RICH detectors for the LHCb experiment

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Abstract

The LHCb experiment is being designed to study CP violation in the B-meson system. It differs from other LHC experiments in its excellent π/K separation in the momentum range 1-150 GeV/ c . This is accomplished by two RICH counters: RICH1 has a 5 cm-thick aerogel radiator and a 95 cm-long C₄F₁₀ radiator while RICH2 has 180 cm-long CF₄ radiator. Cherenkov photons are focused by spherical mirrors onto photodetectors. Three photodetector options are under study: the 127mm diameter Pad Hybrid Photodiode (HPD) with a 2048 silicon pad sensor and analog readout. The 80 mm diameter Pixel HPD with a 1024-pixel silicon sensor and binary readout. The third option is Hamamatsu's multianode photomultiplier (MaPMT). Recent test beam results on the performance of both RICH and photodetector prototypes show a good agreement with the design. Cherenkov ring pattern recognition based on a global log likelihood method are being developed to satisfy the hadron identification requirements.

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1 Particle Identification in LHCb

To take advantage of the large forward-backward $b\bar{b}$ production cross section at the Large Hadron Collider at CERN, the LHCb detector [1] is being designed as a single arm spectrometer with a forward angle coverage of 10-330 mrad. The physics goal of LHCb is to study CP violation and rare decays in the B meson system [2]. To achieve this goal, excellent hadron identification is needed for background suppression and for B flavor tagging. Many important final states have background of the same topology, with one or more pions replaced by kaons or vice versa. As a consequence, the invariant mass of the backgrounds overlap with the signal thus diluting the CP asymmetry to be measured. For example, $B_d^0 \rightarrow \pi^+\pi^-$ has backgrounds $B_{d,s}^0 \rightarrow K^\pm\pi^\mp$ and $B_s^0 \rightarrow K^+K^-$ [3]; $B_s^0 \rightarrow D_s^\pm K^\mp$ has as background $B_s^0 \rightarrow D_s^\mp\pi^+$ and its charge conjugate mode. These two channels have tracks with high momenta and requires particle identification up to $p = 150$ GeV/c. In addition, hadron identification is important for reducing combinatorial background for high multiplicity decay channels such as $B_d^0 \rightarrow \bar{D}^0 K^{*0} \rightarrow K^+\pi^- K^+\pi^-$. Besides background reduction, identification of $K^\pm$ is crucial for the determination of the production state of B by the tagging the flavor of the accompanying B through $b \rightarrow c \rightarrow s$. This requires $K^\pm$ identification down to $p = 1$ GeV/c. Therefore, a good K/ π separation in the momentum range 1-150 GeV/c is essential for the success of the physics of LHCb. Only the RICH technique can cover such a broad momentum range.

2 The RICHes for LHCb

A single RICH cannot satisfy the broad momentum range required by the physics. However, the strong polar angle and momentum correlation can be exploited with a system of two RICHes: RICH1 (Fig. 1), situated upstream of the magnet with 25-300 mrad polar angle coverage and intended for hadron identification of low momentum tracks, has two radiators: 5 cm thick silica aerogel and 95 cm C_4F_{10} gaseous radiators. Spherical mirrors of 190 cm radius of curvature are tilted by 250 mrad in order to focus the Cherenkov light onto two photodetector planes (60×100 cm²) outside the detector acceptance. RICH2 (Fig. 1), downstream and in front of the calorimeter, is intended for high momentum and small polar angle tracks, and uses 180

cm of CF_4 gas as radiator. It covers 10-120 mrad in the bending plane and 10-100 mrad in the non-bending plane. Spherical mirrors of 820 cm of radius of curvature focus light, reflected by a flat mirror, onto two photodetector planes ($72 \times 120\text{cm}^2$) outside the detector acceptance.

The expected single-photon angular resolutions are 1.1, 1.45 and 0.35 mrad for C_4F_{10} , aerogel and CF_4 respectively and the number of detected photons per track are 55, 15 and 30 respectively. A summary of the performance is shown in Table 1.

3 Photodetectors

One of the technically most challenging parts of the LHCb RICH detectors is the photodetectors. A total area of $\approx 3\text{ m}^2$ are needed with a fine granularity of $2.5 \times 2.5\text{ mm}^2$ in order not to limit the Cherenkov angle resolution. With an active area above 73%, a total of 340,000 electronics channels are needed. In addition, single photon sensitivity with high quantum efficiency in both visible and UV region is needed to maximize the number of photons detected. Three photodetector options are under study: Pad HPD, Pixel HPD and multianode PMT (MaPMT).

3.1 Pad HPD

The Pad HPD [4, 5] is a CERN in-house development. It consists of a 127mm diameter glass envelope with borosilicate UV-glass window on which the Bialkali (K_2CsSb) photocathode is deposited (Fig.2). Four electrodes are used to focus the photoelectrons onto the Silicon sensor on the baseplate. The 5 cm diameter Silicon sensor consists of 16 sectors with $128\text{ }1\text{ mm}^2$ pads. They are wired bonded onto the printed ceramics board together with analog readout electronics. An ultra high vacuum plant was built at CERN for the evaporation of the photocathodes. Good quantum efficiency of $> 20\%$ at 400nm has been achieved with an overall uniformity of 10%. The sealing of the envelope and baseplate using cold indium sealing technique was developed and shown to work reliably.

A sealed prototype has been produced with slow electronics (VA3) [6], The results show an excellent signal to noise ratio of 20 for an acceleration voltage of 20kV (Fig.3). Studies are underway to encapsulate LHC speed

electronics (SCT128A) [7].

3.2 Pixel HPD

The Pixel HPD project [8] is co-development with DEP of Netherlands. It consists of an 80mm diameter envelop with S20 photocathode deposited on the interior. Cross-focusing electrodes focus the photoelectrons onto 1024, $500\mu\text{m} \times 500\mu\text{m}$, silicon pixel sensors. The silicon pixels are bump-bonded to binary readout electronics.

A 40 mm prototype tube with $500\mu\text{m} \times 50\mu\text{m}$ pixels has been produced and tested in the lab and in a test beam. The Cherenkov ring, produced by 120 GeV/c pion beam using air as radiator, can be clearly seen in Fig.4.

3.3 Multi-anode PMT

A third option under study is to use the commercially available multi-anode photomultiplier Hamamatsu R5900-M64 [9]. The device is 64-channel tube, arranged as an 8×8 matrix. Each anode has a sensitive area of 2mm^2 with a 0.3 mm gap between two elements. Due to the large dead area at the edge (≈ 4 mm) and the spacing between the elements, the active area coverage is rather poor, only 40%. However, a lens system is being studied to focus the light onto the elements, thus recovering the loss due to the edges (Fig.5).

A first prototype of the lens system has been tested in the test beam this summer and the results are as expected. More beam tests are foreseen in which an MaPMT cluster will be read out by LHC speed electronics.

4 Pattern Recognition

Another challenge of the LHCb RICH detector is the ability to recognize Cherenkov rings from large number of hits due to the high track multiplicity. This is accomplished by the use of a global log likelihood pattern recognition algorithm which compares the number of hits in each pixel with the expected hits from the reconstructed tracks and the background for a given particle hypothesis for the whole event [10]. It starts by assuming that all the tracks are pions and calculates the likelihood. Next, the particle hypothesis for a

given track is varied and only an increase in the likelihood is accepted. The procedure is re-iterated for all tracks until no further improvement is found.

With this algorithm, an overall K/π separation of greater than 3 sigma for the full momentum range required by LHCb can be obtained (Fig.6).

5 Outlook and Conclusion

The design of the LHCb RICH detectors is well under way. Prototypes of the three options for photodetector under study are currently undergoing tests. In addition, by using a global log-likelihood method, the goal of K/π separation between 1-150 GeV/ c can be achieved.

References

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Material	CF ₄	C ₄ F ₁₀	Aerogel
n	1.0005	1.0014	1.03
$\theta_c^{\max}$ [mrad]	32	53	242
$p_{\text{thresh}}(\pi)$ [GeV/ c]	4.4	2.6	0.6
$p_{\text{thresh}}(K)$ [GeV/ c]	15.6	9.3	2.0
$\sigma_\theta^{\text{emission}}$ [mrad]	0.21	0.54	0.36
$\sigma_\theta^{\text{chromatic}}$ [mrad]	0.22	0.54	1.21
$\sigma_\theta^{\text{pixel}}$ [mrad]	0.18	0.72	0.72
$\sigma_\theta^{\text{total}}$ [mrad]	0.35	1.10	1.45
N_{pe}	30	55	15

Table 1: Performance of LHCb RICH radiators

Figure 1: Schematics layout of the LHCb RICH1 (left) and RICH2 (right) detectors.

Figure 2: Cross section view of the pad HPD envelope (top). Below are the baseplate, printed ceramic board and silicon sensor

Figure 3: Pad HPD pulse height where the first 4 photoelectron peak are clearly seen.

Figure 4: Cherenkov ring produced by 120 GeV/ c pions in air radiator using a 40 mm Pixel HPD prototype.

Figure 5: Layout of the multianode PMT (top) and the lens array (bottom)

Figure 6: K/ π separation (in σ) as a function of momentum for RICH1, RICH2 and both.