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Radiation monitoring system for X-FEL

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Abstract

Radiation produced during the operation of linear accelerators poses a potential threat to electronic devices installed in the accelerator tunnel. Therefore, a distributed radiation monitoring system was installed at five various spots in the Free electron LASer in Hamburg (FLASH) tunnel. The presented system allows us to measure radiation produced during the operation of a linear accelerator driving FLASH in real time. The system is composed of two modules: radiation-sensitive sensors and a radiation-tolerant readout system constructed with the application of commercial-off-the-shelf (COTS) components. The neutron dosimeter was constructed using an innovative application of a static random access memory (SRAM), whereas a well-known radiation-sensitive RadFET was used for gamma quantification.

Keywords: radiation monitoring, linear accelerator, radiation-tolerant device, single event upset, static random access memory

(Some figures in this article are in colour only in the electronic version)

1. Introduction

Radiation produced during operation of high-energy accelerators could be detrimental to electronic components and systems used to control the machines. Therefore, electronic systems and power devices utilized in linear accelerators are usually placed in a safe non-radiation area. Hence, two parallel tunnels are usually built: one for the main accelerating modules and another one for control systems. However, a single circular cross-section tunnel is built for the x-ray free electron laser (X-FEL), therefore most of electronic devices used to control the machine will be placed in the same vault as the main beam pipe [1, 2]. Thus, devices will be exposed to bremsstrahlung gamma radiation and photoneutrons produced during the operation of a linear accelerator [3, 4].

A powerful digital low level radio frequency (LLRF) system is required to fulfil the sharp demands of the control system that allows for a reliable operation of the accelerator. The radio frequency phase and amplitude stability must be better than 0.01° and 0.1%, respectively [5]. Currently, digital signal processors (DSPs) and field programmable gate array (FPGA) devices are used to design a digital LLRF subsystem. An exemplary LLRF module is based on the Xilinx Virtex II pro FPGAs. The complex system utilizes additional digital circuits, such as static and dynamic random access memories (SRAMs/DRAMs), Altera FPGA, digital-to-analogue (DAC) and analogue-to-digital (ADC) converters. A main computer with UltraSPARC processor and control electronics are placed in crates and communicate using VersaModule Eurocard bus (VME) interface.

Both types of radiation produced in the tunnel can pose a threat to the complex control system. Gamma radiation is mainly responsible for continuous degradation because of total ionizing dose effect (TID), while neutrons cause displacement damage and generate single event effects (SEE).

1.1. The x-ray free electron laser

The European project x-ray free electron laser (X-FEL) is a fourth generation synchrotron light source capable of producing high-intensity ultra-short wavelength x-ray laser light [6]. The whole machine will be housed in a 3.1 km long tunnel, having a cross-section diameter of 5.2 m. Electronic hardware that controls the laser will be installed in the main tunnel.

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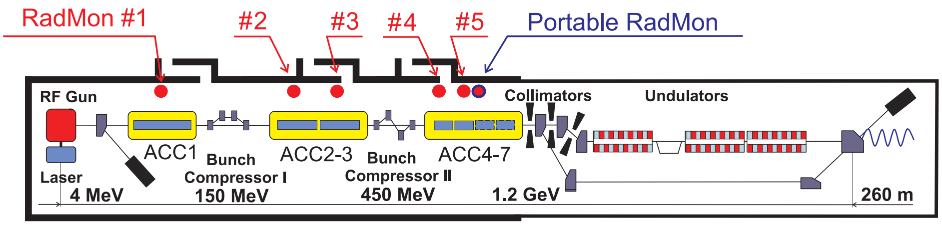

Figure 1. The top view of the FLASH tunnel.

The x-ray laser is under development and the construction of X-FEL is scheduled for years 2008–2012. However, the pilot facility of X-FEL, Free electron LASer in Hamburg (FLASH), has already been in operation at the German national research and accelerator centre Deutsche Elektronen-Synchrotron DESY in Hamburg. The top view and the sketch of the tunnel layout of FLASH are depicted in figure 1.

1.2. Radiation environment of a linear accelerator

A mixed neutron and gamma radiation field is present in the linear accelerator environment. The beam loss pattern in a linear accelerator is difficult to predict because of its strong dependence on machine operation conditions [9]. Therefore, the precise spectra of radiation produced in FLASH are not known.

Radioactive nuclides are mainly generated in high-energy linear accelerator environments because of interactions between the electron beam with cavities, accelerator components and shielding elements[3] [12]. Moreover, electrons accelerated by cavities produced by the dark current from the radio frequency (RF) gun are able to gain energy high enough to generate radiation during collisions. However, the major share of radiation comes from the interaction of field emission electrons with walls of the cavity itself [13].

One can distinguish two main types of radiation produced during the operation of high-energy linear accelerators: bremsstrahlung photons and photoneutrons [3]. GDR photoneutrons interact with the shielding and concrete walls of the accelerator tunnel and yield a further energy reduction (thermalization) [7]. Therefore, thermal neutrons and neutrons with a peak energy distribution near a few MeV can be observed in the high-energy linear accelerator tunnel, like the above-mentioned FLASH.

1.3. Radiation monitoring in a linear accelerator

Ionizing radiation continuously damages electronic components because of the TID effect. Non-ionizing particles are responsible for the displacement or non-ionizing energy loss (NIEL) damage. Moreover, neutrons can mainly affect digital components by single event effects (SEEs). The application of Radiation Monitor (RadMon) may be helpful to estimate and analyse IEL and NIEL damage in electronic components used to design linear accelerator's control systems. Due to the fact that most of electronic components are produced using silicon, it is preferable to measure a gamma radiation dose with reference to the dose

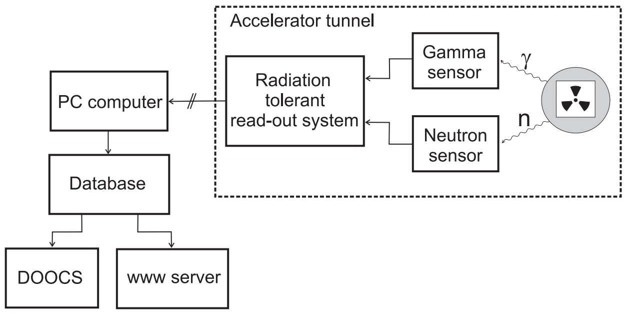

Figure 2. The block diagram of the radiation monitoring system RadMon.

absorbed by silicon dioxide and neutron fluence should reflect damage in silicon.

Knowledge of neutron and gamma doses is crucial to understand and interpret radiation effects on electronic devices dedicated to the operation in the environment of high-energy linear accelerators. Indeed, it is advisable to monitor radiation produced in the FLASH or X-FEL tunnels in real time to estimate the danger and the lifetime of electronic components and devices. Additionally, tough safety regulations support the need to control the radiation environment in the tunnel in real time. The system could also be helpful to choose a suitable place for crates with electronics in the accelerator when the radiation levels are the lowest. The appliance might also be useful to design correct gamma and neutron shielding.

The radiation monitoring system may also help to minimize neutron fluence and gamma radiation doses generated during the operation of the linear accelerator.

2. The distributed on-line radiation monitoring system

The radiation monitoring system RadMon is composed of two modules: radiation-sensitive sensors and the radiation-tolerant readout circuit able to operate correctly in the radioactive environment of the linear accelerator. The block diagram of the radiation monitoring system is presented in figure 2. Measured gamma radiation and neutron fluence in the accelerator's vault are transferred to a PC placed outside the tunnel in a safe, non-radioactive area and then gathered in a database. Data are accessible via the www interface and distributed object oriented control system (DOOCS).

2.1. Requirements for the radiation monitoring system RadMon

There is a strong need to measure both types of radiation, i.e. absorbed gamma dose and neutron fluence in real time.

[3] The cavities of the superconducting linacs driving X-FEL or FLASH are produced of pure niobium.

Therefore, applied neutron and gamma radiation sensors should allow us to quantify accumulated doses and dose rates of radiation present in a linear tunnel. Sensors should have small sensitive volumes to ensure uniform response over the active area. Detectors must measure radiation correctly in the pulsed radiation environment of the FLASH or X-FEL facilities. They should have good enough sensitivity and dynamic ranges. The readout device of the radiation monitoring system should be preferably equipped with a digital interface to enable easy connection of the system to a computer network. Therefore, data measured in a few different places through a linear accelerator can be sent to a main computer and gathered in a database for future display and analysis. The construction of the system should give an opportunity for further extension. Above all, the construction of the system should be cost effective.

3. Neutron fluence and gamma radiation sensors

Silicon sensors were taken into consideration as candidates for the gamma radiation dose and neutron-fluence dosimeters. The primary sensor, neutron dosimeter, was constructed with the application of a commercially available SRAM chip [14, 16, 29]. Silicon SRAMs disclosed a high neutron vulnerability during radiation sensitivity tests of electronic components carried out at DESY [7, 14–16]. Moreover, a SRAM-based sensor has a big advantage because gamma radiation is not able to trigger a single event effect (SEU) [14, 16].

3.1. SRAM-based neutron-fluence dosimeter

The number of soft, recoverable single event upsets generated in a SRAM device increases with the number of neutrons passing through the chip. The suitable pattern should be written to memory before exposure. The calculated number of SEUs detected in the memory can be used to calculate neutron fluence in a similar way as it is for DRAMs [17–20].

Standard memories manufactured by diverse manufacturers reveal different SEU sensitivities to neutron radiation. Some of them are very susceptible to high-energy neutrons, another to thermal neutrons. Memories with error correction code (ECC) circuits are much more SEU resistant and therefore cannot be used as a neutron-fluence detector. A large number of miscellaneous memories were examined with the application of a calibrated ^{241}AmBe(α, n) americium–beryllium neutron source to select the most suitable SRAM as a neutron dosimeter. Auxiliary irradiations were performed initially in the Linac II and the FLASH accelerator tunnels [4].

The performed research reveals that modern, high-capacity memories are at least two orders of magnitude more resistant to neutrons, because of the absence of a borophosphosilicate glass (BPSG)—(n, α) conversion layer. Generally, the devices manufactured in older technologies disclose the highest SEU cross sections.

Finally K6T4008C1B-VB55 512 kB memory fabricated in 0.4 μm technology by Samsung was chosen. The 512 kB memory was subjected to a light water moderated neutron source with $E_{\mathrm{AV}} = 4.1$ MeV for 47 h. The distance between

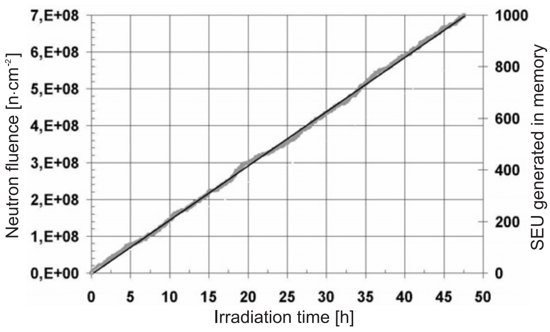

Figure 3. Accumulated neutron fluence and number of SEUs generated in the 512 kB memory irradiated from ^{241}AmBe.

the device under test (DUT) and the source was equal to 6.9 cm. The memory was supplied with 5 V. The accumulated soft errors generated during exposure and calculated accumulated neutron fluence are depicted in figure 3. The applied 512 kB memory supplied with 3.3 V has a cross section equal to 3.18×10^{-13} cm^2 bit^{-1} and sensitivity factor 1.34×10^{-6} cm^2. The memory supply voltage was lowered intentionally to enhance the detector's sensitivity.

The sensitivity factor (SF) S was introduced by multiplying memory capacity D by calculated SEU cross section σ_{SEU}, which is the figure of merit of SRAM-based neutron detector performance:

$$S = \sigma_{\mathrm{SEU}} \cdot D. \quad (1)$$

3.1.1. Methods to increase the sensitivity of the neutron sensor. The sensibility of the selected memory was not good enough to measure the neutron fluence in the FLASH tunnel. An application of higher capacity SRAMs was not possible, because of poor sensitivity, therefore other methods allowing increase in the sensitivity were taken into consideration. A series of irradiations with water moderated americium–beryllium was carried out to investigate the possibility of sensitivity enhancement when SRAM supply voltage is lowered. The Samsung chip is normally supplied with 5 V. In practice, the memory operated when the voltage was higher than 2.7 V. The experiment proved that the SEU sensitivity of the Samsung SRAM chip can be enhanced 3.9 times for 3.3 V required for long-term reliable operation.

Cylindrical moderators made of polyethylene with different diameters ϕ10, 13, 18 cm were used to investigate the ability to enhance the sensitivity of a SRAM-based neutron detector. The tests were carried out in the FLASH accelerator. The ideal shape of the device should be spherical to assure a uniform slowing down of neutrons around a point neutron dosimeter. A quasi-spherical moderator presented in figure 4 was applied instead of the ideal spherical structure. The best results were obtained for the moderator with 9 cm radius when the sensitivity was enhanced 3.9 times. The proposed detector consists of four SRAM devices (total capacity 2 MB), thus the SV is four times larger compared to a single chip. During the experiments two types of 2 MB memory modules were used, flat and sandwich versions, see figure 5. The sandwich structure imitates a point detector better because of more concentrated SVs and therefore it is more suitable for the detector.

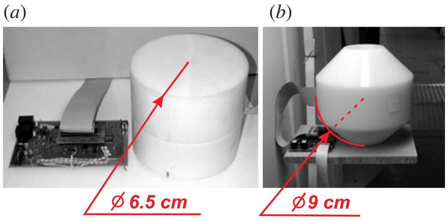

Figure 4. Polyethylene moderators: (*a*) 6.5 cm cylindrical and (*b*) 9 cm semi-spherical moderators.

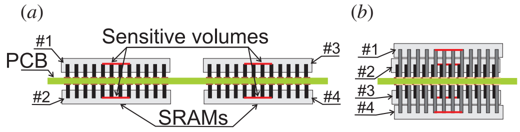

Figure 5. The SRAM-based sensors: (*a*) the flat version and (*b*) the sandwich structure.

The total sensitivity to soft errors was increased 88 times when all methods described above were utilized.

3.2. RadFET dosimeter

The Radiation-sensitive Field Effect Transistor (RadFET) was used as a secondary dosimeter for gamma dose measurement [30]. RadFETs are produced with different silicon oxide thicknesses, thus the required sensitivity can be easily adjusted. The series of irradiation tests used implanted and non-implanted detectors fabricated by NMRC company (100, 400, 1000 nm). The RadFETs were irradiated in two modes, when the electric field across the oxide was equal to 0 and 0.125 MV m^{-1}. The research carried out allows us to choose the 4 kÅ implanted RadFET as a gamma dosimeter because of a good sensitivity, low initial threshold voltage and relatively low fading effect.

4. The readout radiation-tolerant system

The radiation-tolerant system was designed to allow long-term reliable operation in the radiation environment of the FLASH and later the X-FEL. Radiation-hardened components were not used to design the system because of their exorbitant costs. Instead, Commercial-Off-The-Shelf (COTS) devices were employed to design a cost-effective distributed system that can be installed in various places of the accelerator.

Digital devices exposed to radiation suffer mainly because of TID, displacement damage effect and SEEs. The readout system was designed in such a way that it can tolerate SEEs, in particular SEUs and single event latchups (SELs). Therefore, the deployed mechanisms and algorithms allow us to operate in the linear accelerator environment. Selected components were used to assure gamma tolerance up to 500 Gy(Si). The negative influence of gamma radiation and neutron displacement damage can be reduced by the application of suitable shielding.

A few different versions of RadMon readout were designed and examined, while SRAM devices were being tested [4, 10]. Hardware and software methods were used to protect the devices against SEUs. Fast resettable fuses were employed to secure readout systems against SEL. Two different versions of readout devices were designed using double modular redundancy (DMR). Two microcontrollers execute the same code, however only one supervises the memory chip. The system is restarted when a fast comparator detects discrepancy in control signals. A radiation-tolerant microcontroller was implemented in Actel Field Programmable Gate Array (FPGA) device. Hamming codes, triple modular redundancy (TMR) and memory scrubbers were responsible for SEU correction. The last version of the device was also implemented in FPGA. Simple finite state machine (FSM), secured by TMR and Hamming codes, has a huge advantage. In contrast to microcontroller-based devices the memory scanning time is shorter than 100 ms. Application of double redundancy requires restarting both microcontrollers, therefore the scanning time is in the range of dozens of seconds. The radiation-tolerant microcontroller needs 2 min to scan the whole memory.

The SRAM-based sensor should be scanned continuously after an initialization process. However, the short interruptions of memory checking are permitted because the error of measured neutron fluence caused by a system restart is relatively insignificant. When the device is used to trigger an interlock system, the scanning cycle and restart time must be shorter than 100 ms and restarts of the system should be minimized [21].

4.1. FPGA-based radiation-tolerant readout system

The readout system was constructed using FLASH-based ProASIC plus FPGAs made by Actel. The data describing their vulnerability to neutrons and gamma radiation were studied before their selection [22–24]. The cross sections calculated for APA750 are equal to 3.1×10^{-13} cm^2 bit^{-1} for neutrons with energies below 1.5 MeV and 2.4×10^{-13} cm^2 bit^{-1} for neutrons with energies higher than 10 MeV. Single event gate rupture (SEGR) is only expected during FPGA programming when the device is supplied with 16 V. Moreover, in contrast to SRAM-based devices, the FLASH FPGA storage element is not expected to be sensitive to SEU [25]. The maximum allowed TID for the Actel ProASIC fabrication technology should amount to at least 500 Gy(Si) [25, 26].

Thus, the APA ProASIC plus devices are ideally suited as control devices of the readout system. The utilization of FLASH-based FPGAs may eliminate a part of the SEU-generated errors. Nevertheless, single event transients (SETs) can still be triggered in the control logic of FPGA [27].

The device cooperates with a compact version of sensing memory that is composed of four 512 kB stacked memory modules. A simplified block diagram of the FPGA-based reader is presented in figure 6.

The device consists of the main FSM, responsible for supervision of all submodules. The SRAM memory is programmed after restart with a pattern. Suitable information is sent to the main PC 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) in increased and corrected data are written into the memory. The number of detected SEUs is sent to

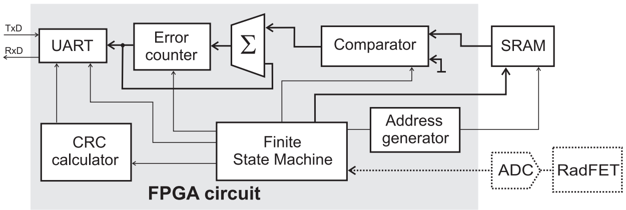

Figure 6. The block diagram of the FPGA-based RadMon.

Figure 7. The wall mounted RadMon detector.

the PC after a whole scanning cycle. A heartbeat frame must be transmitted in a period of time shorter than 1 s to avoid triggering off an external watch dog. The data sent are secured with a 32 bit cyclic redundancy checking (CRC) checksum to avoid transmission errors and to verify the correctness of the reader operation. The digitalized RadFET's threshold voltage is delivered every 10 min. The external watch dog is activated when the readout system does not send any frame after a specified period of time.

5. The RadMon system installed in FLASH

The RadMon devices equipped with 2 MB stacked memory neutron-fluence detectors and the 4 kÅ implanted RadFET dosimeters have been installed in the FLASH tunnel. The devices were built using FPGA-based readout systems. The devices were installed at five selected places on the right-hand side of the accelerating modules AAC1–ACC5 approximately 20 cm from the concrete wall, see figure 1. A photograph of the wall mounted RadMon monitoring system installed opposite ACC1 module is presented in figure 7.

Moreover, a single portable RadMon device was applied to measure radiation in different places near modules ACC4–ACC6. A photograph of the portable system is depicted in figure 8.

The accumulated gamma radiation and neutron-fluence characteristics registered during 2 months of operation of the RadMon installed opposite accelerating module ACC1 are presented in figure 9. During the exposure the SRAM memory registered 48 910 SEUs, while the threshold voltage of RadFET sensor has been increased by 0.26 V. Any restart of the readout system was registered.

The calibration of SRAM memory was executed *in situ* in the FLASH tunnel. A bubble dosimeter was used as a reference dosimeter. The gamma detector was calibrated using a ^{137}Cs source. Obtained calibration factors for dosimeters are depicted in table 1.

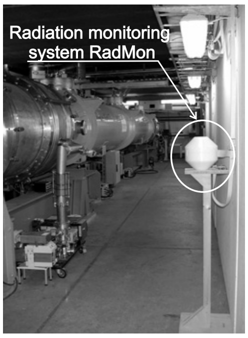

Figure 8. The portable RadMon device.

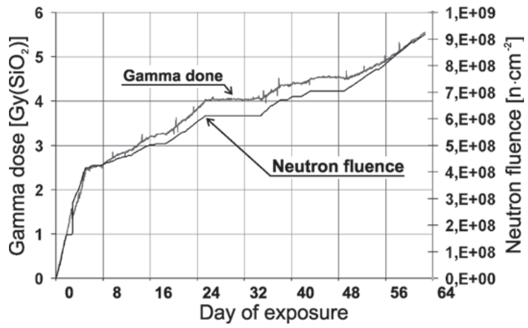

Figure 9. The accumulated dose of gamma radiation and neutron fluence registered in the FLASH.

Table 1. Calibration factors for SRAM-based and RadFET dosimeters.

Calibration factor	SRAM	RadFET
Neutron fluence	1.85×10^4 n cm^{-2}/SEU	–
Silicon kerma	1.17×10^{-3} Gy(Si)/SEU	–
Gamma dose	–	46.3 mV/ Gy(SiO_2)

A calibration factor allowing us to calculate displacement kerma was estimated [28]. Displacement kerma can be helpful during the analysis of displacement damage caused by energy deposited in the form of displacement damage by neutron interactions.

6. Conclusions

A radiation monitoring system dedicated to gauging neutron fluence and gamma radiation in a linear accelerator tunnel was installed and tested in the FLASH tunnel. The application of silicon dosimeters allows us to design a cost-effective and sensitive enough radiation monitoring system for the FLASH accelerator.

The sensitivity of the commercial memories to neutron-provoked SEUs was not sufficient to measure radiation in the FLASH. The sensitivity of the high-capacity memories manufactured in modern technologies should be dramatically enhanced, whereas the feature size and supply voltage are decreased. The number of generated soft errors decreased significantly contrary to expectations. Thus, high-capacity modern memories with low supply voltages are not good candidates for a neutron-fluence sensor. Therefore, the 512 kB Samsung memory manufactured in 0.4 μm technology was chosen as a neutron dosimeter. Three additional methods were proposed to enhance the sensitivity of the detector 88 times.

Indeed, the RadFET and SRAM memories are cost-effective solutions and therefore the on-line monitoring system can be installed inside a long accelerator tunnel. Moreover, the number of SEUs generated in a SRAM can be directly compared with soft errors induced in the accelerator's digital system. Dosimeters can be used for dose rate and absorbed dose real-time monitoring.

The FPGA-based readout allows us to scan the sensing memory incomparably faster than a microcontroller-based system. The parallel nature of the FPGA circuit allows us to supervise a few SRAM chips at the same time. Moreover, the scanning time can be further shortened when more parallel SRAM-based dosimeters are used. However, an application of a distributed sensor that is composed of many SRAMs negatively affects its sensitive volume (SV). On the other hand, the usage of a parallel memory allows us to enhance the overall sensitivity of the sensor. The scanning time is crucial in the case of the usage of the monitoring system to trigger an alarm signal when radiation level increases considerably.

Research allows us to find the most suitable architecture and design of the readout for the on-line radiation monitoring system dedicated to a linear accelerator. The application of various radiation mitigation techniques enables us to design digital readout systems that are able to operate in the radiation environment of a linear accelerator. Systems have been intentionally built using COTS elements to obtain a cost-effective solution. However, an application of commercially available components enables only to mitigate SEE. The resistance to ionizing radiation, in particular to TID, is strictly imposed by the fabrication technology and design of electronic circuits.

The RadFET as well as SRAM memory have limited lifetime. The maximum measured dose for a RadFET dosimeter depends on the gate oxide thickness and the maximum allowed input voltage of the readout circuit. However, there is always a compromise between the sensitivity and the maximum measured dose. The maximum dose of the SRAM sensor is primarily restricted because of the TID damage effect. The applied 4 kÅ RadFET and designed reader should allow us to measure gamma radiation in the FLASH tunnel for five years.

Acknowledgments

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