LHC World Largest Vacuum Systems Being Commissioned at CERN*

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The CERN Large Hadron Collider (LHC) with its 26.7 km of circumference and three different vacuum systems for the beams and insulation vacuum for magnets and liquid helium transfer lines, 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. 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. The noble gases and methane is pumped out by 780 ion pumps. 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 (50 km) and volume (15000 m³). Once roughed using mechanical pumps, the vacuum relies on the cryopumping which allows reaching pressure in the $10^{-4}$ Pa range.

1. Introduction

The Large Hadron Collider (LHC) consists of a pair of superconducting storage rings with a circumference of 26.7 km housed in the tunnel of the former Large Electron-Positron collider (LEP) which was shutdown in November 2000. Thus, requiring the design of two beam channels superconducting magnets (NbTi), commonly called cryomagnets, with 8.3 T magnetic field cooled down to 1.9 K by superfluid liquid helium. Fig. 1 and 2 are schematic views of the LHC cryodipoles. Beams are injected from the SPS (Super Proton Synchrotron) into the LHC through two new transfer lines with a length of 2.7 km each and ejected through two new transfer lines to the dump absorbers installed in dedicated caverns at 750 meters from the ejection point.

The two proton beams of 530 mA intensity at an energy of 7.0 TeV, will circulate in opposite directions serving two high-luminosity experiments (ATLAS and CMS), a heavy ion experiment (ALICE) and a B-physics experiment (LHCb).

The LHC has different vacuum systems covering a wide range of pressure and technologies. The beam vacuum i.e. 54 km of ultra high vacuum ($<10^{-9}$ Pa) allow for the circulating beams, 48 km being at cryogenic (1.9 K) temperature. The insulation vacuum ($10^{-4}$ Pa when the cryomagnets are at 1.9 K) i.e. more than 50 km are necessary to decrease heat load by gas conduction to the cryomagnets and to the liquid helium transfer lines. And finally, the 6.5 km of high vacuum ($10^{-6}$ Pa) which are required in the beam injection and dump transfer lines.

2. Vacuum in Particle Accelerators

2.1 Beam vacuum

In particle accelerators, vacuum is required in the beam pipe mainly to increase the particle beam lifetime i.e. the delay before loosing a particle from the beam due to a collision with the molecules of the residual gas. A long beam lifetime allows also reducing the radiation induced by the lost beam particle to the machine components and infrastructure.

Vacuum is also used to decrease the background to the experiments. The interactions between the particles of the beam and the molecules of the residual gas induce a background to the experiments by a direct effect due to the non-captured particles which interact with the detectors or by an indirect effect due to the nuclear cascade generated by the lost particles upstream the detectors.

In the case of the LHC and as for any collider, the beam vacuum system has to ensure a higher beam lifetime and low background for the experiments as compared to the linear accelerators (LINAC).

Other beam equipment like accelerating radio-frequency cavities with accelerating fields of a few MegaVolts per meter (MV/m) and Electrostatic devices with a few hundreds of kilo-Volts per meter (kV/m) also require UHV vacuum to avoid electrical breakdowns.

2.2 Insulation vacuum

The insulation vacuum is also extensively used in the accelerators with cryogenic transfer lines and superconducting magnets, like LHC, to decrease the heat losses. A rough vacuum ranging between 1 and $10^{-1}$ Pa is enough to allow the cool down. Then, the large pumping speed induced by the cold surfaces will maintain a static vacuum in the $10^{-4}$ Pa range. In the case of the LHC cryomagnets which are cooled by superfluid helium (1.9 K), helium leaks must be avoided since helium gas will
only be partly pumped. Additional pumping speed by means of fixed turbo molecular pumping stations are required to cope with these leaks appearing during the operation of the accelerator.

3. LHC Beam Vacuum

The LHC is a quasi-ring with 8 bending sections (arcs) with cryomagnets and 8 long straight sections (LSS) housing the LHC experiments, collimators, accelerating cavities, beam diagnostics, injections and extractions to the beam dumps. Close to the experiments, the two beams travel through the same vacuum pipe (Fig. 3) and move away until they get completely separated into two different pipes (Fig. 4).

Additional requirements have been identified for the LHC beam vacuum, such as magnet quench limits, i.e. loss of superconducting properties, resistive power dissipation by beam image currents and heat load resulting
from beam gas scattering, scattered protons escaping from the magnetic aperture and lost in the 1.9 K system as well as synchrotron radiation stimulated gas desorption in the arcs of the machine. The continuous heat input to the cryogenic system is directly proportional to the gas density and hence the maximum allowed value for the parasitic heat loads defines an upper limit of the gas density in the beam pipe.

Balancing all above mentioned constraints, results in a beam lifetime of 100 hours for the LHC which imposes the use of an UHV vacuum. As the particles of the beam travel at a speed close the speed of light (300 000 km/s), they will need 90 microseconds to complete one turn of the LHC ring. The specified 100 hours beam lifetime is equivalent to a travelling distance of 1011 km, 4 billions of LHC turns or 280 000 times the distance between Earth and Moon (384 000 km). This long travel has to be covered without any interaction with a molecule of the residual gas.

3.1 Cryo-beam vacuum (arcs & standalones cryomagnets)

By design, the cryo-beam vacuum is a non-baked beam vacuum since the magnet beam pipe (called cold bore) is in contact with the magnet coils and cannot be baked.

All the LHC requirements lead to an innovating conceptual vacuum system design radically different between the arcs at cryogenic temperature and the long straight sections at ambient temperature (RT). For the first time in an accelerator, a “beam screen” is inserted in the cryogenic magnet cold bore. Operated between 5 and 20 K, it will be used to intercept most of the heat load. Indeed, the removal of 1 W at 1.9 K requires nearly 1 kW of electric power. Vacuum pumping requirements are satisfied by the cryopumping of gas on the cold surfaces (beam screen and the magnet cold bore) ensuring the require beam lifetime, whenever H2 and He which are the most critical species, remains within acceptable limits. The holes in the beam screen allow the transfer of desorbed molecules to the magnet cold bore surfaces where these can no longer be re-desorbed.

A long pumping time (2–3 weeks) by means of mobile turbo-molecular pumping stations aim to decrease the pressure in the $10^{-10}$ Pa range. The cold bores and beam screens will follow the cryomagnet temperatures during their cool down resulting in a huge cryogenic pumping speed which will bring the pressures below $10^{-10}$ Pa.

3.2 LSS beam vacuum

The 8 LSS are not all different, some symmetries exist between LSS1 and LSS5 housing respectively ATLAS and CMS detectors, LSS2 and LSS8 housing Alice, LHCb detectors and the two injections, LSS3 and LSS7 housing the collimators (betatron and momentum cleaning), LSS4 housing the radiofrequency and beam instrumentation components (accelerating cavities, dampers, gas profile monitors, etc.) and LSS6 housing the beam dumping systems.

Satisfying the above mentioned criteria, 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 non-evaporable getter coatings (NEG), a technology born and industrialized at CERN. NEG coatings cumulate several advantages, like low electron emission yields and low gas desorption yields, huge pumping speed (except for noble gasses). Their pumping capacity can easily be activated while baking the UHV vacuum system.

To complete the pumping system, some 600 ion pumps are used to pump the non getterable gasses and to provide pressure interlocks to the 270 vacuum safety valves. Pressure readings are provided by 160 Bayard–Alpert gauges and 500 Pirani and Penning gauges.

To achieve and grant the high UHV standards required for all components, more than 330 beam equipments (collimators, instrumentation, radiofrequency equipments,…), 300 magnet vacuum pipes, 1200 drift vacuum pipes and 1800 interconnecting bellows have seen an UHV acceptance test in the laboratory prior to the installation in the tunnel.

Each LSS houses standalone cryomagnets (Fig. 4) with similar design as for the arc cryomagnets which need to be isolated from the RT sectors when the magnets are not at their nominal temperature to avoid saturation of the NEG coatings by the gas load released by the non-baked beam pipes of the cryomagnet. The all
metal sector valves (Fig. 5) ensure the separation between the RT vacuum sectors and cryomagnet beam vacuum, the ion pumps and instrumentation ensure the correct interlocking of the vacuum sector valves.

Following the pump down using mobile turbo molecular pumping stations, the beam pipes will be baked between 230 and 320°C to speed up the thermal outgassing of the material under vacuum and activate the NEG coatings which provide a performing pumping. Hundred of ion pumps complete the pumping scheme i.e. allowing the pumping of noble gasses and methane which are not pumped by the NEG coatings. All together allows achieving pressures lower than $10^{-9}$ Pa i.e. 100 times below the specified dynamic vacuum pressure.

### 3.3 Detector Neam Vacuum

The beam pipe in the detector caverns, the associated instrumentation and pumping represent both an engineering and integration challenge (Fig. 6 and 7). In fact, the space available for the pipes and their bake out equipment is limited since encapsulated in the detector. To maximise the detection limit of the different layers of detectors, the beam pipe material has to be transparent to the particles generated at the collision point. Achieving such a constraint required the use of beryllium and aluminium beam pipes and aluminium bellows instead of using copper or stainless steel materials.

Similarly to the LSS, the detector beam vacuum is an UHV system; the vacuum components are baked and the vacuum pumping relies on the NEG coatings deposited onto the inner surface of the beam pipes. Two ion pumps at the extremities of the detectors ensure the ion stability by pumping the non getterable gasses.

To optimize the collection of forward particles generated at the interaction point, conical beam pipe were designed and installed for example in Alice and CMS.

### 4. LHC Insulation Vacuum

The cryogenic insulation vacuum (Fig. 8 and 9), technically less demanding, impresses by its size (22.4 km, 900 mm diameter) and volume 9,000 m$^3$ for the magnet insulation vacuum and 25 km and a volume of 6,000 m$^3$ for the insulation vacuum of the liquid helium cryogenic transfer lines.

Prior to any cool down of the magnets, the cryogenic insulation vacuum is pumped down using turbomolecular pumping stations down to pressures below $10^{-1}$ mbar, the pump down time (2–3 wks) being driven by the outgassing of the many layers of super isolation contained in the cryostat insulation vacuum. While at 1.9 K, the large cryogenic pumping on the external surface of the magnet cold mass will ensure the required static insulation vacuum.

Therefore, leak detection & leak tightness 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.

The magnet insulation vacuum is characterised by the:
— 250'000 welds, 90'000 of them were made in-situ for an integrated weld length of 100 km.
— 18'000 elastomer joints for an integrated length of 22 km.
— 9 millions square meters (200 m²/m of cryostat) of multi-layer insulation.
— 234 vacuum subsectors with an individual length of 214 m for the magnet insulation vacuum and 429 m for the QRL line. The volume of the magnet subsector is about 80 m³.
— 178 fixed turbo molecular pumping stations resulting in a nominal turbo pumping speed of 0.25 l/s/m of cryostat allow the pumping of helium gas in case of leaks. The roughing and pump down is obtained using 36 mobile primary pump-
5. Injection and Dump Transfer Lines

5.1 SPS to LHC Injection Transfer Lines

Two new beam transfer lines (Fig. 10) with a length of 2.7 km each have been built to allow injecting the 450 GeV beam energy from the SPS into the LHC. The design of these lines was simplified for cost reasons resulting in a minimalist vacuum system.

This project was part of the Russian contribution to the LHC. The magnets and the entire vacuum system has been manufactured and installed in the tunnel by personnel from the Budker Institute of Nuclear Physics (BINP) in Novosibirsk.

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 installation of the vacuum pipes in the tunnel as well as the survey of the vacuum pipes was an issue due to the vertical and horizontal bending (Fig. 11).

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 (Fig. 12 and 13).

The installation of the two SPS to LHC beam transfer lines required the use of: 655 drift pipes, 1200 supports, 1320 bellows and pumping ports, 2500 chain clamps, 120 beam positioning monitors, 585 magnets (dipoles and quadrupoles), 60 roughing valves and 150 ion pumps and gauges.

5.2 Beam Dump Transfer Lines

The nominal LHC beam energy i.e. 362 MJ/beam @7 TeV is enough to melt 500 kg of copper, is equivalent to the energy of a 400 tons TGV train @150 km/h and to 77 kg of TNT.

To avoid the instantaneous melting of the dump absorbers, 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 bloc.

Due to the small extraction angle resulting from the high beam energy, the integration of the dump pipe on top of the circulating beams was challenging (Fig. 14 and 15). The first 300 meters of the line were assembled with...
pipes and bellows fitted with Conflat flanges. The second part of the line i.e. from the end of the LSS to the dump bloc was assembled by welding the pipes in-situ (Fig. 16).

The integration of the dump line above the circulating beams and the associated infrastructure was not obvious and required a specific installation sequence.

After the roughing with mobile turbomolecular pumping stations, the pumping is ensured by 400 l/s ion pumps, 40 pumps for each line.

At the end of the line, a 600 mm windows designed and manufactured at CERN, allows the separation of the beam dump lines under vacuum from the dump bloc kept under a small overpressure of nitrogen. Keeping the graphite dump blocks under nitrogen aim preventing a fire in case an air leak appears near the block while dumping the beams.

6. Conclusions

The LHC and its beam transfer lines will be challenging in terms of operation due to the variety of technologies, performances and expected behaviour in presence of cooling for the insulation vacuum or in presence of beams for the beam vacuum.

The performance will have to be surveyed continuously in order to detect at early stages leaks and required consolidations.

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