RADIATION TOLERANCE ASSURANCE OF TECHNICAL EQUIPMENT IN THE LHC
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RADIATION MONITORING FOR TECHNICAL EQUIPMENT AT THE LHC
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Abstract

In contrast with other accelerators at CERN, a large amount of technical equipment will be located in the LHC tunnel, the underground areas and in the experimental caverns where they will be exposed to radiation. Nearly all these equipment make, to a certain extent, use of commercial microelectronics which is extremely sensitive to radiation damage, both instantaneous damage and cumulative damage. Examples in the TS Department are the electronics for the position sensors of the low beta quadrupoles, the access system, the cooling and ventilation units, the electronics for the electrical distribution, the oxygen deficiency monitors and fire detection systems. The basic effects of radiation on electronic systems and components are well understood because similar problems with radiation are encountered in the aerospace and aviation industry. Since 1998, an efficient and original Radiation Tolerance Assurance approach for the LHC machine has been established. Its aim is to minimise the effects of radiation damage on the LHC performance.

In the LHC tunnel and underground areas, personnel, superconducting magnets, electronic equipment and detectors will be exposed to radiation. This is why there will be four different radiation monitoring systems in the LHC. The RADiation MONitoring (RADMON) system presently developed in the TS/LEA group has been designed to provide an early warning as the radiation levels at the location of the electronic equipment in the tunnel, underground areas and experimental caverns increase.

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1 INTRODUCTION

In January 1997 it was decided that “the base-line LHC machine should use, where advantageous and following suitable testing, electronics located in the arc tunnel [1]”. This decision was based on the understanding that the radiation dose represented the major hazard to electronic equipment in the LHC underground areas and that the annual dose in the ARCs (where most equipment would be located) would be inferior to 1 Gy per year. At the same time, suitable resources were made available for adequate radiation testing.

A year later, in March 1998, the LHC Radiation Working Group (RADWG) was established with the task to verify the radiation tolerance of electronic equipment in the mixed radiation field of the machine tunnel and underground areas. In collaboration with TIS/RP, a suitable area for radiation testing was found in the primary target hall in the SPS North Experimental area (TCC2). This area has a radiation field similar to that in the LHC tunnel but higher dose rates [2]. At the end of the 1998 SPS run, the area was modified for radiation testing and four PMI ionisation chambers were added to measure the total dose.

First radiation tests in the test facility were carried out during the SPS run in 1999. At this point in time, many equipment groups were still considering using electronic equipment such as PCs and complete VME crates in the tunnel. However, the experimental results [3] showed that the failures of the electronic devices were not at all related to the accumulated dose. Thanks to theoretical work done in [4] and the help from the CERN experiments, it was soon realised that the observed damage was caused by single high energetic hadrons and statistical rather than cumulative in nature.

At this point it became clear that all equipment needed to be tested following a standard radiation tolerance assurance method, that some commercial technical equipment could never work reliably in the tunnel, and that all the architecture of some systems in the tunnel needed to be modified. Modifications in the electronics integration were carried out by the Controls Electronic Integration Working Group (CEIWG) in collaboration with the Pit and Surface Integration Working Group (PSIWG). Radiation sensitive standard industrial equipment was relocated to the alcoves whenever possible because radiation levels are expected to be lower there. In addition, PCs and PLCs were moved to the bottom of the pits or to the SR surface buildings and Ethernet connectivity was banned from the tunnel and the RRs.

After the year 2000, the quantity of material to be tested increased rapidly, reaching a maximum in 2002 when more then 40 different experiments were carried out in the LHC radiation test facility at CERN. As the knowledge on radiation effects in electronic components and systems improved, equipment groups expressed interest to carry out detailed radiation tests with a 60 MeV proton beam. The irradiation of individual components allows for a detailed analysis of the propagation of radiation induced errors in a complex electronic design. Together with the LHC experiments, a collaboration was set up with the Paul Scherrer Institute (PSI) in Switzerland and the Université Catholique de Louvain (UCL) in Belgium [5,6] for this purpose.

In 2002 the development of the RADMON on-line radiation monitoring system was started [7]. This system will provide an early warning as radiation levels at the location of the exposed equipment increase. At the same time addition shielding was added to the LHC machine baseline for the RR areas.

In 2004, the number of radiation experiments decreased because the LHC Radiation Test Facility was partially closed and because many equipment groups started with the pre-series production of their electronic equipment. The number of radiation tests in facilities outside CERN
remained relatively high as many equipment groups continue to investigate the radiation behaviour of single components in detail.

2 RADIATION TOLERANCE ASSURANCE

2.1 Integration and layout

The first step in assuring the radiation tolerance of equipment exists in reducing the radiation levels at which the equipment is exposed. This is achieved by optimising the integration and via shielding.

Radiation is taken into account as a constraint during the integration by locating electronics in areas where radiation levels are lowest (Figure 1) whenever possible. For example, the annual total dose under a dipole magnet in the ARC is less than the annual dose predicted under a main quadrupole magnet and the radiation levels in the ARC are in general lower than those in the Dispersion Suppressors. Other constraints are space, signal quality, cabling costs and system architecture. A complete overview of the electronics integration in the LHC tunnel with the simulated radiation levels can be found in [8].

Figure 1: Electronic crates for the Quench Protection System located under a dipole magnet in the String II test facility.

Specific shielding has been designed to reduce the radiation levels in the RRs and in the Long Straight Section around Point 7. This shielding specifically aims at reducing instantaneous radiation damage caused by high energetic neutrons.

2.2 Selection of candidate electronic components and systems

The second step in assuring the radiation tolerance of equipment is reducing the propagation of radiation induced errors in a design. This is extremely difficult for equipment groups that use standard industrial systems such as PLCs and remote I/Os. Radiation tests have shown that very few of such equipment is sufficiently radiation tolerant to be used in the LHC and in many cases, the manufacturer has little interest to modify certain electronic components that are causing errors. This is the reason why nearly all electronic equipment in the tunnel is using custom in-house designs and commercial electronic components that are carefully selected. Some radiation tolerant components can be found in the CERN RadTol database [10] (or references therein) but most often, irradiation data is exchanged directly between electronic engineers at CERN.

2.3 Radiation testing

Radiation testing is a time consuming affair. Radiation test campaigns usually take more than a day as there is also travel and the installation of material. The LHC machine and experiments make use of various test facilities, some of which are at CERN. The LHC Radiation Test Facility in the SPS North Experimental area (TCC2), for example, has been used to test complete systems and to make a pre-selection of candidate components using the trial and error method.
There are also dedicated irradiation facilities outside CERN that are used to test equipment on specific radiation effects. For example, Co-60 sources are used to test equipment on total dose (Figure 2, left) while the PROSPERO fission reactor in the nuclear centre of CEA-Valduc is used to test electronic equipment on the cumulative damage from 1 MeV neutrons (Figure 2, right).

To test electronic equipment on instantaneous radiation errors (single events), CERN makes use of 60 MeV proton beams at UCL and PSI (Figure 3). Single event testing is by far the most complicated as Integrated Circuits are increasingly complex and more performing. Equipment groups are allocated irradiation time in slots of 8 hours minimum, which includes the time for building up the equipment and installing the cables. However, it often happens that other single effects are observed and that more beam time is requested at a later date.
2.4 Statistics on radiation testing

Figure 4 shows the number of hours beam time that have been used for Single Event testing outside CERN. The LHC experiments started working on minimising Single Event errors about 2 years earlier than the LHC machine and the requests today are mainly from the LHC machine equipment groups.

![Figure 4: Evolution of the number of hours of proton beam time used by CERN at PSI and UCL to date.](image)

The large majority of requests for beam time comes from groups in the AB and AT Department and a similar tendency is found for the number experiments carried out in the LHC Radiation Test Facility in TCC2 (Figure 5). There is a clear decline in the number of radiation tests in 2005 because equipment is now being installed in the tunnel. There are still some 4 radiation campaigns scheduled for 2005 which concern equipment for Point 7 (collimation area) or final tests of components before series production.

![Figure 5: The number of experiments in the LHC radiation test facility in TCC2 at CERN (left); the cumulative distribution with respect to the various departments (right).](image)

3 FUTURE PROSPECTS

By adapting a Radiation Tolerance Assurance method for the LHC machine, the number of radiation sensitive components and systems in the LHC tunnel could be reduced significantly. However, this radiation tolerance assurance can only reduce the risk of damage to equipment and never entirely eliminate it.

In general, the equipment groups devoted most of their efforts to eliminate Single Event Errors. Indeed, present day microelectronics has become more sensitive to this damage effect as the total number of bits per electronic system has increased dramatically. This type of radiation damage...
will also appear first when beam begins to circulate in the LHC and their appearance during the sector test is certainly not excluded.

Based on the experience from other HEP laboratories (FNAL and RHIC), the efforts devoted to radiation testing may well increase during the first years of LHC operations. This prediction is based on the fact that not all equipment has been verified on radiation tolerance before installation and that there are areas where the potential hazard of radiation damage was discovered at a time when most equipment designs were already in the phase of series production or reception.

In this respect, it is worthwhile to mention the RRs and UJ76, where many equipment groups decided to install their material assuming that the radiation levels were not significant. This assumption appeared to concern only the total dose and not the flux of high energetic neutrons which are responsible for causing single event errors. As it is very difficult to construct an efficient shielding in the little space that is available in these areas, it may be that some equipment in these areas may be affected by radiation damage during the commissioning of the LHC.

A significant amount of expertise and know-how has been built up over the last few years by the accelerator and physics community of CERN. Together with accurate information from the RADMON radiation monitoring system, this provides a solid basis to tackle such matters when they occur.

REFERENCES
INTRODUCTION

The LHC is different from the previous accelerators that were built at CERN. It will collide two proton beams accelerated from 450 GeV to 7 TeV. In the nominal condition (7 TeV), the stored energy in each of the beam is 350 MJ which is ~10000 times bigger than that in LEP. Radiation will be produced in the tunnel and the underground areas by the interaction of the protons with residual gas molecules inside the beam pipe or with beam screens or collimators and by the proton-proton collisions themselves.

For the LEP the electronics equipment was usually installed in dedicated areas away from the tunnel accelerator. In LHC, this design has been changed following the will to decrease the cabling lengths and the associated cost and to increase the performances of the system (improve the signal quality and decrease the resistive losses). Most of the technical equipment and electronics will thus be installed in the LHC tunnel. Some electronics will be dedicated to the operation of the superconducting magnets, other will be used for the communication (WorldFip and Profibus fieldbus). Beam loss monitors, beam position monitors with their associated readout electronics, pressure sensors, valves, ion pumps and pressure gauges will be installed in the tunnel. There will also be the electronic equipment related to safety of personnel or machine such as oxygen deficiency detectors, quench protection, interlocks and the access system. All these electronics have to operate reliably under radiation. This is thus a priority to ensure a safe operation of the LHC to provide a careful monitoring of the radiation levels all around the LHC tunnel and its underground areas.

Because of the dramatic consequences related to the radiations, different monitoring systems are foreseen in the LHC. They are dedicated to the protection of the machine, of the personnel and the technical equipment. They are introduced in this paper. A special emphasis is made on the RADIation MONitoring (RADMON) system developed in TS/LEA to ensure the protection of the technical equipment.

RADIATION MONITORING AT THE LHC

There are 4 main different systems with their own specific purposes in view to monitor the radiation levels around the LHC accelerator and its underground areas: the Radiation Monitoring System for the Environment and Safety (RAMSES), the RADiation MONitoring (RADMON) system, the Beam Loss Monitors (BLMs) and the Beam Condition Monitor (BCM). An overview of these systems is given in Table 1.

2.1 RAMSES

The Radiation Monitoring System for the Environment and Safety (RAMSES) [1] is dedicated to both the radio protection of personnel and the environment. It will be exploited by the Safety Commission (SC). It will provide measurements of the ambient dose equivalent rate in the LHC underground areas as well as on the surface inside and outside the CERN perimeter. In addition it will monitor gases and fluids released from the LHC installations. RAMSES will generate local radiation warnings and alarms for evacuation from underground areas in case of elevated radiation levels and remote alarms on other monitored variables, which are transmitted to control rooms and shall trigger corrective actions by operators.

2.2 RADMON

The RADiation MONitoring (RADMON) [2] system is dedicated to the protection of the technical equipment around the LHC and in the underground areas. The TS/LEA group takes part in the development, the characterisation and the installation of the different sensors of the RADMON system (see paragraph 2.4). RADMON system aims at reducing the risk of induced failures and the
radiation uncertainties by measuring the radiation levels at the location of some specific technical equipment, by evaluating their performance under radiation and by determining whether they could have experienced radiation induced failures. This system is not intended to protect personnel. It will neither be connected to the interlock system nor will it trigger the beam dump. The monitors will be installed close to the technical equipment as suggested by the simulated radiation levels. Their locations could evolve as we learn more about operating the LHC.

2.3 Beam Loss Monitors

Beam Loss Monitors (BLMs) [3, 4] will be installed all around the LHC accelerator and their main task is to avoid beam losses that could lead to a quench of the superconducting magnets. The BLMs are designed and developed by the AB/BDI group. They will be mainly ionisation chambers and will be located close to the quadrupoles of the machine which represent an aperture restriction (6 BLMs per quadrupole). Secondary Emission Chambers are also foreseen for the regions with very high losses. The system will be calibrated in respect to the quench and damage levels of the magnets.

2.4 Beam Condition Monitor

The Beam Condition Monitors (BCM) [5] is being developed for the LHC experiments and will monitor on-line fast increments of particles fluxes near the interaction point. At the onset of beam instabilities or loss, the BCM will generate an abort signal to the LHC accelerator control to dump the beams. It will thus provide an on-line monitor for the beam conditions, with the possibility to request a beam abort injection and to ramp down the HV of the detector. The development of the BCM is a collaboration between the TS/LEA group and the LHC experiments. The BCM sensors are Chemically Vapour Deposited or CVD diamonds. They will be located very close to the beam pipe and must be able of detecting lost protons from the beam, or collision products from lost protons which travel along the beam.

<table>
<thead>
<tr>
<th>Purpose</th>
<th>Measurement</th>
<th>beam</th>
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<tr>
<td>RAMSES</td>
<td>Radio protection</td>
<td>OFF / ON</td>
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<td>RADMON</td>
<td>Avoid damage to technical equipment</td>
<td>Neutron flux, Hadron flux, Total dose</td>
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<td>BLM</td>
<td>Avoid quench/damage of sc magnet</td>
<td>Particles flux</td>
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<tr>
<td>BCM</td>
<td>Avoid damage to detectors of experiments</td>
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3 RADMON SYSTEM

3.1 Radiation damage to electronic equipment

A large amount of the equipment will be installed in the accelerator tunnel, in the underground areas and in the experimental caverns. The levels of prompt and remnant radiation in these areas will increase with time and with it the risk of radiation damage to equipment. For organic materials such as cable insulation, radiation damage is mainly proportional to the dose and independent on the type of radiation. For inorganic materials such as electronics and metals, the induced radiation damage depends mainly on the energy and the type of particles. In the LHC we could expect cumulative damages that will only appear after a certain amount of time but also instantaneous damages such as a quench of a magnet or the destruction of an integrated circuit due to a single particle hit. This is why the semiconductor electronics are considered as the most radiation sensitive equipment in the tunnel.

3.2 Risk assessment

About 10,000 crates (with semiconductor electronics) are foreseen to be installed in the LHC. These electronics systems are made of commercial-off-the-shelf (COTS) components and are not radiation hard. The risk of having radiation induced failures in the LHC is thus far to be negligible.
The radiation has already been taken into consideration as a constraint at the system level and a reliable operation is expected to be achieved. The radiation levels have been simulated around the accelerator and in the underground areas. These values should however be considered with a limited accuracy as they depend to a large extent on how well we can predict future operating scenarios and machine conditions.

Although most equipment groups have taken radiation into account as an engineering constraint for their system, there still exists a considerable uncertainty on the radiation tolerance. The same uncertainty exists for the radiation levels under which this equipment will have to operate. The RADMON system has been designed to reduce these risks and uncertainties by providing an early warning as the radiation levels at the location of the equipment increase.

3.3 Purpose of the RADMON system

The RADMON system will help to reduce the risk of induced failures and the uncertainty on the radiation environment in the tunnel and the underground areas by measuring the radiation levels at the locations of the equipment and determining whether the equipment could have experienced radiation induced failures.

The comparison between the radiation levels measurements and the corresponding simulations will help to understand the machine operation and in particular to foreseen additional shielding. It may also allow locating abnormal vacuum conditions, alignment errors, faulty corrector magnets and aperture limits.

3.4 Radiation sensors and remote readout

The RADMON system is using active and passive sensors such as ThermoLuminescent Dosimeters (TLDs), RadioPhotoLuminescent Dosimeters (RPLs), Single Event Upsets (SEUs) counters, RADFETS and PIN diodes. The active dosimeters are readout on line via a fieldbus (WorldFip). The passive dosimeters will be removed from their locations during the shutdown periods and then will be analysed in the laboratory to give their dosimetric information.

The RADFETS, pin diodes and SEUs counters are integrated into a single design, the ‘radiation monitor’. This monitor (see Figures 1a, 1b and 1c) is under development in the TS/LEA group and designed to operate up to a total dose of 200 Gy. It can measure with a maximum frequency of 50 Hz the dose, the dose rate, the 1 MeV equivalent neutrons fluence and the hadron (E>20MeV) flux and fluence.

The ‘radiation monitor’ PCBs will be installed inside an aluminium shielding box. A window is machined out to allow for the exposure of the active dosimeters (see Figure 1b). Some TLDs (passive dosimeters) will be attached on the external side of the box (see Figure 1c) to act as cross-check sensors. The 6LiF and 7LiF models are foreseen to be used as they are able to measure absorbed doses between 10-6 Gy and 100 Gy. A cross-check between the different sensors will thus be possible. It will allow the determination of the absorbed dose in case of troubles with the ‘radiation monitor’.

The radiation monitor boxes are connected via a WorldFip fieldbus cables to the junction boxes (see Figure 2). A number of 250 junction boxes will be distributed around the LHC tunnel and its adjacent underground areas. Between 0 and 32 ‘radiation monitors PCBs’ can be attached to a single junction box. For the LHC start-up, 125 ‘radiation monitors’ will be installed in the areas as shown in Figure 3.

On the request of the experiments additional sensors will be installed in the experimental caverns close to the detectors. Radiation monitoring is foreseen in a few hundred different locations in all the 4 caverns using RADFETS, pin diodes, TLDs, RPL dosimeters or a combination of these. The TS/LEA group is involved in the characterisation and installation of these dosimeters. The RADFET and pin diodes can be read out on line from the experiments control room while the TLDs and RPLs need to be removed from their locations and read in the laboratory thereby limiting the temporal resolution of the data. The complete installation of these sensors in the experimental caverns is expected for the beginning of 2006.
Figure 1 – (a) V3.1 Radiation monitor prototype PCB, (b) the radiation monitor PCB inside the shielding box, (c) the radiation monitor box with attached TLDs (in orange)

Figure 2 - Location of a junction box (containing 0 to 32 radiation monitors) in a half cell of the LHC

Figure 3 - Installation of the ‘radiation monitors’ around the LHC (areas coloured in grey).

The installation of the RADMON system relies heavily on many services provided within the TS Department. The electronics design and production of the ‘radiation monitors’ is carried out in collaboration with TS/DEM while the WorldFip cabling is carried out in collaboration with TS/EL. This group is also involved in the electrical powering of the system in the tunnel.

4 CONCLUSIONS

The RADMON system will help to protect the technical equipment that will be installed at the LHC, in the tunnel, in the underground areas and in the 4 experimental caverns. It will provide on line
data on the radiation levels at specific locations when there is a circulating beam. By comparing this information with the simulation results, the risks of induced failure in technical equipment can be reduced. It will also lead to a better understanding of the machine. The RADMON system is using active and passive sensors such as ThermoLuminescent dosimeters (TLDs), RadioPhotoLuminescent Dosimeters (RPLs), Single Event Upsets (SEUs) counters, RADFETS and PIN diodes. The last three are integrated into a single design called ‘radiation monitor’. The active dosimeters will be read out on line via a Fieldbus on several kilometres at a maximum frequency of 50 Hz. Passive dosimeters such as TLDs will be attached to the ‘radiation monitors’ and will provide a secure backup measurement of the total ionising dose. These measurements will also allow to cross-check the experimental data. The remote readout board for active sensors is in the production phase. The installation for the sector test in 2006 will begin at the end of this year, as will the installation of the sensors in the 4 experimental caverns.

REFERENCES
[1] TIS-ST, LHC-P-ES-003 rev 0.1, EDMS Document No. 384721