



Summer Student Report



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ATLAS Forward Proton Time-of-Flight subdetector: detector testbed studies

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Abstract

The ATLAS Forward Proton Detector (AFP) is a detector for forward physics, detecting and reconstructing kinematics of forward going protons. It is positioned about 200 m from the ATLAS interaction point on either side. The detector consists of two types of subdetectors: The silicon tracker and the Time-of-Flight detector.

The main target of this summer student project is to understand the operation of the AFP Time-of-Flight subdetector as well as to study its response and behavior in the CERN based ATLAS Roman Pots laboratory.

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1 Introduction

Since the discovery of the Higgs boson, the particle content of the Standard Model (SM) has been completed. But there are still open questions and new physics to be discovered, e.g. why there is matter-antimatter asymmetry that makes our existence possible or where are instantons which can explain the U(1) problem in the SM or the existence of axions. High-energy physics at colliders like CERN can provide insight here. The ATLAS Forward Proton detector (AFP) is a small forward proton detector that has potential to contribute to explanation of open problems, or to detect a physics beyond the SM.

1.1 Infrastructure

The CERN accelerator complex is used to study proton-proton collisions, see Figure 1. Protons are accelerated in several steps before they collide in one of the interaction points (IP) of the LHC (Large Hadron Collider). First, there is the LINAC4; this linear accelerator injects protons the booster circular accelerator, which delivers the Proton Synchrotron (PS). The protons from the PS are then injected into the Super Proton Synchrotron (SPS), which in turn is injected into the LHC. The LHC can deliver to protons a collision center-of-mass energy up to (currently) 13.6 TeV.

Note that also Ions can be accelerated in place of protons, but these then have other center of mass energies and are not, at the moment, measured by the AFP.

In addition to the LHC, there are a number of other facilities that use accelerated protons at different energies, which can also be seen in Figure 1.

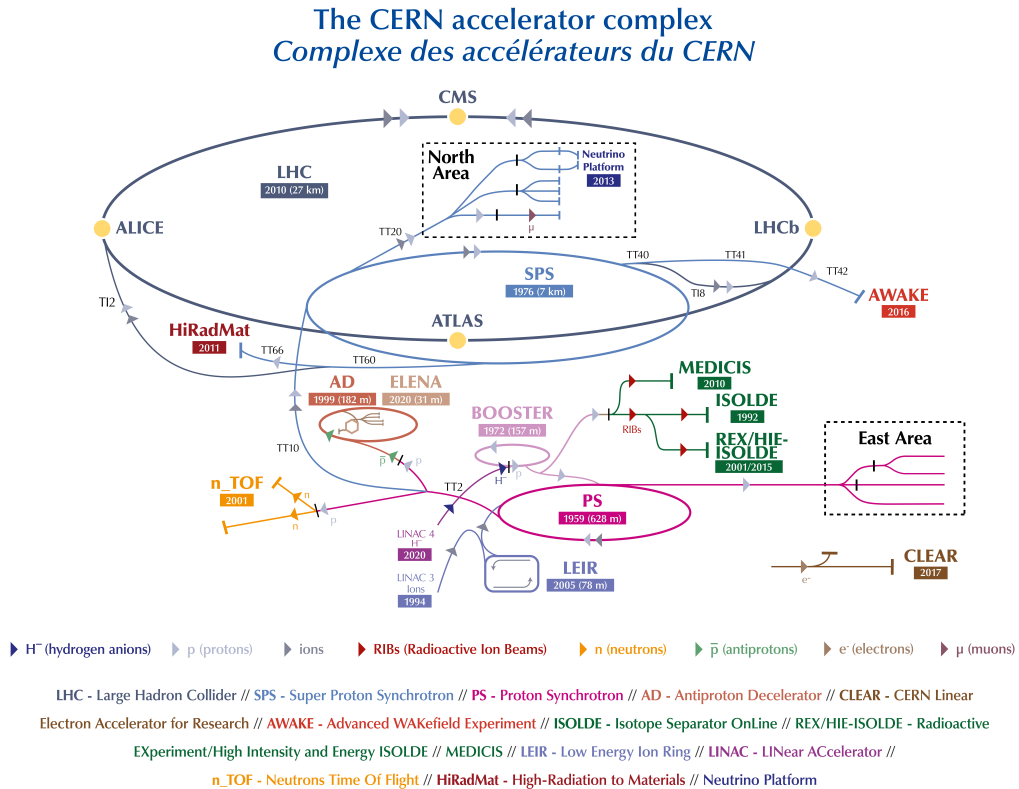


Figure 1: CERN accelerator complex [13].

ATLAS – A Toroidal LHC Apparatu**S**, is one of the two large experiments studying proton-proton collisions, the other one is the CMS (Compact Muon Solenoid). ATLAS is located at Interaction Point 1, IP1, in the center of the accelerator complex, see Figure 1. The ATLAS Forward Proton detector is part of the ATLAS detector.

1.2 ATLAS Forward Proton detector

The goal of the ATLAS Forward Proton detector, the AFP, is to measure forward protons originating from proton-proton collisions at the IP1. Observations can be made of diffractive processes, which involve the exchange of strongly interacting colour-less particles, Pomerons or Odderons, such as:

- elastic scattering (both protons remain intact)
- single diffraction - SD
- double diffraction - DD

These processes can be schematically visualized in the space of kinematic variables η (pseudorapidity) and Φ (polar angle in collisions center of mass) - see Figure 2.

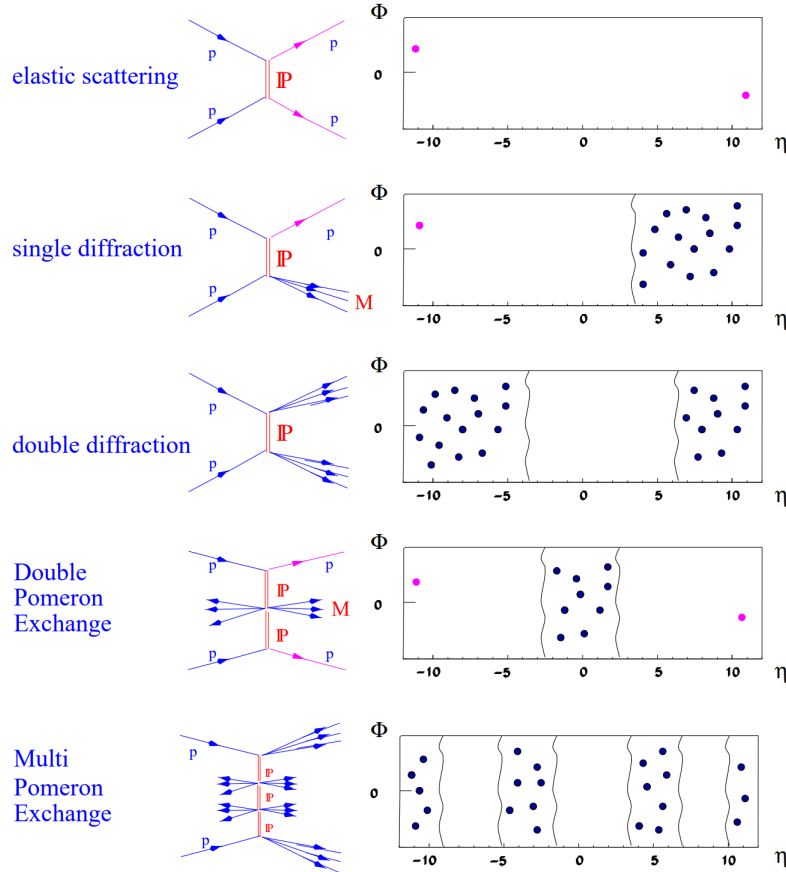


Figure 2: Diffractive process classes (left) with their typical particle distributions in the pseudorapidity–azimuth plane (middle) [12].

More details can be found in the sections devoted to the AFP physics in the AFP Technical Design Report [10].

Since the proton remains intact and propagates in the forward direction during these processes, these protons can be potentially detected if they are separated from the beam. Then the Roman Pot technology is used, allowing the detector to be moved close to the beam once it is stable, and otherwise to be moved into the garage to protect it from the radiation and possible perturbations.

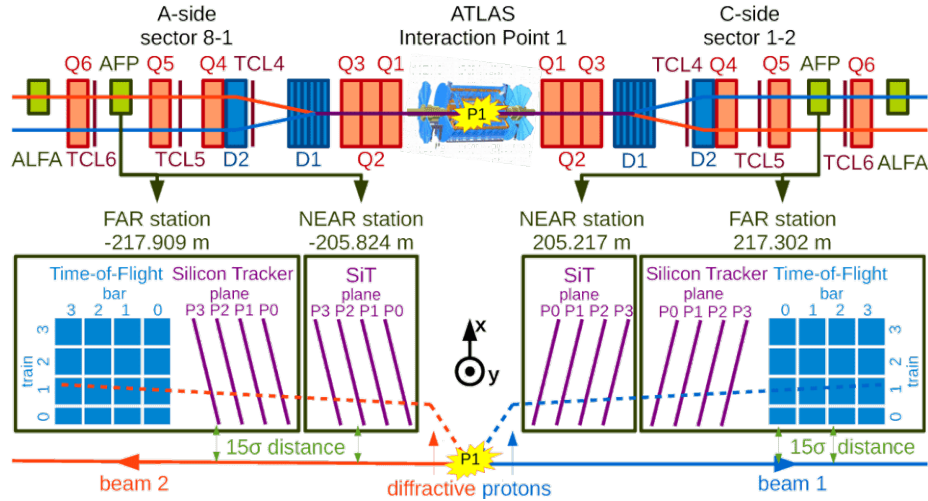


Figure 3: Schematic of the AFP detector and its components as well as which magnetic elements are between IP1 and the AFP compare [1].

The AFP is located on both sides of the interaction point at the distance of about 200 m from the IP1 and consists of two near and two far stations. The near stations consist only of SiT (Silicon Tracker). The far stations consist of both subdetectors: SiT and the Time of Flight (ToF). See Figure 3 and Figure 4.

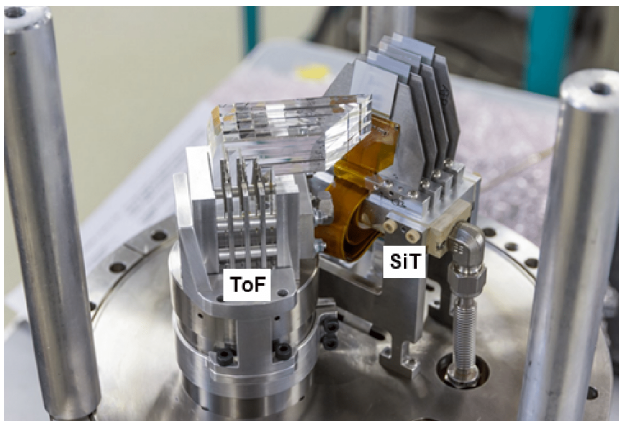


Figure 4: Picture of the AFP detector consisting of the two subdetectors: ToF and SiT [1].

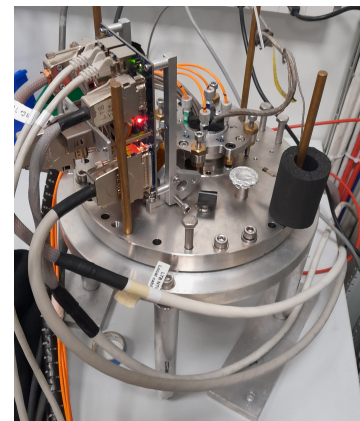


Figure 5: The AFP Roman Pot, laboratory setup. Subdetectors are concealed inside. The electronics of the Local Trigger Board (LTB) is visible on top of the Roman Pot, together with signal and power cables.

1.3 Time of Flight detector

The ToF detector provides information about the time at which the diffractive protons are measured by the detector. From the time difference between the two AFP detectors, at the A and C sides, the distance from the center of the interaction point where the interaction took place can be determined [9]. With this information, the pile-up can be reduced.

The AFP consists of 16 quartz bars arranged in a four-by-four shape, consisting of four trains each with four bars, see Figure 4. The underlying principle of proton detection is that any charged relativistic particle generates Cherenkov light as it passes through the bars. The bars guide the resulting light to a multi-channel plate photomultiplier tube (MCP-PMT) to obtain an electrical signal, which is then processed by the electronics described in the next section.

2 ToF - electronics

To obtain the time information based on the Cherenkov light signal, several intermediate steps are necessary to process the signal. In this section, we focus on the electronic processing chain. In the Figure 6, the electronics of the ToF detector are shown within the red frame.

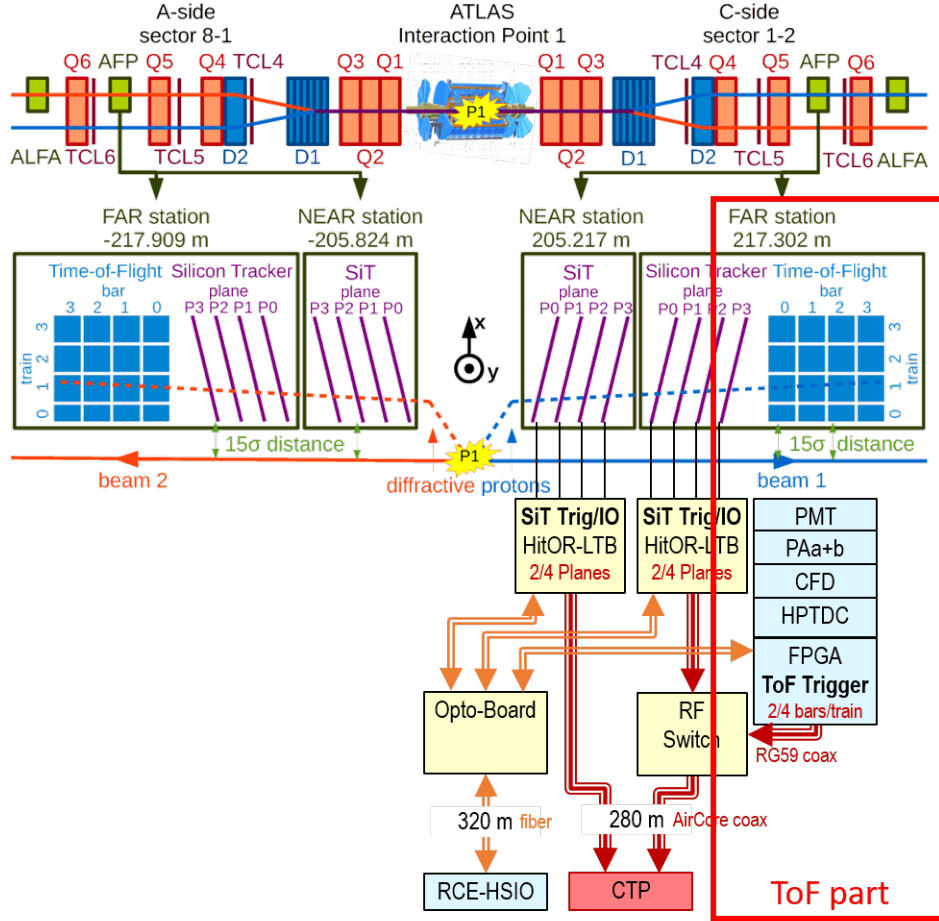


Figure 6: Schematic of the AFP and its electronics [1]. Note that this is the older version without the Digital Trigger Module (see the text).

The signal is processed in the following steps:

1. **MCP-PMT** - Micro Channel Plate Photomultiplier
The conversion of a light signal into an analog electrical signal.
2. **PAa, PAb+c** - Preamplifiers
Amplification of the analog signal. The first stage of preamplification comes directly at the connectors of the MCP-PMT (PAa). The second stage of amplification is then done by the combined NIM module, PAb+c, which stay in the ToF NIM crate.
3. **CFD** - Constant Fraction Discriminator
Triggers on a fraction of the pulse to get a timestamp, the length of the output pulse is by its construction proportional to the amplitude of the input pulse.

4. **DTM** - Digital Trigger Module

Passes data only when set trigger criteria (configuration possible) are met; it's not the traditional approach, it bias the data.

5. **HPTDC** - High Performance Time to Digital Converter

Converts of electrical signals into digital time stamp.

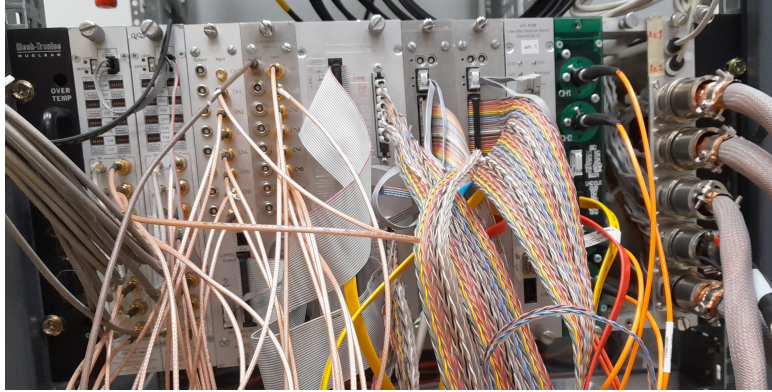


Figure 7: ToF NIM crate in the laboratory, from left to right: two PAbc modules, two CFD modules, one DTM module (double width), two HPTDC modules, precision clock clock distributor module (slave), pulser module.

The setup in the ATLAS Roman Pot (ARP) laboratory is shown in Figure 7. It is identical to the setup in the LHC tunnel. The pulser module is used to test the setup, for more details see [5].

2.1 MCP-PMT

In the detector construction the MCP-PMT, Figure 8, deals with Cherenkov light pulses produced by protons that traverse the bars. To study the MCP-PMT behavior in the lab and for calibration a pulser module is used. A pulse generator sends light pulses at a specific frequency. First task is how the MCP-PMT behaves at different frequencies. Therefore, the amplitudes produced by the PAbc are recorded for different frequencies of the light pulses coming from the pulser, see Figure 9.

Figure 9 shows that the amplitude is stable at around -300 mV up to the frequency of 1 MHz. After a frequency of 1 MHz, the amplitude decreases exponentially.



Figure 8: Photo of the MCP-PMT [1]. It is a miniPLANACON type from Photonics [6] .

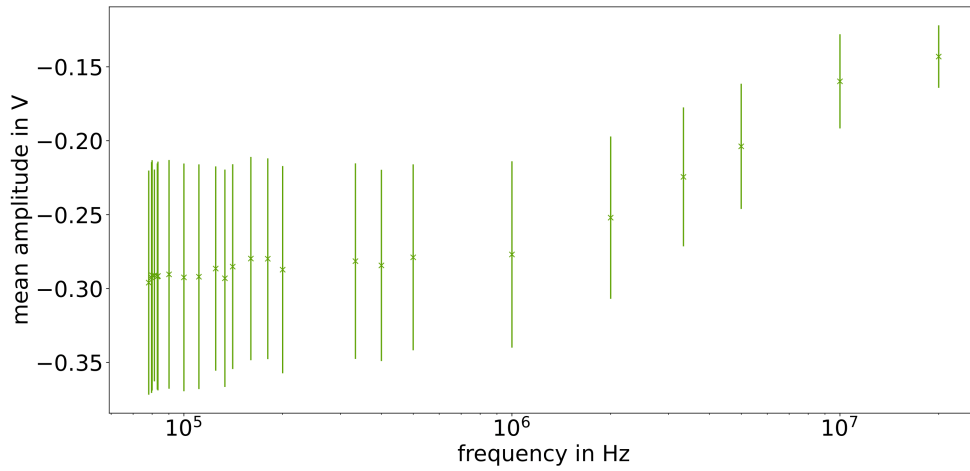


Figure 9: Behavior of the MCP-PMT signal output amplitude as a function of the frequency of the incoming light pulses. Clearly, the amplitude decreases with increasing frequency.

Furthermore, we had a look on the recovery time of the MCP-PMT, see also [14]. Firstly, it gets stressed with a high frequency of light pulses, 20 MHz and the amplitude is measured, after a low frequency 78 kHz is applied the amplitude is measured over time, see Figure 10. It shows that the behavior is the same over the time and directly after starting directly after the change of the frequency. So, there is no huge recovery time as observed in [14]. Also, no gain drop was observed as in the previous measurement, at the low frequencies the amplitude is the same within the uncertainty, see Figure 9.

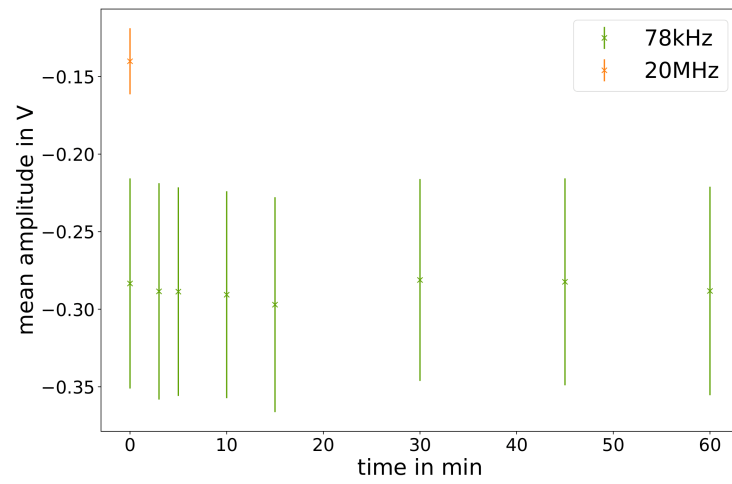


Figure 10: Amplitude behavior of the MCP-PMT output signal over time after being stressed with a high frequency.

2.2 Constant Fraction Discriminator

The Constant Fraction Discriminator (CFD), after the amplification by PAa and PAbc stages.

The results of this section were also presented at the student session 2023 [4].

2.2.1 Working principle

The working principle of the CFD is nicely described by the corresponding article [3]:

CFDs are used to trigger on a fraction of the signal, e.g. in plastic scintillation counters. Another use case is ToF, here the rise times and peak shapes of the signal are similar and differ in pulse heights. These are the requirements for the input signal to make the CFD process work properly and reduce the time walk.

Time Walk is the effect caused by triggering at a certain threshold. As shown in the Figure 11 on the left, the timing of the trigger event shifts according to the different pulse heights. To avoid this, the CFD triggers on the constant portion of the signal so that the different pulse heights provide the same time of the trigger event, on the right of Figure 11.

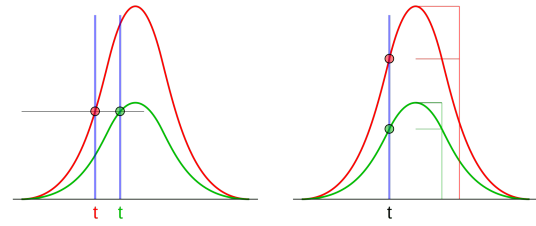


Figure 11: Time walk of threshold triggering (left) in comparison to constant fraction triggering (right), see [2].

This triggering is implemented in the following way and is shown in the logic gate in Figure 12:

- the input signal split in three parts
- one is delayed by time t_d $0 \ll t_d < t_{rise}$ and is connected to the non-inverted input of a comparator
- one may be multiplied by a small factor to emphasis the leading edge (attenuation) and is connected to the inverted input of the comparator
- one is connected to the a non-inverted input of another comparator
- a threshold is connected to the inverted input of this comparator
- both comparator outputs are connected to an and gate which provides the output

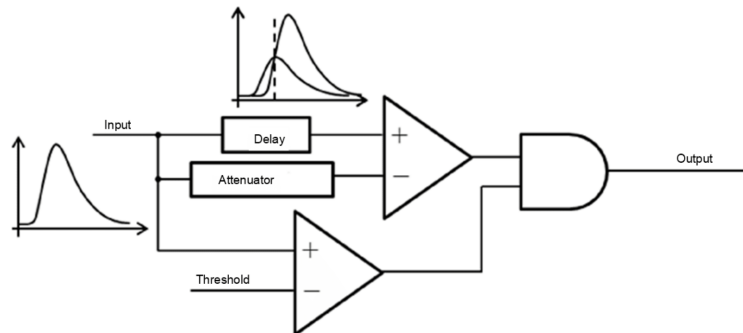


Figure 12: Logic gate of CFD. The input signal is compared to an attenuated input signal, it is used as the output signal, if the input signal exceeds a certain threshold. See [15].

2.2.2 Measuring of CFD modules

We are interested in how the CFD output pulse depends on the amplitude of the signal at the input. We measured the pulse length of the output of the CFD according to the amplitude of the input signal, PAbc module. An example of the signal these two signals is in Figure 14. The result of one combination of MCP-PMT channel, PAbc channel and CFD channel is shown in Figure 13. Other combinations show the same behavior.

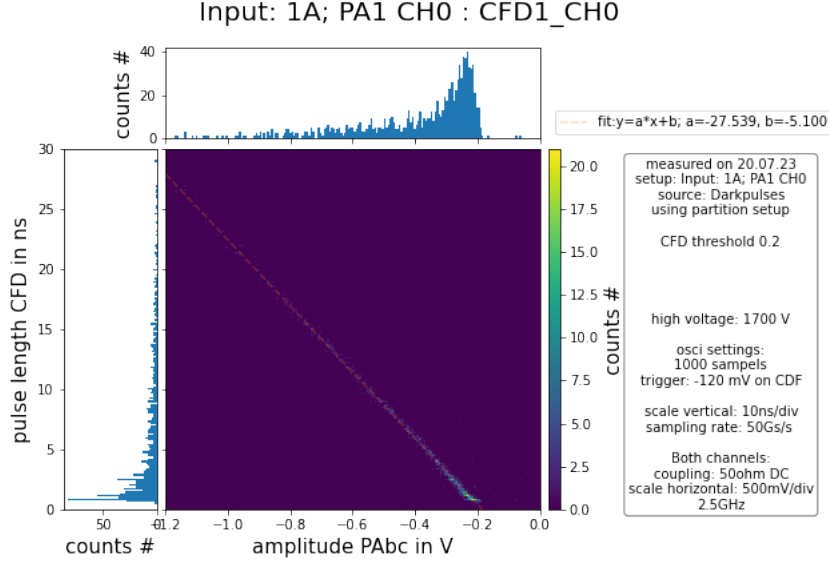


Figure 13: Behaviour of the CFD pulse length as a function of the PAbc input amplitude, which is linear as seen in the centre. To the left and top are histograms of the CFD pulse length and the PAbc amplitude.

We measured in stand-alone mode where the CFD threshold is given, as can be seen from Figure 13, it is 200 mV. The PAbc attenuation can be set on the module in local mode and was set to 0 dB. At a high voltage roughly above 1500 V for the MCP-PMT, there are darkpluses, seen in Figure 14 on the left after PAbc. Samples of 1000 of these events are taken into account for the behavior measurement. In general, the MCP-PMT needs high voltage for measurements based on dark pulses (as triggered by single electron).

There is clearly a linear dependency between the input amplitude and the output pulse length. This linear behavior is meant and allows to recalculate the amplitude of the PAbc from the pulse length from the CFD with a linear equation: $\text{amplitude} = \alpha \cdot \text{pulse length} + \beta$.

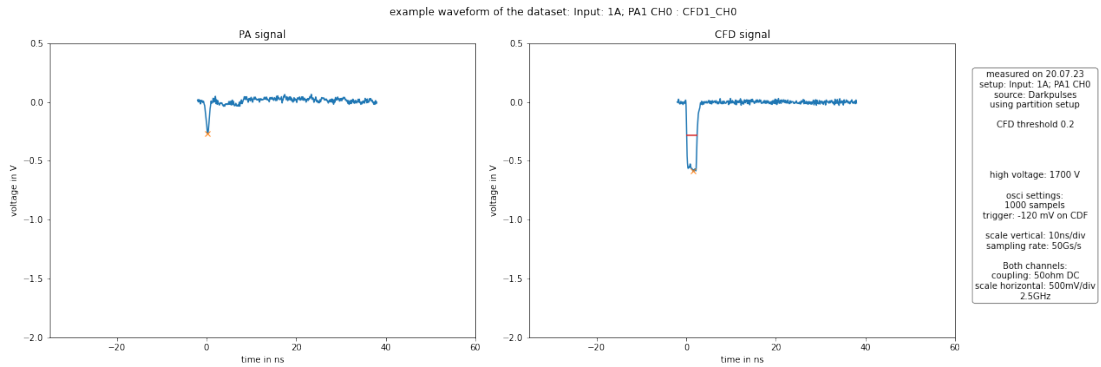


Figure 14: One of the recorded waveforms, on the left there is a typical shape of a dark pulse, on the right the corresponding CFD signal.

3 Tunnel intervention

The motivation for the tunnel intervention was to change the mapping between PAbc and CFD modules, so that train 2 is mapped to the second CFD and train 3 to the first CFD. In addition, it had to be checked if it's also implemented like this in the GNAM¹ plots.



Figure 15: Self-rescue mask on a person.

To be allowed to work in the tunnel one must fulfil all the access requirements, the status and the requirements can be found in ADaMS. The complete several e-learning courses Safety at CERN, Electrical Safety - Facilities, CERN - Beam Facilities and LHC - Machine were required. In addition, the training course Self-Rescue Mask is required, the mask is shown in Figure 15 is needed. All the courses and trainings can be found at the Learning Hub.

The mask is necessary to rescue yourself in case of an Oxygen Deficiency Hazard (ODH) alarm. A deficiency of oxygen can be caused in the tunnel, for example, by a fire or a helium leak or release.

Another risk in the tunnel is radiation, for which a person must take an active dosimeter in addition to the passive dosimeter. The daily dose is limited to $50 \mu\text{Sv}$. In addition, a helmet with a lamp, safety shoes and long pants is the necessary safety equipment.

In order to work in the tunnel, an IMPACT application must be approved in advance, stating why work in the tunnel must be done (plan for the intervention), when and for how long. Once this is approved, the intervention can be performed. For us, the

access was only possible because the LHC was out of service due to a helium leak, and after a few weeks the radiation was low enough for us enter.



Figure 16: An access door to the LHC tunnel.

¹ Online tool to monitor the detector and the beam.

Access to the AFP detector is through the ATLAS site P1. One has to go through a special door to get into the elevator that takes you the 100 meters down, where you again have to go through a door to get into the tunnel, one of these doors is shown in. To pass through these doors you have to have the access rights, all the access rights and what is missing to get the access rights can be found in ADaMS. Once at the bottom, you have to walk to the detector, see Figures 17 and 18.

In Figure 19 the Far Station of the AFP detector on A-Side is shown.



Figure 17: Picture of the far station of the AFP detector on A-Side in the tunnel. The NIM crate lies on the floor of the LHC accelerator tunnel.

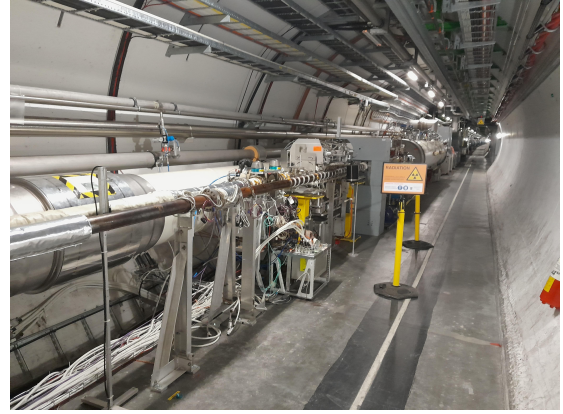


Figure 18: Picture of the far station of the AFP detector on C-Side in the tunnel. The NIM crate lies on the floor of the LHC accelerator tunnel.

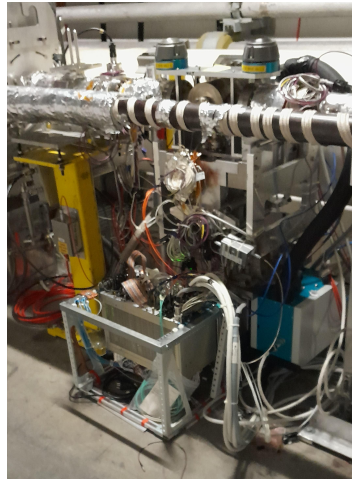


Figure 19: Detailed view of the AFP far station on A-side in the tunnel, at the top the beam lines and in the bottom the electronics.

In order to not overload the TDC the idea is to map the trains consecutive not one by one: Since the trains near to the beam will collect more protons the event rate is higher than the last train. If we want to reduce the overload the two train with the highest event rate should be mapped on different TDC modules. In order to reduce this also the size of the bars is slightly different. The labeling of the bars is shown in Figure 20, in the following the numbers start at 1, so increased by one compared to the figure.

Mapping is in general describing how the connections between the different modules is done.

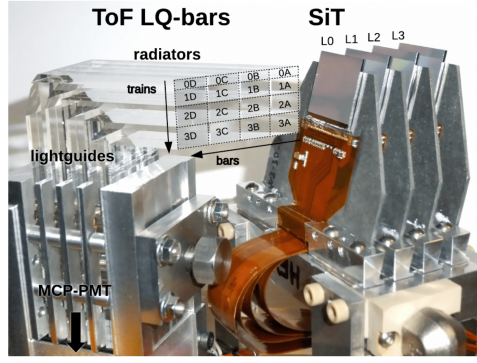


Figure 20: Photo of ToF with labeled bars, in the following the numbers start at 1, so increased by one [1].

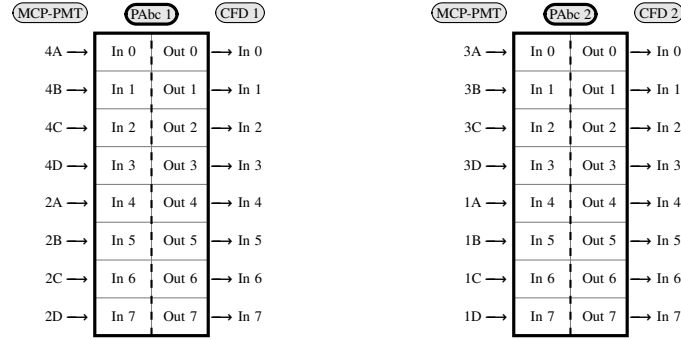


Figure 21: C Side Mapping. PAbc1 on the left and PAbc2 on the right side. For both the inputs of the MCP-PMT on the left and the connections to the CFD on the right.

We started at C-Side, switching the cables between PAbcs and CFDs. To achieve that train 2 as well as 4 resp. 3 and 1 are connected to TDC1 resp. TDC2. Since the plot show the unexpected mapping, we checked the inputs of the PAbcs, which showed the mapping was already applied, see Figure 21. So we reversed the changed wiring back, so that the output channel from the PAbcs are mapped to the corresponding CFD channel. When testing the output of the CFDs via the scope we saw no signal at any of the channels, which indicated that the modules could be broken. We removed the CFDs from the tunnel to check them in the lab, one channel missing in total. The one full CFD from the lab was left in the tunnel.

Later measurements of the modules in the lab showed that at least two DCDC converters, the one for 3.3 V and -5 V, were defective on both motherboards, Figure 22. The daughter cards, Figure 23, could be still functional, so the daughter boards were put on spare motherboards to get fully CFDs, which needs to be tested, see Section 4. However, it is till now unclear what exactly happened to both CFD modules that caused them to break at the same time.

Further plans where for intervention:

for C Side:

- to switch mapping between CFD and DTM to see, if DTM causes smearing on train 3
- to switch SATA cable to longer ones to achieve a time shift of the clocks leading to the movement of the data to a better time for TDCs
- change DTM if the smearing remains

for A Side:

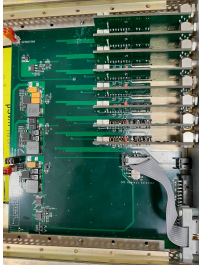


Figure 22: CFD motherboard.

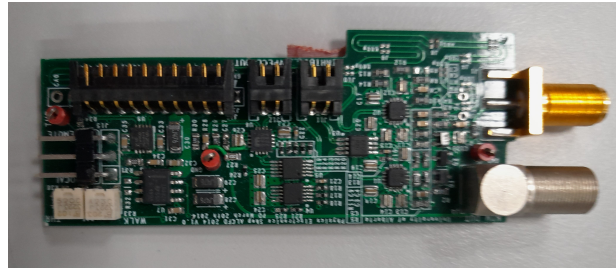


Figure 23: CFD daughter card.

- check problematic channels with scope.

Due to the issue with the CFDs we didn't come to these points, except the testing of the different length of SATA cables.

In a second intervention we focused mainly on A-Side. On the C side, the second CFD from the lab was installed, replacing the previously missing channel with a tunnel daughter card, and we documented the cable length and again the mapping. On the A side there was a problem with the pulser, no light output was visible. The pulser module was replaced with the module from the lab. We checked the mapping, it is shown

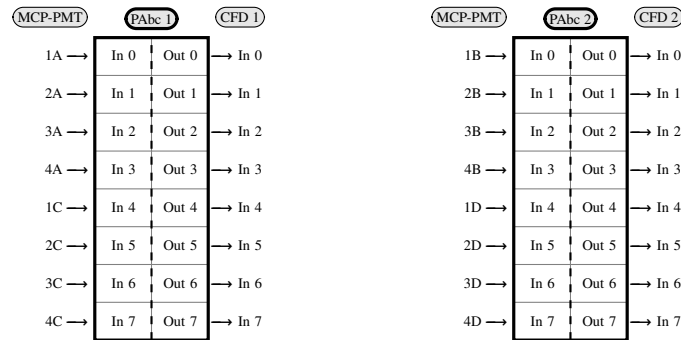


Figure 24: A Side Mapping. PAbc1 on the left and PAbc2 on the right side. For both the inputs of the MCP-PMT on the left and the connections to the CFD on the right.

in Figure 24. The same logic applies as on the C side, as the MCP-PMT is rotated ninety degrees counter clockwise here, with no change in output labels. We have seen that one CFD has too much signal. Since there was a timing problem, we also switched the DTM, but the CFD remained worse. So the CFD was replaced, a spare motherboard and daughterboards from the tunnel were used. Testing the channels showed that channel 1 of CFD 1 was still worse.

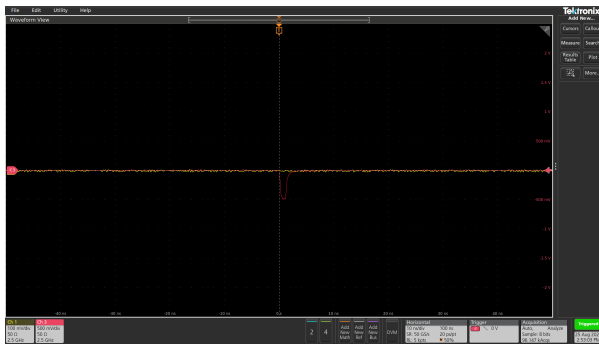


Figure 25: CFD output signal for high threshold 700 mV. Very low level of noise is visible.

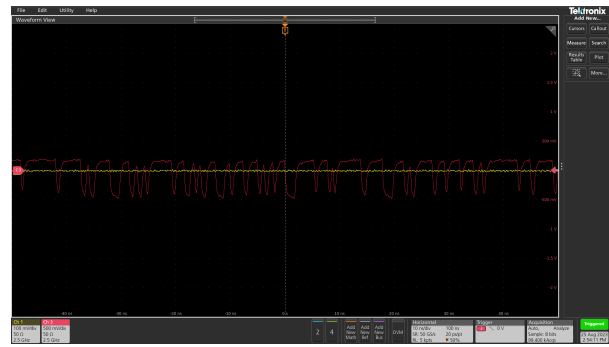


Figure 26: CFD output signal for low threshold 0 mV. A lot of noise is visible.

In the third and last intervention we knew from testing in the lab that the worse signal may be caused by an incorrect jumper configuration on the daughtercards, some daughtercards had jumpers in local position not allowing remote control. To be able to modify the thresholds between the runs it is possible to run the modules in remote mode, so one can modify for example the threshold of the CFDs via config files. But in local mode the threshold is fixed and so we can't configure it, so it is not possible to optimize the thresholds. So we checked on both sides the jumper configuration and indeed the "broken" channel on A-Side was in local mode, also half of the channel each CFD on C-Side was wrongly configured. We tested if it works on both sides by applying a high threshold, 700 mV, and a low threshold 0 mV, the signal as expected is in Figures 25 and 26. When the CFDs are in local mode, both should look the same as when the threshold is at a high voltage, since it is configured as constant at about 400 mV in the local configuration.

By testing there was still an issue with the first CFD on A-Side, it could be solved since the selector for the I²C connection was wrongly it has to be one cable.

After this we see on both sides for all CFDs signal which can change by the change of the configuration file. So the next step was to find the optimal configuration. This was done remotely via the configuration files and with the use of the pulser.

4 Measurement of the CFD modules from the tunnel

Afterwards, the old irradiated modules were released by the Radiation Protection group. We were able to measure the behavior of these modules again. We used the standard remote setup for testing, which can be controlled via the ATLAS TDAQ (Trigger and Data Acquisition) and the DCS (Detector Control System) Figure 27. It is, in principle, a copy of the infrastructure from the tunnel to the ARP laboratory.

The settings of the modules are defined in the configuration files that are loaded via TDAQ when the partition is executed, Figure 28.

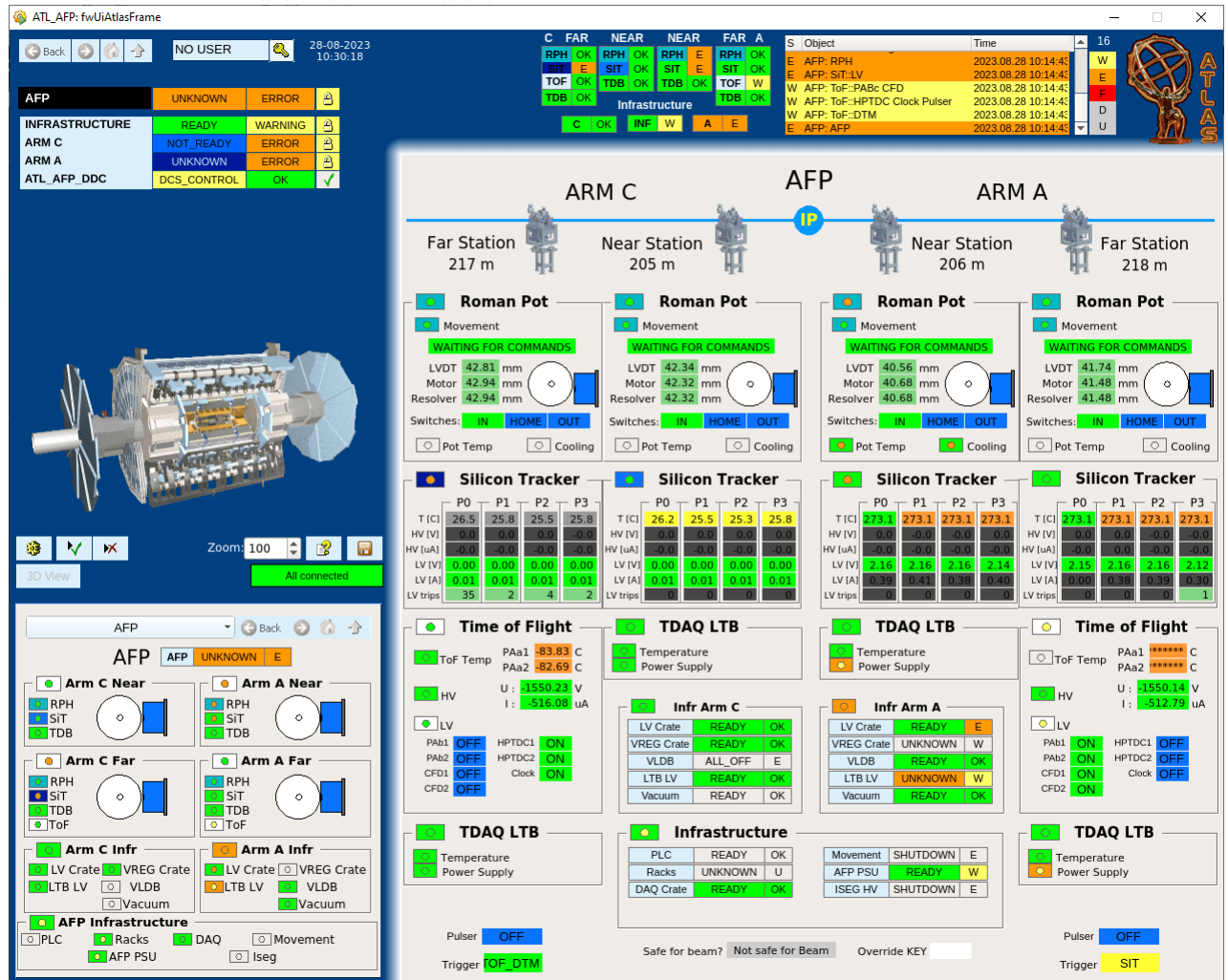


Figure 27: ATLAS DCS interface for the AFP detector.

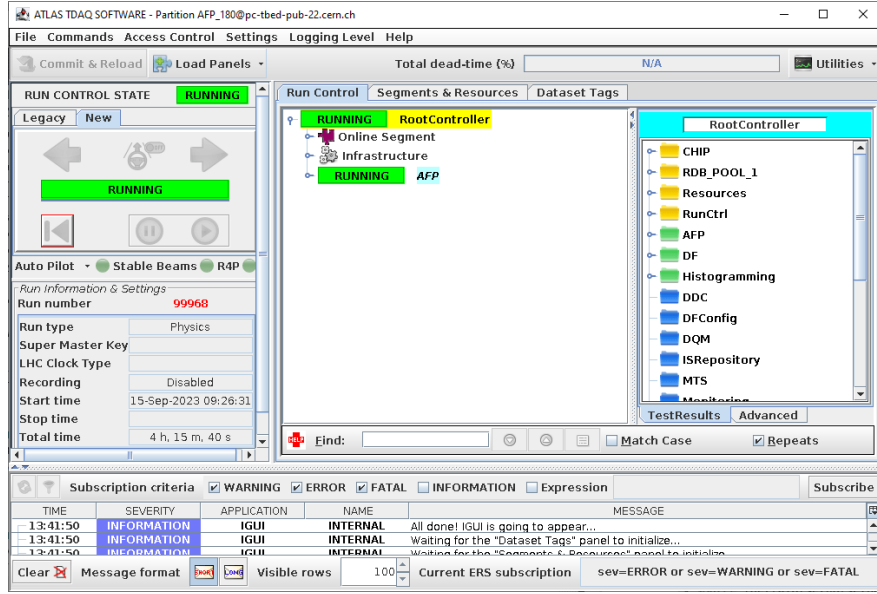


Figure 28: TDAQ software. This is the main GUI where you can run the partition and apply new configurations to the detector setup.

For comparability, the settings from the first measurements of the CFDs are used, so the thresholds for the CFDs were set to 200 mV. In what follows, it is clear that values below 200 mV are truncated, some caused by an inadequate peak finding algorithm, but not all. For the latter case, the cause of the phenomenon is yet unknown.

In case of channel 0 (CH0) of the first CFD (CFD1), comparing the irradiated and non-irradiated measurements, one can see that the linear behavior is basically the same, although there is a small difference in linearity, see Figures 29 and 30.

In addition, in Figure 31 the pulse shape is shown, there you can also see that it acts as the non-irradiated CFD, Figure 14.

In case of the second CFD we see a very different behavior, Figures 32, 33, 35 and 36. It does not have the clear linear behavior anymore and it reacts only on PAbc pulses with amplitudes bigger than 400 mV. The fact that the behavior is not linear can be seen better in the rescaled plot, Figures 38 and 39. Furthermore the waveform of CFD2 CH0 Figure 34, there is a multi-peak structure that does not exist in the non-irradiated CFD, compare Figure 31.

So we have to conclude that the second CFD was damaged and changed its behavior. In the Appendix are the stacked plots for all the waveforms for all measurements.

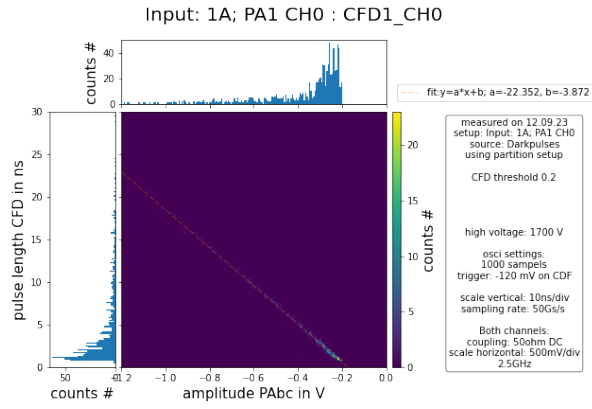


Figure 29: 2d plot of the behavior of the irradiated CFD1 CH0. Settings on the right.

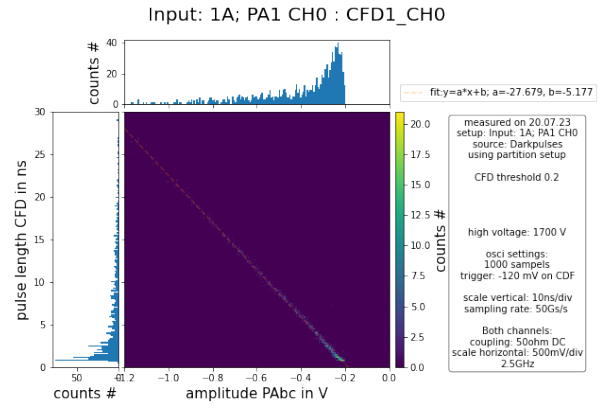


Figure 30: 2d plot of the behavior of the non-irradiated CFD1 CH0. Settings on the right.

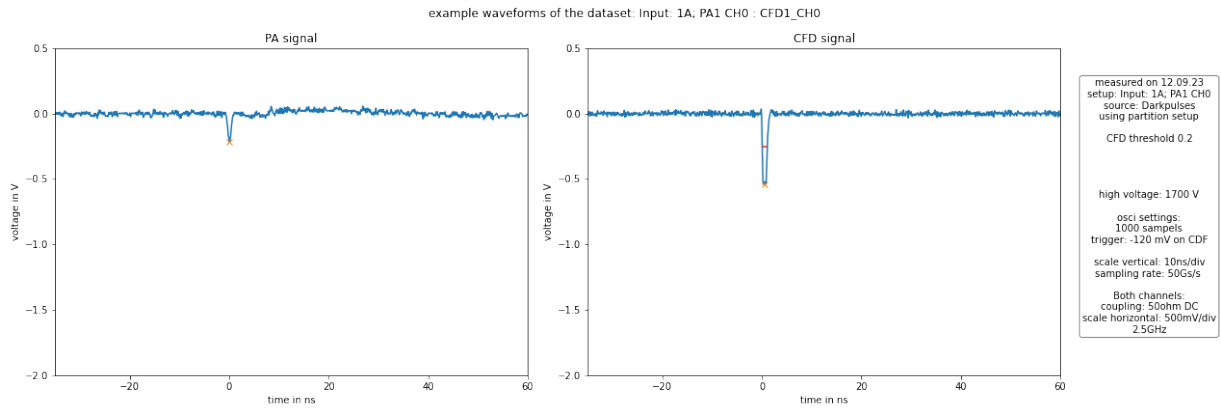


Figure 31: The 42nd recorded waveform, on the left the PAbc signal and on the right the CFD signal for the CFD1 CH0. Settings on the right.

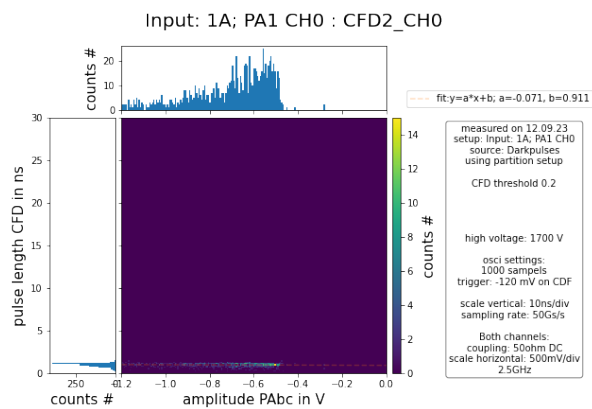


Figure 32: 2d plot of the behavior of the non-irradiated CFD2 CH0. Settings on the right.

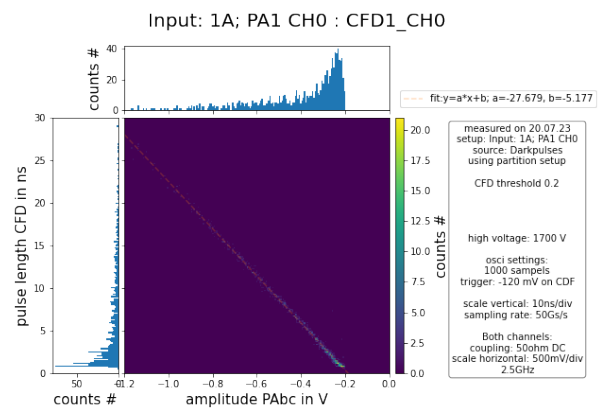


Figure 33: 2d plot of the behavior of the non-irradiated CFD1 CH0. Settings on the right.

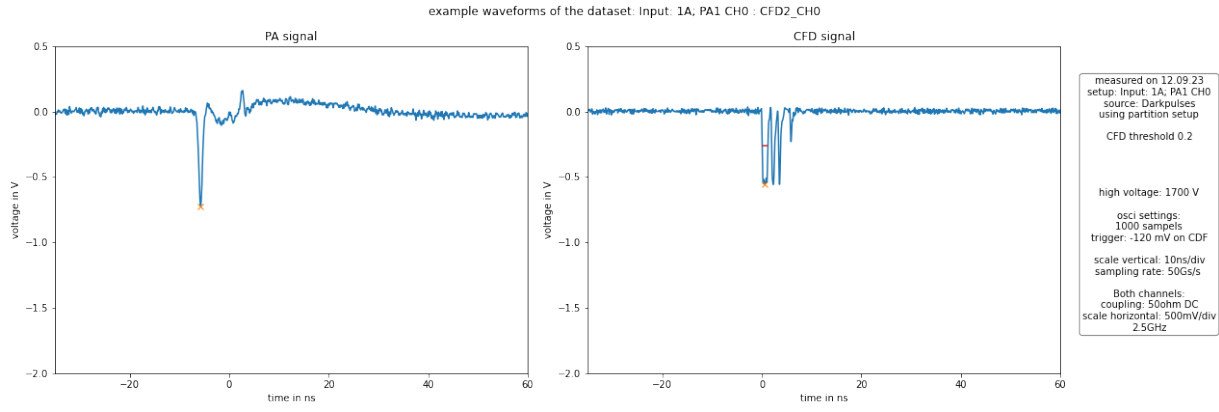


Figure 34: The 42nd recorded waveform, on the left the PAbc signal and on the right the CFD signal for the CFD2 CHO. Settings on the right.

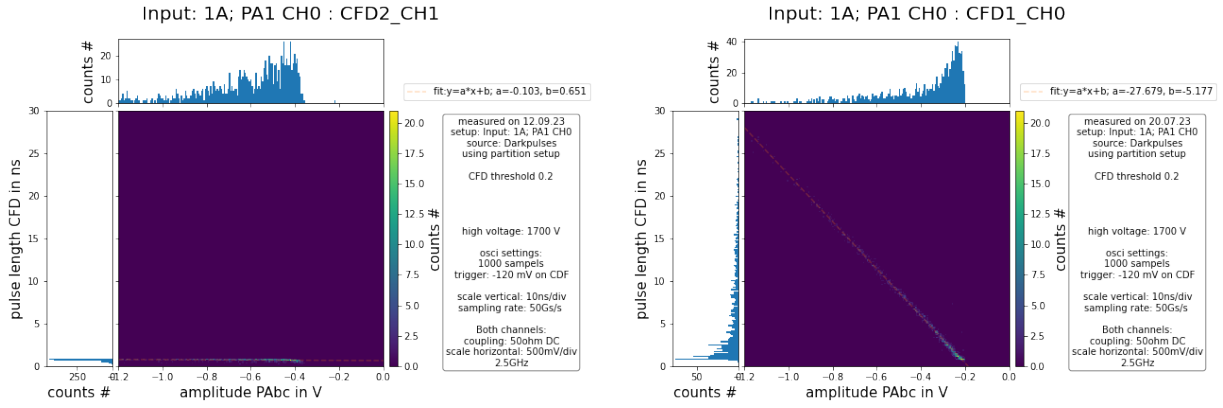


Figure 35: 2d plot of the behavior of the irradiated CFD2 CH1. Settings on the right.

Figure 36: 2d plot of the behavior of the non-irradiated CFD1 CH0. Settings on the right.

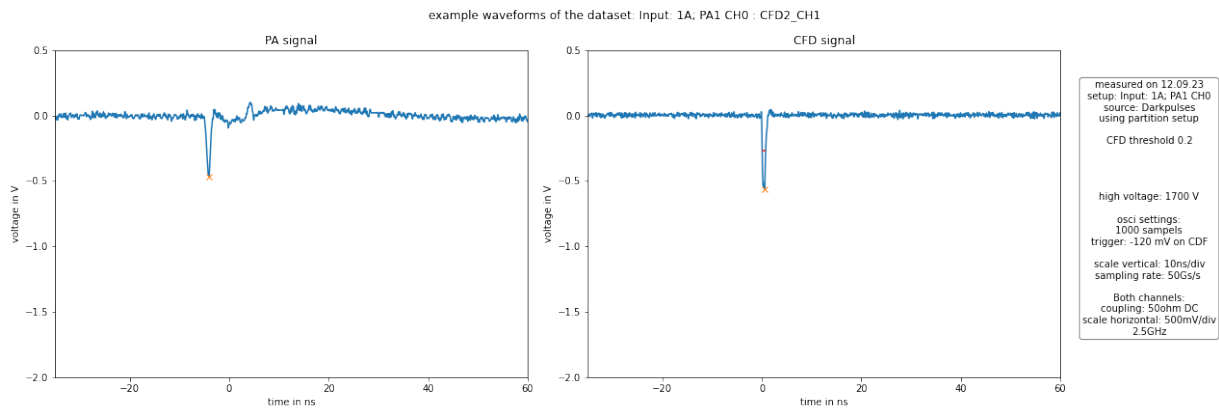


Figure 37: The 42nd recorded waveform, on the left the PAbc signal and on the right the CFD signal for the CFD2 CH1. Settings on the right.

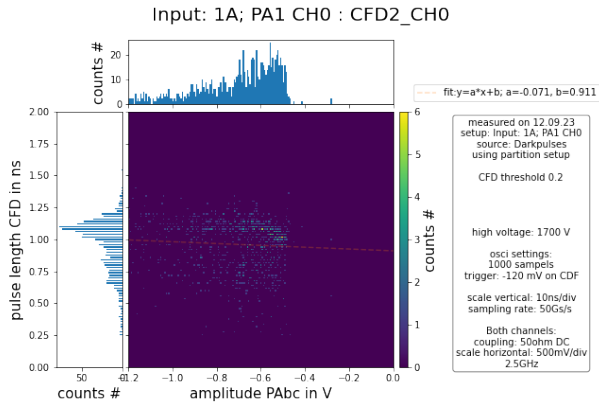


Figure 38: Rescaled 2d plot of the behavior of the irradiated CFD2 CH0. Settings on the right.

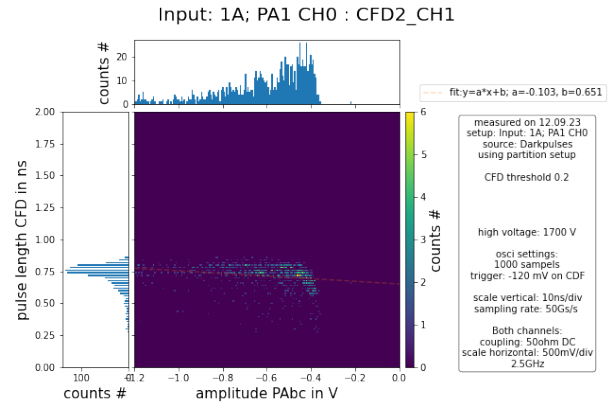


Figure 39: Rescaled 2d plot of the behavior of the irradiated CFD2 CH1. Settings on the right.

There is also the possibility to measure the behavior of the CFDs with the pulser module. To do this we have to lower the high voltage to 1550 V in order to no harm the PMT with the additional light pulses from the four laser diodes. The laser diodes were driven with 5.7 V. Since this is a different light source, the light pulses have a different shape then the darkpulses and so also the PAbc signal, see Figure 42. Nevertheless, in the behavior of the irradiated CFD one has also the linear behavior but the pules occurs in a smaller amplitude interval, see Figures 40 and 41.

Therefore, we consider as better to test MCP-PMT with darkpulses, since a larger amplitude range is covered here and the amplitude distribution can be investigated for both. Especially the larger range allows better linear fits.

We looked at all 16 CFD channels, but as all eight channels for CFD1 look the same, we only recorded data for CFD1 CH0. Regarding CFD2 channels, two slightly different behavior types were observed across the eight channels; thus, we documented both in CH0 and CH1. Our conclusion is that the CFD1 module is working properly and the CFD2 module is broken.

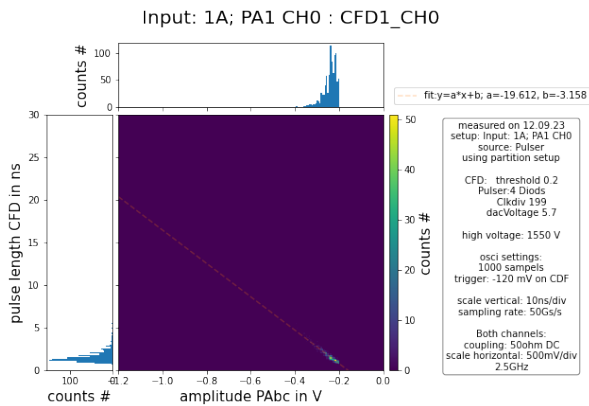


Figure 40: 2d plot of the behavior of the irradiated CFD1 CH0 with the pulser. Settings on the right.

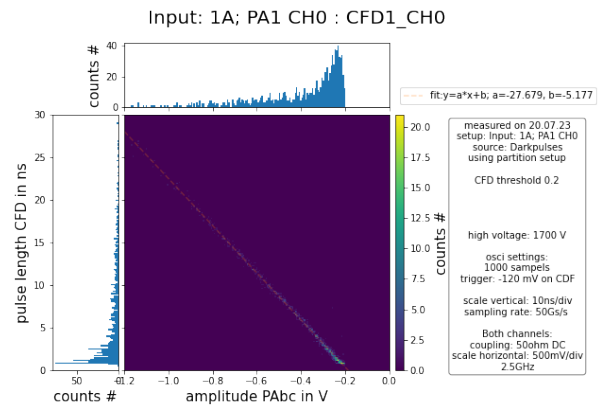


Figure 41: 2d plot of the behavior of the non-irradiated CFD1 CH0. Settings on the right.

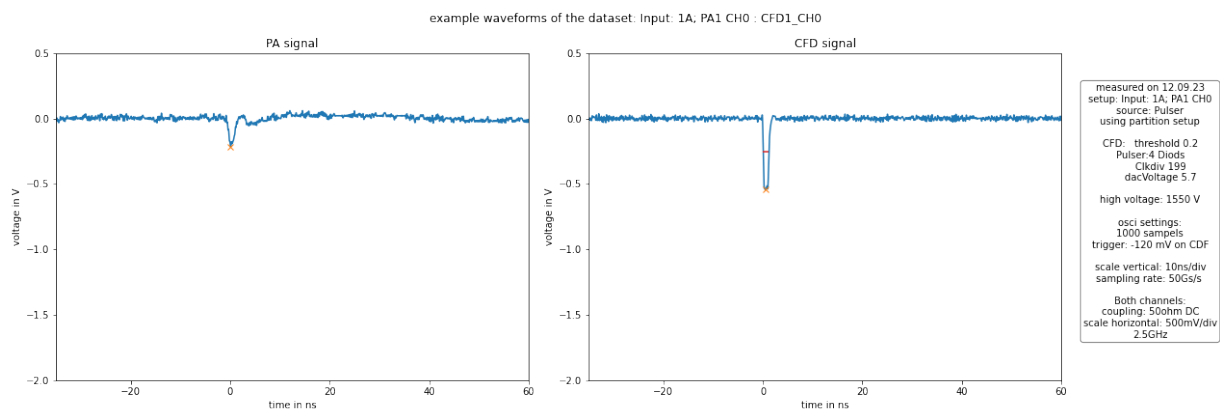


Figure 42: The 42nd recorded waveform, on the left the PAbc signal and on the right the CFD signal for the CFD1 CHO with the pulser. Settings on the right.

5 TDC measurements

At the end of 2022, a loss of data was detected. If the settings of the DTM module is such that the DTM triggers only when four out of four channels in a turn receive a hit, a signal, one would expect to see in the data only events with 4, 8, 12 or 16 channels hit. The number of channels hit is also called multiplicity. However, other multiplicities occur as well in Figure 43 from 2022 and in the data from 2023 Figures 44 and 45. Based on this figures, clearly, the amount of data loss is dependent on the value of pileup μ . For high μ no data were recorded (bin 0), just triggered. See also for the low- μ run 460096 Figures 73 and 74 in the Appendix.

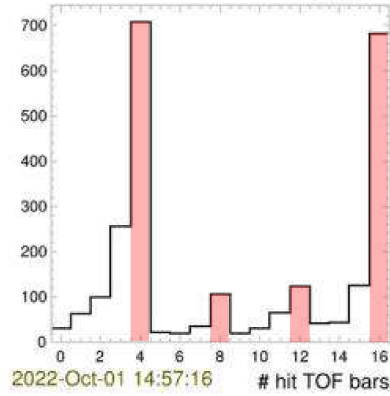


Figure 43: Multiplicity, number of channels hit on the x-axis from a **low μ** run from 2022. Y-axis number of events. In red is marked the expectation.

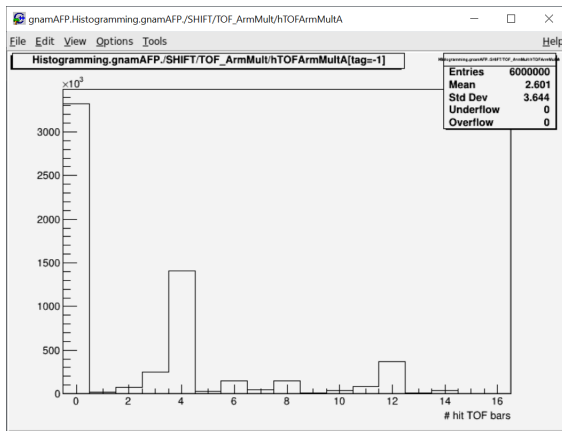


Figure 44: Multiplicity for the 2023 high- μ run 456714. The A-side shows peaks for the number of bars hit next to 4,8,12,16. Especially a large number of events with 0 bars hit.

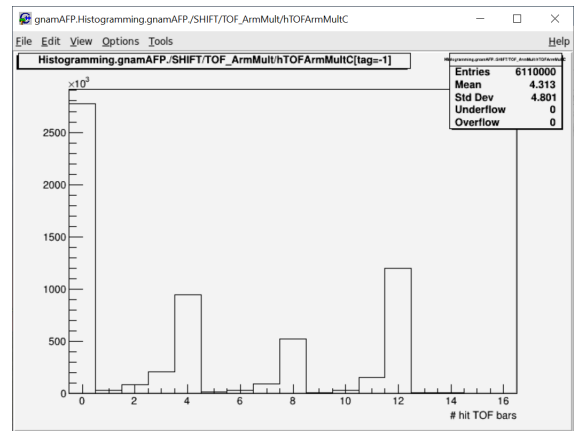


Figure 45: Multiplicity for the 2023 high- μ run 456714. The C-side shows peaks for the number of bars hit next to 4,8,12,16. Especially a large number of events with 0 bars hit.

One possible explanation for the data loss is a saturation of the TDCs. Data can be lost because of high data flow and limited capability of the TDC module. Here we talk about limited capability not just of the HPTDC chips, but about the full module. To check this, one can determine how often errors of the TDC occur.

5.1 TDC - error flags

Each of the 4 TDC chip of the TDC, (actually only 3 of the 4 chips are used), can send error messages over the data stream. The data is generally transmitted in a bit stream. Each data set in the stream is represented by a 32-bit word. In some of these words error message info is encoded.

The first 4 bits are dedicated to the Read Out Drivers (ROD) and the second 4 bits are the link, so for which device e.g. link 9 and 11 are the TDCs. The remaining 24 bits contain the data which can then be decoded as in the AFP TWiki².

Since we are only interested in the errors of the TDCs, we can use only the relevant part of the data encoding, namely the error flag. As shown in Figure 46, bits 18 and 19 indicate which TDC has an error and bits 0 to 14 specify which error it is. There are 15 possible errors, T is the TDC chip number:

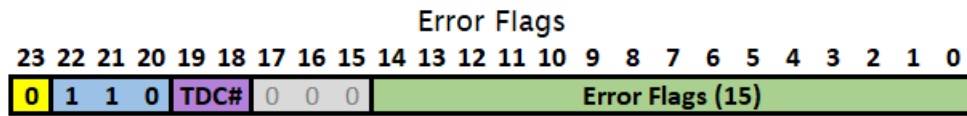


Figure 46: Data encoding for the error flags, [1].

- 0: Hit lost in channel $0+4*T$ from read-out fifo overflow
- 1: Hit lost in channel $0+4*T$ from L1 buffer overflow
- 2: Hit error detected in channel $0+4*T$
- 3: Hit lost in channel $1+4*T$ from read-out fifo overflow
- 4: Hit lost in channel $1+4*T$ from L1 buffer overflow
- 5: Hit error detected in channel $1+4*T$
- 6: Hit lost in channel $2+4*T$ from read-out fifo overflow
- 7: Hit lost in channel $2+4*T$ from L1 buffer overflow
- 8: Hit error detected in channel $2+4*T$
- 9: Hit lost in channel $3+4*T$ from read-out fifo overflow
- 10: Hit lost in channel $3+4*T$ from L1 buffer overflow
- 11: Hit error detected in channel $3+4*T$
- 12: Hit rejected due to programed event size limit
- 13: Event lost (trigger fifo overflow)
- 14: Internal fatal chip error detected

² <https://twiki.cern.ch/twiki/bin/view/Atlas/AFP>; note that the TWiki is constantly updated, here we use the current state.

5.2 GNAM monitoring tool

GNAM is a universal tool, [16], for detectors to monitor hardware functions and to control data acquisition to achieve good data quality. For this purpose, there is the possibility to display different, so called control histograms. For example, there is a one dimensional plot of the hit channels, 2d histogram of hit map, etc. .

The source code for the GNAM histograms consists of three parts, all programmed in C++, and also uses ROOT³. The first part decodes the data from the words and moves data (MyClass) to object containing data of interest. For the display part, there is code to create the actual histograms.

GNAM can be run not only on live data from the tunnel to monitor the status through the shifter, but also on recorded data. Since we are interested in how the behavior is on different runs, we can use recorded data and run GNAM on the recorded data.

Since there are no plots on the errors yet, we first need to decode the error flags, see Section 5.1, and create histograms. The following histograms and decoding were implemented into the GNAM code with the help of the AFP group member, Petr Fiedler:

- Error count, TDC chips over error flags.

and for experts to crosscheck:

- Total error count, TDC over chip
- Error count, TDC chip over words

Another interesting histogram, allowing to link number of errors with the value of pile up (μ) is a histogram showing errors as a function of lumiblock number⁴, which allows information about when and how many the errors occurred. This was implemented, as well as for the fatal errors chips over lumiblock, by myself with the debugging help from Petr Fiedler.

Note that the mapping of the GNAM histograms produced in the laboratory needs to be crosschecked (and re-done) due its difference from the mapping used in the tunnel - we clearly saw that the channels are not mapped according to the AFP HPTDC TWiki information. Also, filling of the histograms must be cross-checked to removed conditions valid in the tunnel but not in the lab. This will lead to removal of many control histograms which are meaningful only for the data taking in the tunnel.

³ ROOT is data analysis software in C++ developed at CERN [11].

⁴ A run consists of lumiblocks, usually ~ 60 s long, in which events are consecutively stored.

5.3 Analysis of results

First, the high μ data from run 456714 in 2023 [7] were analyzed and the plots, mentioned earlier in section Section 5.2 were made.

We see in these plots, Figures 47 and 48, that there were errors. On A-side only *Internal fatal* errors (error number 14) appeared, on C-side we see some TDC 1 chip1 *Hit* errors in channel one and two (error numbers 5 and 8). Moreover. In general, all used chips of any of installed TDC modules produced fatal errors. Also, we see that there is a hot channel on both sides, on A side it is TDC 1 chip1, on C Side it is TDC 1 chip 0. To know if it fits to the TDC channels with the highest flux we need to have a look in the internal mapping of a TDC channel to a TDC chip, some equivalent plots to Figures 21 and 24.

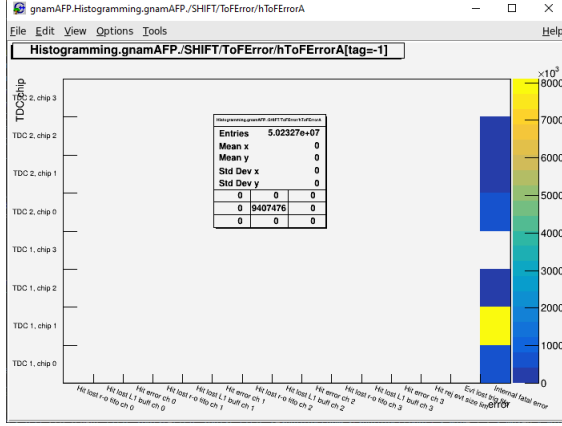


Figure 47: A-side chips over Error. All six used chips show internal fatal errors, with one chip, TDC1 chip 1, being particularly faulty. The data are from high-mu run 456714, 2023.

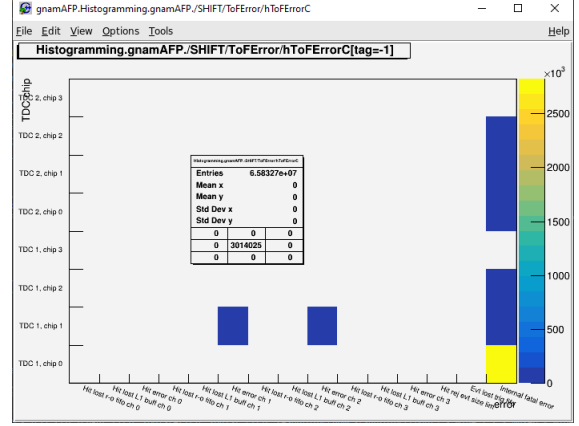


Figure 48: C-side chips over Error. All six used chips show internal fatal errors, with one chip, TDC1 chip 0, being particularly faulty. There are also some hit errors in channels 1 and 2 on TDC1 chip 1. The data are from high-mu run 456714, 2023.

With the plots of the errors over the luminosity, Figures 49 and 50 we see that there is a time distribution for the errors. If we compare it to the run luminosity of the studied run, Figure 51, we can think of a correlation, which needs to be further investigated. It is important to know exactly what an internal error is and how serious complications it causes.

After examining the errors plotted against luminosity in Figures 49 and 50, it is clear that there is a time-dependency of TDC errors distribution. The distribution can be also compared to the time dependency of the luminosity, shown in Figure 51, indicating **a correlation which needs to be further investigated**. As it is seen in Figures 54 and 55 after a average μ of around 35 there is a linear increase of the errors by $\langle\mu\rangle$.

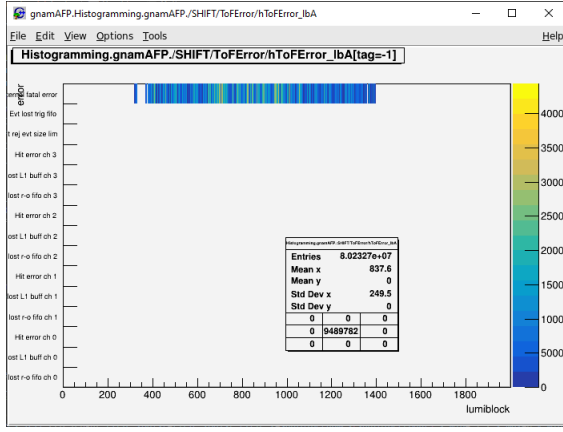


Figure 49: A-side types of errors as a function of lumiblock. The dependency of the distribution of internal fatal errors on time (lumiblock) is clearly visible. The data are from high-mu run 456714, 2023.

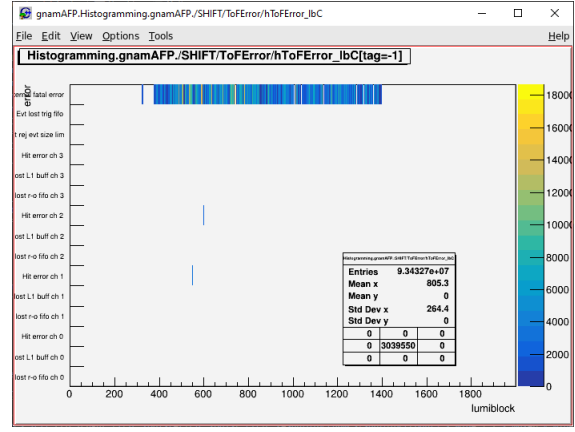


Figure 50: C-side types of errors as a function of lumiblock. The dependency of the distribution of internal fatal errors on time (lumiblock) is clearly visible. The data are from high-mu run 456714, 2023.

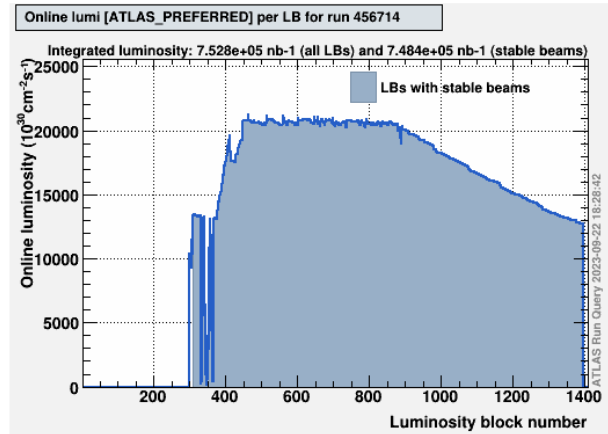


Figure 51: Online luminosity plot of run 456714 based on Run Query [7].

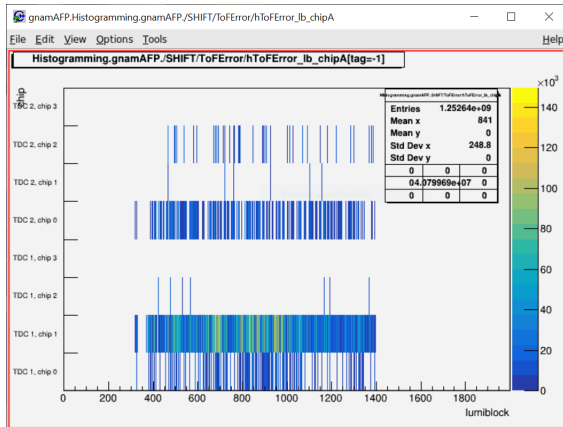


Figure 52: Time distribution of fatal errors for each of the chips on the TDC on A-side.

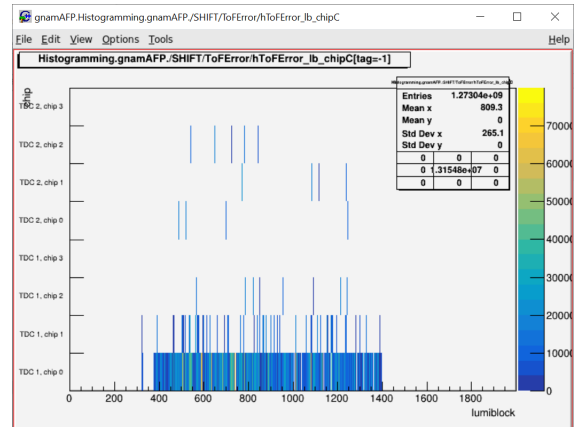


Figure 53: Time distribution of fatal errors for each of the chips on the TDC on C-side.

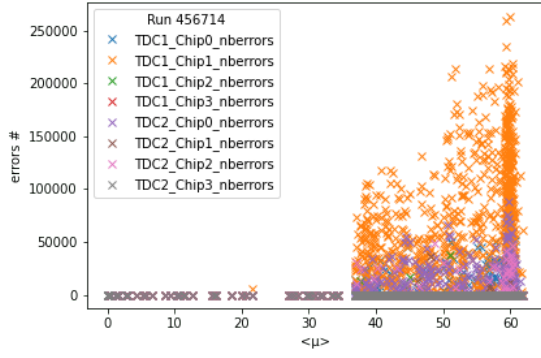


Figure 54: Amount of total chip errors as a function of $\langle\mu\rangle$ for each of the TDC chips on A-side. The number of errors increase after a $\langle\mu\rangle \sim 35$, because the AFP detector is inserted only for the stable beams condition. The data are from high-mu run 456714, 2023.

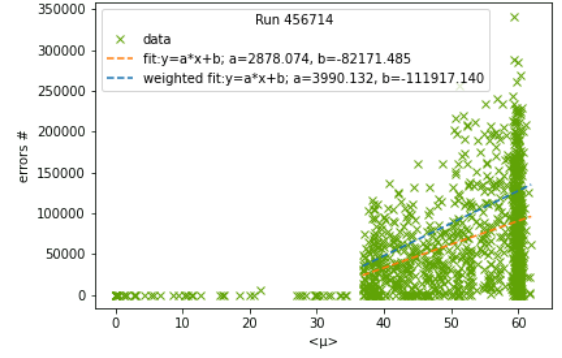


Figure 55: Total amount of total chip errors as the function of $\langle\mu\rangle$ and a corresponding linear, weighted and unweighted, fits. The weight reflects the duration of the lumiblock. The data are from high-mu run 456714, 2023.

[illegible]

The screenshot shows the main window of the "gnamAPP.Histogramming.gnamAPP.SHIFT/ToError/hToErrorC" application. The title bar includes standard Windows controls and menu options: File, Edit, View, Options, Tools, Help.

A search bar at the top contains the text: `Histogramming.gnamAPP.SHIFT/ToError/hToErrorC[tag=1]`.

The plot area displays a histogram of TDC hit counts. The y-axis is labeled "TDC hit" and ranges from 0 to 9000. The x-axis labels represent various detector components: `No lost r-o hit ch 0`, `No error ch 2`, `No lost L1 buff ch 0`, `No lost r-o hit ch 1`, `No error ch 2`, `No lost L1 buff ch 1`, `No lost r-o hit ch 2`, `No error ch 3`, `No lost L1 buff ch 2`, `No lost r-o hit ch 3`, `No error ch 4`, `No lost L1 buff ch 3`, `No lost r-o hit ch 4`, `No error ch 5`, `No lost L1 buff ch 4`, `No lost r-o hit ch 5`, `No error ch 6`, `No lost L1 buff ch 5`, `No lost r-o hit ch 6`, `No error ch 7`, `No lost L1 buff ch 6`, `No lost r-o hit ch 7`, `No error ch 8`, `No lost L1 buff ch 7`, `No lost r-o hit ch 8`, `No error ch 9`, `No lost L1 buff ch 8`, `No lost r-o hit ch 9`, `No error ch 10`, `No lost L1 buff ch 9`, `No lost r-o hit ch 10`, `No error ch 11`, `No lost L1 buff ch 10`, `No lost r-o hit ch 11`, `No error ch 12`, `No lost L1 buff ch 11`, `No lost r-o hit ch 12`, `No error ch 13`, `No lost L1 buff ch 12`, `No lost r-o hit ch 13`, `No error ch 14`, `No lost L1 buff ch 13`, `No lost r-o hit ch 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L1 buff ch 87`, `No lost r-o hit ch 88`, `No error ch 89`, `No lost L1 buff ch 88`, `No lost r-o hit ch 89`, `No error ch 90`, `No lost L1 buff ch 89`, `No lost r-o hit ch 90`, `No error ch 91`, `No lost L1 buff ch 90`, `No lost r-o hit ch 91`, `No error ch 92`, `No lost L1 buff ch 91`, `No lost r-o hit ch 92`, `No error ch 93`, `No lost L1 buff ch 92`, `No lost r-o hit ch 93`, `No error ch 94`, `No lost L1 buff ch 93`, `No lost r-o hit ch 94`, `No error ch 95`, `No lost L1 buff ch 94`, `No lost r-o hit ch 95`, `No error ch 96`, `No lost L1 buff ch 95`, `No lost r-o hit ch 96`, `No error ch 97`, `No lost L1 buff ch 96`, `No lost r-o hit ch 97`, `No error ch 98`, `No lost L1 buff ch 97`, `No lost r-o hit ch 98`, `No error ch 99`, `No lost L1 buff ch 98`, `No lost r-o hit ch 99`, `No error ch 100`, `No lost L1 buff ch 99`, `No lost r-o hit ch 100`, `No error ch 101`, `No lost L1 buff ch 100`, `No lost r-o hit ch 101`, `No error ch`

[illegible]

gnamAFP-Histogramming.gnamAFP./SHIFT/ToError/hToError_lbC

File Edit View Options Tools Help

Histogramming.gnamAFP./SHIFT/ToError/hToError_lbC[tag=1]

error

lumblock

Histogramming.gnamAFP./SHIFT/ToError/hToError_lbC		
Entries	2.670855e+09	
Mean x	186.6	
Mean y	14	
Std Dev x	72.63	
Std Dev y	0	
0	0	0
0	172401	0
0	0	0

30

Also, a very interesting observation is that for run 460096, there some also errors for $\langle\mu\rangle = 0$, which would e.g. suggest errors due to synchronisation of TDCs or still effect of the beams as is visible in Figure 60 where despite practically zero luminosity due to the high intensities of the beams secondaries can be produced and will effect measurement of the forward detectors. The second hypothesis can be tested by selecting affected lumiblocks and checking activity of detectors, which is shown in Figure 61, we see that hypothesis could be disproved.

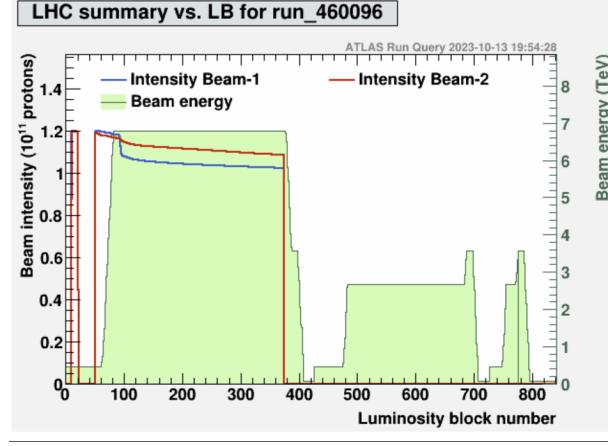


Figure 60: Online luminosity plot of run 460096 based on Run Query [8].

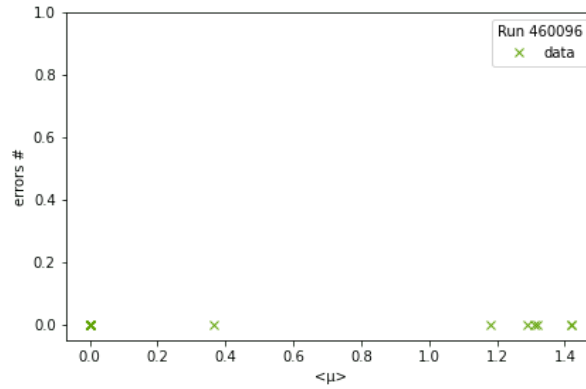


Figure 61: Total number of total chip errors as a function of $\langle\mu\rangle$ for A-side for the 2023 low-mu run 460096, 2023. Only the first 100 lumiblocks taken into account.

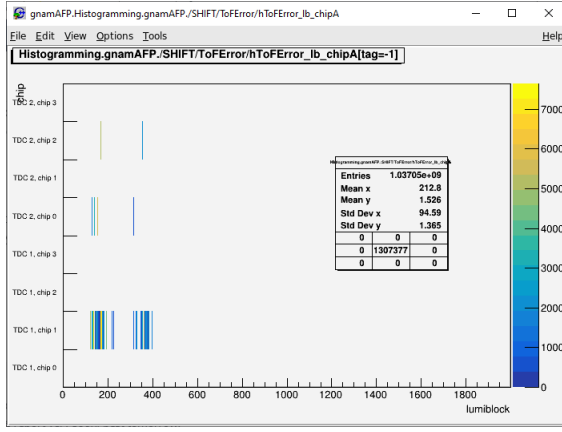


Figure 62: Time distribution of fatal errors for each of the chips on the TDC on A-side.

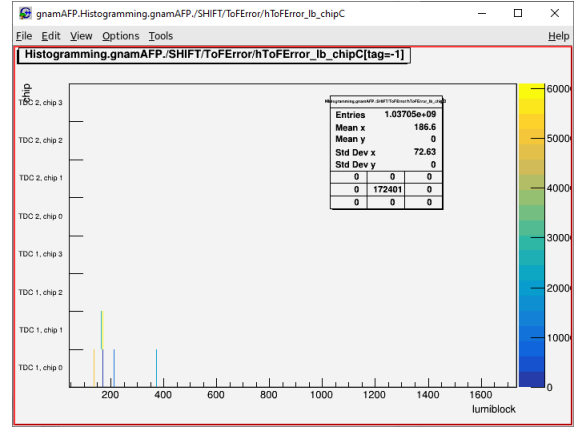


Figure 63: Time distribution of fatal errors for each of the chips on the TDC on C-side.

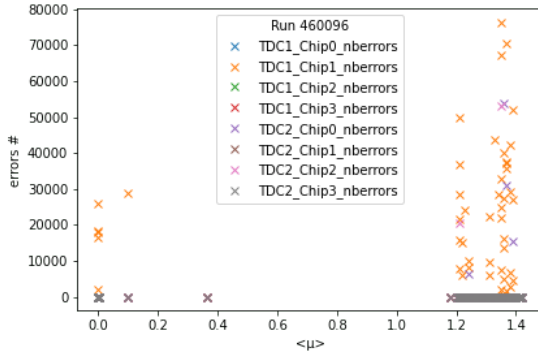


Figure 64: Amount of total chip errors for each of the TDC chip as a function of $\langle\mu\rangle$ for the TDC chips at the A-side; low-mu run 460096, 2023.

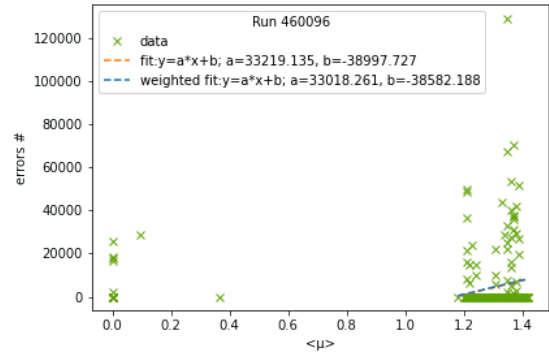


Figure 65: Total number of total chip errors as a function of $\langle\mu\rangle$ for A-side for the 2023 low-mu run 460096, 2023.

All this suggests that the problem of data loss does not have to be explained by a TDC saturation only. Nevertheless a saturation effect can still be valid for a high μ running. To see this we compare both runs.

The histograms of the total number of errors per lumiblock, Figures 66 and 67, show a clear correlation between the online luminosity and the number of errors, see Figures 51 and 60. For Figure 67 also the movement of the AFP detector is visible. Further comparison of the two runs reveals a difference in the mean number of errors per lumiblock and per second per lumiblock (normalized lumiblock), as presented in Table 1.

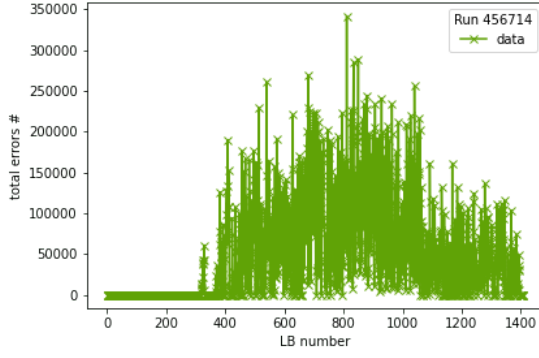


Figure 66: Number of TDC total errors over lumiblock at A-side for the run 456714.

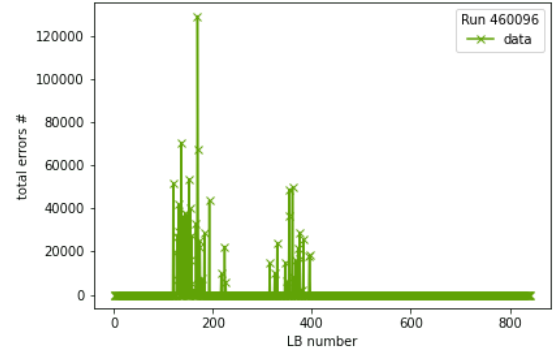


Figure 67: Number of TDC total errors over lumiblock at A-side for the run 460096.

Table 1: Mean of thr errors for run 456714 and 460096

	Run 456714	Run 460096
average μ for the complete run	39.65	0.44
mean number of errors per lumiblock	51 096.57	1554.55
mean number of errors per second per lumiblock	1274.35	27.66

Clearly, the the number of errors is not scaling linearly: ratio of average μ is 0.01, the corresponding ratios of errors is 0.03 for not normalized lumiblocks, and 0.02 for normalized lumiblocks. This conclusion maybe be still affected by the very limited number of analysed data.

It is necessary to investigate further whether this difference is caused by the deviation of μ and the position of the detector and or something else, and what else causes the observed errors.

⇒ A comprehensive study including all data from the tunnel, using standard and pulser-driven runs as well as laboratory runnings, should be done to determine the faulty behaviour of the TDC modules and its dependence on the running conditions. Additionally, an evaluation of their impacts is recommended.

Despite our readiness and effort (provided also from the side of AFP DCS and TDAQ experts), it was not possible to conduct these studies and only a very limited number of data-sets was analyzed. The information about how many observed errors is affecting data taking, i.e. whether the errors are causing just a very small amount of data loss or due to these errors a longer periods of data taking are affected was not provided and could not be measured due to management decision.

6 Acknowledgement

Many thanks to my supervisors Tom Sykora and Christoph Rembser for the project and their support. I would also like to thank everyone from the AFP group whom I worked with and who helped me, among others Elzbieta Banas for her help with the DCS in the lab, Kris Korcyl for his help with TDAQ problematics and preparation of the dedicated partition (only thanks to this the gnam part of the study could be done) and Petr Fiedler who helped me a lot with the creation of the GNAM plots.

Also, I would like to thank all the other people I met during my stay and thank them for the wonderful time we had together, especially to other summer students.

Last but not least, I would also like to thank CERN and all the people who made it possible for me to spend this great time at CERN.

Appendix

Here additional plots can be found.

A Additional plots for Section 4 Measurement of the CFD modules from the tunnel

When stacked plots are used, the message is to show how the original signals look and how they differ, and to show the marked peaks taken for analysis.

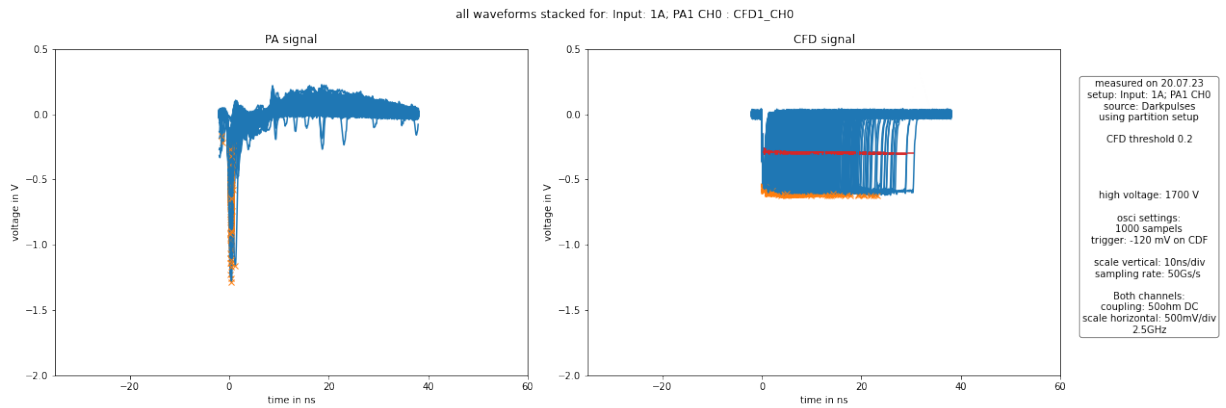


Figure 68: Stacked waveform, on the left the PA signal and on the right the CFD signal for the non-irradiated CFD1 CH0. Settings are given in the table on the right.

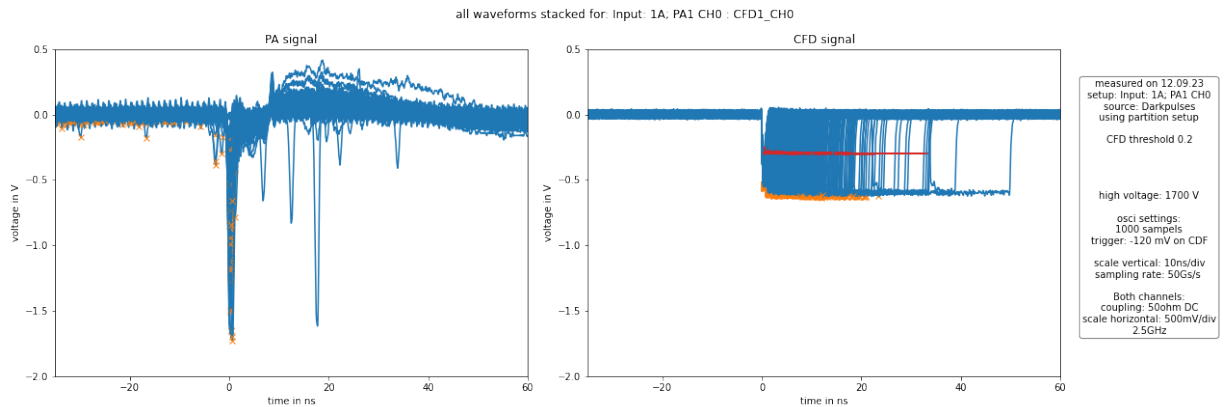


Figure 69: Stacked waveform, on the left the PA signal and on the right the CFD signal for the non-irradiated CFD1 CH0. Settings are given in the table on the right.

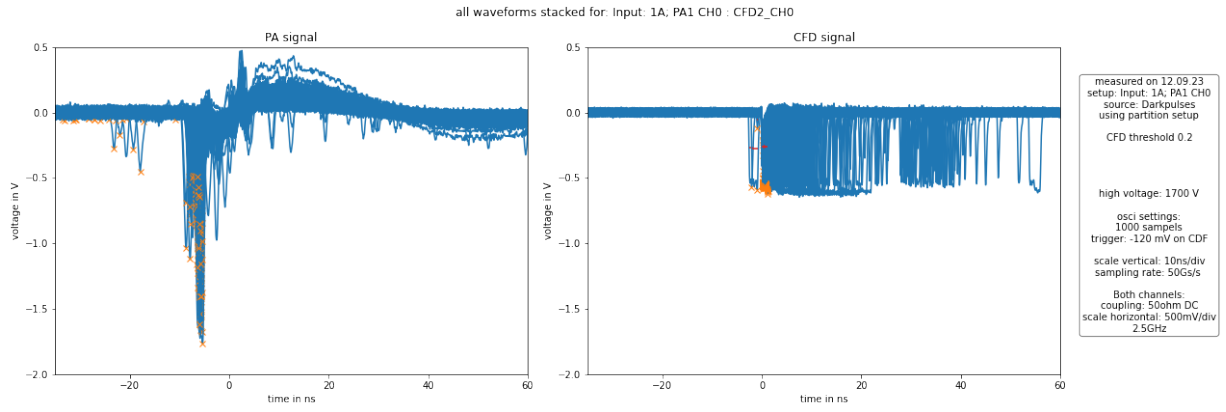


Figure 70: Stacked waveform, on the left the PA signal and on the right the CFD signal for the non-irradiated CFD2 CH0. Settings are given in the table on the right.

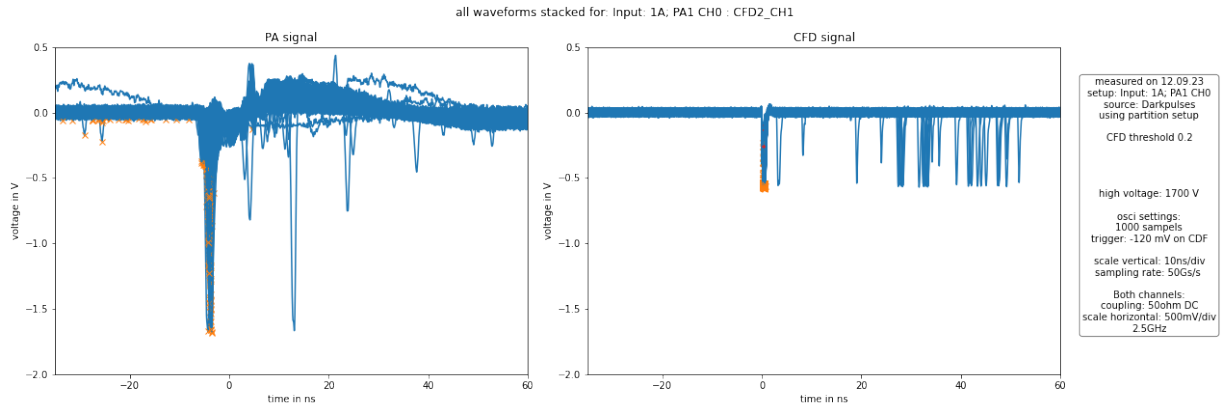


Figure 71: Stacked waveform, on the left the PA signal and on the right the CFD signal for the non-irradiated CFD2 CH1. Settings are given in the table on the right.

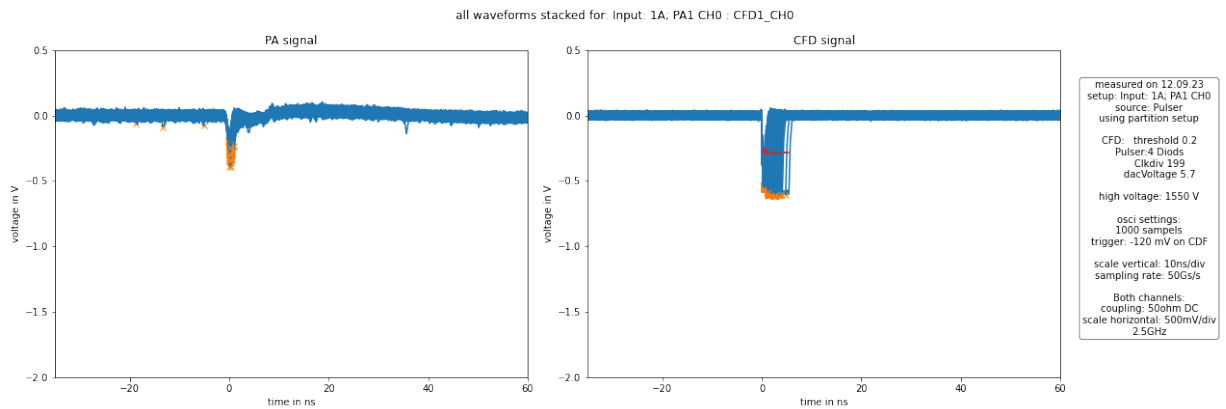


Figure 72: Stacked waveform, on the left the PA signal and on the right the CFD signal for the non-irradiated CFD1 CH0 with pulser. Settings are given in the table on the right.

B Additional plots for Section 5 TDC measurements

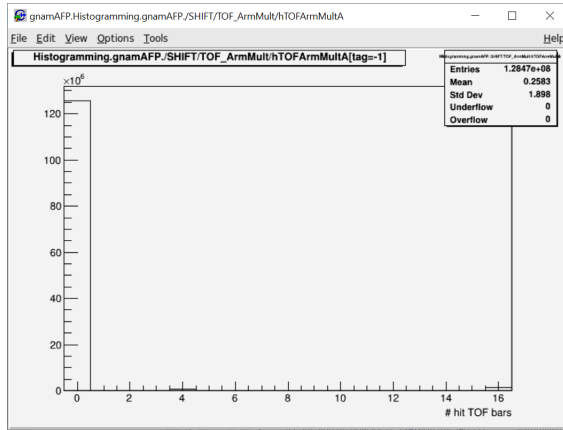


Figure 73: Multiplicity for the 2023 low- μ run 460096 for A-side.

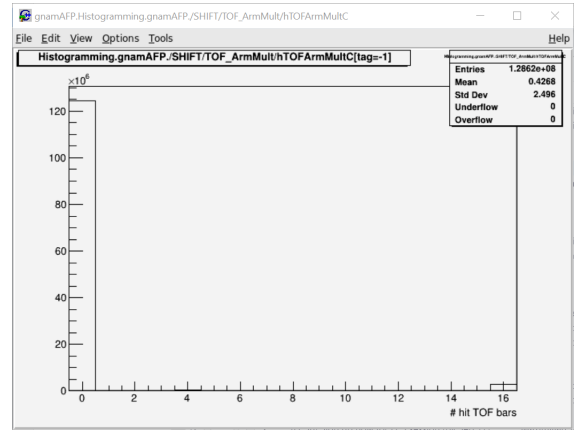


Figure 74: Multiplicity for the 2023 low- μ run 460096 for C-side.

C Additional plots for Section 5.3 Analysis of results

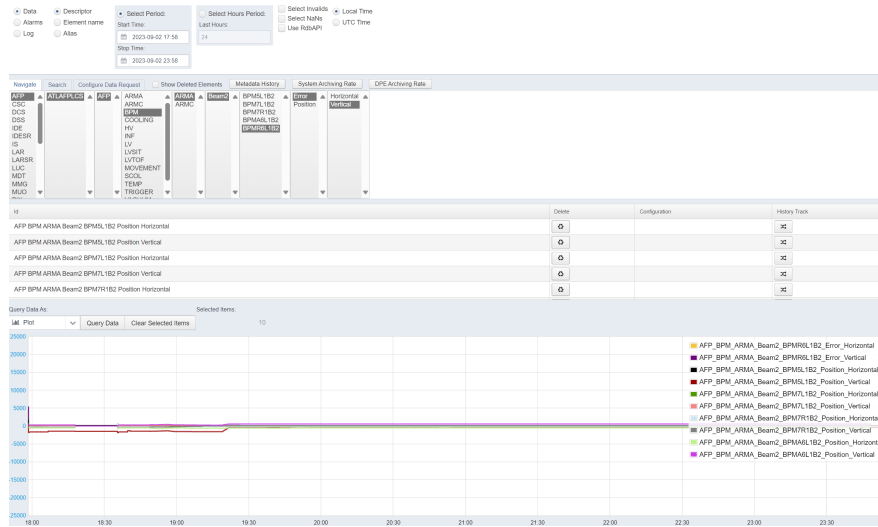


Figure 75: The movement of the beam during the run 460096.

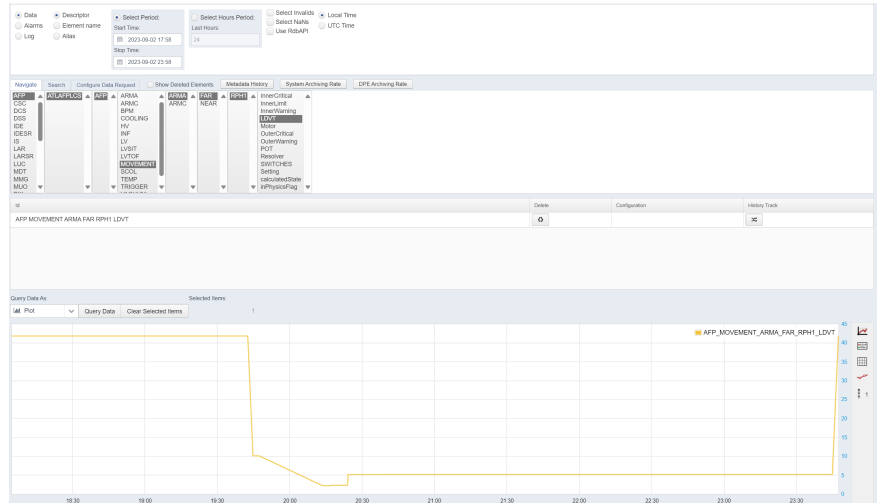


Figure 76: The movement of the AFP detector on A-side during the run 460096.

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