Prepared for submission to JINST

DIRC2015: Workshop on fast Cherenkov detectors
November 11-13, 2015
Castle Rauischholzhausen, Germany

Fast SiPM Readout of the PANDA TOF Detector

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Abstract: For the identification of low momentum charged particles and for event timing purposes a barrel Time-of-Flight (TOF) detector surrounding the interaction point is planned for the PANDA experiment at FAIR. Since the boundary conditions in terms of available radial space and radiation length are quite strict the favored layout is a hodoscope composed of several thousand small scintillating tiles (SciTils) read out by silicon photomultipliers (SiPMs). A time resolution of well below 100 ps is aimed for. With the originally proposed $30 \times 30 \times 5$ mm^3 SciTils read out by two single 3×3 mm^2 SiPMs at the rims of the scintillator the targeted time resolution can be just reached, but with a considerable position dependence across the scintillator surface. In this paper we discuss other design options to further improve the time resolution and its homogeneity. It will be shown that wide scintillating rods (SciRods) with a size of, e.g., $50 \times 30 \times 5$ mm^3 or longer and read out at opposite sides by a chain of four serially connected SiPMs a time resolution down to 50 ps can be reached without problems. In addition, the position dependence of the time resolution is negligible. These SciRods were tested in the laboratory with electrons of a ^{90}Sr source and under real experimental conditions in a particle beam at CERN. The measured time resolutions using fast BC418 or BC420 plastic scintillators wrapped in aluminum foil were consistently between 45 and 75 ps dependent on the SciRod design. This is a significant improvement compared to the original SciTil layout.

Keywords: Particle identification methods; Instrumentation and methods for time-of-flight (TOF) spectroscopy; Scintillators; Photon detectors for UV, visible and IR photons (solid-state); Silicon photomultipliers (SiPMs).

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Contents

1 Introduction

PANDA [1] is one of the major experiments at the new Facility for Antiproton and Ion Research (FAIR) at GSI in Darmstadt, Germany, and will be a part of the High Energy Storage Ring (HESR). The HESR will deliver cooled antiproton beams of 1.5 - 15 GeV/c with excellent performance parameters: $\sim 10^{11}$ stored antiprotons yield luminosities up to $2 \cdot 10^{32}$ cm^{-2} s^{-1} and a momentum resolution down to $\delta p/p = 2 \cdot 10^{-5}$. This allows to address fundamental questions in particle and nuclear physics [2], in particular in the charm and strange quark sector: e.g., search for glueballs and other exotic matter states, precision measurements of charmonium and D meson states, excitation of hypernuclei, etc. For these physics goals an efficient particle identification (PID) is required which in the PANDA experiment will be done by Cherenkov detectors of the DIRC type [3]. However, charged particles with $\beta < 0.68$ fall below the Cherenkov threshold and require the application of other PID techniques.

The PANDA barrel time-of-flight (TOF) detector [4] serves several purposes. Due to material constraints no dedicated start detector close to the interaction point will be available in the PANDA experiment and the PID of low momentum charged particles has to be done with a relative timing technique [5] using at least two tracks. This requires an excellent time resolution which is also necessary to provide precise time stamps for each track. Since the PANDA data acquisition (DAQ) will run in an untriggered mode it is essential to do the event building already at a very early stage in the DAQ chain and discriminate against less important events. This can be achieved by software triggers, but at an average interaction rate of 20 MHz a time resolution of $\sigma_t < 100$ ps is needed to correctly assign different tracks to their corresponding events with >95 % efficiency.

Further, a detector with high time and spacial resolution outside the central trackers and in front of the electromagnetic calorimeter provides seeds for the track finding algorithms, can serve to detect photon conversion taking place in the inner detectors, and will help to discriminate between charged and neutral particles.

The available space for the barrel TOF detector including its sensors, readout electronics, and support structure is limited to 2 cm in radial direction. The major requirements are a radiation length of <2 %, a time resolution of σ_t <100 ps, and a large solid angle coverage. It will be located just behind the barrel DIRC detector in a radial distance of ~50 cm from the beam axis and cover a polar angle range of $22^\circ < \theta < 140^\circ$ and the full azimuthal angle range. The proposed technical layout is a scintillating tile hodoscope composed of several thousands of plastic scintillator tiles (SciTils) of $30 \times 30 \times 5$ mm^3 or a similar size covering a total area of ~5 m^2. The SciTils should provide a very fast time response and a high light yield. They will be read out at two opposite sides by 3×3 mm^2 silicon photomultipliers (SiPMs) and ASICs, which combine compactness, a high photon detection efficiency, very good timing characteristics, and an immunity to the 2 Tesla magnetic field of the PANDA solenoid.

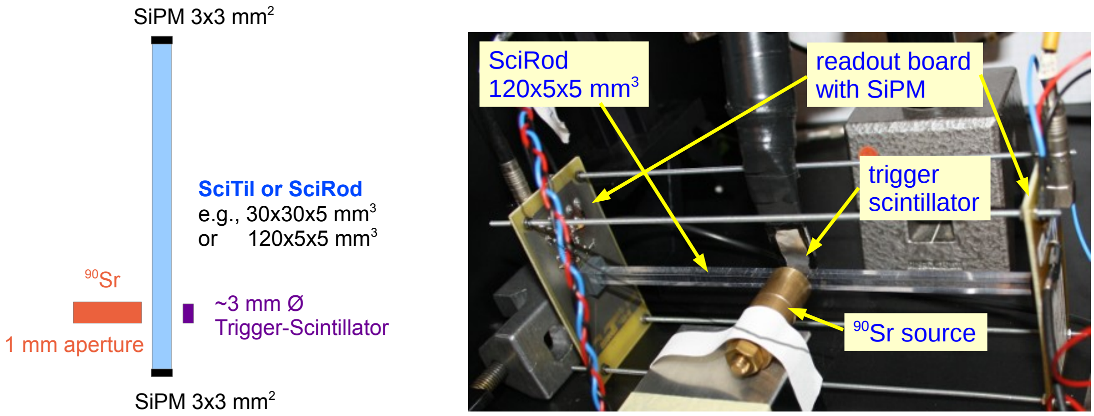
2 Laboratory measurement setup

To identify the optimal SciTil design and readout scheme various scintillator materials and sizes in combination with different SiPM types and arrangements were investigated in a laboratory setup. A schematic and a photograph of the mainly used setup is shown in figure 1: the scintillator (SciTil or SciRod) is irradiated with a collimated ^{90}Sr electron source and read out at opposite sides with one or more SiPMs, which are optically coupled to the scintillator by optical grease.

The ^{90}Sr maximum energy of 2.28 MeV is sufficient that the electrons reach a small trigger scintillator placed just behind the SciTil and opposite to the source. Both the trigger detector and the source can be mounted on an xy-stepper to measure the performance parameters as a function of the position across the SciTil surface. The SiPMs are soldered to small amplifier boards (10× amplification) with connectors for the bias and amplifier voltages and the output signal, which is passively split to measure the timing and the amplitude of the SiPM signals with a VME DAQ system. From the measured time difference $\Delta t = t_1 - t_2$ between the opposite SiPMs the time resolution $\sigma_t = \sigma_{\Delta t}/2$ of the SciTil can be determined, while the integrated signal charge is a measure for the number of detected photo electrons $N_{p.e.}$.

3 Scintillating tiles (SciTils)

The original SciTil design had foreseen a plastic scintillator size of about $30 \times 30 \times 5$ mm^3 read out by two 3×3 mm^2 SiPMs. It was shown [6] that under optimized conditions a time resolution of 82 ps can be reached with a combination of a fast EJ232 plastic scintillator and two KETEK PM3360TS analogue SiPMs centrally place at the opposite rims. With Philips DPC-3200 digital SiPMs time resolutions of 121 ps with a BC408 scintillator and of 90 ps with a EJ228 scintillator were obtained [7]. On the other hand, a position scan across the scintillator surface done by our group shows that the amount of measured photo electrons (p.e.) (figure 2, left plot) depends substantially on the track distance from the SiPMs. As expected, close to an SiPM more p.e. are



(a) schematic (b) photograph

Figure 1: Laboratory setup for time resolution measurements of SciTils/SciRods with a collimated ^{90}Sr source and a small trigger scintillator. The photon readout is done at opposite sides of the scintillator with SiPMs at small amplifier boards. The setup can also be mounted at an xy-stepper.

detected compared to cases when the track traverses the scintillator further away. This gives rise to a time resolution which depends a lot on the track position at the SciTil (figure 2, middle plot): it varies from ~110 ps directly in front of the SiPMs to ~180 ps at the side of the SiPMs with an average time resolution of ~140 ps for the used configuration of a BC408 scintillator and two opposite S12652-050C Hamamatsu MPPCs (SiPMs). In principle, from the time difference between the two SiPMs a position information can be deduced. However, this is not possible in this configuration as seen in the right plot of figure 2. The observed structures in the displayed distributions are caused by the small solid angle coverage of the sensor compared to the full SciTil surface area, which may provoke many reflections of a scintillation photon before it finally hits an SiPM. This deteriorates the time resolution. Our position scan proves that the original SciTil design using a small quadratic-shaped scintillator read out by only two opposite SiPMs is far from optimal.

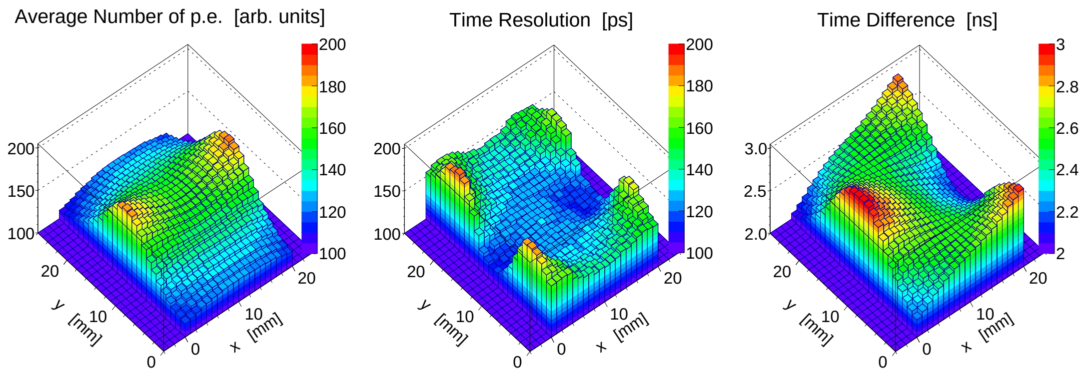


Figure 2: Results of a position scan for the $30 \times 30 \times 5$ mm^3 SciTil with a BC408 scintillator read out by a single Hamamatsu S12652-050C MPPC at the center of opposite rims (y-axis). Plotted are the (uncalibrated) average number of detected photo electrons $N_{p.e.} = \sqrt{N_{pe1} \cdot N_{pe2}}$ (left), the time resolution $\sigma_t = \sigma_{\Delta t}/2$ (middle), and the time difference $\Delta t = t_2 - t_1$ (right).

4 Scintillating rods (SciRods)

4.1 Narrow rods

In a first attempt to improve the time distributions the quadratic-shaped SciTil was replaced by a narrow scintillating rod (SciRod) with a size of, e.g., $120 \times 5 \times 5$ mm^3 read out at the two ends of the rod (see also figure 1). The advantage of this design is that many scintillation photons will be totally reflected along the length of the scintillator, which implicitly leads to a larger solid angle coverage and more collected photons at the SiPMs. Therefore, there will be almost no regions where the photons are reflected several times across the scintillator before they hit an SiPM. On the contrary, most of the photons will reach the SiPMs within a very narrow time window because they all travel about the same distance from their point of creation to the sensor. This should significantly flatten the time difference distribution compared to that of the SciTils and will improve the time resolution.

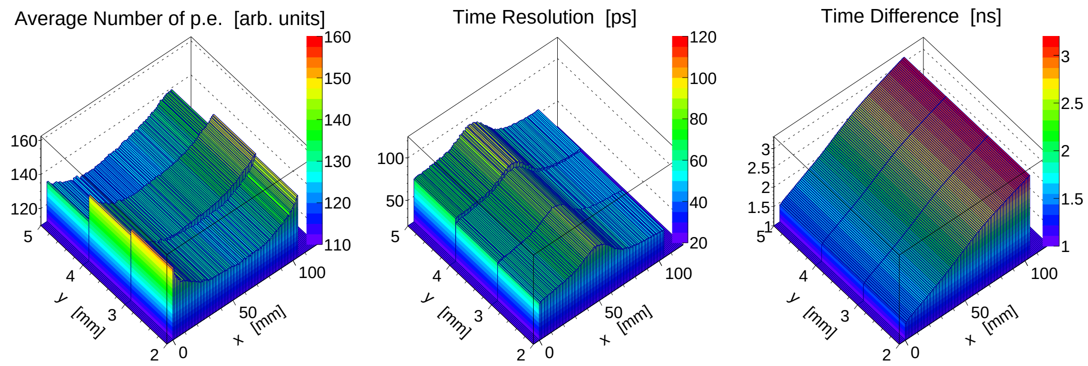


Figure 3: Scan results for a $120 \times 5 \times 5$ mm^3 narrow SciRod with a BC420 scintillator read out by one Hamamatsu S12652-050C MPPC at opposite sides (y-axis): (uncalibrated) average number of detected photo electrons $N_{p.e.} = \sqrt{N_{pe1} \cdot N_{pe2}}$ (left), time resolution $\sigma_{\Delta t}/2$ (middle), and time difference $\Delta t = t_2 - t_1$ (right).

The position scan for a $120 \times 5 \times 5$ mm^3 narrow SciRod displayed in figure 3 shows indeed a much smoother slope in the average p.e. and in the time difference distributions. The latter even allows the determination of the hit position of a traversing particle along the scintillator and thus provides a good position information. The distribution of the time resolution varies only little along the scintillator, with the worst resolution at the rod center. The best time resolution close to the SiPMs goes down to ~55 ps.

In table 1 the time resolutions averaged over $\sigma_t = \sigma_{\Delta t}/2$ measurements of several to many scan points across the scintillator surface are given. From the results it is obvious that with the narrow SciRods time resolutions of well below 100 ps can be reached quite easily even without any optimizations. By trend the time resolution depends on the width and on the length of the rod while the faster BC420 material gives much better results than the BC408 scintillator. In the best configuration with a 5×5 mm^2 cross section rod an average time resolution of ~65 ps was reached. This would correspond to a position resolution of ~20 mm (FWHM).

Table 1: Average time resolutions σ_t in ps for different narrow SciRod configurations. The readout was done with single 3×3 mm^2 Hamamatsu MPPCs at the opposite sides. No wrapping was used for the scintillators.

scintillator size	MPPC	BC408	BC420
$170 \times 5 \times 5$ mm^3	S10362-050P	97 ± 19	
$120 \times 5 \times 5$ mm^3	S12652-050C	81 ± 12	68 ± 10
$50 \times 5 \times 5$ mm^3		83 ± 6	62 ± 5
$120 \times 10 \times 5$ mm^3	S10362-100P	105 ± 18	93 ± 25
$50 \times 10 \times 5$ mm^3	S12572-050P	109 ± 16	

4.2 Wide Rods

The disadvantage of using narrow SciRods for the PANDA Barrel TOF detector is a reduced active area because the wrapping material between the scintillators requires space. In principle this problem can be avoided by the utilization of wider SciRods and reading them out with several SiPMs at the opposite ends. With this setup more scintillation photons will be collected over a wide solid angle and there are almost no regions which do not directly face the SiPMs, similar to the situation in the narrow SciRods. If all SiPMs at one end are connected in series there will be only one readout channel and the number of collected p.e. will be high. In addition the signal rise time will be faster since the total capacity of the sensors is reduced. Overall, a setup with wide SciRods and several SiPMs connected in series should result in a significantly improved time resolution, again with only minor dependence on the track position at the scintillator. A similar setup was used elsewhere [8].

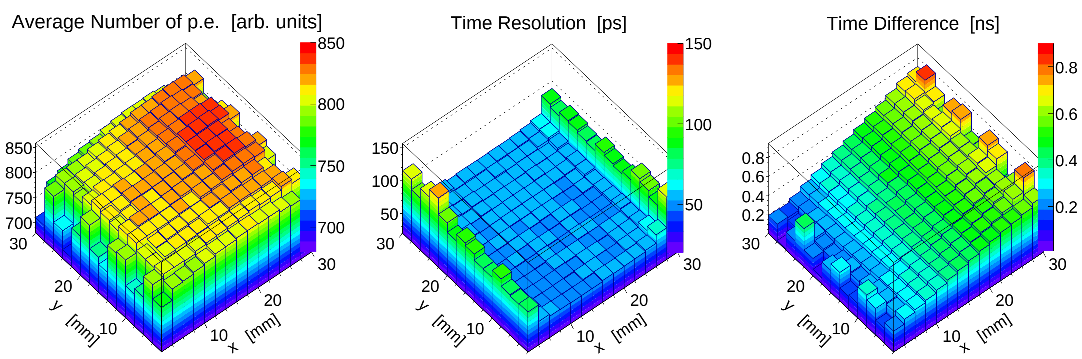


Figure 4: Scan results for a $30 \times 30 \times 5$ mm^3 wide SciRod with a BC420 scintillator read out by four serially connected Hamamatsu S12572-050P MPPCs at opposite sides (y-axis): (uncalibrated) average number of detected photo electrons $N_{p.e.} = \sqrt{N_{pe1} \cdot N_{pe2}}$ (left), time resolution $\sigma_{\Delta t}/2$ (middle), and time difference $\Delta t = t_2 - t_1$ (right).

The results of the position scan for a wide SciRod read out at opposite sides by four SiPMs connected in series are shown in figure 4. The SciRod was of the same size as that of the SciTil discussed in section 3 and in figure 2. Compared to the SciTil the distributions displayed in figure 4 reveal a much smoother dependence on the position, similar to the behavior observed for the narrow SciRods, but with another significant improvement of the time resolution. In particular, the time resolution is almost equal at all positions (except very close to the SiPMs where it is worse for technical reasons). This indicates that wide SciRods with serial SiPM readout are a much better design choice for the barrel TOF detector.

In table 2 the average time resolutions are compared for different scintillator materials and over-voltages of the four Hamamatsu S12572-050P MPPCs at each readout side. The values are obtained from the mean of the resolutions measured at many scan positions across the scintillator surface, while the uncertainties are the standard deviations. The data show that the time resolution gets better when the over-voltage is higher and when the scintillator is wrapped in white paper. The BC418 and BC420 scintillators yield a similar time resolution but it is significantly better than that for the BC408 material. This is consistent with the observation for the narrow SciRods (see section 4.1) and is due to the faster rise and decay times of the BC418/BC420 scintillator material.

Table 2: Average time resolutions σ_t in ps for different wide SciRod configurations with a scintillator size of $50 \times 30 \times 5$ mm^3. Four 3×3 mm^2 Hamamatsu S12572-050P MPPCs were connected in series at the opposite short rims of the scintillator. The given over-voltage is related to the total voltage across all four MPPCs.

wrapping	over-voltage	BC408	BC418	BC420
none	4 V	135 ± 4	92 ± 3	93 ± 4
	6 V	95 ± 2	74 ± 2	72 ± 3
white paper	4 V		79 ± 2	84 ± 3
	6 V		67 ± 2	68 ± 2

More scintillator/SiPM configurations were investigated: various scintillator geometries, with and without wrapping of the scintillator using different materials, and different types of SiPMs from Hamamatsu and KETEK. The measured time resolutions and pulse heights ($N_{p.e.}$) for two wide SciRod designs are listed in table 3. Obviously, with an aluminum foil wrapping the best photo electron yield is obtained, which translates directly into a better average time resolution. With a long scintillator ($120 \times 30 \times 5$ mm^3) a time resolution of 76 ps was measured while with a SciTil sized scintillator ($30 \times 30 \times 5$ mm^3) a resolution of 45 ps was obtained. This is a lot better than the best time resolutions reachable for the SciTil design with only one SiPM per side (see section 3).

Table 3: Average time resolutions and number of detected photo electrons for different wide SciRod configurations. The scintillators were read out at the opposite narrow rims by four 3×3 mm^2 SiPMs (MPPCs) connected in series. Note that the $N_{p.e.}$ values were not calibrated, therefore the values given for the Hamamatsu MPPCs and those of the KETEK SiPMs cannot be compared.

	BC420; $120 \times 30 \times 5$ mm^3 Hamamatsu MPPC S12572-050P			BC418; $30 \times 30 \times 5$ mm^3 KETEK SiPM PM3350TP-SB0		
wrapping	none	white paper	aluminum	none	white paper	aluminum
$N_{p.e.}$ [chan]	658 ± 12	700 ± 15	743 ± 10	321 ± 8	420 ± 3	448 ± 1
σ_t [ps]	83 ± 3	80 ± 2	76 ± 2	53 ± 2	48 ± 1	45 ± 1

5 Test beam experiment

5.1 Setup

The wide SciRod counters with four SiPMs connected in series were tested at the CERN T9 beamline. A hadron-rich beam of 2 to 10 GeV/c was used, which contained mainly pions, kaons, and protons with some electron and muon contaminations. Two TOF stations were set up to identify the mass of the beam particles by measuring their time of flight (TOF) over a distance of $\sim$29 m. Each TOF station consisted of one wide SciRod counter and one Cherenkov radiator read out by a PHOTONIS Planacon two-inch microchannel-plate PMT. The SciRod of the upstream TOF station was a $50 \times 30 \times 5$ mm^3 BC418 scintillator read out by four KETEK PM3350TP-SB0 SiPMs at opposite sides, that of the downstream TOF station was composed of a $30 \times 30 \times 5$ mm^3 BC418 scintillator read out by four KETEK PM3375TP-SB0 SiPMs at opposite sides. The scintillators were wrapped in aluminum foil and the whole scintillator/SiPM configuration was placed inside a light-tight aluminum box (see figure 5).

The SiPM raw signals were amplified and fed into a FPGA-based 16 channel PaDiWa (Panda Dirc Wasa) discriminator board. The timing signals were then processed by the multihit TDCs of the FPGA-based HADES TRBv3 (Trigger and Readout Boards version 3) [9, 10] which additionally delivers a rough pulse height information by applying a time-over-threshold technique. These DAQ boards have a flexible design and provide a time precision down to $\sim$10 ps per single TDC channel. Each channel can save the time information of up to 127 hits per trigger and digest burst hit rates of up to 66 MHz.

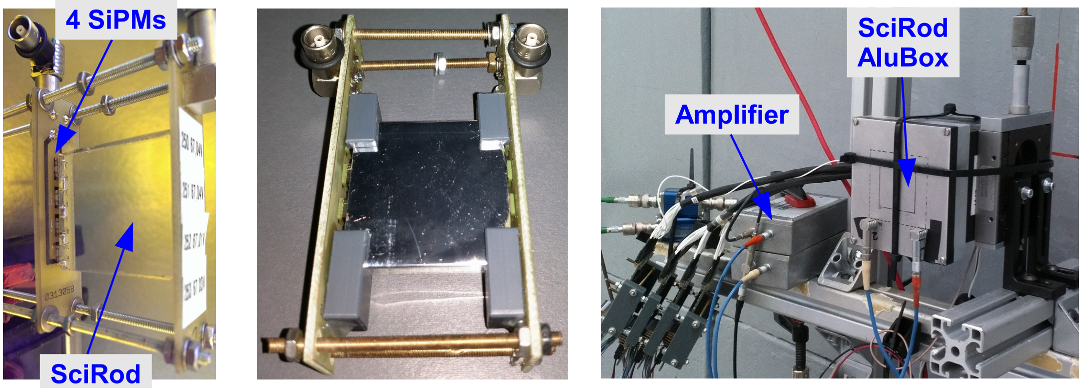


Figure 5: SciRod setup at the CERN T9 beamline. Left: the scintillator is sandwiched between two small boards which contain the 4 KETEK SiPMs connected in series. Middle: the wrapped scintillator and some plastics pieces to hold the scintillator in place. Right: one of the TOF station with an aluminum box containing the SciRod in front of the radiator/MCP-PMT combination; the beam centroid is placed at about the center of the aluminum box. At the left side two amplifier boxes are visible which provide also the bias voltage to the SiPMs.

5.2 Results

The measured TOF distributions for three different beam momenta are shown in figure 6 for the time difference between the downstream and upstream SciRod counters. The data are corrected for time drifts and time walk effects and contain always the full statistics for a beam momentum over the whole data taking period of almost 3 weeks. From these plots it is obvious that a pion/kaon separation up to 5 GeV/c is possible, while pions and protons can be distinguished up to 10 GeV/c. Electrons and pions are indistinguishable at the given conditions. The plotted Gaussian fit provides the TOF resolution for the electron/pion peak and results in a sigma of 117 - 122 ps almost independent of the beam momentum.

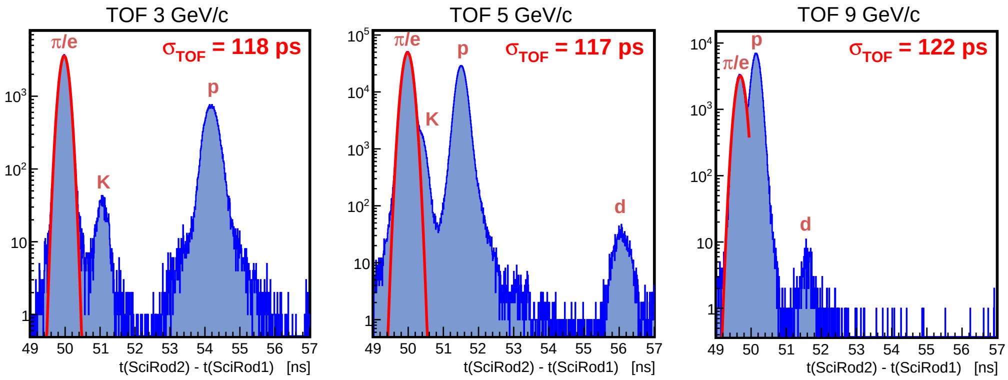


Figure 6: Time-of-Flight distributions for three different beam momenta measured with the two wide SciRod counters of the size $50 \times 30 \times 5$ mm^3 (upstream) and $30 \times 30 \times 5$ mm^3 (downstream). The particle flight path was ~29 m. The Gaussian fit (red curve) at the electron/pion peak provides the TOF resolution.

The special setup of the two individual TOF stations with an independent MCP-PMT and a SciRod counter for each station allows the measurement of six independent time differences (resolutions): MCP1 - SciRod1 (σ_{T1}), MCP2 - SciRod2 (σ_{T2}), MCP2 - SciRod1 (σ_{SM}), SciRod2 - MCP1 (σ_{MS}), MCP2 - MCP1 (σ_{MM}), and SciRod2 - SciRod1 (σ_{SS}). This provides six independent TOF resolutions which can be used to determine the time resolution of each counter separately. An additional parameter taking into account the average time spread caused by beam and electronics effects is necessary to stabilize the solutions.

The six squared TOF resolutions are displayed in figure 7 for a beam momentum of 3 GeV/c. Each bin of the histogram represents one of the above mentioned six time differences. Each squared TOF resolution corresponds to the displayed equation which contains the time resolutions of the individual counters and a beam/electronics resolution. With Minuit [11] this histogram is fitted by a specially tailored function which contains the time resolutions σ_{M1}, σ_{M2}, σ_{S1}, σ_{S2}, and σ_{beam} of the counters as five free parameters. From the data in figure 7 it is clear that the fit works very well which is actually the case for all beam momenta. These fits provide the time resolutions for each of the four counters. We observe that these resolutions do not depend on the beam momentum, while the beam/electronics time resolution does. This is expected because low momentum particles experience more multiple scattering in the detector materials inside the beam than those of large

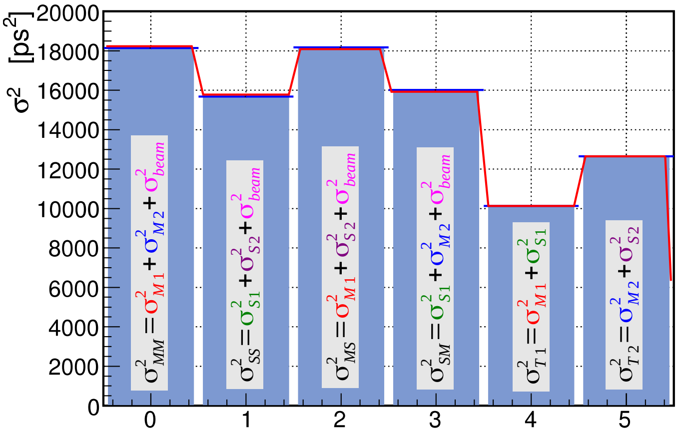


Figure 7: Histogram with the squared TOF resolutions obtained from the six time difference distributions at 3 GeV/c by fitting the electron/pion peak with a Gaussian. The measured data are represented by the blue bars while the Minuit fit is displayed as the histogram with the red line.

beam momenta. The time resolutions for the wide SciRods were measured to be 55 - 70 ps which is roughly consistent with the laboratory measurements.

6 Conclusions

The PANDA barrel TOF detector aims for a time resolution well below 100 ps. With the original SciTil design of a quadratic-shaped $30 \times 30 \times 5$ mm^3 scintillator read out at opposite sides by a single SiPM this goal was just about reached after careful optimizations. However, scans show that the time resolution is very position dependent. We investigated new scintillator geometries and a different readout scheme with more than one SiPM at each of the opposite sides. The time resolution can already be substantially improved by using a long narrow scintillator with one SiPM at the ends. A time resolution of <70 ps was reached with a $120 \times 5 \times 5$ mm^3 fast BC420 scintillator.

Another improvement of the time resolution was achieved with wider scintillators wrapped in aluminum foil and read out by four serially connected SiPMs at the opposite ends. With this technique also for the SciTil geometry of $30 \times 30 \times 5$ mm^3 a much better time resolution of 45 ps was measured almost independently of the traversing track position. In addition, with this time resolution a position resolution of ~15 mm (FWHM) along the scintillator should be possible. These wide SciRods were also tested in a time-of-flight setup at the CERN T9 beamline to identify the beam particles. In this case a time resolution per counter of 55 - 70 ps was measured under realistic experimental conditions over a period of almost three weeks. Clearly, the wide SciRods read out by several serially connected SiPMs are the best design option for the PANDA barrel TOF detector.

Acknowledgments

This work is supported by the German BMBF and GSI Darmstadt.

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