On line radiation monitoring for the LHC machine and experimental caverns

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Abstract

With an unprecedented amount of electronic systems exposed to radiation, reduced operational efficiency due to radiation induced failures in electronic equipment has become a serious issue for the LHC. The RADMON radiation monitoring system presented here has been designed to measure radiation at the location of equipment and to provide an early warning as radiation levels start to increase. Nearly 300 monitors will provide on line measurements of the dose, dose rate, particle flux and particle fluence. The data can be visualised in real time in LHC control rooms and is stored in a database at a rate of 1 Hz. It will be shown that the system allows studying the spatio-temporal distribution of the radiation fields in the LHC.

I. INTRODUCTION

Radiation tolerance assurance of equipment has become a serious issue for the LHC. The LHC will operate with very high stored energy in the beams and a large amount of equipment in the vicinity of the beams will be exposed to radiation. Throughout the years there has been a growing awareness that radiation tolerance needs to be taken into account as an engineering and operational constraint in the LHC design [1]. This resulted in, for example, the reinforcement of radiation shielding, optimised integration of tunnel electronics and the widespread use of radiation tolerant electronic components and materials.

Radiation monitors were proposed in 2003 [2] with the aim to measure radiation at the location of the equipment and to evaluate the performance of technical equipment under irradiation. The monitors measure three components of a complex radiation field independently which allows to separate between the three different radiation damage effects. Experience from other proton colliders [3] had shown that monitoring is indeed very useful to characterise radiation induced failures, to provide insight into the way the machine is operating and to measure the efficiency of the shielding structures.

At present, a total of 284 monitors are being installed in the LHC of which 35 are located in the experimental areas and 249 in the LHC tunnel and the underground areas. The monitors are radiation tolerant to 200 Gy TID and can operate in a magnetic field inferior or equal to 4.6 kGauss. Each monitor has a total of 9 radiation sensors on board : 2 radiation sensitive p-channel MOSFETs ('Radfets') from NMRC [4] to measure the total ionising dose (TID), 3 photodiodes in series to measure the 1 MeV equivalent neutron fluence and 4 x 4 Mbit of static RAM to measure the hadron flux for hadrons with an energy above 20 MeV.

The controls architecture for the radiation monitoring system is using the accelerators controls standard [5] which is based on a three tier architecture, common for present day industrial J2EE applications. The gateway software has been developed in the FESA software development environment [6] for LHC front-end computers which is supported and maintained by CERN. During normal operation, data is send at a maximum rate of 80 Hz via a WorldFIP® fieldbus link to gateways located at the surface.

In what follows, a brief review of the design of the RADMON monitoring device will be given. The controls infrastructure will be described together with the data storage and data displays foreseen for LHC operations. Finally, a few examples will be given on how this system can be used in accelerator operations to reduce the risk of radiation damage to equipment.

II. *RADMON* RADIATION MONITORS

A. *Complex radiation fields*

The complex radiation field in the LHC underground areas is composed of different particles at various energies. Electronic components and systems exposed to such a radiation field will experience three different types of radiation damage which are displacement damage or Non Ionising Energy Loss (NIEL), Single Event Error rate (SEEs) and damage from the Total Ionising Dose (TID). The damage is proportional to, respectively, the 1-MeV equivalent neutron fluence, high energetic hadron flux (E > 20 MeV) and the Total Ionising Dose (TID).

For the radiation monitoring system, the complex radiation field is decomposed in terms of these 3 physical parameters (figure 1) which are considered orthogonal in the region of interest.

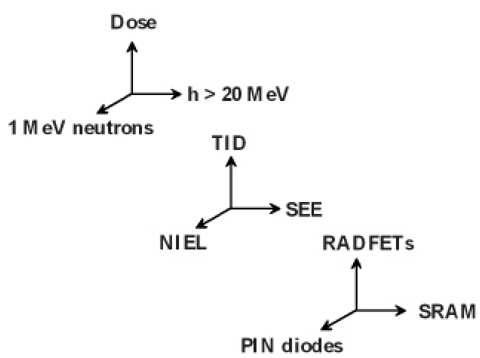

Figure 1: Parameterisation of a complex radiation field and the associated types of radiation damage and radiation sensors.

The radiation monitors measure these three parameters individually and independent of each other. The fluence to dose ratio provides information on the radiation spectrum and can be compared to Monte Carlo simulations. As will be shown in the last section, variations in the radiation spectra due to, for example, a modification in the geometry can be measured.

All measurements are tagged with UTC time (Universal Time Coordinates) and can be directly related to changes in the machine settings. The rate of data storage is 50 Hz for periods of 30 minutes or 1 Hz continuous.

B. Radiation Sensors

Each RADMON radiation monitor is equipped with 2 discrete p-channel MOS Field Effect Transistors or Radfets to measure the total ionising dose. Radfets are very sensitive to radiation because they have very thick gate oxides that enhance the trapping of radiation induced holes. For the RADMON system, 3 different types of Radfets are available with oxide thicknesses of 100 nm, 400 nm and 1 µm that provide a resolution of 100 rad/bit, 4 rad/bit or 1 rad/bit. Although any combination of these 3 types is possible, most monitors have either a 400 nm and a 100 nm or a 1000 nm and a 400 nm Radfet on board as these combinations provide the maximum resolution for a given total dose. The first combination is mainly used in areas with high radiation levels (i.e. 1 kRad or more per year).

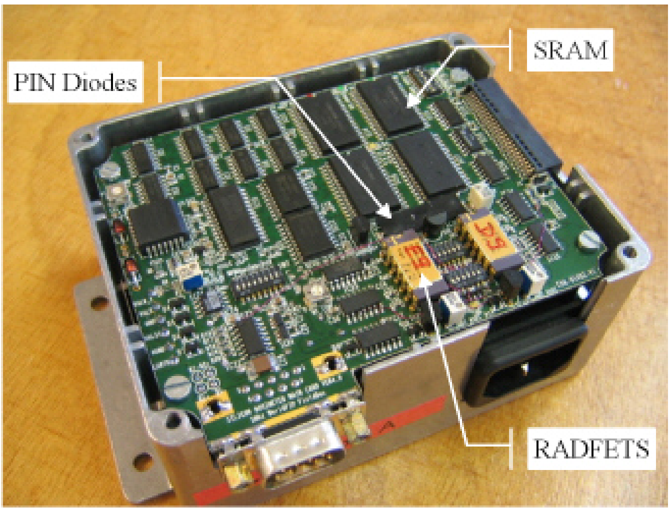

Figure 2: RADMON radiation monitor V4.1

Since their introduction in the 1970's, Radfets have found numerous applications in space, nuclear industry, research and radiotherapy. The devices used in the RADMON monitors are produced by Tyndall National Institute [7] and are equally used for space and medical applications. The response curves for various types of particles are therefore very well known and readily available [7,8].

The 1 MeV equivalent neutron fluence is measured with 3 BPWFS34 photodiodes from SIEMENS. These PIN photodiodes are well known to be sensitive to displacement damage from low energetic neutrons while unaffected by damage from TID damage. When irradiated with 1 MeV neutrons, the variation of the carrier concentration and the change in conductivity in these diodes is such that the forward voltage shift at constant current varies linearly with the neutron fluence. This makes these devices extremely attractive for direct measurements of the 1 MeV equivalent neutron fluence.

Each RADMON monitor has 3 PIN photodiodes. For high neutron fluences, it is sufficient to measure the change in the forward voltage of a singe diode. For lower fluences, the resolution needs to be increased by measuring the voltage of 3 diodes in series. In the latter operational mode, 1 bit corresponds to a neutron fluence of $9\text{x}10^9$ n/cm^2 (1 MeV eq.)

The monitors can equally measure the high energetic hadron flux and fluence with 16 Mbit of static RAM (Toshiba TC554001AF-7L). Hadrons with sufficiently high energy can change reverse the data state of a memory cell without permanently damaging the circuit (Single Event Upset or SEU). The number of memory cells that change their logical state is linearly depended on the hadron fluence to which the devices are exposed.

In the LHC, the hadron flux consists of mainly of neutrons. The SEU cross section of the SRAM memory is very low for low energetic hadrons but rises sharply at 20 MeV and remains approximately constant above this energy [9]. The proton and neutron calibration curves are used to convert the observed SEU rate in the equivalent hadron flux. The SEU sensitivity of the memories can be increased by lowered the bias voltage.

C. RADMON Functional description

The RADMON radiation monitors have been designed to stand at least 10 years of radiation in the LHC arcs assuming nominal operation of the LHC. The tolerance of each device is expressed in the usual 3 parameters is 200 Gy (TID), $2\text{x}10^{12}$ n/cm^2 (1 MeV eq.) and $2\text{x}10^{11}$ h/cm^2 (E > 20 MeV).

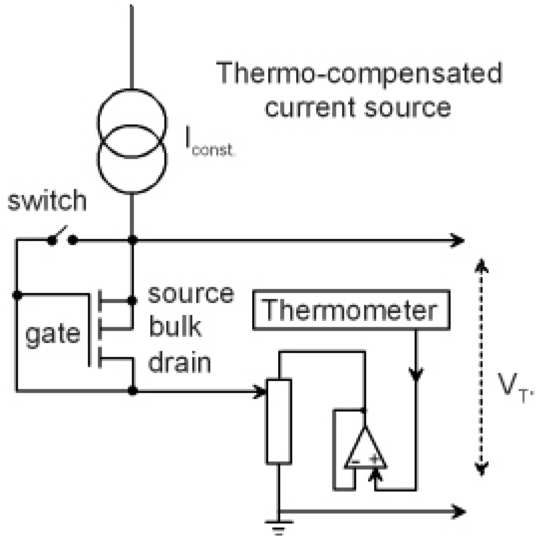

Figure 3: Schematic for the reader circuit of RADFETs during readout phase (switch open)

One of the prime concerns in the design has been the avoidance of error propagation due to Single Events in the readout and field bus communication circuitry. The design was therefore kept as simple as possible using a minimum of components. The monitors do not use programmable devices or CPUs in the design and nearly all registers have been made triplicate modular redundant.

Another important point in the design is the thermo compensation of the analogue read out circuitry required for the Radfets and PIN diodes.

The readout configuration for the Radfets is shown in figure 3. During irradiation, the switch is closed and all terminals are grounded. To readout the Radfet, the switch is opened, and a thermo compensated constant current of 8.7 μA flows from the source to the drain. The threshold voltage needs to be thermally compensated before being converted by the on board ADC. The conversion of the threshold voltage V_T into accumulated dose occurs at the level of the equipment gateway.

The readout mechanism for the PIN photodiodes is essentially the same as the one for the Radfets. The only difference is that the readout current is 1 mA and that the PIN diodes require more important temperature compensation. More details on the analogue readout circuitry, the selected components and their radiation tolerance can be found in [10].

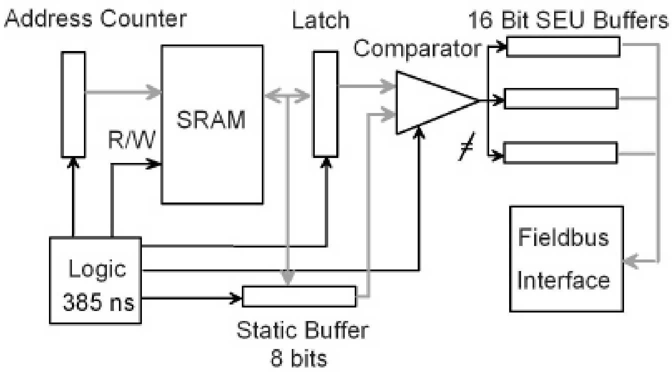

Figure 4: Schematic for the readout of the SEU counters of the RADMON monitors

The schematic for the readout of the Single Event Upset rate in the SRAM memory is given in figure 4. Each monitor has a total of 16 Mbit SRAM on board. The logic generates read-compare-write cycles every 385 ns and takes 700 ms to scan the entire on board memory.

During the reading phase, 8 bits of data are read in parallel from a specific address in the memory and latched into a register. At the same instant, the 8 bit reference pattern is written back at the same location in the memory. The latched bit pattern is checked for radiation induced errors by the comparator. If a SEU has occurred, the contents of all three 16 bit SEU buffer registers are increased by one. Triplication of the registers was needed here because the contents of these registers itself can be corrupted by single events.

D. *RADMON system architecture*

The RADMON system has a 3-tier architecture consisting of a resource tier, a communication tier and a presentation tier (figure 5). The resource tier consists of 284 RADMON radiation monitors on a total of 20 WorldFIP field bus segments (figure 5). The maximum number of monitors on a segment was deliberately limited to 32 to keep the response time sufficiently low.

A WorldFIP segment can be several kilometres long and may use optical fibres or copper as a transport medium. The line speed for the RADMON system is 1 Mbit/s. Each WorldFIP segment is connected to a gateway (an industrial Intel PC) and there are 20 gateways in total. Each gateway is connected to the CERN gigabit Ethernet backbone and to the machine timing network.

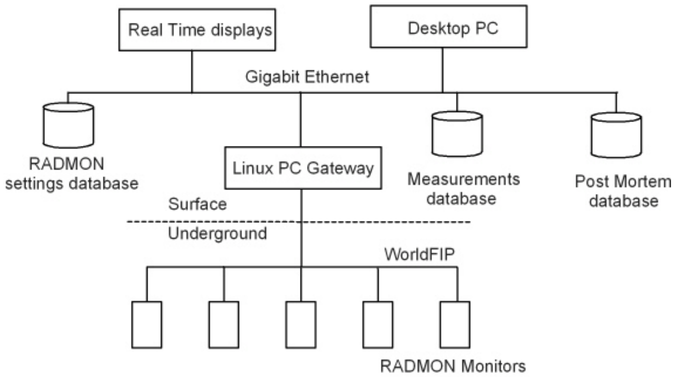

Figure 5: Schematic view of the RADMON system architecture

The entire system is database driven. At start up, the application software on each gateway loads the current settings data from the settings database. The settings file contains information on, for example, the calibration of the sensors and the hardware setting of each device. During the initialisation phase, the hardware address of each monitor is read. The hardware address allows finding the correct settings for that specific monitor in the configuration file.

During operation, measurements are stored in the LHC (oracle) measurement database at a rate of 1 Hz and in a local circular buffer in the gateway at a maximum rate of 50 Hz. The data in measurements database can be accessed by any user at CERN at any time. The contents of the circular buffer are made available upon request. Such requests can be a user request via the Ethernet network or it can be a trigger that arrives via the timing network (a post mortem trigger following a beam loss for example). All data is tagged with Universal Time Coordinates (UTC time) and with the operational status of the machine.

The engineer in charge in the LHC control room can visualise the radiation data on a set of real time displays which are updated at a maximum rate of once per second. There is the possibility to visualise the accumulated dose or fluence per fill for the entire ring or to focus on a specific area of the machine (such as the Long Straight Sections or the injection areas). It is equally possible to display the hadrons flux measured by the SEU counters in the monitors.

III. RADIATION MONITORING IN PRACTICE

A. *Monitoring in the SPS*

At CERN, the monitors have been extensively used in the target hall of the SPS. In this area, the proton beam from the SPS is sent on various primary targets to create secondary particle beams for the physics experiments located further downstream. Monte Carlo simulations [11] have shown that the radiation field in this area is very similar to that which is expected in the LHC regular ARCs.

During the SPS proton in 2006, a single series produced monitor was placed in this area. During the startup of the SPS, the intensity of beam slowly increased and the monitor observed the associated increase in the radiation levels (figure 6).

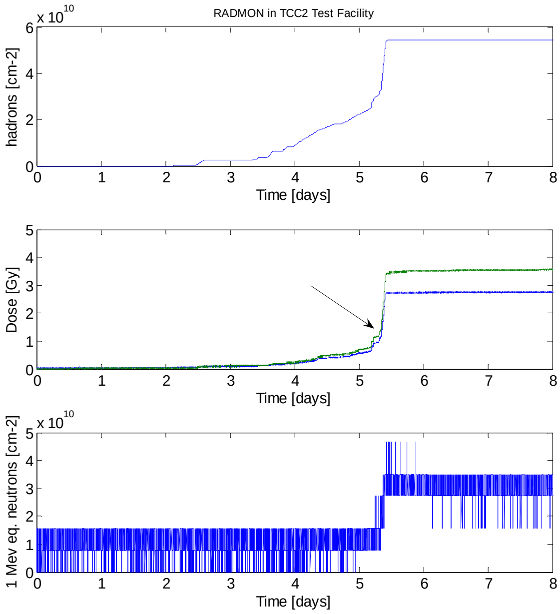

Figure 6: On line radiation measurements in the SPS North Experimental Area during the 2006 proton run.

Five days after the start of the data acquisition, the monitor observed a sharp increase in the dose rate (indicated by the arrow in figure 6) and a simultaneous sharp increase in the hadron flux and the 1 MeV eq. neutron flux. SPS operations were stopped one day later because the beam parameters for the physics experiment further downstream were incorrect. The reason for this anomaly was found to be a faulty bending magnet. The magnet in question deflected the proton beam in the vertical direction by a too large angle. The radiation monitor detected the hadronic shower caused by the losses of the primary protons further upstream.

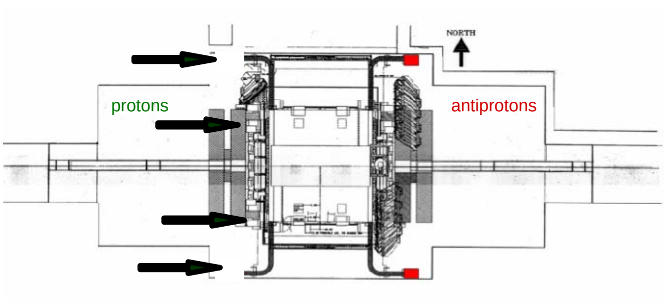

Figure 7: Top view of the CDF detector at FNAL. The 4 large arrows indicate the location of the 4 RADMON monitors

At Fermilab (FNAL), a set of 4 monitors was installed in the collision hall of the CDF experiment (Collider Detector at Fermilab) [12]. CDF is one of the main particle detectors of the Tevatron accelerator which collides protons with antiprotons. At CDF, a number of radiation induced failures have been observed [13] in the electronics in and around the detector and the monitors were installed to identify the various sources and to provide additional information on the composition of the radiation.

Figure 7 shows how the 4 monitors are placed symmetrically around the west side of the detector from which the proton beam is incident (Inner/Outer North West and Inner/Outer South West). Radiation levels at this side of the detector are higher because the proton beam is on average 10 times more intense than the anti-proton beam.

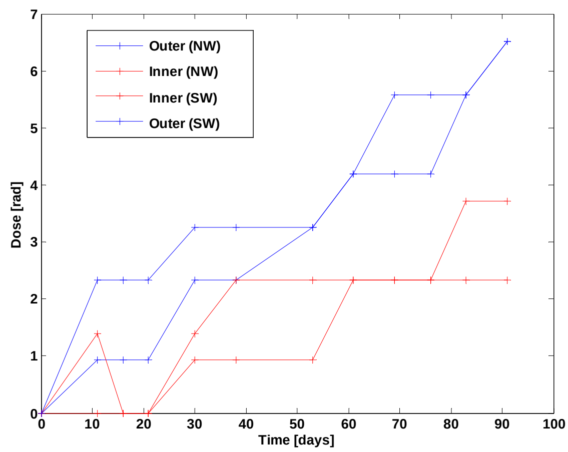

Figure 8: Evolution of the dose in the CDF collision hall during 100 days of luminosity running in 2005.

Figure 8 shows the evolution of the radiation level over a period of nearly 100 days of luminosity monitoring. The radiation levels are relatively low (a few rads) and linear depended on the integrated luminosity as expected. The fluence to dose ratio on the wall of the CDF collision wall was found similar to what has been simulated for the ATLAS cavern wall [14]

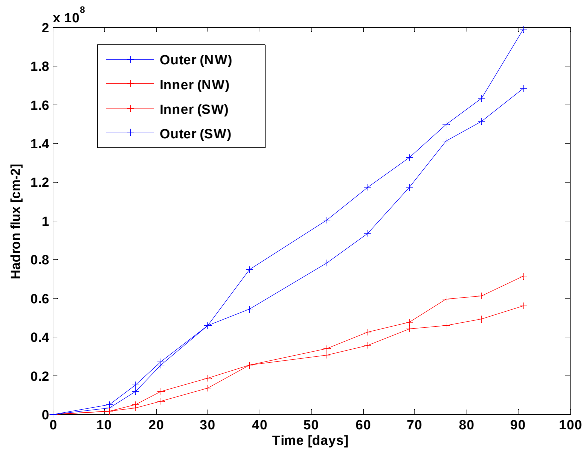

Figure 9: Evolution of the hadron fluence in the CDF collision hall during 100 days of luminosity running in 2005.

Figure 9 shows the evolution of the hadron fluence for the same period. Having a much higher resolution, the SEU counters allow distinguishing the inner and outer detectors regions but they also register small beam losses which are not necessarily related to luminosity. For example, when one of the electrostatic separators (ES) in the Tevatron sparked a small fraction of the beam ended up in the CDF collision hall. The very small losses was detected in some of the SEU counters (Inner SW and Outer SW) but were invisible on the signals from either the Radfets or the PIN diodes. The data register for the Inner and Outer NW/SW detectors read :

```
ONW INW ISW OSW     Time

011 009 167 388     Nov 21 16:12:51 2005
011 009 168 392     Nov 21 16:13:06 2005
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Other diagnostics determined that the beam abort occurred at 16:13 hrs local time. The increase in SEU counts measured by the monitors in the OSW location for this particular event corresponds to a fluence of 1 x 10^7 hadrons/cm^2.

IV. Summary and Conclusions

A certain number of precautions have been taken to deal with the issue of radiation and radiation damage to equipment in the LHC tunnel and experimental areas.

Firstly, radiation tolerant components and radiation tolerant design techniques have been used for all underground equipment that will be exposed. Secondly, radiation sources have been shielded whenever this was reasonably achievable and finally, radiation monitors have been installed to measure radiation levels at the location of the equipment from day one.

In total, nearly 300 monitors are being installed in the LHC underground areas and in the experimental caverns. Each monitor can be read out remotely over a distance several kilometres at frequencies between 1 and 100 Hz. The WorldFIP fieldbus protocol is used to communicate between the monitors in the underground areas and the equipment gateways at the surface buildings. Each gateway is connected to the machine timing network and to the gigabit Ethernet backbone and the gateway software stores data in the LHC measurement database at 1 Hz or in the Post Mortem database at 100 Hz. Measurements are also made visible via real time displays in the control rooms.

An important effort was required to assure the radiation tolerance of the monitors up to a total dose of 200 Gy and a neutron fluence of $2x10^{12}$ cm^{-2} (1 MeV equivalent neutrons). The reason is that the electronics design of a monitor is based entirely on Commercial of the Shelf components whose radiation tolerance needed to be verified via radiation tests outside CERN.

Another important issue in the design has been the thermo stabilisation of the various current sources and the automated thermo compensation of the readings from the radiation sensors.

A number of monitors have been used successfully in the primary target hall of the SPS accelerator at CERN and in the collision hall of the CDF detector at Fermilab. In both cases, the resolution of the monitors was sufficient to provide early warnings if the radiation levels were rising abnormally fast. The combination of

V. References

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