ELECTRONIC COMPONENTS AND SYSTEMS, RADIATION QUALIFICATION FOR USE IN THE LHC MACHINE

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Abstract

Studies, taking into account the expected radiation doses for the different sections in the LHC accelerator tunnel, such as regular arcs and dispersion suppressors, show that electronic equipment can be considered for installation under the magnets [1,2,3,4]. An estimate based on work carried out for String 2, the LHC Magnet String Program [5], and extrapolated to the whole LHC machine gives a total of several thousands electronic crates to be housed under the magnets. This represents a substantial installation and a large expenditure.

In order to qualify electronic equipment for installation in the LHC tunnel, from its radiation hardness point of view at the dose levels considered, an on-line radiation test facility has been created and installed along a secondary beam line in the north experimental area of the SPS accelerator.

The object of this paper is to present the type of electronic equipment and systems planned to be installed in the tunnel of the LHC and to give some preliminary results on radiation tests made for this electronics.

1. THE REGULAR MACHINE LAYOUT

The complete machine layout is described in the Large Hadron Collider Conceptual Design document [6].

For the purpose of this paper and in order to simplify the presentation, we will only consider the regular arc and the Dispersion Suppressors (DS) regions; we will not discuss the Long Straight Sections (LSS), in the middle of which are installed the experiments at the Interaction Points (IP).

The LHC is made of eight arcs separated by insertions. Each of the eight arcs is composed of 23 arc cells, giving a total arc length of 2456 m. All arc cells are made of two identical half-cells.

The layout of an arc half-cell consists of a string of three 14.2m twin-aperture dipoles and one 3.10 m quadrupole separated from the string by 2.42 m. The separation between the dipoles is 1.46 m.

The two dispersion suppressor cells consist of four quadrupoles interleaved with four strings of two dipoles each. There is a total of 16 dispersion suppressors in LHC and their dipoles have the same length as in the arcs.

2. SPACE FOR ELECTRONICS

The LHC proton beams will circulate at 950 mm above the floor of the tunnel. Taking into account the actual size of the dipoles, of the quadrupoles and of the tunnel floor construction tolerance a height of 380 mm and a depth of 800 mm is available for electronic crates. Under each dipole and quadrupole space has to be left free for access to the supporting jacks and to allow access for the magnet transport system. A standard 6U crate with a 2U fan is accounted for a height of 350 mm, for a width of 600 mm with its support structure and for a depth of 800 mm including rear or front connections.

Work, initially carried out for the String 2 [7] and extrapolated to the whole LHC machine, has shown that several thousands electronic crates, or equivalent assemblies, can be housed under the supra conducting magnets.

Space has been allocated to the various data acquisition and control systems, the beam instrumentation, the vacuum, the cryogenics, the corrector power converters, the magnet protection equipment and to the controls. For each of the eight arcs the current estimation of the needs is given in Table 1.

Table 1: Estimation of the Number of Crates per Arc

Systems	Equipment Crates	Control Crates
Magnet Protection	724	208
Vacuum	54	27
Cryogenics		154
Corr. Power Converters		108
Beam Instrumentation	54 (F.E)	27
Controls		27
Total per Arc	**778**	**551**

3. ELECTRONIC EQUIPMENT

3.1 Housing of Electronics

The housing of electronic equipment and systems in the tunnel will have to be designed in such a way that their installation and removal can be done easily either by the owner of the equipment or by installation teams to which the work may be subcontracted. Considering the large number of crates, or equivalent assemblies, the positioning, the connection, the powering and the test in-situ should be as simple as possible and not require special tools.

Equipment located under the magnets at the floor level will have to be protected from shocks, from dust and must adequately be ventilated.

3.2 Type of Crates

The natural choice would be 6U and 3U Euro-Crates, as specified for VME and G64 mechanical standards, with an adequate ventilation. The choice is not limited to this type of crate. For example, complete assemblies of 5 crates are being studied to house four corrector power converters with the network connections and the power distribution located in the middle of this assembly.

As more and more complete industrial systems will be used to control the LHC other shapes of crates will also have to be integrated. One example is the use of electronic modules mounted on standard DIN rail. Industry provides a large choice for this type of equipment.

3.3 Programmable Logic Controllers

Industry offers a vast choice of Programmable Logic Controllers (PLC). These PLCs can be used for process control for the vacuum system, the cryogenics, the power distribution, the machine access systems, the cooling and ventilation systems. Since several years PLCs are also used for typical accelerator systems such as beam transfer equipment, beam extraction systems, beam target electronics and radiofrequency power generators.

For the controls of the LHC it is anticipated that PLCs will be used extensively for most systems. VME crates and modules or ad-hoc assemblies will remain the best choice for fast beam instrumentation and for very special systems.

In order to limit the diversity of PLC equipment to be used in LHC a study of the industrial offer has been made by an ad-hoc working group and a CERN recommendation for their use has been published, [8].

3.4 Input/Output Modules

Here again industry offers a large diversity of input/output modules for analogue and digital acquisition and control, for steeping motor control and for sensor interfaces. In addition, some special modules may have to be designed if they are not available commercially.

The mounting of these I/O modules is usually done on rails, conforming to the DIN standard, which can be housed under the dipoles, as explained above, or even be fixed directly onto the magnet’s wessel, close to the sensors.

4. NETWORKS

4.1 High Speed Networks

As Beam Instrumentation (BI) electronics must be installed close to the Beam Position Monitors (BPM) and to the Beam Loss Monitors (BLM) to provide measurements with the required precision, high speed point to point links to these BI crates will be required.

It has been decided to use point to point Ethernet segments for the high speed links available in the tunnel. Ethernet interfaces exist for all types of electronic crates, VME, VXI, G64, PCI, CompactPCI, PCs and also for industrial PLCs. In addition, the bandwidth provided by an Ethernet connection is also adequate for BI crates. The layout of the LHC tunnel requires Ethernet segments, of up to 800 m long, to be drawn between the 16 underground alcoves and the most distant BI crates located in the mid-arcs. Up to 12 Ethernet segments drawn to the left and 14 segments to right of each alcove are needed.

For 800 m point to point Ethernet segments and half-duplex transmission a good quality coaxial cable will be used to avoid intermediate electronic repeaters.

In order to provide each BI crate with the full bandwidth of 10 MBit/s Ethernet each alcove will house an Ethernet switch, thus providing a total bandwidth capability of up to 260 MBit/s per alcove. Under the floor of the tunnel, mono-mode optical fibres, laid in a drain, will link the 16 alcoves to the 8 Intersection Points (IP) where the experiments are installed. Gigabit Ethernet, ATM or SDH (the final choice remains to be done) will connect the 8 LHC points to the Central Control Room located on the CERN Prévessin Site.

4.2 Fieldbuses

A large variety of fieldbuses are offered by industry. A CERN working group has made a study of available fieldbuses. Taking into account the application of fieldbuses at CERN this working group has selected three standard fieldbuses and has made a recommendation for their use for the construction of the LHC machine and for its experiments, [9].

The use of only three fieldbuses has been recommended. Profibus and WorldFIP are preferred for the control of the machine for reasons of long distance transmission capability while CAN is the choice for the experiments.

Conceptually Profibus is a Command/Response fieldbus; like the MIL-1553-B which has been used extensively over the past 10 years for the control of CERN's accelerators.

Profibus is an industrial fieldbus well supported by a large number of manufacturers. Many interfaces exist for analogue and digital input/output modules, for stepping motor controllers, for sensors and actuators. Industrial PLCs, of different performance levels are available and provide all the necessary Profibus drivers and the development software facilities needed.

WorldFIP implements a Producer/Consumer concept in which a single command can be recognised and executed simultaneously by a variable number of consumers. Such a concept allows WorldFIP to offer real-time control capabilities. WorldFIP will be used for the transmission of the universal time and for the precise synchronisation of accelerator equipment.

WorldFIP is also an industrial fieldbus well supported by manufacturers but to a less extend than Profibus. WorldFIP will be used for controls applications where the real-time performance, the universal time distribution or the machine event synchronisation are required.

CAN implements a Producer/Consumer concept similar to that of WorldFIP, with in addition a priority access mechanism to the medium to resolve the contention problem. The drawback of this feature is that, for a given operation frequency, this medium access mechanism limits inherently the bus length.

CAN has been adopted for LHC experiments as it offers a large choice for protocol and interface chips which can be incorporated into dedicated electronic designs.

4.3 Real-Time Communication

WorldFIP and ATM channels are planned to be used as the real-time communication networks, [10].

For the control of the orbit stability of the two counter rotating proton beams it is currently proposed to implement a global feedback system; the sensors being the 972 BPMs and the 964 Correction Power Converters (CPC) being the actuators. The current plan is to implement a real-time beam orbit correction using a sampling rate of ten times per second, [11,12].

The beam position information, generated by the BPMs, will be pre-processed in the 248 BI crates. These crates will be connected to each private Ethernet segment and to WorldFIP fieldbuses, dedicated to BI. Every 100 ms, this BPMs real-time information will be sent to the central control room via WorldFIP fieldbuses and ATM transmission channels for computation. The new current reference values will then be sent down via ATM channels to each of the CPCs. All CPCs are connected to and controlled via another set of dedicated WorldFIP fieldbuses.

4.4 Machine Timing

The LHC machine equipment requires precise timing information, [13].

The most important timing is a precise universal time reference (Universal Time Co-ordinates, UTC) to synchronise all CPU clocks to better than a millisecond. To this purpose each of the 8 LHC access points plus the central control room are equipped with GPS antennas and reception equipment. The universal time reference is received and conditioned in commercially available VME modules and is locally distributed to all systems which need this time reference.

From each intersection point the GPS time is propagated both sides to the adjacent alcoves, distant of 943 m, via the Inter-Range Instrumentation Group (IRIG-B) standard transmission cable. In alcoves the IRIG-B signal is regenerated and made available to time-stamp local data acquisition and controls.

The magnet quench protection system, for example, will generate over 4000 possible inputs to the beam dump trigger system. In order to perform meaningful post mortem analysis, all related systems actions will have to be time stamped. Due to the uniform distribution of the major systems throughout the LHC complex, it will be essential to use the GPS as the source of time reference.

4.5 Beam Synchronous Timing

A Beam Synchronous Timing (BST) distribution is required by BI equipment to identify particle bunches. This BST information will be derived from the 40 MHz bunch clock, from the 11 kHz turn clock and from the machine events. The BST information is created in 24 stations (16 alcoves and 8 IPs) and distributed to all the beam instrumentation crates installed in the tunnel.

5. RADIATION QUALIFICATION

Before installation in the LHC tunnel, electronic equipment and systems must be fully tested and qualified for standing the radiation levels to which they will be exposed, depending on their position along the collider.

The absorbed dose levels have been calculated to be of the order of 1 Gy per year under the middle dipole of a regular half-cell and of 12 Gy per year under the Short Straight Section (SSS) quadrupole at a distance of 700 mm from the proton beams [1,2,3,4]. At such dose levels, no major radiation-damage problems are to be expected, and designers plan to use Commercial Off The Shelf (COTS) electronic components and systems.

5.1 CERN On-Line Radiation Test Facility

In order to do systematic radiation tests on to qualify all electronic equipment to be installed in the LHC machine tunnel, CERN has decided in 1998 to create a radiation test zone in one of the Super Proton Synchrotron (SPS) north experimental areas. A test zone, was settled along a secondary beam line of the SPS accelerator, some 100m downstream of a particle-conversion target (T6).

This radiation test area, fully operational since the start-up of the SPS in March 1999, provides all the required facilities: high power electrical supply for the test of power converters, compressed air for the test of pneumatic electro-valves, radio communication, video observation, CAN, Profibus and WorldFIP fieldbuses, connections to the accelerator control network and to the office LAN. In addition, numerous coaxial and twisted pair cables for analogue and digital signals have been laid between the radiation test zone and the local control room distant of some 200 m. In the local control room experimenters have installed their PCs, workstations and measurement instruments for the monitoring and the remote control of their experiment, if necessary. Some systems have been connected from this local control room to the general CERN office LAN, thus providing the experimenter with all the facilities needed to monitor and control his experiment from his office.

5.2 Irradiation Conditions

A 400 GeV-proton beam hits a metallic target (T6), muons are collected downstream and guided toward physics experiments. The radiation field around such target is typical of a proton accelerator; it includes mainly gammas and neutrons, plus some high-energy particles. The gamma spectrum extends from a few hundred keV to several hundred MeV, but is mainly between 1 MeV and a few MeV. The neutron spectrum is about the same, but it also includes a large quantity of low-energy neutrons thermalized by concrete shielding. The presence of other particles is very low, but it is not excluded that some hadrons (protons, neutrons, pions) and muons of high energy create particular effects in digital electronics. The radiation field is characterised by means of passive solid-state dosimeters and active semi-conductor dosimeters [14]. Measurements show that the radiation field is not homogeneous, neither in intensity, nor in nature; the weekly absorbed doses vary between 10 to more than 50 Gy, depending on the location, while the neutron fluences (1 MeV equ.-Si) vary from 10^{11} to 2.10^{12} n.cm^{-2}, moreover the neutron spectrum also changes.

CERN radiation experts recognise that these irradiation conditions are similar to those that will exist in the tunnel of the future LHC where the dose-rate and the neutron spectrum will also change from place to place.

5.3 Radiation Monitoring and Calibration

From 1999, on-line monitoring of the radiation doses, to which the equipment is exposed, is available in the local control room and on the Web. The test zone has a surface of some 8 square meters. The monitoring of the dose rate is done by four ionisation chambers (3 litres of air), located at each corner of the test zone at a height of 800 mm (= beam height). These monitors are connected to the CERN radiation monitoring system, “ARCON”. The radiation data is stored in the central ORACLE Data-Base which can be consulted at leisure by the experimenters to retrieve historical data and to correlate it to the results obtained from his experiment. The doses are stored day after day, every hour and the data is kept at disposal for several years.

In addition, the absorbed doses are also integrated by passive solid-state dosimeters (polymer-alanine, radio-photo-luminescent glasses, and MOS dosimeters). The measurement of the neutron fluence uses the activation technique (radioactive isotopes are created in metals) and silicon PIN diodes. After exposure, these dosimeters are regularly exchanged and measured; the latter are measured in the laboratories of the French Atomic Energy Commission (CEA) in Valduc.

5.4 Tested Material

In 1998, passive radiation-tests have been done on some electronic components and systems during three distinct irradiation campaigns, where doses of 20 Gy, 50 Gy and 140 Gy have successively been reached. After each irradiation campaign all the material was taken out, let cool-down and tested to check its correct operation. If still operational the same samples where then exposed again for the next irradiation campaign. The total integrated dose has been close to 220 Gy and the neutron fluence was of the order of 2e12 n.cm^{-2} (eq.1MeV-Si). The tests included industrial Programmable Logic Controllers from various manufacturers, electronic modules conforming to the VME and G64 Bus Standards, Fieldbuses like Profibus, WorldFIP and CAN, Power Supply equipment and Components used for the LHC Cryogeny [15].

In 1999, new electronic components and systems have been included in the irradiation programme such as digital positioners, quench protection equipment, additional CAN, Profibus and WorldFIP interfaces, industrial PLCs, power converters, optical fibres and data-transmission equipment, fire and gas detectors, etc… [16].

5.5 Preliminary Results

In 1998, the lack of proper infrastructure in the area allowed only passive tests to be carried out. During the three campaigns of passive tests some components, mainly opto-couplers, analogue to digital converters and some PLC input/output modules showed loss of functionality.

This year, the zone was fully equipped for on-line radiation tests and the irradiation campaign has started in May. The target doses are of the same order as last year but the material under test remains permanently under irradiation unless a failure appears. In this case the sample is taken out, let cool-down and then is analysed to identify the defective component(s).

In 1999, after a few weeks of irradiation, having reached dose levels between 20 and 200 Gy, and neutron fluence of the order of a few 10^{12} $n.cm^{-2}$ (1MeV equ.-Si), the measurements show disquieting results for some components and promising results for other ones.

Some type of opto-coupler degraded progressively right from the beginning of the irradiation; the CTR dropped to less than 20% at 20 Gy. Another opto-coupler model still continues to work properly after a dose of 100 Gy showing a CTR derating of only 5%, [17].

Within the framework of the protection system for supra conducting elements different kind of electronic devices have to be qualified with respect to radiation tolerance. The irradiation tests started with the main components of quench heater power supplies, aluminium electrolytic capacitors and phase control thyristors. The different type of thyristors passed the ongoing tests up to a received dose of about 55Gy (=$5.5.e10^{15}ncm^{-2}$) without any functional degradation, whereas some of the tested capacitors showed a significant increase of the leakage current. The measured DC capacitance remained constant for all tested specimens, [18].

For the cryogenics electro-pneumatic positioners valve have been tested in passive mode last year at up to 220 Gy. This year, they are remotely controlled using compressed air to energise them; their movement can also be observvwed by means of a remote CCD camera and a video monitor situated in the local control room. The detailed analysis of the results has been published in a report, [19].

The PLCs and associated Profibus fieldbus equipment could not be effectively tested, because their operation was controlled and driven by a RAM memory which was corrupted after only a few hours in operation. A new experimental set-up has now been placed into the test zone it comprises only simple I/O modules and Profibus interfaces.

Good results were obtained from two experiments using a total of six WorldFIP Fieldbus interfaces with MicroFIP protocol chips. A continuous write/read/compare operation showed only one single error since the beginning of the irradiation campaign.

All six interfaces still operate today with some 300 Gy total integrated dose.

Memory tests have been done with different types of memory chips mounted on a VME PowerPC board. Continuous write/read/compare operation showed:

- DRAM 512 Kbytes, up to 25 Gy, no error,
- EEPROM 512 Kbytes, up to 25 Gy, no error,
- NVRAM 8 Kbytes, during 21 hours up to 10 Gy, 7 errors,
- SRAM 512 Kbytes, exposed during 61 hours up to 4,5 Gy, 652 errors and then during 143 hours up to 10 Gy, 1863 errors.

Three standard VME power supplies, well known and used in large quantities since many years at CERN, broke down very rapidly. The first after 250 hours with a dose of 14 Gy, the second after 126 hours with a dose of 10 Gy and the third after 6 hours with a dose of less than 0.3 Gy. All three showed the same fault: a power MOSFET transistor breakdown, probably due to single event failures.

For the cryogenic system, the high-precision resistors and the associated capacitors used in the construction of conditioners for thermometry have undergone successfully the radiation tests; only a tiny fraction of a percent deviation has been noticed, [20].

No errors have been detected in the Actel antifuse-based FPGAs, an error rate of 2 to 10 bit-error per day has been measured in the HP G-link, which makes both of these components suitable for use at the dose rate and fluences of the LHC, [21].

Tests on a 200 meter fibre cable, containing 12 mono-mode fibres and 12 multi-mode fibres, have been done. As expected, the multi-mode fibres showed an attenuation of some 50db per km while the mono-mode fibres only a loss of 8 dB per km at a dose of 80 Gy.

The CCD camera degraded progressively, the number of white spots increased continuously, at 25 Gy the picture was still visible but at 30 Gy the camera stopped working. This camera has been replaced by a new one.

The GSM repeater, used for mobile telephones, revealed a degraded operation at 20 Gy and went out of operation at 30 Gy.

The fire and gas detectors which have been exposed went faulty at 20 Gy and 25 Gy, respectively.

Analogue and digital telephone equipment went definitely faulty. An RNIS bus did not reply anymore after some 15 days operation having received a dose of some 30 Gy.

5.6 Improvement Plan for the On-Line Radiation Test Facility.

Following the first year of exploitation of this on-line radiation test facility experimenters have expressed their wish for some improvements.

In particular a radiation protected zone is needed to install the responder modules, power supplies and some measurement equipment. This will be possible in a gallery perpendicular to the present beam lines. Sample measurements have shown that a radiation dose ten times lower than in the active zone can be guaranteed in that place.

In order to better understand the tests results some experimenters would like to know the particle composition of the beam, the energy spectrum of the particles, the geographical in-homogeneity of the beam and the reliability of absolute calibration of the radiation measurements.

A study of these requirements is being done and an improvement plan of the on-line radiation test facility is being drawn-up and will be discussed with the experimenters. The implementation is planned to be done during the next winter shutdown of the SPS accelerator.

6. CONCLUSIONS

At the time of publication we have several preliminary radiation results on electronic components and systems to be installed in the tunnel of the LHC machine.

More statistic is needed but experimenters can already draw some conclusions for their particular application. Identification and replacement of sensitive components will improve the radiation hardness of this electronic equipment.

These preliminary results demonstrate clearly that testing and qualification of all COTS electronic equipment for the machine will be necessary, despite the low level of radiation expected in LHC tunnel.

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8. REFERENCES

[1] K.M. Potter, H. Schönbacher, G. R. Stevenson, “Estimates of Dose to Components in the Arcs of the LHC due to Beam-Loss and Beam-Gas Interactions”, LHC Project Note 18, November 24, 1995.

[2] M. Tavlet, “Radiation Environment around High-Energy Particle Accelerators and in Physics Detectors”, Radecs'94, L'Onde Electrique, Vol.75, No 3, 1995.

[3] L. Coull, R. Schmidt, T. Spickermann, “Beam Losses, Radiation Dose and Electronic Equipment in the LHC Arcs”, LHC Project Note 109, September 26, 1997.

[4] K. Wittenburg, R. Schmidt, T. Spickermann, “Radiation Dose for Equipment in the LHC Arcs”, LHC Project Report 274, February 11, 1999.

[5] R. Saban et al., “The LHC Magnet String Programme: Status and Future Plans”, LHC Project Report 279, presented at PAC99, March 29 – April 2, 1999, New York, USA.

[6] The Large Hadron Collider Conceptual Design, The LHC Study Group, CERN/AC/95-05 (LHC) October 20, 1995.

[7] R. Saban, “Space requirements under the dipoles” CERN Internal Notes, September to December, 1998.

[8] R. Rausch et al., “Recommendations for the Use of Programmable Logic Controllers (PLCs) at CERN”, CERN-SL 98-007 (CO), April 1998.

[9] G. Baribaud et al., “Recommendations for the Use of Fieldbuses at CERN”, CERN-SL 96-58, June 1996.

[10] P. Ribeiro et al, “ A large Scale Flexible Real-Time Communications Topology for the LHC Accelerator”, 11th IEEE, NPSS, Real-Time Conference, June 14-18, 1999, Santa Fe, New Mexico, USA.

[11] Q. King et al, “Developments in the High Precision Control of Magnet Currents for LHC”, LHC Project Report 293, PAC’99, March 29 – April 2, 1999, New York, USA.

[12] C. Bovet, H. Schmickler et al, “LHC Beam Instrumentation” CERN SL-99-015 BI, PAC’99, March 29 – April 2, 1999, New York, USA.

[13] G.Beetham and J.B. Ribes, “GPS Precision Timing at CERN”, CERN SL-99-011 CO, PAC’99, March 29 – April 2, 1999, New York, USA.

[14] M. Tavlet and M. E. León Florián, “Dose and Neutron-Fluence Measurements in mixed Gamma-Neutron Fields by Means of Semi-Conductor Dosimeters”, Radecs'93, IEEE Cat. N° 93TH0616-3, pp 27-32,1994.

[15] R. Rausch and M. Tavlet, “Radiation Test Programme on COTS Components needed for the Large Hadron Collider at CERN”, Radecs'98.

[16] L. Adams, Brunel University, UK and P. Jarron, R. Rausch, M. Tavlet CERN, CH, “COTS Needs for the Large Hadron Collider and Detectors at CERN”, Los Angeles, February 7-10, 1999.

[17] H. Burkhart, B. Hallgreen, “Front-End I/O via CAN Bus of the ATLAS Detector Control System” LEB98 Workshop, 21-25 September 1998, Rome, Italy.

[18] F. Rodriguez-Mateos, R. Denz et al., “The Protection System for the Superconducting Elements of the Large Hadron Collider at CERN”, LHC Project Report 283, PAC’99, March 29 – April 2, 1999, New York, USA.

[19] R. Trant and W. Hees, “Evaluation of Electro Pneumatic Valve Positioners for LHC Cryogenics”, LHC Project Note 100, May 17, 1999.

[20] J. Casas, “Preliminary Test for Radiation Tolerant Electronic Components for the LHC Cryogenic System”, LEB99 Workshop, 20-24th September, 1999, Snowmass, Colorado, USA.

[21] Z. Meggyesi, “FPGA Design in the Presence of Single Event Upsets”, LEB99 Workshop, 20-24th September, 1999, Snowmass, Colorado, USA.