

MEASUREMENTS, ALARMS AND INTERLOCKS IN THE VACUUM CONTROL SYSTEM OF THE LHC

G. Pigny, F. Antoniotti, J.P. Boivin, N. Chatzigeorgiou, J. Gama, P. Gomes, P. Krakowski,
H. Pereira, H. Vestergard
CERN, Geneva, Switzerland

Abstract

In the LHC beam pipes and cryostats, the pressure measurement covers a wide range, from 1500 mbar down to 10^{-11} mbar and even lower. If vacuum deteriorates, alarm signals are generated and sent to other systems, like cryogenics, accelerating cavities, kicker magnets. In addition, an unacceptable pressure rise in beam pipes generates interlocks to close the adjacent sector valves, thus isolating the sector, so that the pressure rise does not propagate. This pressure interlock is simultaneously forwarded to the beam interlock system.

This paper describes the instrumentation, the interlocks and alarms logic used in the vacuum control system of the LHC. We analyze the possible signal degradation caused by ionizing radiation or due to cable length, shielding and grounding. During the first LHC long shut down, several corrections were applied to mitigate radiation effects and improve signal integrity. The tests performed for the vacuum control commissioning and LHC machine checkout are also presented.

VACUUM MEASUREMENT

Vacuum gauges in accelerators have to cover about 15 decades of pressure. The direct pressure gauges, which measure the force per unit area, are gas-type independent. They cover the rough and medium vacuum ranges. The indirect pressure gauges, which measure a pressure-dependent property of the gas, are gas-type dependent. They can cover a wider range of vacuum, from the rough to the ultra-high vacuum range [1].

The membrane gauge covers the range from 0 to 2 000 mbar. It is composed by a thin silicon crystal layer used as a membrane, whose deformation induces a piezo-resistive effect on the four resistances of a Wheatstone bridge. The resistance variation is a function of the pressure. The signal to be read across the bridge is in the mV range.

The Pirani gauge covers the range from 1 000 to 10^{-4} mbar. The measurement is based on the dependence of the thermal conductivity on the gas pressure. A filament is heated and maintained at a constant temperature. The current needed to maintain this temperature depends on the gas conductivity and therefore is a measure of the pressure. The signal delivered by the amplifier is in the Volt range. Above 1 mbar the measurement becomes non-linear, and depends on the gas species

The Penning gauge covers the range from 10^{-5} down to 10^{-11} mbar; it is also called inverted magnetron cold cathode gauge. It is composed by a thin cylindrical anode rod, surrounded by a cathode. A high voltage (HV)

potential of 3kV creates a high electric field between the two electrodes, which favors the ionization of gas molecules. Around the electrodes, a permanent magnet produces a field that forces the free electrons into spiral paths, thus increasing the probability of ionizing more molecules. The ionization current is a function of the pressure. In the low range of measurement, the current can be as low as the pA; a high quality HV triaxial cable is used for signal transmission.

In the range from 10^{-5} down to 10^{-9} mbar, the Sputter Ion Pump can be used to measure the pressure, in addition to its pumping function. It is composed by several Penning cells, with the particularity of Titanium cathodes and a potential of 7 kV. The principle of vacuum measurement is the same as for the Penning gauge. In the low range of measurement, the current can be as low as 100 nA, and high quality HV triaxial cable is used for signal transmission.

Finally, to measure down to 10^{-12} mbar, the Bayard-Alpert gauge is used. A heated filament emits electrons which are accelerated by the grid potential (+150 V). On their path, these electrons ionize gas molecules, which are gathered by a collector. The collector current is a measure of the ionization and therefore of the gas pressure. It can be as low as 100 fA. High quality triaxial cable is used for this measurement.

INTERLOCKS AND ALARMS

Alarms are binary signals sent to the operators' console, e-mail or SMS, to draw their attention to particular equipment status or situations. There are also alarms directly cabled to other systems, for information or to be used in their control logic.

Interlocks are binary signals used within the vacuum system to prevent entering undesired states. They have a higher priority than the normal process logic or the operator's commands. Apart from the beam permit interlock, the vacuum control system does not interlock any other external systems directly.

The detection of a pressure rise, above a predefined threshold, can be used to produce alarms or interlocks. The gauges used for alarms or interlocks can be the Membrane, Pirani, Penning and Ion Pump [2].

Interlocks for the Vacuum Sector Valves

The beam pipes are divided in "vacuum sectors" that can be isolated by "sector valves" (VVS), to avoid the propagation of leaks over a large volume.

Upon the detection of a pressure rise above a predefined level, these valves will close in 1 to 3 s, depending on the model.

The LHC itself is divided in 8 “machine sectors”. Each one consists of a curved section (ARC + DS) of about 2.8 km where all magnets are cryogenic and kept at 1.9 K in a continuous cryostat. At each side of the continuous cryostat, there is a long straight section (LSS) of some 300 m. Here, a sequence of cryogenic stand-alone magnets (SAM) alternates with sectors of bare beam pipe at room temperature, before arriving to the experimental or technical caverns.

The continuous cryostat, the room temperature sectors and the SAMs have vacuum sector valves at their extremities. During the recent long shutdown (LS1), one of the targets was to minimize the risk of a pressure wave created in the ARC to propagate and damage the SAMs or other equipment.

The sector valves at the end of the continuous cryostat were improved for a faster closing (less than 1 or 2 s). New Penning gauges were added further upstream (Q12, Q13) of the valves, to interlock them on an early detection of the pressure wave front.

In general, a sector valve is interlocked by several neighboring pressure measurements, either to make it close or to enable its aperture. The pressure thresholds can be set individually for each gauge, but preference is given to an uniformity of values all around the machine. A valve closed by a pressure interlock will also propagate it to its 2 neighbor valves, to further isolate the faulty sector.

Figure 1 shows the typical interlock configuration between two vacuum sectors at room temperature.

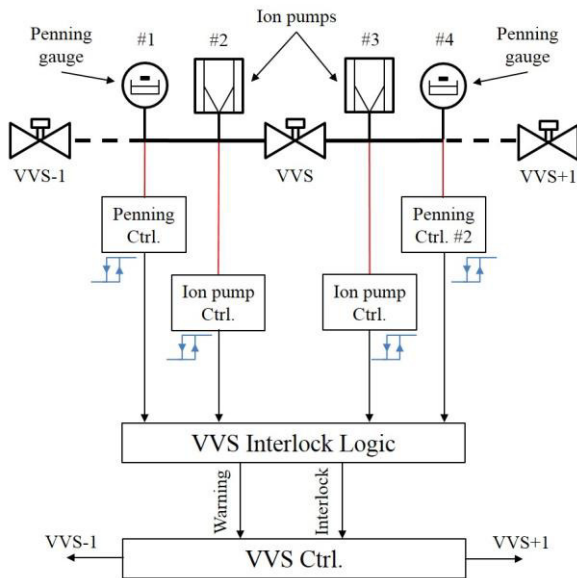


Figure 1: VVS interlock configuration.

Table 1 summarizes, for different configurations, the thresholds and the fraction of neighboring gauges needed OK, to allow or keep valve opening. The valves at the end of the continuous cryostat have an additional condition on the 2 new gauges.

Table 1: Thresholds and Logic for the Sector Valve Interlocks

	Rising [mbar]	Falling [mbar]	# to allow open	# to force close
continuous cryostat	$2 \cdot 10^{-6}$	$1 \cdot 10^{-6}$	4 OK /4 + 2	3 bad /4 + 2
room temperature	$2 \cdot 10^{-6}$	$1 \cdot 10^{-6}$	4 OK /4	3bad /4
SAM	$2 \cdot 10^{-6}$	$1 \cdot 10^{-6}$	3 OK /3	2 bad /3
dump lines	$7 \cdot 10^{-5}$	$5 \cdot 10^{-5}$	4 OK /4	3 bad /4

Interlocks to the Beam Interlock System (BIS)

As a closed sector valve would be in the beam path, and thus damaged, the beam must be stopped before that may happen. Indeed, the beam can be extracted from the LHC and dumped in less than 300 μ s, which is much faster than any valve closing (1 - 3 s).

Therefore, a pressure interlock triggering a valve closing is simultaneously forwarded to the BIS [3]; and so is the information of any valve losing the open state, due to a neighbor valve closing or for any other reason.

Alarms to the Cryogenic System

If the pressure rises, the thermal isolation degrades and the cryogenic system might need to prevent the start of some cryo-compressors or even to stop them.

Each insulation volume around the cryogenic distribution line (QRL) or the cryo-magnets is equipped with a triplet of gauges (Membrane, Pirani and Penning). The first two are used to generate alarms to the cryogenic system, at 500 and 0.1 mbar, respectively.

Alarms to the RF & ADT Systems

If the vacuum degrades inside a radiofrequency (RF) accelerating cavity, the high electrical field may ionize the residual gas and damage the cavity.

For each of the 8 cavities in each beamline, the RF system has its own Penning gauges, to follow the pressure inside the cavities, and to produce the necessary interlocks. These are not available on the vacuum system.

The pressure in the beam pipes outside of an RF module (group of 4 cavities) is used to produce an alarm, combining one Penning gauge ($1 - 4 \cdot 10^{-7}$ mbar) and two ion pumps ($1 \cdot 10^{-6}$ mbar).

For the transverse dumpers (ADT), located upstream and downstream of the modules, the RF system receives the analog reading and a Penning alarm ($1 - 5 \cdot 10^{-7}$ mbar).

Alarms to the Kickers Systems

The injection kicker magnets (MKI) insert the beam coming from the transfer lines into the LHC orbit; there are 4 MKI tanks at point 2 and 4 other at point 8.

The dilution kicker magnets (MKB) sweep the beam in an ‘e’ shape, distributing it over a wide dump surface; there are 5 MKB tanks on each side of point 6.

As the kicker magnets are powered by high-voltage pulses, if vacuum degrades, galvanic isolation becomes a concern and the kickers may have to be stopped. If pressure rises in the MKI, there cannot be injection into the LHC. If

pressure rises in the MKB, the beam should be dumped before the situation gets worse. Table 2 shows the thresholds and the fraction of neighboring gauges needed to send an alarm to the kicker systems.

Table 2: Vacuum Information Sent to the Kicker Systems

	Rising [mbar]	Falling [mbar]	alarm sources	# to send alarm
MKI (4 tanks / beam)	2.10^{-8}	1.10^{-8}	1 gauge	1 bad /1
MKB (5 tanks / beam)	2.10^{-5}	1.10^{-5}	1 gauge 2 pumps	2 bad /3

Their control systems receive binary alarms and analog pressure readings, from the associated Penning gauges and ion pumps.

RADIATION ENVIRONMENT

Service Areas

The majority of LHC vacuum controls are located in underground service areas, shielded from tunnel radiation. During the next 20 years, as the energy and intensity of the beam will increase, those service areas will see an increase of the High Energy Hadron (HEH) fluence rate by one order of magnitude. The electronics installed in those areas may suffer Single Event Effects (SEE).

Solutions, such as additional shielding, relocation or redundancy of critical vacuum controls must be taken into consideration. For example, due to the level of radiation caused by the collimation system at point 7, all vacuum controls equipment in UJ76 has been moved into the TZ76 gallery, during the LS1. This concerned 27 racks; the associated 280 cables were extended by up to 180 m. In this gallery, the HEH fluence rate will be much lower and the SEEs negligible ($< 10^6 \text{ cm}^{-2}\text{y}^{-1}$) [4].

LHC Tunnel

All the gauges in the LHC tunnel are subject to ionizing radiation. Depending on their location, the levels of radiation may vary: in the ARCs, the Total Ionizing Dose (TID) will be less than 10 Gy/y; but in the LSS it will be much higher than that. The lifetime of the gauges must be better than 10 years.

Gauges in low radiation zones are “active”: the signal-conditioning electronics is incorporated in the gauge head. They are locally powered and send their readings on 0-10V through standard multi twisted-pair cables, over up to 1000 m, to the PLCs in the service areas.

The gauges installed in higher radiation zones are “passive”, with the electronics located in a service area, up to 500 m away. Power and signal are carried by special HV cables, according to the gauge type.

The cables in the tunnel accumulate radiation over the time, which progressively degrades their characteristics, eventually destroying them. Also, transient effects might be observed due to radiation-induced conductivity of the insulation of HV cables. Upcoming tests at CHARM

facility (CERN) will give more information on radiation-induced effects on HV cables.

Irradiation Tests on Active Gauges

Priority has been given to test the gauges and electronics to be installed in the tunnel. This concerns the Membrane, Pirani, and Penning gauges, of which the first two are used to generate alarms for the cryogenic system, and are thus more critical for the machine operation.

Irradiation tests have been carried out in 2002 in the TCC2 facility at CERN, on a set of commercial Pirani/Penning active gauges. This facility provided a mixed field similar to that of the LHC.

The Pirani electronics provided correct readings up to 20 Gy, and saturated under-range at 50 Gy. For the Penning electronics, correct readings were obtained up to 40 Gy, saturating under-range at 60 Gy. Therefore, it was decided to use the commercial Penning electronics and to design a radiation tolerant Pirani electronics.

A set of commercial active Membrane gauges has been irradiated at the cyclotron of the University of Louvain (Belgium), in 2003. The source was a 60 MeV proton beam, with a flux of $8.10^7 \text{ cm}^{-2}\text{s}^{-1}$. The best gauge stood up to 200 Gy, with a good stability.

In 2015, a new irradiation test has been carried out at Fraunhofer Institute. A gamma radiation source of ^{60}Co has been used for 20 days to produce up to 500 Gy, which is higher than 10 years of operations in the arcs. Three samples of commercial Penning and CERN-designed Pirani electronics have been irradiated. One sample of each was placed outside the radioactive field as a reference while vacuum was simulated by resistors.

The worst Penning electronics sample was measuring pressure one decade too high already at 15 Gy, and two decades too high at 20 Gy, before falling quickly under-range. The Pirani electronics re-designed at CERN in 2002 stood up 500 Gy, with slight variations around the reference measurement.

The analysis of these tests are still ongoing and the results will contribute to define the strategy against radiation effects to electronics for future consolidations in the LHC.

SIGNAL INTEGRITY

Vacuum Measurement in the ARCs

The readout electronics for the Penning, Pirani and Membrane gauges in the ARCs are installed in a box placed above some of the dipoles. In one ARC, 28 boxes are installed. They are connected, through multi twisted-pair cables, to one of the two ARC PLCs, installed in service areas.

The Pirani and membrane electronics are locally powered, while the Penning electronics are powered from the PLC digital outputs. The 0-10V analog output of each gauge is routed through a twisted pair directly to the PLC analog input module. Moreover, each PLC analog input module provides an analog ground, isolated from the earth, used mainly by the Penning electronics.

The Penning and Pirani gauges located by the middle of the ARCs, where the cable lengths may reach 1 000 m, often shown malfunctions. Some Penning gauges could not be switched on for measurement. Moreover, by switching on or off a Penning gauge, the nearby Pirani and Penning gauges could be disturbed.

Corrective Actions

During the LS1, an investigation took place. Measurements on the output signal of the concerned Penning gauges showed a strong common mode voltage, unacceptable by the analog input module specifications.

The wire resistance on the shared powering return path was too high; the current consumption of the Penning signal-conditioning electronics brought up a voltage across the wire. As the reference for the Penning electronics is based on the common power lead, isolated from earth, this common-mode voltage was also present at the input of the analog input module of the PLC.

Moreover, the cause of measurement cross-talk between gauges installed at different places was explained by the fact that they shared the same analog ground.

An equivalent circuit has been simulated in PSpice, to understand the behavior of the interconnected analog grounds. The simulations indicated that the analog ground connections between two separated gauge electronics generated a current flowing from one to the other, depending of the status of each gauge. This created an additional DC offset to the measurement, of the order of some mV. In the range of measurement, this might correspond to one order of magnitude in pressure.

The solution finally implemented consisted in adding parallel wires, to decrease the resistance on the return path for the Penning supply. Thus, the common mode voltage has been successfully reduced within the manufacturer specifications and solved the first issue.

On the other hand, the analog ground connections have been removed, to avoid complex ground loops between different channels.

LHC COMMISSIONING

The commissioning of all vacuum measurement, alarm and interlock channels was carried out during the last months of the LS1. Each element of the chain has been tested with and without simulators. The vacuum sector valves were actuated and their status checked.

The signal transmission from the vacuum control system to the BIS has been checked in all points of the LHC. The interlocks and alarms have been triggered and checked for each system (vacuum sector valves, BIC, cryogenics, RF cavities, ADT, MKI and MKB).

The equipment involved in vacuum interlocks and alarms amounts to: 300 sector valves, 230 pairs of gauges, 590 Penning gauges, 350 ion pumps [5].

Machine Checkout

The systematic verification of interlocks and alarms has been performed during the LHC machine checkout phase

[6]. The goal was to check all the interlock sources for the vacuum valves, and confirm that their status were sent correctly to the BIS, for dumping the beam.

An automated test sequence was written in the vacuum SCADA, and its results stored in xml files.

After all the vacuum valves have been opened to set the vacuum interlock to true in the corresponding BIS, each of the N (3 or 4) devices are switched off (and back on) one by one, to see if the valve open-enable is lost (and recovered).

Then, N-1 devices (3 or 2) are switched off to see if the corresponding valve closing-interlock is triggered. The time stamps are stored for: the valve closing-interlock; the loss of valve open-status; the reaching of the valve close-status; the vacuum user permit event, when the BIS receives the interlock from the vacuum. For each valve, the right sequence of all time-stamps is verified, as well as the valve travelling time, from opened to closed.

The test checks also if the corresponding alarms for Penning gauges, ion pumps, and sector valves are present in the LHC Alarm Service (LASER).

CONCLUSIONS

The vacuum measurement chains, alarms and interlocks must be reliable and are crucial to insure the good operation of the LHC. The effects of ionizing radiation and the issues with signal integrity must be understood and minimized, to improve the system reliability. Attention must be paid to the calibration, settings and tests of every measurement chain.

During the LS1, important actions have been performed in this direction: racks relocation against radiation effects; grounding and cabling modifications for signal integrity improvements; systematic test of each interlock and alarm, from front-end hardware to the SCADA. Additionally, some cabling and Database errors were found and corrected. The vacuum interlocks are part of the LHC machine protection; during machine checkout, they were fully verified up to the BIS.

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