

RCU2 testing and design

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Master Thesis

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1 Abstract

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3 Acronyms

CERN	European Council for Nuclear Research
OCL	Oslo Cyclotron Laboratory
UiB	University in Bergen
DUT	Device Under Test
RCU	Readout Control Unit
RCU2	Readout Control Unit 2
ALICE	A Large Ion Collider Experiment
LHC	Large Hadron Collider
FPGA	Field Programmable Gate Array
SEE	Single Even Effect
SEU	Single Event Upset
IC	Integrated Circuit
PCB	Printed Circuit Board
LVDS	Low-Voltage Differential Signaling
NI	National Instruments
DAQ	data acquisition
SPI	Serial Peripheral Interface
SF2	SmartFusion2
CML	Current-Mode Logic
LVPECL	Low Voltage Positive Emitter Coupled Logic
SRAM	static RAM
PM-tube	PhotoMultiplier Tube
JTAG	Joint Test Action Group
UART	Universal Asynchronous Receiver/Transmitter
LET	Linear Energy Transfer
SOC	System On a Chip

4 Introduction

At European Council for Nuclear Research (CERN) in Switzerland there are being conducted experiment on fundamental structure of the universe. This is done by accelerating particles up to a energy of 7 TeV per proton, and then crash with a other particles with same energy. This experiment is done by connecting several accelerators with higher and higher energies together, the largest one is called Large Hadron Collider (LHC), and is the largest particle accelerator ever built, installed in a 27 km long tunnel. To detect what is happening to the particles when crashed, there has been build several detectors that is placed in the tunnel. One of these is called the A Large Ion Collider Experiment (ALICE) detector. The ALICE detector is using electronics to measure and detect what is happening under a crash.

The Physics and research group at the University in Bergen (UiB) has been working with CERN on the ALICE project since it started. One of the main boards used in the ALICE detector is the Readout Control Unit (RCU). Now there has been decided that a new RCU board shall be made, that is called Readout Control Unit 2 (RCU2). Everything that are going to be used at CERN has to be made sure that it can survive in the radiation level that can occur there. Therefore every Integrated Circuit (IC) planned to be used for the design of the RCU2 board has to be tested for radiation to be sure that it won't fail when it is installed in the ALICE detector.

4.1 How to test

The radiation in the LHC is dominated by high energetic neutrons and protons, mostly neutrons with a estimated fluence of $(0,6 - 1,1) \times 10^{11} \text{ neutrons/cm}^2$. Therefore it would be preferable to test our electronics with a neutron beam, but since there are few labs who can produce a neutron beam compared to proton beam most of the electronics is only tested at OCL with a proton beam. There has been done experiment that compares SEU induced by neutrons and protons [2], and the result shows that it is possible to use a proton beam instead of proton beam with small deviations. By comparing a Proton beam with a neutron beam of 21MeV we see that we get 10-25% less SEU cross section for a proton beam compared to a neutron beam. If we increase the energy to 88MeV then we get close to none deviations.

The tests that are done through this thesis are so called dose-tests. That is irradiation up to a level where an error can clearly be seen or when a high enough dose has been reached without detecting errors. Current consumption and the outputs of the IC are monitored through the whole irradiation process. The dose that we could expect at CERN for a 10 year period in the ALICE detector is estimated

to be approximately 0.6 kRad from Pb-Pb collisions that will be run 1 month a year and a little higher for p-p collisions that will be run 10 months a year [7] and [5]. Therefore we could expect a dose of 1-2 kRad during the time it will be used at CERN. If a IC survives more than 5 times of what we would expect at CERN, we could say that it passes the test, that means if it survives more than 5-10 kRad, the device is approved to be used in the RCU2 design.

4.2 About this work

When I started working with my thesis in the autumn of 2013 the schematic layout for the RCU2 was basically finished, and most of the component was decided, but not everyone had been tested. So what I have been working on in my thesis are thinking and planning how to test the different IC. In most of the cases I designed a simple test Printed Circuit Board (PCB) which I connected to data acquisition (DAQ) board from National Instruments (NI). By the use of this DAQ the functionality of the IC was tested and current consumption was monitored. For the more advanced IC like the SmartFusion2 (SF2)System On a Chip (SOC)Field Programmable Gate Array (FPGA), I used a starter-kit when designing the test. To measure the low current going into the SF2 chip I also made a current measurement PCB for that purpose. I started my thesis work with making test boards for 8 different ICs. These consist of; power regulators, bus transceivers, limiting amplifier, multiplexer/demultiplexer and buffer. For every each of the different test board that was made I also made labVIEW programs, to control and monitor the tests. After these test board was made working and had been tested, I started working on designing test for the SF2 SOC FPGA. The tests were made on a SF2-starter kit, but with the RCU2 in mind, so that when the hardware for the RCU comes, it will be easy to implement the test on that. I also made two more test board for two IC that was added to the design at a late stage. That was a comparator and a Current Shunt Monitor.

5 Radiation and Radiation effect on Semiconductor devices

Radiation and radiation effects are a known challenge when designing electronics which are going to be used at CERN. There is therefore of highest importance to know about these effect, how they effect the electronics, how much damage they can cause and how we can protect and prevent the radiation effect to do damage.

Everything in this chapter is based on these references [6], [4], [3] and [1] if not otherwise stated.

5.1 Interaction of Radiation With Matter

Radiation is defined as a process which energy in the form of energetic particles or electromagnetic waves is transmitted through a medium or space. Radiation is normally divided into two categories, that is

- Charged radiation
- Neutral radiation

Charged radiation consist of charged particles like protons(p), alpha(α) and beta(β) particles and heavier ions. Neutral radiation consist of neutrally charge particles like neutrons(n) and photons from gamma(γ) and X-rays. Particles who interact with a material will deposit some or all of its energy in the interaction, and can either interact with atoms, electrons, nucleus or the particles inside a nuclei. How much energy is deposited and which of these a particle will interact with is depended on the energy, mass, the charge of the particle and what material it interacts with. One of the main difference between charged particle and neutral particle is the charged particles will be effected by the Coulomb force, that is the attraction or repulsion of particles or objects because of their electric charge. In the next sections we will look more closely on how a charged particle and neutral particle interact with matters.

5.2 Charge particle and their Interaction with Matters

When a charged particle with high speed is passing through a material it will experience multiple elastic and inelastic collisions with the atoms in the material, resulting in slowing down or stopping the particle. When a particle collide with

a atom there are several process that can contribute to the loss of energy of the particle. They are:

- Inelastic scattering towards atomic electrons
 - Excitation and ionization
- Elastic scattering towards atomic electrons
 - Ramsauer Effect
- Inelastic scattering towards Nuclei
 - Nuclear reaction
- Elastic scattering towards Nuclei
 - Rutherford/Nuclear scattering
- Other processes
 - Bremsstrahlung and Cerenkovstråling

Which of these that contributes to most of the loss of energy is depended on the initial energy, velocity, mass and charge of the particle as well as the properties of the material it collides with. For example, for heavy charge particles(protons or heavier ions), inelastic collisions with the atomic electrons in a material will contribute to most to the energy loss of the particle. A common expression for these processes is called "stopping power".

5.2.1 Stopping Power

If we have a particle with a given energy passing into to a material, where dE is the mean energy that the particle losses by traveling through a path segment, dx , of the material. Then $-\frac{dE}{dx}$ is the stopping power or also called the "rate" of energy loss for the particle. The stopping power depends on the type and energy of the radiation and on the properties of the material it passes.

The classical expression that describe the stopping power is the *Bethe Bloch formula*, and is written as you can see in equation 1.

$$S = -\frac{dE}{dx} = \frac{n_A Z_A Z^2 e^4}{4\pi\epsilon_0 m_e V^2} \left[\ln\left(\frac{2m_e v^2}{I}\right) - \ln\left(1 - \frac{v^2}{c^2}\right) - \frac{v^2}{c^2} \right] \quad (1)$$

n_A	Number of atoms per unit volume
Z_A	Average atomic number of the material
Z	Atomic number of particle
e	Electron charge
c	Speed of light
ϵ_0	Vacuum Permittivity
m_e	Electron rest mass
v	Particle velocity
\bar{I}	Effective material ionization potential

5.2.2 Specific Stopping Power

Another way of looking at stopping power, is by looking at energy loss as function of mass per area 2. Here $\xi = \rho x$ and ρ is the density of the material. The extension for specific stopping power is normally given as [$\frac{\text{MeVcm}^2}{\text{g}}$]

$$S = -\frac{dE}{\xi x} \quad (2)$$

From this formula we see that if considering different particles with the same velocity, then the only factor that changes are Z^2 . Therefore heavier particles will experience larger energy loss in a material than lighter ones. In figure ?? we can see specific energy loss for different particles in air. We can see that the value of $\frac{dE}{dx}$ for different types of particles approaches a near-constant broad minimum value at energies above several hundred MeV, where their velocity approaches the velocity of light.

At low particles energies, where charge exchange between the particles and absorber becomes important, the Bethe Bloch formula begins to fail. That is because the positively charged particles will then tend to pick up electrons from the absorber, which effectively reduce its charge and consequently linear energy loss, and will at the end become a neutral atom.

5.2.3 Linear Energy Transfer (LET)

When it comes to radiation protection Linear Energy Transfer (LET) is often used instead of stopping power. LET is energy that is deposited in a local volume. For low energies, LET is often said to be equal stopping power, even though the particle energy that turn into photons may escape the local area. For higher energies, small particles like ionized electrons can escape the local volume. The local volume is defined by the ones that looks at the energy loss, and can be everything from part

of a molecule and a hole organ. An alternate definition of LET are as you can see in equation 3

$$L_\Delta = \left(-\frac{dE}{\xi x} \right)_\Delta \quad (3)$$

where Δ is the upper energy limit for the secondary electrons included in the calculations. If Δ is set to ∞ , all secondary electrons are included in the calculations, making LET the same as stopping power.

5.3 Neutral particle and their Interaction with Matter

5.3.1 Neutrons

Neutrons are subatomic structure that are present in most atomic nuclei. Neutrons carry no charge and can therefore not interact with matter by means of the coulomb force, which dominates the energy loss mechanisms for charged particles. Neutrons can also penetrate several centimeters into matters without any type of interactions, making neutrons hard to detect. When neutrons undergo a interaction, it is with the nucleus of the absorbing material. This can result in total disappearance of the neutron resulting in one or more secondary radiations, or change of the direction of the neutron. The secondary process of neutrons can largely ionizing.

5.3.2 Photons

Photons may appear from gamma rays or X-rays. Photons has as neutrons no charge, and are therefore not effected by the coulomb force, additionally photons has no rest mass and travel in constant speed of light. The energy of a photon is given in the formula $E = hf$ where f is the frequency of the particle and h is the Planck's constant. There are three main process a photon may react with matters, they are:

- Photo electric effects
- Compton scattering
- Pair production

6 The test boards and preparations for testing

6.1 The IC which where tested

The ICs that was going to be tested as mentioned in the previous section consist of power regulators, bus transceivers, limiting amplifier, multiplexer/demultiplexer, buffer, comparator, current shunt monitor and FPGA.

We wanted to have at least two PCB for each of the IC that was going to be tested, to have more test data on each of the IC. But we started to make one PCB for all of the IC, something like a prototype, to see that the design was working. If they worked at first try, a new PCB was made, so that we had two test boards of each kind. But some of these didn't work, and had to be modified. This was often fixed with just adding capacitors and resistors on the PCB or cutting routes or adding wires. When the prototype was made working a new design and PCB was made from the experienced gained from the prototype. Therefore some difference may exist between the first boards and the second boards. The second version was tested first, in case we didn't have time to test both of the versions. Later in this thesis the second board that was made are marked with ₁ and the first board was marked with ₂, that is because this was tested first. Two of the ICs (ADN2814 and MAX3748) was only made one version of, since we didn't have any spare IC at the time to make a new PCB. All of the test PCBs had a mark on the back indicating the center of the IC, this was used to pinpoint the center during the tests.

To supply and measure everything on the test boards, data acquisition (DAQ) devices from National Instruments were used. The DAQ devices we used are called USB-6009, USB-6008 and USB-6501. USB-6009 was used as the main one, and the other were used when needed more digital or analog inputs or outputs. USB-6009 has 8 single-ended analog input (AI) channels, 2 analog output (AO) channels and 12 digital input/output (DIO) channels, and also a 2.5 V and 5.0 V signal. The analog outputs has a limit of 5 mA, but some of the ICs that was tested required more than that. For these cases the 5 V signal was used, that can deliver current up to 200 mA. More information on the DAQs can be seen in the datasheets in appendix 10.1.

6.1.1 TPS51200

This is a power regulator, special designed for DDR RAMs. Can be used for DDR, DDR2, DDR3 and DDR4 applications. On the RCU2, this is going to be used to supply a DDR3 RAM with 0.75 V.

The PCB was designed after a recommended setup for DDR3 application from the datasheet. Input voltage was set to 3.3 V. Voltage over resistor R1 (See figure 1) was measured and used to calculate current consumption. Output voltage was also monitored.

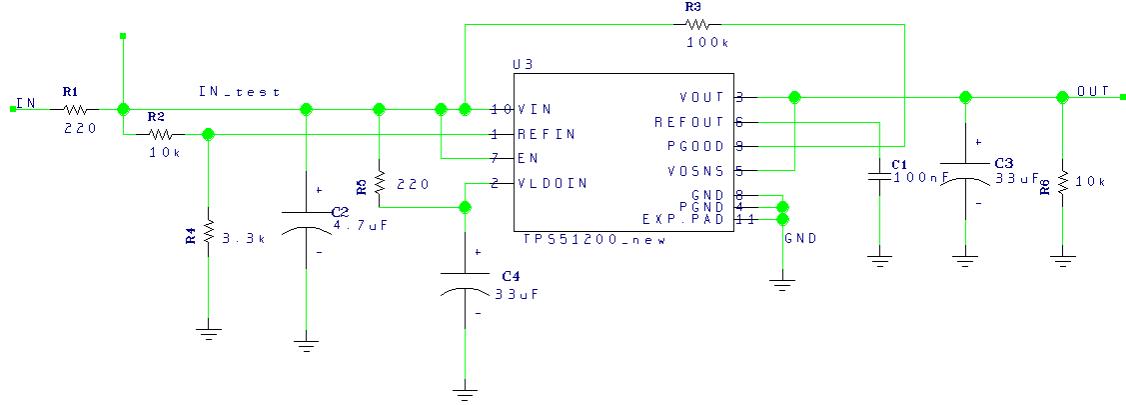


Figure 1: Schematic for the TPS51200 test board

6.1.2 MIC69302WU

This is a ultra low dropout power regulator. On the RCU2 this is going to be used to regulate a 3.3 V signal to 1.2 V and power everything that requires 1.2 V on the board.

This has been designed as a adjustable regulator. That means that by changing R1 and R2(see figure 2) you can adjust the output voltage, see equation 4. For the two test boards we had a input voltage of 3.3 V. Voltage over resistor R?(See figure 2) was measured and used to calculate current consumption. Output voltage was also monitored. We used 10k Ω for both R1 and R2 which gave us 1 V on the output.

A different PCB was also made with this IC. This was used to supply 3.3V to the PCB that requires more than 5 mA which is the maximum the analog outputs the DAQ form NI can deliver. This was design with resistor values of $R? = 20 \Omega$, $R1 = 5.6k \Omega$ and $R2 = 1k \Omega$, which gives us 3.3 V output. This PCB was used to supply SY89831U, ADN2814 and MAX3748

$$V_{out} = 0.5 \times \left(\frac{R1}{R2} + 1 \right) \quad (4)$$

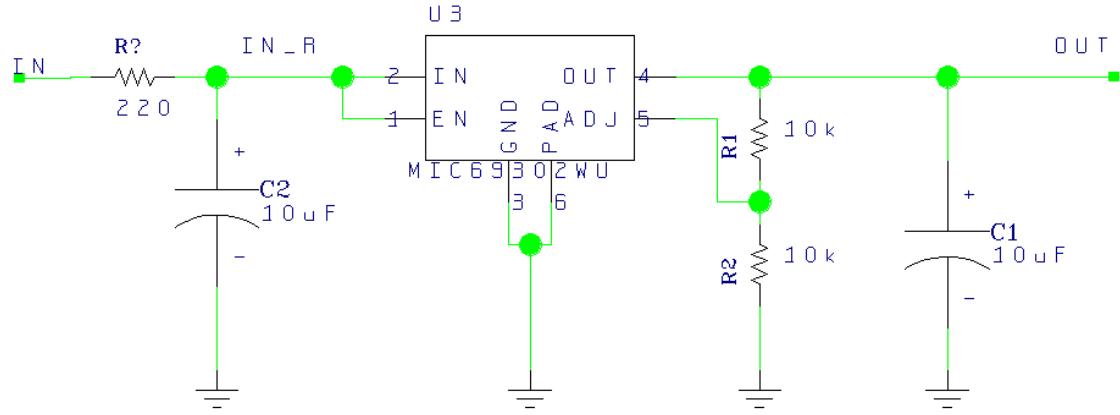


Figure 2: Schematic for the MIC69302WU test board

6.1.3 SN74AVCB164245

This is a 16-bit noninverting bus transceiver, with configurable voltage. Used for level shifting for digital signals. An application example could be to convert a 16-bit digital signal that goes from 0 V to 1.5 V to a 16-bit signal that goes from 0 V to 3.3 V. The input and output high value can be set to anything between 1.4 and 3.6 V, the low value is set to 0 V. On the RCU2 this is going to be used as a bus transceiver with 1.5 V in and 3.3 V out.

For the test board the supply voltages(VCCA and VCCB, see figure 3) was set to 3.3 V, to make it more simple to test. Voltage over resistor R1(See figure 3) was measured and used to calculate current consumption. To make sure that the circuit didn't drag current through the inputs on the chip we used a pMOS transistor that was connected as seen in figure 3. This made the current for the inputs come from the supply pin, and not from the digital signal IN. The outputs was measured digitally. The first version of this board didn't work. The output didn't change according to the input. We found out that this was because there were no load on the outputs. So a output resistor was added to each of the outputs to make a load, and then it worked.

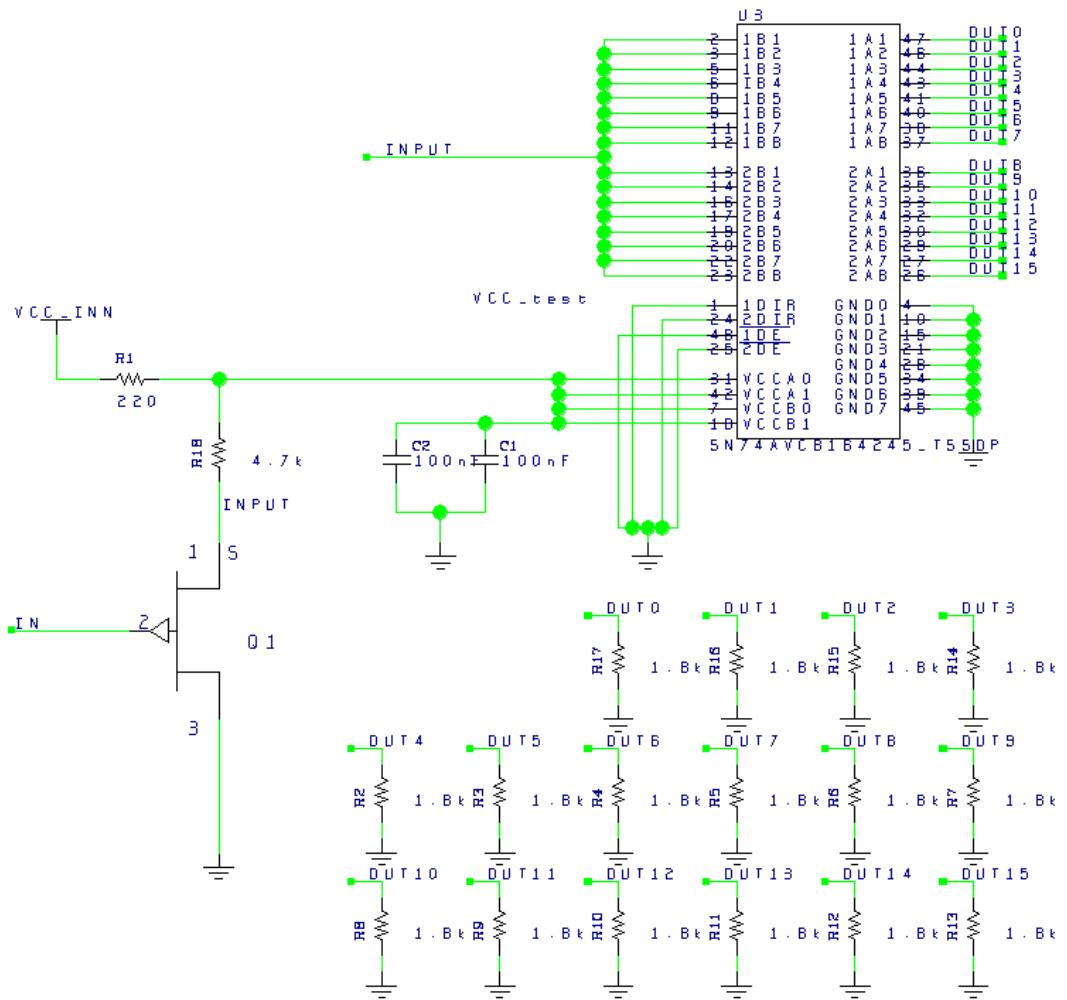


Figure 3: Schematic for the SN74AVCB164245 test board

6.1.4 SN74AVC2T245

This is a dual-bit noninverting bus transceiver, with configurable voltage. It has the same function as SN74AVCB164245, but this only has two inputs. On the RCU2 board, this is planned to be used to convert a 2.5V Serial Peripheral Interface (SPI) signals to a 3.3V SPI signals.

As for SN74AVCB164245 a 3.3 V supply was used for both VCCA and VCCB, see figure 4. Voltage over resistor R1(See figure 4) was measured and used to calculate current consumption. The output signals was monitored digitally. The first version made was missing output load, and wouldn't work. By adding a resistor as load, it started working.

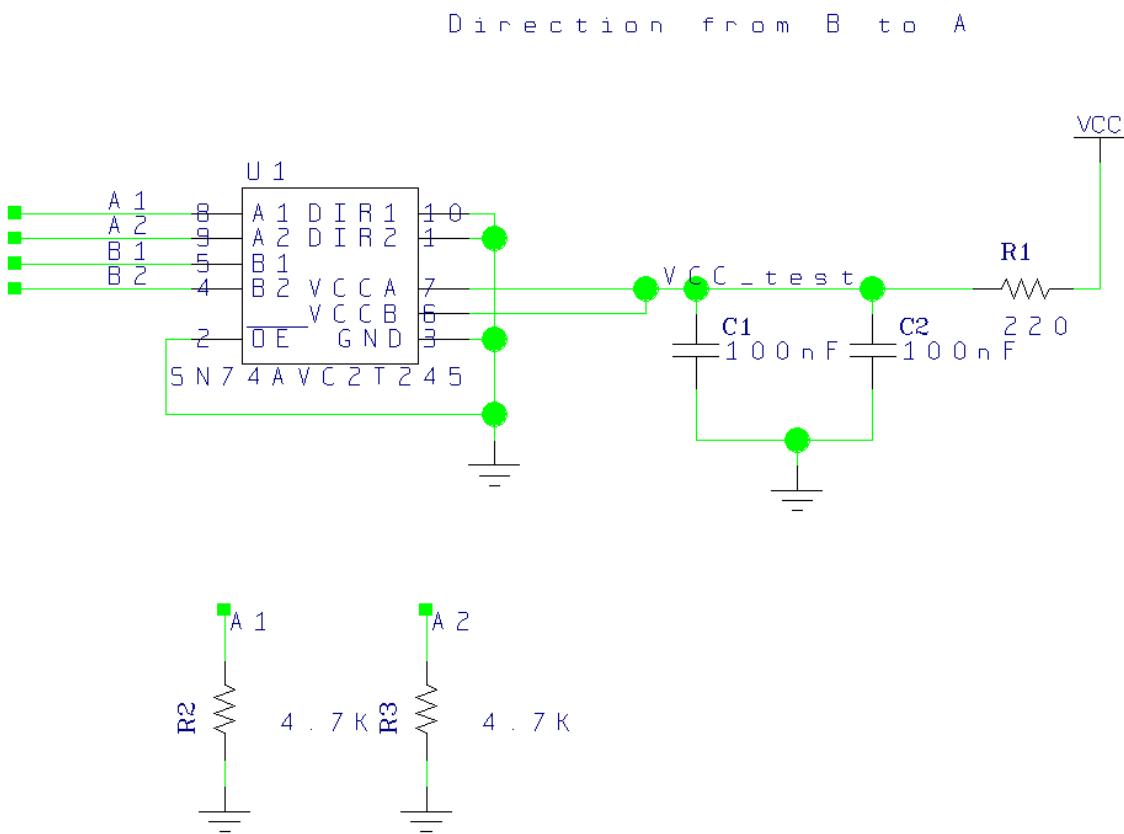


Figure 4: Schematic for the SN74AVC2T245 test board

6.1.5 QS3VH257

This is a Quad 2 to 1 multiplexer/demultiplexer with high bandwidth bus switch. On the RCU2 this is going to be used to switch between two Joint Test Action Group (JTAG) connection.

Supply voltage was set to 3.3 V. Voltage over resistor R1(See figure 4) was measured and used to calculate current consumption. For the Select input a analog output signal was used. The input signals was set digitally, and the outputs was measured digitally.

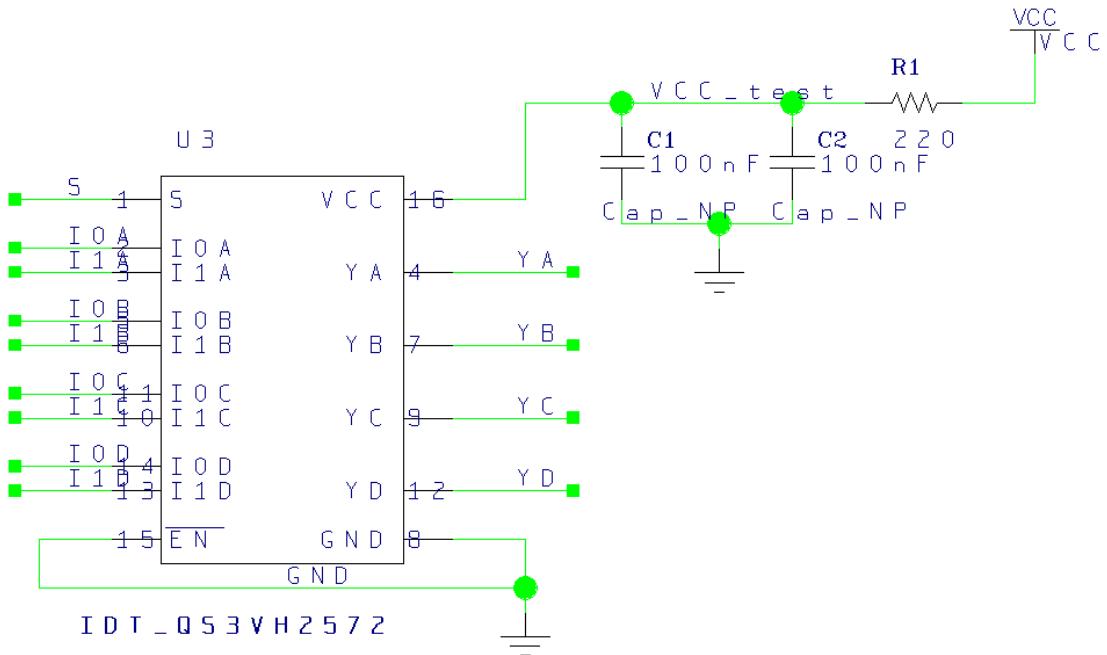


Figure 5: Schematic for the QS3VH257 test board

6.1.6 SY89831U

This is a high speed, 2GHz differential Low Voltage Positive Emitter Coupled Logic (LVPECL) 1 to 4 fanout buffer optimized for ultra-low skew applications. Used on the RCU2 to produce 4 clock signal out of 1.

The input signal to this IC is differential. The DAQ device we were using doesn't have a differential output signal, so here we had to use a little trick to make it work. We used two single-ended output signal that was set to the opposite of the other, and every 100 ms the values switch, so that when IN+ was 3.3 V IN- was 0 V, and when IN+ was 0 V IN- was 3.3 V. The outputs was measured by the analog inputs of DAQ USB-6501.

This IC requires a large current typically around 60 mA, and we could therefore not use the analog outputs. So we had to use the modified version of the MIC69302WU PCB, that will supply us with a 3.3 V signal up to a current of 200 mA.

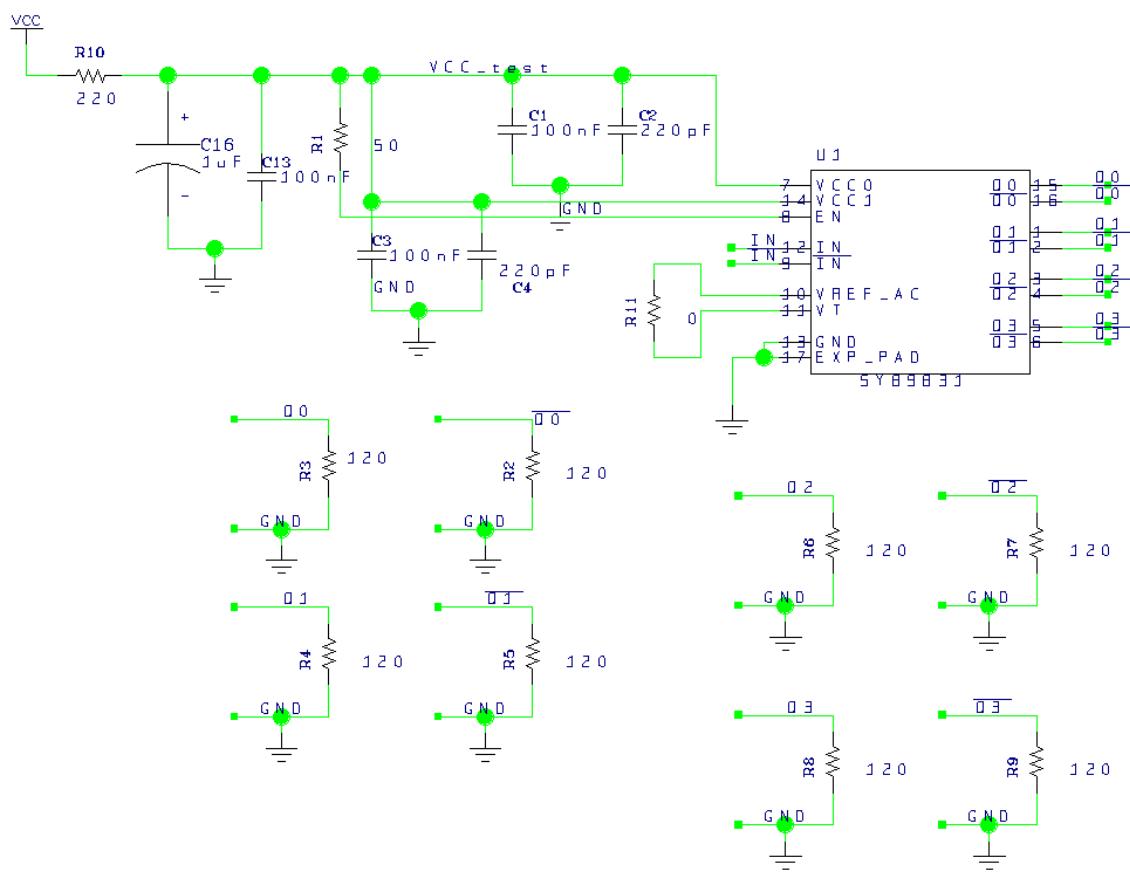


Figure 6: Schematic for the SY89831U test board

6.1.7 ADN2814 and MAX3748

These two boards are used for the same purpose, and the one of them that performs best will be chosen to be used on the RCU2. ADN2814 is a clock and data recovery IC with integrated limiting amplifier. Works in rate of 10 Mb/s to 675 Mb/s. Gives out a Low-Voltage Differential Signaling (LVDS) clock and data signal. MAX3748 is a limiting amplifier. Works in rate of 155 Mb/s to 4.25 Gb/s. Gives out a Current-Mode Logic (CML) data output signal.

These ICs are going to be used to make a stable LVDS or CML signal from an optical transceiver. The signal from the optical transceiver is a Manchester coded signal consisting of data and clock. There are a few differences between the two ICs. MAX3748 comes in a smaller package and uses less power and works in higher rates, but it doesn't have a clock return function as ADN2814 has. Both works for our specific use, therefore we will see from the test results which one will be used.

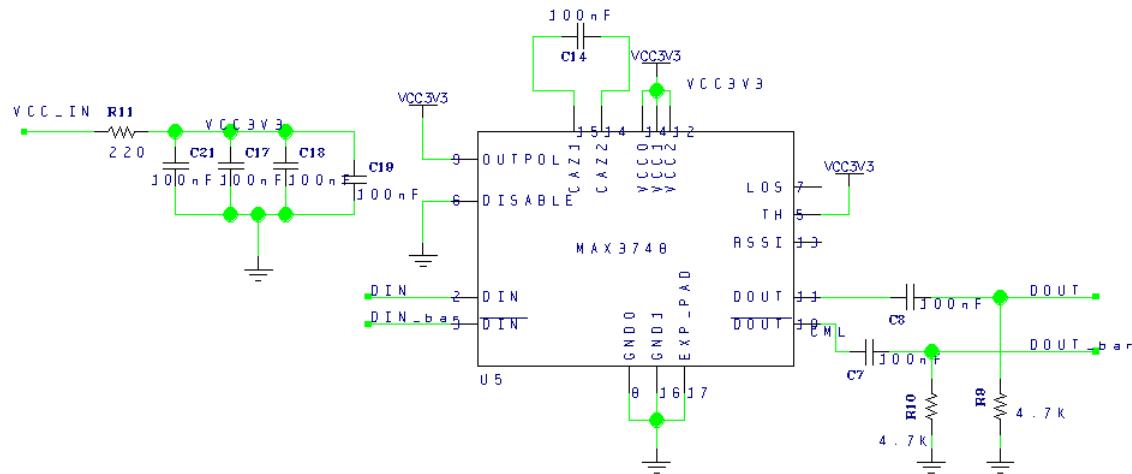


Figure 7: Schematic for the MAX3748 test board

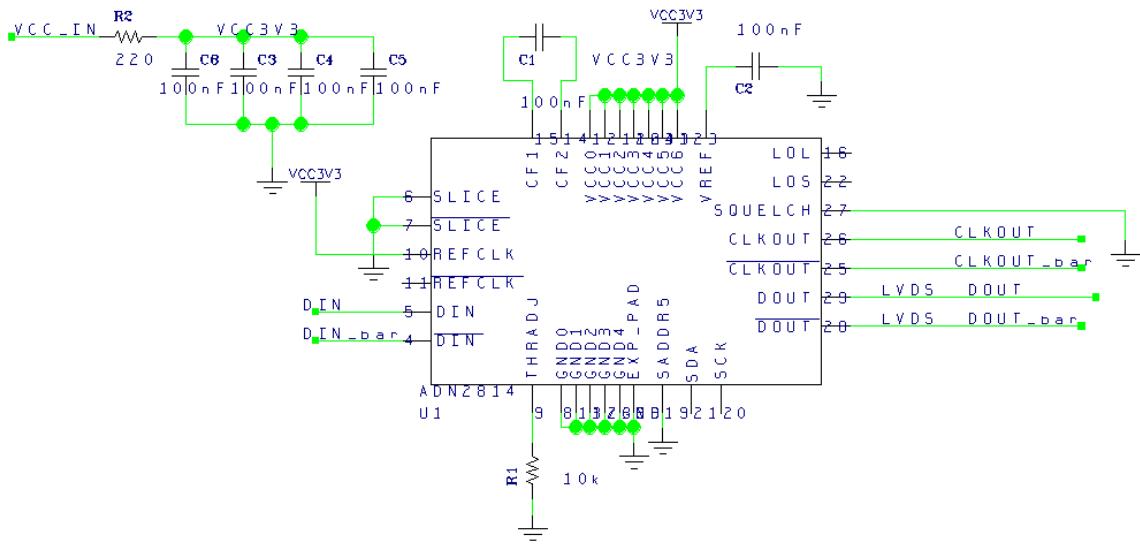


Figure 8: Schematic for the ADN2814 test board

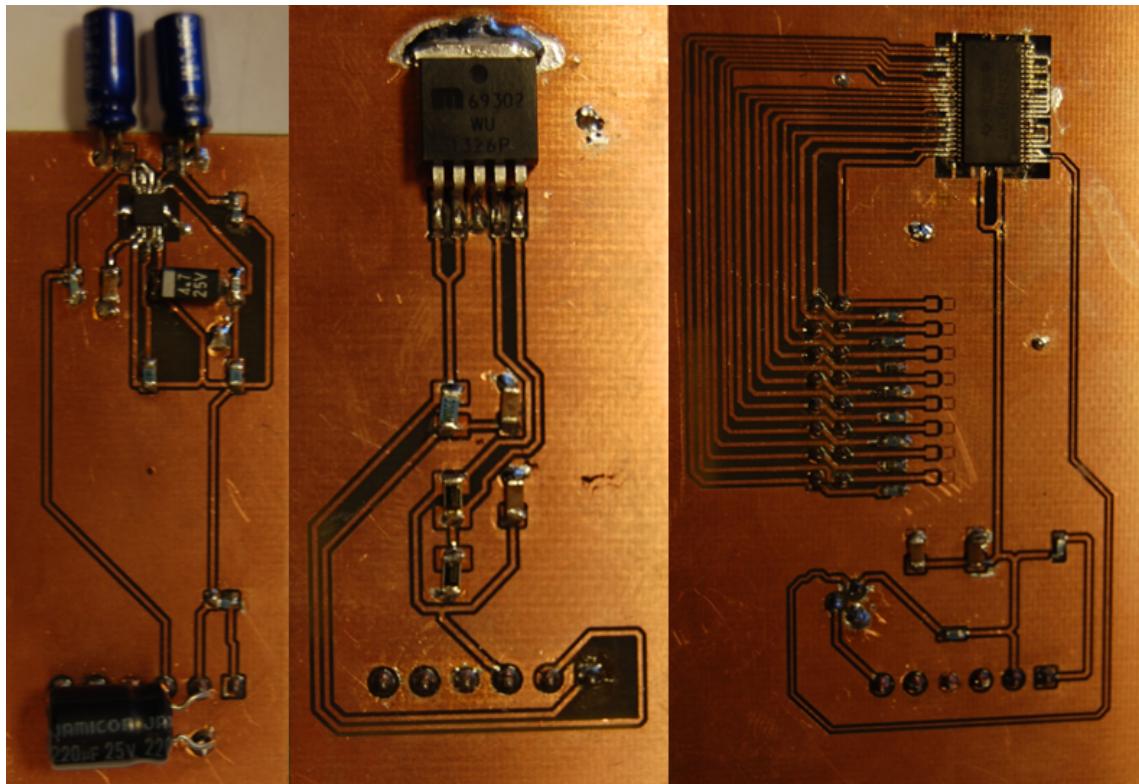


Figure 9: Picture of PCB boards, from left we have, TPS51200, MIC69302WU and SN74AVCB164245

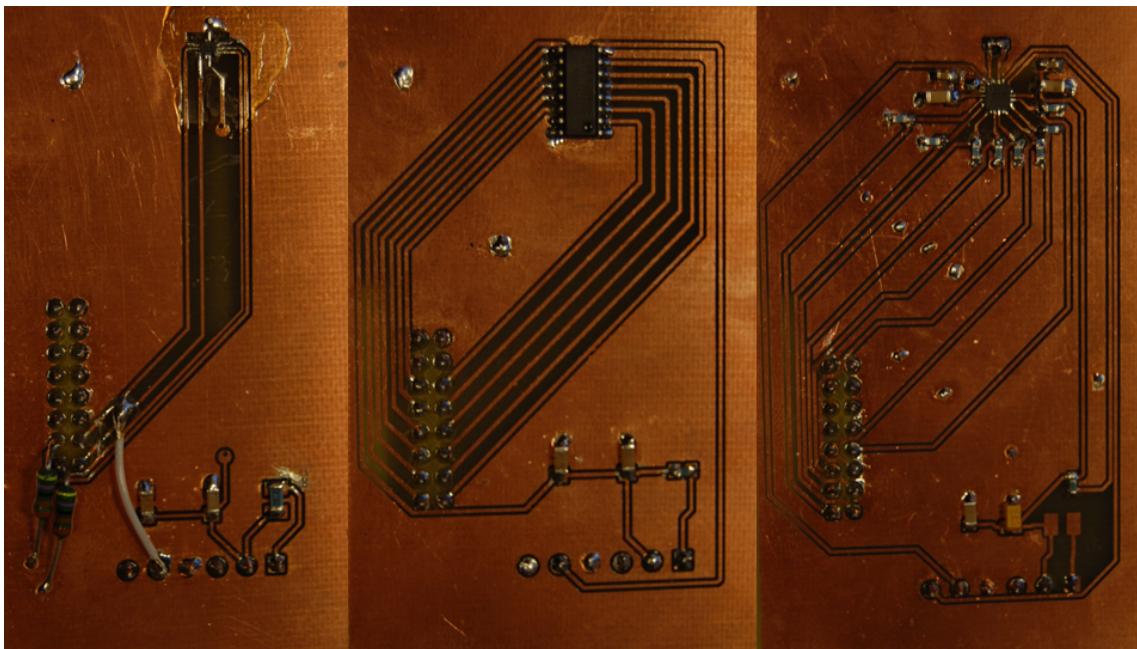


Figure 10: Picture of PCB boards, from left we have, SN74AVC2T245, QS3VH257 and SY89831U

6.1.8 Software

To monitor the outputs and control the inputs and the supply voltage, a simple labVIEW program was made for each of the different PCBs. In these programs time from start, current consumption and the status of the output signal (or the output voltage for the regulators) can be measured and monitored. In figure 12 you can see an example of a labVIEW program used for SN74AVC2T245.

6.1.9 SmartFusion2 (SF2)

The two limiting amplifiers (ADN2814 and MAX3748) required a more advanced inputs, and therefore a SmartFusion2 (SF2) starter kit are going to be used in addition to labVIEW. The SF2 board was used to code a clock and data signal into a differential Manchester signal and to decode the differential Manchester signal back to clock and data after it has gone through the IC. The SF2 was also used to compare the original signal with the signal coming out from the IC. A picture of the Smart Design can be seen in figure 13. This consists of IP-cells from Microsemi and some VHDL code that has been made.

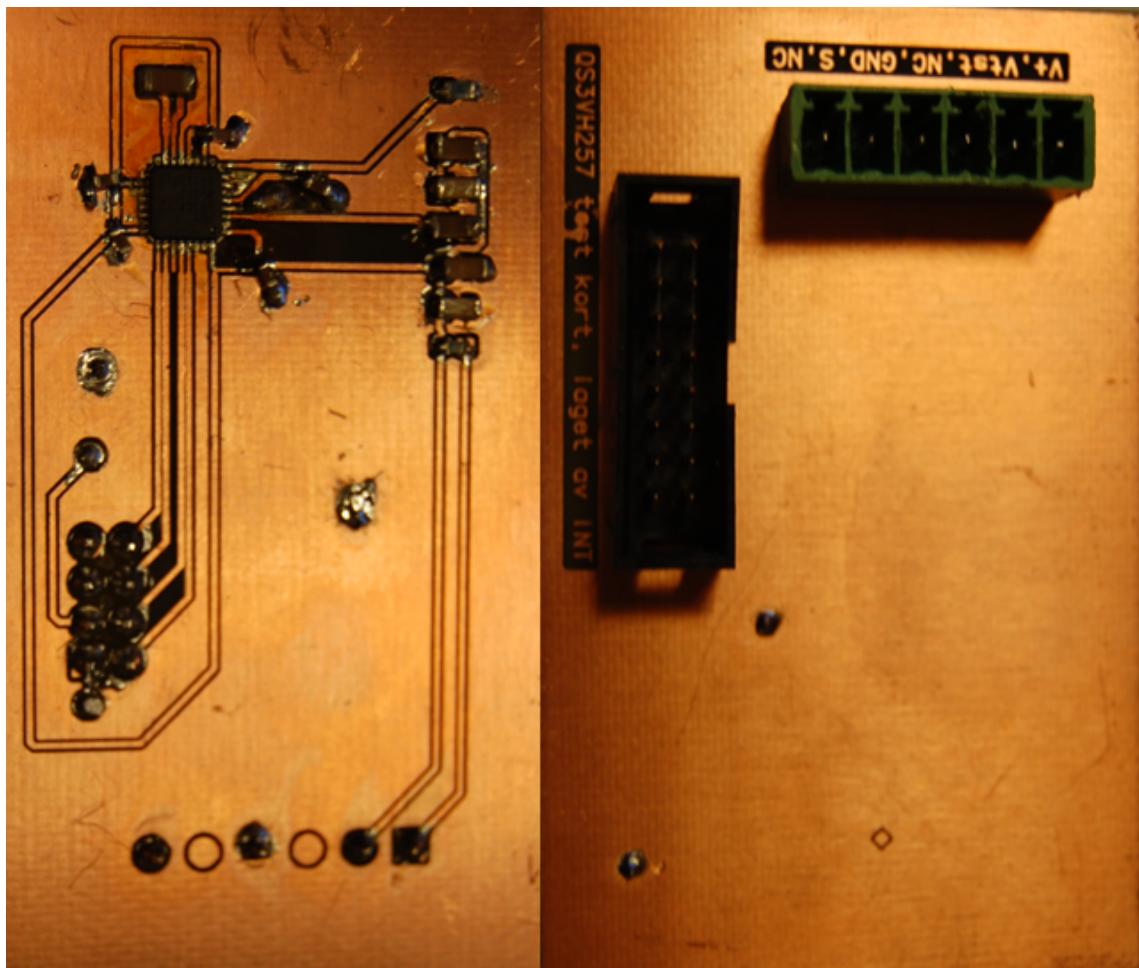


Figure 11: Picture of PCB boards, from left we have, ADN2814, MAX3748. plus an example of a back side QS3VH257, you can see the mark at the top indicating the center of the IC

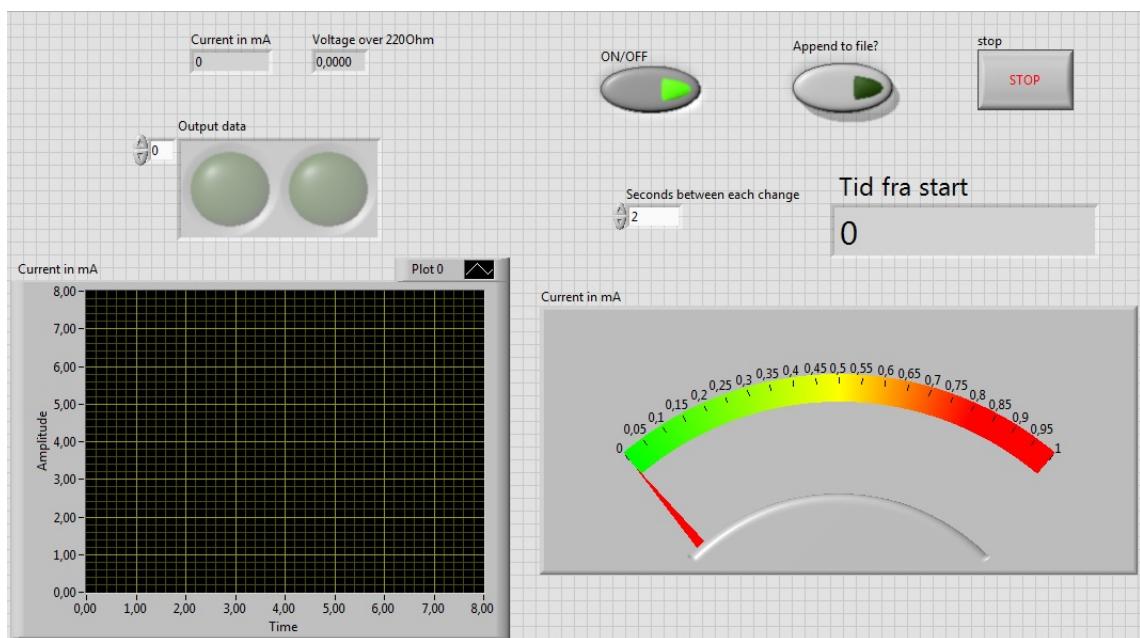


Figure 12: LabVIEW program for SN74AVC2T245

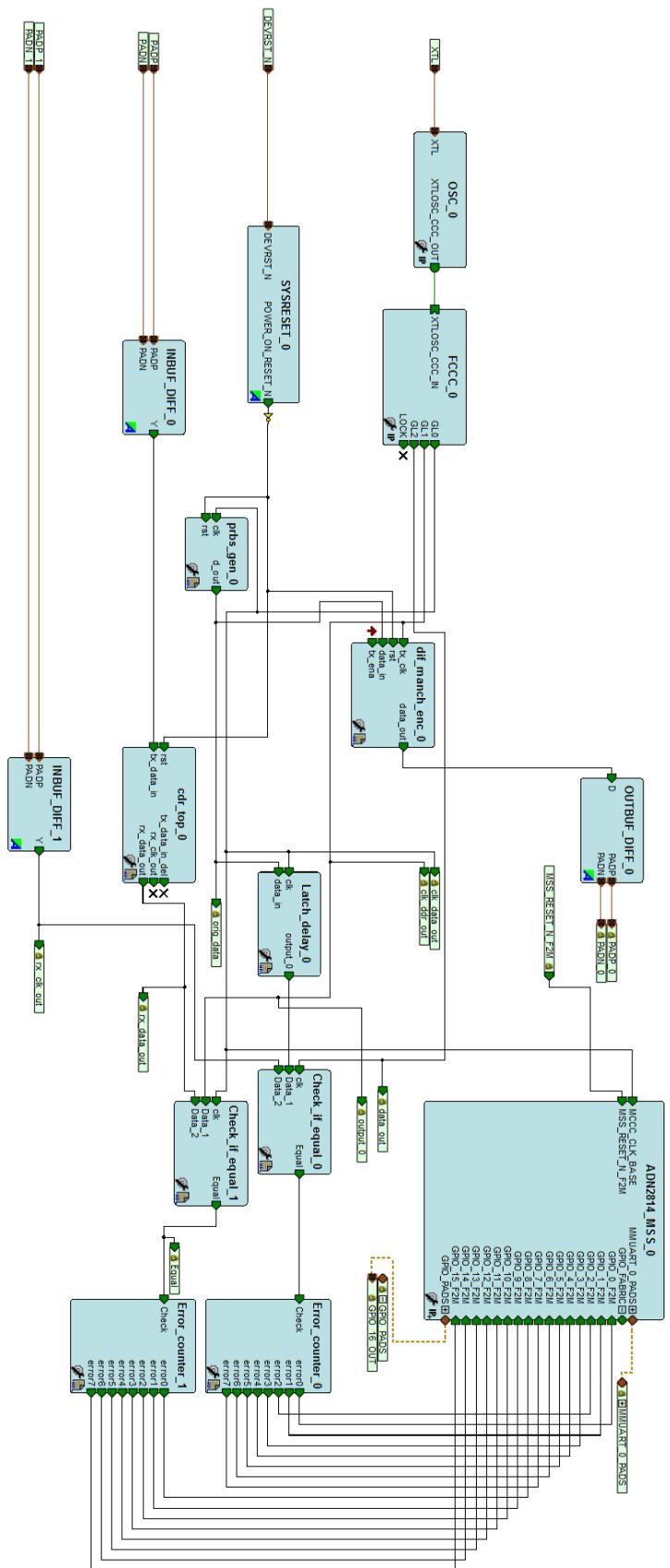


Figure 13: Smart Design for ADN2814

7 Testing at Oslo Cyclotron Laboratory (OCL)

7.1 About OCL

Oslo cyclotron Laboratory is located at the Department of physics at the University of Oslo, and was opened in 1978. The cyclotron is of the type MC-35 and was made by Scanditronix AB from Sweden. This is the only accelerator in Norway for ionized atoms used in basic research. The cyclotron can accelerate protons, deuteron, 3He and 4He , with energies and intensities as seen in the table 1 bellow. A drawing of the lab can be seen bellow in figure 14. The laboratory is divided in tree; the control room, the inner experimental hall and the outer experimental hall. The cyclotron is placed in the inner hall, and a beam is sent through pipes to the outer hall. There is vacuum inside the cyclotron and the pipes, so that you should not suffer energy loss from collision with air molecules. With magnet you are able to regulate the beam to your desired pipe exit. There are also several cups put on the pipeline which makes it possible to block the beam. These can be used to stop the beam during an experiment, so you are able to go into the experimental area and do changes on your setup. When the cyclotron is running and the beam is on, you are not allowed to enter the inner experimental area.

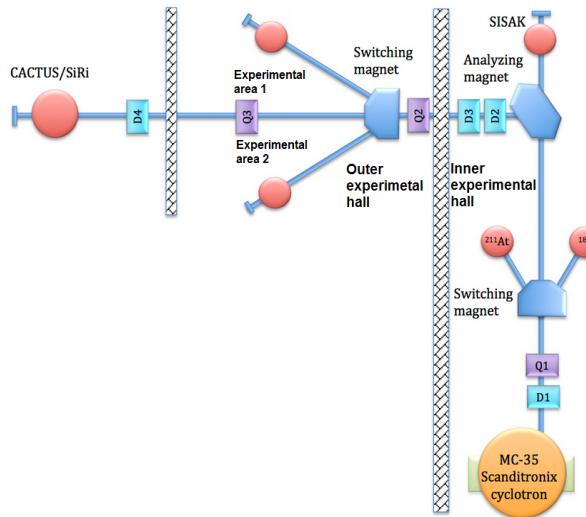


Figure 14: Out-lay of the OCL

Ionized beam particle type	Energy(MeV)	Intensity(μ A)
Proton	2-35	100
Deuteron	4-18	100
3He	6-47	50
4He	8-35	50

Table 1: Ionized beam particle data table

7.2 Experiment setup and equipment

The experiment setup was placed in the outer experimental hall in experimental area 2. The experimental setup as well as the equipment used can be found in the figure and table bellow. The equipment was kept in close to the same height around 140-150cm (so that we wouldn't have to think about three dimensions). Beam exit was in a height of 141.5cm.

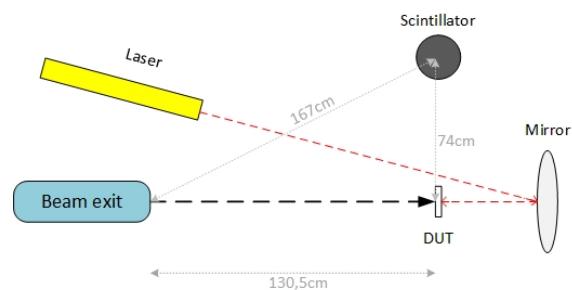


Figure 15: Experimental setup seen from above

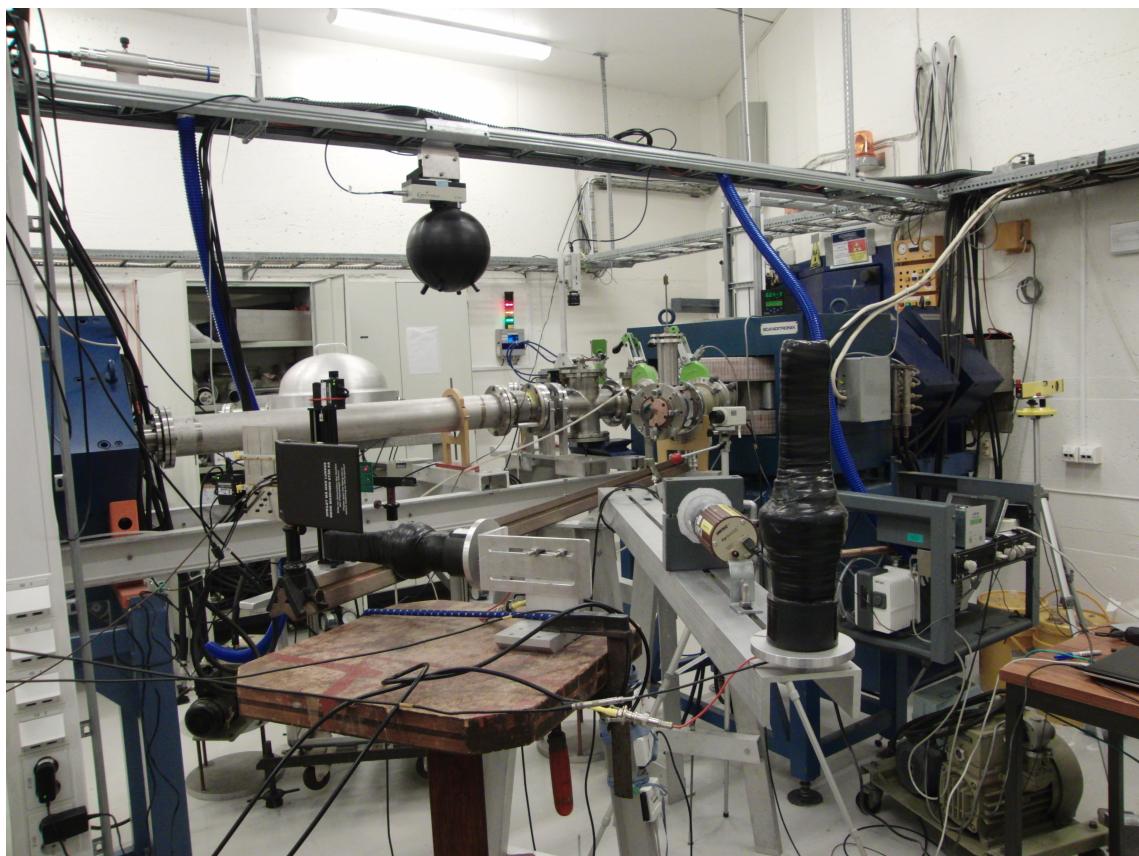


Figure 16: Picture of the experimental area

Equipment	Explanation
Scintillator	A plastic scintillator with photomultiplier. Was used to measure relative radiation. We had two of these, one that was placed right under Device Under Test (DUT) and one that was placed 75cm away from DUT. We only used the one 75cm away during the experiment.
High voltage regulator	Voltage for the photomultiplier. 800V was used
8 test boards	TPS51200, MIC69302WU, SN74AVCB164245, SN74AVC2T245, QS3VH257, SY89831U, ADN2814 and MAX3748
SRAM-board	A PCB board with 4 static RAM (SRAM) cells that was used to characterise the beam and to measure scintillator counts
SF2 starter kit	A starter kit board with the Smart Fusion 2(SF2) chip.
Computer	A VPN connection was set on a computer inside the experimental hall, so that we were able to control the experiment from the control room. The computer was running LabView to control the experiment. Data was also saved on the computer
USB DAQ	Data acquisition board form National Instruments(NI). Used to establish analog and digital connection to the test boards and send data to the computer.
Radiation film	A film that reacts when radiated with protons. Used to identify the beam.
Counting controller	A device that counts either rising or falling edges of a signal.
leveled laser	This was used to pinpoint the center of the beam.
Mirror	Used to reflect the laser beam to the backside of the test boards.
XY-controller	Connected to the computer so we can change the position of the test boards from outside the experimental area

Table 2: Equipment used in the experiment

7.3 Measurement equipment and test boards

7.3.1 SRAM board

A SRAM memory chip is very sensitive to Single Event Effect (SEE), and can be used to measure relative radiation by constantly checking for Single Event Upset (SEU).

The method of detecting an Single Event Upset (SEU) in a SRAM is rather

straight forward, as can be seen in the flow diagram of figure 17. There is an initial startup phase where a known pattern is written to all the addresses in the SRAM. When the startup phase is done, the value from the first address is read back and compared to a known value by XORing the known value with the one read. If they are not equal a SEU has occurred, and a the XOR-function will go high and a 1 will be added to a SEU counter. The correct value is then written back to the address and the system moves on to the next address.

A checkerboard pattern, a pattern of alternating ones and zeros, is used when writing to the SRAM. To check for stuck bits, the bit pattern in the whole address space is inverted after each read.

From earlier experiment with the SRAM chip [8], the cross section(the probability that an incoming particle will induce an SEU) is known, and is found to be to be $1.14 \times 10^{-6} \text{ cm}^2$. By counting number of SEU during an experiment, we can by dividing on the cross section find how many particles that hits the chip. The SRAM board that we used consist of 4 SRAM chips, a flash based FPGA, connections and supporting electronics. The FPGA on the SRAM PCB is designed with RS485 two-way communication which makes it possible to edit firmware as well as sending data out. Through the experiment the SRAM PCB was connected with RS485 to Opal Kelly XEM3001 which gave us connection to a computer. On the computer we ran a LabVIEW program, that made us able to monitor data, as well as doing some settings. The SRAM board also had an optical input for scintillator counts, so we could by the use of this board also monitor scintillator counts.

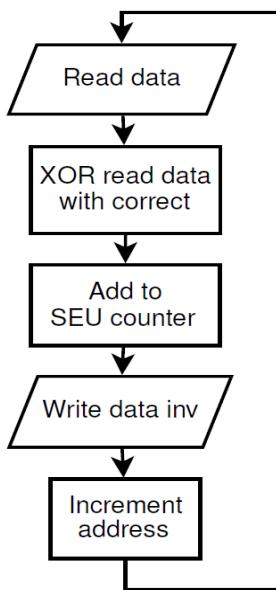


Figure 17: Flowchart for SEU detection

In figure 18 bellow you can see how the labVIEW program looked like. From here we can monitor SEU on all the 4 SRAM cells, see scintillator counts, reset counters, see time from start as well as other things. SRAM1-10 as you can see on

the left side, is different SRAM-board, the board we used was SRAM6.

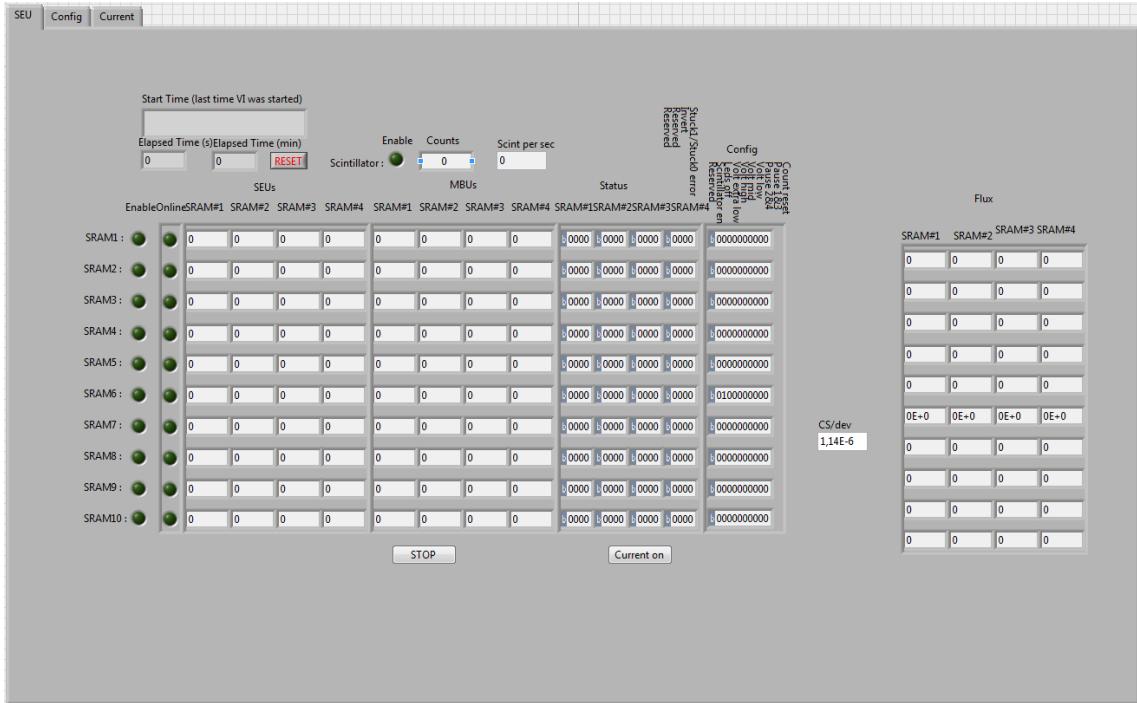


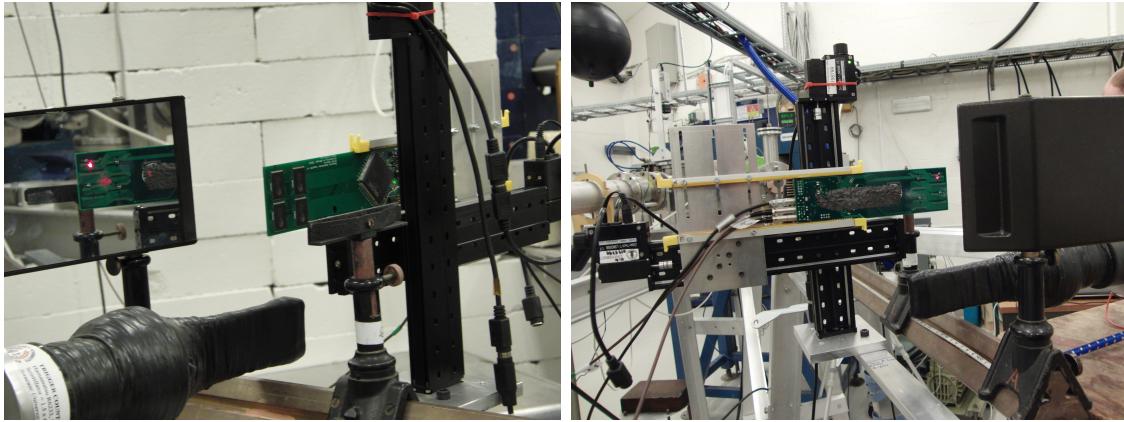
Figure 18: LabVIEW program for the SRAM

7.3.2 Scintillator counter

A scintillator is a material that gives out light when it is exposed to ionised radiation. A scintillator can be used as a stand alone equipment, but then only to detect that there are radiation, by seeing that it lights up. To get a more accurate measurement, we will need a PhotoMultiplier Tube (PM-tube). The PM-tube converts light pulses to current by an electron avalanche process. This process is very sensitive to radiation. [6] The pulses could be measured with the SRAM board or a counter of some kind, we used the SRAM board to measure scintillator counts during the experiments.

7.3.3 X-Y-positioning system

The X-Y-positioning system is a system that makes it possible to mount our PCBs and move them in X and Y direction. This could be controlled directly on the X-Y-system or through a labVIEW program on the computer. This was used when doing the beam profile as discussed in chapter 7.4.2, to be able to do changes on the position from the control room. In figure 19 you can see a picture of the front and back of the X-Y-positioning system.



(a) SN74AVC2T245 board1

(b) SN74AVC2T245 board2

Figure 19: X-Y-positioning system upfront and behind, with SRAM-board mounted

7.4 Preparation and characterization of the beam

Before we could start testing of the PCB, the cyclotron had to be made ready for a proton beam and the magnet controlling the direction had to be put in the right position to get the beam out in experiment area 2.

7.4.1 Purpose of tests

The purpose of testing these board is to see if they are able to survive in a radiated area as we will find in the LHC, see section 4.1. To make sure that we know the limit of the ICs, the ICs was irradiated until a error occurred, current consumption drastically increased or the IC received a much higher dose than was required without error. Every IC that has been tested, are ICs that are going to be used in creation of the new RCU2 board.

7.4.2 Beam setup

When the beam was set, we could start the characterization of the beam. The first thing to do is to get an understanding of the beam, and see that it hits around the area that we expect at our test position 130.5 cm from beam exit. This was done by using radiation films that turns black when exposed to radiation. One of these was placed right in front of the beam exit and one in front of Device Under Test (DUT) area to see how the beam looks like at the two positions. This gave us a rough center position. A more precise calibration was done by the use of the SRAM board and the scintillator. By measuring the relation between scintillator counts on the scintillator which was in a locked position and SEU on the SRAM that was connected to the XY-position system(which made the SRAM freely to move), we were able to find a more precise position of the beam center by seeing which position gave us highest SEU counts compared to scintillator counts. When the beam center is found and everything works as it should, the laser was placed in a position so that the laser beam points to where we had found center of the beam to be. After that we could replace the SRAM board with the PCB that we were going to test. This had to be done every day at startup, before we could start the actual tests.

We were able to control the intensity(Current) of the beam freely from the control room inside the limitation of the beam (for protons that is up to 100 μA), but we kept us in the area between 100 pA to a few nA. This way the radiation dose to the test boards can be controlled. The beam intensity could be measured by putting a Faraday Cup(FC) in front of the beam. But the FC had to be removed when tests were running, since it will block the beam.

We were running 3 labVIEW programs at all time through the experiment, one for controlling the XY-position system, one for the SRAM board(to measure SEU and scintillator counts when calibrating and to get scintillator counts during the tests) and one program for each of the test boards. The SRAM and test board programs were constantly saving data on the disk.

8 Results and calculations from beam test at OCL

The radiation was done in 5 days divided in two periods 13.11.13-15.11.13 and 28.11.13-29.11.13. I had made two version of most of the boards, the exception is ADN2814 and MAX3748 which I only made one version of. The boards that where tested the first time are: *TPS51200₁, MIC69302WU₁, SN74AVCB164245₁, SN74AVC2T245₁, QS3VH257₁* and *SY89831U₁* tested in that order. The second time, we started with the two limiting amplifier IC, since those hadn't been tested before. So the order the PCB was tested the second period was: *ADN2814, MAX3748, SY89831U₂, TPS51200₂, MIC69302WU₂, SN74AVCB164245₂, SN74AVC2T245₂*. The first time at OCL we were given an beam of 28 MeV, but the second time the lab personnel manage only to produce a beam of 25MeV. When the beam gets out through the beam exit the energy will be reduced by crashing with air particles(21keV per cm), so at DUT area the beam was approx 25 MeV and 22 MeV.

The result is presented after type, so that the two boards of the same type is presented together.

8.1 Calibration process

As explained in chapter 7.4.2, we had to start by finding the center of the beam. In table 3 you can see the results from our calibration 15.11.2013. You can see that position x = -2,5 and y = -1 gives highest relation between SEU on the SRAM and scintillator counts. A total of 4 tests in that position was done and the average value gives us 0,0948. This value was used to calculate from scintillator counts to SEU. cross section(the probability that an incoming particle will induce an SEU) is known for the SRAM board. The cross section (CS) is given in equation 5.

$$CS = 1,14e - 6 \quad (5)$$

8.2 Test results

The tests was controlled and monitored through a LabVIEW program for each of the different IC. When testing ADN2814 and MAX3748 there was also needed a SF2 board to produce a input signal, and compare the input with the output signal. A complete result of the tests can be found in appendix 10. The point of this test was to see that these ICs would survive in a radiated area. The total dose of 10 years in the ALICE detector is estimated to be a 1-2 kRad, see section 4.1. If a IC survives

Calibration test nr.:	x	y	Scint rel	SEU(SRAM)	SEU(SRAM)/sc
1	-0,8	-1	27798	1463	5,26E-02
2	-1,3	-1	17721	1239	6,99E-02
3	-1,8	-1	12904	1203	9,32E-02
4	-2,3	-1	13361	1276	9,55E-02
5	-2,8	-1	12786	1238	9,68E-02
6	-3,3	-1	12342	1156	9,37E-02
7	-2,5	-1	11696	1223	1,05E-01
8	-2,5	-1,5	11027	1075	9,75E-02
9	-2,5	-2	11835	1063	8,98E-02
10	-2,5	-0,5	15593	1540	9,88E-02
11	-2,5	0	12620	1034	8,19E-02
12	-2,5	-1	65280	5999	9,19E-02
13	-2,5	-1	52752	4803	9,10E-02
14	-2,5	-1	57229	5250	9,17E-02

Table 3: Calibration tests 15.11.2013

more than 10 times that, we can be quite sure that it will survive the radiation it will receive at CERN. In table 4 and 5 you can see how long each ICs has been exposed too radiation, the dose they have been received and if an error occurred.

Device	Exposed time[s]	Dose[Rad]	Error
<i>TPS51200</i>	2065	41800	No
<i>MIC69302WU₁</i>	2240	164000	No
<i>SN74AVCB164245₁</i>	967	65200	No
<i>SN74AVC2T245₁</i>	860	4600	Yes
<i>QS3VH257₁</i>	795	52800	No
<i>SY89831₁</i>	1251	93500	No

Table 4: Tests at OCL 15.nov 2013

Device	Exposed time[s]	Dose[Rad]	
<i>ADN2814/run1</i>	1273	20200	Yes
<i>ADN2814/run2</i>	2286	324900	Yes
<i>MAX3748</i>	2384	442200	No
<i>TPS51200₂</i>	-*	-*	-*
<i>MIC69302WU₂</i>	1385	383800	No
<i>SN74AVCB164245₂</i>	526	201400	No
<i>SN74AVC2T245₂</i>	478	161600	No
<i>QS3VH257₂</i>	264	110300	No
<i>SY89831U₂</i>	921	165800	No

* The board wouldn't work at test time

Table 5: Tests at OCL 27-28.nov 2013

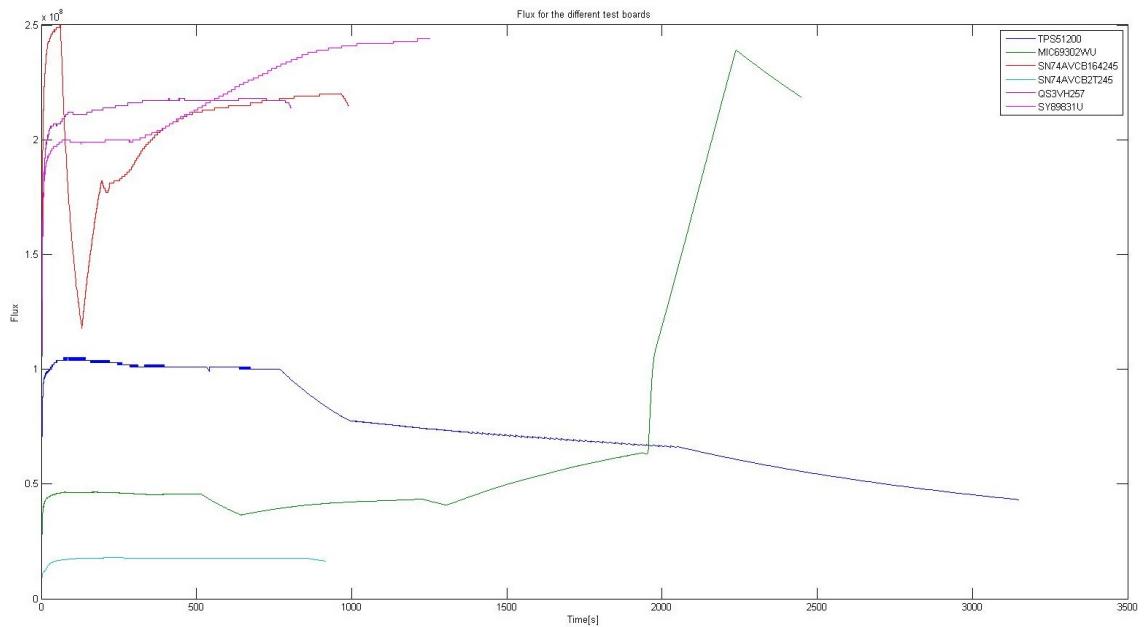


Figure 20: flux for each component radiated 15.11.2013

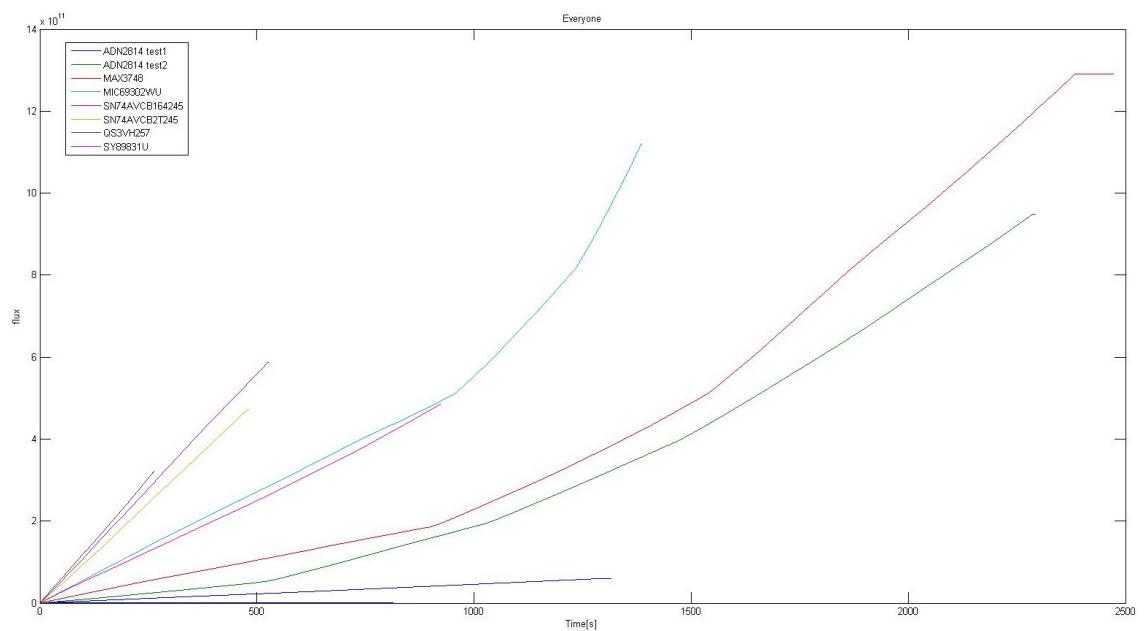


Figure 21: flux for each component radiated 15.11.2013

In figure 20 and 21 you can see graphs of flux vs time for the different test boards. The reason the graphs don't go as linear as one would expect, is that the beam sometimes stopped and had to restarted, and that we increased and decreased the intensities as we wanted.

8.2.1 TPS51200

This was the first board that was tested. The intensity was a little low on this test. To make the testing process faster the intensity was increased during the later experiments.

The IC worked after a dose of 40kRad, but we could see a little increase in current after a dose of 25 kRad. The output voltage is close to stable, a few mV up and down, but not noteworthy. Two PCBs of this type was tested, but only one worked when we was at OCL to do the testing.

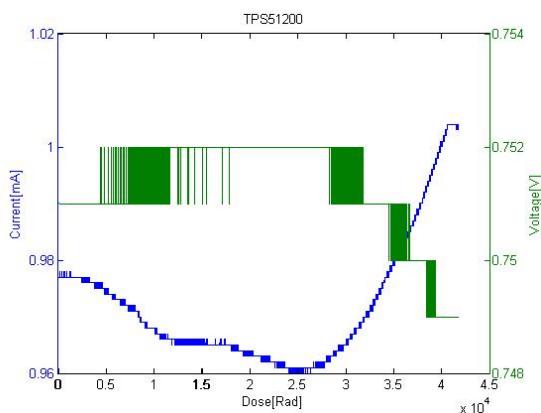


Figure 22: TPS51200 - Current/Voltage vs Dose

8.2.2 MIC69302WU

The first board was tested 15.11.13 and the second board was tested 28.11.13. During the test of the first board we increased the intensity of the beam quite allot, that can be seen from the flux graph, in figure 20.

This IC had an unexpected reaction to irradiation. You can see from both of the graphs that the current is decreasing and voltage is increasing, normally we would expect the opposite, or at least that the current would increase. As seen from the graph in figure 23 it starts quite early to decrease in current, but as you can see it also stabilize after a while. The output voltage is mostly stable, there were a increase of 2% on both of the tests.

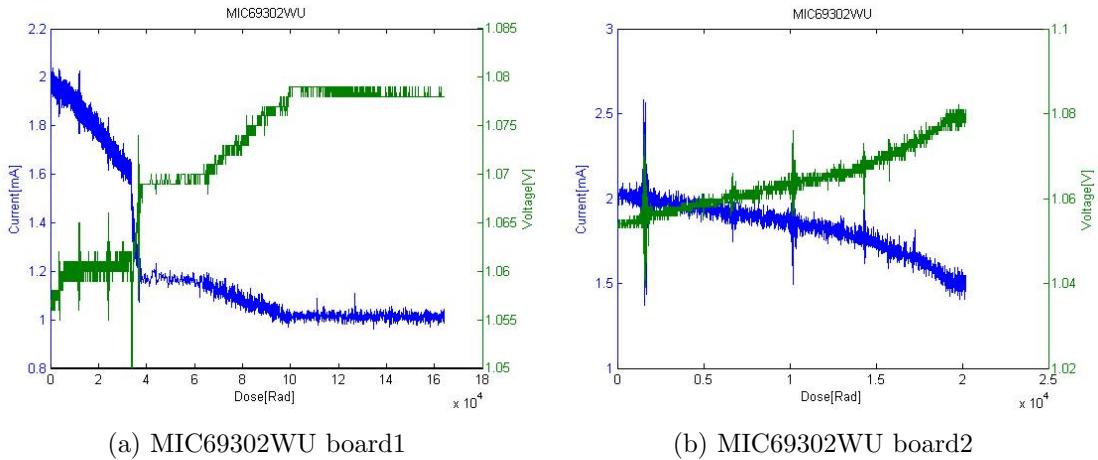


Figure 23: MIC69302WU - Current/Voltage vs Dose

8.2.3 SN74AVCB164245

It can be seen that the characteristics on the two test board are different, the reason for this is maybe because of different output load. The reason for the “jumps” in current is because the output is constantly changing from on to off, with a gap of 4 seconds. This chips is not effected by radiation before a dose of approx 40kRad. That is more than enough for the purposes we are going to use this for.

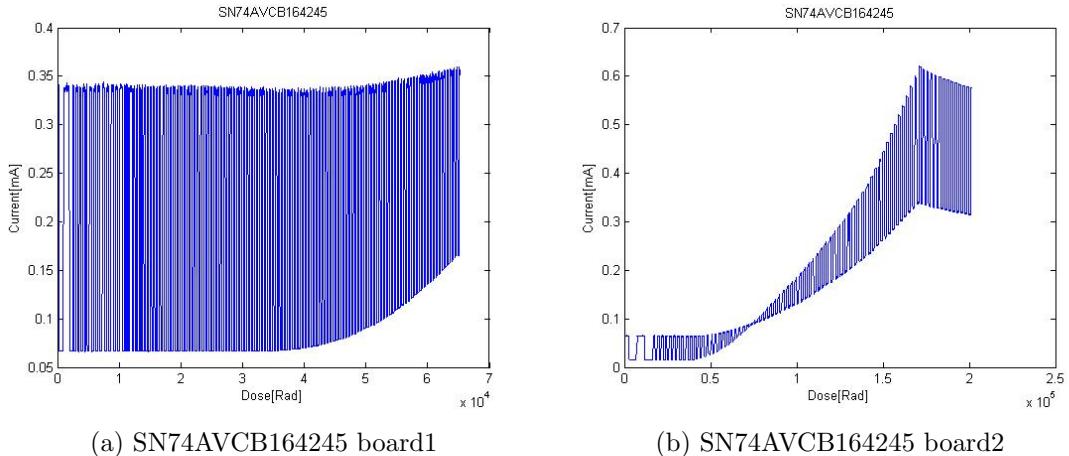


Figure 24: SN74AVC2T245 - Current vs Dose

8.2.4 SN74AVC2T245

Something went wrong on the first test. After 740 s and a dose of 98 Rad the chips output was stuck at 1. The reason for this is unknown, I fear that this might be defected before we started the test, since it gives a totally different characteristics than test board nr 2. The input was switching from high to low every 4 second. If

we look at the test results from board 2, the current goes unchanged up to 40 kRad, and that is more than enough.

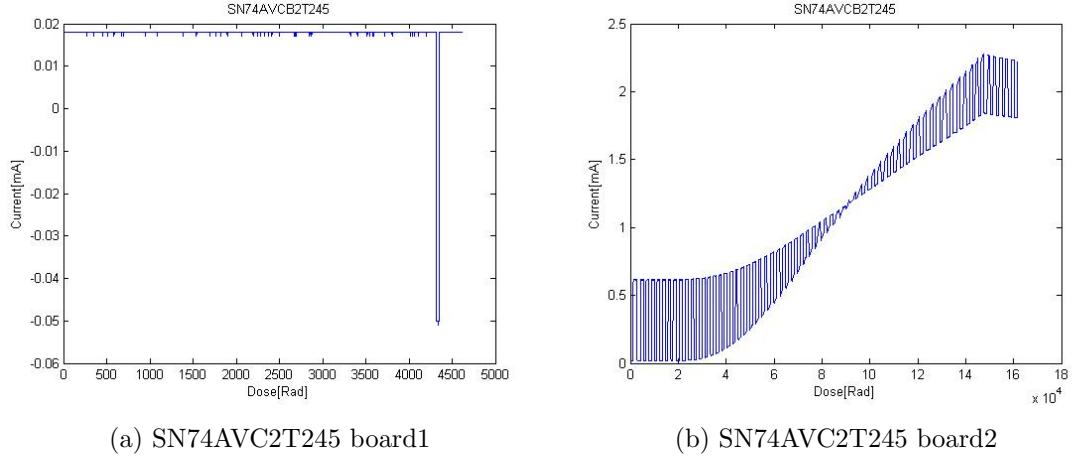


Figure 25: SN74AVC2T245 - Current vs Dose

8.2.5 QS3VH257

The select input was changed every 4 second and the inputs(I0A, I0B, I0C, I0D, I1A, I1B, I1C and I1D) was inverted every 18 second.

The two test boards worked fine through the tests. We see that we have small increase in current before 30 kRad, after that it increases quite allot. We couldn't see any errors on the output during the experiment, but it should probably not be exposed to more than 30 kRad.

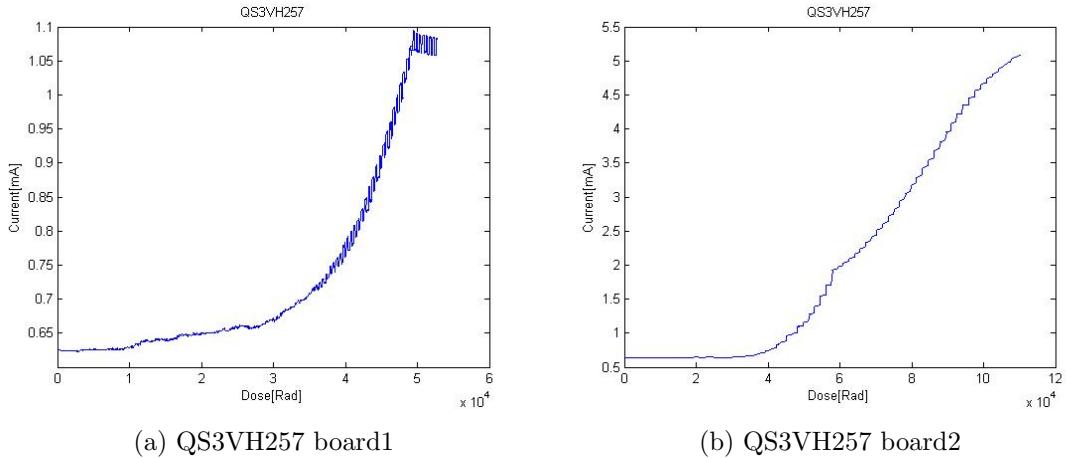


Figure 26: QS3VH257 - Current vs Dose

8.2.6 SY89831

This IC required a high current to work, and since the labVIEW DAQ device only delivers 5mA on the analog outputs, a combination of the modified MIC69302WU as described in section 6.1.2 and the 5V output on the DAQ was used. This gave us a output of 3.3 V and a current limit of 200 mA. Here a 20Ω resistor was used to measure current instead of a 220Ω resistor, this was to reduce the voltage drop over the resistor because of the high current consumption.

A difference in characteristics can also be seen here. This may be because two different footprint for the PCB was used, and therefore some difference can be seen. We see a small increase in current on both of the boards, but not noteworthy, compared to how much current this IC is using.

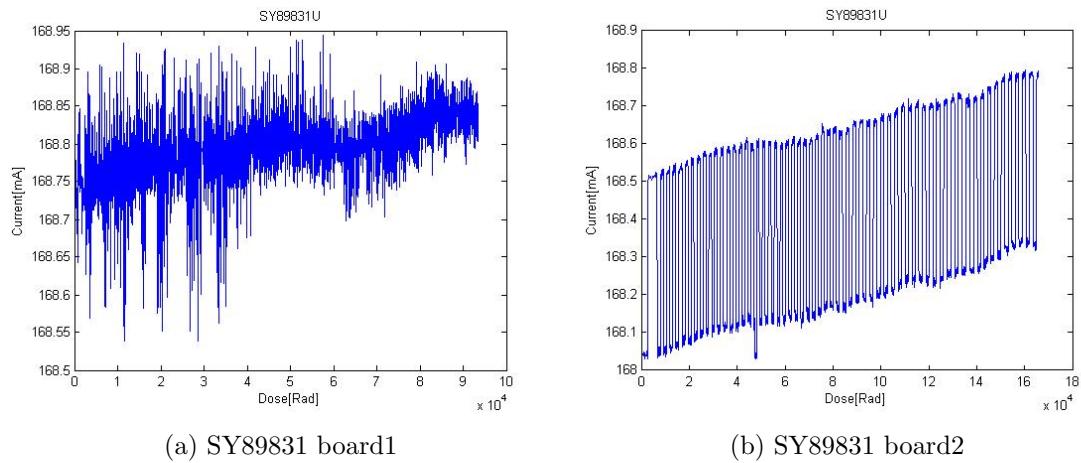


Figure 27: SY89831 - Current vs Dose

8.2.7 ADN2814

This IC is a little special and was hard to get a good test on. This is a clock and data return circuit, with a limiting amplifier. The SF2 board was used to code a clock and data into a differential Manchester signal, that was sent into the IC. Out of the IC we get a LVDS clock and LVDS Manchester signal. The Manchester coded data signal was decoded on SF2 board, so that we get out a clock and data. The data was tested by delaying the original data through a few D-latches, so that the original and returned data was close to synced. Then we could compare the original data with the one from the IC through a XOR-function. This function was triggered by a 80 Mhz clock from the SF2 board. If they aren't equal when the clock rises, a 1 will be added to a counter. The value of the counter was constantly sent through the UART of the SF2 board.

The way the clock was tested was a little harder process since the clock was so fast

(160 Mhz). This was solved, was by adding a third clock with the same frequency (160 Mhz) that was 90° of from the two others, when this goes high I called on the XOR-function, to see if the two other clocks are the same. if they are alike, nothing happens, if they are not the program adds 1 to a counter, which constantly writes its current value to a Universal Asynchronous Receiver/Transmitter (UART). The problem here is that for each time the SF2 board was programmed the clock was slightly different, that made either the clock out of sync or the data out of sync, so the code didn't always work as it should. This circuit also requires allot of current, therefore the same solution as for SY89831 was used, using MIC69302WU as a power supply and measure the current on that PCB.

The current didn't change before a dose of 200 kRad had been received, but we got a clock error at a dose of ~ 11 kRad, and a data error after a dose of ~ 8 kRad. How good this test really is, could be discussed, since we don't have any data on the clock and data, other than that the XOR-function failed. What really failed, and how much is impossible to know. It could be a slightly delay on a clock or the data, or maybe the clock just disappeared for a moment.

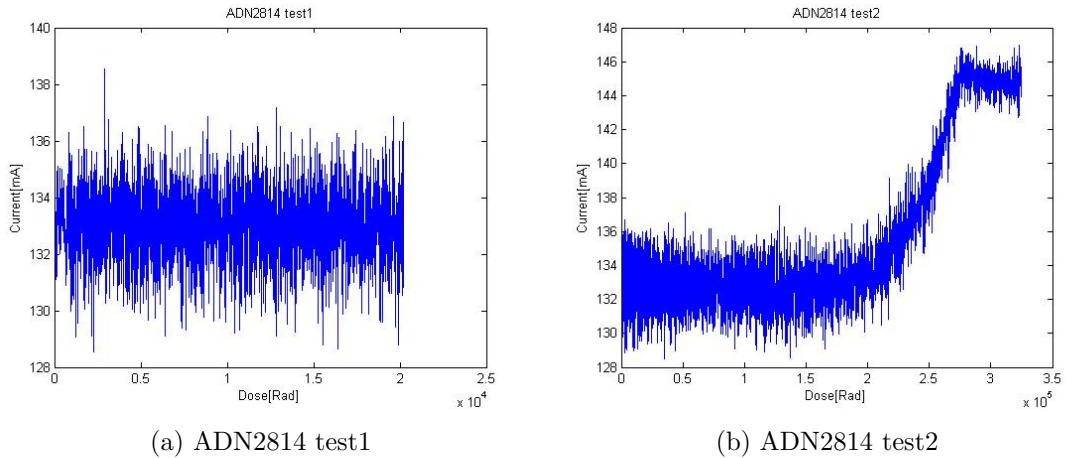


Figure 28: ADN2814 - Current vs Dose

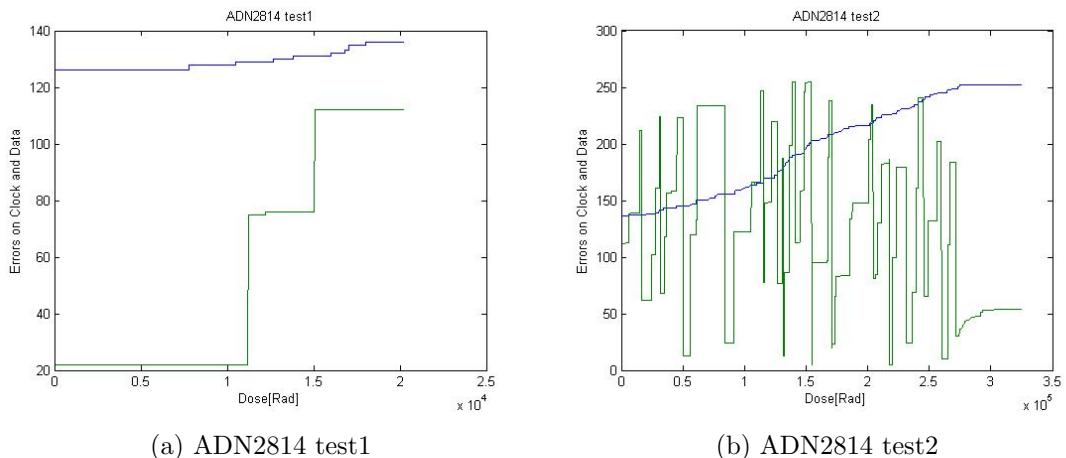


Figure 29: ADN2814 - Relative errors vs Dose

8.2.8 MAX3748

This circuit has the same purpose as ADN2814, the difference is that this one only return the limited Manchester coded signal, and no clock. The process for testing the data is the same as for the ADN2814. The decoding process return clock and data, but since they are related to another, a error on the clock would mean an error at the data. So by measuring data, we can be sure that there are no clock errors as well.

After a dose of over 400 kRad this chip still worked, and current consumption was stable through the hole irradiation process.

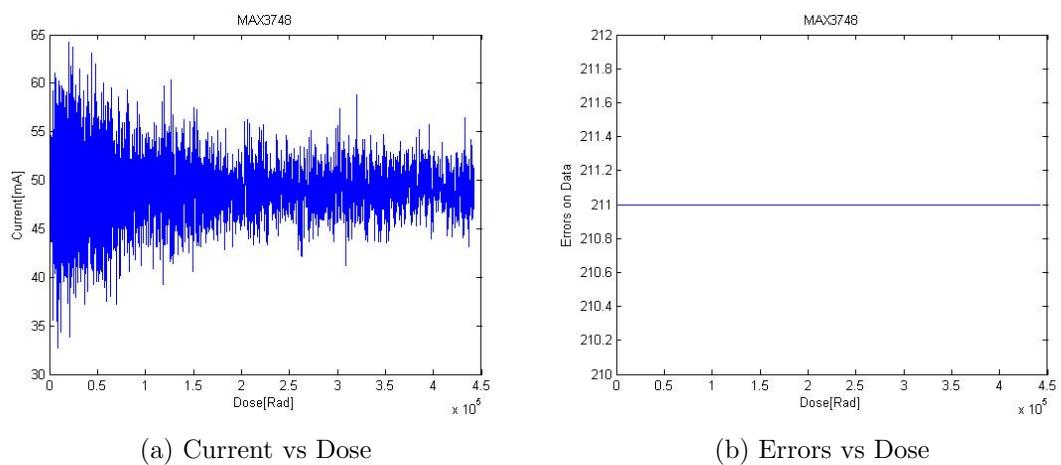


Figure 30: MAX3748

8.3 Calculation of dose

After a radiation test on one of the PCB, we knew the exposed time and scintillator counts. From the calibration we got the relation between scintillator counts and SEU on the SRAM, and the cross section for the SRAM is known. We start by calculating SEU from the conversion factor found in the calibration process, for 15.11.13 this was 0.0948 and for 28.11.13 this factor was 0.0473. Then we calculate the fluence at DUT as seen in equation 6, and by this we can calculate the flux, see equation 7. To calculate the dose from here we need to know some more factors. We run a simulation on a program called FLUKA. This program is used to simulate particles in different environment. We simulated a proton beam of 28MeV and 25MeV in air, and inserted the distance from BE(Beam exit). The results can be seen in table 6. Then we had enough information to calculate the dose. As seen from equation 8 we are able to find the Fluence at BE. And from there we can calculate the dose at DUT, see equation 9.

Fluka simulation results 28MeV	
Dose/primary particle at DUT[Gy]	4,08E-10
Primary particles at Beam exit	1
Primary particles at DUT	0,1331
Beam intensity reduction at DUT	7,513148009

Table 6: FLUKA simulation with 28MeV proton beam

$$Fluence_{DUT} = \frac{SEU}{CS} \quad (6)$$

$$Flux = \frac{Fluence}{time} \quad (7)$$

$$Fluence_{BE} = \frac{fluence_{DUT}}{primary_particles_{DUT}} \quad (8)$$

$$Dose_{DUT}[Gy] = Fluence_{BE} \times \frac{Dose}{primary_particle_at_DUT} \quad (9)$$

$$1Rad = 100Gy \quad (10)$$

8.4 Discussion of the result

Most of the testing was done 15.nov and 28.nov. The other days was used to get familiar with the instruments and equipment that was being used, to prepare the setup and setting up the beam. There are almost impossible to get the same beam two days at a row. Each day of testing is therefore different from each other. Since the testing was conducted in two periods and a total of 4 test days, there are allot of uncertainties regarding the beam. And that is also why we had to do calibration each day at start-up.

When we were going to measure the intensity at the beam exit, we placed a Faraday cup in front of the beam, and connected it to a amperemeter on the control panel, but since the current is so small, the measuring instrument will be affected by air currents, and there are also allot of uncertainties in the instruments. Therefore we only used the Faraday cup and the amperemeter, to get a rough estimate of the actual intensity.

The are also some uncertainties regarding the DAQ device form NI. When measuring digital signal, we don't know if it goes from 0 V to 3.3 V as we would expect. Maybe in reality the low voltage is actually 0.4 V and high voltage is actually 2.8 V. If this is the case, it could be a problem with using this in our design.

As said before in 7.4.2, if a component survives 10 times more than what it will receive in a period of 10 years in ALICE, that is 1-2 kRad, than it can be used in the design of RCU2. Having that in mind, I would say that every component tested would have a green flag even though we had some errors when testing SN74AVC2T245 and ADN2814. Since the result after testing board two of SN74AVC2T245 was positive we can assume that something was wrong with the first board. When it comes to ADN2814, it would be nice to have more time in the lab to test this even more, since the test done gave us so unclear results. If a better test would be made, I'm sure that this would perform much better.

9 Conclusion

10 Appendix

10.1 datasheets

Calibration test nr.:	x	y	Scint rel	SEU(SRAM)	SEU(SRAM)/sc
1	0	0	23813	1971	8,28E-02
2	0	-0,5	37930	3867	1,02E-01
3	0	-1	27527	2817	1,02E-01
4	0	-1,5	34413	3360	9,76E-02
5	0	-2	32713	2763	8,45E-02
6	0,5	0	38753	2709	6,99E-02
7	-0,5	0	23420	2483	1,06E-01
8	-1	0	20611	2232	1,08E-01
9	-1,5	0	21014	2410	1,15E-01
10	-1,5	0	20676	2260	1,09E-01
11	-2	0	35787	3776	1,06E-01
12	-2,5	0	27847	2512	9,02E-02

Table 7: Calibration tests 14.11.2013

Calibration test nr.:	x	y	Scint rel	SEU(SRAM)	SEU(SRAM)/ sc
1	-0,8	-1	27798	1463	5,26E-02
2	-1,3	-1	17721	1239	6,99E-02
3	-1,8	-1	12904	1203	9,32E-02
4	-2,3	-1	13361	1276	9,55E-02
5	-2,8	-1	12786	1238	9,68E-02
6	-3,3	-1	12342	1156	9,37E-02
7	-2,5	-1	11696	1223	1,05E-01
8	-2,5	-1,5	11027	1075	9,75E-02
9	-2,5	-2	11835	1063	8,98E-02
10	-2,5	-0,5	15593	1540	9,88E-02
11	-2,5	0	12620	1034	8,19E-02
12	-2,5	-1	65280	5999	9,19E-02
13	-2,5	-1	52752	4803	9,10E-02
14	-2,5	-1	57229	5250	9,17E-02

Table 8: Calibration tests 15.11.2013

Fluka simulation results 28MeV	
Dose/primary particle at DUT[Gy]	4,08E-10
Primary particles at Beam exit	1
Primary particles at DUT	0,1331
Beam intensity reduction at DUT	7,513148009

Table 9: FLUKA simulation with 28MeV proton beam

Fluka simulation results 25MeV	
<i>Dose primary particle at DUT</i> [Gy]	2,94E-10
Primary particles at Beam exit	1
Primary particles at DUT	8,57E-02
Beam intensity reduction at DUT	11,6713352

Table 10: FLUKA simulation with 25MeV proton beam

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