# WP 1 - RADIATION ENVIRONMENT AND ELECTRONICS

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The proton computed tomography (proton CT) *Digital Tracking Calorimeter* (DTC) setup as investigated in the "*DTC design recommendations*"(Bergen pCT group, 2017) was implemented in the Monte Carlo (MC) code FLUKA(Böhlen et al., 2014; Ferrari et al., 2005) and MC simulations were performed to investigate and evaluate the induced radiation environment inside and surrounding the DTC. This is done with respect to the radiation hardness of the DTC ALPIDE chips and placement of *Field-programmable Gate Arrays'* (FPGAs') around the DTC.

## MAIN FINDINGS

1. ALPIDE DTC chips are sufficiently radiation hard for clinical proton CT purposes. Based on the ALPIDE chip specifications from the ALICE ITS upgrade (Mager, 2016) and assuming a beam intensity of 1E9 protons per second; the ALPIDE chips will not reach their *Total Ionizing Dose* (TID) and *Non-Ionizing Energy Loss* (NIEL) limits until after 937 hours and 718 hours of irradiation respectively.

2. Additional dose to the DTC and FPGAs when present during proton therapy is almost negligible (~3% increase compared to proton CT). The additional flux from proton therapy however, can in some cases result in up to 40% more secondary particles hitting the FPGAs, this is however more prevalent at larger distances (>100 cm) where the flux is relatively low.

3. A FPGA located between 1-200 cm from the side of the DTC perpendicular to the beam direction is exposed to radiation doses between 6.1E-3 rad/s and 8.6E-6 rad/s depending on its distance from the DTC. The closer the FPGA is to the DTC, the more dose is deposited in the FPGA.

4. The > 20 MeV hadron flux per $cm^2$ at the FPGA locations is between 85000 and 120 $hadrons/cm^2/s$ relative to the distance from the DTC. Assuming a flux of 1E9 protons/second and typical FPGA specifications, the first *Single Event Upsets* (SEU) in the FPGAs will likely begin occurring after 25 seconds if located at 10 cm and after 376 seconds at 50 cm during irradiation.

## METHODS

The MC code FLUKA, version 2011.2c.6, was used to simulate a typical proton CT and proton therapy setting using a cylindrical water phantom (patient phantom) with a diameter of $22\ cm$ and $14\ cm$ in height placed directly in front of the DTC as illustrated in **Figure 1.** The DTC is based on the modelled as detailed in the work package document "*DTC design recommendations*" (Bergen pCT group, 2017), however $4\ mm$ thick aluminium absorbers and a total of 40 layers were used to model the DTC inside FLUKA for the purpose of investigating the radiation environment. The DTC dimensions are in this case $28\ x\ 18\ x\ 18\ cm^3$.

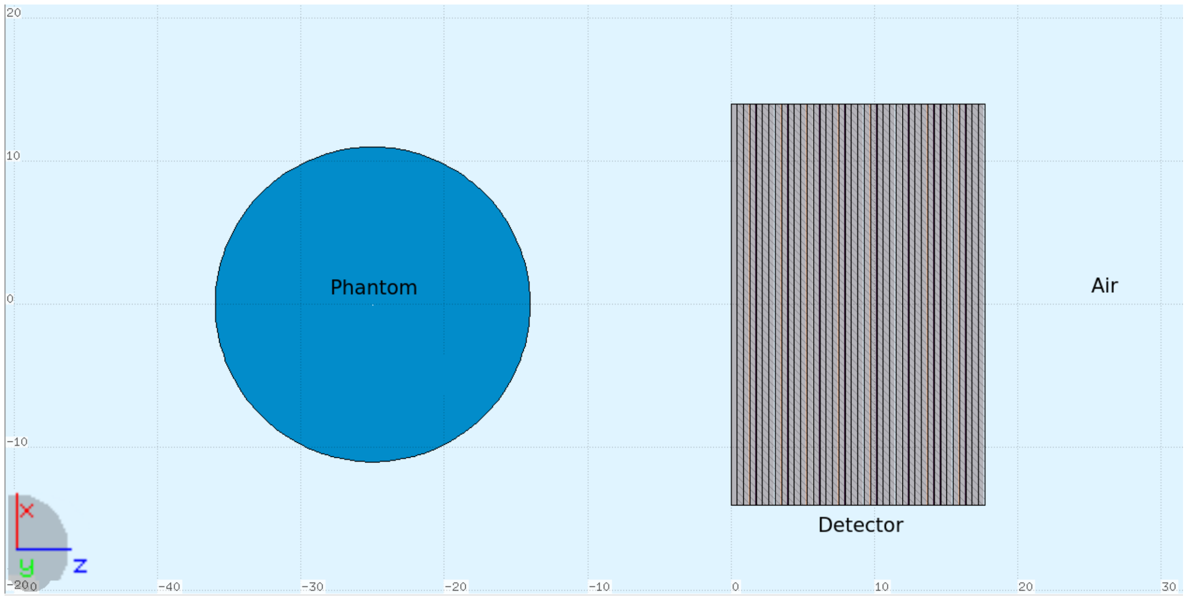

***Figure 1:*** *The geometry setup as viewed from the top-down (along the y-axis), the proton beam starts 50 cm downstream from the front-face of the DTC (Detector). The protons move along the z-axis and passes through the patient phantom (at least 22 cm of water), and at least 28 cm of air, before hitting the DTC. The grid scale is in cm.*

The potential FPGAs were placed at the side (along the x-axis) around the middle point of the DTC at $1, 3, 5, 7, 9, 10, 50, 100$ and $200\ cm$ distances from the DTC edge as illustrated in **Figure 2**. The FPGA's are made of silicon and their dimensions were $1\ x\ 1\ x\ 18\ cm^3$, which is larger than your typical FPGA, but allows for better statistics from the point of view of the simulations. The results are concurrently normalized by FLUKA to "per gram" in the case of dose [GeV/g], and "per square centimeter" in the case of fluence [n/$cm^2$], which can be extended to the actual dimensions of the FPGA when known.

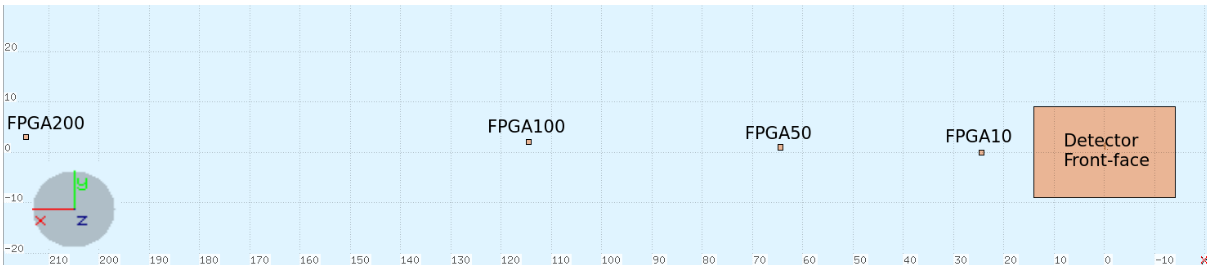

***Figure 2:*** *The geometry setup of the FPGA's as viewed in the beam-eye view (along z-axis). The four FPGA's are named with respect to their distance from the edge of the DTC (Detector), 200, 100, 50 and 10 cm respectively. The grid scale is in cm.*

All geometries and their relative positions are depicted in 3D in **Figure 3.**

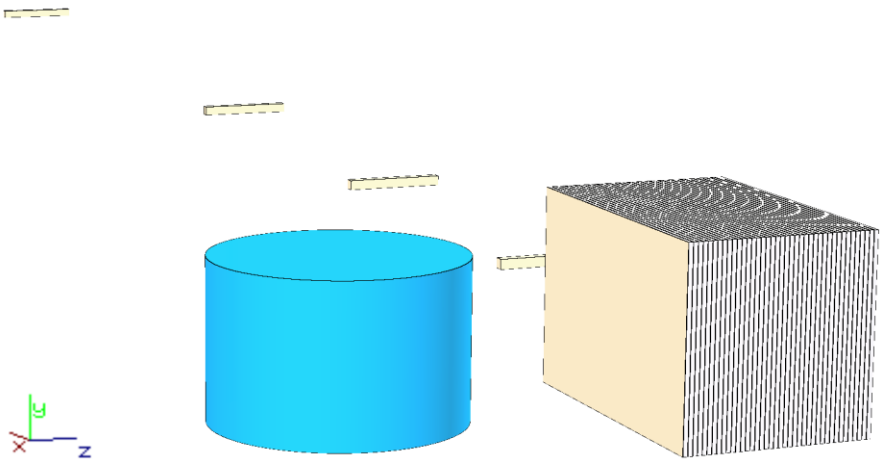

***Figure 3:*** *The geometry setup viewed in 3D. The patient phantom is placed directly in front of the DTC and covers about 80% of the sensitive area of the first layer of the DTC.*

The proton CT and proton therapy settings are investigated separately due the difference in involved proton energies and the spread of the proton beams. In proton CT the beam has a cross-section of $24\ x\ 14\ cm^2$ which covers the patient phantom and most of the DTC front-face while consisting of mono-energetic $230\ MeV$ protons that fully penetrates the patient phantom before hitting the DTC. The dose distribution from primary protons inside the DTC after having penetrated the patient phantom is depicted in **Figure 4**.

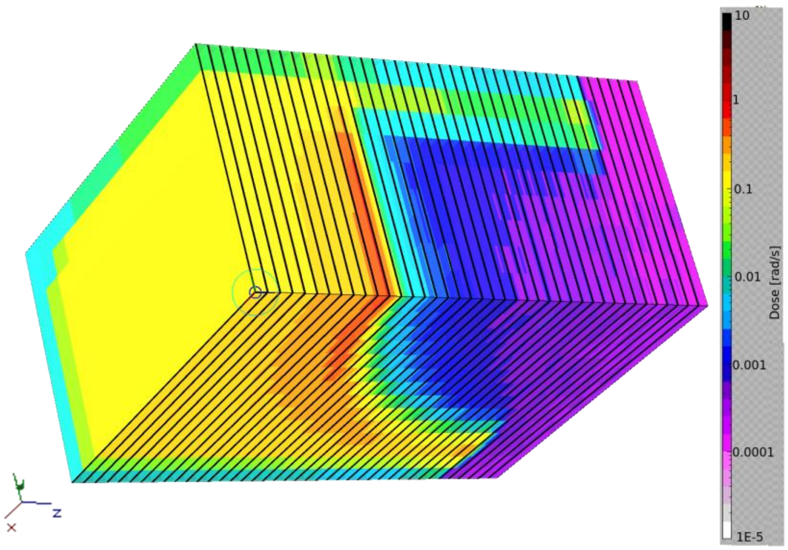

**Figure 4*:*** *A 3D representation of a clipped upper-left quadrant of the DTC overlaid with dose. Each voxel is* $1\ x\ 1\ x\ 1\ cm^3$*and depicts the dose distribution of primary protons inside and on the surface of the DTC during proton CT.*

In the proton therapy setting, the beam has a cross-section of $5\ x\ 5\ cm^2$ and consists of protons with energies between $147 - 174\ MeV$ forming a spread-out Bragg peak (SOBP) intended to cover a $5\ x\ 5\ x\ 5\ cm^3$ *target volume (TV)* at 15-20 cm depth inside the water phantom. Due to the dimensions of the patient phantom, this TV is formed at the very end of the patient phantom and might results in more energetic neutrons exiting the patient phantom than what would otherwise be typical. However, this does not change the results or distributions in any considerable way with respect to the deposited dose in the DTC or FPGAs as the majority of dose here comes from proton CT.

The scoring quantities available in FLUKA that are of interest concerning the radiation environment and damage to electronics are; *"DOSE"*, the total ionizing dose deposited $[GeV/g]$, *"HADGT20M"*, which scores the fluence of hadrons with energy > 20 MeV $[n/cm^2]$, and *"SI1MEVNE"* which scores the 1 MeV neutron equivalent fluence $[n/cm^2]$. Total dose and 1 MeV neutron equivalent fluence is related to cumulative radiation damage effects like TID and NIEL respectively, and > 20 MeV hadrons is related to single event effects such as SEU (NEA OECD, 2016).

The simulation results as calculated by FLUKA are inherently normalized to "per primary" (or "per primary proton" in this case). These results were then manually normalized with respect to the number of protons present during irradiation as dictated by the beam intensity, assumed to be $1E9$ protons per second. This was assumed for both proton CT and proton therapy, thus keep in mind that all results given in per second assume this beam intensity.

Calculation of the potential number of SEU follows **Equation (1)** by multiplying the > 20 MeV hadron fluence with the SEU cross section inherent to the FPGA, and the chosen configuration memory (Røed, 2017).

$$\#SEU = hadron\ fluence * SEU\ Cross\ section * configuration\ memory \qquad \mathbf{(1)}$$

# RESULTS

The fluence of > 20 MeV hadrons and 1 MeV neutron equivalents, as well as the total deposited dose, were scored in each of the four FPGA structures as well as inside the DTC. Additionally, "overview plots" of the hadron and neutron fluences surrounding the phantom, DTC and FPGAs' were obtained inside a $4\ cm$ slice in y-direction centered around the center of the DTC and covering a $400\ x\ 400\ cm$ area overlapping the beam, patient phantom, DTC, and FPGAs. The hadron fluence overview for both proton CT and proton therapy are found side-by-side in **Figure 5**, and the neutron fluence overview for both proton CT and proton therapy are found side-by-side in **Figure 6**.

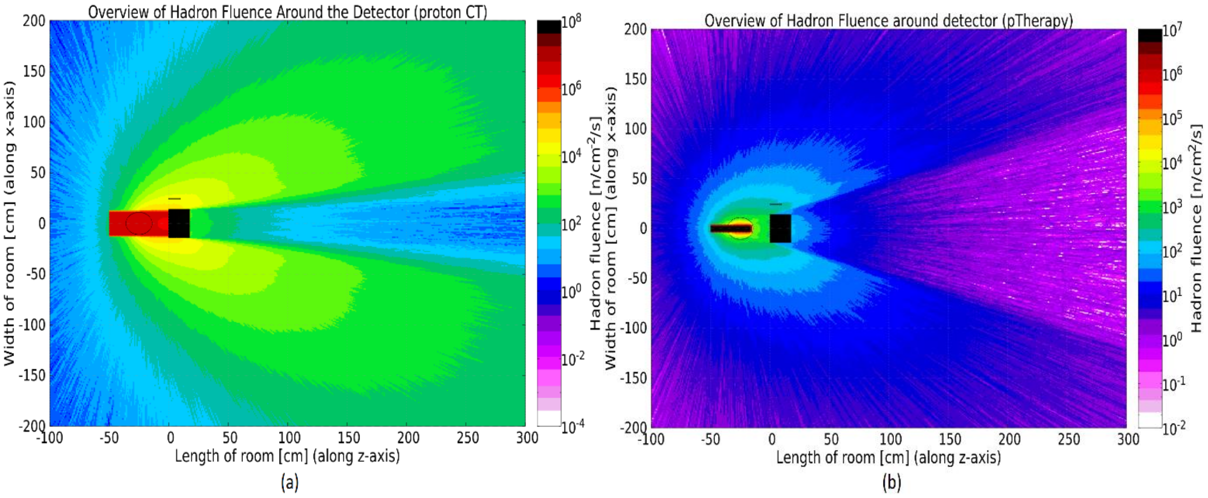

**Figure 5:** *The hadron fluence during the proton CT setting is depicted in the plot to the left (a), and for proton therapy in the plot to the right (b). The results are normalized to per second (#hadrons/$cm^2$/s) assuming a beam intensity of 1E9 protons/s. The following geometries are marked:*

*The water phantom (circular outline), the first FPGA located at 10 cm (small rectangular outline) and the DTC (large black rectangle).*

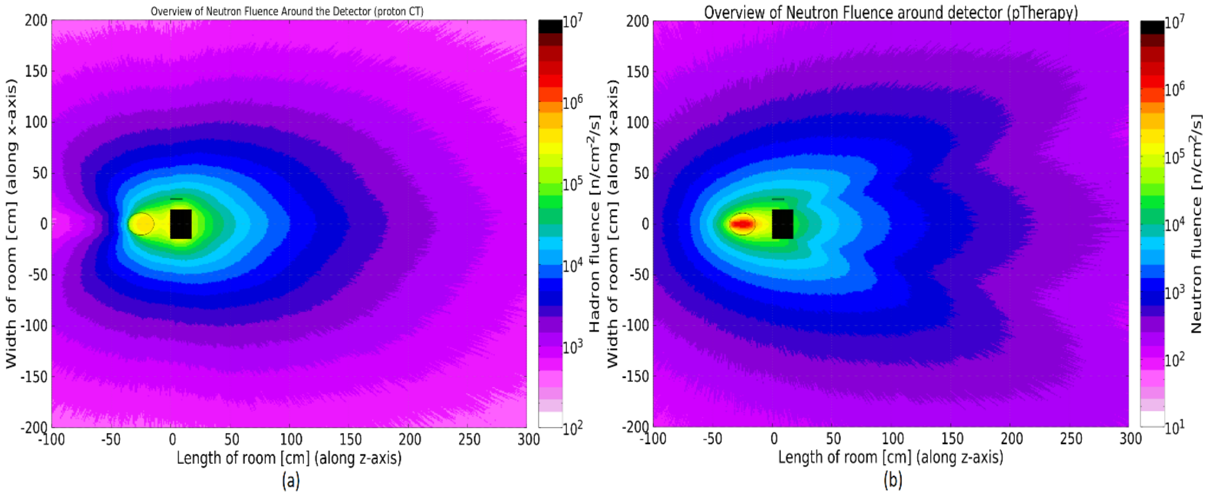

**Figure 6:** *The neutron fluence around the patient phantom (circular outline), first FPGA (small rectangular outline) and DTC (Black rectangle). The proton CT setting is the plot to the left (a) and the proton therapy in the plot to the right (b). Results are normalized to per second (#neutrons/*$\mathbf{cm}^2$*/second) assuming a beam intensity of 1E9 protons/s.*

More specifically, the >20 MeV hadron and 1 MeV neutron equivalent fluence as a function of the lateral distance from the centre of the DTC up to 200 $cm$ away from the edge of the DTC, are depicted in **Figure 7** below.

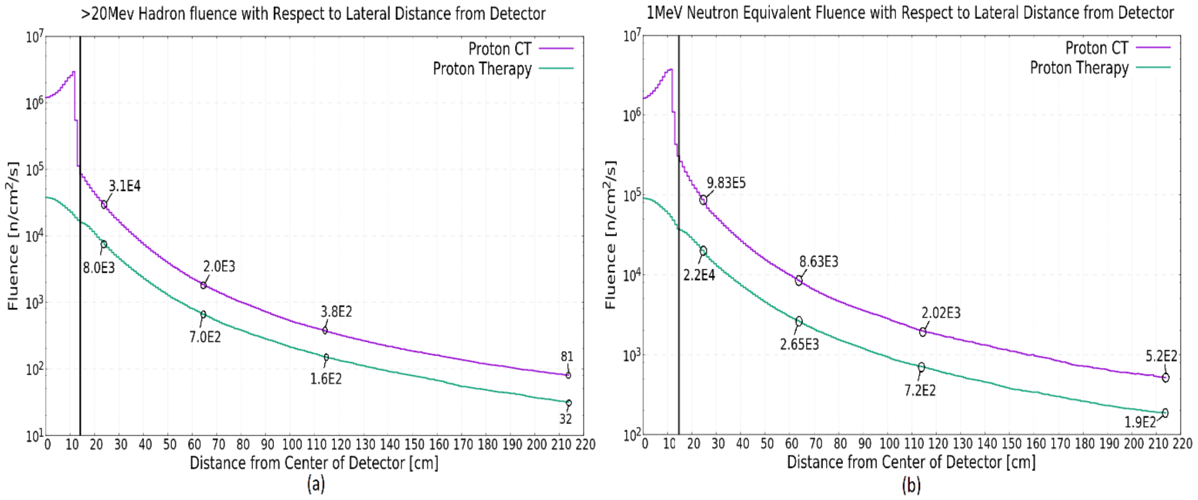

**Figure 7:** *The plot to the left (a) is the >20 MeV hadron fluence and the plot to the right (b) is the 1 MeV neutron equivalent fluence as a function of lateral distance from the center of the DTC. The edge of the DTC is at 14 cm and marked with a black vertical line. The four FPGA locations at 10, 50, 100 and 200 cm from the edge of the DTC are marked with black circles and noted with the calculated fluence in those positions.*

As for the DTC, the total dose deposited per second inside the DTC, which is of concern to the TID and radiation hardness of the ALPIDE chips, is presented in **Figure 8.** It is worth noting that the results are focused on the maximum dose that occurs around the Bragg peaks located close to the 5 $cm$ depth inside the DTC.

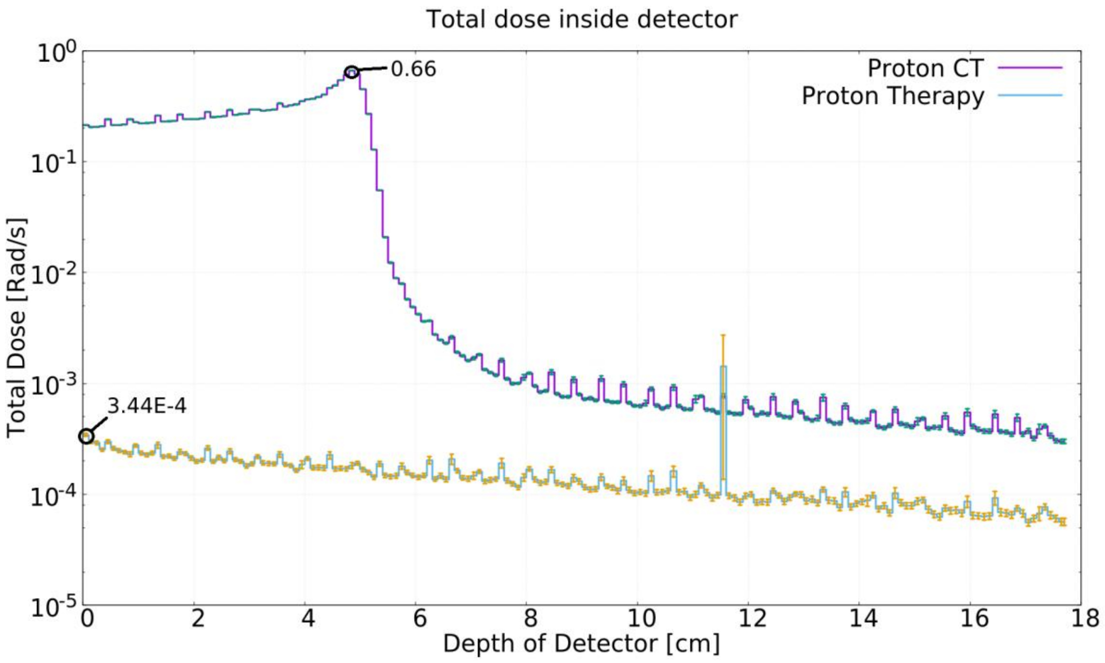

**Figure 8:** *Total dose deposited inside the DTC. Dose is normalized to rad per second by multiplying the FLUKA results (given in GeV/g/per particle) with the factor 1.602176487E-7 (to go from GeV/g to Gray [J/kg]) and then with a factor 100 to go from Gy to rad. The maximums in proton CT and proton therapy are marked with small black circles and noted with the total deposited dose there.*

Similarly, the 1 MeV neutron equivalent fluence inside the detector, of special concern to the NIEL limit of the detector chips, is shown in **Figure 9.**

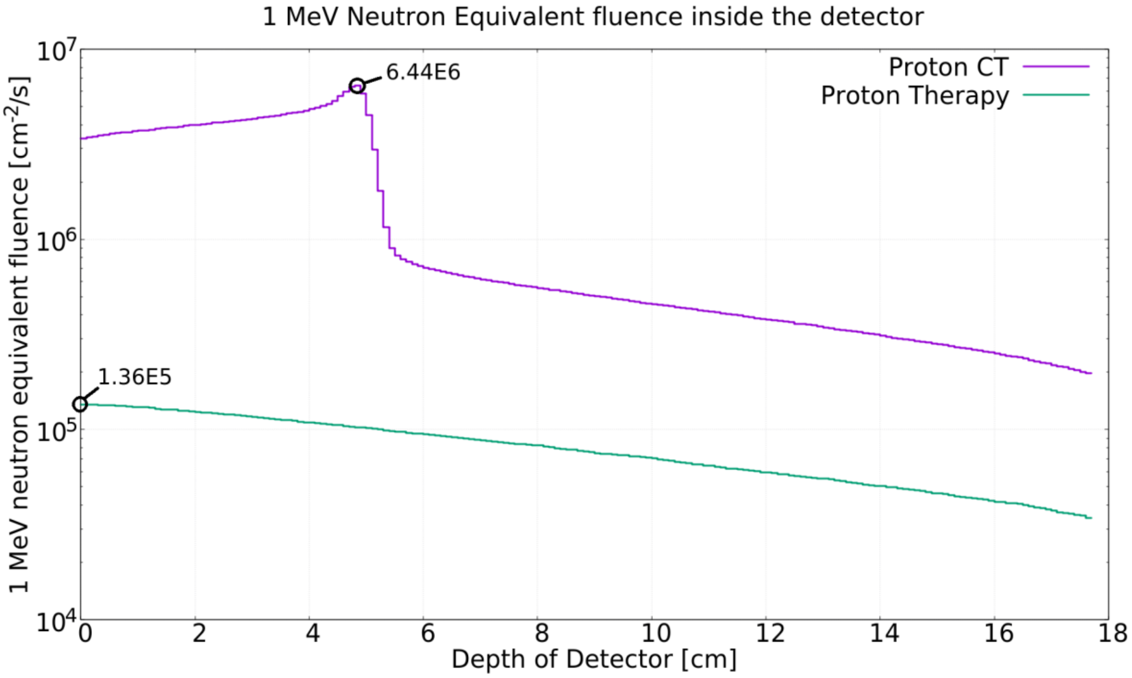

***Figure 9:*** *1 MeV neutron equivalent fluence per cm*$^2$ *per second (1/cm*$^2$*/s) inside the detector. The maximum, found around the Bragg-peak in the proton CT setting and inside the first layer in proton Therapy, is marked with black circles and noted with the amount of fluence there.*

## Lifetime and health of DTC and FPGAs

Combining these results and looking up the design specifications of the ALPIDE chips concerning its TID and NIEL limits, and considering typical FPGA radiation hardness and SEU cross section, then the “lifetime” and “health” of the components can be estimated to a first order approximation.

## Lifetime of the DTC

From the dose and neutron equivalent fluence results from inside the DTC we can estimate that roughly a maximum of 0.8 rad are deposited inside the Bragg-peak per second, and assuming that the Bragg-peak is located inside the same layer every time, combined with the radiation hardness specifications of the ALPIDE chip where the TID limit is $2.7E6\ rad$ and the NIEL limit it is $1.7E13\ n_{eq}/cm^2$ (Mager, 2016). Then the lifetime of the ALPIDE chip, and in extent the DTC, is estimated and collected in **Table 1.**

**Table 1:** *The time before reaching both the TID and NIEL limits are evaluated based on the observations in* **Figure 8** *(Total dose) and* **Figure 9** *(1 MeV neutron equivalent).*

| | **Radiation time before reaching the TID limit** | **Radiation time before reaching the NIEL limit** |
|---|---|---|
| **Proton CT** (Beam intensity 1E9 protons/s) | 3.375E6 seconds<br>(56250 minutes)<br>(937.5 hours) | 2.640E6 seconds<br>(43995 minutes)<br>(733 Hours) |
| **Proton CT + Proton Therapy** (Beam intensity 1E9 protons/s) | 3.373E6 seconds<br>(56225 minutes)<br>(937.1 hours) | 2.585E6 seconds<br>(43086 minutes)<br>(718.1 hours) |

## Dose to the FPGAs

The total dose to potential FPGAs located at 1, 3, 5, 7, 9, 10, 50, 100 and 200 cm distance laterally from the DTC is collected in **Table 2**. Once the FPGA specification and radiation hardness is known, these numbers can be used to roughly estimate their lifetime.

**Table 2:** *Total dose deposited per second to the FPGAs. The contribution from proton Therapy is observed to be less than a few percent.*

| | **Dose to FPGAs per second [rad/s]** | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **FPGA1** | **FPGA3** | **FPGA5** | **FPGA7** | **FPGA9** | **FPGA10** | **FPGA50** | **FPGA100** | **FPGA200** |
| **Proton CT** (Beam intensity 1E9 protons/s) | 6.0E-3 ± 9.4E-5 | 4.7E-3 ± 8.8E-5 | 3.6E-3 ± 7.2E-5 | 3.1E-3 ± 7.7E-5 | 2.5E-3 ± 6.1E-5 | 2.1E-3 ± 4.3E-5 | 1.4E-4 ± 4.3E-5 | 2.7E-5 ± 5.4E-6 | 6.9E-6 ± 3.1E-6 |
| **Proton CT + Proton Therapy** | - | - | - | - | - | 0.2E-3 ± 4.9E-5 | 1.5E-4 ± 1.6E-5 | 3.0E-5 ± 6.6E-6 | 8.6E-6 ± 4.1E-6 |

## HEALTH OF THE FPGAS

The flux of > 20 MeV hadrons affect the health of the FPGA related to potential and expected SEU that they can cause. The flux of hadrons at each of the FPGA locations are collected in **Table 3**.

**Table 3:** *Number of >20 MeV hadrons per* $cm^2$*per second at each of the FPGA locations.*

| | Flux of >20 MeV Hadrons per second per cm^2 [1/$cm^2$/s] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **FPGA1** | **FPGA3** | **FPGA5** | **FPGA7** | **FPGA9** | **FPGA10** | **FPGA50** | **FPGA100** | **FPGA200** |
| **Proton CT** (Beam intensity 1E9 protons/s) | 84983 ± 331 | 68526 ± 309 | 55145 ± 258 | 44027 ± 241 | 35886 ± 225 | 30763 ± 36 | 1966 ± 11 | 384 ± 5 | 81 ± 2 |
| **Proton CT + Proton Therapy** | - | - | - | - | - | 38783 ± 53 | 2662 ± 17 | 539 ± 8 | 113 ± 3 |

Assuming a typical and conservative FPGA SEU cross section of $10^{-14}\ cm^2/bit$, and a 100 Mbit configuration memory, the expected number of SEU for each of the four FPGAs can be estimated using the SEU formula **Equation (1)** (Røed, 2017). These results are presented in **Table 4**. Once the real FPGA specifications are known, these can be calculated a new.

**Table 4:** *Number of SEU per second in each of the FPGA placements.*

| | Number of Single Event Upsets per second[1/cm^2/s] | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| | **FPGA1** | **FPGA3** | **FPGA5** | **FPGA7** | **FPGA9** | **FPGA10** | **FPGA50** | **FPGA100** | **FPGA200** |
| **Proton CT** (Beam intensity 1E9 protons/s) | 0.085 | 0.069 | 0.055 | 0.044 | 0.036 | 0.031 | 1.97E-3 | 3.8E-4 | 8.1E-5 |
| **Proton CT + Proton Therapy** | - | - | - | - | - | 0.039 | 2.66E-3 | 5.4E-4 | 1.1E-4 |

Conservatively, every ten bitflip will cause a functional error in the FPGA (Røed, 2017).

The results presented here are consistent with results in the proton CT literature concerning the use of FPGAs; an excerpt from the article “A Fast Experimental Scanner for Proton CT:Technical Performance and First Experience With Phantom Scans” (Johnson et al., 2016) published by the Loma Linda University Medical Center (LLUMC) proton CT group using “Xilinx Spartan-6 FPGAs”, state:

*“In a typical beam test, for example, 2.5 billion events with a total of 1.8E11 bytes were acquired with zero errors of any kind detected.”*

Based on the simulations performed here and on the first order approximations made concerning lifetime and health of electronics, the FPGAs’ appear to be in little danger of failing or causing unwanted effects when placed a reasonable distance (> 50 cm) away from the DTC. However, when the exact dimensions and type of FPGA and DTC have been decided upon and designed, or improved insight into the necessary number of protons or time needed to perform a typical proton CT image with the DTC, then new simulations can and should be performed to account for any new structural changes or insight.

Bergen pCT group, W., 2017. Detector Design Recommendations, pCT-WP1-01-rev.1.

Böhlen, T.T., Cerutti, F., Chin, M.P.W., Fassò, A., Ferrari, A., Ortega, P.G., Mairani, A., Sala, P.R., Smirnov, G., Vlachoudis, V., 2014. The FLUKA Code: Developments and Challenges for High Energy and Medical Applications. Nucl. Data Sheets 120, 211–214. https://doi.org/10.1016/j.nds.2014.07.049

Ferrari, A., Sala, P.R., Fasso, A., Ranft, J., 2005. Fluka: a multi-particle transport code. CERN 2005-10 INFNTC0511 SLAC-R-773 55, 100.

Johnson, R.P., Bashkirov, V., DeWitt, L., Giacometti, V., Hurley, R.F., Piersimoni, P., Plautz, T.E., Sadrozinski, H.F.-W., Schubert, K., Schulte, R., Schultze, B., Zatserklyaniy, A., 2016. A Fast Experimental Scanner for Proton CT: Technical Performance and First Experience With Phantom Scans. IEEE Trans. Nucl. Sci. 63, 52–60. https://doi.org/10.1109/TNS.2015.2491918

Mager, M., 2016. ALPIDE, the Monolithic Active Pixel Sensor for the ALICE ITS upgrade. Nucl. Instrum. Methods Phys. Res. Sect. Accel. Spectrometers Detect. Assoc. Equip. 824, 434–438. https://doi.org/10.1016/j.nima.2015.09.057

NEA OECD, 2016. Materials & Related Scorings.

Røed, K., 2017. Personal communication (UiO).