THE CERN LHC - WORLD'S LARGEST VACUUM SYSTEMS

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Abstract

With the successful circulation of beams in the Large Hadron Collider (LHC), its vacuum system became the World's largest vacuum system under operation. This system is composed of 54 km of UHV vacuum for the two circulating beams and about 50 km of insulation vacuum around the cryogenic magnets and the liquid helium transfer lines. The LHC complex is completed by 7 km of high vacuum transfer lines for the injection of beams from the SPS and their dumping. Over the 54 km of UHV beam vacuum, 48 km are at cryogenic temperature (1.9 K), the remaining 6 km are at ambient temperature and use extensively non-evaporable getter (NEG) coatings, a technology that was born and industrialised at CERN. The cryogenic insulation vacuums, less demanding technically, impress by their size and volume: 50 km and 15000 m^3. Once cooled at 1.9 K, the cryopumping allows reaching pressure in the 10^{-4} Pa range. This paper describes the LHC vacuum system, its behaviour in presence of beams as well as the detailed actions undertaken to recover its integrity after the electrical short which happened in a quadrupole bus-bar on 19th of September 2008.

INTRODUCTION

The Large Hadron Collider (LHC) consists of a pair of superconducting storage rings installed in the former LEP collider tunnel. The LHC design was based on the two beam channels superconducting magnets (NbTi, 1.9 K) technology. Beams are injected from the SPS into the LHC and ejected to the dump absorbers through new transfer lines operated under a high vacuum.

This system is composed by 54 km of UHV vacuum for the circulating beams and 50 km of insulation vacuum around the cryogenic magnets and the liquid helium transfer lines. Over the 54 km of UHV beam vacuum, 48 km of this are at cryogenic temperature (1.9 K). The remaining 6 km of beam vacuum containing the insertions for "cleaning" the proton beams, radiofrequency cavities for acceleration as well as beam-monitoring equipment is at ambient temperature and uses non-evaporable getter (NEG) coatings – a vacuum technology that was born and industrialized at CERN.

The cryogenic insulation vacuums while technically less demanding, impress by their size and volume: 50 km and 15000 m^3. Once cooled at 1.9 K, the cryopumping allows reaching pressures in the 10^{-4} Pa range.

Such large beam vacuum systems require sectorisations at cold-warm transitions, to create vacuum sectors in long or fragile zones or to allow the installation of beam components which need an ex-situ conditioning. For the beam vacuum, the 303 sector valves allowed creating RT vacuum sectors with a maximum length of 110 m while

having a valve at each cold-warm transition. The arc beam vacuum, with a total length of 2.8 km, is not sectorized.

The insulation vacuum of the arcs cryomagnets and of the cryogenic transfer lines (QRL) has been sectorized to work with reasonable lengths, respectively 214 m and 429 m. The sectorisation is made at three different levels: 104 vacuum barriers between the magnets, 64 for the cryogenic transfer lines and 272 for the jumpers i.e. the link between QRL and magnets.

BEAM VACUUM SYSTEM

The LHC is a quasi-ring with 8 bending sections (arcs) with cryomagnets and 8 long straight sections (LSS). Some symmetries exist between LSS1 (ATLAS) and LSS5 (CMS), LSS2 (Alice, TI2 injection) and LSS8 (LHCb, TI8 injection), collimation in LSS3 and LSS7. LSS4 (radiofrequency and beam instrumentation) and LSS6 (beam dumping systems) are different. Close to the experiments, the two beams are travelling through the same vacuum pipe; elsewhere they run completely separated in two different beam pipes.

The LHC beam vacuum system was design [1,2] to comply with resistive power dissipation by beam image currents, heat load resulting from beam gas scattering, scattered protons escaping from the magnetic aperture and lost in the 1.9 K system, synchrotron radiation stimulated gas desorption in the arcs of the machine as well as cryomagnet quench limit. The required 100 hours beam lifetime (equivalent to 10^{15} $H_2.m^{-3}$) aims to keep negligible the beam-gas scattering, thus requiring an UHV beam vacuum system.

In the arcs (Fig.1) and by design, the beam vacuum is a non-baked vacuum since the beam pipe (called cold bore) is in contact with the magnet coils which cannot be baked. The beam and vacuum requirements lead to the use, for the first time in an accelerator, of a "beam screen" [3]. Inserted in the cryomagnet cold bore and operated between 5 and 20 K, it aims to intercept most of the heat load. Indeed, the removal of 1 W at 1.9 K requires nearly 1 kW of electric power. The cryopumping of gas on the cold surfaces ensures the required beam lifetime. The most critical species (H_2 and He) are kept within acceptable limits by means of holes in the beam screen allowing the transfer of desorbed molecules to the magnet cold bore surfaces where they can no longer be re-desorbed. A theoretical calculation shows that the huge cryopumping will bring the pressures well below 10^{-10} Pa.

In the LSS (Fig.2), satisfying the beam and vacuum stability requirements implied the design of complex transitions, radiofrequency shielding and the development of ultra-thin (0.3 mm) bake-out equipment using the wrapping technology of a steel heating band isolated by

polyimide bands. The pressure requirements are satisfied by the use of UHV technologies associated to TiZrV non-evaporable getter coatings (NEG). NEG coating cumulates several advantages, like low electron emission yields, low gas desorption yields, huge pumping speed except for noble gasses and methane (CH_4). NEG pumping capacity can easily be activated during the bake-out of the UHV vacuum system. The pumping scheme is completed using 807 ion pumps uniformly distributed to remove the non-getterable gasses preventing ion instability and providing pressure interlocks to the 303 vacuum safety valves. Pressure readings are provided by 170 Bayard-Alpert gauges, 442 Pirani and 642 cold cathode Penning gauges. To achieve UHV standards, each component in the vacuum beam line (>2300) has seen an UHV acceptance test in the laboratory prior to its installation in the tunnel. All normal conducting magnets chambers (~300) and drifts space chambers (~1200) have been NEG coated.

Figure 1: Picture of an LHC arc showing the magnet cryostat envelopes.

Figure 2: Picture of a long straight section showing a standalone cryomagnet (left) and the QRL line (right).

The detector beam pipes (Fig.3), their associated instrumentation, pumping and bake-out equipment were both an engineering and integration challenge since encapsulated in the detectors. To maximise the detector resolution, transparent materials (beryllium and aluminium) have been used for beam pipes and bellows.

Similarly to the LSS, the vacuum pumping relies on the NEG coating; ion pumps at the extremities of the detectors prevent the ion instability.

Figure 3: Installation of the last experimental beam pipe in the centre of the ATLAS detector.

INSULATION VACUUM SYSTEMS

The insulation vacuum is used in the LHC to decrease the heat losses between the cold parts at liquid helium cryogenic temperature and the external envelope at room temperature. The cool down of the cryomagnets can start after 2-3 weeks of roughing using mobile and fixed turbomolecular pumping stations. Once at cold, the resulting huge pumping speed induced by the cold surfaces will maintain a static vacuum in the 10^{-4} Pa range. To cope with the limited pumping of helium gas, leak tightness was carefully followed-up and 178 turbomolecular pumps have been distributed along the arcs and in the standalone cryomagnets.

Under operation and despite the impressive numbers: more than 250,000 welds (~100 km), 18,000 elastomer joints (~22 km) and 9 million square metres of multi-layer insulation (MLI), the operating pressures are in the 10^{-5} Pa range, as expected. Pressure readings are provided by 576 Pirani and membrane gauges and 641 cold cathode Penning gauges.

TRANSFER LINES VACUUM SYSTEMS

Interconnected with the LHC main ring in the LSS, four new high vacuum transfer lines were designed, installed and commissioned: 2 for injecting from SPS (TI2/TI8, 2.7 km each) and 2 for dumping in the dump blocks installed in dedicated caverns (TD62/TD68, 0.75 km each).

In total for the injection transfer lines, 655 drift pipes, 1200 supports, 1320 bellows and pumping ports, 120 beam positioning monitors, 585 magnets and 150 ion pumps and gauges have been used.

The aperture requirements were drastically different for the dump lines. Indeed, to avoid the instantaneous melting of the dump absorbers (362 MJ/beam @ 7 TeV), the beams have to be diluted. A spiral path is obtained by a combined vertical and horizontal deflection resulting in

beam pipes of increasing diameters up to 600 mm upstream of the beam dump absorbers. The small extraction angle resulted in critical integration issues as the installation on top of the LHC main ring required, in practice, to complete the installation of the main ring before starting the installation of the dump lines. At the end of the line, a 600 mm window designed and manufactured at CERN, allows the separation of the beam dump lines under vacuum from the graphite dump absorbers kept under a small overpressure of nitrogen preventing a fire in case an air leak appears near the absorbers while dumping the beams.
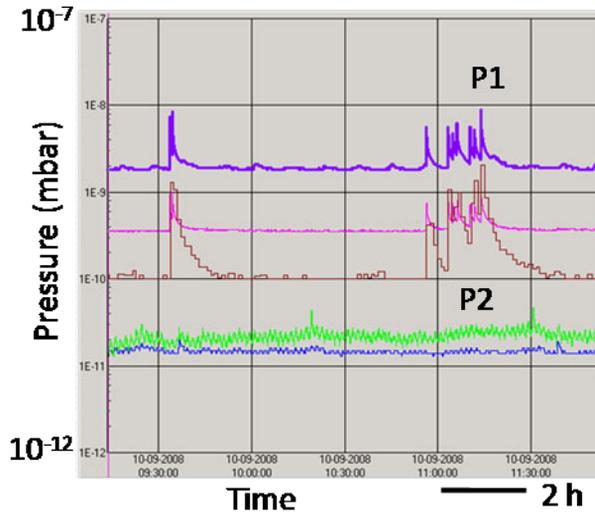
Figure 4: Pressure rise observed in the LHC-LSS induced by a single bunch beam impacting the collimator jaws.
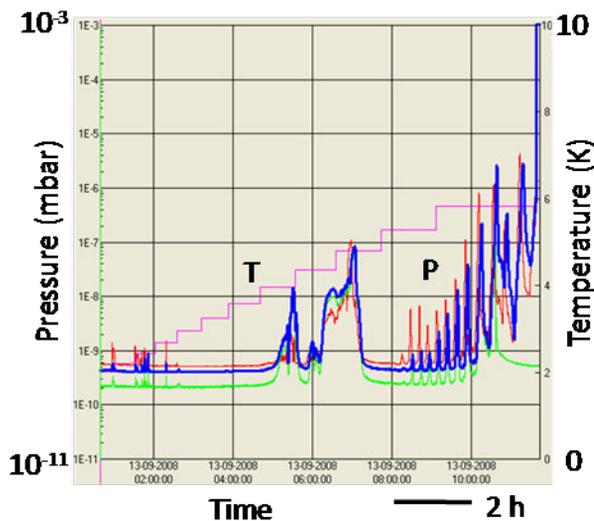
Figure 5: Hydrogen partial pressure oscillation resulting from minor temperature variation around 5 K.

FIRST OPERATION WITH BEAMS

As announced, beams were circulating in the LHC on the 10th of September'08 in both apertures. To avoid beam losses tripping the cryogenic magnets, the first injections were made step-by-step allowing for orbit corrections before sending the beams through the next

bending section. At each step, the beam was stopped by the collimators which jaws were closed on purpose. Even the low intensity (5.10^9 p/bunch, single bunch) beams induced a factor 10 in pressure rises at the location of their stoppage (Fig.4).

At cold, the pressure in the beam pipe is strongly dependent from the temperature and small variations can lead to pressure oscillations of hydrogen and helium (in case of leaks). An illustration can be observed in Fig.5 which shows a hydrogen oscillation in the beam screen induce by temperature oscillations around 5-6 K.

As expected, the static pressures in the RT vacuum sectors with NEG coatings are in the 10^{-10} Pa range (Fig.6), the pressure indications being dominated by the local outgassing of the gauge port [4].
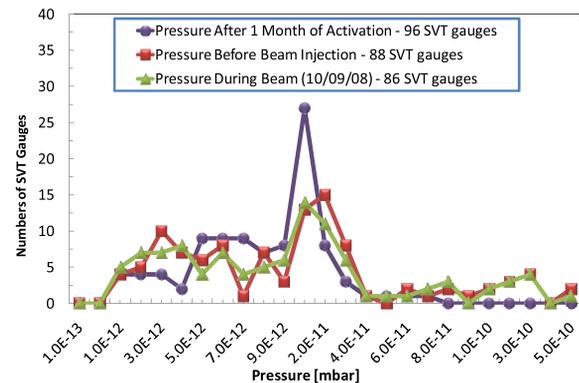
Figure 6: Static pressure distribution in the NEG-coated sectors of the LHC-LSS.

DAMAGES TO THE BEAM VACUUM AFTER THE INCIDENT IN SECTOR 3-4

On 19 September 2008, during the powering test of the main dipole circuit in sector 3-4, an electrical fault occurred producing an electrical arc and resulting in mechanical and electrical damages, release of helium from the magnet cold mass, venting and contamination of the insulation and beam vacuum enclosures (Fig.7 and 8).

Short Review of the Sequence of Events

Following the incident and for safety reasons, the access to the tunnel around the damaged zone ("D-zone") was not allowed. After about a week, priority was given to the protection of the upstream and downstream beam vacuum parts of sector 3-4 which remained at cryogenic temperature. The objective was to install vacuum plugs to close the volumes in order to avoid the cryogenic pumping of the incoming air and the formation of urge condensation and ice blocks inside the beam screens and cold bores. By doing so, the D-zone was sacrificed.

Once the entire sector was at RT temperature (about 6 weeks later), the upstream and downstream beam vacuum parts of the D-zone were carefully inspected using the endoscopy technique. A 100 m in span endoscope was used requiring the removal of the magnet interconnections every 204 m corresponding to 4 half-cells. Table 1

summarises the result of this extensive endoscopic campaign which was completed in December'08.

a   b   c
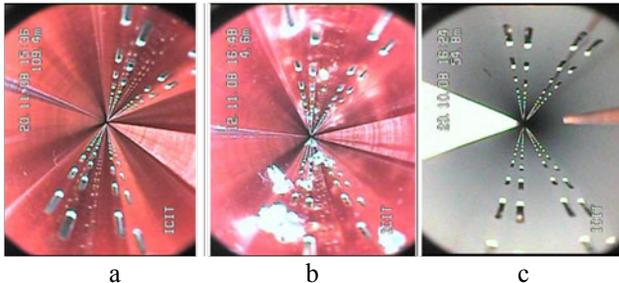
Figure 7: MLI (a) and soot (c) as appearing by endoscopy inside the beam screen compared to a clean BS (a).
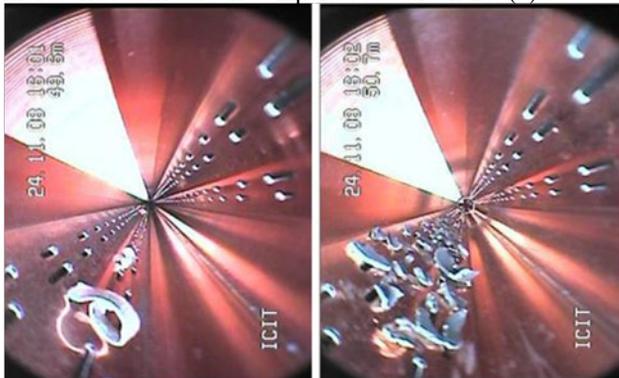
Figure 8: Metallic debris as appearing by endoscopy inside the beam screens.

Table 1: Contamination by MLI or soot as observed in the tunnel after the incident. The second number refers to the situation in the tunnel after removing the 53 magnets of the D-zone which had to be refurbished at the surface.

Status	V1 Magnet	V2 Magnet	V1 %	V2 %	Total %
Ok	54/49	39/30	26/31	18/19	22/25
MLI	124/111	129/124	58/69	61/78	59/73
Soot	35/0	45/6	16/0	21/4	19/2
Total	213/160	213/160	100	100	100

The entire sector 3-4 was affected on both apertures since the arc beam vacuum is not sectorized. As shown by Fig.9 and in Table 1, the contamination extended to the entire arc, the soot remained, luckily, confined within the D-zone [5].

Resulting from the very fast helium depressurisation of the beam vacuum and even though the closing of all sector valves in the area was triggered (set at 4.10^5 Pa) by the fast pressure rise, the pressures rose from 10^{-9} Pa up to 10^2 Pa (A7R3) and 5 Pa (A7L4) respectively for the RT sectors upstream and downstream the arc 3-4. The difference can be explained by the fact that the incident took place in the left part of the sector 3-4 and that the sector A7L4 has 60 % more volume than the A7R3. It has to be noted that the beam vacuum in the RT sectors on the other side of the standalone magnets were not affected.

Resulting from the fact that the entire arc remained at temperatures lower than 5 K following the incident, only dry helium was in the vapour state. Therefore and as

expected, the partial venting of the RT vacuum sectors did not saturate the NEG coatings. Indeed, after resuming with a turbomolecular pumping station, the pressures went down in the 10^{-9} Pa range. For completeness, these 2 twin-sectors were slowly vented with dry nitrogen and inspections did not reveal any traces of soot, MLI or metallic debris. Following the visual inspections, the twin-sectors were pumped down and baked in order to activate the NEG coatings. The ultimate pressures are consistent with the pressures achieved in the other RT sectors.
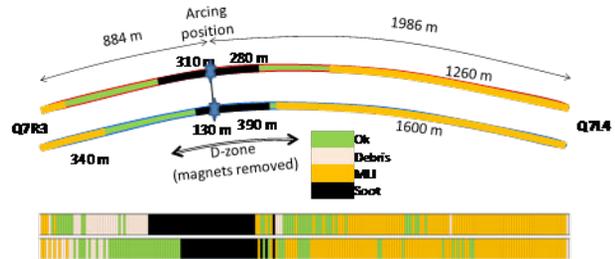
Figure 9: Schematic view of the results of the endoscopy in the sector 3-4.

BEAM VACUUM RECOVERY

Soot Removal

As shown by Fig.9, the beam vacuum magnet pipes contaminated by soot were all within the D-zone at the exception of 6 magnets within the half-cell 19R3 and 20R3. All other magnets, 53 in total (14 quadrupoles and 39 dipoles) were removed from the tunnel and treated at the surface. Among these 53 magnets removed from the tunnel, only 16 have been recovered to be reinstalled in sector 3-4 (7 MQ and 9 MB), requiring the exchange of 13 beam screens which were heavily contaminated by soot. The beam screens of the remaining 5 magnets (2 MQ and 3 MB) were conforming and were not exchanged.

The 6 magnets left in the tunnel had only one aperture contaminated by soot. These beam screens were cleaned in-situ mechanically. The operation required in total 50 passages per aperture alternating wet (alcohol) and dry foams until their appeared free of soot. The remaining traces, enhanced by the use of grazing incidence lighting, can be explained by a local oxidisation of the copper of the beam screen due to the ice plugs formed during the incident.

The missing 37 magnets (7 MQ and 30 MB) were replaced by spare magnets equipped with new beam screens.

MLI and Debris Removal

The systematic endoscopy of both apertures, cm-by-cm 4.8 km in total for the two apertures, revealed the presence of the following types of debris: metallic debris (coming from the RF fingers, cold bore, beam screen and bellows), MLI and fibres. The dispersion along the arc and apertures (see Fig.9) is not explained, the metallic debris were all localised in the left side of the sector 3-4

as a huge quantity of MLI and fibres were localised in the right side of the sector 3-4.

To speed up the removal of the MLI and fibres, all quadrupole/dipole (QQBI) interconnections were opened to provide an access to the beam pipes every 50 meters. At locations where metallic debris were found, interconnections at the extremities of the magnet concerned were removed.

Due to the excessive quantity of MLI and fibres at some locations, it was decided to proceed in two steps: an automatic pumping/venting of the sector followed by a local blow-up of the remaining dusts using a gas nozzle.

The pumping/venting cycle (20" pumping, 8" flat top and 2" venting) resulted in pressure variations between atmosphere and 8.10^4 Pa (800 mbar). The resulting air speed is about 20 m/s which correspond to an estimated drag force of 70 g. This process was applied during at least 1 h (120 pumping/venting cycles) to remove all MLI and fibres inside the beam screens.

The second step was introduced to remove the MLI and fibres behind the RF fingers of the interconnections, between the beam screens and cold bores or hanged to the beam screen pumping slots. The MLI and fibres removal inside the RF fingers being challenging, the nozzle position and efficiency is monitored using an endoscope. A filtered nitrogen flow (2 bar.l/s) is locally blown through the pumping slots behind the beam screens or through the RF fingers allowing the debris to be brought back inside the beam aperture where they can be suck-up as shown by Figure 10. The cleaning efficiency was evaluated in the laboratory on a real mock-up showing that 10 passages at 3.2 m/min and 5 to 10 minutes on top of the RF fingers (PIMs and nested bellows) are required to achieve the specified cleaning efficiency: two dust (<1 mm2)/magnet and 1 fibre (<3 mm)/half-cell [5]. A final endoscopy made by an independent team defines if the beam pipes can be released for the interconnections. In total, 12 passages (fist and final endoscopies and 10 cleaning passages) were required which is equivalent to 58 km of beam pipes which have been cleaned and inspected cm-by-cm! Less than 20 % had to be re-cleaned consequently to their rejection after the final endoscopy.
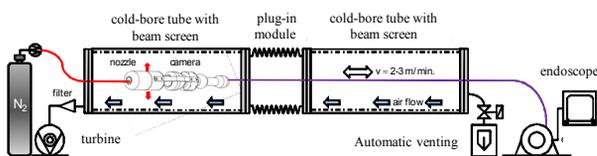
Figure 10: Schematic view of the systems used to remove the MLIs, fibres and debris from the beam pipes.

Status and Future Milestones

The RT vacuum sectors (A7R3 and A7L4) are operational to their nominal parameters and the consolidation of the collimation system is foreseen to be completed by end of June'09 in LSS3 and LSS7.

In sector 3-4, 90% of the beam vacuum length was cleaned by end of April'09; the completion is expected by first week of May'09.

CONCLUSIONS

After 3 years of installation, the vacuum systems of the LHC and of its transfer lines showed their readiness by allowing beams circulations on the 10th of September'08. The static pressures were as expected in the LHC Design Report and no dynamic effect was observed due to the low intensities circulating in the ring.

The incident of sector 3-4 spoiled all the beam tubes in the arc. The systematic endoscopic inspection of the beam tubes revealed that about ¾ of them were polluted with super insulation debris after removing the D-zone. It was then mandatory to clean in-situ the contaminated beam pipes and to evaluate the cleaning efficiency and consequences of the remaining dust for the future operation.

Fortunately, the incident was far from the arc extremities and thanks to the vacuum interlocks system, as shown by endoscopic inspections and vacuum performances, the vacuum sectors outside the arc 3-4 were saved from pollution.

Surely, the operation of the LHC will be challenging due to the variety of technologies, performances, expected behaviour in presence of beams and collateral damages in case of incidents.

ACKNOWLEDGEMENTS

REFERENCES

[1] Angerth, B. and al., "The cold vacuum system of the Large Hadron Collider", CERN-LHC-Note-284, Geneva, 1994 - 4 p.

[2] Grobner, O, "Overview of the LHC vacuum system", Vacuum 60 (2001) 25-34.

[3] Cruikshank, P. and al., "Mechanical Design Aspects of The LHC Beam screen", CERN-LHC-Project-Report-128, Geneva, 1998 - 4 p.

[4] Bregliozzi, G., "Achievement and evaluation of the beam vacuum performance of the LHC long straight sections", Proceedings EPAC2008, Genova (2008).

[5] Baglin, V., "Vacuum system: how to get ready for beams?", proceeding of the LHC Chamonix workshop, Chamonix (2009) CERN.