Standalone, battery powered radiation monitors for accelerator electronics

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Abstract

A technical description of the design of a new type of radiation monitors is given. The key point in the design is the low power consumption inferior to 17 mW in radiation sensing mode and inferior to 0.3 mW in standby mode. The radiation monitors can operate without any external power or signal cabling and measure and store radiation data for a maximum period of 800 days. To read the radiation data, a standard PC can be connected via a USB interface to the device at any time. Only a few seconds are required to read out a single monitor. This makes it possible to survey a large network of monitoring devices in a short period of time, for example during a stop of the accelerator.

I. INTRODUCTION

The Large Hadron Collider (LHC) is high energy, high intensity p-p collider that is using superconducting magnets to bend the two counter rotating proton beams on a circular orbit. To operate the accelerator, a large amount of electronic equipment is need for the powering, the vacuum, the quench protection system and the beam instrumentation. To reduce overall cabling costs and to improve on the S/N ratio, electronic systems have been placed under the superconducting magnets along the 27 km long underground tunnel where they will exposed to particle radiation caused by the interaction of protons with material. An increase in radiation levels may damage the components and systems and these may eventually stop working correctly.

An on line radiation monitoring system was installed and commissioned in the LHC in 2007 [1]. On line monitoring provides timely information on the evolution of the radiation fields but has the drawback that it requires extensive signal and power cabling. Furthermore, once the cabling has been installed, the location of the on line measurements has to be at maximum 25 m from the cable junction box which is a constraint if uncertainties exists on the spatial distribution of the radiation.

The standalone version presented here overcomes these problems and does not need external powering or signal cables. The monitor design is based on the same principles as the on-line version but is less complex and produced at much lower cost. In addition, the circuitry for the constant current generation, voltage sources and for the AD conversion is integrated in a USB readout interface that is not exposed to radiation. The USB interface can be connected to and powered by any (portable) PC which facilitates measurements in the field, for example during a technical stop of the accelerator. Apart from the radiation data, the number of clock cycles between the start of the measurements (initialisation) and the moment of readout is also provided which makes it possible to compute a time averaged dose rate and the associated particle flux. The readout software is based on LabView and is using the standard firmware and software that is delivered with the USB interface module.

The monitor has a total of 3 batteries on board. Two of these are used to power the cyclic operations during data taking when the monitor is in radiation sensing mode. One battery is required for the long term data storage when the monitor is in standby mode. The 2 main batteries provide 8.5 A/h which is sufficient to operate 150-220 days, depending on the setting. When the voltage from the main batteries becomes insufficient, the monitor switches automatically from radiation sensing mode to standby mode. When switching to standby mode, the data on the neutron fluences is stored in triplicate storage registers powered by the backup battery. The corresponding elapsed timed is stored too which makes it possible to compute the time averaged neutron flux. In back up mode, an additional 500-600 days of data storage is possible. At present 4 prototypes are under evaluation and being prepared for radiation tests in the field.

II. HARDWARE DESIGN

A. Radiation Sensors

The monitor presented here measures the total integrated ionising dose in Silicon in Gray, the 1 MeV equivalent neutron fluence per cm^{2}and the fluence of nucleons (protons, neutrons) per cm^2 with a threshold energy of 20 MeV.

The radiation sensors consist of 2 radiation sensing MOSFETs (RADFETS®) from Tyndall Ltd [2] of different oxide thickness, 6 SIEMENS BPW 34FS Photodiodes in series [3] and 8 x 4 Mbit of Static Random Access Memory (SRAM) TC554001AF-7L from Toshiba[4].

Radfets are radiation sensing Mosfets that have been designed to measure the total ionising dose in Silicon. When exposed to ionising radiation, electron-hole pairs are created in the gate oxide which leads to a change in the threshold voltage. The change of the threshold voltage varies approximately linearly with the dose absorbed. Radfets were chosen as radiation sensors for total dose because they do not need external power when in radiation sensing mode.

The Photodiodes are used in series to enhance the overall sensitivity to detect low energy neutrons. When exposed to particle radiation, the carrier lifetime, the resistance and the carrier density are all changing and the end result is a near linear variation of the forward voltage at constant current injection. As with Radfets, the pin diodes do not need to be powered when in radiation sensing mode.

The 32 Mbit of SRAM memories are used to measure the fluence of hadrons. Single hits from ionizing particles can change the logic state of the data stored in the memory. The amount of logic changes (Single Event Upsets) is approximately proportional to the hadron flux. In contrast with the other sensor types, the SRAM memory is always powered and constantly accessed with a read-compare-write cycle. The cyclic scanning of the memory and byte-by-byte comparison with a reference pattern is responsible for most of the power consumption when the monitor is in radiation sensing mode.

B. *Operating principles*

In radiation sensing mode, the radfets are connected as shown in figure 1 (left) with the gate connected to the drain and the bulk to the source. In this configuration the radfet is not using any power.

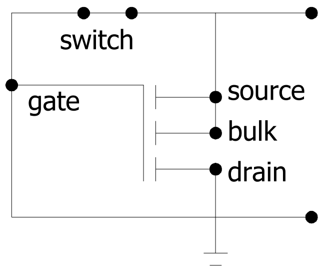

Figure 1: Schematic of a RADFET in radiation sensing mode (switch closed)

To readout the radfet, an external current source is connected and the switch is opened. The variation of the threshold voltage V_t at constant current is proportional to the total accumulated dose. The forward voltage V_t is measured via an external signal cable connected to an USB interface which connect to any standard desktop PC (see below).

The operating scheme for the diodes is near identical to that shown in figure 1 with the Radfet replaced by 6 diodes in series. The forward voltage V_t is measured identically.

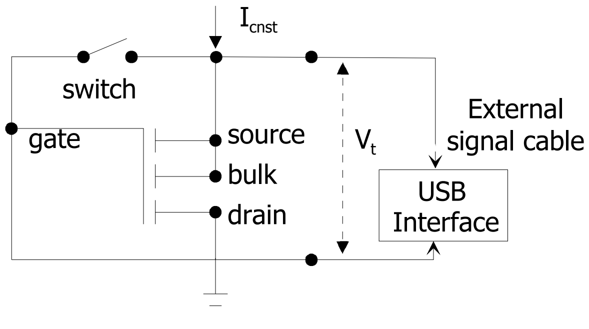

Figure 2: Schematic of a RADFET in reader mode (switch open).

The value of the threshold voltage V_t has a strong dependence on the temperature which should not be interpreted as a variation of the radiation levels. Close to the radiation sensors, a platinum-chip temperature sensor (Jumo PCA 1.1501.1M) sensor provides a temperature measurement at the moment of readout. The temperature induced variations of the threshold voltage V_t can then be corrected for in software in the PC.

The readout of the SRAM memory is shown in figure 3. The 32 Mb SRAM is organized as 8 * 512Kbytes. Every 1.7ms, a specific location in the memory is addressed and an 8 bits word is read from location and compared to the reference word in the static buffer. If radiation has modified the contents of word in the memory, the comparator will increase the contents of the SEU counters by one count. After the comparison the reference word is written back at the same location of the memory.

At start up, the entire SRAM memory is initialised and the reference word is written at each address location. To refresh and initialise the entire memory, the cycling is reduced to 385 ns for a period 1.6 seconds with an external switch. This operation consumes a significant amount of power and is only used at start up.

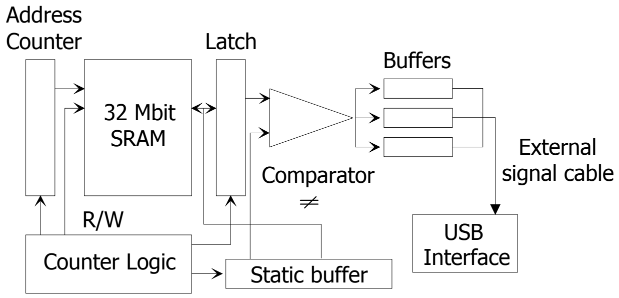

Figure 3: Schematic for the cyclic readout of the memory.

There are 3 identical data storage buffer counters to minimise the possibility of radiation induced errors in the counting. Via an external signal cable the contents of these 3 buffers can be read out using the USB interface module that is connected to a PC. In the unlikely event that the data in one of the counters is corrupted, majority voting is used.

Table 1: Operational data for SRAM counter.

Task	High Sensitivity	Low Sensitivity
Biasing Voltage	3 V	5 V
Memory Refresh time	2 hours	2 hours
Power Consumption	12 mW	17 mW
Max. operating time	220 days	148 days
Max. Data storage	595 days	523 days

To increase the sensitivity to neutrons, the memory can be operated at 2 different bias voltages. The lowest voltage provides the highest sensitivity and the longest operating time (table 1).

Each monitor has a unique identifier which consists of a 64 Bit ROM registration number that is factory laser written into the chip (Maxim DS2433 4 kB 1-wire EEPROM). This assures absolute identity because no two parts can be identical.

C. *Battery power*

The 2 main batteries for the monitor are Lithium Thionyl Chloride Batteries (Li-$SOCl_2$). Lithium batteries were chosen because they have been used for various space mission (Mars pathfinder Rover, Deep Impact Mission etc), because they have the highest specific energy (up to 500Wh/kg) and because they have shown to be radiation tolerant to total dose up to 6 kGy. Another advantage is the low self-discharge rate of these kind of batteries.

For the monitor presented here, two SL2770/T Li-$SOCl_2$ batteries type C from TARDIAN® are used. These batteries have a nominal voltage of 3.6 V and a capacity of 8.5 Ah. The configuration is cylindrical and spirally wound (power cell type).

A first radiation test consisted in exposing these batteries to a total dose of 200 Gy from gamma rays from a ^{60}Co source. At a dose rate of 360 Gy/hr, the batteries were connected in series to an external load (resistance) simulating the radiation monitor. No significant variation of the output voltage or current was observed after a total dose of 200 Gy. These results are in line with the radiation data that was accumulated for the Galileo space mission where batteries of this type were exposed to 6 kGy [4]. The radiation tolerance to neutrons of Lithium Thionyl Chloride Batteries is still relatively unknown also in literature and needs to be investigated in forthcoming radiation tests.

A single backup battery powers the data buffer counters when the main batteries are wearing out. This is a Li/MnO2 button cells battery of very small size type CR2477NRV-LF from RENATA with a nominal capacity of 3 V and 950 mA/h. The Li/MnO2 battery is relatively cheap and provides the best practical volume/capacity ratio. It has also a very low self discharge and excellent storage capacities. A disadvantage is that the discharge voltage slope may vary over the battery life time. When exposed to ionising radiation up to 200 Gy in a similar experiment as described above, no noticeable variation of the output voltage was observed. Forthcoming radiation tests will have to make this issue more precise.

D. USB interface and PC software

The USB interface module contains all functionality that is required to digitize and permanently store the radiation data from the monitor on a standard PC. The interface performs digital and analogue I/O, generates the constant current required to read out the Radfets and PIN diodes and transmits serial data to the USB bus and vice versa. A 12 bit ADC converts the analogue data from the temperature and radiation sensors. The powering of the module from the host PC is via the standard USB 2.0 interface.

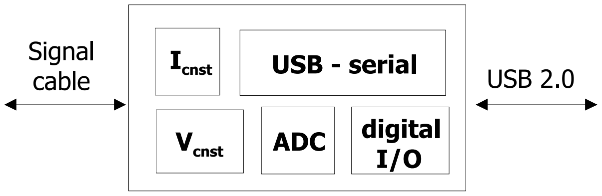

Figure 4: The USB interface module which connects the monitor to any standard desktop or portable PC.

The USB interface module is a commercial serial to USB converter of type USB I/O 24 R from Elexol®. This device is shipped with a standard set of drivers and dynamic linked libraries for Windows OS. The I/O is carried out via 3 ports of 8 bits each. Port A is used to communicate the status of the monitor. This includes information on the powering mode which can be on main batteries or in backup powering mode. Port B of the interface is used to send commands to the monitor. In total there are 19 different commands to address all different sensors and buffers on the monitor. On port C, the response of the monitor is presented following a command on port B. With each response, the data status is also communicated. To read out the 12 bit ADC for example, 2 commands are needed. On the second response, the 4 remaining bits communicate the status of the monitor and the validity of the response.

A Labview application has been written to perform the data reading in a cyclic manner and to display the data for analysis. To generate the final data, a series of 50 measurements is made which are then time-averaged and achieved. This is to mitigate the influence of noise and to be able to provide data below the single bit resolution of the ADC. Such a series of measurements requires a total time of approximately 1 second so that several devices can be measured in relatively short period of time.

E. Assembly and final presentation

Each monitor has 2 PCBs of 4 layers each. The mother board assures the powering of the device, the timing and the long term data storage. The radiation sensors and the temperature sensors are located on the upper PCB which is plugged in the mother board. The main batteries are located underneath the motherboard and they use approximately 80% of the available space. The entire assembly is bolted in a aluminium casing using steel fixations (see figure 5).

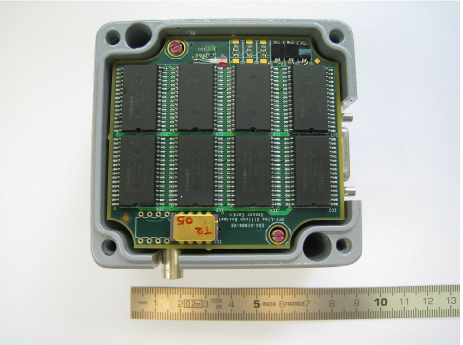

Figure 5: Fully Assembled Radiation Monitor

To avoid damage during transport into the accelerator tunnel, the aluminium casing can be sealed with an aluminium lid. The device can be fixed to any support using standard DIN rail. Only when the device is placed in its final position, the device is initiated and the on board clock is started by manipulating small push buttons.

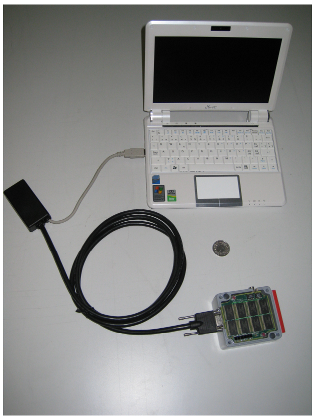

Figure 6: Readout configuration

It is important to verify the status of the device at regular intervals to ensure that the main batteries are still operational. In addition, accumulating radiation data at arbitrary intermediate intervals can provide a more precise estimate of the fluence to dose ratios at the location of the monitor. To read out the devices in the field, small portable EEPCs are used which have sufficient autonomy to read out various devices. Figure 6 shows the configuration for reading out a monitor with the USB interface module. The module is connected with a signal cable to the monitor and with a USB 2.0 connection to the portable PC.

III. EXAMPLES OF APPLICATIONS

Two typical applications where these monitors can be of use are found in the experimental caverns of the LHC where the protons beams are colliding and the main LHC particle detectors are located. Both applications have to do with measuring radiation in the vicinity of electrical equipment that is often in movement such as the access lifts and the overhead cranes that are used to take the particle detectors apart during a shutdown period.

Another example is to measure integrated radiation levels at specific locations where the use of electronic equipment may be envisaged at a later point in time. It is not always possible to use Monte Carlo simulations in such a situation either because the beam operating conditions are unknown, the geometry of the area is too complex or simply because simulations would too time consuming. The data from the monitor will provide a clear engineering constraint for the radiation tolerance of this equipment.

Alternatively, when electronic equipment close to a beam line is showing erratic behaviour on a regular basis, the use of a standalone monitor can be considered to rule out the impact of radiation damage.

Finally, when electronic equipment is exposed to radiation, a monitor placed at the same location can provide information on the type of radiation damage that is caused (i.e. damage from total dose or from high or low energy neutrons).

IV. FUTURE WORK

One of the key points in the design is the radiation tolerance of the main and backup batteries. In particular, little has been published in literature about the radiation tolerance of Li batteries to neutrons. So far, no degradation has been observed when these batteries are exposed to gamma radiation from a ^{60}Co source but a more complete characterisation in different radiation fields and especially in neutron dominated fields, will be needed to make this issue more precise.

Another important issue is the cross calibration of the radiation sensors. The sensors are identical to those used in the on line version and have been extensively tested in dedicated radiation facilities over the last 5 years. To cross check the data from the monitors, it is planned to equip some devices with passive dosimeters. In addition, some devices will be placed around the CERN accelerators at the same location of ionisation chambers which provide on line data on the total ionising dose.

Finally, the temperature coefficients of each radiation sensor will have to be measured individually as a function of accumulated dose and neutron fluence. Only a precise knowledge of the evolution of the temperature coefficients will enable to determine the total ionising dose and the 1 MeV equivalent neutron fluence with a high accuracy.

V. CONCLUSIONS

The stand alone radiation monitor design presented here is based on the successfully operated on line radiation monitoring system which is presently in use in the CERN accelerator complex. The devices provide a cost effective solution to survey the evolution of the time integrated radiation levels in terms of the total ionising dose, the 1 MeV eq. Neutron fluence and the hadron fluence h > 20 MeV. Another key point is that no external signal or power cabling is required which makes it possible to measure at practically any location at any time when there is circulating beam in the CERN accelerators. .

The readout is non destructive, fast and can be carried out at any time with the device in situ. It is thus possible to read out a large quantity of devices during a technical stop or short shutdown of the accelerator complex. The interface with a host PC is using the standard USB 2.0 protocol and the associated LabView software is easy to use.

Future radiation experiments will focus on the radiation tolerance of Litium batteries in neutron rich environments. Li batteries have already shown excellent performance with respect to damage from total ionising dose.

VI. REFERENCES

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