Mitigation of radiation and EMI effects on the vacuum control system of LHC

G. Pigny, a,1 P. Gomes, a P. Krakowski b and B. Rio a

a CERN, CH-1211, Geneva 23, Switzerland
b Faculty of Physics and Applied Computer Science, AGH University of Science and Technology, al. A. Mickiewicza 30, 30-059 Krakow, Poland
E-mail: gregory.pigny@cern.ch

ABSTRACT: The 26 km of vacuum chambers where circulates the beam of the Large Hadron Collider (LHC) must be maintained under Ultra High Vacuum (UHV) to minimize the beam interactions with residual gases, and allow the operation of specific systems. The vacuum level is measured by several thousands of gauges along the accelerator. Bad vacuum quality may trigger a beam dump and close the associated sector valves. The effects of radiation or Electromagnetic Interferences (EMI) on components that may stop the machine must be evaluated and minimized. We report on the actions implemented to mitigate their impact on the vacuum control system.

KEYWORDS: Hardware and accelerator control systems; Beam-line instrumentation (beam position and profile monitors; beam-intensity monitors; bunch length monitors)
1 Introduction

The electronic devices of the vacuum control system are mainly located in the service areas. These underground areas are shielded from the accelerator tunnel. Beam interactions with residual gases, collimators, and other equipment (e.g. due to beam instabilities) are the source of ionizing radiation, with a rich and varied energy spectrum. With the rising of LHC’s energy and intensity, some service areas have become too much exposed to these radiations, despite the available shielding, and can lead to malfunctions due to Single Event Effects (SEE). This resulted in an increase of equipment failures leading to beam dumps, which are time consuming for the machine operation.

Some equipment is installed in the tunnel, without any shielding, and is subject to ionizing radiation, of a level depending on the location. The vacuum in the arcs is currently measured by active gauges, producing an analogue signal sent along a twisted pair to the PLC installed in the protected areas. In order to better understand their tolerance, and for future upgrade, radiation tests are needed.

Radiation is not the only source for disturbance or system failures: the electromagnetic environment in the tunnel and service areas is rich in interference sources. Given the dimensions of the machine, long cables are required to connect the instrumentation to the controllers; ground loops and coupling issues can easily become problematic and must be avoided, especially when signal levels are very low.
2 R2E related activities

2.1 LS1-R2E vacuum activities in point 7

2.1.1 Expected radiation level in UJ76

According to FLUKA simulations, the integrated dose at point 7 of the LHC in UJ76 would stay below 1 Gy per year but the flux of hadrons with $E > 20$ MeV could reach up to $10^9 \text{cm}^{-2} \text{y}^{-1}$ [1]. At such level, one does not expect any radiation damage resulting from the Total Ionising Dose (TID). However, the risk of SEE becomes high as many of the equipment installed in UJ76 are composed with Commercial off-the-shelf (COTS) components. They can be modified from one series to another without notice and for which we have little tractability, thus making radiation tests and the quantification of reliable SEE cross sections not possible. Their replacement with radiation tolerant electronics would have required an important development program and could not be envisaged within the required timescale.

TZ76 gallery spans over 370 m from the bottom of the PM76 shaft to the UJ76 area and its amount of radiation is much reduced. The flux of hadrons with $E > 20$ MeV decreases rapidly when entering the TZ76 gallery. The drop is about one order of magnitude every 10 m away from UJ76. One thus expects to stay below $10^7 \text{cm}^{-2} \text{y}^{-1}$ after 20 m from the TZ76-UJ76 junction [1].

It was so decided to relocate all the UJ76 equipment into the TZ76 gallery during the First Long Shutdown 1 (LS1).

2.1.2 Vacuum control racks relocation

27 racks dedicated to the vacuum control system are located in the UJ76. They contain the readouts of the pressure gauges, controls of the pumping groups and sector valves, and ion pump high voltage power supplies. These contain standard Programmable Logic Controller (PLC) and I/O units that are known to be SEE sensitive. A wrong measure of a pressure gauge would not directly affect the running conditions of the LHC, but its processing may result in the decision to close sector valves. A sector valve could also be activated by a SEE in its control system. In both cases, a hard wired signal drives the Beam Interlock Controller (BIC) to trigger a beam dump. For instance, during the last runs of 2012, switching power supplies in valve controllers were destroyed several times. Moreover, blockings of PLC were observed, most probably due to radiation-induced effects.

In order to follow the vacuum racks removal, 282 cables must be extended from the UJ76 to the TZ76 by a maximum length of 180 m. Moreover, 198 new cables will be installed for controllers’ inter-connexions in TZ76, and new features will be added, such as remote reset for slave PLC. 48 patch panels will be used for the connexions in UJ76 of these extensions: 8 existing racks will be used to install them. Several types of connectors are implemented, from the standard multi-pins low voltage connectors to the special mixed high voltage connectors for the sputter ion pumps, or triaxial high voltage connectors for the penning gauges. Each patch panel regroups the same type of equipment and the same type of connectors and cables. Each cable number is also indicated on the front and back panel of the patch to make the maintenance much easier. The space between patches and between the front and the back of the racks must be carefully managed in order to receive the huge quantity of cables.
2.1.3 Schedule

This project will require the complete shutdown of vacuum controls for more than a year. The Non-Evaporable Getters (NEG) activation and the bake-out of the vacuum chambers will require a minimal local control system to meet the established schedule of the LS1. The activities started in May 2013 and should finish in June 2014. All the equipment in UJ76 has been disconnected, the patch panels have been installed and the cabling removal and arrangement are finished. The local controls in the tunnel have been installed in order to allow the starting of mechanical activities for vacuum. After the cabling campaign for the cable extensions, the vacuum controls will be relocated in TZ76 in two phases. The first one will allow the cool down of the magnets at the beginning of the ARC at both sides of Point 7; the second will concern the controls for all equipment installed in the long straight sections.

2.2 Active gauges

2.2.1 Vacuum measurement in the ARC

In the accelerator areas where the estimated radiation was considered as acceptably low, and where the distance to a service area was quite large, “active” gauges were installed in the vicinity of the quadrupole. These consist of a pair of Pirani-Penning gauges with its attached readout electronics [2]. However, it had been decided to move their readout electronics to the middle of the first dipole after quadrupole, where the radiation is 8 times less. This solution had been implemented in order to minimise destructive influences of accumulated dose and possibility of SEE. Figure 1 shows the readout electronics position relative to the magnets and to the sensor heads. Two local cables connect the Pirani and the Penning sensors to their readout electronics.

2.2.2 Radiation tests

The complex radiation field in the LHC underground areas is composed of different particles at various energies. Electronic components and systems exposed to such a radiation field will experi-
Table 1. Expected annual radiation levels for the ARC areas, where vacuum equipment is installed. These values are meant as a peak radiation levels. The ultimate operation corresponds to the nominal LHC operation improved by an overall factor of four [4].

| ARC     | HEH \( \text{[cm}^{-2}\text{y}^{-1}] \) | 1-MeV eq. \( \text{[cm}^{-2}\text{y}^{-1}] \) | Dose \( \text{[Gy y}^{-1}] \) |
|---------|----------------------------------|---------------------------------|------------------|
| Nominal | \( 1.0 \times 10^9 \)           | \( 4.0 \times 10^9 \)          | 2                |
| Ultimate| \( 4.0 \times 10^9 \)           | \( 1.6 \times 10^{10} \)       | 8                |

ence three different types of radiation damages: displacement damage or Non Ionising Energy Loss (NIEL), SEE and damage from the TID. The damage is proportional to, respectively, the 1-MeV equivalent neutron fluence, High Energy Hadron (HEH) flux \( (E > 20 \text{MeV}) \) and the dose [3].

According to the table 1, the ultimate operation values have been used to set the expected dose that electronics should stand in this area. Considering a lifetime of 10 years, the target TID should be 80 Gy. Gamma radiation source of \(^{60}\text{Co}\) will be used during one month to produce up to 500 Gy in order to know the maximum dose before failure. Three samples will be irradiated and one reference will be placed outside the radioactive zone. During the irradiation, the measurement of the readout electronics will be done on-line, while vacuum will be simulated by using resistors.

In parallel, a new and more accurate active gauge and its readout electronics are under evaluation. It is also planned to test it under radiation with the same conditions as above and to evaluate its probable life time.

3 EMI related activities

3.1 Bayard-Alpert ionization gauge measurement system

A study was conducted, to reduce noise on high precision vacuum measurements with Bayard-Alpert ionization gauge. The first improvements were applied during the 2012 winter technical stop.

The ionization current provided by the gauge is proportional to the vacuum pressure. It is read by an electrometer input stage, with automatically switching gain, depending on the current level. For very low currents \( (\sim 1 \text{pA}) \), the gain could be as high as \( 10^{12} \text{V.A}^{-1} \); this implies that the measurement signal is very sensitive to noise coupling. The bandwidth of the signal goes from DC to some Hz, vacuum being a quite slow phenomenon. To measure the ionization current from the Bayard-Alpert gauge, a triaxial cable is used, with a high insulation resistance, for very low leakage currents. It can be longer than 200 m, even up to 300 m in some cases.

3.2 Cabling non-conformity

Each of the 170 triaxial cables has been tested. The continuity has been checked and the insulation measured; a reflectometer has been used to measure the conductor length and identify any splices or non-conformities.

The main problem found was the internal shielding discontinuity when the cable was composed of several segments. Coaxial BNC connectors had been used between segments, instead of triaxial connectors. Due to this discontinuity, a long section of the internal shield was floating without any voltage reference.
Figure 2 summarizes the results of the test campaign: the detailed distribution of the internal shield discontinuity along the LHC is given in [5].

Floating internal shielding makes the central conductor more vulnerable to the noise pick-up. To reduce the coupling to the central conductor, the internal shielding continuity had to be established. All these discontinuities have been identified and repaired, by using the appropriate triaxial connection.

3.3 Shielding connection and noise coupling

Ground loops can be a source of noise and interference. This is especially true when multiple ground points are separated by a large distance and are connected to the main ground, in particular when low-level analogue circuits are used. A difference in ground potential between two points may induce a noise voltage into the circuit. The ground potential is usually the result of other currents flowing through the ground impedance [6]. The coupling between the shield and the central conductor can be both capacitive and inductive due to the mutual capacitance and inductance between the shield and the conductor. Figure 3 shows the standard ground connections for the triaxial cable: the external shield is connected to the ground at both sides, while the internal shield is connected to the ground receiver side only.

To reduce ground loop issues, hybrid ground connection can be applied: figure 4 shows an example for the triaxial cable. At sensor side, the external shielding is now connected to the ground through capacitors, avoiding AC noise voltage coupling to the signal. The paralleling of 6 capacitors, all around the conductor decreases the series inductance by a factor of 6. Like before, at the receiver end, both the external and internal shieldings are connected to the ground.

This solution has been used for the cases where noise coupling was still present despite the good shielding continuity. The capacitors have been integrated in a small box between the end of the triaxial cable and the gauge.
3.4 Front end electronic improvement

The modifications of the electronics in the controller were prepared during 2012 and applied in
the field during 2013. They concerned the electrometer card and the firmware of the controller for
the current reading and calibration: to bias the measurement and to make a better filtering before
sampling to be less susceptible to electromagnetic interferences.

The firmware of the controller has been modified to take into account these modifications.

The aim was to reduce the input gain of the first amplifier stage, while increasing the gain and
lower the cut-off frequency of the second stage, before the ADC.

Furthermore, the signal has been biased at the middle of the ADC input range to increase the
noise margin, by avoiding signal clipping when strong noise voltage is coupled into the circuit.

4 Conclusion

The vacuum control relocation for the R2E project matches well the schedule; particular attention
must be paid after the cabling campaign, during the equipment installation and commissioning,
due to the tight schedule constraints before the restart of the LHC. The tests of the cables and
patch-panel connexions must be done carefully as well.

The radiation test of our active gauges should be performed before the end of 2013. They will
allow to have a better knowledge about the life time of our equipment in the ARC areas, and to take
the appropriate decisions for future modifications.

Finally, the actions performed to mitigate the noise on the Bayard-Alpert gauges reading have
given good results. The experience gained and used techniques can be applied to other type of
gauges and measurement systems.
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