Design of a disc DIRC detector for the WASA experiment

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A B S T R A C T
A Disc DIRC counter is foreseen for the WASA experiment at the COSY proton storage ring in J"ulich. It shall improve the proton kinetic energy measurement in the forward direction by measuring the proton speed at the two per mille level. The segmentation into four quarter-discs allows to incline the radiator relative to the incoming particles. This lowers the threshold velocity for light propagation inside the DIRC radiator. The construction of a full-scale quarter disc prototype is envisaged within a year.

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1. Introduction

The WASA [1] detector setup which is currently installed on the COSY storage ring in J"ulich is a fixed target experiment scattering cooled protons circulating in the ring off an internal pellet target.

One objective of the WASA-at-COSY collaboration is the study of fundamental symmetries. For instance the $\eta$ meson decay channel into three neutral pions violates the isospin conservation. For such rare decays a very good $\eta$ missing mass resolution in the reaction $pp \rightarrow pp\eta^*$ is mandatory, requiring a matching resolution for the proton energy. At $p = 3.35$ GeV/c (only 44 MeV above threshold in the centre-of-mass system) the phase space for outgoing protons as shown in Fig. 1 is contained inside an angle of $\theta = 13^\circ$ relative to the beam axis.

2. DIRC-at-WASA measuring energy

The WASA-at-COSY collaboration is planning to build a focussing disc DIRC\textsuperscript{1} counter to measure the proton energy. Called DIRC-at-WASA, it shall improve the kinetic energy resolution in the forward direction for 400–800 MeV protons by measuring the proton speed at the 10/3 level. Usually the purpose of such RICH-type Cherenkov counters measuring the velocity is particle identification as is the case for the BaBar-DIRC\textsuperscript{2} and the DIRC counters [3] of the future PANDA [4] experiment. In the case of WASA, however, this velocity is converted to a proton energy as in the forward direction the WASA experiment has no magnetic field and hence cannot measure the momentum.

3. DIRC-at-WASA within WASA-at-COSY

The forward detectors of the WASA experiment (see Fig. 2) instrument $\theta$ angles from 3$^\circ$ to 17$^\circ$. The DIRC-at-WASA focussing disc DIRC shall replace the first two layers of the Forward Range Hodoscope, immediately downstream of the forward tracking and trigger detectors. The three remaining hodoscope layers continue to measure the $dE/dx$ profile and thus provide particle identification. The segmentation into four quarter elements allows to angle the radiators away from a perpendicular orientation relative to the beam axis. This lowers the threshold velocity (and energy) for having a non-zero fraction of the photons propagating by total internal reflection inside the DIRC radiator material. For the chosen 20\degree inclination angle the black line in Fig. 1 shows the energy threshold depending on the proton angle.

4. Quarter-disc element

The quarter elements of the CEARA\textsuperscript{2} design [5] are mechanically independent boxes. The optical components are shown in Fig. 3. These are one quarter-circle radiator disc and 16 Focussing Light Guides (FLG) each instrumented with two multi-pixel photomultipliers.

The 40 mm thick radiator disc and the 50 mm wide FLGs are made of acrylic glass (Degussa PLEXIGLAS GS Block farblos, normals 222 R"ohm). The smooth top and bottom surfaces of the cast raw material do not require any polishing. The bulk transmission and the effects of the expected radiation load are discussed in Section 8.

Due to the limited available space a Siudak-plus/Erlangen FLG type [5] has been chosen. This FLG geometry requires some kind of

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\textsuperscript{1}DIRC: Detection of Internally Reflected Cherenkov light.

\textsuperscript{2}Cherenkov-Emissions-Analysierender Ringscheiben-Apparat.
mirror coating as there is no total internal reflection on the curved surface. The focussing performance is shown in Section 5, machining effects and the mirror coating effects are discussed in Section 7.

The focal plane of each FLG shall be instrumented with two $8 \times 8$ square pixel Hamamatsu H8500 multi-anode phototubes. Initially the optical coupling is done with Saint Gobain optical grease.

5. Focussing light guide

The selected FLG shape (each of the 16 rim elements in Fig. 3 and the right component in Fig. 4) is inscribed in a cuboid of $200 \times 165 \times 50$ mm$^3$. It images an angular range of $35^\circ$ onto a focal plane length of 96 mm. This covers photons from the proton energy range of interest and also the velocity range up to saturated particles ($\beta = 1$) at a hardly reduced $\sigma_\beta$ resolution.

Regarding the optical optimisation of this extruded shape, the photon direction vector component normal to the drawing plane in Fig. 4 decouples, but light ray position and angle on entering the light guide still span a two-dimensional parameter space. By design there is a single one-dimensional shape for the light guide curvature, and hence the focussing cannot be perfect over the focal plane range. For convenience the focal surface is chosen to be flat. Nevertheless, the optimised curvature (parametrised with polynomial coefficients $c_2$ to $c_5$) achieves a focussing quality better than $\sigma = 0.4$ mm (see Fig. 5) over the instrumented range.

6. Detector resolution simulations

Charged particles punching through the radiator disc and the Cherenkov photon propagation have been simulated and the detector resolution determined in analysing the photon hit patterns with PHYSICA [6] macro programmes. The charged particle

![Fig. 1. Simulated phase space for ejectile protons in the reaction $pp \rightarrow pp\gamma'$.](image)

![Fig. 2. WASA setup with the DIRC counter downstream of the tracking and trigger counters followed by a three layer plastic scintillator hodoscope.](image)

![Fig. 3. One DIRC-at-WASA quarter element, with 16 focussing light guides (in grey) attaching to the radiator disc in front (in blue). Each FLG is instrumented with two Ma-PMTs (in dark red).](image)

![Fig. 4. Side cross-section of the inclined quarter element with the radiator disc to the left and the FLG to the right. The line on the FLG surface shows the 96 mm long instrumented focal plane area. Sample light paths are shown for two protons.](image)

![Fig. 5. Focussing quality of a Siudak-plus/Erlangen type focussing light guide designed to attach to a 40 mm thick radiator disc. The solid line gives the $\pm \sigma$ focus size, the dotted line the value $\sqrt{\Delta z}$ to compare with pixel size. The dashed lines give the minimum, median and maximum positions in the light ray set relative to the averaged position.](image)
trajectory includes angular straggling, and the wavelength dependence of the refractive indices is parametrised with Sellmeier coefficients.

The detector geometry consists of a 40 mm thick acrylic glass quarter disc with 650 mm radius starting 1652 mm downstream of the target vertex. For the wavelength interval $\lambda$ from 400 to 600 nm the Photon Detection Efficiency is set to 20% (about 0.2 eV). The simulations here assume idealisations like perfectly parallel disc surfaces, no bulk light absorption and 100% reflectivity for total internal reflection and the mirror surface plus neither detector noise nor light from background particles.

One can obtain velocity and tracking information by analysing solely the DIRC photon hit pattern. However, adding vertex information from external tracking detectors significantly reduces the error for $\beta = v/c$. The angular precision at entrance into the disc as supplied by the upstream tracking is set to $\sigma_{\theta} = 0.87$ mrad per coordinate.

Fig. 6 gives the detector resolution for protons emitted from the target vertex at polar angle $\theta = 8^\circ$ and azimuthal angle $\phi = 45^\circ$ relative to the beam axis. The top part gives $\sigma_\beta$ versus $\beta$, which is the intrinsically determined quantity in the DIRC analysis. With the above described idealisations, in particular 100% reflectivity, the $\sigma_\beta$ resolution is better than two per mille. The bottom part gives the same data plotted as energy error $\sigma_T$ versus kinetic energy $T$ which are the quantities used to describe the performance of detector components within the WASA experiment.

GEANT4 simulations that include the DIRC-at-WASA performance within WASA-at-COSY for benchmark physics channels are underway.

### 7. Optical studies

The optical properties of the components have to be measured, in particular the focussing light guide which is a novel piece.

Space constraints for DIRC-at-WASA do not allow to use total internal reflection geometry, the preferred option for FLGs. Hence one has to resort to a mirror coating of the curved surface. We find the reflecting foil VM2000 clamped to a FLG to have an angle-averaged reflectivity of about 80% which is better than the reflectivity of a sputtered aluminium coating we have applied onto an acrylic glass test piece.

The finish of the diamond-equipped polishing head (Firma Reichel, Ingelheim) on the side surfaces of a sample focussing light guide has surface periodicities of $l=0.06$ mm. Fig. 7 shows the diffraction pattern from a laser beam on a screen in position of the

**Fig. 6.** Detector resolution obtained from simulations, plotted as $\sigma_\beta$ versus $\beta$ in the top part and $\sigma_T$ versus $T$ in the bottom part, for protons of $\theta = 8^\circ$ target angle.

**Fig. 7.** Laser beam passing through FLG imaged onto a paper screen positioned in the focal plane. The main focus is strongly overexposed to show the diffraction structure.

**Fig. 8.** Intensity scan in the focal plane with a vertical slit 0.3 mm wide of a laser beam passing through a FLG. The main peak is reflection on the VM2000 mirror foil, the diffractive structure is due to the tool advancing 0.06 mm per revolution. The pixel size of the photon detectors will be 6 mm.
focal plane. Together with the reflection from the VM2000 mirror foil the non-zero diffraction orders are visible. A position scan measuring the intensity through a 0.3 mm wide vertical slit into a 10 mm diameter sensor [7] (see Fig. 8) shows that the main maximum contains 82% of the overall light power.

The simulations as described in Section 6 assume perfect reflectivity, hence the ideal resolution as presented in Fig. 6 needs to be scaled up accordingly to account for these non-perfect reflectivity contributions.

8. Transparency and radiation hardness

Test pieces of 50 mm thickness were cut from the acrylic glass raw material and measured in a spectrophotometer [8]. The transmission curve (labelled 0 Gy in Fig. 9) shows that the acrylic glass we use is transparent above λ \approx 400 nm.

The DIRC-at-WASA radiation load is estimated to be not more than 100 Gy in unfavourable locations. After irradiating a 50 mm thick acrylic glass piece with 1000 Gy using the $^{60}$Co irradiation facility in Giessen, the transmission drops by about 15% in the 400 to 450 nm range (line “ratio” in Fig. 9).

9. Current activities and outlook

The current Phase I activity of DIRC-at-WASA is the construction of a quarter disc element. Because of significant amplification variations from pixel to pixel we have decided to instrument each phototube pixel individually in this first prototype. Available electronics on our shelves allows us to instrument 512 pixels, hence we are going to instrument the eight middle focussing light guides with one PMT each.

In Phase II we plan to prototype full quarters of different disc DIRC designs. While a focussing design [9] measures angles directly, a ToP design [10] precisely measures photon arrival times, and by applying trigonometry to the photon path lengths the photon Cherenkov angles can be determined. Both CEARA focussing disc DIRC models and a multi-chromatic time-of-propagation disc DIRC [11] are foreseen. In Phase III, DIRC-at-WASA with the full four quarter elements will form an integral part of the WASA-at-COSY detector setup.

The DIRC-at-WASA counter shall serve a further purpose: It is prototyping the disc technology in a real accelerator environment for the future PANDA experiment at FAIR. The PANDA Cherenkov detector community is eagerly awaiting the experience from WASA in operating such a DIRC type in a hadron machine environment.

10. Conclusions

The CEARA design proposed for DIRC-at-WASA achieves a velocity resolution at the two per mille level according to simulations. A first prototype is currently being built.

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