Cherenkov Detector with a Focusing Aerogel Radiator

A.Yu. Barnyakov, M.Yu. Barnyakov, V.S. Bobrovnikov, A.R. Buzykaev, S.A. Kononov, E.A. Kravchenko*, A.P. Onuchin, V.V. Porosev
Budker Institute of Nuclear Physics, Novosibirsk, Russia
A.F. Danilyuk, V.L. Kirillov
Boreskov Institute of Catalysis, Novosibirsk, Russia
T. Fukushima, A. Kuratani
Dept. of Physics, Chiba Univ., Chiba, Japan
I. Adachi, S. Nishida, Y. Unno
IPNS, KEK, Tsukuba, Japan
K. Fujita, D. Hayashi, T. Iijima, Y. Kozakai, Y. Mazuka
Dept. of Physics, Nagoya Univ., Nagoya, Japan
M. Iwabuchi
Dept. of Physics, Toho Univ., Funabashi, Japan
T. Nakagawa, T. Seki, T. Sumiyoshi
Dept. of Physics, Tokyo Metropolitan Univ., Tokyo, Japan
A. Gorišek, S. Korpar, R. Pestotnik
J.Stefan Institute, Ljubljana, Slovenia
P. Križan
Faculty of Mathematics and Physics, Univ. of Ljubljana, Ljubljana, Slovenia

In the proximity focusing RICH one of the main factors determining precision of ring radius measurements is the finite thickness of radiator. A Focusing Aerogel RICH (FARICH) counter gives the possibility to reduce this effect by means of using of multilayer aerogel.
The technique for multilayer aerogels production (SAN–MULTI) has been developed. A few samples consisting of four and two aerogel layers have been produced.
GEANT4 simulation program has been developed. It was shown that velocity resolution of $5 \cdot 10^{-4}$ is achievable. This permits us to have π/K separation at the level more than 3σ up to momentum 8.0 GeV/c and π/μ separation up to momentum 1.6 GeV/c. The technical requirements on on the thickness spread of the individual layers and on the accuracy of refractive indices in the layers have been worked out.
A novel method to measure refractive index variations by means of digital X-ray detector was suggested and tested.

1. Introduction

In aerogel RICH detectors with proximity focusing the finite thickness of a radiator is one of the decisive factors determining precision of particle velocity measurement, especially when the distance between radiator and photodetector plane is small. This is the case of detectors built for colliding beams experiments. In 2004–2005 the first publications of two groups devoted to the development of RICH detectors based on multilayered aerogel have appeared. These are the publications [1–4] of physicists from Belle detector (KEK,Japan) and publication [6] of physicists from Novosibirsk (Russia) working on the BaBar detector(SLAC, USA).

It was suggested to use a stack of two aerogel tiles with different indices of refraction as a radiator. The idea is to reduce the width of ring (rings) of Cherenkov cone image on photons detection plane. Two options have been considered:

- **Single ring.** Refraction index and thickness of each layer are adjusted in such a way that Cherenkov rings from different layers are superimposed on each other.
- **Multi–ring.** Refraction index and thickness of each layer are adjusted so that ring images from different layers have different radii and are clearly separated from each other.

The next step in the development of this technique was done when first samples of monolithic aerogel tiles with layers having different indices of refraction were produced[4, 6].

2. Monte Carlo simulation

GEANT4 simulation program has been developed to describe a FARICH detector. The model has further assumptions:

- Pixel size of the photodetector is smaller than the coordinate spread due to chromaticity and can be neglected.

*Corresponding author, E-mail: E.A.Kravchenko@inp.nsk.su

- Dispersion of aerogel index of refraction was obtained from wavelength dependence of quartz index scaling it in accordance with aerogel density.
- No scattering on aerogel–air boundary.
- Photons that had undergone Rayleigh scattering and Fresnel reflection were discarded assuming they can be efficiently suppressed by a reconstruction procedure.

The geometry of the model is far from optimum and could be considered as an example. Distance from aerogel entrance surface to photodetector window was 100 mm. The light scattering length in aerogel was assumed equal to 40 mm at 400 nm. The PMT detector parameters were taken as for Burle 85011 microchannel plate PMT[5]: the photon detector had borosilicate window with bialkali photocathode with maximum quantum efficiency of 24%, both photoelectron collection efficiency and active area fraction are accounted for by total efficiency factor of 50%.

In the Monte Carlo studies β was calculated using radius position of a detected photon. The β-vs-radius dependance was calibrated with a preliminary set of simulation runs. In case of multi-ring radiator this dependence was calibrated for each ring. Also boundaries between rings were determined to choose a corresponding β-vs-radius dependence. During simulation measured values of β for each photon were averaged with weights corresponding to photon's ring to obtain a track's measurement of β.

The simulation was performed for 4 different aerogel radiators: single layer aerogel (n = 1.07) with tile thicknesses 12 mm and 24 mm, 6-layered single ring radiator, and 3-layered 3 rings radiator (Tab. I). More information about simulation could be found at [6].

Table I Thickness of layers and index of refraction for 6-layered and 3-layered radiators.

Option	**Layer**	h, **mm**	**n**
6-layered single ring	1	4.0	1.070
	2	4.2	1.064
	3	4.4	1.059
	4	4.6	1.054
	5	4.8	1.050
	6	5.0	1.046
3-layered 3 rings	1	10.0	1.070
	2	10.0	1.037
	3	10.0	1.070

The β resolution for track vs $\beta\gamma$ is presented in Figure 1 for normal beam incidence , and in Figure 2 for 30° particle dip angle. Single layer, 24 mm thickness aerogel tile shows the worst resolution. The resolution with 12 mm thickness aerogel is better, but in this case number of photoelectrons is significantly lower. This can be critical for detectors with high background. 3-layered 3 rings radiator has good resolution in wide momentum range. The best resolution in high momentum region we have got for 6-layered single ring radiator. Degradation of resolution at low momentum for this radiator is caused by defocusing effect – the rings from different aerogel layers do not coincide any more.

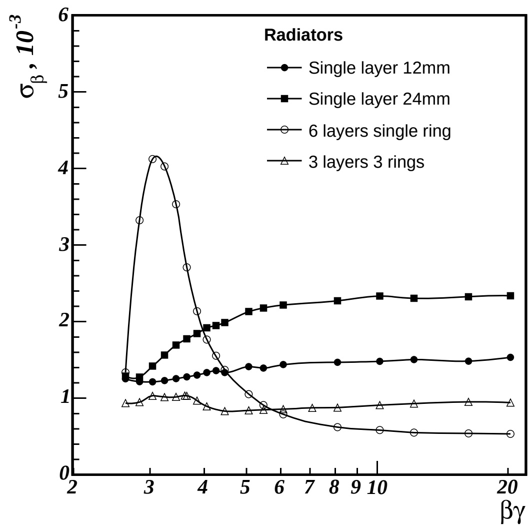

Figure 1: β resolution for track vs $\beta\gamma$. Normal particle incidence.

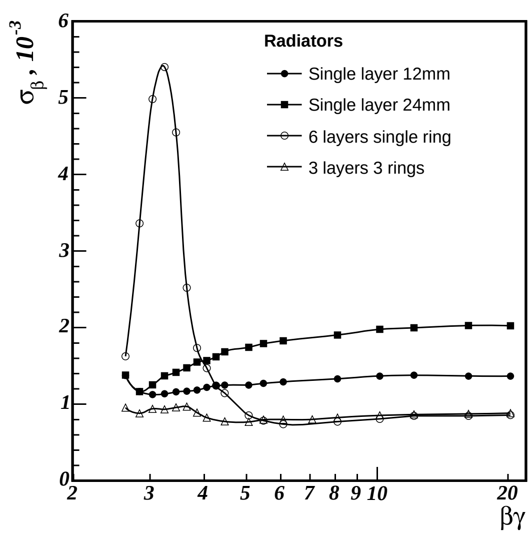

Figure 2: β resolution for track vs $\beta\gamma$, 30° particle dip angle.

6-layered single ring radiator would allow us to separate pions and kaons at the level $\geq 3\sigma$ up to 8.5 GeV/c momentum. The pion/kaon separation for 30° particle dip angle will be up to 6.5 GeV/c momentum. In this case the focusing condition for 6-layered radiator gets worse and π/K separation for 6-layered and 3-layered radiators becomes almost identical in high momentum region. For single layer and 3-layered options separation does not depend much on particle angle.

The additional potential of the system would be to separate pions and muons up to 1.6 GeV/c momentum where other particle identification methods are not working (Fig. 3).

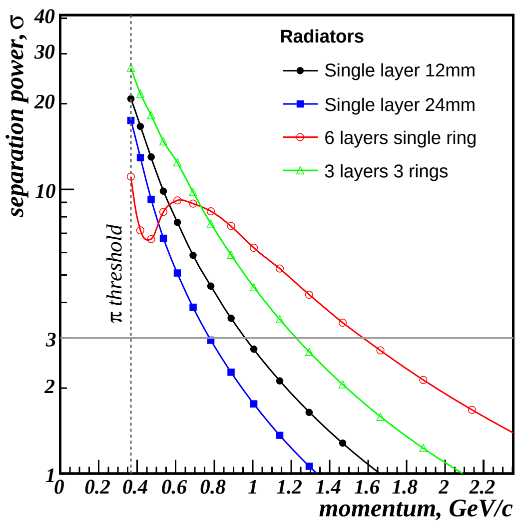

Figure 3: μ/π separation vs $\beta\gamma$. Normal incidence.

3. Requirements on aerogel refractive index

With the help of Monte Carlo code we have investigated technical requirements on multilayred aerogel. In this work we present results for the 6–layered single ring radiator. This is the most complex case. Technical requirements for the multi ring option are much simpler.

To develop criteria on the accuracy of index of refraction we varied indices of layers by two methods:

- "correlated" — all layers change their refractive indices proportionally;
- "anti-correlated" — odd membered layers increase their refractive indices, even membered layers decrease.

In the Figure 4 the dependence of the resolution from the change in the refractive index of the layers is presented. The change in the refractive index is expressed in the units of $\Delta(\mathrm{n}-1)/(\mathrm{n}-1)$ because this is almost equal to the relative change in aerogel density.

One can see that "correlated" change of the refractive indices in the layers does not affect the resolution. The "anti-correlated" case is more complicated. The $\pm 2\%$ distortion off the optimal index in the layers will cause 20% deterioration of the resolution.

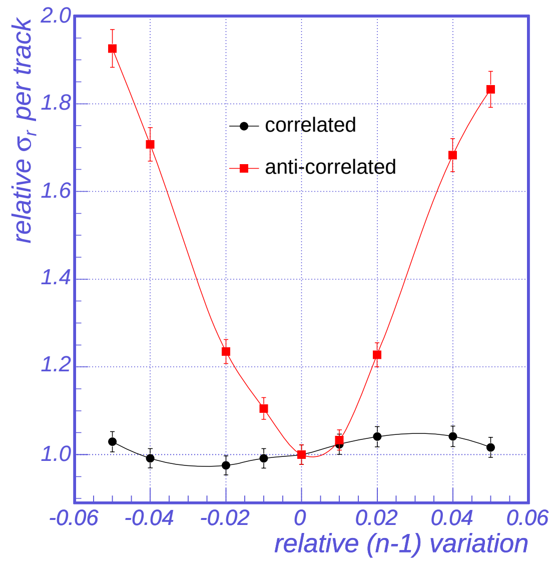

Figure 4: The dependence of the resolution vs the variation of the refractive index of the layers.

The criteria on the accuracy of the thickness of the layers have been developed. We also examined two cases – "correlated" and "anti-correlated". In the Figure 5 the dependence of the resolution from the change in the thicknesses of the layers is presented. In this case the "correlated" change of the thicknesses of the layers will cause larger deterioration of the resolution than the "anti-correlated" change. Nevertheless, the dependence of the resolution from this parameter is rather weak. 10% discrepancy between real and optimal thicknesses will cause 20% deterioration of the resolution.

4. Measurement of refractive index variations

The variations of the refractive index within aerogel block is the important factor which influence performance of RICH detectors.

Basically, such variations could be described as transverse and longitudinal.

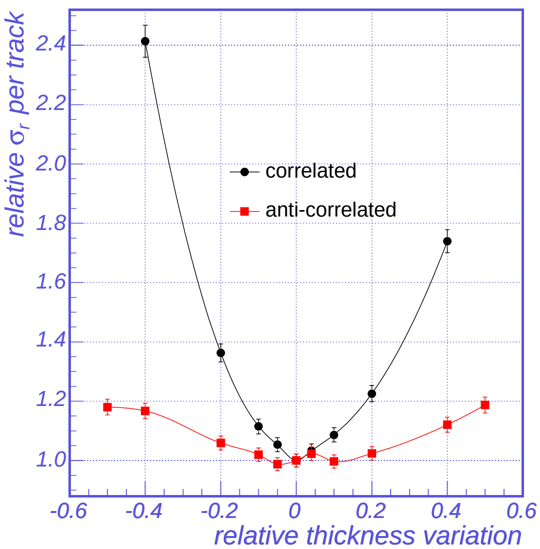

Figure 5: The dependence of the resolution from the change in the thickness of the layers.

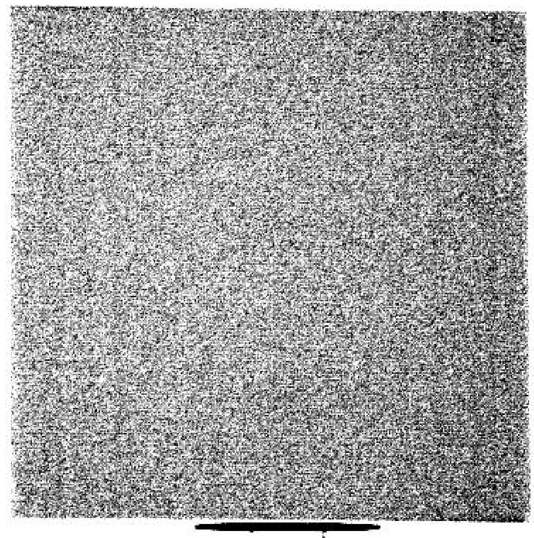

Figure 6: The X-ray image of aerogel block, top view. Darker area represents larger amount of material.

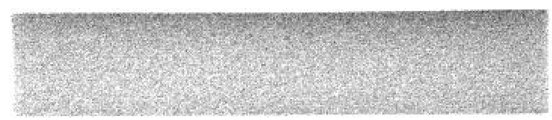

Figure 7: The X-ray image of aerogel block, side view.

The transverse variation of the refractive index in different points on aerogel block will result in different measured Cherenkov angles. Such variations could be measured by optical methods [7] or calibrated with particles.

The longitudinal variation of the refractive index (variations in the depth of aerogel block) will cause direct deterioration of detector resolution. The optical methods are rather complicated in this case[7].

In this work we suggest the new method to measure the refractive index variations within the volume of aerogel block, both transverse and longitudinal.

The are two possible origins of refractive index variations in aerogel: density variations and variations of the impurities. For hygroscopic aerogel produced in Novosibirsk the main impurity is the absorbed water. The amount of water in aerogel is on the level of few percent. So it can not cause noticeable variations of the refractive index. Density variations directly cause refractive index variations. The dependence of refractive index over density of aerogel (ρ) is known: $\mathrm{n} = \sqrt{1 + 0.438 \cdot \rho}$ [8].

To measure the variation we suggest to use digital X-ray detector. Several photographs have been done with aerogel block, n=1.05, $123 \times 123 \times 25\mathrm{mm}^3$. The photographs are presented in the Figures 6 and 7. The images were taken by low noise digital X-ray detector developed in Budker Institute of Nuclear Physics, pixel size 0.4 mm[9].

On the images one can see the distribution of amount of material. To find the density distribution several corrections need to be applied: background subtraction, geometry corrections, thickness corrections. On the Figure 8 the density variation along horizontal line in the middle of the block (Fig. 6) is presented. The slope in aerogel density is observed, $(\rho_{max} - \rho_{min})\rho_{mean} = 1.8\%$. Such density variation corresponds to refractive index variation $\Delta\mathrm{n} = \pm 0.00044$.

On the Figure 9 the density variation along vertical line in the middle of the block (Fig. 7) is presented. The variation in aerogel density is observed with minimum at the depth of 18 mm, $(\rho_{max} - \rho_{min})\rho_{mean} = 3.0\%$. Such density variation corresponds to refractive index variation $\Delta\mathrm{n} = \pm 0.0015$.

The observation of longitudinal variation is a new result. Currently we investigate possible origins of such effect and looking what factors during production could effect the scale of this variation.

5. Test beam measurements

Several samples of multilayered aerogel produced in Novosibirsk have been tested with the beam at KEK. The test beam setup is described in [10].

Three samples have been tested: 2-layer, 4-layer, single block with continuous refractive index variation. The index of refraction in the layers was mea-

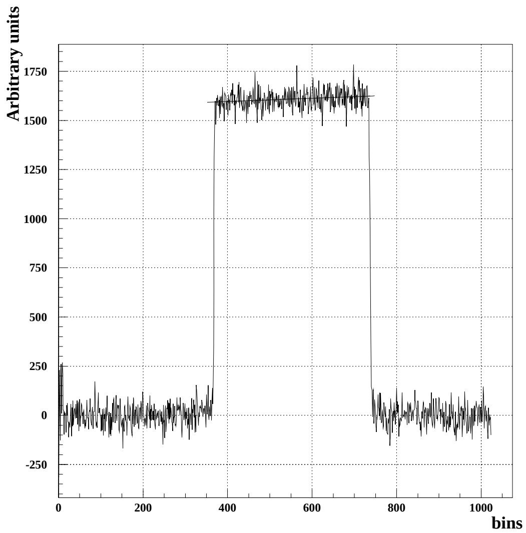

Figure 8: The transverse density variation in the middle of the block.

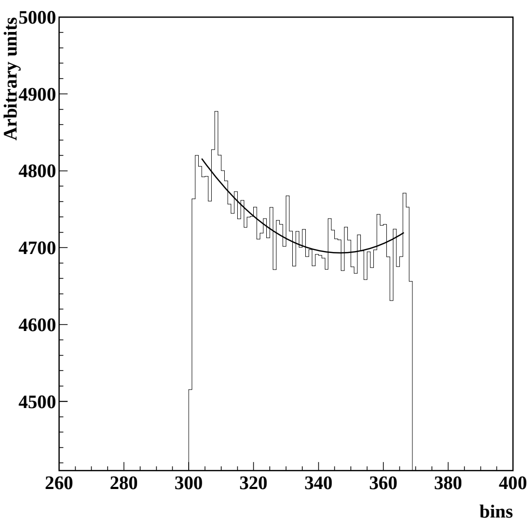

Figure 9: The longitudinal density variation in the middle of the block.

sured by optical method at $\lambda = 405$nm, light scattering length is presented for the wavelength 400 nm (Table II). The longitudinal variation of the refractive index was observed in the single layer block. This was actually a surprise. This block was produced with the same procedure as one investigated with X-ray detector for which analogous variation was observed independently. This block was measured at two distances between radiator and photodetector plane – 200 mm and 600 mm where maximum focusing effect is anticipated.

Table II Parameters of the blocks.

	index	**d, mm**	**L_{sc}, mm**
4-layer	1.0473	6.0	34.9
	1.0447	6.0	
	1.0421	6.0	
	1.0416	6.9	
2-layer	1.0486	14	30.6
	1.0409	14	
Single layer with variation	1.0532	19.5	~ 45
	1.0525		
	1.0517		
	1.0510		
	1.0513		
	1.0510		
	1.0509		
	1.0506		
	1.0505		

The Cherenkov angle distribution of detected photons for 4-layer aerogel block is presented in Figure 10. The values for the measured Cherenkov angle, angle resolution for one photoelectron, number of detected photoelectrons in the ring, number of photoelectrons in the background were received from the fit of experimental data. The angle resolution for track was calculated using formula $\sigma_\Theta(\text{track}) = \sigma_\Theta(\text{1p.e.})/\sqrt{\text{Npe}}$

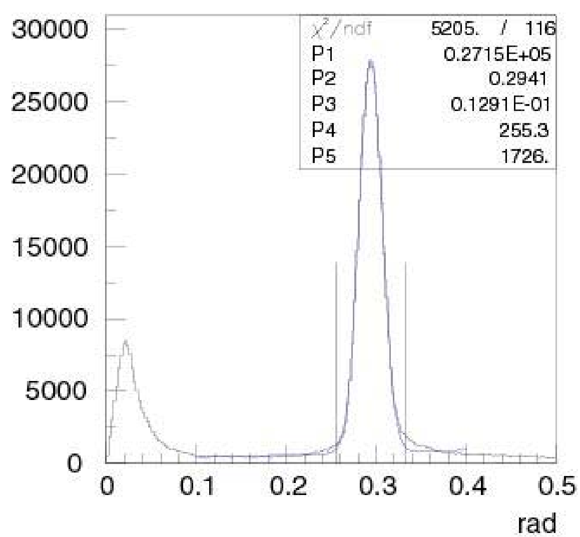

Figure 10: Cherenkov angle distribution, 4-layer block.

Test beam results are presented in Table III. The sequence of refractive indices in the 4-layer sample was not optimal. This explains why resolution for this option is almost the same as for 2-layer option. The small number of detected photoelectrons for single layer when it is placed at the distance of 600mm

Table III Test beam results. Measured Cherenkov angle (Θ_c), Cherenkov angle resolution for one photoelectron($\sigma\Theta_c$(1 p.e.),Cherenkov angle resolution for one track($\sigma\Theta_c$(track), number of detected photoelectrons in the ring (Npe), number of photoelectrons in the background (Nbg), signal to noise ratio (S/N).

	Θ_c, rad	**$\sigma\Theta_c$, mrad**		**Npe**	**Nbg**	**S/N**
		1 p.e.	**track**			
4-layer	0.2941	12.9	4.7	7.4	0.5	14.9
2-layer	0.2983	13.8	4.9	7.9	0.6	12.5
Single layer with variation	0.3152	12.4	4.6	7.2	0.5	13.3
Single layer with variation, base 600 mm	0.3089	5.9	2.2	1.3	0.6	2.0

is due to the limited acceptance of the photodetector array.

6. Conclusions

The technique for multilayer aerogels production (SAN–MULTI) has been developed. Several samples of aerogel tiles were produced with two and four layers, as well as a sample with a continuous variation.

GEANT4 simulation program has been developed. It was shown that velocity resolution of $5 \cdot 10^{-4}$ is achievable. This permits us to have π/K separation at the level more than 3σ up to momentum 8.0 GeV/c and π/μ separation up to momentum 1.6 GeV/c. The technical requirements on layers thickness spread and on the accuracy of refractive indices in the layers have been worked out.

The novel method to measure refractive index variations by means of digital X-ray detector was suggested and tested.

Several samples of multilayered aerogel have been tested with particle beam at KEK. The Cherenkov angle resolution per track is $4.6 \div 4.9$ mrad.

Acknowledgments

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