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Performance simulation of BaBar DIRC bar boxes in TORCH

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ABSTRACT

TORCH is a large-area precision time-of-flight detector based on the DIRC principle. The DIRC bar boxes of the BaBar experiment at SLAC could possibly be reused to form a part of the TORCH detector time-of-flight wall area, proposed to provide positive particle identification of low momentum kaons in the LHCb experiment at CERN. For a potential integration of BaBar bar boxes into TORCH, new imaging readout optics are required. From the several designs of readout optics that have been considered, two are used in this paper to study the effect of BaBar bar optical imperfections on the detector reconstruction performance. The kaon-pion separation powers obtained from analysing simulated photon hit patterns show the performance reduction for a BaBar bar of non-square geometry compared to a perfectly rectangular cross section.

1. Introduction

The TORCH [1] detector is a large-area precision time-of-flight (A=30 m^2 at σ=10–15 ps) DIRC Cherenkov detector. Foreseen at z=9.5 m distance from the LHCb interaction point (IP) it is intended to provide positive particle identification (PID) of 2–10 GeV/c kaons in the LHCb experiment at CERN. The addition of TORCH into LHCb is to be proposed for a future upgrade, most likely for an installation during LS3 (around 2025) after completion of the current R & D phase.

The BaBar DIRC [2] was a key part of the BaBar experiment which ran at SLAC. The twelve BaBar DIRC bar boxes with rectangular cross section quartz bars inside are still in storage at SLAC, awaiting an envisaged redeployment into future experiments. Several BaBar DIRC bar boxes could form the side parts of the TORCH time-of-flight wall, with standard TORCH modules in the high occupancy inner region. Such a hybrid scenario (Fig. 1, LHCb coordinate system used) requires new readout optics, either as one unit per individual bar box (left), or as a single unit common to 4 bar boxes (right).

Optical readout designs [3,4] have been developed and optimised via ray-tracing studies. It was found that despite the bar box window being a large diameter optical aperture, suitable focussing can be achieved for enough photons. For all designs identified as viable, the PID power stems mostly from the fraction of detected photons for which the photon angle can be measured with high precision.

2. Scope of simulations

While being a time-of-flight detector, TORCH also has to measure the photon angle, necessary for correcting for the dispersion of the Cherenkov radiator material. Non-squareness of the radiator cross section blurs this angle information.

Two aspects make the BaBar/TORCH combination rather sensitive to non-squareness of the radiators. Firstly the smaller radiator width of 35 mm compared to 660 mm of the TORCH standard design causes more reflections on the sides. Secondly the focussing quality varies with position, and most information content is present in the middle of the photon hit pattern where the focussing is best, matched by two rows of MCP-PMTs which doubles the vertical TORCH angular resolution.

The quartz bars produced for the BaBar DIRC exceeded the non-squareness specification which was set to < 0.4 mrad (compare < 1.5 mrad for standard TORCH), but the single photon angle resolution of the BaBar DIRC photon camera was about one order of magnitude lower than that required for a BaBar/TORCH application. Quality control data for these bars is still available [5], however simple estimations do not suffice to tell how much the known deviations from perfect geometry would affect the BaBar/TORCH PID capability.

The simulations presented in this paper are targeting this question. They provide a relative performance comparison between typical real-life and ideal rectangular cross section BaBar bars. They do not aim at

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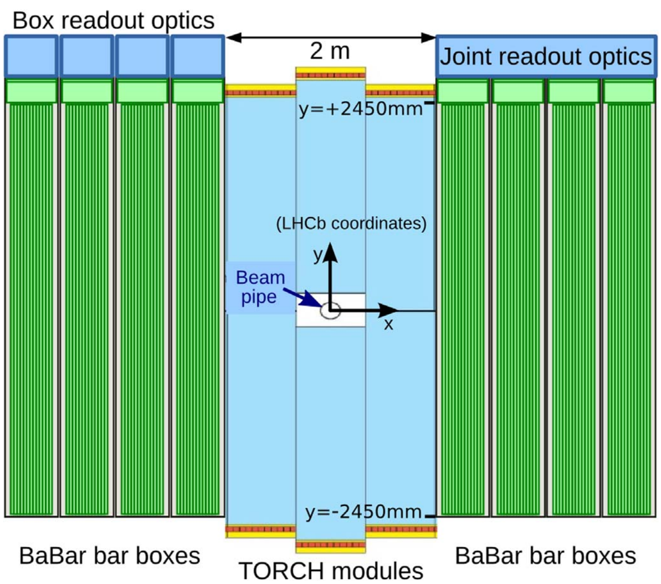

Fig. 1. Modular design geometry TORCH modules around the beam pipe, the areas left and right being covered with 4 BaBar bar boxes each. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

accurate absolute K/π separation values. The simulations use single particles in zero magnetic field, no secondary particles, assume perfect bulk transmission, neither Fresnel nor scattering losses at surfaces, and perfect mirror coatings. Due to these simplifications and approximations in these simulations which use existing program code, one should make allowance for 10–20% systematic errors in the absolute values of the PID separations.

3. Optical readout designs and photon hit patterns

Two of the previously developed optical readout designs (Figs. 2 and 4) were considered. Both designs feature one reflection off a mirror-coated curved surface. Figs. 3 and 5 (Focal plane x the same as LHCb x) show many-particle photon hit patterns for 10 GeV/c kaons on straight tracks from the IP.

Design 1 shown in Fig. 2 uses one single mirror [3]. Cylindrical in its coarse shape, it is made out of spherical mirror slices. The design has the merit of having no change in refractive index. The log-likelihood analysis used here can cope with the multiple small segments in the hit pattern (Fig. 3). However, it is felt that the pattern recognition required in the full experiment may prove difficult.

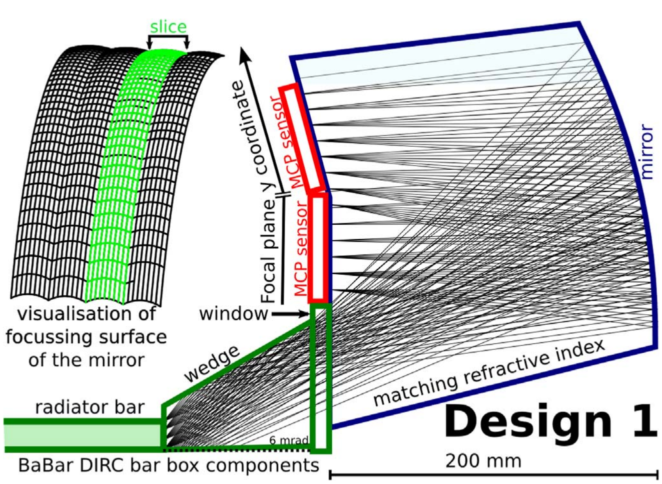

Fig. 2. Design 1 has two MCP-PMT sensor rows which are individually positioned and oriented. The expansion volume on the right consists of a quartz-like optical medium. The angle resolution compared to TORCH standard module optics is doubled.

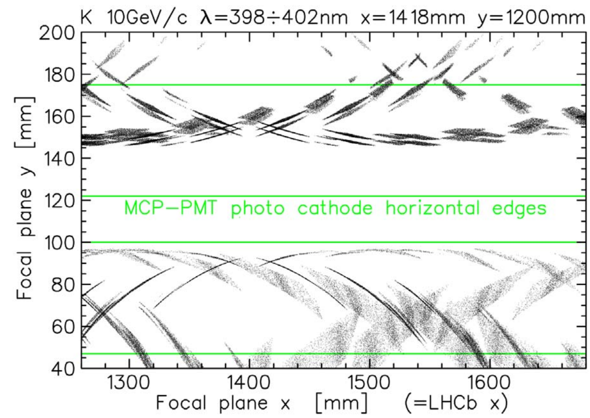

Fig. 3. Idealised photon hit pattern on focal plane for Design 1, assuming homogenous light intensity at the bar to wedge seam and monochromatic photons. Hence the pattern wings are continuous and can be thin.

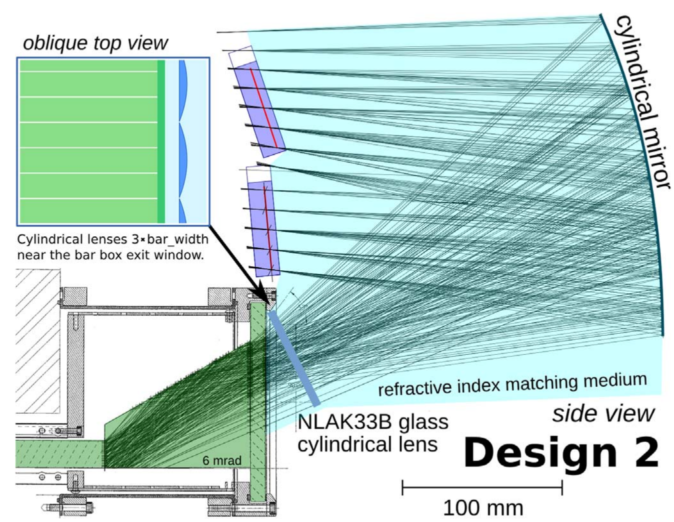

Fig. 4. Design 2 uses a set of cylindrical lenses combined with one cylindrical mirror, all immersed into a quartz refractive index matching medium.

Design 2 shown in Fig. 4 uses a set of cylindrical lenses focussing in a plane perpendicular to the drawing combined with one cylindrical mirror focussing in the plane of the drawing [4]. Two media of different refractive index are needed: lenses are NLAK33B glass, embedded in a material quartz-like in refractive index and dispersion. It was checked that the 105 mm lens pitch doesn't cause a periodic structure in the PID performance.

The idealised photon hit pattern (Fig. 5) shows continuous lines. In this paper PID performances are shown for Design 2. The performance for Design 1 is found to be slightly poorer, with a stronger dependence on the vertical impact point.

4. PID performance from simulations

From the IP 10 GeV/c kaons and pions travel on straight tracks and enter TORCH at (x,y). The Focal plane x direction is discretised into 6.625 mm wide columns. Gaussian smearing with the standard TORCH σ_t=50 ps time resolution and σ_s=0.1 mm Focal plane y resolution is applied, justified for the latter by the centroiding technique used in the MCP-PMT readout [6]. The K/π separation results are derived from analysing the 3-dimensional photon hit data with a log-likelihood analysis algorithm. The reference patterns contain 1500 photons in

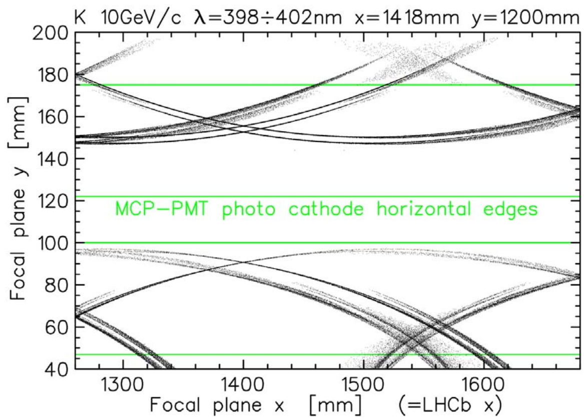

Fig. 5. Idealised photon hit pattern on focal plane for Design 2, assuming homogenous light intensity at the bar to wedge seam and monochromatic photons.

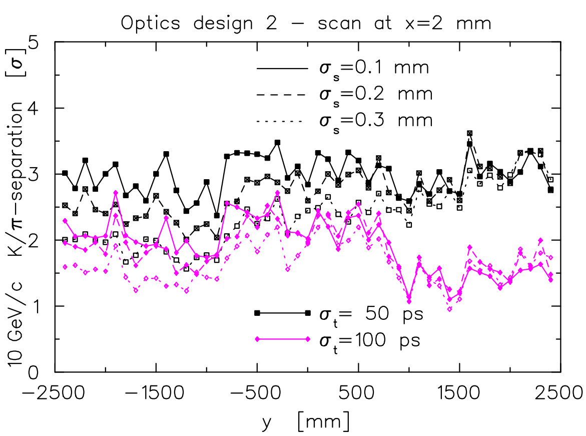

Fig. 6. Design 2 PID performance in sigma separations, obtained from log likelihood analysis, for several position resolutions σ_s and time resolutions σ_t.

each of the 56 detector pixel columns, assuming 7×2 MCP-PMTs for one single BaBar box readout optics. Each data point is based on analysing 100 pion and 100 kaon events.

Curves for different time and spatial resolutions in Fig. 6 show that time resolution is important for charged particles crossing the radiator near the readout optics (positive y), whereas spatial resolution matters for particles crossing the radiator far away from the readout optics (negative y).

When simulating the non-squareness of BaBar bars the top and bottom faces are set to be perfectly parallel. For each side reflection the tilt angle is randomly selected from a Gaussian distribution of width σ_F. The resulting smearing was confirmed to being equivalent to a fixed trapeze cross section.

The black solid line in Fig. 6 (repeated in Figs. 7 and 8) shows the reference PID performance for perfectly rectangular radiator bars. Simulations with x=2 mm are also valid for a bar box oriented perpendicularly towards the LHCb IP.

Black, red and brown graphs in Fig. 7 show the performance reduction for non-squareness values σ_F increasing from 0.0 to 0.2 and 0.5 mrad. In the BaBar DIRC bars quality control data [5] the middle 50% of the BaBar bars face-side squareness RMS angle values lie between 0.13 and 0.33 mrad with 0.21 mrad median value. The green graph shows the PID power for 0 mrad BaBar bar box prism bottom wedge angle. About two thirds of the green data points are above the corresponding black points (6 mrad standard value), pointing to a marginally improved PID performance in the single particle analysis case.

In Fig. 8 the red and magenta graphs (σ_F=0.2 mrad bar non-

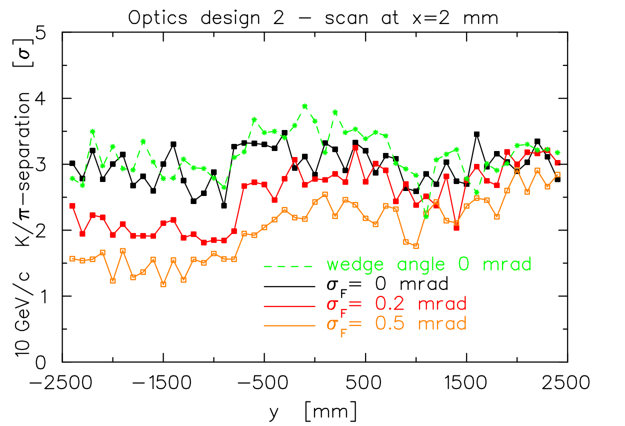

Fig. 7. PID performance comparison for several non-squareness values σ_F. Black points σ_F=0 mrad. Red and brown points show the reduction in K/π separation when orientation errors are applied to the two BaBar bar side faces. For the green points the wedge bottom angle is changed from 6 to 0 mrad. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

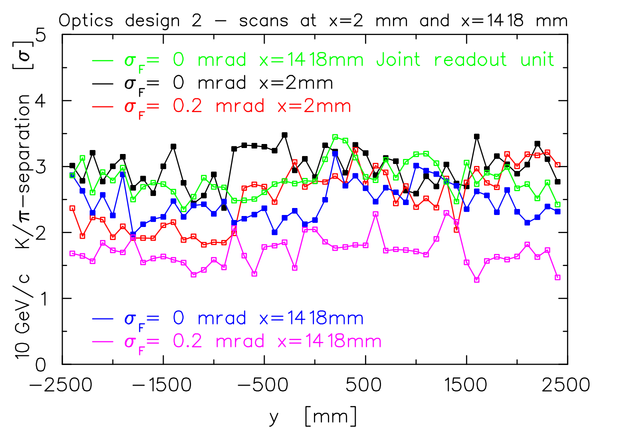

Fig. 8. PID performance as a function of horizontal position (black and blue graphs) showing reduced PID for σ_F=0.2 mrad bar side imperfections (red and magenta graphs). Green graph gives PID for a joint readout optics volume. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

squareness) show that the PID performance reduction depends on the x coordinate. This reduction is more pronounced for larger x and positive y values. One also finds for x=1418 mm an improved PID performance for a joint readout optics volume covering a row of 4 bar boxes (green line, configuration as shown in Fig. 1 right) compared to an individual box readout (blue line, Fig. 1 left).

5. Conclusions

Studies for Design 2 show a decrease in PID performance when one adds squareness errors for the rectangular bars that are typical for BaBar bars [2,5] into the simulation. Given the range of BaBar bars non-squareness values one may expect performance variations between different BaBar bar boxes.

Given that for x=1418 mm the PID performance reduction is larger than for x=2 mm one may consider to orient BaBar bar boxes perpendicular to the incoming particles. A similar improvement can be achieved by using a joint readout optics volume for a row of 4 bar boxes as fewer photon hit pattern segments would then fold back onto themselves.

A suitable optical arrangement has been found for integrating the BaBar bar boxes into TORCH, but the non-squareness of the radiator bars would have some impact on the performance.

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