Studies of Proximity Focusing RICH with aerogel radiator using Flat panel multi-anode PMT (Hamamatsu H8500)

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Abstract

A proximity focusing ring imaging Cherenkov detector using aerogel as the radiator is studied for the upgrade of the Belle detector at KEK-B-factory. We have constructed a Cherenkov counter by using a 4×4 array of 64-channel flat panel multi-anode PMTs (Hamamatsu H8500) with a large effective area and aerogel samples made with a new technique to obtain higher transmission length at a high refractive index ($n = 1.05$). Multi-channel PMT readout is carried out using analog memory chips. The detector was tested at the KEK-PS $\pi 2$ beam line on November, 2002 and various aerogel samples were used to evaluate the detector performance systematically. Typical angular resolution was around 13 mrad, and the average number of detected photoelectrons was around 6. We expect that pions and kaons can be separated with 4σ level at 4 GeV/c.

1 Introduction

Silica aerogel is a unique material with refractive index (n) in the range between gases and a liquids or a solids. Its refractive index can be easily controlled from $n = 1.01$ to 1.06 where Cherenkov photon is emitted for charged pion but not for kaon in a few GeV/c momentum region. So it is widely used for the elementary particle or nuclear experiment as a threshold type Cherenkov detector to separate charged pions and kaons [1]. In the Belle experiment at KEK [2], a threshold type Cherenkov detector (Belle-ACC) [3] which uses aerogel as a radiator is operated, and provide kaon identification efficiency of 88% while suppressing the pion misidentification probability of 8% up to 3.5 GeV/c [4].

A new production method of hydrophobic aerogel with a high transmission length and n in the interval between 1.01 and 1.03 was developed in the construction period of Belle-ACC [5]. Such an improvement in the quality allows the use of aerogel radiator in a ring imaging Cherenkov counter (RICH) [6]. In the HERMES experiment at DESY, a RICH counter is used with a dual-radiator (aerogel and gas), and mirrors to focus the Cherenkov photons [7]. A similar detector is also designed to use for the LHCb experiment at CERN [8].

We are studying the feasibility of a RICH counter with aerogel radiator for an upgrade of Belle-ACC at the forward end-cap region [9]. Since this part is now optimized for pion/kaon separation needed in the tagging for B meson flavor, and covering the momentum range below 2 GeV/c, then separation at high momentum region around 4 GeV/c is not adequate, where the separation of 2 body decays such as $B \to K\pi$ and $\pi\pi$ is desired. In order to achieve a π/K separation for a wider momentum range, a ring imaging type of the detector is needed. Due to spatial restrictions, such a counter has to be the proximity focusing type. To cover the identification in the lower momentum region (around 0.7 GeV/c) as well as in the region up to 4 GeV/c, the aerogel has to have a higher refractive index, $n = 1.05$. The first beam test of such a detector was carried out in 2001 at the KEK-PS $\pi 2$ beam line [10]. These tests used an array of multi-anode PMTs (Hamamatsu R5900-M16) for photo-detection. The detected number of photoelectrons was 2.7 per ring for 2 cm thick aerogel tile with $n = 1.05$, and the Cherenkov angle resolution per photon was 10 mrad. These results were consistent with expectations. The number of detected photons was, however, rather low, partly because only 36% of the detector surface was covered by the photo-cathodes, and partly because the transmission length of the aerogel with $n = 1.05$ could not be made large enough. For the second beam test we have improved the aerogel transmission by optimizing the materials used in the production process. The active area fraction of the photon detector was increased by employing the recently developed flat panel PMTs Hamamatsu H8500. Although this type of PMT is not immune to magnetic field, and therefore cannot be applied in the Belle spectrometer, we consider this device as an intermediate step in our development. The paper is organized as follows. We first present the experimental set-up with flat panel PMTs, briefly review the improvement in aerogel production, describe the measurements, and finally discuss the results.

2 The experiment set-up

2.1 Flat panel PMT

This time, we introduced 64 channel multi-anode PMT (Hamamatsu H8500) for photo-detection because of their large effective area. 16 PMTs were used with a 4×4 array and aligned with 52.5 mm pitch as shown in Fig.1. The surface of each PMT is divided into 64 (8×8) channels with 6.0 mm $\times$ 6.0 mm pixel size. Therefore, the effective area of the photon detection is increased to 84%. At the back of each PMT, analog memory board is attached to read out multi-channel PMT signal as described later. Among 16 PMTs, 8 PMTs were delivered in January, 2002, and remaining PMTs were delivered in October, 2002. Since the manufac-

ture method of the PMT was still under developing, the tubes experience a large variation in quantum efficiency and gain. The quantum efficiency at 400 nm varies between 16% and 25%; the tube gain varies from $1 \cdot 10^6$ to $6 \cdot 10^6$ when the maximal allowed high voltage of -1100 V is applied to the photo-cathode [12]. The PMTs from the later batch show a slightly better performance.

2.2 Aerogel radiator

The hydrophobic aerogel with low refractive index ($n = 1.01 \sim 1.03$) as developed for the Belle-ACC, is characterized by a high transmission length ($\sim$40 mm at a wave length of 400 nm) which was not achieved before. However, the transmission length of aerogel with a higher refractive index, $n = 1.05$ fell to below a half compared with that of $n = 1.03$. Keeping in mind that for a collider experiment a hydrophobic aerogel is preffered to a hydrophilic one, we reexamined the production technique of aerogel by a joint development with Matsushita Electric Works Ltd.

As a result, we found that the important factors to determine the transmission length are the solvent and the selection of precursor to be used for its production. Originally, we used the methyl-alcohol for the solvent, and methyl-silicate as a precursor [5]. When we applied di-methyl-formamide (DMF) [11], and changed the supplier of the precursor, we could improve the transmission length of the aerogel.

Fig. 2 shows the refractive indices of aerogel and the relation to transmission length which were used in this beam test. The refractive index was determined by measuring the deflection angle of laser light (He-Ne: 632.8 nm) at a corner of each aerogel tile; the transmission length are measured by a photo-spectrometer (Hitachi U-3210). In addition to the samples produced with the new technique at Matsushita Electric Works Ltd. and Chiba university, samples from BINP (Novosibirsk) were tested [13]; for comparison, we also tested the samples used in the previous beam test. The thickness of prepared aerogel sample ranges from 10 mm to 25 mm. Various thickness up to 50 mm were tested by stacking these samples. Note that in the production of the aerogel samples at BINP propenol is used as the solvent, and the resulting aerogel is hydrophilic. Note also that the Matsushita aerogel samples produced with the new technique have a very similar attenuation length as the BINP samples. Also original method is tried for Matsushita and Chiba University. The transmission length for $n\sim1.05$ samples used in the first beam test was around 15 mm, but this was increased to 45 mm for Matsushita's sample with new production method.

2.3 Beam set-up

For the beam test pions with momenta between 0.5 GeV/c and 4 GeV/c were used. Beside the RICH detector under study, counters for triggering, tracking and particle identification were employed.

The set up of the aerogel RICH is shown in Fig. 3. Two RICH counters were placed in a light shield box and tested simultaneously. Each RICH is composed of a layer of aerogel radiator and a photo-detection plane, parallel to the radiator face at a distance of 20 cm. The upstream Cherenkov counter is the detector under study; the downstream counter was employed in the previous beam test. Since the latter uses a well known photo-detector, multianode PMTs Hamamatsu R5900, we regard it as a reference.

The particle identification was done to remove other particles than pions. Two CO_2 gas Cherenkov counters were equipped in the beam line to exclude electrons. Also an aerogel counter was equipped and used to exclude protons for the high momentum region. This detector was also used to exclude muons for the low momentum region around 0.5 GeV/c.

The particle trajectories were measured with multiwire proportional chambers (MWPC) attached in both the upstream and downstream ends of the light shield box. These 5×5 cm^2 MWPCs, with 20 μm diameter, gold-plated tungsten anode wires at 2 mm pitch and with 90% Ar + 10% CH_4 gas flow, are read out by delay lines on the x and y cathode strips.

The trigger signal was generated as the coincidence of signals from several 5×5 cm^2 plastic scintillation counters and anode signals of the MWPCs for a valid tracking information.

2.4 Readout electronics

For the beam test a new read-out system was designed by using analog memory chips. The analog memory chip is based on a chip developed by H. Ikeda [14] for a cosmic ray experiment. We have borrowed the chips from NASDA [15], and developed the chip control system. In the analog memory chip signals of 32 channels are preamplified, sampled in 1 μs intervals, and stored in a 8 steps deep analog pipeline. Fig. 4 shows a schematic view of the readout system with this analog memories. Two analog memories are attached to each 64 channel PMT, and are controlled by the analog memory controller for every 4 PMTs (256 channels). When the gate pulse is inputted from the trigger signal, a control signal will be sent to every 4 PMTs from the controller, and the difference of the value in the analog memory between the latest and the first train is fed to the output. Then the obtained output values in each channel are summarized by 256 channels as a serial signal with $10\mu s$ time period per channel. Thus, the signal of 1024 channels is converted into a serial signal of 4 channels. The analog memory controller output this serial signal and synchronized control signals, then these signal are read by 12 bit VME ADC (DSP8112, MTT Co.) with fast conversion time, $5\mu s$.

2.5 Reference RICH

The reference RICH was instrumented with multi-anode PMTs, Hamamatsu R5900-M16, the same photon detector as in the previous test [10]. The quantum efficiency of the PMTs is around 26% (at 400 nm), and the gain was around $6 \cdot 10^6$ when -960 V was applied to the

photo-cathode. The PMTs were grouped in a 2×6 array at 30 mm pitch. Due to a limited number of available PMTs and read-out channels, only a part of the Cherenkov ring was covered with photon detectors.

3 Measurement and results

The data taking was done mostly using π^- beam at 3 GeV/c. To evaluate the detector performance systematically, we take the data for different samples of aerogel with various transmission length and thickness. Also the data was taken by changing the π^- momentum from 0.5 to 4.0 GeV/c.

Most of the test measurements were performed with a π^- beam at 3 GeV/c. To systematically evaluate the detector performance, data were taken with different aerogel samples with various transmission length and thickness. Data were also taken by varying the π^- momentum in the range from 0.5 GeV/c to 4.0 GeV/c.

A few typical events are displayed in Fig. 6. The hits on PMTs can be associated with the expected position of the Cherenkov ring. The hit close to the center of the ring is due to the Cherenkov radiation generated by the beam particle in the PMT window. The distribution of accumulated hits is shown in Fig. 7. Cherenkov photons from aerogel radiator are clearly seen using flat panel PMT with a low background level. The background events seen on the whole surface of the detector is considered as Rayleigh scattering photons when they transverse the radiator.

The pulse height distribution of the Cherenkov photons detected in flat panel PMT is shown in Fig. 5. The raw data were corrected as follows. A common-mode base line was subtracted and signals due to cross-talk stemming from the read-out electronics were removed. We also applied the threshold cut to suppress the pedestal noise contribution. In Fig. 5, signal mainly containing one photoelectron is clearly separated from pedestal peak. However, please note that the situation is much different for each PMT because there exists large variation of the performance as described before.

3.1 Cherenkov angle resolution for single photon

Fig. 8(a) shows the typical distribution of Cherenkov angle distribution for single photon. The angular resolution was obtained from a fit of this distribution with a Gaussian signal plus and linear function for the background. Fig. 9 shows the resolution in the Cherenkov angle for the π^- beam at 3 GeV/c and 20 mm thick aerogel samples. The resolution was around 13 mrad independent on the refractive index. The main contributions to the resolution of Cherenkov angle come from uncertainty in the emission point and from pixel size of the PMT. The first contribution is estimated as $\sigma_{emp} = d \sin\theta_c \cos\theta_c / L\sqrt{12}$, where d is the aerogel thickness, θ_c is

Cherenkov angle and L is the distance from the aerogel to the surface of the PMT. The second contribution is $\sigma_{pix} = a\cos^2\theta_c/L\sqrt{12}$, where a is the pixel size. The measured variation of the resolution with the thickness of aerogel is shown in Fig. 10 together with expectations. For the radiator thickness d an effective value was calculated by taking into account the influence of Rayleigh scattering. By comparing the measured resolution and the expected values we observe a rather good agreement. There is, however, a discrepancy between the two which can be accounted for by a contribution of about 6 mrad. The discrepancy could arise from the effect of aerogel (non-flat aerogel surface and possible non-uniformities in refractive index due to position variation and chromatic dispersion) which are subject to further investigation. The uncertainty in the track direction is expected to be negligible at 3 GeV/c, but increases considerably at low momenta (0.5 GeV/c) due to the effect of multiple-scattering as seen in Fig. 11.

3.2 Photoelectron yield

Fig. 8(b) shows the typical distribution of number of hits distribution within $\pm 3\sigma$ from the Cherenkov angle peak. Number of hits for signal was estimated by subtracting the background from the fits to the Cherenkov angle distribution. The number of detected photons (N_{pe}) depends on the aerogel thickness and the effect of scattering. It is expressed as $N_{pe} = C\int_0^d\int \epsilon(\lambda)\lambda^{-2}\sin^2\theta_c e^{-\frac{x}{\Lambda(\lambda)\cos\theta_c}}d\lambda dx \approx C'\sin^2\theta_c\Lambda\cos\theta_c(1-e^{-\frac{d}{\Lambda\cos\theta_c}})$, where Λ is the transmission length of aerogel at wave length 400 nm [1] and $\epsilon(\lambda)$ is wavelength dependent photon efficiency at the surface of the PMT window and the photo-cathode. Fig. 12 shows the dependence of number of detected photons with aerogel thickness. As expected from the above expression, the number of photons does not linearly increased with the aerogel thickness, but saturates due to the scattering effect in aerogel. Fig. 13 shows the dependence of number of photons with transmission length. From the figure the benefit of the improvement in the transmission length of the $n = 1.05$ aerogel from around 15 mm, as used in the previous beam test, to 45 mm using the new production technique becomes evident. The dependence on pion momentum, displayed in Fig. 14, is fitted with the form expected from the Cherenkov relations, and shows a good agreement. For pions with momenta above 1 GeV/c, the number of detected Cherenkov photons was typically around 6 for aerogel samples with $n = 1.05$.

The performance of the RICH counter under study was in the same set-up compared with the performance of the reference counter with a well known photon detector, Hamamatsu R6900-M16 multi-anode PMTs. Since the two counters have a different active area fraction (80% for the flat panel PMTs, and 36% for the R5900-M16 PMTs at 30 mm pitch) and a different acceptance, the comparison of the photon yields was made by normalizing to the full active surface. While the flat panel yield for a particular case was 6.3, which results in 7.9 if extrapolated to the full active area, the corresponding number for the R5900-M16 is

[1] The transmission length is measured by a photo-spectrometer. However this measurement is affected by Rayleigh scattering photons due to finite acceptance of the photo-spectrometer, therefore the correction is applied to the value.

11.5. It appears that this difference is mainly due to the rather low amplification of some of the flat panel tubes employed. This, in turn, causes inefficiencies in single photon detection with a given threshold. If the best tube in the set is normalized to the full acceptance, the corresponding number increases to 11, and gets roughly consistent with the yield from the R5900-M16 PMTs. It is therfore expected that an even better separation between kaons and pions will be possible with improved PMTs.

3.3 Particle Identification

Finally, we estimate the performance of pion/kaon separation in the momentum range around 4 GeV/c, which is of considerable importance for the Belle experiment. If we take into account a typical measured value for the single photon angular resolution, σ_c $\sim$13 mrad, and the number of detected photons $N_{pe} \sim 6$, typical for 20 mm thick aerogel samples with $n = 1.05$, we can estimate the Cherenkov angle resolution per track to be $\sigma_c/\sqrt{N_{pe}}$ =5.3 mrad. This naive estimate is also confirmed by the direct measurement shown in Fig. 15. From this we can deduce that the at 4 GeV/c, where the difference of Cherenkov angles for pions and kaonsis 23 mrad, a 4σ separation between the two is possible. As an additional cross check we have also collected data with the pion beam of 1.1 GeV/c, which can be used to represent the kaon beam of 4 GeV/c (apart from a slightly larger sigma due to multiple scattering). As can be seen from Fig. 15, the two peaks are well separated. Thus, the proximity focusing aerogel RICH seems to be promising for the upgrade of the Belle PID system at the forward region.

4 Conclusions

We report the test beam results of proximity focusing RICH using aerogel as a radiator. To obtain larger photoelectron yields, we used flat panel multi-anode PMT with a large effective area and a recently developed aerogel samples which have higher transmission length than before. We also developed a multi-channel PMT read-out system using analog memory chips. A clear Cherenkov ring from aerogel radiator could be observed, and the number of photons was enhanced compared to previous tests. We have performed a systematic study of the detector using various sample of the aerogel. Typical angular resolution was around 13 mrad and detected number of the photoelectron was around 6. The pion/kaon separation at 4 GeV/c is expected to be around 4σ.

However, we still have some issues which have to be solved for the implementation in the Belle spectrometer. The most important item is the development of the PMT which can be operated under the strong magnetic field (1.5T). An example of such a candidate for such a device is multi-anode H(A)PD. Of course, for a good candidate its ability to detected efficiently single photons on a large active area has to be demonstrated. The other item is the mass production of the aerogel sample. While we have demonstrated that the new production method increases significantly the transmission length of the $n = 1.05$ aerogel, the production method has to

be adapted to stable good quality manufacturing. We will study these items at the next stage towards the real detector construction for the upgrade of the Belle detector.

5 Acknowledgment

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[15] We are grateful to Dr. T.Goka of NASDA for providing us their chips.

Figure Captions:

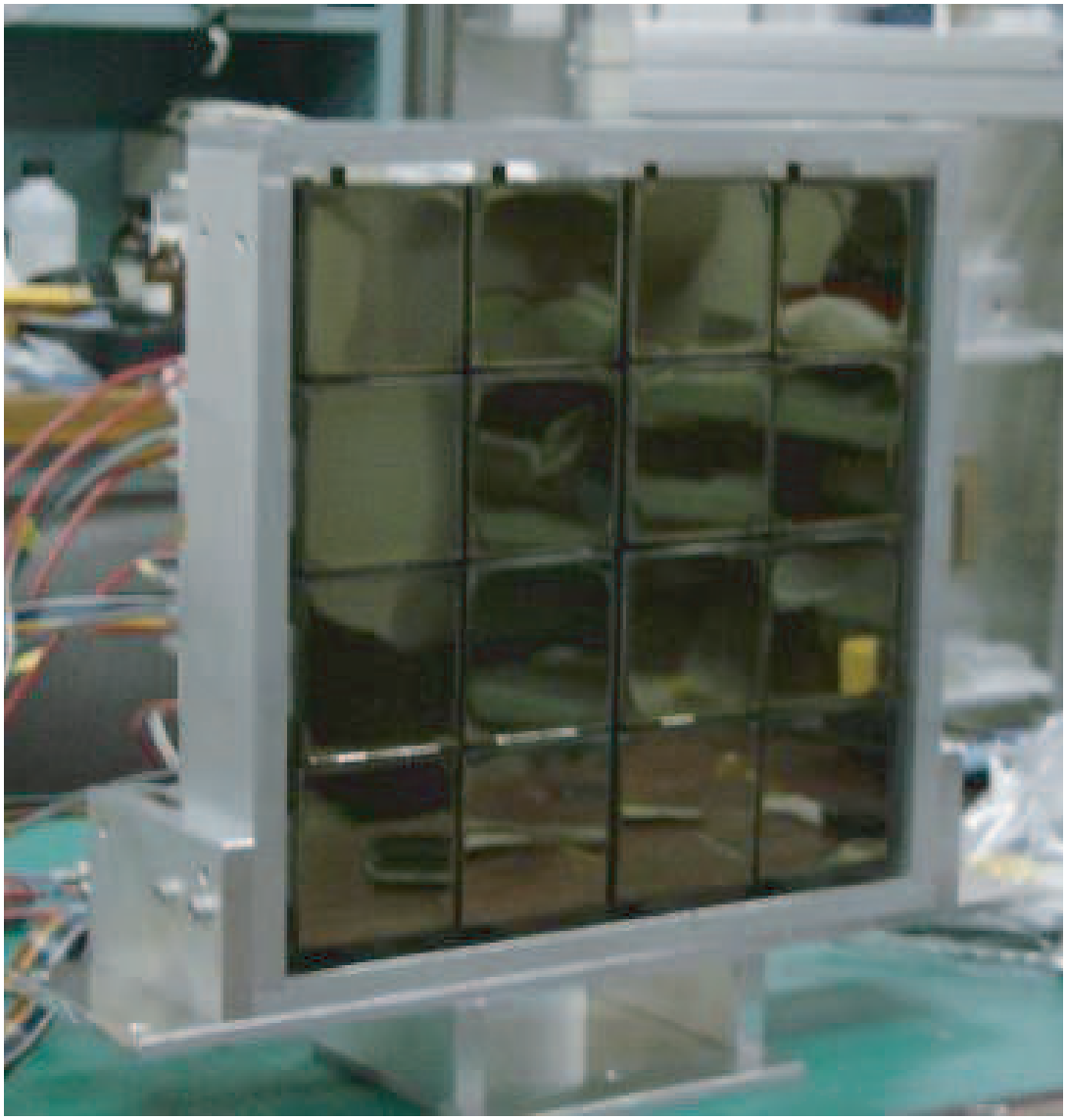

Fig. 1. Photon detector, an array of 16 H8500 PMTs, mounted at a 52.5 mm pitch.

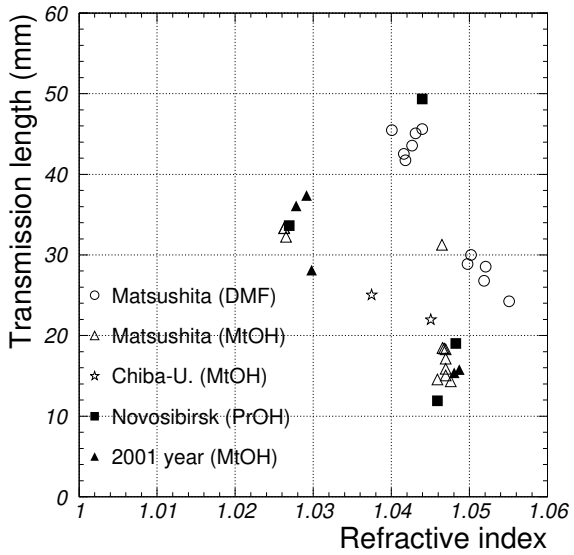

Fig. 2. Transmission length at 400 nm and refractive index for the aerogel samples used in the test.

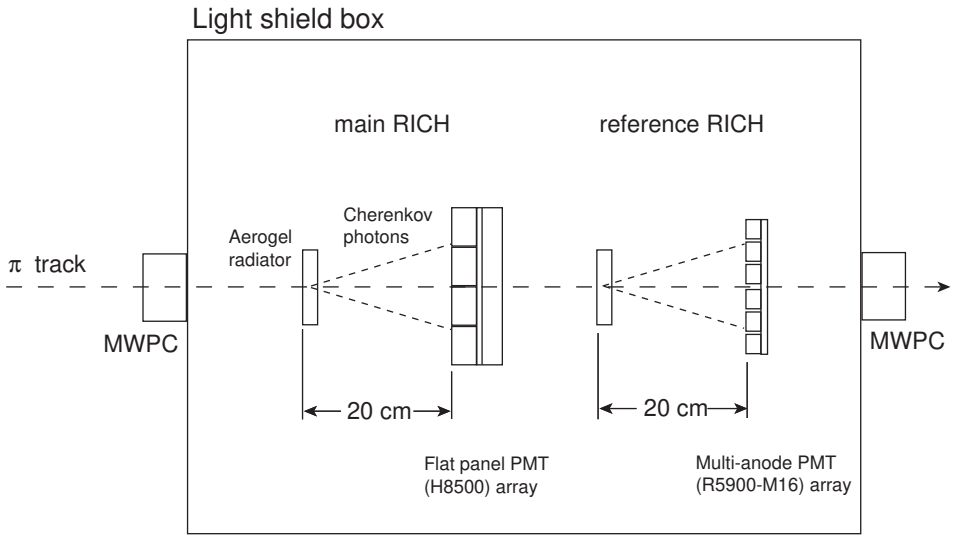

Fig. 3. The experimental set-up

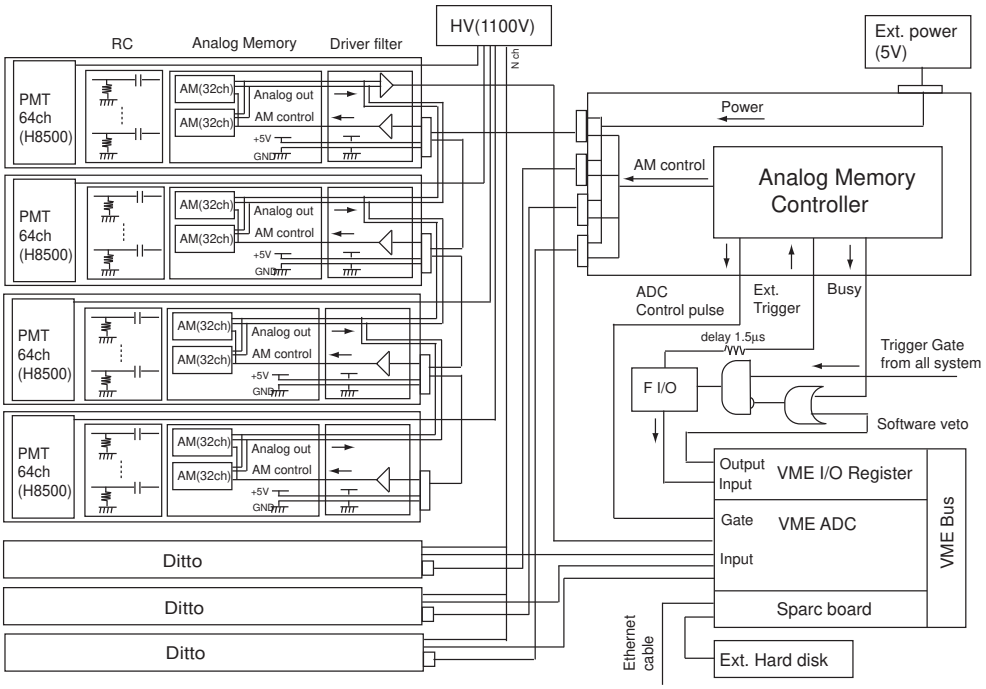

Fig. 4. Schematics of the read-out system for the flat panel PMTs.

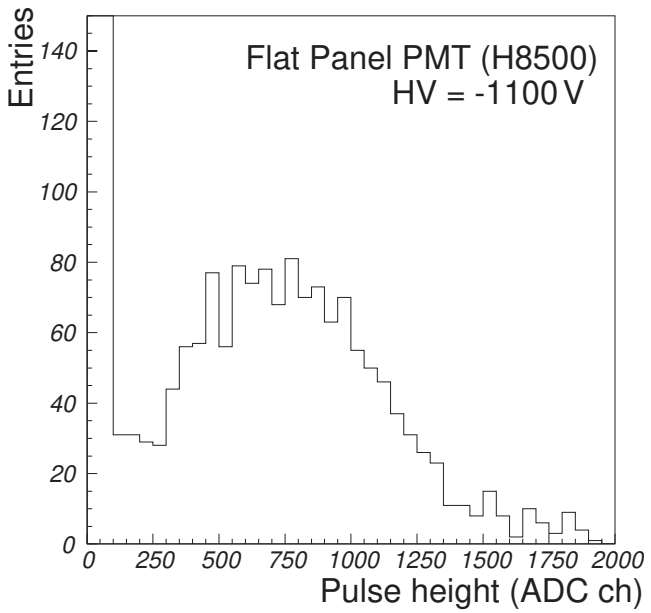

Fig. 5. Pulse height distribution for the flat panel PMT (H8500) for the region within 3σ of the Cherenkov peak. Data was corrected with the procedure described in the text. In this figure, the pulse height distribution for the best PMT was shown.

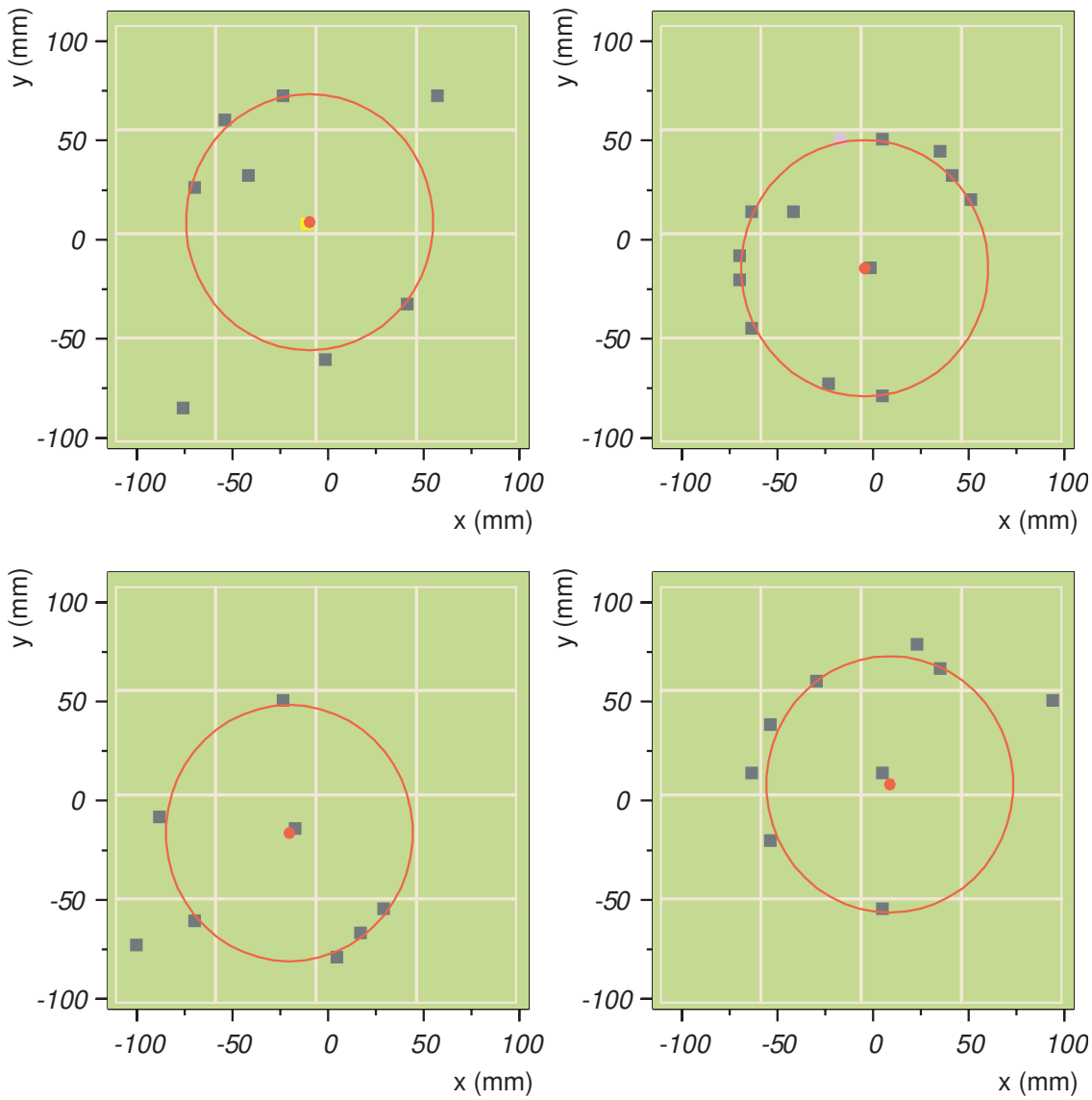

Fig. 6. Some examples of event hit patterns for 3 GeV/c pions. The circle corresponds to the Cherenkov ring as expected from the measured beam position. The dot corresponds to the impact point of the track upon the PMT window.

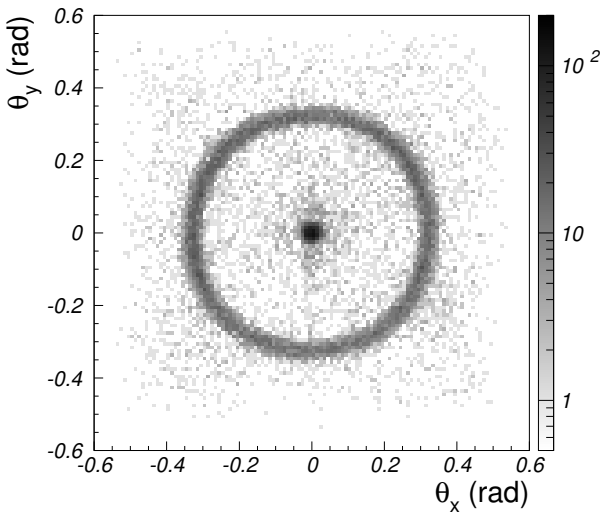

Fig. 7. Distribution of PMT hits in the Cherenkov x, y space for the 3 GeV/c pion beam.

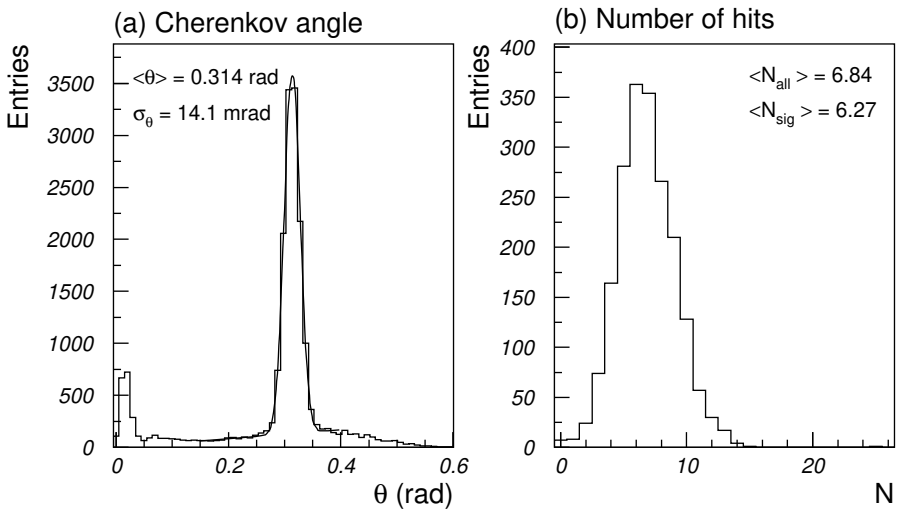

Fig. 8. Distribution over the Cherenkov angle for single photons (a), and the number of detected photons per ring (b), both for a 20 mm thick aerogel radiator sample with $n = 1.05$ and a transmission length of 30 mm.

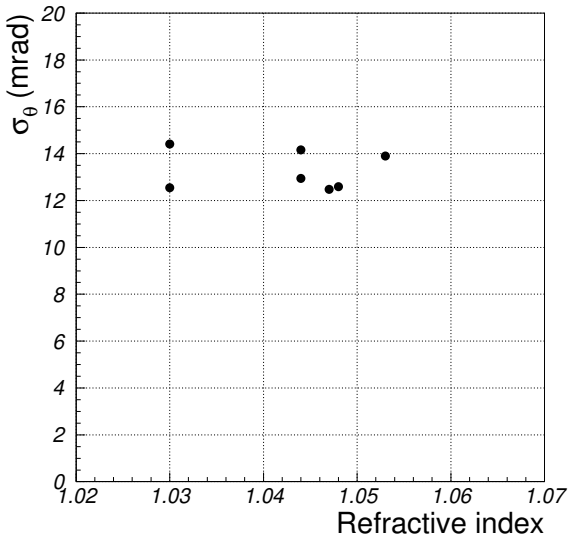

Fig. 9. Typical angular resolution for 20 mm thickness aerogel samples.

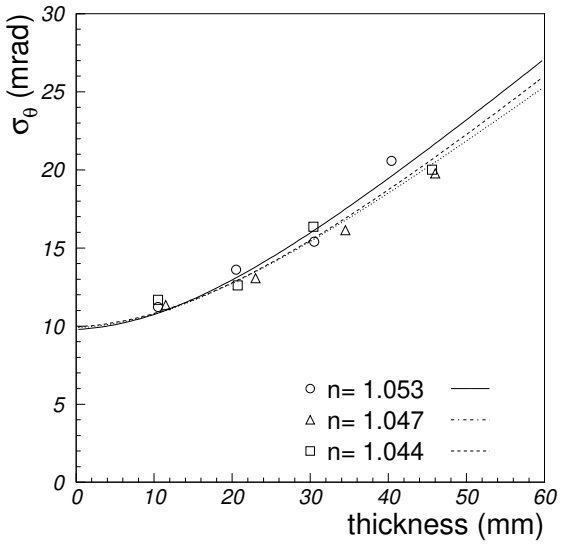

Fig. 10. Angular resolution as a function of the aerogel thickness. The symbols corresponds to the data for the different samples and the c urves are fits to data with function described in the text.

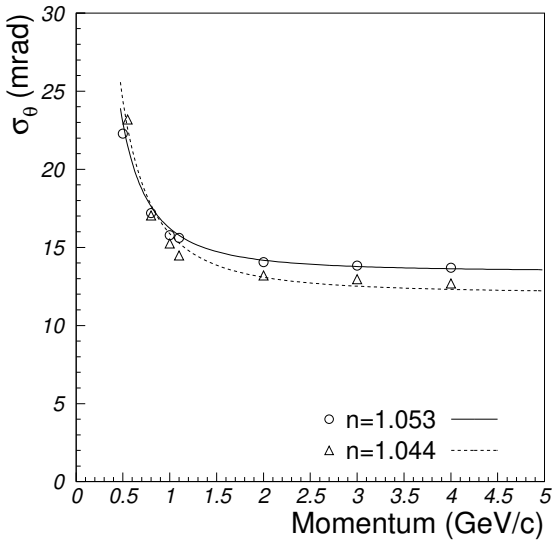

Fig. 11. Angular resolution as a function of the charged particle momentum for two different samples. The symbols corresponds to the data and the curves are fits including the effect of multiple-scattering.

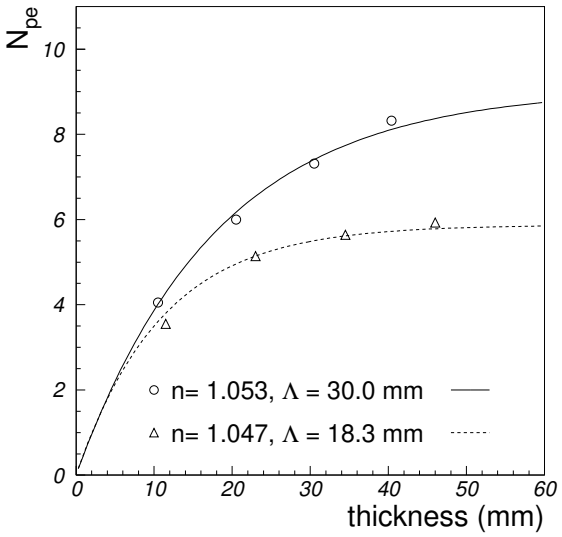

Fig. 12. Number of detected photons per Cherenkov ring as a function of the aerogel thickness. The symbols corresponds to the data and the curves are fits described in the text.

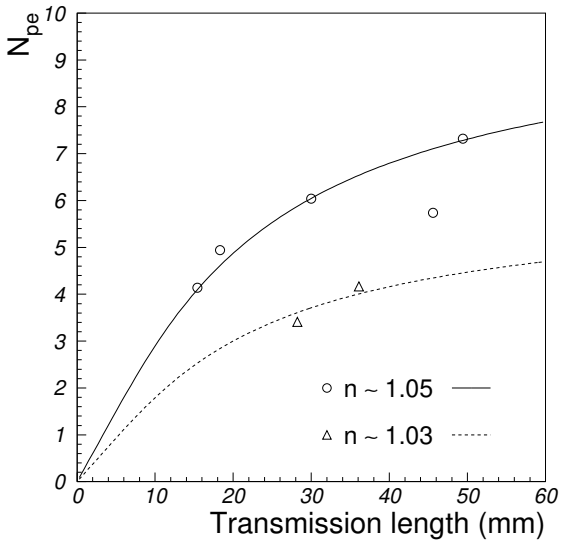

Fig. 13. Number of detected photons per Cherenkov ring for 20 mm thickness aerogel samples as a function of the transmission length. The symbols corresponds to the data and the curves are fits described in the text.

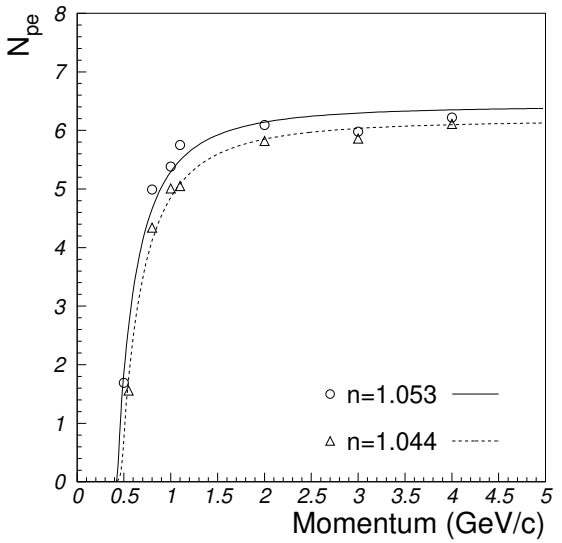

Fig. 14. Number of detected photons per Cherenkov ring as a function of the charged particle momentum. The symbols corresponds to the data and the curves are fits described in the text.

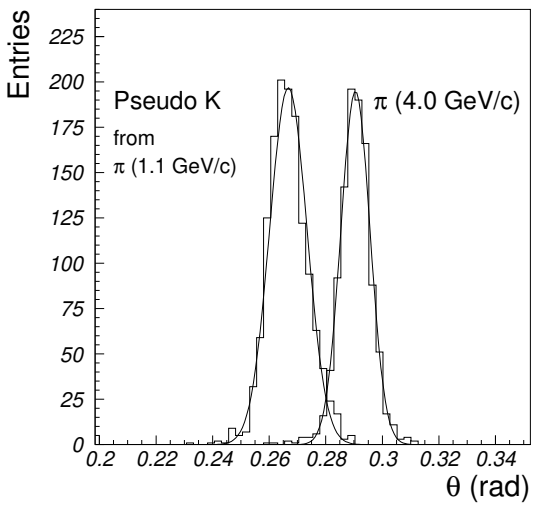

Fig. 15. Cherenkov angle per track for pions of 1.1 and 4.0 GeV/c. Pions at 1.1 GeV/c are used to represent the kaon beam of 4 GeV/c. Angular resolution for pions and kaons are 5.2 mrad and 6.6 mrad and two peaks are separated by 4σ.