Study of Proximity focusing RICH with multiple refractive index aerogel radiator

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We have pioneered a new proximity focusing ring imaging Cherenkov detector with a radiator composed of multiple aerogel layers of various refractive indices, combined in focusing or defocusing configurations. The thickness of such a radiator can be increased without degradation of single photon Cherenkov angle resolution leading to a larger number of detected photons and improved Cherenkov angle resolution per track. A prototype was tested in 1-4GeV/c pion beams at KEK. We achieved a Cherenkov angle resolution per track $\sigma_{track} = 4.4$ mrad and $N_{p.e.}$= 8.5, which corresponds to a 5.1 σ K/π separation at 4 GeV/c.

1. Introduction

Proximity focusing ring imaging Cherenkov (RICH) detector with an aerogel radiator has been studied for the Belle particle identification upgrade at the KEK B-factory. In the present Belle detector, a threshold type aerogel Cherenkov counter(ACC) is used for K/π separation. However, in the forward end-cap, ACC does not provide sufficient separation in the high momentum region up to 4 GeV/c, which is very important for studies of two body decays such as $B \to \pi\pi$ and $K\pi$. This has motivated us to carry out R&D studies of a proximity focusing RICH detector [1].

In the RICH counter, good K/π separation requires good resolution of the Cherenkov angle per track $\sigma_{track} = \sigma_\theta/\sqrt{N_{p.e.}}$, where σ_θ is the Cherenkov angle resolution for a single photon and $N_{p.e.}$ is the number of detected photons. The number of photons may be increased by using a thicker radiator, but the single photon angular resolution is degraded due to the emission point uncertainty. The key question is how to increase the number of detected photons without degrading the single photon angular resolution.

To answer this question, we have introduced a novel idea with the “multiple radiator” [3]. This report reviews results based on Ref.[3] and presents measurements of beamtest in 2005. First we present our concept and configuration of RICH with dual radiator scheme. Next the experimental set up is described and the results of measurements and analysis are given.

2. RICH with multiple refractive index radiator

In this concept, aerogel radiator layers with different refractive indices are stacked. The dual radiator configurations are shown in Fig.1. In the first combination, the aerogel tile with the lower refractive index is positioned upstream. If the indices of the two radiators are well adjusted, the corresponding two rings overlap. This represents a sort of focusing of the photons within the radiator, and eliminates or at least considerably reduces the spread due to the emission point uncertainty. Note that aerogel is a perfect material for such a tuning of refractive indices since it can be produced with any desired refractive index in the range $n = 1.006 - 1.07$. In the following this combination will be referred to as “focusing combination”. The other possibility is a “defocusing combination”, in which the aerogel tile with higher index is positioned upstream. If the difference of the indices of the two aerogel tiles is appropriately chosen, the two radiators produced two well separated rings with good resolution.

An extension of the dual radiator combination is to use more than two aerogel radiators (“multiple radiator”). For the focusing combination, the indices of aerogels should gradually increase from the upstream to the downstream layer (Fig.2).

This report discusses the focusing configuration. Results of the defocusing configuration are presented in [3].

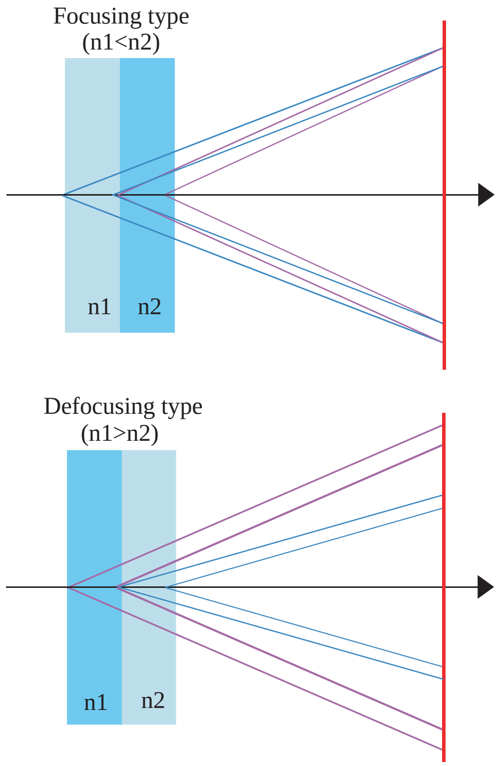

Figure 1: Principle of a dual radiator ring imaging Cherenkov counter: focusing radiator (top) and defocusing radiator (bottom).

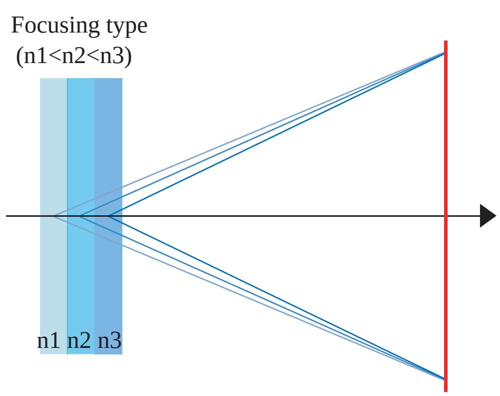

Figure 2: Principle of multiple radiator RICH with three layers. Only photons from the middle of each layer are shown.

3. Beam test setup

We have performed three beam tests in March and June 2004, and December 2005. The tests were carried out at the KEK-PS π2 and T1 beam lines, where pions with momenta of up to 4 GeV/c are available. The experimental set-up shown in Fig.3 is basically the same as the one described in detail in [2]. The particle trajectories are measured with two multi-wire proportional chambers (MWPC) at the upstream and downstream ends of the light-shield box. The test counter is composed of one or more layers of aerogel radiator; the photon detector array placed parallel to the radiator face at a distance of 20 cm. Multi-anode PMTs (Hamamatsu H8500) are positioned in a 4 $\times$ 4 array and aligned at a 52.5 mm pitch. The active surface of each PMT is divided into 64 (8$\times$8) channels with 6.08 mm $\times$ 6.08 mm pixel size. Because this type of PMT is not immune to the magnetic field and cannot be employed in the Belle detector, this device is considered as an intermediate step in our development.

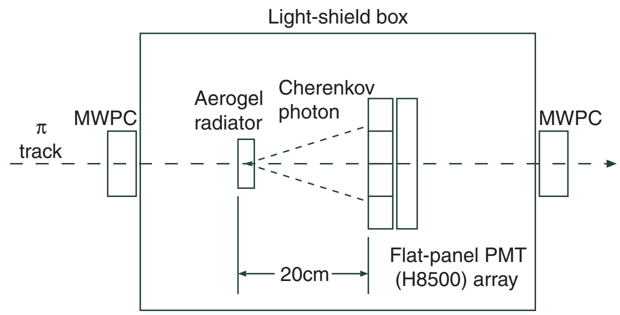

Figure 3: Experimental set-up

As radiators the same set of aerogel samples was used as in the test with single refractive index [2]. These aerogel samples have indices between 1.01 and 1.05; the transmission lengths (Λ) measured with a 400 nm laser are within 25-40 mm. In addition, we also used aerogel samples produced by using dimethyl-fiormamide (DMF) as the solvent [5] with refractive indices up to 1.07 and Λ of around 40 mm. We also tested multiple-layer aerogel samples produced at KEK [5] and BINP (Novosibirsk) [7], where a single tile is comprised of more than two layers with different indices.

4. Measurement and results

The basic parameters of the counter are the Cherenkov angle resolution for a single photon σ_θ and the number of detected photons $N_{p.e.}$. The Cherenkov angle for each detected photon is calculated from the position of PMT hit channel and tracking information given by MWPCs. We assume that the photon is emitted in the middle of the combined radiator. The resolution σ_θ is obtained by fitting the Cherenkov angle distribution with a Gaussian function for the signal and a second order polynomial for the back-

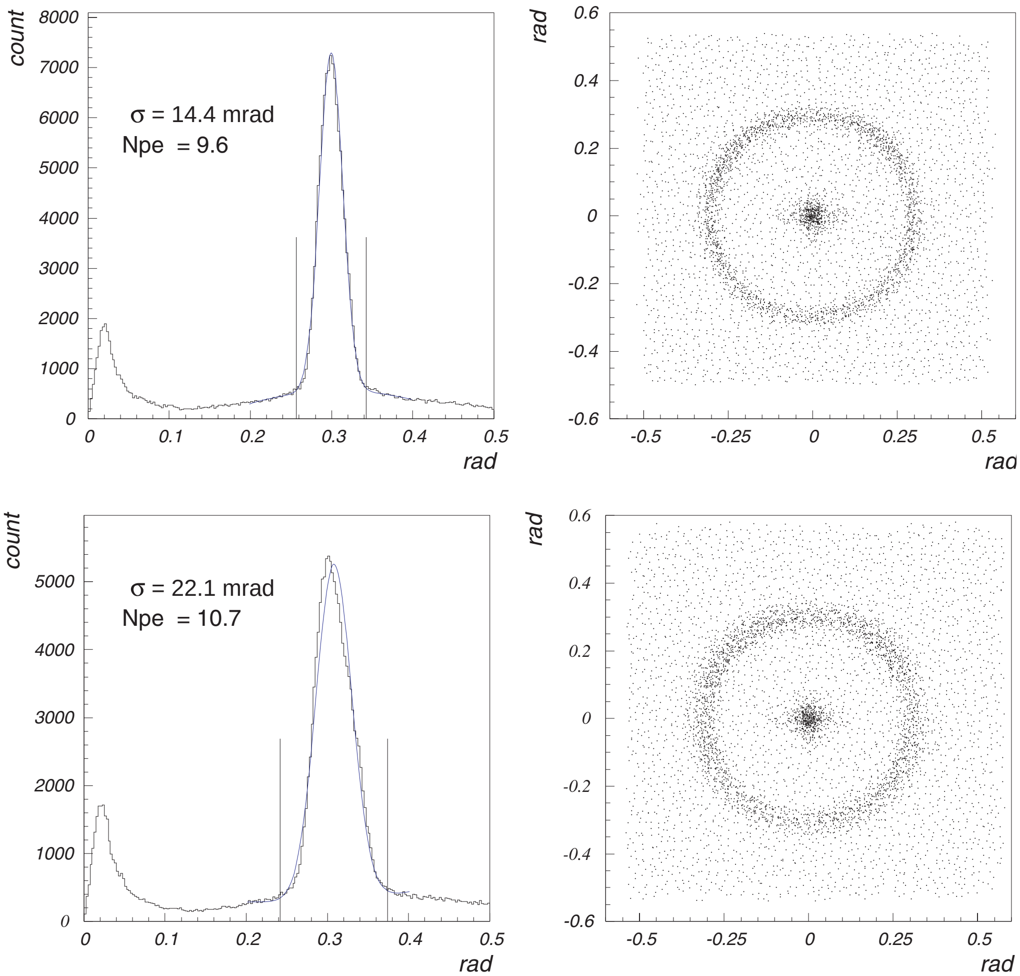

Figure 4: The accumulated distribution of Cherenkov photon hits depending on the corresponding Cherenkov angle (left) and the Cherenkov ring (right) for a 40 mm focusing configuration with refractive indices of 1.047 and 1.057 (top) and a homogeneous radiator (bottom)

ground, $N_{p.e.}$ is estimated by counting the number of hits within $\pm 3\sigma$ from the average Cherenkov angle and subtracting the number of background hits obtained from the fits to the Cherenkov angle distribution.

4.1. Test result with dual layer radiator

We first tested the focusing dual radiator combination of aerogel tiles of $n = 1.047$, $\Lambda = 34$ mm in upstream, and $n = 1.057$, $\Lambda = 25$ mm in the downstream position. Both tiles have a thickness of 20 mm.

We also tested the combination of aerogel tiles of equal refractive index (n=1.047). In Fig.4, we compare the data for two 40 mm thick radiators. The improvement is clearly visible. For the focusing configuration, the single photon resolution σ_θ is 14.4 mrad, and the average number of detected photons amounts to $N_{p.e.} = 9.6$. The Cherenkov angle resolution per track is calculated to be 4.8 mrad, corresponding to a 4.8σ K/π separation at 4 GeV/c. In the case of the single radiator, $N_{p.e.}$ is 10.7, σ_θ is 22.1 mrad, and $\sigma_{track} = 6.8$ mrad.

4.2. Test results with multiple layer radiators

In order to study the multiple layer radiator RICH in the focusing combination, we prepared a dual radiator configuration with indices of 1.046 and 1.051, and a triple radiator configuration with indices of 1.046, 1.051, and 1.056. The thickness of each radiator is 10 mm. Therefore the dual radiator is 20 mm thick, and the triple radiator is 30 mm thick. The performance of these combinations is compared with the single refractive index combination with $n = 1.047$ and radiator thickness of 10, 20, and 30 mm.

Fig.5 shows $\sigma_\theta, N_{p.e.}$ and σ_{track} for each radiator. $N_{p.e}$ increases as the radiator becomes thicker, and there is no significant difference of $N_{p.e.}$ between single and multiple refractive index combinations. On the

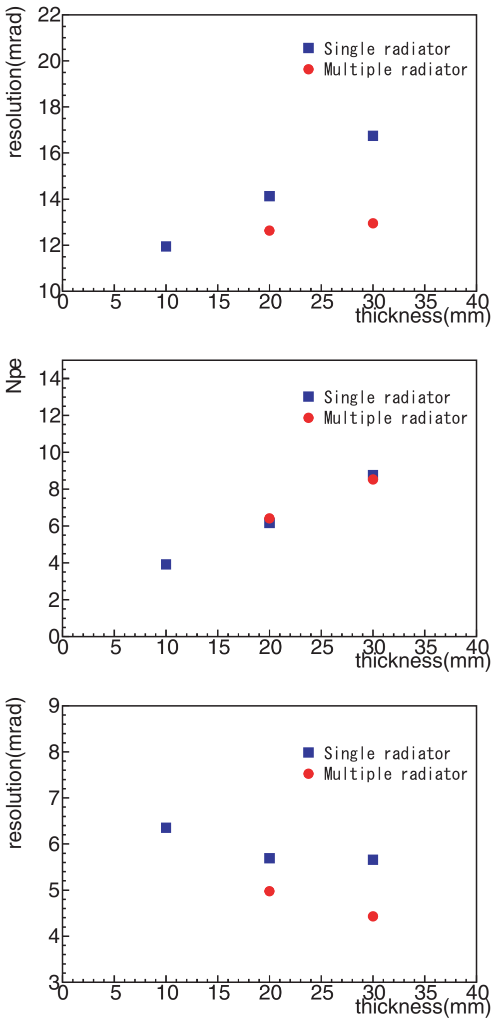

Figure 5: Single photon resolution (top), number of detected photons (middle), and single track resolution (bottom) for the focusing multiple and single refractive index RICH combination. The multiple radiator with a 20 mm thick radiator is a dual radiator, while that with 30 mm is a triple radiator.

other hand, σ_θ of the single radiator RICH becomes considerably worse as the radiator becomes thicker, σ_θ for the multiple radiator remains almost the same. As a result, σ_{track} is improved by introducing the multiple radiator combination. The triple radiator with 30 mm gives the best σ_{track} of 4.4 mrad corresponding to 5.1 σ K/π separation at 4 GeV/c.

4.3. Optimization of multiple radiator configuration

We measured σ_θ for dual radiators with various refractive indices in the downstream position in order to optimize the focusing configuration. The upstream index is fixed to $n_1 = 1.045$. The result is shown in Fig.6 and is consistent with the calculation based

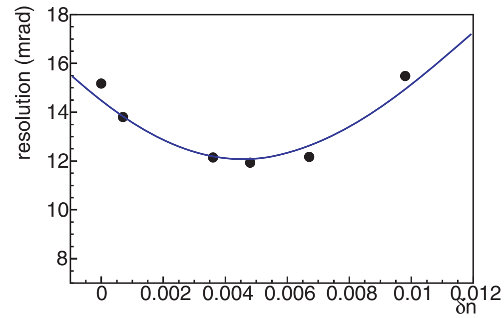

Figure 6: Resolution of Cherenkov angle for single photons (σ_θ) versus the difference in refractive indices (δn) of two radiator layers for the case of the upstream index n_1=1.045. The solid line is the result of a fit based on [6]

on the model discussed in [6] and shown as the solid line. The model calculate the rms of the distribution of Cherenkov photons from both layers and estimates the contribution of the emission point uncertainty for the Cherenkov angle resolution. The optimal difference δn in refractive indices of the two radiators is found to be 0.005. We note that the minimum in σ_θ is quite broad, a departure of δn by $\pm$ 0.003 from the optimal value only increases σ_θ by about 1.0 mrad. The performance is thus robust enough against fluctuation of $\pm 6\%$ in $n-1$ of produced aerogel.

4.4. Boundary effect

Cherenkov photons crossing the side of aerogel tile are refracted, reflected or scattered. Therefore, we loose the Cherenkov photons emitted near the edge or the corner of the radiator. We prepared hexagonal and square aerogel tiles and measured the boundary effect using test beam data for comparison. Hexagonal sample was produced by cutting a square tile with a size of $100 \times 100 \times 10$ mm^3 into three using a water-jet machining device. Fig.7 shows the number of detected photons depending on the beam incident point around the boundaries. The dotted line is the result of a fit based on the model where it is assumed that Cherenkov photons which cross the boundary are lost. Photon yield decreases to 1/3 in the corner. In the case of square aerogel tile, this ratio is 1/4. Although the hexagonal aerogel tile looks promising, further studies are needed before deciding which of the two shapes should be employed in the final design of the upgraded Belle detector.

5. Conclusion

We have pioneered a new technique to increase $N_{p.e.}$ without degrading σ_θ by using multiple layers of aerogels with different refractive indices combined in a fo-

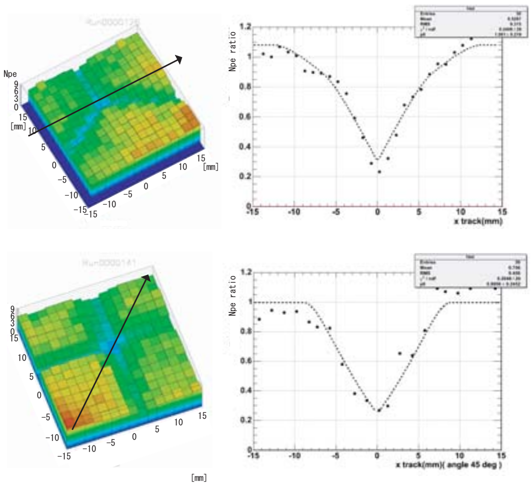

Figure 7: $N_{p.e.}$ distribution around boundaries (left) of hexagonal (top) and square (bottom) aerogel tiles. The variation of $N_{p.e.}$ along the direction indicated with a black line is shown on the right (points), together with a simple model based on the assumption that all photons crossing the boundary are lost (dotted curve).

cusing configuration. In the triple focusing radiator configuration, we have achieved a $\sigma_{track} = 4.4$ mrad and $N_{p.e.} = 8.5$, which corresponds to a 5.1 σ K/π separation at 4 GeV/c. This means that our RICH counter meets the requirement for the Belle detector upgrade. The method has been extensively studied in the beam tests, and is being further optimized (number of layers, their thickness and refractive index) for the final design.

Acknowledgments

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