The PANDA Barrel Time-of-Flight Detector

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Abstract

The barrel-Time-of-Flight detector is one of the outer layers of the multi-layer design of the $\bar{\text{P}}$ANDA target spectrometer, covering an angle of $22° < \theta_{lab} < 150°$. $\bar{\text{P}}$ANDA, which is being built at the FAIR facility, will use cooled antiprotons on a Hydrogen or nuclei target, to study broad topics in hadron physics.

The detector is a scintillating tile hodoscope with an SiPM readout. A single unit consists of a $90 \times 30 \times 5$ mm^3 fast plastic scintillator tile and 3×3 mm^2 SiPM photosensors on both ends. Four SiPMs are connected in series to overcome the limited sensor size of a single SiPM sensor and to improve the time resolution drastically (100 ps to 50 ps).

While the PANDA experiment is equipped with DIRC detectors for PID of faster particles, the barrel TOF complements the setup by providing additional PID information with a π/K separation of 4 sigma up to the Cherenkov threshold.

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1. Introduction

The $\bar{\text{P}}$ANDA experiment, which is being built at the FAIR facility in Darmstadt Germany, will use cooled antiprotons on a Hydrogen or nuclei target [1]. The Barrel Time-of-Flight detector (B-TOF) is a thin, cylindrically shaped, scintillating tile hodoscope with excellent timing performance and is one of the outer layers of the multi-layer design of the $\bar{\text{P}}$ANDA target spectrometer.

The High Energy Storage Ring (HESR) in which the $\bar{\text{P}}$ANDA experiment will be placed, is foreseen to deliver a high luminosity of up to 2×10^{32} cm^{2}s^{-1} with a debunched beam. In order to disentangle overlapping detector hits of different $\bar{p}p$ annihilation reaching an average interaction rate of 20 MHz, the overall detector needs excellent timing capabilities to be delivered by the $\bar{\text{P}}$ANDA B-TOF.

The detector is designed to achieve a time resolution below 100 ps and provides the interaction times of events as well as particle identification (PID) information below the Chrenkev threshold complementing the barrel DIRC[1], the main PID detector around the interaction point, and excels at lower particle velocities. It is designed with a minimal material budget in mind mainly consisting of 5 mm thin plastic scintillator tiles read out on two sides by a serial connection of 4 SiPMs each. The signal transmission is embedded in a large 16-layer PCB in micro strip lines.

2. Particle Identification

A simulation of the separation power for protons, Kaons and Pions (p,K,π), shown in figure 1, based on the B-TOFs performance, using a standard time-of-flight based calculation presents an excellent detector performance with a separation power of $> 3\sigma$ for K/π below 0.8 GeV/c transverse momentum [2] complementing the barrel DIRC, $\bar{\text{P}}$ANDAs main PID detector around the interaction point, and extending the experiments PID capabilities to lower momentum particles.

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[1] Detection of Internally Reflected Cherenkov light

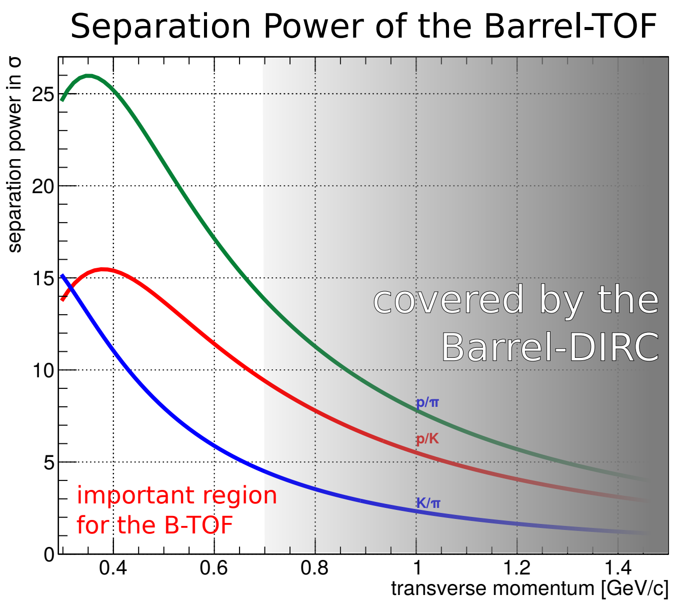

Figure 1: A simulation of the separation power of protons, Kaons and pions achievable with the B-TOF using a conventional time of flight technique, comparing the B-TOF performance with the B-DIRC coverage marked in grey.

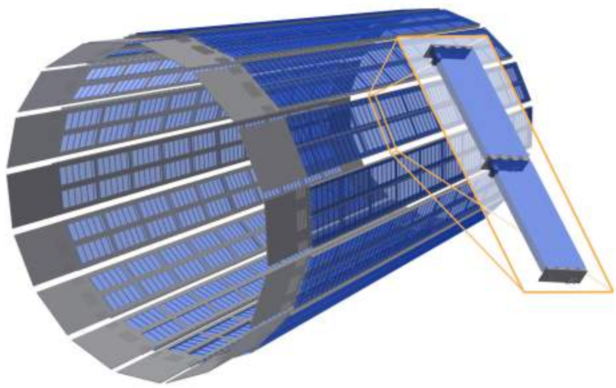

Figure 2: Schematic design of the full Barrel Time of Flight detector setup (2460 mm long, radius of $r \approx 50$ cm) with 16 segments, covering an azimuthal angle of $\theta = 22°$ to $150°$ around the interaction point, with scintillator tiles in blue and the large PCBs in gray.

At higher momenta the separation power decreases. The PID in the region of the aforementioned 0.8 GeV/c which roughly corresponds to the Cherenkov-threshold of protons in fused silica [3] is covered by the P̄ANDA-DIRC detectors. For the transverse momentum one can not define a hard cut off for the sensitivity of the barrel DIRC since the Cherenkov effect is subject to the absolute momentum. The transverse momentum however is a good measure in this case because for one, the tracking detectors have a position resolution in radial direction which is superior to the resolution in beam direction, and secondly the transverse momentum dictates when slow particles will be caught in the magnetic field.

This simulation of the time of flight performance was done using Geant4 and P̄ANDARoot incorporating path and momentum information provided by the P̄ANDA tracking system as well as timing information of the B-TOF, assuming a time resolution as the standard deviation of the scintillating tiles of 75 ps. As shown in figure 4 this time resolution includes a considerable safety margin.

For these calculations the knowledge of an ideal start time was assumed, which for a lack of a start time detector in P̄ANDA will not be given but calculated using information of the timing and tracking system.

3. Detector Setup

The Barrel Time-of-Flight Detector is made up of 16 fully independent segments, as seen in figure 2, which are capable of acting as standalone detectors. They are arranged in a cylinder with a ~0.5 m radius around the interaction point of the experiment, covering an azimuthal angle of $22° < \theta_{lab} < 150°$ and share a common mechanical frame with the Barrel DIRC detector with each element sitting right behind a DIRC radiator. 120 scintillating tiles per module are structurally supported and electrically connected by a large 16-layer PCB acting as the backbone of each segment, with the front-end electronics sitting on the side of the PCB in front of the interaction point. Since P̄ANDA is a fixed target experiment we expect the main radiation exposure to be in beam direction on the other side of the electronics.

This PCB is designed to mimic coaxial cables using microstrip lines [4] shielded by ground layers. Two shielding schemes are being tested, one using separate ground layers for each line such as with individual coaxial cables and the other with a global ground interconnected by vias. The different designs for the signal transmission layout are being studied, examining the necessary degree of separation between the individual signal lines in order to reduce potential crosstalk as well as how to keep the material budget and signal attenuation as low as possible.

Each of the 1920 scintillating tiles in total is made of Eljen-Technologies EJ-232, equivalent to BC-422, and has the following dimensions; $87 \times 29.4 \times 5$ mm^3. The short sides of these tiles are read out by 4 Silicon Photo-Multipliers (SiPMs) connected in series. This connection form has two key advantages compared to an individual connection of each SiPM. It increases the photo-sensitive readout surface of each tile without increasing the number of channels necessary for the readout electronics. At the same time, although the pulse height is reduced the SiPM response is improved by reducing the rise and fall time of each signal as seen in figure 3 due to the reduction of the effective capacitance over the four connected SiPMs compared to the capacitance of a single SiPM, which leads to an improved timing performance.

4. Detector Performance Studies

Prototypes of scintillating tiles of various thicknesses from 3 mm up to 6 mm read out by 4 SiPMs in series on each short side were tested at the university of Erlangen. The tests were

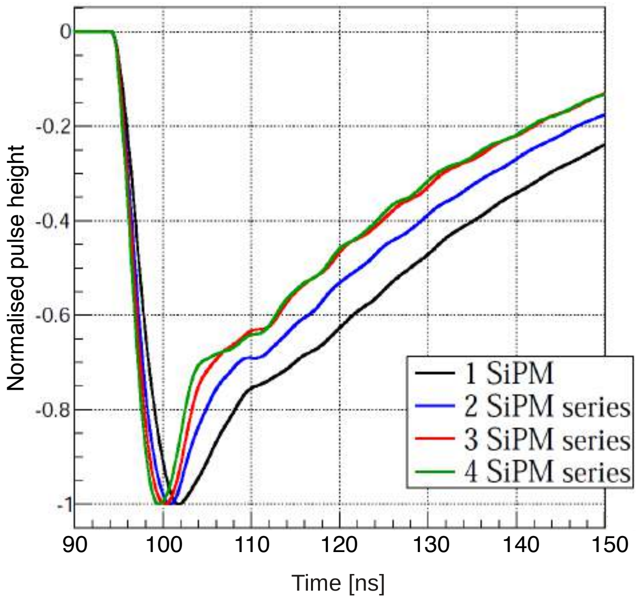

Figure 3: Normalized responses of multiple SiPMs in different degrees of serial connection, from a single SiPM to a connection of 4 SiPMs in series, showing a reduction of the detector response time by adding SiPMs to the connection with diminishing returns.

performed in a decommissioned radiation facility well suited for the measurements due to its low noise environment.

To improve the performance of the detector in comparison to the standard design with 5 mm thick tiles and four 3×3 mm SiPMs [6] there are several possibilities. Increasing the number of serially connected SiPMs would increase the sensitive area, but would drive up the cost. Using larger SiPMs would also increase the sensitive area but also drive up the cost. An almost cost neutral approach would be to optimize the scintillator tile thickness.

It was also hypothesized that a better match of the scintillator thickness to the sensitive area of the SiPMs (3×3 mm^2) would result in an improved photon collection efficiency which potentially then would improve the time resolution of the tiles or at least the material budget can be reduced without sacrificing the timing performance.

Using a ^{90}Sr beta source and a motorized arm the $87 \times 29.4 \times l$ mm^3 scintillator tiles are scanned, measuring the timing of the left and right SiPMs as well as the amount of detected photons for different scintillator thicknesses l, varying from 3 to 6 mm. A small scintillating crystal on a single SiPM placed on the other side of the tile was used as a trigger for the data acquisition ensuring a full penetration of the electron through the scintillator.

Using this setup a time resolution distribution, shown in figure 4, with a mean of ~ 51 ps with good homogeneity of $\sigma = \pm 3$ ps along the tile was achieved.

Comparing the time resolution delivered by the different scintillator tiles it becomes apparent that the relative increase of the sensitive area does not outweigh the the reduction of produced photons due to the shorter path of the particles in the scintillator, leading to a worsening of the time resolution by $\sim$ 20% compared to 5 and 6 mm tiles. A scintillator of 6 mm thickness on the other hand does not show a significant improvement compared to 5 mm. So in order to reduce material in the detector, 5 mm scintillator tiles will be used.

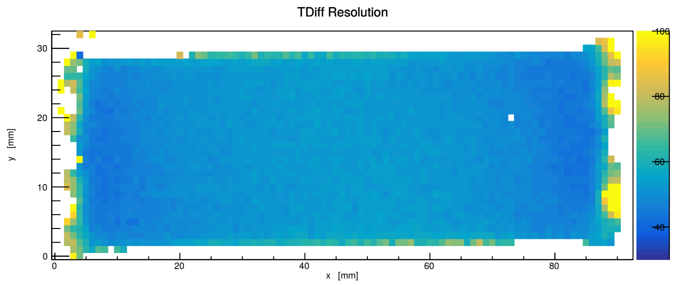

Figure 4: Scan of the timing performance of one 5 mm thick scintillating tile read out by four SiPMs connected in series, delivering a mean time resolution of 51 ps.

In order to guarantee a scintillator thickness with variances below the 10% margin of error from production [5], the option of milling and polishing the scintillator down to the desired strength was considered. Treatment of scintillator surfaces can be a delicate process and damage might degrade the performance and longevity of the tiles. The effects of such a procedure were measured but no adverse effect could be observed as the time resolution showed no significant difference to a non treated tile.

For small-sized applications the addition of a quenching agent (Benzophenone) into the scintillator material might improve the time resolution by absorbing the slow emission component and is meant for "*ultra-fast*" timing applications. Eljen-Technologies *EJ-232Q0.5* was chosen for these measurements as it has the lowest dose of added quenching agent. Overall this however leads to a significant reduction of detected photons and hence to a worse time resolution of 70.8 ± 6.9 ps and a worse uniformity.

In addition to providing interaction times, the detector uses the relative timing information of the SiPMs on the left and right side of the scintillator to produce position information along the long side of the scintillator (x). The measured effective light propagation time inside the scintillator of 0.122 ± 0.013 mm/ps leads to an effective position resolution of 12.8 ± 1.1 cm in x direction. The position in y direction can not be resolved better than the 29.4 mm corresponding to the tile size since the SiPMs can not be read individually.

5. Relative TOF

The $\bar{\text{P}}$ANDA detector will not be equipped with a start time counter, hence a conventional time-of-flight measurement with a reasonable resolution will not be possible. For that reason the relative time-of-flight method, combining information of multiple hits of the same annihilation, utilizing information from various detectors for path length and momentum information, will be used, which is capable of determining the annihilation time as well as the particle identity simultaneously.

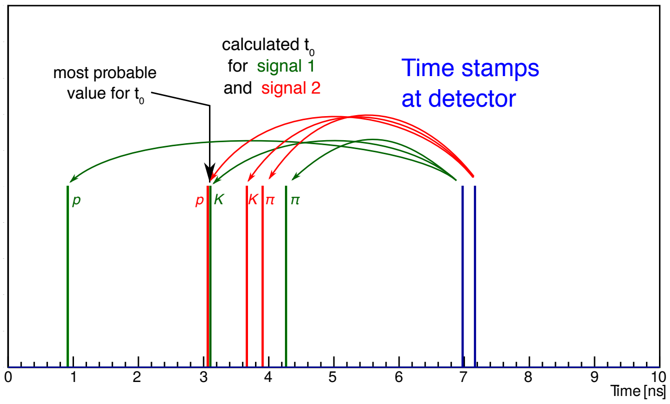

Figure 5: Visual description of the relative time-of-flight method. Two and potentially more time stamps in a single event are registered. For these hits various mass assumptions (p, K, π) are made and using tracking information respective creation times (t_0) calculated. Where multiple assumed t_0s pile up we find our annihilation time.

When multiple hits are registered that all result from the same annihilation of anti-proton and proton, we permute through possible mass assumptions for each these hits and using the tracking information are able to determine the respective hypothetical creation time t_0. This is done for all registered hits belonging to this event and the resulting distribution is then examined for pile ups. Considering all hits are expected to have originated from the same annihilation at the same time, the correct mass assumptions should all line up to a single point in time with an uncertainty given by the measurement error. This time is then assumed to be the annihilation time.

A visual example of this procedure is shown in figure 5 assuming two hits in the B-TOF. For each of these hits multiple mass assumptions are made and their respective t_0 calculated and displayed in green for one hit and red for the other. Where two particles line up, in this case a Kaon for the first hit and a proton for the second, we found our annihilation time.

Put mathematically it is a minimization of the functional equation (1) comparing permutations of the masses,

$$\Psi_{W_{(m_1,\ldots,m_N)}} = \sum_{i=1}^{N} \frac{(t_{i,0} - t_0)^2}{\sigma^2_{TOF}} \qquad (1)$$

where $t_{i,0}$ is the respective assumed interaction time for particle i with the mass assumption m_i, t_0 is the weighted mean of the $t_{i,0}$ distribution and σ^2_{TOF} is the $\bar{\text{P}}$ANDA timing resolution, a combination of the B-TOF time resolution as well as the momentum and track length resolution.

This method delivers a time resolution for the annihilation time of 71 ps for an event with three hits. When analyzing events with more hits the performance only improves.

6. Conclusion

The $\bar{\text{P}}$ANDA barrel Time-of-Flight detector shows excellent separation power below the Cherenkov threshold and thereby complements barrel DIRC the main PID detector nicely. It uses small organic scintillating tiles read out by a serial connection of 4 SiPMs on each short side, along large PCBs that offer mechanical support as well as signal transmission form the detectors to the front-end electronics at the back end of the board. Prototype tests in the lab confirmed the ideal scintillator thickness of 5 mm and were able to achieve a time resolution of ∼ 51 ps and a position resolution of ∼1 cm. With no start time counter the realative TOF method has to be utilized and delivers an annihilation time resolution of ∼71 ps.

Acknowledgments

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