# A novel type of proximity focusing RICH counter with multiple refractive index aerogel radiator

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A proximity focusing ring imaging Cherenkov detector, with the radiator consisting of two or more aerogel layers of different refractive indices, has been tested in 1-4 GeV/c pion beams at KEK. Essentially, a multiple refractive index aerogel radiator allows for an increase in Cherenkov photon yield on account of the increase in overall radiator thickness, while avoiding the simultaneous degradation in single photon angular resolution associated with the increased uncertainty of the emission point. With the refractive index of consecutive layers suitably increasing in the downstream direction, one may achieve overlapping of the Cherenkov rings from a single charged particle. In the opposite case of decreasing refractive index, one may obtain well separated rings. In the former combination an approximately 40% increase in photon yield is accompanied with just a minor degradation in single photon angular resolution. The impact of this improvement on the $\pi$/K separation at the upgraded Belle detector is discussed.

## 1. Introduction

Proximity focusing ring imaging Cherenkov (RICH) counters with non-gaseous radiators have the advantage of smaller size and are thus well suited as particle identification devices within more complex particle spectrometers with tight space constraints. Such a detector with aerogel as radiator is envisaged for the upgrade [1] of the particle identification system of the Belle spectrometer at the KEKB collider [2,3]. In the present Belle detector, a threshold-type Cherenkov detector (ACC) [4] enables a good $\pi/K$ separation. However, ACC does not provide sufficient separation for high momentum particles around 4 GeV/$c$ in the forward end-cap region, and a proximity focusing RICH with aerogel as radiator is being studied as a candidate for the detector upgrade.

Different aerogel radiators as well as different photon detectors have been investigated in search of an optimal counter, which would provide the required 4-5 $\sigma$ pion-kaon separation in the 1-4 GeV/c momentum range [5]. Good velocity resolution of a charged particle track requires good resolution of the Cherenkov angle of a single photon and many detected photons. The number of

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photons may be increased by increasing the radiator thickness, but the price to pay is an increased uncertainty of the emission point, i.e. single photon angular resolution. However, by judiciously choosing the refractive indices of consecutive aerogel radiator layers, one may achieve overlapping of the corresponding Cherenkov rings on the photon detector. This represents a sort of focusing of the photons within the radiator, and eliminates or at least considerably reduces the spread due to emission point uncertainty. Another possibility is the opposite, i.e. to obtain separate rings from separate aerogel layers in which the emission point uncertainty is given by the thickness of the corresponding layer. One may also try combinations of the two main schemes. Note that such a tuning of refractive index for individual layers is only possible with aerogel, which may be produced with any desired refractive index in the range 1.006-1.06.

While the principle was first discussed in [6], the present work reports on measurements made with different combinations of aerogel radiator layers. First we present estimates of the relations between the radiator thicknesses and refractive indices in order to obtain either overlapping of the Cherenkov rings or their adequate separation. Next the experimental apparatus is described and the results of measurements and analysis are given. Finally, we discuss the possibilities of such a detector to meet the expectations for the upgrade of the Belle particle identification system.

## 2. RICH with multiple refractive index radiator

The key issue in the performance of a proximity focusing RICH counter is to improve the Cherenkov angle resolution per track $\sigma_{\mathrm{track}} = \sigma_\theta/\sqrt{N_{\mathrm{p.e.}}}$. By using a thicker aerogel radiator, the average number of detected photons $N_{\mathrm{p.e.}}$ can be increased, but the single photon Cherenkov angle resolution $\sigma_\theta$ degrades due to the increased uncertainty in the photon emission point. As can be seen from Fig. 1, the optimal thickness should be around 20 mm, which was also verified in previous investigations [5].

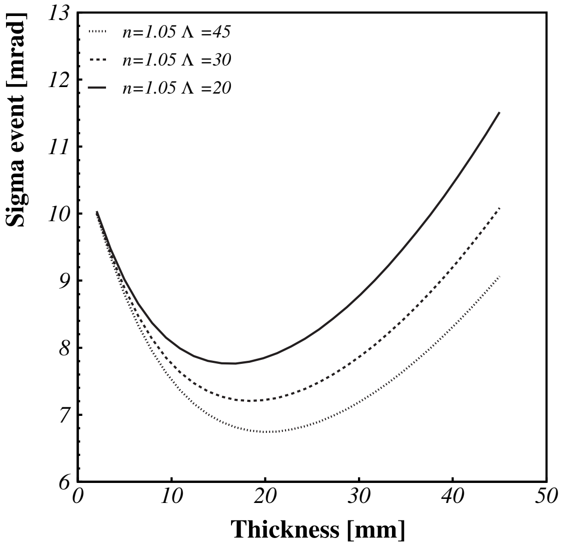


Figure 1. The variation of the figure of merit, $\sigma_\theta/\sqrt{N_{\mathrm{p.e.}}}$, with radiator thickness in the case of a single radiator, proximity focusing RICH, for three different transmission lengths at 400 nm ($\Lambda$ in mm).

One way to solve this problem is to use a "dual radiator" scheme, where one images Cherenkov photons from two aerogel radiators with different refractive indices as shown in Fig. 2. In the first combination (Fig. 2.b) two aerogel radiators are used with slightly different indices, where the one with the lower refractive index is positioned upstream. If the indices of the two radiators are well adjusted, the corresponding two rings overlap. In the following this combination will be referred to as "focusing combination".

The other possibility is a "defocusing combination", in which the aerogel with higher index is positioned upstream (Fig. 2.c). If the difference of the indices of the two aerogel tiles is appropriately chosen, the two radiators produce two well separated rings with good resolution.

A naive 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

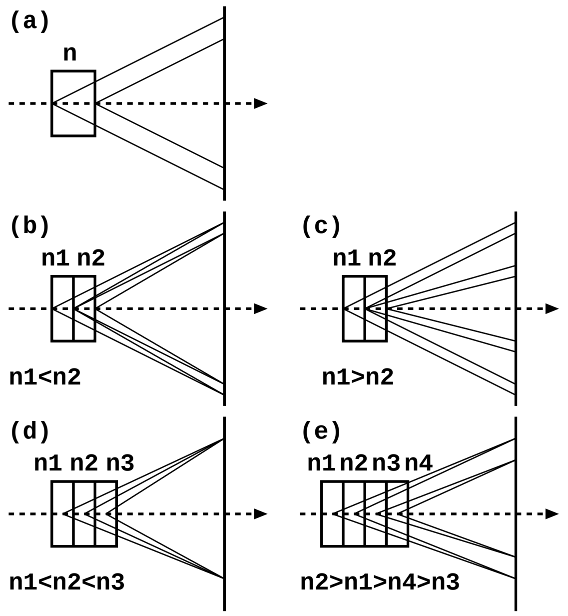


Figure 2. Principle of dual radiator and multiple radiator ring imaging Cherenkov counter: (a) single radiator, (b) focusing dual radiator, (c) defocusing dual radiator, (d) focusing multiple radiator and (e) defocusing multiple radiator RICH. Only photons from the middle of the radiator are shown in (d) and (e).

increase from the upstream to the downstream layer. Again, if the index of each layer is well chosen (Fig. 2.d), the angular resolution of the ring will not be appreciably deteriorated in spite of a thicker radiator. The defocusing dual radiator may be extended to four radiators by introducing the focusing combination in every two layers as shown in Fig. 2.e. In this case, the RICH has four radiators with different indices where the first two radiators in the upstream position create a larger ring, and the other two radiators a smaller ring.

## 3. Radiator parameters and expected performance

The relation between the refractive indices in the focusing combination in the dual radiator case is derived as follows. Neglecting the refraction at aerogel boundaries and denoting the thickness of a single radiator tile as $d$, the distance between the center of the downstream radiator and the photon detector plane as $L$, and the Cherenkov angles in both upstream and downstream radiator as $\theta_1$ and $\theta_2$ respectively, the condition that the two rings should overlap can be written as $L \tan\theta_2 = (L+d)\tan\theta_1$. From this condition the following approximate relation can be derived

$$n_2 - n_1 = \frac{d}{n_1 L}\big[n_1^2 - 1 - \frac{(mc)^2}{p^2}\big],$$

where $m$ and $p$ are the pion mass and momentum.

The optimization of the radiator parameters thus clearly depends on the kinematical region the counter should cover. In the case of the upgrade of the Belle particle identification system, the indices are optimized for tracks with $p = 4$ GeV$/c$, the highest particle momenta from two-body $B$ decays. As can be seen from Fig. 3, the overlap of the two rings remains sufficiently good even at lower momenta, so that the emission point error (full line) does not significantly increase with respect to the single radiator case of half the thickness (dashed line).

Similarly, since the relation derived above is valid only for perpendicularly incident tracks, the performance has to be checked also as a function of incidence angle. As shown in Fig. 4, only a modest increase in the emission point error is expected up to the maximal angle of incidence in the present application to the Belle upgrade (around 30°).

For the dual radiator in the defocusing combination, the requirements are much less demanding. The two rings have to be well separated, and none of them should coincide with the ring corresponding to the other particle species. If one requires for the case of $\pi/K$ separation that the kaon ring from the upstream radiator (corresponding to the angle $\theta_1(K)$) is separated by $k\sigma_\theta$ from the pion ring from the downstream radiator tile (corresponding to the angle $\theta_2(\pi)$), one arrives at the following expression $(1+d/L)\tan\theta_1(K) - \tan\theta_2(\pi) = k\sigma_\theta/\cos^2\theta_2(\pi)$, from which one may derive a relation between $n_1$ and $n_2$. For a specific example with $d/L = 0.1$,

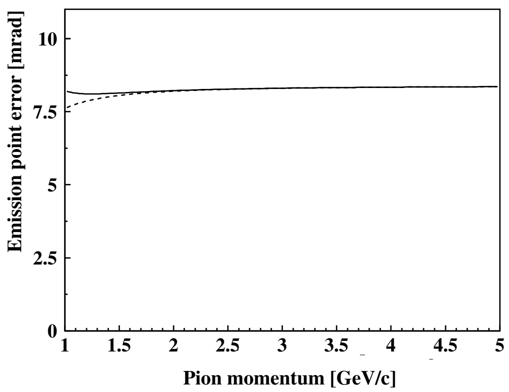


Figure 3. Emission point error for a focusing combination (two 2 cm thick tiles with refractive indices 1.05 and 1.042 at a distance of 18 cm from the photon detector) as a function of momentum for perpendicularly incident pions (full line) compared to the single radiator of half the thickness (dashed).

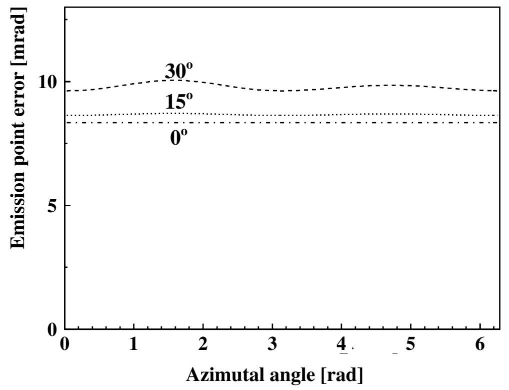


Figure 4. Emission point error for the focusing combination (same as in Fig. 3) as a function of the azimuthal angle around the track direction for 4 GeV/$c$ pions entering the counter at different angles of incidence (0° full line, 15° dash-dotted, 30° dotted).

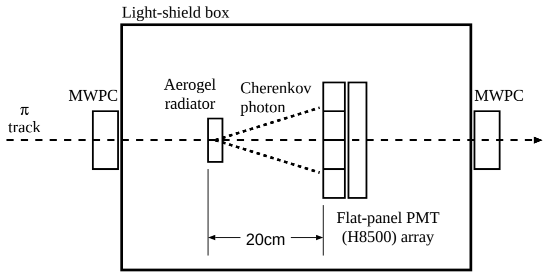


Figure 5. The experimental set-up.

$n_1 = 1.05$, $p = 4$ GeV/$c$ and $\sigma_\theta = 14$ mrad, values typical for such a counter, we get $n_1 - n_2 = 0.031$ for $k = 10$.

Note that for both the focusing and defocusing combinations the performance of the counter can be further optimized by varying the ratio of the thicknesses of the two radiators and the total thickness of the radiator.

## 4. Experimental Apparatus

We have performed two beam tests in March and June 2004. The tests were carried out at the KEK-PS $\pi 2$ and T1 beam lines, where pions with momenta up to 4 GeV/$c$ are available. The experimental set-up shown in Fig. 5 is basically the same as in the previous beam test [5]. The counter is composed of one or more layers of aerogel radiator and a photon-detection plane, parallel to the radiator face at a distance of 20 cm.

Multi-anode PMTs (Hamamatsu H8500) were used as photo-detectors. A total of 16 PMTs were positioned in a $4 \times 4$ array and aligned at a 52.5 mm pitch. The surface of each PMT is divided into 64 ($8 \times 8$) channels with 6.0 mm $\times$ 6.0 mm pixel size. This type of PMT is not immune to the magnetic field and cannot be applied in the Belle spectrometer, so this device is considered as an intermediate step in our development. For the final design, we plan to use the Hamamatsu HAPD or the BURLE Micro-Channel Plate PMT [7].

As radiators the same set of aerogel samples was used as in the tests with single refractive in-

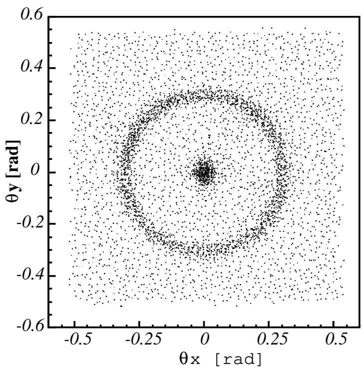


Figure 6. A typical distribution of PMT hits in the Cherenkov $x$, $y$ space with two 20 mm thick radiators ($n = 1.047$ and $n = 1.057$) in the focusing combination.

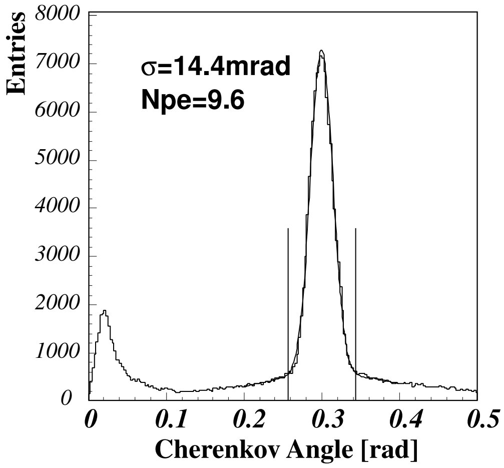


Figure 7. Distribution of the Cherenkov angle for accumulated single photons from 4 GeV/$c$ pions in the case of a focusing dual radiator combination with 20 mm thick radiators ($n = 1.047$ and $n = 1.057$).

dex radiators [5]. These aerogels have indices between 1.01 and 1.05; the transmission lengths at 400 nm ($\Lambda$) are around $30 - 40$ mm. In addition, newly produced aerogels with refractive indices up to 1.07 were used, as well as two-layer aerogel samples [8], where a single tile is comprised of two layers with different indices.

## 5. Measurements and results

A typical distribution of accumulated hits on the photon detector is shown in Fig. 6. Cherenkov photons from the two aerogel radiators are clearly seen as a single ring with a low background level. The hits near the center of the ring are due to Cherenkov radiation generated by the beam particle in the PMT window.

### 5.1. Test results with dual radiators

We first tested the focusing dual radiator combination with aerogel tiles of $n = 1.047$, $\Lambda = 34$ mm in the upstream position, and $n = 1.057$, $\Lambda = 25$ mm in the downstream position. Both radiators have a thickness of 20 mm. Figure 7 shows the resulting distribution of the Cherenkov angle for single photons. Note that the Cherenkov angle is calculated by assuming that the photon is emitted in the middle of the combined radiator. The basic parameters of the counter, the resolution and the number of detected photons, are obtained by fitting to this distribution a Gaussian function for the signal and a second order polynomial for the background. The resulting single photon resolution $\sigma_\theta$ is 14.4 mrad, while the average number detected photons amounts to $N_{\rm p.e.} = 9.6$. The Cherenkov angle resolution per track is calculated to be 4.8 mrad, corresponding to a $4.8\sigma$ $\pi/K$ separation at 4 GeV/$c$.

For comparison, measurements were also performed for single radiator cases when only the upstream or the downstream aerogel tile of the dual radiator is used. For the upstream and downstream radiator, the measured yield was 6.9 and 7.5 photons per ring, respectively. The single photon resolution was 13.8 mrad for the single radiator in the upstream position.

The single photon resolution $\sigma_\theta = 14.4$ mrad for the dual radiator is similar to that for the single radiator of half the thickness, while the number of detected photons is larger for the dual radiator. In the dual radiator RICH, a fraction of photons emitted in the upstream radiator is scattered in the downstream aerogel. Therefore,

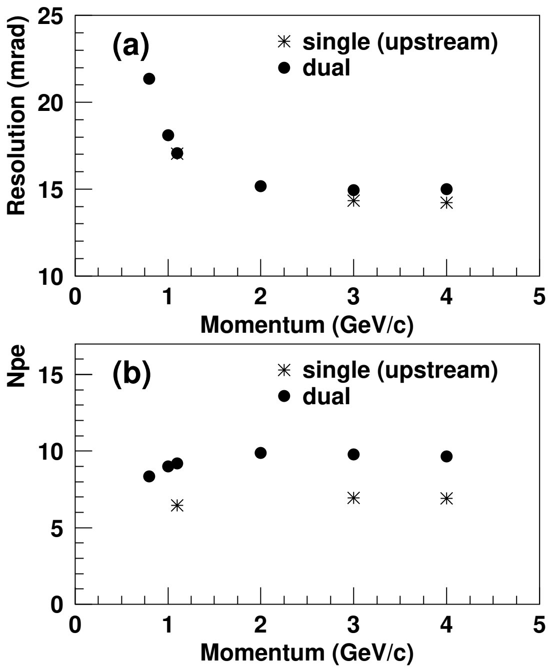


Figure 8. Momentum dependence of the single photon resolution (a) and the number of detected photons (b) for the dual radiator focusing combination compared to the single radiator.

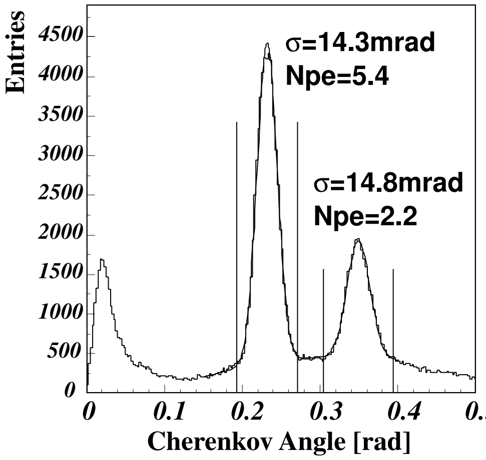


Figure 9. Distribution of the Cherenkov angle of single photons from 4 GeV/$c$ pions for a defocusing dual radiator RICH with $n_1 = 1.057$ and $n_2 = 1.027$.

the photoelectron yield is expected to be $N_{\mathrm{p.e.}} \sim N_1 \exp(-d_2/(\cos\theta_1 \Lambda_2)) + N_2 = 10.6$, where $N_1$ ($N_2$) is the number of the detected photons in the single radiator RICH with only upstream (downstream) radiator, $\theta_1$ is the Cherenkov angle in the upstream radiator, while $d_2$ and $\Lambda_2$ are the thickness and transmission length of the downstream radiator. This is consistent with the measured value of 9.6.

We also measured the momentum dependence of $N_{\mathrm{p.e.}}$ and $\sigma_\theta$ as shown in Fig. 8. Note that although the overlap of the rings from two radiators is optimized for a certain momentum, the variation of $\sigma_\theta$ is for the dual radiator RICH similar to that of the single radiator RICH over the full kinematic range. The increase in $\sigma_\theta$ at lower momenta is consistent with the contribution from multiple scattering.

For the defocusing dual radiator set-up, we used a combination of radiators with $n = 1.057$ and $n = 1.027$. Each radiator had a thickness of 20 mm. The single photon Cherenkov angle distribution for this combination is shown in Fig. 9. Two well separated rings are clearly seen. The sum of the number of photons from the two rings is larger than that from a single radiator with a thickness of 20 mm, while the resolutions are almost the same. Note that unfortunately the transparency of the downstream radiator was low ($\Lambda = 19$ mm) in this particular measurement; the use of a typical sample of $n \approx 1.03$ with the transmission length around 30 mm would considerably increase the light yield at the outer ring.

We also tested a two-layer aerogel tile with indices of 1.060 and 1.030 in the defocusing combination. We could observe two well separated rings on the photon detector. However, the photon yield was rather low because of a short transmission length of the radiator. This is due to the production procedure for such kind of tiles, which has not been optimized yet.

### 5.2. Tests with multiple radiators

In order to study the multiple 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 was 10 mm, such that the dual radiator is 20 mm thick, and the triple radiator is 30 mm thick. The performance of these set-ups is compared with the single radiator combination with $n = 1.046$ and radiator thickness of 10 mm, 20 mm and 30 mm.

Figure 10 shows $\sigma_\theta$, $N_{\mathrm{p.e.}}$ and $\sigma_{\mathrm{track}}$ distributions against the thickness of the radiators. $N_{\mathrm{p.e.}}$ increases as the radiator becomes thicker, and there is no significant difference of $N_{\mathrm{p.e.}}$ between single and multiple radiator combinations. On the other hand, $\sigma_\theta$ of the single radiator RICH increases considerably as the radiator gets thicker, but $\sigma_\theta$ for the multiple radiator case increases only slightly. As a result, $\sigma_{\mathrm{track}}$ is improved by introducing the multiple radiator combination, and the triple radiator with 30 mm gives the best $\sigma_{\mathrm{track}}$ of 4.5 mrad.

We also tested a defocusing multiple radiator with four radiator indices of 1.051, 1.056, 1.029 and 1.034 in a combination shown in Fig. 2.e. We compared it with a defocusing dual radiator RICH with radiators of $n = 1.056$ and 1.025. The total thickness of aerogel radiators was 40 mm in both cases. The measured values of $\sigma_\theta$ and $N_{\mathrm{p.e.}}$ are listed in Table 1. As expected, we find that the multiple radiator RICH has a better overall angular resolution at roughly the same photon yield.

## 6. Conclusion

We have studied dual and multiple radiator combinations of the proximity focusing aerogel RICH detector. For the focusing combination, we confirmed that the number of detected photons could be increased without deteriorating angular resolution compared to the single radiator RICH. In the triple radiator configuration we have achieved a Cherenkov angle resolution per track of $\sigma_{\mathrm{track}} = 4.5$ mrad, which corresponds to a $5.1\sigma$ $K/\pi$ separation at 4 GeV/$c$.

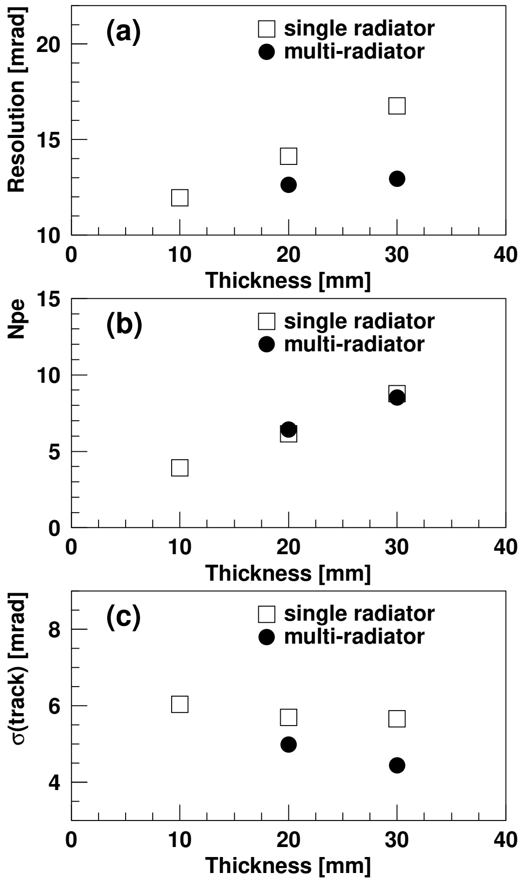


Figure 10. Single photon resolution (a), number of detected photons (b) and single track resolution (c) for the focusing multiple radiator RICH combinations. The multiple radiator with a 20 mm thick radiator is a dual radiator, while that with 30 mm is a triple radiator.

Table 1
Performance of the defocusing combination: single photon angular resolution and photon yield for the multiple radiator and dual radiator combinations.

| RICH | Inner ring | Outer ring |
|---|---|---|
| Dual radiator | $\sigma_\theta = 15.0$ mrad, $N_{\mathrm{p.e.}} = 4.6$ | $\sigma_\theta = 14.6$ mrad, $N_{\mathrm{p.e.}} = 1.7$ |
| Multiple radiator | $\sigma_\theta = 13.7$ mrad, $N_{\mathrm{p.e.}} = 3.8$ | $\sigma_\theta = 13.0$ mrad, $N_{\mathrm{p.e.}} = 2.1$ |

In the defocusing dual radiator RICH, we observed two rings with good angular resolution that were well separated. We also succeeded to improve the resolution of each ring with a RICH with four radiators.

Although the dual and multiple radiator proximity focusing RICH looks promising both in the focusing and defocusing combination, further studies are needed before deciding which of the two combinations should be employed, and how many radiators should be used in the final design for the upgraded Belle detector. The method of reconstruction and the effect of background will be studied in detail, especially for the defocusing combination where two rings are produced.We also plan to test the multiple radiator RICH with even more layers, and investigate the production of multi-layer aerogel tiles with a large transmission length.

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