

# LHC: THE WORLD'S LARGEST VACUUM SYSTEMS BEING COMMISSIONED AT CERN

J.M. Jimenez, CERN, Geneva, Switzerland.

## Abstract

When it switches on in 2008, the 26.7 km Large Hadron Collider (LHC) at CERN, will have the world's largest vacuum system operating over a wide range of pressures and employing an impressive array of vacuum technologies. 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 accelerating the protons 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 pumping scheme is completed using 780 ion pumps to remove noble gases and to provide pressure interlocks to the 303 vacuum safety valves. Pressure readings are provided by 170 Bayard-Alpert gauges and 1084 gauges (Pirani and cold cathode Penning).

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

This paper describes the vacuum systems and the challenges of the installation and commissioning phases.

## INTRODUCTION

The Large Hadron Collider (LHC) consists of a pair of superconducting storage rings installed in the former LEP collider. Thus, requiring the design of two beam channels superconducting magnets (NbTi) cooled down to 1.9 K by superfluid liquid helium. Beams are injected from the SPS into the LHC and ejected to the dump absorbers through new transfer lines operated under a high vacuum.

Such a large beam vacuum system requires a sectorisation to separate the cold from the ambient temperature vacuum sectors, to create vacuum sectors in long or fragile zones or to allow the installation of beam components which need an ex-situ conditioning. In total, 303 sector valves have been installed, 70% of them isolating a cold sector from one at ambient temperature. For the insulation vacuum and to work with reasonable lengths i.e. 214 m for the magnet insulation vacuum and 429 m for the QRL line, 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. The pressure monitoring is given by 974 gauges (Pirani, piezo and cold cathode).

## BEAM VACUUM

### Main Ring Beam Vacuum

The LHC is a quasi-ring with 8 bending sections (arcs) with cryomagnets and 8 long straight sections (LSS). The 8 LSS are not all different, 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 pipes.

The LHC beam vacuum system was design 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<sup>15</sup> H<sub>2</sub>.m<sup>-3</sup>) aims to keep negligible the beam-gas scattering, thus requiring an UHV beam vacuum system.

In the arcs and by design, the beam vacuum is a non-baked beam 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". 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 require beam lifetime. The most critical species (H<sub>2</sub> 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 these can no longer be re-desorbed. A theoretical calculation shows that the huge cryopumping will bring the pressures well below 10<sup>-10</sup> Pa.

In the LSS, satisfying the beam and vacuum stability requirements implied the design of complex transitions, radiofrequency shielding and the development of an 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), a technology that was born and industrialized at CERN. NEG coating cumulates several advantages, like low electron emission yields, low gas desorption yields, huge pumping speed except for noble gasses and methane (CH<sub>4</sub>). NEG pumping capacity can

easily be activated during the bake-out of the UHV vacuum system. The ion pumps (780) which are uniformly distributed are used for removing the non getterable gasses ensuring ion instability. Vacuum protection and instrumentation is obtained by means of sector valves (303), Bayard-Alpert (170), Pirani (442) and cold cathode Penning gauges (642). 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 magnet chambers (~300) and drifts space chambers (~1200) have been NEG coated (Fig.1).



Figure 1: LSS picture showing a standalone cryomagnet and ambient vacuum sectors.

The detector beam pipes, 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 pipe and bellows. Similarly to the LSS, the vacuum pumping relies on the NEG coating; ion pumps at the extremities of the detectors ensure the ion instability.

### Beam Vacuum Installation

The installation of the arc beam vacuum started at the surface where the beam screens were inserted in the cold bore of the cryomagnets. In the tunnel, pump-down and leak detections were the main activities following the interconnection of the cryomagnets. In total, 229 leaks (3.34%) have been found and fixed in the tunnel.

The installation of the LSS was driven by the installation of the standalone cryomagnets and by the availability of machine components. This resulted in difficulties to complete vacuum sector in the second half of 2006. As from the January 2007, the situation was improving and the installation speed reached 100 m/week (Fig.2) all included i.e. the installations of supports and vacuum chambers, survey, interconnect closure, pump-downs, leak detections and bake-outs. About 10% of the machine had to be reopened for consolidation.

As expected, the installation of the vacuum system in the experimental areas was strongly linked to the installation of the detectors. The excellent preparation of each step of the installation allowed completing the

vacuum systems of all detectors including ATLAS and CMS in 12 weeks.

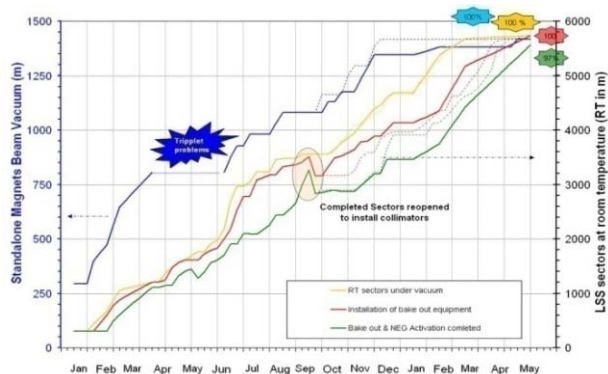


Figure 2: LSS installation rates (Jan'07 to May'08).

The performances of the LHC vacuum systems rely on the distributed pumping i.e. NEG coatings in the ambient temperature sectors and cryopumping in the cold sectors resulting in low gas transmissions. Therefore, a pressure gauge can only provide an indication of the pressure close to its location. Small leaks cannot be “seen” and cryomagnet quenches induced by the beam-gas scattering will occur before a pressure increase is detected.

The recovery time after interventions on the vacuum systems will be longer than for any other CERN accelerator. In the arcs, a long pump-down time (2-3 weeks) using mobile turbo-molecular pumps is required to decrease the pressure below  $10^{-4}$  Pa in order to reduce as much as possible the beam screen coverage during the cool down. This duration cumulates with the warm-up/cool down duration (6-8 wks). The LSS cryomagnets will behave similarly to the arc magnets except that they need to be isolated from the NEG coated sectors when not at their operating temperature avoiding cross-contamination by the gas load released by the non-baked beam pipes of the cryomagnets.

Similarly, any intervention on the sectors at ambient temperature will require a bake-out and the activation of the NEG coatings. Following a pump-down using mobile turbo-molecular pumps, the components are baked (230-320°C) to speed up the thermal outgassing prior to activating the NEG coatings. All these steps allow achieving pressures lower than  $10^{-9}$  Pa i.e. 100 times below the specified dynamic vacuum pressure.

### New SPS to LHC Injection Transfer Lines

The two beam transfer lines with a length of 2.7 km each have been built to allow injecting the 450 GeV beams from the SPS into the LHC. The design of these lines was simplified for cost reasons resulting in a minimalist and reliable vacuum system. As part of the Russian contribution to the LHC, the magnets and the entire vacuum system has been manufactured and installed in the tunnel by the Novosibirsk's Budker Institute of Nuclear Physics (BINP).

The main challenges were the manufacturing of the weld-free racetrack and nearly-elliptical magnet vacuum pipes and their insertion inside the magnet poles. The

vacuum installation and survey was critical due to the vertical and horizontal bending of the lines. At their arrival inside the LHC main ring, the transfer lines have a tangential path with a small injection angle resulting in tight integration issues. Sixteen weeks were required to install the 2.7 km of vacuum system i.e. 170 m/wk. The installation of the second half of the TI2 line – in the path of the magnet transportation, had to wait until the complete transportation of the cryomagnets. In total, 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.

*New LHC Beam Dump Transfer Lines*

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.



Figure 3: LSS picture showing the dump line installed on top of the circulating beam pipe.

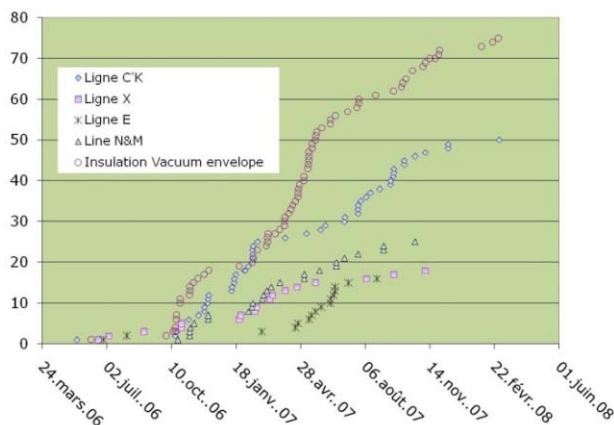


Figure 4: Number of leaks found during the installation.

Due to the small extraction angle resulting from the high beam energies, the integration of the dump pipes on top of the circulating beams was challenging (Fig.3). The first 300 meters of the line were assembled with pipes and bellows fitted with Conflat™ flanges as the second part of the line i.e. from the end of the LSS to the dump absorbers was assembled by welding the pipes in-situ. Ion pumps (400 l/s - 40 in each line) ensure the required

pressure ( $10^{-4}$  Pa) after a pump-down using mobile turbo-molecular pumps. 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.

In practice, the installation of the dump lines started once both LSS and arcs were completed resulting in co-activities with the hardware commissioning.

**INSULATION VACUUM**

The insulation vacuum is used in the LHC to decrease the heat losses between the cold parts at liquid helium (LHe) cryogenic temperature and the external envelope at ambient temperature. A rough vacuum ( $10^{-1}$  Pa) is enough to allow for the cool down. The pump-down by means turbo-molecular pumps takes between 2-3 weeks, mainly driven by the outgassing of the many layers of superisolation contained in the cryostat insulation vacuum. Then, the huge pumping speed induced by the cold surfaces will maintain a static vacuum in the  $10^{-4}$  Pa range. Due to the negligible pumping of helium, leaks must be avoided. Therefore, leak detection & leak tightness (Fig.4) are key issues and each sub-component, component, weld, circuit was leak tested individually before getting installed in the tunnel. Then, each sub-assembly and assembly was again leak tested.

More than 250'000 welds, 90'000 of them made in-situ for an integrated weld length of 100 km and 18'000 elastomer joints for an integrated length of 22 km have been used. Nine million square meters (200 m<sup>2</sup>/m of cryostat) of multi-layer insulation have been used to decrease the thermal losses, resulting in a huge outgassing after venting to atmosphere. Fixed turbo-molecular pumps (178) resulting in 0,25 l/s/m pumping speed allowing the pumping of helium gas in case of leaks.

**CONCLUSIONS**

After 3 years of installation, the LHC vacuums and transfer lines are completed and the final commissioning is ongoing mainly on the sector valves since there cannot be opened until the cryomagnets are at their operating temperature. Their operations will be challenging due to the variety of technologies, performances and expected behaviour in presence of beams.

**ACKNOWLEDGEMENTS**

The work presented here is the result of several years of work and studies of many colleagues working with and in the field of vacuum science at CERN and in the world through collaborations. It would be a challenge in itself to name all the people involved. After so many years, the imminent start of the LHC in the coming months is the result of their effort.