5 years Radiation Testing of electronic components and systems for the LHC experiments and the LHC machine : summary and future

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Abstract

A summary on the last 5 years radiation testing of equipment for the LHC project in dedicated facilities outside CERN is presented. The proton irradiation facilities in CRC Louvain la Neuve and in the Paul Scherrer Institute have given an important contribution to the design of the LHC equipment. The intensive testing efforts from CERN groups in the last 5 years underline that radiation tolerance has become a design and operational constraint for the LHC. Radiation testing will most likely continue during the LHC commission phase when radiation induced equipment failures will start to appear.

I. INTRODUCTION

Already some 10 years before the startup of the LHC, the requirement for radiation tolerant electronics for the LHC experiments was given a very high priority [1]. At that moment, it had become clear that the radiation tolerant designs and radiation hard components would be needed for the inner detectors where the expected dose rates are of the order of a Mrad per year at nominal beam intensity. Commercial off the shelf components and systems were suggested for use on the cavern walls where the expected dose rates are of the order of 100 Rad/year.

In 1998, a proposal to study radiation tolerant electronics was made by the LHC Electronics Board, stressing the importance that all the LHC experiments consider this problem. Initial studies focussed on the tolerance to damage from the total ionising dose but it was soon realised that single event errors were of much bigger concern since they were not taken into account in earlier design phases of the equipment. A specific simulation study [2] revealed that testing with protons at energy of 60-200 MeV is sufficient to compute the Single Event Error rate in a radiation environment such as that of the LHC. Protons also ionise and give displacement which means that all radiation effects could be tested simultaneously with a single radiation source.

The irradiation facilities at the UCL Louvain la Neuve in Belgium and the Paul Scherrer Institute (PSI) in Villingen (Switzerland) provided protons in this energy range and a specific collaboration agreement aimed at components testing for the LHC between CERN and these Institutes was initiated in the year 2000. These facilities have now been used by the LHC experiments for nearly 6 years, representing more than 600 hours of beam time. In 2005, the neutron irradiation facility at the Svedberg Laboratory began contributing to the LHC project by making available their neutron and proton irradiation facilities. Some 54 hours of beam time have been used by LHC groups at TSL to date.

The importance of radiation tolerant electronics for the LHC accelerator was recognised in 1999 when it was decided that the baseline of the machine was to locate equipment under the main magnets in the 27 km long accelerator tunnel. Initial radiation studies focussed mainly on the total dose tolerance but Single Events were soon recognised as a major issue. In 2001, the first machine equipment was irradiated in the proton facilities mentioned here above under the same agreement. Up to date, nearly 350 hours of beam time have been used by the machine equipment groups.

Although organised in entire different ways, the joined irradiation campaigns for machine and detector equipment groups proved very beneficial and efficient for all parties involved. This success underlines the importance of sharing experience and exchanging information on the radiation tolerance of electronic components and systems between CERN users and the radiation effects community at large. For the last 5 years, results on tested components have been presented at the LHC Radiation day [3], a yearly CERN event that takes place in December. In this paper we will summarise on the user experience from the last 5 years and predict the future needs for these facilities in particular in view of a luminosity upgrade of the LHC.

II. RADIATION TEST FACILITIES

A. *Proton Irradiation facilities*

The main proton irradiation facilities used by CERN are located at the Paul Scherrer Institute in Villingen (Switzerland) and the Catholic University UCL in Louvain la Neuve (Belgium). Both institutes are also involved in other ways in the LHC project and consider the use of their proton irradiation facilities as part of their contribution to CERN and to the LHC project in particular.

At PSI, there are 2 proton irradiation facilities (PIF, [4]). The low energy line (figure 1) provides protons at energies between 6 and 63 MeV at a maximum flux of 1 x 10^9 protons cm^{-2} s^{-1}. The maximum beam size in this facility has a diameter of 90 mm, 90% of the beam being distributed uniformly in an inner circle of 50 mm.

Due to its regular monthly availability with short notice, the low energy line at PSI has proven most popular for CERN users and more than 95% of the CERN irradiation experiments at PSI were conducted here. This represents approximately 370 hours of beam time over the last 5 years.

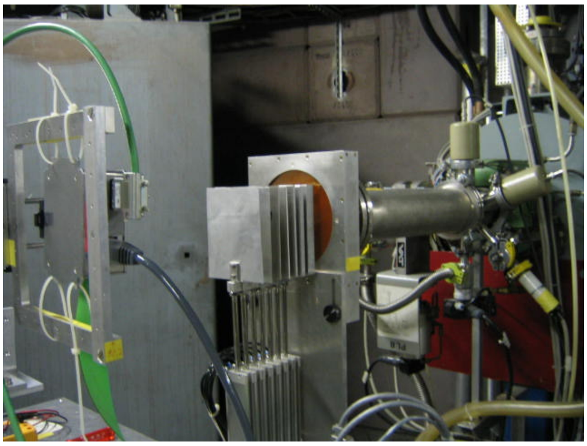

Figure 1: Irradiation of equipment for the LHC in the low energy Proton Irradiation Facility at the PSI.

The high energy line at PSI provides protons with energies between 35 and 250 MeV at a maximum flux of 2.5 x 10^8 protons cm^{-2} s^{-1} (neutron background 10^{-4} per proton per cm^2). The beam profiles in this line are Gaussian shaped and have a FWHM of 6 cm. The maximum beam diameter is about 90 mm.

The high energy beam line has been used occasionally by CERN groups for specific studies on, for example, power electronics for which concerns existed on destructive SEEs at high proton energies. Another example application was to complete a full single event upset cross section curve for proton energies ranging from 10 to 250 MeV.

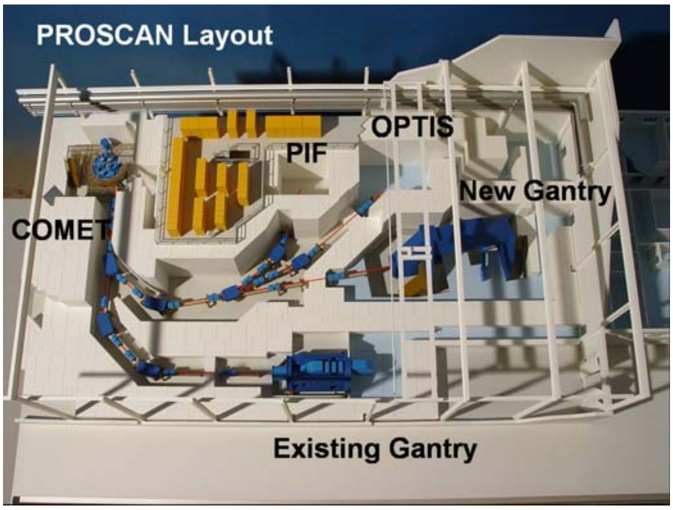

Figure 2: The new PROSCAN Proton Irradiation Facility at PSI for protons with energies between 10 and 250 MeV.

The low and high energy proton facilities at PSI will soon merge into a single facility (the PROSCAN Project, see figure 2) providing a wide range of energies from 5 to 255 MeV. In May 2005 the new COMET cyclotron, designed specifically for medical applications, was installed and commissioned. This superconductive 250 MV facility is also used to generate protons for the irradiation of electronic components and systems. The temporary test area where the PIF facility is installed is operational since January 2006 and the first CERN user group will conduct experiments for the LHC project in this facility in the fall of 2006. The final PIF experimental area will be commissioned in the first half of 2007.

Figure 3: The LIF proton irradiation facility at UCL at LLN

The LIF (Light Ion Facility) at the Cyclotron Research Centre (CRC) of UCL in Louvain la Neuve [5] (figure 3) provides proton beams with energies from 10 to 67 MeV at a maximum flux of 1 x 10^9 protons cm^{-2} s^{-1}. The beam profiles in this line are flat with a beam size of about 10 cm in diameter and less then 10% intensity variation over the irradiated surface. From the year 2000 onwards, some 18 irradiations campaigns for the LHC project took place at the LIF in UCL representing more than 500 hours of beam time.

Figure 4: Proton Irradiation of large objects at TSL in Uppsala.

In 2005, because of the need for high energy proton and neutron irradiations of relatively large complete systems, contacts were established with the Svedberg Laboratory (TSL) in Uppsala (Sweden). TSL can provide proton beams over a circular area 27 cm in diameter, which allows for the irradiation of complete systems in a single run (see Figure 4). Proton energy ranges is 20-180 MeV at a maximum flux of 1.4 x 10^8 protons cm^{-2} s^{-1} for a beam area of 27 mm in diameter [6]. The neutron irradiation facility at TSL provides neutrons with energies up to 180 MeV at a maximum flux of 6 x 10^5 neutrons cm^{-2} s^{-1}. The beam size for neutrons can equally have diameter of 27 mm although not at the maximum neutron intensity. The neutron irradiation facility has been used occasionally by CERN equipment groups for specific studies and is considered complementary to proton irradiation experiments.

Table I summarises on the total number of irradiation campaigns and beam time in the various facilities since the year 2000.

Table 1: Cumulative number of CERN campaigns and beam hours used for the LHC project since the year 2000

Irradiation Facility	Irradiation Campaigns	Total Beam time in hours
PIF (PSI)	15	382
LIF (CRC/UCL)	18	539
TSL (Uppsala)	4	54

B. *Irradiation facilities for cumulative effects*

A significant amount of equipment for the LHC project has been tested for total dose effects in the gamma irradiation facilities from CIS-bio International in the nuclear research centre of CEA-Saclay in Paris [7]. Presently, two irradiators are available (named ‘POSEIDON’ and ‘PAGURE’) one of which is routinely used for industrial purposes.

The PAGURE irradiator has a ^{60}Co source of 14 kCi and provides dose rates from 3 kRad/hr to 100 kRad/hr for large volume and up to 2 MRad/hr for small volumes. In the latter case, the equipment must fit in a cylinder 5 cm in diameter and 5 cm height. This irradiator is frequently used for the irradiation of electronic components and material testing.

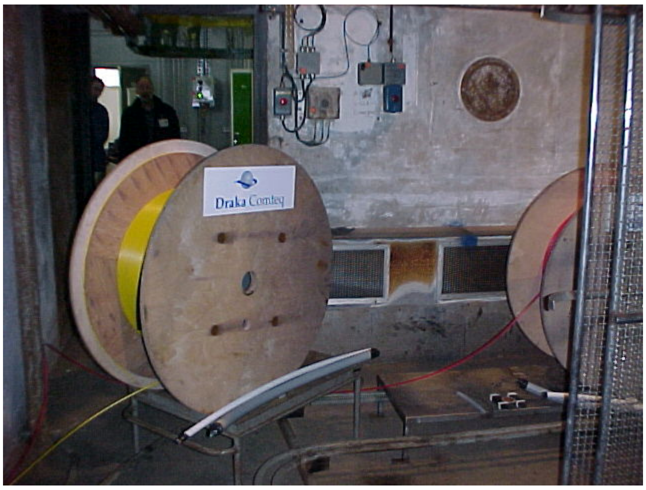

Figure 5: Gamma Irradiation of Optical Fibres for the LHC in the POSEIDON irradiator.

The POSEIDON irradiator (figure 5) also has an intense ^{60}Co source but can accommodate much larger volumes. The available dose rate in this irradiator varies between 3 kRad/hr and 500 kRad/hr. POSEIDON is used frequently used for industrial applications but long continuous irradiation periods can be obtained during the weekends.

A number of displacement damage irradiation tests for the LHC project have been carried out with the PROSPERO nuclear rector (figure 6) located at the military research facility of CEA-Valduc close to Dijon in France [8]. PROSPERO is composed of a ^{235}U core surrounded by a ^{238}Ureflector and a thick steel hood which reduces the gamma dose. It produces a degraded fission spectrum and is operated in a delayed critical state with a continuous power from 3 mW to 3 kW. The average energy of the neutrons is 0.8 MeV.

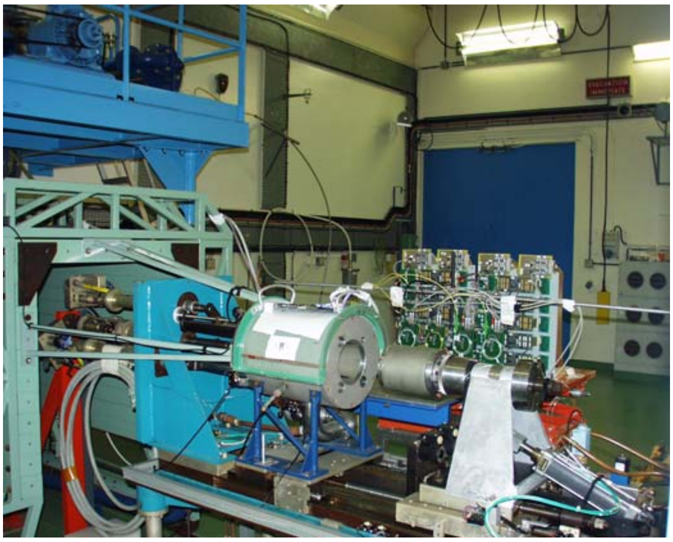

Figure 6: Neutron irradiation of LHC equipment with the PROSPERO fission reactor

This reactor operates in steady state mode and at 3 kW, the maximum fluence is 10^{14} 1 MeV equivalent neutrons per cm^2 for equipment that is placed close to the reactor core during approximately 3000 seconds. The maximum neutron flux is 3.6 x 10^{10} neutrons cm^{-2} s^{-1} and the associated dose rate from gammas in that case is 3.5 Rad/s. Other fluence to dose ratios can be obtained by increasing the distance with respect to the reactor. At 4 m for example, the neutron fluence is reduced by a factor 1000.

Alternatively, the neutron flux can be reduced by operating the reactor at lower power (minimum power 3 mW) while the neutron spectrum can be modified by placing the samples in shielding boxes made of polyethylene, Cadmium, or Boraflex

Table 2 gives a summary of the number of campaigns that have been carried in either of the facilities mentioned above since the year 2000 as well as the total number of different equipment groups involved.

Table 2: Cumulative number of CERN irradiation campaigns for Displacement and Total Dose since the year 2000

Irradiation Facility	Irradiation Campaigns	Equipment groups involved
PROSPERO (Dijon)	5	11
CIS Bio (Saclay)	6	12

In order to make the campaign more efficient, the radiation campaigns usually involve various CERN users groups from both experiments and the machine. Most campaigns take about 2-3 days to complete (including the set up of the experiments and post irradiation measurements). CERN is presently using these facilities on a regular basis and 1-2 times per year.

III. User Experience

A. *Single Event Error tests*

Proton beam irradiation has been by far the most important tool used by CERN equipment groups to evaluate SEE sensitivity of components and systems. The main reasons are probably that proton beams can be used to study single events, total dose and displacement damage in a single test and that the results allows for a straightforward extrapolation of the SEE rate in the LHC environment. As compared to irradiation with heavy ions or neutrons, proton test have relatively low costs and are easy to obtain. Proton irradiations are carried in air instead of vacuum which reduces the complexity of the test set up and shortens the overall time needed to characterise a device. Stopping, starting or adjusting the intensity of the beam is straightforward. Finally, proton beams are sufficiently penetrating to allow irradiation of electronic components in their packaging.

The aim of most user groups has been to obtain a reasonable estimate of the single event error rate of their devices and/or entire system during nominal operation at the LHC. SEE tests were therefore performed at the highest available proton energy (typically 60 MeV as recommended in simulation studies [2]) to compute the error cross section by dividing the total number of errors observed in an irradiation run by the total proton fluence during the run. By assuming that all hadrons above 20 MeV have the same cross section, it is then possible to compute the error rate in the (simulated) radiation environment of the LHC [2]. Although not very accurate, this procedure proved easy to follow for non experts in the field and a good trade-off between the time constraints imposed by the LHC construction schedule and the limited resources available.

Based on our experience over the last few years, a successful SEE test is usually the result of a very careful preparation. Each user group responsible for an electronic system or sub-system for the LHC is also responsible for the radiation test. Users therefore need to acquire at least a minimum knowledge on the subject of radiation effects. The irradiation schedule and beam parameters have to be prepared in advance, preferably with the help of knowledgeable person in the field. The test set up should be completed 1-2 weeks in advance and the devices under test should be available and tested with the SEE test set up. On line visualisation of the test data is highly recommended as it allows for a first check of the data after each run. The number of accesses to the irradiation area and the exposure of the users to ionising radiation can be minimised if the setup has the possibly to reset and power cycle the devices under test remotely. Furthermore, a good mechanical and electrical interfacing between the test facility and the SEE test setup is needed to avoid problems related to, for example, EM interference, stray light or polarity inversion.

Some user groups use the same SEE test set up in consecutive experiments. The setup is then modified and improved over time. This has the advantage that slightly activated cables, connectors or mechanical support structures can be temporarily stored at the radiation facility and re-used at a later point in time.

Single Event Errors have been a concern during many radiation tests for the LHC project to date. In some cases, SEEs occurred in components or systems where they could be expected. In other cases, SEEs occurred while the experimenters were mainly interested in studying the TID tolerance of the equipment. . For custom made in-house designs a few proton irradiation sessions of 8 hours each could be sufficient to make the system design sufficient radiation tolerant and to proceed to series production. . If the constraint of radiation tolerance was added to an existing design (COTS or custom build equipment from Industry) the lead time was in general much longer.

B. *Cumulative damage tests*

Grouped cumulative damage test for the LHC project are carried out once to two times per year. Usually, equipment groups from the accelerator and the experiments decide on a joined expedition to optimise resources and to reduce the amount of equipment that needs to be transported. The campaigns are supervised and prepared by a knowledgeable person from CERN but each user group remains responsible for its own test.

Again, the key point for a successful test has proved to be a very careful preparation together with a setup that interfaces correctly with the facility and that has been tested extensively before departure. Irradiation conditions and user requests have to be combined several weeks beforehand into a feasible irradiation plan.

Neutron irradiations with the PROPERO fission reactor are performed in a single run and a campaign usually takes 3 days to complete. The setting up and testing of the equipment in the reactor hall can take an entire day and represents an important part of the work as there is no possibility to interrupt the test. All exposed material becomes very radioactive after the irradiation and access to the reactor hall is prohibited for several days. Post irradiation measurements are therefore carried out at the facility itself on the final day of the campaign.

Total Dose irradiations experiments with gamma rays from a ^{60}Co source provide more flexibility because they can be interrupted for short periods of time. As material does not become radioactive, it is possible to adjust the test setup or exchange the devices under test.

It is often difficult to estimate the degradation of the components or systems at a given dose rate before the test. Many users therefore begin their experiments at a low dose rate for a short period of time. After a first evaluation of the equipment at a predefined dose, the dose rate can then be increased by decreasing the distance between the equipment and the source.

Although this approach gives the user a first impression, it makes the study of dose rate effects and annealing behaviour more complicated or even impossible.

IV. Future Prospects

Figure 7 shows the evolution of the proton beam time usage by the LHC experiments over the last few years. The high luminosity experiments CMS and ATLAS have been the main users of the proton facilities probably because they incorporate a large amount of equipment in their detectors and because they have the most severe radiation environment. Testing for the smaller, low luminosity experiments ALICE and LHCb started at a later point in time and required less beam time.

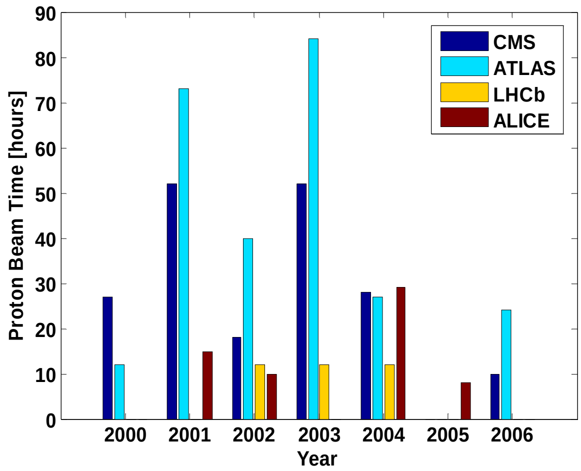

Figure 7: Proton beam time used by the LHC experiments.

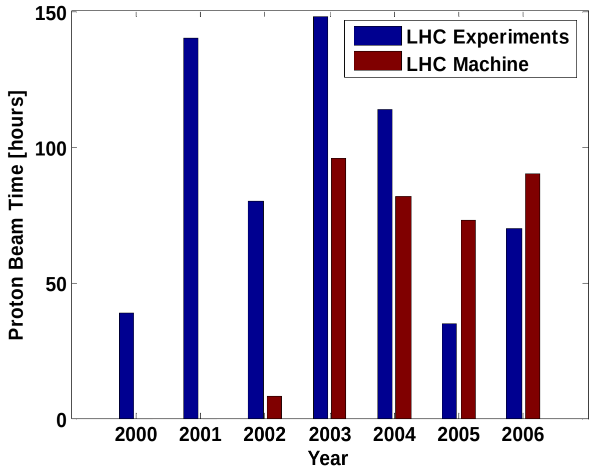

Figure 8: Total proton beam time used for the LHC experiments and the LHC machine.

In 2003, the requests for beam time surged as many groups needed to validate their systems before starting series production of the equipment (figure 7). In the 2 years following the series production and in some cases already installation, the need for beam time decreased.

In 2006, the observed increase of requests from the LHC experiments originates from equipment that was developed late with respect to the LHC schedule, namely the power supplies for the distribution of the low voltage to the experiments. Early prototypes having being designed without radiation tolerance in mind, and due to the complexity of the equipment, several testing cycles were necessary to eventually converge to an architecture and components that could satisfy the radiation tolerance specifications.

The observed increase of requests from the LHC machine in the same period originates mainly from the Beam Loss Monitoring (BLM) system and the RADMON radiation monitoring system. Both systems needed detailed calibration runs for the various sensors or chambers.

This tendency makes us believe that radiation tolerance assurance studies for the machine will probably continue at approximately the intensity in the years to come. In 2007, the request for beam time should decrease as the equipment installation and commissioning activities will be in full swing.

The LHC commissioning run at low beam intensity and low energy (450 GeV) is presently foreseen in December 2007. This event will make the issue of radiation damage to equipment and in particular the issue of SEE rates more specific. Areas with a potential risk of radiation damage to equipment when operating at higher beam intensities will emerge. Furthermore, despite all efforts to assurance the radiation tolerance of LHC equipment, first radiation induced equipment failures will probably appear.

The request from the LHC experiments in the near future will be mainly driven by the LHC upgrade programmes. A small fraction may come from groups that operate equipment in the experimental areas as radiation damage in the experimental areas is only expected when the first beams with physics intensity are put into collision in 2008. At his point, the issue of radiation shielding of the experiments will have become more precise.

V. ACKNOWLEDGEMENTS

Proton irradiation tests have been of crucial importance for the design and the construction of electronic components and systems for the LHC machine and experiments. We would like to acknowledge the contributions from the Cyclotron Research Centre of the “Université Catholique de Louvain la Neuve” (UCL), the Paul Scherrer Institute and The Svedberg Laboratory. In particular the help, from G. Berger (CRC), W. Hajdas and R. Brun (PSI) and A. Prokofiev (TSL), their extremely good will, their knowledge of their facilities were not only appreciated, but absolutely essential in the setting up of the agreements with their Laboratories, and in the success of every irradiation campaign.CEA-DAM and Cis-Bio International are thanked for their contributions with special thanks to N. Authier and his collaborators.

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