The PANDA DIRCs

C. Schwarz, A. Ali, A. Belias, R. Dzhygadlo, A. Gerhardt, M. Krebs, D. Lehmann, K. Peters, G. Schepers, J. Schwiening, M. Traxler, L. Schmitt, M. Böhm, A. Lehmann, M. Pfaffinger, S. Stelter, M. Düren, E. Etzelmüller, K. Föhl, A. Hayrapetyan, I. Köseoglu, K. Kreutzfeld, M. Schmidt, T. Wasem, C. Sfienti, A. Barnyakov, K. Beloborodov, V. Blinov, S. Kononov, E. Kravchenko and I. Kuyanov

a GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany
b Goethe University, Frankfurt a.M., Germany
c FAIR, Facility for Antiproton and Ion Research in Europe, Darmstadt, Germany
d Friedrich Alexander-University of Erlangen-Nuremberg, Erlangen, Germany
e II. Physikalisches Institut, Justus Liebig-University of Giessen, Giessen, Germany
f Institut für Kernphysik, Johannes Gutenberg-University of Mainz, Mainz, Germany
g Budker Institute of Nuclear Physics of Siberian Branch Russian Academy of Sciences, Novosibirsk, Russia

E-mail: C.Schwarz@gsi.de

ABSTRACT: The PANDA experiment at the FAIR facility adresses open questions in hadron physics with antiproton beams in the momentum range of 1.5–15 GeV/c. The antiprotons are stored and cooled in a High Energy Storage RING (HESR) with a momentum spread down to $\Delta p/p = 4 \cdot 10^{-5}$. A high luminosity of up to $2 \cdot 10^{32}$ cm$^{-2}$s$^{-1}$ can be achieved. An excellent hadronic particle identification (PID) will be provided by two Cherenkov detectors using the priciple of Detection of Internally Reflected Cherenkov light (DIRC). In the forward direction from polar angles of $5^\circ$ to $22^\circ$, the Endcap Disc DIRC (EDD) separates pions from kaons up to momenta of 4 GeV/c. Between $22^\circ$ and $140^\circ$ the Barrel DIRC cleanly separates pions from kaons for momenta up to 3.5 GeV/c. This article describes the design of the Barrel DIRC and of the Endcap Disc DIRC and the validation of their designs in particle beams at the CERN PS.

KEYWORDS: Cherenkov detectors; Performance of High Energy Physics Detectors; Detector design and construction technologies and materials; Data acquisition concepts
1 Introduction

The Facility for Antiproton and Ion Research (FAIR) close to GSI Darmstadt in Germany is currently under construction. The tunnel for the synchrotron is being dug out and the concrete sections are being poured. Four large experiment collaborations are the scientific pillars of the project. Three of them, CBM, NUSTAR, and APPA will pursue the traditional physics of GSI Darmstadt with heavy ion beams. The fourth, PANDA (antiProton ANihilation at DArmstadt), will benefit from a new available antiproton production chain. Antiproton beams with unprecedented intensity and quality are stored and accelerated in the High Energy Storage Ring (HESR) in the momentum range between 1.5 to 15 GeV/c and annihilate with a fixed target. The experiments with charmed quarks will shed light on strong QCD in a beam momentum range where perturbation theory is still valid, but the influence of strong QCD becomes visible. The accumulation of up to \(10^{11}\) antiprotons yields a luminosity of up to \(2 \times 10^{32} \text{cm}^{-2}\text{s}^{-1}\). The momentum resolution of the beam is improved by stochastical cooling to \(\Delta p/p = 4 \times 10^{-5}\) and enables high precision spectroscopy. Here, resonances produced in formation experiments are scanned by beams with different momenta and their widths can be determined with an energy resolution in the order of \(\Delta E \approx 50 \text{keV}\). Above the threshold for open charmed mesons the identification of kaons with Ring Imaging CHERenkoV counters (RICH) becomes an important task for the PANDA experiment. The detector consists of two parts, the target spectrometer around the fixed target and the forward spectrometer for the measurement of the forward boosted reaction products. In the forward spectrometer a focusing aerogel RICH [1] provides charged PID. The target spectrometer contains two RICH counters. They have to fit into the space inside of a surrounding lead tungsten calorimeter. The required space of a traditional RICH leads to an increase in size and costs of the calorimeter. Therefore, the DIRC principle was chosen. Here, the radiator acts also as a lighguide and preserves the information of the Cherenkov angle of the photons of the charged particle over many internal reflections. From polar angles between 22° and 140° the Barrel DIRC will distinguish kaons from pions up to momenta of 3.5 GeV/c with a separation power of 3 standard deviations (s.d.) [2–4]. In the forward direction from polar angles of 5° to 22° the Endcap Disc DIRC (EDD) [5, 6] provides pion-kaon separation of 3 s.d. up to momenta of 4 GeV/c. The requirements for the kaon momenta come from GEANT4 [7] simulations of the phase space for several reaction channels. The following sections describe the design of the DIRCs and the results of experiments in test beams.

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2 The design

The successfully operated BaBar DIRC and the development work for the SuperB FDIRC inspired the design of the PANDA Barrel DIRC (figure 1). An improvement is the smaller readout volume, made from synthetic fused silica, which is easier to integrate and is less affected by unwanted radiation coming from the accelerator. It is located within the yoke of the solenoid magnet of the target spectrometer and is divided in 16 prisms, 300 mm long with an opening angle of $33^\circ$. An array of $2 \times 4$ pixelated Microchannel Plate Photomultiplier Tubes (MCP-PMTs) attached to the upstream end of the prism using a RTV-silicone cookie allows the operation of the readout within a magnetic field of 1 Tesla. The tubes are expected to survive 10 years of the operation of the PANDA experiment [8]. Each MCP-PMT has an $8 \times 8$ anode grid with a pixel pitch of 6.5 mm. Due to the fast detector response and the frontend electronics using the DiRICH system [9] a timing precision of 100 ps is achievable [2–4]. Each prism matches a bar box with three radiator bars made from synthetic fused silica. The bars are 17 mm thick, 53 mm wide, and 2400 mm long. One radiator bar consists of two 1200 mm long pieces glued together end-to-end. Photons hitting the downstream end of the radiator are reflected back by a mirror towards the readout volume. For a precise angular measurement of the photons from the large cross section of the radiator bars focusing optics is needed. Space limitations and the positioning of the photodetectors in the magnetic field favor the use of a lens system. A picture of three lens triplets are shown in figure 2. The lens is glued to the upstream end of the bar and a RTV-silicone cookie couples the lens system to the prism.

While the design of the Barrel DIRC utilizes the experience from the BaBar DIRC and the SuperB FDIRC, the Endcap Disc DIRC is a novel approach. The EDD uses four 20 mm-thick fused silica
Figure 2. Three focusing lens triplets built by Befort Wetzlar Optics [10], each being a lanthanum crown glass lens between two fused silica pieces with flat outer surfaces. They focus the light from the radiator bar on the back side of the prism.

radiator plates forming a disc (figure 3) in front of a lead tungstate forward endcap electromagnetic calorimeter. The reflections of the photons at the polished faces of the plate conserve the internally reflected Cherenkov angle during their propagation towards the outer rim. The sides of the outer rim are equipped with focusing elements and MCP-PMTs as photon sensors. The four quadrants are optically isolated and the photons reflected on the interior sides. The quadrants are stabilized by a holding cross mounted to a ring shaped mounting frame. The EDD and the forward endcap electromagnetic calorimeter are planned to be fixed on opposite sides of the same mounting frame. Each quadrant has 24 readout modules (ROM) with attached MCP-PMTs. Each ROM consists of 3 focusing elements (FELs) as expansion volumes with a cylindrical mirror at the backside (figure 4).

Figure 3. Schematic of the Endcap Disc DIRC.
The EDD in total consists of 96 ROMs, 96 MCP-PMTs, and 288 FELs. The position of the hit FEL and the position of the charged particle on the radiator from the tracking system determine the azimuthal direction of the photon. The polar angle of the photon is measured by the highly segmented anode of the MCP-PMT with $3 \times 100$ pixels. An ASIC read out board is connected to the MCP-PMT anode. This readout board of the EDD is being developed by PETsys [11].

3 Experiments with test beams

Since 2008 various PANDA DIRC prototypes have been evaluated with particle beams at CERN, DESY, and GSI. Here, we focus on the test campaign at the CERN-PS in 2018, when the Barrel DIRC and the EDD prototypes were installed in the T9 beamline. The mixed hadron beam contained

Figure 5. The Barrel DIRC setup from top (a) and the side (b). The colored histogram (c) shows the accumulated hit pattern for a polar angle of $20^\circ$. 
Figure 6. Difference of the maximum likelihood for the arrival time of photons from protons/pions at 7 GeV/c (equivalent to kaons/pions at 3.5 GeV/c) at a polar angle of 20°.

primarily pions and protons, which were cleanly tagged by a time-of-flight system. For the Barrel DIRC most runs were taken at a momentum of 7 GeV/c. At this momentum the difference in the Cherenkov angle between protons and pions is close to that between kaons and pions at a momentum of 3.5 GeV/c, which is the designed upper momentum limit of the Barrel DIRC. In this campaign the possible reduction of the number of MCP-PMTs for cost optimization, different optical couplings, and housing and cable routing of the frontend electronics were studied. The setup with a 35 mm wide radiator bar is shown in figure 5 a) and b). A radiator bar, made from synthetic fused silica, was mounted on a turntable. By rotation of the turntable the polar and azimuthal angle between the radiator and the beam could be adjusted. Cherenkov photons going to the left end of the bar in figure 5 a) were reflected by a flat mirror towards the right side of the bar. Here, a three-layer spherical lens couples the bar to a 300 mm deep prism. The middle part of the lens is made from N-LaK33B glass [12] and is sandwiched between two synthetic fused silica pieces. It has a defocusing and a focusing surface to yield a sufficiently flat focal plane on the backside of the prism, equipped with an 2 × 4 matrix of MCP-PMTs. A side view of the prism with the MCP-PMT array is shown in figure 5 b). In the beam tests the MCP-PMTs XP85012/A1-Q from PHOTONIS [13] were used. The colored histogram in figure 5 c) shows the accumulated hit pattern of Cherenkov photons for beam particles with a momentum of 7 GeV/c hitting the bar at a polar angle of 20°. The electronics for the readout was based on the Trigger Readout Board version 3 (TRB3) of the HADES collaboration [14] and measures the time of arrival and the time over threshold of logical signals coming from PADIWA discriminator boards [15] plugged onto the MCP-PMTs. The timing offsets and the timing precision of the full readout chain were determined using a 405 nm Picosecond Injection Laser (PiLas) [16]. The measured timing precision showed on average values of 190 ps after walk correction. There are two reconstruction algorithms to determine the performance of the detector [17, 18]. The “geometrical reconstruction” uses the position of the detected photons to make a track-by-track maximum likelihood fit. The “time imaging” employs both, the position and time of arrival of detected photons to perform directly the maximum likelihood fit. The difference
Figure 7. The setup of the Endcap Disc DIRC (left) is a radiator plate with 3 ROMs attached. Each ROM contains three focussing lightguides read out by one pixelated MCP-PMT. The prototype could be moved horizontal and vertical for position scans and rotated around the vertical axis for angular scans. The colored histogram (right) shows the accumulated hit pattern for many events.

of the maximum likelihood using the time imaging of photons for protons and pions is shown in figure 6. The separation power for protons and pions of 4.8 s.d. at a momentum of 7 GeV/c and a polar angle of 20° clearly exceeds the PANDA PID requirements.

The Endcap Disc DIRC prototype used a synthetic fused silica plate (500 × 500 × 20 mm³) placed on a vertical and horizontal adjustable table. In addition, the prototype could be rotated around the vertical axis. During the beam test several vertical and horizontal position scans and angular scans were performed. One edge of the radiator plate was equipped with 3 ROMs (9 FELs) and different photon detectors from PHOTONIS [13] and HAMAMATSU [19] (figure 7, left). The opposite edge of the radiator was connected to a PiLas laser to calibrate time differences between

Figure 8. Reconstructed Cherenkov angle for different vertical positions (left) and for different angles of the incident beam (right) are compared to predictions from GEANT4 simulations.
the electronic channels. In this campaign the version of the TOFPET ASIC, which was optimized for positive signals from silicon photomultiplier, showed problems with the negative polarity from the MCP-PMTs, resulting in a loss of hit detection efficiency. The problem is understood and a new ASIC version is in production. The number of detected Cherenkov photons per trigger as a function of beam position and channel number at 7 GeV/c for pions is shown on the right side in figure 7. The channel number and the beam position are a measure for the polar and azimuthal angle of the Cherenkov photons, respectively. Each measured Cherenkov hit was reconstructed by using a geometrical reconstruction algorithm [20]. The results of the position (figure 8, left) and angular scans (figure 8, right), first published in [6], agree with expectations from GEANT4 simulations.

4 Outlook

Following the successful performance validation with particle beams and the completion of the technical design reports the DIRCs have entered the construction phase. The Barrel DIRC components with the longest production time, the radiators, have been ordered from Nikon [21]. The tendering of the MCP-PMTs is at an advanced stage. For the EDD the component fabrication will start. However, there are still important R&D topics: the latest generation of the Barrel DIRC readout electronics, the DiRICH system [9], originally designed for multianode-PMTs, needs the adaption of the discriminator input stage to the fast signals of MCP-PMTs. The coupling between the bar boxes and prisms and between the MCP-PMTs and the prism will be done with RTV-silicone cookies and is subject of ongoing tests. The material of the bar boxes can be aluminum or carbon fiber reinforced polymer (CFRP). Long-term outgassing tests of CFRP and its effect on the surfaces of the radiator will show if this material is better to minimize the material budget. The next generation of the TOFPET ASIC for the EDD compatible with both polarities will be tested in the Giessen Cosmic Station (GCS) [22].

The experimental hall for the PANDA detector will be ready to move in and to install first basic elements, like the solenoid, in 2022. The Barrel DIRC will then be installed in 2023/2024 and subsequently commissioned. At the same time one quadrant of the EDD will be installed as a prototype followed by a complete installation in 2026/27.

Acknowledgments

This work was supported by HGS-HIRe, HIC for FAIR. We thank the CERN staff for the opportunity to use the beam facilities and for their on-site support.

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