Chapter 5

Vacuum system

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5.1 Overview

The LHC has three vacuum systems: the insulation vacuum for cryomagnets, the insulation vacuum for helium distribution (QRL), and the beam vacuum. The insulation vacua before cool-down do not have to be better than 10^{-1} mbar, but at cryogenic temperatures, in the absence of any significant leak, the pressure will stabilise around 10^{-6} mbar. The requirements for the beam vacuum are much more stringent, driven by the required beam lifetime and background at the experiments. Rather than quoting equivalent pressures at room temperature, the requirements at cryogenic temperature are expressed as gas densities normalised to hydrogen, taking into account the ionisation cross sections for each gas species. Equivalent hydrogen gas densities should remain below 10^{15} H_2 m^{-3} to ensure the required 100 hours beam lifetime. In the interaction regions around the experiments, the densities will be below 10^{13} H_2 m^{-3} to minimise the background to the experiments. In the room temperature parts of the beam vacuum system, the pressure should be in the range 10^{-10} to10^{-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 2’900 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; and 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.

5.2 Beam vacuum requirements

The design of the beam vacuum system takes into account the requirements of 1.9 K operation and the need to shield the cryogenic system from heat sources, as well as the more usual constraints

Table 5.1: The nuclear scattering cross sections at 7 TeV for different gases and the corresponding densities and equivalent pressures for a 100 h lifetime.

GAS	Nuclear scattering cross section(cm^2)	Gas density (m^{-3}) for a 100 hour lifetime	Pressure (Pa) at 5 K, for a 100 hour lifetime
H_2	$9.5\ 10^{-26}$	$9.8\ 10^{14}$	$6.7\ 10^{-8}$
He	$1.26\ 10^{-25}$	$7.4\ 10^{14}$	$5.1\ 10^{-8}$
CH_4	$5.66\ 10^{-25}$	$1.6\ 10^{14}$	$1.1\ 10^{-8}$
H_2O	$5.65\ 10^{-25}$	$1.6\ 10^{14}$	$1.1\ 10^{-8}$
CO	$8.54\ 10^{-25}$	$1.1\ 10^{14}$	$7.5\ 10^{-9}$
CO_2	$1.32\ 10^{-24}$	$7\ 10^{13}$	$4.9\ 10^{-9}$

set by vacuum chamber impedances. Four main heat sources have been identified and quantified at nominal intensity and energy:

- Synchrotron light radiated by the 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.

Intercepting these heat sources at a temperature above 1.9 K has necessitated the introduction of a beam screen. The more classical constraints on the vacuum system design are set by the stability of the beams, which sets the acceptable longitudinal and transverse impedance [29, 30], and 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 [31, 32] and are given in table 5.1, 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.

5.3 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 with 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 in each SSS (i.e. at each quadrupole). An actively-cooled beam screen is inserted into the cold bore of all magnets, connection cryostats and shuffling modules containing the current leads.

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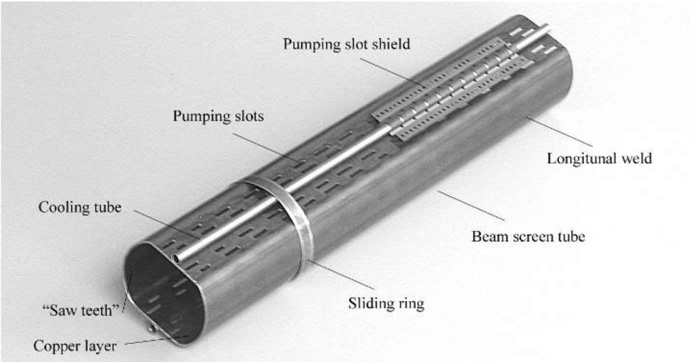

Figure 5.1: Conceptual design of the LHC beam screen.

5.3.1 Beam screen (figure 5.1)

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. A saw-tooth pattern on the inner surface in the plane of bending helps the absorption of synchrotron radiation.

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. The helium temperature is regulated to 20 K at the output of the cooling circuit at every half-cell, resulting in a temperature of the cooling tubes between 5 K 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. 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 tube, to improve the centering and to provide good thermal insulation. Finally, since the electron clouds can deposit significant power into the cold bore through the pumping slots, the latter are shielded with copper beryllium shields clipped onto the cooling tubes. The net pumping speed for hydrogen is reduced by a factor of two, which remains acceptable.

5.3.2 Cold interconnects (figures 5.2 and 5.3)

Beam vacuum interconnects ensure the continuity of the vacuum envelope and of the helium flow, as well as a smooth geometrical transition between beam screens along the 1'642 twin aperture superconducting cryomagnets installed in the continuous cryostat. The physical beam envelope must have a low electrical resistance for image currents and minimise coupled bunch instabilities [29]. It must also have a low inductance for the longitudinal single-bunch instability. The maximum DC

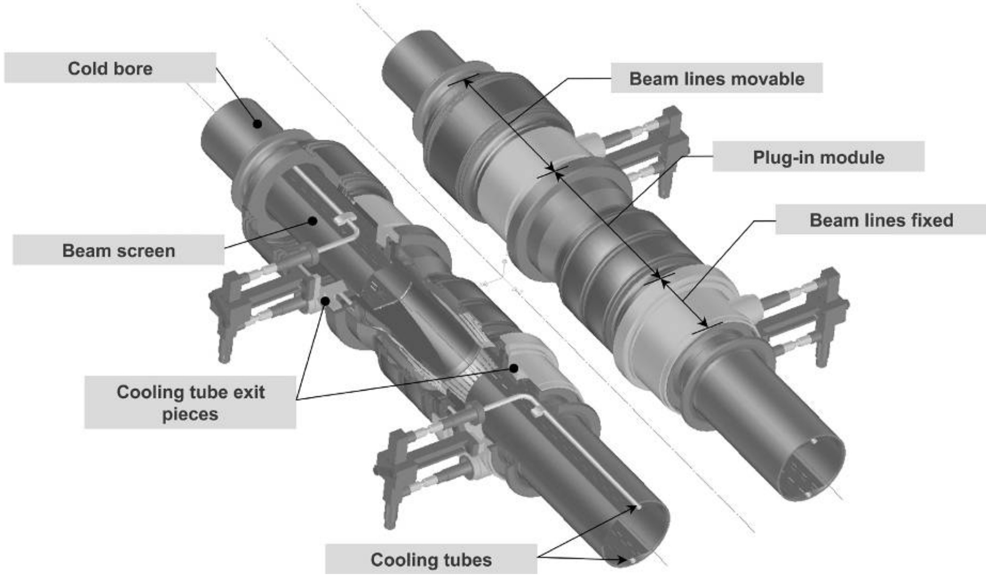

Figure 5.2: Layout and components of the interconnects for the LHC arc beam vacuum.

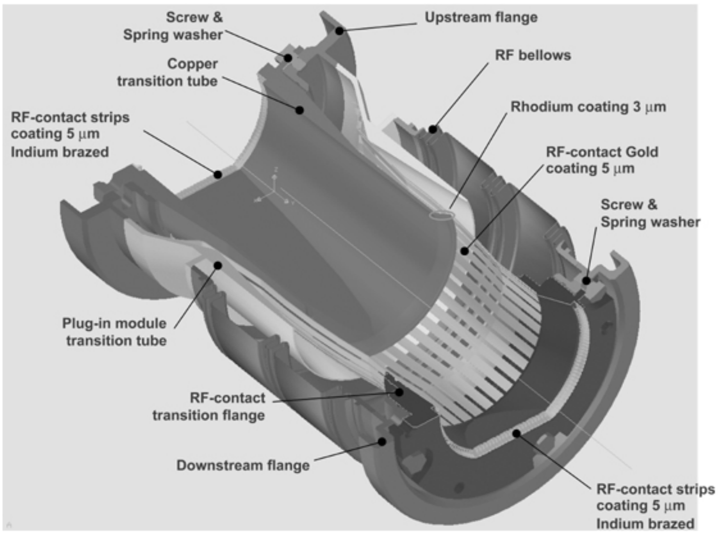

Figure 5.3: Details of the interconnect "plug-in module".

resistance allowed at room temperature for a complete interconnect is 0.1 mΩ. In order to meet these requirements, a complex interconnect module integrates a shielded bellows to allow thermal expansion, as well as for compensation of mechanical and alignment tolerances between two adjacent beam screens. 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.

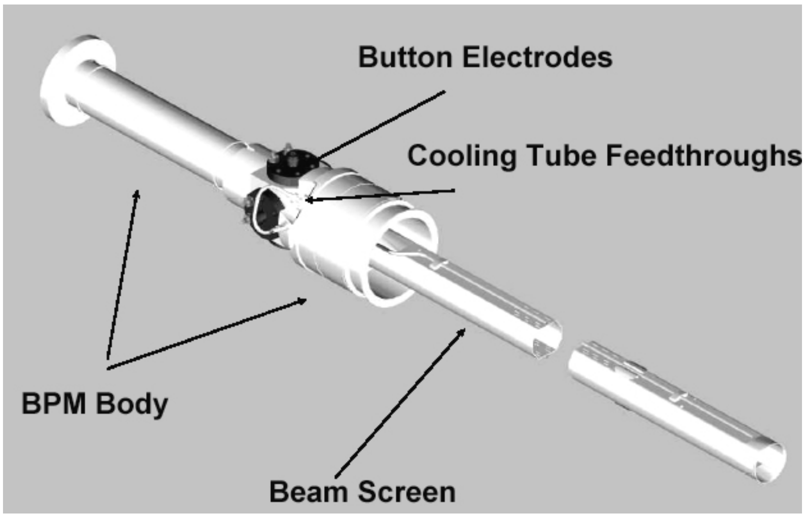

Figure 5.4: Principal layout of an arc beam position monitor.

5.3.3 Beam position monitor bodies and supports (figure 5.4)

A beam position monitor (BPM) equipped with four button electrodes is installed on each beam in every short straight section in the continuous cryostat of the arc. In a few places, a strip-line monitor replaces the button type. The body holding the electrode, 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. The BPM body is actively cooled in series with the beam screen. A thin copper layer (100 μm) is electrodeposited on both the BPM body and the support to ensure low DC resistance and uniform cooling over the drift length.

5.4 Beam vacuum in the insertions

Room temperature chambers alternate with stand-alone cryostats in the IRs. The room temperature part includes beam instrumentation, accelerating cavities, experiments, collimation equipment, and the injection and ejection kickers and septa, as well as some of the dipole and quadrupole magnets where 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.

5.4.1 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 is adapted to the aperture requirements, which means that the flat part with the cooling tubes can be either vertical or horizontal. 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.

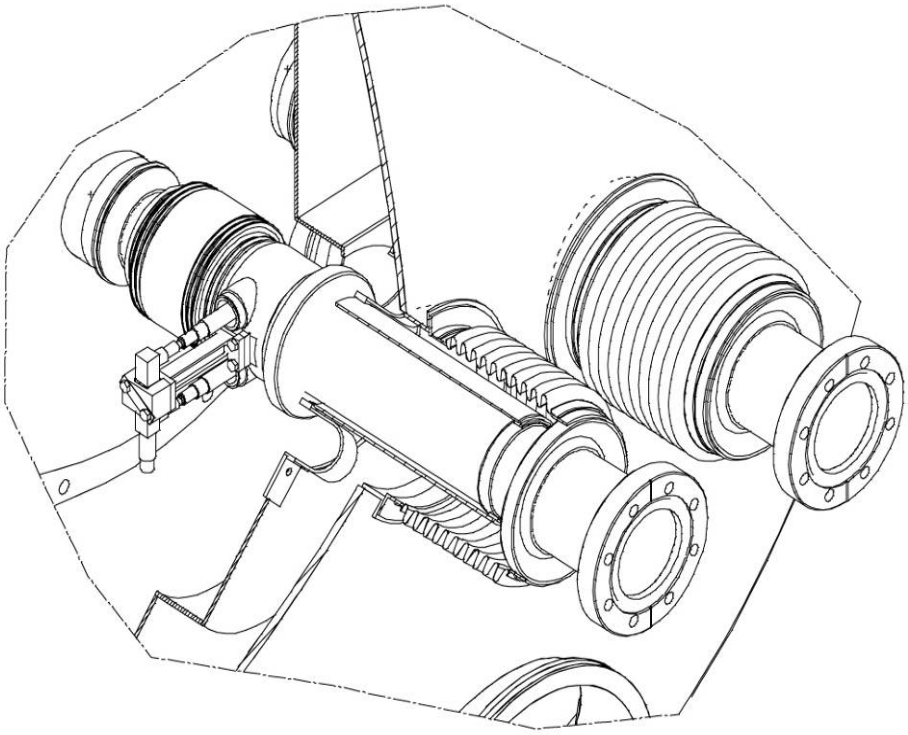

Figure 5.5: Details of a cold-to-warm transition.

5.4.2 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. Other complications come from the beam screens that are rotated by 90° in some locations as compared to the arc, and the occasional need to integrate pumping ports into interconnects, leading to non-standard solutions. The combined interface variations result in 24 different interconnect assemblies to be used in the 278 cold beam vacuum interconnects of the DS sections and LSSs.

A cold-to-warm transition (CWT) has to be installed for the beam vacuum tubes at the end of every cryostat (figure 5.5) 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. 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 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 is 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).

5.4.3 Room temperature beam vacuum in the field free regions

The baseline for the room temperature 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^{TM} flanges. The thickness of the copper is 2 mm, and the chambers are coated with TiZrV non evaporable getter (NEG) [33]. After activation at low temperature (200°C), the getter 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. The chambers are connected by means of shielded bellows modules, some of them including pumping and diagnostic ports.

5.4.4 Beam vacuum in room temperature magnets

A number of room-temperature magnets, most of them located in the cleaning insertions around Points 3 and 7, will be equipped with extruded OFS copper chambers, with either elliptic or circular cross-sections, and fitted with standard DN100 Conflat^{TM} 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.

5.4.5 Bake-out and NEG activation

The required pressures in the insertion regions, and the need to activate the NEG coating, call for a bakeout system able to heat every component to 250°C (300°C for uncoated chambers). The baseline is to have mobile heating and regulation equipment. However, in the many highly radioactive areas around the ring, permanently installed heating equipment may become mandatory to reduce the radiation dose to 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 demounting them. They also need significantly less manpower.

For the chambers in 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, see figure 5.6. This technique allows the space required for heating and insulation to be reduced to 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 bakeout sequence is optimised to take into account the NEG activation. In the first part of the bakeout 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 (figure 5.7) takes about 65 hours.

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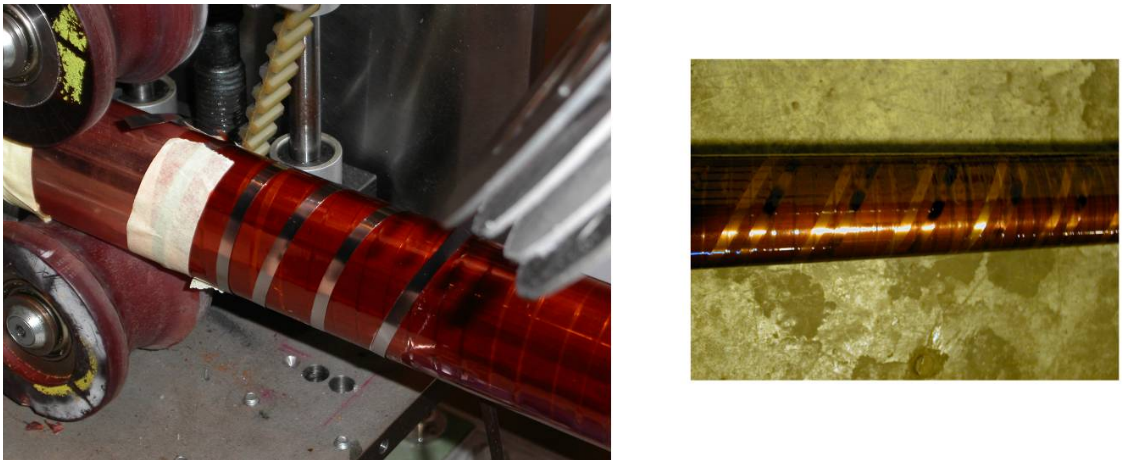

Figure 5.6: Wrapping of the stainless steel strips as bakeout heaters and a close up view of a finished chamber before the addition of the aluminised layer.

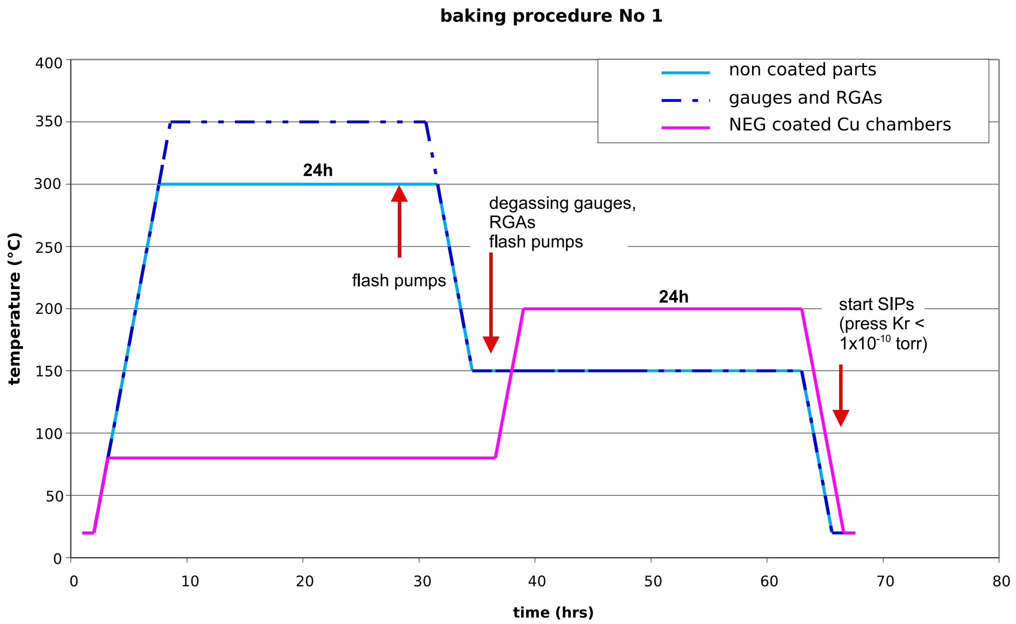

Figure 5.7: Proposed bakeout cycle with NEG activation.

5.5 Insulation vacuum

The insulation vacuum includes the magnet cryostats and the QRL, see table 5.2. Vacuum barriers at the jumper connections maintain separation of the two systems, however, longitudinal vacuum barriers can be by-passed. The configuration of the insulation vacuum barriers and cryogenic circuits permit warming of individual machine cells. 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 5.2: Main characteristics of the insulation vacuum sectors.

	Cryomagnet	**QRL**
Volume (m^3)	80	85
Length (m)	214	428
MLI (m^2/m)	200	140
Sectors per arc	14	7

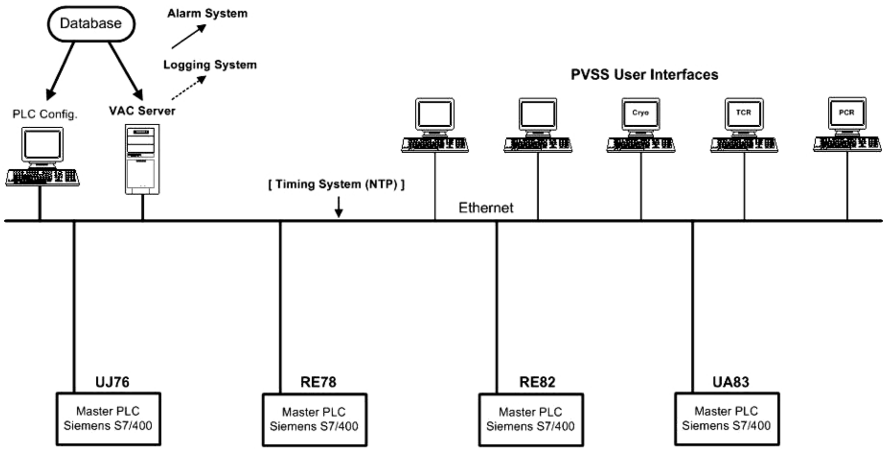

Figure 5.8: Architecture of the higher level of the vacuum control system, example for Sector 7-8.

5.6 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 (see figure 5.8).

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 hard-wired 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 specific requirement of the vacuum control system 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.