Estimation of radiation effects in the front-end electronics of an ILC electromagnetic calorimeter

Valeria Bartsch, Martin Postranecky, Matthew Warren, Matthew Wing

Abstract—The front-end electronics of the electromagnetic calorimeter of an International Linear Collider detector are situated in a radiation environment. This requires the effect of the radiation on the performance of the electronics, specifically FPGAs, to be examined. In this paper we study the flux, particle spectra and deposited doses at the front-end electronics of the electromagnetic calorimeter of a detector at the ILC. We also study the occupancy of the electromagnetic calorimeter. These estimates are compared with measurements, e.g. of the radiation damage of FPGAs, done elsewhere. The outcome of the study shows that the radiation doses and the annual flux is low enough to allow today's FPGAs to operate. The Single Event Upset rate however lies between 14 minutes and 12 hours depending on the FPGA used and therefore needs to be considered in the design of the data acquisition system of the electromagnetic calorimeter. The occupancy is about 0.002 per bunch train not taking into account the effect of noise which depends on the choice of the detector.

I. INTRODUCTION

In this paper we simulate the energy spectra at the location of the front-end electronics, the energy deposited in the layers of the electromagnetic calorimeter (ECAL) and the number of hits in the ECAL component of the International Linear Collider (ILC), the layout of which is described in chapter III.

The motivation for this study is derived from our work in order to establish a data acquisition (DAQ) system being able to handle the amount of data anticipated from a highly segmented calorimeter. These calorimeters can be used in order to track particles throughout the calorimeter with particle flow algorithms.

As input, beamstrahlung remnants and physics events arising for a TESLA like collider with a centre-of-mass energy of 800 GeV have been considered. The main machine background is the production of hadrons in $\gamma\gamma$ interactions, where the photons are from beamstrahlung. The principal physics processes, i.e. those which have a high rate, are the production of hadrons in two-photon events, Bhabha scattering, $t\bar{t}$ and WW production.

In chapter V the estimates are compared with measurements of radiation damage and susceptibility to Single Event Upsets (SEUs) of FPGAs done elsewhere. In chapter VI the same simulations have been used to estimate the occupancy of the electromagnetic calorimeter.

II. RADIATION DAMAGE

In this section three failure mechanisms due to radiation damage are introduced: SEUs which change the state of the electronics, increase of the leakage current which can lead to errors of the electronics, and cluster displacements which leads to a non-reversible failure of parts of the electronics.

Single event upsets can occur in the electronics if a particle (typically a neutron, proton or pion above a certain threshold energy which is about 20 MeV) traverses it. The traversing particle transfers energy to a nucleus in the sensitive volume which creates a large ionization along its short path. If the deposited energy in the sensitive volume is higher than the threshold energy the electronics changes its state, in other words an upset has been triggered. Protons, neutrons and pions produce SEUs with the same probability if they traverse above an energy of 20 MeV [12], [13]. Below this energy the protons and pions undergo the Coulomb repulsion between the atomic nucleus and the proton or pion whereas the neutron does not carry a charge and therefore does not interact electromagnetically with the atomic nucleus. This means that neutrons below 20 MeV have a higher probability to cause SEUs than protons and pions. The cross section approximates a step function [12]; below a threshold energy, not enough electron-hole pairs are created to change the state of the circuit, whereas above that threshold energy enough energy is created. Due to geometrical uncertainties like the injection of the particle at an angle, the cross section is not exactly a step function. Typically the changes in the electronics due to a SEU can be reset in FPGAs and therefore SEUs do not lead to permanent damage. However in order to reset the FPGAs at a reasonable rate one needs to know the rate at which SEUs occur.

Ionizing radiation damages MOS devices primarily through building up positive charge in the oxide layers of the transistors and trapping negative charges at the interface between silicon and silicon-dioxide. After a particle traverses the dioxide and creates electron-hole pairs most of the electrons and holes do not recombine. The holes move in the electric field caused by the gate voltage to the interface between silicon and silicon-dioxide. They either become trapped still in the dioxide and build up a trapped oxide charge or they reach the interface between the silicon and the silicon-dioxide where they act as traps for electrons. The number of the traps is proportional to the energy deposited in the device and therefore roughly proportional.
to the absorbed dose. Ionizing radiation affects the current-voltage characteristic curves of a CMOS structure leading to a breakdown of the device at a dose of about 1 kRad to $10^7$ kRad depending on the FPGA type as measured e.g. in [1].

Displacement damage occurs when collisions between incident particles and lattice ions cause the relocation of the recoiled silicon ions. It depends on the fluence. Displacement damage would cause a reduction in carrier lifetime within the conducting channel. This could lead to changes in device timing and distortion of signals leading to a failure of the electronics. This should not be a concern for the low flux expected at the electromagnetic calorimeter of the ILC detector. Studies for the LHC have shown that FPGAs showed no problems at a fluence of $10^{14}$/cm$^2$ [2].

II. GEOMETRY

The detector design on which the study is based is the TESLA detector design [3]. Although newer, slightly different detector designs are available [4], [5], the effects described in this paper should be similar for any of those designs. In addition to radiation effects in the electronics the study gives estimates on the highest radiation dose and flux expected in the ECAL. These values are important for both the electronics and the detector components in the calorimeters.

The FPGAs discussed in this paper are part of the front-end electronics (FE) of the electromagnetic calorimeter (ECAL) of the ILC detector. For the studies, a magnetic field of the TESLA detector solenoid which has the value of 4 T has been simulated. A cross section of the inner parts of the detector is shown in figure 1. The barrel section of the ECAL has an eight-fold geometry, each of which consists of 40 slabs stacked on top of each other. In the direction of the beamline the barrel ECAL consists of 25 slabs. The front end electronics is located at the end of the slabs of the ECAL which are 26 cm wide. In total the ECAL has 8000 slabs each with one FPGA with an area of 1 cm$^2$. The ECAL covers a pseudorapidity $\eta$ range of $-1.1 < \eta < 1.1$, therefore no $\eta$ dependence of the particles’ energy spectrum is expected. It is assumed that the FPGAs connected to the end cap of the ECAL are also located at about 1.8 m away from the beam pipe. Some components of the DAQ system need to be located on the detector and therefore in a radiation environment.

IV. ENERGY SPECTRUM, FLUENCE AND RADIATION DOSE AT THE AREA OF THE FPGAS

To quantify radiation effects one needs to simulate the energy spectrum of the particles traversing the FPGAs, because these particles cause the radiation damage. In the following, physics events and machine backgrounds will be discussed.

In order to generate the energy spectrum, the processes with the largest cross sections and the expected event rates which have a high enough energy in order to traverse the detector and reach the volumes of the ECAL front-end electronics have been chosen. The selection was done with the help of the TESLA TDR [3]. The most probable events according to the TESLA TDR are $t\bar{t}$ events, WW events, Bhabha scattering and hadrons produced in two-photon events, here called QCD events so as to distinguish them from the beamstrahlung remnants as shown in table I. All processes have been generated using PYTHIA [6] and fed into the detector simulation MOKKA [7]. The resulting particle spectra come from the development of showers in the ECAL.

The centre-of-mass energy of the ILC accelerator is not yet known and might change during its lifetime. It is presumably between 500 and 800 GeV. In order to study a worst-case scenario two effects have to be taken into account: on one hand the probability that a jet reaches the housing of the front-end electronics increases with energy, on the other hand the production cross section which typically decreases with higher centre-of-mass energy. Therefore the simulation is done at a centre-of-mass energy of 800 GeV with the production cross section expected at a centre-of-mass energy of 500 GeV or 800 GeV, choosing the highest production cross section.

For QCD events the beam is composed of electrons, positrons and photons allowing photon interactions to contribute to hadron production. All significant contributions to QCD physics events including those from virtual photons to the total cross section independent of $Q^2$ range are obtained. Bhabha, WW and $t\bar{t}$ events do not have significant photon contributions and therefore have been generated defining the beam to be composed only of electrons and positrons. The WW events were generated with a cut $|\eta| < 2$ in order to reduce the memory allocation of the detector simulation which is proportional to the number of particles simulated. Thus backscattered secondaries are not taken into account for


<table>
<thead>
<tr>
<th>process</th>
<th>number of events/h</th>
<th>generated events</th>
</tr>
</thead>
<tbody>
<tr>
<td>$t\bar{t}$</td>
<td>50-70</td>
<td>110</td>
</tr>
<tr>
<td>Bhabha $(\theta &gt; 20\text{mrad})$</td>
<td>$1.2 \times 10^6$</td>
<td>4149</td>
</tr>
<tr>
<td>WW</td>
<td>800-900</td>
<td>183</td>
</tr>
<tr>
<td>QCD</td>
<td>$(7.9) \times 10^6$</td>
<td>1987</td>
</tr>
<tr>
<td>$\gamma\gamma$ events</td>
<td></td>
<td></td>
</tr>
<tr>
<td>(machine background)</td>
<td>$4.1 \times 10^7$</td>
<td>2301</td>
</tr>
<tr>
<td>pair production</td>
<td>$10^{11}$</td>
<td>20000</td>
</tr>
</tbody>
</table>

**TABLE I**

**PHYSICS EVENTS AND MACHINE BACKGROUND WHICH ARE MOST RELEVANT FOR THE SEU RATE IN THE FPGAS [3].**


WW events. The WW, $t\bar{t}$ processes are negligible compared to the QCD process due to their small rates as can be seen in table I. The Bhabha scattering process is negligible because the final state particles are scattered in the forward and backward regions.

For the machine background two types of backgrounds have been considered: machine background arising from incoherent pair production and machine background from $\gamma\gamma$ interactions, where the photons are from beamstrahlung. A possible beam loss which effects the detector has not been studied in the scope of this paper. The $\gamma\gamma$ interactions will be called beamstrahlung remnants. The incoherent pair production points into the very forward region of the detector. $\gamma\gamma$ interactions create hadrons, in turn creating jets which can point into the barrel region of the calorimeter. It has been shown that this process is important for the occupancy of the tracking detector [8].

The event rates expected for a TESLA detector at a collision energy of 800 GeV are summarized in table I. The energies of the colliding photons and the outgoing electrons and positrons from pair production have been generated with GUINEAPIG [9]. Special care was taken that there were no cuts made at this stage of the simulation. The energies of the photons were the input collision energies in PYTHIA for an effective photon collider. All particles in the final state were further processed within the MOKKA detector simulation, as with the physics processes discussed previously. For the pair production process the electrons and positrons were used directly in the MOKKA simulation. In the MOKKA simulation, about 25 events out of 20000 have particles traversing the ECAL, however there are no events with particles traversing either the barrel part of the ECAL or the region of the FPGAs. Thus the machine background from the pair production is lower than the machine background from the $\gamma\gamma$ interactions as shown later in this paper. Therefore this process was discarded for further analysis and just the beamstrahlung remnants were analysed further.

After normalising the events to the area covered by the FPGAs the energy spectra of pions, protons and neutrons in the shower are shown in figure 2. Neutrons, protons and pions create SEUs whereas the other particles do not generate enough electron-hole pairs in silicon in order to generate SEUs. Therefore only these particles need to be considered in the scope of the SEU study. The particle spectra of all particles have been used though in the subsequent calculations of the fluence.

Fig. 2. Energy spectrum of protons, pions and neutrons at the FPGA for $t\bar{t}$, WW, Bhabha, QCD events and the machine background $\gamma\gamma \rightarrow \text{hadrons}$ events

The fluence is calculated from the energy spectra using the equation given in [10]. The 1 MeV neutron equivalent flux is $2 \times 10^6/\text{cm}^2$ per annum.

The radiation dose is obtained from the depositions of charged particles in the silicon volume and it influences the increase of leakage current. It has been checked that the fourth silicon layer of the ECAL receives most of the energy deposition. For the simulation of the radiation dose the same events as for the simulation of the energy spectrum have been used. The radiation dose is estimated to be 0.13 Rad/year.

**V. COMPARISON OF THE ESTIMATED DOSES AND FLUENCES WITH MEASUREMENTS ON CURRENT FPGAS**

In [17] it is found that the radiation dose at which three FPGAs start creating errors is above 42kRad. This is a factor $>10^5$ higher than the radiation dose we expect per year at the point of the FPGAs at the ILC. This means that we do not expect any problems with this kind of radiation dose.

Tests checking that FPGAs do not fail due to non-ionizing energy loss effects up to a fluence of $1.9 \times 10^{13} \text{n/cm}^2$ have been performed for the ATLAS detector at the LHC [2] and it has been confirmed that the current FPGAs are not affected by this type of damage. We expect a much lower flux at the ILC and therefore we do not expect a failure of the FPGAs...
Taking the highest number of hits the occupancy is $2 \times 10^{-3}$. Contributions from noise will increase the occupancy. These studies are beyond the scope of this paper. In addition to these numbers on the occupancy in the ECAL barrel, studies on the occupancy in the endcaps and the hadronic calorimeter are in preparation.

Table II

<table>
<thead>
<tr>
<th>type of FPGA</th>
<th>year of publication</th>
<th>$E_{\text{threshold}}$ in MeV</th>
<th>$\sigma_{\text{SEU}}$</th>
<th>SEUs per h</th>
</tr>
</thead>
<tbody>
<tr>
<td>Virtex II X-2V100 and Virtex II X-2V6000</td>
<td>2004 [15]</td>
<td>5</td>
<td>$8 \times 10^{-9}$</td>
<td>0.55</td>
</tr>
<tr>
<td>Altera Stratix</td>
<td>2004 [16]</td>
<td>10</td>
<td>$10^{-7}$</td>
<td>4.20</td>
</tr>
<tr>
<td>Xilinx XC4036XL</td>
<td>2003 [12]</td>
<td>20</td>
<td>$3 \times 10^{-9}$</td>
<td>0.09</td>
</tr>
<tr>
<td>Virtex XQVR300</td>
<td>2003 [17]</td>
<td>10</td>
<td>$2 \times 10^{-8}$</td>
<td>0.84</td>
</tr>
<tr>
<td>8046RP</td>
<td>1998 [18]</td>
<td>20</td>
<td>$10^{-8}$</td>
<td>0.29</td>
</tr>
</tbody>
</table>

SEU CROSS SECTION AND THRESHOLD ENERGY FOR DIFFERENT FPGAS AS PUBLISHED, RATE OF SEU IN THE ECAL CALCULATED FROM THIS.

In Table II the threshold energy $E_{\text{threshold}}$ versus SEU cross section $\sigma_{\text{SEU}}$ for several FPGAs is listed as found in literature. Some papers give the cross section per bit, whereas some papers present the cross section per device. In order to normalise the results it was assumed that one device has one million bits[12]. Unfortunately only proton data are available. Therefore, in order to do an estimate for this study, for protons, neutrons and pions below 20 MeV, the same cross section was assumed for each.

For the existing measurements the SEU rate for the FPGAs in the ECAL has been calculated. It varies between 14 minutes and 12 hours depending on which FPGA is used. The SEU rate is dominated by the QCD events and the $\gamma \gamma$ machine background events. The relative contribution of the beamstrahlung remnant events to the SEU rate is about a factor one thousand higher than of the QCD events. However there does not seem to be a dependence of the SEU rate on the production year of the FPGA. Because the size of the circuits within the FPGA will continue to decrease it seems certain the threshold energy of a SEU will decrease. This means that in future it will become more important to measure the SEU cross section $\sigma_{\text{SEU}}$ for protons, neutrons and pions.

Measurements to study the SEU upset rate with the final FPGA for the front-end electronics and several radiation monitoring devices are described in [14].

VI. OCCUPANCY

With the same simulated data we were able to estimate the occupancy of the electromagnetic calorimeter. The occupancy is defined as the number of cell hits within a bunch train divided by the total number of electromagnetic calorimeter cells, $31 \times 10^6$. The occupancy is important for the DAQ system design because it determines, together with features of the electronics, the data rates which need to be handled. Therefore an estimate is given here. In order to get to the number of cell hits per bunch crossing the $t \bar{t}$, WW, Bhabha, QCD events and beamstrahlung remnants have been combined taking into account the cross section of Table I. In order to get a realistic distribution, the number of events $N_{\text{ev}}$ has been Gaussian distributed with a sigma of $\sqrt{N_{\text{ev}}}$. The mean number of hits is about 66000, the highest number of hits about 72000.

VII. CONCLUSION

This study estimates effects of the radiation damage on the front-end electronics of the electromagnetic calorimeter in the TESLA design. For this study detector simulations using PYTHIA and MOKKA have been performed for physics events and beamstrahlung remnant events which occur frequently according to the TESLA TDR. In this study WW, QCD, $t \bar{t}$, Bhabha, beamstrahlung pair production and $\gamma \gamma \rightarrow$ hadrons were simulated. Particle spectrum traversing the ECAL front-end electronics was generated. The energy depositions in the each layer of the ECAL were calculated. The $\gamma \gamma \rightarrow$ hadrons machine background and QCD events dominate.

The radiation dose of the fourth ECAL layer was estimated to be around 0.13 Rad per year and therefore does not cause any problematic increase of the current of today’s FPGAs. Errors do occur at radiation doses of about 42kRad as measured e.g. in [17]. The estimated flux of $2 \times 10^6$/cm$^2$ per annum is too small to cause enough cluster displacements to affect the operation of today’s FPGAs. It is about a factor $10^3$ smaller than the annual flux of the ILC vertex detector which is dominated by machine background and about a factor of $10^9$ smaller than the flux of the inner LHC detectors.

Therefore this study shows that today’s FPGAs are able to handle the radiation damage caused by physics events and beamstrahlung photon interactions in the front-end electronics of the ECAL. In order to estimate the SEU rates in the whole ECAL, the particle spectra and cross sections for the SEU upsets of today’s FPGAs as found in literature were used. It has been shown that the SEU rate with today’s FPGAs lies between 14 minutes to 12 hours for all of the FPGAs in the TESLA ECAL. This requires the FPGAs in the ECAL to be reset at a higher rate to mitigate these effects.

With the help of the simulations the occupancy resulting from physics events of the ECAL barrel could be determined. It is estimated to be $2 \times 10^{-3}$ per bunch train. Again these simulations only comprise physics events and beamstrahlung remnants. It is expected that this number will rise when noise is considered.

VIII. ACKNOWLEDGEMENTS

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REFERENCES