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Monte Carlo study of a Belle II proximity focusing RICH with aerogel as a radiator

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ABSTRACT

A proximity focusing RICH will be installed in the forward direction of the Belle II spectrometer, inside a super conducting solenoid coil with the magnetic field of 1.5 T. Photons emitted in the sequence of two different aerogel radiator layers will be registered by the Hybrid Avalanche Photo Diodes. By detecting more than 11 photons per incident 4 GeV/*c* pion, with 15 mrad single photon Cherenkov angle resolution, the designed detector should enable an efficient separation of kaons from pions in the wide range of particle momenta from 0.5 GeV/*c* up to 4 GeV/*c*.

The particle separation will be based on a two-dimensional extended maximum-likelihood analysis. The position dependence of the efficiencies for identification of pions and kaons shows a very homogeneous response over the detector area. The performance on the edge of the detector is improved by employing planar mirrors to reflect the Cherenkov photons on the detector plane. The results show that by using a designed detector configuration the kaon pion separation efficiency of more than 95% can be achieved at a very low pion misidentification probability of 1%. In the low momentum region (0.5 GeV/*c*–0.8 GeV/*c*) the variation of detected number of photons due to matching of aerogel refractive index and the gaps between the sensitive areas on the detector plane results in a slightly decreased separation efficiency.

1. Introduction

The Belle II spectrometer at the SuperKEKB e^+e^- collider will be dedicated to precise measurements of rare processes in decays of *B* and *D* mesons and tau leptons. It will collect a 50 times larger data sample as compared to the Belle experiment. Due to much higher event rates and background, a significant upgrade of the detector components is needed [1].

In the small space between the central drift chamber and the electromagnetic calorimeter, in the forward end-cap region of the spectrometer, a particle identification device, which should enable the identification of charged particles in the range from 0.5 to 4 GeV/*c*, is foreseen. Due to a very limited available space we have decided for the proximity focusing RICH with aerogel as the radiator.

2. Simulation

In order to optimize the detector design and to enable physics analyses, the detector has been simulated in the Belle II analysis and simulation framework (BASF2) [2], based on Geant4 simulation package [3]. In the simulation, the detector geometry close to the final design structure has been built: the aerogel RICH occupies a donut like space around the beam pipe. The entrance Al wall is

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followed by two 2 cm thick layers of trapezoidal aerogel with refractive indices 1.045 and 1.055 [4]. A focusing combination of aerogels is used to improve the Cherenkov angle resolution [5]. In the radiator Cherenkov photons are emitted and are propagated through an expansion volume to the photon detector. The sensors, 420 Hybrid Avalanche Photo Diodes [6], are positioned in seven concentric rings. A bi-alkali photo cathode with a peak quantum efficiency of 30% is used for the detection. In the Monte Carlo simulation the detector response is simulated and the registered hits are used in the reconstruction, where the extended two-dimensional likelihood functions are calculated [7–9].

3. Particle identification

Particles are identified by evaluating the likelihood function for different particle hypotheses h. The likelihood function is constructed as a product of probabilities p_i of individual pixels i being hit:

$$L = \prod_{\text{all pixels}} p_i \tag{1}$$

where the probability of pixel i recording m_i hits is Poissonian:

$$p_i = \frac{e^{-n_i} n_i^{m_i}}{m_i!}. \tag{2}$$

Here n_i is the expected i.e. the calculated average number of hits on the particular pixel and depends on the hypothesis h. Probabilities for a pad to be hit ($m_i > 0$) or not ($m_i = 0$) are

$$p_i = \begin{cases} e^{-n_i} & \text{for } m_i = 0 \\ 1 - e^{-n_i} & \text{for } m_i > 0. \end{cases} \tag{3}$$

When we separate contributions of hit and non-hit pixels and constrain the number of expected hits N for a given hypothesis to the sum of expected average number of hits on the detector we arrive at

$$\ln L = -N + \sum_{\text{hit } i} \ln(e^{n_i} - 1). \tag{4}$$

The advantage of this approach is that it requires calculation of the average number of hits, i.e. the hit probabilities n_i, only for the hit pixels.

4. Results

Cherenkov angle distributions of the simulated detector were compared to the test beam distributions and a good agreement has been found; in the test beam on average 11 photons were detected per incident 4 GeV/c pion, with 15 mrad single photon Cherenkov angle resolution [10]. In the simulation, the particles were simulated at the interaction point and propagated to the detector. The average kaon identification efficiency as a function of particle momentum is plotted in Fig. 1. For the pion misidentification probability of 1% the efficiency is well above 95% for most of the momentum region of the detector in the Belle II environment.

In Belle II, the incident angles of particles on the Ring Imaging Cherenkov Detector are in the range from 17 to 34°. When the tracks are close to the outer border of the detector as shown in Fig. 2, part of the photons is absorbed in the walls and the identification efficiency drops. The performance on the edge of the detector can be improved by placing planar mirrors on the outer edge of the photon detector to reflect the Cherenkov photons on the detector plane (Figs. 2 and 3). With such a modification, the number of detected photons is increased and the identification efficiency remains high also at the detector border. In Fig. 4 we plot the kaon identification efficiency for

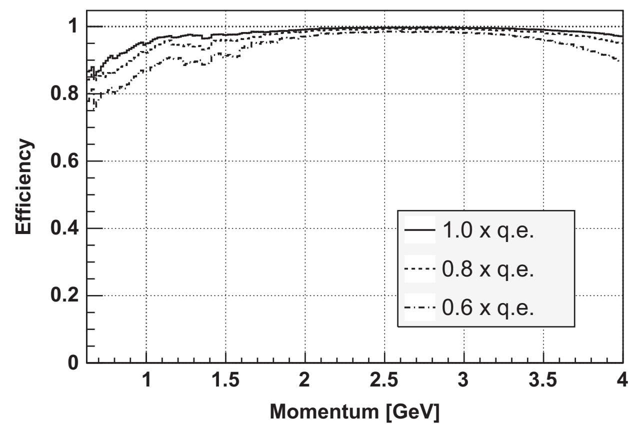

Fig. 1. K identification efficiency as a function of momentum for different photon detection efficiencies and pion misidentification probability of 1%.

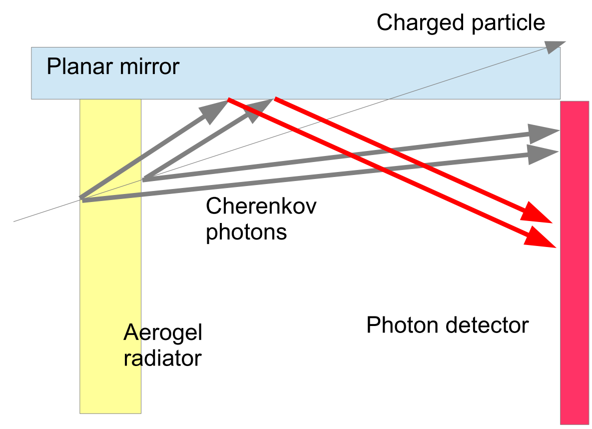

Fig. 2. Effect of the side mirrors: part of the photons is partial reflected on the side planar mirrors.

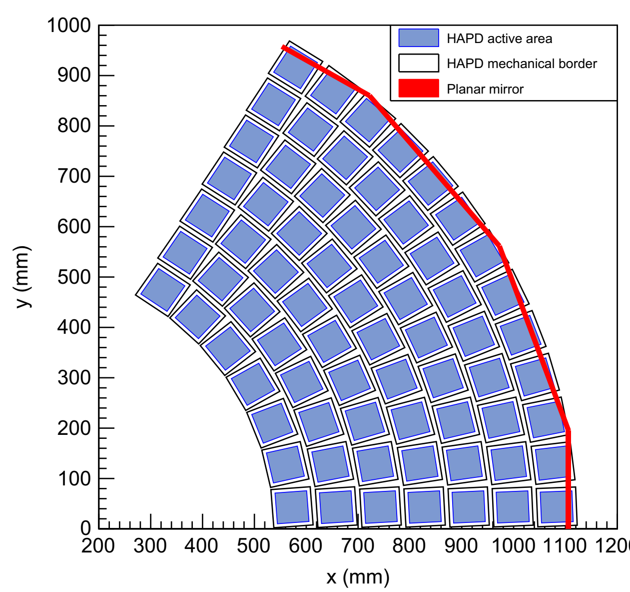

Fig. 3. One sextant of the photon detector: the photons are recorded by seven rings of HAPD photo sensors. The filled squares denote the sensitive area of the HAPD sensors. Planar mirrors are positioned perpendicularly at the outer edge of the photon detector.

3 GeV/c tracks as a function of track incidence radius on the radiator plane. Note the slight decrease of the kaon identification efficiency at around 94 cm, which is due to ambiguities in the

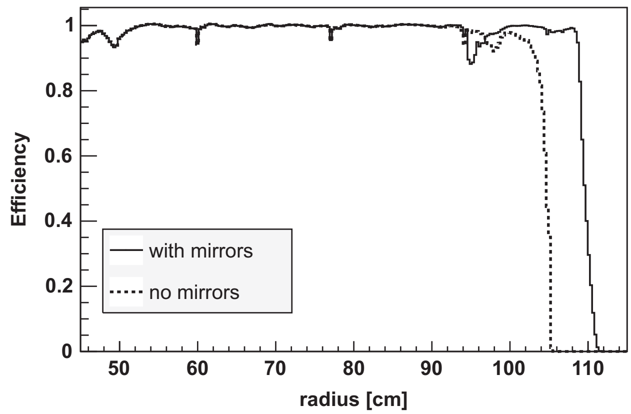

Fig. 4. Kaon identification efficiency with and without mirrors for 3 GeV/c particles and 1% misidentification probability.

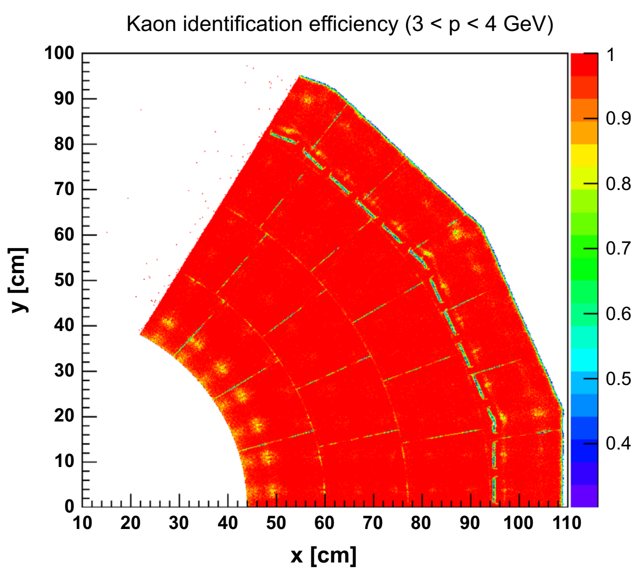

Fig. 5. Kaon identification efficiency variation in one sextant of the aerogel RICH detector.

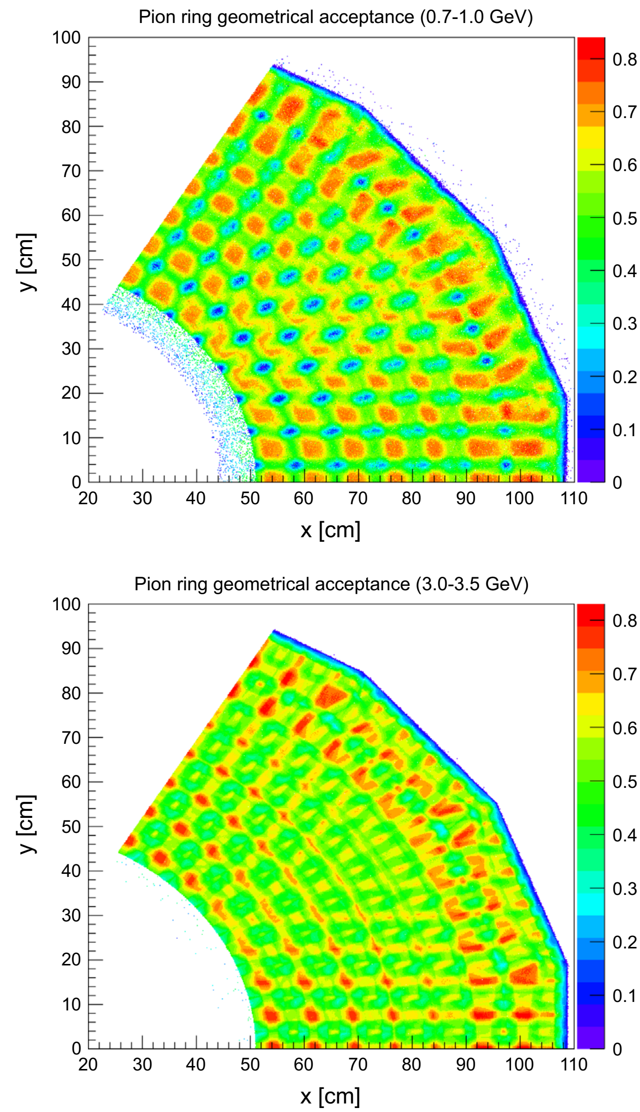

Fig. 6. Pion ring geometrical acceptance variation in one sextant of the aerogel RICH detector for tracks in the low momentum region from 0.7 GeV/c to 1 GeV/c (top) and high momentum region from 3.0 GeV/c to 3.5 GeV/c (bottom).

reconstruction of the photon path. The efficiency drops when the direct and the reflected photons from different hypothesis (partially) overlap on the photon detector.

We have studied the robustness of the device by investigating the identification efficiencies with a decreased quantum efficiency of the sensor. In Fig. 1, kaon identification efficiency is plotted as a function of momentum for three different quantum efficiencies. As expected, the most prominent decrease of the kaon identification efficiency is in the lower momentum region. The decrease is negligible in the range of kaons from two body B decays (3 GeV/c –3.5 GeV/c).

One of the key requirements is also the uniformity of kaon identification. In Fig. 5, the spatial dependence of the kaon identification efficiency for 3 GeV/c particles is plotted. The efficiency is uniform over a wide area of the detector. For the low momentum region the kaon identification efficiency is decreased for the areas on the detector where particles hit the center of the photo sensors, while the Cherenkov photons hit the inactive regions between HAPD sensors. The effect is clearly seen in the two-dimensional plot of the geometrical acceptance (Fig. 6), where the acceptance drops to about 0.2. For high momentum tracks the variation in the pion ring acceptance from 0.4 to 1 results in much more uniform identification efficiency.

5. Conclusions

We have studied the kaon/pion separation capabilities for different detector configurations of the Belle II aerogel RICH. The data were simulated using Geant4 based software and reconstructed using maximum likelihood method for different detector configurations. The kaon identification efficiency is high over most of the kinematic region (0.5 GeV/c–4 GeV/c) and the response is homogeneous over all the detector area. The influence on the performance due to different incidence angle, photon detection efficiency and background was studied, however little sensitivity was found.

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