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THE RADIATION TOLERANT READOUT SYSTEM FOR SRMBASED NEUTRON DETECTOR

D. MAKOWSKI, M. GRECKI, B. S WIERCZ, A. NAPIERALSKI
TECHNICAL UNIVERSITY OF ŁÓDŹ, POLAND

B. MUKHERJEE, S. SIMROCK
DEUTSCHES ELEKTRONEN-SYNCHROTRON, GERMANY

Abstract

Bremsstrahlung gamma radiation and photoneutrons are produced during the operation of high energy linear accelerators. The functionality of electronic devices that are placed inside accelerator tunnels can be jeopardized because of the negative influence of generated radiation. Therefore, a radiation monitoring system able to gauge neutron fluence and gamma dose in real time was constructed. Radiation-sensitive dosimeters cooperate with a readout system. The readout continuously measures both types of radiation and sends quantified data to a main computer. The system is also placed in the tunnel, hence it must be insensitive to radiation or able to tolerate induced malfunctions. A few different readout systems were designed. This work presents the application of different readouts designed using commercial of the shelf (COTS) components. The presented hardware was tested with americiumberyllium neutron source. Finally, the systems were irradiated in a linear accelerator tunnel to estimate their immunity and suitability for a long-term reliable operation in the radioactive field.

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THE RADIATION TOLERANT READOUT SYSTEM FOR SRAM-BASED NEUTRON DETECTOR

*D. MAKOWSKI, *M. GRECKI, **B. MUKHERJEE, *B. ŚWIERCZ,
**S. SIMROCK, *A. NAPIERALSKI

*TECHNICAL UNIVERSITY OF ŁÓDŹ, POLAND

**DEUTSCHES ELEKTRONEN-SYNCHROTRON, GERMANY

KEYWORDS: Radiation Tolerant System, Neutron Flux Measurement, Dose of gamma radiation, Single Event Upset

ABSTRACT: Bremsstrahlung gamma radiation and photoneutrons are produced during the operation of high energy linear accelerators. The functionality of electronic devices that are placed inside accelerator tunnels can be jeopardized because of the negative influence of generated radiation. Therefore, a radiation monitoring system able to gauge neutron fluence and gamma dose in real time was constructed. Radiation-sensitive dosimeters cooperate with a readout system. The readout continuously measures both types of radiation and sends quantified data to a main computer. The system is also placed in the tunnel, hence it must be insensitive to radiation or able to tolerate induced malfunctions. A few different readout systems were designed. This work presents the application of different readouts designed using commercial of the shelf (COTS) components. The presented hardware was tested with americium-beryllium neutron source. Finally, the systems were irradiated in a linear accelerator tunnel to estimate their immunity and suitability for a long-term reliable operation in the radioactive field.

INTRODUCTION

Electronic control systems of the Free Electron Laser at Hamburg (FLASH), that is also known as VUV-FEL, are installed inside its tunnel [1]. The laser is driven by a 1.2 GeV linear accelerator, therefore radiation generated during FLASH operation can pose a real threat to electronic systems and subsystems [2, 3, 4]. Ionizing radiation continuously damages electronic components because of the total ionizing dose (TID) effect [5, 6]. Non-ionizing particles are responsible for displacement damage [7, 8]. Moreover, neutrons can affect components by single event effects (SEEs), in particular single event upsets (SEUs) [9, 10, 7, 8, 6]. Therefore, it is advisable to monitor radiation produced in the FLASH tunnel in real time to estimate the danger and their life time. Moreover, a radiation monitoring system may help to minimize neutron fluence and gamma radiation dose generated during the FLASH operation.

High-density FPGA circuits were employed to design a dedicated digital control system of the FLASH laser to obtain a high stability of the amplitude and phase of RF field supplying accelerating modules [11]. An exemplary board of the control system is illustrated in Figure 1. The presented digital system is mainly based on Xilinx Virtex II pro and thus may be sensitive to SEUs [12, 13]. The device communicates with an external SUN computer using a VME interface. Indeed, processing data are stored in dynamic and static random access memories (DRAMs, SRAMs) that can be also sensible to SEUs [14, 14, 15, 16]. Therefore, a monitoring of both types of radiation may be very useful especially in the initial phase of the FLASH development. Moreover, knowledge concerning the amount of generated upsets in a calibrated sensing memory may be utilized to estimate

Fig. 1. An exemplary FPGA-based control board SimCon 3.1L

vulnerability of the used electronic components to neutrons present in the accelerator tunnel. Silicon dosimeters are the most suitable sensors for radiation monitoring system because damage of the FLASH electronics are going to be correlated with gauged radiation doses. A SRAM-based dosimeter was designed and calibrated to quantify neutron fluence and SEUs induced in electronics [17, 18]. It has been proved that the number of induced SEUs in SRAM is proportional to neutron fluence. A RadFET dosimeter was applied to measure ionizing doses. The system equipped with the radiation-tolerant readout is called RadMon. A few various digital readout systems were designed to carry out irradiation experiments and emerge the most suitable radiation-tolerant device to compose a distributed system. Such a monitor allows to quantify neutron fluence and gamma dose in a few different places in FLASH. The block diagram of a four-channel monitoring system is depicted in figure 2. Further, the system is going to be installed in a much higher number of places in the next version of FLASH

Fig. 2. The block diagram of a distributed radiation monitoring system

Fig. 3. A block diagram of the RadMon device

laser, thus the construction of the readout should be cost-effective.

A REVIEW OF RADIATION-TOLERANT READOUT SYSTEMS

Various solutions were taken into consideration to design the readout system. The usage of Rad-Hard devices results in a dramatical increase of designing costs, therefore they are not good candidates for such a system. Finally, commercial of the shelf (COTS) components were chosen despite their vulnerability to radiation. Therefore, the electronic readout must be designed in such a way that it can tolerate malfunctions caused by radiation. In addition, gamma radiation and neutron displacement damage can be further reduced by the application of suitable shielding.

The application of redundancy to design RadMon readout

A modular redundancy was used to enable a faultless operation of the RadMon in the accelerator tunnel. Nevertheless, the memory is continuously reading short interruptions of the read-out system that are acceptable [19]. Therefore, a double modular redundancy (DMR) was used to protect the system against SEUs [20, 21]. The advantage of DMR is the low excess of hardware in comparison to other hardening methods, e.g. triple modular redundancy (TMR). The schematic diagram of the designed system is presented in figure 3. Two identical microcontrollers handle the SRAM device. The signals generated by microcontrollers are connected to a data comparator. An interrupt is generated when the comparator detects an inconsistency. Then, microcontrollers send information

to a PC and the system is restarted. An additional watchdog was applied to assure a reliable operation of the system. The PC generates a hard-reset signal and writes a new pattern into the SRAM device in case of a general RadMon's failure that is not corrected by DRM. The RadMon device cooperates with a master PC computer, therefore the device must be able to realize commands delivered from the PC. During the normal operation, the system periodically sends "live" frames to the PC. A hard reset is generated after the power disconnection or when the "live" frame is not delivered to the PC at the appointed time. This procedure assures the reliable operation of the RadMon, even if the system is crashed. The first prototype of RadMon (version 1.0) was built with an application of two ATMEL's 8051-family microcontrollers and a TTL-based control logic. The system was able to supervise a maximum of 128 kB memory supplied from 5 V. The old TTL technology was chosen intentionally, because is much more resistant to radiation [19]. Highly advanced, low-voltage devices with reduced feature sizes are more susceptible to both SEE and TID. The doses of radiation generated in Linac II were not known, therefore a robust solution was required to investigate the influence of radiation as well on the readout as SRAM device.

Two microcontrollers manufactured by Microchip were used to design the second prototype of RadMon. The system, supplied from 3,3 V, is able to handle up to 128 MB SRAM chip employed as a neutron fluence detector. Microcontrollers operate synchronously executing the same program and therefore supply identical control signals to peripheral devices. However, the scanned memory and auxiliary devices are controlled only from the master device (microcontroller 1), see Figure 3. A digital comparator based on FPGAs produced by Actel was utilised as a voter. The digital voter is radiation sensitive, thus the system will be restarted when neutrons generate SEU or SET in the main logic. However, the configuration of the employed FPGA is stored in a FLASH memory that is much more immune to SEU than SRAM. During the RadMon operation, additional parameters are measured: supply current and temperature of the memory. The measured memory supply current increases because of the TID effect. Knowledge of memory temperature is necessary to make an unavoidable temperature correction of the measured SRAM current. The analysis of memory and board supply currents provide information about TID damage effect and dangerous Single Event LatchUps (SEUs) [22]. The device is protected against SEL using a current limited power supply and polymer-based resettable fuses. No SEL was observed in the tested devices in Linac II and TTF2 tunnels [22].

The first version of the RadMon has a serious disadvantage, the maximum operable memory was limited to 128 kB. The whole system was designed in 5 V technology, therefore it was possible to connect only 5 V memories. The one cycle scanning time was below 1 second. The second device was designed using low voltage circuits therefore the memory supplied from 2.5 up to 5 V can be employed with capacities up to 128 MB. The system is able to scan memory within 30 s.

Fig. 4. The block diagram of the FPGA-based RadMon

An application of programmable circuits to design readout system

Field Programmable Gate Array (FPGA) devices are often used to design digital circuits because of a high speed of data processing and flexibility. The configuration of a FPGA circuit is usually stored in a SRAM, hence the device can be easily and quickly programmed many times. An application of the FPGAs significantly simplifies the designing process of electronic circuits.

Indeed, programmable devices can be used to design an efficient readout for the RadMon system. In addition, the adaptation of FPGA allows to reduce the scanning time of the sensing memory and system restarts in case of single event functional interrupt SETI. However, the configuration SRAM of a programmable circuit can be violated when exposed to neutrons because of the occurrence of SEUs. A readout circuit designed with an application of FPGA should tolerate radiation-provoked errors and therefore operate reliably in a linear accelerator tunnel. From the other side, an utilisation of FLASH-based FPGAs may eliminate a part of SEU-induced malfunctions. Nevertheless, single event transients (SETs) can be still induced in the control logic in both FPGA-type circuits. The RadMon was implemented in a commercial FPGA to examine its suitability for the usage in a radiation-tolerant readout. FLASH-based devices made by ACTEL were taken into consideration.

*A radiation tolerant readout implemented in FPGA

ACTEL APA 600 programmable circuit was chosen to construct the fourth version of the RadMon readout. The device cooperates with a more compact version of four 512 kB stacked memory module [16]. Configuration data are stored in the internal FLASH memory of ACTEL circuit that is much more immune to SEUs comparing to SRAM. The principle of operation is similar to the previous version of RadMon 2.0. A simplified block diagram of the FPGA-based reader is presented in figure 4. The device consists of the main finite state machine (FSM) responsible for the supervising of all submodules. The SRAM memory is programmed after the restart. Suitable information is sent to the main PC computer when the programming is finished and verified. Then, the continuous scanning process of the memory begins. When an error or errors are detected the error counter (EC) is increased and corrected data are written into the memory. The number of detected SEUs is sent to the PC after a whole scanning cycle. A live frame must be transmitted in the period of time shorter than 10 seconds to avoid triggering off an external watch-dog. The send data are

Fig. 5. The block diagram of the FPGA-based readout system of FIFO memory

secured with a 32-bit CRC control sum to avoid transmission errors and to verify the correctness of the reader operation. The digitalised RadFET's threshold voltage is delivered every 10 minutes. *FLASH-based FPGA as a radiation tolerant readout The fifth version of the readout system dedicated for supervision of FIFO memory was also implemented in the ACTEL FPGA. A lower density programmable circuit APA150 was utilised because of the simplified construction of the FIFO reader. The block diagram of the reader is illustrated in figure 5. The reader uses almost the same submodules as the version 4 of the RadMon. However, the memory interface is slightly different. The address counter was eliminated. The output 9-bits data bus of the FIFO is connected to a comparator, while logical zeros are delivered to its inputs. The main FSM generates only write and read signals, which are shifted in a phase.

A selective TRM was applied to immunize designed readers against neutron provoked SEUs. The FSMs, which control reader's operation, i.e. a CRC calculator, a universal asynchronous receiver transmitter (UART), a serial peripheral interface (SPI), a address generator and the main control circuit, are the most crucial elements of the system, because of the radiation immunity. Circuits were implemented under a Libero IDE with a Synplify synthesiser. The Synplify can generate three types of state machines one-hot, gray and sequential. Even though the synthesiser produces a highly optimal final implementation of FSMs that were immunised using TRM, their application in circuits operating in a harsh radioactive environment cannot be acceptable. Synplify optimizes away all transition states and logics that cannot be reached to enhance both a speed and circuit area. However, FSM can be obstructed in the invalid state when a SEU is induced in the FPGA structure. Therefore, the FSM has to be designed in such a way to enable transitions from all invalid states into the defined safe state. All type of FSMs can be employed to jump into the reset state in case of a soft error, while a self-defined sequential machine must be applied to jump into other safe state, while the invalid state is reached. Parameters of the employed FSMs are summarized in table 1. One can notice that the total number of states for the onehot FSM is much higher than usable states. A onehot machine is very efficient with regards to both occupied resources and speed. Nevertheless, this type of FSM is suitable to low number of states' applications. All FSMs in the presented readers were equipped with a reset logic for illegal states.

TABLE 1. The summary of the readout FSMs

Submodule	FSM type	Number of states	Total number
Control FSM	safe, gray	31	32
CRC calculator	safe, onehot	8	248
UART	safe, gray	20	32
SPI	safe, onehot	9	503
Address generator	safe, onehot	6	58

Fig. 6. A standard flip-flop with an asynchronous reset and preset that was modified using TMR

A Synplify synthesiser was applied to implement selective and conventional TRMs. Firstly, a standard description of the readout was prepared using a Vhsic Figure description language (VHDL). The synthesis was then executed, however input-output cells were not implemented. A piece of software was written to substitute automatically a collection of flip-flop primitives with their tripled versions equipped with voting circuits. Moreover, the software allows applying the redundancy of desired selectively chosen submodules. The exemplary modified D-type flip-flop is depicted in figure 6. The circuit was ready for a final synthesis when the substitution process was finished. The amount of required resources was increased significantly after the synthesis depending on the used redundancy method.

The comparison of the consumed FPGA resources is presented in table 2¹. The amount of used storage elements was increased 2.9 times when the TRM was utilized. The usage of selective triple modular redundancy (STRM) allows to save some FPGA resources, the factor was equal to 2.7. Additional combinational primitives were also required for voters. Moreover, the readout of the FIFO memory was simplified comparing to the RadMon 4. In particular, the number of required input-output pins was smaller and therefore a lower density FPGA APA 150 was used. Almost three times more flip-flops were required when TRM was employed. The RadMon 5 may be further simplified when a dedicated memory will be

¹An APA150 programmable circuit was used to design the readout dedicated for a FIFO memory, while the standard SRAM version employed APA600 device. Hence, the RadMon supervising the FIFO memory was synthesised intentionally for larger APA600 FPGA to facilitate their comparison

TABLE 3. Restarts of the RadMon 2 devices

Device	Malfunction type	Time of operation
RadMon 2.1 2 MB bare	Desynchronisation	845
	Desynchronisation	1210
RadMon 2.2 1 MB in moderator	Desynchronisation	305
	Desynchronisation	840
	Denial of service	1219
RadMon 2.3 2 MB in moderator	Desynchronisation	45
	Desynchronisation	409
	Desynchronisation	1350

used, the IDT FIFO memory needs a lot of connections to enable its initialisation. The desired memory may only have three control signals read, write and reset (not counting data buses), see figure 5.

*IRRADIATION TESTS OF DIFFERENT RADMON READER VERSIONS

Designed readers were subjected to radiation during experiments with an application of different memories. The devices were irradiated with americium-beryllium neutron source and inside Linac II and FLASH tunnels. During sensitivity tests with ²⁴¹AmBe no significant malfunctions were observed. The devices, similarly to sensing SRAMs, were placed in the nearest proximity of the neutron source. All above mentioned systems were able to read the memories and therefore supply numbers of induced SEUs.

However, short interruptions in the RadMons' operations were observed when the devices were irradiated in accelerator tunnels. It should be emphasised that DRM does not allow to maintain the correct operation of a system when an error is induced in critical module. Therefore, registered restarts of systems were necessary to enable a correct measurement of SEUs in the RadMons' sensing memory.

Three systems, based on RadMon 2 readouts, were equipped with different memories and placed in FLASH tunnel for two months. The registered malfunctions of the systems are gathered in table 3. The systems were installed opposite the accelerating module AAC1 approximately 20 cm from the concrete wall. Most of the failures of readouts were detected by comparators and eliminated by restarts of the systems. However, data measured by RadMon 2.2 were not send to PC computer after 1219 hours of operation. The PC computer had to generate a reset signal after 150 s to revive the system. However, exact details of the failure are not known. The history of the next three-month operation of RadMon 2.0, that supervised 2 MB memory sensor and gauged neutron fluence and gamma radiation in the FLASH tunnel is depicted in table 4. The RadMon 2.0 operates reliably even if a few desynchronisations occurred. No other problems were detected. RadMon 4 and RadMon 5 devices were installed in FLASH tunnel at the same time. The readout systems of RadMon 4 and RadMon 5 were operating much better than RadMon 2. No radiation-caused system restarts were recorded. The neutron fluence quantified by RadMon 4 was comparable with the fluence gauged

TABLE 2. The comparison of occupied FPGA-resources of various RadMon reader versions

Device version	FPGA resources		Tiles		Gates	
	Core cells	I/O pads	Logic	Storage	Logic	Storage
Readout system of a 32-bit SRAM device based on APA600 FPGA						
RadMon 4	12.6 %	37.2 %	2158	559	4387	4328
RadMon 4-TRM	22.3 %	37.2 %	3188	1599	6375	12369
RadMon 4-STRM	21.7 %	37.2 %	3126	1537	6251	11873
Readout system of a FIFO memory based on APA150 FPGA						
RadMon 5	11.1 %	26.9 %	1938	495	3853	3813
RadMon 5-TRM	20.1 %	26.9 %	2926	1452	5836	11178

TABLE 4. Restarts of the RadMon 2 devices

Device	Malfunction type	Time of operation
RadMon 2 2 MB with moderator 3 month test	Desynchronisation	393
	Desynchronisation	427
	Desynchronisation	429
	Desynchronisation	487
	Desynchronisation	501
	Desynchronisation	661
	Desynchronisation	902
	Desynchronisation	942
	Desynchronisation	1152
	Desynchronisation	1207
	Desynchronisation	1557
	Desynchronisation	1605

by RadMon 2.0. The system cooperating with a FIFO memory does not measure any SEUs. The memory was insensitive to neutrons during sensitivity tests. However, the system does not demonstrated any faultiness.

CONCLUSIONS

The application of COTS elements allows to design a reliable and cost-effective readout for RadMon monitoring system. A few different versions of the system were built and tested. Performed tests show that both microcontroller- and FPGA-based systems are able to operate correctly when subjected to neutron influence from americium-beryllium. However, a long-term irradiation in the target environment of the linac driving the FLASH laser reveals the advantage of FPGA-based system over the microcontroller version. The FPGA-based readout allows to scan the sensing memory incomparably faster. The parallel nature of the FPGA circuit allows to supervise a few SRAM chips at the same time. Moreover, the scanning time can be further shortened when more SRAMs will be used. However, an application of distributed sensor that is composed of many SRAMs negatively increase its sensitive volume (SV). From the other side, the usage of a parallel memory allows to enhance the entire sensitivity of the sensor.

Restarts of the RadMon 2.0 were unavoidable to guarantee a reliable operation when the desynchronisation was detected. Such a behaviour of the readout can be tolerated during a normal operation assuming that the restarts

occurs adequately sparsely. The external watch-dog was activated only once when the microcontroller-based system did not send any frame.

Data transmitted from all RadMon systems were not stored in the data base when the computer network was damaged. Therefore, a dedicated bus is required to enhance the reliability of the distributed system and measurement of radiation doses.

An employment of FPGA devices shortens the full cycle scanning time below 100 ms. The scanning time is crucial in case of the usage of the monitoring system to trigger an alarm signal when radiation level increases considerably. The response time is much more important than the sensitivity of the monitor for such an application.

The tested FIFO memory was insensitive to the neutron influence during sensitivity tests, hence it cannot be used for radiation detection. However, the application of FIFO memory can simplify the construction of the readout system and the detector. Concluding, a radiation-sensitive FIFO may be an ideal candidate for the neutron fluence detector.

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THE AUTHORS

Dariusz Makowski*, Mariusz Grecki, Bartłomiej Świercz are affiliated to the Department of Microelectronics and Computer Science, Technical University of Łódź, Poland. Bhaskar Mukherjee, Stefan Simrock are affiliated to the Deutsches Elektronen-Synchrotron DESY, Germany
e-mail: *dmakow@dmcs.p.lodz.pl

REFERENCES

- [1] A. Schwarz, “The European X-Ray free electron laser project at DESY”, *26th International Free-Electron Laser Conference*, pp. 85–89, August 2004.

- [2] R. Brinkmann, "Accelerator Layout of the XFEL", *XXII International Linear Accelerator Conference*, vol. 1, pp. 2–7, August 2004.
- [3] G. Materlik and Th. Tschentscher, "Technical design report, PART V-The x-ray free electron laser", *Deutsche Elektronen-Synchrotron DESY*, 2001.
- [4] A. Gamp, "From the TESLA Test Facility to the VUV-FEL user facility", *12th Mixed Design of Integrated Circuits and Systems MIXDES*, pp. 789–793, June 2005.
- [5] G. Barbottin and A. Vapaille, *Instabilities in Silicon Devices, New Insulators, Devices and Radiation Effects*, Elsevier, 1999.
- [6] T.P. Ma and P. V. Dressendorfer, *Ionizing radiation effects in MOS devices and circuits*, Wiley, 1989.
- [7] G. Messenger and M. Ash, *The Effects of Radiation on Electronic Systems*, ISBN 0-442-25417-2. Van Nostrand Reinhold Company Inc., 1986.
- [8] L. Adams A. Holmes-Siedle, *Handbook of Radiation Effects*, Oxford University Press, 2004.
- [9] R. Peterson, "Radiation-induced errors in memory chips", *Brazilian Journal of Physics*, vol. 33, no. 2, pp. 246–249, June 2003.
- [10] P.K.Saxena and N.Bhat, "SEU reliability improvement due to source-side charge collection in the deep-submicron SRAM cell", *IEEE Transactions on Device and Material Reliability*, pp. 14–17, March 2003.
- [11] S. Simrock, "State of the art in rf control", *LINAC 2004 - Proceedings, Germany*, August 2004.
- [12] A. Lesea J. Fabula, J. Moore, and S. Drimer, "Neutron-Induced Soft Error Sensitivity Characterization of FPGAs", *MAPLD International Conference Presentation*, 2004.
- [13] R. Katz, "A scientific study of the problems of digital engineering for space flight systems, with a view to their practical solution", Tech. Rep., NASA Office of Logic Design, 2005.
- [14] D. Makowski, M. Grecki, B. Mukherjee, S. Simrock, B. Świercz, and A. Napieralski, "SRAM-based passive dosimeter for accelerator environments", *7th European Workshop on Diagnostics and Instrumentation for Particle ACcelerators, DIPAC2005*, June 2005.
- [15] D. Makowski, M. Grecki, B. Mukherjee, S. Simrock, B. Świercz, and A. Napieralski, "The application of SRAM chip as a novel neutron detector", *2005 NSTI Nanotechnology Conference and Trade Show Nanotech 2005*, May 2005.
- [16] D. Makowski, M. Grecki, A. Napieralski, S. Simrock, and B. Mukherjee, "A distributed system for radiation monitoring at linear accelerators", *IEEE Transactions on Nuclear Science (TNS)*, p. in print, January 2006.
- [17] D. Makowski, M. Grecki, B. Mukherjee, S. Simrock, B. Świercz, and A. Napieralski, "The application of SRAM chip as a novel neutron detector", *2005 NSTI Nanotechnology Conference and Trade Show Nanotech 2005*, May 2005.
- [18] D. Makowski, M. Grecki, B. Mukherjee, S. Simrock, B. Świercz, and A. Napieralski, "SRAM-based passive dosimeter for accelerator environments", *7th European Workshop on Diagnostics and Instrumentation for Particle ACcelerators, DIPAC2005*, June 2005.
- [19] D. Makowski, M. Grecki, B. Mukherjee, S. Simrock, and B. Świercz, "Radiation tolerant system for neutron fluence measurement", *12th Mixed Design of Integrated Circuits and Systems, MIXDES*, 2005.
- [20] P.K. Samudrala, J. Ramos, and S. Katkoori, "Selective triple Modular redundancy (STMR) based single-event upset (SEU) tolerant synthesis for FPGAs", *IEEE Transactions on Nuclear Science*, vol. 51, no. 5, pp. 2957–2969, 2004.
- [21] R. Katz, R. Barto, P. McKerracher, B. Carkhuff, and R. Koga, "SEU hardening of field programmable gate arrays (FPGAs) for space applications and device characterization", *IEEE Transactions on Nuclear Science*, vol. 41, no. 6, pp. 2179–2186, 1994.
- [22] D. Makowski, M. Grecki, A. Napieralski, S. Simrock, and B. Mukherjee, "A distributed system for radiation monitoring at linear accelerators", *RADIATION and its Effects on Component and Systems RADECS*, p. in print, September 2005.