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Radiation hardness of the optical ribbon transmitter for the Level-0 muon trigger

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Abstract

In this note we present the radiation hardness tests performed on the Agilent HFBR-772BP ribbon optical transmitter. It carries data between the muon detector and the muon trigger. We irradiated it with a proton beam of 250 MeV/c at the Paul Scherrer Institute in December 2003. The component works within its specification up to a total dose of ~15 kRad, corresponding to an integrated flux of 2.5×10^{11} p/cm^2. This limit is a factor 7 above the total dose expected for the muon frond-end electronics after 10 years of operation. The cross-section for single event upsets is equal to $(4.5\pm0.1)\times10^{-10}$ cm^2 per single optical link. The corresponding inefficiency on the level-0 muon trigger is below 10^{-10} and therefore negligible. This component match well the requirements of the trigger interface implemented in the muon fond-end electronics.

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1. Introduction

The transport of the information from the muon Off Detector Electronics (ODE) to the muon trigger processing boards is described in details in [1]. The binary data are serialized and pushed through 1248 high speed optical links. The ODE is expected to receive a maximum radiation dose of 2.2 kRad in 10 years of LHCb running, as shown in Table 1 [2], when the ODE of station M1 is located in the tunnel under the RICH2. The maximum flux of hadrons with energy above 20 MeV is expected to be smaller than 1.9×10^{10} p/cm^2 and the 1 MeV neutron equivalent flux below 3.4×10^{11} part/cm^2. We have already measured the sensitivity of components involved in the muon trigger interface, located in the ODE [1], except the ribbon optical transmitter.

In this note, we explain how we measured the sensitivity of the optical transmitter Agilent HFBR-772BP[3] to radiations. The irradiation campaign took place at PSI during Winter 2003, using a proton beam of 250 MeV/c. Four components were irradiated up to a fluence of 2.5×10^{11} p/cm^2, corresponding to a total dose of 15 kRad [4].

In Section 2, we describe the experimental set-up used while in Section 3, we give the results obtained.

Tableau 1: Maximum radiation levels for 10 years of muon off detector electronics operation (including a safety factor 2) [2]. Numbers for station M1 have been conservatively taken identical to those of station M2. M1 ODE will be located in a tunnel below RICH2.

	Total Dose (kRad)	Hadrons > 20 MeV (part/cm²)	1 MeV neutron equivalent (n/cm²)
M1	2.2	1.9×10^{10}	3.4×10^{11}
M2	2.2	1.9×10^{10}	3.4×10^{11}
M3	0.68	7.9×10^{9}	1.8×10^{11}
M4	0.39	5.3×10^{9}	1.9×10^{11}
M5	0.32	4.5×10^{8}	2.6×10^{11}

2. Experimental set-up

The set up consists of 3 main components:

1. the *emitter board* contains the optical transmitter we want to irradiate;
2. the *optical ribbon cable*;
3. the *receiver board* is the muon trigger Processing Board, described in [5].

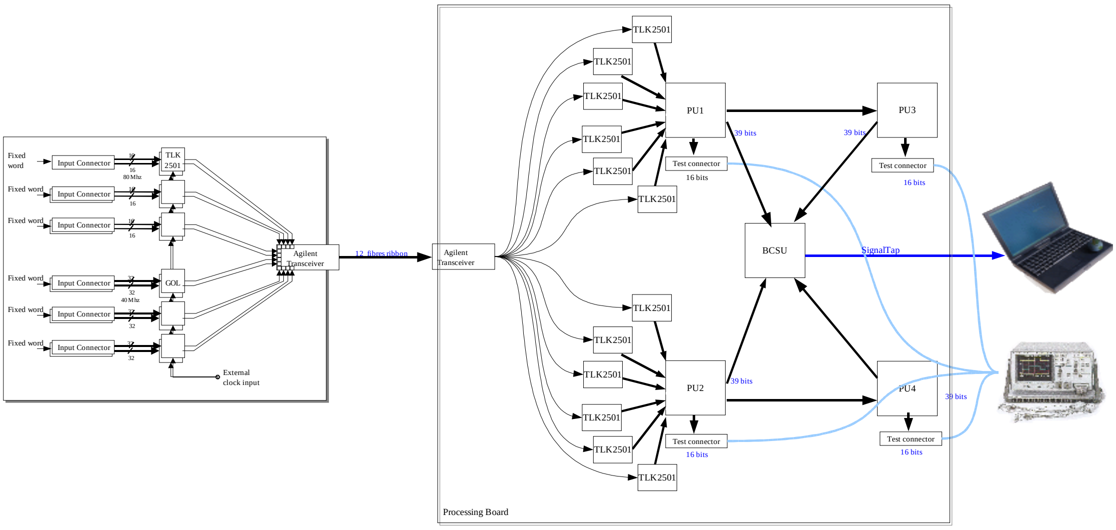


Figure 1: Set-up of the SEU measurement, with the emitter board on the left and the muon processing board on the right They are connected through a ribbon cable, 110 meters long, merging 12 single optical fibres.

An overview of the experimental set-up is shown in Figure 1. A picture of this set-up is shown in Figure 2. The behaviour of the data transmission is monitored with two independent ways:

1. a laptop connected to the JTAG port of the processing board provides an on-line monitoring;
2. a logical analyser, connected to test connectors of the processing board records data for off-line analysis.

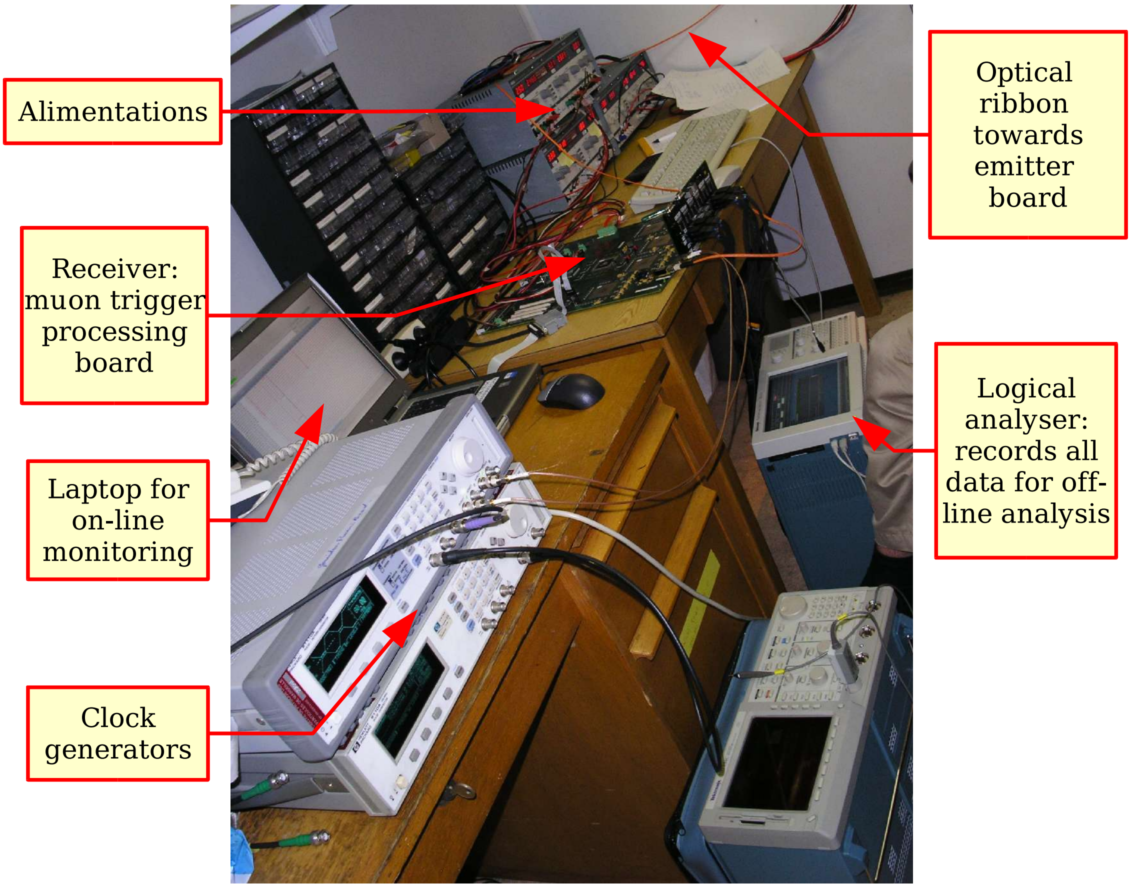


Figure 2 : Picture of the experimental set-up in the counting room at PSI.

2.1. The emitter board

On the emitter board:

- 12 serializer chips (TLK 2501 from Texas Instrument) convert 80 MHz 16-bit data word into 1.6 Gbit/s serial data;
- 1 parallel optical transmitter from Agilent drives 12 single optical links at 1.6 Gbit/s, merged into a ribbon cable.

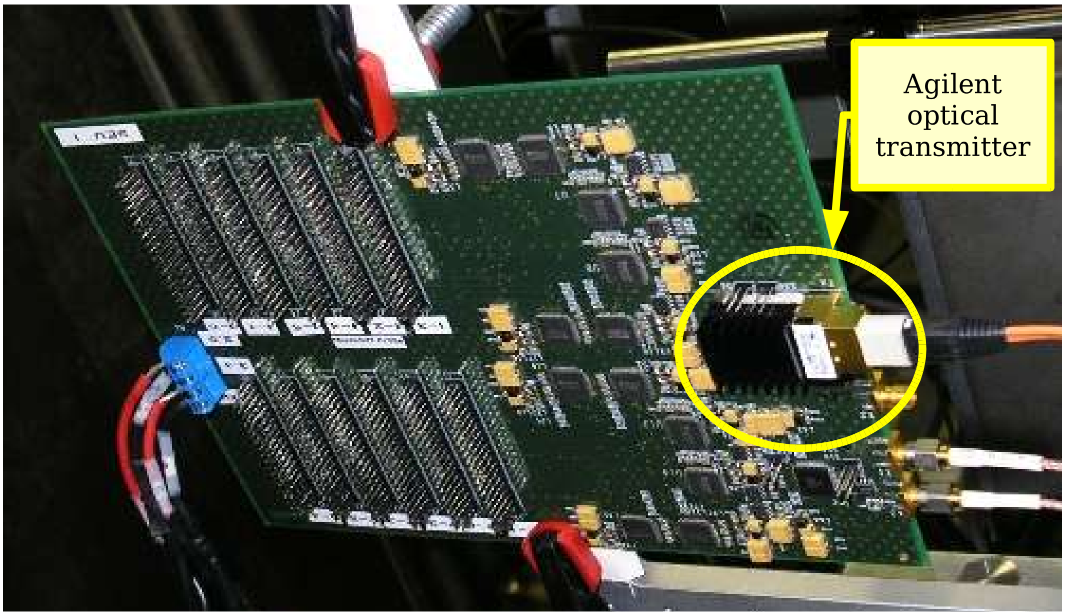


Figure 3: Picture of the emitter board with the Agilent optical transmitter.

The clock is provided by an external generator. A picture of the emitter board is shown in Figure 3. The HFBR-772BP transmitter from Agilent is a high performance optical module for parallel optical data communication applications. This 12-channel device provides a cost effective solution for short distance communication (until 300 meters) and allow up to 30 Gbit/s aggregate bandwidth. This module is designed to operate on multi mode fibre at a nominal wavelength of 850 nm. The transmitter device is mounted on a 100 positions FCI Meg-Array receptacle, so that it will be possible to replace it easily with a compatible device. The power consumption is 1.5 W for all the 12 channels.

2.2. The receiver board

For this test, we use the prototype of the muon trigger processing board, described in [5]. On this board:

- 1 parallel optical receiver from Agilent is connected to the ribbon cable receiving 12 optical signals at 1.6 Gbit/s ;
- 12 TLK2501 deserializers recover the original 16-bits data from the high speed signal and sends them to 2 FPGAs called Processing Units (PU);

- the 2 PUs send their data to test connectors connected to a logic analyser. They also send their data to a FPGA called "BSCU" which performed a comparison with the emitted data and sends the results to a laptop via the JTAG port.

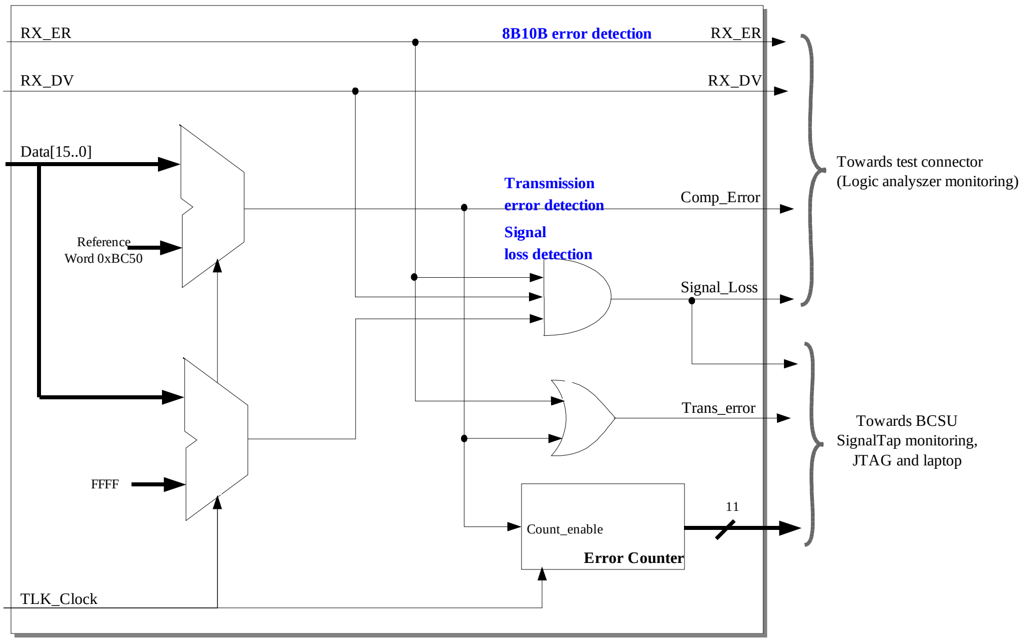
2.3. Error detection principle

In case of de-synchronization, the receiving TLK2501 is not able to re-synchronize itself unless it receives 2 successive ordered pattern containing the following 8b10b code [6]: [<K28.5,D5.6>,<K28.5,D16.2>] or [<K28.5,D16.2>,<K28.5,D16.2>]. This sequence is produced by de-asserting the *TX_DV*, of the TLK2501 during 2 consecutive cycles. As the emitter board has no embedded intelligence, it is not possible to trigger such a sequence. For this reason, the TLK2501s implemented on the emitter board drive continuously the *TX_ER* and *TX_DV* signals at the low state. Therefore, a continuous sequence of consecutive <K28.5,D16.2> ordered sets is emitted. This correspond to a fixed data value of 0xBC50 on the reception side.

It is possible to detect a transmission error by comparing the received data with the fixed pattern 0xBC50. If such error occurs, the *Comp_error* flag is raised. An additional method consist monitor the *RX_ER* and *RX_DV* signals. The *RX_ER* bit is activated each time a received code does not belong to the 8b10b vocabulary. Both methods are implemented within the FPGAs of the processing board. Their principle is illustrated in Figure 4.

Due to the very large number of signals needed by the application, few pins are left on each FPGA for test purpose. We had to limit the number of signal to monitor to the strict minimum. For each of the 12 data path we chose to record only the *RX_ER* and *RX_DV* signals from the TLK2501s and the *Comp_error* and *Signal_Loss*[1] issued from the error detection logic. These signals were recorded with the help of a logic analyser.

1 *Signal_Loss* is a logical "AND" between *RX_ER, RX_DV* and the result of the comparison between the received data and the word FFFF, as shown in Figure 4.



Reception			
Encoded 10 bits output	**RX_DV**	**RX_ER**	**Data received**
IDLE [<K28.5,D5.6>, <K28.5, D16.2>]	0	0	**0xBCC5** or 0x**BC50**
Carrier extend (K23.7)	0	1	**0xF7F7**
Normal data character	1	0	Normal data character
Error	1	1	**0XFEFE** if reception of an error propagation code
			0xXXXX if invalid code
			0xFFFF if loss of signal

Figure 4: Principle of error detection.

During a state acquisition the logic analyser is blind. We can not see the level of the recorded signal. We have implemented a real time monitoring of the error count and of the afore mentioned signals with Signal Tap[2]. By this way we were able to determine when the optical emitter crashes by dose effect.

2 Signal Tap is a function provided with some Altera FPGAs. It allows to monitor some signals and send their state through the JTAG link to the development system where they are displayed just like a logic analyser would do.

2.4. Set-up at PSI

The emitter card is placed on a 250 MeV/c proton beam. Only the optical transmitter is irradiated, as shown in Figure 5 and 6. The beam size on the board is 4 cm in diameter. The flux of the proton beam can be chosen together with the duration of irradiation.

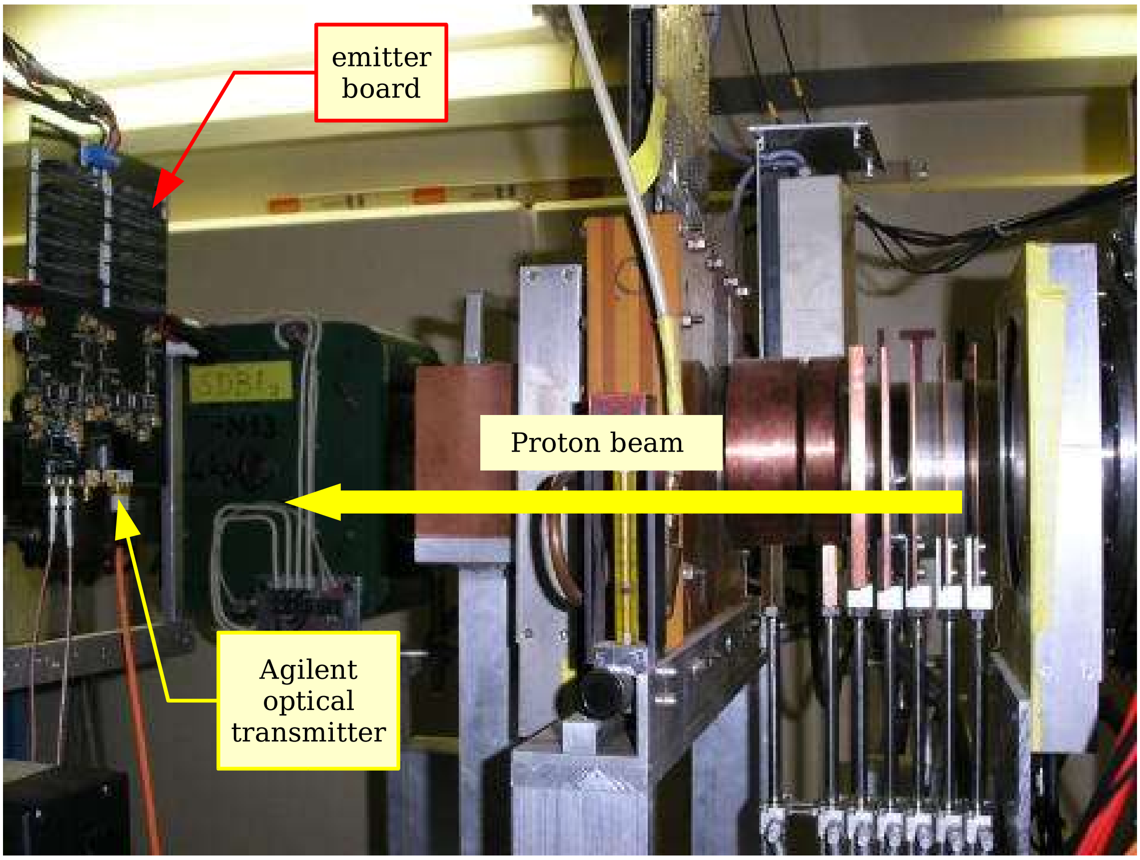


Figure 5: Experimental set-up on the proton beam at PSI.

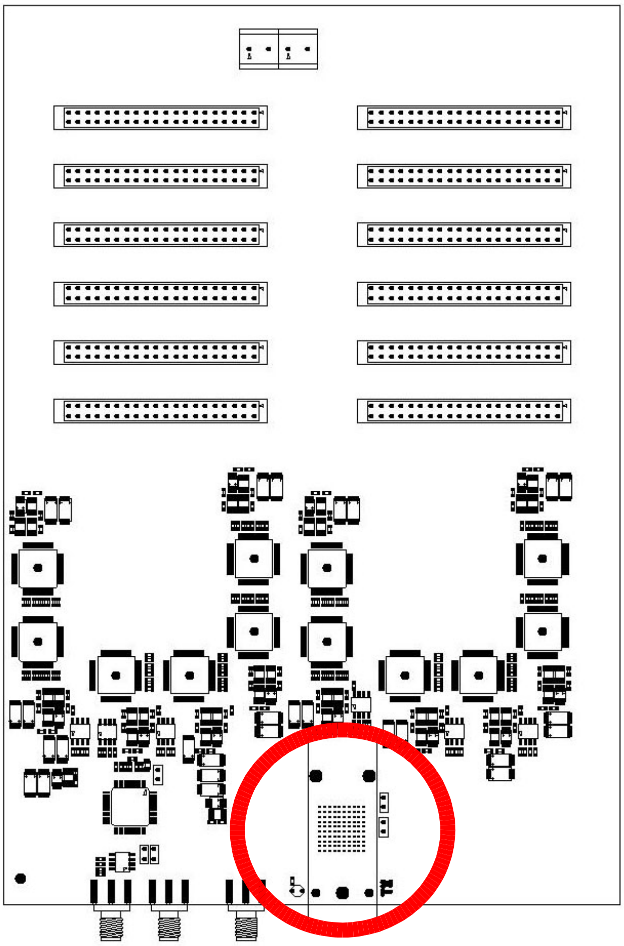


Figure 6: Scheme of the emitter board. The circle around the optical transmitter indicates the irradiated zone. The twelve TLK2501 serializers are also visible.

We irradiated successively 4 emitter boards, increasing progressively the proton fluence up to $\sim 2.5\times10^{11}$ p/cm^2. Meanwhile, we count the number of SEU and record the results with the logical analyser. In the following, we present only the results for 3 emitter boards since, for one of them, the logical analyser truncated data.

3. Results

During the test, we have observed ~4000 SEUs, for the 3 devices. For nearly all cases, *Signal_loss* is set to 1. The laser driver has 12 digitally controlled independent channels, each with its own laser bias current and modulation current [7]. When a SEU occurs, the intensity of the light emitted by the VCSEL decreases below the detection threshold. It is why we mostly observe that the signal is lost on the receiver site. When the signal disappears the synchronization is lost too. The time to go back to a normal situation is 79 ns with a RMS of 48 ns, as shown in Figure 7.

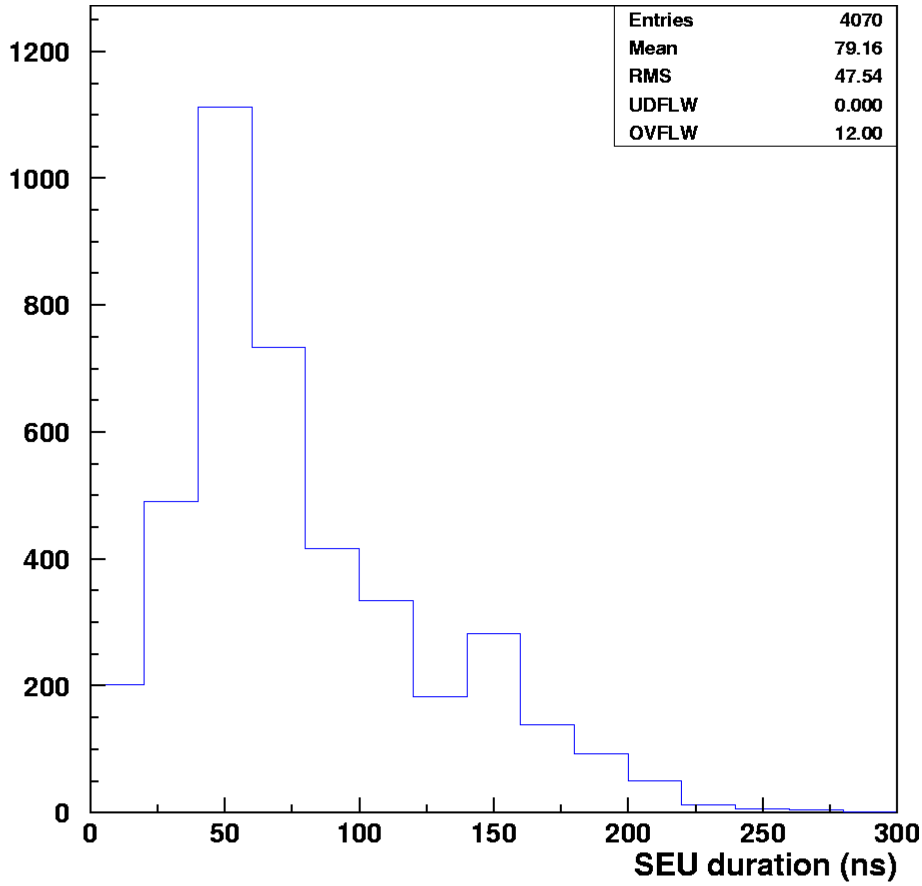


Figure 7: Duration of SEU, for the 12 optical links and the 3 irradiated devices.

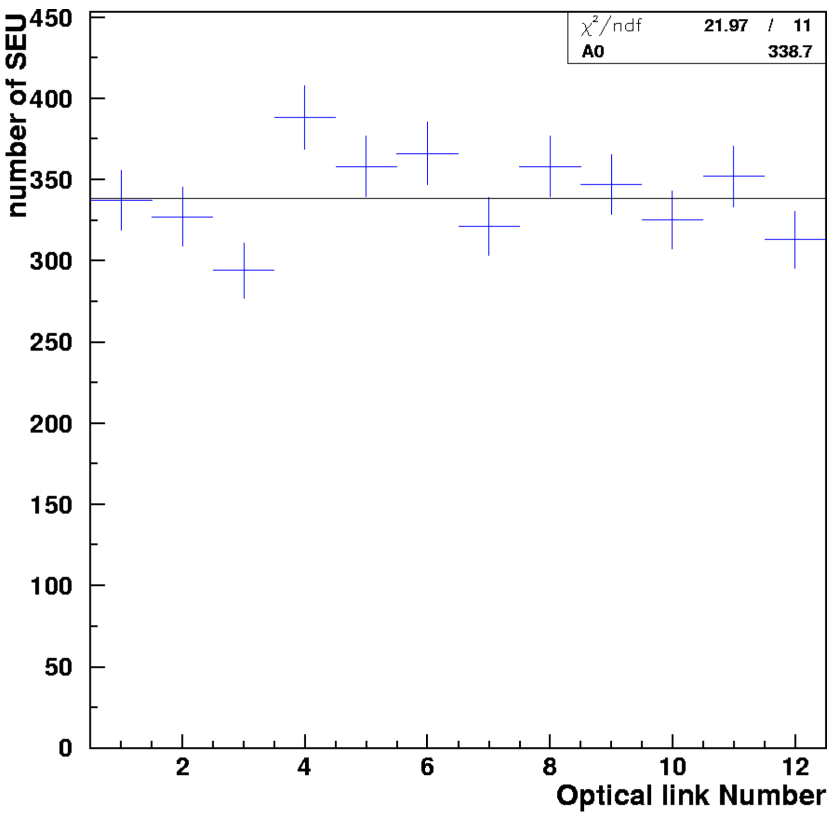


Figure 8: Number of SEU observed on each optical link, for the 3 irradiated devices.

The number of SEUs observed does not depend on the optical link number, as shown in Figure 8. When one link fails, the eleven other work properly.

The rate of SEUs as a function of the the fluence is flat, as shown in Figure 9. The component works up to a fluence of ~2.5×10^{11} p/cm^2, i.e. a total dose of 15 kRad. Above this dose, identical for the 3 irradiated devices, the transmitter does not work any more. Note that dead component can be replaced at any time since it is mounted on a 100 positions FCI Meg-Array receptacle.

The number of SEUs per single optical link, averaged over the three devices is 113±6. The average fluence accumulated on each component being 2.5×10^{11} p/cm^2, we conclude that the SEU cross section is $(4.5\pm0.1)\times10^{-10}$ cm^2 per optical link of the Agilent transmitter.

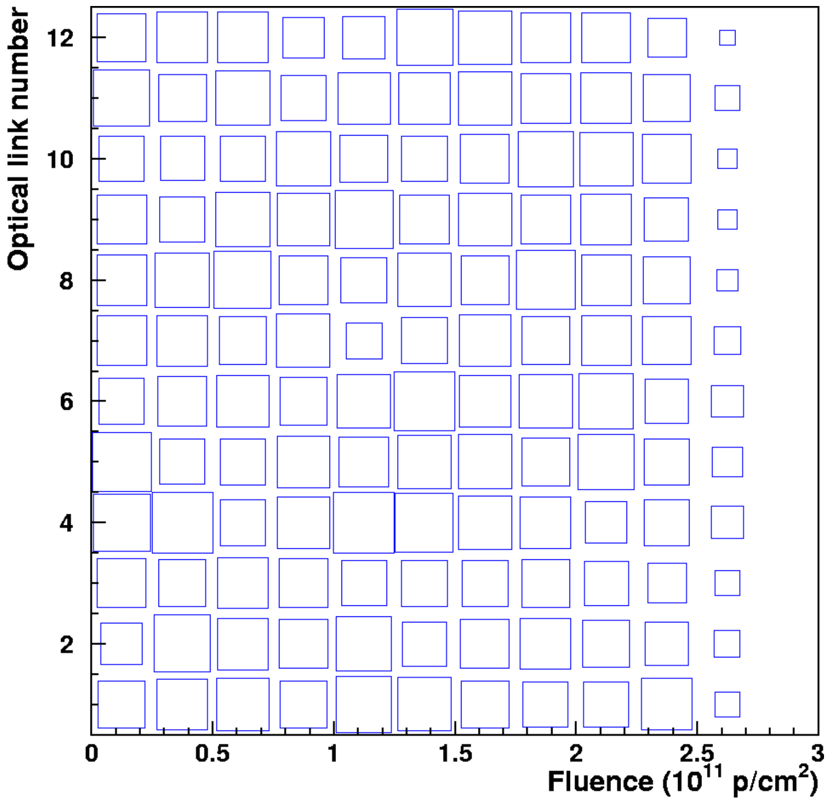


Figure 9: The surface of each box is proportional to the number of SEU observed for a given optical link (x-coordinate) and a given fluence (y-coordinate).The artefact around a fluence of 2.5×10^{11} p/cm^2 is a binning effect. The components do not work after 2.5 to 2.6×10^{11} p/cm^2.

Using Table 2, we can compute the average number of SEUs per year, for all optical links included in the muon trigger. The maximum number of hadrons with energy above 20 MeV on the muon ODE is given in column 1, for each muon station and for 1 year of LHCb operation. If we multiply those numbers by the SEU cross-section computed above, we obtained the average number of SEUs per optical link in one year of operation, as shown in column 2. The number of optical links per muon station is given in column 3. Multiplying column 2 and column 3, we obtain the number of SEUs expected per muon station, in column 4. Summing these 5 lines, we get an average number of SEUs for the whole muon system of 736. Assuming one year of LHCb is 10^7 s, one optical link over 1248 will loose its synchronization every ~3h40min.

In average, a link is blind during one LHC cycle, i.e. 3564×25ns = 89 µs. Indeed, at the end of each LHC cycle, each link is automatically resynchronized [5].

Form these numbers, we compute the trigger inefficiency due to SEU effect on trigger optical stage implemented in the muon ODE. In addition to the Agilent transmitters, this stage contains 1 QPLL chip, 12 GOL chips and 1 chip to distribute the clock. The GOL SEU cross-section is $\sim 3.2\times10^{-13}$ cm^2 [8], well below the one of the Agilent transmitter. The QPLL and the clock distribution chip SEU cross-sections are not yet known but these chips are designed to be radiation resistant. Therefore, we neglect their effect in the following estimation.

When a link is not working, the associated PU is inefficient, since in most of the cases, one link carry data from one station and the trigger algorithm require a coincidence between the five stations to find a muon candidate.

Assuming the LHC work 20 hours per day, the number of LHC cycle per day is $20\text{h}\times3600\text{s}/(3564\times25\times10^{-9}\text{s}) = 8\times10^{8}$, and the number of dead PUs per day is ~5.3. Therefore the trigger inefficiency is given by $(1/192)\times(5.3/8\times10^{8})=3.5\times10^{-11}$, where 192 corresponds to the total number of PU in the muon trigger. This number is completely negligible compared to the 4% inefficiency of the muon trigger algorithm, when it selects for example $B_s \rightarrow J/\psi\,\phi$ events [9].

Tableau 2: Radiation level and number of SEUs expected for each muon station after 1 year of running. Numbers for stations M1 have been conservatively taken identical to those of station M2. M1 ODE will be located in a tunnel below RICH2.

	Hadrons > 20 MeV (part/cm²)	Number of SEUs per optical link	Number of optical links per station	Number of SEUs per station
M1	1.9×10^{9}	0.9	384	346
M2	1.9×10^{9}	0.9	240	216
M3	7.9×10^{8}	0.36	240	86
M4	5.3×10^{8}	0.23	192	44
M5	4.5×10^{8}	0.23	192	44

We do not have yet any results concerning the displacement damages since the irradiated boards are kept by PSI for safety reasons. These measurements will be done when the boards are back in Marseille.

4. Conclusion

The electronics interface between the muon detector and the Level-0 muon trigger is located in a place where a total dose less than 2.2 kRad is expected during the 10 years of LHCb running.

The Agilent HFBR-772BP is a commercial component with well known properties and behaviour. It is designed to work in an environment free of radiation. The transmitter tolerate a maximum dose of 1.5 kRad, when we impose a safety factor of 10.

The SEU cross-section is $(4.5\pm0.1)\times10^{-10}$ cm^2 per optical link of the Agilent transmitter. To have a negligible impact on the data transmitted, each link has to be re-synchronized at the end of each LHC cycle.

This component provides a very compact solution to transport a large amount of data using a small surface of the printed board circuit. Therefore, the Agilent HFBR-772BP match well the requirements of the trigger interface implemented in the muon frond-end electronics.

References

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