CHAPTER 12
VACUUM SYSTEM

12.1 OVERVIEW

LHC has the particularity of having not one, but three vacuum systems: insulation vacuum for cryomagnets, insulation vacuum for helium distribution line (QRL) and beam vacuum. The vacuum levels are of course very different. Driven by the requirements for the cryogenic system, the room temperature pressure of the insulation vacuum before cool-down does not have to be better than 10 Pa (10^{-1} mbar). At cryogenic temperatures, in the absence of any significant leak, the pressure will stabilise around 10^{-4} Pa (10^{-6} mbar). The requirements for the beam vacuum are much more stringent, driven by the requested beam lifetime and background to the experiments. Rather than quoting equivalent pressures at room temperature, the requirements at cryogenic temperature are expressed as gas densities and normalised to hydrogen taking into account the ionisation cross sections for each gas species. Equivalent hydrogen gas densities should remain below 10^{15} \text{H}_2 \text{m}^{-3} to ensure the required 100 hours beam lifetime [1]. In the interaction regions around the experiments the densities will be below 10^{13} \text{H}_2 \text{m}^{-3} to minimise the background to the experiments [2]. The requirements for the room temperature part are driven by the background to the experiments as well as by the beam lifetime and call for a value in the range from 10^{-8} to 10^{-9} Pa (10^{-10} and 10^{-11} mbar).

All three vacuum systems are subdivided into manageable sectors by vacuum barriers for the insulation vacuum and sector valves for the beam vacuum. Sector lengths are 428 m in the QRL and 214 m for the magnet insulation vacuum. The beam vacuum is divided into sectors of various lengths, in most cases the distance between two stand-alone cryomagnets. However, there are no sector valves in the cold arc, leading to a length for this single sector of approximately 2900 m.

A number of dynamic phenomena have to be taken into account for the design of the beam vacuum system. Synchrotron radiation will hit the vacuum chambers in particular in the arcs; electron clouds (multipacting) could affect almost the entire ring. Extra care has to be taken during the design and installation to minimise these effects, but conditioning with beam will be required to reach nominal performance.

12.2 BEAM VACUUM REQUIREMENTS

The LHC presents several original requirements with respect to classical vacuum systems. It has to provide adequate beam lifetime in a cryogenic system, where heat input to the 1.9 K helium circuit must be minimised and where significant quantities of gas can be condensed on the vacuum chamber. The following four main heat sources have been identified and quantified at nominal intensity and energy:

- Synchrotron light radiated by the high energy circulating proton beams (0.2 W m^{-1} per beam, with a critical energy of about 44 eV);
- Energy loss by nuclear scattering (30 mW m^{-1} per beam);
- Image currents (0.2 W m^{-1} per beam);
- Energy dissipated during the development of electrons clouds, which will form when the surfaces seen by the beams have a secondary electron yield which is too high.

Reducing the heat input to the cryogenic system introduces constraints on the design (e.g. the necessity of a beam screen), on the materials (e.g. the introduction of a copper layer) and on the gas density to be achieved in the LHC vacuum system. In addition, other more classical constraints are set by the lifetime, the stability of the beams, which in turn sets the acceptable longitudinal and transverse impedance [3, 4] and locally by the background conditions in the interaction regions.

The vacuum lifetime is dominated by the nuclear scattering of protons on the residual gas. The cross sections for such an interaction at 7 TeV vary with the gas species [5, 6] and are given in Tab. 12.1, together with the gas density and pressure (at 5 K) compatible with the requested 100 hour lifetime. This number ensures that the contribution of beam-gas collisions to the decay of the beam intensity is small as compared to other loss mechanisms; it also reduces the energy lost by scattered protons in the cryomagnets to below the nominal value of 30 mW m^{-1} per beam.
Table 12.1: The nuclear scattering cross sections at 7 TeV for different gases and the corresponding densities and equivalent pressures for a 100 h lifetime

<table>
<thead>
<tr>
<th>GAS</th>
<th>Nuclear scattering cross section (cm²)</th>
<th>Gas density (m⁻³) for a 100 hour lifetime</th>
<th>Pressure (Pa) at 5 K, for a 100 hour lifetime</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂</td>
<td>9.5 \times 10^{-26}</td>
<td>9.81 \times 10^{14}</td>
<td>6.710^{-8}</td>
</tr>
<tr>
<td>He</td>
<td>1.26 \times 10^{-25}</td>
<td>7.410^{14}</td>
<td>5.110^{-8}</td>
</tr>
<tr>
<td>CH₄</td>
<td>5.66 \times 10^{-25}</td>
<td>1.610^{14}</td>
<td>1.110^{-8}</td>
</tr>
<tr>
<td>H₂O</td>
<td>5.65 \times 10^{-25}</td>
<td>1.610^{14}</td>
<td>1.110^{-8}</td>
</tr>
<tr>
<td>CO</td>
<td>8.54 \times 10^{-25}</td>
<td>1.110^{14}</td>
<td>7.510^{-9}</td>
</tr>
<tr>
<td>CO₂</td>
<td>1.32 \times 10^{-24}</td>
<td>7 \times 10^{13}</td>
<td>4.910^{-9}</td>
</tr>
</tbody>
</table>

12.3 BEAM VACUUM IN THE ARCS AND DISPERSION SUPPRESSORS

The two beams are confined in independent vacuum chambers from one end of the continuous cryostat to the other, extending from Q7 in one octant to Q7 in the next octant. Cold bores of an inner diameter of 50 mm, part of the cryomagnets, are connected together by so-called cold-interconnects which compensate length variations and alignment errors. A beam position monitor, with an actively cooled body, is mounted on each beam at every short straight section. An actively cooled beam screen is inserted into the cold bore of all magnets, connection cryostats and shuffling modules. Initially foreseen to intercept the power deposited by the synchrotron radiation at a temperature higher than 1.9 K, it will also collect the power deposited by electron clouds during the conditioning phase and limit the condensed gas coverage on the surfaces exposed to the impact of energetic particles.

12.3.1 Beam Screen

A racetrack shape has been chosen for the beam screen, which optimises the available aperture while leaving space for the cooling tubes. The nominal horizontal and vertical apertures are 44.04 mm and 34.28 mm, respectively. Slots, covering a total of 4% of the surface area are perforated in the flat parts of the beam screen to allow condensing of the gas on surfaces protected from the direct impact of energetic particles (ions, electrons and photons). The pattern of the slots has been chosen to minimise longitudinal and transverse impedance and the size chosen to keep the RF losses through the holes below 1 mW m⁻¹. A thin copper layer (75 µm) on the inner surface of the beam screen provides a low resistance path for the image current of the beam [7].

The manufacturing process starts by co-laminating a specially developed low permeability 1 mm thick austenitic stainless steel strip with a 75 µm copper sheet and rolling a saw-tooth structure which will intercept photons at normal incidence, thereby reducing the amount of reflected photons. The pumping slots are punched into this composite strip, which is then rolled into its final shape and closed by a longitudinal weld.

![Conceptual design of the LHC beam screen](image.png)

The beam screen is cooled by two stainless steel tubes with an inner diameter of 3.7 mm and a wall thickness of 0.53 mm, allowing for the extraction of up to 1.13 W/m in nominal cryogenic conditions [8]. The helium temperature is regulated to 20 K at the output of the cooling circuit at every half-cell (see Chap. 11 of this report), resulting in a temperature of the cooling tubes between 5 and 20 K for nominal
cryogenic conditions. The cooling tubes are laser welded onto the beam screen tube and fitted at each end with adaptor pieces which allow their routing out of the cold bore without any fully penetrating weld between the helium circuit and the beam vacuum (Fig. 12.2).

So-called sliding rings with a bronze layer towards the cold bore are welded onto the beam screen every 750 mm to ease the insertion of the screen into the cold bore, to improve the centring in the cold bore and to provide good thermal insulation [9].

Finally, as it was recognised that electron clouds could deposit significant power into the cold bore through the pumping slots, the latter are shielded with a structure made of copper beryllium and clipped onto the cooling tubes. The net pumping speed for hydrogen is reduced by a factor of two [10], which remains acceptable.

The beam screen is fixed onto the cold bore at one extremity of the cryomagnet. At the other extremity, a bellows is inserted between the beam screen and the cold bore, to allow for differential expansion between the two. The extremities of the beam screen are gold plated to satisfy the requirement of low electrical resistance of the interconnection.

During operation, in particular when a quench occurs in the magnet, the beam screen is submitted to two types of loads due to the eddy currents induced by the rapidly changing field and the very low resistance of the copper layer at cryogenic temperatures [11]. On one hand, the beam screen is submitted to a horizontal expansion force and on the other hand it is pushed laterally against the cold bore. The latter is the consequence of an asymmetry of the magnetic field integrals in the magnet yoke. Both aspects have been tested under representative conditions in the test String and the design was validated.

12.3.2 Cold Interconnects

Beam vacuum interconnects ensure the continuity of the beam vacuum envelope and of the helium flow in the cooling tubes, as well as a smooth transition between beam screens along the 1642 twin aperture superconducting cryomagnets installed in the continuous cryostat. The physical beam envelope must have a low electrical resistance to carry the image current and minimise coupled bunch instabilities [3]. It also must have a low inductance to minimise the longitudinal single bunch instability. The maximum dc resistance allowed at room temperature for a complete interconnect is 0.1 mΩ. In order to meet these requirements, a complex interconnect module which integrates a shielded bellows to allow thermal expansion as well as for compensation of mechanical and alignment tolerances between two adjacent beam screens, is required.

![Figure 12.2: Layout and components of the interconnects for the LHC arc beam vacuum](image)

The shielding of the bellows is achieved by means of a set of sliding contact fingers made out of gold-plated copper-beryllium, which slide on a rhodium-coated copper tube. A set of machined copper pieces is used to adapt the racetrack shape of the beam screen to the circular shape of the shielded bellows module. These adaptation pieces also allow the routing of the cooling tubes in and out of the cold bore. The chosen design allows for mounting all adaptation pieces when the beam screen is inserted into the cold bore, before lowering the cryomagnet to the LHC tunnel, leaving the installation and welding of the shielded bellows
module, also called the “plug-in module”, as the only in-situ operation. It also satisfies the design criterion which excludes any welds between liquid helium and beam vacuum.

Figure 12.3: Details of the interconnect “plug-in module”

12.3.3 Beam Position Monitor Bodies and Supports

A beam position monitor (BPM) equipped with four button electrodes will be installed on each beam at every short straight section in the continuous cryostat of the arc. In a few places, a strip-line monitor replaces the button type.

Figure 12.4: Principle layout of an arc beam position monitor

The body holding the electrodes and the connecting “drift length” to the cold bore form an integral part of the beam vacuum chamber, by extending the cold bores of the quadrupole magnets. In this configuration, the beam screen is welded to the BPM body at one extremity and to the cold bore of the magnet, via an expansion bellows, at the other extremity. The BPM body is actively cooled in series with the beam screen, which makes it a rather complex item. A thin copper layer (100 µm) is electrodeposited on both the BPM body and the support to ensure low DC resistance and uniform cooling of the drift length [12].

12.3.4 Pumping and Diagnostics

Initial pumping of the beam vacuum pipe in the arcs and dispersion suppressor is made using mobile pumping groups, connected at regular intervals. Two access ports are available at most of the short straight sections, one for each beam pipe. The number of pumping groups to be connected as well as the required pumping time before cooling down is still under study. The final choice will be made based on the requirement to minimise the initial gas quantity condensed on the inner wall of the beam screen. During
operation at cryogenic temperatures, the pumping solely relies on cryopumping of the cold bore and beam screen.

In the cold beam vacuum system, the strong distributed pumping of the beam pipe and the small conductance between the measuring equipment and the beam vacuum drastically reduce the value of systematic pressure measurements. Therefore, the pressure will be checked during the pre-evacuation stage to prevent condensing a gas layer which is too thick on the cold surfaces due to insufficient pump-down. Under normal operating conditions, the pressure will not be recorded, but in the case of perturbed beam conditions, a mobile diagnostic equipment can be connected to the beam vacuum system through roughing valves mounted at every straight section.

12.4 BEAM VACUUM IN THE INSERTIONS

Room temperature chambers alternate with stand alone cryostats in the Insertion Regions (IRs). The room temperature (RT) part includes beam instrumentation, accelerating cavities, experiments, collimation equipment, the injection and ejection kickers and septa, as well as some of the dipole and quadrupole magnets when superconducting elements are not used. In these regions, the vacuum systems for the two beams sometimes merge, notably in the four experimental insertions, but also in some special equipment like the injection kickers and some beam stoppers.

12.4.1 Beam Screen

The beam screen is only required in the cold bores of the stand-alone cryostats. It is derived from the arc type, but uses a smaller (0.6 mm) steel thickness and comes in various sizes, to match different cold bore diameters. The orientation of the beam screen in the cold bore has to be adapted to the requirements for apertures, which means that the flat part with the cooling tubes can also be vertical, as opposed to the horizontal orientation in the arc. Furthermore, the orientation is different for the two beams in the same twin-aperture magnet in most cases [13]. Tab. 12.2 shows the orientation of the beam screens. For example, HV indicates that beam 1 has the smallest beam screen aperture in the horizontal direction and beam 2 has the smallest beam screen aperture in the vertical direction, as illustrated in Fig. 12.5.

![Diagram of beam screen orientations](image)

Figure 12.5: Definition of beam screen orientation

The saw-tooth structure has been abandoned for these beam screens, since synchrotron radiation hitting the screen in these regions is at least ten times less intense than in the arc and because fitting the saw teeth at the appropriate location of the beam screen would be too expensive [14].

Some stand-alone magnets will operate at 4.5 K instead of 1.9 K. In this case, provisions must be made to pump the hydrogen out of the beam path. This is achieved by fixing a cryosorber on the pumping slot shields. Recent developments at BINP (Novosibirsk, Russia) have resulted in a carbon fabric, easier to use than charcoal, which is likely to provide the required pumping speed and capacity [15].
Table 12.2: Cold bore and beam screen sizes, beam screen orientations

<table>
<thead>
<tr>
<th>Cold Bore</th>
<th>Interaction Region</th>
</tr>
</thead>
<tbody>
<tr>
<td>Operating Temp (K)</td>
<td>Nominal ID/OD (mm)</td>
</tr>
<tr>
<td>4.5</td>
<td>#50/53 (replaces 46/49)</td>
</tr>
<tr>
<td>1.9</td>
<td>50/53</td>
</tr>
<tr>
<td>1.9</td>
<td>53/57</td>
</tr>
<tr>
<td>4.5</td>
<td>#62.98/66.7 (replaces 60/64)</td>
</tr>
<tr>
<td>1.9</td>
<td>62.98/66.7</td>
</tr>
<tr>
<td>4.5</td>
<td>69.08/73</td>
</tr>
<tr>
<td>1.9</td>
<td>74/78</td>
</tr>
</tbody>
</table>

* Increased cold bore diameter as recommended by LCC. Cooling efficiency with reduced gap to be confirmed by July 2003
* DFBA shuffling module

12.4.2 Cold Interconnections and Cold-Warm Transitions

The required interconnections between multiple magnets in a single stand alone cryostat (e.g. the inner triplet) are based on the design of the arc type. In some cases, however, they not only have to compensate for thermal expansion and minor alignment errors, but also for beam separation and cold bore diameter transitions in the adjacent beam pipes. Another complication comes from the fact that the beam screens are rotated in some locations by 90° as compared to the arc, leading to non-standard solution for the routing of the cooling tubes (see Fig. 12.6). It is also sometimes required to integrate pumping ports into interconnects.

Figure 12.6: Example of non-standard routing of the cooling tubes when the beam screen is rotated by 90°.
The combined interface variations result in 24 different interconnect assemblies to be used in the 278 cold beam vacuum interconnects of the LHC Dispersion Suppressors and Long Straight Sections. The use of modular subassemblies and components shared among design variants, has optimised the design and reduced the number of different pieces to a minimum.

A cold-to-warm transition (CWT) has to be installed for the beam vacuum tubes at the end of every cryostat (Fig. 12.7) as an interface between the cryogen-cooled beam pipes and the room temperature beam pipes. Each circulating beam will pass 108 CWTs per turn (superconducting cavities excluded). In total there will be 200 individual CWTs taking into account that most elements have two apertures.

On the cold side, the CWT connects either to a beam screen and cold bore or to a beam position monitor. On the room temperature side, it connects to the insulation vacuum end cover and a pumping station for the beam vacuum. A thermal anchor at a temperature below 100 K on the CWT intercepts a major part of the conductive heat from room temperature. This thermal anchor is connected to the thermal shield of the cryo-assembly.

The CWT compensates for the longitudinal and transverse thermal displacements of the cold bores and beam screens with respect to the insulation vacuum end cover. It also allows the differential thermal displacements between the beam screen and the cold bore. The concept of the beam vacuum interconnects for the arcs has been adopted and the design will be adapted to the corresponding cold bore dimensions in each case. The final design of the CWT is a compromise between beam impedance and thermal impedance requirements. The heat load to be intercepted by the thermal anchor at 100 K will be less than 6 W per CWT, while the static heat load to the 20 K level must remain below 2.5 W per CWT (1.3 W by thermal radiation and 1.2 W by thermal conduction) [16].

12.4.3 Room Temperature Beam Vacuum in the Field Free Regions

The baseline for the room temperature (RT) beam vacuum system is to use 7 m long OFS copper chambers, with an inner diameter of 80 mm and fitted with standard DN100 Conflat™ flanges. The
thickness of the copper is 2 mm and the chambers are coated with TiZrV non evaporable getter (NEG) [17], which after activation at low temperature (200°C) provides distributed pumping and low outgassing to maintain a low residual gas pressure, as well as a low secondary electron emission yield to avoid electron multipacting. These chambers will be connected by means of shielded bellows modules, some of them including pumping and diagnostic ports. A significant effort has been put into the design to build up the RT beam vacuum system with a much reduced number of variants for the different components. In particular, the interconnects, based on the design of the cold parts, come with only three lengths of bellows and three different diameters. The adaptation for changing diameters is made out of a set of inserts. Fig. 12.8 gives an overview of the main components used.

Figure 12.8: Standard layout of the RT beam vacuum system between two cryostats.

The 7 m long chambers are supported by three supports, one fixed and two mobile. A removable adjustment system allows the alignment of the chambers, without having to integrate the alignment means into the supports. The required sector valves are installed in the RT part of the vacuum system, in most cases.
next to a stand-alone cryostat. They are combined with a pumping and diagnostic port, for a set of gauges, an ion pump and a roughing pump port.

Unfortunately, this simple baseline design cannot be used everywhere. Two examples of more complicated layouts are given in Figs. 12.9 and 12.10, showing the portion of the LSS where two beam lines merge into a single one, for IR8L and IR2R. For the latter, the requirements of the Zero Degree Calorimeter (ZDC) ask for an inner diameter of the vacuum chamber upstream of the experiment as large as 797 mm. For the four insertion regions with experiments, a special vacuum chamber must merge the two physical beam tubes into a single one. In IR 1 and 5, this is done in the neutron absorber (TAN), whereas for IR 2 and 8 a special chamber has to be designed. In all cases, great care was taken to keep the beam vacuum chamber as smooth as possible.

![Figure 12.10: Layout of the RT beam vacuum system at right of IR point 2](image)

12.4.4 Beam Vacuum in Room Temperature Magnets

A number of room-temperature magnets, most of them located in the cleaning insertions (IR3 and IR7), will be equipped with extruded OFS copper chambers with either elliptic or circular cross-sections and fitted with standard DN100 Conflat™ flanges. The thickness of the copper is 2 mm and the chambers are NEG coated. The MBXW (also referred to as D1) chambers are an exception in so far as they have a wall thickness of 3 mm and are fitted with DN150 flanges. The initial cruciform shape in the MQW magnets was abandoned for an elliptic cross-section to provide sufficient aperture and allow baking the vacuum chamber to 250°C while keeping a sufficiently low temperature on the magnet yoke. However, as for the beam screen, the orientation of the elliptical chambers will vary depending on the location in the machine.

![Figure 12.11: Initial and final cross-section for MQW chambers and example of orientation in the magnet yoke.](image)
In the case of the MQW magnets, where the magnets cannot be reopened, the chambers must be inserted into the magnet yoke for installation. This requires that one flange be welded in situ, with very little space available between the magnet coil and the flange.

12.4.5 Beam Vacuum in Special Equipment and Experimental Areas

The details of the beam vacuum in special equipment (RF cavities, septa and kickers, etc.) can be found in the chapters of this report describing the specific equipment. Their design must comply as much as possible with the technical choices made for the standard RT parts, in particular in terms of flanges and bake-out temperatures.

The description of the vacuum system in the experiments is in Chap. 19 of this report.

12.4.6 Pumping

Pumping ports will be integrated in the interconnect modules, in most cases close to a sector valve. Initial pumping is made with mobile, bakeable, pumping stations. The permanent pumping is done with a limited number of sputter ion pumps (typically one every 28 metres) and the NEG coating.

12.4.7 Diagnostics

The room temperature part of the beam vacuum system is baked and very efficiently pumped by the NEG. It therefore requires reliable measurement of low pressures (10⁻⁹ Pa range) and gas composition to check the background conditions for the adjacent experiments (IR 1, 2, 5 and 8) or to have early detection of anomalies such as the development of a leak or the saturation of the NEG coating. On the other hand, the pressure detection system triggering the interlocks for the valves needs reliable sensors in a higher pressure range, typically 10⁻⁷ to 10⁻⁴ Pa.

One Pirani gauge per sector is used to monitor the pressure evolution during the initial pump down from atmospheric pressure. It can also be used as a source of an interlock for the sputter ion pumps and the cold cathode gauges. Every sector is equipped with two cold-cathode gauges, installed in the vicinity of the sector valves. Hot cathode gauges, either permanently installed or available on mobile diagnostic stations, will allow measurement of pressures below the reliable operational range of the cold-cathode gauges, typically below 10⁻⁸ Pa. Finally, residual gas analysers, most likely mounted on mobile stations, will allow qualitative measurement of the beam vacuum after bake-out and NEG activation. They may also provide useful information about the saturation level of the NEG coating.

12.4.8 Bake-out and NEG activation

The required pressures in the insertion regions and the need to activate the NEG coating, call for a bake-out system able to heat every component to 250°C (300°C for uncoated chambers). The final choice on how to heat the standard chambers is not made yet. The baseline is to have mobile heating and regulation equipment. However, as it becomes more and more evident that there will be many very highly radioactive areas around the ring, permanently installed heating equipment may become mandatory to reduce the radiation dose to the personnel during maintenance activities.

For the standard chambers, classical methods, like heating tapes and insulation shells are likely to be the cheapest for permanently installed equipment, heating jackets can be used for removable heating equipment. Although more expensive than tapes, jackets are much more robust when it comes to mounting and dismounting them. They also need significantly less manpower.

For the chambers in the room temperature magnets, an original concept of a wound sandwich made out of stainless steel as heating elements and polyimide foils as insulation material has been developed and validated. This technique allows the space required for heating and insulation to be reduced to less than a mm (typically 0.3 mm). Aluminising the top layer of the polyimide further reduces the radiated power. A considerable cost reduction can be obtained compared to using coaxial heaters.
The proposed bake-out sequence must be optimised to take into account the NEG activation. In the first part of the bake-out cycle, all non-coated elements will be heated to 300°C (gauges and gas analysers to 350°C) for 24 hours, while the coated parts are left at 80°C to prevent absorption of water without an early activation of the NEG. The temperature of the non-coated parts is then reduced to 150°C and 24 hours of NEG activation at 200°C can start. The whole process (Fig. 12.13) takes some 65 hours [18].

12.4.9 Sectorisation

The proposed sectorisation is a compromise between costs, complexity and a number of operational and safety requirements [19]. The strategy used was to start by protecting the arcs, the experimental areas and delicate equipment. In addition, considerations like power limitations for bake-out or reducing the number of potential interventions in high radiation areas were taken into account. Finally, whenever there was a need for a sector valve based on the above-mentioned criteria, the valve was moved close to the cold-to-warm transition leading to a sector valve at each cold-to-warm transition. The result of this approach is that the beam vacuum system will be split into 230 sectors of varying length. All sectors belonging to stand-alone cryostats in the LSS can be isolated and impose no constraints on cool-down or NEG activation cycles.

Only two different types of sector valves are required (DN63 and DN100), some of them are recuperated from LEP, the others are off-the-shelf equipment procured in industry.
12.5 BEAM DUMP LINES

The two beam lines designed to transport the proton beams to the dump (TDE), are located in the underground tunnels TD62 and TD68. The beams are kicked out of their circulating orbit by the extraction kickers (MKD) in the horizontal plane and extracted vertically from the ring by the septa (MSD). The beams are then blown-up by the diluters (MKB, see Chap. 17 of this report) before reaching the dump blocks (TDE) at the end of the dump lines. After the diluters, the beam will follow a spiral with an increasing radius (from 50 mm up to 300 mm). Therefore, the vacuum envelope has an increasing cross section up to the dump located at about 630 m downstream from the diluters. The beam dump lines are designed such that the beam never interacts with the vacuum chamber.

The LHC beam dump vacuum system has been designed to be simple, reliable, maintenance free and inexpensive. A pressure below $10^{-5}$ mbar is enough to satisfy the requirements in terms of acceptable radiation doses produced from beam-gas scattering. However, in order to allow the use of maintenance free sputter ion pumps without decreasing dramatically their lifetime, the pumping system was designed to maintain a pressure of $10^{-6}$ mbar [20].

In total 33 sputter ion pumps are installed in each line on pumping ports welded to the standard tubes (Fig. 12.15). The first pump down to $10^{-6}$ mbar will be made using mobile turbo-molecular pumping stations connected to roughing ports.

![Figure 12.14: Example of sectorisation: left side of IR2 (ALICE experiment) and IR4 (RF equipment)](image)

![Figure 12.15: Pressure profile, distribution of ion pumps, vacuum chamber diameters and beam stay clear along the beam dump line starting downstream of the diluters (MKB) down to the dump (TDE).](image)
The vacuum line will be made by in situ welding of stainless steel 304 L tubes of suitable diameters chosen from the industrial standards available. Bellows will be used approximately every 12 m, in order to cope with misalignments (±5 mm) and tilts between adjacent elements.

The supporting structure is designed to take the weight of the vacuum line and its instrumentation. In total, about 60 supports will be used per dump line.

The leak detection will be made using a special tooling developed for the leak testing of the welds in the interconnection of the cold magnets. A “clamshell” will be fixed around the weld to be leak tested, pumped down by a mobile turbo-molecular pumping station connected to a leak detector and, finally, the helium will be injected inside the tube directly onto the weld. No leak must be detectable on any joint of the vacuum chamber when measured with a calibrated helium detector with a sensitivity of better than $10^{-9} \text{ Pa m}^3 \text{ s}^{-1}$.

12.6 INSULATION VACUUM

The insulation vacuum system includes the magnet cryostats and the QRL. Vacuum barriers at the jumper connections maintain separation of the two systems, however, longitudinal vacuum barriers can be bypassed. The configuration of the insulation vacuum barriers and cryogenic circuits permit warming of individual machine cells [21]. The insulation vacuum is characterised by the large volumes that need to be pumped and the large amount of multilayer reflective insulation (MLI), which introduces a high gas load. This requires high-capacity mobile pumping groups (64 m$^3$ h$^{-1}$) and an appropriate strategy for leak detection to provide an acceptable pump-down time.

Table 12.3: Main characteristics of the insulation vacuum sectors

<table>
<thead>
<tr>
<th></th>
<th>Cryomagnet</th>
<th>QRL</th>
</tr>
</thead>
<tbody>
<tr>
<td>Volume (m$^3$)</td>
<td>80</td>
<td>85</td>
</tr>
<tr>
<td>Length (m)</td>
<td>214</td>
<td>428</td>
</tr>
<tr>
<td>MLI (m$^2$/m)</td>
<td>200</td>
<td>140</td>
</tr>
<tr>
<td>Sectors per arc</td>
<td>14</td>
<td>7</td>
</tr>
</tbody>
</table>

The vacuum instrumentation is classified as either permanent or mobile and its layout is similar on the cryomagnet and QRL vacuum systems [22]. Mobile instrumentation has been designed to avoid intrusion into the equipment transport zone in the tunnel (‘stay-clear’ area). The choice of permanent instrumentation is constrained by the expected radiation dose in the LHC tunnel. Typical vacuum instrumentation requirements per vacuum sector are shown in Fig. 12.16.

Figure 12.16: Typical insulation vacuum instrumentation
Table 12.4: Proposed leak test scenario for the arc insulation vacuum

<table>
<thead>
<tr>
<th>Leak Test Scenario</th>
<th>Time per arc</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Weld all interconnects</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leak test V1 &amp; V2 after each 214 m</td>
<td>2 days x 15 sectors</td>
<td>Volume gets big!</td>
</tr>
<tr>
<td>Close W bellows – without shields, MLI</td>
<td></td>
<td>To localise He leaks</td>
</tr>
<tr>
<td>1st pumping of insulation vacuum sector</td>
<td>4 days x 15 sectors</td>
<td></td>
</tr>
<tr>
<td>Leak test RT envelope of vac sector</td>
<td>2 days x 15 sectors</td>
<td></td>
</tr>
<tr>
<td>Complete Arc (or Sector)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Leak test (low pressure) He circuits of arc</td>
<td>8 days</td>
<td>Many leak detectors</td>
</tr>
<tr>
<td>Leak/pressure test He circuits of arc</td>
<td>2 days</td>
<td>Many repairs?</td>
</tr>
<tr>
<td>Vent ins. vacuum &amp; open all W bellows</td>
<td>2 days x 15 sectors</td>
<td></td>
</tr>
<tr>
<td>Repair leaks on He circuits (clamshells)</td>
<td>1 day x 15 sectors</td>
<td></td>
</tr>
<tr>
<td>Close all W bellows – with shields, MLI</td>
<td>2 days x 15 sectors</td>
<td></td>
</tr>
<tr>
<td>Re-pump insulation vacuum sector</td>
<td>1 day x 15 sectors</td>
<td></td>
</tr>
<tr>
<td>Leak test RT envelope (W bellows only)</td>
<td>2 days</td>
<td></td>
</tr>
<tr>
<td>Repeat pressure test if necessary</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The permanent turbo-molecular pumping group is placed at the vacuum barrier by-pass, giving the advantage that two permanent groups can pump a single vacuum sector and providing redundancy in case of pump failure. During steady-state LHC operation, the pumping group only operates if helium leak rates are above the design values [23].

The leak test sequence is shown in Tab. 12.4. In order to apply the time-of-flight (TOF) technique, the thermal shields and MLI are not immediately installed. Once the installation of the arc is complete, the helium circuits can be leak tested using the hood-global technique. The circuits are collectively evacuated to <1 mbar and then individually or collectively vented to helium via the QRL. The pressure can then be increased in each circuit to the test pressure. Both remote and manual operation of the QRL cryo-valves will be necessary during these activities. Any unacceptable leak will be localised longitudinally within the 214 m vacuum sectors [24].

After the necessary repairs, all the bellows of the outer envelope must be reopened to install the radiative insulation, thermal shields and MLI, followed by a leak test of the bellows seals. If a vacuum sector has no helium leaks, the reopening activities can be made in the shadow of repair activities in another vacuum sector.

12.7. VACUUM CONTROLS

The controls for the three vacuum systems are based on an industrial solution using PLCs and a central SCADA supervision system connected via Ethernet to the master PLCs.

![Architecture of the higher level of the vacuum control system, example for sector 7-8](image)
A Profibus™ link is used to connect slave PLCs and mobile equipment to the master PLCs. The slave PLCs control off-the-shelf or CERN developed hardware control crates, which are hardwired to pumps, gauges and valves in the tunnel. In order to minimise the cabling costs, signal and control wires are grouped into large multicore cables and locally dispatched to the equipment via junction boxes. Most of the control equipment is located in radiation free areas, such as the alcoves. However, the gauges in the arcs are supplied by local equipment situated in areas where the expected annual dose remains below 10 Gy per year.

Extensive tests have been performed in the North Area of the SPS on the radiation resistance of commercially available vacuum control equipment. Based on these tests and on the requirement to minimise the cables, the power supplies for the cold cathode gauges can be bought from industry, while those for the Pirani gauges have been developed in house. The turbo-molecular pumps needed for the insulation vacuum can also be supplied by industry.

One specificity for the vacuum controls is the requirement to dynamically reconfigure the layout. This is a consequence of using mobile pumping and diagnostic equipment. It must be possible to detect equipment when it is connected or disconnected from the Profibus™ link, without having to manually update a database. A prototype link with mobile equipment has been successfully tested in the laboratory. The general architecture and the SCADA program have been operational in the SPS since 2002, thus validating the concept.

**12.8 OPERATIONAL ASPECTS**

In the cold part of the LHC vacuum system, running at 1.9 K, all gases except hydrogen have a low enough vapour pressure ($4 \times 10^{-13}$ Pa for CO at 20 K) when condensed on the beam screen surface, as long as the beam screen surface is kept at a temperature below 20 K. Hydrogen will be pumped on the 1.9 K surface of the cold bore through the pumping slots of the beam screen. The strong dynamic effects that the LHC vacuum

![Figure 12.18: Architecture of the lower level of the vacuum control system, also showing the integration of mobile equipment.](image-url)
system will experience, as well as the usage of “saturable” pumping elements like NEG or cryosorbers, impose some running-in and operational constraints.

12.8.1 Beam Screen Cool-Down

To minimise transient effects linked to temperature variations of the beam screen, it is therefore important to begin an annual run with as low a coverage of the surface as possible [25]. This can be achieved by keeping the temperature of the beam screen above 90 K (temperature at which CO₂ is no longer cryopumped) during the full cool-down cycle of the magnets, implying a “plateau” at the end of the cool-down sequence [18]. This procedure has been tested in String2 and does not require additional time, as it is done in the shadow of the cool-down sequence.

12.8.2 Beam Screen Warming-up

In order to remove physisorbed gas layers accumulated on the beam screen, desorbed from the cold bore during a magnet quench and to avoid any transient effect, it must be possible to heat the beam screens in adjacent magnets. The temperature of the beam screen during this operation must be at least that reached by the cold bore after a quench at ultimate conditions. The present running-in and commissioning scenarios should avoid that warming up of the beam screen in a complete arc is required between two long shutdowns. However, in the unwanted case of oscillations of the beam screen temperature around 25 K, intermediate warming up of the beam screen would be required [26].

12.8.3 NEG Reactivation

NEG surfaces have a limited capacity for gas molecules [17], and the pumping speed reduces as the saturation coverage is reached. If the performance of the NEG has noticeably deteriorated during machine operation, NEG coated surfaces can be reactivated by raising their temperature to 200°C for 24h or 250°C for 2h [18].

12.8.4 Vacuum Conditioning

As mentioned in Sec. 12.1, beam conditioning will be required to achieve the design gas densities. A tentative running-in and commissioning scenario has been studied [25]. The vacuum conditioning of the cryoelements is divided into three phases: operation below electron cloud threshold, scrubbing of the vacuum chamber to reduce electron cloud effects and nominal operation. Gas load due to synchrotron radiation has been shown to require little or no vacuum conditioning [27]. Electron-stimulated molecular desorption, triggered by the electron cloud, has been shown to decrease with increasing
beam time. In the SPS, experimental results indicate that the design conditions could be reached in LHC within a few days [28].

Due to the NEG properties, the electron cloud as observed in the SPS [29] should not appear in the LHC room temperature elements. Thus only gas desorption due to synchrotron radiation exist. Provided adequate lumped pumping of hydrocarbons is available, very little or no vacuum conditioning of the NEG vacuum chambers will be required [30].

REFERENCES

[8] E. Hatchadourian et al., LHC Project Report 212


