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Tests of trigger detectors based on plastic scintillators coupled to silicon photomultipliers

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Tests of trigger detectors based on plastic scintillators coupled to silicon photomultipliers

Marco Alberto Ayala Torres

Abstract

The performance of several trigger counters based on plastic scintillators with silicon photomultiplier readout is investigated with cosmic rays. Efficiency and time resolution are measured using digital waveform analysis. The obtained results are relevant for trigger subsystems of BM@N and MPD experiments. The results show very high efficiency and good timing performance of the counters.

1 Introduction

In modern high energy physic experiments Silicon Photomultipliers (SiPMs) have a potential to replace traditional Photomultiplier Tubes (PMTs) in many applications, such as trigger detectors, time-of-flight hodoscopes, and calorimetry. Compared to PMTs the SiPM sensors provide similarly high photon detection efficiency and very good time resolution, but in addition they offer compactness, ability to operate in a magnetic field and low power consumption. On the other hand, a single SiPM has a relatively small sensitive area, and therefore arrays of many SiPMs are required in applications where scintillators have large areas.

Because the event rate in many high energy physics experiments is very high, trigger detectors are typically based on either fast plastic scintillators or Cherenkov radiators coupled to PMTs or SiPMs. Basic requirements for such trigger detectors are high efficiency of particle detection and very good time resolution.

In current research we evaluated the response of several simple scintillation counters to cosmic ray particles. The choice of scintillators and SiPMs was based on their availability and relevance to the trigger detector systems in the experiments **M**ulti-**P**urpose **D**etector (MPD) and **B**aryonic **M**atter at the **N**uclotron (BM@N) . One of the goals of my research project during the Summer Student Program at JINR was to obtain broader knowledge of the detector systems and scientific potential of the experiments at **N**uclotron based **I**on **C**ollider f**A**cility (NICA). Therefore, in addition to the details of the test measurements some general information about MPD and BM@N is provided in the sections 4 and 5 of the report, respectively.

2 The Nuclotron-based Ion Collider fAcility (NICA)

NICA is a modern accelerator complex at Joint Institute for Nuclear Research (JINR) in Dubna, Russia. It has been in development and preparing for more than 7 years (NICA White Paper published in 2011). The expected start of the collider operation is in the year 2021.

The NICA project 1 will be developed in three stages and the experimental program will be covered by three detectors: Barionic Matter at Nuclotron (BM@N), MultiPurpose Detector (MPD) and the Spin Physics Detector (SPD) [1].

The project it was designed in three parts. At the first stage, the Nuclotron complex will be upgraded to accelerate high intensity heavy ions beams to the energies $1-5\ GeV/nucleon$ and provide them to the fixed target experiment BM@N.

At the second stage, nucleus-nucleus collisions will be studied in the collider mode by the MPD experiment.

At the last stage, colliding beams of polarized protons and deuterons will be added and become available for the studies of spin physics by the SPD experiment.

In the collider mode the center-of-mass (c.m.s.) energy will be $\sqrt{s}_{NN} = 4\,GeV - 11\,GeV$ for $Au + Au$ and up to 27 GeV for $p + p$ Thus, the experimental program of NICA covers two areas: study of hot strongly interacting nuclear matter at highest baryonic densities and study of proton and deutron spin physics [2].

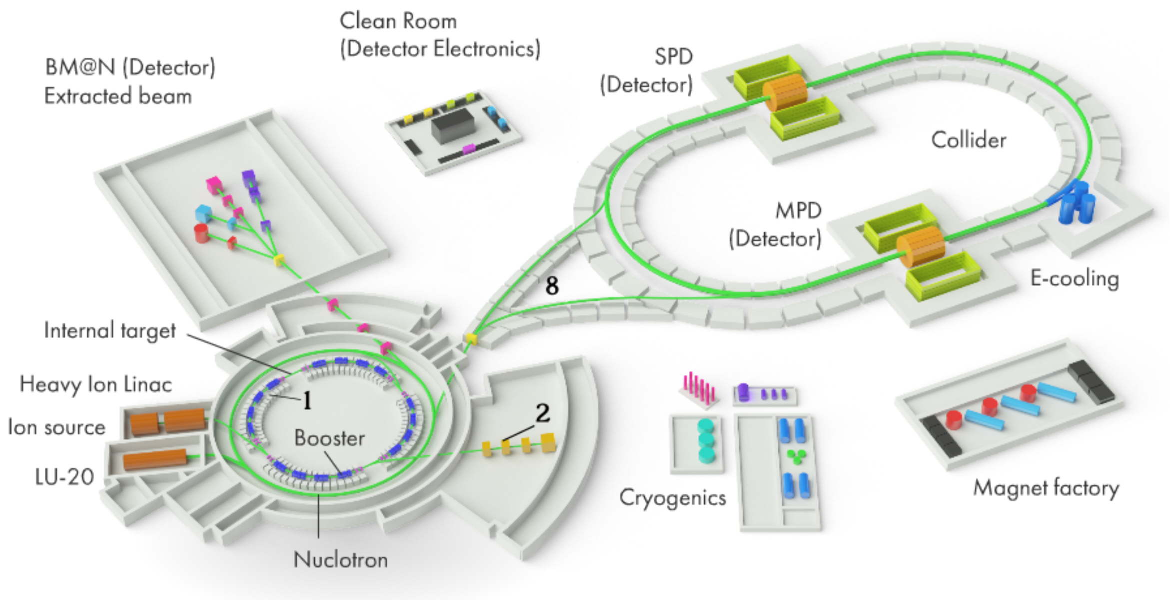


Figure 1: The principal components of the NICA accelerator complex appear. **Image taken from http://nica.jinr.ru/complex.php**

3 Experimental Setup

Cosmic rays are commonly used to test and calibrate the detectors in the absence of a test beam. Compared to radioactive sources, cosmic rays provide considerably lower count rate, but on the other hand, they allow to test thick detectors.

During my project, three series of test measurements were done:

1. Efficiency of a single strip of the planned multi-channel FFD Cosmic Stand which will be used to test the modules of the Fast Forward Detector (FFD) for MPD;

2. Efficiency of a single strip of the Barrel Detector (BD) for BM@N;

3. Time resolution between two small SiPM-based scintillator counters.

All three series of measurements were performed within the same setup with slightly different placement of the counters with respect to each other.

Four SiPMs Sensl Micro FC-60035-SMT were available for the tests. SiPMs of this type with similar front-end electronics are used in the Barrel Detector for BM@N and will be used in the FFD Cosmic Stand. These SiPMs have 6×6 mm^2 sensitive area and 35 μm microcell size (18980 microcells). The breakdown voltage is 24.5 V, while the operation voltage is typically set above the breakdown voltage by $2 - 5$ V (overvoltage). The Fast Output was used for the signal read-out. In this mode the rise time of the output pulses is about 1 ns.

The experimental setup and read-out electronics are shown schematically in fig. 2 and fig. 3, respectively. Tested counters were placed above a trigger counter, which provided the start signal for data read-out. The trigger counter was made of a single scintillator bar and two PMTs (Hamamatsu XP2020). Light from the scintillator was detected by the PMTs at two ends of the bar and the coincidence of the signals from two PMTs provided a trigger for a CAEN N6742 digitizer. A single digitizer module can sample pulses in 16 input channels, and incoming pulses can at the same time have negative and positive polarity. Therefore, 2 channels were used to sample negative pulses from the trigger PMTs and 4 channels to sample positive pulses from the SiPMs of the test detectors.

The sampling frequency of the digitizer was set to highest (default) frequency of 5 GHz, which allowed to read-out 1024-bin-long waveform records with 0.2 ns time bin.

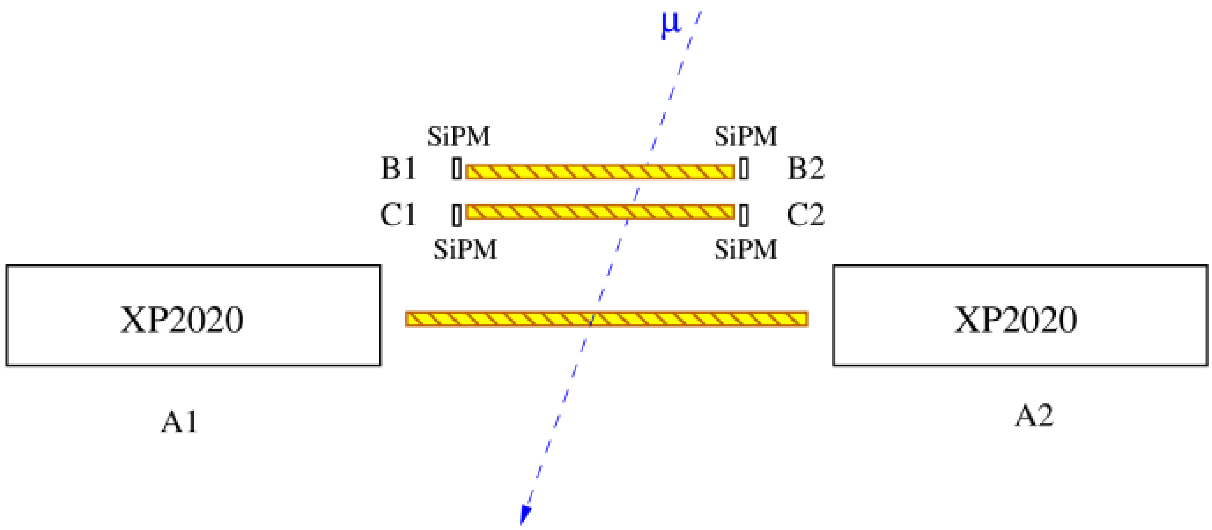
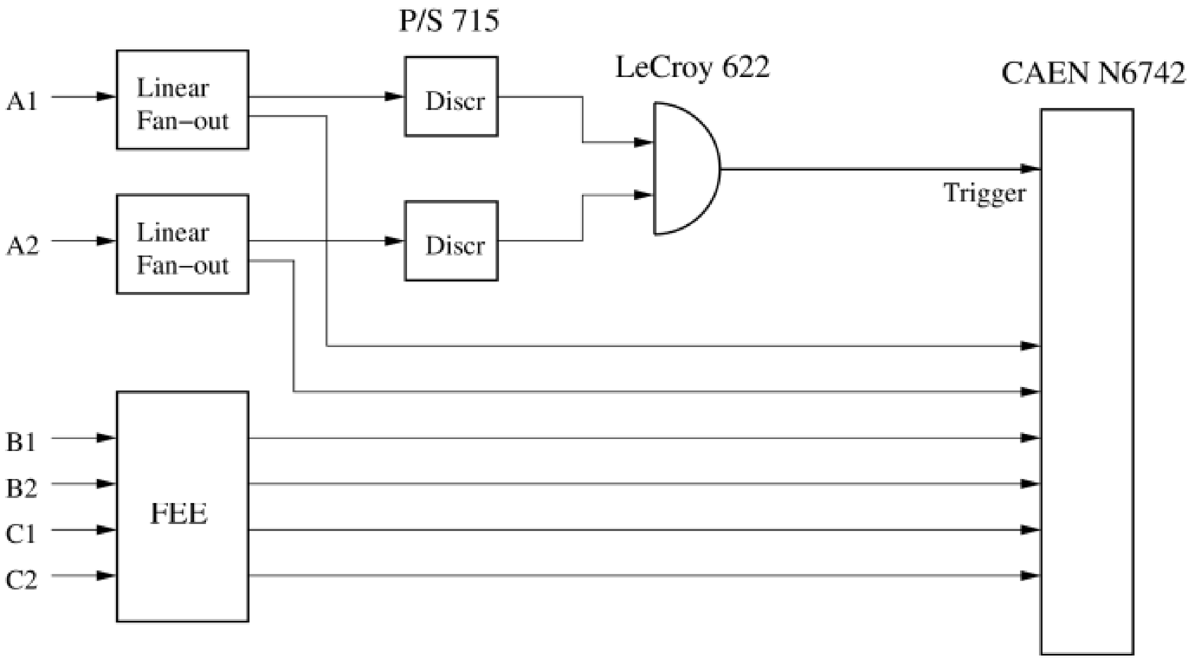


Figure 2: Schematic layout of the experimental setup.

Recorded datasets were analyzed offline on the event-by-event basis. In the offline analysis only those events were selected, in which within a certain time window not only the pulses from the trigger PMTs were present, but also from the test SiPMs (normally all of them if the cosmic muon passed all the counters).

In order to simplify the modifications to the setup between different tests, all the counters were placed in a large black box. Since the breakdown voltage of the SiPMs depends on the temperature and taking into account that during several-hours-long data taking the front-end electronics of the SiPMs and voltage dividers of the PMTs could heat up the air inside the box, the temperature inside and outside of the box was measured and compared before and after data accumulation. No difference in the temperature inside and outside of the box at the end of the data taking period was detected (with 1^o C precision).



(a) (b) (c) (d) (e)

Figure 3: Read-out electronics and components. a) FANOUT system, b) LeCroy 622 and P/S 715, c) CAEN N6742 d) SIPMs power supplies e) PMTs power supplies.

4 Evaluation of the MPD FFD Cosmic Stand strips

4.1 MPD Experiment

MPD is a large collider experiment based on the solenoidal superconducting magnet ($\overrightarrow{B} = 0.66\ T$) designed to study relativistic heavy ion collisions in the energy range $\sqrt{s}_{NN} = 4\ GeV - 11\ GeV$ [3]. Existing experimental data suggest that nuclear matter created in heavy ion collisions at high energies can have such a combination of temperature and baryon density that quarks and gluons are no longer contained in baryons, but form the Quark-Gluon Plasma (QGP). At NICA energies the produced nuclear matter has very high baryon density and might be at mixed phase between hadronic phase and QGP.

In order to establish a possible transition to the deconfinement phase, the experiments measure several observables, such as irregularities in strange particle production, change in the hydrodynamic flow of nuclear matter, and high event-by-event fluctuations in the number of producing particles. Therefore, the experiments like MPD have to provide nearly 4 angular coverage and should be able to detect hundreds of particles produced in a single nucleus-nucleus collision at high energies.

The design of the MPD allows the detection of charge hadrons, electrons and protons in heavy-ion collisions at high luminosity. The leptons resulting from the decay of mesons, provide information about the Quark Gluon Plasma (QGP) phase structure, while the detection of photons allows to estimate the QGP temperature[1]. Processes studied with MPD were simulated using MpdRoot.

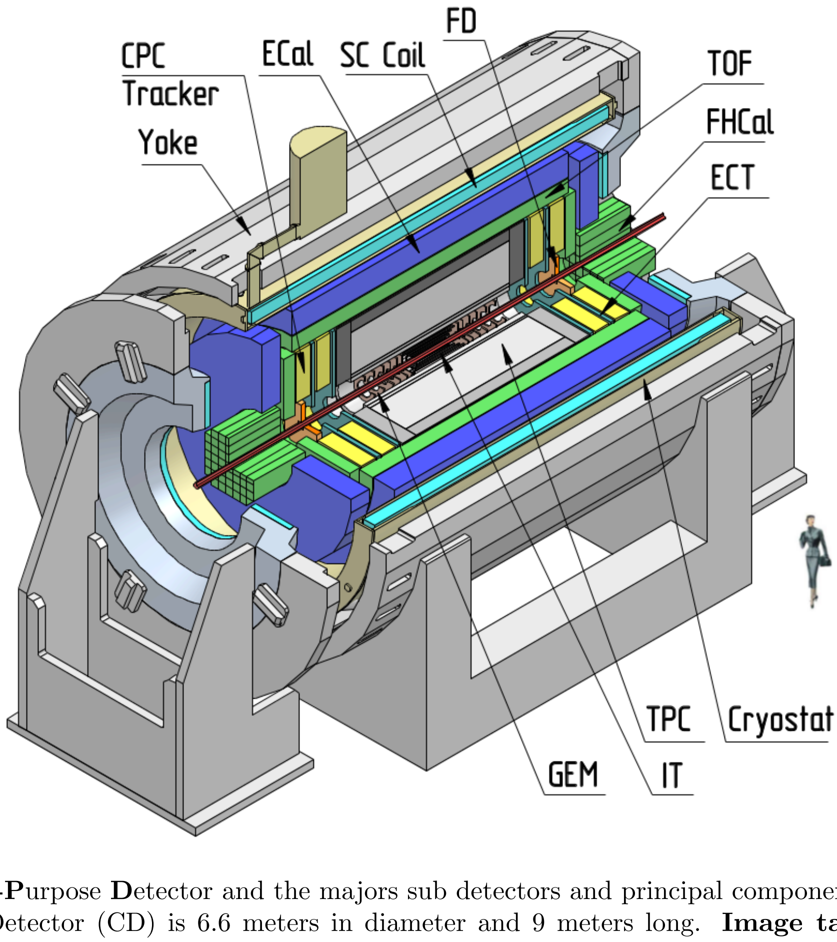


Figure 4: The **M**ulti-**P**urpose **D**etector and the majors sub detectors and principal components appear. The MPD Central Detector (CD) is 6.6 meters in diameter and 9 meters long. **Image taken from http://nica.jinr.ru/projects/mpd.php**

[1]This can provide information about the medium and particle production mechanism

The MPD will have different sub detectors designed that studying characteristics of numerous secondary particles produced in Interaction Point (IP) (registers charged hadrons, light nuclei, electrons and gammas) within a wide interval of pseudorapidity. The majors are the Time Projection Chamber (TPC), Time Of Flight (TOF) system, the Electromagnetic Calorimeter (ECal), Zero Degree Calorimeter (ZDC), the Inner Tracker (IT), the End Cap Tracker (ECT), and two forward spectrometers based on toroidal magnets (fig. 4) [3, 4]. They will detect particles produced in mid-rapidity region. Trigger for the read-out of different sub-detectors will be formed by the **F**ast **F**orward **D**etector (FFD), which in addition is designed to provide start time information for the time-of-flight measurement.

FFD will consist of 40 modules, each of which has a 10 mm thick Lead converter and 15 mm thick quartz radiator. Test and initial calibration of such thick detectors cannot be done with radioactive sources and require either a test beam or cosmic ray calibration.

4.2 FFD Cosmic Stand

The purpose of the FFD Cosmic Stand is to provide a test setup for evaluation of the response of the FFD modules with cosmic muons. At the time of my Summer Student Program the FFD Cosmic Stand was in the early stages of preparation.

The selection of cosmic muons in the stand will be done by four planes of scintillator counters: X1 and Y1 planes at the top of the stand, and X2, Y2 planes at the bottom of the stand. The FFD modules will be placed between the top and bottom pairs of planes. Each plane of the stand will cover $50 \times 50\ cm^2$ and will be composed of 10 scintillator strips $50 \times 5 \times 1\ cm^3$. Light from scintillator strips will be detected at two ends by two SiPMs Sensl Micro FC-60035-SMT. Because the SiPMs have $6 \times 6\ mm^2$ sensitive area, while the cross section of the strip is $50 \times 10 mm^2$, no more than 7% of incoming light can be collected by each of the SiPMs.

Whether the signal from SiPMs will have sufficiently high amplitude to allow efficient detection of cosmic muons was the subject of the tests with FFD Cosmic Stand strips.

4.3 Efficiency measurement

Two cosmic stand strips were tested in the configuration shown in fig. 5. Scintillator $240 \times 10 \times 5 mm^3$ was used in the trigger counter.

The SiPMs were placed at the ends of the strips without optical grease as will be done in the actual FFD Cosmic Stand. In order to increase the efficiency of the individual strips in the FFD Cosmic Stand the analog signals from the two SiPMs will be linearly summed and after that sent to a discriminator. In our test we simulated this linear fan-in in the offline analysis by adding two digitized waveforms within pairs B1, B2 and C1, C2 as illustrated in fig. 6. The summed B1+B2 and C1+C2 waveforms were then processed in amplitude and noise analysis.

The amplitude distributions of the signals were measured with two combinations of bias voltage for SiPMs and voltages for the FEE two stage amplifiers:

1. bias voltage of 27.0 V and amplifier voltages 7.0 V, 7.0 V;
2. bias voltage of 29.0 V and amplifier voltages 6.0 V, 6.0 V.

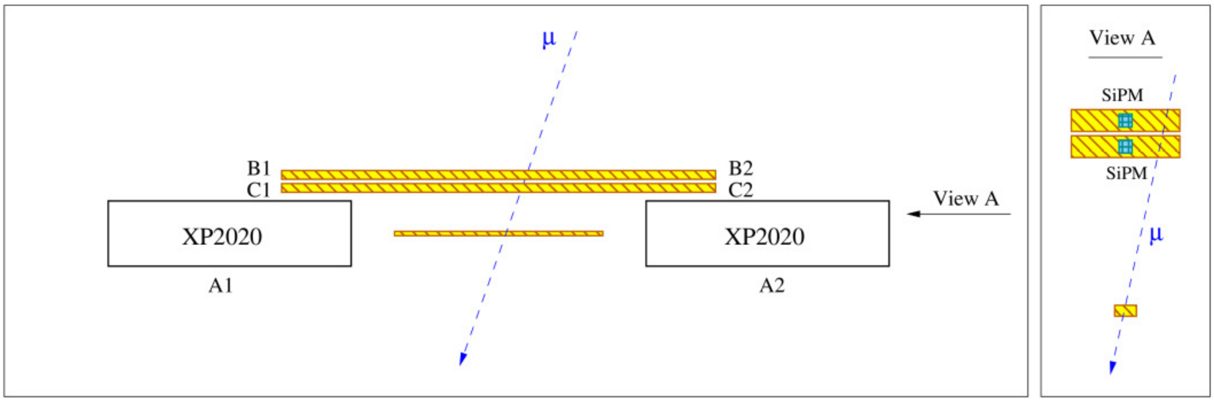
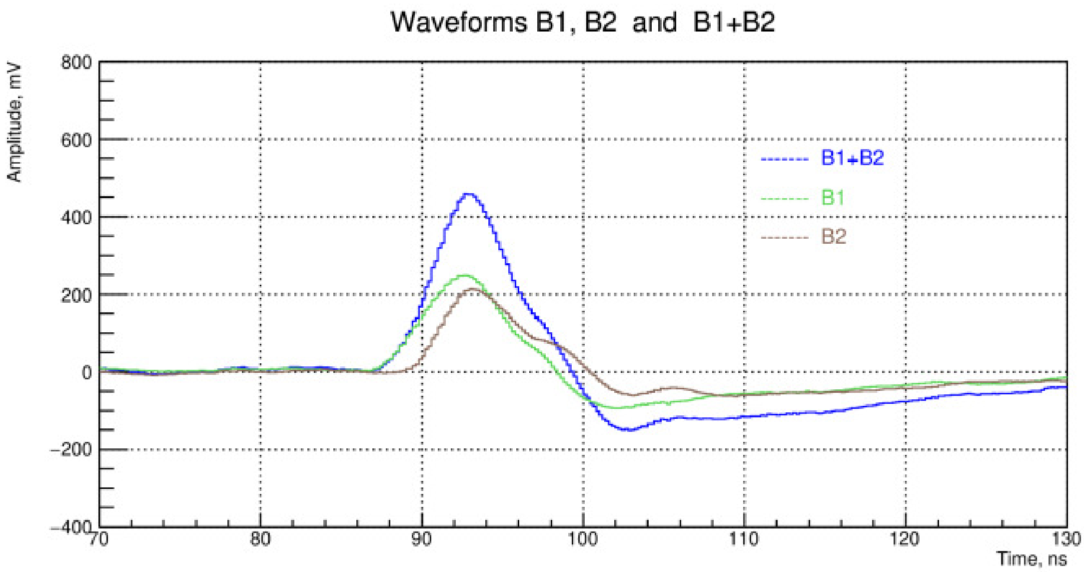
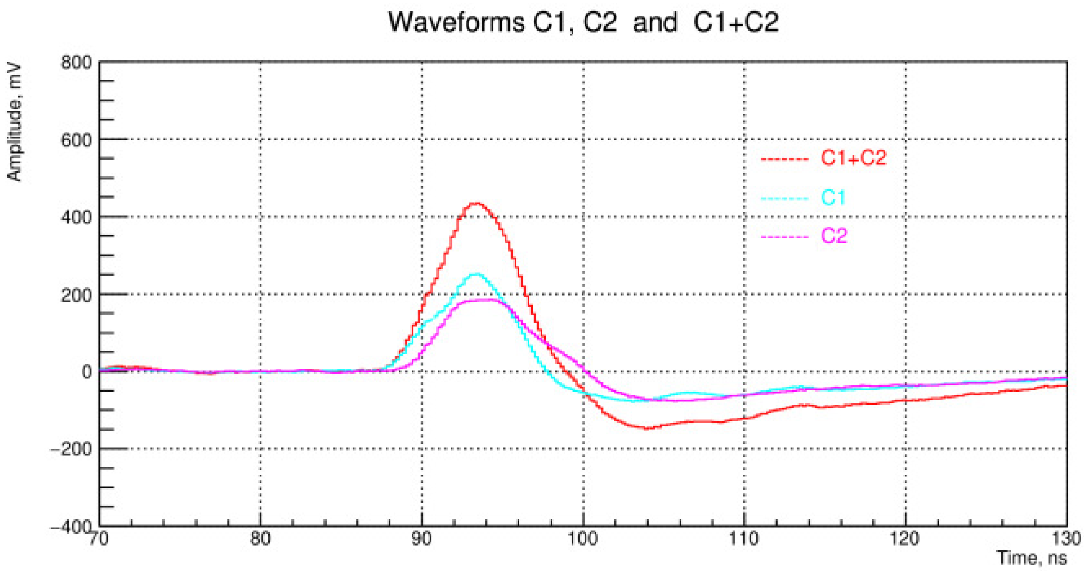


Figure 5: Placement of the counters in the cosmic stand efficiency measurement.



(a)



(b)

Figure 6: Digitized pulses from single SiPMs and summed waveforms.

The second combination of voltages resulted in higher signals from the detectors (fig. 7, two top pictures). Events for the amplitude distribution B1+B2 were selected by requiring large pulses in C1+C2 and vice versa. One can see that the amplitude distributions of B1+B2 and C1+C2 are similar. Additional events with low signals in B1+B2 can be understood taking into account the geometry of the test setup. Some of the cosmic muons can cross the counter C without crossing the counter B.

In addition to the geometry shown in fig. 5, the measurement was repeated with a different position of counters B and C relative to the trigger counter A. In the second case the counters B and C were shifted off center by 10 cm. No significant change in the amplitude distributions was observed, which suggests a good uniformity of the response (fig. 7, two bottom pictures).

With a threshold set to $50 - 100$ mV one can expect high detection efficiency if the overvoltage is set close to a maximum allowed value (bias voltage $+29.0$ V). However, higher overvoltage will increase the rate of noise pulses.

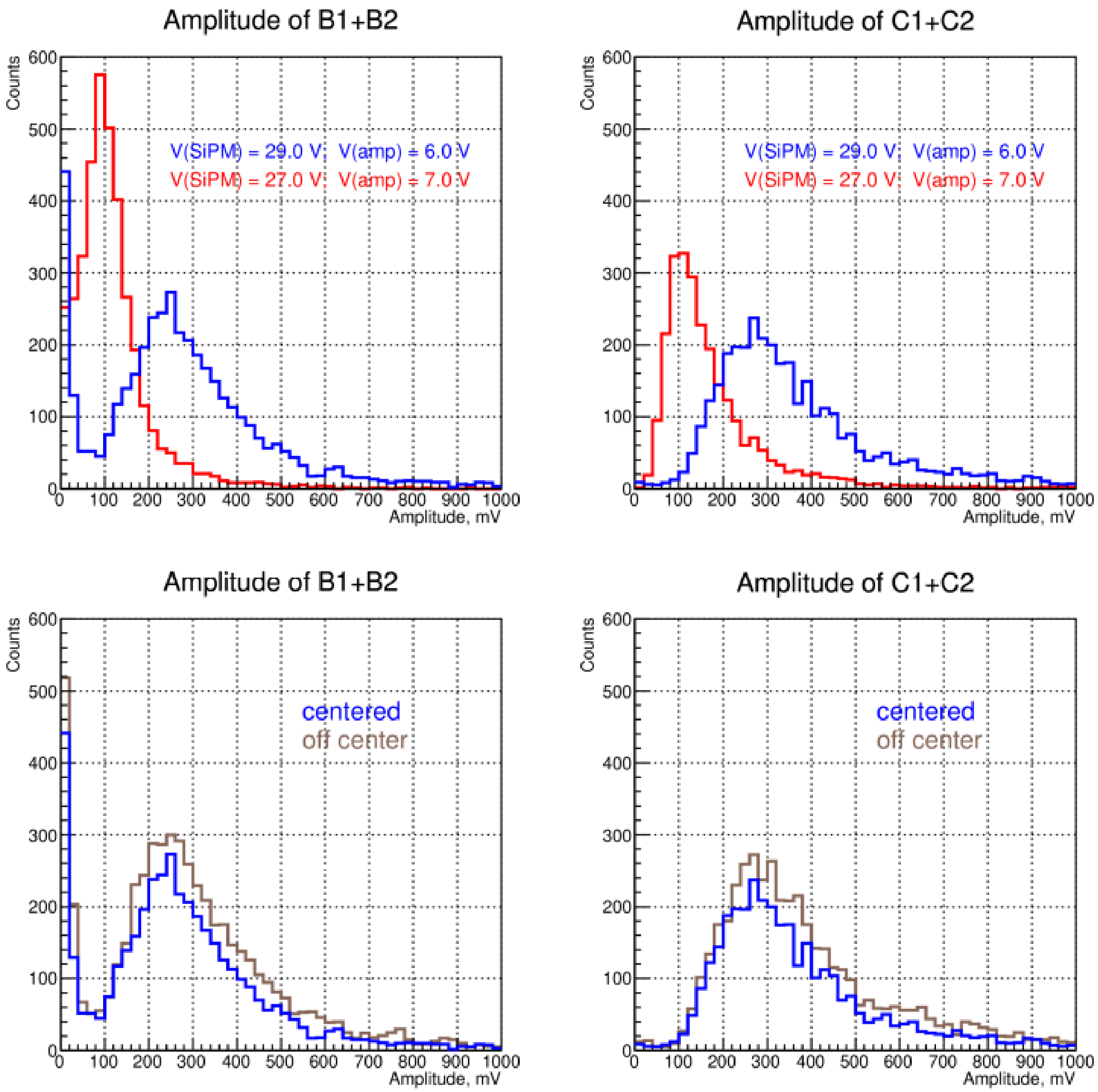


Figure 7: Amplitude distributions of the summed pulses.

4.4 Noise rate estimation

Overall duration of the recorded waveforms was 204.8 ns with pulses from cosmic rays appearing in the region $70 - 150$ ns (as can be seen in the examples in fig. 6). The time window, which precedes this region, was used to estimate the rate of noise pulses. Time window of first 40 ns ($0 - 40$ ns) was chosen.

This estimation was done for the dataset with high bias voltage settings and thresholds 50 mV, 75 mV and 100 mV. In total 38933 events were recorded with high bias voltage settings. Among these events the count of events when within the time window $0 - 40$ ns there was at least one pulse above the threshold of 50 mV, 75 mV and 100 mV was $144, 12, 2$ and $1096, 77, 4$ for counters B1+B2 and C1+C2 respectively.

From these numbers the probability to have 0 counts above threshold $P(0)$ within time window $T = 40$ ns was calculated, and assuming Poisson statistics one can estimate an average number of pulses above threshold within the selected time window as $-log(P(0))$. Noise rate in a single cosmic stand strip is then

$$N_1 = -\log P(0)/T. \tag{1}$$

Low data statistics allow one to estimate the noise rate only by the order of magnitude.

For the high overvoltage settings one can expect the noise rate from a single cosmic stand strip N_1 of about $10^5 - 10^6, 10^4 - 10^5, 10^3$ per second for the threshold values of 50 mV, 75 mV and 100 mV respectively.

Because each of the X1,Y1,X2,Y2 planes of the FFD Cosmic Stand will consist of 10 such strips, the rate of noise counts in each plane will be 10 times higher, and the overall expected $4 - fold$ coincidence rate is

$$N_{noise} = 4\tau^3(10\ N_1)^4, \tag{2}$$

where τ is a coincidence time window in the FFD Cosmic Stand, which will be chosen within the range of $20 - 40$ ns.

For the thresholds of 75 mV and 100 mV the noise count rate is expected to be less than 1 Hz.

One can conclude that despite the small active area of the SiPM compared to the cross-section of the strips, the response of the tested cosmic stand strips should meet the requirements of efficient detection of muons with a low noise rate.

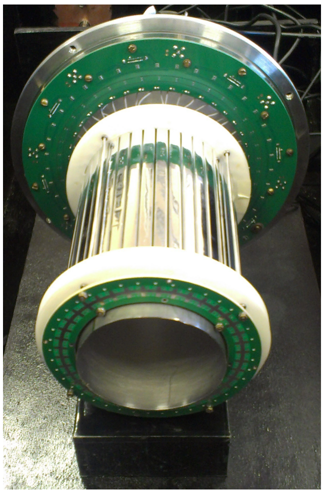
5 Evaluation of the BM@N Barrel Detector strips

5.1 BM@N Barrel Detector

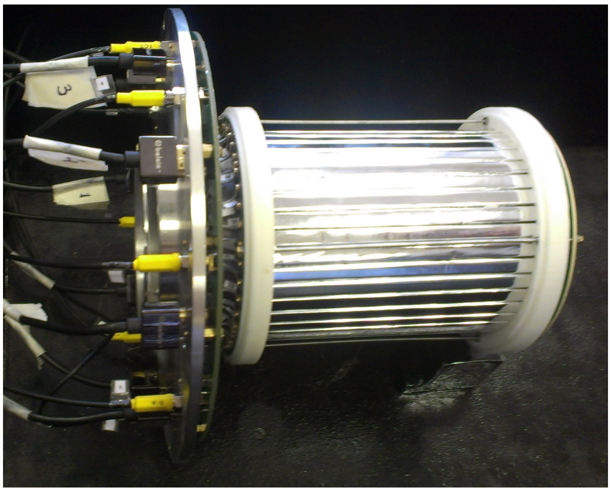
BM@N is the first experiment at the accelerator complex of NICA[5]. The experiment will study interactions of relativistic heavy ion beams with fixed targets.

The Nuclotron will provide a variety of beams from protons to gold ions with energies ranging from 1 to 6 GeV per nucleon. The spectrometer consists of several tracking, time-of-flight and calorimeter sub-systems and will measure charged particle spectra, hyperon and hyper-nuclei production and anisotropic flow in nuclear collisions.

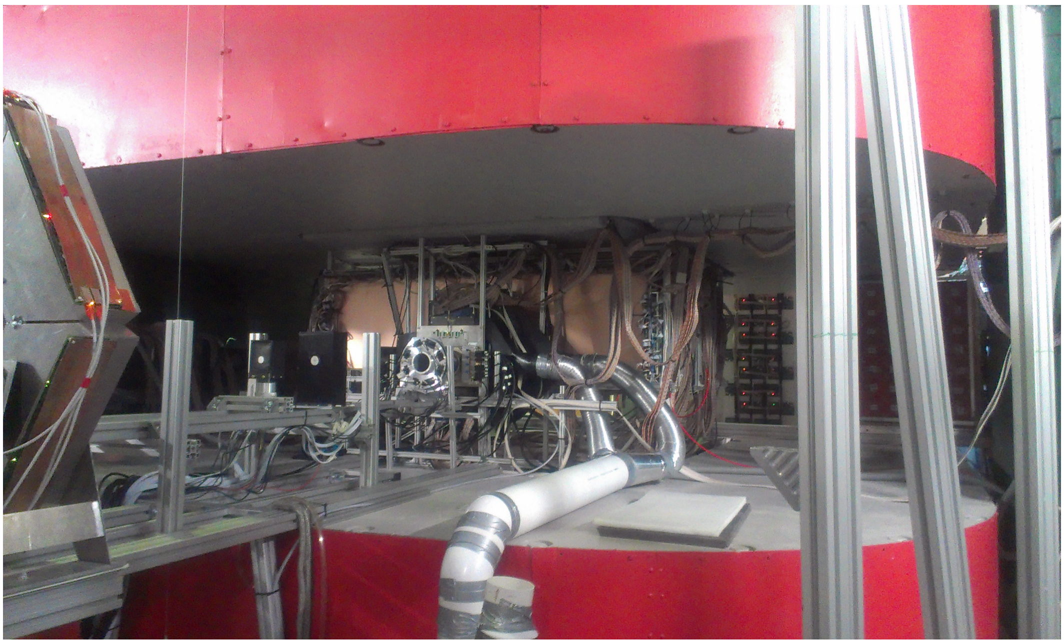
The Barrel Detector (BD) is located in the target area of the spectrometer. It surrounds the target and consists of 40 strips $150 \times 7 \times 7\ mm^3$ made of BC-418 scintillator and wrapped in Al-mylar. Light from each strip is detected on one end by a single SiPM Sensl Micro FC-60035-SMT. Active area $6 \times 6\ mm^2$ of the SiPM matches $7 \times 7\ mm^2$ cross-section of the strip and provides good light collection efficiency [6]. No optical grease between the scintillator and SiPM is used in the actual detector. Picture of the assembled Barrel Detector is shown in fig. 8 and its scheme is shown in fig. 9.



(a)



(b)



(c)

Figure 8: Barrel Detector a) and b). c) Position inside of BM@N

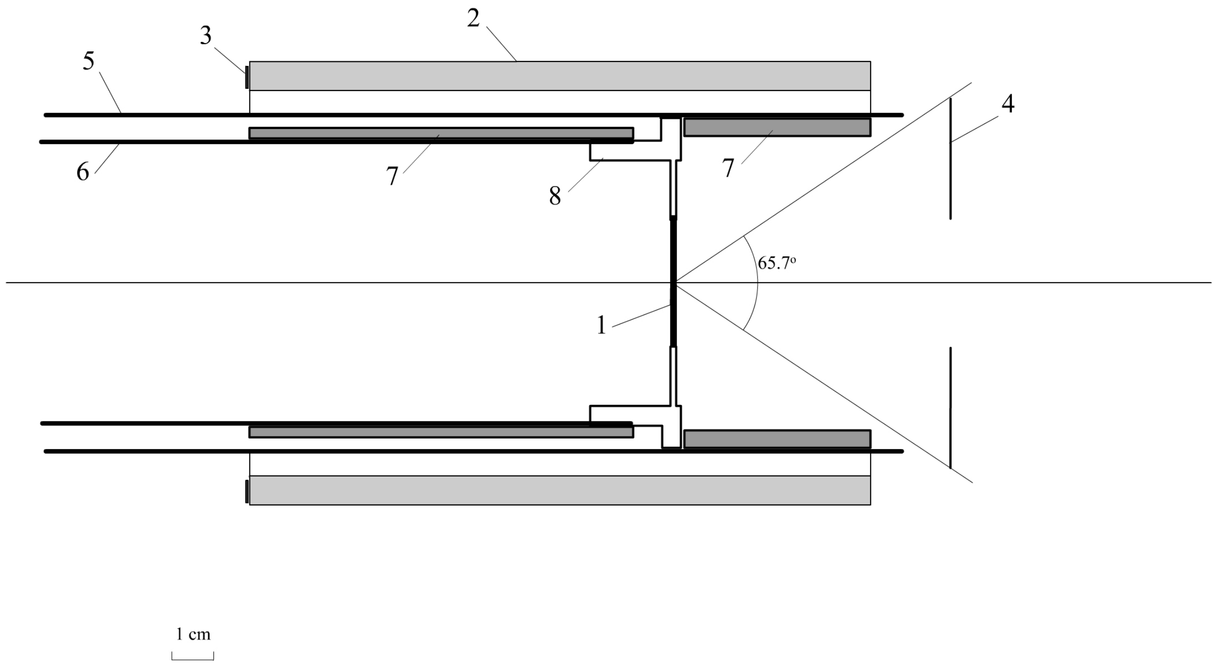


Figure 9: Detailed view of Barell Detector components. 1 - target, 2 - scintillator strips, 3 - SiPMs.

In the BM@N experiment the Barrel Detector should register charged particles emitted in the nuclei-nuclei collisions at large angles close to the target. The number of detected hits on average depends on the impact parameter of the collision and is used to select the most central collisions. Therefore, high efficiency for the minimum ionizing particles is the most important requirement for the BD detector.

5.2 Efficiency of a single strip

The Barrel Detector was fully assembled and used in the experiments in 2017 and 2018 with beams of Carbon, Argon and Krypton. After assembly of the detector four spare strips were left and they were used in the current test. Three of these strips were visually clean, the fourth one was wrapped in Al-mylar with optical grease for some previous tests and looked dirty. It was expected that light collection in this strip will be poor, but it was nevertheless also included in the measurement. Placement of the strips with respect to the trigger counter is shown in fig. 10. Two $50 \times 5 \times 1$ cm^3 scintillator strips from the FFD Cosmic Stand were used for the trigger counter.

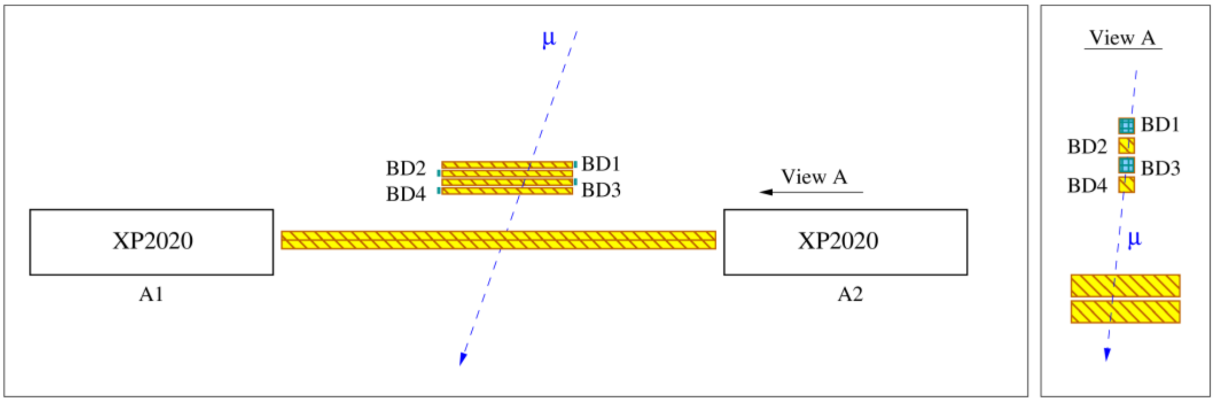


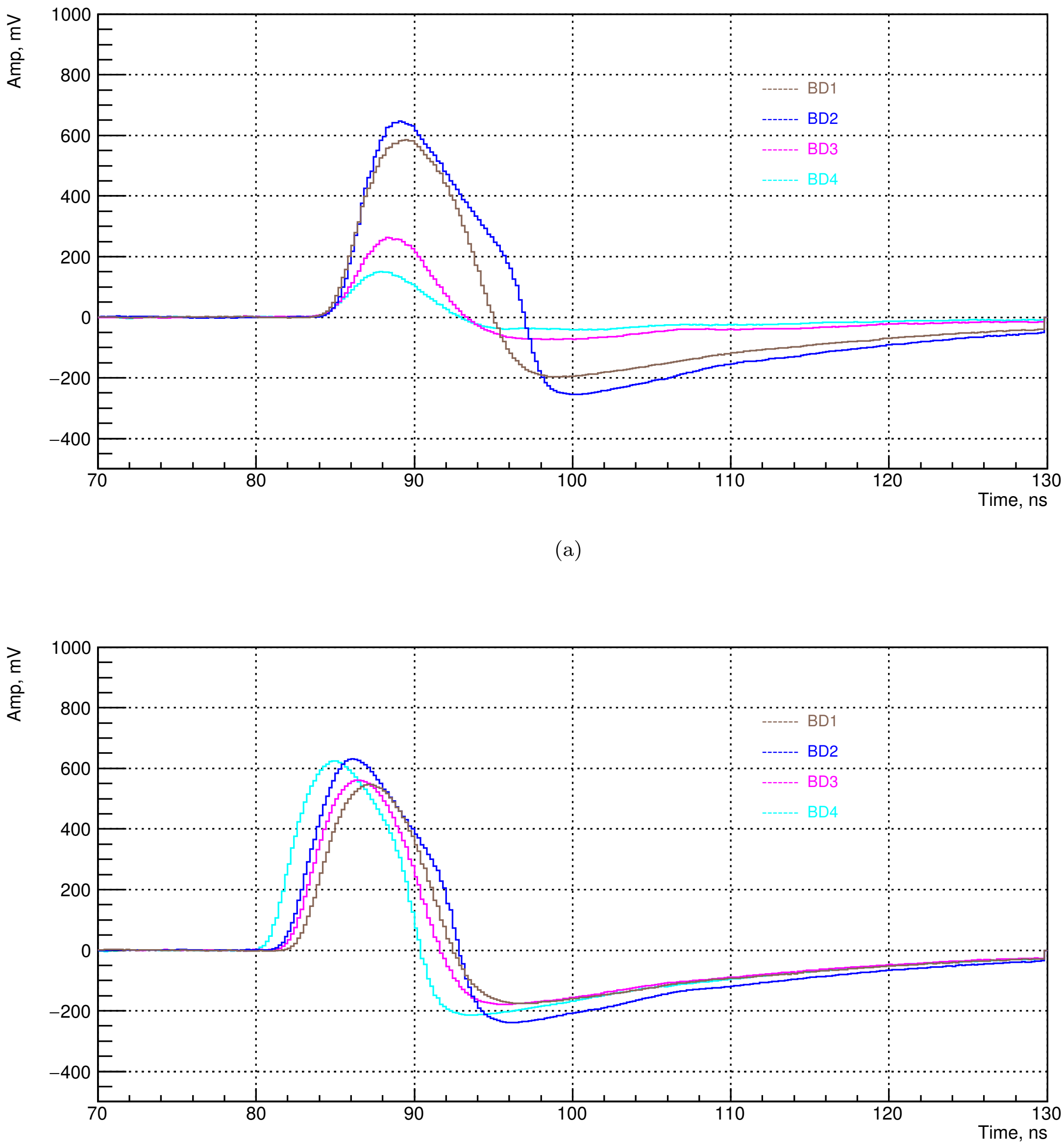
Figure 10: Placement of counters in the evaluation of Barrel Detector strips.

Overvoltage of the SiPMs was set to 1.75 V which corresponds to the voltage used in the BM@N run in March-April 2018. Similarly, the voltage for the two amplification stages in FEE was set to 5.000 V, 5.000 V, exactly as was chosen in the experiment.

The SiPMs B1, B2, C1, C2 were renamed as BD1, BD2, BD3, BD4, but otherwise the readout scheme shown in fig. 3 was left unchanged. The events in which both PMT's and at least three of the BD strips showed signals above the noise level were selected in the analysis.

Typical analog pulses from each of the BD strips and pulse height distributions are presented in fig. 11.

In the BM@N run in March-April 2018 the pulse height of the signals from BD was obtained by measuring time over a certain threshold. Such an approach allows one to extend the linearity of the response to the pulses which would saturate an ADC or a waveform digitizer.



(a)

(b)

Figure 11: Digitized pulses from BD Strips.

In order to model such an approach in the current test, the pulse height distributions presented in fig. 12 show the distributions of the width of the pulses above the threshold of 50 mV.

Comparison of the pulse height distributions measured in this test with the distributions obtained in the actual experiment exceeded the scope of this study.

Amplitude distributions from four tested BD strips are shown in fig. 13. The strip dirty from optical grease (BD3), as expected, showed poor resolution. The pulse height spectrum from the strip BD2 represent the most clean measurement of the efficiency, because high signals in BD1 and BD4 would guarantee that cosmic muon fully crossed BD2.

As a conclusion of this test one can state that detection efficiency for minimum ionizing particles if they fully cross the BD strips should be close to 100%.

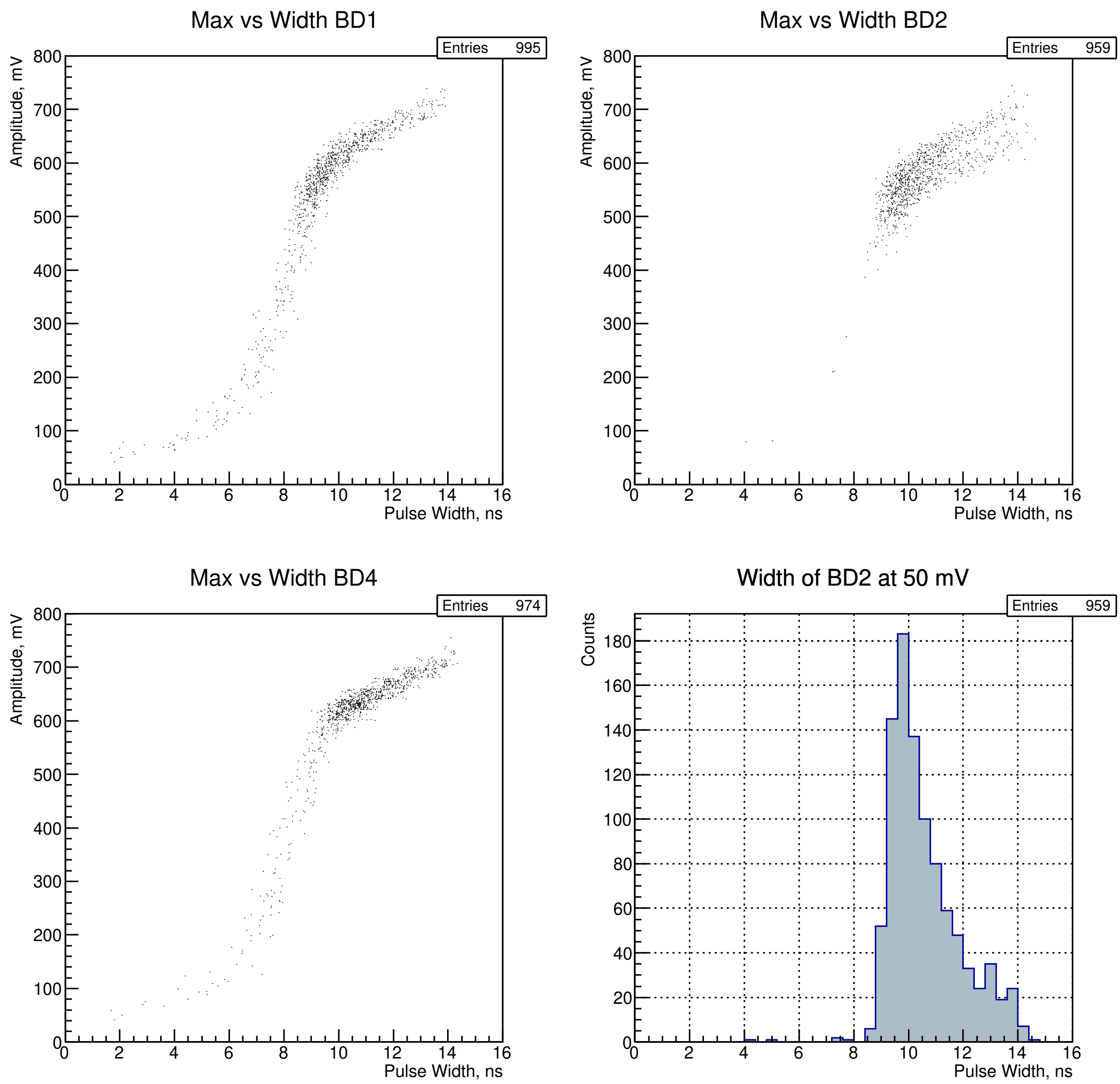


Figure 12: BD Strips: pulse width versus amplitude

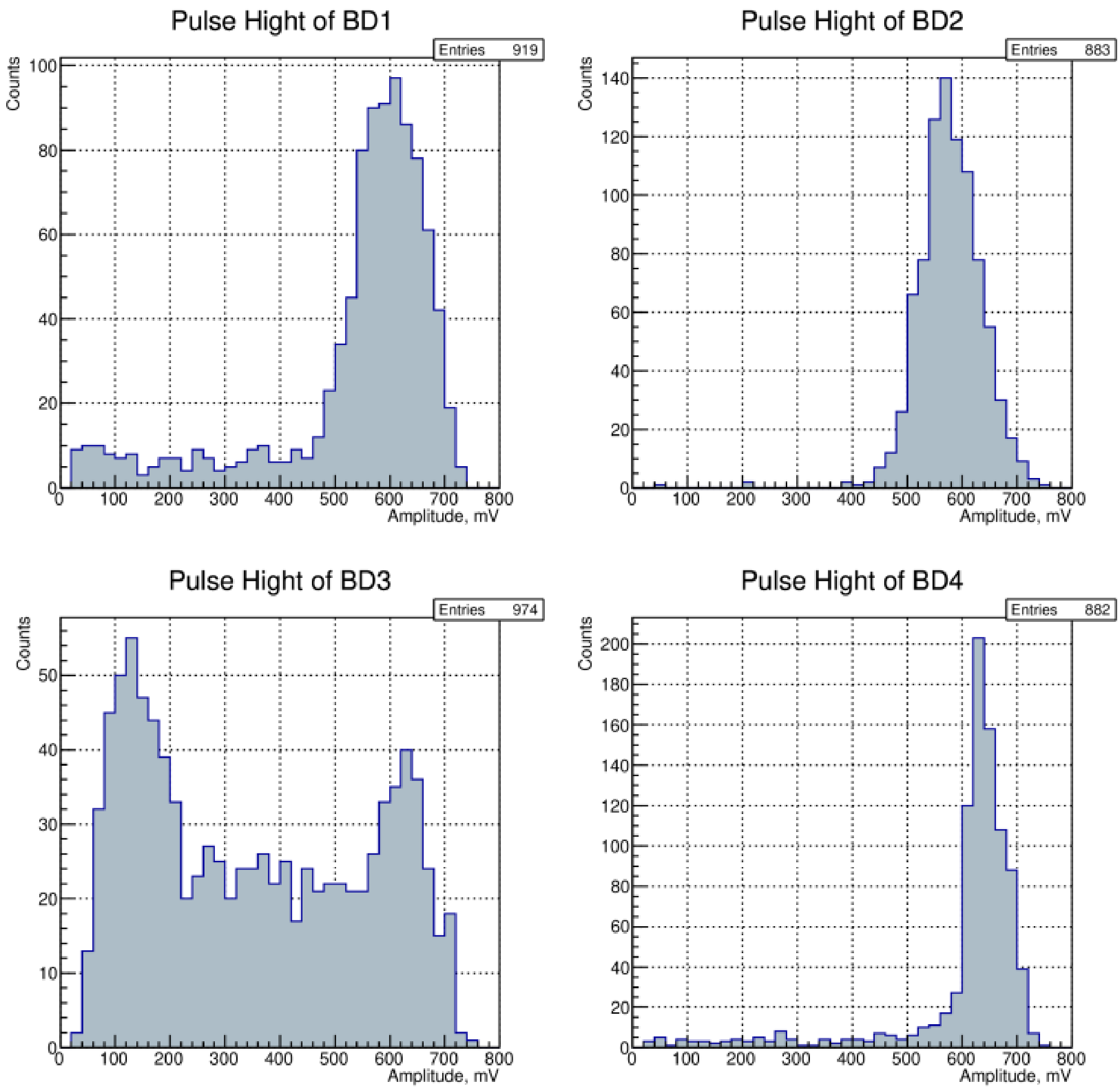


Figure 13: Amplitude distributions of the signals from BD strips.

6 Time resolution tests

6.1 Timing trigger detectors in MPD

The efficiency of the interaction trigger in MPD provided by the FFD sub-system will be close to 100% for central collisions of heavy nuclei, such as $Au + Au$, but significantly lower for peripheral collisions of heavy nuclei, proton-proton collisions and collisions of light nuclei [7]. This reduction of efficiency is due to limited acceptance of the FFD and much lower particle multiplicity in collisions of protons or light nuclei.

In order to increase the efficiency for low multiplicity events, the MexNICA Group [8] of the MPD collaboration proposed to add to the setup another detector, **Be**am-**Be**am Counter Detector (BE-BE), with functionality similar to the FFD, but with larger acceptance. The proposed BE-BE detector [8] is based on an array of hexagonal plastic scintillators and light sensors. SiPMs are considered among possible light sensors of the detector.

The BE-BE detector will provide not only the Level-0 trigger, but can enhance MPD capability to determine centrality of the events and improve reaction plane resolution. In addition, similar to the FFD, the BE-BE detector can provide start time for time-of-flight measurements.

Therefore, time resolution of scintillator counters with SiPM light sensors was one of the points of interest to me during my Summer student program.

6.2 Time resolution measurement

Scintillators with hexagonal shape were not available for the tests, and the measurements were performed with two strips $150 \times 7 \times 7\ mm^3$ of BC418 placed as shown in fig. 14 (two of the three clean Barrel Detector strips from the previous test were chosen). Scintillator $240 \times 10 \times 5\ mm^3$ was used in the trigger counter.

The light produced in each $150 \times 7 \times 7\ mm^3$ strip is detected by two SiPM coupled at the ends of the strip. Two sets of measurements were done, when the SiPM was coupled to scintillators without optical grease, and with optical grease Rhodorsil. In both cases the bias voltage of the SiPMs was set to 26.5 V.

Distributions of the amplitudes of the signals from the detectors are shown in fig. 15.

Even without the optical grease amplitudes of the signals were large and close to the saturation limit of the FEE amplifiers.

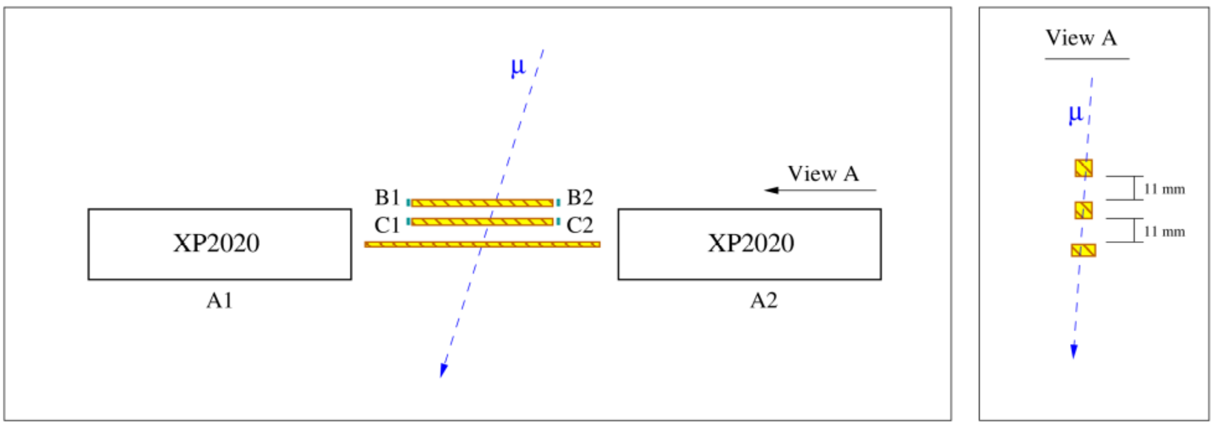


Figure 14: Placement of counters in the time resolution test.

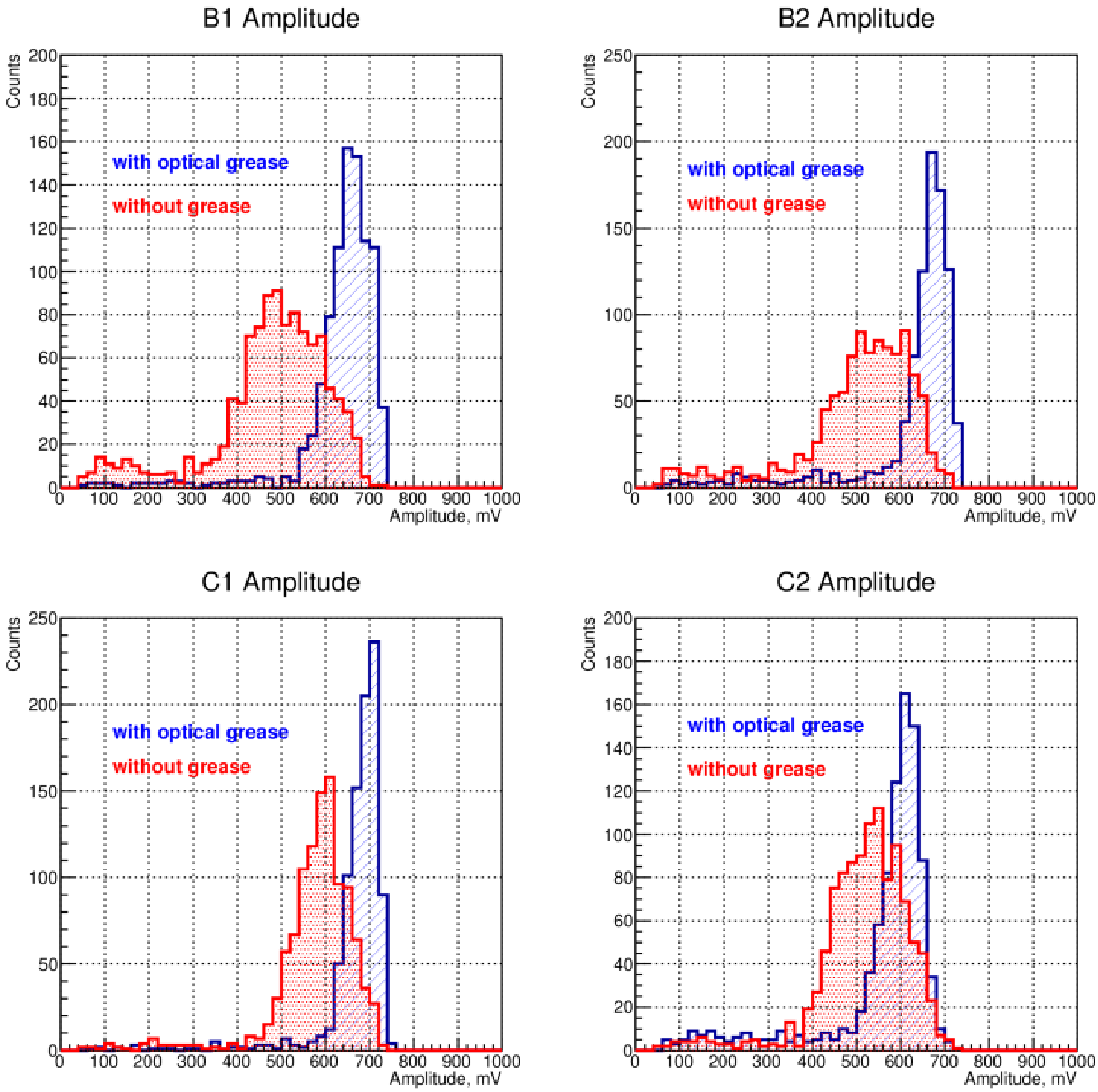


Figure 15: Pulse height distributions in the time resolution test.

The procedure to calculate the arrival time of the signals is illustrated in fig. 16. Two points in which the front of the signal crosses thresholds of 20% and 50% relative to the pulse maximum was determined, and the front of the signal in the region between these two points was fitted with a straight line. The intersection of the extrapolation of this line with the baseline of the waveform was accepted as the signal arrival time ($t0$).

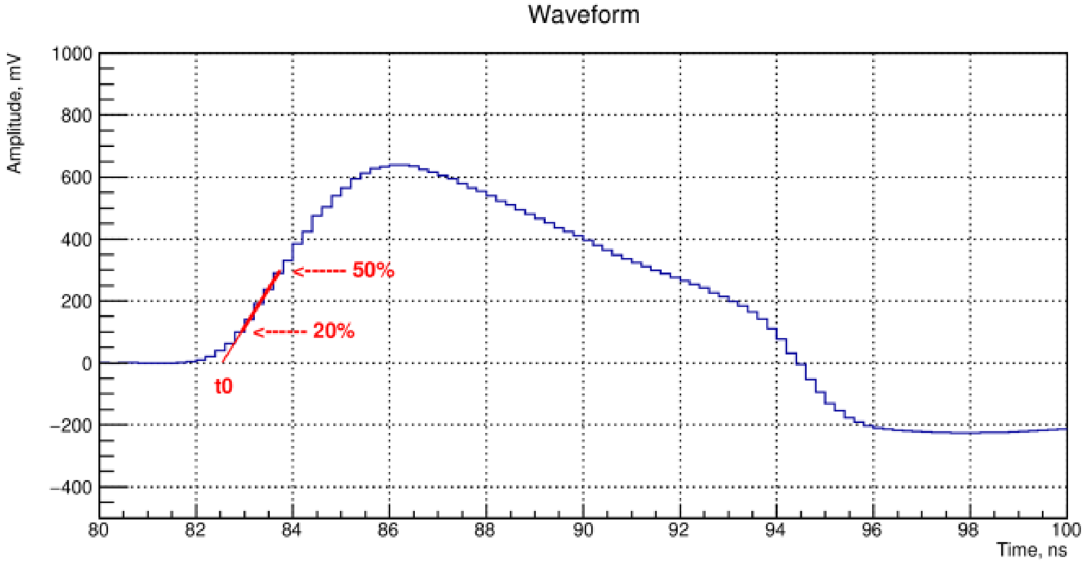
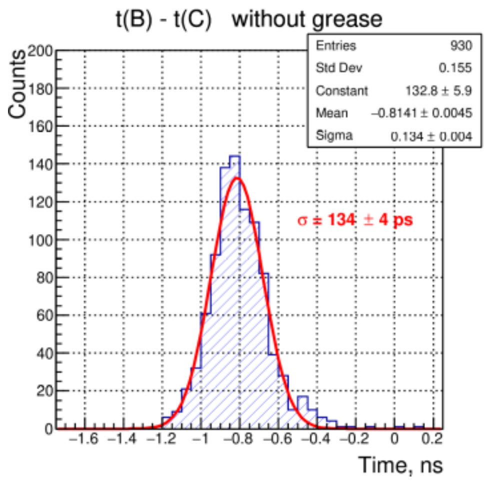


Figure 16: Determination of the signal arrival time.

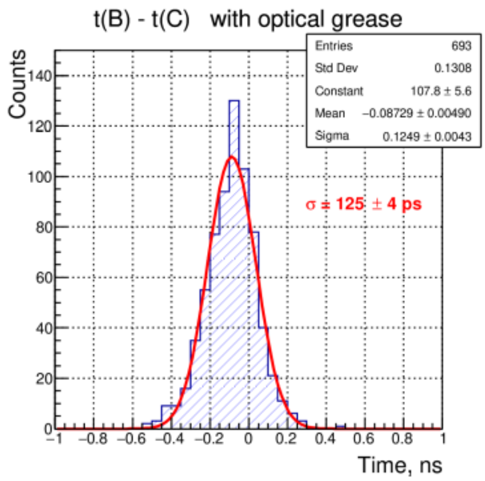
The impact times in the detectors A, B and C were calculated as $t_A = \frac{1}{2}(t0_{A1} + t0_{A2})$, $t_B = \frac{1}{2}(t0_{B1} + t0_{B2})$, $t_C = \frac{1}{2}(t0_{C1} + t0_{C2})$, respectively.

The distribution of the difference between impact times in counters B and C, $(tB - tC)$, is presented in fig. 17. Additional light collected in the case when optical grease is applied improves the time resolution from 134 ± 4 ps to 125 ± 4 ps. The time resolution between pairs of counters A and B, A and C was also determined (250 ± 7 ps, 248 ± 7 ps without optical grease, and 242 ± 8 ps, 246 ± 8 ps with optical grease, respectively).

Assuming that the contribution from the detectors B and C is the same, one can estimate that the time resolution of the single detector is 88 ± 3 ps with the optical grease, and 95 ± 3 ps without. The obtained resolution can depend on the procedure chosen for the calculation of the arrival time of the signals. Other methods of defining the arrival time were not evaluated in this study.



(a)



(b)

Figure 17: Time resolution between counters B and C.

Conclusions

Scintillation counters with SiPMs can serve as simple and at the same time very efficient trigger detectors with high time resolution. They are being used for testing several subdetectors of the MPD experiment, and as trigger detectors in the BM@N experiment. In addition, they are considered as possible detectors in the Beam-Beam counter of the MPD.

In the absence of a test beam, cosmic rays provide a good alternative for testing and calibrating particle detectors. Despite relatively low event rate, even small detectors can be efficiently studied with cosmic rays.

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