On features of aerogel produced in Novosibirsk

Alexander Barnyakov on behalf of BINP Aerogel team

OUTLINE:

Optical and other parameters of Novosibirsk aerogel

Status of aerogel R&Ds in Novosibirsk

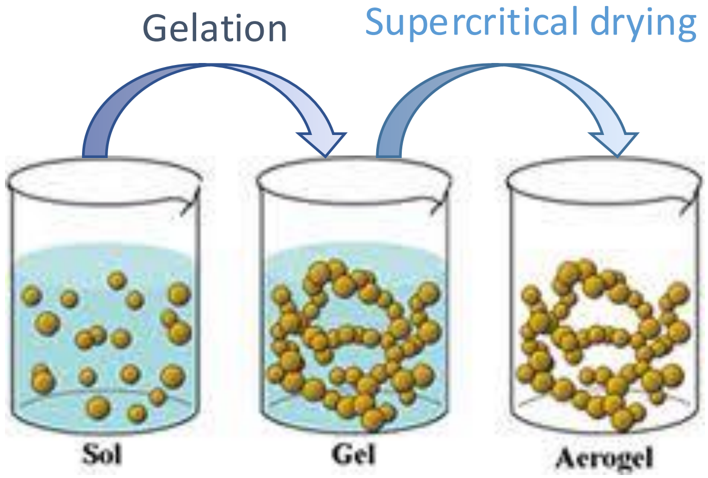
Test beam with hadrons at IHEP (Protvino, Russia) with FARICH

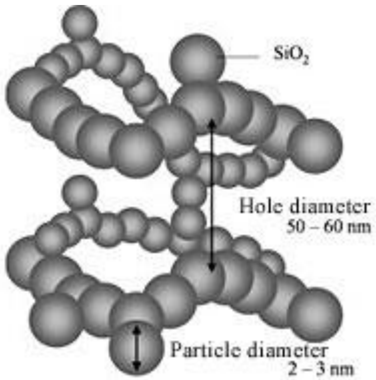
Summary

Aerogel properties and features

Silica aerogel

- Silica aerogel was first produced in 1931 by Samuel S. Kistler
- Lightest solids. Close the nature's gap in refractive index between gases @ STP ($n\text{-}1 \lesssim 10^{-3}$) and liquids/solids ($n \gtrsim 1.3$).
- 3D network of SiO_2 nanometer sized pellets and 50-100 nm pores
- Now produced by sol-gel method out of silicon alkoxide $Si(OR)_4$



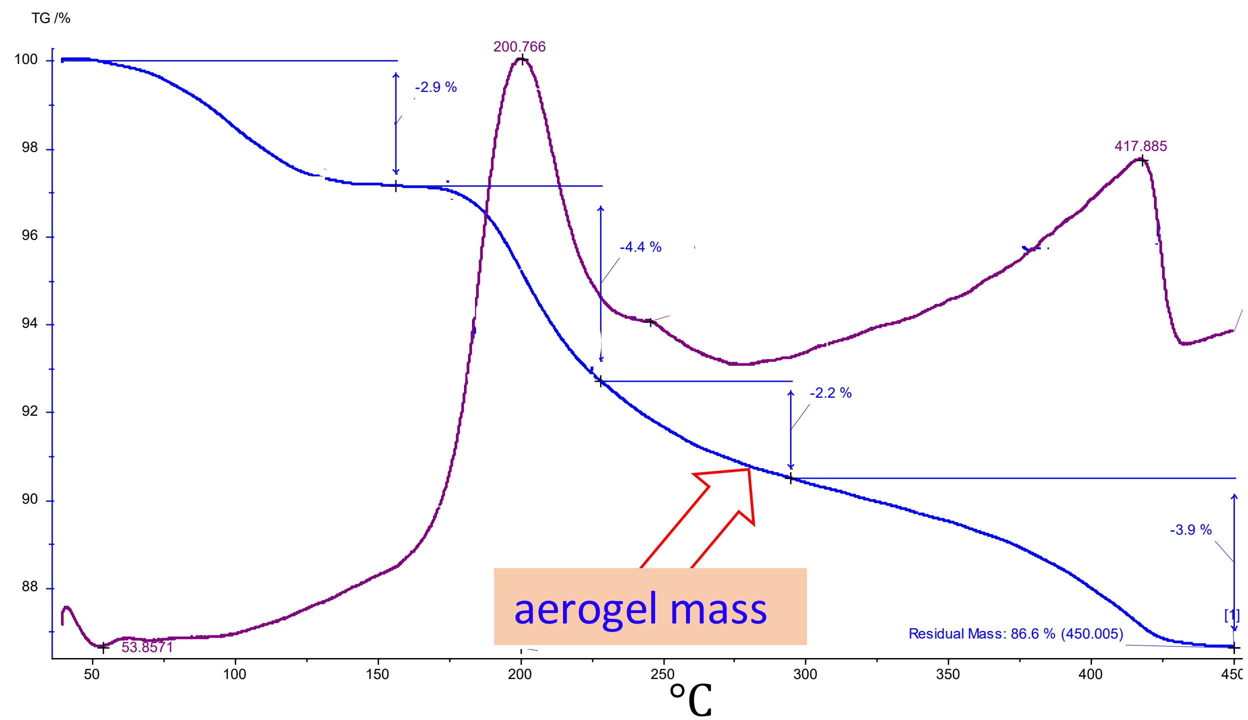


Production method

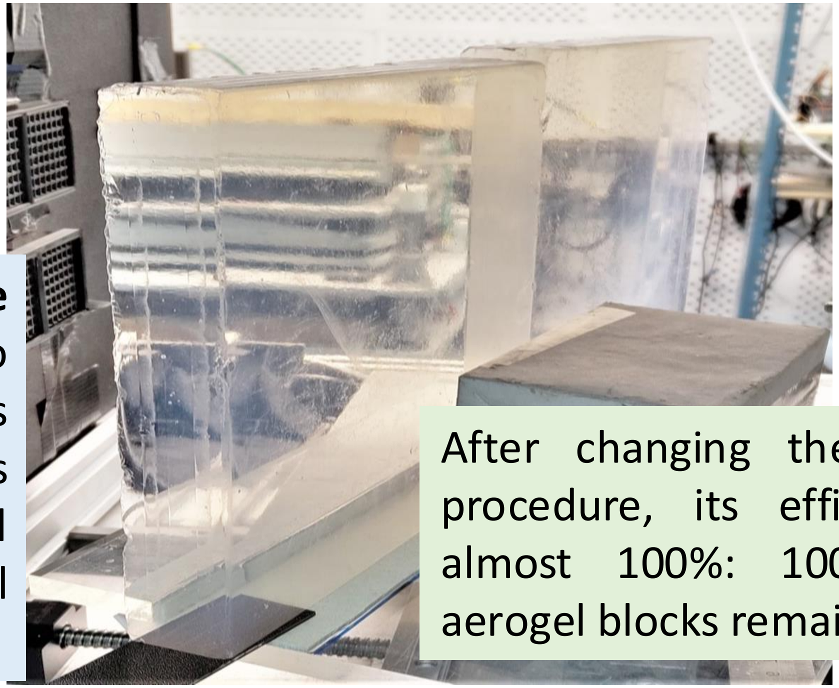
- Production method:
- Synthesis of the alcogel:
- $Si(OR)_4 + 2H_2O \Rightarrow SiO_2 + 4HOR$
- alkoxide water silica alcohol
- Supercritical drying in the autoclave to remove alcohol P_{max}=100 atm, T_{max}= 260°C
  - methanol – P_{cr}=81 atm, T_{cr}=230°C
  - isopropanol – P_{cr}=53 atm, T_{cr}=235°C
  - 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 99.8%
- Inner surface 800 m^2/g

Aerogel annealing



- Up to about 120 °C, the annealing process involves heat absorption (desorption of water and organic matter).
- Starting from 170 °C, heat generation begins to increase and mass decreases – organic matter burns out.
- Heat release at 417 °C is presumably the afterburning of organic matter.



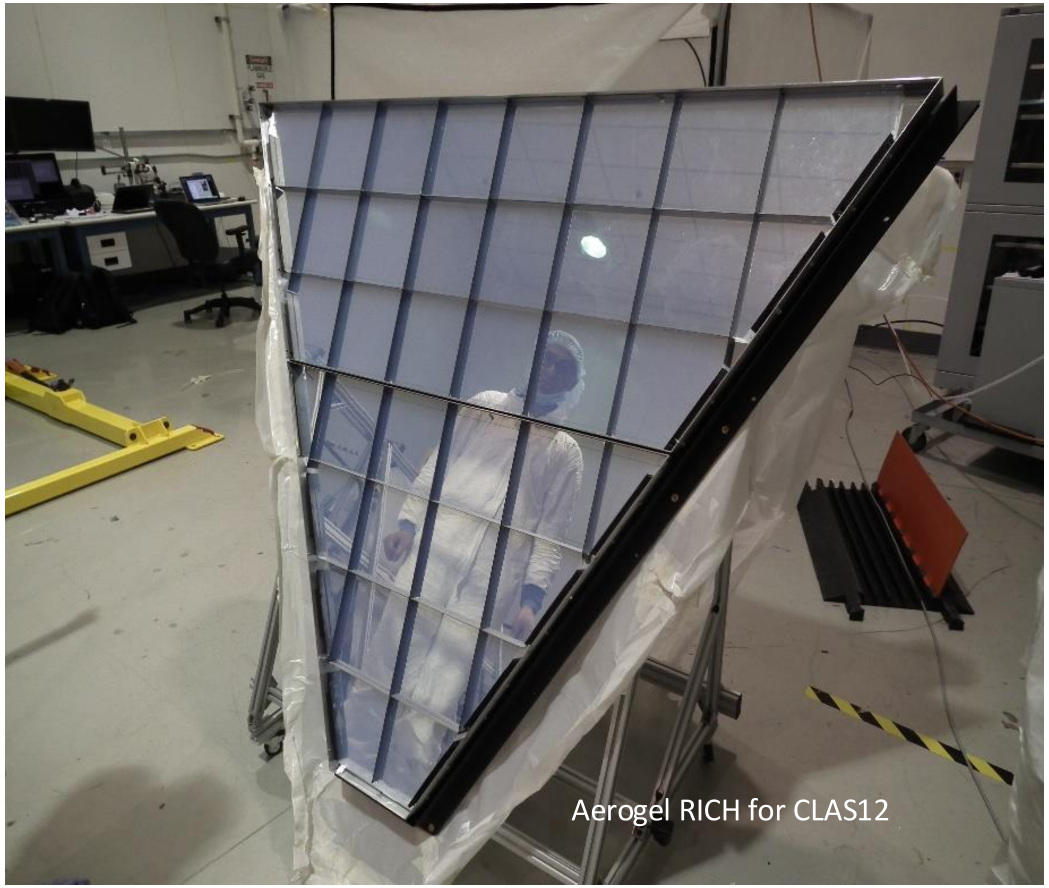
In 2023, the procedure for annealing aerogel in an air atmosphere was changed to increase its transparency. The process of heating to the organic burnout temperature (approximately 170 °C) has become smoother (taking longer), and the aerogel annealing stage is also included in this cycle without raising the temperature for several hours at 170 °C, so that the organic matter contained in the aerogel burns out without destroying the source block.

After changing the annealing procedure, its efficiency was almost 100%: 100% of the aerogel blocks remain intact.

History of aerogel radiators in Novosibirsk

The history of the Novosibirsk aerogels began in 1986.

- KEDR ASHIPH system (VEPP-4M – BINP):
  - π/K-separation in the momentum range 0,6÷1,5 GeV/c.
  - Aerogel $n = 1{,}05$ (V~1000 L).
- SND ASHIPH system (VEPP-2000 – BINP):
  - π/K-separation in the momentum range 300÷870 MeV/c.
  - Aerogel $n = 1{,}13$ (V~9 L).
- DIRAC-II (PS – CERN):
  - π/K-separation in the momentum range 5,5÷8,0 GeV/c.
  - Aerogel $n = 1{,}008$ (V~9 L).
- AMS-02 aerogel RICH (ISS):
  - Search for antimatter, study of cosmic rays.
  - Aerogel $n = 1{,}05$ (S~1 m^2).
- LHCb aerogel RICH (LHC – CERN):
  - π/K-separation in the momentum range 5,5÷8,0 GeV/c.
  - Aerogel $n = 1{,}03$ (S~0,5 m^2), aerogel tile 20x20x5 $см^3$.
- CLAS-12 aerogel RICH (J-Lab):
  - π/K- & K/p-separation at level 4σ with several momentum GeV/c.
  - Aerogel $n = 1{,}05$ (S~6 m^2), aerogel tile 20x20x2-3 $см^3$.



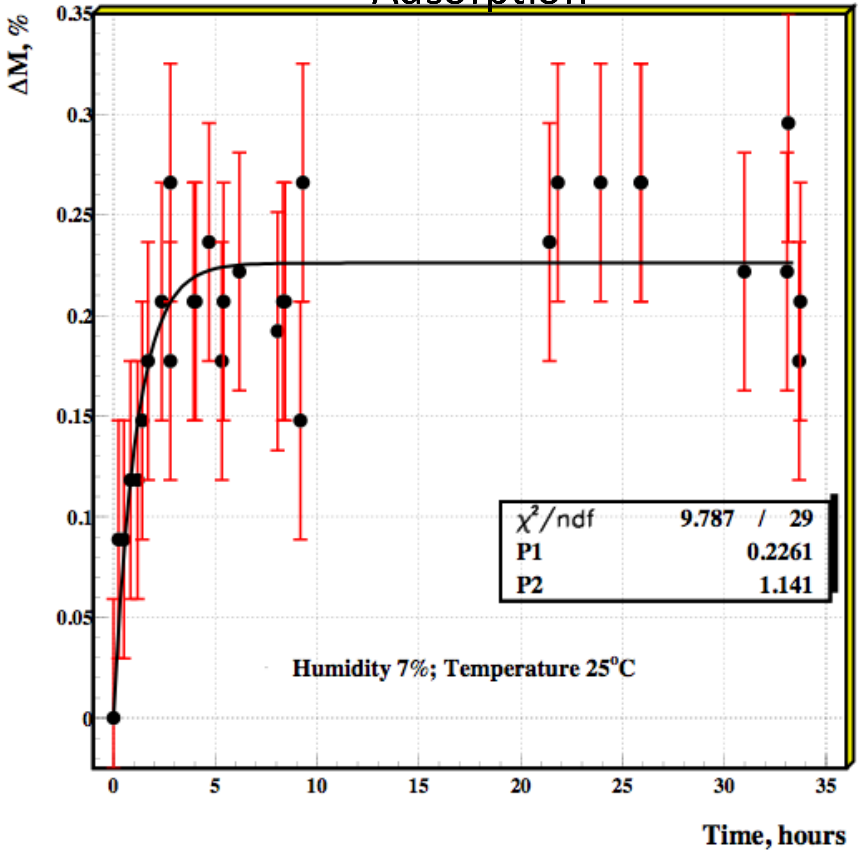
Aerogel RICH for CLAS12

Hydrophilic aerogels

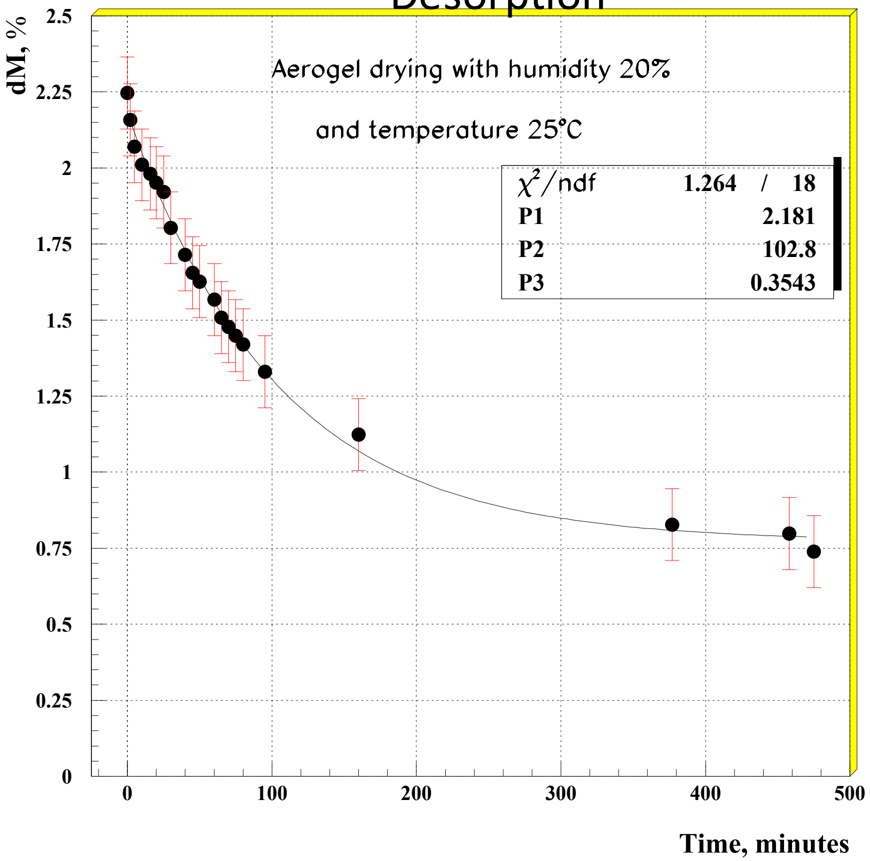
- Aerogel with bulk density 0.24 g/cm^3 has internal surface area by 10^6 times larger than external.
- There are a lot of OH−groups at the aerogel SiO_2 surface. These groups are primary adsorption centres which are able to attract hundreds of the H_2O molecules per each.
- In the hydrophobic aerogels OH−groups are exchanged by hydrophobic radicals such like $Si(CH_3)_3$
- Influence of adsorbed water on optical parameters of hydrophilic aerogels produced in Novosibirsk are very well studied already.
- Heating of hydrophobic aerogel up to above 175℃ makes it hydrophilic. Also more active radicals are able to replace $Si(CH_3)_3$ – groups and change aerogel optical parameters.
- Before the finalization of any aerogel based counters design it is necessary to investigate influence of materials which are going to be used in the construction on aerogel transparency.

Water adsorption by aerogel

Adsorption

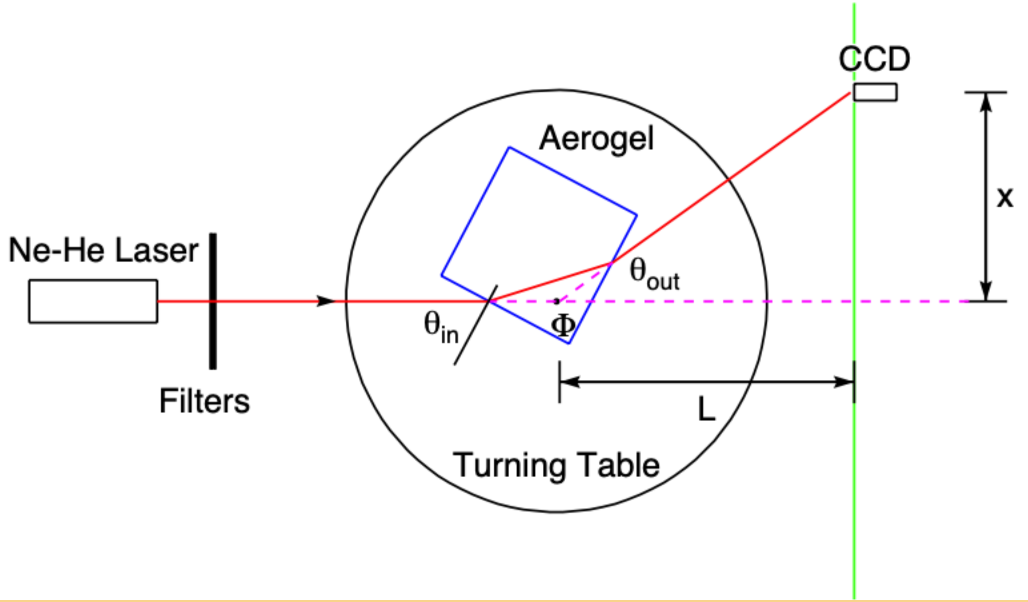


Desorption



- Water adsorption and desorption are the fast processes with time constant about 1 hour.
- Amount of adsorbed water depends on relative humidity of invironment.
- Rayleigh light scattering is changed proportionaly to amount of adsorbed water
- Light absorption length connected with chemical boundings of impuritues with OH-groups and takes more time (1-2 monthes) see details in *A.Yu.Barnyakov et al., NIM A598 (2009) 166-168*

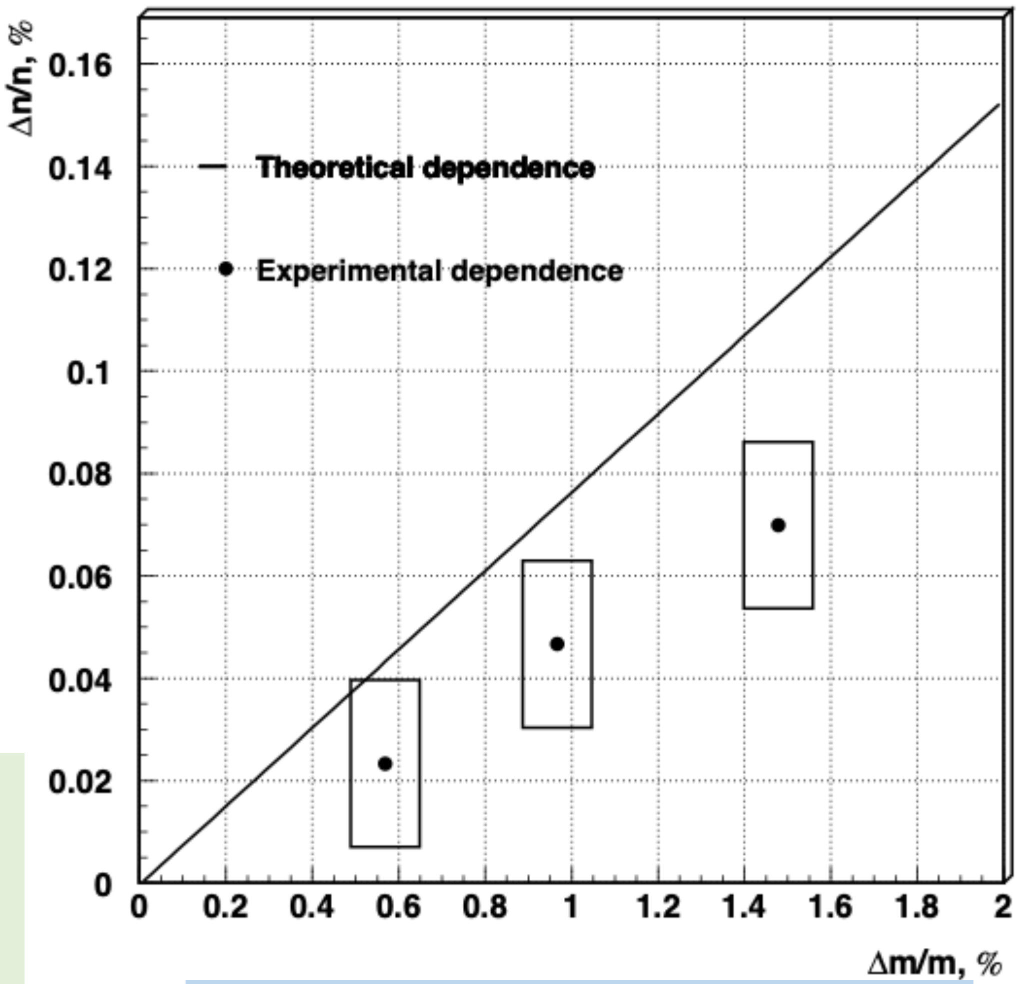
Refractive index



Impirical relation is used for fast determination of n:

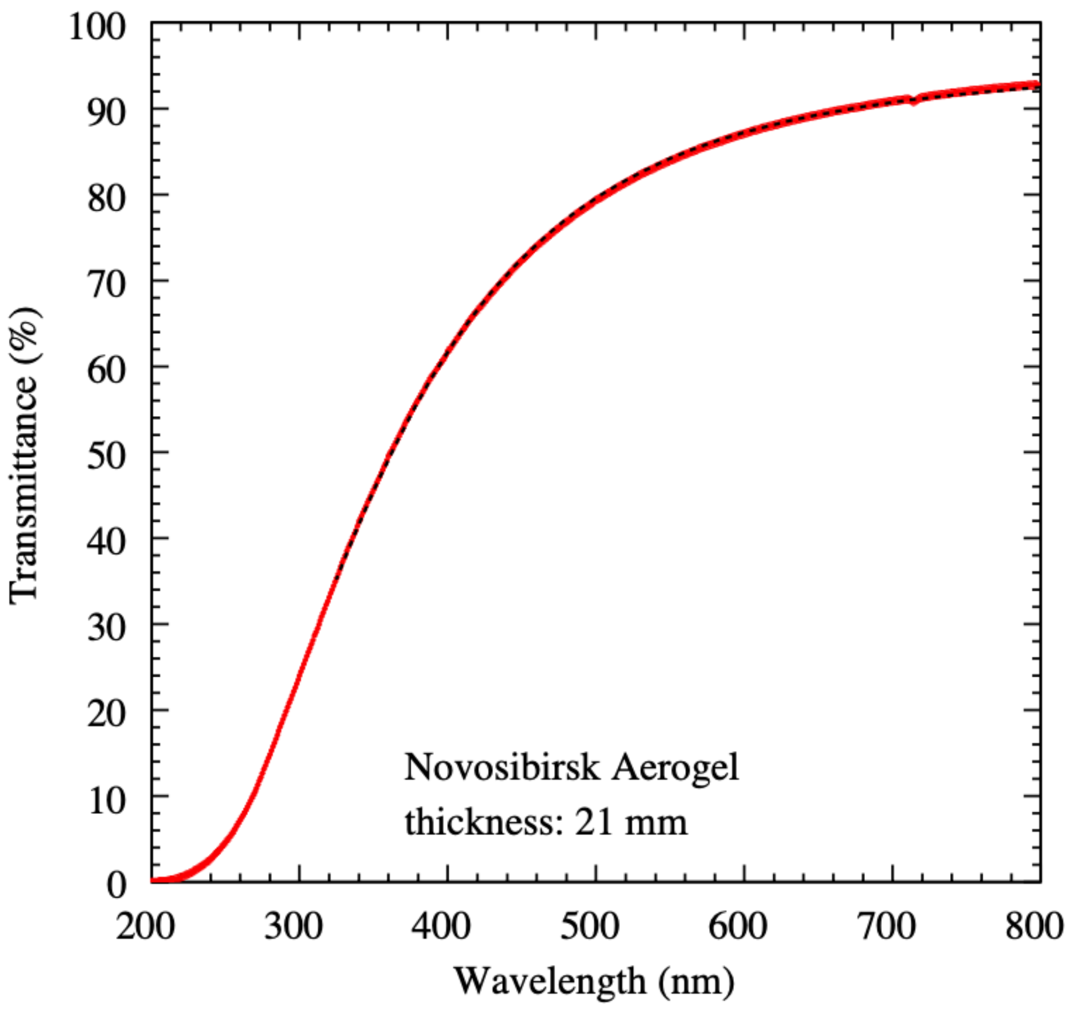
$$n^2 = 1 + 0.438 \cdot \rho \left[{}^{g}/_{cm^3}\right]$$

For theoretical dependence Lorentz-Lorentz formula was used, which was expressed to calculate refractive index of gases mixtures but it very often works for other mixtures.



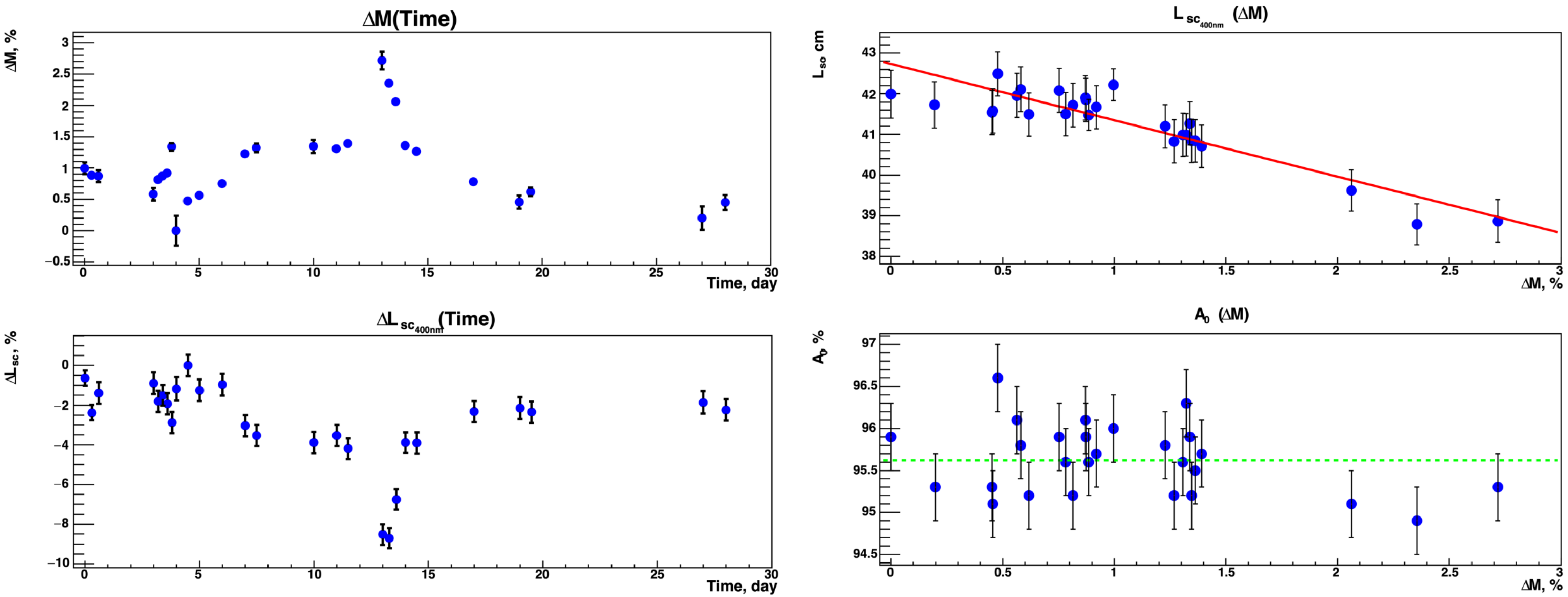
n dependence on water adsorption

Aerogel transmittance and parameters of Rayleigh scattering



- Hunt formula to fit the transmittance (T) usually are used in two variations:
- $T(\lambda) = \frac{I}{I_0} = A_0 e^{-\left(\frac{d}{L_{sc}^{400} \times \left[\frac{\lambda}{400}\right]^4}\right)}$
- or
- $T(\lambda) = \frac{I}{I_0} = A_0 e^{-\left({C \cdot d}/{\lambda^4}\right)}$
- where d – aerogel thickness, L_{sc}^{400}– light scattering length at 400 nm and C – so called clarity, A_0 – coefficient responsible for light absorption and scattering at the surface of aerogel samples.

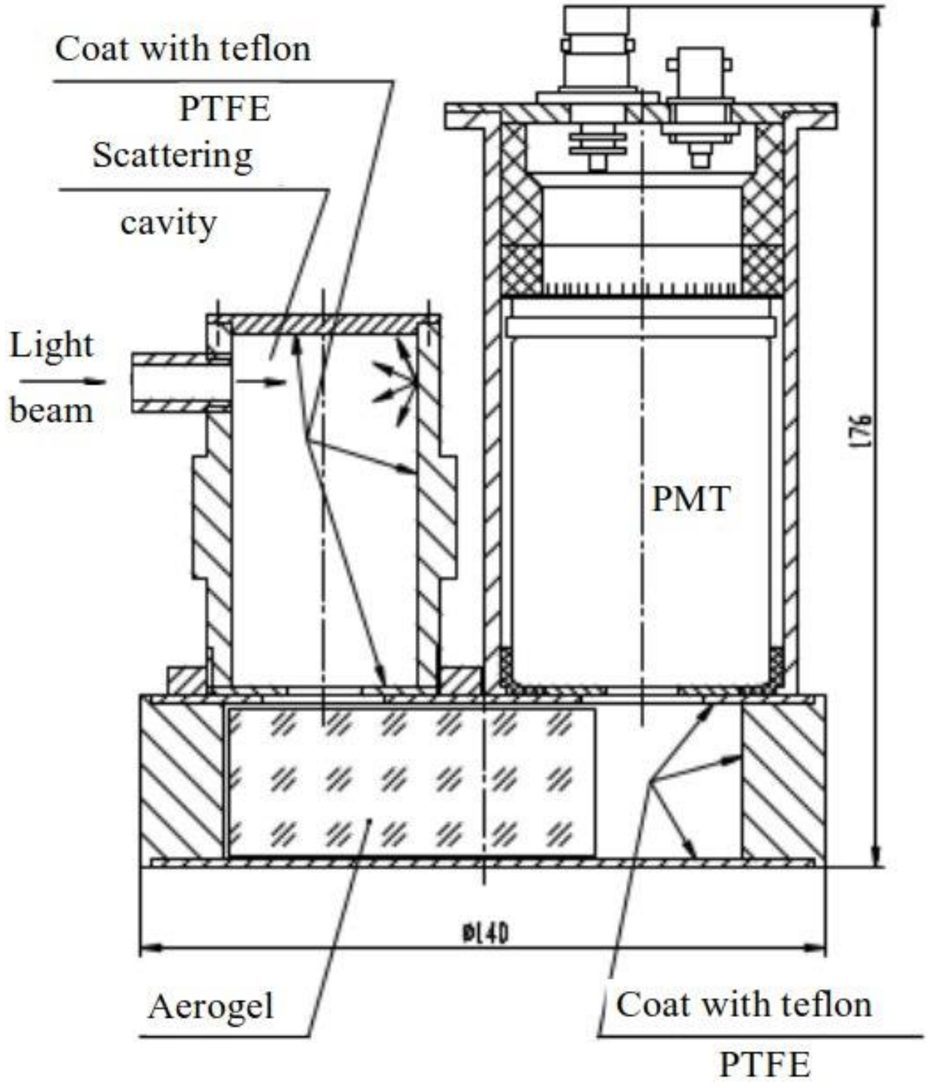
Influence of adsorbed water on Raleigh light scattering



Raleigh light scattering in aerogel strongly dependce on amount of adsorbed water the effects of light scattering length decrease in normal conditions doesn't exceed 10% (L_{sc}(400 nm) drops from 43 to 38 mm).

T. Bellunato, et al., NIM A 527(3) (2004) 319

RLC & Light absorption length measurement



- Relative light collection (RLC):

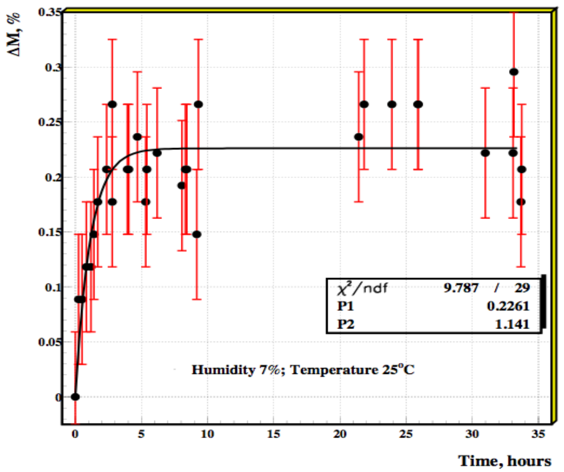
$$RLC(\lambda) = \frac{LC_{aer}(r(\lambda),\ L_{sc}(\lambda),\ L_{abs}(\lambda))}{LC_{box}(r(\lambda))} = \frac{I_{aer}(\lambda)}{I_{box}(\lambda)}$$

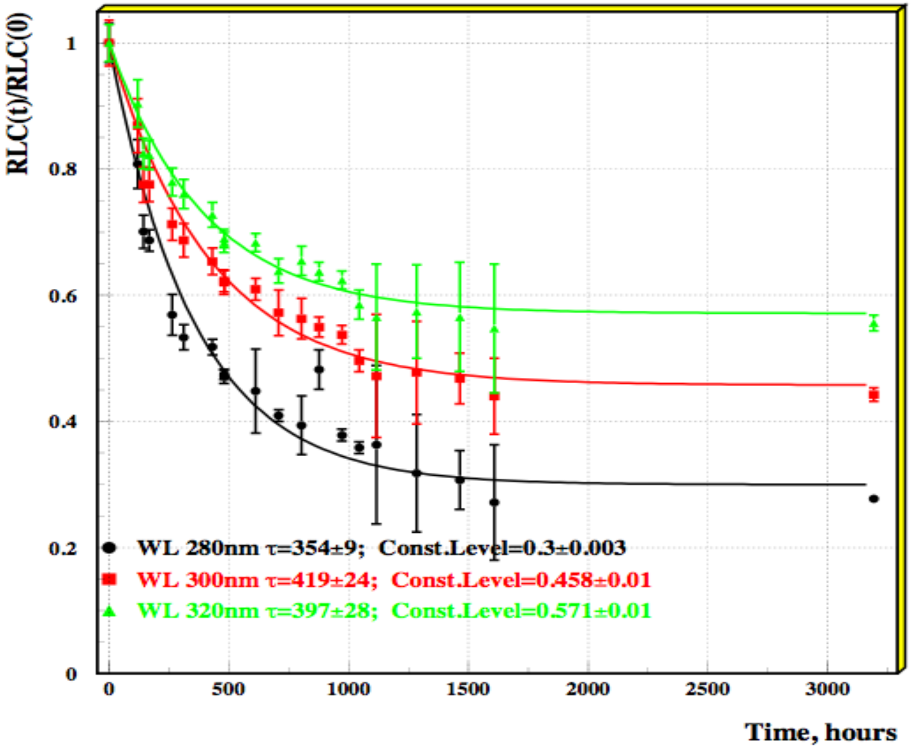
- Light scattering length $\left(L_{sc}(\lambda)\right)$ determined by Raleigh scattering in aerogel is measured from fit of aerogel transparency data.
- To determine reflective coefficient $\left(r(\lambda)\right)$ of PTFE a special data are took with "Scattering cavity" coupled to PD
- Monte-Carlo simulation is used to evaluate light absorption length $\left(L_{abs}(\lambda)\right)$ from $RLC(\lambda)$ measured data

Light collection degradation due to water adsorption

- Aerogel internal surface is 10^6 times greater than external. Adsorption of water is very fast process (1-2 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	

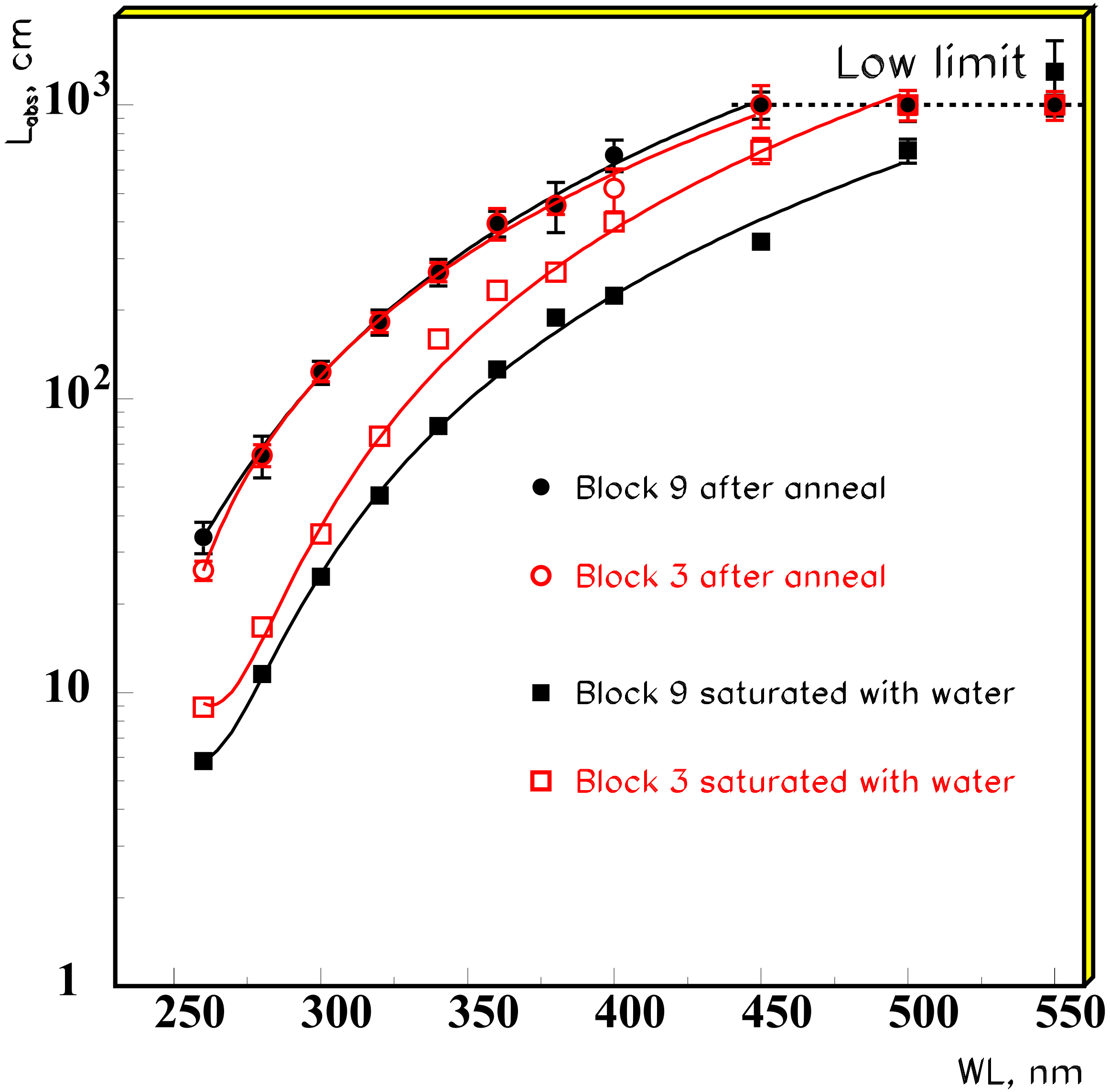




Aerogel light absorption length degradation due to water adsorption

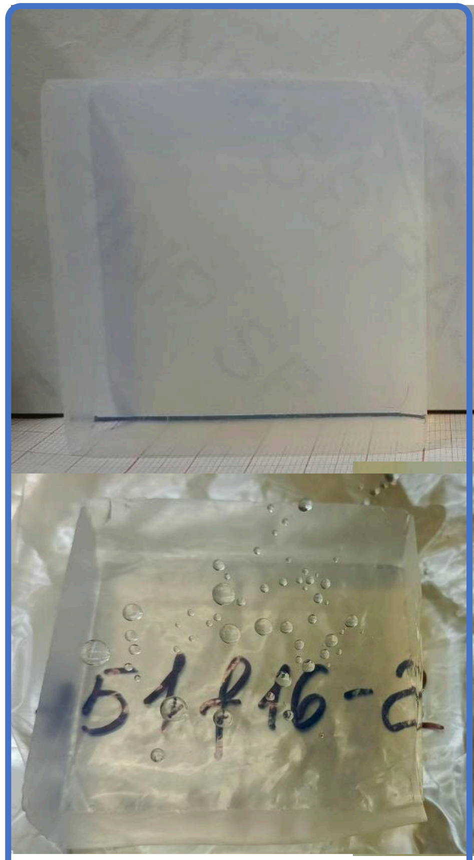
- The refractive index (n-1) and light scattering length depends on amount of adsorbed water and are changed less than 10% after water adsorption of 2-4% of aerogel mass.
- The light absorption length (L_{abs}) in different aerogel samples after baking is the same, but after water impregnation could 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.

•A.Yu.Barnyakov et al., NIM A598 (2009) 166-168



The first experience with hydrophobization #1

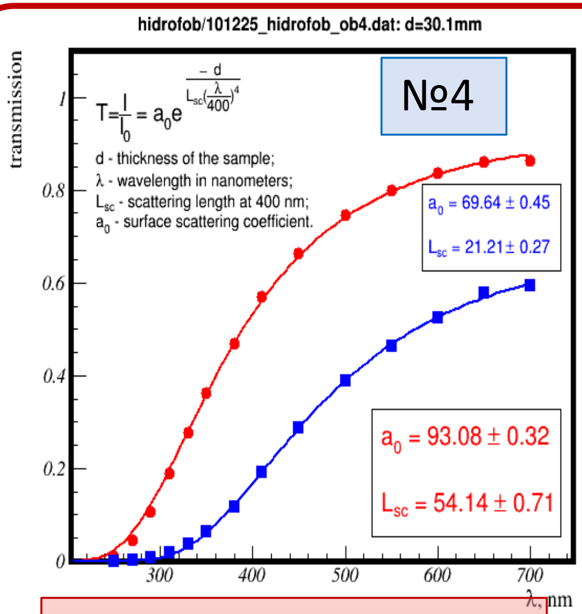
- Production of thick hydrophobic tiles is limitted by large time of fabrication because the clarification processes have to be done at low temperatures (below 175˚C)
- The main idea is to produce thick multilayer aerogels with standard Novosibirsk's procedure when optical clarification is obtained due to burning of the most organic additions in aerogel and after that make hydrophobization in the vapors of the **H**exa**M**ethyl**D**i**S**ilasane ([(CH3)3Si]2NH)



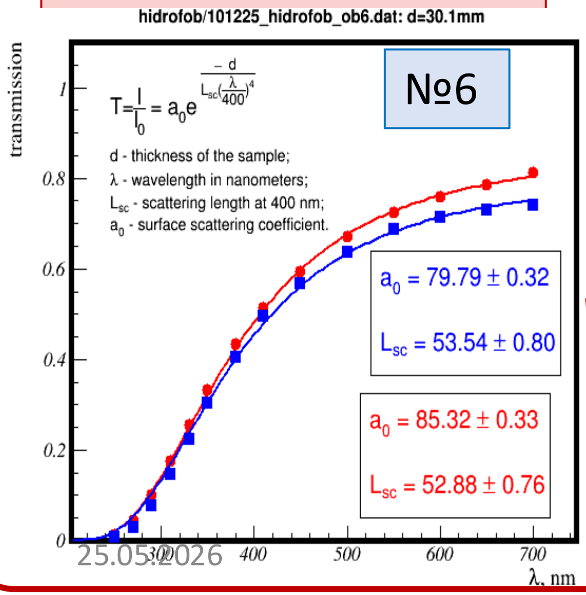
Hydrophobic

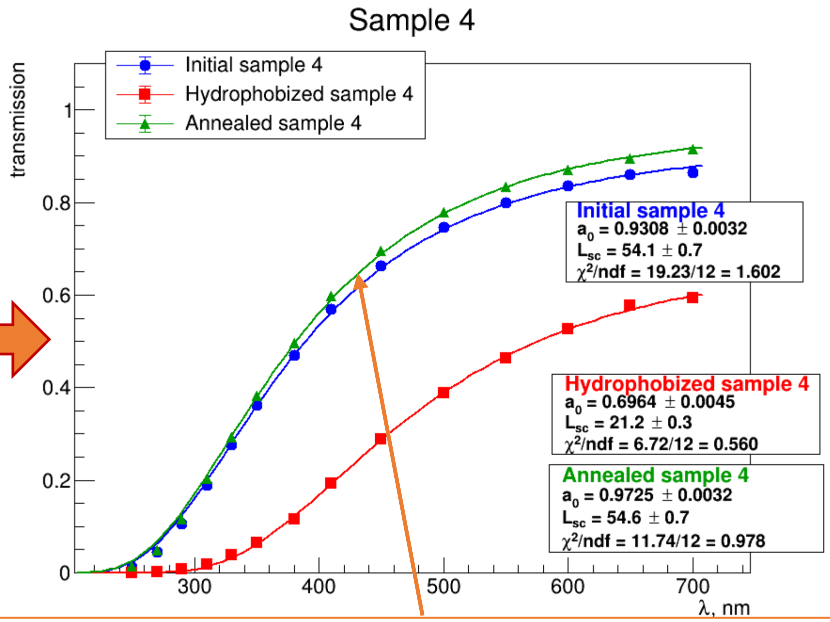
Hydrophilic

The first hydrophobization experience #2



HMDS – 5% (3 samples)





- It was shown, it is possible totally restore optical transparency of hydrophobic aerogels with help of annealing (5 hours at 500˚C)

- Hydrophilic aerogel (left) totally destroid in contact with water, while after hydrophobization it can be tooled by water-jet cutting machine

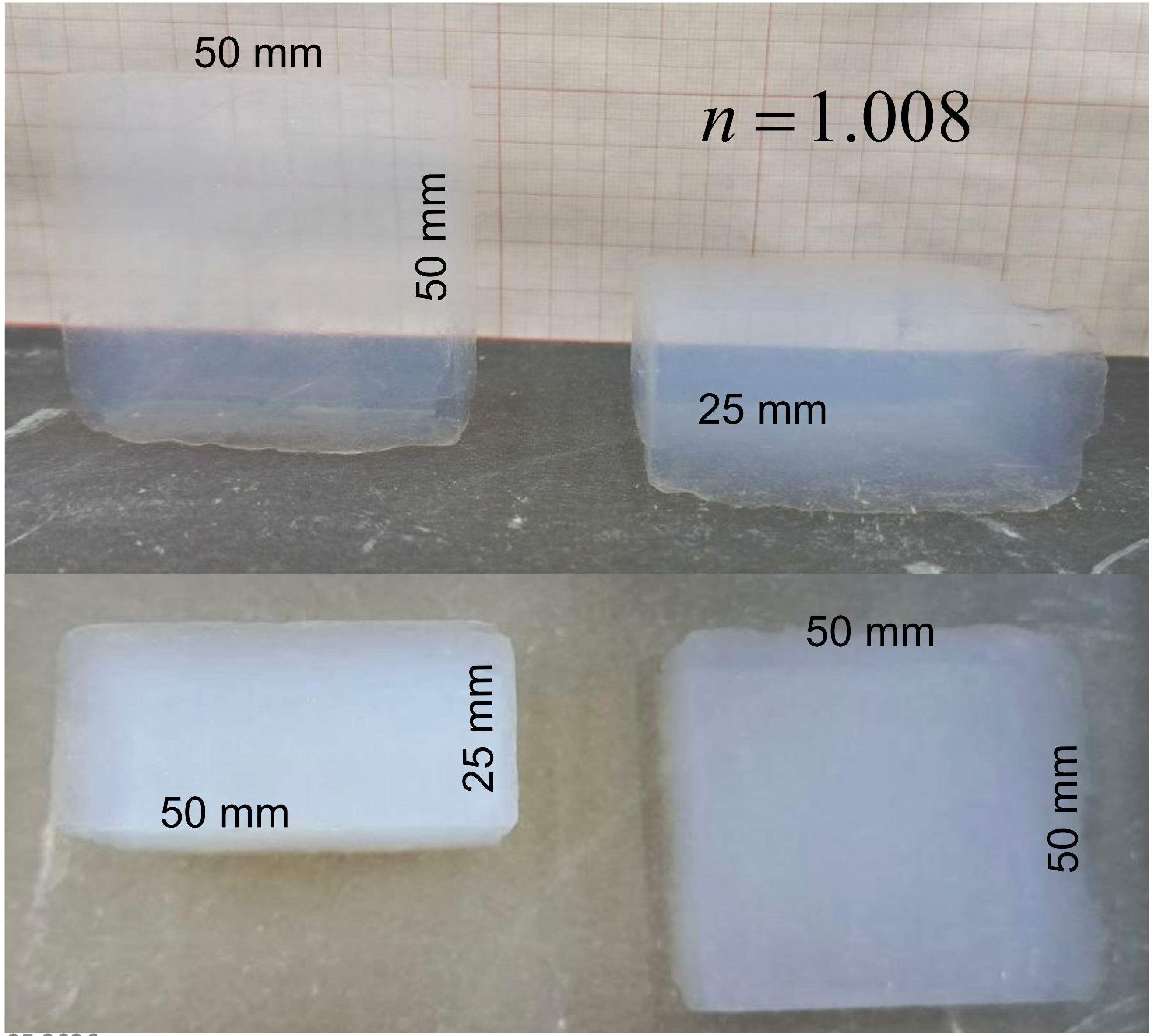
- Influence of hydrophobisation on aerogel transparency has not been studied well yet

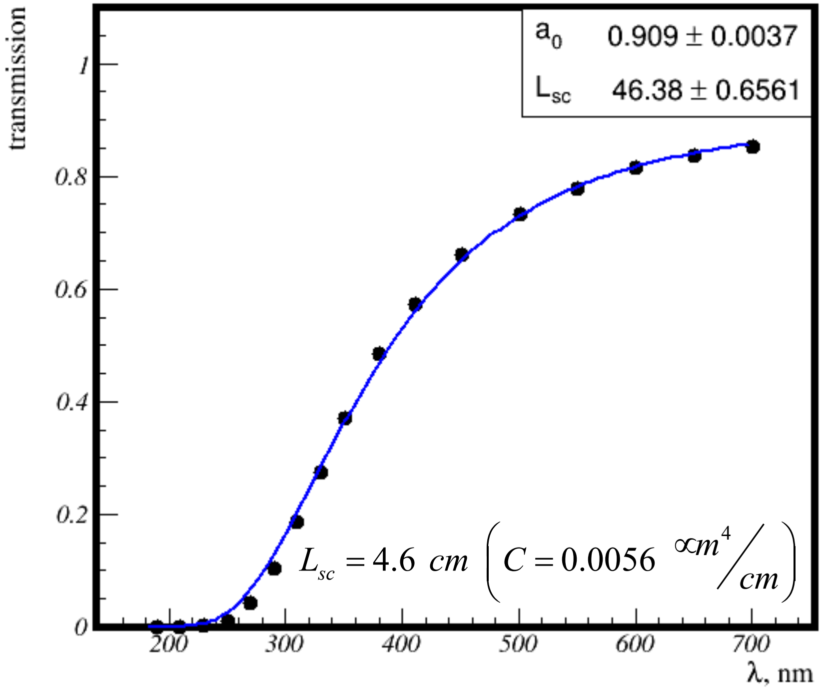
The first practical output:

We can produce aerogels as we need (highly transperant, thick and so on), then make tooling after hydrophobization and restore its tranparency before the assembling the detector.

Ultralight aerogel for CEPC-PID

Aerogel with n=1.008 (Novosibirsk)



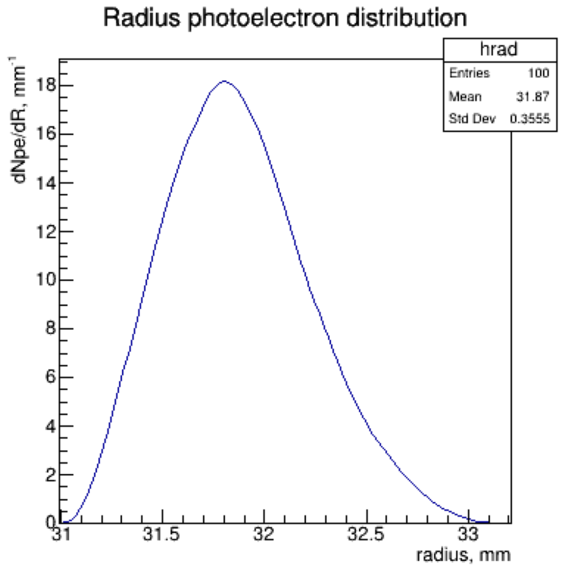


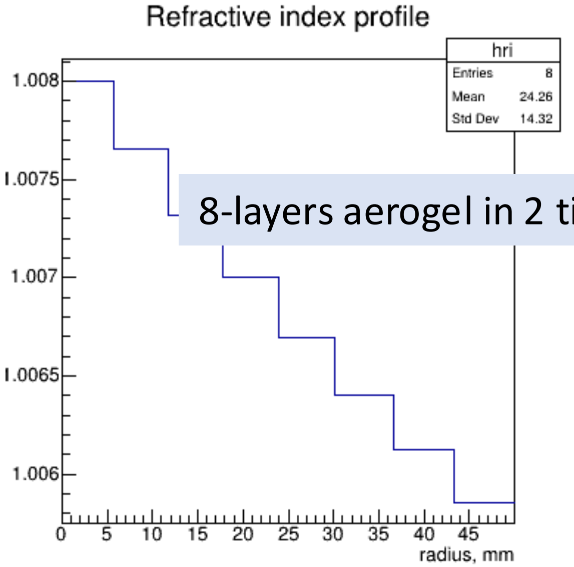
$$T = \frac{I}{I_0} = a_0 \cdot e^{-\frac{d}{L_{sc} \cdot \left(\lambda/400\right)^4}} = a_0 \cdot e^{-\frac{C \cdot d}{\lambda^4}}$$

d – thickness of a sample,
λ – wavelength in nanometers,
Lsc – scattering length at 400 nm,
a_0 – surface scattering coefficient,
C – clarity coefficient

FARICH option for π/K–separation at 30 GeV/c

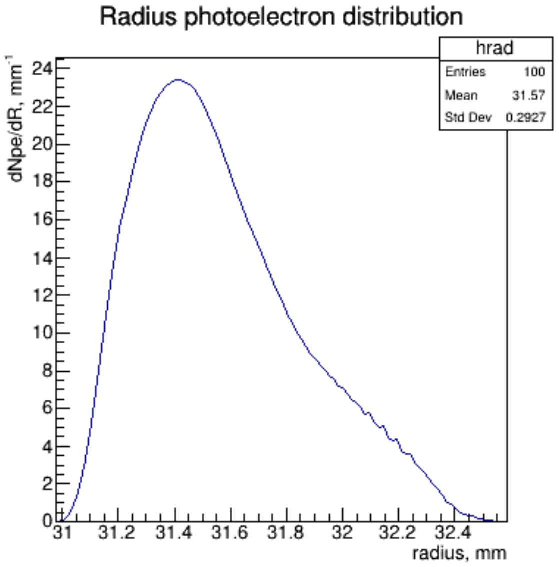
8-layer aerogel n_{max}=1.008; pixel≈0.2mm

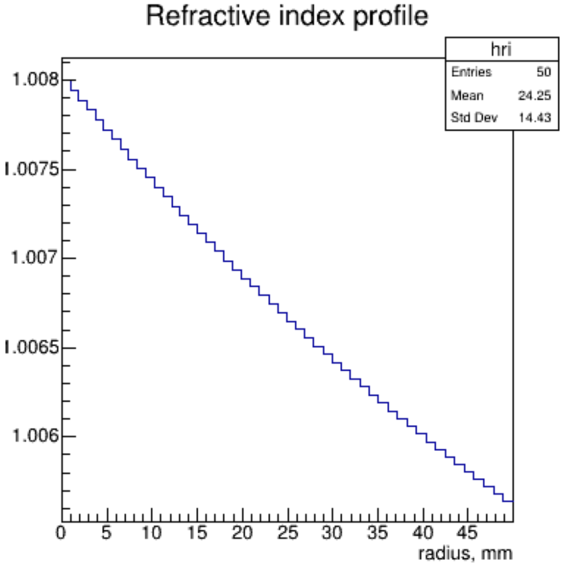




8-layers aerogel in 2 tiles

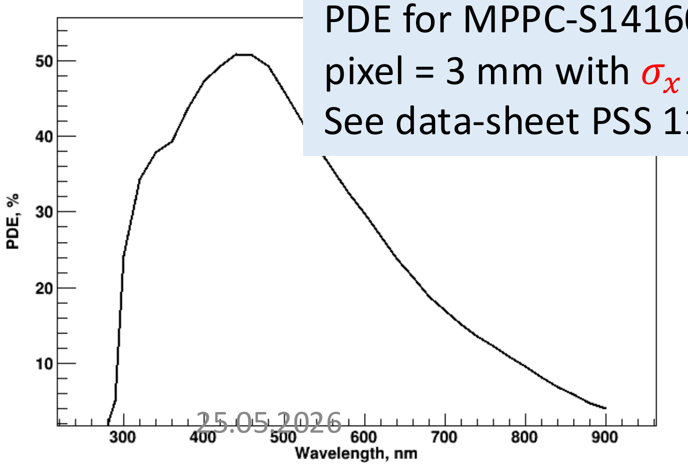
Gradient aerogel n_{max}=1.008; pixel≈0.7mm





Focal distance is 300 mm

The possibility to produce of gradient aerogel was demonstrated in *NIM A766 (2014) 88-91 and NIM A766 (2014) 235-236*



PDE for MPPC-S14160 (Hamamatsu)
pixel = 3 mm with $\sigma_x \approx 0.2mm$
See data-sheet PSS 11-3030-S (NDL)

- $N_{pe} \approx 16$
σ_C^{tr}≈0.33 mrad!!!

- $N_{pe} \approx 16$
σ_C^{tr}≈0.33 mrad!!!

It looks good enough for reliable π/K–separation @ 30 GeV/c

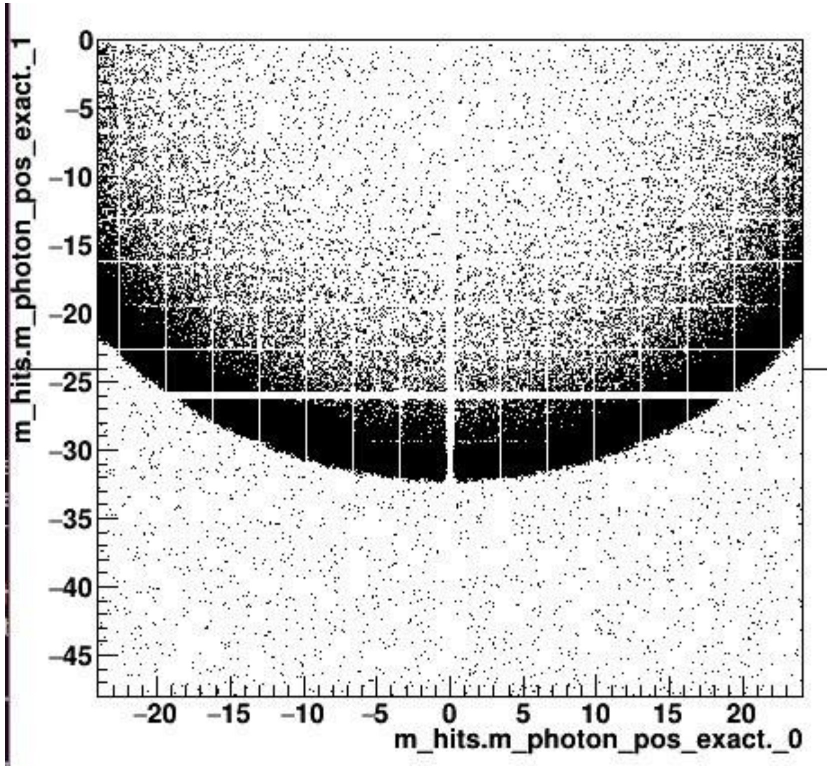
G4sim

8-layers aerogel n_{max}=1.008 (2 tiles)

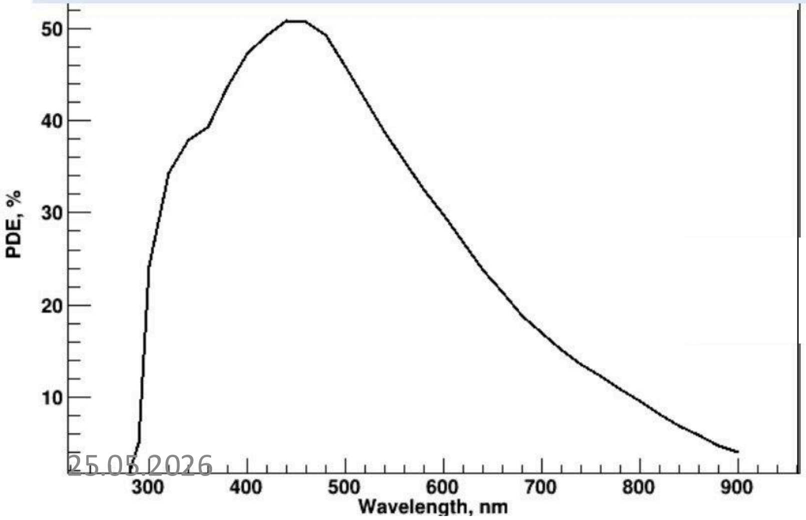
1) 1.0055, t = 8.24
2) 1.0058, t = 8.02
3) 1.0061, t = 7.80
4) 1.0064, t = 7.59

5) 1.0068, t = 7.38
6) 1.0072, t = 7.18
7) 1.0076, t = 6.99
8) 1.0080, t = 6.80

- L_{abs} is taken from *NIMA494 (2002) 491–494*
- $L_{sc}(\lambda)=L_{sc}(400nm)\cdot\left(\frac{\lambda}{400}\right)^4$
- $n(\lambda) = \sqrt{1 + a_0 \cdot \frac{\lambda^2}{\lambda^2-\lambda_0{}^2} \cdot \frac{(n(400)^2-1)}{a_0 \cdot \frac{400^2}{400^2-\lambda_0{}^2}}}$, where λ_0=83.22 nm and a_0=0.05639 is taken from *Eur. Phys. J. C 52, 759–764 (2007))*



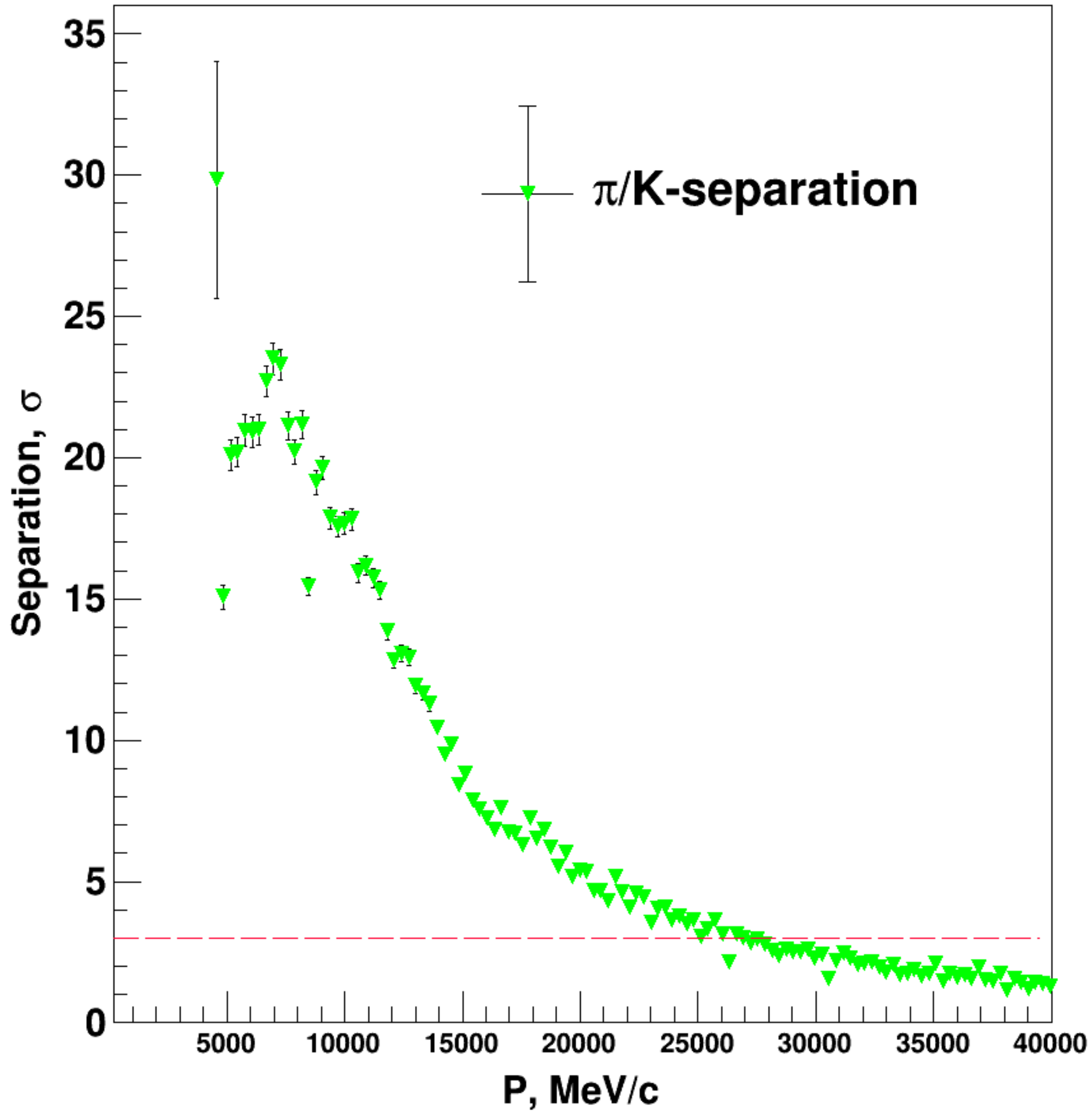
PDE for MPPC-S14160 (Hamamatsu)

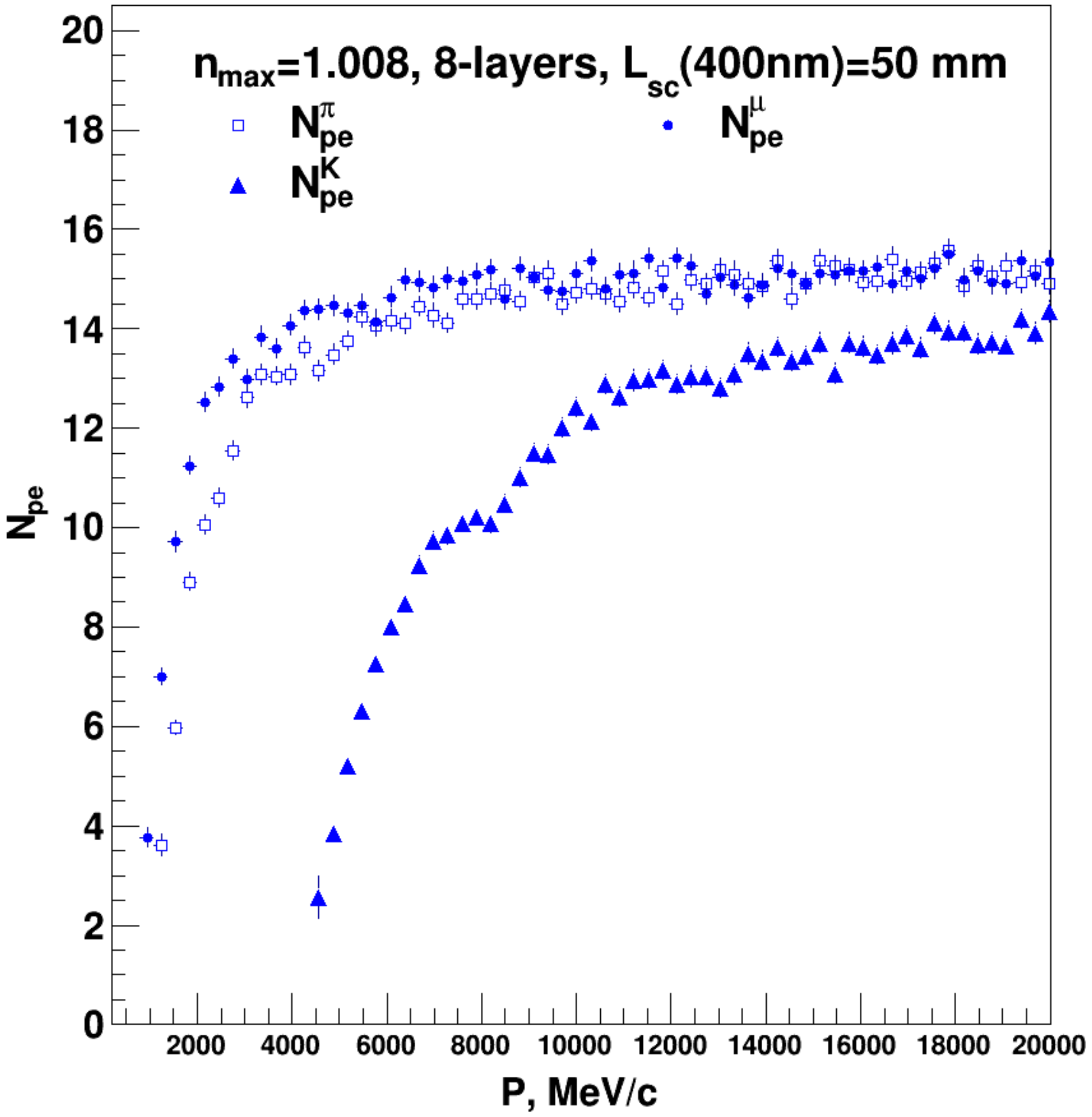


pixel = 3 mm & $\sigma_x \approx 0.2mm$

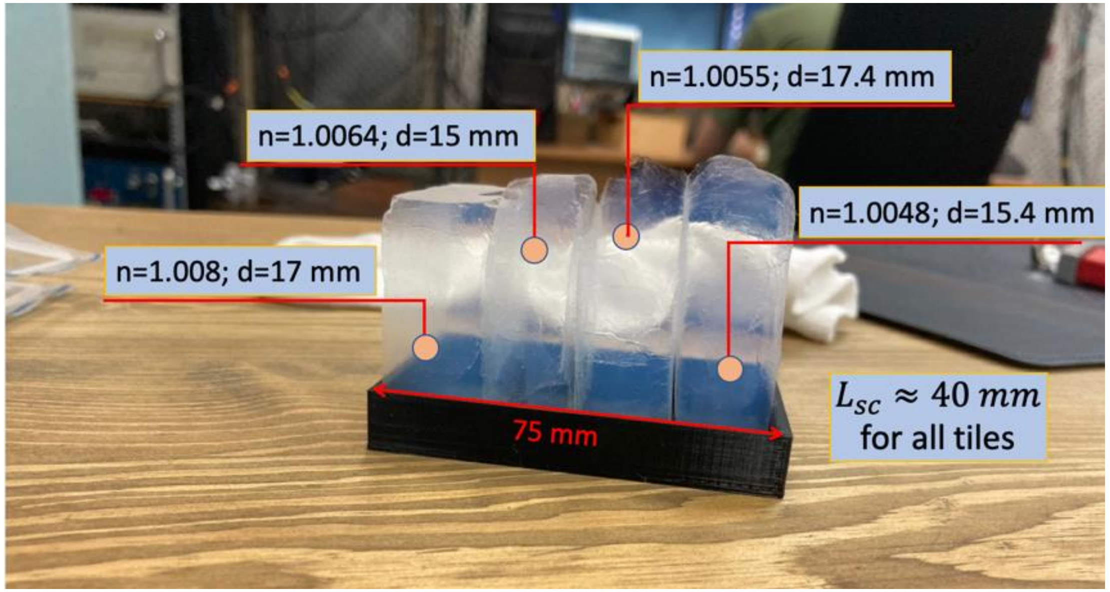
Focal distance is 300 mm

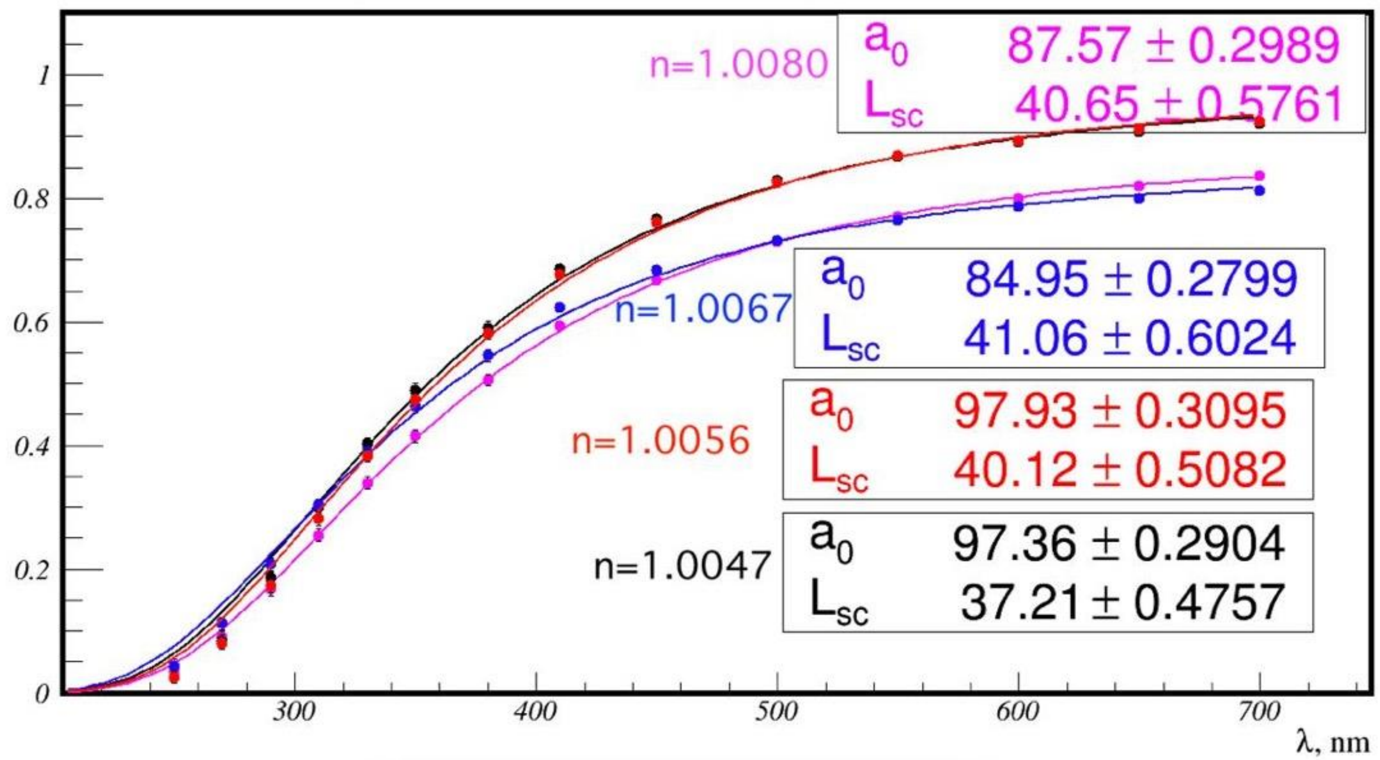
FARICH option for π/K–separation at 30 GeV/c: G4sim results





Some practical results of 2025

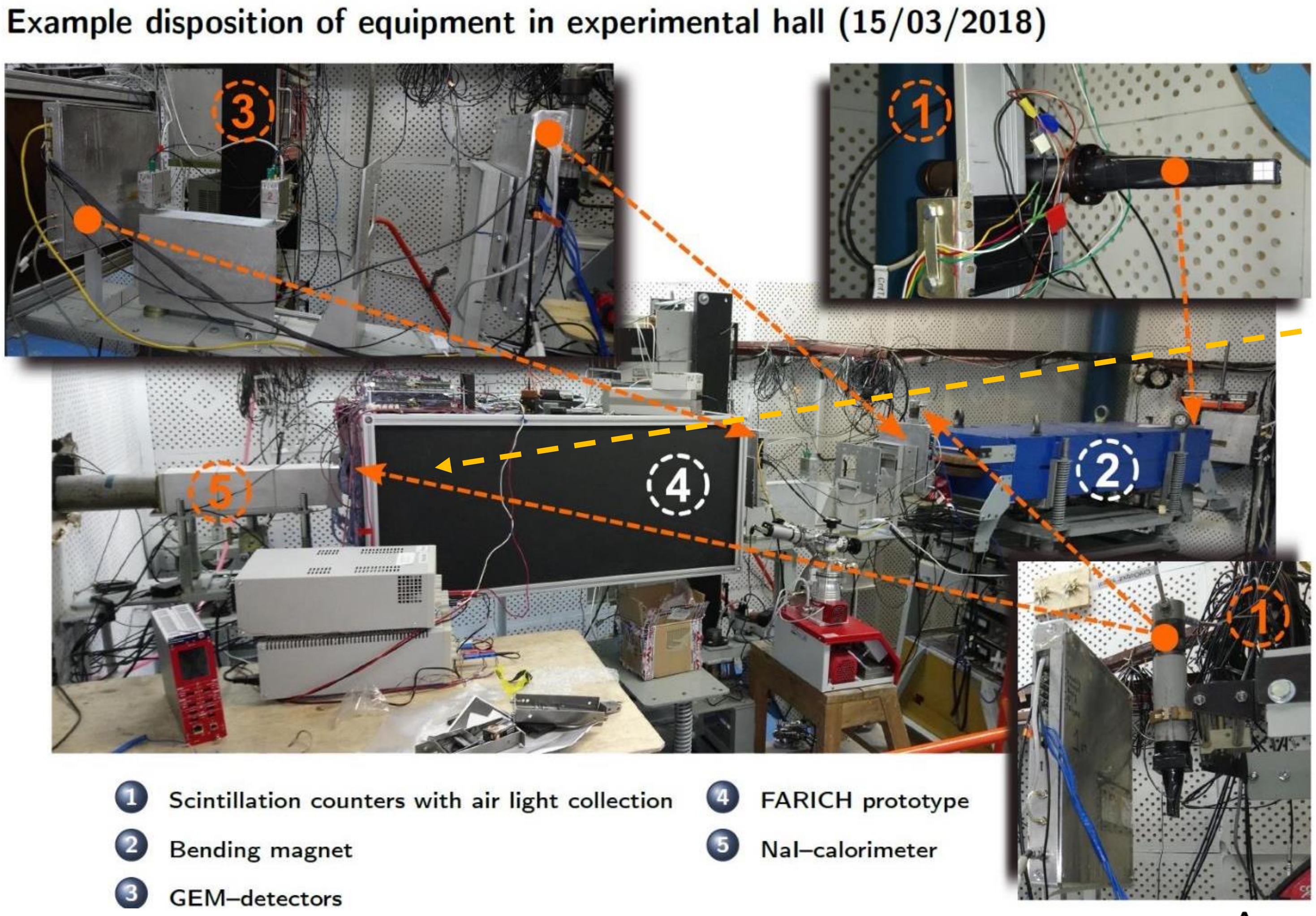


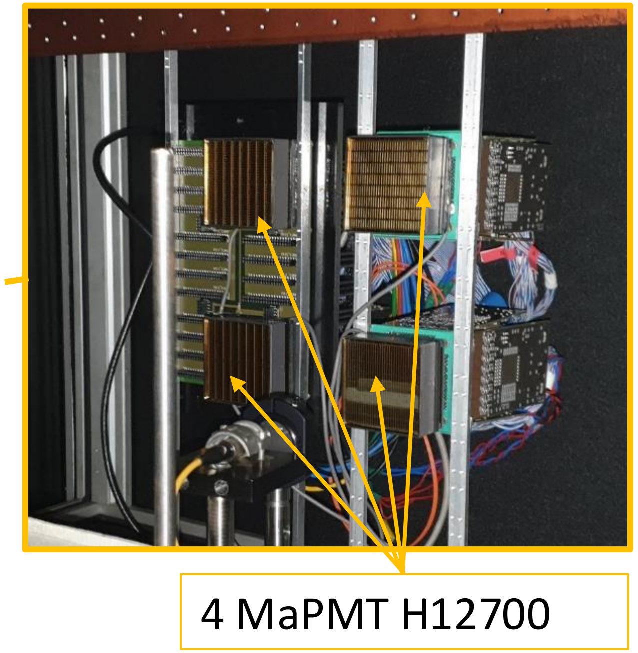


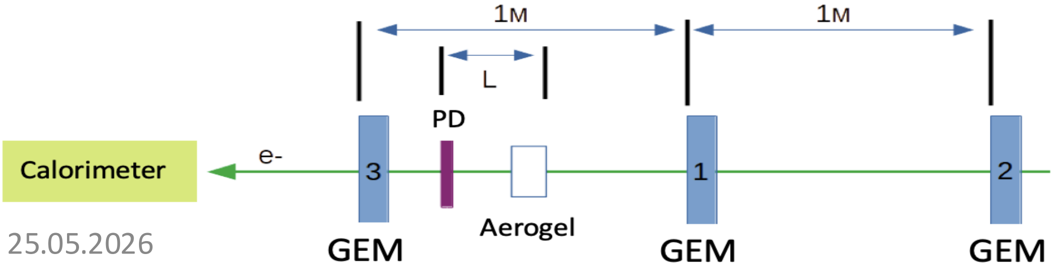
In 2025 for the first time ultra-light SiO_2 aerogels with high transperancy were produced in Novosibirsk!

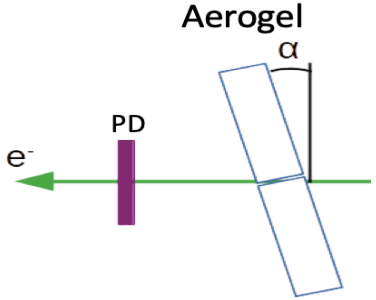
Some BINP beam test results

BINP beam test facility





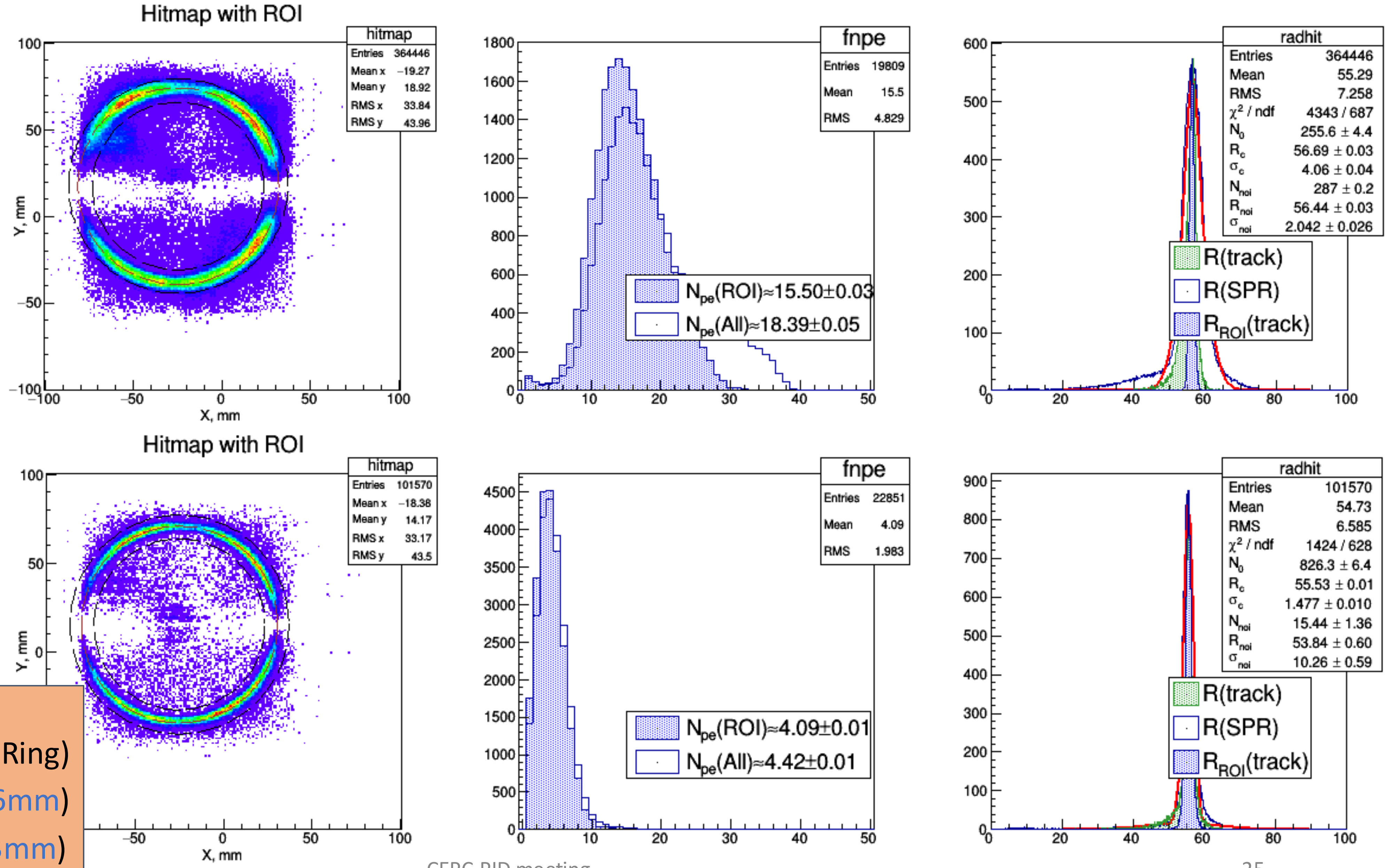




Beam test results with 4-layer aerogel n_{max}=1.046

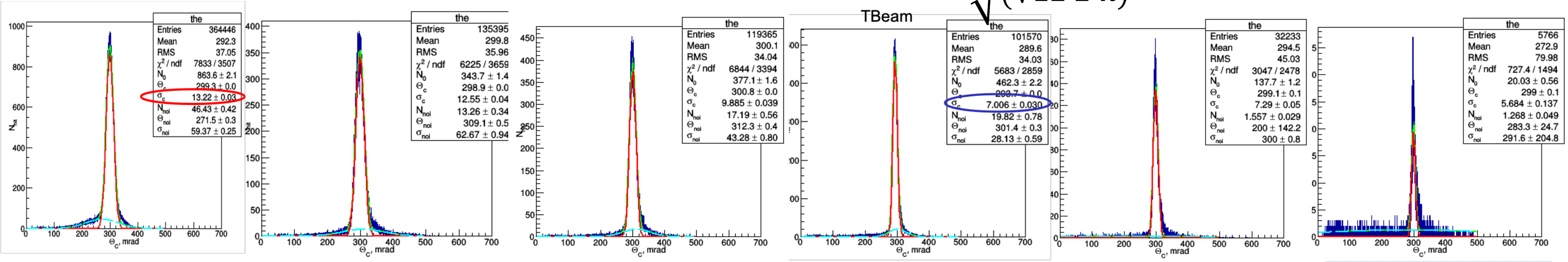
Pixel 6x6 mm
Geom.Eff. ~ 80%

Pixel 3x3 mm
Geom.Eff. ~ 20%

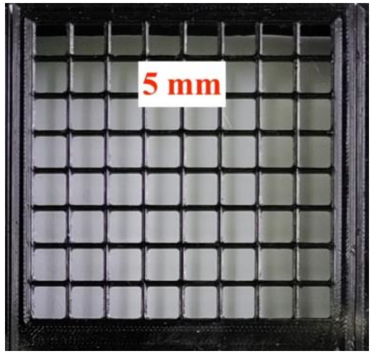


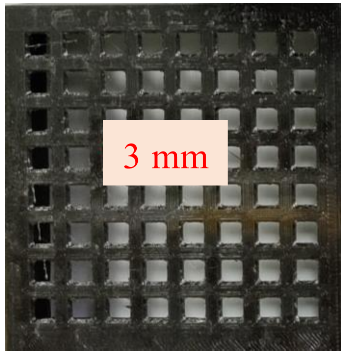
Main results:
- N_{pe} ≈ 16 (~ 0.8 of Ring)
- $\sigma_\theta^{1pe} \approx 13.5\ mrad$ (■ 6mm)
- $\sigma_\theta^{1pe} \approx 7.0\ mrad$ (■ 3mm)

Approach with masks: $\sigma_{\theta_C}^{1pe} = \sqrt{\frac{\Delta_{pix}^2}{\left(\sqrt{12}\cdot L\cdot n\right)^2} + \sigma_{aer}^2 + \sigma_{trk}^2}$

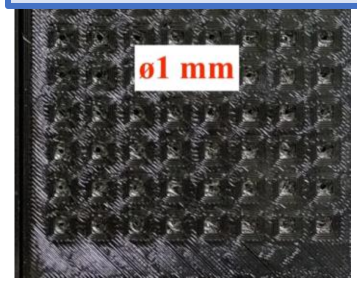


No mask: $6\times 6\ mm$





$\sigma_{aer} \approx$ 5.6 mrad

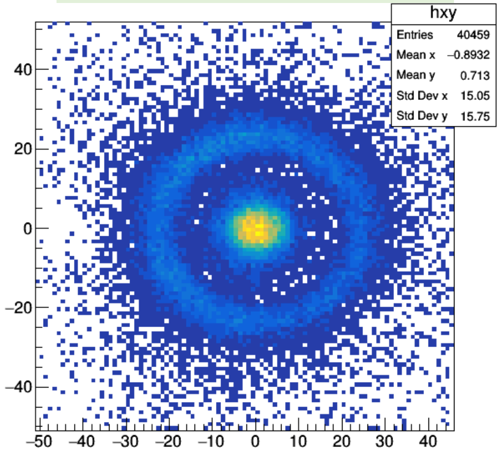


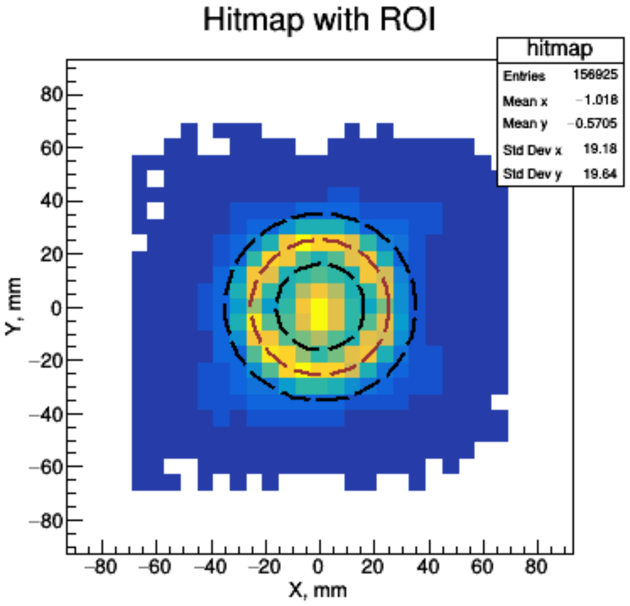
04/23: L≈200 mm	12/23: L≈180 mm	12/23: L≈180 mm	04/23: L≈200 mm	12/23: L≈180 mm	12/23: L≈180 mm
Geom.Eff. ~ 80%	Geom.Eff. ~ 56%	Geom.Eff. ~ 36%	Geom.Eff. ~ 20%	Geom.Eff. ~ 9%	Geom.Eff. ~ 2%
$N_{pe} \approx 16$	$N_{pe} \approx 12$	$N_{pe} \approx 8$	$N_{pe} \approx 4$	$N_{pe} \approx 2$	$N_{pe} \approx 1$

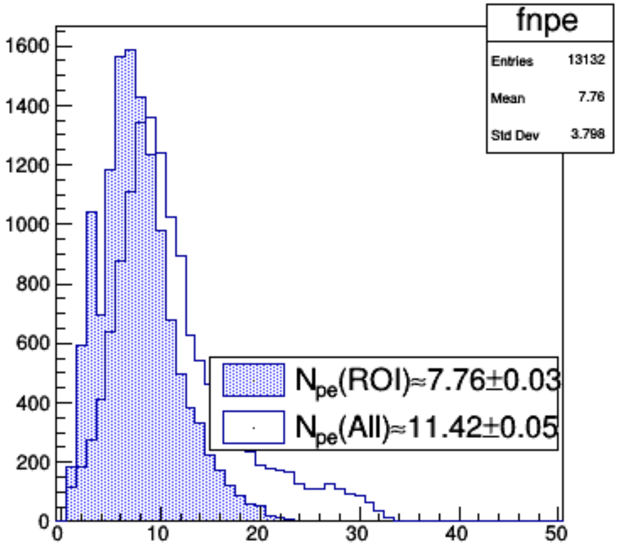
π/K: – 5.5 GeV/c	6 GeV/c	6.5 GeV/c	8.0 GeV/c	8.5 GeV/c
μ/π: – 1.2 GeV/c	1.4 GeV/c	1.5 GeV/c	1.6 GeV/c	1.7 GeV/c

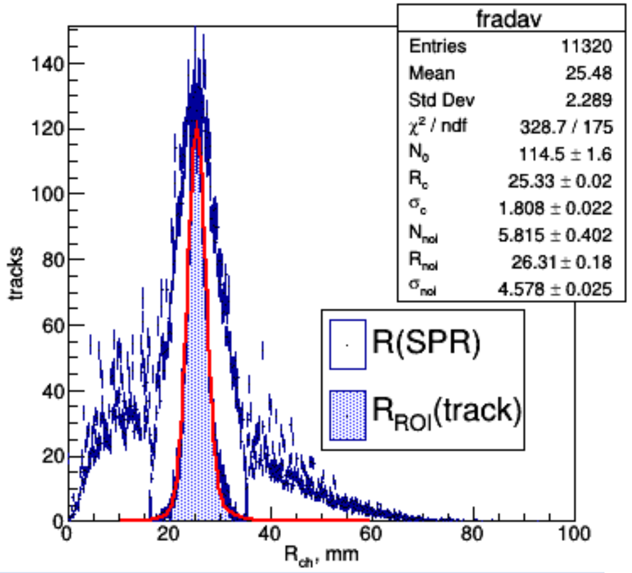
RICH based on aerogel n=1.008: some beam test results

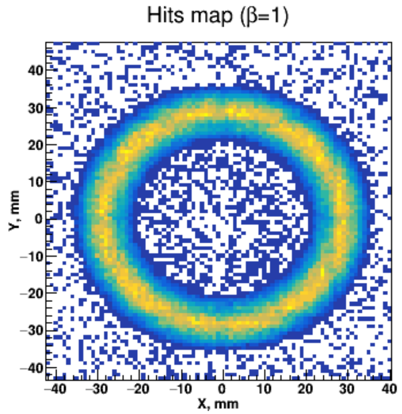
Tbeam e^-@2.5GeV
- t_{aer}=25+25=50 mm
- L_F=200 mm











Geant4 sim.:
- t_{aer}=60 mm
- L_F=250 mm

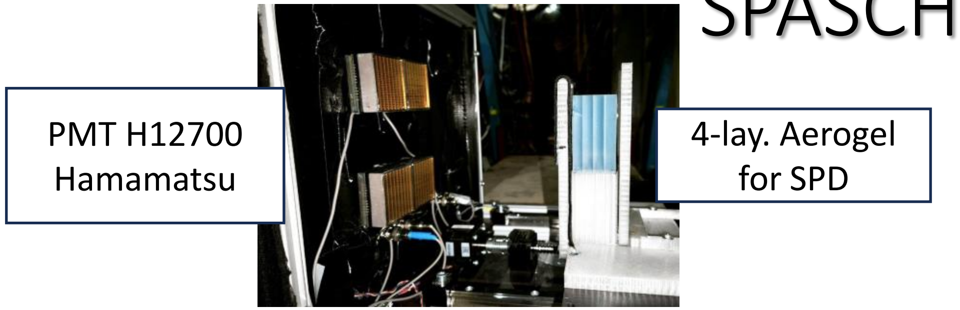
TBeam results reconstructed w/o track information:
- MaPMT H12700 with QE(400nm) ≈ 20%
- Pixel 6x6 mm
- L_F=235 mm
- Aerogel with n≈1.008
- **Main results:**
  - 1 tile 25 mm → **3.8pe**
  - stack of 2 tiles 25+25=50 mm → **7.8pe**
  - stack of 3 tiles 25+25+25=75 mm → **8.7pe**

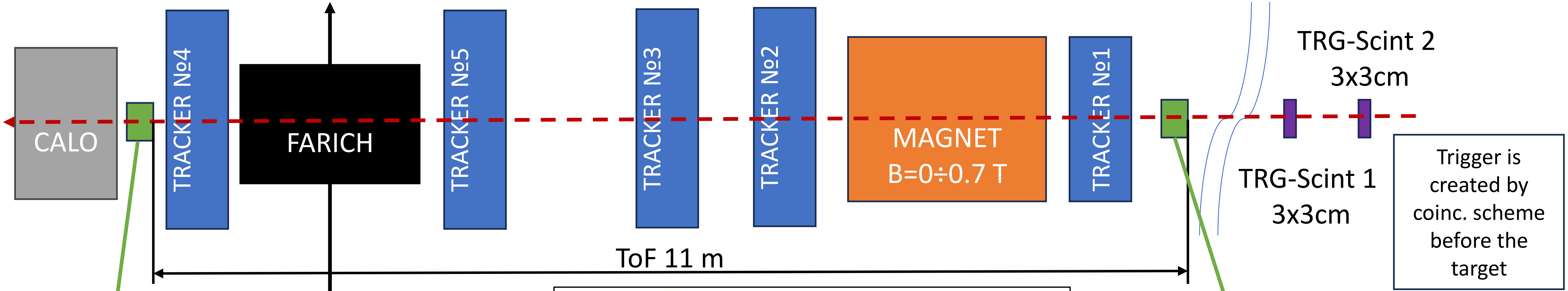
OUTPUT:
- SiPM based photon detector with PDE(400nm)=45÷50% will alow us to detect 10÷20 ph.e. for relativistic tracks
- RICH based on aerogel with n=1.008 and pixel 3x3mm is able to provide π/K-separtion at P=10 GeV/c
- ***Proximity focusing system and PD with $\sigma_x \leq 1\,mm$ is required to reach π/K-separation above 20 GeV/c***

The first experience with FARICH beam test at IHEP (Protvino)

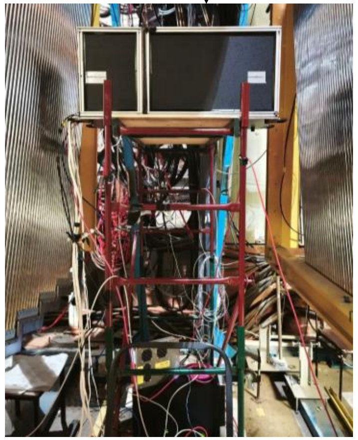
Mixed hadrons tests with new prototype at SPASCHARM@U-70 (IHEP, Protvino)

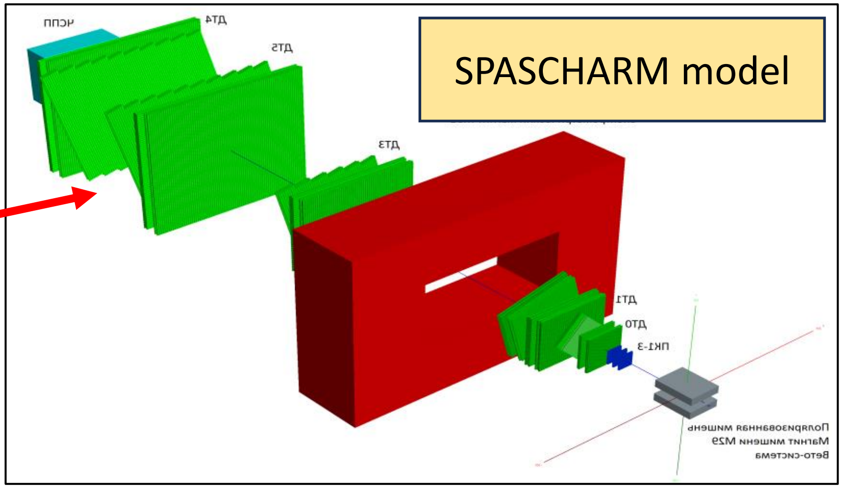
- **Main particles** – protons;
- **Secondary –** produced from Al-target;
- **Momenta** 1.5≤P≤10 GeV/c;





MCP-PMT
ToF2 ø18mm





MCP-PMT
ToF1 ø18mm

Collected data:

Date	aerogels	P, GeV/c	Number, events	Comments
12.03.2026	460f5 4-layer SCTF	5	425k	n_{max}=1.046, t=35 mm, 230x230 mm^2
13.03.2026	467_8 3-layer SPD	5	400k	n_{max}=1.040, t=40 mm, 100x100 mm^2
	467_1 4-layer SPD	5	340k	n_{max}=1.040, t=40 mm, 100x100 mm^2
	467f10_1 4-layer SCTF	5	230k	n_{max}=1.046, t=35 mm, 200x60 mm^2
	467f10_1 4-layer SCTF	3	600k	n_{max}=1.046, t=35 mm, 200x60 mm^2
14.03.2026	467_1 4-layer SPD	3	600k	n_{max}=1.040, t=40 mm, 100x100 mm^2
	467_8 3-layer SPD	3	600k	n_{max}=1.040, t=40 mm, 100x100 mm^2
	460f5 4-layer SCTF	3	200k	n_{max}=1.046, t=35 mm, 230x230 mm^2
	460f5 4-layer SCTF	1,5	50k	n_{max}=1.046, t=35 mm, 230x230 mm^2
15.03.2026	460f5 4-layer SCTF	6	1M	n_{max}=1.046, t=35 mm, 230x230 mm^2
	467_8 3-layer SPD	6	600k	n_{max}=1.040, t=40 mm, 100x100 mm^2
	467_1 4-layer SPD	6	600k	n_{max}=1.040, t=40 mm, 100x100 mm^2
	467_1 4-layer SPD	10	600k	n_{max}=1.040, t=40 mm, 100x100 mm^2
	460f5 4-layer SCTF	10	600k	n_{max}=1.046, t=35 mm, 230x230 mm^2
	467_8 3-layer SPD	10	600k	n_{max}=1.040, t=40 mm, 100x100 mm^2

New 3- & 4-layers radiators for SPD were tested with radiator for C-Tau.

An amount of collected was triggers from 200k up to 1M.

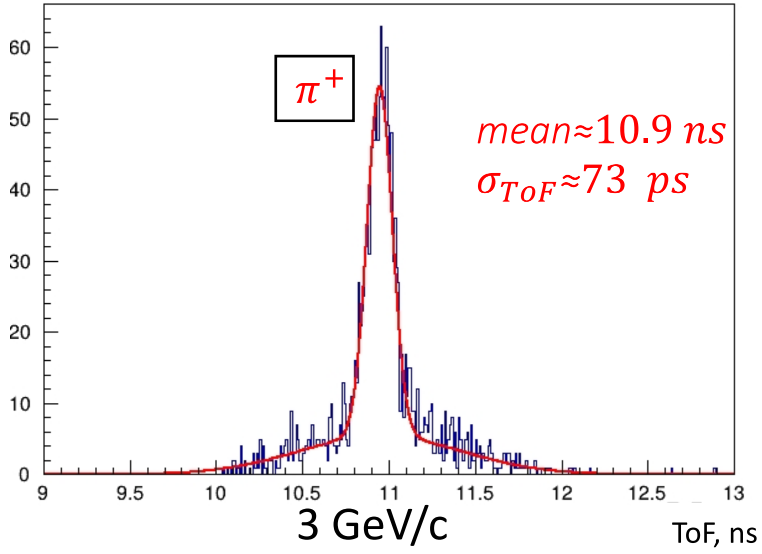
Samples were tested at the base of ~200 mm.

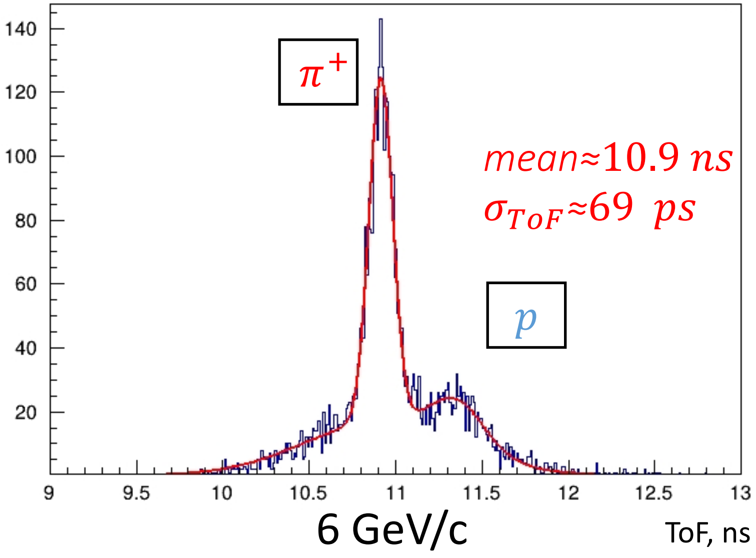
Preliminary results: ToF

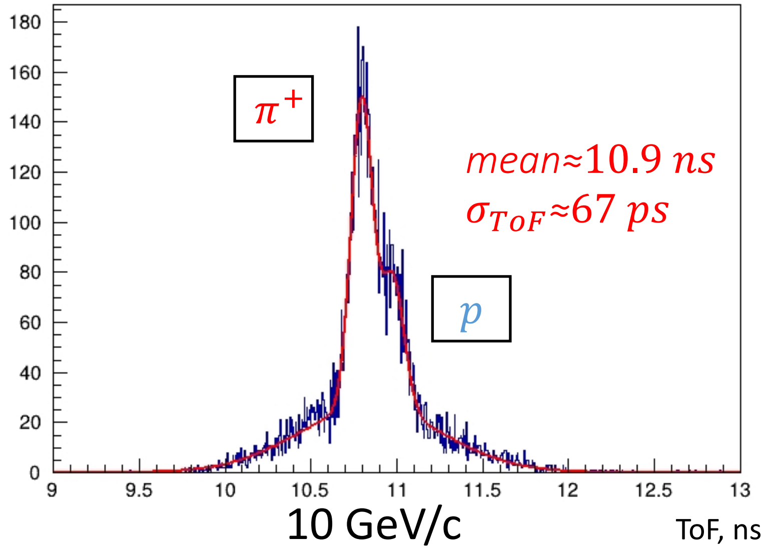
Initially, the projected time-of-flight system must have a time resolution of 20 ps using our standard electronics. But it was impossible to synchronized with the trigger from SPASCHARM.

Solution: We used the prototype's electronics to read the signal from the ToF. But then the resolution is unclear.

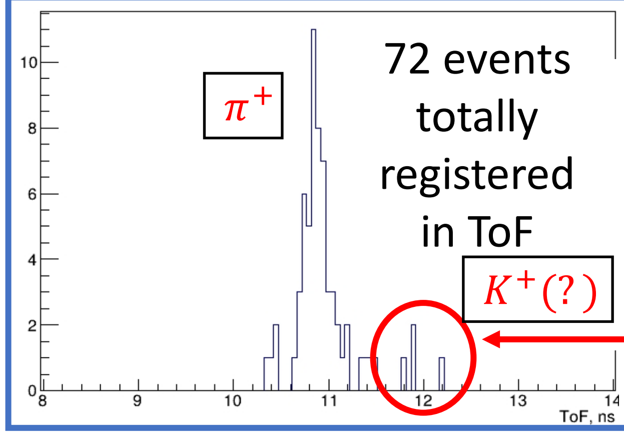
- *Therefore, it is necessary to estimate the resolution of new ToF. For this, we can consider the pion peaks*







- *Estimated σ ~70 ps*
- The contribution of the momentum spread (10%) is *insignificant. So,* the resolution is determined mainly by the electronics.
- We also estimated the beam composition. Roughly speaking: π^+ (~75%), p (~20%), K^+?, e^+? according to the data from ToF.



ToF@1.5 GeV/c

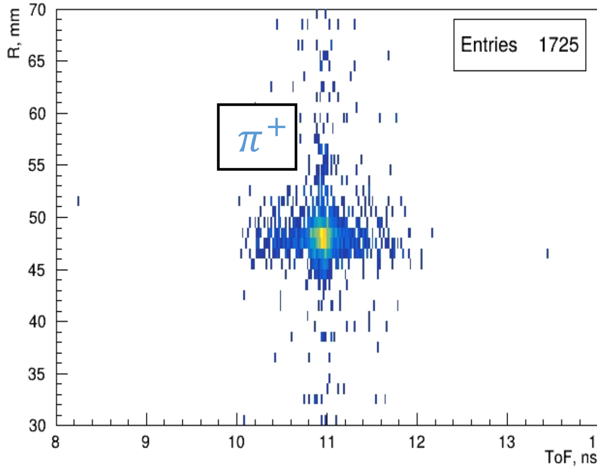
Potentially there are *Kaons* at SPASCHARM@1.5 GeV/c
-> Possibility to test other systems (our ASHIPH).
We will collect more data in the future

Preliminary results: 3 & 6 GeV/c

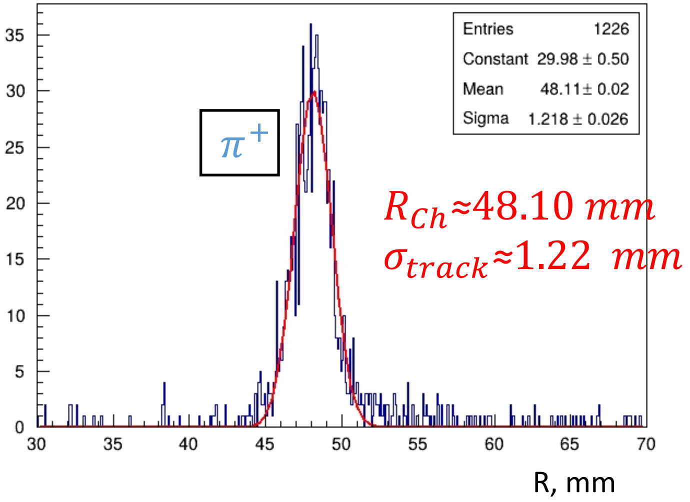
- Without a tracking information and knowledge of momenta

3 GeV/c:

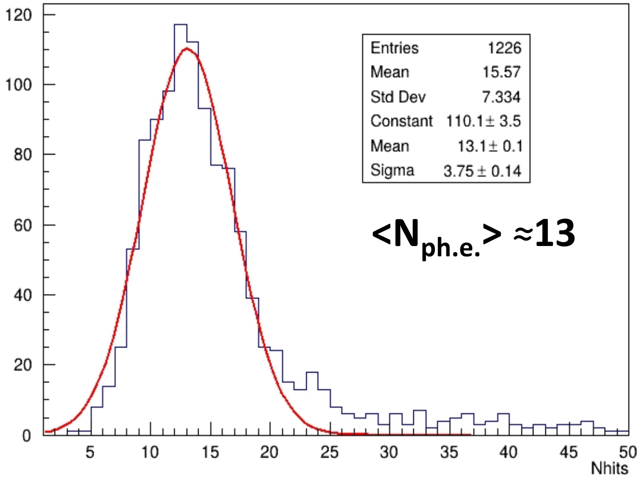
R vs ToF



Recon. R distribution.
(fine Time cut && ToF cut)

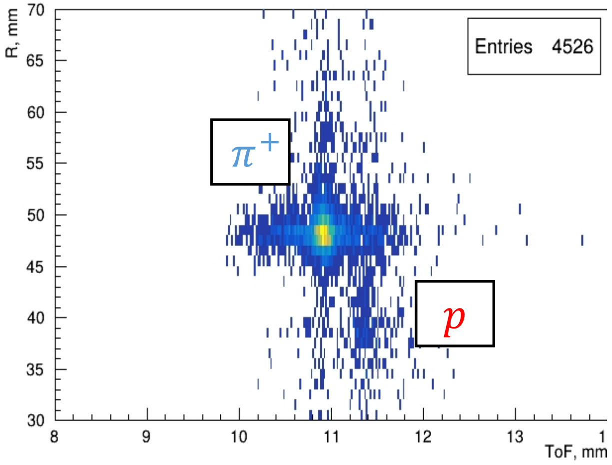


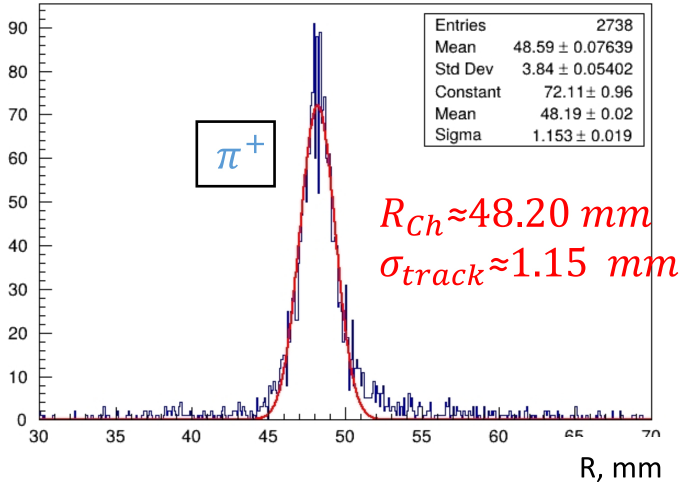
Photoelectron distribution



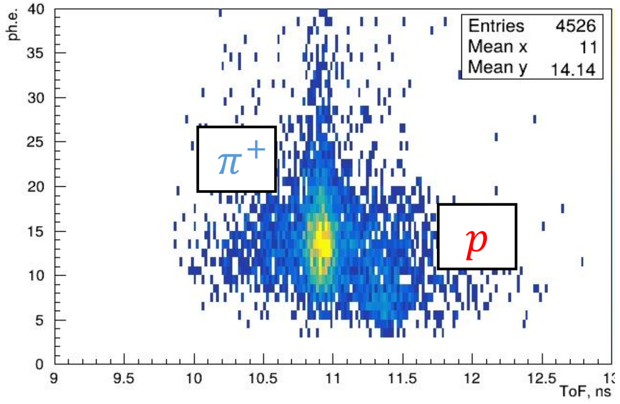
- **For demonstration a small part of the statistics was used.**
- **Without tracks and momenta there are only few things to study**

6 GeV/c:

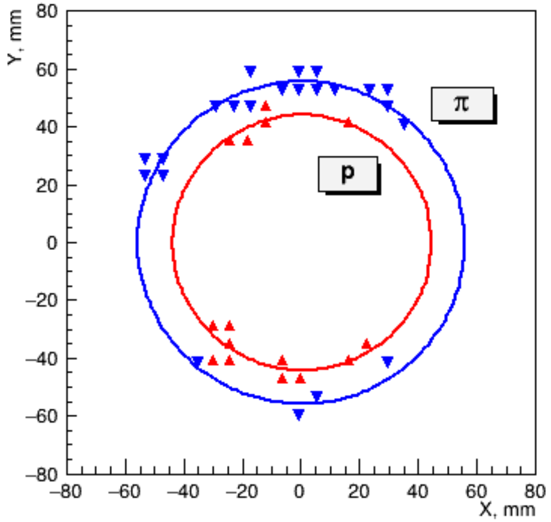




Num. of photoelectrons vs ToF

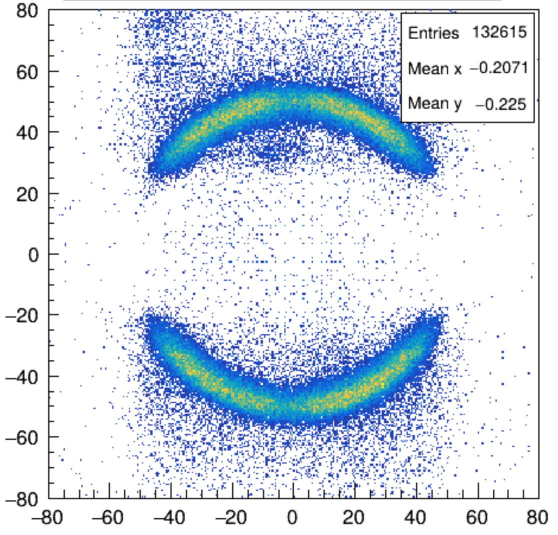


Circle comparison between π^+ *and* p @6 GeV/c

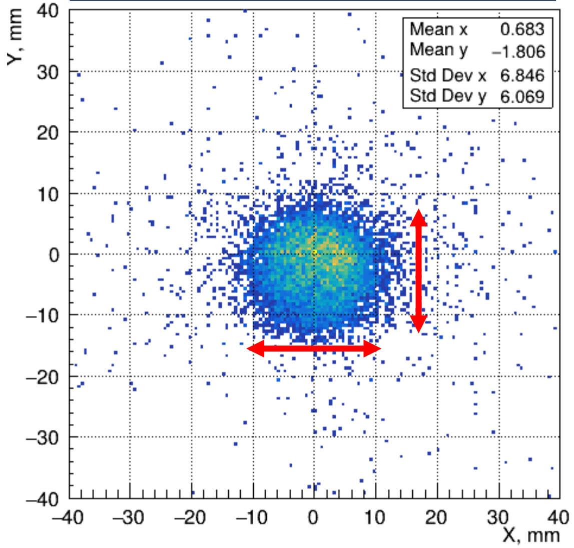


Preliminary results of *π/K-separation from* 10 GeV/c tests

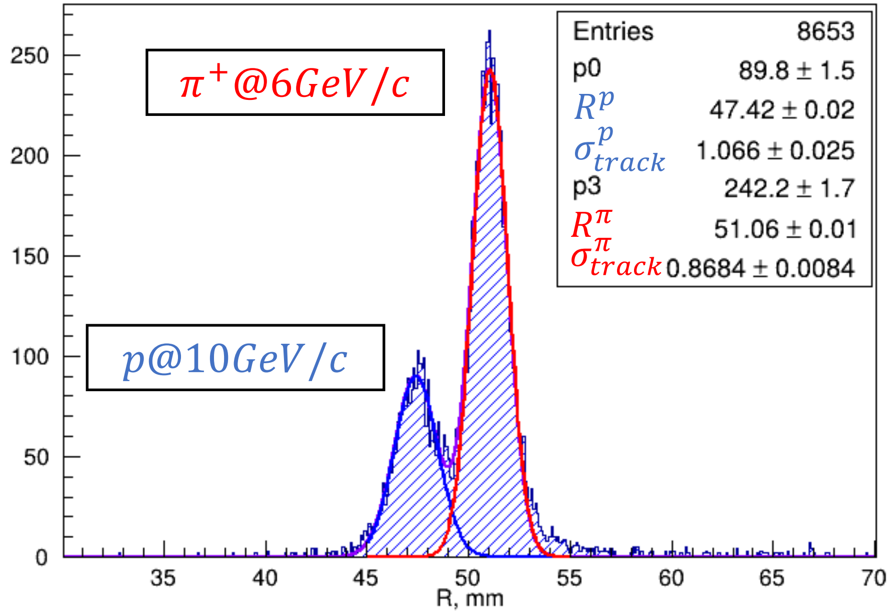
The image of hits.
Y vs X



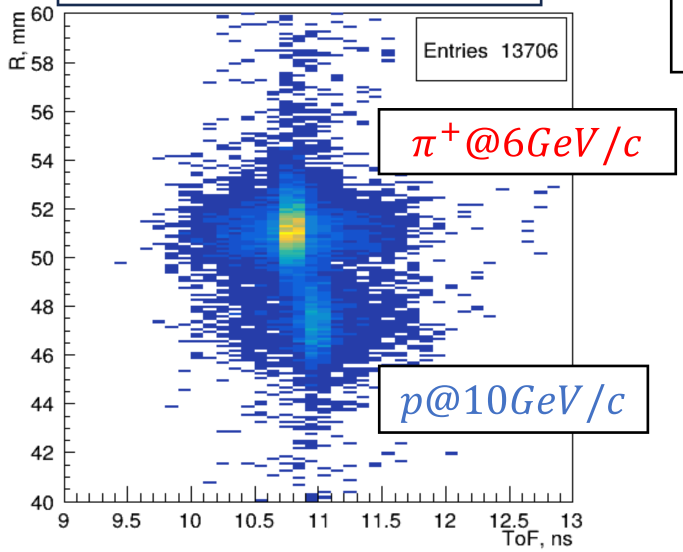
Reconstructed centers of circles (ToF != 0)



The distribution of recon. R for *p* and π^+(ToF != 0)



R [mm] vs ToF [ns]



Spot size is close to 18 mm (for X&Y)
Size of PMT with MCP was ø18mm

$$N_\sigma = \frac{(R^\pi - R^p)}{0.5(\sigma^\pi_{R_{track}} + \sigma^p_{R_{track}})}$$

An obtained average number of the photoelectrons@10GeV/c:
For *protons* $\langle N_{ph.e.} \rangle \approx 11$
For *pions* $\langle N_{ph.e.} \rangle \approx 13$

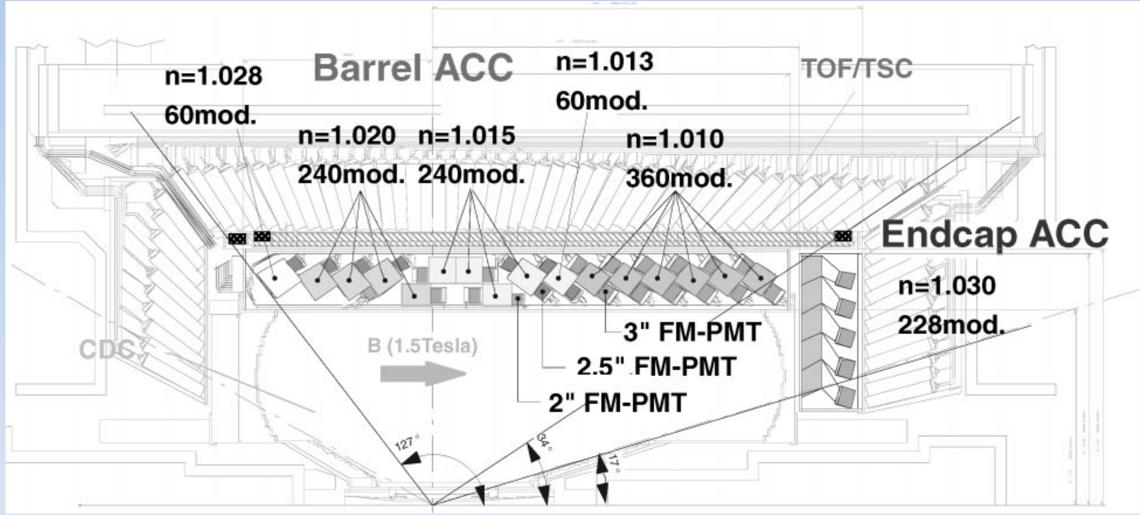
It's hard to identify $K^\pm$ without tracks and momenta (+small amount of ph.e. & geom.eff.~0.6)@6GeV/c. Nevertheless, there were a lot of Protons.
p@10 GeV/c -> K@ 5.4 GeV/c
π/p ~ 3.7 σ @ P = 5.4GeV/c

Summary

- The accumulated at the BINP experience of production and expluatation of the aerogel based Cherenkov counter allows us to propose and develop FARICH concept for PID system of the CEPC project
- It was shown in G4 simulation that reliable π/K separation up to 28GeV/c is achievable with help of the FARICH based on 8-layer aerogel with n_{max}=1.008
- Beam tests with electrons confirm our G4-sim expectation that N_{pe} from relativistic tracks could be more than 10
- Beam line SPASCHARM at U-70 accelerator complex of IHEP (Protvino) could be a very useful beam test facility for the nearest 3 years future
- Next steps are development of the proper full CEPC-FARICH simulation and prototyping with and consequent beam tests

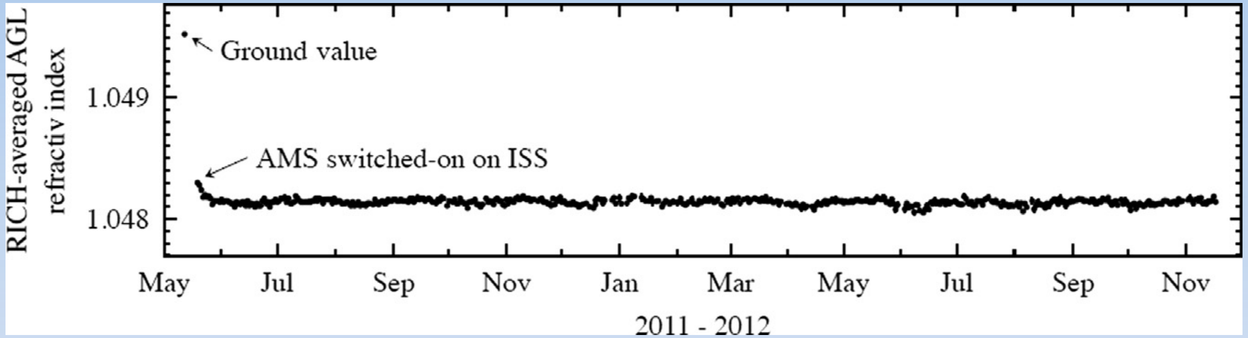
Comparison of “Novosibirsk” and “Chiba University” aerogels(2)

Hydrophobic aerogel



Belle ACC → **no degradation**

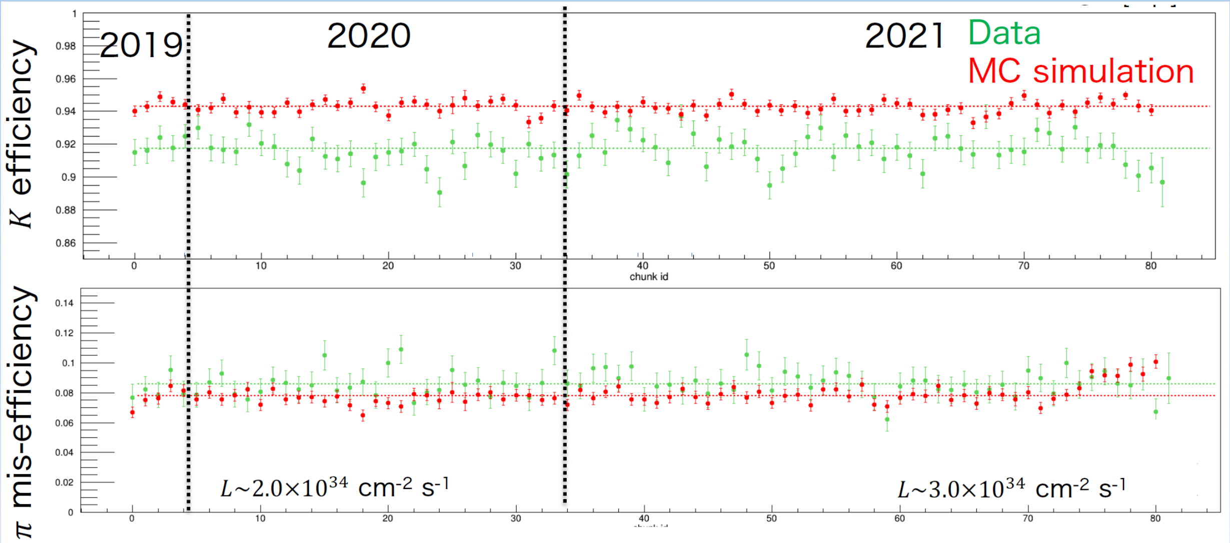
Hygroscopic aerogel



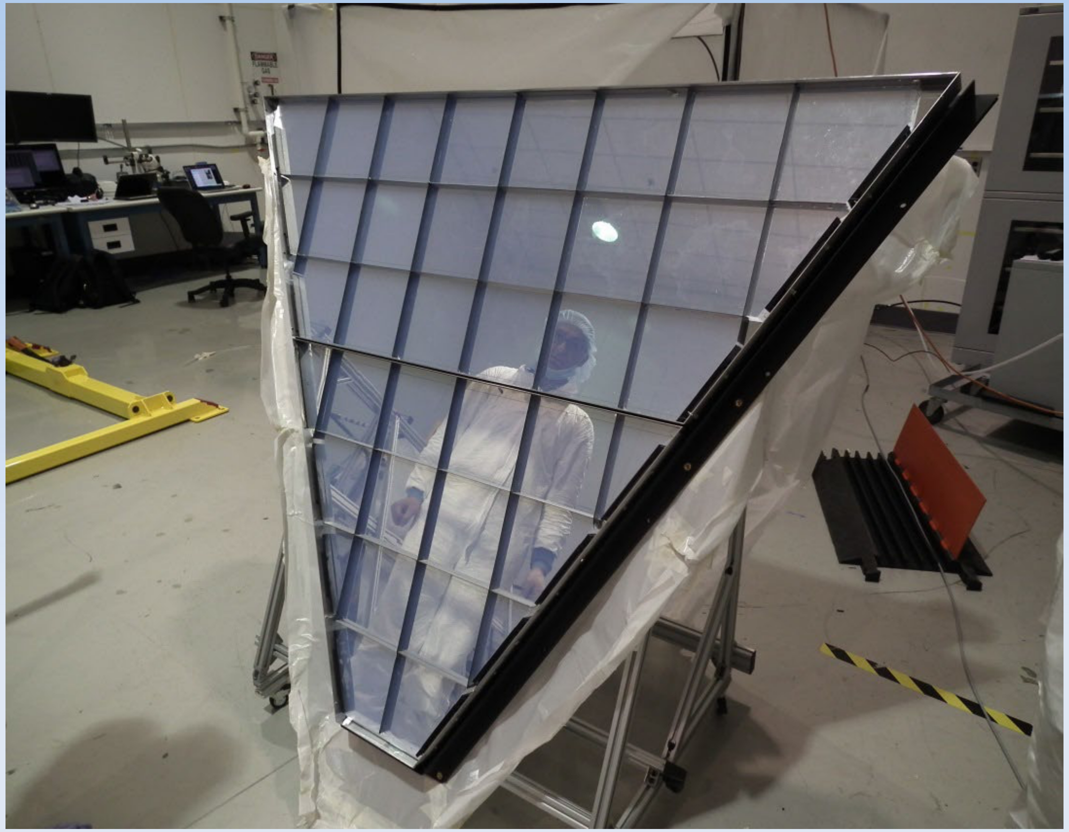
AMS-02 RICH → **no degradation**

Comparison of “Novosibirsk” and “Chiba University” aerogels(2)

Hydrophobic aerogel



Hygroscopic aerogel



Belle II ARICH → **no degradation**

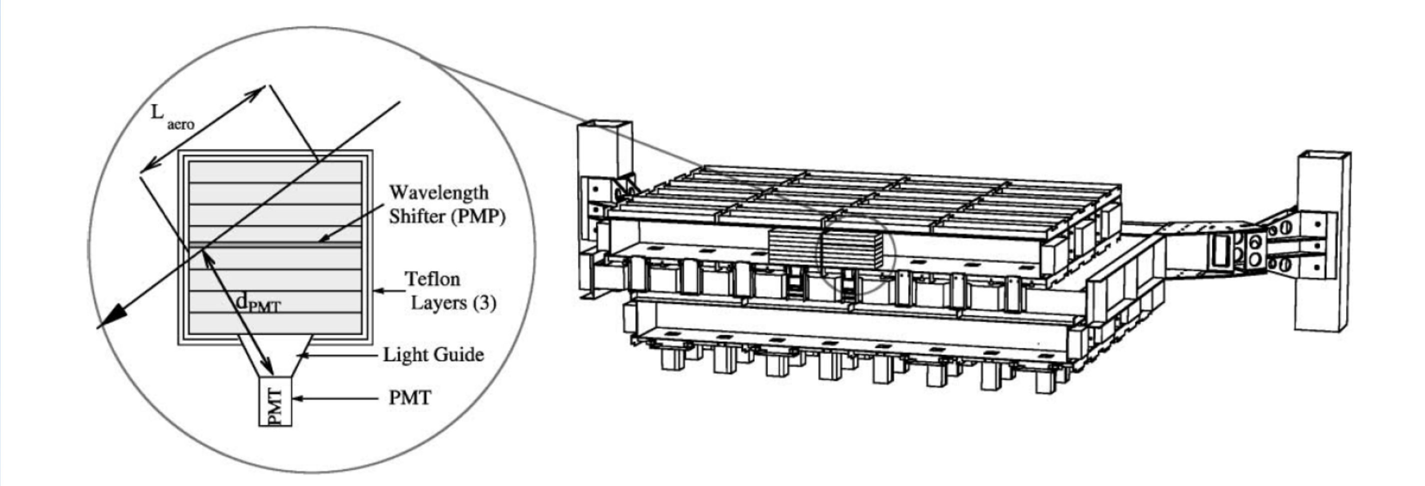
Lsc(400) = 40 mm

CLAS12 RICH → **4—9% drop after 4 years (aerogel+PMT)**

Lsc(400) = 50 mm

Comparison of “Novosibirsk” and “Chiba University” aerogels(2)

Hydrophobic aerogel



“irreversible optical losses and mechanical degradation are induced by pefluorocarbons and liquid alcanes.”
A.K. Gougas et.al., NIMA421(1999)249

The hygroscopic aerogel has survived after the strong absorbtion of C4F10 in LHCb RICH.

AMS-01 ATC ⇒ **70% drop from 5 pe to 1.5 pe after 1 year**

Comparison of “Novosibirsk” and “Chiba University” aerogels(3)

Hydrophobic aerogel

PROS

- Good stability

CONS

- Maximum thickness 20 mm
- Minimal refractive index n = 1.012 (?)

Hygroscopic aerogel

PROS

- Good transparency
- Maximum thickness 50 mm
- Low refractive index n < 1.008
- **CONS**
- Moderate stability