rate of 10 A/s, when at a value of 8.7 kA, a resistive zone developed in the electrical bus in the region between dipole C24 and quadrupole Q24. The first evidence was the appearance of a voltage of 300 mV detected in the circuit above the noise level: the time was 11:18:36 CEST. No resistive voltage appeared on the dipoles of the circuit, individually equipped with quench detectors with a detection sensitivity of 100 mV each, so that the quench of any magnet can be excluded as initial event. After 0.39 s, the resistive voltage had grown to 1 V and the power converter, unable to maintain the current ramp, tripped off at 0.46 s (slow discharge mode). The current started to decrease in the circuit and at 0.86 s, the energy discharge switch opened, inserting dump resistors in the circuit to produce a fast power abort. In this sequence of events, the quench detection, power converter and energy discharge systems behaved as expected.

Sequence of events and consequences

Within the first second, an electrical arc developed and punctured the helium enclosure, leading to release of helium into the insulation vacuum of the cryostat. The additional power reaching the helium enclosure produced the onset of a pressure rise above the nominal 0.13 MPa. After 3 and 4 s, the beam vacuum also degraded in beam pipes 2 and 1, respectively. At the same time, the insulation vacuum started to degrade in the neighboring subsector 19-21. In the following seconds, electrical noise induced in the quench detectors of several other magnets by the fast power abort, triggered the firing of heaters thus provoking quenches in subsector 23-25. Within 20 s, several provoked quenches occurred at other locations in the sector, and at 20 s, the insulation vacuum also degraded in the other neighboring subsector

27-29. In all cases, the self-actuated quench relief valves on the helium enclosure opened at their set point of 1.7 MPa, and contained the pressure rise to below 2.0 MPa, except in subsector 19-21 where it reached a maximum of 2.1 MPa. The spring-loaded relief discs on the vacuum enclosure opened when the pressure exceeded atmospheric, thus relieving the helium to the tunnel. They were however unable to contain the pressure rise below the nominal 0.15 MPa absolute in the vacuum enclosures of subsector 23-25, thus resulting in large pressure forces acting on the vacuum barriers separating neighboring subsectors, which most probably damaged them. These forces displaced dipoles in the subsectors affected from their cold internal supports, and knocked the Short Straight Section cryostats housing the quadrupoles and vacuum barriers from their external support jacks at positions Q23, Q27 and Q31, in some locations breaking their anchors in the concrete floor of the tunnel. The displacement of the Short Straight Section cryostats also damaged the "jumper" connections to the cryogenic distribution line, but without rupture of the transverse vacuum barriers equipping these jumper connections, so that the insulation vacuum in the cryogenic line did not degrade.

About 2 t of helium, corresponding to the volume contained in the magnet cold mass of subsectors 19-21, 23-25 and 27-29, were rapidly discharged and eventually released to the tunnel, producing a cloud which triggered the oxygen deficiency hazard detectors installed on the tunnel vault and tripped an emergency stop, thus switching off all electrical power and services from sector 3-4. In the subsequent leakage from the open circuits, and before restoration of electrical power enabled to actuate cryogenic valves, another 4 t of helium were lost, though at much lower flow rates. The total loss of inventory thus amounts to about 6 t, out of 15 t initially in the sector.

Inspection and diagnostics

After restoring power and services in the tunnel and ensuring mechanical stability of the displaced magnets, one proceeded to open the cryostat sleeves in the interconnections between magnets, starting from subsector 23-25. This confirmed the location of the electrical arc, showed absence of electrical and mechanical damage in neighboring interconnections, but revealed contamination by soot-like dust which also propagated in the beam pipes over some distance. It also showed damage to the multilayer insulation blankets of the cryostats.

The number of magnets to be repaired is at maximum of 5 quadrupoles (in Short Straight Sections) and 24 dipoles, but it is likely that more will have to be removed from the tunnel for cleaning and exchange of multilayer insulation. The exact numbers will be known once the ongoing inspections are completed. Spare magnets and spare components appear to be available in adequate types and sufficient quantities for allowing replacement of the damaged ones during the forthcoming shutdown. The extent of contamination to the beam vacuum pipes is not yet fully mapped, but known to be limited; *in situ* cleaning is being considered to keep to a minimum the number of magnets to be removed. The plan for removing/reinstallation, transport and repair of magnets in sector 3-4 is being established and integrated with the maintenance and consolidation work to be performed during the winter shutdown. The corresponding manpower resources have been secured.

Preliminary recommendations

Recommendations made by the task force aim at two different goals, namely to prevent any other occurrence of this type of initial event, and to mitigate its consequences should it however reproduce accidentally. Possible precursors of the incident in sector 3-4 are being scrutinized in the electrical and calorimetric data recorded on all sectors, in order to spot any other problem of the same nature in the machine. An improvement of the quench detection system is under way, to generate both early warnings and interlocks, and to encompass magnets, bus bars and interconnects. It will be implemented before any further powering of the LHC circuits at higher current. The relief devices on the cryostat vacuum vessels will be increased in discharge capacity and in number, so as to contain a possible pressure rise to below 0.15 MPa absolute even in presence of an electrical arc. The external anchoring of the cryostats at the locations of the vacuum barriers will be reinforced to guarantee mechanical stability. The personnel access rules during powering will also be reexamined, to further exclude human presence not only in the machine tunnel, but also in the neighboring caverns and technical areas underground.

The technical parameters of the LHC are beyond precedent, and the energy stored in the superconducting magnets huge. Consequently, operation of this machine will always comprise a certain technical risk. We are however convinced that the repair actions under way and the improved protection systems to be implemented will ensure safe powering in the future.