RADIATION CONSTRAINTS IN THE DESIGN AND CONCEPTION OF LHC CONTROL SYSTEMS

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Abstract

The radiation constraint for the design and conception of LHC controls systems is described. One of the criteria when selecting electronic components is their radiation tolerance. Complete control systems are designed to operate reliable even when data is occasionally being corrupted by high energetic particles. Radiation also has an impact on the architecture, layout and integration of a control system. Finally, development costs, system functionality, reliability and the overall life span of a radiation tolerant control system are discussed.

INTRODUCTION

The LHC (Large Hadron Collider) is technologically more complex than any of the previous accelerators that have been built at CERN. This is partially due to the use of superconducting technology and the tight constraints that are imposed on beams for physics. The increased technological complexity has a clear impact on the various controls systems.

First, many low level electronics are placed close to the beam in the accelerator tunnel rather than in the surface buildings. This improves the signal quality and reduces cable costs and resistive power losses. Many of the LHC power converters for example, will be placed under the cryostats of the main magnets in the accelerator tunnel.

Second, there is a preference for the use of complex programmable devices such as microprocessors and FPGAs. Such devices are relatively cheap, easy to use and high performing. They allow local treatment of data thereby reducing the need for high bandwidth communications in the tunnel.

Another aspect is that many electronics in the tunnel use a large amount of static or dynamic memory to store the operational settings of the machine, raw diagnostic data or the equipment status.

Finally, the use of standard industrial controls equipment has been preferred whenever possible. Industrial controls systems are presently envisaged for electrical distribution, cooling and ventilation, vacuum,

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cryogenics, access, interlocks and radio frequency.

All these aspects have made the assurance of the radiation tolerance of the LHC controls more complicated.

In the remainder of this paper, a short description of the radiation in LHC tunnel will be given followed by an overview of the basic radiation damage effects in electronic devices. The guidelines to minimise risks of radiation damage or propagation or radiation induced errors in the various LHC control systems are described. Examples of common choices for electronic components and design techniques are given followed by a discussion on the reliability and the overall life span of control systems under radiation.

RADIATION IN THE LHC TUNNEL

Radiation in the underground areas and in the accelerator tunnel is produced when protons interact with the nuclei of the residual gas atoms (beam gas interactions) or with the nuclei of the atoms of any other material surrounding the beams such as beam screens collimators, magnets, cables, cryostats or the beam dump (point losses).

These primary reactions produce secondary particles such as neutrons, pions, kaons and other protons. Some of these secondary particles have sufficient energy to interact again and cause the production of tertiary particles and so on. This phenomenon is called a hadronic cascade.

The fragments of the struck nuclei produced in the hadronic cascade are radioactive and decay on a timescale between a fraction of a second and many days. The accelerator thus continuous to produce radioactivity even though there are no more circulating beams.

These physics effects have been simulated in detail with Monte Carlo codes [1]. For these simulations, is assumed that the LHC is operating at nominal intensity and energy in physics mode, i.e. with two colliding proton beams.

An example of a result of such a simulation is shown in figure 1 [2]. The figure shows the energy spectrum for neutrons, protons and charged pions in a specific part of the LHC tunnel where electronics will be installed. Such a radiation spectrum is called complex because it is composed of several types of particles at different energies.

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Figure 1 : Typical spectrum of the radiation field in the LHC tunnel for the case of thin shielding material around the beam pipe (data from [2])

From a given energy spectrum, it is difficult to judge what electronic components will degrade, to what extend and what consequences this may have for the functionality of the system.

A common solution is to parameterise a complex radiation spectrum in terms of the total absorbed dose in silicon (expressed in term of Joules per kg or Gray), the 1 MeV equivalent neutrons per cm² and the number of hadrons with energy above 20 MeV per cm². The reason is that these three parameters are directly related to the three different radiation damage effects in electronic devices: Total Ionising Dose (TID) damage, Displacement Damage and Single Event Errors (SEE).

The radiation spectra in the LHC tunnel differ from location to another. In the regular ARCs for example, radiation is mainly due to beam-gas interactions. Since all magnets in the ARC region are superconducting, some radiation shielding is provided by the cryostats of the superconducting magnets. Radiation levels in the ARC are therefore lower and most electronic equipment will be located here.

In the Dispersion Suppressor (DS) regions, radiation is mainly caused by direct proton losses and annual radiation levels can 7-10 times higher than in the ARCs.

Table 1 : Annual radiation levels under the magnets in the LHC regular ARCs and in the Dispersion Suppressor (DS) (data from [2]).

Radiation Levels	ARCs	DS
Total Ionising Dose in Gy [Si]	10	70
1 MeV eq. neutrons per cm ²	5 x 10 ¹¹	5.9 x 10 ¹²
Hadrons $E > 20$ MeV per cm ²	3.5 x 10 ¹⁰	3.8 x 10 ¹¹

At locations where the magnets are warm, the beam pipe is not shielded and many more fast neutrons will be present.

RADIATION EFFECTS IN ELECTRONICS

In the complex radiation field in the LHC tunnel, electronics will degrade via 3 different damage mechanisms [3] :

- Surface damage caused by ionizing radiation (in the tunnel mainly gamma rays and electrons) and that is proportional to the total absorbed dose in the device.
- **Displacement damage** caused by energetic particles (in the tunnel mainly neutrons) that create damage in the bulk of electronic devices and that is proportional to the number of particles per surface unit incident on the device.
- Single Event Errors caused by hadrons (in the tunnel mainly neutrons) with energy above 10 MeV and that are proportional to the number of particles per surface unit incident on the device.

Total Ionising Dose

Surface damage is a cumulative effect and concerns nearly all types of electronic components. The tolerance of a device is expressed in terms of the Total Ionising Dose or TID it can tolerate. In CMOS technologies, total dose damage causes the threshold voltage of transistors to shift and the noise and leakage current to increase.

The ionising radiation modifies also the conductance of the device and this may be observed as an increase of the current consumption for systems that are near their Total Ionising Dose limit.



Figure 2 : Increase of the current consumption of a C32 DSP from Texas Instruments TMS320C32PCM40 under irradiation with 60 MeV protons (data from [4])

Total dose effects may have influence on systems that are based on voltage comparison. For example, it was found that some pressure gauges that measure in the range between 1 and 1500 mbar absolute pressure are extremely sensible to Total Dose effects. These devices became unusable after 20-25 Gy. Most CMOS technologies can stand at least 10-15 Gy.

Displacement Damage

Displacement damage is also a cumulative effect and affects mainly bipolar technology and devices such as optocouplers, photodiodes etc. In contrast with surface damage, electronics sensitive to displacement damage continue to degrade even when not powered on. An example of displacement damage on a switched mode modular power supply is shown in figure 3.



Figure 3 : Variations of the output voltage of 2 modules of the VERO PK55 triple switched mode power supply (5 V, 5A) under radiation.

The output voltage of the two modules under test starts to increase when the total fluence of 1 MeV equivalent neutrons is around $4x10^{11}$ per cm². The degradation of the power supply modules continues even when the power is temporarily switched off.

Single Event Errors

Single Event Errors (SEEs) are statistical in nature and will occur from the moment that sensitive electronic equipment is exposed to radiation. Other than with cumulative effects, SEEs are caused by a single ionising particle.



Figure 4 : Single Bit Errors in the SRAM memory of the WorldFIP fieldbus interface when irradiated with 60 MeV protons (data from [8]).

There are many types of Single Event Errors but it is often convenient to think in terms of soft and hard SEEs. Soft SEEs occur when the data stored in a device is corrupted. Hard SEEs is when a device or a part thereof is permanently destroyed by the impact of a single ionising particle at a critical location in the device.

There are many kinds of soft SEEs. Well known is the corruption of data in SRAM or DRAM memory. In

complex devices such as microprocessors, this can cause the device to produce the wrong output value or to stop functioning all together. In either case, a soft or hard reset will bring the device back to correct operation.

Hard SEEs can destroy a component in a fraction of a second. A frequently occurring hard SEE is the so called single event burn out which occurs in, for example, power electronics such as MOSFETs and IGBTs.



Figure 5 : Failed power MOSFETs in a hybrid circuit of a VME power supply (picture from [5]). Note the loss of the wire bonds on the silicon indicating a burn out event.

At this point, most of the efforts in making LHC machine electronics radiation tolerant are dedicated to the mitigation of Single Events Errors.

TOLERANT DESIGNS

Selection of hardware

Based on the simulated radiation levels, the first task is to evaluate different candidate components and technologies that could be used.

Electronic equipment in the regular ARCs will have to resist a total dose of 100 Gy in 10 years of operation. Fortunately, there are many operational amplifiers and voltage comparators that can sustain such a dose without any significant performance degradation. Figure 6 for example, shows the gain decrease obtained on operational amplifiers AD620 that have a TID of 180 Gy [6]. CMOS technology can usually resist doses of at least 50-80 Gy or more.

Displacement damage may have an impact on designs that have to use laser diodes, opto couplers or bipolar transistors. Opto couplers of type HP 6N139 are a popular choice for use in power supplies. Some laser diodes from Infinion, Mitshubishi and Modulight show good resistance to displacement damage. Voltage comparators such as the LM1xx are suitable for use in the LHC ARCs. In general, the 1 MeV equivalent neutron fluence should exceed 10¹¹ per cm² in order to observe any significant component degradation from displacement damage.



Figure 6 : Gain decrease of operational amplifiers AD620 due to total ionising dose damage (data from [6]).

Single Event Errors can be expected in complex devices such as ADCs, DPSs, µprocessors, FPGAs, DSPs etc. Antifuse technology such as the A54SX series from Actel is usually preferred above SRAM based devices such as Xilinx CPLDs. The configuration data in antifuse technology cannot be altered by the impact of high energetic particles. SRAM or DRAM memory should be combined with an Error detection and correction (EDAC) algorithm. EDAC algorithms are commercially available from, for example IDT (IDT49C456A 32/64 bit). Triple Modular Redundancy (TMR) techniques can be used on both antifuse and SRAM based devices. This technique exists in triplicating the data and the functionality to eliminate faults using majority voting.

Power electronics such as MOSFETs and IGBTs are also sensitive to Single Event Errors. In some cases it is sufficient to operate such devices at lower drain source voltage such that radiation currents are not sufficiently strong to destroy the device. The reduction may have to be as high as 50 %.

The selection of complete industrial systems can only be based on radiation data. Good collaboration with the manufacturer is mandatory to obtain information on the electronic components that are used. For the LHC machine it was possible to identify various types of standard commercial systems that can work reliable in the tunnel. For example three different types of switched modular power supplies from different manufacturers were found [7]. Other examples are pressure gauges, oxygen deficiency detectors, field bus interface cards and optical repeaters.

Communication in the tunnel

The most common architecture for LHC machine control systems consist of two layers with a fieldbus network (WorldFIP, ProfiBus or CANbus) connecting low-level electronics in the tunnel or in an underground area to a gateway located in one of the surface buildings.

Fieldbus technology is a popular choice because the equipment interfaces are very radiation tolerant. Figure 7 shows the CC131 μ FIP interface card that is used in many different low level electronics.



Figure 7: CC131 MicroFIP fieldbus interface at 1 Mbit/s.

The ASIC (VLSI) chip with the FIP protocol has 15 blocks of 8 bytes of SRAM based memory sensitive to SEU. The SEU cross section of these registers is 1.10^{-9} cm² per bit and the TID tolerance is more than 600 Gy [Si] (see also figure 4). Similar results have been obtained for the Profibus and CANbus low level interfaces.

Triplicate logic and "command-response" operation can eliminate the propagation of radiation-induced errors. This widely used technique exists in storing data on a board in flash memory that is not sensitive to SEU. Upon request (a "command"), data is written at three different locations in the SRAM memory (triplicate logic) and immediately transmitted over the fieldbus (response). Because the data resides for a very short time in the SEU sensitive SRAM, it is very unlikely that all memory location get corrupted at the time.

So far, it has not been possible to identify any radiation tolerant Ethernet interfaces. Ethernet connectivity is only available in the underground areas of the LHC that are shielded from radiation.

Operation and maintenance

Cumulative Radiation damage has been anticipated in most LHC control system designs. In some cases, the progressive degradation of electronic components due to cumulative damage will be measured during the annual shutdowns. On line calibration methods are also used at regularly intervals. Other equipment groups have set up specific methods for the management of spares. Either all spares are purchased at the same moment from the same production batch or a few randomly picked samples from a specific production batch are tested beforehand to decide whether the next batch can be accepted.

Single Event Errors are of more concern because they can occur any time when there are circulating beams. In contrast with cumulative radiation damage, replacement of the equipment is not a solution. Thermal protection circuitry against hard SEE has been used in some designs. Most designs based on complex devices mentioned above use watchdogs and a remote reset to be able to recover after a functional interrupt.

Another issue is the activation of electronic material in the tunnel. Electronics that fail during operation and have to be taken out and temporarily stored in area with no radiation. When the remnant activity is sufficiently low, the module can be send off for repair.

SUMMARY

Many controls electronics for the LHC machine will have to operate reliably in a mixed radiation field composed of various kinds of particles at different energies. At present, around 10.000 electronic crates are being installed under the cryostats of the main magnets in the LHC tunnel. These electronics will be subject to cumulative radiation damage and to single event errors induced by fast neutrons when the accelerator is operating.

Radiation tolerance has therefore been taken into account as a constraint in the design of the electronics and in the architecture, layout, integration and operation of control systems. For control systems that rely on commercial off the shelf devices, a selection based on radiation data is mandatory. It is also highly desirable to establish a good collaboration with the manufacturer.

Guidelines for the radiation tolerance assurance of electronics for the LHC machine have been established and are followed as close as reasonably achievable.

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