Large high-vacuum systems for CERN accelerators

To cite this article: P Strubin 2008 J. Phys.: Conf. Ser. 114 012001

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Large High-Vacuum Systems for CERN Accelerators

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Abstract. CERN operated over the more than 50 years of its existence particle accelerators and storage rings ranging from a few tens of metre to 27 km, the size of its latest project, the Large Hadron Collider (LHC) which is under construction and will be started in 2008.

The challenges began with the Intersection Storage Rings (ISR) in the seventies. With a beam pipe length of 2 x 1 km, this accelerator required innovative solutions like bake-out and glow discharge to achieve the required static vacuum level, fight against beam-induced pressure increases and cancel beam neutralisation by trapped electrons. The vacuum system of the Large Electron Positron (LEP) storage ring (in operation between 1989 and 2001) of a total length of 27 km had to cope with very high levels of synchrotron power. The beam vacuum system of LHC (2 x 27 km) integrates some parts at 1.9 K and others at room temperature and will also have to cope with dynamic effects. In addition to the beam vacuum system, LHC requires insulation vacuum for the superconducting magnets and the helium distribution line. Whereas the required pressure is not very low, the leak detection and localisation is significantly more demanding for the insulation vacuum than for the beam vacuum because of the large volumes and the thermal insulation.

When the size of an accelerator grows, the difficulties are not only to get a clean and leak tight vacuum system, but also to be able to measure reliably pressure or gas composition over long distances. Furthermore, in the case of LHC the integration of the beam vacuum system was particularly difficult because of the complexity induced by a superconducting magnet scheme and the reduced space available for the beam pipes. Planning and logistics aspects during installation, including the usage of mobile pumping and diagnostic means, were much more difficult to manage in LHC than in previous projects.

1. The evolution of the requirements
The vacuum system of an accelerator, be it small or large, is driven by the performance wanted for the beams. Larger accelerators usually mean higher beam energy, which can induce more dynamic effects. But what makes a large vacuum system different is that a trade-off must be found between performance and cost. The first large accelerator, or rather storage ring, at CERN was the Intersecting Storage Rings (ISR), designed in the 60’s, a 26 GeV proton storage ring with a design current of 20 A per beam. At that time, as much as the size, the challenge was to achieve stable UHV conditions with a circulating beam. The Super Proton Synchrotron (SPS) was built in the 70’s initially for fixed target physics up to 450 GeV. The size jumped from two rings of 1 km each to one ring of 6 km. The SPS was later upgraded as a proton-antiproton (p-pbar) storage ring, with a design current of 20 A per beam. At that time, as much as the size, the challenge was to achieve stable UHV conditions with a circulating beam. The Super Proton Synchrotron (SPS) was built in the 70’s initially for fixed target physics up to 450 GeV. The size jumped from two rings of 1 km each to one ring of 6 km. The SPS was later upgraded as a proton-antiproton (p-pbar) storage ring, which required significant improvement of the vacuum system. In December 1981, CERN Council authorised the Large Electron Positron collider (LEP), with a first phase of two 50 GeV lepton beams and the possibility to increase the energy up to 125 GeV per beam in a second phase. This was a new significant increment in size with a ring of 27 km of circumference. Finally, the next large accelerator at CERN, the Large Hadron...
Collider (LHC), combines the difficulties of size (also 27 km, as it reuses the LEP machine tunnel) and cold vacuum, as it is a superconducting device.

1.1 ISR

When the Intersecting Storage Rings (ISR) were designed, there was no or little knowledge about dynamic pressure behaviour for proton accelerators. In the design report of this accelerator [1], the requirements were set as:

- Average pressure along the ring: $10^{-9}$ mbar
- Pressure in the experimental areas: $< 10^{-11}$ mbar

The first value was essentially required to achieve a good enough beam lifetime, which was defined to be 12 hours between two filling cycles. The second value was required to reduce the background to the experiments, in particular for the experiments aiming at measurements of the proton-proton elastic scattering cross section. These values were nevertheless very demanding for a vacuum system of two times 1 km in circumference. Based on the results of a small study machine (CESAR) [2], the need for an all-metal bakeable system was identified. The sealing technique of CESAR was based on gold seals between flat stainless steel flanges and found to be not very reliable (some 5% of leaks either before or after bake-out). Therefore it was decided to use the novel technology of ConFlat flanges which used OFHC copper gaskets. This technology has since then become a de-facto standard for all bakeable UHV vacuum systems. The initial pumping system was mainly based on sputter ion pumps. No dynamic effects were expected, except what is called beam “neutralisation” which causes electrons created in beam-gas interactions to modify the space charge of the beam. Pairs of so-called “clearing electrodes” located at each end of every bending magnet and biased to +3 kV and +6 kV cured this problem [3].

Although the pressure achieved without beam in the early days of operation was as expected, it soon became evident that there were dynamic effects which led to localised pressure run-away (Figure 1), resulting in a complete beam loss at levels of 3 to 4 A of beam current (to be compared to the design value of 20 A per beam). This was traced back to ion induced desorption, when ions created by beam-gas interactions are accelerated towards the wall of the vacuum chambers, kicking out gas molecules from the bulk of the wall. Many investigations [4] resulted in the need for more pumping speed by means of titanium sublimation pumps and for argon glow-discharge [5] to reduce the desorption coefficient of the vacuum chambers. Hence, the requirements for the ISR vacuum system changed considerably as compared with the design values.

Also in the ISR, bunch induced electron multipacting was observed for the first time at CERN [6]. However, the ISR beams were only bunched during injection, therefore this phenomena was never a serious limitation.

![Figure 1. Pressure bumps in ISR.](image)

1.2 SPS

The Super Proton Synchrotron (SPS), with a circumference of more than 6 km and 6 access pits spaced by about 1 km was already a significant jump in the size of an accelerator. Its vacuum system was initially designed to accelerate and eject beams of up to 450 GeV onto fixed target physics experiments. The basic requirement was to reach $3 \times 10^{-7}$ mbar in 24 hours after a venting to air. The vacuum system is an all-metal design, but without bake-out. With the installed pumping system, based on mechanical roughing pumps and a large number of sputter ion pumps, the average pressure was typically $10^{-8}$ mbar 2 months after an intervention.
In a second phase, the SPS was converted to a p-pbar storage ring, calling for a lower pressure to minimise beam blow-up. The required maximum average pressure level was estimated to $2 \times 10^{-9}$ mbar [7]. This was achieved by doubling the number of sputter ion pumps in the arcs and adding a titanium sublimation pump on the port of every sputter ion pump (that is every 13 m in the arcs). Local bake-out was introduced in the vicinity of the colliding points.

In a more recent period, the vacuum system of the SPS had to be significantly improved on the mechanical side to reduce the longitudinal impedance of the whole accelerator when operating with high intensity beams as an injector for CNGS and LHC [8]. More than 1000 shields had to be installed in the pumping ports.

1.3 LEP

The Large Electron Positron collider (LEP) set a different scale for accelerator vacuum systems, with a circumference of almost 27 km and 8 access points, increasing the distance between any two access points to more than 3.3 km. As it was aiming at storing leptons, dynamic effects were considered from the very beginning. A pressure in the low $10^{-9}$ mbar range (nitrogen equivalent) was considered acceptable, but the partial pressure of argon had to stay below $5 \times 10^{-10}$ mbar. This is because the main effect is bremsstrahlung on the nuclei of gas molecules rather than beam-gas interactions [9]. In straight sections where the physics experiments were located the pressure had to be in the low $10^{-10}$ mbar because scattered particles would have contributed to the background in the detectors. These requirements called for a bakeable all-metal vacuum system.

The main problem to achieve these requirements stems from the synchrotron radiation which desorbs large quantities of gas from the wall of the vacuum chamber via the production of photoelectrons. Therefore the above quoted pressure levels have to be understood as values in presence of the beams. In order to limit the cost by installing a smaller pumping system than would be required to achieve the performance at start-up, it was accepted to rely on the effect of “beam cleaning” [10]. Many preliminary experiences run at DCI (France) allowed to validate this scenario (Figure 2). The initial pressure with 2 beams of 1 mA each was $10^{-8}$ mbar, decreasing to $3 \times 10^{-9}$ mbar for 2 x 3 mA after an integrated beam dose of 1000 mA h (Figure 3).

Figure 2. Desorption measurements for LEP

Figure 3. Beam cleaning in LEP

Because of the distributed nature of the desorption by synchrotron radiation, the best choice was a distributed pumping system as it was used at PETRA (Desy, Germany) where a system of linear ion pumps was implemented, using the field of the bending magnets rather than permanent magnets. As the field of the LEP bending magnets was too low, the ion pumps were replaced by a NEG strip, with additional distributed lumped ion pumps for the non-reactive gases [11].

A further requirement for the LEP vacuum system was to intercept as much as possible of the synchrotron power (71 W m$^{-1}$ initial, up to 1 kW m$^{-1}$ at 100 GeV per beam) and not let it spread into the tunnel where damages to components would have been expected, as well as the production of ozone and nitric oxides. The lower part of the spectrum of synchrotron radiation could be intercepted
by the vacuum chamber itself, made out of aluminium and water-cooled. The higher energy part of the spectrum required adding a lead shield onto the chamber, benefiting from the available cooling.

**LHC**

The Large Hadron Collider (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 $10^{-1}$ mbar. 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 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 $10^{15}$ H$_2$ m$^{-3}$ to ensure the required 100 hours beam lifetime [12]. In the stand-alone superconducting magnets of long straight sections around the experiments the densities will be below $10^{13}$ H$_2$ m$^{-3}$ to minimise the background to the experiments [13]. The requirements for the room temperature part are driven by the background to the experiments, by the beam lifetime as well as by the necessity to minimise activation of the components. This calls for a pressure value in the range $10^{-10}$ to $10^{-11}$ mbar, hence a bakeable vacuum system.

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 and desorbed from 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, Figure 4), on the materials (e.g. the introduction of a copper layer on the beam screen) 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 [14, 15] and locally by the background conditions in the interaction regions. The requested vacuum lifetime of 100 hours is dominated by the nuclear scattering of protons on the residual gas. Meeting this requirement also reduces the energy lost by scattered protons in the cryomagnets to below the nominal value of 30 mW m$^{-1}$ per beam.

Whereas the pumping of the cold parts is ensured by the bore of the vacuum chamber which is at 1.9 K (4.5 K in some standalone magnets), the novel technology of NEG coating [16] has been chosen for the room temperature part, with a limited number of sputter ion pumps for the non-reactive gases. In addition to provide very high pumping speeds for reactive gases, the NEG coatings also significantly reduce the secondary emission yield, helping to fight against the electron cloud phenomena.
2. Assessing the performance

Total pressure and composition of the residual gas are the most common ways to assess the performance of the vacuum system in an accelerator. Pressure can be gathered from various types of gauges, but also from the current of sputter ion pumps. Residual gas composition requires the use of sophisticated analysers. Indirect measurements can also give an idea of the quality of the vacuum. Beam lifetime may give an early indication of a developing leak [17]. Measurement of the electrons produced during beam-gas interaction has also been used in the ISR.

A common difficulty to the pressure measurements in large accelerators is the need to collect the signals over long cables, in an electrically noisy environment. Using the modern industrial approach of having the signal conditioning as close as possible to the sensor (also known as active gauges) is often not possible because of the radiation level. However, this approach will be used in the arcs of LHC in areas where the total annual integrated dose is expected to stay below 1 Gy.

2.1 Total pressure gauges

The most common tool to assess the performance of an accelerator vacuum system is based on several types of total pressure gauges. Pirani and capacitance gauges are used to monitor the initial pump-down. In general, their purpose is mainly to show a trend rather than provide precise measurements. For example, following the pressure slope during the pump-down of the insulation vacuum in a string of LHC magnets may help identifying a large leak. Whereas Pirani gauges can be used with long cables, although at the expense of limited precision and careful adjustment at atmospheric and low pressures, capacitance gauges need active electronics close-by. Therefore they can only be used in low radiation area. The main disadvantage of Pirani gauges, inherent to their working principle, is their sensitivity to temperature. For LEP, a compensation method was used which allowed operating the gauge with a reasonable precision between room temperature and 150º C [18].

For the pressure range between $10^{-6}$ and $10^{-11}$ mbar, the most robust gauges are the cold cathode gauges, in particular of the inverted magnetron type. They are based on the measurement of the discharge current in a plasma created by ionisation of the rest gas. These gauges can be run over a long cable if the latter has a double shielding. Whereas the outer shielding carries the return current of the gauge, the inner shielding, usually connected at one end only to the power supply, minimises the effect of ground loops and of changes in capacitance of the cable induced by movements (typically vibrations when the cable runs by mechanical equipment). Although quite robust, cold cathode gauges tend to get contaminated when operated at pressures higher than $10^{-5}$ mbar over long periods. Also metal vapours, caused by sputtering, can cause insulator leakage when operated at pressures above $10^{-4}$ mbar [19, 20].

The hot cathode gauges are covering the same pressure range as the cold cathode gauge, with the possibility to read even in the $10^{-12}$ mbar range (or below, but only in clean laboratory conditions). Also based on an ionisation process, the hot cathode gauge uses a filament to produce the ionising electrons. The currents to measure are even lower than for the cold cathode gauges (as low as a few pA in the $10^{-11}$ mbar range) and the same kind of precautions (e.g. double shielded low noise cables) have to be taken to operate them in an accelerator. The heating current of the filament normally
requires a transformer close to the gauge head to minimise the cross section of the cables. Hot cathode
gauges deliver a more reliable measurement as they are less prone to contamination, but the risk of
burning the filament usually requires an external interlock (e.g. via a Pirani gauge). They are therefore
mainly used when there is a real need to measure very low pressures, either because of the requirement
of the accelerator (e.g. a low energy ion storage ring like LEIR at CERN) or for specific diagnosis
(e.g. assess the performance of the NEG coated vacuum chambers in LHC).
An additional convenient method to measure total pressure is to use the current from the sputter ion
pumps. Even in vacuum systems with distributed NEG pumping, there is a need for sputter ion pumps
for the non-reactive gases, which adds measuring points for free. Their useful measuring range
extends from $10^{-4}$ to $10^{-9}$ mbar in an accelerator. This method has been extensively used in the SPS
arcs [21]. To minimise the cost of cabling and power supplies, pumps are frequently powered in
parallel, calling for the possibility to measure the current of the pump on the high voltage connection.

2.2 Residual gas analysers
Residual gas analysers are even more difficult to use in accelerators. Similar to a hot cathode gauge
for the ionisation process, they also require an RF system which in most cases does not allow long
cables between the analyser head and the power supply. A frequent application at CERN is on mobile
diagnostic stations used after the commissioning of the vacuum system. This allows certifying the
initial gas composition, for instance after bake-out and NEG commissioning.
They have been used in the ISR in specific locations where the radiation level was low, allowing for
the understanding of the pressure bumps. Later on, residual gas analysers were also used in LEP, in
so-called “pilot sectors”, allowing for following the evolution of the partial pressures as a function of
the beam dose. Although located below the bending magnets and protected with lead shielding, they
suffered from reliability problems because of the radiation level.

2.3 Indirect measurements
Indirect measurements can sometime also give useful indications of the performance of an accelerator
vacuum system. The ISR required clearing electrodes to avoid beam neutralisation. The current
collected on the electrodes is directly proportional to the ionisation of the rest gas by the beam, hence
proportional to the pressure when normalised to beam current [22]. Note that this was only possible
because the ISR beams were not bunched during coast.

3. Specificity of large vacuum systems

3.1 Dividing the system into manageable units
Because of their size, the vacuum systems of large accelerators must be divided into sectors of
reasonable length and complexity to allow for maintenance or modification work. This is achieved
with so-called sector valves, the type of which has to be adapted to the global requirements of the
accelerator in terms of leak tightness, impedance and reliability.
ISR set again a challenge in this respect by requiring sector valves that would be bakeable while
remaining leak tight. This required considerable mechanical engineering and development work, as
such devices simply did not exist before. The solution finally chosen was to have a small volume
between two sealing plates, which could be independently pumped to create a differential vacuum in
case of a leak on one of the two sealing surfaces. Each of the 8 experimental zones was isolated from
the rest of the two rings by 4 sector valves. Additional valves were installed around critical elements,
like kickers or RF cavities.
Each arc of the SPS is divided into 8 sectors with additional valves around special equipment like RF
cavities or kickers. The initial valves were equipped with an indium seal, today they have all been
replaced by valves equipped with the more reliable seal developed and patented by VAT, “Vatring”.
In the case of LEP there was an additional constraint. The valves had to be equipped with so-called
RF-shields to ensure a smooth and continuous path of the vacuum duct when in open position. Such
valves are nowadays available from industry, although with some limitation on the bake-out
temperature. LEP was divided into vacuum sectors of 474 m in the arcs, with additional valves around
special equipment like RF cavities or beam separators, requiring a total of more than 200 valves.
For LHC, 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 helium
distribution line 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, to
separate the cold from the room temperature parts. However, there are no sector valves in the cold
arc, leading to a length for this single sector of approximately 2900 m. As LEP, LHC requires RF-
shielded valves.

3.2 Mechanical pumping equipment: fixed versus mobile
The initial pump-down of a vacuum system relies on mechanical pumping stations, in most cases a
roughing pump coupled to a turbo-molecular pump, with a high vacuum valve to connect the pumping
group to the vacuum system and a set of gauges. At pressures below $10^{-4}$ mbar, only static pumps are
used, which don’t need maintenance, except for reactivation of getter pumps (which can usually be
done remotely, under vacuum).
All ISR sectors were equipped with permanently installed pumping stations. Because of the design of
the sector valves, there was always a pumping station with three isolation valves at the location of a
sector valve. In this way, it was possible to individually pump-down the sectors on each side of the
sector valve, but also the intermediate volume between the two sealing plates of the sector valve.  Additional simple pumping stations were also available.
The SPS was initially also equipped with permanent pumping stations, which were mainly connected
to the vacuum system at the locations of the sector valves to allow a single station to pump-down two
adjacent sectors. The advantage of fixed pumping stations is that they can be started remotely before
an intervention while the accelerator is still operating. This proved very useful at some stage, when
many magnet vacuum chambers started to develop leaks and had to be changed in a minimum of time.
However, this scenario was more and more often compromised when the pumping stations would not
start remotely, due to radiation damages. Another drawback of fixed stations is that their maintenance
can only be done during shutdown periods, when there are anyway many other maintenance activities
to complete. If the pumping station is installed in a zone where the radiation level is relatively high,
this maintenance activity exposes the personnel to unnecessary dose levels. Some ten years ago, the
SPS has been progressively modified to use mobile pumping stations. The use of mobile equipment,
however, requires for a manual roughing valve to be permanently installed at every pumping port.
Once the pump-down is completed, a blank flange is mounted on the roughing valve and the small
volume behind the valve is then pumped via a pinch-off tube and left under static vacuum. Care has
been taken to locate the pumping ports in areas where radiation is low to minimise the dose received
by personnel when connecting and starting-up the pumping station.
Because of its size, the choice was made at the design stage of LEP to use mobile pumping equipment
to save cabling and equipment costs. A total of 60 pumping stations were procured for LEP, out of
which 20 were equipped with additional diagnostic means, including a residual gas analyser. They
were mounted on a frame with wheels so as to be easily moved around in the LEP tunnel.
LHC will exclusively use mobile pumping stations for the beam vacuum. The location and means to
connect the stations to the vacuum system must be carefully studied, as there will be areas with high
radiation levels. For the insulation vacuum, initial pump-down is also done using mobile, high
capacity, roughing pumps. But in order to cope with small helium leaks on the insulation vacuum of
the magnets and the helium distribution line, fixed pumping stations will be installed at every vacuum
barrier, able to pump on both side of the vacuum barrier.
In addition to save cost, the clear advantage of mobile pumping stations is that they can be maintained
outside of shutdown periods and in a radiation free environment.
3.3 Integration and logistics aspects

LHC is by far the most complex accelerator ever built at CERN. The mix of cold and room temperature parts, the two closely spaced parallel beam lines, the slope of the ring tunnel all contributed to the difficulties which were encountered during the installation and the alignment of the LHC vacuum system. Many interferences between the vacuum system and other elements were discovered at a very late stage, often during the installation phase, despite a so-called 3-D digital mock-up. The late design of some equipment, like the collimation system, resulted in inexact or incomplete models and is the cause, among other reasons, of these difficulties.

Several thousands of components (vacuum chambers, transitions, bellows, valves, gauges, pumps and supports) had to be transported from their test and storage places on the surface to the tunnel location where they had to be installed. They were transported in batches, typically one batch per vacuum sectors, over an average distance of more than 10 km between the surface and the final location in the ring tunnel. Only a careful preparation and planning allowed minimising the occurrence of wrong or incomplete deliveries to the workplaces.

The many simultaneous activities in the same tunnel areas represent another constraint when building such a large and complex accelerator.

4. Vacuum Controls

The earlier accelerators, ISR and SPS, had their various equipment cabled to their power supplies or control equipment located in so-called auxiliary or service buildings. The power supplies or control equipment were then connected to the computer system, essentially based on input / output concentrators (e.g. CAMAC). The latter were finally connected to one or more central computers.

The access to the service buildings was always granted, also during operation. Some local controls were available in the machine tunnel, for instance to start and stop pumping stations or connect them to the vacuum system.

For LEP, where a sector could be as long as 474 m and equipped with 6 lumped pumping stations and 6 portable power supplies to activate the NEG pumps, “local” did no longer have a real meaning. For this reason, it was decided from the beginning to use “distributed intelligence” and to connect the various autonomous devices via a fieldbus. The operators, in the machine tunnel or from outside, could control the equipment via portable consoles, connected to the same fieldbus. The system was laid out in such a way, that an operator had a full overview in the machine tunnel of all equipment (pumping stations, pump and gauge power supplies and valve controllers) in one vacuum sector at any time. A second controls layer connected this first level to the common LEP controls network, giving access to the vacuum system from the control room, the offices or even from home for remote diagnostic.

Based on the positive experience with distributed controls, SPS was renovated a first time in the early 90’s. The equipment (pumps, gauges and valves) were connected to local control units with some processing and data reduction capability, based on the G64 standard and programmed in PASCAL. These local control units were then connected to one more powerful processor (based on the VME standard, running an UNIX like operating system) in every service building [20].

A second renovation was carried out in 2000. As more and more positive experience was made with industrial Programmable Logic Controllers (PLCs), it was decided to replace the G64 control units by PLCs and the VME based computers by standard industrial PCs. Lower level PLCs, controlling the individual equipment, are connected to so-called “master” PLCs using the manufacturer’s fieldbus. The “master” PLC is used as interface to normalise the representation of the equipment and connected via Ethernet to a central server running the alarm, data logging and user interface programs. The new SPS vacuum control system was the prototype of the LHC system [21]. The only addition for LHC was the possibility to control mobile equipment (pumping and diagnostic stations, bake-out regulation racks). The operators use a portable PC running the same user interface as the one available in the control room to monitor and operate the vacuum system, via WiFi access everywhere in the LHC machine tunnel and service areas.
The bottom line of the evolution of vacuum controls in large accelerators is the possibility to access all vacuum equipment, fixed or mobile, from everywhere. Today, industrial process controllers can fulfill this requirement.

5. Conclusions
There are many more aspects that could be covered when reporting on large accelerator vacuum systems, like vacuum for physics experiments, reliability, procedures (including bake-out and NEG activation, pumping before cool-down and during warm-up, leak detection of large volumes), etc. CERN has acquired a long experience in large vacuum systems. Many aspects of ultra-high vacuum have been pioneered in the ISR and progressively developed to become quasi-industrial standards. With the increase in beam energies and intensities, dynamic phenomena have to be taken into account, like electron clouds. In this field also, CERN has contributed a lot to the understanding of the problems and to the remedies to avoid them, like glow discharge, beam scrubbing or NEG coatings. The expertise CERN holds in the field of vacuum technology is today applied in industrial applications like medical accelerators. Specific technologies like NEG coatings will play an important role in future accelerators (e.g. for SPL or CLIC), as will our understanding of the behaviour of a cold vacuum system (e.g. for ILC). The leak detection procedures developed for the insulation vacuum of LHC could also be applied for ITER.

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