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RADIATION QUALIFICATION OF COMMERCIAL OFF-THE-SHELF P-I-N RECEIVERS FOR THE TTC SYSTEM

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Abstract

The sensitivity to Single Event Upsets (SEUs), Total Ionizing Dose (TID) and Non Ionizing Energy Loss (NIEL) is presented for two commercial off-the-shelf p-i-n receivers selected for use with the Timing Trigger and Control Receiver ASIC (TTCrx). Bit Error Rate (BER) measurements were made during the SEU tests with protons and used as a post-irradiation qualification for the total dose tests with neutrons and gamma rays. Both devices met the radiation tolerance constraints set by the ALICE, ATLAS, CMS and LHCb experiments. However, the TrueLight receiver displays a higher robustness to SEU.

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1 INTRODUCTION

Two types of optical receivers, chosen to work with the Timing Trigger and Control Receiver ASIC (TTCrx)[1], were studied to evaluate their performance degradation when exposed to radiation. Two manufacturers, Agilent and TrueLight, offer an eligible product consisting of a p-i-n photodiode coupled to a pre-amplifier. The TTCrx will be used by all the LHC experiments. Around 20 000 of these chips will be produced. A similar number of receivers will also have to be purchased. Because of a difference in price of over 50%, the choice of the manufacturer will also have a significant impact on the overall cost of the TTC project. In order to make this choice in the most effective conditions, one has to know how the components are going to be affected by the radiation received when operated inside the LHC experiments during the expected 10-year lifetime. A series of tests was carried out on these optical receivers to evaluate the resistance to protons, neutrons and γ-ray radiation. Single-Event Upset (SEU) tests are based on proton irradiation. They aim to evaluate how much the devices are subject to upsets, latch-up, or other Single-Event Effects (SEEs). The Total Ionizing Dose (TID) tests enable the effects of the cumulated ionizing dose deposited in the oxides of the electronic components to be measured. Finally, the Non Ionizing Energy Loss (NIEL) tests measure the effects of displacement damage in silicon induced by neutrons. As a final result of these combined tests the reader will be provided with an evaluation of the radiation tolerance of the two candidate devices.

2 EXPERIMENTAL

2.1 Test method

In order to evaluate the contribution of each type of radiation in the ageing process of the devices, the survey was broken down into three phases: SEU, TID, and NIEL tests. For reliability and legitimacy it was decided that the tests should be carried out according to the rules of the policy described in ATLAS document ATC-TE-QA-0001.

2.2 Samples tested

Because of their commercial availability and their compliance with the requirements of the TTCrx, samples from two manufacturers were selected. No data were available concerning device behaviour under any type of radiation. Relevant characteristics of the two devices tested are shown in Table 1.

Table 1
Agilent and TrueLight devices data comparison

Manufacturer and type	Technology	Measured power consumption	Measured input optical power range
Agilent HFBR-2316T	Bipolar	7 mA	Max. –11 dBm Min. –25 dBm
TrueLight TRR-1B43-000	CMOS	31 mA	Max. –0 dBm Min. –31 dBm

Each device was given an identification number, labelled, and tested to ensure its proper functionality prior to irradiation according to document ATC-TE-QA-0001. The devices tested originated from batches with different identification numbers. Since no information was released on the homogeneity of these batches, the devices were tested as though they originated from unknown batches. As described in the ATLAS test method, while only 11 devices would need to be tested when emanating from an homogeneous batch, 22 are required when no manufacturing information is available. This larger number of devices tested also guarantees a greater flexibility for the future purchase of the selected components.

2.3 Test set-up

A test system was designed in order to characterize and monitor the behaviour of the Devices Under Test (DUTs) before, during, or after irradiation. It focuses on the monitoring and recording of two key parameters: The power consumption and the Bit Error Rate (BER).

The BER is the number of bit errors divided by the total number of bits transmitted. This parameter is an efficient way to record the upsets induced by a proton beam on the optical receivers under test. It was also used to measure the device performance after irradiation with γ-rays or neutrons.

The power consumption is also relevant since it quantifies how the pre-amplifier transistors have been affected by the radiations.

Figure 1 shows a schematic of the test set-up.

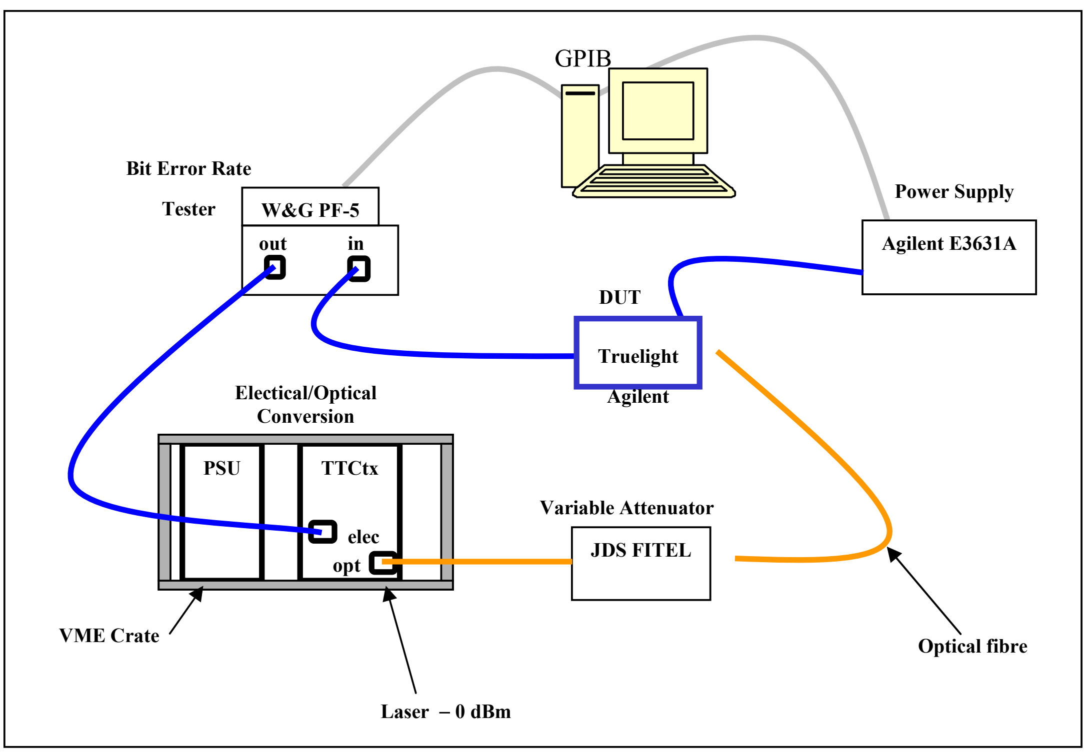

Figure 1: Test set-up

The data flow is produced by a Bit Error Rate Tester (BERT) from W&G. A given pattern of 9 bits is continuously generated and sent at a bit rate of 160 MHz. This speed was chosen to match the data rate flowing through the optical fibre hooked up to the TTCrx in normal use. The output of the BERT is connected to the input channel of a VME module designed at CERN and called TTCtx. This device converts the received electrical signal into its optical equivalent. The light-emitting source is a 0 dBm laser whose optical power is attenuated in a JDS variable attenuator. This allows the tuning of the optical power sent to the DUT and the exploration of its sensitivity range. The optical path uses multimode optical fibre.

The response of the DUT to the signal carried by the optical fibre is amplified and transmitted back to the BERT by ECL drivers. The test board is designed in such a way that testing of both types of device can be effected by swapping a set of dedicated mezzanine boards. Each mezzanine is independently powered by a remotely controlled Power Supply Unit (PSU). This allows an accurate measurement of the power consumption of the DUT.

The BERT extracts the BER by comparing its outgoing signal with the incoming signal from the DUT.

Both the BERT and the PSU are controlled and monitored by a PC through a GPIB connection. A dedicated user interface allows one to record the number of errors detected, the evolving BERT, and the power consumption with time.

Depending on the type of test, this system was used either in a real-time fashion when running during the irradiation (SEU) or as a post-irradiation characterization set-up (TID and NIEL). As further described in Section 3.2, an irradiation set-up was built to hold devices during the TID tests. It consists of a set of PCBs on which the DUTs are plugged and properly biased. The NIEL test made use of an aluminium plate on which the samples were standing. This is an easy way to both hold the DUTs and keep all their pins shorted.

2.4 Test planning

In order to ensure the significance of the tests, each experiment (ATLAS, ALICE, LHCb and CMS) was asked to communicate the required radiation tolerance constraints. These are shown in Table 2.

Table 2

Constraints for each experiment

Experiment	TID constraint	NIEL constraint
ATLAS	3.5 kGy (350 krad)	3.2×10^{13} n/cm^2
LHCb	7.2 kGy (720 krad)	1.67×10^{13} n/cm^2
CMS	0.25 kGy (25 krad)	5×10^{12} n/cm^2
ALICE	0.01 kGy (1 krad)	5×10^{8} n/cm^2

Defining the constraints for the SEU was not so straightforward. The goal of the SEU test is to gather enough statistics to be able to predict the probability of occurrence of an upset in a particular environment. It is more about collecting a sufficient number of events than reaching a calculated fluence. The goal should then be to see at least a hundred errors during the time allocated to each test.

The number of devices of each type along with the maximum constraints values is given in Table 3.

Table 3
Number of samples per test and constraint values

Test type	No. of samples	No. of reference devices	Constraint	Value
SEU	4	–	No. of errors	>100
TID	20	2	Total dose	750 krad
NIEL	20	2	Fluence	7×10^{13}n/cm^2

The irradiation facilities were chosen to meet the irradiation requirements listed above. Their coordinates can be found in Table 4.

Table 4
Irradiation facilities

Test type	Institute	Source characteristics	Address
SEU	CRC	60 MeV protons 1×10^8p/cm^{2}s	Chemin du Cyclotron, 2 B-1348 Louvain la Neuve(LLN) Belgium
TID	UCL/CMAT	Three Co^{60} sources 100 krad/h	Chemin du cyclotron, 2 B-1348, Louvain la Neuve Belgium
NIEL	Prospero	Flux <5 10^{14} n/cm^{2}s	CEA Valduc F-21120 Is-sur-Tille France

The following sections describe the irradiation set-ups along with the practical execution of the tests.

2.4.1 SEU tests

A beam time of 8 hours was allocated to this test at the CRC at LLN. Three goals were identified:

1. Test four devices of each type according to the ATLAS recommendation.
2. Quantify the impact of the source optical power on the BER during irradiation.

3. Determine how the BER is affected by the beam incidence angle on the DUT.

Table 5 shows a breakdown of the test for each type of component listing the amount of time used for each step.

Table 5
SEU test planning

Step number	Step description	Sample number	Duration in min
1. Optical power tuning	OP = –5 dBm	1	15
	OP = –14 dBm		15
	OP = –22 dBm		15
2. Influence of beam angle	OP = –22 dBm θ = 45°		5
3. SEU	OP = –18 dBm	2	20
		3	20
		4	20
		5	20

The automated measurement interface allowed the data in the BERT and the PSU to be fetched every 30 seconds. The BER, the number of errors, and the current in the DUT were sampled over the duration of the test. Upon completion these values were saved in a text file. A latch-up protection was also implemented using the current limitation feature of the PSU.

In order to avoid putting the instruments inside the experiment hall, thus preventing valuable equipment from being activated, 30-m long cables were used to connect the board holding the DUT to the BERT. Similarly, a 110 m long optical fibre carried the data flow from the attenuator to the DUT.

2.4.2 TID tests

In order to expand the boundaries of this test it was decided not only to meet the maximum required doses but also to largely exceed them. Five devices of each type were given a 2 Mrad dose to learn more about their radiation tolerance threshold.

Because of the complexity of monitoring 20 devices simultaneously during irradiation, it was decided to irradiate the properly biased samples and to perform functional tests at given doses. The course of the three days of tests is shown in Table 6.

Table 6
Course of the TID tests

Day	Samples irradiated	Functional test at	TID at end of test
1. TrueLight	10	100 krad	
		200 krad	
		300 krad	
		400 krad	
		500 krad	
	10+6	1 Mrad	6 devices: 500 krad 10 devices: 1 Mrad
2. Agilent	10	100 krad	
		200 krad	
		300 krad	
		400 krad	
		500 krad	
	10+6	1 Mrad	6 devices: 500 krad 10 devices: 1 Mrad
3. 2-Mrad test	5 Agilent 5 TrueLight	2 Mrad	5 Agilent: 2 Mrad 5 TrueLight: 2 Mrad

Owing to a lack of space on the irradiation site, only 6 components instead of 10 of each type could be irradiated up to 500 krad.

Each functional test consisted of plugging a DUT in the test set-up and running it until the measured BER reached 10^{-9}. This takes around 2 minutes. The value of the current consumption of the DUT is also recorded.

2.4.3 NIEL tests

As advised in the ATLAS policy on radiation-tolerant electronics, the devices to be exposed to the neutron beam of Prospero were not biased and had all pins shorted. The post-irradiation inspection consisted of the same protocol as the functionality check during the TID test.

Since no online monitoring of the DUT was possible, it was decided to perform three fluence steps. Only seven devices of each type would actually reach the final constraint. In the event of irreversible damage it would make it easier to locate the destructive fluence threshold.

Table 7 shows the three steps followed for the test on each type of device.

Table 7
Fluence steps during the NIEL test

No. of devices = f (fluence)	2×10^{12} n/cm^2	1×10^{13} n/cm^2	7×10^{13} n/cm^2
Agilent	6	7	7
TrueLight	6	7	7

3 RESULTS AND DISCUSSION

3.1 Proton radiation effect

3.1.1 Influence of the optical power

By increasing the source optical power the signal-to-noise ratio is expected to rise. This is because the noise level created by the protons in both the p-i-n diode and the pre-amplifier remains independent of the optical power. To highlight this effect three successive tests with three values of optical power were performed. Table 8 shows the results obtained for both the Agilent and TrueLight devices.

Table 8
BER as a function of source optical power

BER = f (OP)	–5 dBm	–14 dBm	–18 dBm	–22 dBm
Agilent		3.78×10^{-9}	4.46×10^{-8}	5.80×10^{-7}
TrueLight	7.12×10^{-12}	1.72×10^{-10}		5.77×10^{-8}

It already seems that the devices from TrueLight present a better behaviour when exposed to the proton beam. When looking at the BER obtained for an optical power of –22 dBm an order of magnitude can be observed between the two types of device. This result is particularly relevant because it corresponds to the optical power available at the output of the TTCvx modules. These modules are based on a LED and not on a laser like the TTCtx (used for these tests). Nevertheless these results are not statistically significant and need to be confirmed by more tests as described in Section 3.1.3.

It is also interesting to note that as far as the optical power is concerned the behaviour of the two devices is very similar. The S/N ratio varies in the same proportion as the optical power. Figure 2 shows some linearity in the evolution of the BER as a function of the optical power. This can be particularly interesting for the end-user to determine the best-suited optical power, i.e., BER for his application.

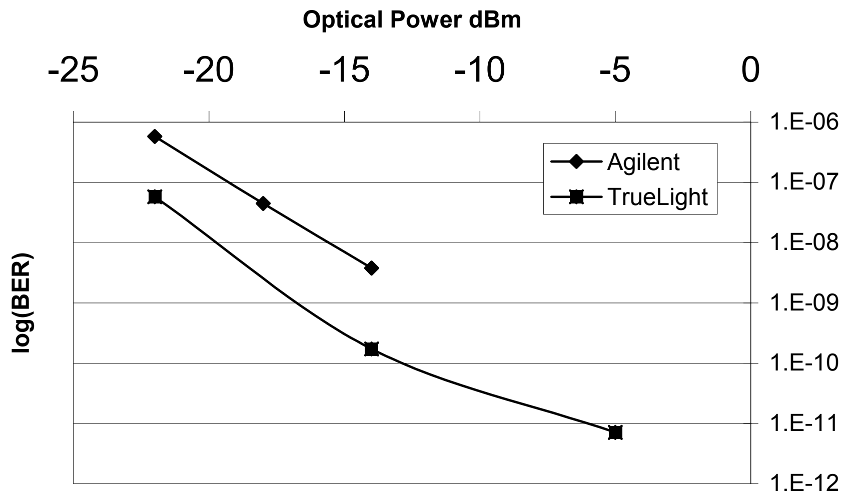

Figure 2: BER plotted as a function of source optical power

3.1.2 Influence of the incidence angle

Since the scope of these tests is to define whether the two products will work properly with the radiation environment of the LHC experiments, the most unfavourable scenario was considered. As a result the beam incident angle was chosen to maximize the section of active area crossed by the protons in the p-i-n diode. Previous work [2] showed that interactions occur mainly in this part of the device. This implies an incident angle of 90° as shown in Fig 3.

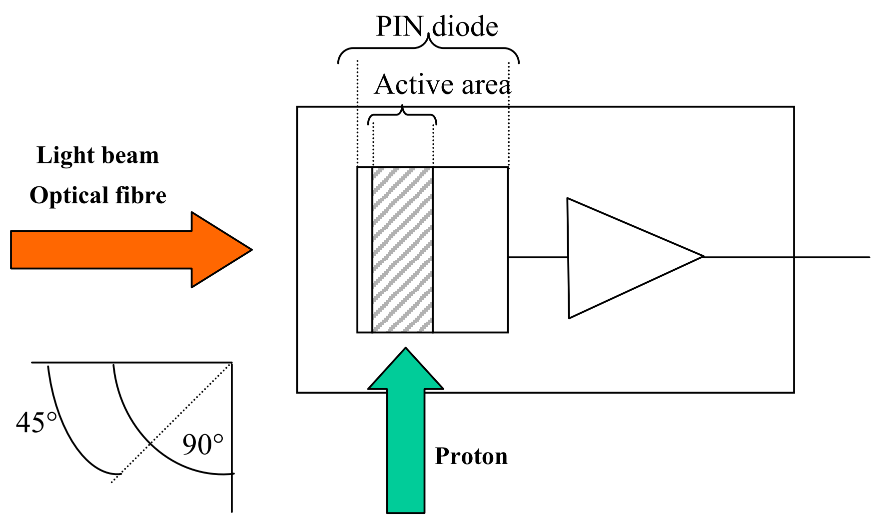

Figure 3: Proton beam incident angle on the DUT

By flipping the DUT by 45° a drop in the error rate was observed. This corresponds to a smaller section of active area crossed by the protons. The results for the two types of devices are shown in Table 9.

Table 9
BER as a function of the beam incident angle

BER = f (inc angle) at OP = –22 dBm	90°	45°	Drop by a factor
Agilent	5.80×10^{-7}	1.58×10^{-8}	36
TrueLight	5.77×10^{-8}	2.15×10^{-9}	26

Once more the behaviour of the two devices is very similar. This result also highlights the fact that when going away from the worst-case situation the BER drops roughly by a factor 30.

3.1.3 Influence of the proton beam

To confirm the first results obtained on a single device in Section 3.1.1, four more devices of each type were exposed during 20 minutes to a beam of 60 MeV protons with a flux of 108 p/cm2s. A medium value of optical power was chosen and set to -18 dBm. The results of this test are presented in Table 10.

Table 10
BER for a 10^8 p/cm^{2}s flux of 60 MeV protons

	Average BER	Standard deviation
Agilent	2.5×10^{-8}	1.9×10^{-8}
TrueLight	4.67×10^{-9}	8.4×10^{-10}

When looking at the mean values of the BER, the results confirm the first intuition developed in Section 3.1.1. As far as resistance towards the proton-induced errors is concerned, TrueLight components seem to behave better than the Agilent ones. As in Section 3.1.1 there is an order of magnitude between the performance of the two manufacturers. The high standard deviation obtained for the Agilent devices reveals a significant inhomogeneity in the robustness of these devices to SEU.

During all these tests no significant increase in the power consumption of the DUTs could be detected. The current values remained equal to what had been measured before irradiation thus showing no evidence of other SEEs.

3.1.4 Relevance for the LHC

It is interesting to evaluate what the BER of the two devices would be in the LHC experiments. Since the tests were performed in the worst-case situation the corresponding value for the LHC would be an absolute maximum rating. The maximum predicted fluence of hadrons above 20 MeV (relevant for SEU) should occur in the ATLAS experiment and should reach a level of 1.5×10^{13} H/cm2. The total beam time of the LHC cumulated over the 10-year lifetime is assumed to be equivalent to 8×10^7 s at full luminosity. A first approximation can be given by simply calculating the corresponding values of the BER for the flux inside the LHC.

The corresponding values of the BER in both the LHC (predicted) and during the tests at LLN are given in Table 11.

Table 11
Approximated values of BER in the LHC

Facility	Flux of hadrons	BER	
		Agilent	TrueLight
LLN	1×10^8 H/cm^{2}s	2.5×10^{-8}	4.67×10^{-9}
LHC	1.9×10^5 H/cm^{2}s	4.7×10^{-11}	8.9×10^{-12}

These results show that the calculated values of BER are already good enough to allow the qualification of both devices for use at the LHC. It is still very unlikely that there will be a precise 90° angle between the beam and the optical receivers. As was shown in Section 3.1.2 a more realistic value of BER should be smaller by a factor 30. This would give values of BER in the range of 10^{-13}-10^{-12} that are far above the requirement of the TTC system.

3.2 Gamma radiation effect

As explained in Section 2.4.2, 16 devices of each type were irradiated at the UCL facility. The samples were placed on 5 × 6 cm boards, biased and placed between three Co^{60} sources. The inhomogeneity due to the complex geometry of the irradiation set-up was evaluated to be 15%. Figure 4 shows the irradiation site.

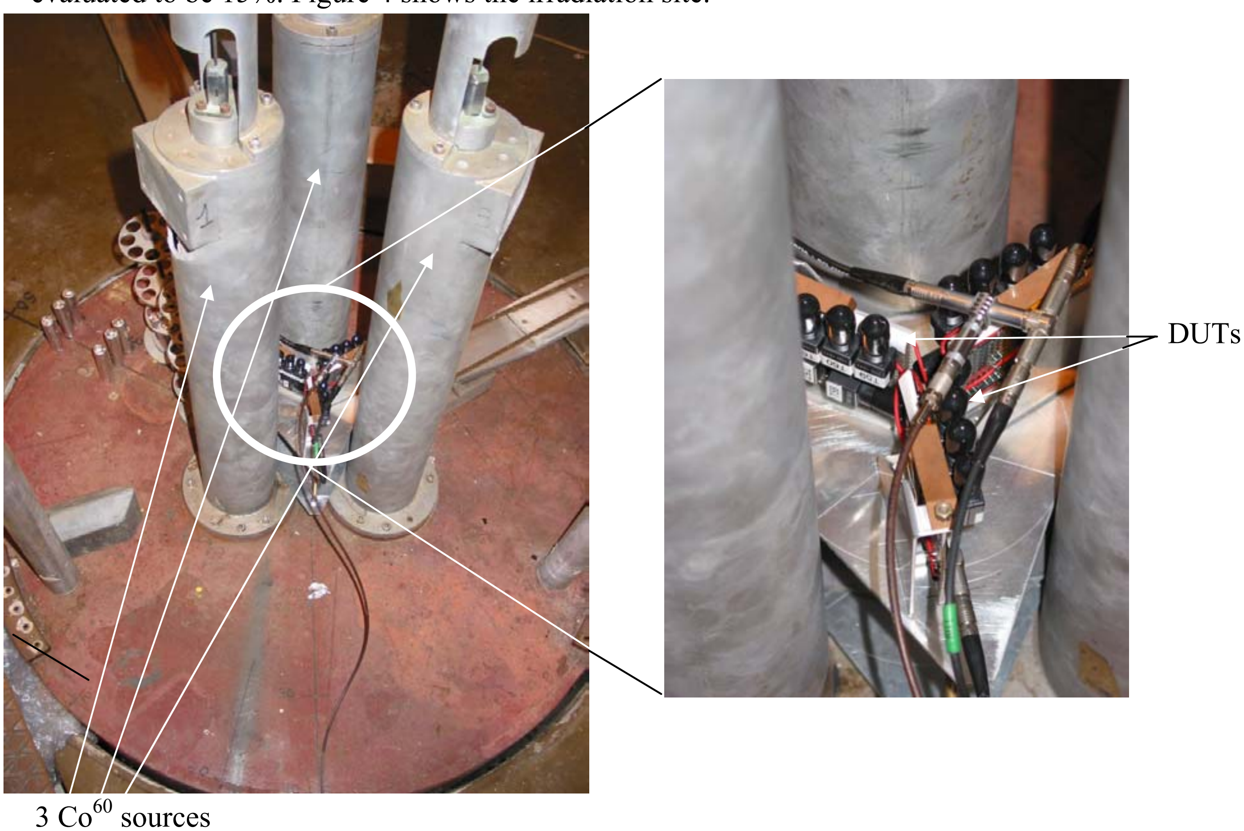

Figure 4: Pictures of the TID irradiation site

The total dose was measured using water samples according to the Fricke dosimetry method. Using tables listing the mass attenuation coefficients, a difference of 10% in the absorbed dose was calculated between H_2O and SiO_2/Si. Table 12 lists the corrected values of TID received by the irradiated samples.

Table 12
Devices damaged during the TID test

No. of samples	TID	No. of damaged devices that recovered when operated	No. of damaged devices that recovered after 2 weeks at room temperature	No. of damaged devices that did not recover
6 Agilent	450 krad	0	0	0
10 Agilent	850 krad	0	0	0
6 TrueLight	450 krad	0	0	0
10 TrueLight	900 krad	0	0	0
5 Agilent	1.8 Mrad	0	0	0
5 TrueLight	1.8 Mrad	2	2	0

These results show that both types of device can cope with the constraints set by the experiments. When exploring a wider range of doses, the TrueLight devices seem to be more affected by the radiations than the Agilent ones. While only one passed the 1.8 Mrad test, two devices did not work initially (power consumption 50% lower and no output signal) but recovered after a few seconds while being tested. The two remaining devices recovered after a storage period of two weeks at room temperature. This spontaneous recovery is very encouraging since there will be a lot of dead time (no beam) in the 10-year period of activity of the LHC and the dose rate will be much lower.

For the other tests with maximal TID up to 900 krad no significant increase in power consumption could be detected in the DUTs. Similarly the output swing range remained stable and close to what had been measured before irradiation.

3.3 Neutron radiation effect

The tests in Prospero were performed following exactly the planning presented in section 2.4.3. The samples got activated to levels making it impossible to transport them immediately after irradiation. Eventually, after a cool down period of 5 weeks, the post irradiation tests took place at CERN. All the devices passed the characterisation procedure, thus showing that there was no performance degradation due to neutron interaction.

4 CONCLUSION

The scope of these combined tests was to give a full picture of the respective behaviours of the two candidate devices towards radiation. When gathering the results of the TID, NIEL, and SEU tests, both devices reached the level of performance required for their qualification. The influence of the angle of incidence on the BER was also brought to light. Selecting the angle that most favoured the proton-induced errors provided data for the worst-case scenario. The fact that both devices passed the tests under the most severe condition is promising since it is very unlikely in practice that such an unfavourable environment will be met. The values of BER provided in this report should then be regarded as absolute maximum ratings. It was also shown that by increasing the source optical power the user could significantly reduce the BER in the optical receivers. This can be very useful for the end-user who may want to bring the BER to a value compliant with the redundancy and correcting processes of his system.

When coming to the point of selecting one of the two devices a few additional results should be considered. The SEU tests showed that the TrueLight devices were more resistant to proton-induced upsets. An order of magnitude in BER was recorded between the devices in competition. In addition the much lower cost of the TrueLight optical receivers gives them a significant advantage.

Acknowledgements

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References

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