Conceptual Design of a Multi-Chromatic Time-of-Propagation Endcap DIRC for PANDA

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Abstract

In this report a new concept for the PANDA Endcap DIRC is proposed, incorporating both the time-of-propagation (TOP) technique and a chromatic correction based on dichroic mirrors which split the spectral range of the Cherenkov photons. This combination of technologies allows both to avoid the decrease of resolution usually connected with dispersion and to lengthen the travel path of light inside the radiator, thus leading to larger time differences in the time-of-propagation measurement which makes it less challenging to discriminate different particle species at large momenta.

Introduction

The currently discussed design of the PANDA PID system comprises three Cherenkov detectors: (i) the interaction region is cylindrically surrounded by a Barrel DIRC detector, covering scattering angles of more than ±22°, while the forward region is equipped with an (ii) Endcap DIRC with an angular coverage of up to ±22°. This Endcap DIRC has the geometry of a circular disc and contains an aperture for the (iii) Far Forward RICH detector, which covers scattering angles smaller than ±5° vertically and ±10° horizontally. The concept presented in this report is intended for the Endcap DIRC.

Requirements and boundary conditions

An efficient and capable PID system is crucial for the physics objectives pursuit by PANDA. In the forward region a clear separation of pions and kaons up to momenta of 4 GeV/c is necessary. Although this momentum region is easily accessible with e.g. Aerogel RICH detectors, very limited space and acceptable material budget impose additional limitations. A detector like the above-mentioned Aerogel RICH would require a substantial amount of space to place sufficient radiator material into the flight path of particles, which would require shifting the Electromagnetic Calorimeter (ECAL) further downstream by a significant distance, increasing the costs for the ECAL by up to several million Euros. Considering this, a very compact PID detector, based on the DIRC (Detection of Internally Reflected Cherenkov radiation) principle seems to be a very attractive solution.

Such an Endcap DIRC has to cover the acceptance range of ±(5° - 22°) vertically and ±(10°-22°) horizontally, corresponding to a circular disk with 1.78 m diameter of ‘active’ radiator material inside the acceptance when placed 2.2 m downstream of the IP. This disk could be placed inside the magnet yoke and there would still be enough space left to add a margin (increasing the diameter by a few centimetres) to install optical components and readout. The DIRC disk could be made of quartz (fused silica) or Plexiglas® with a thickness of the approx. 2 cm, thus reducing the material budget in front of the ECAL to an acceptable limit.

Several readout options have been discussed, which can be categorised in two classes: *(a)* guiding the Cherenkov light out of the magnet yoke and placing the photon detectors outside and *(b)* installing the complete photon detection system inside the magnet yoke and feeding the electrical signals from photon detectors out of the magnet yoke. Option *(a)* seem to be much more ambitious from an optical point of view and would require either a very complicated lightguide geometry or a substantial number of holes in the return yoke of the magnet while option *(b)* would require a very compact photon readout system which has to be resistant to strong magnetic fields of up to approx. 1.5 T.

The reconstruction of the Cherenkov angle requires the detection of at least two different coordinates that can be either two position coordinates (impact point of a Cherenkov photon on the photo detection plane) or a combination of (one or two) position coordinate(s) and the time of propagation (TOP) of the Cherenkov light, as the arrival time of Cherenkov photons is obviously connected to the Cherenkov angle under which these photons propagate through the DIRC radiator. Therefore one can distinguish between two basic options: (i) detection of photons in two position coordinates (like used in the BaBar DIRC detector) and (ii) detection of photons in one single spatial coordinate and measurement of the time of propagation (a concept currently studied by BELLE for an upgrade towards the Super-B factory). A third option is the combination of these two, where two position coordinates and in addition the time of propagation is detected, resulting in a "3D-DIRC" with considerable redundancy and extensive costs for the readout system.

In general, the application of the TOP technology requires both a highly accurate reference time and an extremely demanding readout system, which is able to resolve time differences in the order of tens of picoseconds. The TOP DIRC detector design discussed at BELLE relies on the precise timing supplied by the bunch crossing of the KEK-B e+/e- storage ring; the TDC measurement starts when the collision occurs and ends when the Cherenkov photons are detected, therefore resulting in a combination of the time of flight of the particle from the IP to the DIRC detector plus the time of propagation of the light inside the DIRC radiator. As PANDA cannot rely on a bunch crossing as reference timing it will be quite an additional challenge to provide detectors which deliver a sufficiently precise reference time with a stability in the order of a few picoseconds.

An additional complication in DIRC detectors arises from the fact that chromatic dispersion can spoil the resolution as the photons in the Cherenkov cone cover a wide range in wavelength and the index of refraction of the radiator material, $n = n(\lambda)$ might vary significantly. One solution is to restrict the spectral range like e.g. in the BaBar DIRC Detector, where an optical cement used to join the parts of the detector cuts of photons in the UV below 280 nm.

Especially the time of propagation measurement might be affected as the time measurement is determined by the group velocity whereas the measurement of the Cherenkov angle is dominated by the phase velocity of the light (Fig. 1).

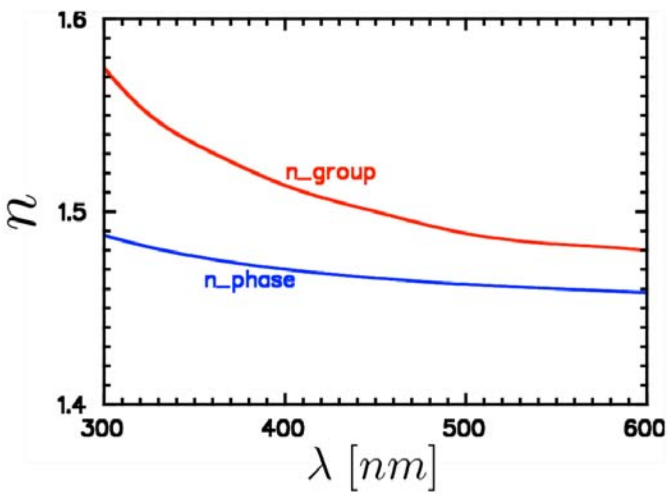

Fig. 1: *Group and phase velocity in fused silica (courtesy K. Foehl).*

In consideration of all these options and boundary conditions imposed by the overall PANDA concept, a favourable set of design features seems to include:

i. A compact readout which can be installed inside the return yoke of the solenoid to avoid complicated light guide geometry and holes in the yoke which would otherwise be necessary to extract the Cherenkov photons if the photon readout would be placed outside.

ii. The application of the TOP concept to limit the number of readout channels (which would be much larger if one would go for a 2-dimensional position readout) and to avoid a space consuming focusing system (e.g. expansion volumes).

iii. A photon detector technology which is fast enough for a TOP measurement and robust in magnetic fields of the strength expected in the circumferential region of the return yoke

iv. A method of chromatic correction evading the degrading of resolution usually associated with dispersion due to variations in the refractive index of the radiator material.

The general idea of a Multi-Chromatic Time-of-Propagation DIRC

The Multi-Chromatic TOP DIRC Detector presented in this report consists of a circular disk (made of Fused Silica or Plexiglas®) with a thickness of approx. 2 cm and a diameter slightly exceeding the size needed for covering the acceptance of up to ±22°. Assuming a position of 2.2 m behind the IP this would correspond to a diameter of roughly 1.8 m. The centre of this disk comprises a rectangular hole to clear space for the beam pipe and to minimize the material budget in front of the far forward detectors which cover the acceptance of scattering angles smaller than ±5° vertically and ±10° horizontally.

The central idea of the chromatic correction consists in the use of dichroic filters which allow for splitting the spectral range covered by the Cherenkov light into disjunctive domains. Such filters are commercially available and take advantage of multilayer coating, which results in high reflectivity for some part of the spectral range and high transmission for another part (Fig. 2). Of course the exact geometry as well as the number of splits of the spectral range need to be studied in detailed Monte Carlo simulations. Perhaps a scenario where one cuts away the UV part of the spectrum and splits the remaining part into two ranges will turn out to be a sensible solution. Therefore subsequently the concept will be exemplified assuming two spectral ranges, a violet-blue range (denoted by “blue”) and a green-red range (denoted by “green”).

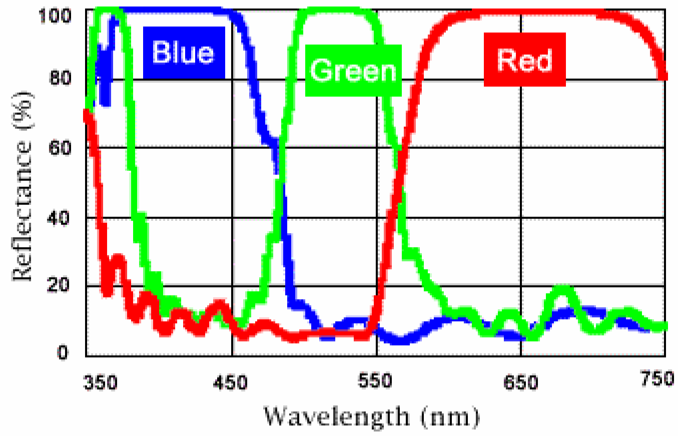

Fig. 2: *Example for reflectance curves of commercially available dichroic mirrors as function of the wavelength.*

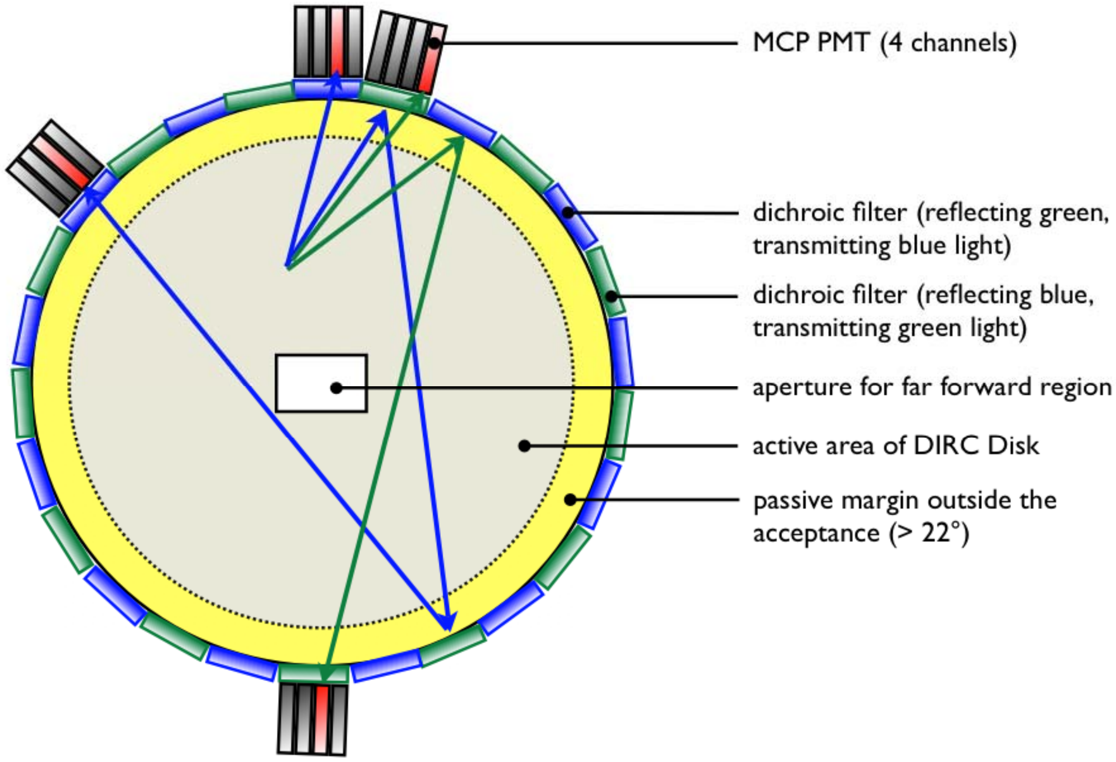

Fig. 3: *Sketch of the basic concept of the proposed Multi-Chromatic TOP DIRC: The Cherenkov light is reflected by dichroic mirrors at the edge of the disk such that the average path length of the photons is increased and that dispersion effects are minimized by separating the photons according to their wavelength.*

The Cherenkov light is split into these two spectral ranges by two types of dichroic filters: “green” filters transmit green light and reflect blue, “blue” filters vice versa. These dichroic filters are arranged alternating around the circumference of the DIRC disk (Fig. 3). Behind these dichroic filters are Multi-Channel-Plate Photomultipliers (MCP PMTs) with photocathodes that are matched to the wavelength range transmitted by the respective filter type to detect Cherenkov photons with sufficient quantum efficiency. Both the filters and the MCP PMTs are mounted using optical grease of appropriate index of refraction to minimise the influence of surface roughness, as dents will in the ideal case be filled with optical grease of the same refractive index (Fig. 4). Thus small roughness of the surface at the edge of the disc should not be an issue anymore and the requirements for the polishing quality of the edge of the disc becomes much less demanding.

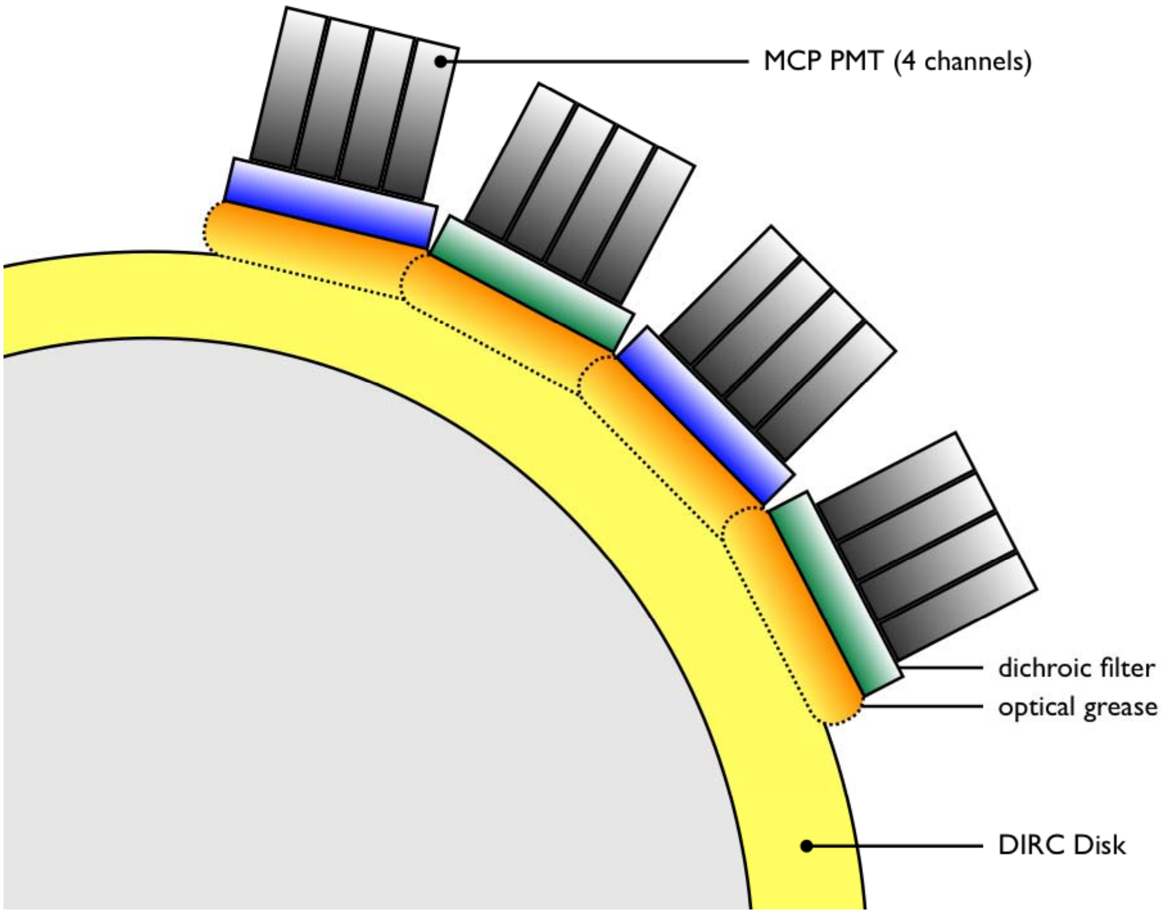

Fig. 4: *The dichroic filters are attached to the edge of the DIRC disk using optical grease of matching refractive index to minimise the influence of surface imperfections.*

In the setup depicted in Fig. 3 photons of a certain colour have certain probabilities to be reflected at the border of the disc, such that there will be photons arriving at a PMT after a small TOP and others at a large TOP. As each reflection extends the path length of the photons and therefore the TOP significantly, it is possible to reconstruct (based on the TOP) unambiguously how many reflections occurred and (based on the transmission range of the dichroic filter in front of the PMT where the photon is finally detected) the colour and therefore which path the photon took. For the setup with only two spectral ranges the probabilities that photons are detected directly or after one, two, three, … reflections are 50%, 25%, 12.5%, 6,25%, … respectively.

As the emission point of the Cherenkov light is known from the PANDA tracking detectors, for each detected photon at the DISC edge one can calculate from the known positions of the mirrors, from the polar angle of the PMT channel and from the measured TOP which path the photon took. A precisely measured TOP can than be used to extract the Cherenkov angle of the individual photos and thus discriminate between different particle hypotheses (pion vs. kaon, etc). As the same particle produces very different path lengths, the relative TOPs should be sufficient to discriminate between the particle hypotheses, so that no start counter for an absolute time measurement is needed.

If there are several Cherenkov light emitting particles in the DISC, there is of course an overlap of the photon patterns in the 2-dimensional space (TOP vs. polar angle). However, with a sufficient granulation and resolution, reconstruction software based on a likelihood algorithm with different particle hypotheses can distinguish from which particle which pattern appears. A Monte Carlo simulation has to show where the limitations of this method in multiplicity are.

An additional complication is the hole in the centre. This hole can either be made black (absorbing) to absorb photons or made reflecting to mirror the photons and make the patterns even more complex.

The most suitable photon detectors seem to be channel plates with photocathodes that are matched to the wavelength of the mirrors (Fig. 5, 6).

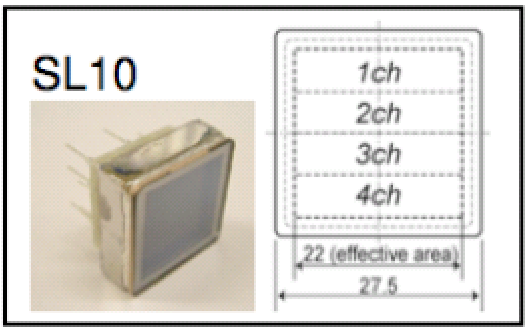

Fig. 5: *Prototype of a Multi-Channel Plate PMT developed by Hamamatsu in close collaboration with the University of Nagoya for a TOP DIRC detector for the BELLE / Super-K Factory Upgrade. Detectors like this SL10 prototype are capable of time resolutions of* σ_{TTS} *= 30 ps in magnetic fields up to 1.5 T.*

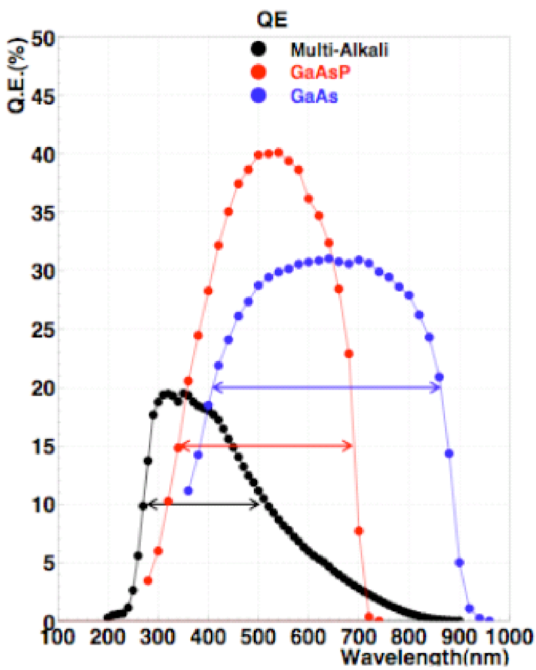

Fig. 6→: *Quantum efficiency of different photocathode materials tested by the University of Nagoya.*

For a disc of approx. 5.65 m circumference (R = 90 cm) about 283 MCPs (assuming 4-channel MCPs of 2 cm width) would be needed with a total of 1132 fast TDC readout channels. This seems to be a reasonable and affordable number.

It is clear that we cannot guarantee at this stage of consideration that the above proposed Multi-Chromatic Time-of-Propagation DIRC really works, is realizable and shows a high performance. Like for any other new detector system, detailed Monte Carlo studies and prototypes are absolutely required.

Some first Monte Carlo estimates of the performance of an Endcap TOP DIRC

Introduction

The Monte Carlo code developed by R. Schmidt was originally designed to simulate the performance of an Endcap (Disk) DIRC where the Cherenkov light is extracted from the disc by prisms, which are placed at an outer ring of the disc surface. The light that penetrated the prism was projected onto a cylindrical screen as shown in Fig. 7. In this set-up the perpendicular z-coordinate was a measure of the Cherenkov angle. For our new design as described in this report, the relevant quantity is the time of propagation (TOP) of light that exits the disc at the outer side after zero, one, or several reflections by the externally mounted wavelength-selective mirrors. A details simulation of such a set-up will be done in future. For this report we did some first rough estimates of the performance of a TOP-DISC-DIRC, ignoring the reflections on the mirrors.

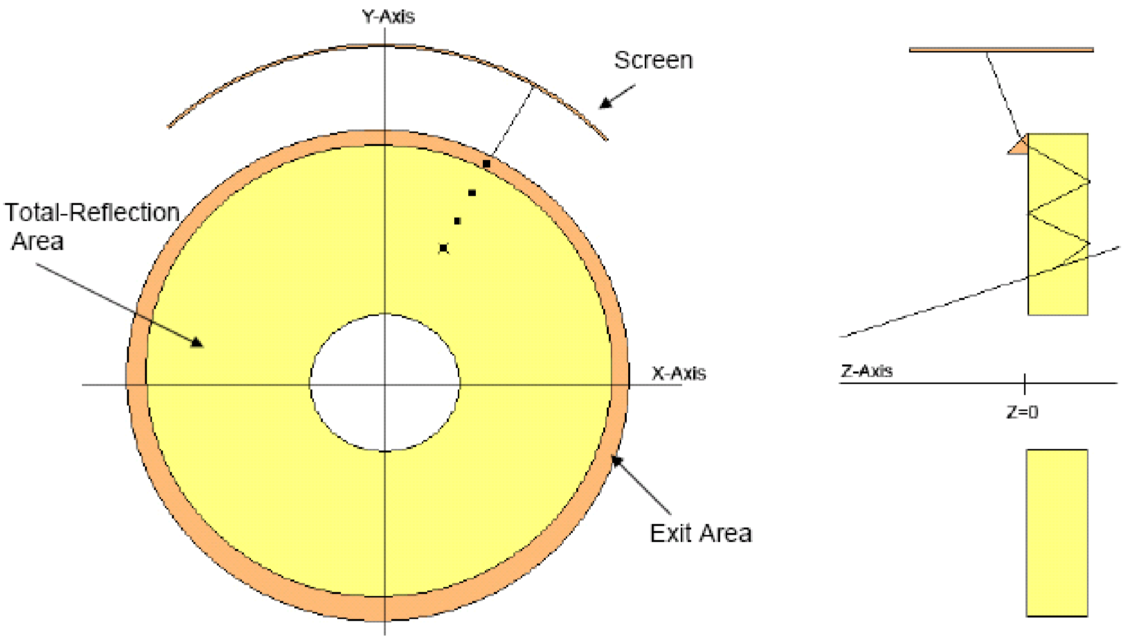

Fig. 7: *The geometry of the DISC DIRC as simulated in the Monte Carlo*

In more detail, the Monte Carlo as used to produce the plots in this report simulates the TOP-DIRC Endcap as described below:

- The disc is made of fused silica with a wavelength dependent index of refraction (see Fig. 10). Its thickness is 2 cm. The light leaves the disk at a distance r=145 cm (measured from the centre of the disk) when it encounters a prism.

- The disc is placed 300 cm downstream of the PANDA vertex where a particle at an angle of 15° is produced. The particle penetrates the disc at r_p=80,4 cm. The particle can be a pion or kaon.

- The Monte Carlo simulates the emission of Cherenkov photons at random points of emission in the disc within its thickness and at random azimuthal angles within the Cherenkov cone, using the correct wavelengths and cross sections.

- The Cherenkov photons are propagated through the material of the disc taking the wavelength dependent time of propagation and the total reflection angles at the disc boundaries into account.

- The light propagation stops when the photon enters a prism. In future the prisms will be taken out of the Monte Carlo and the light will be propagated to the externally mounted mirrors. For a first estimate the TOP at the entrance of the prism will be used.

Properties of Cherenkov radiation

The number of emitted Cherenkov photons per photon energy interval is approximately constant as shown in Fig. 8a. This leads to the effect that the broader the wavelength range of the detector is, the better the statistical precision will be. This is true as well for the UV range, as for the range at large wavelengths (i.e. red). Only when plotted as a function of wavelength, the density of photons peaks in the UV range (see Fig. 8b).

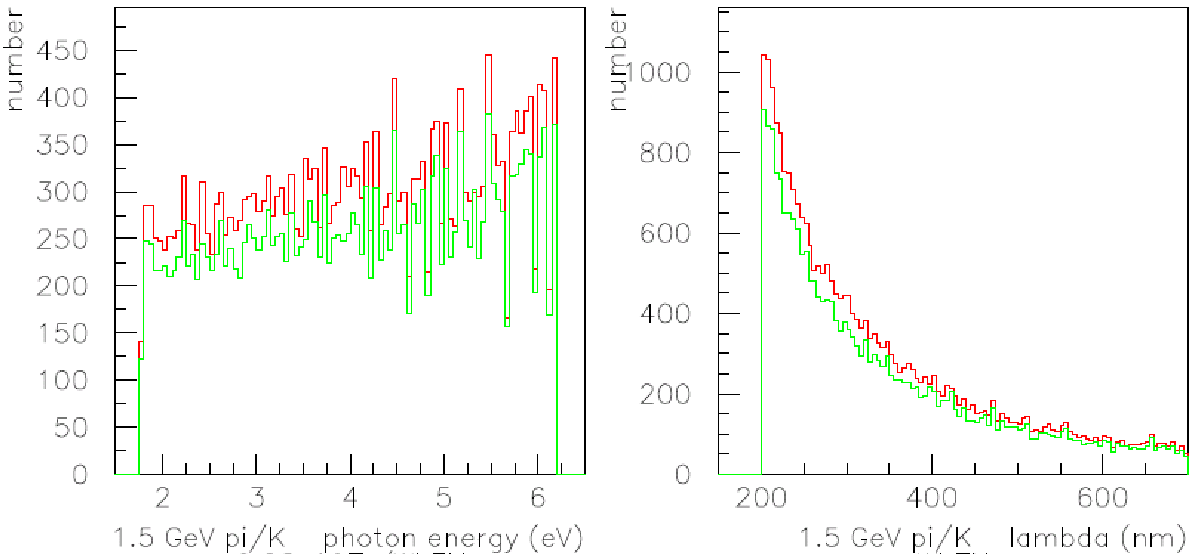

Fig. 8: *Yield of emitted Cherenkov photons (a) per photon energy interval (left panel) and (b) plotted as function of the wavelength (right panel).*

The production of Cherenkov radiation shows a threshold behaviour, which depends on the velocity of the particle. It can be used for particle identification if the momentum of the particle is known. Fig. 9 shows the number of Cherenkov photons as a function of the particle momentum for pions and kaons and different wavelength selections. It is obvious how the photon statistics drops when the wavelength is restricted in the UV range.

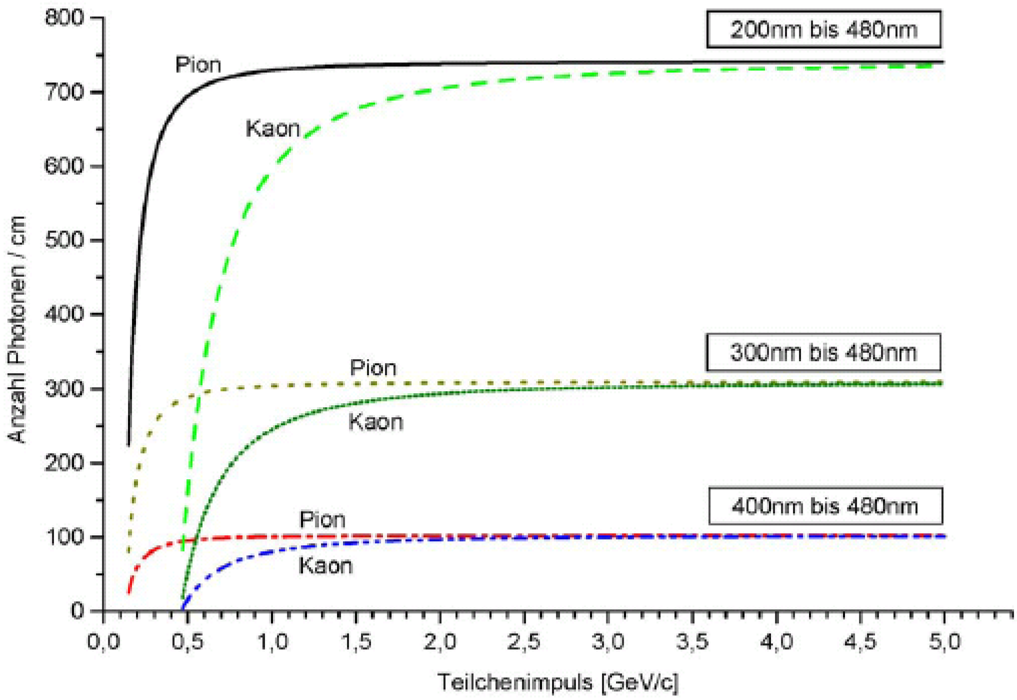

Fig. 9: *Number of Cherenkov photons as function of the particle momentum for pions and kaons in three different ranges of detected wavelength.*

Due to the wavelength dependence of the index of refraction as shown in Fig. 10 for fused silica, the Cherenkov angle becomes dependent on the wavelength. This dispersion of the Cherenkov angle results in a smearing that may reduce the resolution of the detector. When measuring the time of propagation, a second wavelength effect disturbs the resolution: the group velocity of a photon wave depends on the gradient of the index of refraction function and leads to a wavelength dependent time of propagation. This effect is especially large in the UV-near region where the slope of the index of refraction function reaches its maximum value. To minimize the effect, the detected range of wavelength is restricted to 400-700 nm in the simulation.

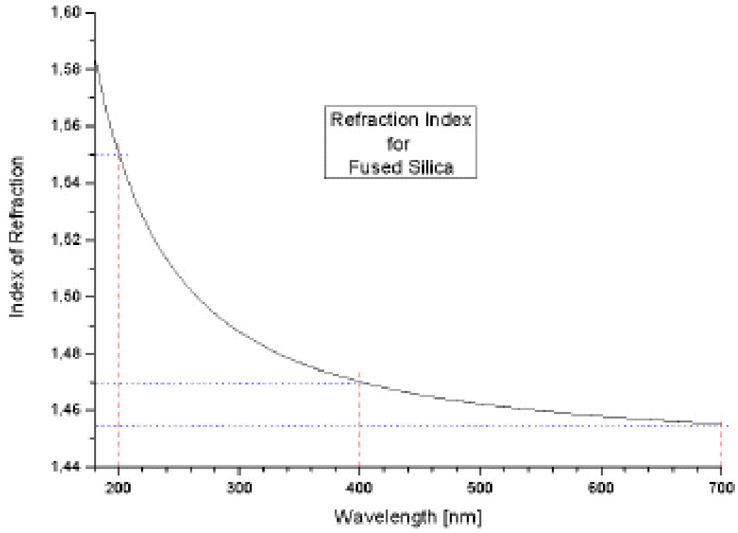

Fig. 10: *Index of refraction for fused silica.*

Simulation of time of propagation

Fig. 11 shows the TOP for pions and kaons of 1.5 GeV and 4 GeV as a function of the polar angle phi, which is the angle around the disc centre. Phi=0° is defined as the angle that corresponds to the position at which the particle penetrates the disc. The 1.5 GeV plot shows two features: the phi-range for pions (±75°) is larger than for kaons (±65°). This is due to the different Cherenkov angles of the two particles. Secondly, the TOP is typically a bit smaller for pions then for kaons. This is again an effect of the different Cherenkov angles which leads to a different path length and therefore different TOP for the two particle types. The effect is small compared to the smearing of the photons already at 1.5 GeV and hardly visible at 4 GeV. There is also a fine structure visible in the plots. This structure comes from the fact that in the current simulation the light is measured at discrete prisms.

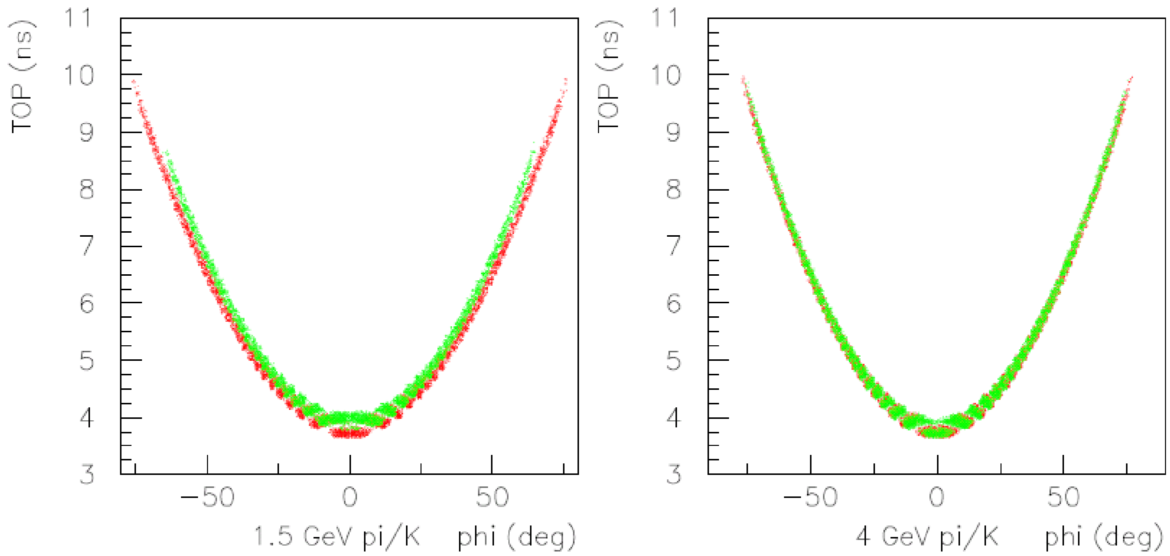

Fig. 11: *Time of propagation (TOP) of pions and kaons with a momentum of 1.5 GeV/c (left panel) and 4 GeV/c (right panel).*

In a next step an empirical function “corrected TOP”=TOP-3.823-0.00106*phi**2 is used to correct for the large time differences of the phi dependence. As a result the “corrected TOPs” show up relatively flat as a function of phi as shown in Fig. 12.

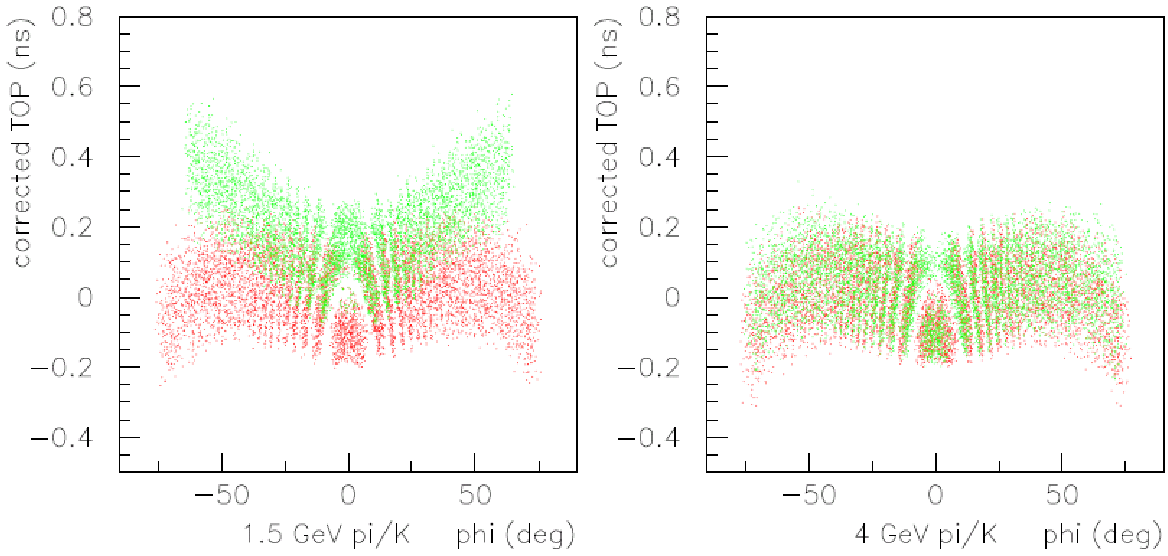

Fig. 12: *Corrected TOP for pions and kaons of 1.5 GeV/c (left panel) and 4 GeV/c (right panel). Here the phi dependence is taken into account using an empirical correction function. See text for details.*

The projections of these curves are shown in Fig. 13. The overlap is obvious. Each of the above plots contains about 30 pion and 30 kaon events.

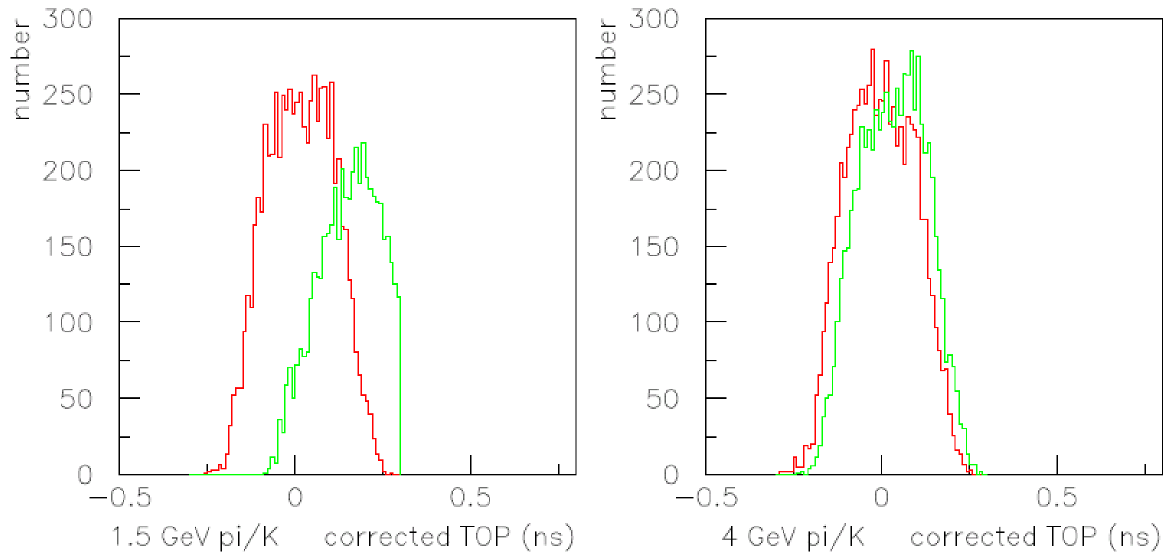

Fig. 13: *Projection of the corrected TOP in picoseconds as shown in Fig. 12. The left panel displays the distribution for pions/kaons of 1.5 GeV/c, the right panel for pions/kaons of 4 GeV/c.*

The conclusion of the above projection is that the photon distributions overlap for pions and kaons, and that the average values are significantly different. The next question now is if these differences are large enough to distinguish between pions and kaons for individual events. Therefore the above average corrected TOP value has been calculated for each individual event. Fig. 14 shows that these individual averages show still a significant different for pions and kaons. The differences are about 200 ps for 1.5 GeV particles and 40 ps for 4 GeV particles.

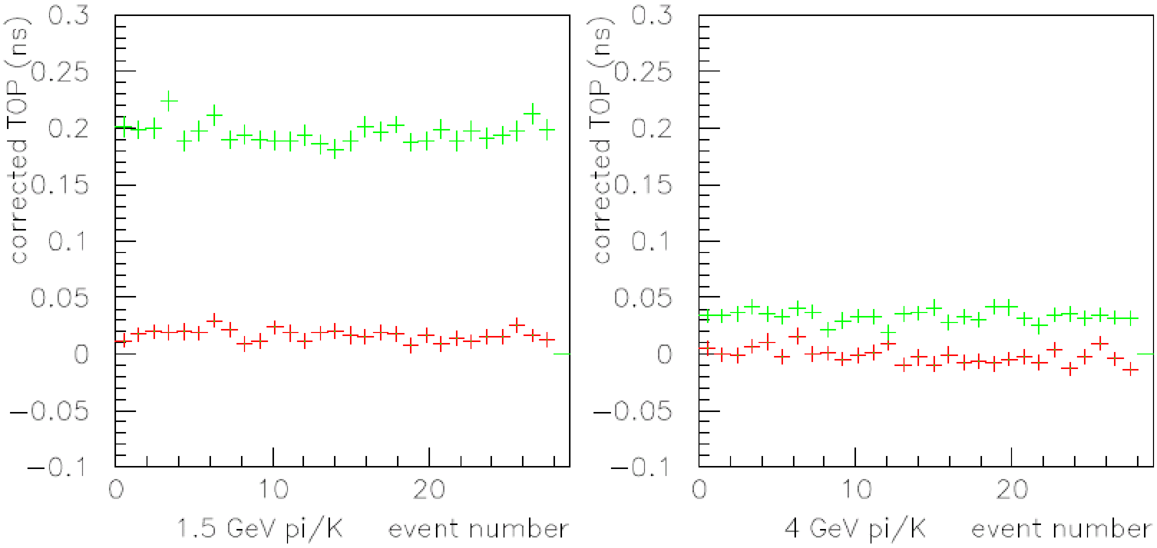

Fig. 14: Average value of the corrected TOP for individual events for 1.5 GeV/c (left panel) and 4 GeV/c (right panel). Even at momenta of 4 GeV/c the TOP for pions and kaons is significantly different.

The simulations up to now assume a 100% photon transmission and detection. Deleting every 2nd photon leads to the results as shown in Fig. 15. Here the separation is the same as before, but the fluctuations have increased because the photon statistics in only half of what it was before.

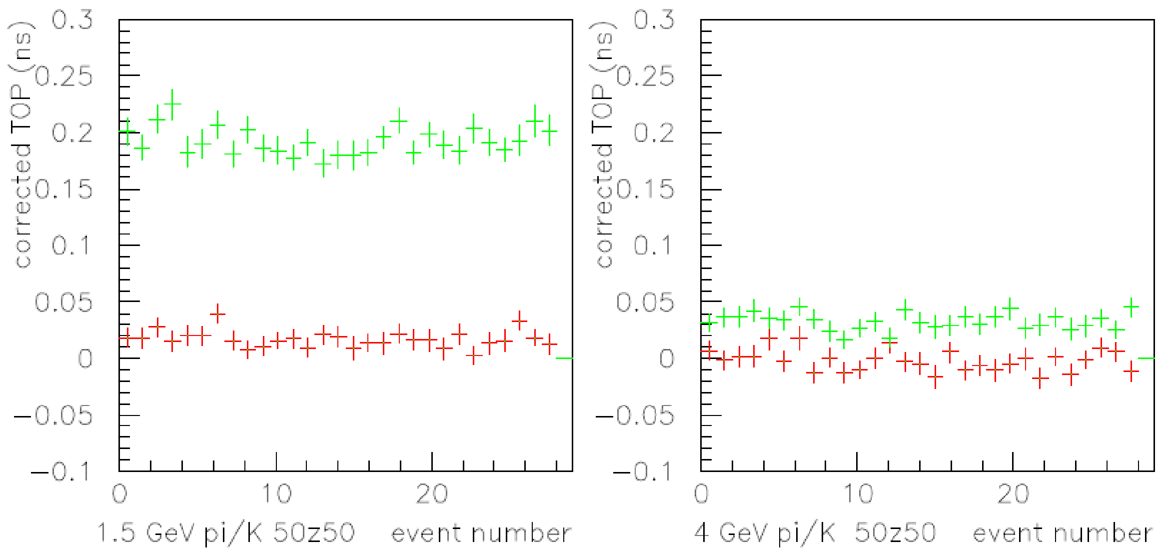

Fig. 15: *Here the number of photons has been reduced by a factor of two compared to Fig. 14, resulting in an increase of fluctuations while the separation of the pion/kaon signal in average remains unchanged.*

Summary

A conceptional design for a Multi-Chromatic TOP DIRC detector has been presented. The chromatic correction is achieved using dichroic filters, which split the spectral range into disjunctive regimes. The Cherenkov light is then detected with MCP-PMTs with photocathodes, which have sufficient quantum efficiency for the range of wavelength transmitted by the respective filters. MCP-PMTs have an extremely high time resolution (~30 ps) and work reliably in strong magnetic fields (tested up to 1.5 Tesla). The dichroic filters are arranged alternating around the circumference of the DIRC disk, increasing the effective path length for a good part of the photons and therefore also increasing the propagation time differences between photons emitted under different Cherenkov angles. Affixing the dichroic filters to the edge of the DIRC disk with optical grease with a matching index of refraction (like used e.g. in the BaBar DIRC detector for joining the fused silica bars) might eliminate perturbation which would otherwise arise from imperfections on the exit surface of the disk edge.

Although the design proposed in this report needs to be tested and optimized in extensive detailed Monte-Carlo studies, first simulations look promising. It encourages us to follow up this idea, either until the method is disproved, or until we have built a working prototype of such a detector.

Acknowledgements

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