



LHC: The world's largest vacuum systems being operated at CERN

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ABSTRACT

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With the successful circulation of beams in the Large Hadron Collider (LHC), its vacuum system becomes the world's largest vacuum system under operation. This system is composed of 54 km of ultra high vacuum (UHV) for the two circulating beams and about 50 km of insulation vacuum around the cryogenic magnets and the liquid helium transfer lines (QRL). 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 vacuum systems, less demanding technically, impress by their size and volume: 50 km and 15,000 m³. Once cooled at 1.9 K, the cryopumping allows pressure in the 10^{−4} Pa range to be attained.

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1. Introduction

The Large Hadron Collider (LHC) consists of a pair of superconducting storage rings installed in the tunnel of the former Large Electron–Positron (LEP) collider. Its design is based on two beam channel superconducting magnets (NbTi) cooled down to 1.9 K by superfluid helium. Beams are injected from the Super Proton Synchrotron (SPS) into the LHC and ejected to the dump absorbers through new transfer lines operated under a high vacuum. The LHC vacuum system is not a single vacuum system but has 3 vacuum sub-systems impressive by their size and volume (50 km and 15,000 m³) beam vacuum and insulation vacuums for the cryomagnets and helium transfer lines (called QRL).

2. Beam vacuum

2.1. Main ring beam vacuum

The LHC is a quasi-ring with 8 bending sections (arcs) with cryomagnets and 8 long straight sections housing the 4 large physics detectors as well as beam instrumentation, accelerating cavities, collimators, injections and ejections of beams (Fig. 1). 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 designed [1–6] 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 loss in the 1.9 K system, synchrotron radiation stimulated gas desorption in the arcs of the machine as well as the quench limit of the cryomagnet. The required 100-h beam lifetime (equivalent to a density of hydrogen molecules of 10¹⁵ m^{−3}) aims to keep the beam-gas scattering negligible, 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” [6–8]. Inserted in the cryomagnet cold bore and operated between 5 and 20 K, it reflects the design complexity of the LHC vacuum system. As from the initial specification which aimed to intercept the heat loads, the four main types being synchrotron light, energy loss by nuclear scattering, image currents and electron clouds, the beam screen has to insure vacuum stability, low photo-electron reflection and avoid the high order modes (HOM > 2 GHz) trapping while optimising the beam aperture.

A racetrack cross-section shape allows integrating the two helium cooling capillaries. Various shapes were manufactured to adapt to the different magnet apertures, the orientation inside the cold bore being adjusted to the magnet position along the ring to optimise the beam aperture. The quasi-randomised pattern of the pumping slots has been chosen to minimise the higher order modes (HOM) coupling between the bunched beams and the cold bore tube.

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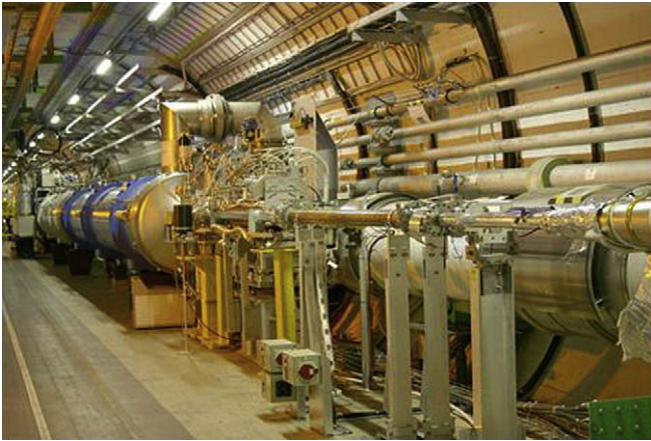


Fig. 1. Picture of the long straight section (LSS) showing a stand-alone cryomagnet and the room temperature vacuum sectors. Close to the wall on the right side, the cryogenic transfer line (QRL).

The manufacturing process includes co-laminating of a low permeability 1 mm thick austenitic stainless steel strip with a 75 μm high purity copper sheet, rolling of the saw-tooth structure, partial annealing treatment (to restore the mechanical properties of the stainless steel and to increase the Residual Resistivity Ratio (RRR value) of the copper layer), punching of the pumping slots, rolling to the final shape and longitudinal laser welding. The centering of the beam screen in the cold bore is obtained by sliding rings with a bronze layer welded every 750 mm onto the beam screen. The copper beryllium shields “clipped” onto the cooling capillaries intercept the electrons from the cloud escaping through the pumping slots, providing also a support for the carbon fibre cryosorber material required to increase the hydrogen pumping capacity in the magnets operated at 4.5 K.

The cryopumping of gas on the cold surfaces ensures the required beam lifetime. The most critical species, hydrogen and helium, 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 are condensed in a stable manner.

In the long straight sections (LSS), satisfying the beam and vacuum stability requirements implied the design of complex transitions, radio frequency 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 with TiZrV non-evaporable getter coatings (NEG), a technology that was born and industrialised at CERN. The 780 ion pumps which are uniformly distributed are used for removing the non-getterable gases preventing ion instability. Vacuum protection is obtained by means of 303 sector valves.

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 prevent the ion instability.

The installation of the arcs and LSS was driven by the installation of the cryomagnets and by the availability of machine components requiring permanent adjustments of the installation sequence [9].

2.2. Vacuum instrumentation

The pressures are monitored using 170 Bayard–Alpert, 442 Pirani and 642 cold cathode Penning gauges. The current of the ion pumps is also used as a pressure indicator. In the cold beam vacuum sectors, in the absence of any leak and once cooled at 1.9 or 4.5 K, the pressures decrease below 1×10^{-10} Pa, pressure levels well below the resolution of the cold cathode gauges and the ion pumps. Similar pressure values are expected in the sectors at ambient temperature once the NEG coated vacuum chambers get activated. Only the Bayard–Alpert gauges can provide reliable pressure indications, which could, however, be compromised by local ionisation of the residual gas induced by beam losses.

When the cold cathode Penning gauges and the ion pumps are measuring pressures below their resolution, the monitoring interface indicates default values: 5×10^{-9} and 1×10^{-11} mbar (5×10^{-7} and 1×10^{-9} Pa) for the Penning gauges and 5×10^{-11} mbar (5×10^{-9} Pa) for the ion pumps. To warn the operators and users, this instrumentation appears in dark green. Fig. 2 shows the pressure profile in the eight long straight sections corresponding to the beam 1 (Red beam). The dark green bars correspond to the gauges and ion pumps operating under range. Failing instrumentation appears in red and white indicates equipment which is switched off. It is essential to keep in mind that the performances of the LHC beam vacuum system rely on the distributed pumping, i.e., NEG coatings in the sectors at ambient temperature and cryopumping in the cold sectors, resulting in low gas transmission. Subsequently, a pressure gauge can only provide an indication of the pressure close to its location.

Therefore, in the arcs, small leaks cannot be “seen” and cryomagnet quenches induced by the beam-gas scattering will occur before a pressure increase is detected. In the sections at ambient temperature, measurements made in the laboratory and *in situ* in the ring confirmed that the ion gauges are measuring the local pressure which is dominated by the outgassing of the vacuum port [10].

2.3. Vacuum behaviour with beams

On the 10th of September 2008, the LHC was operated with beams at injection energy (450 GeV). Even with low intensity (up to 5×10^9 p/bunch) single bunch beams, pressure rises have been observed all around the ring. After optimising the beam orbit using the correctors, the remaining pressure rises were located, as expected, on the beam stoppers used during the process of injection.

The injections of the first beams in both rings were made step by step to allow for beam orbit optimisation and avoid quenching the superconducting magnets. At each step, the beam orbit was optimised to reduce beam losses. Fig. 3 shows the pressure rises upstream of the Alice detector. Similar behaviour has been observed elsewhere when stopping the beams. In the evening of the 11th of September, the clockwise beam (beam 1) was stored for about 4 h. The optimised beam orbit led to negligible pressure rises all around the ring.

Switching the LHC to the “operation” mode implied keeping all sector valves open. Thus showing the co-dependency between the cold and the ambient temperature beam vacua in case of cryogenic instabilities. In fact, in normal operating conditions, i.e., cryomagnets at their nominal temperature and NEG coatings activated, the pumping speed and sticking coefficient reduce the gas exchange.

The pressure, being dependent on the temperature in the cold areas, means temperature variations will induce a gas release which will affect the upstream and downstream sectors at ambient

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