Development of DIRC counters for the PANDA Experiment at FAIR

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Abstract

The PANDA experiment at the planned FAIR facility at GSI, Darmstadt, aims at measuring hadronic final states with unprecedented precision and luminosity. Superior particle identification of charged and neutral particles is mandatory to fulfil PANDA's physics aims. DIRC (Detection of Internally Reflected Cherenkov light) counters are foreseen for charged particle identification. A barrel DIRC will cover the central region while a disc DIRC will provide particle identification in the forward region.

Three DIRC concepts differing in the radiator geometry and method for dispersion correction are studied. The barrel DIRC uses a novel imaging system and aims at exploiting a 3D reconstruction to mitigate dispersion effects. Two concepts are investigated for the forward disc DIRC. One concept employs passive dispersion correction and focussing light guides for image reconstruction. Alternatively, time-of-propagation measurements and a wave-length dependent photon detection system are investigated. The three detector designs share common developments such as investigating radiator properties and photon detection systems, and use the same test beam facilities.

Key words: Particle Identification methods, Cherenkov detectors

1. Introduction

The PANDA experiment at the planned FAIR facility at GSI, Darmstadt [1], aims at measuring hadronic final states with unprecedented precision and luminosity [2]. A versatile detector system covering the full solid angle, providing excellent particle identification and measuring momenta up to 15 GeV/c is mandatory to fulfil PANDA's physics aims, such as the search for exotic charmed mesons and glueballs [3].

The broad physics program to be addressed by this new facility poses significant challenges for the design and construction of the detector. In particular, the detector should provide:

- full angular coverage and good angular resolution for charged and neutral particles
- particle identification for a large range of particles and energies
- high resolution over the required wide range of energies
- high rate capability especially for the detectors close to the target and in forward direction.

The PANDA experiment was therefore designed as a multipurpose detector system surrounding an internal target.

The detector design is shown in Fig. 1. Its design is based on a combination of a central detector (target spectrometer (TS)) within a 2 T solenoidal magnetic field covering laboratory angles larger than 5° , complemented by a forward spectrometer (FS) equipped with a dipole magnet to measure particles at the most forward angles. Combining these two spectrometers allows full angular coverage over the wide range of energies to be taken into account. Both TS and FS will permit the detection, identification and energy/momentum reconstruction for charged and neutral particles.

The detector is expected to operate at an average interaction rate of $2 \times 10^7 s^{-1}$ with an average multiplicity of 5-7 charged tracks and several neutral particles.

Detectors for charged particle identification comprise coarse measurements of the deposited energy in the tracking detectors, precision Time-Of-Flight detectors, electromagnetic calorimeters, muon chambers and an array of Cherenkov detectors based on the DIRC principle [4, 5, 6]. These detectors will be complemented by a more conventional RICH detector, Time-of-Flight detectors and calorimeters in the far forward region. Photon identification and reconstruction relies on the performance of a highly segmented PWO calorimeter [7].

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Figure 1: Sideview of the PANDA target spectrometer. The \bar{p} -beam is entering from the left impinging on a Hydrogen target. The target region is surrounded by a micro-vertex tracker and a large volume central tracking device. Particle identification is provided by DIRC counters placed in front of an electromagnetic calorimeter. The target spectrometer is enclosed in the return yoke of a 2 T super-conducting magnet. The forward spectrometer is not shown. The location of the barrel and disc DIRC counters is indicated.

2. PANDA's DIRC detectors

PANDA will feature two DIRC detectors - a DIRC in barrel geometry surrounding the target region [8] and a disc DIRC in the forward region [9, 10]. Both systems aim at incorporating dispersion corrections and focussing optics. They will be equipped with very fast photon detection systems. While the radiator geometry of the barrel DIRC follows the design pioneered by BaBar [11], its optical system will be completely redesigned. The forward disc DIRC (suggested, but not constructed previously for Belle [12]) is a completely new design. The design of the disc DIRC consists of a disc built from fused silica of about 2.2 m diameter with dispersion correcting LiF plates, focussing light guides and fast photon detection systems instrumenting the rim [13]. Time-Of-Propagation methods are investigated as an alternative [14].

2.1. The Barrel DIRC

The barrel DIRC has to provide particle identification over a polar angular range of $22^{\circ} < \theta < 140^{\circ}$. Particle momenta are moderate, allowing to use a radiator of comparatively high refractive index (n=1.47 for $\lambda = 400$ nm) favouring total internal reflection. This will also allow the detector design to be compact. This choice of refractive index allows to positively identify Kaons with a momentum p > 0.46 GeV/c.

The barrel DIRC will consist of 96 optically separated fused silica bars, 2.2 m in length and lateral dimensions of $17 \times 35 \text{ mm}^2$. Each bar will be equipped with focussing optics to image the Cherenkov cone created in each bar on a multi-pixel photon detection system [15]. The end of each bar will be shaped as a lens to allow good photon separation and to facilitate image reconstruction.

A fast photon detection system, with an overall timing resolution better than 100 ps, will allow to correct for dispersive effects by measuring the photon's time-of-propagation along the bar. The barrel DIRC will use the reconstruction of two spatial co-ordinates to reconstruct the Cherenkov angle and the timeof-propagation measurement to correct for dispersion and thus constitutes a so-called 3D-DIRC [16].

2.2. The Forward Disc DIRC

The forward disc DIRC is designed to provide particle identification for particles emitted at polar angles of $5^{\circ} < \theta < 22^{\circ}$. Its design is challenging. The lower momentum threshold is given by the refractive index of the material and is thus the same as for the barrel DIRC. However, the forward disc has to be able to cover a larger momentum range, requiring a larger dynamic working range for the detector. The average photon rate per channel will be higher. The disc geometry implies a more complex pattern, spread out over a number of photon detection devices. Two alternative designs are being studied. Both designs will use a fused silica disc of approximately 1.1 m radius and 15 mm thickness, instrumented around the rim. The radiator will be glued from six pieces.

The focussing disc DIRC (FDD) design employs optical elements to correct dispersive effects and to image the Cherenkov cone on the photon detection plane. The reconstruction will be done in two spatial co-ordinates, with precise timing information aiding event correlation and minimising false identifications due to overlapping events. A moderate time resolution on the order of 100 ps is therefore sufficient. Also, the average light path is shorter than in the barrel DIRC, easing the requirements on the surface quality of the radiator [13].

The alternative design relies on the reconstruction of one spatial co-ordinate and the photon propagation time to reconstruct the Cherenkov angles, thus minimising the number of read-out channels required. Dispersion correction will be achieved by using dichroic mirrors for coarse selection of the Cherenkov photon wavelength. This design, however, will need a better optical quality of the radiator due to longer light paths and a single photon time resolution better than 50 ps [14].

3. Prototyping and testing

The design and construction of a DIRC detector can be separated into four broad categories [16]:

- photon generation
- photon transport
- photon detection
- image reconstruction.

Each of these aspects must be studied individually, but can partly be addressed in common for all PANDA DIRC detectors. Photon generation and photon transport are mainly governed by the optical and mechanical properties of the radiator, the glue and other common components. The suitability of candidate radiator materials for all PANDA DIRC detectors, e.g. with regard to radiation hardness, has been reported previously [17]. Other areas, e.g. the focussing optics, dispersion correction and image reconstruction have to be studied for each detector system individually.

3.1. Testing the Barrel DIRC Prototype

A prototype of a segment of the Barrel DIRC counter was tested in a pure proton beam with a kinetic energy of 2 GeV, corresponding to $\beta = 0.95$. The set-up consisted of a fused silica radiator coupled to an expansion box with multi-channel photon detection at its back. The photon detection and readout electronics are the candidates selected for the full apparatus. The aim of this test was to identify Cherenkov hit patterns for a known particle species under different angles of incidence. The focussing optics was studied independently [15].



Figure 2: The observed Cherenkov ring pattern with the expected position (dotted lines). The shaded area indicates the acceptance of the expansion volume.

The proton beam hit the quartz bar at a fixed distance from the expansion box but under different, adjustable angles of incidence. A scintillator paddle was used as coincident trigger. Four 8x8 pixel Planacon 85011 MCP-PMTs were attached at the rear side of an expansion box filled with Marcol-81 oil. The radiator bar was coupled to this expansion box with a focussing lens. The oil has a refractive index similar to that of the radiator and thus minimises image distortions of the Cherenkov rings. The NINO-discriminators [18] of each amplified (x10) MCP-PMT channel were set to thresholds of 44 mV. Finally, 2 HADES-TRB (TRBv2) were used for the readout [19].

The observed photon pattern within the acceptance of the four MCP-PMTs is shown in Fig. 2. The left top detector lies not completely within the acceptance of the expansion volume indicated by the grey shaded area. The left bottom detector suffers from broken electronic channels. The expected ring structures as indicated by the dotted lines are clearly seen. This pattern changes in the predicted manner when the angle of incidence is changed.

3.2. Testing the Forward Disc DIRC

Two alternative detector systems are being developed for the forward disc DIRC. A key parameter for both of them is the number of photons in a given section of the detector as a function of the impact point and angle of incidence of the incoming particle. Using the same test beam source as discussed above, the number of photons for different distances and as a function of the angle of incidence was studied. The radiator dimensions and surface properties are representative of the full detector design. The radiator was directly coupled to a single channel PMT and read-out using standard electronics. The results are shown



Figure 3: The observed number of Cherenkov photons (triangles) as a function of the angle of incidence measured in the focussing disc DIRC prototype. The distribution follows the expected trend for not fully absorbent edges ($\eta = 0.5$), as indicated by the results of a LITRANI simulation (circles). A highly absorbent rim ($\eta = 0.9$) would follow the trend indicated by the squares.

in Fig. 3. The experimental number of photons for each angle (triangles) is a result of a multi-parameter fit [20] to the response of a single channel PMT viewing the end of the radiator. The results are compared to LITRANI [21] simulations which were performed for two absorption coefficients for the rim, $\eta = 0.5$ (circles) and $\eta = 0.9$ (squares). The experimental data points follow the trend and magnitude of the simulation with not perfectly absorbing edges.

3.3. Photon Detection Systems

The requirements for a photon detection system are very similar for all three detector concepts. The DIRC principle relies on a fast, single-photon capable, position-sensitive photon detection system. Employing imaging optics allows to equip the barrel and disc DIRC with very similar photon detectors. Candidate photon detector systems are thus selected and evaluated to match the requirements for all three detector designs. Multi-pixel photon detection systems based on micro-channel plates for amplification of the initial photoelectron are the most promising candidates [22]. The application in the PANDA DIRC system requires a single-photon time resolution on the order of 100 ps (better than 50 ps in the case of the Time-of-Propagation DIRC), sufficient gain in a magnetic field of up to 2 T and the ability to detect photons at a rate of 1-2 MHz/cm². Several candidate systems have been tested, among them Burle



Figure 4: Single-photon time resolution for three candidate photon detection systems based on micro-channel plates. The contribution of the photon source and the read-out electronics has not been de-convoluted. All systems meet the barrel DIRC and FDD requirements in terms of time resolution.

PLANACON 85011 with 25 μ m MCP pore diameter, Hamamatsu R10754 with 10 μ m MCP pore diameter and a single channel MCP-PMT with 6 μ m MCP pore diameter provided by the Budker Institute, Novosibirsk [23]. The results for the single-photon time resolution are shown in Fig.4. A dependency of the single-photon time resolution on the pore diameter of the MCP itself is observed. All candidates meet the timing requirements for the barrel DIRC and the FDD.

The rate stability as a function of incident photon rate is depicted in Fig. 5. The rate stability of all tested candidate systems is at the limit for the application in PANDA, especially for the higher photon rates expected in the forward detectors. Similarly, the overall lifetime of MCP-PMTs is of major concern.



Figure 5: Relative gain for five photon detection candidate systems based on micro-channel plates as a function of the incident photon rate. Primary photon rates of 1-2 MHz/cm² are expected for the PANDA DIRC counters, which is where most current systems reach their limit.

4. Conclusion

The PANDA experiment at the planned FAIR facility will employ DIRC detectors for particle identification in the central detector. DIRC counters offer superior particle identification capabilities in a limited space. A successful operation of DIRC counters for PANDA relies on excellent radiator qualities, a high-rate, single-photon capable, highly granular photon detection system with fast timing properties and measures to correct for dispersion effects. PANDA will employ a barrel DIRC around the target which will operate in a 3D mode for Cherenkov image reconstruction and dispersion correction. In the forward region, a disc DIRC with either passive optical dispersion correction or a Time-of-Propagation DIRC will be installed.

A step-wise approach in the design was adopted. Prototypes for each detector system have been constructed and are currently being tested using test beams consisting of single particle species. The detector prototypes work according to their expectations. The test results will feed into the next generation of tests using mixed particle beams to fully establish the particle discrimination power of these detector system.

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