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

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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. Physics events and hadron events that originate from the machine background, have been simulated and radiation spectra in the area of the detector housing the front-end electronics have been estimated. It is not yet possible to make a final prediction of the absolute effect of this radiation as the type of FPGA and the final design parameters of the accelerator will not be decided for several years. Therefore measurements are proposed which can be made in order to estimate the radiation damage for any given FPGA. The estimates are made using energy spectra at the location of the front-end electronics as well as energy deposition in the ECAL. The radiation damage is estimated by using energy spectra and energy depositions produced for this part of the detector. The method, but not the particle spectrum and the energy depositions, is applicable for electronics in any part of the detector.

Key words: ILC, CALICE, radiation damage, SEU, FPGA

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1 Introduction

In this paper we study the radiation effects (which are introduced in chapter 2) on the front-end electronics of the electromagnetic calorimeter (ECAL) component of the International Linear Collider (ILC), the layout of which is given in chapter 3. In order to do this, particle spectra (from the products of both machine background and physics collisions) in the area where front-end electronics are located and energy depositions in the ECAL are studied. This is detailed in chapter 4. As input, machine background 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. The principal physics processes, i.e. those which have a high rate, are the production of hadrons in two-photon events, $t\bar{t}$ and WW production. In chapter 5 the estimates are compared with reported effects of radiation damage in FPGAs. In chapter 6 the same simulations have been used to estimate the occupancy of the electromagnetic calorimeter.

2 Radiation damage

In this section three failure mechanisms due to radiation damage are introduced: single event upsets (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 and generates enough electron-hole pairs in the active area of the silicon material such that a change in the state of the circuit occurs. Typically these changes 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.

The leakage currents in FPGAs increase due to the creation of deep level traps between the valence and the conduction band of silicon. The leakage current increases linearly with the radiation dose. Charge carriers can be easily lifted into the conduction band and therefore the leakage current increases. Depending on the magnitude of the increase, electronics could show errors when the leakage current is similar to the current flowing when the state of the electronics changes. It is difficult to counteract these errors, but they only occur
at high radiation dose of about 3 kRad to 300 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) which is significantly higher than the fluxes expected at the electromagnetic calorimeter of the ILC.

3 Geometry

The FPGAs discussed in this paper are part of the front-end electronics (FE) of the electromagnetic calorimeter (ECAL) of the ILC detector as proposed in the TESLA TDR (3). Although newer, slightly different detector designs are available citeILD, SiD, the effects described in this paper should be similar for any of those designs. For the studies, a magnetic field of the TESLA detector solenoid which has the value of 4 T has been simulated. 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 pipe.

4 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, physics events which occur most of-
ten and 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 ac-
cording to the TESLA TDR are $t \bar{t}$ events, WW events and hadrons produced
in two-photon events, here called QCD events so as to distinguish them from
the machine background as shown in table 1. All processes have been gener-
ated using PYTHIA (6) and fed into the detector simulation MOKKA (7). The
resulting particle spectra come from the development of showers in the ECAL.

In PYTHIA, events at a centre-of-mass energy of 800 GeV have been gen-
erated. This has been done in order to give a worst case estimate for the
radiation damage because the higher energy implies a higher cross section of
particles hitting the FPGAs, a higher number of showers and a higher number
of particles in each shower. Therefore, the higher the radiation damage. Al-
though the events have been generated at a centre-of-mass energy of 800 GeV,
the production cross section for a centre-of-mass energy of 500 GeV, which is
typically slightly higher than the cross section at 800 GeV, has been chosen
according to the TESLA TDR.

For QCD events the beam is composed of electrons, positrons and photons
allowing photon interactions to contribute to hadron production. With the
option $\text{MSTP}(14) = 30$ one automatically obtains a realistic first approxima-
tion to all significant contributions to QCD physics to the total cross section
independent of the $Q^2$ range. WW and $t \bar{t}$ events do not have significant pho-
ton 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 WW events. The WW
and $t \bar{t}$ backgrounds are negligible compared to the QCD background due to
their small rates as can be seen in table 1.

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. 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 background 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 1. 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 PYHTIA 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 background 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 background from the pair production is lower than the background from the $\gamma\gamma$ interactions as shown later in this paper. Therefore this background was discarded for further analysis and just the $\gamma\gamma$ machine background was 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 1. 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. 1. Energy spectrum of protons, pions and neutrons at the FPGA for $t\bar{t}$, WW, QCD events and the machine background $\gamma\gamma \rightarrow$ hadrons events

The fluence is calculated from the energy spectra using (10). The 1 MeV neu-
tron equivalent flux is $2 \times 10^6 / \text{cm}^2$ per annum. This 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 $10^8$ smaller than the flux of the inner LHC detectors.

The radiation dose is the electromagnetic energy deposited in a silicon volume and it influences the increase of leakage current. There are two ways to get an estimate for the radiation dose. One way is to calculate the energy deposition from the particle spectra, another way is to simulate the energy deposition in the silicon layers of the ECAL and calculate the radiation dose. The energy deposition in 300 $\mu$m of silicon as a function of each particle is an estimate. It is tabulated in (11). With this estimate one gets a radiation dose of $7 \times 10^{-4}$ Rad/year.

The second approach is a worst case scenario. It has been checked that the fourth silicon layer of the ECAL receives most of the energy deposition. With the current MOKKA simulation it is not possible to distinguish between electromagnetic and non-electromagnetic interactions. Only electromagnetic energy depositions contribute to the radiation dose. Therefore we are overestimating the radiation dose. For the simulation of the radiation dose the same events as for the simulation of the energy spectrum have been used. From this simulation the radiation dose is estimated to be 0.13 Rad/year. The two estimates differ by about a factor of 200, but since the numbers are small and significantly lower than safe limits of 3 to 300 kRad we conclude with this discrepancy.

5 Estimate of the effects of radiation damage on current FPGAs

A literature search (1; 17) shows that 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 the fluence 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 propose that this measurement should be done for a given FPGA, however we do not expect a failure of the FPGAs.
In order to estimate the SEU rate, it is necessary to measure the SEU rate of FPGAs irradiated with protons, neutrons and pions. 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 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.

In table 2 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. This is definitely a systematic error in this study which cannot be quantified. If the threshold value of the FPGA chosen for the calorimeter in the end is below 20 MeV it would be advisable to measure for different traversing particle types.

The SEU rate is dominated by the QCD events and the $\gamma\gamma$ machine background events. The relative contribution of the machine background events to the SEU rate is about a factor one thousand higher than of the QCD events. 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. So we advise that the SEU rate of a selected FPGA should be determined before choosing it for the ECAL. 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).
6 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 cells hits within a bunch train divided by the total number of electromagnetic calorimeter cells, \(31 \times 10^6\). The occupancy is important for the data acquisition system of the electromagnetic calorimeter. Therefore an estimate is given here. In order to get to the number of cell hits per bunch crossing the \(t\bar{t}\), WW, QCD events and the machine background events have been combined taking into account the cross section of table 1. In order to get a realistic distribution, the cross section of each physics process has been Gaussian distributed. The mean number of hits is about 66000, the highest number of hits about 72000. 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.

7 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 machine background events which occur frequently according to the TESLA TDR. In this study WW, QCD, \(t\bar{t}\), pair production and \(\gamma\gamma \rightarrow \text{hadrons}\) events were simulated. The particle spectrum of particles traversing the ECAL front-end electronics were generated. The energy deposits in the each layer of the ECAL were calculated. The \(\gamma\gamma \rightarrow \text{hadrons}\) machine background and QCD events dominate.

The radiation dose of the fourth ECAL layer was estimated to be around 0.13 Rad per year due to physics events and therefore does not cause any problematic increase of the current of today’s FPGAs. The estimated flux of \(2 \times 10^6/\text{cm}^2\) per annum is too small to cause enough cluster displacements to affect the operation of today’s FPGAs. Therefore this study shows that today’s FPGAs are able to handle the radiation damage caused by physics events 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 machine background. It is expected that this number will rise when noise is considered.

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List of Figures

1. Energy spectrum of protons, pions and neutrons at the
FPGA for t\bar{t}, WW, QCD events and the machine background
\gamma\gamma \rightarrow \text{hadrons events}
<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>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 (machine background)</td>
<td>$4.1 \times 10^7$</td>
<td>2301</td>
</tr>
<tr>
<td>pair production (machine background)</td>
<td>$10^{11}$</td>
<td>20000</td>
</tr>
</tbody>
</table>

Table 1
Physics events and machine background which are most relevant for the SEU rate in the FPGAs (3).

<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 in the ECAL 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 XC4036XLA</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>

Table 2
SEU cross section and threshold energy for different FPGAs as published, rate of SEU in the ECAL calculated from this.