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Radiation test of commercial of the shelf (COTS) optical transceivers in the frame of the beam position monitor (BPM) consolidation project for the Large Hadron Collider (LHC)

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Abstract: The consolidation of the Large Hadron Collider (LHC) beam position monitor (BPM) requires the deployment of about 5000 single-mode radiation-tolerant optical transmitters, working at 10 Gbps during 20 years of operation. While the use of the custom devices being designed at CERN remains the baseline for the project, 8 commercial of the shelf (COTS) optical transceivers have been evaluated as an alternative. This paper presents the results of the full characterization in radiation of these COTS devices, including cumulative effects and single event effects (SEE), evaluated during both data transmission and reception.

Keywords: Radiation damage to electronic components; Data acquisition circuits; Accelerator Subsystems and Technologies; Instrumentation for particle accelerators and storage rings - high energy (linear accelerators, synchrotrons)

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1 Introduction

The consolidation of the Large Hadron Collider (LHC) Beam Position Monitor (BPM) [1] aims to replace the current BPM system during the Long Shutdown 4 (LS4, i.e. 2032–33). The new BPM system shall reuse the same infrastructure as the current one (i.e. coaxial cables, optical fibres), constraining the digitization of the analogue signals to be performed close to the pick-ups. To cope with the radiation levels expected during High-Luminosity LHC (HL-LHC) operation [2], the front-end electronics shall be as simple and reliable as possible, whilst the back-end will process the incoming raw data. Following this approach, the analogue signals from each BPM will be digitized in the front-end by a 12-bit Analogue-to-Digital Converter (ADC) at 1.25 Gsps. The digitized data will be directly forwarded in parallel through 4 single-mode optical transmitters working at 10 Gbps. These 4 optical signals will be multiplexed over a single optical fibre towards the back-end. This scheme will require about 5000 optical transmitters. The baseline for the electro-optical interface in the tunnel side is a single-mode radiation-tolerant dual transmitter named CWDM SM-VTTx [3], developed at CERN by EP-ESE-BE. Nevertheless, due to availability issues of the Transmitter Optical Sub-Assembly (TOSA) for the CWDM SM-VTTx, the evaluation of an alternative option based on Commercial Off-The-Shelf (COTS) optical transceivers has been conducted.

To validate the feasibility of the alternative option, a radiation test campaign has been carried out in the COmpact MEdical Therapy cyclotron (COMET) [4] at Paul Scherrer Institute (PSI). This cyclotron provides a 200 MeV proton beam that allows the performance of radiation tests at the component level, with conditions relevant to CERN applications. To maximize the probability of finding a suitable COTS candidate, 8 single-mode optical transceivers from 4 different standards (SFP+, SFP28, QSFP+ and QSFP28) [5, 6] have been selected as Devices Under Test (DUTs). The main characteristics of the 4 standards and the different DUTs are listed in tables 1 and 2 respectively. During the test, all DUTs operated at the same line rate (10 Gbps) and were irradiated up to a Total Ionizing Dose (TID) of 500 Gy and a Displacement Damage Equivalent Fluence (DDEF) of 8.51E11 1 MeV neq.cm-2. All presented test data were recorded in the campaign of November 2022 and documented in a radiation test report [7].

Table 1. Main characteristics of the SFP+, QSFP+, QFP28 and QSFP28 standards.

Main characteristics of the SFP+, QSFP+, SFP28 & QSFP28 standards			
Standard	#Channels	Line Rate/Channel (Gbps)	Connector Type
SFP+	1	~10	LC
SFP28	1	up to 25	LC
QSFP+	4	~10	LC
QSFP28	4	up to 25	LC

Table 2. Devices Under Test (DUTs).

Devices Under Test (DUTs)					
DUT	Model	Standard	Test types	#Samples	Vendor
DUT-1	DDCChh-QLCA	QSFP28	TID/DD (ΔTx_{Pavg}, $\Delta Rx_{Sensitivity}$, $\Delta lifetime$) SEE (SEU, SEFI, SEL)	1	Broadex Technologies
DUT-2	D1TThh-QLCA				Broadex Technologies
DUT-3	FTLC1156RDPL				Finisar
DUT-4	QFPQL010410D	QSFP+			Skylane Optics
DUT-5	D133bb-SLHC	SFP28			Broadex Technologies
DUT-6	FTLF1436P4BCV				Finisar
DUT-7	D13399-SLHA	SFP+			Broadex Technologies
DUT-8	ET5402-LR				Edge-Core Networks

Both SFP and QSFP optical transceivers can be divided into three main blocks which are the transmitter (Tx), the receiver (Rx) and the control. The Tx is composed of an electro-optical interface named Transmit Optical Sub-Assembly (TOSA), featuring a laser diode and a laser driver. The Rx is composed by an opto-electrical interface named Receiver Optical Sub-Assembly (ROSA), featuring a PIN photodiode and a Trans-Impedance Amplifier (TIA). The TIA plays a crucial role in determining the initial Signal-to-Noise Ratio (SNR), as it is the first stage of amplification and directly conditions the signal from the PIN photodiode. Additionally, the Rx may feature a post-amplifier that can contribute to improving the overall system SNR, particularly in scenarios where the noise contributions of subsequent stages are significant. Finally, the control block, accessed via an electrical serial bus named Inter-Integrated Circuit (I2C), is usually composed of one or more ICs that monitor and control the optical transceivers (e.g. measure optical power), as well as store relevant information (e.g. vendor ID). Figure 1 illustrates the main components of a typical optical transceiver.

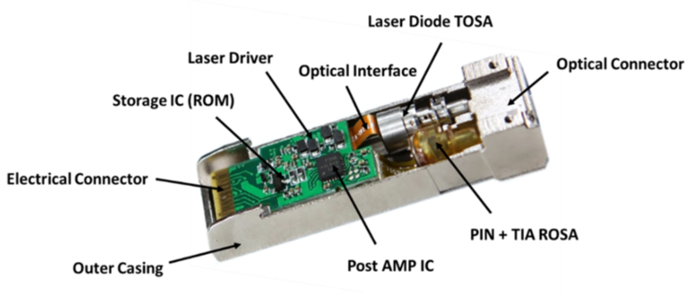

Figure 1. Main components of a typical optical transceiver.

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2 Test setup

To obtain the full characterization of the DUTs in terms of radiation tolerance, cumulative effects and SEE have been evaluated during both data transmission and reception. Each type of test required a dedicated setup. The main features of both test setups are described in the following subsections.

2.1 Cumulative effects test

Cumulative effects (e.g. TID, DDEF) have been evaluated through "offline" analysis. The aim of this test was to evaluate the impact of cumulative effects on the lifetime, optical power of the transmitter and sensitivity of the receiver by comparing measurements before and after irradiation. Figures 2 and 3 illustrate the block diagram and an image respectively of the offline measurement setup of the Rx sensitivity for the cumulative effects test.

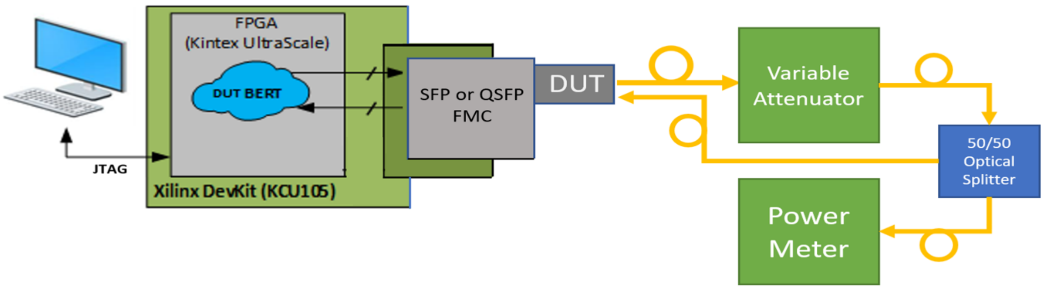

Figure 2. Block diagram of the offline measurement setup for the Rx sensitivity test.

Figure 3. Image of the offline measurement setup for the Rx sensitivity test.

2.2 Single events effects test

SEE (e.g. Single Event Latch-up (SEL), Single Event Transient (SET), Single Event Upset (SEU)) have been evaluated through "online" analysis. The aim of this test was to evaluate the impact of SEE on the Bit Error Rate (BER), Loss Of Lock (LOL) and control registers by monitoring the DUT in real-time during irradiation. Based on the measurements of the online analysis, SEE cross-sections for the different DUTs have been calculated. Figure 4 illustrates the block diagram of the BER test setup of the QSFP for SEE test, whilst figure 5 illustrates an image of a QSFP DUT ready to be tested with beam.

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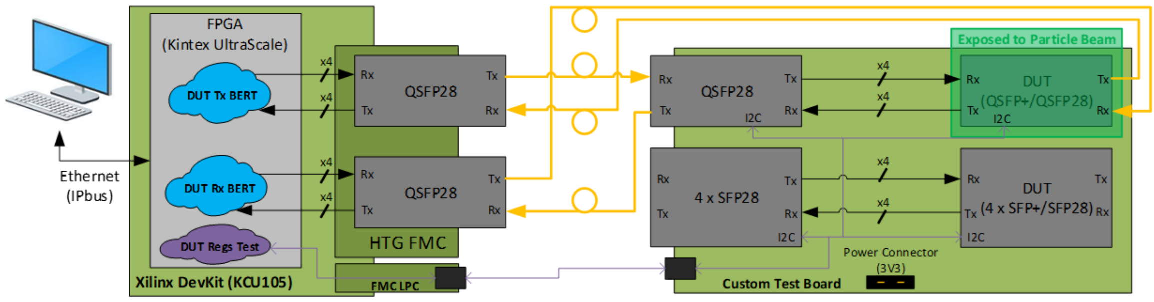

Figure 4. Block diagram of the BER test setup of the QSFP for SEE test.

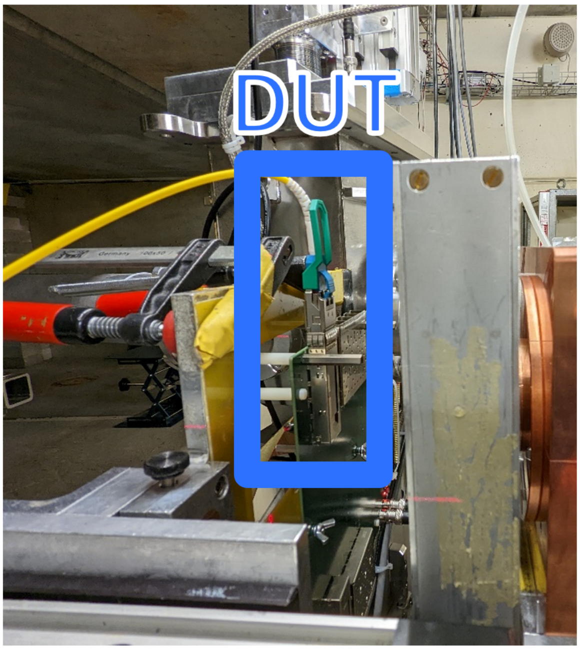

Figure 5. Image of a QSFP DUT ready to be tested with beam.

3 Test procedure

3.1 Cumulative effects test

For the measurement of the optical power of the transmitter, the Average Output Power (Pavg) of the DUT was directly measured with the optical power meter (in dBm). The value given by the optical power meter required adjustment for losses of the optical link.

For the measurement of the receiver sensitivity, a Bit Error Rate Test (BERT) in the FPGA, generated a Pseudo-Random Bit Sequence (PRBS) which was sent as a serial stream to the transmitter of the DUT. Then, the transmitted optical signal was attenuated and split in two. Half was sent to the receiver of the DUT and was checked by the BERT core. The other half was sent to an optical power meter. The sensitivity was set as the average optical power in the Rx at a BER $<$ 1E-12 (following the industry standard) [8].

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3.2 Single events effects test

The SEE test has been performed in real time, measuring the different parameters of interest of the DUT during irradiation. This test may be divided into three main subtests based on the parameters of the DUT to be measured.

- The first subtest evaluated destructive effects. SEL has been monitored by measuring in real time the current consumption of the DUT. The power supply featured a current limitation designed to prevent the destruction of the DUT in the event of an SEL. Due to the variety in internal architectures of COTS devices and the absence of detailed information from manufacturers, coupled with the unpredictable nature of SEL incidents, establishing a current threshold and a specific response time for the limiting circuit to prevent component damage is challenging. Consequently, the current limitation was configured with a threshold of 3 A and a response time of 1 ms for power cutoff, based on empirical data. For SFP DUTs, the average current was approximately 450 mA, with peaks up to 1 A observed during SEL. For QSFP DUTs, the average current was about 2 A, with peaks up to 2.5 A during SEL. It is important to note that, due to limitations in the test setup, it was not possible to differentiate the exact cause of these current peaks. They might not be solely attributable to SEL but could also result from undesirable states of logic induced by SET or SEFIs. However, in the context of our application, this distinction is not critical since the observed current peaks did not lead to the destruction of the DUT.

- The second subtest evaluated the BER and LOL of the serial communication. The number of bit errors and their rate allow us to differentiate the type of SEE. For instance, a single-bit error indicates a SEU or a LOL with no recovery indicates a SEFI. For this test, it is considered LOL when the number of consecutive bit errors exceeds a predefined threshold (1E3 errors).

- The third subtest evaluated the internal EEPROM of the DUT. This memory is accessed via I2C interface and during irradiation it was periodically read and its content stored in a file.

4 Test results

The results of the cumulative effects test are presented in table 3. This table compares the measurements of the Tx average power and Rx sensitivity for all DUTs before and after irradiation. The difference (delta) between the pre-irradiation and post-irradiation measurements of the Tx average power and Rx sensitivity are detailed in the columns labelled 'Tx Pavg (dBm)' and 'Rx@(BER<1E-12) (dBm)', respectively. Notably, all cells in these columns are highlighted in green, signifying that all DUTs successfully passed the cumulative effects test. The acceptance criterion for the DUTs is based on their delta values being below the set threshold for this test, which is 0.5 dB. This threshold is considered negligible within the context of the LHC BPM Consolidation project, underscoring the robustness of the DUTs against cumulative effects.

The results of the SEE test are illustrated in table 4. This table shows the cross-section of different SEE and their impact on different parameters of all DUTs. The cross-sections highlighted in violet colour represent the upper limit cross-sections calculated considering that we had 0 events and a specific Confidence Interval (CI) of 95% [9, 10].

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Table 3. Results of the cumulative effects test.

Offline Measurements						
DUT	Pre-Irradiation		Post-Irradiation		Delta Pre-Post Irradiation	
	Tx Pavg (dBm)	Rx@(BER<1e-12) (dBm)	Tx Pavg (dBm)	Rx@(BER<1e-12) (dBm)	Tx Pavg (dBm)	Rx@(BER<1e-12) (dBm)
DUT-1	6.41	-11.01	6.21	-11.06	0.20	0.05
DUT-2	8.45	-7.99	8.68	-8.31	-0.23	0.32
DUT-3	7.75	-9.62	7.54	-9.58	0.21	-0.04
DUT-4	5.88	-8.73	6.06	-8.52	-0.18	-0.21
DUT-5	-0.71	-8.34	-0.41	-8.15	-0.30	-0.19
DUT-6	-0.94	-9.12	-1.11	-9.25	0.17	0.13
DUT-7	-0.15	-12.76	-0.39	-13.01	0.24	0.25
DUT-8	-0.84	-15.90	-0.81	-16.15	-0.03	0.25

Table 4. Results of the SEE test.

Cross Section (σ) (cm²/device)							
DUT	I2C EEPROM			Loss of locks		Bit Errors	
	SEFI (& SEL/LOL)	SEFI	Short SEFI	LOL (& SEL)	LOL	Rx	Tx
DUT-1	5.34E-11	2.29E-11	<2.84E-11	9.15E-11	<2.84E-11	2.34E-09	2.57E-10
DUT-2	3.76E-11	5.64E-12	1.51E-11	5.64E-11	<6.92E-11	1.27E-10	8.90E-10
DUT-3	3.69E-09	<5.48E-9	<5.48E-9	3.69E-09	1.85E-09	No Data Acquired	
DUT-4	3.99E-09	<2.46E-9	<2.46E-9	Continuous LOL		No Data Acquired	
DUT-5	<3.69E-11	<3.69E-11	<3.69E-11	Continuous LOL		No Data Acquired	
DUT-6	I2C Continuously Faulty			1.18E-11	<4.32E-12	3.52E-11	1.18E-12
DUT-7	I2C Continuously Faulty			1.18E-12	4.70E-12	3.72E-08	<4.32E-12
DUT-8	I2C Continuously Faulty			9.25E-12	<8.54E-12	SEFI after 250 Gy	

The results are divided into three main sections with their respective columns named “I2C EEPROM”, “Loss Of Locks”, and “Bit Errors”. Each of these columns is divided into sub-columns, based on the type of cross-section measured.

The “I2C EEPROM” section shows the SEFI cross-sections of the I2C interface communicating with the EEPROM of the DUT. It is important to mention that, due to the sensitivity of the I2C interface to SEE during the test, it was not possible to evaluate single memory elements of the EEPROM. Instead, the SEFI cross-section of the I2C interface was obtained. The SEFI cross-sections of the I2C EEPROM interface are divided into three categories. The first category (shown in column “SEFI (& SEL/LOL)”) provides the cross-section of SEFI in the I2C EEPROM requiring a power cycle to recover, which occurred in the presence of SEL or LOL. The second category (shown in column “SEFI”) provides the cross-section of SEFI in the I2C EEPROM requiring a power cycle to recover, occurring without the presence of SEL or LOL. The third category (shown in column “Short SEFI”) provides the cross-section of SEFI in the I2C EEPROM that recover after some time without the need for a power cycle.

The “Loss Of Locks” section shows the LOL cross-sections of the serial communication. The LOL cross-sections are divided into two categories. The first category (shown in the column “LOL (& SEL)”) provides the cross-section of LOL that occurred in the presence of SEL. The second category (shown in the column “LOL”) provides the cross-section of LOL that occurred without the presence of SEL.

The “Bit Errors” section shows the bit error cross-sections of the serial communication that occurred without the presence of LOL or SEL. The bit error cross-sections are divided into two categories. The first category (shown in the column “Rx”) provides the bit error cross-section of the receiver. The second category (shown in the column “Tx”) provides the bit error cross-section of the transmitter.

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Since, in the LHC BPM Consolidation project, the selected DUT will only be used for data transmission and the monitoring of different parameters via I2C EEPROM is not a requirement, the criteria for the acceptance of the DUT is based on the cross-sections of the "Loss of Locks" section and the "Tx" cross-sections of the "Bit Errors" section.

The acceptance threshold for the previously mentioned cross-sections is 5E-12. Based on this acceptance threshold and the expected DDEF at the arcs and alcoves during HL-LHC operation [2], it is reasonable to expect about 8000 errors at the system level (5000 channels) with a CI of 95% over the expected 20 years of LHC BPM Consolidation operation. The previously mentioned number of errors was calculated using a software tool developed at CERN [11]. This number of errors corresponds to an expected Mean Time Between Failures (MTBF) at the system level of about 22 hours, calculated using the formula shown next. This MTBF is acceptable for the LHC BPM Consolidation project due to the system's intrinsic redundancy (without taking into consideration other sources of errors, only the simultaneous failure of consecutive channels may lead to potential errors in beam position measurements).

$$\text{MTBF (hours)} = \frac{\text{Total Operation Time (hours)}}{\text{Total Number Of Failures}}$$

According to the established criteria and acceptance threshold, only DUT-6 and DUT-7 passed the test. The rows corresponding to these DUTs in table 4 are highlighted in green colour, indicating their successful performance.

It is important to mention that this test represents a pessimistic scenario since the DDEF achieved during the test (8.51E11 1 MeV neq.cm-2) is significantly higher than the expected annual DDEF during HL-LHC operation at the locations of the LHC BPM Consolidation electronics (1.6E10 1 MeV neq.cm-2). Further tests at the Cern High energy AcceleRator Mixed field facility (CHARM) [12], providing a more representative environment, are under evaluation.

5 Conclusion

The cumulative effects test was successfully passed by all DUTs. The offline measurements performed before and after irradiation showed minimal variations in both Tx Pavg and Rx sensitivity ($\Delta < 0.5$ dBm), as well as no impact on the lifetime of the components. Based on these results, it is reasonable to assume that cumulative effects would pose a negligible impact on these components during HL-LHC operation in the arcs and alcoves.

The SEE test was passed by 2 DUTs (DUT-6 and DUT-7). It can be considered that the Tx of both components operated within acceptable limits during the test. However, the I2C EEPROM interfaces of both components presented extremely high sensitivity to SEFI. Based on these results, it is reasonable to assume that, both DUT-6 and DUT-7 could be selected as transmitters for applications during HL-LHC operation in the arcs and alcoves when online monitoring of the I2C EEPROM is not a requirement.

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