Design of the Focussing Disc DIRC for PANDA

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Simulation and Physics Performance

Requirements from the PANDA Physics Program

The PANDA collaboration will pursue a large variety of physics topics ranging from precision spectroscopy of Charmonium states, the hunt for new form of hadronic matter to studying Hypernuclei, medium modifications of hadron properties and the study of nucleon structure in electromagnetic or exclusive final states. It is therefore difficult to optimise the performance of the detector system taking all the different physics topics and their respective detector requirements into account.

The PANDA Collaboration formed a Technical Assessment Group for its Particle IDentification needs (PID-TAG). The PID-TAG in consultation with the collaborators working on the *PANDA Physics Book* defined a number of benchmark channels to evaluate the detector performance. The channels chosen for detectors in the forward region are the production of glueballs decaying into $\Phi\Phi\eta$ and the open charm channels $D_s D_{s0}^*$ and D^+D^-.The chosen reaction channels represent one of the major science topics, the search for glueballs, while the other channels represent both states with a significant particle multiplicity and contributions to one of the other major science topics, the precision spectroscopy of charmonium states.

Glueball

A glueball of mass 3670 MeV is produced by a 15 GeV/c antiproton and decays into phi and

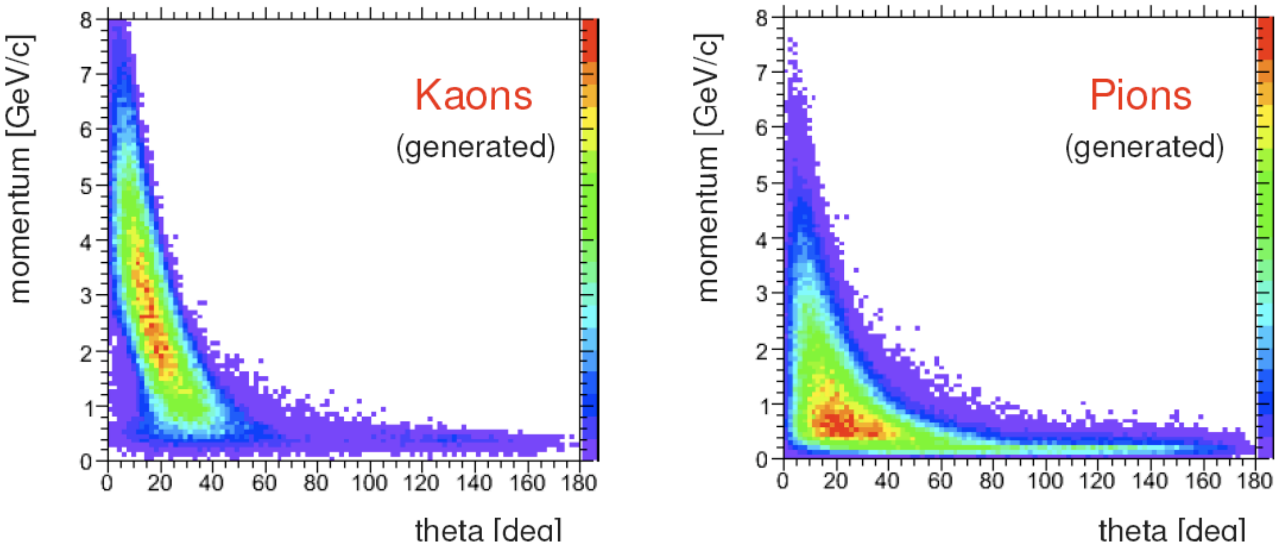

Figure 1: Simulated distribution of kaons and pions from a possible glueball decay

eta mesons, which in turn decay into kaons, pions and photons. Figure 1 illustrates that a large fraction, if not the majority of all kaons and pions is detected in the angular range covered by the Disc DIRC (5-20 degrees). A closer analysis of this reaction shows that without the Disc DIRC the background increases so much that the measurement of this reaction becomes impossible. The figure also indicates the momentum region for which the focussing disc DIRC has to operate. In 23% of all events at least one track is detected in the forward region (< 5 degrees) covered by the forward spectrometer. These events could not be reconstructed correctly without the dipole magnet of the forward spectrometer.

Open Charm states

This reaction channel D_sD_{s0}*was studied with 40k signal events and about 6 Mio background

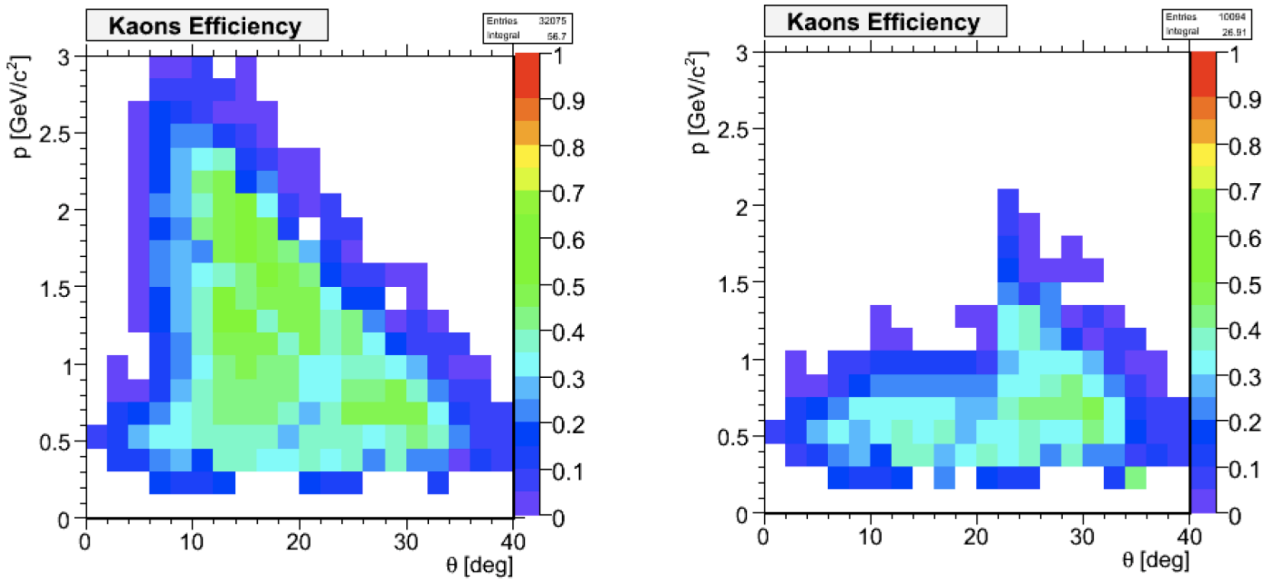

Figure 2: Efficiency for kaons with (left) and without (right) the FDD information.

events. The D_s mesons ultimately decay into kaons and pions. Without the Disc DIRC the signal/background ratio of the reaction becomes about one order of magnitude worse. This is due to a drastically lowered kaon identification as well as a worsened background rejection. The right part of figure 2 illustrates the gap in the kaon identification for otherwise identical reconstruction.

The reaction channel D^+D^- was studied in addition. For this reaction only the charged decays of the D-mesons into one kaon and two pions were considered, hence there are 6 charged particles in the final state. The average multiplicity per event in the Disc DIRC in this case is 2. Dependent on the selected particle identification cuts, the detection efficiency for this channel

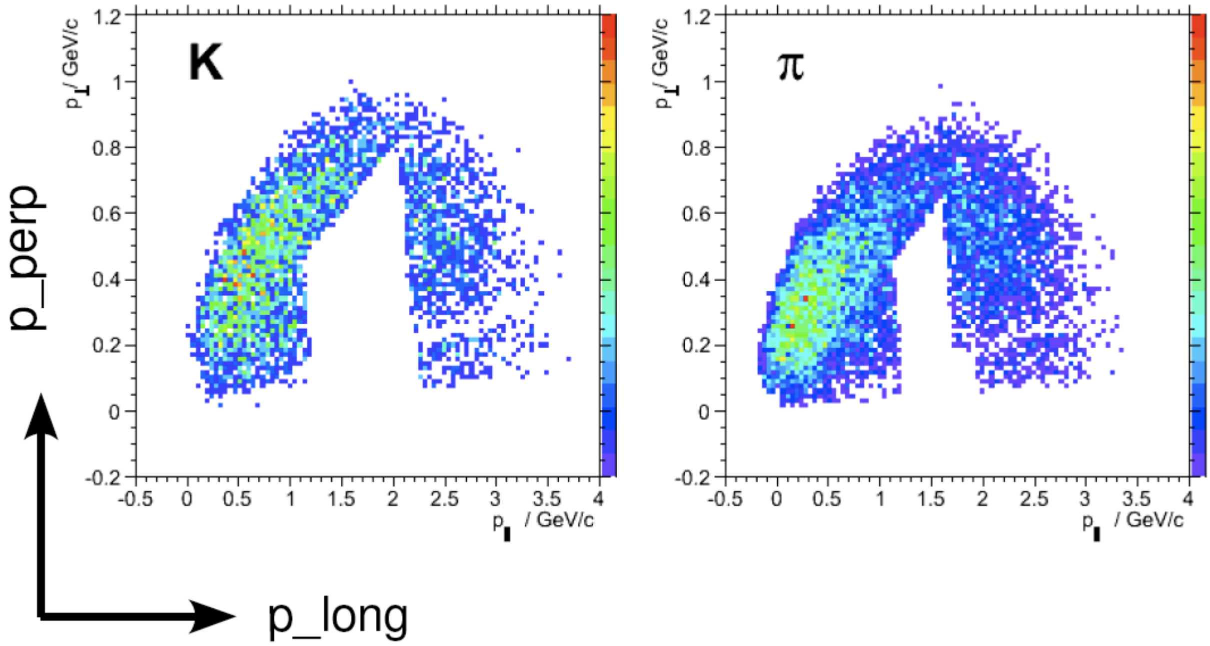

Figure 3: Momentum distribution for kaons and pions without the information from the FDD. A clear gap is visible where this information is missing.

drops by up to two orders of magnitude without the Disc DIRC. The absence of the Disc DIRC leads to a hole in the acceptance of the detector which will make the physics analysis even more difficult. The loss in acceptance will severely hamper the partial wave analysis for these states. Taking these arguments together this makes this measurement practically impossible without the Disc DIRC.

The channels discussed above provide the particle mixture and momentum distribution on which to assess the performance of the focussing disc DIRC. As problems might be expected from overlapping pattern generated by the decay products of high momentum vector mesons ($\rho \rightarrow \pi^+\pi^-$, $\phi \rightarrow K^+K^-$), these particles were studied as well. In addition we studied the reconstruction of kaons in the presence of random noise with various noise levels.

Particle multiplicities were studied using the DPM generator and PYTHIA. Particles were tracked using GEANT 4. The detector response was either parametrised based on stand-alone calculations (fast simulation mode) or event lists were generated by an event generator and tracked through a GEANT 4 detector model until impinging on the focussing disc DIRC detector. The results were fed into a stand-alone optical simulation of the detector set-up. The histogram on the right depicts the average and maximum multiplicities of particles within the focussing disc DIRC acceptance for four beam momentum settings simulated with DPM for the standard PANDA simulation settings. An example hit patters for a DPM generated event is given below for a beam momentum of 10 GeV/c.

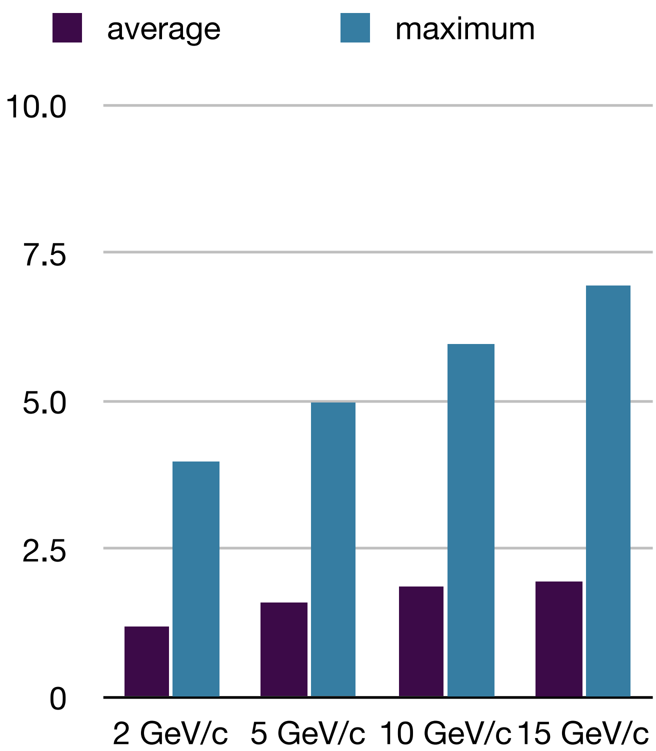

Figure 4: Simulated multiplicity in the focussing disc DIRC for four different beam momenta.

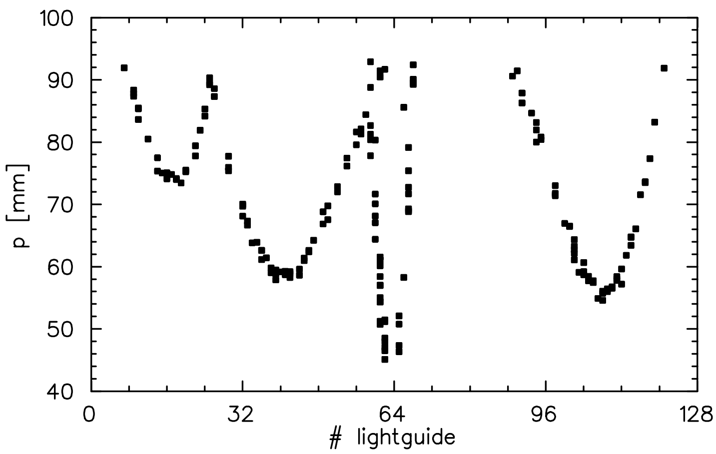

Figure 5: Simulated hit distribution from the DPM generator for a four particle event.

The evaluation of the influence on the PANDA physics programme was performed using the so-called *Fast Simulation* mode. The output of detailed simulation studies on the detector performance were parameterised as functions of particle species, momentum and polar angle to save computing time. The detector response parametrisation was generated from the standalone optical simulations detailed below. A complete analysis of the reaction channels with and without the information from the forward disc DIRC was performed for each reaction channel under consideration.

Optical Design

The optical design of the focussing disc DIRC detector was carried out using two independent optical calculations. Bulk properties were calculated using a set of RooT macros taking the measured transmission curves, given surface quality, parametrised photon detection responses and the dispersion curves of the materials involved into account. Individual photon tracking and the calculation of hit pattern used in the performance evaluation were calculated using a series of PHYSICA scripts. Both versions of code were independently developed and cross checked with each other.

The focussing optics and light guide shapes were also optimised using PHYSICA and cross checked using the MATHEMATICA package RAYICA. The latter was also employed in designing the planned test bench experiments.

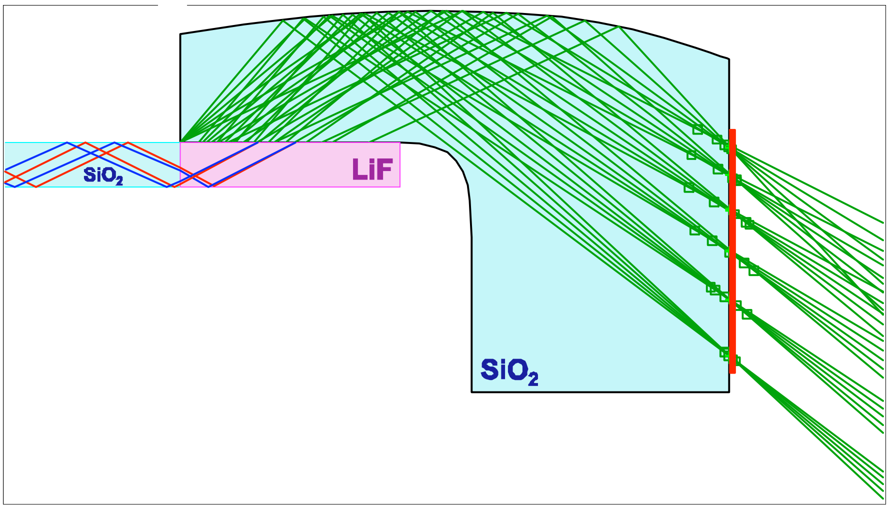

Figure 6: Focussing light guide with dispersion correction and PMT surface. The green lines indicate the ray traced light path for the focussing scheme.

Figure 6 shows the result of the PHYSICA calculations. The coloured lines inside the radiator and LiF are for illustrative purposes only. The green lines in the light guide represent the actual calculated light path for the given geometry. The dependence of the size of the focal point as a function of the position on the focal plane is visible. The size of the focal point is always smaller than the pixel pitch.

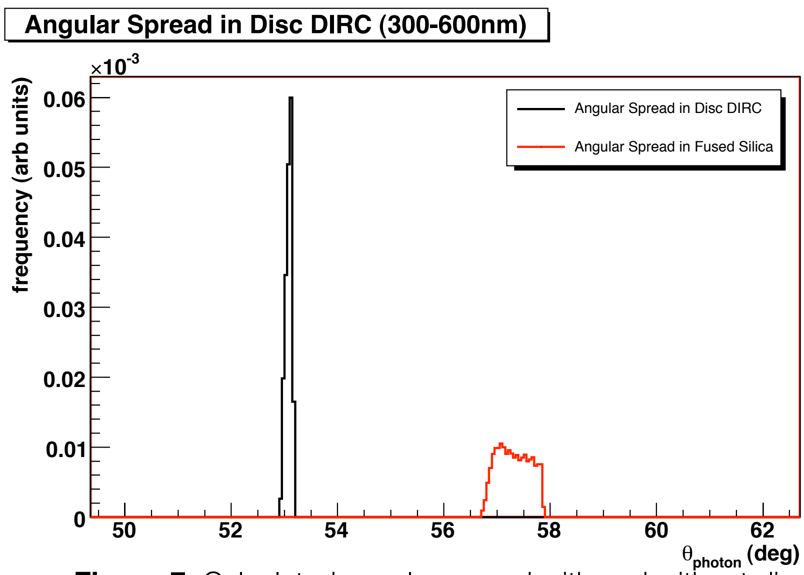

Figure 7: Calculated angular spread with and without dispersion correction. The improvement is clearly visible.

The influence of the LiF is shown in the figure 7, calculated with the RooT packages developed. A significant improvement in the angular spread of the detected light (black curve) is observed compared to the angular spread of light leaving the fused silica radiator (red curve). The calculations were performed over the accepted wave-length range given by the response function of conventional photo-cathodes. This reduction in angular spread translates into a performance improvement for the overall focussing disc DIRC design by mitigating dispersive blurring while leaving the valuable time information free to be used to discriminate between events.

Reconstruction

The reconstruction of the Cherenkov angle uses the geometrical information provided by the strip position on the PMT plane and the position of the light guide. A sample search possible hit roads are depicted below for particles with overlapping hit pattern. The purely geometrical reconstruction is possible within the limited resolution with an algorithm rejecting the overlapping sections.

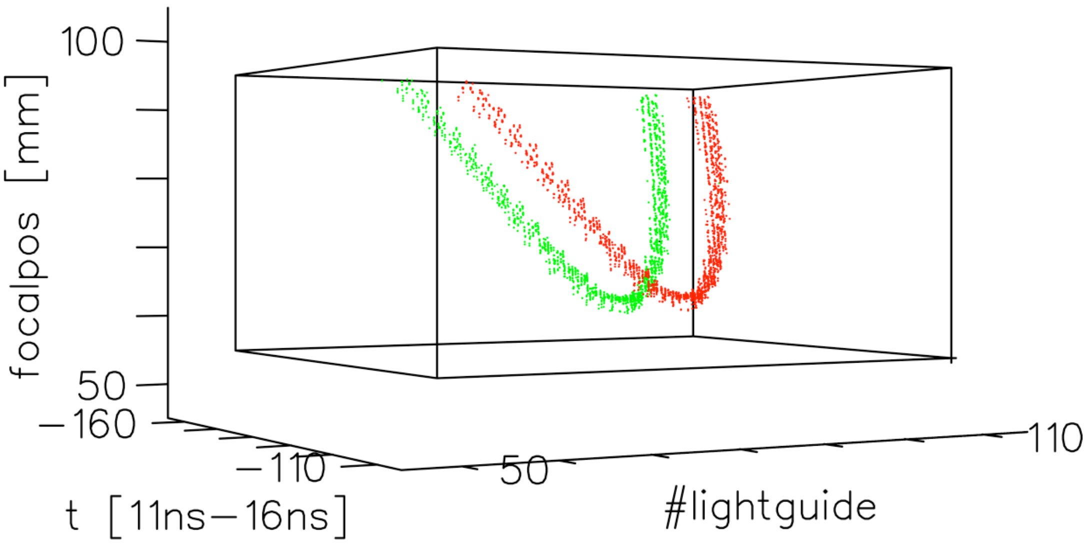

Figure 8: Reconstruction roads for two particles reconstructed in two spatial dimension and one time dimension. The figure shows a clear improvement in separation when the time information is included.

Given the very good time resolution achievable with the envisaged photon detection and readout system, the relative timing of the photons can be used as an additional variable to separate the patterns without sacrificing photon information. The result of this analysis is depicted in figure 8 shown above. The separation clearly improves with a full three dimensional reconstruction.

These hit patterns can be reconstructed for pions, kaons and protons to provide an indication of the projected performance of the focussing disc DIRC. Integrated over the full angular range, the example is given in figure 9.

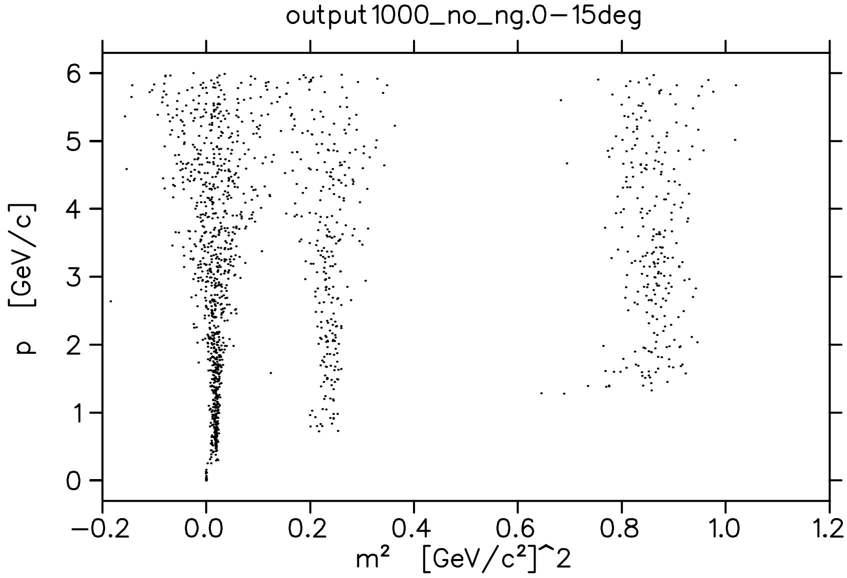

Figure 9: Reconstructed mass squared for pions, kaons and protons as as function of the particle's momentum illustrating the separation of particle species.

The reconstruction of single K^+ in the presence of noise was studied for three different noise levels: no noise, a signal to noise of S/N = 1/1 and a signal to noise ratio of S/N=1/6 to study the robustness of the current reconstruction algorithm. The figure to the right shows the generated hit pattern for a single K^+ in the presence of 100 additional noise hits (S/N = 1/1). A template for a possible hit distribution can be formulated using tracking information. This defines a road in two spatial and one time dimension into which candidate photon hits have to fall. These candidate hits can then be used to calculate the Cherenkov angle and ultimately

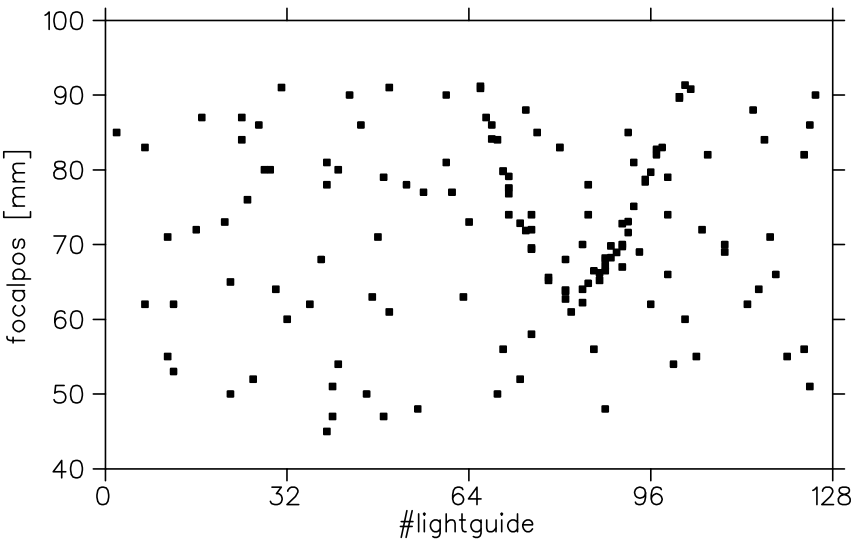

Figure 10: Single kaon hit pattern with 100 noise hits added to study the robustness of the pattern recognition.

the mass of the particle.

The results for the reconstructed Kaon mass in the presence of the three noise scenarios outlined above is shown in the figure to the right. The black line represents the undisturbed mass distribution, the green line the S/N = 1/1 scenario and the red line the scenarios with a S/N=1/6. No significant loss in resolution even at high noise levels is visible. A Gaussian to the each distribution yields the same width within the error of the fit.

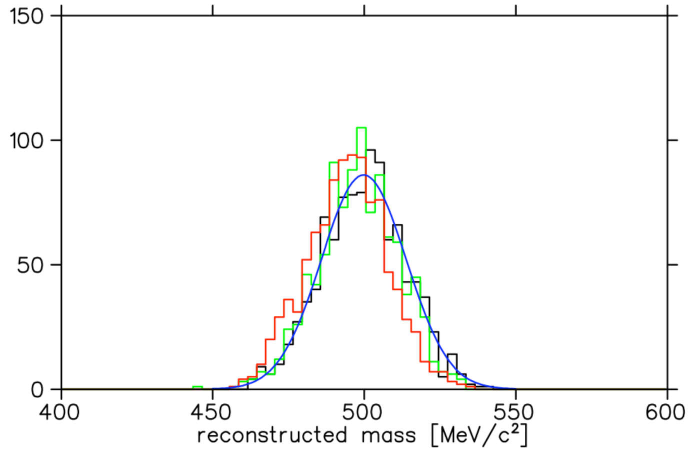

Figure 11: Single kaon reconstructed for the three different noise levels with a sample fit overlayed. All fits give the same parameters within the error of the fit.

Performance criteria and test results

Photon Creation and Photon Transport

A highly transparent solid radiator is at the heart of a DIRC detector. The material chosen has to fulfil a number of design criteria. Its refractive index should be matched to the particle identification task at hand. Furthermore, the refractive index should allow light transport by total internal reflection. The material should be mechanically stable and should take a good optical finish. Its transparency should match the accepted wave-length band of the photon detection system chosen. This is an optimising criterion. Usually, the photon detection system is chosen after the radiator material is decided. For applications in a high rate hadronic physics experiment the radiator material should not alter its properties significantly under the irradiation dose expected.

Design Criteria

The thickness of the disc is given by the required number of photons to reconstruct and image, the radiation length tolerated by subsequent detector systems and the mechanical stability of the system. Considering the latter, mechanical stability has to be ensured at each stage of the manufacturing process as well. The other dimension are given by the solid angle to be covered by the detector system. Light expansion volumes for better image quality have to be additionally considered.

The focussing disc DIRC for PANDA has to cover a polar angle of 5°< θ < 25°. An aperture of 5° in vertical direction and 10° in horizontal direction has to be kept for the primary beam and not to obstruct the acceptance of the forward spectrometer. In addition with the z position allocated for the centre of the detector, this leads to a disc of 1100 mm radius, 20 mm thickness and a rectangular aperture of 730 x 365 mm^2. The thickness is a compromise between a minimum radiation length and mechanical stability for surface treatment.

The material chosen for the radiators is Hereaus Suprasil 311, a 3D fused silica. The size of the largest single piece fabricated according by Hereaus is 800x1100 mm^2. The disc for the focussing disc DIRC will therefore consist of 6 individual pieces to minimise the number of glue joints necessary and to facilitate assembly.

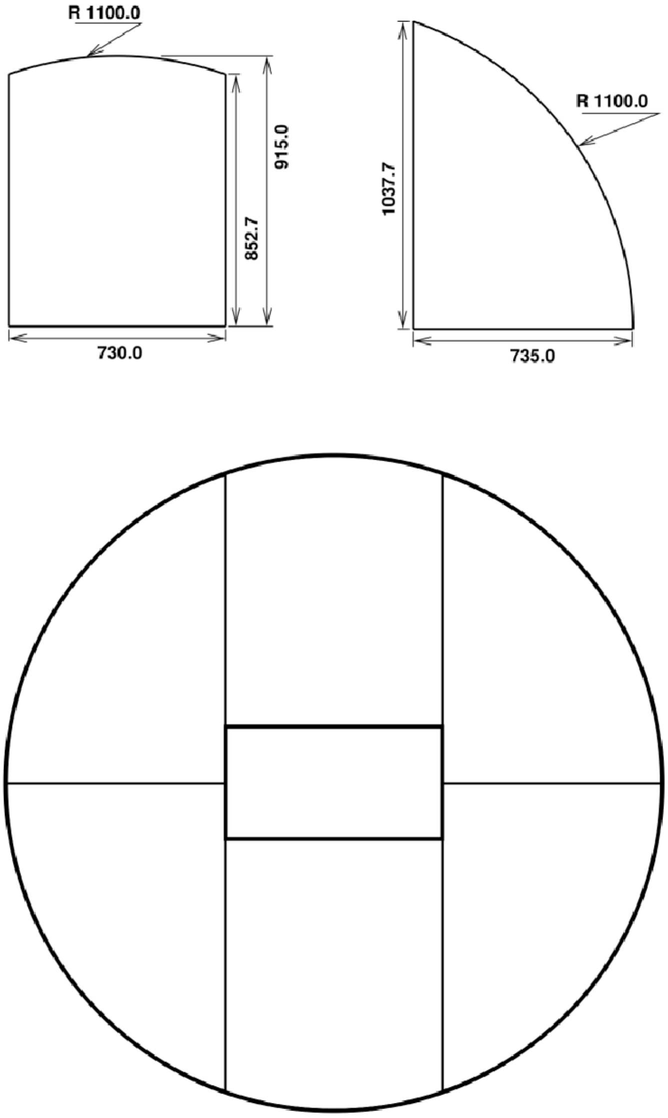

Figure 12: Outline of the mechanical dimensions of the radiator disc.

Surface quality

Cherenkov light is a rather faint light source. In an imaging Cherenkov counter, each individual photon carries information. The conservation of each Cherenkov photon produced is therefore extremely important. Cherenkov photons in a DIRC application will be lost be imperfect reflection on the radiator surfaces. As the geometrical dimensions and the refractive index of the detector are fixed, the number of surface reflections for Cherenkov photons created by particles of given momentum and track parameters can be calculated. Clearly, the number of surface reflections will be a function of the spatial co-ordinates on the detector surface.

A requirement for the surface quality of the disc can be derived from the expected number of reflections and the probability to lose a photon with each reflection. This gives a design criterion for the surface treatment of the disc. The surface roughness should be about 2 nm.

Additional care has to be taken at the joints. In general, neither the refractive index nor the dispersion properties of the glue envisaged are the same as the radiator material. This can lead to partial image distortion and ghost hits at odd geometrical location in coincidence with the real event thereby complicating the pattern recognition task substantially.

Figure of Merit

The figure of merit for the design of the disc DIRC is derived from the optical quality of the radiator, the dimensions of the disc and the response function of the Planacon MCP-PMTs. The number will differ from the conventional calculation of N_0 and will depend on the point of impact of the particle. As the detector is radially symmetric, the figure of merit will be a function of the particle's polar angle only.

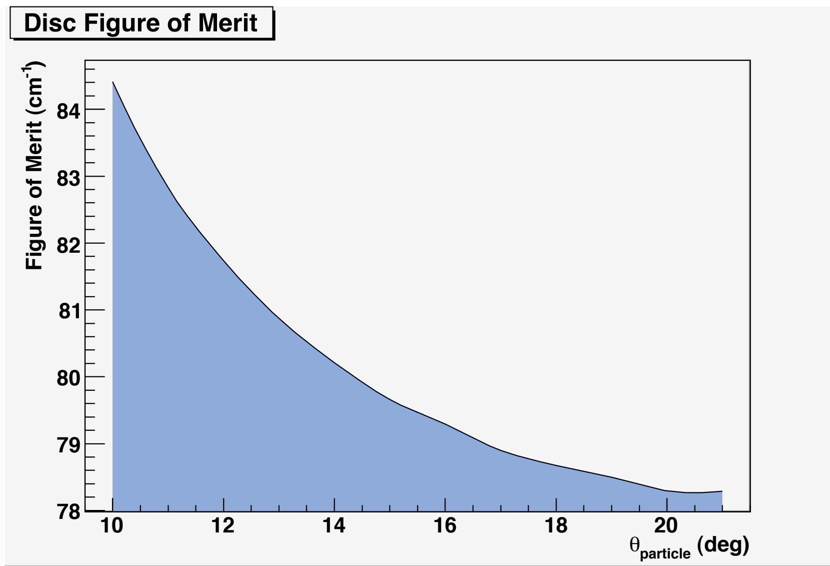

Figure 13: Figure of merit for the focussing disc DIRC.

The number of photons detected will furthermore depend on the fraction of the Cherenkov cone where the combined Cherenkov angle and the inclination angle of the charged particle fulfil the total reflection condition. For finite dip angles, only a fraction of the Cherenkov cone will be trapped inside the disc. Therefore the number of photons expected is higher for low inclinations although these photons undergo a larger number of reflections.

The total number of photons expected from each particle depends on N_0, the radiator thickness and $\sin^2\theta_C$. The total number of photons per particle is about 100.

Polishing

Polishing fused silica surfaces to the required quality is possible for industrial manufacturers. The quality assurance necessary, however, makes this solution prohibitively expensive. The PANDA collaboration will therefore polish the radiator surfaces itself. The workshop at INFN

Ferrara polished samples which were later tested for their surface quality using AFM. A surface smoothness of 0.6 nm was achieved. On a larger scale, the polishing reaches a smoothness of 2 nm deemed sufficient for the application envisaged.

Additional testing procedures are developed at GSI, Germany enabling tests for larger samples. These testing procedures follow the ones described in the literature by comparing the relative intensity of two laser beams. The test set-up is flexible enough to accommodate the large pieces needed for the construction of the radiator disc.

Radiation hardness

The project leader is the spokesman of an international collaboration testing the radiation hardness of candidate radiator materials. The expected radiation dose in the forward region over the lifetime of PANDA is ~100 krad. Data on candidate materials exposed to gamma radiation are available from BaBar[1]. It was therefore decided to irradiate the samples using the proton beam at KVI, Groningen, The Netherlands. The beam energy was 150 MeV. Radiation doses of 10 krad, 100 krad, 1 Mrad and 10 Mrad were deposited in samples of Corning 7980, Suprasil 1 and Lithosil as well as EPOTEK glue on a Corning 7980 substrate, LiF and a variety of glasses. The procedure and relevant results are documented in references 5 and 6.

No loss in transmission or surface alteration were found for all fused silica samples. LiF develops a well know absorption band at higher doses. No radiation damage for the glue was

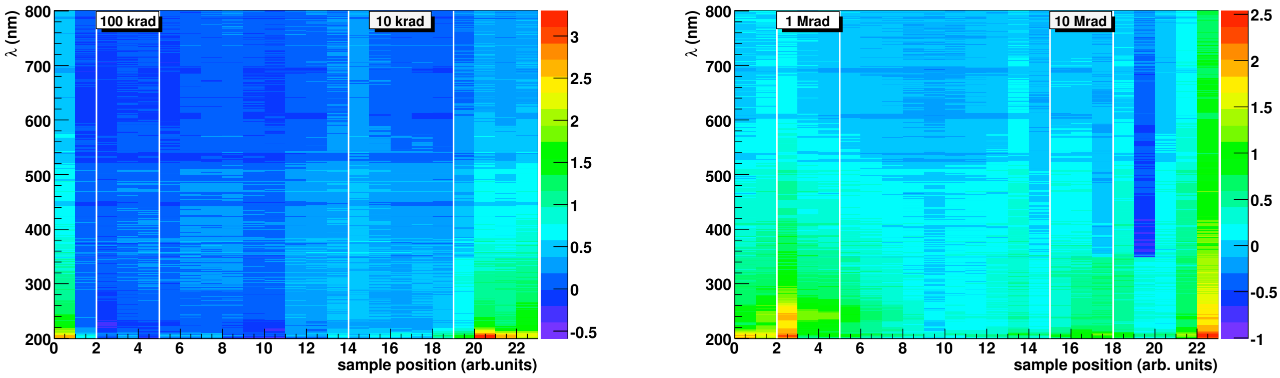

Figure 14: Results of the radiation hardness tests for four different dosages delivered. No radiation damage was observed.

found at the expected PANDA dose.

Cherenkov Imaging

The focussing system is optimised to correct for the finite width of the radiator plate. The design of the focal plane has to take the mechanical constraints, construction space, size of

[1] J. Schwiening et al., Nucl. Instr. Meth. A 515 (2003) 680

available photon detection systems and the orientation of the photon detection system inside the magnetic field into account. The building space available for the installation of the focussing disc DIRC detector limits the possible size of the focussing systems and accompanying read-out. The limitations are given by the inner dimensions of the solenoid return yoke, the need for cable routing and surrounding detector systems. As the focussing light guide system is to be manufactured from fused silica it will contribute significantly to the overall weight of the detector system. The focal plane has to be optimised in two different aspects. Most importantly, the size of the image on the focal place should be as small as possible. Additionally, the orientation of the focal plane should be perpendicular to the direction of the magnetic field lines to minimise the impact of the magnetic field on the performance of the photon detection system. The width of a single light guide is a free optimisation parameter controlled by available photon detection systems and the necessary resolution in one spatial co-ordinate. As the circumference of the disc is given by the geometrical constraints, the number of light guides fitted around the circumference is a direct measure for their width and thus both the available number of measurements in phi and their resolution.

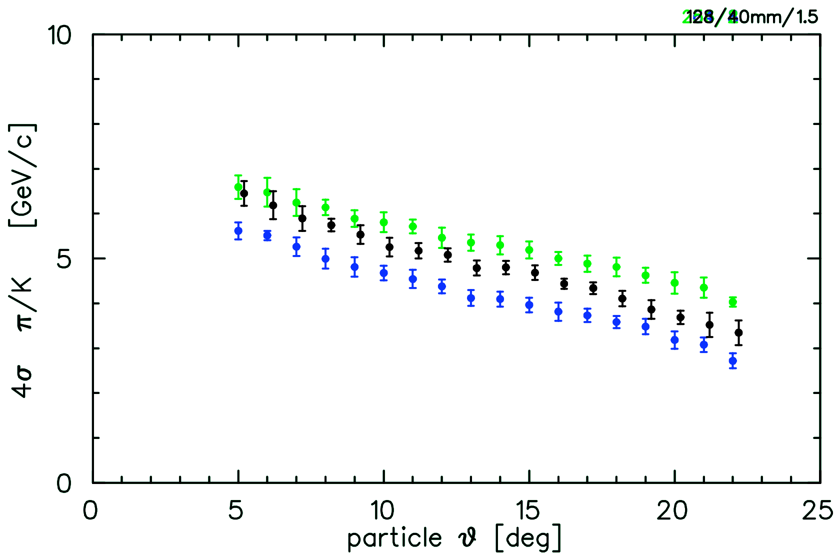

Figure 15: Simulated performance as a function of polar angle for three different light guide width. Refer to the text for details

The figure on the right shows the default scenario (black symbols) with 128 light guides compared with a reduction to 64 light guides (blue symbols) and an increase to 256 light guides (green symbols) for the same pixel pitch. Reducing the number of light guides significantly decreases the performance, while doubling the number of light guides leads to a moderate gain. The envisaged number of 128 light guides is a compromise between the number of read-out channels and an acceptable performance.

The limitations on mechanics and construction space favour a small light guide design with a lateral dimension smaller than 15cm. This allows a focal plane matching the installation of commercially available 50x50mm^2 multi-pixel photon detectors to be constructed. Depending on the position on the focal plane, the image size on the focal plane varies from 0.4mm to

1mm. The variation is due to the tilted construction of the focal plane to optimise the orientation in the magnetic field. The size of the image is well matched to a pixel size of 1.5 mm. The lateral dimension is given by the size of the photon detection system. The optical calculations predict an optical performance acceptable to the planned detector performance.

Photon Detection system

The reconstruction of the Cherenkov image requires the reconstruction of two spatial co-ordinates. Additional measurements can be used to over-constrain the system and thus improve the detector performance and suppress background. Designs using two spatial co-ordinates plus a timing measurement in their reconstruction are known as 3D DIRC systems. The FDD for PANDA relies on the reconstruction of two spatial co-ordinates. A reasonably precise time information will be employed to aid in the reconstruction of the Cherenkov pattern and for background suppression.

PANDA does neither foresee a common start detector to provide a time reference nor is the bunch spacing between beam bunches available as a common time reference. Using the time-of-propagation differences of photons of different wavelength to correct for dispersive effects is therefore not conceivable in the present design.

Requirements

Area and pixel size

The photon detection system of the PANDA focussing disc DIRC requires a a strip pitch of 1.5 mm. The active area of the PMT has to be matched to the focal plane of the focussing light guides. In the design of the focussing light guides a focal plane area of 50x50 mm^2 was assumed to match likely photon detection candidates like the Burle Planacon MCP-PMTs or Hamamatsu H9500 MAPMTs. The required strip pitch is then given by the resolution of the optical focus. To achieve the envisaged

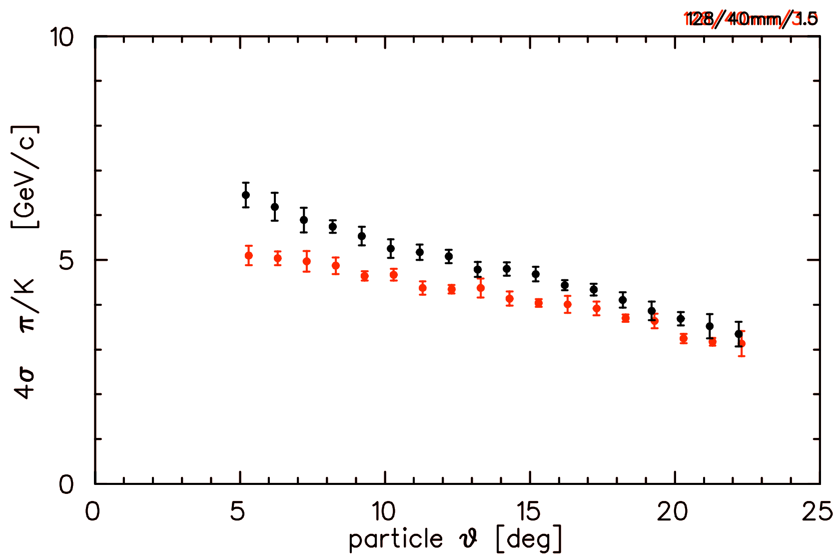

Figure 16: Comparative study of two different pixel sizes. Refer to text for details.

performance, each PMT features 32 strips of 1.5 x 51 mm^2. The influence of the strip pitch is shown in the figure to the right comparing the default option of 1.5mm strip pitch (black symbols) with a larger strip pitch of 3mm (red symbols). Clearly, a smaller strip size enhances the performance. A further reduction of the strip size will not enhance the performance much further without a significant redesign of the focussing optics unlikely to be realised within the geometrical constraints.

Monte Carlo studies artificially worsening the focussing disc DIRC peformance by a factor two corresponding to a larger pixel size and/or smaller number of light guides were performed for the channel discussed above. In all cases, a decrease of a factor of two results in worsening the signal efficiency by about 20% relative. For final states with small branching ratios and low overall reconstruction efficiency, this reduction in signal efficiency will make the measurement much more difficult.

Spectral range

Cherenkov photons are produced in a white spectrum as a function of the photon energy. The radiator material and the LiF chosen for dispersion correction are transparent for visible and ultraviolet light and are nor restricting the spectral sensitivity of candidate photon detection systems. The spectral range will be restricted to $\lambda > 300$ nm by optical glue. Conventional cathode materials like Bi-Alkali are therefore sufficient. The comparatively large wavelength band for detected photons requires dispersion correction measures.

Rate

The number of detected photons is given by the charged particle rate, he radiator thickness, the quality of the light transport system and the quantum efficiency of the photon detection system. PANDA plans to run at an average interaction rate of 20 MHz. Simulations predict an average charged particle multiplicity of 3 for the maximum beam momentum when running with a Hydrogen target. Each charged particle will on average produce 100 photo-electrons. The total photo-electron rate of the device is therefore 6 GHz distributed over 4096 channels. This corresponds to a rate of 1.46 MHz per pixel or 46.7 MHz per PMT.

Magnetic field

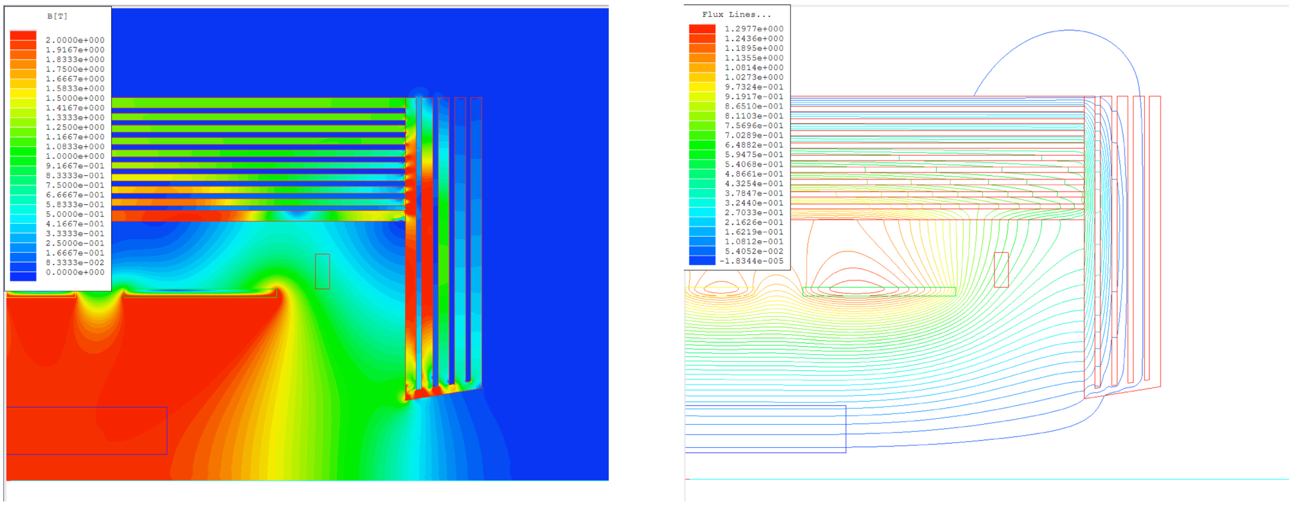

Figure 17: Magnetic field maps showing the strength of the solenoidal field in the FDD readout region

The compact design of the PANDA target spectrometer requires the photon detection system and initial digitisation stages to be located inside the return yoke of the target solenoid. The photon detection system is exposed to a magnetic field of 0.8 - 1.0 T. The available construction space allows a moderate optimisation of the PMT orientation relative to the magnetic field lines. The compact design and high geometrical filling factor necessary do not allow the installation of magnetic shielding. A suitable photon detection system should therefore work inside a magnetic field of up to 1.2 T (allowing for a safety margin of 20% in the prediction of the magnetic flux).

Time resolution

The design of the focussing disc DIRC does not require extreme time resolutions. It is not suggested to use the photon time of propagation to reconstruct the Cherenkov angle or to mitigate dispersive effects. Time-resolution will however help in the event correlation and more importantly in the image reconstruction and background suppression.

Available Candidates

Summarising the requirements outlined above, the focussing disc DIRC needs a pixelated photon detection system capable to work in a 1.2 T magnetic field and with a rate of 1.46 MHz per pixel. The pixel size can in principle be adjusted within the space limits for the focussing light guide elements. Note, however, that adjusting the size of the focal plane might require larger light guides and larger or more PMTs thus increasing the mechanical weight and the cost of the system. Three possible solutions were investigated.

Planacon Micro-channel Plate PMTs

Photonis Burle Planacon series offer a 64 channel or 1024 channel multi-pixel PMT system using conventional photo cathode material, but a 25μm micro-channel plate for signal amplification. The use of a micro-channel plate for signal amplification allows a compact construction, ensures fast timing properties and renders the device insensitive to magnetic fields. The pixels are defined by the anode plane and are thus easily customisable, The active area is $51x51mm^2$. Selecting the 1024 channel version with a custom anode plane will give a 32 channel PMTs with read-out strips of 1.5mm pitch.

The quantum efficiency of the Planacon 85011 is given by the manufacturer as 25% at 400nm. The wavelength of maximum response is 400nm. The spectral response 185 to 660 nm. The active area ration is 0.47. The pixel-to-pixel uniformity is quoted as 1:1.5.

Photonis is producing the same PMT with a micro-channel plate of 10μm pore diameter as well to reduce the sensitivity to magnetic fields. A prototype is being tested by the PANDA DIRC groups.

The reported drawback of MCP-PMTs is their poor lifetime attributed to ion feedback to the cathode material. This is mainly due to poor vacuum conditions during the manufacturing process. Currently, the manufacturer states a lifetime of 30 C. Photonis is replacing part of their old manufacturing equipment to provide higher quality micro-channel plates. They estimate a lifetime increase to 300 C. The PANDA collaboration will receive sample PMTs for testing in Summer 2008. If the lifetime is still found unsatisfactory, an additional layer of Al_2O_3 could be added between cathode and MCP, increasing the lifetime but lowering the collection efficiency. This technique was successfully tested at Novosibirsk and by Hamamatsu.

With an operational gain of $5x10^5$ as successfully tested for 10μm plates and the particle rates stated above, a lifetime of 300 C corresponds to 6 years of PANDA operation. These upgraded 1024 channel Planacon MCP-PMTs with 10μm pore diameter and a customised anode plane are the current candidate read-out system for the focussing disc DIRC.

Two Planacon 64 channel MCP-PMTs with 25 μm pore diameter were purchased for testing purposes from existing grants. Additionally, one 64 channel prototype was made available for testing by Photonis. These tests are performed in collaboration with the University of Erlangen,

Hamamatsu H9500 Multi-anode PMTs

Multi-anode PMTs use a segmented anode and dynode structure to provide a correspondence between the position of the photon when entering the cathode and the readout pixel.

The Hamamatsu H9500 series provides 256 3x3mm^2 pixels combined with a conventional photo-cathode. The active area is 49x49mm^2 and the overall dimensions are very compact. The MAPMT provides an excellent packing density of 89%. The outer dimensions make is a valid candidate for the focussing disc DIRC photon detection system. The noise characteristics are very good as well. The PMT can be operated without pre-amplification.

The quantum efficiency of the H9500 is given as 20% at 420nm. The wavelength of maximum response is 420nm. The spectral response is 300 to 650 nm.

Several drawbacks make the application unlikely. The available pixel pitch is twice as big as the one required from the Cherenkov imaging system. While this per se is not an ultimate drawback, it would require larger light guides with higher material costs and a more complicated mechanical set-up. The main drawback lies in the sensitivity of these devices to magnetic fields. The gain drops rapidly even in small to moderate magnetic fields. The mechanical design and compactness prevents the installation of effective magnetic shielding. Additionally, the pixel-to-pixel uniformity of MAPMTs shows large deviations. The typical uniformity is quoted as 1:5 Last not least, the transit time spread of these MAPMTs is larger compared to MCP-PMTs hampering precise timing measurements.

Two samples were purchased from existing grants and are currently under test in collaboration with the University of Erlangen.

SiPMT arrays

The novel development of semiconductor photon detection devices capable of low light detection provides a highly efficient, compact, easily customisable and magnetic field resistant alternative to the more conventional photon detection solutions outlined above. The PANDA collaboration is investigating the use of these devices for both their DIRC counters especially as multichannel versions become commercially available. An additional attractive feature of these devices is the possibility to integrate part of the read-out electronics into the design. The manufacturing process is comparatively cheap.

Operating a photon detection system for an imaging Cherenkov counter requires the detection of single photons. This poses an inherent difficulty for semiconductor devices as thermal noise is indistinguishable from a signal generated by a single photon hit. Reducing thermal noise by cooling the device is a viable option currently under study at the University of Glasgow in collaboration with SensL.

Currently available multi-channel versions have an active area of 13x13mm^2 with a comparatively large housing. Along with the noise rate of 22.5 kHz/mm^2 at a temperature of -20°C for a cooled SiPMT and the amount of development required the application of SiPMTs is not deemed timely for use within the PANDA focussing disc DIRC.

PMT Tests

Performance tests of candidate photon detection systems are performed in collaboration with the University of Erlangen. Results are e.g. reported in References 3 and 6. The details of the test procedures are not repeated here. Two test set-ups were used. One set-up allowed the test of the candidate systems inside a magnetic field provided by a dipole magnet at FZ Jülich, Germany with a maximum field of 2.05T. The PMTs were illuminated using a PiLas fast laser pulser with an emission wavelength of 372 nm. Signals were amplified by Ortec VT 120A amplifiers and readout by a CAMAC based data acquisition system. A schematic is given below. Fast oscilloscopes (LeCroy WavePro7300A 3GHz, 20 Gs) were used for precise timing tests.

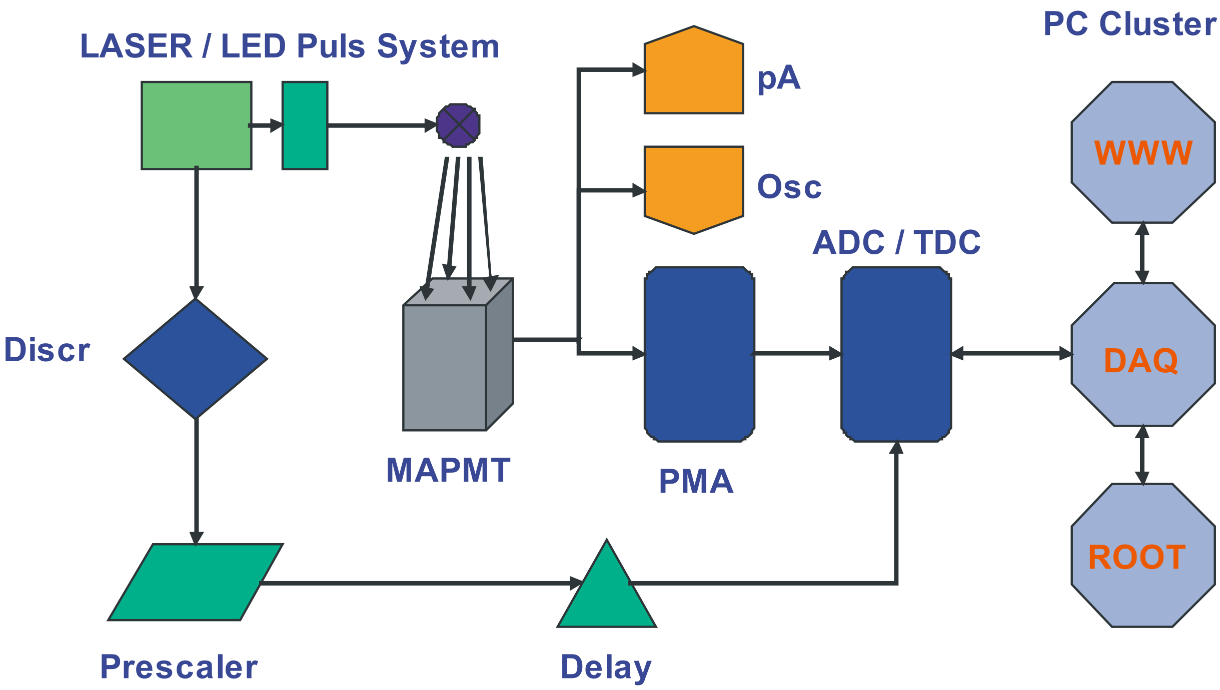

Figure 18:Schematic of the set-up used for the PMT tests presented.

A single channel MCP-PMT provided by the Budker Institute Novosibirsk was measured for comparison as well. Sample results reproduced from Ref. 3 are shown below.

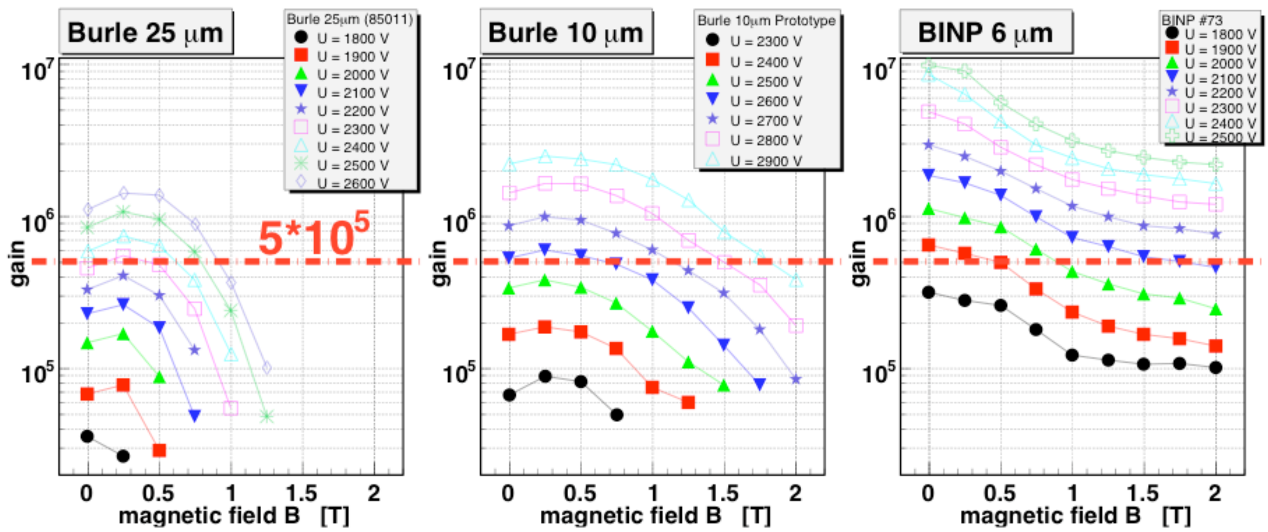

Figure 19: Performance for three MCP PMT candidates tested in a magnetic field

The 25µm version falls short of the expectations for PANDA requiring an operation close to the maximum recommended voltage for magnetic fields above 1 T expected at the PANDA FDD readout location. The Burle 10 µm version performs well. An upper limit of 60 ps was found for the time resolution of this model inside a magnetic field.

The time resolution outside a magnetic field and for different preamplifiers (Ortec VT120A, Ortec 9306, Hamamatsu C5594) and discriminators (LeCroy 821, LeCroy 620 CLR, EG&G CF4000, Ortec 934) were tested using the same light pulser system and oscilloscope specified above. The best performance for single photon signals was achieved using the Ortec VT120A amplifier and the EG&G CF4000 CFD.

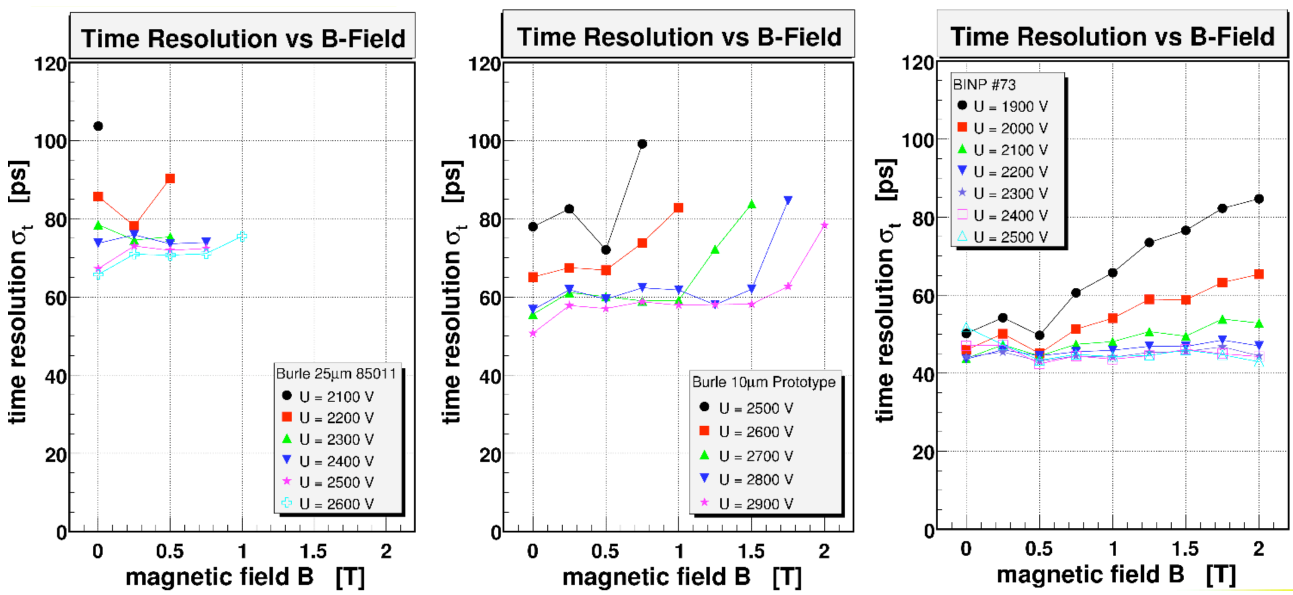

Figure 20:Time resolution measured as a function of the magnetic field strength for three MCP-PMTs

The time resolution was studied inside a magnetic field as well. Only a moderate influence of magnetic fields on the time resolution for magnetic fields of up to 1.5 T was found for the 10 µm Planacon version. The single photon time resolutions measured outside a magnetic field and corrected for electronic effects and the finite laser pulse width using the Ortec VT120A amplifier and LeCroy 821 discriminator are 45ps for the 25µm Planacon, 37 ps for the 10 µm Planacon 20ps for a single channel MCP-PMT from the Budker Institute, Novosibirsk. The time resolution for the Hamamatsu H9500 was measured to be 160ps.

Electronics system

The electronics system has to provide the readout for 4096 photon detection channels. The design presented here is optimised for the application of Planacon MCP-PMTs with 32 channels per PMT. Each PMT is considered to be a separate entity allowing for a very modular approach. This modular approach allows flexibility in the instrumentation and facilitates the operation and maintenance of the system.

The PANDA data acquisition system requires each detector component to be self-triggering. A signal over threshold has to be digitised and a time-stamp for this occurrence has to be stored and transferred to the master event builder. The minimum information to be stored is thus 16 bits for the channel ID, 8 bits for the time difference to the next time-stamp and 16 bits for the time-stamp itself. Each hit will therefore correspond to 5 byte of data. Adding one byte for safety, each channel will produce 6 bytes per hit or 292 MB/s. The full system will therefore generate 36 GB/s.

The design criteria for the focussing disc DIRC electronics require a single photon hit capability with a rate of 1.5 MHz/pixel and a time resolution better than 500 ps. The time window is evaluated from the arrival times of photon belonging to the fastest and slowest particle within the same event. Any better time resolution will aid in the reconstruction of overlapping patterns.

The performance of the electronics is aimed at the performance obtained in tests with commercially available preamplifier and discriminator systems. The development of a dedicated ASIC does not seem to be necessary. The design therefore relies on a discrete analogue solution developed with STFC Daresbury. In parallel, investigations are ongoing to use a bought-in ASIC, e.g. the NINO chip used by the ALICE RPC-TOF.

The analogue circuit can therefore be designed to match the performance of commercially available products. The digitisation will either use a TDC board developed by the GSI detector laboratory providing 100 ps resolution. The combined time resolution of the system will then be 112 ps. Alternatively, on-board FPGAs Virtex 5 clocked at 550 MHz divided into 4 phases could be used. Each clock cycle would give ±450ps timing and a corresponding time resolution of 265ps.

The cooling power of the electronics system was estimated conservatively using the high power consumption of the Hamamatsu C5594 preamplifier. This preamplifier uses on average 1.4 W per channel resulting in a power consumption of 94 W per 32 channel card. The total cooling power required is therefore 12 kW. The cooling requirement will be lower in case of an ASIC based solution.

The standard size of each card is 32x28 cm^2 with 3 cm spacing to allow for cooling. This requires the installation of 5 crates.

Mechanical Design

The mechanical design of the focussing disc DIRC detector depends on the installation location. In its final location it will be positioned directly in front of the forward ECAL. The holding frame has to follow the octagonal structure given by the inner shape of the magnet yoke. It is foreseen to route cables out at the corners of this octagon. This will include the cabling of the disc DIRC.

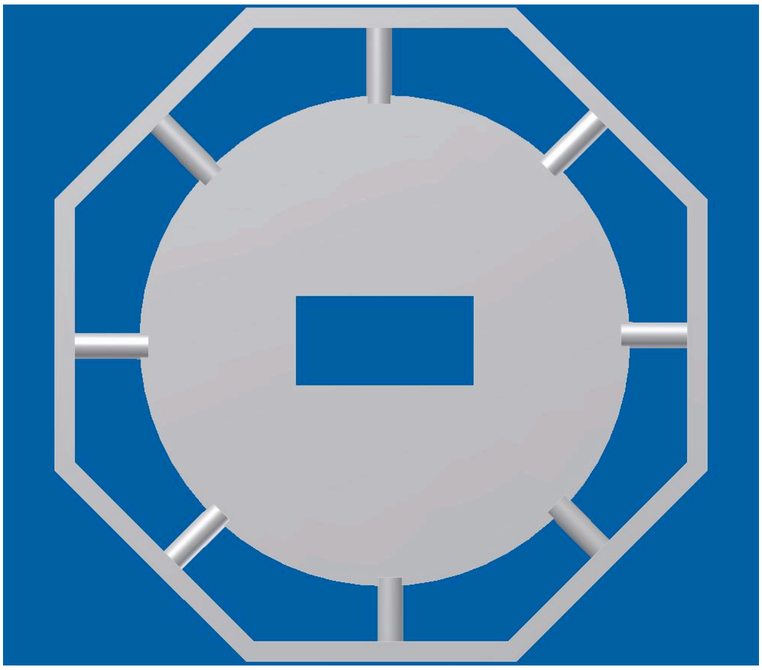

Figure 21:Sketch of the mechanical design for the housing.

The disc itself will be contained in a light tight vessel. The vessel itself will feature an aperture matching the projected geometry of the forward spectrometer. The vessel and the holding frame will be built from stainless steel as it is non-magnetic and easy to machine.

The disc itself will be supported by a holding structure making use of the space between the light guides. This space is available in any case as the geometrical dimensions of the envisaged PMT system do not allow a very dense packaging of light guides around the circumference of the disc. Additional support structures can be attached around the central hole. The contact surface with the sides of the radiator disc has to be minimal to ensure total reflection conditions for most of the surface. Since the disc will be mounted vertically, this does not pose a great challenge provided the outer housing is rigid enough not to bend inwards to the disc itself. Nylon placeholders are foreseen to guarantee a minimum distance.

Published Work

The research and development of the PANDA DIRC counters has already led to several recent presentations at conferences with reviewed and published proceedings

1. K. Föhl et al.: *The DIRC detectors of the PANDA Experiment at FAIR*, RICH 2007
2. C. Schwarz et al.:*The Barrel DIRC of the PANDA Experiment,* RICH 2007
3. A. Lehmann et al.: *Performance Studies of Microchannel Plate PMTs in High Magnetic Fields,* RICH 2007
4. P. Schönmeier et al.: *Disc DIRC Endcap Detector for PANDA@FAIR,* RICH 2007
5. M. Hoek et al.: *Radiation Hardness Study on Fused Silica*, RICH 2007
6. B. Seitz et al.: *A Focussing Disc DIRC for the PANDA Experiment*, IEEE NSS 2007
7. G. Schepers et al.: RICH for PANDA, 10th International conference on instrumentation for colliding beams, 2008

Further tests and prototyping

Photon detection system

The gain behaviour and time resolution of the most likely photon detection candidates has already been established. The next steps in detailed studies for the photon detection system are:

Measuring the level of cross talk between neighbouring channels: The envisaged application relies on a correlation of photon detection channel and the geometrical point of impact on the cathode. The simple correlation is usually spoiled by the presence of optical and electrical cross talk. Cross talk inside the PMT system can be studied at this stage of the development phase already while cross talk within the read-out electronics is an additional complication to be tested once the read-out boards are designed.

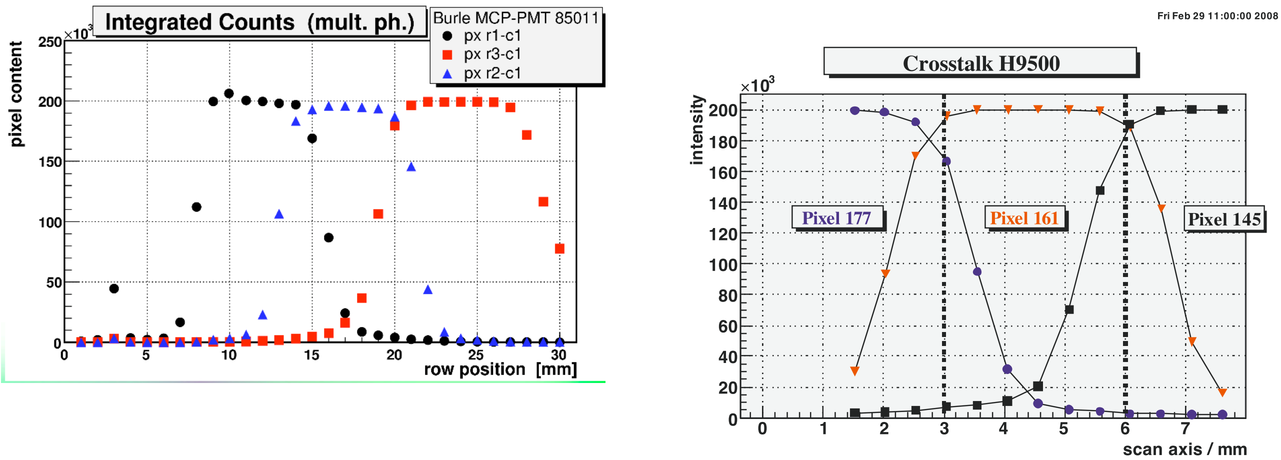

Figure 22:Cross talk studies for the Planacon MCP-PMT and Hamamatsu H9500 MAPMT

The programme for the measurement of optical cross talk foresees the use of similar equipement as was used in the tests so far. The main difference is that the light source will be mounted on two linear stages to allow for a precision scan of the PMT surface. Studies have started already using the H9500 and the 25 µm Planacon. The cross talk in these models is not negligible and has to be accounted for in the analysis routines. The measurements will be extended to the 10 µm Planacon series till May 2008.

Once optical cross talk is understood, the same test set-ups will be used for electrical cross talk testing and the quality assurance of all PMTs eventually purchased. Given the tight schedule for the delivery of the completed detector system, all test stands are designed with mass testing capabilities in mind.

Lifetime of MCP-PMTs: Although cross talk behaviour has not been studied for the Planacon MCP-PMTs, their other properties, in particular their modest sensitivity to magnetic fields and their excellent timing properties make them the most promising candidate for the focussing disc DIRC photon detection system. The main obstacle to be resolved is the limited lifetime of these devices. As only one 10 μm prototype is available to the PANDA collaboration at present, no lifetime tests were performed as part of the ongoing evaluation programme. It is agreed with the company to test their updated models also regarding the lifetime and gain drops in the second half of 2008. The date is given by the pre-fabrication tests done by the manufacturer. If the lifetime is still not found to be sufficient, the use of a thin Al_2O_3 layer with an according loss of collection efficiency will be the next logical step. The manufacturer is willing to try this as well.

Focussing Optics and Dispersion Correction

Prototype light guides were manufactured from Plexiglas. LiF dispersion correction plates similar to the ones envisaged in the final application are available. First tests using the Plexiglas light guides to conventional PMTs have begun. Optical benches are prepared at the participating institutions to measure the beam spot sizes for different colours with the aid of monochromators and CCD cameras. These tests will prove the focussing scheme quantitatively as well as the effects of the dispersion correction.

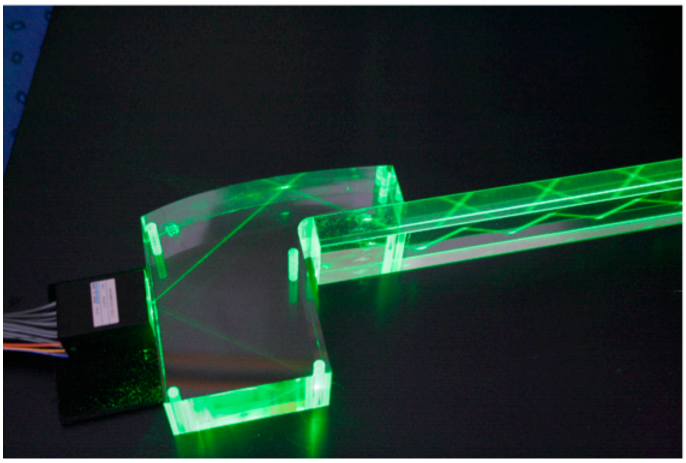

Figure 23: Photograph of the inital tests with the focussing light guide and a MAPMT

Detector Prototyping

Detector prototypes and testing is one of the main objectives of the current EPSRC grant. Given time and financial constraints, individual components had to be evaluated and tested to a near final stage prior to the construction of a meaningful detector prototype. This is now achieved for all but the electronics. The detector prototypes will therefore rely on commercially available VME electronics for data acquisition. This limits also the number of possible read-out channels.

Tests are currently underway using cosmic radiation and a 15mm fused silica radiator in proximity imaging coupled to a H9500 MAPMT. When the Planacon MCP-PMTs return from tests at the University of Erlangen, similar tests will be performed with them as well. These tests allow to understand the light generation and response of the photon detection system to low light signals. For central hits, a characteristic 1/r dependence from the geometry of light generation is expected.

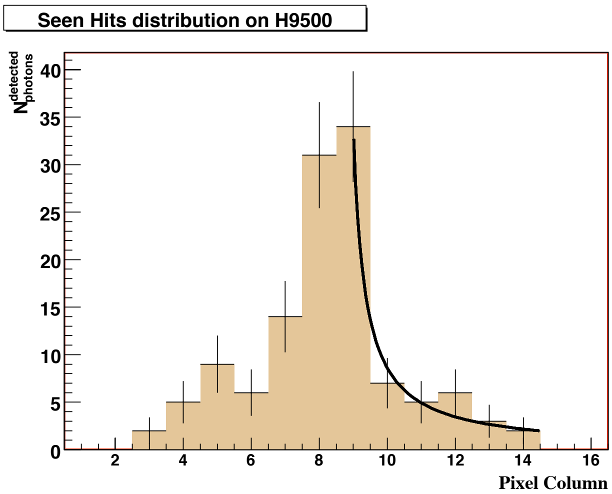

Figure 24:Expected distribution of hits from Cherenkov light generated by cosmic radiation in proximity optics registered by H9500 MAPMT

In a next step, a focussing mirror will be used to image internally reflected Cherenkov light onto a PMT surface. In parallel, the amount of light created will be monitored by a single channel HAPD with single photo electron resolution. This set-up will then be subsequently extended to include a LiF dispersion plate, a similar sized fused silica plate for comparison and last not lest the focussing light guide in its final geometry. This sequence of tests allows the step-by-step understanding of the individual components contributing to the final signal.

Two larger fused silica slabs of 500x70x20 mm^3 are ordered and expected to arrive by August 2008. They will be used to evaluate the polishing quality of the supplier and the PANDA workshops involved. They provide a large enough extension volume to represent a typical light path for photons expected in the PANDA focussing disc DIRC and could test the effects of glue joints both in the radiator and between radiator, LiF and light guides as well as the coupling of the PMTs.

The prototype detectors will be tested at the Alpha-X facility at the University of Strathclyde, which provides a laser Wakefield accelerated electron beam of up to 1 GeV with excellent timing properties and adjustable bunch charges. This test beam is available through a SUPA collaboration and can be flexibly scheduled. The test beam will provide performance data for ß=1 particles and provide tests for the timing response. Repeated tests with the final read-out electronics are foreseen at later stages as part of the electronics testing.

Upon successful completion of the first tests in an electron beam, tests with mixed hadron beams either at GSI or FZ Jülich are planned for 2009. Additionally, there is the possibility to join a 3.5 GeV proton test run at GSI in September 2008.

Assembly

Assembly environment and collaboration

The assembly of the complete detector system will be performed at GSI, Germany in collaboration with other groups involved in the construction of the PANDA DIRC detectors. The PANDA Detector set-up features two particle identification counters based on the DIRC principle. The similarities between the two designs allow the participating groups to benefit from synergy effects in particular aspects of the design (polishing, joints, photon detection system) and construction, esp.. by sharing expertise and personnel. This collaboration is additionally formalised in a bid for a *Joint Research Activity* within the HadronPhysics 2 bid of EU FP 7 led by the PANDA UK project leader. In particular, this means that independently of the outcome of the funding bid the following additional manpower will be available for the construction and assembly of the focussing disc DIRC detector[2] : 4 FTE from the University of Gießen, 4 FTE from GSI Darmstadt, 2 FTE from the University of Erlangen, 3 FTE from INFN and University of Ferrara and 1.2 FTE from FZ Jülich.

The following text is an excerpt of the requirements to the host laboratory for the assembly of both DIRC counters. This is basically agreed upon, but subject to change as the development progresses.

Environment: *For assembly, installation, operation and maintenance we need a temperature stabilised, humidity controlled environment. Might want to flush the surfaces/containment with dry nitrogen. Temperature gradient towards final installation and running should be kept small (this might be an issue if parts of the detector are close to the cooled ECAL or magnet)*

Maintenance*: This subject is divided into two parts, regular maintenance operation and replacements and repairs. We do not need to schedule regular maintenance intervals, serviceable parts (e.g. filters for a dry nitrogen system) can be arranged on the outside (either On-Detector or Off-Detector). Replacing parts will be more difficult as they most likely are In-Detector. If the readout is inside the yoke of the magnet (as in the current design options), repairs require opening the magnet and retracting the endcap ECAL. The endcap DIRC might*

[2] Numbers based on the submission of participating institutions for the *Joint Research Activity*

have to slide out as well before it becomes accessible. Given an average amount of failures, this probably means that the endcap DIRC has to be moved out during the detector down-time for minor repairs and replacements.

Space requirements:

Storage: *After assembly only minor space is needed for storage of tools, replacements etc.*

Mounting area: *detector of 2.4m diameter, accessible from all sides during assembly, so about 40 m^2 dust free area. Ideally, this should be done at GSI to reduce transport risks. Smaller parts (e.g. focussing light guides, PMT boxes ...) will be tested and assembled out-side (Glasgow, Edinburgh)*

Utilities: *only necessary for dry nitrogen (may be centralised system with Barrel DIRC), cool-ing should also come from central supply.*

Mounting*: self contained vessel assembled outside (lying flat, then turned upwards for in-stallation), slide inside detector from upstream part on rail system. This should already pro-vide coarse alignment. Fine adjustment by optical marks on the surface which in then in turn are referenced to the interior (this require survey during assembly). Otherwise, 'just' cabling up. This will require a 1t crane to move the detector to the rail system. Number of support points can be just a few, depending on the design of the box. The detector will use common mount points with the forward ECAL.*

Resources: *dry nitrogen supply lines,, cooling*

Cables*: HV supply lines for 128 photon detection devices, 128 flat ribbon cables for digitised signals, LV supply lines for In-Detector electronics, probably some cooling lines or vents to get rid of the processor heat. If the readout and digitisation is inside light tight box, some kind of cooling will be needed. This could come from the central cryo system or placed on the outside of the box. Probably a good solution would be to have a limited number of extrusion points symmetric around the detector (4-8).*

Support*: The endcap dirc will weigh about 750 kg (200 kg for a fused silica disc, similar amount for support structure, plus light guides and readout). It should be a self supporting frame which needs to be attached to the forward ECAL housing and aligned with respect to the beam line. The whole support probably should move out on some kind of rail system for maintenance work. Any veto areas will depend on the design of the support structure. As this will be a light tight box with rather thin walls in the active area of the detector, it is to be ex-pected that only the rim will allow for sufficient rigidity to hold anything of substantial weight or force. The detector will be mounted on the forward ECAL and moved into position on a rail system attached to the corners of the octagon.*

To summarise the requirements above: The focussing disc DIRC detector will be assembled close to the final installation in a moderate clean room atmosphere. Necessary supply lines and cabling are tentatively agreed within the Technical Assessment group on Integration, the PANDA Technical Board and Technical Co-ordinator.

Alternative Solutions

Introduction[3]

The original design (termed default in the discussion to follow) was agreed upon in a technical board meeting in 02/2007 taking the needs of the focussing DIRC proposal into account as well as a slight design change for the forward EMC and the Muon chambers. Most of the mechanical design for the forward Cherenkov detectors is based on a CAD model using these boundaries. The detector is located at 1975 mm in Z-direction, will have a octagonal shape with on outer diameter of 2400mm and are allowed a total thickness of 65 mm in Z-direction. Work has been carried out and is ongoing to design a detector delivering on the physics performance and to match these mechanical boundary conditions with a DIRC based project. The detectors were accommodated in the design of the solenoid magnet, leading to a slightly asymmetric return yoke configuration and a net magnetic force along the z-axis in the detector.

As it was realised that the tracking system would need modifications and to keep investment costs under control, it was suggested to look into a more compact configuration. At the same time, the drift chambers originally foreseen were suggested to be replaced by GEM counters. Most importantly, it was suggested to look into the possibility of moving the forward endcap Cherenkov counters from its default location behind the cryostat into the cryostat at z=1800mm, directly behind the barrel calorimeter. This would allow for an outer radius of 930 mm and a thickness of 150 mm. In particular, it was suggested to look into a proximity focussing RICH detector using the third tracking station as a combined photon/charged particle detector by depositing CsI on the first GEM foil.

In the following, the default options and its performance will be discussed and contrasted versus several detector solutions based on the proximity imaging scheme.

Benchmark values

The discussion of the detector performances to follow will make use of some common benchmarks and performance estimators used in the literature. In addition, a couple of rela-

[3] Abridged notes prepared for the PANDA Technical board, but delivered orally

tions evaluating the performance of the different detector types discussed without using a full simulation will be used. They are mainly taken from Glaessel (NIM A 433 (1999) 17). Where possible, the results obtained by these approximation were cross-checked with performance data of existing detectors or prototypes.

It should be noted, that this section compares design ideas and their possible performance. No attempt is made to provide answers to all possible design and performance obstacles. Where possible, performance data from other detectors are given as guidelines for the expected performance and an estimate for PANDA is given, together with the currently perceived R&D risks.

Proximity Imaging Solutions

Liquid radiator proximity RICH using CsI GEMs: Proximity focussing RICH detectors use the most simplest imaging geometry. Their resolution depends on the optical quality and crucially on the ratio of radiator thickness to stand-off distance, the distance between the creation and detection of the photon. Using liquid or solid radiators yielding enough Cherenkov photons, the radiator can be kept rather slim, which in turn only require moderate stand-off distances on the order of 100 mm. The ALICE HMPID detector is build in this fashion using a C_6F_{14} liquid radiator and CsI-photon cathodes in an MWPC. This requires a UV optic. It is proposed to use the same radiator technique and combine the third tracking station with a CsI coated GEM photon detector. The detector will be thicker along the beam direction than the DIRC detector previously described, but can be essentially moved to any position along the beam axis. The estimated performance and the ALICE/STAR test results show a significant decrease in performance compared to the DIRC solutions.

Solid radiator proximity RICH using CsI GEMs: One of the main drawbacks of using the ALICE design is the use of C_6F_{14}. This radiator is rather sensitive to impurities and radiation damage requiring a purification system. Using a fused silica disc with a properly machined surface as radiator circumvents the problem while keeping the geometrical advantages of the design. Initial studies show a further reduction of performance mainly due to strong dispersive effects in the UV region.

Aerogel proximity RICH using PMTs: The Belle endcap Cherenkov threshold counter will be replaced by a proximity imaging RICH counter using an Aerogel radiator and conventional BiAlkali based multi-pixel PMTs as photon detectors. Using a so-called focussing radiator scheme, prototypes show excellent performances. The main technological challenge for these detector is to realise a photon detection matrix in a strong magnetic field. Recent developments in the field of proximity focussing HAPDs seem to make such a detector realistic.

The large number of pixels required should the detector be placed behind the EMC, but inside the cryostat merit a detailed look at the costs of such a design.

Performance Comparison

Note: The numbers N_0 and N_{pe} are evaluated on the same basis. This leads to a slight overestimation of the focussing disc DIRC performance as differences in losses due to multiple reflections from photons stemming from different impact positions are not fully considered.

	Focussing Disc DIRC	Liquid Radiator Proximity Imaging	Solid Radiator Proximity Imaging	Aerogel Proximity Imaging
X_0	0.17	0.2	0.24	0.14
N_0 (1/cm)	124	60	57	76
N_{pe}	135	36	68	18
p_{min}(GeV/c)	0.6 (0.2)	0.84	0.56	2.75
p_{max} (GeV/c)	6.5	3.3	2.8	7.5
σ_θ	0.45	4.1	3.9	2.7
Δt	< 500 ps	O(10 ns)	O(10 ns)	O(ns)
Overall length	< 100 mm	~180 mm	~180 mm	~ 250 mm
Read out	TDC	TDC/ADC	TDC/ADC	TDC
N_{ch}	4096	> 35000	> 35000	35000
Photon detection	MCP PMT	CsI GEM	CsI GEM	PMT
spectral range	UV/VIS	VUV	VUV	VIS
pattern	2D + t	2D + t	2D + t	2D + t

The performance comparison shown in the table above favours a solution based on the DIRC technology, even taking the more realistic performance evaluation presented in the preceding chapters into account. It should be noted, that the performance of the proximity imaging solutions is mainly limited by the ratio or radiator thickness to stand-off distance. Only the Aerogel proximity imaging solution provides a shorter radiation length and therefore smaller impact on the detectors downstream. Its overall geometrical dimensions are unfavourably large, though, as for the other proximity imaging options.. All alternative solutions investigated require a significantly larger number of channels due to the proximity imaging scheme. The CsI coated GEM detectors are a novel development. The use of conventional wire chambers was considered for the PANDA forward tracking system, but was abandoned in favour of GEM detectors due to the higher rate capabilities of the latter. A similar argument applies for the use of photo-sensitive wire chamber read-out. The read-out of photo-sensitive GEM counters would require both a TDC signal for precise timing and an ADC signal to distinguish between signal generated by photons and charged particles. The Aerogel Proximity imaging solution faces similar challenges to the DIRC options in terms of photon detection systems, albeit with a significantly larger number of PMTs. The timing resolution for the Aerogel Proximity option is given for a conventional PMT system, otherwise it will be comparable to the focussing disc DIRC. In terms of the threshold momentum and the dynamic range[4], the focussing disc DIRC option is best suited to the PANDA requirements, while the Aerogel proximity option would only offer discrimination power at higher momenta. From the options considered, the focussing disc DIRC option best matches the performance and space limitation given for PANDA.

[4] following the equations of Glaessel et al. Nucl. Instr. Meth. A 433 (1999) 17

Summary

The focussing disc DIRC is an integral ingredient for the physics programme at PANDA. The hadron identification provided by this detector is crucial for the reconstruction of mesons from their decay products. It should be stressed, that the partial wave analysis necessary to establish the quantum numbers of newly discovered states relies on an excellent coverage of angles and momenta. Monte Carlo studies show, that measurements in certain reaction channels will not be feasible without a highly performant disc DIRC.

Simulation tools were developed for the design and performance evaluation of the focussing disc DIRC. They interface with the more general event generators and fast simulation programmes used by the PANDA collaboration, but take more details into account. From these programmes hit pattern for different final states can be generated which feed into a pattern reconstruction programme. The results of this pattern reconstruction programme are then used to evaluate the performance of the detector itself. The pattern recognition benefits from a reconstruction in two spatial and one time co-ordinate. No performance degradation in the presence of significant noise levels was observed. Also, the current algorithms perform well for higher multiplicities inside the focussing disc DIRC.

The design of the detector follows the physics aims and the mechanical construction of the PANDA detector. The angular coverage and the need of an opening not to impede the performance of the forward spectrometer give the radial size and shape of the radiator disc. Its thickness is determined by mechanical stability and the required number of photons, while keeping the impact on the following detectors in terms of radiation length minimal. From the inner diameter of the yoke and the radius of the disc follows the space available for the focussing optics, dispersion correction and photon detection system. Given these space constraints, a compact focussing light guide is designed yielding focal points which correspond to a pixel size of 0.96 - 1.49 mm. The size of the focal point suggests a read-out pitch of 1.5 mm.

The photon detection system should thus provide a pitch of 1.5 mm and a strip width of about 50 mm to keep the number of read-out channels reasonable. It has to work inside a magnetic field of 1.2 T. The rate capability can be estimated following the background simulations with the DPM model and the optical calculations. Each strip will on average receive a photon rate of 1.47 MHz at full beam momentum.

The candidate photon detection system that meets these requirements best, are Planacon 10µm multi-channel MCP-PMTs which are tested to meet the PANDA FDD requirements. From these tests, also specifications for the read-out electronics can be derived which were fed into the initial design. The main open question with this type of detector, is their limited lifetime. The company expects to increase the lifetime by a factor of 10 using a new production techniques. Prototypes will become available in the second half of 2008 for evaluation. Should they be found to be unsatisfactory, an additional protective layer could be implemented, reducing the quantum efficiency, but increasing the lifetime by a factor of 5-6.[5]

The adoption of existing and thus proven technologies was evaluated to provide alternative solutions. The ALICE HMPID detector, the CLEO-c RICH and studies on Aerogel Proximity Imaging counters for a Belle upgrade were considered. These alternatives do not meet the performance provided by a DIRC type detector and have inherent technological risks in their adaptation to PANDA.

We therefore believe that the focussing disc DIRC will provide the best particle identification detector solution for the angular and momentum range required by the PANDA physics programme and that whilst a full prototype test is still pending, tests performed on individual components show that the design is mature and under control.

[5] N. Kishimoto et al. Nucl. Instr. Meth. A 564(2006) 204