Fermilab

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FINAL REPORT

Mu2e Experiment: Tracker panel's circuit analysis

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0. Mu2e

Physics in this moment is observating the three main discovery frontiers: Cosmic, Energy and Intensity.

During the next decades the research at the Intensity Frontier will concentrate on ultra-rare processes, including muon-to-electron conversion that will improve our knowledge about the universe

Intensity Frontier searches will be the base on which we can understand discoveries made on the other frontiers and other theories for physics beyond the Standard Model.

Mu2e, observing muon-to-electron conversion, will help us to understand why particles in the same category, or family, decay from heavy to lighter, more stable mass states. For many decades Physicists have searched for this and proceeding on this way is fundamental to understand what is going on beyond the Standard Model.

Electrons are responsible for the electricity that lights our houses, Muons are some sort of heavier cousin of the electron, but we're not sure just what the relationship is. Mu2e experiment will help us understand that relationship, and so will give a punch to the modern physics research.

Construction of the experiment has begun, and first beam commissioning is expected to start in 2020.

1. Introduction

When I arrived for the first time at Fermilab I had a little background on the Standard Model and all the other aspects about particle physics.

Here a little brief on the aims of the experiment and his main structure.

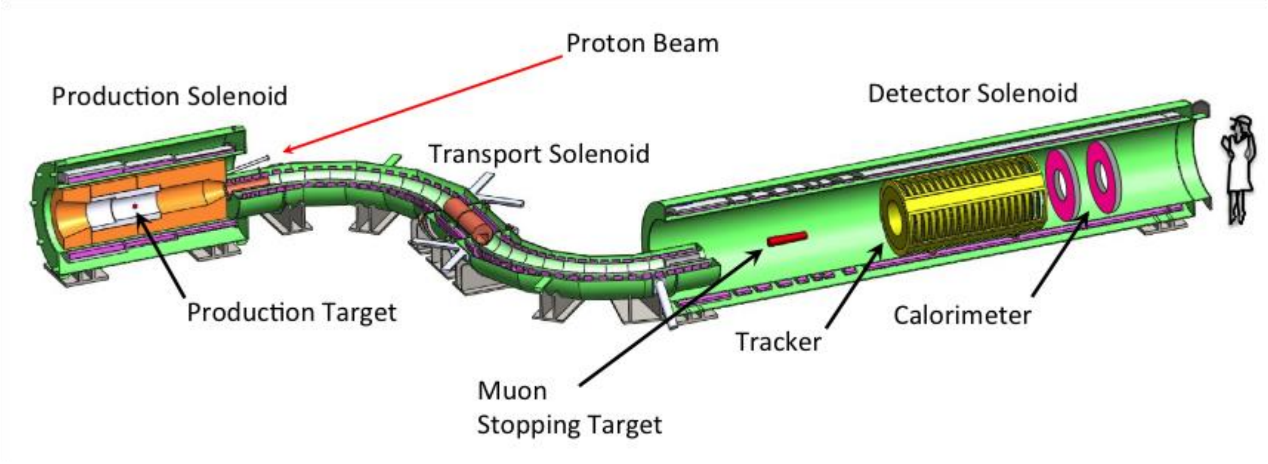
1.1. What is Mu2e?

Mu2e (Muon-to-Electron Conversion Experiment) is a particle physics experiment at Fermilab. The goal of the experiment is to identify physics beyond the Standard Model.

It will study the conversion of muons to electrons without the emission of neutrinos. Observing this process will help to narrow the range of plausible theories, the experiment will be 10,000 times more sensitive than previous muon to electron conversion experiments and probe energy scales up to 10,000 TeV.

1.2. How is the structure of the experiment?

The Mu2e apparatus will be 92 feet (28 m) in length and will consist of three sections. The total cost of the experiment is $271 million.



Muon production

A section of Tevatron collider will be used to generate an 8 GeV proton beam. These protons will collide with a tungsten production target in the production solenoid generating a cascade of particles including pions, which decay into muons.

Mu2e will produce between 200 and 500 quadrillion muons per year, for every 300 protons hitting the production target, about one muon will enter the transport solenoid.

Transport

The 4.5 Tesla magnetic field of production solenoid will direct some of the particles produced into an S-shaped transport solenoid (2 Tesla). It consists of 50 separate superconducting electromagnets, which will select muons by charge and momentum, and carry the desired muons to the detector.

Detection

Entering the detector solenoid, the muons will stop in an aluminum target as thick as ten layers of aluminum foil. Any muons which convert into electrons without emitting neutrinos will enter the detector with an energy of around 105 MeV.

The detector itself consists of two components: a straw tracker to measure the momentum of particles and an electromagnetic calorimeter to identify particle interactions, to identify what type of particle passed through the tracker and to confirm the measurements of the tracker. For example, an electron with energy of around 105 MeV will indicate that the electron originated in a neutrinoless muon conversion.

To disturb the path of the electrons as little as possible, the tracker uses as little material as possible. The wire chamber tracker consists of panels of 15-micron-thick straws, the thinnest straws ever used in a particle physics experiment. Electronics at each end of the straws will record the signal produced when electrons interact with the gas in the straw, allowing the trajectory of the electrons to be reconstructed.

1.3. How is the tracker's structure?

The Mu2e tracker will be made of more than 20,000 straw tubes, each of which is 5mm in diameter. The straw is made of 15 micron mylar, and inside and outside have an aluminum coating. Inside there is a layer of gold for good conductivity and at the center of each straw there is a gold-plated tungsten wire, 25 microns in diameter.

The tracker will operate in a vacuum, with 1 atmosphere of $ArCO_2$ gas inside the straws and charged particles will pass through them, leaving a trail of ions.

The inner surface of a single straw is at ground, and the sense wire at the center is a ~1500V positive voltage. The electrons will drift toward the sense wire, where the electric field is strong enough for the electrons to gain enough kinetic energy to ionize more atoms of the gas. This creates an avalanche, which is then detected by the electronics.

The tracker is composed by many panels, each panel consists of 2×48 straws distributed on two staggered layers and we need 6 panels to form a plane. A station is obtained through two planes and the tracker contains 18 stations.

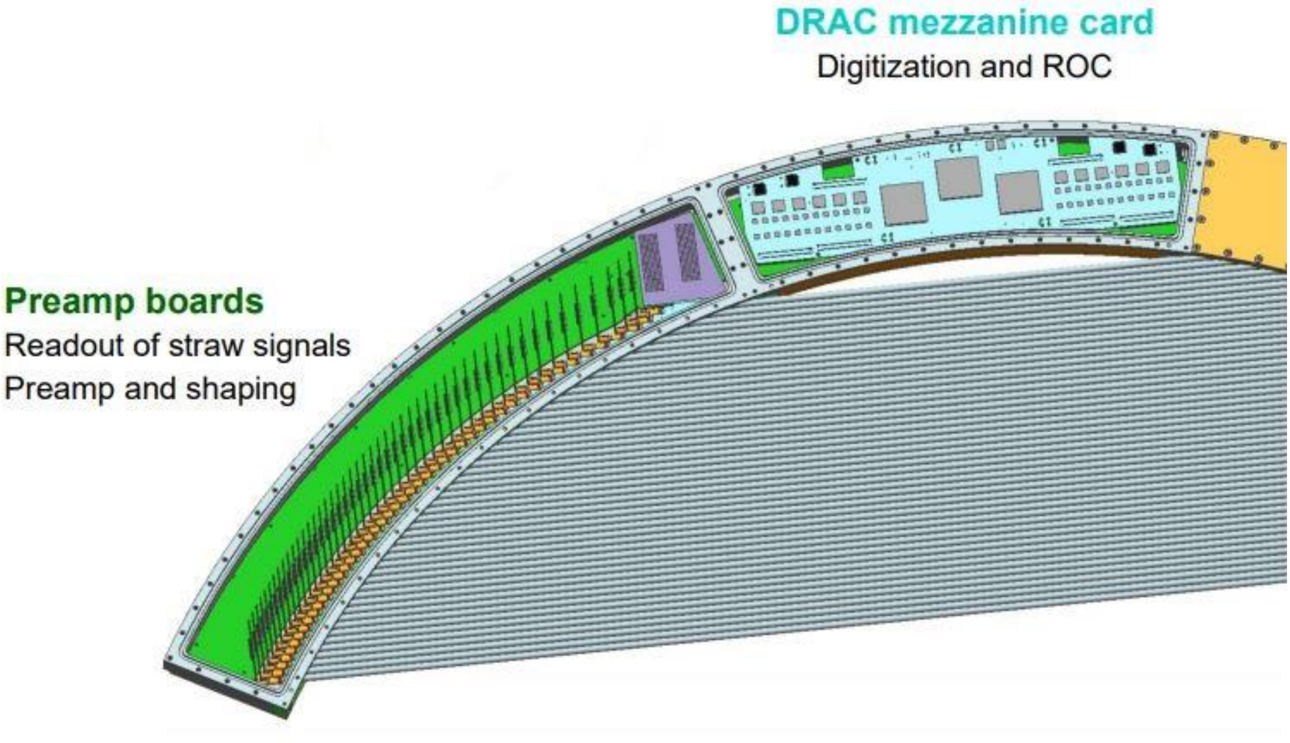
2x48x6x2x18 = 20 736 straws

The panels are connected as shown in the figure and their rotation, added to the planes' one, is used for stereo reconstruction. The tracker length is about 3.2 meters.

1.4. How is the electronics of a panel?

The electronics is composed by an analog and a digital part, it is directly connected to the straws and the combination of both parts lets us to filter and amplify the signal. From that we acquire voltage and timing samples.

The datas we acquire are organized in records, through which we can analyze the signal coming form tracker's straws and evaluate the health status of the system, too.



Analog circuit

This part of the circuit is very important, its aim is to detect and amplify signals coming from straws and make them readable from digital part.

As we can see from the figure above, we have the main board, in green, that contains 48 daughter boards, each one of these has two preamplifying circuits, each preamplifier is connected directly to a straw.

The same structure is replicated on the other side of the straw itself (under the yellow panel).

We can distinguish the two sides because one of them is connected to a calibration circuit, this gives the name CAL to that part, and the other side is called HV.

Signal coming from preamps is amplified by a differential amplifier, we have 96 of them, one for each straw, and we are interested in the voltage value we have at the differential output.

Digital circuit

The analog signal is digitalized through ADCs and TDCs, used to acquire information about timing and signal amplitude.

The “brain” that controls a panel is called ReadOut Controller (ROC) and it’s an FPGA. Then we have two more FPGAs, one for the CAL side and one for the HV side; through them we acquire records by the way to analyze and process signals we receive.

The whole sampling system is triggered by comparators, they switch their status when they detect a signal coming from an amplifier.

After the trigger signal the ADCs connected to the amplifiers though which the signal is flowing are turned on and the panel starts acquiring datas.

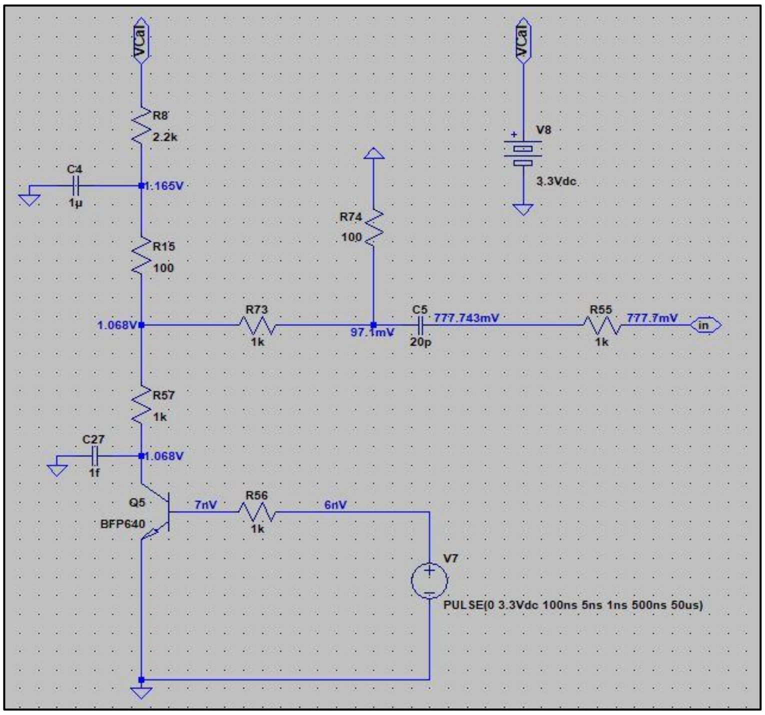
The system we used to test the prototype of the panel we have in LAB3, at Fermilab, is composed by the panel itself and a microcontroller (Raspberry Pi) that allows us to control the device.

2. Work

The first period I was in Fermilab I worked on the schematic of the analog amplifying circuit, I spent my time fixing some unwanted features and analyze some aspects of timing and his behavior.

Then I moved to the LAB3, there I started acquiring digital records from the panel itself and few weeks later I connected a scope to the output of the preamps for a further analysis. The aim was to collect more information about the digitalization system, and to compare the simulations with the real calibration signal (acquired from the scope).

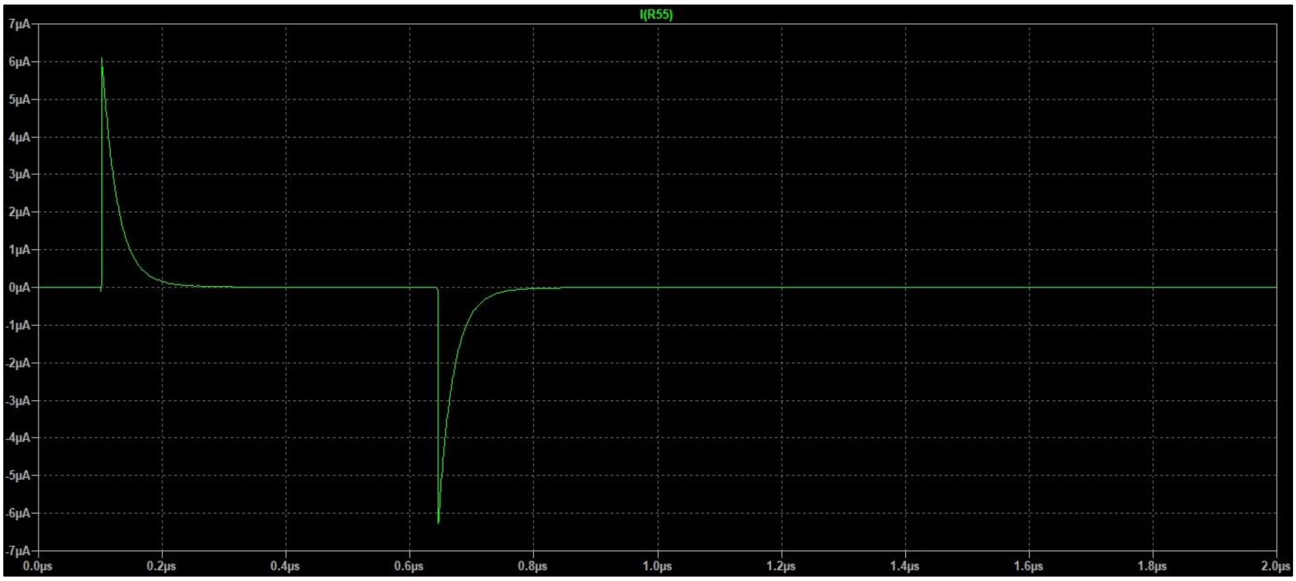
2.1. Negative peak rejection



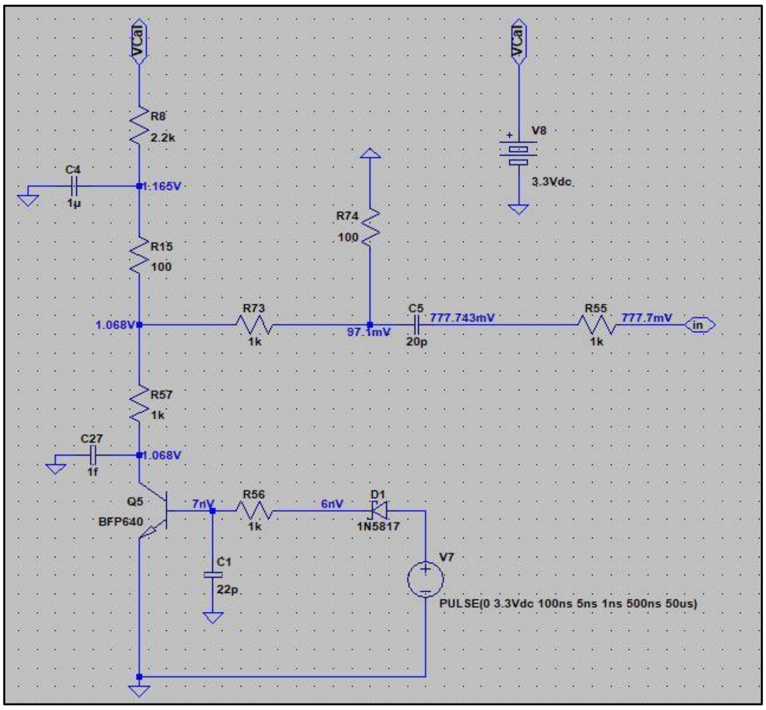
In the figure on the left is showed the *Calibration Circuit*, now we are using it to test the system and then, while the experiment is working, to calibrate it. Here we are interested in the current that flows through R55 resistor, because that is the **calibration current**. So it is very important and on that depends the behavior of the whole tracker.

The pulse generator V7 (representing the calibration pulses from the ROC) turns on the Q5 bipolar transistor and each pulse corresponds to a pulse in the calibration current I(R55).

Observing results it seems to be a dependence between the current and the **variation of the derivate of the voltage** applied at the base of Q5 bipolar transistor. This explain why, if we plot the I(R55), we obtain the two peaks: the positive (due to the rising

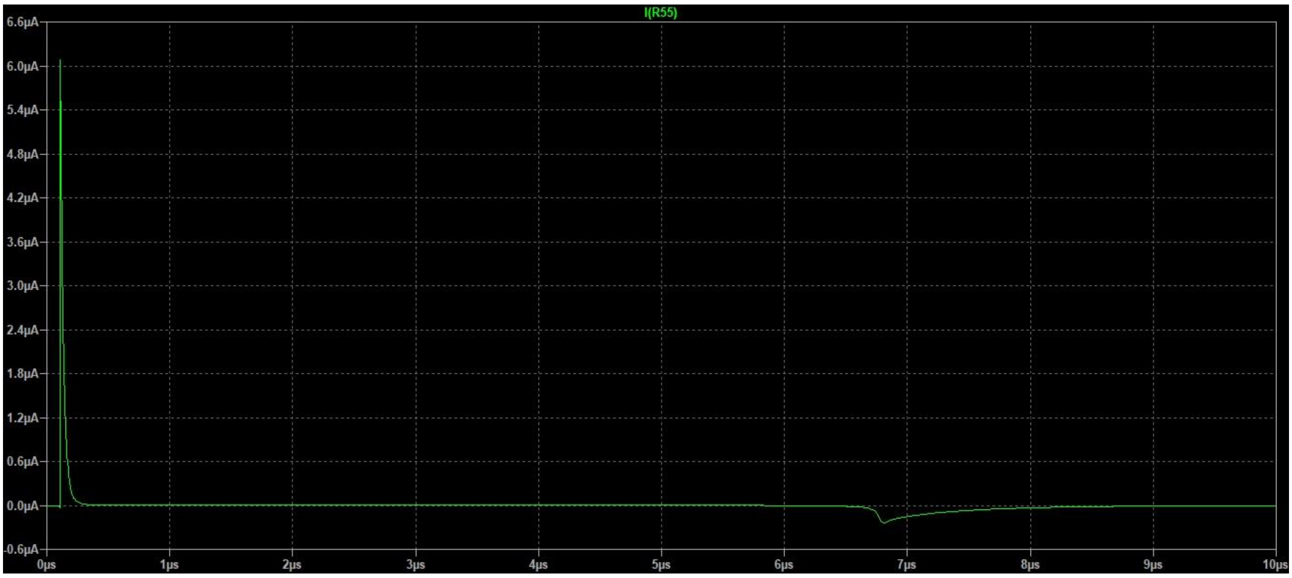


edge of the pulse) is the wanted one, the negative (due to the falling edge) instead must be rejected.



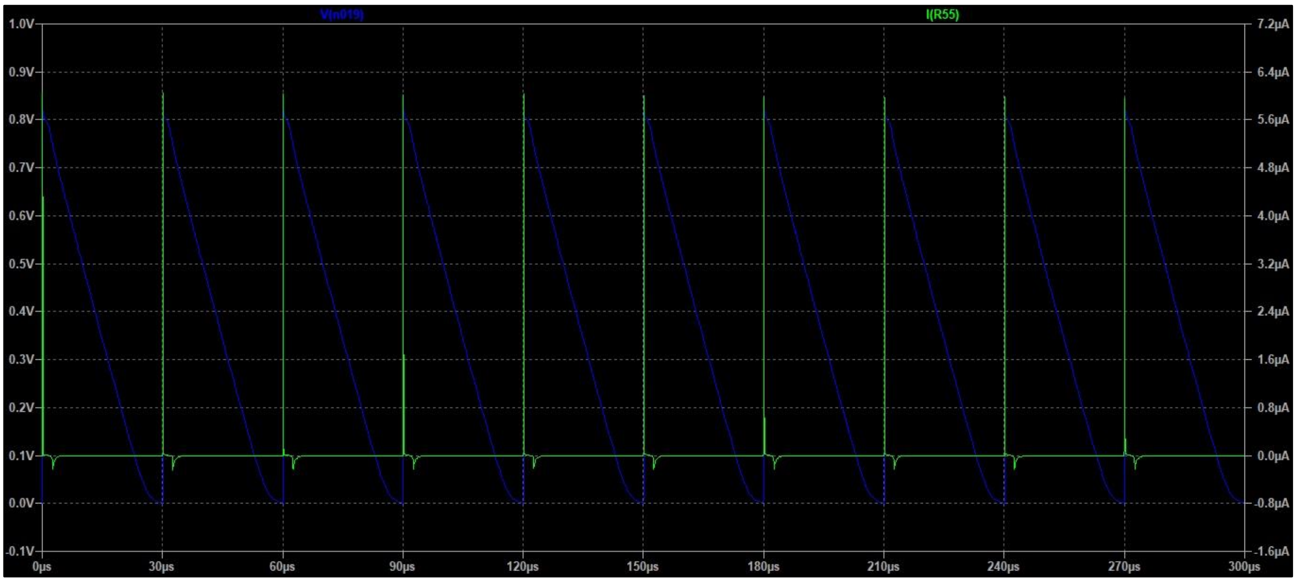
As we can observe from the figure if we add a **Schottky diode and a capacitor**, connected to the base of Q5 transistor, there is a nearly complete rejection of the negative peak.
An interesting thing is that the diode allows us to correct only the negative current pulse, keeping the signal pulse unchanged, and that's also the reason why we chose a Schottky. In fact, it has a low direct bias voltage and that's fundamental if we want to reach the same voltage and current levels we had before.

We also need a diode there because we are **interested in a constant discharging of the transistor's base**, that corresponds to a smoother variation of voltage in that point and also to a significative reduction of the negative peak.
The reverse bias current is very important, because through that we discharge Q5's base and the capacitor we put in the circuit (there will be a deeper analysis on the capacitor in the next pages) and it lets us to obtain the result we were interested in.
Easily we can say that we reduce the speed of derivate's variation at the base introducing a constant current, this allows us to discharge linearly the base, which means no variation of the derivate of the signal, and at the same time no negative peaks.



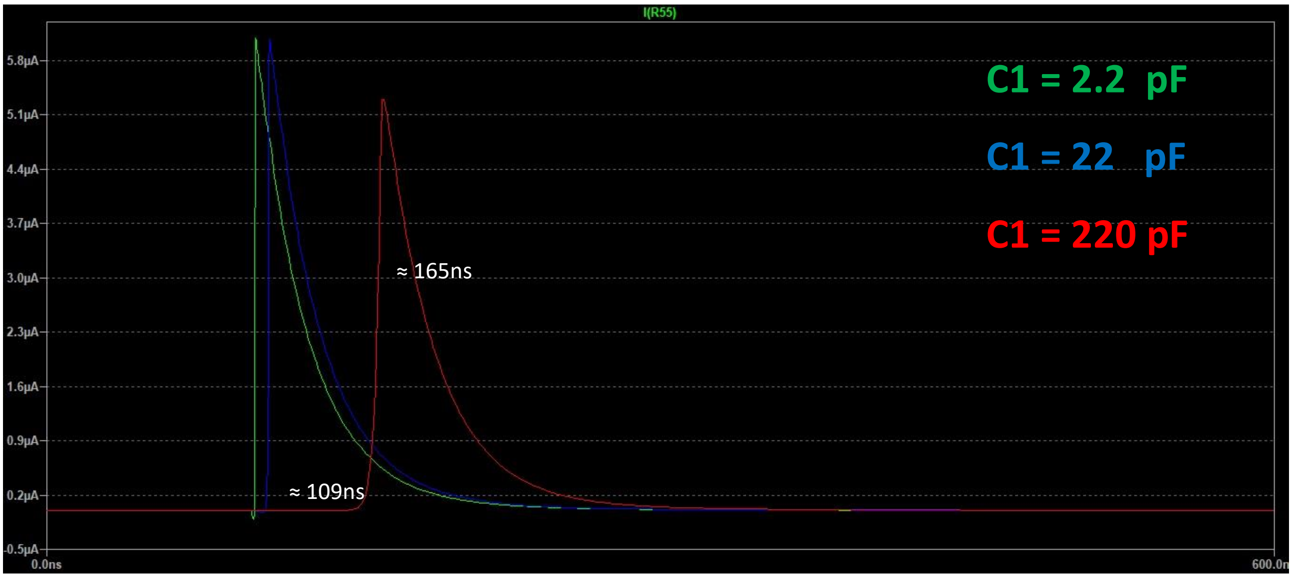
In the figure we can see the results we obtained. We have a significative reduction of the negative peak, but we maintain the same shape and levels for the signal peak.

As we have already said, the main features of the diode we were interested in were: his direct bias voltage and his reverse bias current. To guarantee a faster discharge, that allows to have a frequency that's enough to calibrate correctly the system, the RB current has to be bigger than the one we expect for a normal diode.

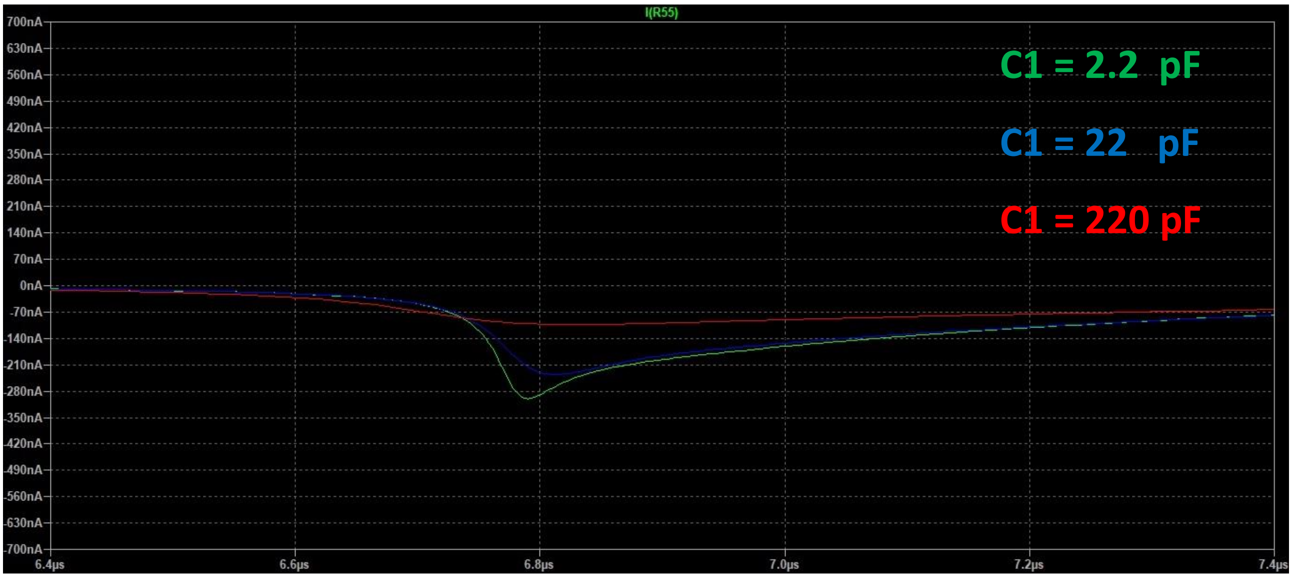


In the graph above we plotted many pulses. To have a correct behavior for the circuit we have to wait for the complete discharge of the capacitor, using these devices the minimum period is nearly 30us, that corresponds to a 30kHz frequency (enough for us).

Another aspect we had to consider were delays. To reduce the negative peak amplitude, more than only diode's one, we need C1 capacitor, bigger it is and more we rejection we have.



In the graph above we receive the pulse at 100ns. The green plot is nearly simultaneous to the pulse, the other ones instead are delayed, delay's value and signal's amplitude depends from capacitor size.



At the same time also the amplitude of the rejected negative peak is connected to C1. We can see from the plot above that bigger it is, stronger is the rejection we have. So this point could be a trade off between the frequency we want to obtain and the rejection we want to obtain.

The diode N5817 we put in the circuit has both the characteristic we wanted: it has a reverse bias current at 25°C of I_B=1 mA and a forward bias voltage of V_F = 0.5 V.
Unfortunately it is hard to find in a SMD version. However, for the aims of the analysis, it was the fastest way to obtain some results, without spending too much time looking for other devices (it's easy to find on internet other diodes surface mounting which have nearly the same proprieties).

2.2. Aging and disturbs

Another aspect of the system we have to consider are **aging effects** (connected to parasitic ones) that could affect the circuit.

Especially we were interested in the delay that could be introduced and the stability it has during hours, days and years.

In fact, if the delay, between the pulse we use to calibrate and the output signal, is constant, can easily fix it through a software. So, to be sure that the timing records we acquired are correct, we have to prove that that delay doesn’t change for the whole lifetime of the experiment.

Instead, if the delay we obtain is variable, we cannot predict his value, then we cannot fix it through a software. This means that there is no way to know if the timing records we’re acquiring are correct or not.

The delay variation may be caused by devices’ aging, voltage supply oscillation, temperature variation or other many disturbs that could affect the circuit.

To test the circuit’s features and to analyze his behavior we simulated the circuit changing some aspects of the schematic:

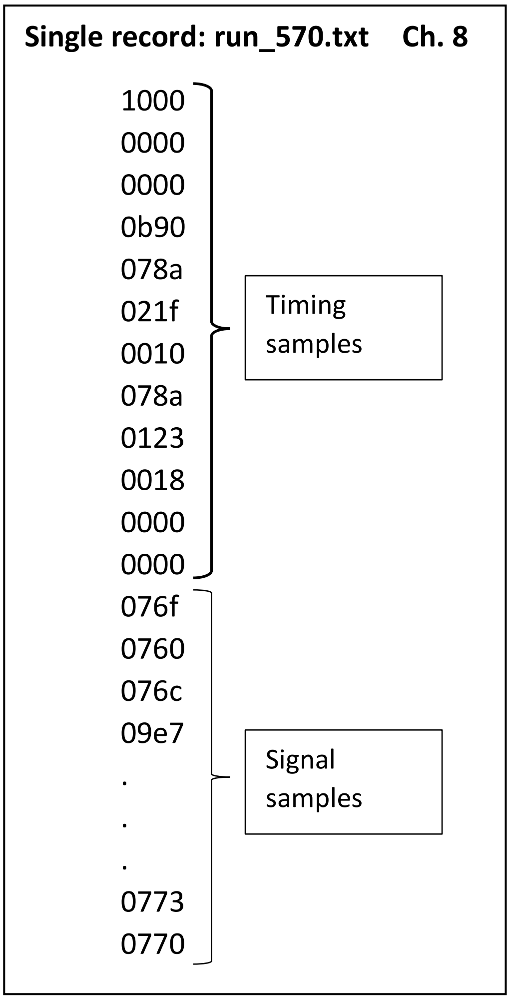
- **Voltage supply**: we changed the supplies connected to the circuit to evaluate if an unexpected variation might cause a variation in pulses timing. We expect to have a disturb no more than 5% (we tried also with 10%), but we had no interesting results. It seemed only to affect the values of voltages and currents in the circuit, but to have no effect on timing features.
- **Temperature**: the next step was trying with a temperature sweep simulation. We swap the temperature on a range of 10°C, at low temperature and at 25°C.
  However, we didn’t register any significative results regarding the delay and timing.
- **Passive components**: capacitor and resistor have respectively a tolerance around 5% and 1%. We modified the value of each component trying to find a point that was particularly responsible of a timing variation, but also in this case we found nothing.
- **Active components**: we added parasitic (low value capacitances) where we expected them to be, such as between base and emitter, base and collector of every bipolar transistor. The result was that we had no significative variation in timing, except for a single point of the circuit. In fact, when we had a capacitor between the base and the emitter of Q5, if its value is big enough, we obtain a delay of the current though R55. Of course the delay is proportional to the capacitor’s value.

So, in conclusion we can say that there’s only a point in the circuit that can introduce a delay easily evaluable through simulations, and it it’s the same capacitor we analyzed in 2.1 paragraph.

2.3. Analysis digital records

We acquired directly from the panel a great quantity of digital records. We needed them to obtain an analysis of real output of the entire system, after amplification and digitalization. To do that we connected to a Raspberry Pi linked to the panel itself and to a laptop.

The digital circuit is composed by a sampling system for signal (ADCs and FPGAs) and time (TDCs and FPGAs), that part is activated by a certain number of comparators. These devices have the role of monitoring the signal coming from both sides of straws and send a trigger to converters if they detect something, when that happens the system starts acquiring datas and storing them into memory.



Single record: run_570.txt Ch. 8

```
1000
0000
0000
0b90
078a
021f
0010
078a
0123
0018
0000
0000
076f
0760
076c
09e7
.
.
.
0773
0770
```

The codes we have in the Raspberry board let us to decide from which side of panel acquire records (CAL or HV side), how many records do a single run have (es. 40, 50, 80…), the number of samples for each record (es. 8, 16, 32…) and the quantity of samples to show before we had the trigger (es. 0, 1…). There are many other features, but these are the ones we were interested.

The datas we acquired were packed in a particular way. A file is an array of 4 hexadecimal digits, it is divided in many records (we could decide the number of records) and each record is composed partly from timing samples and partly from signal samples.

Through a python code we extracted timing and signal's shape information, trying to give an evaluation on how the system works.

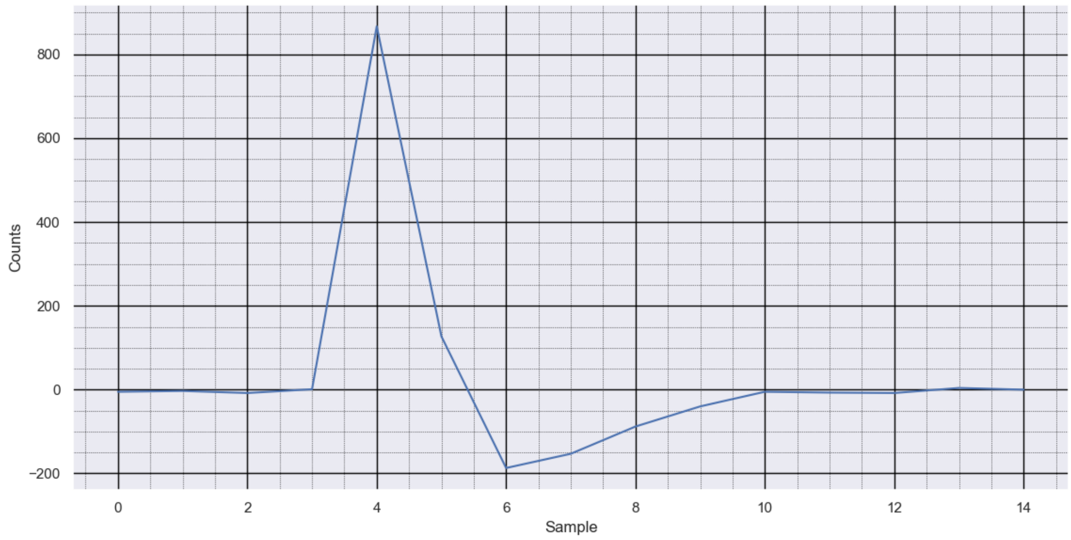
The analysis we did was on Channel 8, CAL side and we acquired 10 files, each one of 50 records and a record was composed by 16 samples.

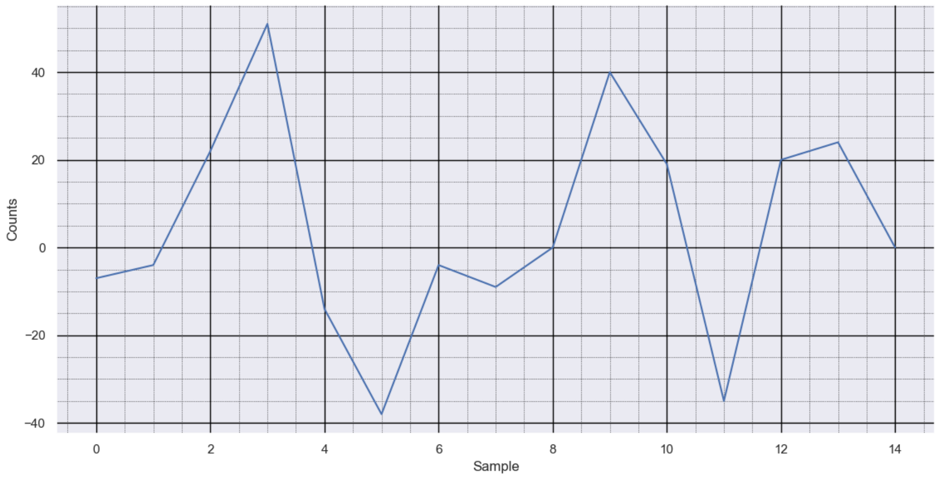
As result we had 3 different types of records:

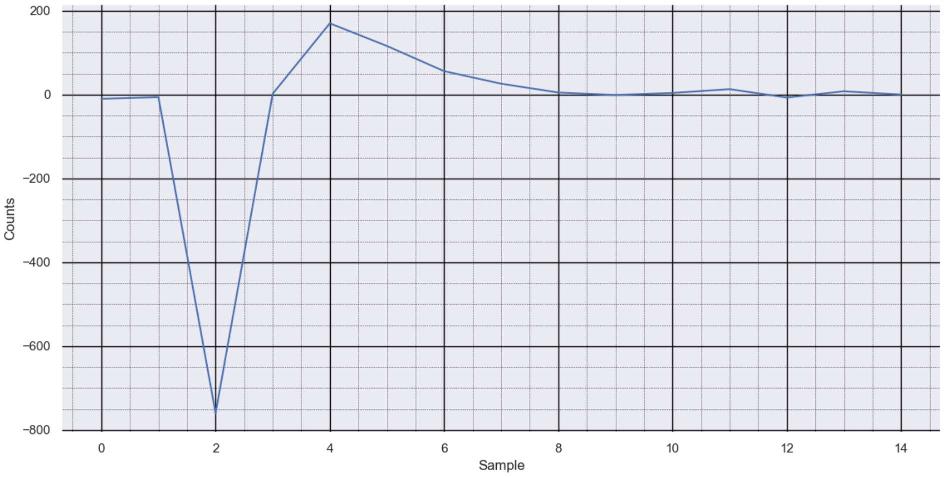
- *Noise*
- *Negative peaks*
- *Signal peaks*

This means that these events can cause a trigger of sampling circuits and the system starts acquiring datas, giving us the results as records.

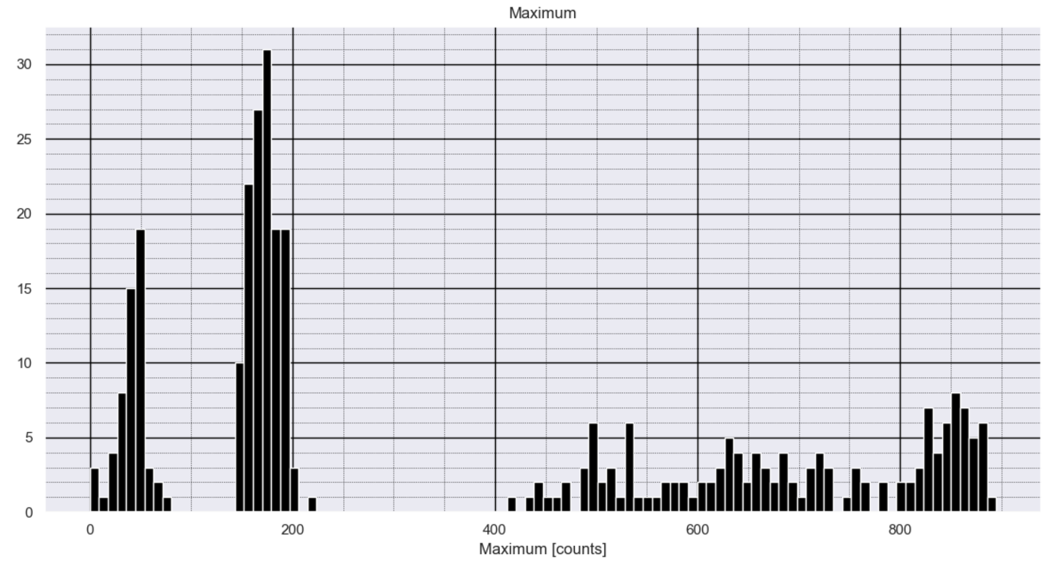
Here are displayed 3 examples for each type of record, and it's clear that we can easily distinguish them, not even from the shape they have, but also from the amount of counts.







This feature allows us to add a code “filtering”, in order to analyze only timing features regarding the signal peak. The python code I wrote allows the user to choose the trigger level and select only the useful records.

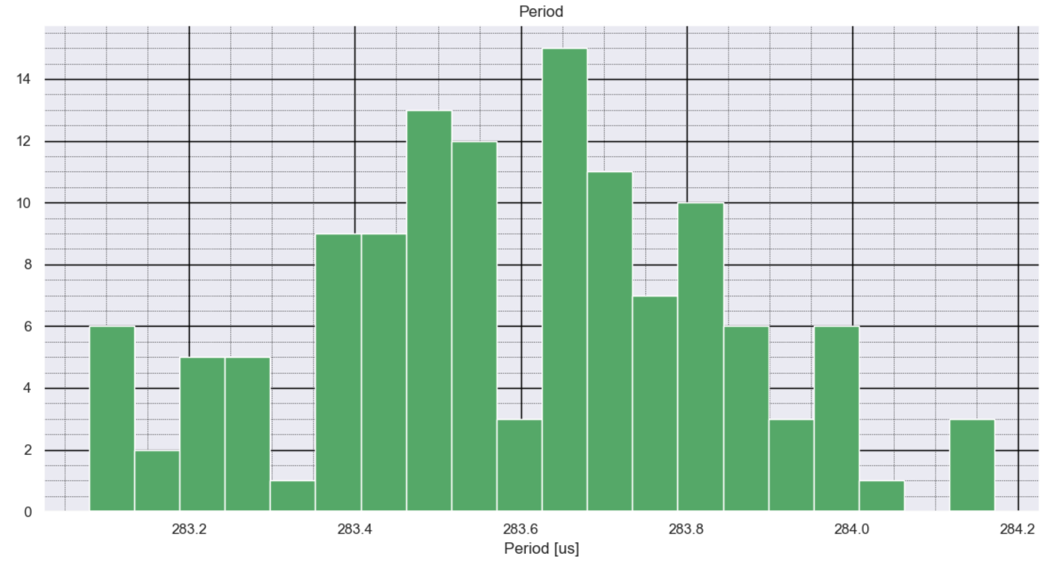


As we can see from the picture the maximums of records are divided in three main groups. The lower one is noise, then we have the middle one, which contains negative peaks, finally the last distribution (with high values for counts) is the one of peaks.

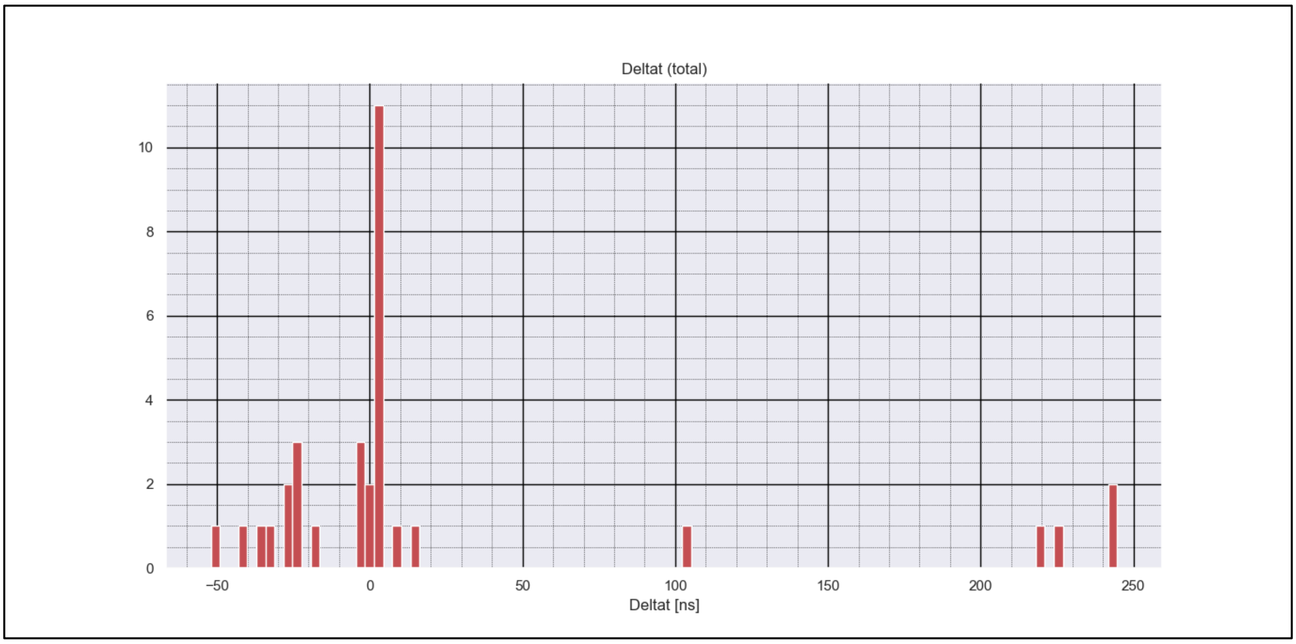
The way the maximums are divided lets us to select only signal peaks, so we can easily analyze only the records we are interested in.

Once we found the way to unpack records and filter them we had to calculate the period we receive signal pulses and the delay we have between the two sides of the tracker (CAL and HV times).

The graph below shows the **periods**’ distribution we had in the record we acquired.



As we can see from the picture the average value for period is nearly 283.6 us, that corresponds to a frequency of 3.5 kHz, as we expected.



Here instead we have the distribution of **Deltat**.

We call Deltat the difference between the moment the signal reaches the HV side and the moment the signal reaches the CAL side of the system.

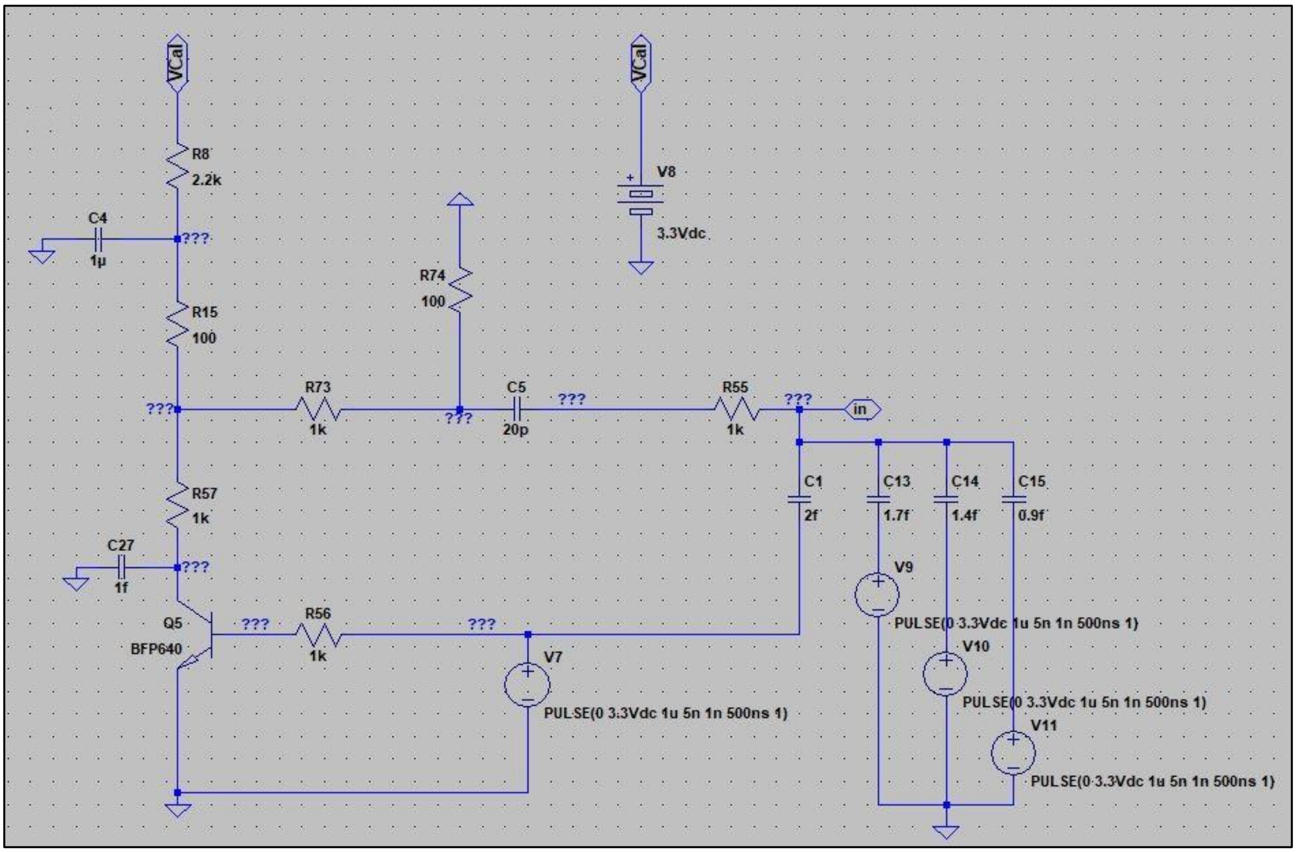
Unfortunately the datas we acquired weren't correct. In fact, we expected to have a distribution of values not larger than 4 ns, around an average value we don't really know (it was the thing we wanted to find).

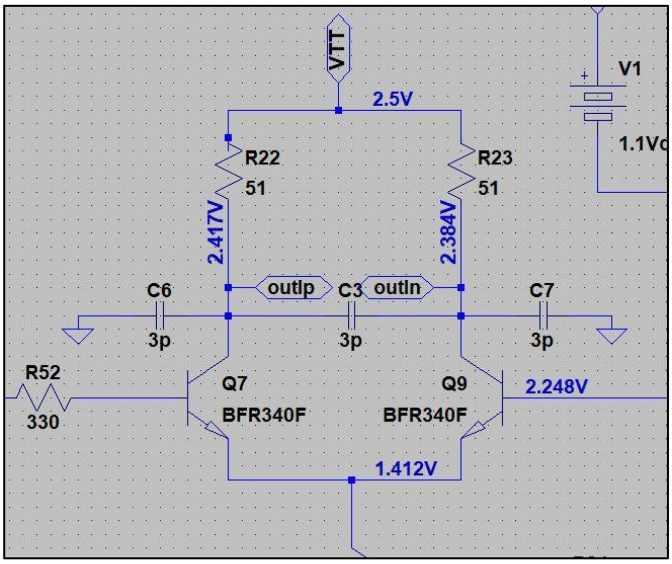
This could be caused by an error in system's firmware or in the code we used to acquire samples. So it has been impossible for us to know the real distribution of Deltat and to make an accurate analysis.

2.4. Scope records VS Simulation records

This study is very interesting because through that we understand which the main **differences between the simulation and real system** are.

To do that we had to connect a scope to the output of a preamp (CAL side in our case) and to acquire signal records (signal and negative peaks). Once we finished with acquisition we elaborated datas offline, trying to match them with the simulations as more as possible.

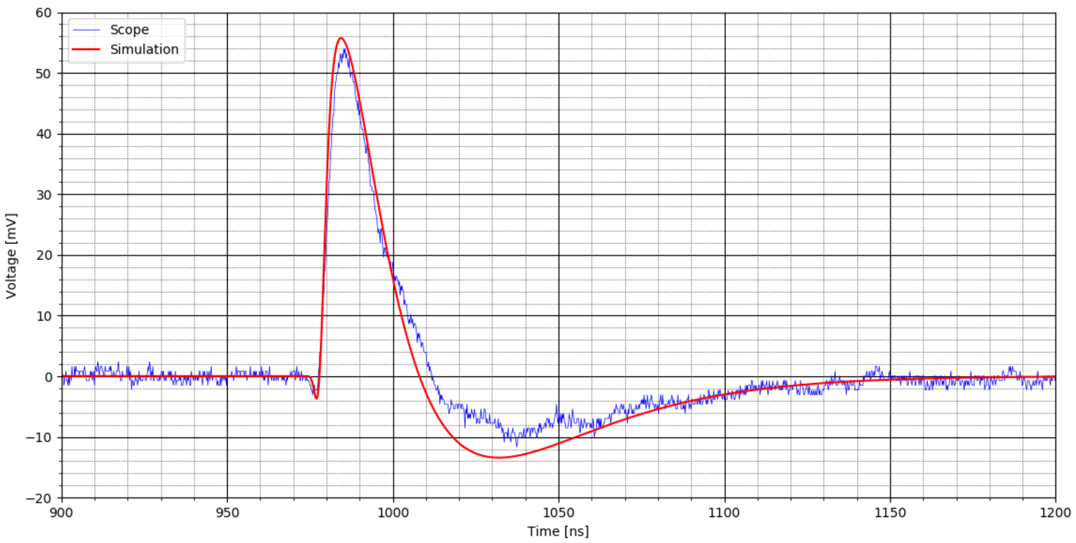


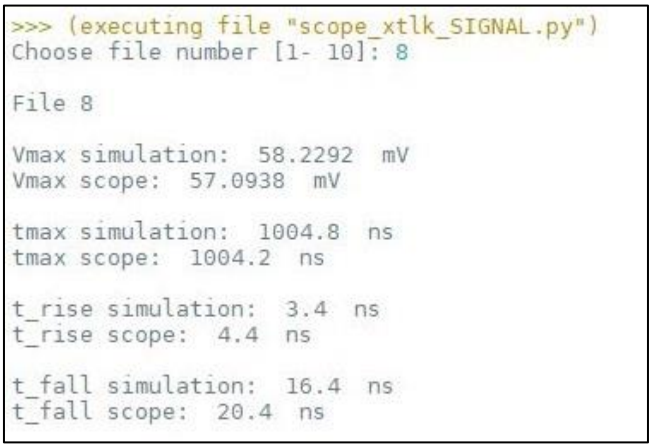


V9, V10, V11 have been added to simulate the **crosstalk between different lines** of the circuit. In fact, the system lets us to analyze at the same time 4 different preamps (HV and CAL side).

Before start acquiring datas its important to check the operating continuous voltage at the output of the CAL preamp (it depends from temperature) and try to obtain the same values in LTspice, changing voltage supplies. This passage is very important because it gives us a better match and lets us to get a more accurate analysis

The system allows us to decide which line turn on and which turn off. The effects of our choices are very clear in results we had.





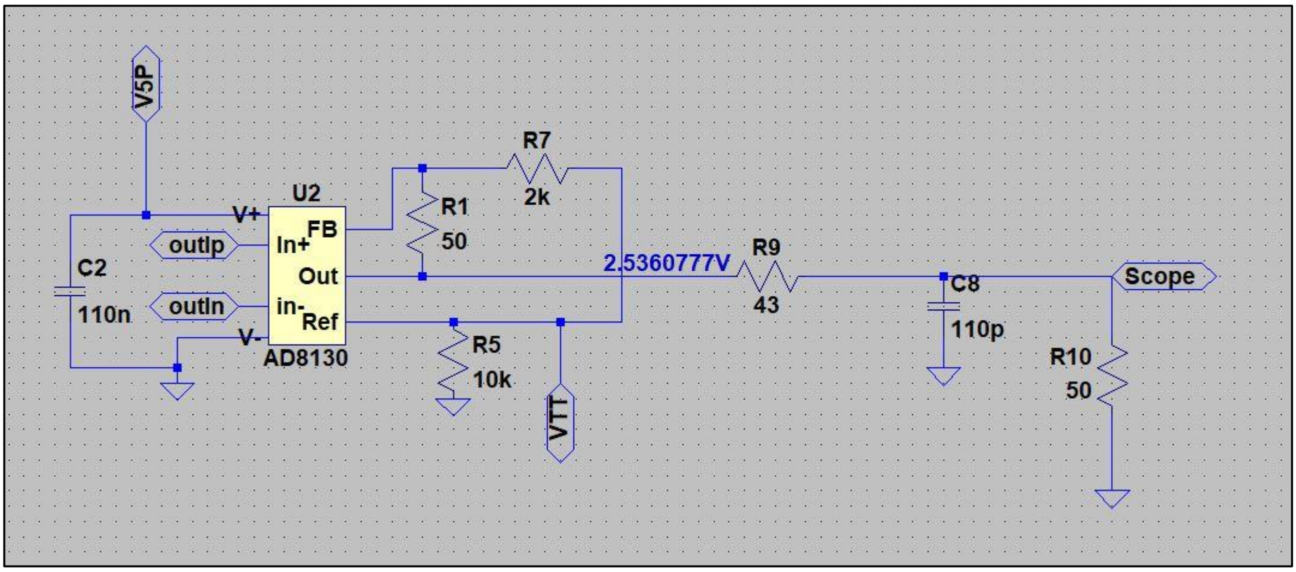
```
>>> (executing file "scope_xtlk_SIGNAL.py")
Choose file number [1- 10]: 8

File 8

Vmax simulation:  58.2292  mV
Vmax scope:  57.0938  mV

tmax simulation:  1004.8  ns
tmax scope:  1004.2  ns

t_rise simulation:  3.4  ns
t_rise scope:  4.4  ns

t_fall simulation:  16.4  ns
t_fall scope:  20.4  ns
```

The graph above shows the comparison between scope and simulation of a signal peak when other lines are turned off, so without crosstalk.

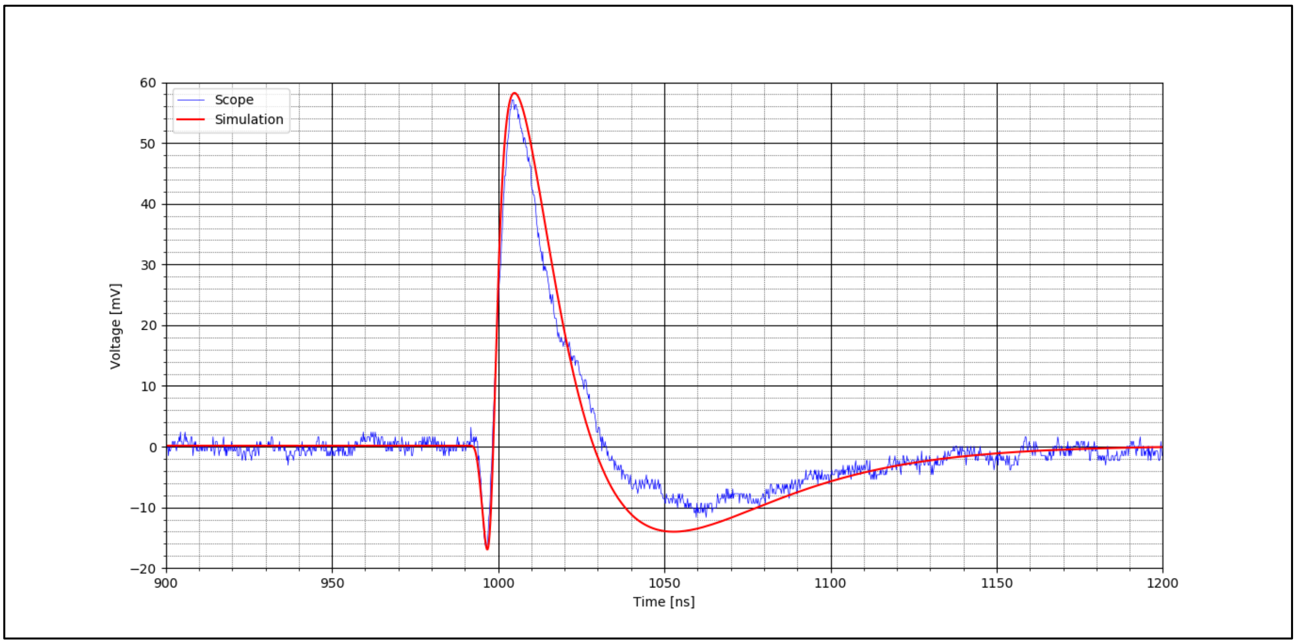
The tiny little negative peak probably is caused by self-coupling and interferences between the pulse line and the input of CAL preamp.

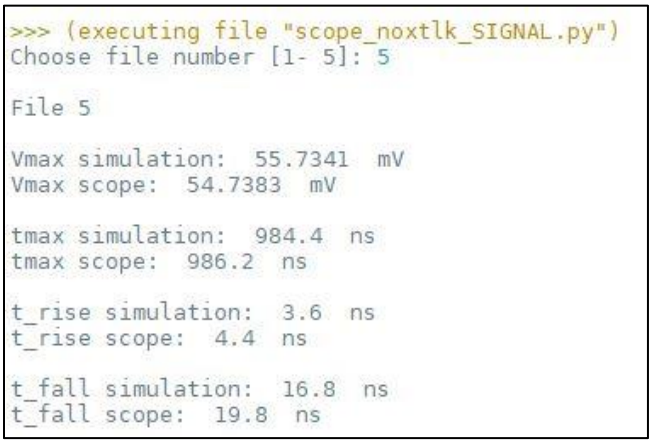
As we can see on the left we used the *tmax* to synchronize the two records and we can observe that the maximums reached are nearly the same.

However, from the graph is also clear that we have a mismatch of shape after the pulse and, if we focus on the rising edge, we can notice that simulation's one is quicker than scope's one (see datas above). This happens even if we added a low pass filter after the scope to recreate the frequency loss of the circuit. We have the same for the falling edge.



If we turn on all the other lines signal's shape clearly changes. In the following plot is shown what we obtain.





```
>>> (executing file "scope_noxtlk_SIGNAL.py")
Choose file number [1- 5]: 5

File 5

Vmax simulation:  55.7341  mV
Vmax scope:  54.7383  mV

tmax simulation:  984.4  ns
tmax scope:  986.2  ns

t_rise simulation:  3.6  ns
t_rise scope:  4.4  ns

t_fall simulation:  16.8  ns
t_fall scope:  19.8  ns
```

Here we can observe the same timing difference than before. We reach the same maximum value at the same moment, but we still have different rising and falling time between scope and simulation.

In the figure is evident the presence of crosstalk, the little negative peak we had before now is huge and reaches lower voltages. This effect, as we have already said, is connected to the coupling between the lines that cause an interference in the signal we observe.

If we want to go further in this analysis, we can turn on the lines with different combinations, and through that we have been able to estimate approximately the value of the coupling.

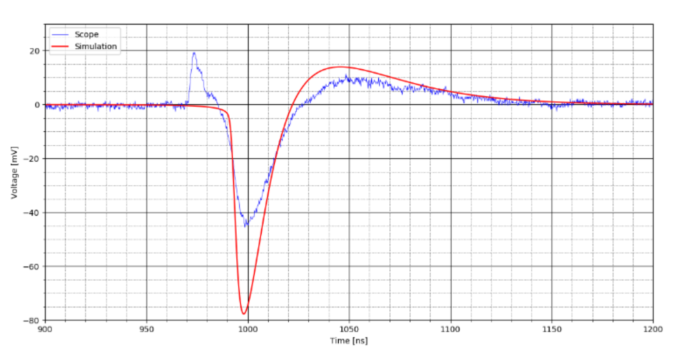
After doing that we focused on the negative peaks. We did the same considerations on the new records we acquired, we compared the simulation and the scope's datas, but also this time the results weren't what we expected to have.

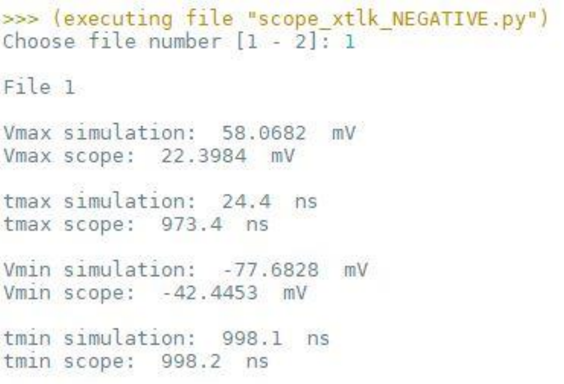
In fact the shape of the pulse is very different from reality to simulation, even if we add or the crosstalk, we still had the same shape (it has a great mismatch regarding the minimum it reaches and the timing features).

The only difference we can notice from scope records is that the tiny little positive peak, before the negative one, is increased when we turn on the other lines (first picture on the left).

Unfortunately, we didn't find the way to obtain the same result in the simulation, so it is largely clear that this part needs a deeper analysis.

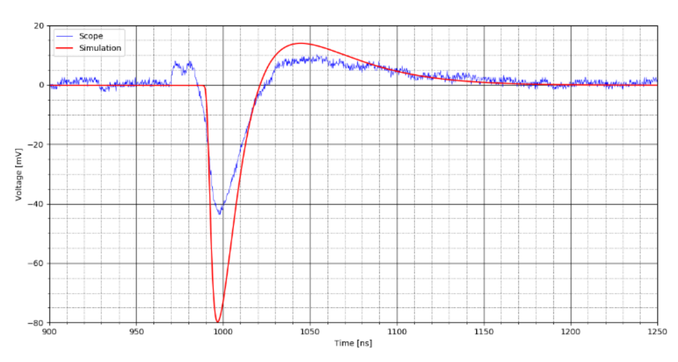
Negative Peak with crosstalk

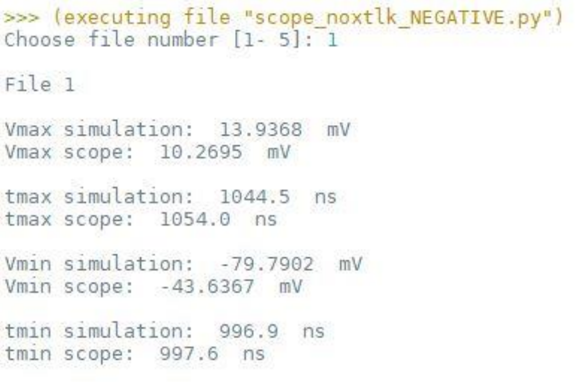




```
>>> (executing file "scope_xtlk_NEGATIVE.py")
Choose file number [1 - 2]: 1

File 1

Vmax simulation:  58.0682  mV
Vmax scope:  22.3984  mV

tmax simulation:  24.4  ns
tmax scope:  973.4  ns

Vmin simulation:  -77.6828  mV
Vmin scope:  -42.4453  mV

tmin simulation:  998.1  ns
tmin scope:  998.2  ns
```

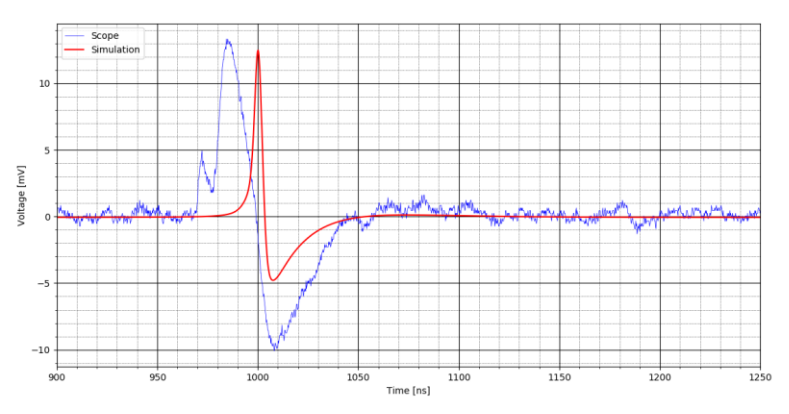
Negative Peak without crosstalk





```
>>> (executing file "scope_noxtlk_NEGATIVE.py")
Choose file number [1- 5]: 1

File 1

Vmax simulation:  13.9368  mV
Vmax scope:  10.2695  mV

tmax simulation:  1044.5  ns
tmax scope:  1054.0  ns

Vmin simulation:  -79.7902  mV
Vmin scope:  -43.6367  mV

tmin simulation:  996.9  ns
tmin scope:  997.6  ns
```

The thing that is interesting to see is that even if we turn off the other lines we still measure a little positive peak. That means that this effect isn't connected only to capacitance coupling, but also to other effects (probably parasitic).



To better understand what was going on we decided to turn off the supply of the calibration circuit (Vcal). From that voltage depends the amplitude of the current through the R55 resistor.

On the left we can see that two graphs are really different, but the thing that's important to notice is that we still have a signal even if the calibration circuit is turned off. This effect may be caused by some parasitic in the circuit or some polarization currents of the transistor.

The aim of this studies is to completely understand what causes this pulse and try to fix it changing the circuit. This part is really important, the little positive peak we have when we record the negative peak is the one that cause the activation of the sampling circuit we talked in 2.3 paragraph. So, if we solve this problem, automatically when will stop negative peaks triggering the ADCs and we will acquire more correct datas (the noise will be still there).

3. Conclusions

At the end of this internship we reached many interesting results connected each other that can help us to understand the way the system really works.

From the first analysis of the circuit we found a possible way to remove the negative peak just adding two components to the circuit and, at the same time, we discovered how parasitic affects the circuit, focusing on the more sensible parts.
That's important by the moment we start acquiring real datas for the experiment, because want to be sure that everything is working correctly and nothing unpredictable and unexpected is happening.

The period we spent analyzing the records, acquired directly from the panel and the scope, let us to have a clearer idea of what was necessary to fix first.
In fact we found out that the shape of the negative pulse causes the trigger of the ADCs, reason why we have not only signal and noise records when we acquire datas.
Then, going deeper in this analysis, we discovered which were the parasitic that more affected the system, and which were they real effects on the whole system.

Unfortunately there was so much to do and so much to understand but we didn't have enough time to get everything done.
However, this is a good starting point for everyone who wants to study deeply this system and it gives an idea of which are the problems we have to fix and the order they should be faced up.

4. Bibliography

I. *http://www.fnal.gov/*

II. *The Straw-tube Tracker for the Mu2e Experiment*
MyeongJae Leea, on behalf of Mu2e collaboration
Lawrence Berkeley National Laboratory, Berkeley, California 94720, USA

III. *The Mu2e Tracker and Calorimeter Systems*
S. Giovannella (INFN LNF)

IV. *Proposal to Search for $\mu^- N \rightarrow e^- N$ with a Single Event Sensitivity Below 10^{-16}*
Mu2e Experiment