Single Event Upset tests of an 80Mbit/s optical receiver

F. Faccio[1*], G. Berger[2], K. Gill[1], M. Huhtinen[1], A. Marchioro[1], P. Moreira[1], F. Vasey[1]

[1] CERN, CH-1211 Geneva 23, Switzerland
[2] Cyclotron Research Center, UCL, B-1348 Louvain-la-Neuve, Belgium

Abstract

The sensitivity to SEU (Single Event Upset) is presented for a rad-hard 80Mbit/s receiver developed for the CMS Tracker digital optical link. Bit Error Rate (BER) measurements were made while irradiating with protons and neutrons, using different beam energies, various incident angles, and a wide range of optical power levels in the link.

As expected the photodiode is the most sensitive element to SEU. The fake signal induced by direct ionisation dominates the bit-error cross-section for protons incident on the photodiode at large angles and low levels of optical power. Comparison of the neutron and proton bit-error cross-sections demonstrate that nuclear interactions contribute significantly to the proton induced SEU errors, particularly at higher levels of optical power.

I. INTRODUCTION

The CMS Tracker timing, trigger and slow control system[1] will use approximately 1000 digital optical links transmitting binary data at 80Mbit/s. Over a lifetime of 10 years, devices inside the CMS tracker will be exposed to more than 10^{14}particles/cm^2 and to ionising doses of the order of 100kGy[2]. The optical receivers inside the CMS tracker therefore have to be radiation resistant.

Previous studies have demonstrated the radiation hardness of InGaAs/InP photodiodes for this application[3]. In addition, the receiver chip is an ASIC[4] developed using a 0.25μm commercial CMOS process employing radiation tolerant layout practices[5], also achieving the required radiation tolerance[6]. Although both the photodiode and the ASIC satisfy the radiation hardness requirements, in terms of total ionising dose and particle fluence, no SEU test had yet been made on the receiver.

In the CMS radiation environment, errors can be introduced in the transmission of either the clock or the data along the slow control transmission lines. Though the error mechanism is not identical to a bit upset in a digital circuit, we will refer to it as SEU since its net effect is the corruption of one bit of digital information. The impact of these errors on the CMS Tracker system depends on their frequency: it is therefore important to measure the SEU sensitivity of the optical receiver.

The optical receiver is shown schematically in Figure 1. The circuit features an Automatic Gain Control (AGC) loop, allowing detection of input signals over a wide dynamic range (-20dBm to –3dBm according to the circuit specifications[1,4]) with minimum noise. The AGC provides compensation for any radiation-induced drop in quantum efficiency of the PIN photodiode, or attenuation in the optical signal due to losses at the various fibre connections. A second feedback loop compensates for photodiode leakage current (up to 100μA), and the circuit outputs an LVDS signal.

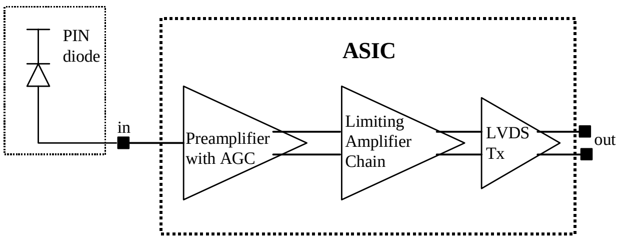

Figure 1: Schematic view of the optical receiver, which includes the PIN diode and the receiver ASIC.

Similar previous studies by Marshall and co-workers[7,8] showed that SEU in digital optical links under proton radiation was caused by (direct) ionisation in the photodiode. In our system the photodiode is again expected to be the most sensitive element in terms of SEU. This is due to its relatively large sensitive volume for charge collection. Bit-errors can generally occur during reception of a '0' input signal, if an incident particle deposits enough energy to generate a current greater than half the amplitude of the input signal modulation.

In the present study, the use of both proton and neutron irradiation allows the SEU contributions to the bit-error-rate (BER) from both direct ionisation and secondary ionisation (through nuclear scattering) to be clearly distinguished. In operating environments where incident particles can arrive from many directions, and under particular operating conditions, both of these mechanisms can be significant causes of SEU.

* corresponding author e-mail: Federico.Faccio@cern.ch

II. EXPERIMENTAL DETAILS

The BER of the circuit was measured using the setup shown in Figure 2. The optical power was modulated at 80Mbit/s with 3.2mW amplitude emitted from a 1.3µm wavelength InGaAsP laser. The photodiode was a Fermionics type FD80S-8F InGaAs/InP detector with 80µm diameter and approximately 2µm thick active InGaAs layer on an InP substrate. Using a variable optical attenuator, different power levels into the receiver could be selected. Transmission errors were detected using a commercial bit-error-rate tester. The bit-error cross-section, defined as the ratio between the number of errors and the incident particle fluence, was calculated for each exposure.

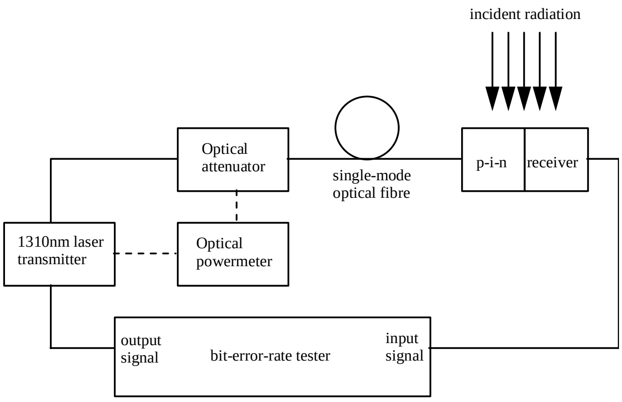

Figure 2: Setup used to measure the bit-error-rate in the laboratory and during proton and neutron irradiation.

The first measurements were made at CERN under relatively noise-free laboratory conditions. The circuit performed well within the nominal specifications of BER<10^{-12}[1] for optical power greater than -20dBm (10µW).

The BER measurement was then repeated whilst the photodiode and receiver chip were exposed together to protons (59MeV), followed by neutrons (32MeV and then 62MeV). The irradiation tests were made at the CYCLONE facility in Louvain-la-Neuve[9]. The proton and neutron beams were generated as pulses at a rate of 18.3MHz, with each pulse being approximately 7ns in duration. The proton beam was monoenergetic with a flux of $1\text{-}4{\cdot}10^{8}cm^{-2}s^{-1}$. The neutron beam was 50% monoenergetic[9], such that half the particles were within ±2 MeV of the nominal value and the remainder had energies distributed almost uniformly over lower energies down to 2MeV. The neutron flux was $1.0{\cdot}10^{6}cm^{-2}s^{-1}$ at an energy of 62MeV and $5.5{\cdot}10^{5}cm^{-2}s^{-1}$ at 32MeV. Under these experimental conditions the cross-section was not sensitive to the detailed time-structure of the beam or the different fluxes used.

The sequence of tests made under different conditions of irradiation (particle type and incident angle), and ranges of optical power levels, are outlined in Table 1. In order to be consistent with earlier studies[7,8] a beam angle of 90° corresponds to particles incident in the direction parallel to the diameter of the photodiode, with 0° being orthogonal to the diameter. This convention is illustrated in Figure 3.

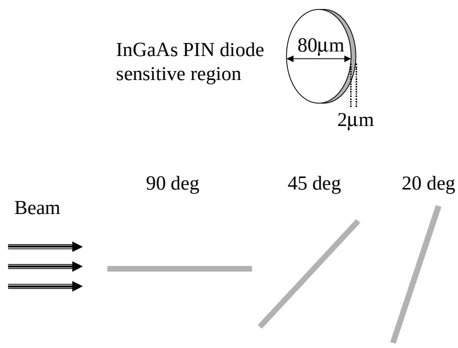

Figure 3: Sensitive region of the InGaAs photodiode, and its orientation to the beam during the experiment.

Table 1: Summary of the BER measurements made at the CRC facility.

Particle type and flux	Test sequence
59MeV protons, $1\text{-}4{\cdot}10^{8}cm^{-2}s^{-1}$	control BER measurement (beam off) 90° angle, P_{opt}=-20dBm, chip shielded 90° angle, P_{opt}=-20dBm, photodiode shielded 90° angle, -30dBm< P_{opt} <-10dBm 45° angle, -30dBm< P_{opt} <-10dBm 20° angle, -30dBm< P_{opt} <-13dBm 80° angle, -30dBm< P_{opt} <-13dBm
62MeV neutrons, $1.0{\cdot}10^{6}cm^{-2}s^{-1}$	control BER measurement 90° angle, P_{opt}=-20dBm 45° angle, P_{opt}=-20dBm
32MeV neutrons, $5.0{\cdot}10^{5}cm^{-2}s^{-1}$	90° angle, -28dBm< P_{opt} <-20dBm

III. RESULTS AND DISCUSSION

A. Bit-error cross-section for protons

The data from the control sequence of BER measurements outlined in Table 1 (together with CERN lab measurements) are shown in Figure 4, where the BER is plotted as a function of the optical power amplitude at the photodiode. These control measurements, made before the beams were switched on, show that the BER was slightly greater in the CYCLONE irradiation areas than in the laboratory at CERN. This is expected to be due to additional noise pick-up in the beam areas.

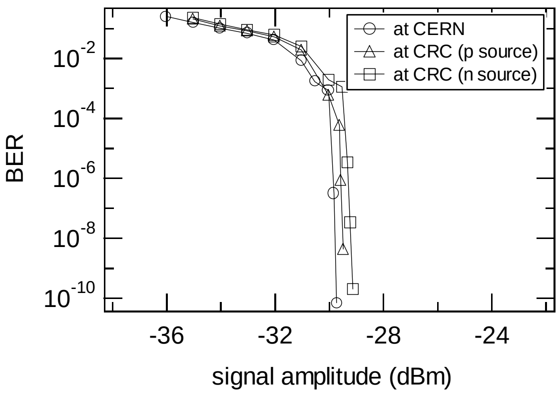

Figure 4: Control measurement of BER performed in the proton and neutron irradiation areas (with the beam off), compared with the data measured at CERN.

The first measurements using the proton beam were made with either the photodiode or the receiver circuit shielded from the protons. We found that the BER was dominated by upsets originating in the photodiode and not in the receiver chip, consistent with earlier tests[7,8]. Subsequent exposures were then made without shielding.

Figure 5 shows the bit-error cross-section over a wide range of optical power levels, measured with 59MeV protons at different angles of incidence.

Overall, the large bit-error cross-section under proton irradiation at 90° incidence is consistent with direct ionization from the protons in the InGaAs layer. The path length for ionization in the active volume could be up to 80µm, generating a charge of up to 10^5 electron-hole pairs in the active region[8]. This figure has to be compared with the photo-induced signal of 6300 electron-hole pairs per microwatt (at 1310nm wavelength). Direct ionization therefore causes the increase in the bit-error cross-section for optical power levels <32µW (-15dBm). The maximum error cross-section for the proton data (at 90° incidence) is also consistent with the geometrical cross-section of the active InGaAs layer. At 90° incidence the photodiode presents a target of cross-sectional area approximately 160µm^2, which is close to the measured maximum cross-section of 200µm^2.

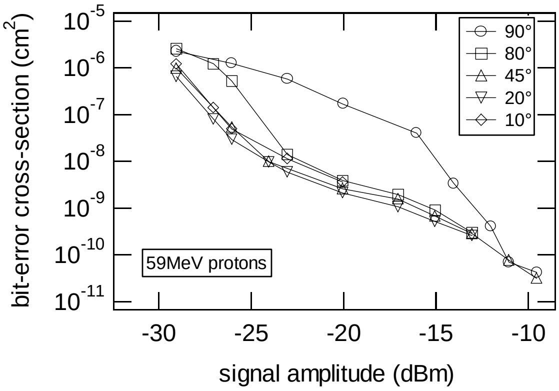

Figure 5: Cross-section measured with 59MeV protons for various incident angles.

For the protons incident at lower angles a much smaller bit-error cross-section was measured than at 90°. This is because the particles traverse a much smaller distance in the active layer of the photodiode for lower incident angles. The charge generated by direct ionization is reduced in proportion to the decrease in path length in the active region. For example, at 45° the path-length is approximately 3µm and the signal from direct ionization is limited to ~4000 electron-hole pairs. Direct ionisation should therefore not contribute significantly to the measured bit-error cross-section for optical power greater than 1.3µW (-29dBm), which is in relatively good agreement with the data in Figure 5, when energy loss fluctuations are taken into account.

For higher optical power levels, the mechanism primarily responsible for SEU is nuclear scattering. The energy deposited via secondary ionisation from a nuclear recoil can be much greater (up to several MeV[10]) than that produced by primary ionisation, giving rise to errors even at high optical power levels. No strong angular dependence is expected, explaining the convergence of the data for protons (at any angle) at higher optical power levels.

B. Simulation of proton induced SEU

Using a modified version of FLUKA code, simulations of 60MeV proton interactions in the active volume of the InGaAs photodiode have been made in order to confirm our interpretation of the data. The simulations were made in two parts in order to separate the contribution due to direct ionization from the secondary ionization due to the slowing down of heavy recoiling atoms or nuclear fragments, generated by nuclear interactions.

The first of these contributions was studied with the FLUKA code, including production of δ-electrons down to very low threshold. Fluctuations of the energy loss and the spatial distribution of the energy deposition were included. The second part of the simulation consists of the generation of the nuclear recoils and their transport. The methodology for this part of the simulation is described in detail in Ref. [10].

Figure 6 shows the simulated SEU cross-sections for protons incident at different angles. The SEU cross section was determined as being the probability of having ionizing energy deposition above one half of the optical signal amplitude.

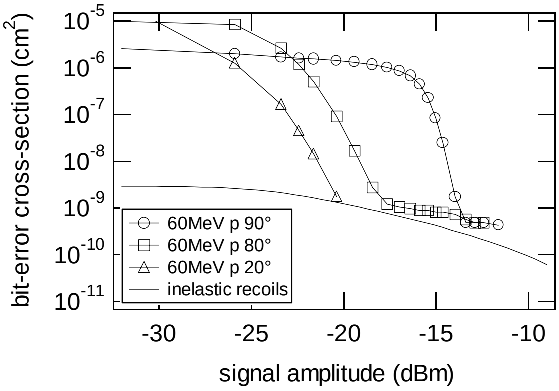

Figure 6: Bit-error cross-sections determined from simulation of 60MeV protons incident at various incident angles.

For low levels of optical power, the direct ionization component is dominant at all angles. The saturation value of the cross-section at low power levels increases with the angle and corresponds to the projected cross-sectional area of the sensitive volume. The simulations did not consider the different sensitivity of the circuit when tranmitting a '1' or '0' therefore the agreement between cross-section and projected area is exact.

The simulated direct ionization component, which included detailed production and transport of delta-electrons, then decreases at optical power levels above a certain threshold. This is where the path length of the proton in the active volume is insufficient to generate enough ionization to cause an upset. Note that for angles <90° this decrease in SEU rate is spread over a larger range of optical power since fluctuations in the energy deposition (straggling) have a greater relative importance, compared to 90° incidence.

At higher optical power levels, the bit-error cross-section is then dominated by secondary ionization from heavy recoils due to inelastic nuclear scattering. There is little angular dependence since the recoils are emitted almost isotropically.

The simulation results therefore confirm our interpretation of the measured bit-error cross-sections, in terms of the contributions from both direct and secondary ionization. There is however some disagreement between the simulation and measured data, which arises from the inaccuracy of the modeling procedure. For example, the simulations did not include the detailed time-response of the circuit to the pulses generated by the incident particles.

Due to the AGC function, the preamplifier has a widely varying bandwidth characteristic. When operating with an input optical signal with 10µW modulation the circuit bandwidth is 100MHz. This is compared to 850MHz when the input optical signal modulation is 500µW[4]. This gain-bandwidth variation is expected to be the cause of the increase in SEU cross-section in the 90° data (in Figure 5) as the optical power decreases, in contrast to the saturation predicted by the simulation. As the optical power decreases the current pulses induced by the incident particles are more greatly amplified (and are also of a longer duration). The circuit therefore becomes much more sensitive to errors, with multiple bit-errors (>1 consecutive bit-error) also being possible. In addition, errors during transmission of '1' level can also occur due to the undershoot following the current pulse.

There are some other minor discrepancies in the simulation results for direct ionization at 80° and 90° incidence. These points also include the heavy recoils, but for the sake of simplicity, the entire recoil energy is deposited at the point of nuclear scattering. Non-ionizing energy loss is therefore counted also as ionization, leading to cross-section values in excess the actual inelastic recoil contribution.

C. Bit-error cross-section for neutrons

The data from the sequence of BER measurements outlined in Table 1 with 32MeV and 62MeV neutrons are shown in Figure 7, compared with the data for 59MeV protons incident at 45°. The similarity between the bit-error cross-sections for 60MeV neutrons and 59MeV protons (at 45°) confirms the contribution of nuclear interactions to the proton BER. The interaction cross-sections for nuclear scattering are very similar for neutrons and protons at this energy, ~530mb according to FLUKA code.

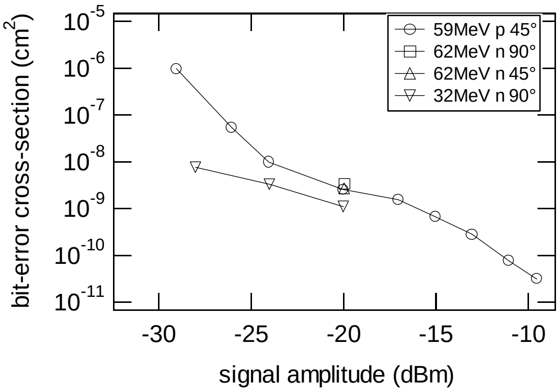

Figure 7: Cross-section for 32MeV neutrons (at 90° angle) and 62MeV neutrons (at 45° and 90°) compared with 59MeV protons at 45°.

D. System implications

The particle flux foreseen in the CMS tracker where the optical receiver will be installed can reach the level of $10^6 cm^{-2}s^{-1}$. This includes all hadrons above about 5MeV with pions and protons being the dominant particles. Due to the high magnetic field in the inner detector, only charged hadrons with energy above about 100MeV will arrive in the tracker volume where the optical receiver will operate. The energy spectrum of the charged hadrons in the tracker will be peaked around 200MeV, and at this energy, charged particles deposit 2.3 times less energy by direct ionisation than the 60MeV protons used in our experiments. Moreover, only a small fraction of these charged hadrons have the probability of crossing the photodiode at 90°. For these reasons we expect that secondary ionization, and not direct ionisation, will dominate the radiation-induced errors in the optical receiver in the CMS tracker.

An estimate of the BER performance of the optical receiver in the real environment can therefore be obtained directly from the measurements presented in the previous Sections. We have assumed that the data for 59MeV protons at 45° incidence is representative of the contribution to SEU from all hadrons above 20MeV. This is the same as assuming that the inelastic nuclear interaction cross-sections for the various hadrons encountered in the CMS Tracker are identical to that for 59MeV protons. This assumption has been validated, for the case of particles incident on silicon, in recent simulations[10].

Under conditions where the BER is dominated by radiation-induced errors, the following relation applies,

$$\mathrm{BER} = \frac{(\text{error cross-section})\cdot(\text{particle flux})}{\text{transmission rate}}$$

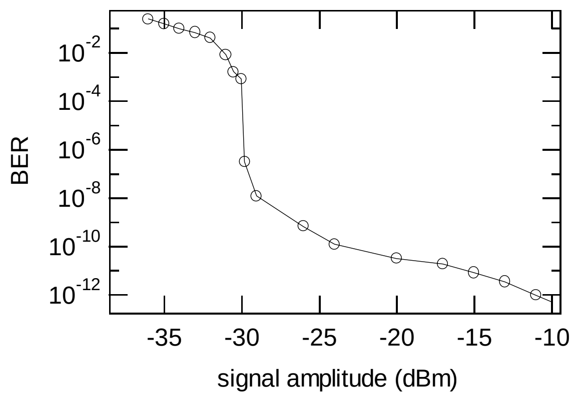

Figure 8: Estimated BER for optical receiver in the CMS Tracker environment, represented as the combination of measurements performed with 59 MeV protons at 45° (normalized to a particle flux of $10^6 cm^{-2}s^{-1}$) and the BER measured in the lab in the absence of beam.

Figure 8 shows the expected performance of the optical receiver in the CMS Tracker for an incident particle flux of $10^6 cm^{-2}s^{-1}$. The results suggest that BER=$4x10^{-11}$ is achieved at -20dBm. The BER decreases with increasing optical power and, under typical operating conditions where the optical amplitude is at least -10dBm, the BER is $<10^{-12}$.

IV. CONCLUSION

The BER performance of the CMS Tracker digital optical link receiver has been measured in the laboratory and during irradiation of the receiver with 59MeV protons and 32MeV and 62MeV neutrons with various incident angles.

SEU was observed under irradiation in the form of bit-errors (conversion of '0' to '1'), predominantly due to ionization in the photodiode. This effect was due to either direct ionization (for protons only) or secondary ionization from the recoil of a struck nucleus (for both protons and neutrons).

Direct ionization was most important for incident protons with beam-angles close to 90° and secondary ionization became important when the particles were incident at lower angles or under conditions of high optical power. The influence of secondary ionization was confirmed by the similarity in the bit-error cross-section for neutrons and protons.

In the CMS tracker environment, secondary ionisation is expected to be the dominant cause of radiation-induced transmission errors. A BER of $4x10^{-11}$ is estimated for an optical signal amplitude of –20dBm, the worst case in the receiver specifications.

REFERENCES

[1] F. Vasey, "CMS Tracker Optical Control Link Specification, Part 1: System", Available at: http://cms-tk-opto.web.cern.ch/cms-tk-opto/

[2] CMS Tracker Technical Design Report, CERN LHCC 98-6 (1998).

[3] K. Gill, C. Aguilar, V. Arbet-Engels, C. Azevedo, J. Batten, G. Cervelli, R. Grabit, F. Jensen, C. Mommaert, J. Troska and F. Vasey, "Comparative Study of Radiation Hardness of Optoelectronic Components for the CMS Tracker Optical Links", Proceedings of the 1998 RADECS Workshop, p.67, 1998.

[4] F. Faccio, P. Moreira, A. Marchioro, K. Kloukinas, and M. Campbell, "An amplifier with AGC for the 80Mbit/s Optical Receiver of the CMS digital optical link", Proceedings of the Fifth Workshop on Electronics for LHC Experiments, p.189, 1999.

[5] G. Anelli, M. Campbell, M. Delmastro, F. Faccio, S. Florian, A. Giraldo, E. Heijne, P. Jarron, K. Kloukinas, A. Marchioro, P. Moreira, and W. Snoeys, "Radiation tolerant VLSI circuits in standard deep submicron CMOS technologies for the LHC experiments: practical design aspects", IEEE Trans. Nucl. Sci. Vol. 46 No.6, p.1690, 1999.

[6] F. Faccio, P. Moreira, A. Marchioro, C. Azevedo and F. Vasey, "An 80Mbit/s radiation tolerant optical receiver for the CMS digital optical link", Proceedings of SPIE, Volume 4134, 2000.

[7] P. Marshall, C. Dale and K. LaBel, "Space Radiation Effects in High Performance Fiber Optic Data Links for Satellite Data Management", IEEE Trans. Nucl. Sci., Vol.43, No.2, 1996 (and references therein).

[8] P. Marshall, C. Dale and K. LaBel, "Charged particle effects on optoelectronic devices and Bit Error Rate measurements on 400Mbps Fiber based data links", Proceedings of Conference on Radiations and their Effects on Devices and Systems (RADECS93), St.Malo, September 13-16, p.266, 1993.

[9] G. Berger and G. Ryckewaert. "CYClotron of Louvain la Neuve (CYCLONE) Test Facility", Paper Presented at NASA Symposium, Goddard SFC, 1997.

[10] M. Huhtinen and F. Faccio, "Computational method to estimate Single Event Upset rates in an accelerator environment", Nucl. Inst. and Meth. A450, p.155, 2000.