5 December 2008

FOLLOW UP OF THE INCIDENT OF 19 SEPTEMBER 2008 AT THE LHC

This report completes the analysis and diagnostics of the incident that occurred on 19 September 2008 in sector 3-4 of the LHC, and presents the main consequences on the repair, consolidation and restart of operation of the LHC. It follows from and complements the interim report of 16 October 2008,
http://cdsweb.cern.ch/record/1135729/
with particular emphasis on the 2009 activities and prospective schedule. Reference is made to the 16 October 2008 interim report for basic information on the LHC layout and terminology.

Confirmation of first observations and further analysis

After sector 3-4 was warmed up to room temperature, magnet interconnections were opened and systematically investigated, thus providing a large volume of documentation: geometrical, mechanical and electrical measurements, visual inspections, and photographic data base. Analysis of this documentation, and results of electrical, thermal and mechanical simulations essentially confirmed the chain of events mentioned in the 16 October 2008 report, in particular the effects linked with the original fault and the subsequent collateral damage.

As the primary evidence (the defective bus connection between two magnets) was destroyed by the incident, the precise origin of the fault will always remain speculative; however, defects similar to the inferred original fault have been reproduced in the laboratory by application of large non-conformities in the procedures on samples of bus bar interconnections.

As far as collateral damage is concerned, it is fully understood that the safety relief devices on the cryostat vacuum enclosure had been designed for lower helium discharge rates than that encountered in the 19 September 2008 incident (considered as "beyond design"), and that the axial forces resulting from over-pressurization of the vacuum enclosure exceeded the yield point of magnet supports, thus leading to their displacement and secondary damage.

Sensitive detection methods based on integration and filtering of measured voltages during powering tests, and independently on calorimetry in superfluid helium were validated and implemented in other sectors of the machine. They revealed no other case of abnormal resistance in magnet interconnections performed upon installation in the tunnel, but two connections, built in industry inside two magnet cold masses, show values of their joint resistance largely outside the expected range. These have nevertheless been able to achieve full nominal performance during their individual testing before their transport into the tunnel, as well as during power tests of the complete sectors.

Summary of observed damage

The 3 km-long continuous cryostat of sector 3-4 contains 154 superconducting dipoles and 55 “short straight sections” (SSS) housing superconducting quadrupoles, as well as many corrector magnets of different types. In total, 66 contiguous magnet interconnections were opened, thus encompassing substantial buffer areas on each side of the “damaged zone”. This enabled *in situ* inspection to determine the magnets to be removed from the machine tunnel, and by difference those which can safely be left in their positions. A total of 53 magnets, 39 dipoles and 14 SSS will be removed from the tunnel and brought to ground level, where they will be thoroughly inspected and either cleaned or repaired. This process has started, with already 19 dipoles and 9 SSS taken out, and is due to be completed by the end of 2008.

In addition to damage to magnets, contamination of the beam vacuum pipes by soot from the electrical arcs and chips of multilayer insulation has also been surveyed, by systematic endoscopy along the whole length of the continuous cryostat, i.e. up to the vacuum sectorization valves. No contamination by soot has been found outside the 53 magnets removed from the tunnel, which will have their beam vacuum pipes replaced or cleaned at ground level. Contamination by chips of multilayer insulation has been found over long distances away from the position of the original incident. These chips are however only deposited on the beam pipe surface, from where they can be removed by local vacuum cleaning: an *ad hoc* procedure for this operation has been developed and is being validated in the laboratory.

Damage to the cryogenic distribution line is limited to mechanical deformations of four jumper connections which have already been cut and removed.

Actions of consolidation

In addition to the new sensitive detection methods mentioned above, which will be systematically applied on the LHC sectors as part of the re-commissioning procedure following maintenance interventions, a dedicated system to detect the appearance of abnormal electrical resistance on the high-current bus bars and interconnections has been designed, validated on prototypes and will be implemented in the whole machine: this implies the manufacturing and installation of some 2000 additional electronic crates, and the pulling of some 160 km of signal cables during the 2008-2009 shutdown.

Mitigation of the consequences of any further incident, which could give rise to massive release of helium and subsequent pressure rise in the insulation vacuum enclosure, will be achieved by increasing the number and size of relief devices on the cryostat vacuum vessels, thus ensuring that the design overpressure of 0.5 bar is never exceeded. The worst case for this type of event has been revised in the light of the 19 September incident, leading to the following actions. Available flanges on the SSS cryostats will be equipped with new full-flow relief devices, thus yielding an increase by a factor 8 of the discharge cross-section; this modification can be made *in situ* on cold sectors. In addition, a large port will be cut on each dipole cryostat, and fitted with a full-flow relief device; this modification will be done on warm sectors and gradually implemented on the whole machine. Overall, the discharge cross-section will be eventually increased 40-fold, thus allowing to cope with a helium discharge twice as high as that of the 19 September incident while keeping overpressure within allowed limits. In addition, quadrupoles with a vacuum barrier will have their anchors in the concrete floor of the tunnel strengthened.

Repair plan

Upon their transport to ground level and thorough inspection, magnets removed from the tunnel are categorized into three classes, according to the type and level of damage or contamination observed.

In the case of very light or no damage/contamination, they can be **re-used** without disassembly of their cryostat, with only the vacuum beam pipes either replaced or cleaned: as of today, 9 dipoles fall into that category.

In the case of contamination of the cryostat and multilayer insulation, magnets will be **re-conditioned**; this means that their cryostats will be disassembled, cleaned and the multilayer insulation replaced, but their active part ("the cold mass") conserved. As of today, 5 SSS fall into this category.

In the case of damage affecting the connections at the coil ends of the cold mass, or in case of doubt about their integrity, magnets will be **rebuilt with new cold masses**, for which spares are available: this concerns 30 dipoles (out of which 16 are already assembled in their cryostats), and 9 SSS (out of which 5 are already assembled in their cryostats).

All magnets to be re-installed in the tunnel, whether re-used, re-conditioned or rebuilt with new cold masses, will undergo cold power tests at nominal level, thus ensuring their mechanical and electrical integrity in operating conditions, as well as their sound operational performance. For this purpose, the cryogenic test station that was used to test all the LHC magnets upon reception at CERN, will be reused, its full cryogenic capacity being restored by re-connecting it to the large cryogenic plant normally serving sector 1-2 of the LHC.

Spare magnets and cryostat components, including elements of the beam vacuum systems, are available in sufficient quantities to begin repair work. Additional orders have been placed to restore depleted stocks of spare parts and feed the repair workshops without interruption. Experienced staff previously involved in series assembly and installation of LHC sectors has been made available and redeployed on the repair and re-installation tasks.

All main components for repair of the cryogenic line jumpers are available. Repair in the tunnel will proceed from beginning of January 2009, and be completed by mid-February 2009.

The first two new magnets have already been installed in their tunnel positions this week in sector 3-4, as replacement for removed magnets. It is foreseen to complete re-installation of all magnets in sector 3-4 by the end of March 2009. Interconnections work will start beginning of February 2009, and will be completed by mid May 2009. After final pressure tests and cooldown, the repaired sector will be available for powering by the end of June 2009.