Cherenkov detectors with aerogel radiators

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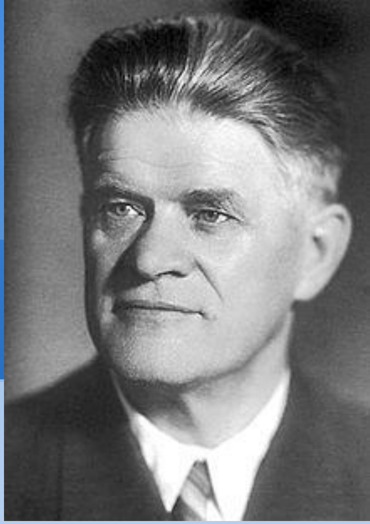
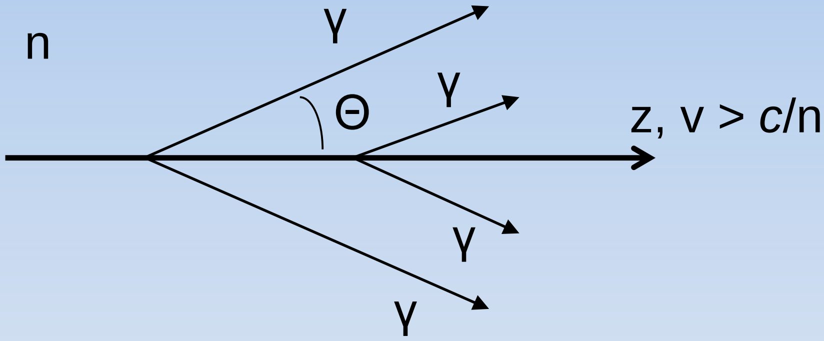
Cherenkov radiation and its main features



Year of discovery: 1934

- The direction of Cherenkov light and intensity both depend on particle velocity
- The quadratic dependence of the intensity on charge of the particle
- Instantaneous flash, no decay time
- Low intensity
- Cherenkov photons 100% linear polarized



$$\cos\theta = \frac{1}{n\beta}, \qquad \beta = \frac{v}{c}$$

$$\frac{d^2N}{dx d\lambda} = \frac{2\pi\alpha z^2}{\lambda^2}\left(1 - \frac{1}{\beta^2 n^2(\lambda)}\right)$$

Why we want to use aerogel?

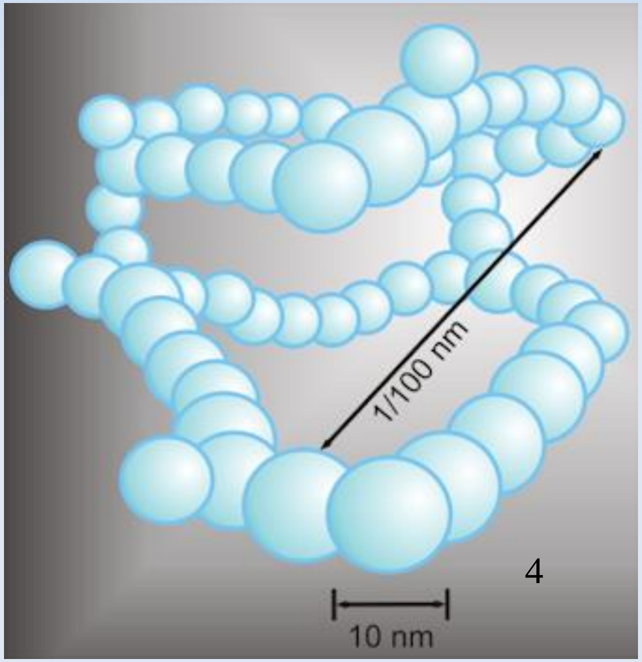
- In the range of momenta below 700 MeV/*c* pions and kaons are identified be means of TOF or dE/dx methods.
- To identify pions and kaons above 700 MeV/*c* it is possible to use Cherenkov threshold counter having P_{thr}(π) = 400--500 МэВ/*c* => **n=1.03-1.06 !** => **AEROGEL**

	n	$P\pi$, MeV/*c*	PK, MeV/*c*
Fused silica	1.458	132	465
Water	1.33	159	563
Freon 114, 1 atm	1.0014	2640	9330
CO_2, 1 atm	1.00043	4760	16800
CO_2, 10 atm	1.0043	1500	5320
C_2H_4, 25 atm	1.02	600	2460

What it is -- Aerogel?(1)

Aerogel was first synthesized by Samuel Stephens Kistler in 1931

S.S.Kistler, "*Coherent Expanded Aerogels and Jellies*", Nature, 1931,vol. 127, p. 741



Aerogel – is a porous material with pore dimension less than visible light wavelength.
It is a classical **nanomaterial**.The most widespread are silicon dioxide aerogel, although aerogels based on metal oxides, carbon, gelatin and others exist.

What it is -- Aerogel?(2)

Production method:

- Synthesis of the alcogel:

  $Si(OR)_4 + 2H_2O \Rightarrow SiO_2 + 4HOR$

  alkoxide water silica alcohol

- Supercritical drying in the autoclave to remove alcohol P_{max}=100 atm, T_{max}= 260°C
  - methanol -- P_{cr}=81 atm, T_{cr}=230°C
  - isopropanol -- P_{cr}=53 atm, T_{cr}=235°C
  - carbon dioxide -- P_{cr}=73 atm, T_{cr}=31°C

Aerogel parameters:

- Density 0.003 до 1.0 g/cm^3 *(fused silica ρ=2.2* g/cm^3 *)*
- Refractive index

  $n \approx 1 + 0.2 \cdot \rho[g/cm^3] \Rightarrow$

  (n = 1.0006 ÷ 1.2)
- Porosity up to 99.8%
- Inner surface 800 m^2/g

How it all began?

- 1973
- n=1.01—1.06 (1.2 using sintering)
- $L_{sc}(400)$ = 6 mm
- There is a Cherenkov light from aerogel!
- *‘The are no evident signs of scintillations in aerogel’!*

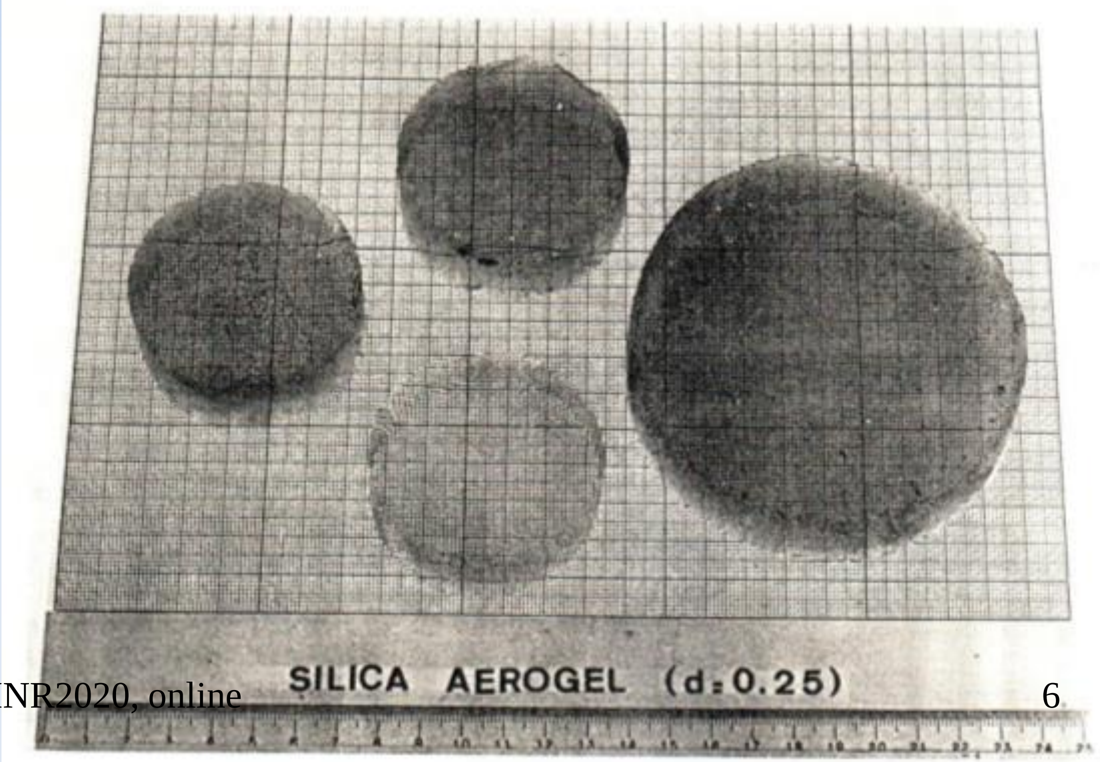
NUCLEAR INSTRUMENTS AND METHODS 118 (1974) 177–182; © NORTH-HOLLAND PUBLISHING CO.

SILICA AEROGELS USED AS CHERENKOV RADIATORS

M. CANTIN, M. CASSE, L. KOCH, R. JOUAN, P. MESTREAU, D. ROUSSEL
Service d'Électronique Physique, Centre d'Études Nucléaires de Saclay B.P. nº 2, 91190 Gif-sur-Yvette, France
and
F. BONNIN, J. MOUTEL, S. J. TEICHNER
Laboratoire de Thermodynamique et Cinétique Chimique, Université Claude Bernard, 69000 Lyon, France

Received 3 December 1973

Silica aerogel is a porous and transparent solid material. Its index of refraction is a function of its density, and it can be freely adjusted between at least 1.01 and 1.06, and up to values as high as at least 1.20 by heating. As a Cherenkov radiator it replaces gases under high pressure, eliminating all the problems associated with their container.

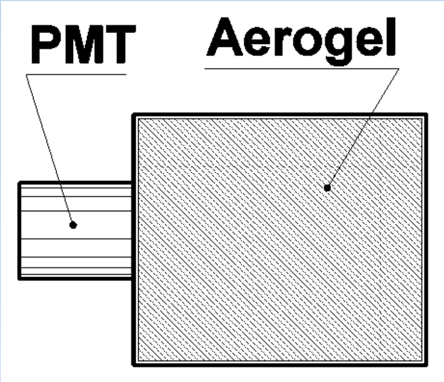


How to construct threshold aerogel counter?

$$LC \approx \frac{k}{1 - R(1 - k)}$$

$k = S_{\text{фк}}/S_{\Sigma}$,
R-reflection coefficient on the walls

Diffusive light collection



Diffuse reflection coefficient on the walls -- 95-99% (BaSO4,Teflon, Millipore paper)

TASSO aerogel threshold Cherenkov detectors

H. Burkhardt et.al., NIM184(1981)319

- 1976- start of the R&D
- The first large scale detector with aerogel, 32 detectors, V_{Σ}=2000 l
- Large counters 0.35x1.0x1.5 m
- n=1.020—1.026
- L_{sc}(400) = 20 mm
- Npe = 3.9 (problems with degradation)

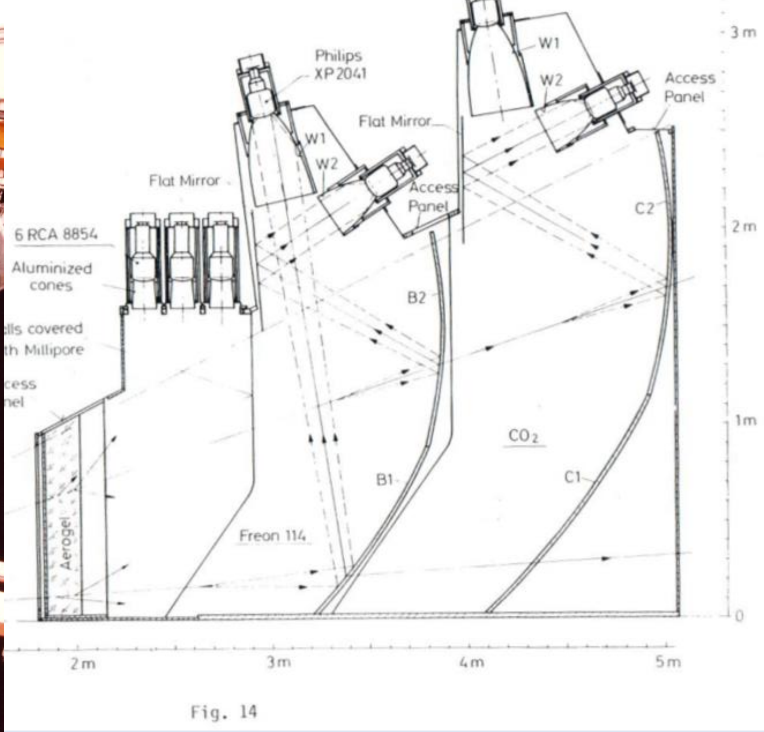


Fig. 14

Yes, this is possible!

KEDR aerogel counters with direct light collection(1)

- 1982 – SLAC instrumentation conference, talk of Gunter Poelz on TASSO Cherenkov Counters
- Start of the R&D at 1986 as part of KEDR project together with Boreskov Institute of Catalysis
- 1988 – the first aerogel samples produced at BIC
- 1990 – test of the first prototype on cosmic muons

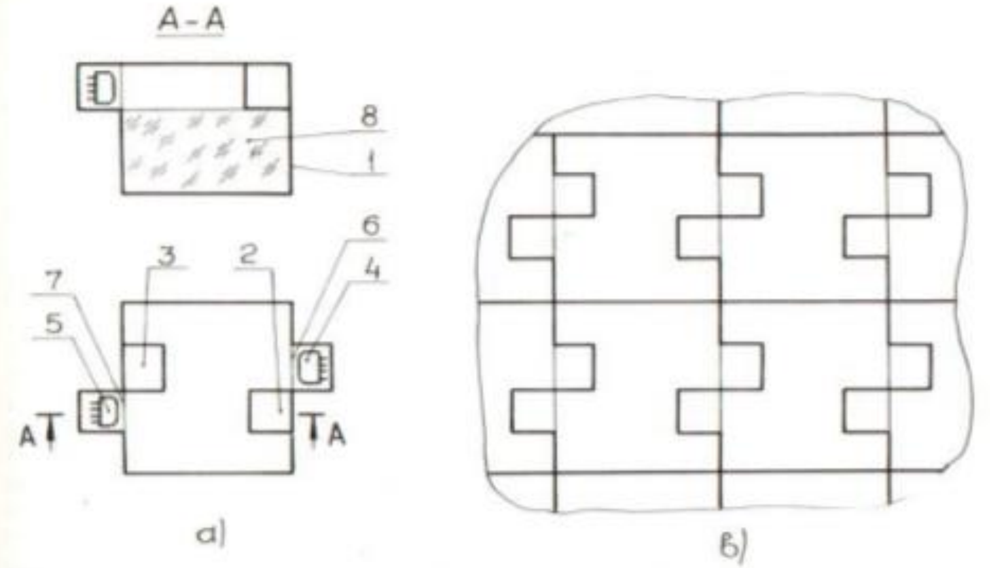


Fig.1 (a) Design of Cherenkov counter
1 - walls of counter
2,3 - pockets for installation of phototubes for neighbour counters
4,5 - phototubes
6,7 - windows in walls
8 - aerogel
(b) Layout of counters in barrel part of detector

KEDR aerogel counters with direct light collection(2)

- n=1.035, 10 cm thickness
- $L_{sc}(400)$ = 20 mm
- 2 Fine Mesh Hamamatsu R2490-01PMTs (working magnetic field 2 T!)
- Npe = 6.3 (for β=1 particle)
- But! For the whole system 360 Hamamatsu FM PMT are required.

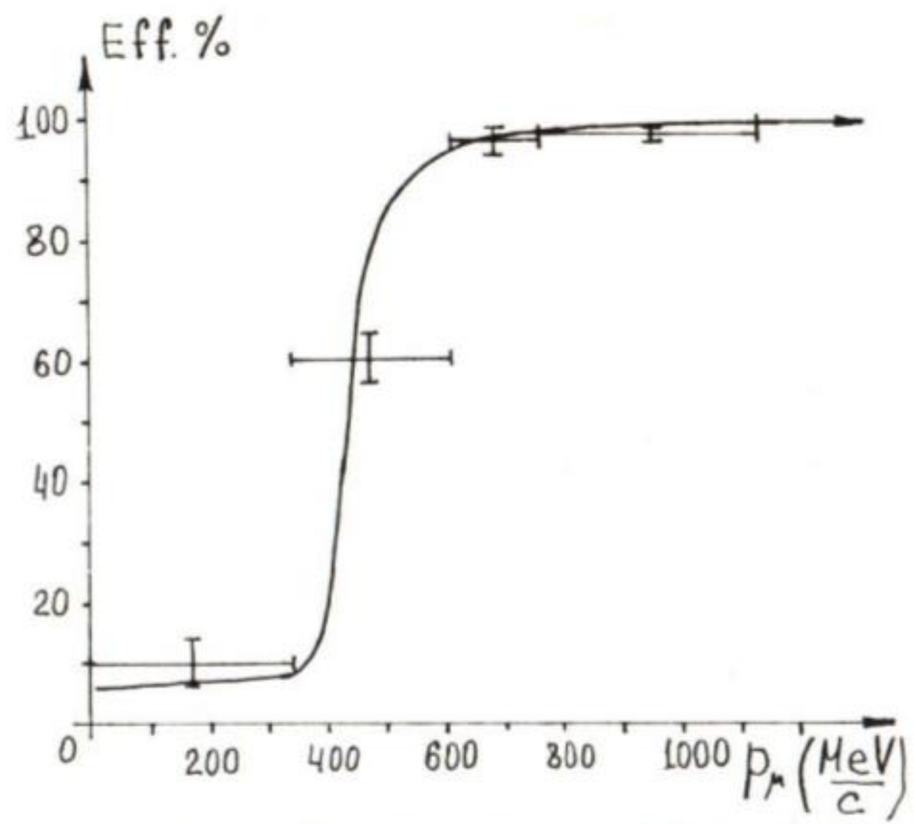


Fig.4 Detection efficiency of muons versus their momentum in Cherenkov counter prototype.

Era of high transparency aerogel

L.W.Hrubesh, T.M. Tillotson, J.F. Poco "*Characterization of ultralow-density silica aerogels made from a condensed silica precursor*", MRS Proc. 180(1990)315

One-step technology

- Direct alcogel synthesis

$Si(OR)_4 + 2H_2O \Rightarrow SiO_2 + 4HOR$

alkoxide water silica alcohol

- $L_{sc}(400) \sim 20$ mm

Two-step technology

- A mixture of oligomers preparation
- $Si_kO_l(OR)_m(OH)_n \Rightarrow SiO_2$+alcohol
- $L_{sc}(400) > 35$ mm

Two-step technology was implemented at BIC in 1992

Belle aerogel Cherenkov counters

- 1992 – seminar of A.Onuchin at KEK on aerogel threshold detector development
- 1994 – approval of KEKB with Aerogel Cherenkov Counters as baseline for PID
- Very intensive R&D both on aerogel production and detector design
- 1124 detectors equipped with 2024 Fine Mesh PMTs (2, 2.5, 3 inch)
- n=1.01—1.03, V_{Σ}=2000 l, high transparency hydrophobic aerogel
- Npe = 20—26(!)
- In operation 1998-2010
- **Full success of the project!**

T. Iijima et al./Nucl. Instr. and Meth. in Phys. Res. A 379 (1996) 457–459

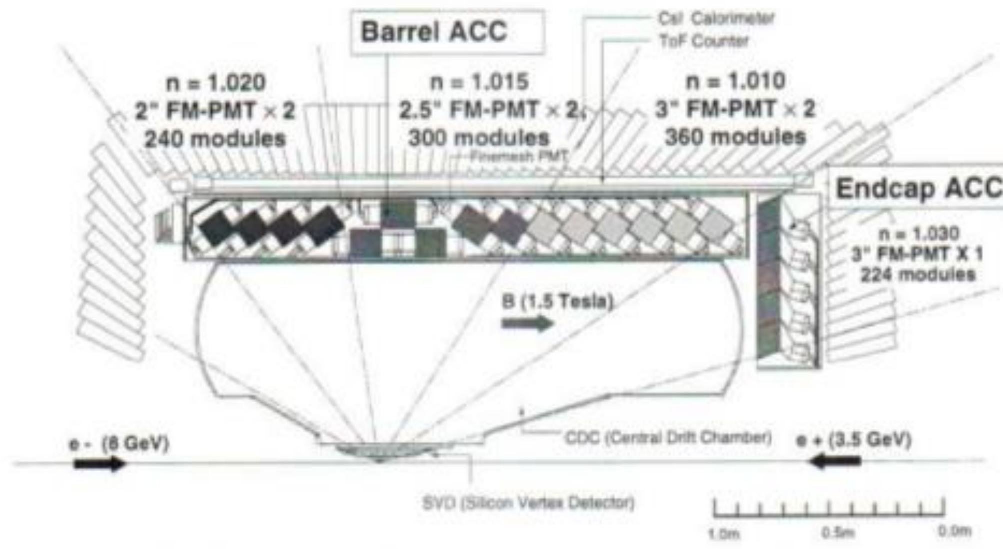


Fig. 1. Design of the BELLE aerogel Cherenkov counter system (as of March 1996).

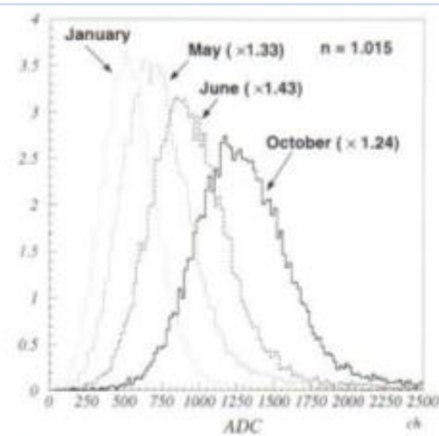
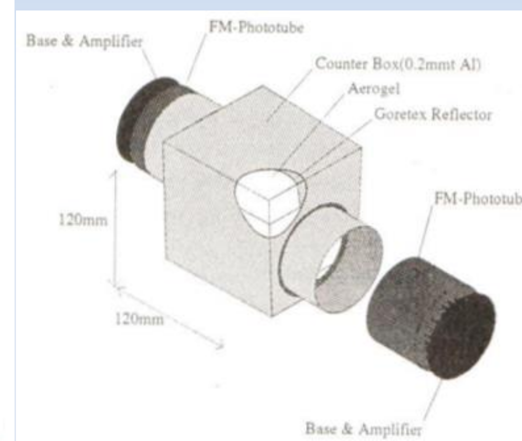


Fig. 2. Pulse height spectra obtained with n = 1.015 aerogels in beam tests in the past one year. The counter configuration and PMT gains are the same for all measurements.



Aerogel threshold counters with wavelength shifters(1)

At λ=400 nm

- L_{sc}~ 40 mm, L_{abs}~ 4-5 m

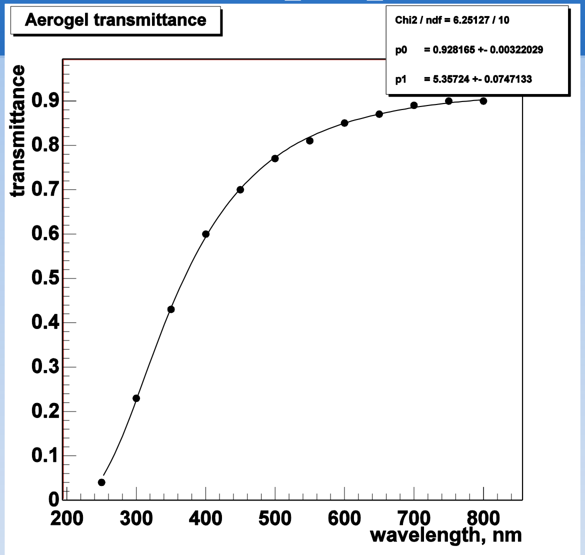
At λ=300 nm

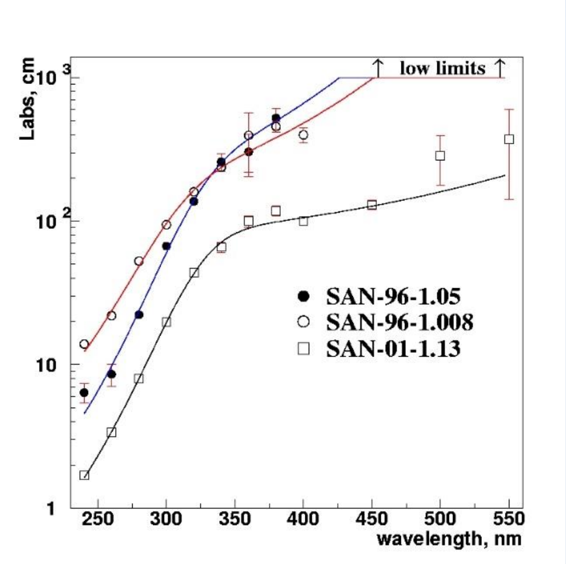
- L_{sc}~12 mm, L_{abs}~ 0.5-1 m

But!

- dN/dλ ~$1/\lambda^2$
- At ~300 nm Number of Cherenkov photons is 3 times larger than at ~400 nm

The idea is to absorb Cherenkov photons at short wavelengths and re-emit at large where aerogel transparency is better.



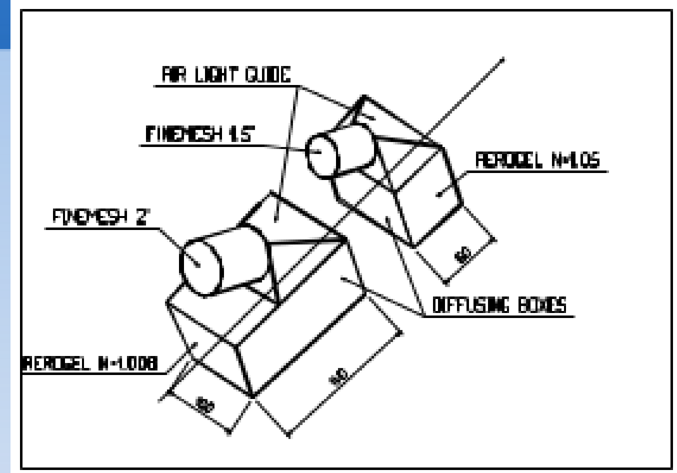


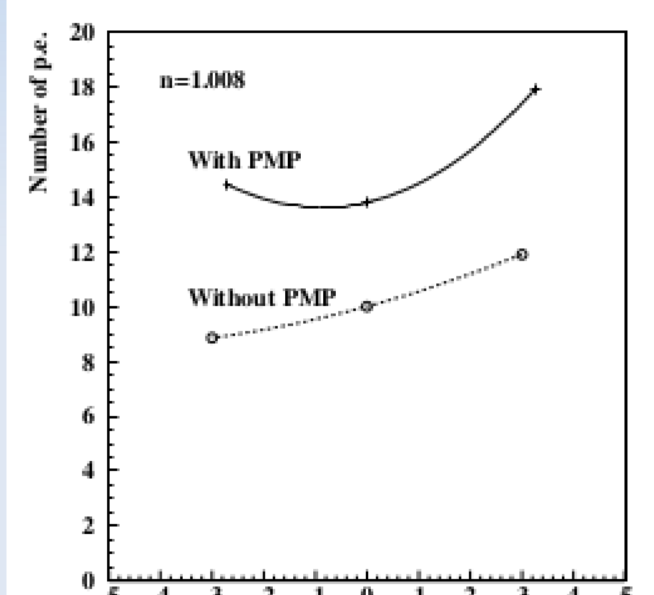
Aerogel threshold counters with wavelength shifters(2)

Several aerogel detectors used wavelength shifters to increase signal:

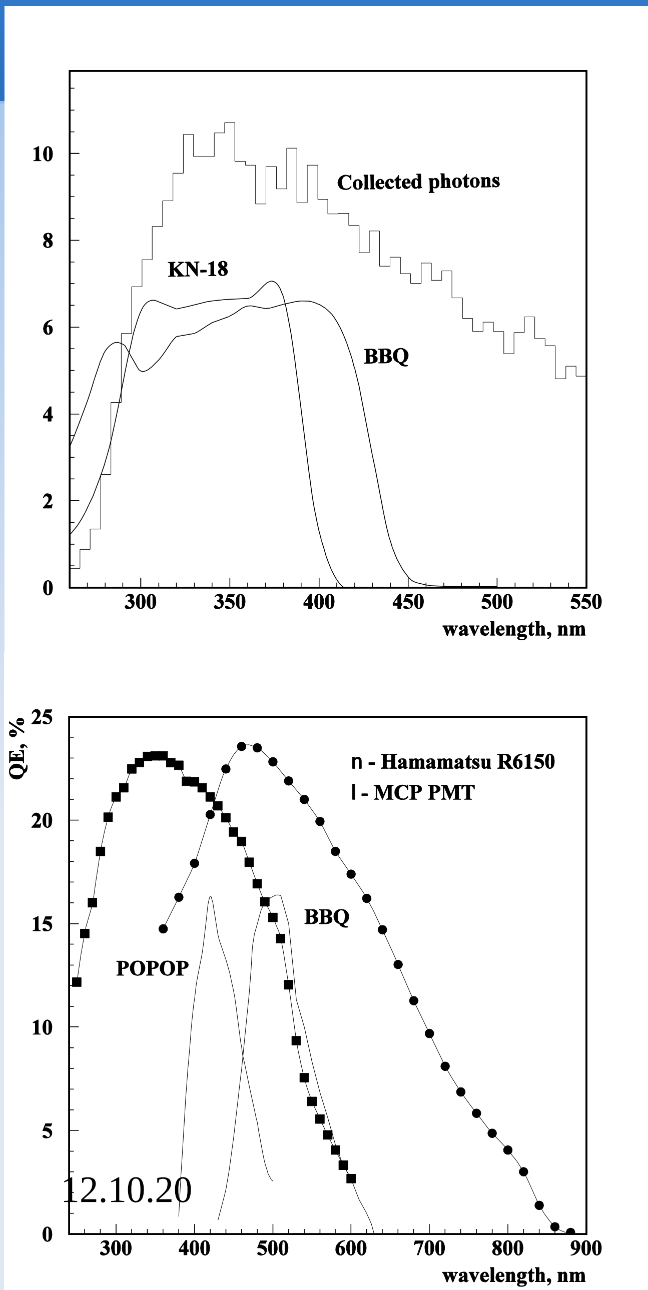
- The prototype of aerogel Cherenkov detector for BaBar tested PTFE reflector impregnated with PMP dye
- AMS-01 Aerogel counters used 25 µm tedlar film soaked in PMP. Suffered a fast degradation
  Npe = 5 -> 1.5 (n=1.035)
- DIRAC uses Teflon foils coated with p-terphenyl. This gave 50% increase of light yield and also increase under threshold efficiency to 40%. (n=1.008, Npe=4)

In these detectors the re-emitted light came back to aerogel and only after that has been collected on the PMT

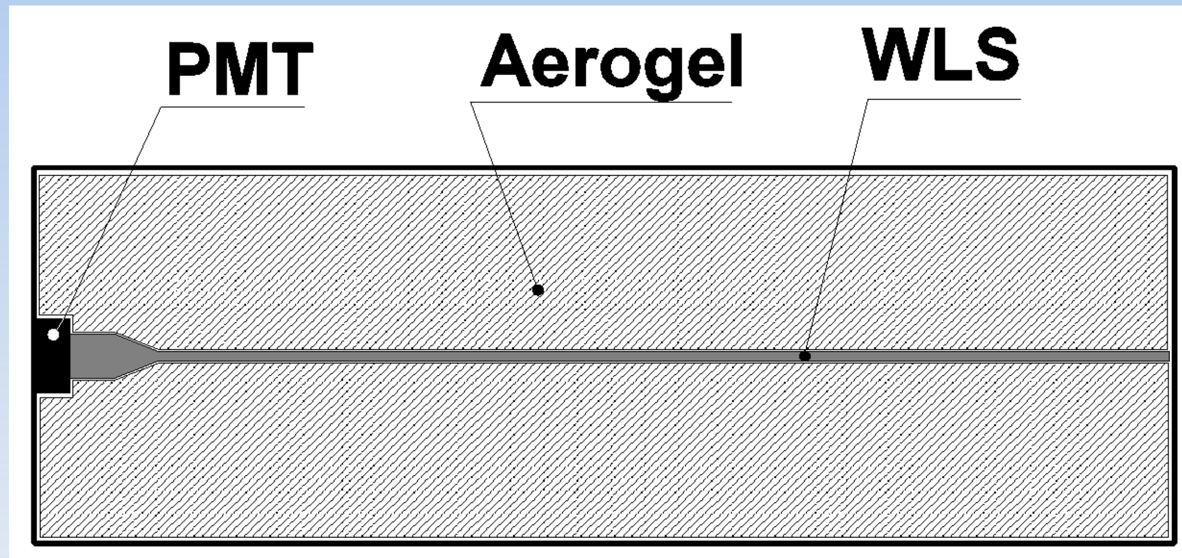




ASHIPH detectors



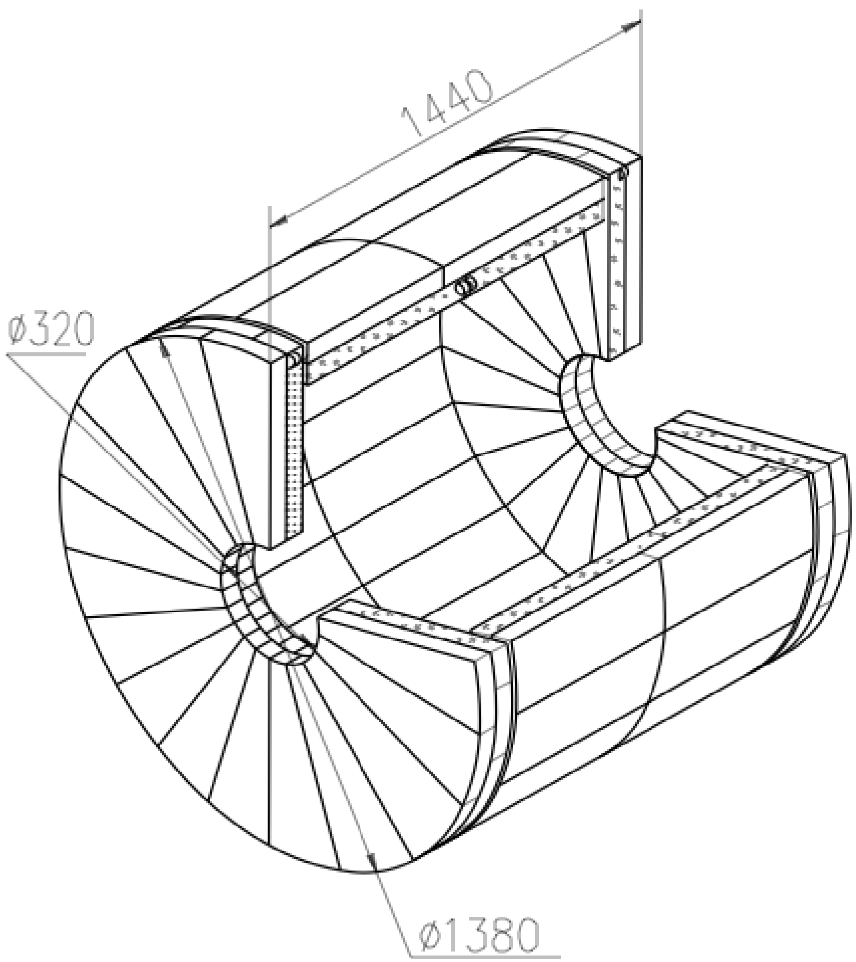
Aerogel SHIfter and PHotomultiplier



PMMA light guide doped with BBQ dye
is used as wavelength shifter

Suggested at BINP. A.Onuchin et.al. NIM A315(1992)517

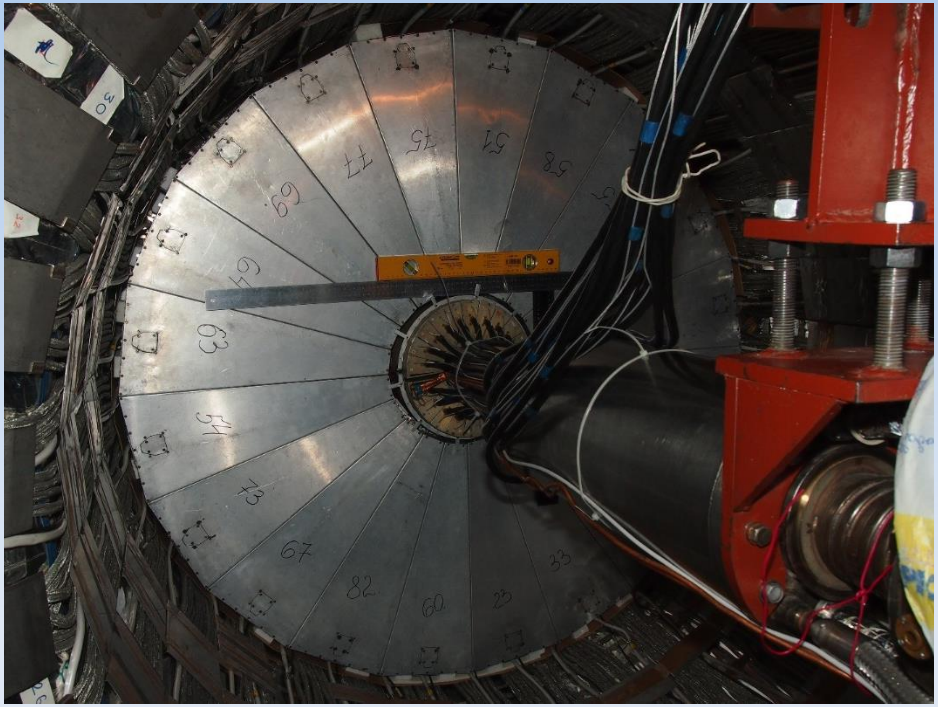
KEDR ASHIPH system



- 160 counters in 2 layers
- Solid angle 96% of 4π
- n=1.05, V_{Σ}=1000 l, high transparency SAN-96 aerogel
- π/K- separation in the momentum range 0.6÷1.5 GeV/*c*
- 160 MCP PMTs, photocathode diameter ø18mm, able to work in the magnetic field up to 2 T
- Fully installed in the detector in 2013. Now in operation.

-> talk of I.Ovtin

KEDR ASHIPH system(2)

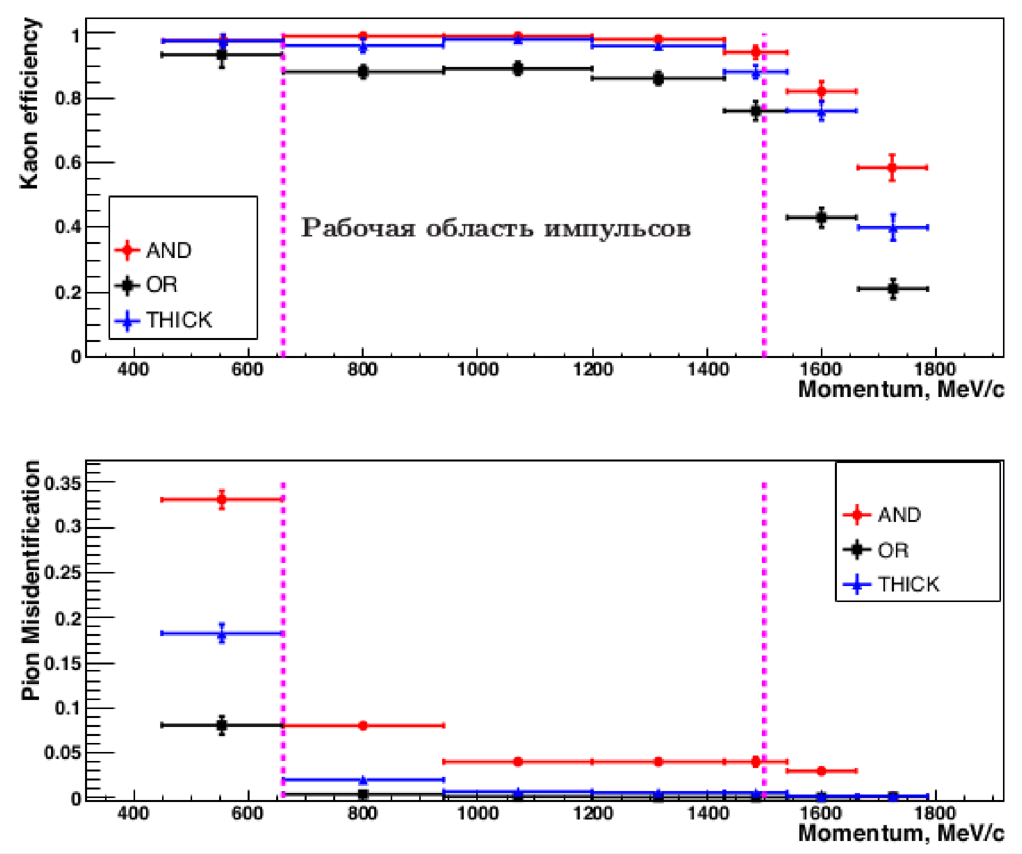


Endcup counters

Barrel counters

KEDR ASHIPH system(2)

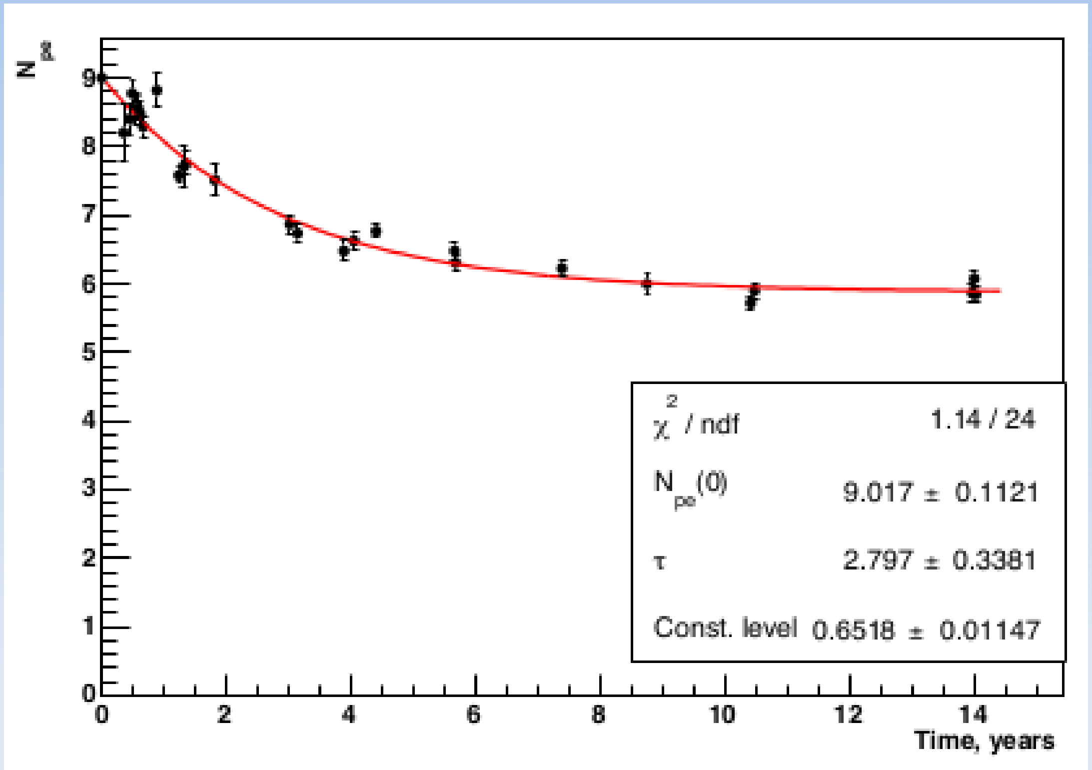
- Npe = 6.4±0.2 – layer 1
- Npe = 5.0±0.2 – layer 2
- Npe = 10.9±0.2 – sum of the signals in 2 layers (80%)
- π/K separation at 1.2GeV/*c* is 4.3σ



-> talk of I.Ovtin

ASHIPH long term stability

A prototype of the endcap ASHIPH counter are under operation since 2000. From time to time it is tested in Cosmic Ray Telescope (CRT). Its signal degradation now has stabilized at the level of 60% from initial value.



Ring Imaging Cherenkov detectors with aerogel radiators

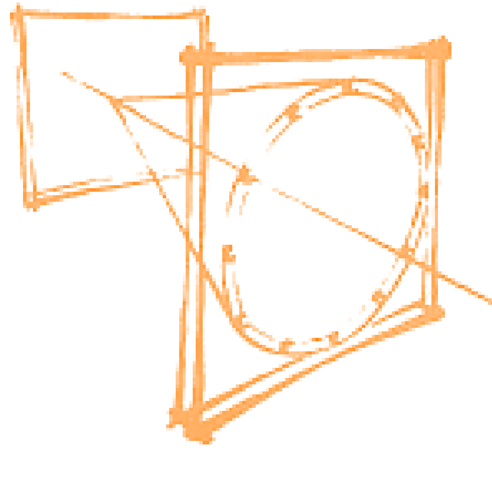
If the Cherenkov radiation angle is measured, the precision in the determination (identification) of particle masses will be higher than in threshold counters.

In the 1980s and 1990s, a whole series of RICH detectors were constructed:

- CRID, SLD detector, SLAC(C_6F_{14} n=1.277, C_5F_{12}/N_2 n=1.0017)
- RICH, Delphi detector, CERN, (C_5F_{12}|C_6F_{14}, C_4F_{10})
- RICH, CLEOIII detector, Cornell, (LiF, n=1.50)
- DIRC, детектор BaBar, SLAC, США (SiO_2, n=1.47)

Main problem – they do not provide pion-kaon identification in the range of momenta 4—10 GeV/*c*

Material with n=1.03-1.05 is needed. Aerogel!



$$\cos\theta = \frac{1}{n\beta}$$

- A.Roberts, Nucl. Instrum. and Methods 9(1960)55
- J.Seguinot and T.Ypsilantis, Nucl. Instrum. and Methods 142(1977)377

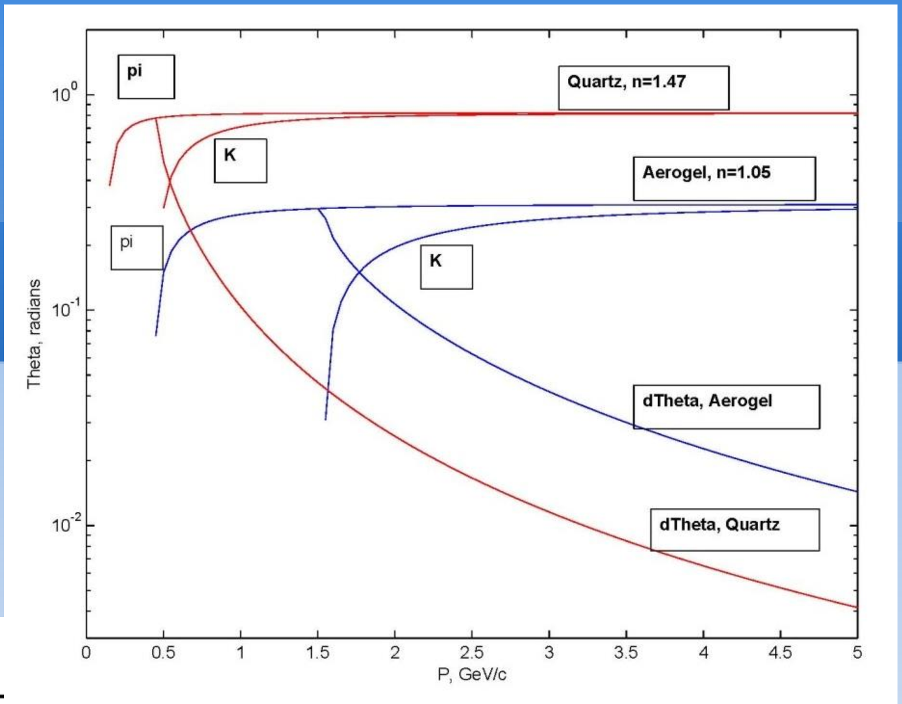
Peculiarities of aerogel use in RICH detectors

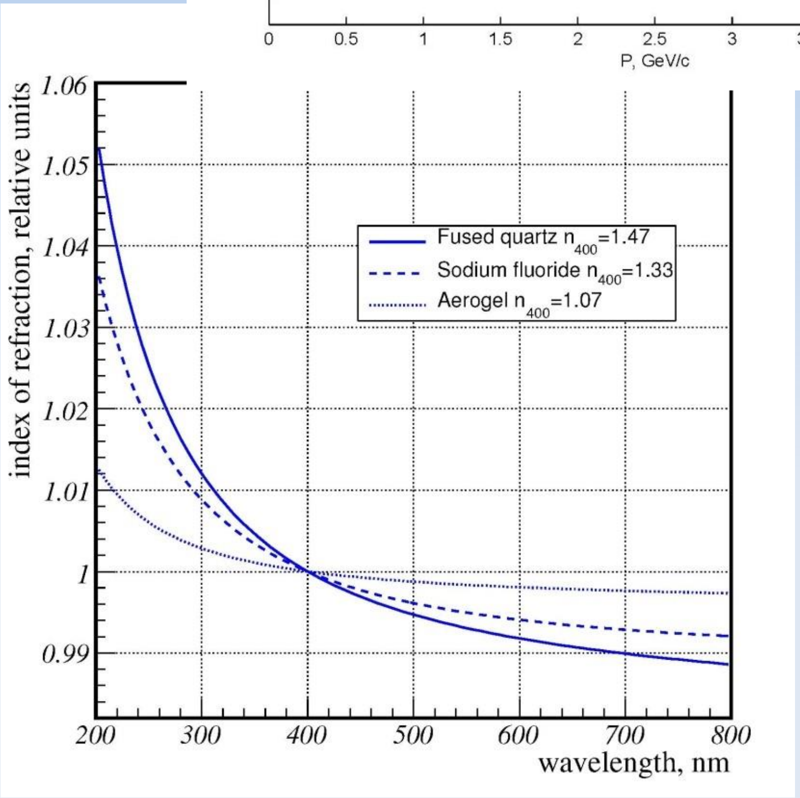
$$N_{out} = N_0 \frac{L_{sc}}{h}\left(1 - e^{-\frac{h}{L_{sc}}}\right), \qquad L_{sc} \sim \frac{1}{\lambda^4}$$

- For a long time, it was considered impossible to use aerogels in RICH detectors owing to the strong scattering of light.
- 1991 – the first experimental observation of Cherenkov ring from aerogel using photography method(A.I.Vorobiov, V.P.Zrelov, J.Ruzichka, "*On some peculiarities of Vavilov-Cherenkov radiation in aerogels*", In Frascati 1991, Physics and detectors for DAPHNE, the Frascati Phi-factory* 551-556) (This was `Novosibirsk` aerogel!)
- The first RICH with aerogel was proposed D. Fields in 1994
- 1995 г– Aerogel RICH for LHCb was suggested. The requirement on minimal light scattering length was elaborated. $\mathrm{L_{sc}} \gtrsim 26\ \mathrm{mm}$ (400 nm) (J.Seguinot, T.Ypsilantis, NIM A368(1995)229)
- 1995-1996 г. – two-step aerogel production was optimized, L_{sc} =40-50 mm (400 mm) (A.R.Buzykaev et.al, NIM A379(1996)465)

Why Aerogel in RICH?

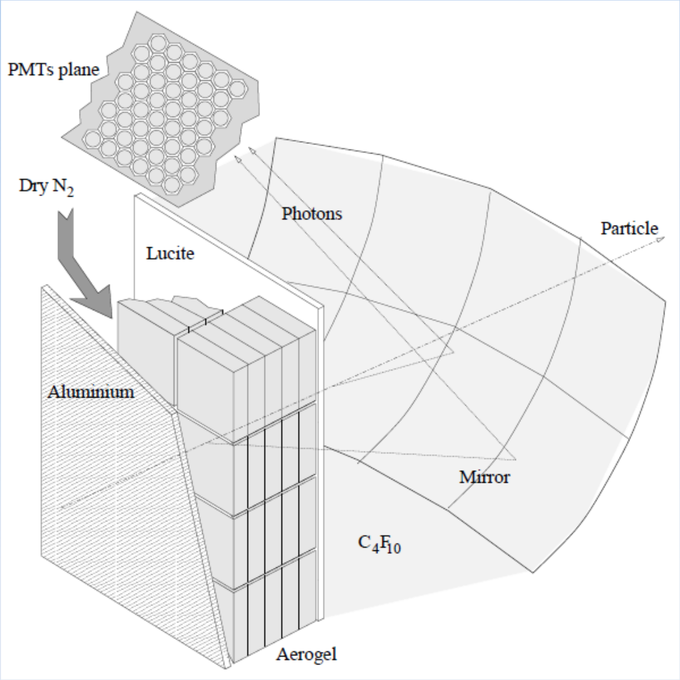
- The difference of Cherenkov angles for different particles is larger
- Aerogel refractive index dispersion is smaller
- The large number of detected photons from high refractive index radiators can not compensate these effects (~ $1/\sqrt{N_{pe}}$)

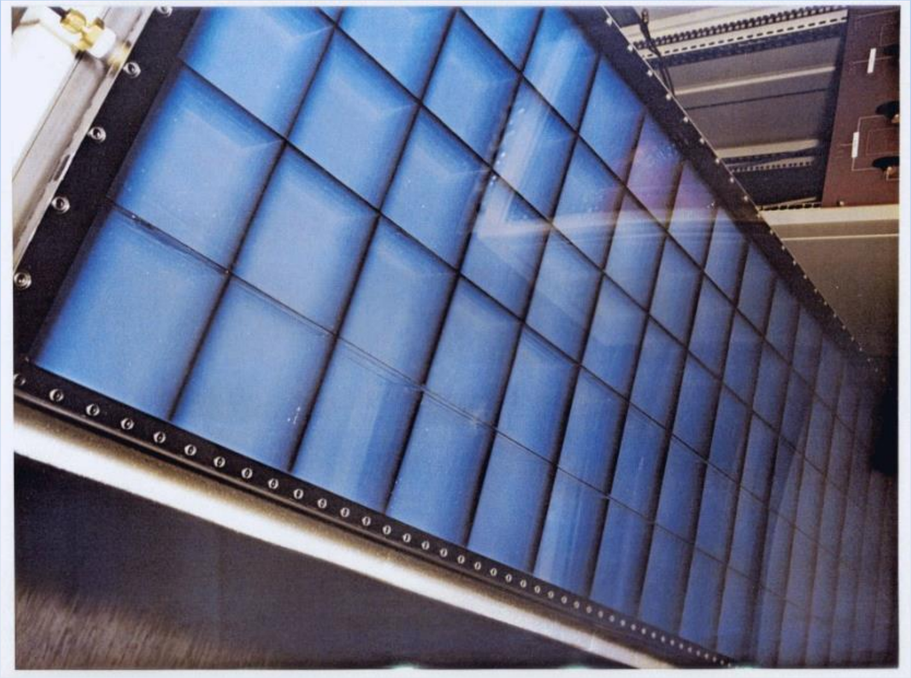




The first aerogel RICH

Hermes RICH (DESY, Германия)



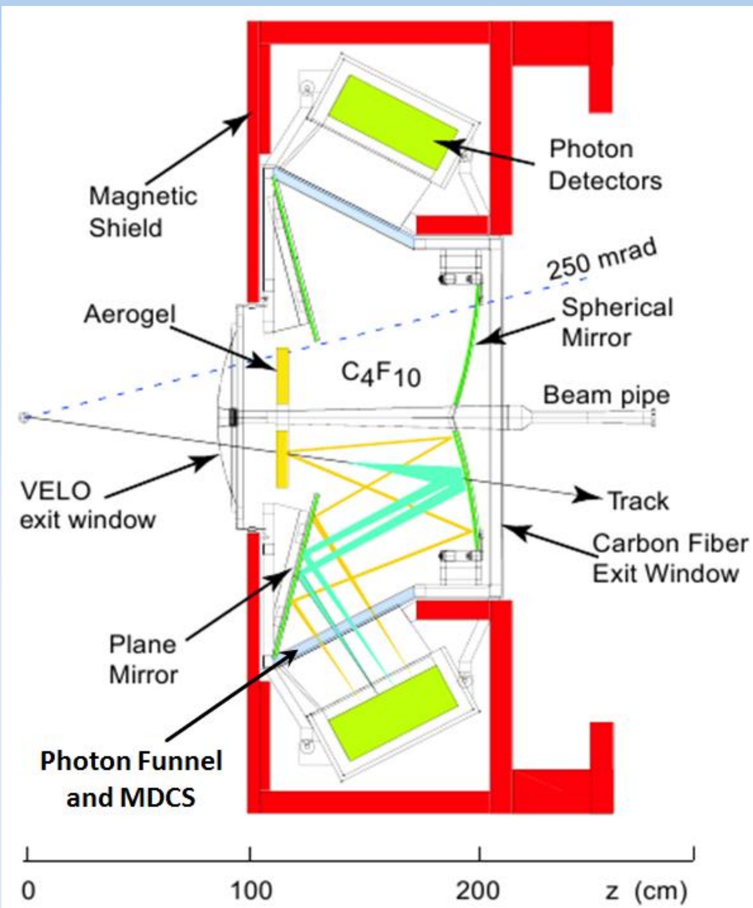


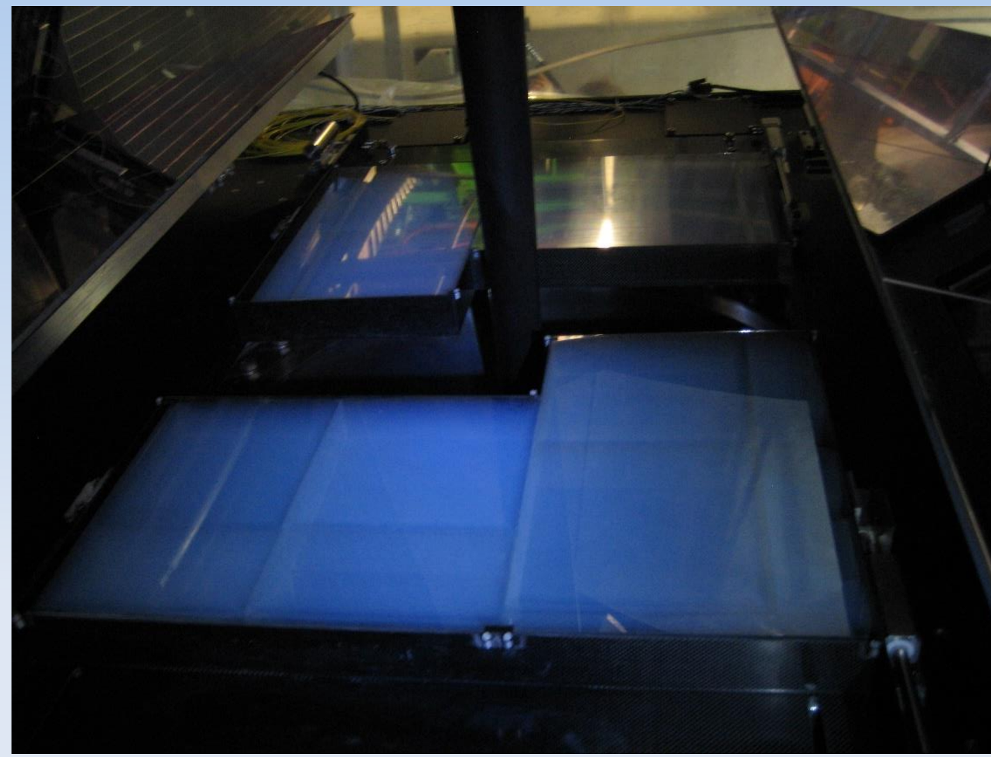
Start of the design – 1996
Start of the operation -- 1998

Matsushita aerogel, n=1.03

Aerogel in LHCb RICH1

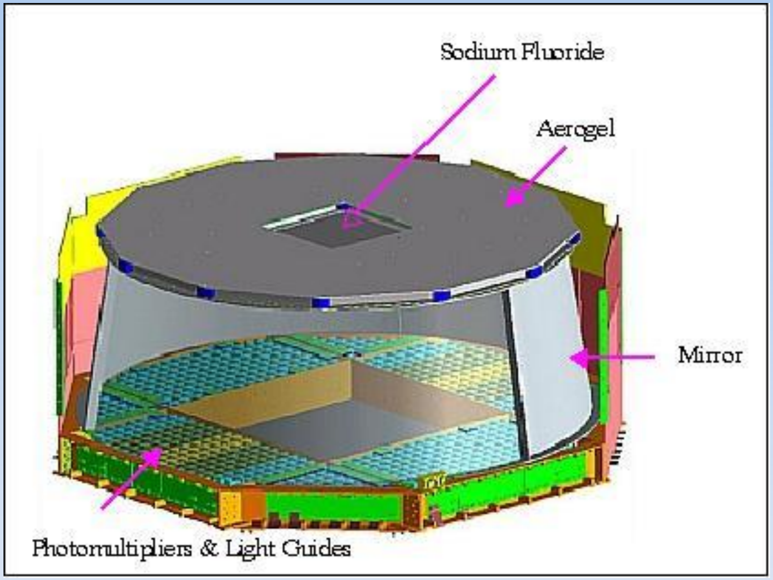
LHCb RICH1 (CERN, Швейцария)





BIC/BINP production, n=1.03, 20x20x5 cm tiles
Aerogel did not work. – small number of photoelectrons in the ring + strong pile-up noise

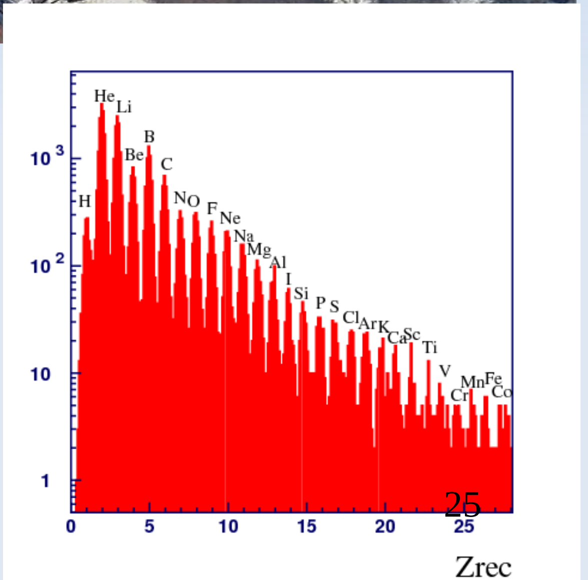
Aerogel RICH at AMS-02 at ISS



Measurement of Z of the nucleon, $N_{pe} \sim Z^2$

BIC/BINP production, n=1.05

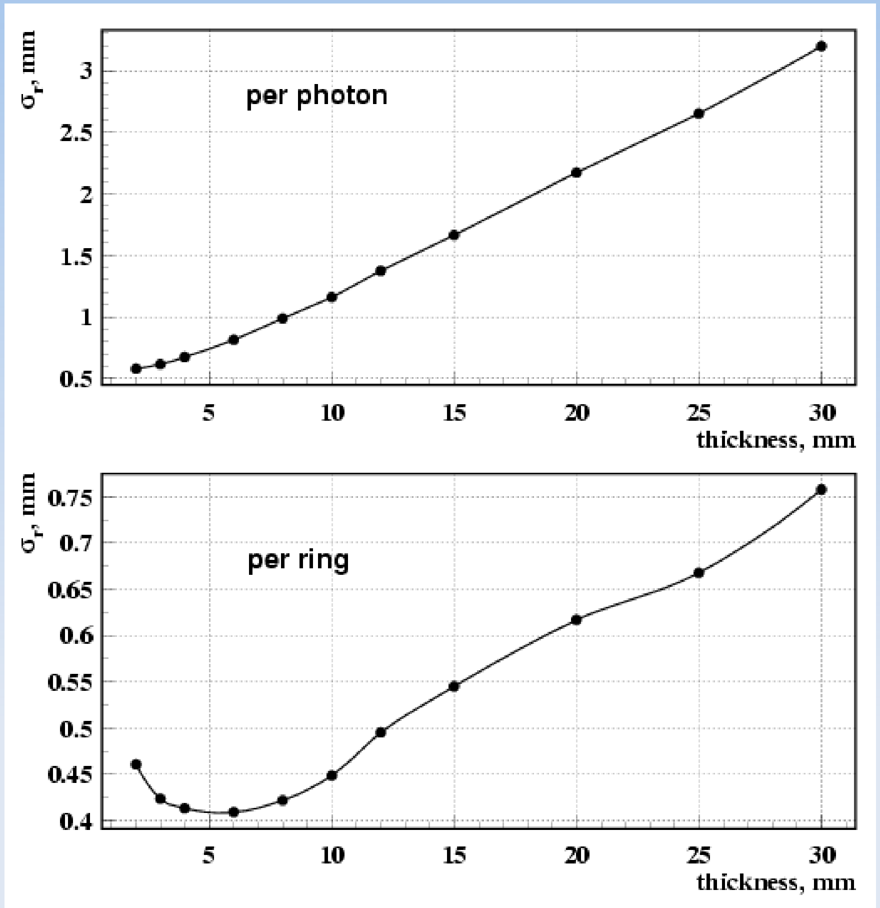
-> the talk of F. Giovacchini



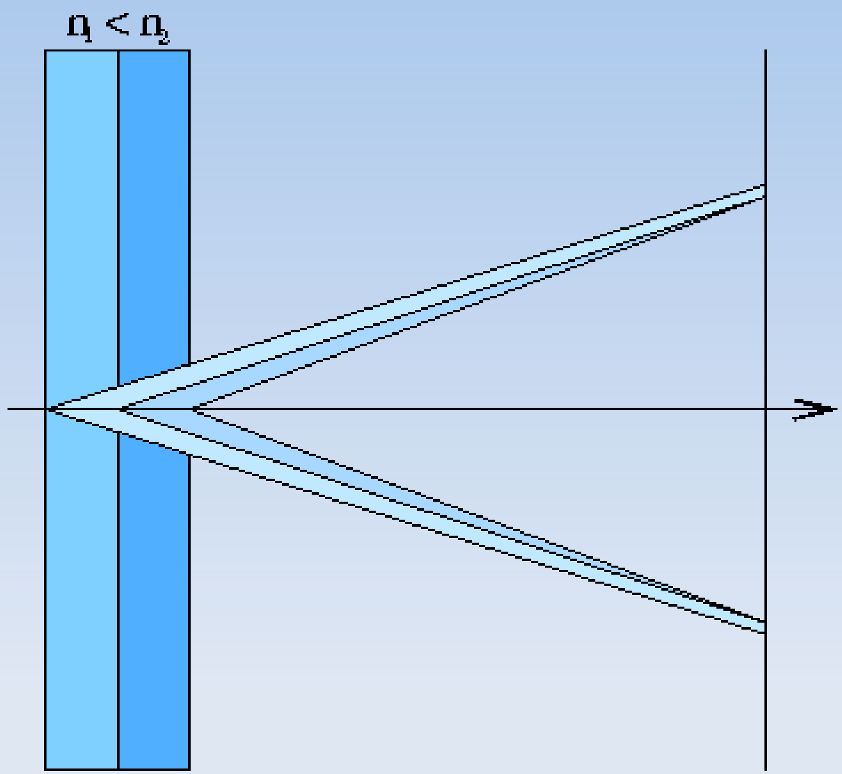
What is the idea of Focusing Aerogel RICH?

Proximity focusing RICH:

- Increasing thickness of aerogel we increase number of detected photons which lower Cherenkov angle resolution($\sigma_\Theta \sim \sigma_{1pe}/\sqrt{h}$)
- Increasing thickness of aerogel we enlarge the width of Cherenkov ring thus increasing Cherenkov angle resolution ($\sigma_\Theta \sim h$)

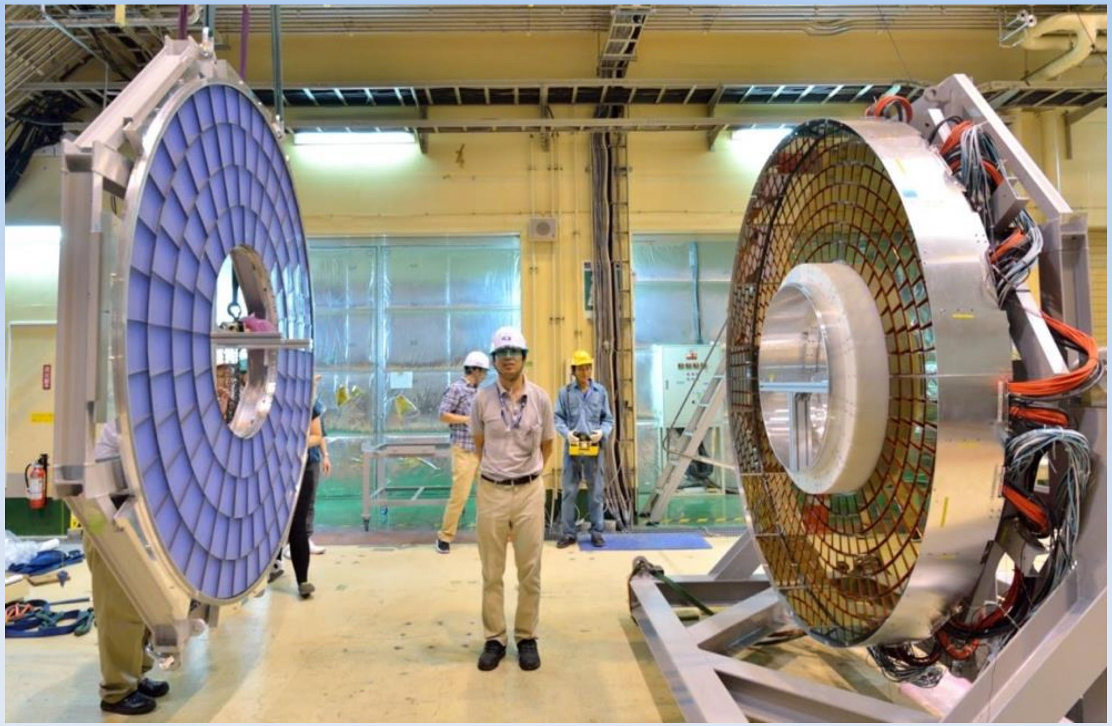


Further progress – Focusing aerogel RICH!



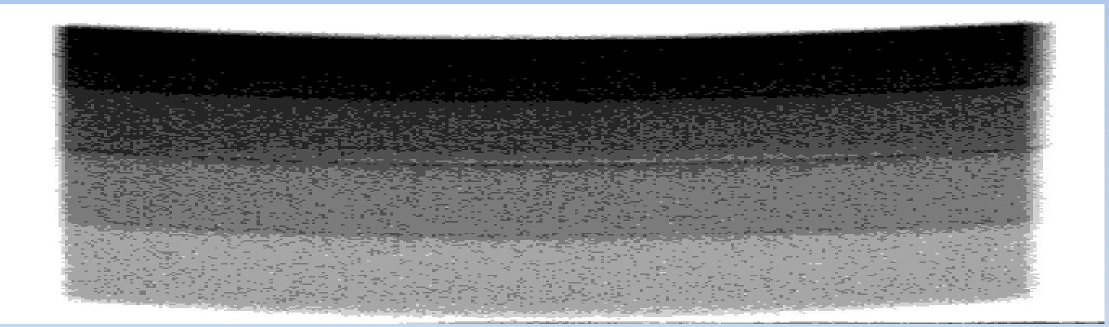
Suggested in 2004

2017



T.Iijima et al., NIM A548 (2005) 383
A.Yu.Barnyakov et al., NIM A553 (2005) 70

Aerogel sample



	n	h, mm
Layer 1	1.050	6.2
Layer 2	1.041	7.0
Layer 3	1.035	7.7
Layer 4	1.030	9.7

- 100x100x31 mm^3
- Lsc(400nm)=43 mm
- $n^2=1+0.438*\rho$

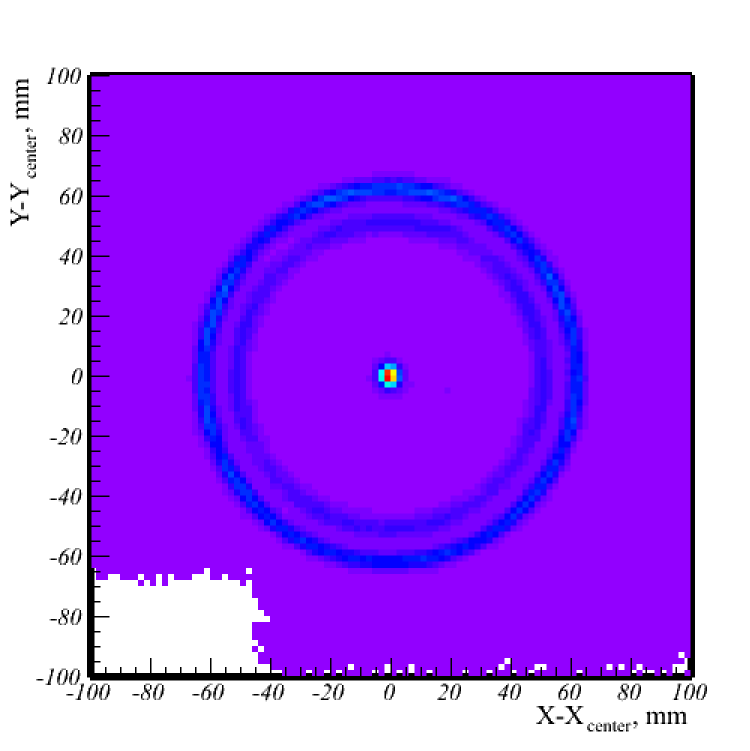
FARICH prototype with DPC detectors

- 4-layer aerogel
- n_{max} = 1.046
- thickness 37.5 мм
- ‘focusing’ at 200 мм

Photon detector 20x20 sm^2

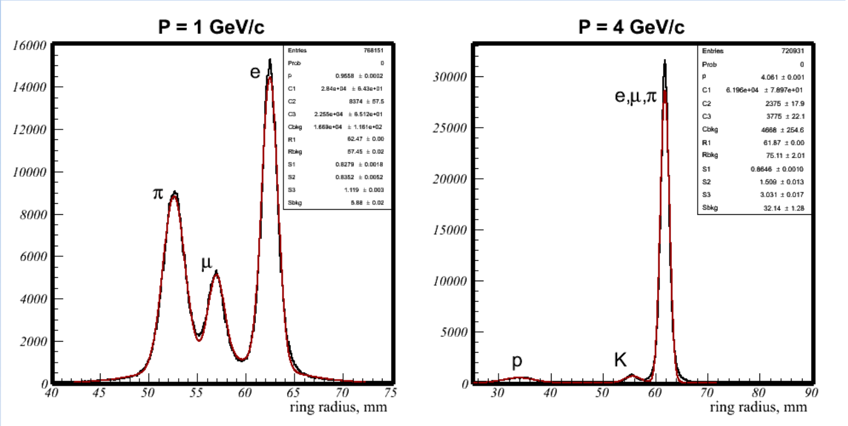
- Sensor type- DPC3200-22
- 3200 micro pixels in one pixel,
- 3x3 modules = 6x6 tyles = 24x24 matrixes = 48x48 pixels
- 576 time channels
- 2304 amplitude (coordinate) channels
- Pixel dimension 3.2x3.9 mm^2
- Cooled to -40° C to work in single photon mode

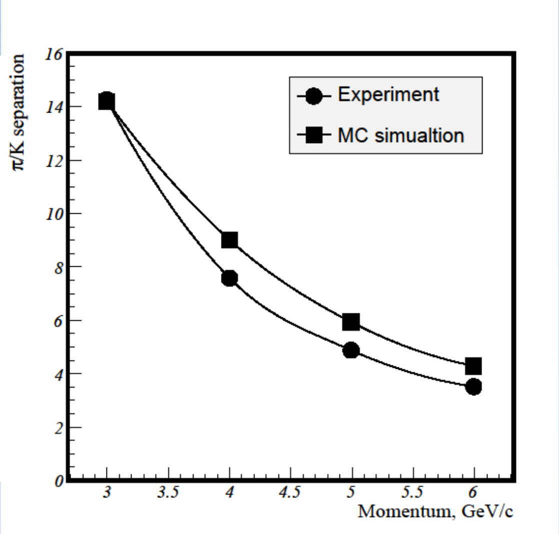
Cherenkov rings



Test beam results

Resolution on Cherenkov ring radius^

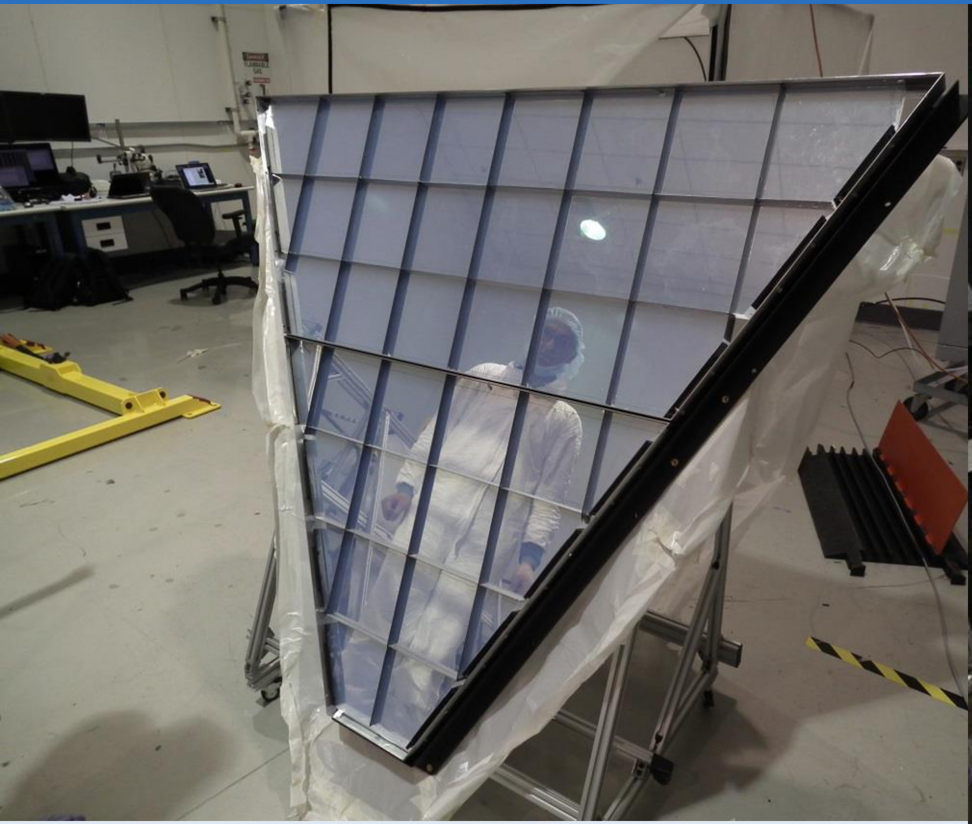


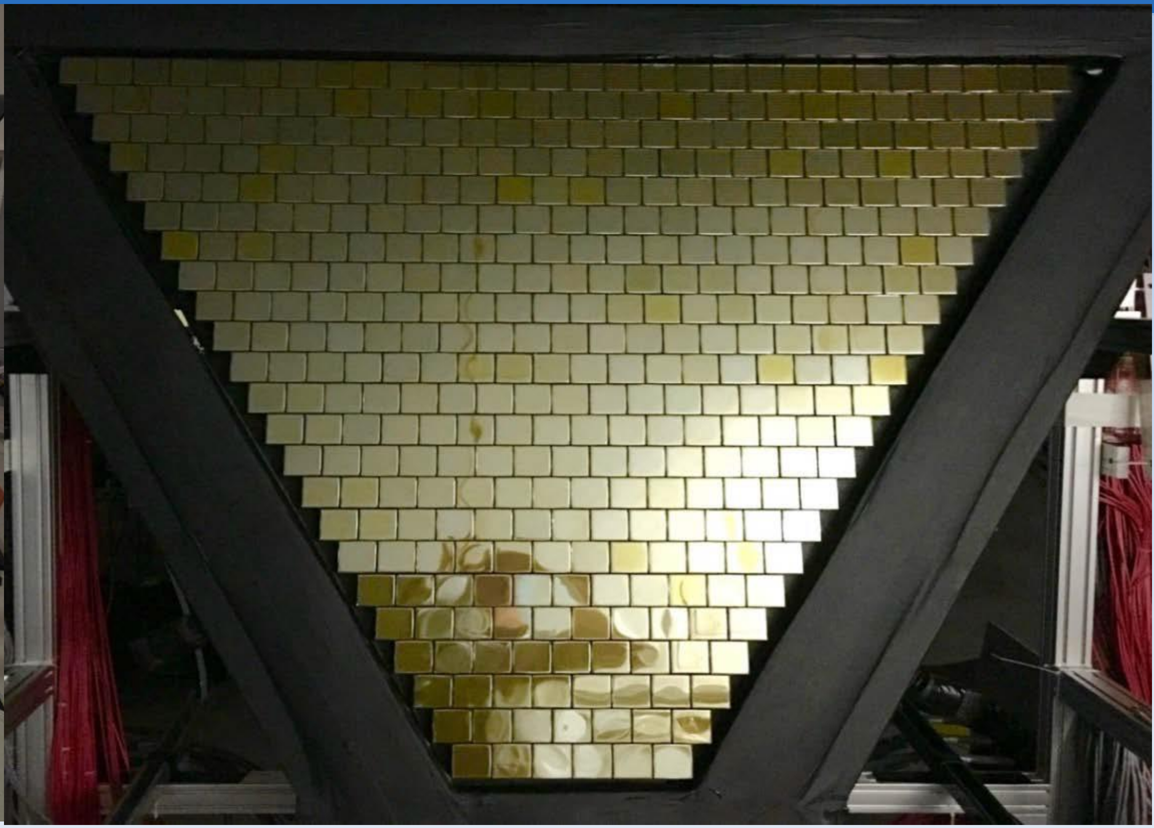


μ/π: 5.3σ @ 1 ГэВ/*c* 2.3 time better than SuperB FDIRC
π /K: 7.6σ @ 4 ГэВ/*c* 1.4 times better than Belle II ARICH
π /K: 3.5σ @ 6 ГэВ/*c* **But 2.6 times worse than in initial (ideal) simulation**

A.Yu. Barnyakov, et al., Nuclear Instruments & Methods in Physics Research A (2013), http://dx.doi.org/10.1016/j.nima.2013.07.068, Article in Press

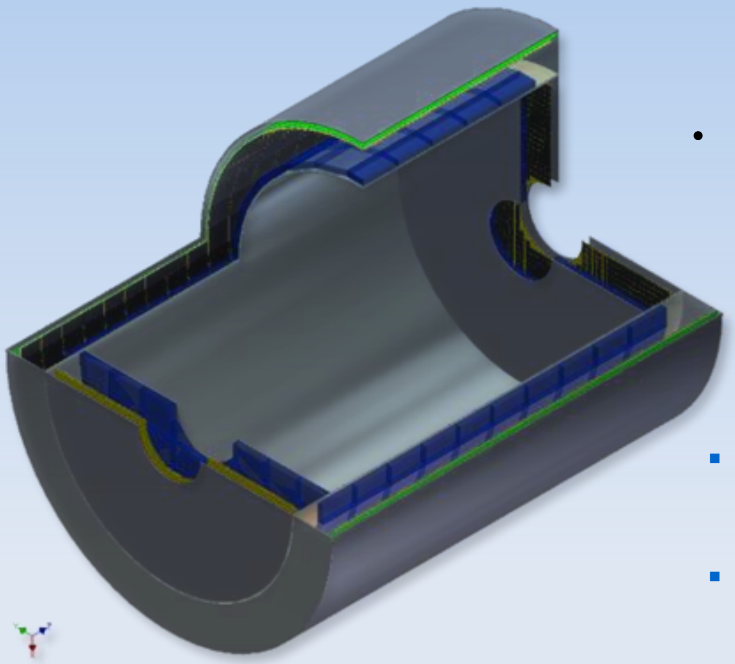
Aerogel RICH for CLAS12





-> Talks of Marco Mirazita and Marco Contalbrigo

Future plans at BINP: Focusing Aerogel RICH for the Detector at Super Charm-Tau Factory



Main motivation

- **Search for lepton number violation decay $\tau \to \mu\gamma$ at the level of 10^{-9} requires μ/π identification in the momentum region 0.5 to 1.5 GeV/*c* for background suppression from $\tau \to \pi\pi^0\nu$ (*Br*=0.25)**

Main parameters of FARICH

- Focusing aeroge radiator n_{max}=1.07, 4 layers
- Photon detector SiPM type, ~3x3mm^2, step 4 mm
- Photon detector area: 20 m^2
- Radiator area: 14 м^2
- ~1 million of channels

Спасибо за внимание

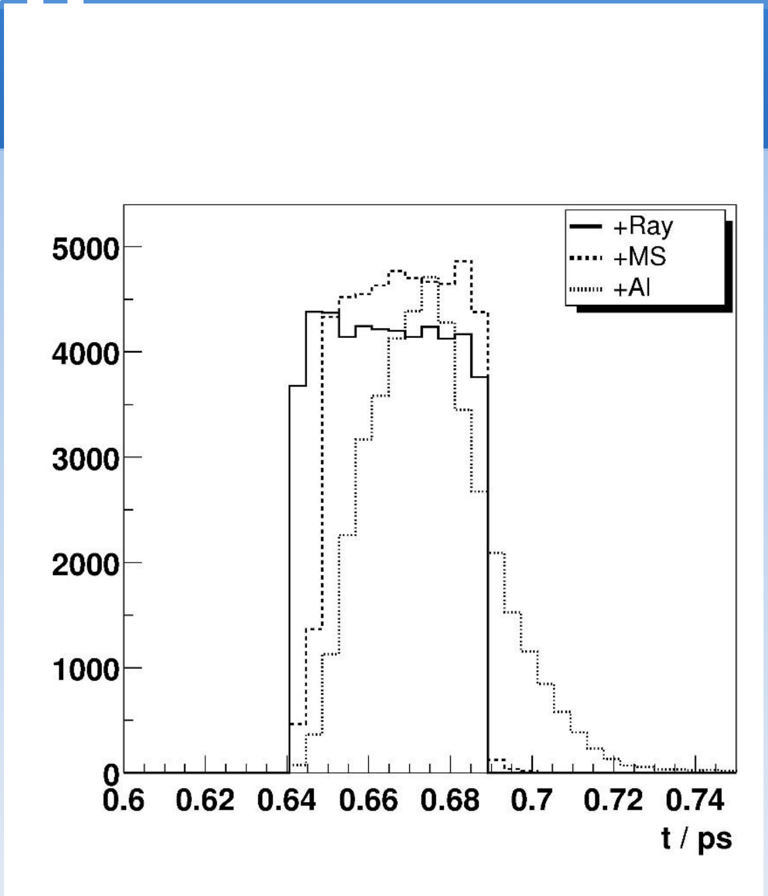
Additional slides

Detectors with record timing resolution

The task:

Measurement of the longitudinal profile of particle beam

- Transition radiation used usually.
- Advantages of Cherernkov radiation:
  - Higher intensity
  - Directionality



	n=1.01	n=1.03	n=1.05	n=1.01
h, mm	20	2	1	1
RMS, пс	0.58	0.110	0.091	0.017

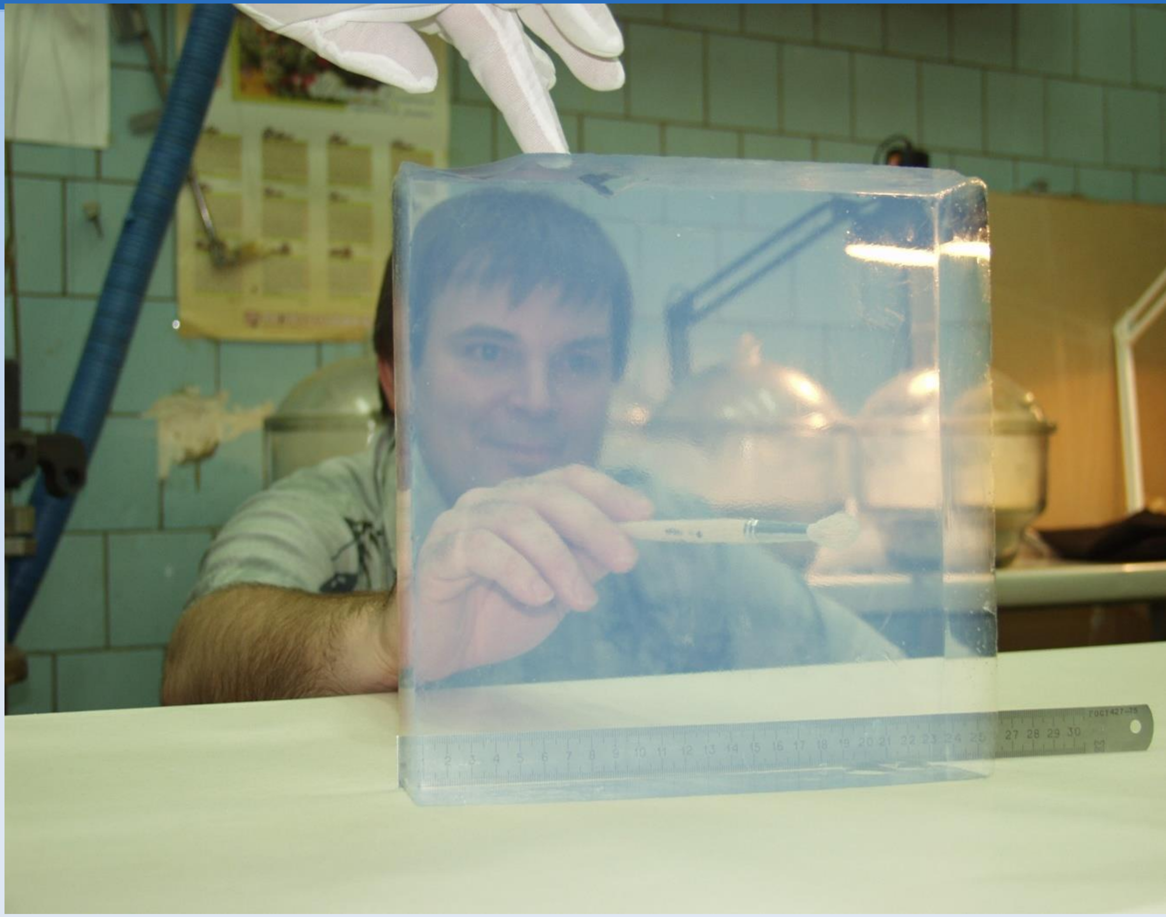
J.Bahr, A.Onuchin et.al., NIM A538(2005)597

Разработка аэрогеля для Черенковских счетчиков в Новосибирске

Aerogel development has started in 1986 (KEDR detector project)

More than 3000 liters have been produced:

- 2000 liters – KEDR and SND ASHIPH counters
- ~ 1 м^2 LHCb RICH,
- ~ 2 м^2 AMS02 RICH
- ~ 5 м^2 CLAS12 RICH

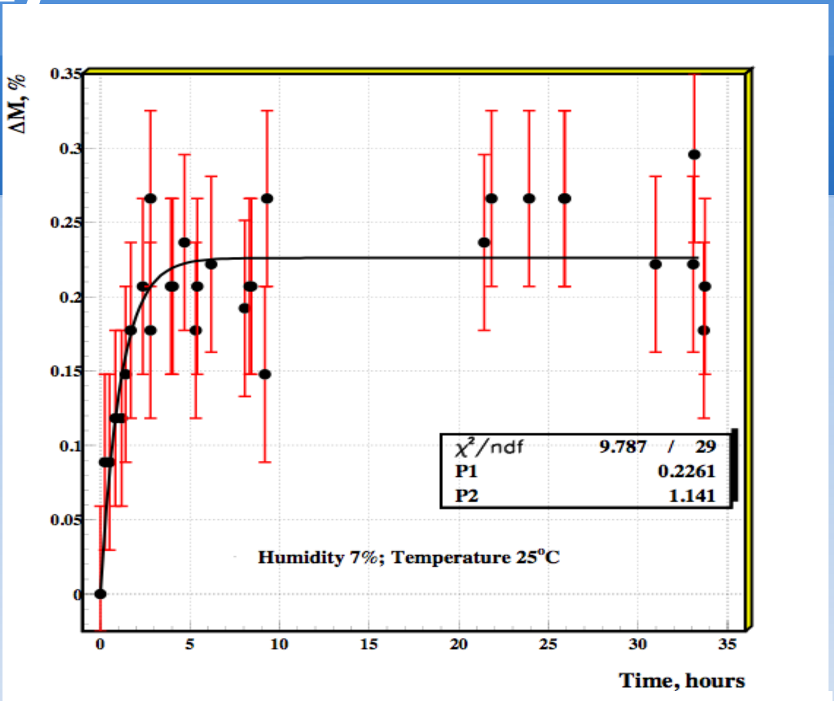


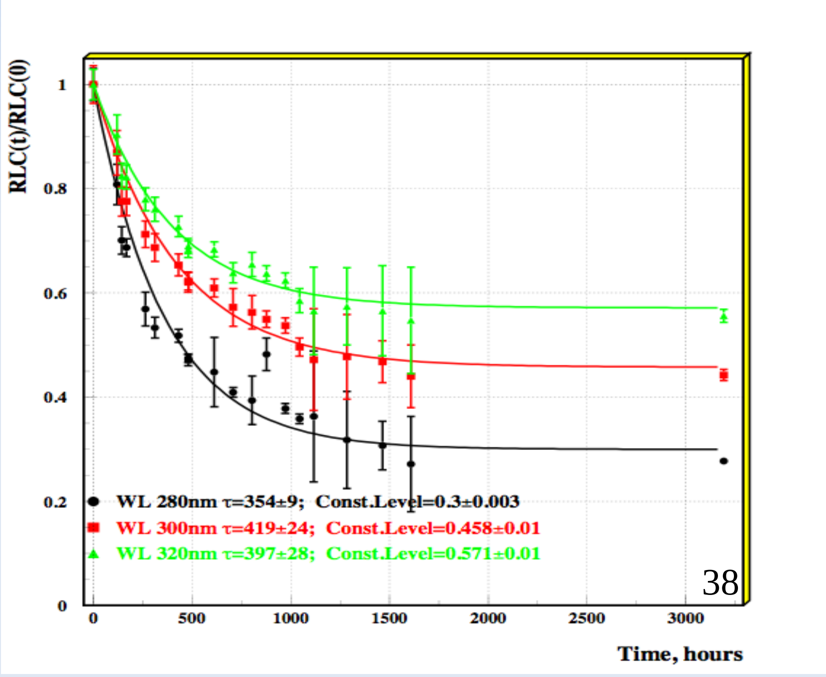
n = 1.006 – 1.06 (1.13)

Aerogel degradation due to water adsorption(1)

- Aerogel internal surface is 10^6 times greater than external. Adsorption of water is very fast process (1-10 hours).
- Degradation of the light absorption length is very slow process (1-2 months) after water absorption.
- The time and the level of the degradation are depend on the impurities in aerogel from raw materials and production procedure (Fe, Mn, Cr, etc.).

Concentration of metals in aerogel, ppb				
Fe	Cu	Mn	Cr	Ni
500	56	7	26	





Aerogel degradation due to water adsorption(2)

- The refractive index (n-1) and light scattering length depends on amount of adsorbed water and are changed less than 10% after water adsorption of 2-4% of aerogel mass.
- The light absorption length (L_{abs}) in different aerogel samples after baking is the same, but after water impregnation could be very different
- It is possible to make aerogel selection after water impregnation
- One atom Fe is able to attract 6 molecules of water
- To achieve maximum degradation of L_{abs} it is enough to adsorb 1ppm of water.

(NIM A598 (2009) 166-168)