Electronics and their radiation tolerance for the control of the LHC machine

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Abstract

Approximately 20.000 electronic crates are presently being installed in the LHC tunnel and in the underground areas for the control of the LHC machine. During operation with circulating beams, many of these electronics have to operate in a complex radiation field dominated by fast neutrons in the GeV energy range. Radiation tolerance has therefore been taken into account as an engineering constraint during component selection, during the integration and in the design and architecture of the various control systems.

I. INTRODUCTION

The Large Hadron Collider (LHC) is technically more complex than any of the previous accelerators build at CERN and the physics operation margins are very tight. This has had a clear impact on the design and the integration of the controls electronics for the machine.

Many low-level controls electronics are located close to the beampipe to improve the signal quality to reduce cabling costs and to reduce Ohmic losses in the power cables. For example, there will be around 10.000 crates under the cryostats of the main magnets that contain the low level electronics for beam instrumentation (BPMs, BLMs), Quench Protection, Cryogenics, Power Converters (orbit correctors), Vacuum and magnet position Surveying [1].

There is a tendency to use complex programmable devices such as ASICs, EEPROM based CPLDs (Complex Programmable Logic Devices, SRAM based µprocessors or devices with flash memory. This makes the low-level control systems more flexible and allows for easy switching between operational modes (calibration, proton run, ion run). For example, all LHC power converters will be controlled by a custom designed digital controller [2] based on a HC16 microprocessor, a TI DSP and 8 Xilinx CPLDs of the 95000 series. The computing power is used to calculate the reference current signal for the magnets in real time, which makes the incorporation of feedback signals possible [3].

Finally, there is a preference for using complete COTS systems (Commercial Off the Shelf) such as those used in the automation industry. These eliminate the need for a specific custom development and may lead to overall reduction of costs. For example, the use of PLCs (Programmable Logic Controllers) in combination with digital or analogue remote I/O modules is presently envisaged for the Cooling and Ventilation system, the Electrical Distribution system, Interlocks, Vacuum and the RF system.

Finally, most electronic engineers prefer using the latest technology that has the highest performance, a high density of bits and low power supply voltage.

These trends in the use of microelectronics for the LHC machine have made the assurance of the radiation tolerance more complicated. In the complex radiation field in the LHC tunnel, all electronic equipment will degrade due to Total Dose Effects, Displacement Damage and Single Event Effects. However, already the scale of the LHC project excludes the use of specific radiation hard components such as those used in space or military applications. Most engineers therefore guarantee the radiation tolerance of their electronic equipment at the system level, using multiple identical circuit paths, error correction codes, latch up protection and robust power supplies. Some simple digital or analogue I/O modules without µprocessor can be used for the control of processes that evolve on a timescale of seconds (slow control) and that can tolerate an occasional soft or hard reset.

In this paper, an overview of the LHC machine electronics will be given. It will be shown how radiation was taken into account as engineering constraint in the design and the integration.

II. STANDARD CONTROLS ARCHITECTURE FOR MACHINE EQUIPMENT

The most common architecture for LHC machine control systems consist of two layers as shown in figure 1. A fieldbus network (WorldFIP, ProfiBus or CANbus) connects low-level electronics in the tunnel or in an underground area to gateways located in one of the surface buildings.

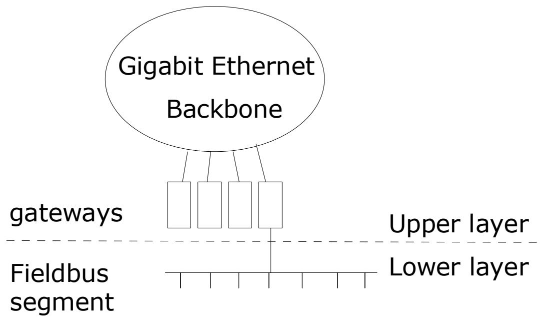

Figure 1: Two layered architecture for LHC machine controls.

The gateways are connected to the CERN gigabit Ethernet backbone which provide connectivity with the control room.

WorldFIP fieldbus is a popular choice for the control of the machine because the protocol allows for deterministic data traffic and the equipment interface has excellent radiation tolerance. Figure 2 shows the CC131 µFIP interface card that is used in many different electronics.

Figure 2: CC131 MicroFIP fieldbus interface at 1 Mbit/s.

The ASIC (VLSI) with the FIP protocol has 15 blocks of 8 bytes of SRAM based memory sensitive to SEU [4]. The SEU cross section of these registers is 1.10^{-9} cm^2 per bit and the TID tolerance is more than 600 Gy [Si].

Profibus and CANbus low level interfaces have also been tested on their radiation tolerances with similar results. In either case, the SRAM based registers were found to be sensitive to SEUs. but triplicate logic and "command-response" operation can minimise the propagation of radiation induced errors. This technique exists in storing data on a board in non SEU sensitive memory. Upon request (command), data is written at three different locations in the SRAM memory (triplicate logic) and immediately transmitted over the fieldbus (response).

Gateways are either VME based Power PCs, PLCs or industrial PCs. In order to avoid any problem with radiation, gateways are not placed in the tunnel but in the eight SR surface buildings, in the alcoves (REs) or at the bottom of the pits. This also facilitates installation and maintenance and gateways can be accessed when beam is circulating.

III. MODULAR POWER SUPPLIES

Modular power supplies are small power converters that can deliver up to 60 Watts (figure 3). They are used for the powering of electronics or complete electronic crates in areas with radiation but they also drive equipment such as the quench heaters in the main cryostats of the LHC. In total, approximately 12.000 power supplies will be installed in areas with radiation and this motivated an in-dept study of the radiation tolerance of these devices.

Most of these module use one of the three common technologies which are : switch mode power converter with bipolar technology and transformer coupling, switched mode power converter with a MosFET and transformer coupling or serial regulation technology.

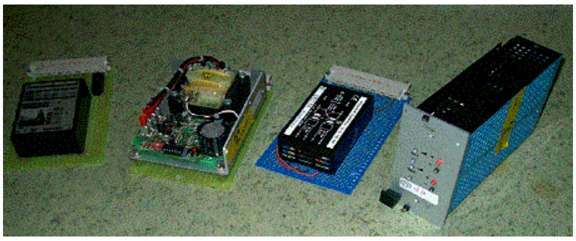

Figure 3: Examples of modular power supplies (60 W).

Input of the modules is 220 Volt and outputs are either 5±0.25 Volt (digital) or +12 Volt, +15 Volt, -12 Volt –15 Volt or ±0.5 Volt (analog).

Initial radiation tests showed that many standard COTS modules do not operate reliable in the presence of radiation. So far, a total of 43 units of 13 different types from 8 manufacturers have been tested on their radiation tolerance. Most power converters show damage and performance degradation due to cumulative effects. Figure 4 shows degradation due to displacement damage of a module that was operating under radiation in the complex radiation field of the LHC test facility.

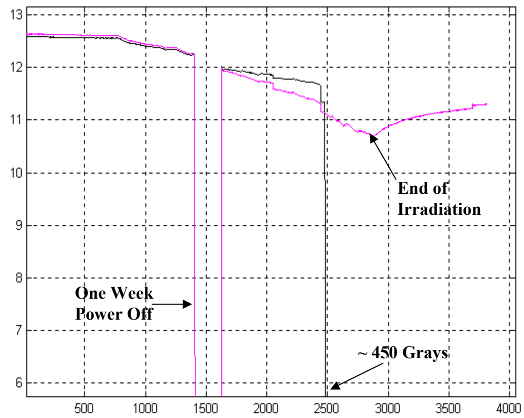

Figure 4: Output voltage (Volts) of LFE151K230 module (serial regulation, 50 mA load) as a function of time under irradiation.

have a rather large Single Event cross-section. Most radiation-induced errors were hard single events that destroyed the device.

A detailed study of the radiation tolerance of various suitable and commercially available modular power supplies started back in 1999. So far, remarkable good radiation tolerance has been observed on the SYKO ROS01.2205.15 (24V) and the Huhn Rohrbacher ACT 50 2 (24 V) STP6NB90 & 2SK2605.

In some cases, it was possible to collaborate with the manufacturer to modify single components to improve the SEU cross-section dramatically. For example, it was sufficient to change the MOSFET on the SIEMENS PS307 2A (24 V) to make it SEE free up to a total fluence of 10^{11} hadrons per cm^2 with energy above 20 MeV.

IV. MACHINE CONTROL SYSTEMS - EXAMPLES

A. Quench Protection System

The Quench Protection System protects the Main Dipole and the Quadrupole magnets via local quench detectors, quench heaters, cold bi-pass diodes and an energy extraction system [5]. Quench heaters are heating strips that are powered by the quench heater power supplies in case of a quench. There are 4 units per main dipole and 2 units per main quadrupole adding up to a total of 6200 units of which 6000 units have to operate reliable in a complex radiation field (required tolerance : TID – 200 Gy, NIEL – $2x10^{12}$ 1 MeV eq. Neutrons and SEE free).

Figure 5: Quench Heater power supplies for the LHC main dipoles

The components that are used in the system have been selected on their radiation tolerance. The performance under LHC like radiation of various candidate components was studied in the complex field of the LHC radiation test facility. The finally selected components include : aluminium electrolytic capacitors (4.7 mF/500V) NE556 bipolar timers & linear voltage regulators, the REF102 and LT1236 Voltage regulators, AD210BN Isolation amplifier and a particular type of plasma control thyristor (Semikron SKT80/18E).

The data acquisition part of the local quench detectors is based on the AduC812BS microcontroller and the µFIP interface at 1 Mbit/s described above. In combination with an external voltage reference, the AduC µconverter can operate reliable up to a TID of 650 Gy, $5.2x10^{13}$ 1Mev eq. Neutrons and $4.8x10^{11}$ high energetic (GeV) neutrons.

B. BLM/BPM system

The acquisition electronics for Beam Loss Monitors (BLM) and the Beam Position Monitors (BPMs) are housed in the same crates. Approximately 420 crates will be installed under the cryostats of the main magnets in the tunnel.

Figure 6: Electronics crate for the LHC BLM/BPM system. Right : WBTN card – Left : linear power supply and the calibration card.

The Wide Band Time Normaliser (WBTN) is the front-end electronics card for the BPMs [6] and has been deigned for high speed applications. The card is using wideband transistors (BFQ19, BFQ149), high speed diodes (BA592, HSMS2814) and ICs from the MC10EL family (coax, drivers, TTL, MUX, flip-flops and logic gates). The power supply for the crate is a linear power supply based on transformer coupling in combination with a LM 7805 and a LM 333T. The calibration card is based on Xilinx 9536 and allows to modify the operational mode of the BPM acquisition system.

Although Radiation test are still ongoing, first results have shown that the Xilinx CPLD and the voltage regulators are the most sensitive to radiation damage. The use of Radhard voltage regulators LHC4913 and LHC7913 is presently being investigated.

The Beam Loss Monitor acquisition system is based on a current to frequency converter with a very high dynamic range [7]. During operation, the BLM electronics reads out the current from the ionisation chambers that can vary between picoAmps and mAmps and that is translated into a signal with a frequency between 10^{-2} and 10^{-6} Hz.

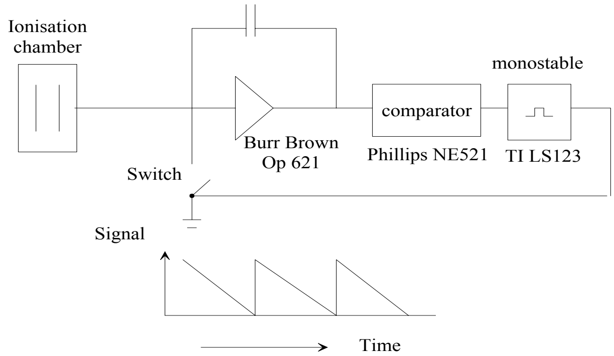

Figure 7: Schematic of the acquisition system for the LHC Beam Loss Monitors.

All components on the acquisition card (NE521 N Philips comparator, SN74LS123 BN monostable from TI, OPA627 AP from TI and the C130AA STJ 176 JFET from ST) were individually irradiated with a 60 MeV proton beam. No SEE was been observed but minor drifts due to cumulative damage effects (NIEL and TID) occurred after a TID of 140 Gy. Additional radiation tests are planned for later this year.

C. Power Converters for the magnets

The LHC will have more than 1700 power converters to drive the current in the magnets of which more than 1000 will have to operate in an environment with radiation.

Each power converter has a digital controller and a powering part and both require the use of various radiation sensitive elements. For example, in the power part (figure 8) there are isolated power supplies, transistors (logic and power), optocouplers and analog measurements.

Figure 8: Powering Part for the LHC orbit corrector magnets at 60 A,±8V

Initial radiation tests of the power part of the LHC orbit corrector power converters [8] showed that optocircuits and auxiliary power supplies are weak points and do not sustain more than a TID of 10-20 Gy and 1.6×10^{12} 1 MeV eq. Neutrons. In 2001, the powering part of three LHC pre-series orbit corrector power converters and their sub circuits were tested on their radiation tolerance. The inverter driver and the communications proved to be weak points in the converter power part while no significant degradation was observed in the sub circuits after a TID of 200 Gy in a mixed field.

The digital controller generates the current reference, performs the current regulation and monitors the power converter state [2]. The core of controller is based on two microprocessors : the Motorola M68HC16Z1CFC16 at 16 MHz and the Texas Instruments TMS320C32PCM40 at 32 MHz. These devices use external SRAM controlled by an EDAC (Error Detection And Correction) algorithm to avoid error propagation from Single Event Upsets in the SRAM. The EDAC circuitry is based on the IDT49C456A 32/64 bit commercially available chip.

Figure 9: SEU test of the digital controller for the LHC power Converters at UCL Louvain la Neuve (60 MeV protons)

Specific SEE radiation tests were carried out with a beam of 60 MeV protons, irradiating individual components on 3 different pre series controller boards. The measured SEU cross section of the registers of the HC16 is 5×10^{-15} cm^2 per bit while the registers of the C32 DSP chip have a SEU cross section of 2×10^{-14} cm^2 per bit. The SEU internal SRAM of both ICs is similar : 1×10^{-13} cm^2 per bit. The total dose limit of most components is more than 100 Gy [Si], which would provide sufficient margin for use in the LHC tunnel. Radiation tests in the LHC Radiation Test Facility are presently continuing.

V. Conclusions

The complexity and the performance of the LHC machine requires complex electronic components and systems close to the beam pipe. At present, some 12.000 electronic crates are being installed in the installed in the tunnel and the RR underground areas.

At either side of the high luminosity experiments CMS and ATLAS, fast neutrons will propagate several hundred meters downstream to degrade the electronics performance and reliability through SEEs. Interactions of protons with residual gas molecules create a complex field will degrade electronics in the regular parts of the machine (ARCs).

Radiation tolerance is considered as a constraint in the design and the conception of electronic boards. Radiation levels have also been taken into account during the integration. Although none of these preventive actions can eliminate the risk of irreversible radiation damage to the machine, they compromise between cost effectiveness, development time and system rliability.

Radiation tests in an LHC like environment have shown that standard COTS components with sufficient radiation tolerance can be found. In custom designs, classical SEU mitigation techniques such as triplicate logic, latch up protection and EDAC algorithms can reduce the Single Event Error rate to an acceptable level.

Many LHC control systems will be using complete COTS systems such as those used in the automation industry (such as PLCs, pressure valves or pressure gauges with integrated electronics). Large-scale radiation tests with participation of the manufacturer allowed identifying digital I/O modules that are sufficient radiation tolerant. Collaboration of the manufacturer combined with tight control over purchasing and spare management is recommended.

Finally, a detailed study of the radiation tolerance of power converters has been carried out. Suitable standard commercial modular power supplies (60 W) were found to power some 10.000 electronic crates in the LHC tunnel. Specific SEU radiation tests were carried out for the power converters for the LHC orbit corrector magnets (powering part and digital controller).

VI. References

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