Monte Carlo Simulations of the TCC2 radiation test facility at CERN

Author(s) / Div-Group: K. Tsoulou, T. Wijnands, C. Pignard, R. Rausch / AB-CO, H. Vincke / TIS-RP

Keywords: Monte Carlo Simulation, TCC2, radiation field

Summary

The hard radiation environment of the Large Hadron Collider (LHC) demands for a careful choice of COTS (Components Off The Shelf) and custom made electronics that will be installed in the tunnel. All the electronic equipment should be tested on their radiation tolerance. For this purpose we use dedicated radiation facilities and the TCC2 test facility at CERN, where there is a mixed radiation field similar to that of the LHC. To achieve optimum results on the electronics radiation tolerance it is essential to study thoroughly the complex radiation field in the test facility at CERN. For this purpose a detailed Monte Carlo simulation of the test area was carried out and the calculations were compared with dosimetry measurements already available.

1. Introduction

The LHC radiation test facility described in this study allows the qualification of a large amount of COTS and custom made electronic equipment of different complexity and radiation tolerance. Initial Monte Carlo simulations [1] have shown that the energy spectra and the type of particles in the test zone are similar to what can be expected in the accelerator tunnel while the dose rates are significantly higher (> 1 Gy/day in the test area compared to the 1 - 10 Gy/year in the tunnel) [2]. Although detailed studies of specific damage mechanisms are not possible, the test zone provides enough space and irradiation time to allow for large scale testing of various COTS (components and complete systems) and improvement via the trial and error method. In addition, the test zone is used to validate hardware and software modules for dedicated irradiation campaigns outside the laboratory (in particular Single Event Effect tests with proton beams).

In this paper, we present the results of a detailed Monte Carlo simulation of the complex field in the radiation test zone. The results are compared with experimental measurements consisting of Total Ionizing Dose (TID) measured by ionization chambers (PMI) and polymer-alanine dosimeters (PAD), displacement damage measured by PIN diodes and Single Event Upsets (SEUs) induced in static RAM memory (SRAM).

Good correspondence between simulation and experiment values shows that physics operation of the test zone is now well understood.
2. The TCC2 radiation test facility

The TCC2 radiation test zone is situated in the Primary Target Hall in the North Area of the Super Proton Synchrotron (SPS) complex at CERN. The test zone is a ‘parasitic’ radiation test area that makes use of primary protons from the accelerator that are not used by the fixed target experiments situated further downstream (Figure 1). During operation, the SPS accelerator ejects high-energy protons (400 GeV/c) that hit the primary target T6.

Some of the protons interact with the target material and create hadronic showers. Other protons do not interact and pass through the target material without losing any significant amount of energy. All charged particles exiting the target (mainly protons, pions, kaons and muons) are bent by the dipole magnets after the primary target. Only charged particles with the correct energy can traverse the dump collimator (TAX) and reach the fixed target experiments further downstream. Charged particles with low energies are strongly deflected and eventually hit the shielding wall. High-energy charged particles, such as protons at 400 GeV/c, are barely deflected and hit the TAX where they initiate again hadronic cascades.

When the beam is on, the electronic equipment situated in the radiation test area behind the TAX is irradiated with a variety of particles (protons, neutrons, pions, kaons, gammas) with energies up to several GeV. Since the type of particles and the energy spectra are similar to what has been predicted for the LHC accelerator tunnel [1], this area is ideal for final tests of complete systems (series production) before the installation in the LHC tunnel takes place.

3. Monte Carlo Simulation

The FLUKA [3] Monte Carlo code was used for this simulation that took into account all the beam line in the test area (74 m long) starting from the primary target (T6) until the radiation test area after the TAX (Figure 1). The whole calculation was divided into two phases. The first covered the interaction of the 400 GeV/c protons with the T6 target including the production and transport of all particles up to a surface defined by the front face of the TAX (51.12 m downstream T6). The properties of all particles reaching this surface were recorded in a file. In the second phase the recorded particles were started at this dividing plane to be treated further downstream using biasing techniques in order to increase statistics.

Figure 1: Top view of the radiation test facility at CERN. 400 GeV/c protons hit the primary target (Be) and are dumped 51m downstream on the dump collimator (TAX). Part of the beam (mainly pions and kaons) is lead further downstream to other experiments. The radiation test area (marked with the dashed frame) is situated just after the TAX, where a large amount of hadron showers are created.
Total energy deposition in air and energy deposition by $e^-/e^+/$gammas only were scored in a mesh covering the test area from the floor up to the height of the beam line. Due to line symmetry along the beam line (at the heights of interest), similar values are expected to correspond at the respective regions above the beam line. Figure 3 (a - d) shows the total energy deposition at different horizontal levels, starting from 40 cm above the concrete floor, in Gy per proton incident on the primary target (T6). In a normal operation day in 2002, $4.71E+16$ protons on average hit the T6 target. In the area there are several dosimeters situated at the positions 1 – 10, also shown in Figure 3. From this picture it seems that the sites with the highest doses are those close to the dosimeter positions 2 and 3 near the TAX and the first dipole magnet.

Integrated particle fluences of neutrons and charged hadrons were scored in a similar mesh covering the test area. Figure 4 (a-d) shows contour plots of the total hadron fluence at various horizontal levels. These pictures indicate that the relevant hadron fluence decreases further away from the TAX. From the calculated values it was derived that more than 70% of the hadrons in the test area are neutrons.

Most of the electronics under test are installed between the dosimeter positions 2 and 3. Therefore, at this area, the particle fluences were scored as a function of the particle energy using parallelepiped-scoring regions ($40 \times 40 \times 100$ cm). The calculated Fluence-to-Dose ratios for neutrons with $E > 100$ keV and $E > 1$ MeV and charged hadrons plus neutrons with $E > 20$ MeV and $E > 100$ MeV are presented in Table 1. The given numbers are the mean values of eight parallelepiped scoring regions covering the area between positions 2 and 3 (from 30 cm below to 50 cm above the beam line). For comparison, the values that have been predicted [2] for the areas of the highest dose in the LHC tunnel (alongside the dipoles) are also shown.

4. Comparison with experimental data

The total dose accumulated in the test zone was measured by polymer-alanine dosimeters (PAD) and an on-line dosimetry system based on ionisation chambers (PMI) placed at the positions 1-10 shown in Figures 3 and 4. PMI dosimeters were designed to measure remanent dose during beam-off periods for radiation protection purposes around the accelerators at CERN.
Figure 3: Total dose (in Gy per proton incident on T6 target) in the radiation test area at various horizontal levels above the concrete floor a.) 40 - 60 cm, b.) 60 - 80 cm, c.) 80 – 100 cm, d.) 100 – 120 cm. The beam line is at 120 cm and the dosimeters within the level 100-120 cm above the floor, but the geometry is drawn at all levels as a reference. The measurement positions (1-10) are also shown. In a normal operation day (24 hours) in 2002, 4.71E+16 protons on average hit the T6 target.
Figure 4: Total hadron fluence (neutrons and charged hadrons – the neutrons dominate more than 70% of the hadron fluence) in the radiation test area at various horizontal levels above the concrete floor a.) 40 - 60 cm, b.) 60 - 80 cm, c.) 80 – 100 cm, d.) 100 – 120 cm. The beam line is at 120 cm and the dosimeters within the level 100-120 cm above the floor, but the geometry is drawn at all levels as a reference. The values are the integral fluence in cm$^{-2}$/proton incident on T6. In a normal operation day (24 hours) in 2002, 4.71E+16 protons on average hit the T6 target.
Fluence-to-Dose ratios (cm$^{-2}$·Gy$^{-1}$)

<table>
<thead>
<tr>
<th>Energy Threshold</th>
<th>Radiation test area</th>
<th>LHC tunnel</th>
</tr>
</thead>
<tbody>
<tr>
<td>&gt; 100 keV neutrons</td>
<td>4.9E+10</td>
<td>5.3E+10</td>
</tr>
<tr>
<td>&gt; 1 MeV neutrons</td>
<td>1.2E+10</td>
<td>1.2E+10</td>
</tr>
<tr>
<td>&gt; 20 MeV hadrons</td>
<td>4.2E+09</td>
<td>3.7E+09</td>
</tr>
<tr>
<td>&gt; 100 MeV hadrons</td>
<td>2.1E+09</td>
<td>1.6E+09</td>
</tr>
</tbody>
</table>

Table 1: Fluence-to-Dose ratios calculated in the radiation test area for neutrons and hadrons above various energy thresholds. For comparison, the respective values calculated in [2] for the LHC tunnel are shown. These values refer to the areas of the highest dose in the LHC installation sites, i.e. alongside the dipoles.

Table 2: Experimental and simulated values of doses (in Gy/day). The dosimeter data (by PMI and PAD) are the mean values of the accumulated doses in the period 8/8 - 4/9/2002. The simulation calculated the doses from all particles and $e^+$/gammas at the dosimeter positions 1-10 shown in Figures 3 and 4. The hadron dose was derived from the difference of the two others. The calculations are the mean values of three independent simulation runs.

Table 3: Experimental and simulated fluences (in cm$^{-2}$/day) of neutrons (E > 100 keV and E > 140 keV) and hadrons (E > 20 MeV) are presented, as measured at the sites 1-10 shown in Figures 3 and 4. The neutron values for E > 140 keV are scaled to 1 MeV equivalent fluence in Silicon in order to compare with the PIN diode measurements.
When there is no beam, access to the test zone is allowed and the ionization chambers measure the dose from remanent gamma radiation only. During the beam operation the dose seen by the chambers is much higher. In this case, all particles contribute to the dose seen by the ionisation chambers. We used the PMI reading values obtained during beam operation to compare them with our simulation results. The PMI measurements (mean values of the daily readings during the period 8/8 – 9/4/2002) and their simulated counterparts are presented in Table 2. Away from the TAX (positions 9 and 10) the dose rate is relatively low (Figure 3) and there is good agreement between simulated and measured dose (PMI). The dose measured with alanine dosimeters is at least 4 times higher than that of PMIs, which may be attributed to the presence of neutrons. In the vicinity of the TAX (positions 1 to 8) the dose rates are significantly higher. Better agreement between alanine measurements and simulated values is obtained with the exception of the measurements at position 2. The discrepancy between simulated and PMI values may be explained by saturation effects as observed in [4]. Detailed studies of the behaviour of a PMI chamber with associated electronics in a pulsed radiation field with high dose rates are presently ongoing.

The hadron fluence in the zone was measured with dosimeters based on static RAM memory (SRAM). These dosimeters consist of 4 chips of the Hitachi HM628128DLP-5 memory cells mounted on a printed circuit board powered by a battery. Charged with a fixed pattern, the dosimeters were placed in the zone at the location of the ionization chambers and read out a week later. The number of SEUs gives an indication of the high-energy hadron fluence at these locations. The memory cells have been calibrated with a 60 MeV proton beam (Figure 5) and are in good agreement with the data produced in [5]. For the analysis of the dosimeter data, we assume identical cross sections for all types of hadrons.

Moreover, displacement damage was measured with Harshaw PIN diodes. The calibrated diodes are short-circuited and placed in the zone and read once a week. The diodes measure displacement damage and are sensitive to all neutrons with energy >140 keV [6]. The measurements are expressed in 1 MeV eq. neutrons in silicon.

Table 3 lists the above PIN and SRAM measurements as well as the calculated neutron and hadron fluences at cylindrical air regions at the positions 1-10 shown in Figures 3 and 4. All experimental data are the mean values of the accumulated measurements during the period 8/8 - 9/4/2002. The neutron fluences for energies > 140 keV correspond to the PIN diode.
measurements, and for this reason they have been scaled to 1 MeV eq. fluence in Silicon
using the data by M. Huhtinen [7] and G. Lindström [8]. The hadron (neutrons and charged
hadron) fluences for energies > 20 MeV correspond to the SRAM measurements.

In Table 3, the simulated neutron values are - with the exception of position 2 -
constantly lower than the corresponding PIN diode measurements. This may be attributed to
the non-zero response of the PIN diodes to charged particle fluence as studied by B. Camanzi
[9]. According to the same study, the diode placed in position 2 is suspected to have reached
the inconsistent non-linear region.

Sensitivity to low energetic particles and saturation effects may also at the origin of
fluences measurements with the SRAM memory and the simulated values.

5. Conclusions

A complete Monte Carlo simulation of the pulsed radiation field in the LHC radiation
test facility in TCC2 has been carried out. The simulation accounts for the entire beam line,
i.e. from the primary target T6 up to the TAX collimator, including magnetic field and
collimators. The simulation confirms earlier claims that the radiation spectra in the TCC test
facility are near identical to that in the LHC ARCs. Dose rates are orders of magnitude higher,
which make this area ideal for testing of electronic components and final tests of complete
systems.

The simulated values have been cross-checked with a variety of dosimeter
measurements that were taken during the 2002 campaign when the M2 beam was operated in
physics mode. At low dose rates, good agreement has been found between the simulations and
the dose measured with PMI ionisation chambers. At higher dose rates, the simulated values
are in good agreement with the alanine dosimeters. The simulated values have also been
compared to the fluences measured with SRAM memory and PIN diodes.

We suspect that dose rates and/or the dynamics of the radiation field cause saturation
effects that make these dosimeter measurements less precise. This work has also made clear
that more detailed studies on this subject are needed.

Experiments are presently ongoing and we expect to present more detailed data on high-
level dosimetry at the end of the 2003 campaign.

The dosimetry of a mixed radiation field is a non-trivial problem and needs careful
investigation. A miscellany of Monte Carlo calculations and different dosimeter
measurements can be a valuable tool for this kind of problems. However, the limitations of
the dosimetry instruments should be always taken into account in order to interpret the
measurements correctly. More experimental data regarding SEU or TID, which are currently
being accumulated, will offer a better insight to the dosimetry of the TCC2 radiation facility
as well as the radiation tolerance of COTS tested in the zone.

6. Aknowledgements

Exploitation of the LHC radiation test zone would not be possible without the help of
CERN Radiation Protection group (TIS/RP). Special thanks to G. R. Stevenson who
contributed to the simulation work and to D. Perrin and M. Tavlet for the dosimetry
measurements.
7. References