Rad-tol Field Electronics for the LHC Cryogenic System

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***Abstract*: The field electronics for the LHC cryogenic system will be subjected to neutron and gamma radiation. Its baseline design is based on COTS and a DMILL ASIC. The COTS include anti-fuse FPGA's, WorldFIP fieldbus interface and discrete integrated circuits.**

***Index Terms*: Accelerator control systems, Total Ionising Dose, Single Event Effects, Single Event Upset, Latch-up, WorldFIP.**

I. Introduction

THE instrumentation for the future LHC (Large Hadron Collider) cryogenic system will be exposed to harsh environmental conditions: residual radiation produced by the LHC machine circulating proton beams, thermal management problems, humidity, electromagnetic perturbation, etc. In addition the high accuracy and precision impose low parameters dispersion between the electronic cards that measure the same thermodynamic variable. Table I shows the measurements uncertainty requirements versus the machine main magnets temperature.

Space or military electronic technologies are incompatible with the budget of the project but on the other hand it will be possible to replace defective components during routine maintenance campaigns. Within this framework, we are obliged to use Commercial Off The Shelf (COTS) electronic components that have been previously qualified for operation under radiation.

The radiation levels expected inside the LHC tunnel depend on the location. They will be 4 to 10 Gy(air) and $2\cdot10^{12}$ n·cm^{-2} per year along the regular arcs where the beams are steered by a dipolar magnetic field and are not subjected to head-on collisions, the arcs length represent over 80 % of the LHC total circumference. Around interaction or cleaning points the dose will exceed 1000 Gy(air) and $5\cdot10^{14}$ n·cm^{-2} per year [1].

TABLE I: MEASURE UNCERTAINTY REQUIREMENTS VERSUS TEMPERATURE

Temperature Range (K)	Uncertainty (K)
1.6 - 2.2	± 0.01
2.2 - 4.0	± 0.02
4.0 - 6.0	± 0.03
6 - 25	± 1
20 -300	± 5

The system is designed to work with moderate radiation levels (100 Gy (air)) and will be "radiation tolerant" grade. This paper presents the global system design and the validation tests performed on different devices and subsystems. Design strategies to mitigate SEE (Single Event Effects) due to high energy particles interacting with the digital devices are also discussed.

II. System Architecture

Fig. 1 shows the system architecture for measurement channels. The main components are a front end implemented in a radiation-hard ASIC, 16-bit ADC, anti-fuse FPGAs and a communication fieldbus interface. The system is modular and can have up to eight 2-channel input cards interfaced with a single communications card. The maximum number of channels is 15 and this number is imposed by the memory size embedded in the fieldbus interface.

The FPGAs are used to emulate operations typically found in microprocessors and to multiplex digital signals. To increase the FPGAs radiation tolerance the operations are done in triplicate logic. The analog signal conditioning is adapted to the sensors that will be used in the LHC cryogenic system, mainly variable resistance type thermometers (T) and resistive bridge pressure transducers (P).

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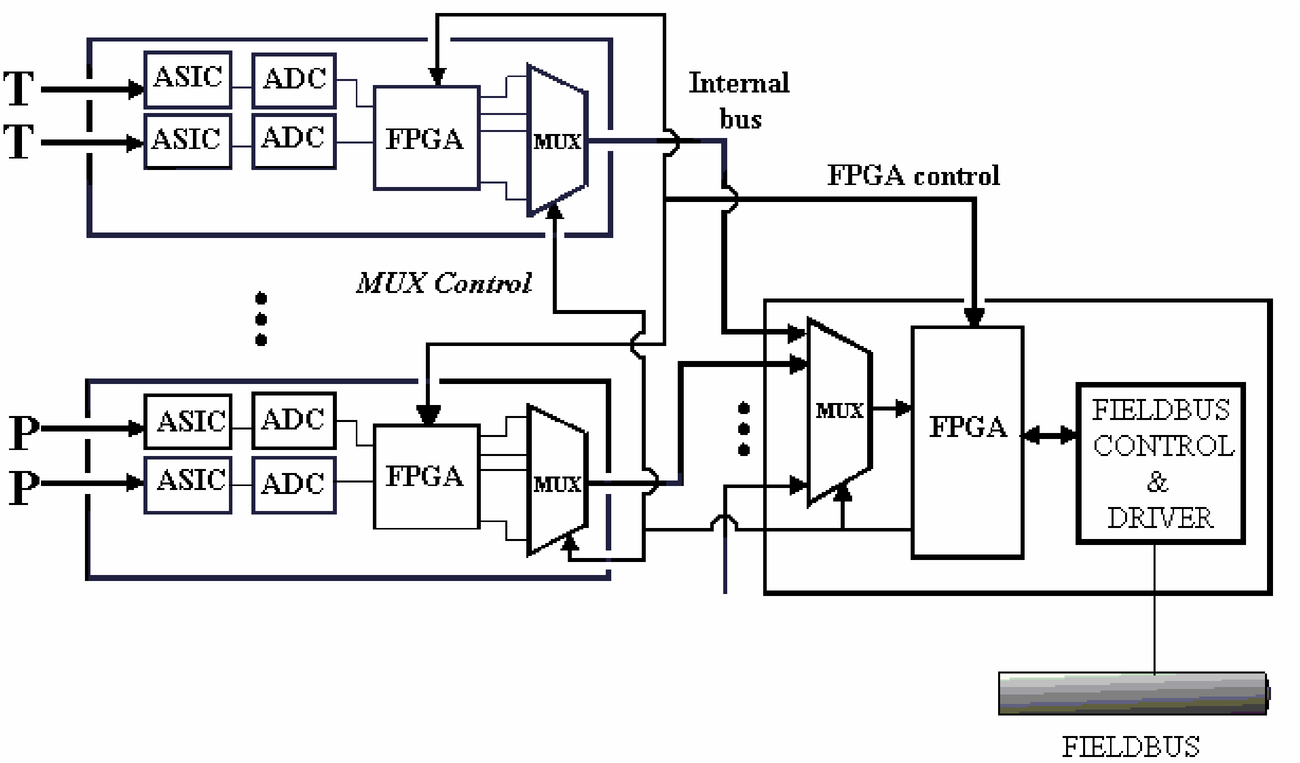

Figure 1: System architecture

The system is auto-calibrated by using a high precision and low thermal drift (10 ppm/K) thin film NiCr resistor every time a variable measurement is taken. The resistor is almost insensitive to the LHC machine environment including the radiation. With this technique we are able to correct, up to a certain limit, the radiation and ambient temperature effects on the electronic devices and thus avoid the use of potentiometers (which are always a non-negligible additional cost to the system due to the calibration protocol).

Fig. 2 shows the auto-calibration procedure for a thermometric sensor. An AC current $I_{+/-}$ is sent to the sensor and the reference resistor that is connected in series. The direction of the current can be changed. An analog switch *CK1* selects the thermometer or the reference resistor. Finally, the voltage drop at the resistive element is amplified by a differential amplifier of gain *G*.

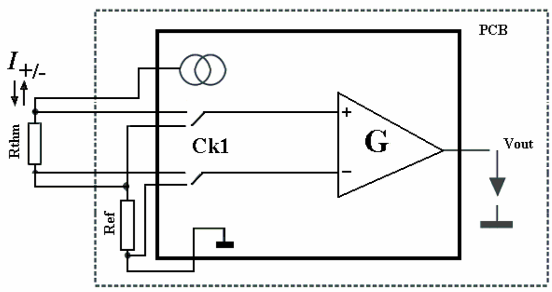

Fig. 2: Auto-calibration procedure

This way, the ASIC can do four different measures: The reference voltage, the sensor voltage with positive an negative sense of current. The value of these voltages is calculated as:

$$\begin{aligned} V_{Rthm+} &= V_{ERR} + G\cdot(I\cdot R_{thm} + V_{th}) \\ V_{Rthm-} &= V_{ERR} + G\cdot(-I\cdot R_{thm} + V_{th}) \\ V_{REF+} &= V_{ERR} + G\cdot(I\cdot Ref) \\ V_{REF-} &= V_{ERR} + G\cdot(-I\cdot Ref) \end{aligned} \qquad (1.a\text{-}1.d)$$

V_{ERR} is the output offset of the system, *G* is the differential amplifier gain, *I* the excitation current, R_{thm} the thermometric resistance, *Ref* the reference resistor and V_{th} the voltage due to the thermocouple effect. The thermometric resistance is calculated by using the equation (2):

$$R_{thm} = \frac{V_{Rthm+} - V_{Rthm-}}{V_{REF+} - V_{REF-}}\cdot Ref \qquad (2)$$

With (2) the thermocouple effects and the offset are automatically corrected. The calculated thermometric resistance depends on the current source stability but not on its precision. The variability of radiation performances within and between productions batches has been taken into account in the design by adding security margins.

Fig. 3 shows the measured temperature of 5 thermometers and the deviation versus the reference thermometer. The dashed lines represent the tolerance imposed by the uncertainty requirements.

III. Component Selection

The selection of components has included when possible designs already qualified for radiation environments and otherwise COTS have been selected according to data found

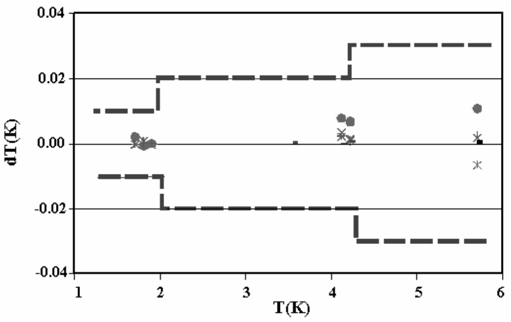

Fig. 3: Temperature measurements on 5 different thermometers. Dashed Line: uncertainty tolerance.

in the literature and our own radiation qualification campaigns.

Radiation hardened components include the sensors' front-end ASIC made with DMILL technology and a voltage regulator, LH 4913, developed by CERN and fabricated by ST microelectronic.

Anti-fuse FPGA's made by ACTEL are used to perform all digital operations. The fieldbus interface is a Microfip C-131 card made by Alsthom, which implements the WorldFIP fieldbus communication protocol. This communication card uses a signal transformer instead of optical insulators that are commonly found in other fieldbus products like profibus. This is one of the main reasons for the excellent immunity against radiation that was reported at CERN during the first irradiation campaigns. The ADS7807 converter, a commercial successive approximations 16 bits ADC by Texas Instrument Inc., was selected after evaluating various candidates (using fast bipolar technologies, successive approximation techniques, etc).

IV. RADIATION QUALIFICATION

Radiation tests have been performed on electronic devices and subsystems in order to study their behavior in terms of total dose (TD) and SEE against different type of particles mainly neutrons, gamma rays and protons. The neutron tests are performed by the Universidad Complutense de Madrid (UCM, Spain), at the ITN experimental reactor in Lisbon, Portugal. Information concerning these tests can be found in [2-4]. SEE on the digital devices, the ADCs and the communication system (including their dynamic memory) are investigated by using the cyclotrons of the Université Catholique de Louvain (Belgium) and of the PSI facility in Villigen (Switzerland). The system is validated at TCC2 area (a CERN test facility which is assumed to represent in terms of total dose and energy spectrum, the LHC radiation environment).

A. SEU Tests

The communication card Single Event Upset error cross section is experimentally estimated to be $s = 104 \times 10^{-12}$ errors·cm^{-2} [5]. To increase the SEU rate, the communication card was refreshed only after detecting corrupted data. The cross section estimation is based in a method proposed in [6]. A 60 MeV proton beam with an intensity of $2{\cdot}10^8$ p·cm^{-2}·s^{-1} was used. The SEU probability is roughly independent on the proton energy above 40-50 MeV and we can assume that the SEU cross section is proportional to the sensitive volume of the devices. Fig. 4 shows the variation of the SEU cross section as a function of the critical energy (E_{CRIT}) and the sensitive volume (SV) size [6]. A shift from "0" to "1" were found in a 97% of the detected SEU.

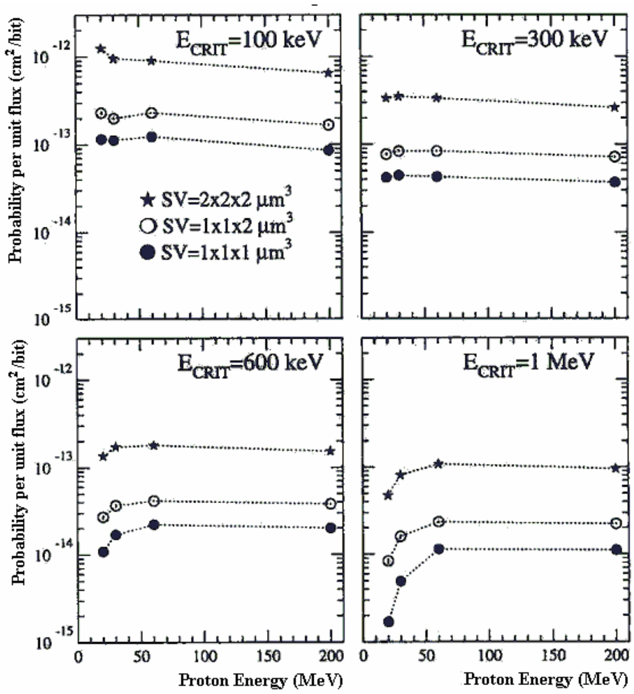

Fig.4: SEU cross section as a function of E_{CRIT} and SV size

To increase the radiation hardness the overall system implements dynamic memory refreshment strategies and all the microcontroller logic is done in triplicate by using an anti-fuse ACTEL FPGA. This device compares three digital words and selects that one that is repeated. Therefore, a corrupted data can be detected and rejected by this voting system. It is very unlikely that two words were simultaneously corrupted so the system tolerance increases. Some simulations have shown that the number of errors per year in the cryogenic system will be 7188 if no protection strategy is used. Nevertheless, it would be reduced to 0.1 errors per year if they are used. As expected no SEU is detected in the protected system with the same beam conditions when performing error cross section measurements.

Finally, no SEU was detected in the ADC converter in the same beam conditions.

B. Tests on Total Ionising dose

The effects of TID were analysed mainly in the CMOS devices: ADCs, FPGAs and communication cards. A 60 MeV proton beam induces a high ionisation dose in a short period of time on the Device Under Test (DUT). It is useful to study leakage current effects, and to perform destructive tests to estimate the lower TID boundary (because the short irradiation time prevents self-healing of the device by annealing).

Fig. 5 shows the increment on current supply versus TID on board tests with most important devices obtained at both the UCL and PSI cyclotrons. The supply current does not change up to 125 Gy. Then, it shows a great increase and the highest value is reached at 350 Gy. Though it decreases a little before becoming independent on the TID, the supply current is about four times the initial value. A direct consequence of the increase of the consumption is the growth of operation temperature and the diminution of the expected lifetime of the component.

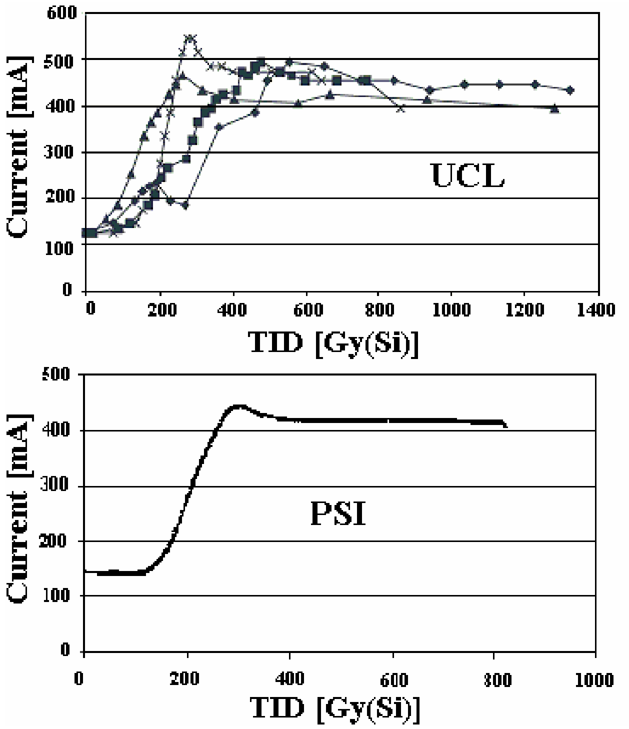

Fig. 5: Current increment of test board s*vs* TID

Seven communication cards have been tested and the results are qualitatively identical in what concern TID effects. They tolerate at least 700 Gy. On-board detection and error correction algorithms will not be implemented in the final LHC system because the refreshment strategy has demonstrated to be good enough.

The temperature measurement uncertainty requirements impose the use of an ADC with a minimum precision of 14-bit. A commercial successive-approximation 16-bit ADS7807 converter has been selected after radiation tests performed on it. Fig. 6(a) shows the degradation of the calculated sensor resistance (1) as a function of the TID and the resistor sensor value, when the ADC and their control FPGA are irradiated with the proton beam.

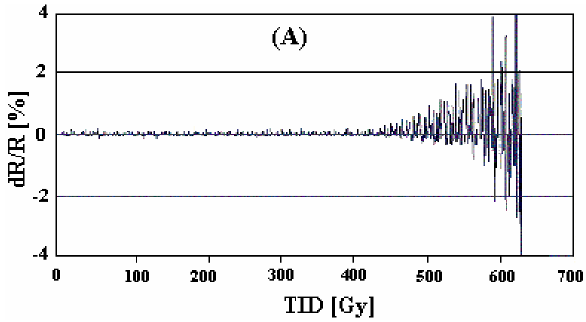

Fig. 6: (a) Uncertainty induced by ADC digitations

The figure 6(b) shows the current consumption increment induced by both elements on the system. It is important to remark that no SEU were detected.

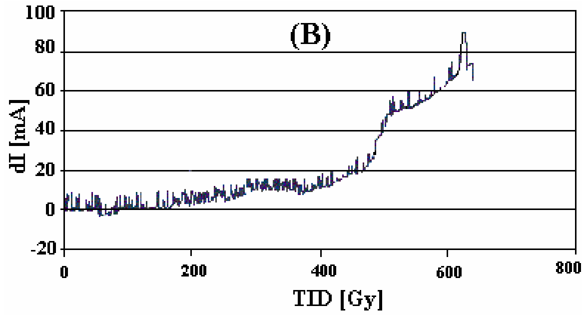

Fig. 6 (b): ADC and its associated FPGA current consumption

C. *Displacement damage by neutrons*

The most sensitive device is the ADS7807 A/D converter. The failure cause is that it has an internal voltage reference whose output value is affected by neutrons (Fig. 7). Therefore, when using its internal reference it fails at very low neutron fluence, but when using an external reference it survives up to $5 \cdot 10^{13}$ n·cm^{-2}.

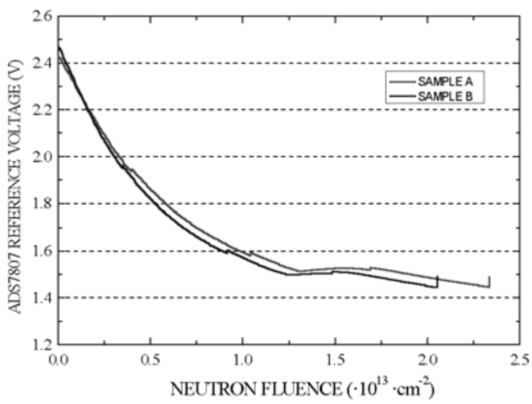

Fig. 7: ADS7807 voltage reference vs. neutron fluence

The ASIC provides two voltage references, with output values of 1.2 and 2.5 V. Some neutron tests have shown that these references can tolerate a neutron fluence up to 10^{14} n·cm^{-2} (figs. 8-9) and it can be used as the converter reference.

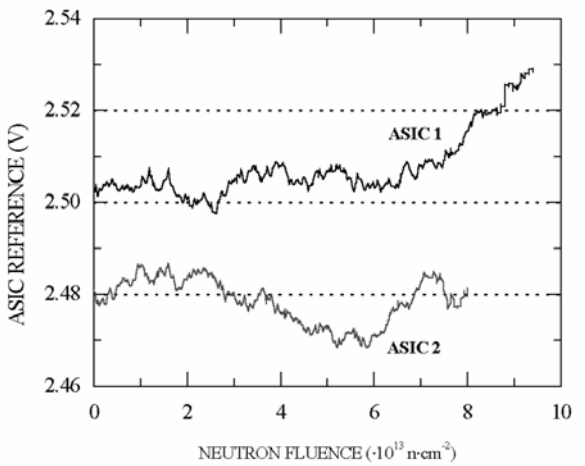

Fig. 8: ASIC reference voltage. Two samples were tested.

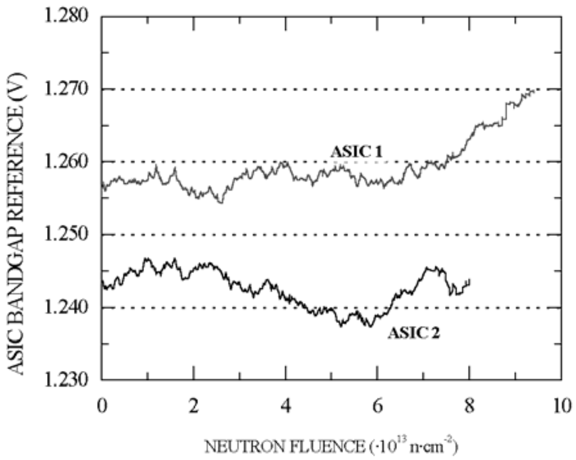

Fig. 9: ASIC bandgap reference

Moreover, neutron tests were carried out on some useful devices. As expected, high accuracy resistors can tolerate neutron fluences up to 10^{14} n·cm^{-2}. Also, commercial rad-tol instrumentation & operational amplifiers were found (INA111, OPA627). Finally, these tests showed that the AD565 D/A converter could work with an external reference up to $5 \cdot 10^{13}$ n·cm^{-2}. These devices are made in bipolar technology and so they are TID tolerant enough. These tests are widely explained at [2]-[6].

I. CONCLUSION

The main electronic sub-systems for the LHC cryogenic system are presented. The most fragile component is the 16-bit ADC that for two samples exhibited a survival dose of TID 500 Gy. For most of the LHC tunnel this yields a usable lifespan of 10 years.

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