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The PANDA DIRC Detectors at FAIR

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Abstract: The PANDA detector at the international accelerator Facility for Antiproton and Ion Research in Europe (FAIR) addresses fundamental questions of hadron physics. An excellent hadronic particle identification (PID) will be accomplished by two DIRC (Detection of Internally Reflected Cherenkov light) counters in the target spectrometer. The design for the barrel region covering polar angles between 22° to 140° is based on the successful BABAR DIRC with several key improvements, such as fast photon timing and a compact imaging region. The novel Endcap Disc DIRC will cover the smaller forward angles between 5° (10°) to 22° in the vertical (horizontal) direction. Both DIRC counters will use lifetime-enhanced microchannel plate PMTs for photon detection in combination with fast readout electronics. Geant4 simulations and tests with several prototypes at various beam facilities have been used to evaluate the designs and validate the expected PID performance of both PANDA DIRC counters.

Keywords: Particle identification methods; Cherenkov detectors; Performance of high energy physics detectors.

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Contents

1 Particle Identification of PANDA

The PANDA experiment [1] will be one of the four flagship experiments at the new international accelerator complex FAIR (Facility for Antiproton and Ion Research) in Darmstadt, Germany. PANDA will perform unique experiments using the high-quality antiproton beam with momenta in the range of 1.5 GeV/c to 15 GeV/c, stored in the HESR (High Energy Storage Ring) to explore fundamental questions of hadron physics in the charmed and multi-strange hadron sector and deliver decisive contributions to the open questions of QCD [2]. The cooled antiproton beam colliding with a fixed proton or nuclear target will allow hadron production and formation experiments. Two complementary operating modes are planned, named high luminosity and high resolution. The high luminosity mode with a momentum resolution of $\Delta p/p = 10^{-4}$ and stochastic cooling will have a luminosity of $2 \cdot 10^{32} cm^{-2} s^{-1}$. For the high resolution mode $\Delta p/p = 4 \cdot 10^{-5}$ will be achieved with electron cooling for momenta up to p = 8.9 GeV/c. The cycle-averaged luminosity is expected to

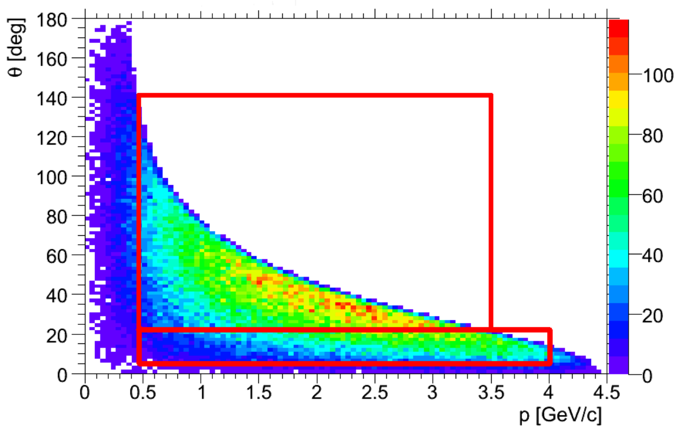

Figure 1. Intensity of kaons from $J/\psi \to K^+K^-\gamma$ from simulated antiproton proton annihilations at $\sqrt{s} = 3.1$ GeV/c as function of polar angle θ and momentum p. The top and bottom rectangles denote the acceptance of the Barrel DIRC and the Endcap Disc DIRC, respectively.

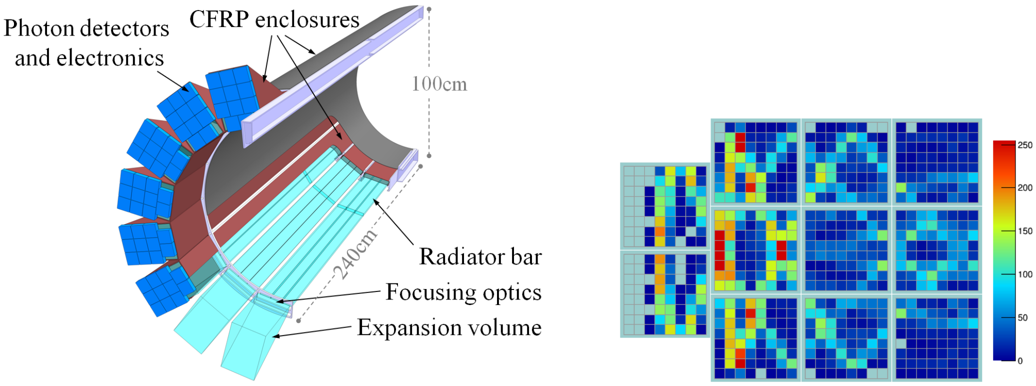

Figure 2. Left: Schematic of the Barrel DIRC baseline design. Only one half of the detector is shown. Right: Geant simulation of the baseline geometry of the PANDA Barrel DIRC. The colored histogram shows the accumulated hit pattern from 1000 K^+ at 3.5 GeV/c momentum and 55° polar angle.

be $10^{31} cm^{-2} s^{-1}$. Excellent Particle Identification (PID) is crucial to the success of the PANDA physics program. The PID system comprises a range of detectors using different technologies. Dedicated PID devices, such as several Time-of-Flight and Cherenkov counters and a Muon detection system, are combined with PID information delivered by the Micro Vertex Detector and the Straw Tube Tracker as well as by the Electromagnetic Calorimeter. The DIRC concept was introduced and successfully used by the BaBar experiment [3, 4] where it provided excellent π/K separation up to 4.2 GeV/c and proved to be robust and easy to operate. The PANDA Barrel DIRC, modeled after the BaBar DIRC, will surround the interaction point at a distance of about 50 cm and cover the central region of polar angles $22° < \theta < 140°$ while the novel Endcap Disc DIRC will cover the smaller forward angles, $5° < \theta < 22°$ and $10° < \theta < 22°$ in the vertical and horizontal direction, respectively. As shown in Fig. 1 the Barrel DIRC needs to separate pions from kaons for momenta up to 3.5 GeV/c with a separation power of at least 3 standard deviations (s.d.) while the Endcap Disc DIRC aims for a PID up to particle momenta of 4 GeV/c with at least 4 s.d. separation.

2 Barrel DIRC

Since the space limits for the PANDA Barrel DIRC are tight, several design modifications were required compared to the BaBar DIRC. Due to the optical and mechanical specifications the fabrication of the radiator bars remains one of the dominant cost drivers for DIRC counters. A significant cost reduction is only possible if fewer pieces have to be polished. Detailed physical simulation studies demonstrated that reducing the number of bars per bar box from 5 (32 mm width) to 3 (53 mm width) does not affect the PID performance since the lens system is able to correct for the increase in bar size. The overall design of the PANDA experiment required that the large water tank used by the BaBar DIRC is replaced by a compact expansion volume (EV), placed inside the detector. Fused silica as material and separated smaller units as expansion volume were already favored by the SuperB FDIRC [5] and the Belle II TOP [6]. The baseline design of the PANDA Barrel DIRC detector [7] is shown in Fig. 2 (left). Sixteen optically isolated sectors, each compris-

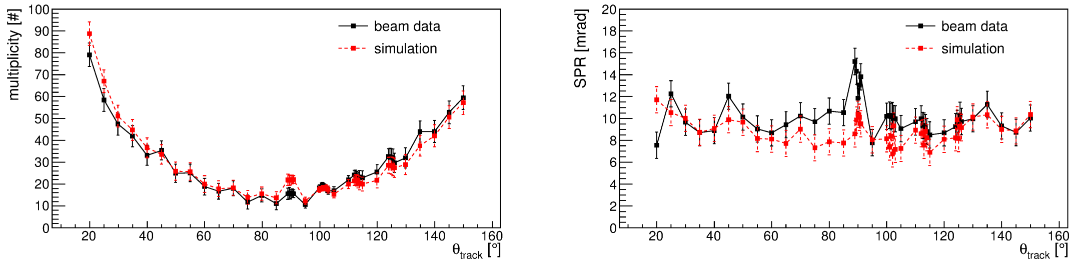

Figure 3. Photon yield (left) and SPR (right) as a function of the track polar angle for the narrow bar and the 3-layer spherical lens for tagged protons at 7 GeV/c beam momentum in data (black) and Geant simulation (red). The error bars correspond to the RMS of the distribution in each bin. The use of lower-quality, older sensors affected predominantly the angles around 90° (left and right).

ing a bar box and a solid fused silica prism, surround the beam line in a 16-sided polygonal barrel with a radius of 476 mm and cover the polar angle range of $22° < \theta < 140°$. Each bar box contains three bars of 17 mm thickness, 53 mm width, and 2400 mm length, placed side-by-side, separated by a small air gap. A flat mirror is attached to the forward end of each bar to reflect photons towards the read-out end, where they are focused by a 3-component spherical compound lens on the back of a 30 cm-deep solid prism, made of synthetic fused silica. The location and arrival time of the photons are measured by an array of 11 lifetime-enhanced Microchannel Plate PhotoMultiplier Tubes (MCP-PMTs) [8] with a spatial and timing precision of about 2 mm and 100 ps, respectively. The MCP-PMTs are read out by an updated version of the HADES trigger and readout board (TRB) [9] in combination with a front-end amplification and discrimination card mounted directly on the MCP-PMTs [10]. A detailed physical simulation of the PANDA Barrel DIRC was developed in Geant4 [11] and an accumulated hit pattern from these simulations is shown in Fig. 2 (right).

The goal of the test beam campaign at the CERN PS in 2015 and 2016 was the validation of the PID performance of the baseline design and of the wide plate. The prototype comprised the essential elements of one PANDA Barrel DIRC sector: A narrow fused silica bar ($17.1 \times 35.9 \times 1200.0$ mm^3) or a wide fused silica plate ($17.1 \times 174.8 \times 1224.9$ mm^3), coupled on one end to a flat mirror, on the other end to a focusing lens, and the fused silica prism as EV (with a depth of 300 mm and a top angle of 45°). A very fast time-of-flight (TOF) system [12], positioned directly in the beam, was used for π/p tagging. The reconstructed photon yield as a function of the track polar angle is shown in Fig. 3 (left) for the configuration with the narrow bar radiator and the 3-layer spherical lens. The number of Cherenkov photons from the beam data (black) ranges from 12 to 80 and is in agreement with simulations (red). The single photon Cherenkov angle resolution for the same data set is shown in Fig. 3 (right). The beam data and simulation are consistent within the RMS of the distributions for the forward and backward angles. Most of the data were taken with the beam momentum of 7 GeV/c. The π/p Cherenkov angle difference at this momentum (8.1 mrad) is close to the π/K Cherenkov angle difference at 3.5 GeV/c (8.5 mrad). The design with the narrow bar and the spherical lens is found to meet or exceed the PID requirements for PANDA. It is robust against timing deterioration and delivers excellent π/K separation for the imaging reconstruction methods.

The prototype tests demonstrated that the figures of merit and the π/K separation power of the geometry based on narrow bars exceeded the PANDA PID requirements for the entire pion and kaon phase space. After improving several key aspects of the prototype configuration in 2016, the observed π/p separation power for the wide plate is $2.8^{+0.4}_{-0.2}$ standard deviations (s.d.) without focusing. With the 2-layer cylindrical lens the π/p separation is $3.1^{+0.1}_{-0.1}$ s.d., in good agreement with the prototype simulation, which predicts a $3.3^{+0.1}_{-0.1}$ s.d. separation value. However, the design with narrow bars provides a larger margin for error and can be expected to perform significantly better.

3 Endcap Disc DIRC

The forward region of the target spectrometer will be equipped with a Endcap Disc DIRC and it will be the first time that this type of detector will be used in a high-performance 4π experiment [13]. The detector will be divided into four independent quadrants which form a disc with a diameter of about 2 m and an active area of roughly 3.5 m^2. Each quadrant consists of one 2 cm thick radiator with 27 Read-Out Modules (ROMs) attached to its outer sides (see Fig. 4). One ROM combines three Focusing Elements (FEL) with one MCP-PMT and the corresponding readout electronics. Current MCP-PMT options have a segmented anode of 6×128 pixels (Hamamatsu) or 3×100 pixels (Photonis). The curved side of the FEL is coated with a reflective aluminum surface and optimized to match the position resolution of the MCP-PMTs. An optical longpass or bandpass filter is foreseen to reduce the chromatic error and to limit the number of photons for a longer lifetime of the photocathode of the MCP-PMT. For every charged track crossing 2 cm fused silica 22 detected photons are expected within a wavelength range of $365 - 400nm$. The ToFPET ASIC [14] is foreseen for the readout of the MCP-PMTs . Geant4 simulation results [11] of the expected

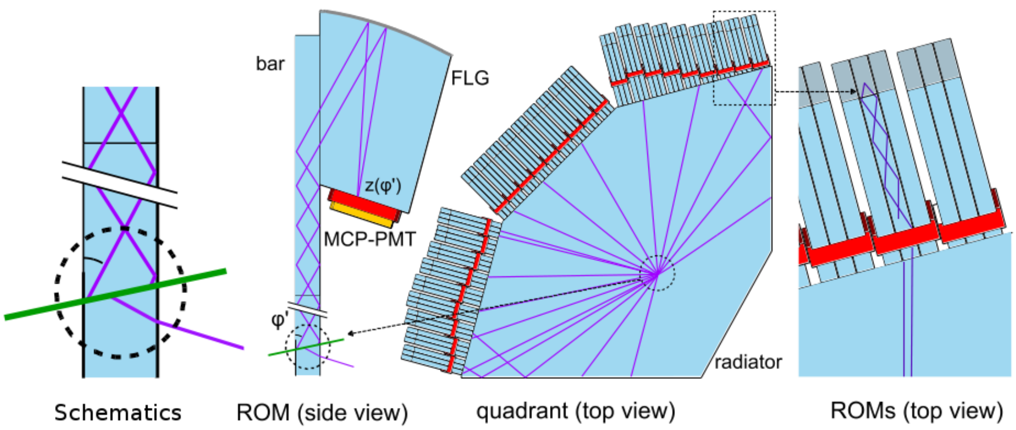

Figure 4. Schematics: A charged particle traverses the radiator plate and emits Cherenkov photons (violet lines) at certain angles. Most of them undergo total internal reflection and are thus trapped inside the plate. ROM side view: The photons are guided by a rectangular bar (prism) and focused by a focussing element (FEL) with a cylindrical mirror. They are registered by an MCP-PMT that measures the position of the photon within a wavelength range that is defined by a filter. Quadrant, top view and ROM, top view: The azimuthal angle is determined from the position of the prism where the photon is registered.

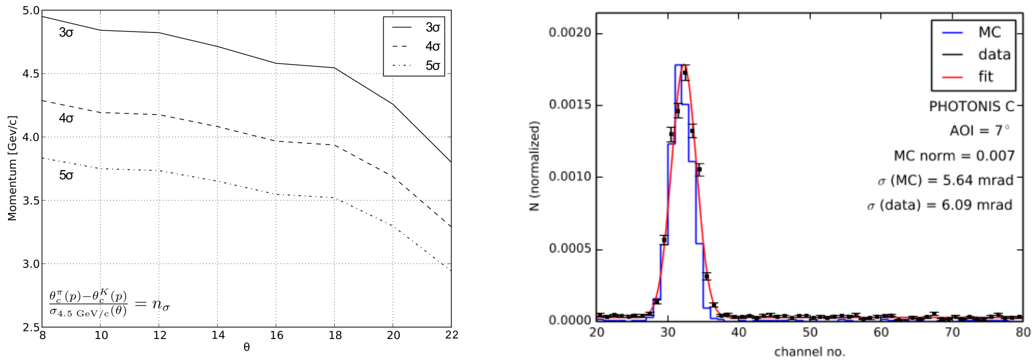

Figure 5. Left:Pion/kaon separation computed from the distribution of reconstructed Cherenkov angles for a ROM consisting of a 2" tube with 0.5 mm pixel width. Right: Comparison of data and Monte-Carlo of the single-photon resolutions at 10 GeV/c beam momentum.

separation power are shown in Fig. 5. The goal of a PID with at least 4 s.d. separation up to particle momenta of 4 GeV/c is achievable for polar angles up to 16°. For larger angles, the charged track is too close to the rim of the disc deteriorating the angular resolution. A larger disc could remedy this effect, but would not fit into the PANDA detector due to spatial requirements. A prototype test was done at the T9 beam line of PS East Area at CERN in 2015 together with the Barrel DIRC. The polished radiator was a $500 \times 500 \times 20$ mm^3 plate made of NIFS-S by Nikon. The optical system was completed by three FEL/prism pairs which had been coupled to the radiator. A figure of merit for the performance of the Endcap Disc DIRC is the single photon resolution which can be measured with a single FEL. Fig. 5 shows the accumulated photon hits for a fixed angle of the hadron beam with respect to the DIRC radiator at 10 GeV/c. The x-axis represents the channel or strip numbers of the MCP-PMT anode. One channel corresponds to 3.5 mrad. The beam test demonstrated the good agreement of the simulation with the experimental data.

4 Conclusion

The beam test with the PANDA Barrel DIRC prototype at CERN in 2015 and 2016 successfully validated the PID performance of both radiator geometries, the narrow bar with the spherical lens, and the wide plate with the cylindrical lens. The PANDA Barrel DIRC design with narrow bars provides a larger margin for error and can be expected to perform significantly better during the first PANDA physics run due to the dependence of the wide plate geometry on excellent timing. Due to these key performance advantages, the geometry with the narrow bars and the 3-layer spherical lens was selected as the baseline design for the PANDA Barrel DIRC. After initial tests of component prototypes (optics, photon detectors, readout) of the Endcap Disc DIRC in the lab demonstrated the expected performance, a large system prototype was used in 2015 at the T9 beam line at CERN to measure the single photon resolution. The radiator and FELs were made of high quality fused silica, with a design and quality comparable to the final one. The reconstruction of Cherenkov photons and the single photon resolution of the prototype agree well with Monte Carlo expectations.

Acknowledgments

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References

[1] PANDA Collaboration, *Technical Progress Report, FAIR-ESAC/Pbar*, (2005).

[2] PANDA Collaboration, *Physics Performance Report for PANDA: Strong Interaction Studies with Antiprotons*, arxiv:0903.3905.

[3] BABAR DIRC Collaboration, I. Adam et al., *The DIRC particle identification system for the BaBar experiment*, *Nucl. Instr. and Meth. Res. Sect. A* **538** (2005) 281.

[4] P. Coyle, *The DIRC counter: a new type of particle identification device for B factories*, *Nucl. Instr. and Meth. Res. Sect. A*, **343** (2004) 292.

[5] B. Dey et al., *Design and performance of the focusing DIRC detector*, *Nucl. Instr. and Meth. Res. Sect. A*, **775** (2015) 112.

[6] P. Krizan, *Particle identification at Belle II*, *JINST* **9** (2014) C07018.

[7] R. Dzhygadlo et al., *The PANDA Barrel DIRC International Workshop on Fast Cherenkov Detectors - Photon detection, DIRC design and DAQ*, *JINST* **11** (2016) C05013.

[8] A. Lehmann et al., *Recent Developments with Microchannel-Plate PMTs RICH2016 Proceedings of the Ninth International Workshop on Ring Imaging Cherenkov Detectors, Bled, Slowenia, September 5-9, 2016*, to be published in *Nucl. Instr. and Meth. Res. Sect. A*.

[9] C. Ugur et al., *A 16 channel high resolution (<11 ps RMS) Time-to-Digital Converter in a Field Programmable Gate Array*, *JINST* **7** (2012) C02004.

[10] M. Cardinali et al., *Frontend electronics for high-precision single photo-electron timing using FPGA-TDCs*, *Nucl. Instr. and Meth. Res. Sect. A* **766** (2014) 231

[11] S. Agostinelli, *Geant4 A simulation toolkit*, *Nucl. Instr. and Meth. Res. Sect. A* **506** (2003) 250.

[12] M. Böhm et al., *Fast SiPM Readout of the PANDA TOF Detector*, *JINST*, **11**, (2016) C05018.

[13] M. Dueren et al., *The Endcap Disc DIRC of PANDA RICH2016 Proceedings of the Ninth International Workshop on Ring Imaging Cherenkov Detectors, Bled, Slowenia, September 5-9, 2016*, to be published in *Nucl. Instr. and Meth. Res. Sect. A*.

[14] M.D. Rolo et al., *TOFPET ASIC for PET applications*, *JINST*, **8** (2013) C02050