Development of aerogel based RICH detectors

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on behalf of BINP Aerogel group

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- **Aerogel RICH in the HEP**
- **Aerogel R&Ds at the BINP**
  - **FARICH technique progress**
  - **FARICH with dual aerogel radiator concept**
  - **Aerogel RICH with Fresnel lens**
- **Summary**

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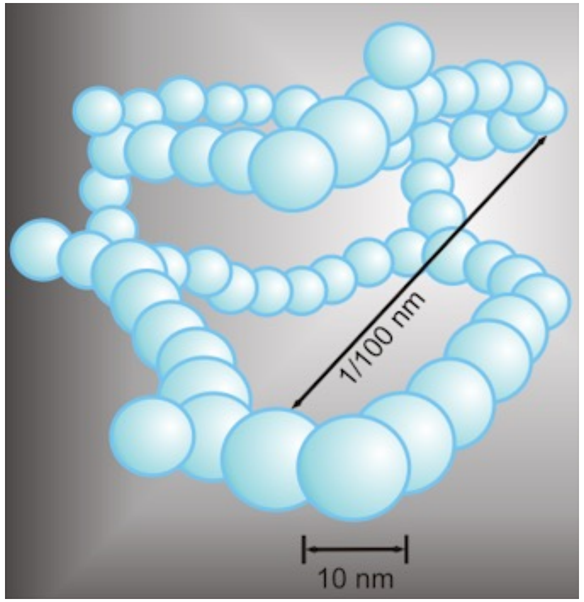
Institute of High Energy Physics Chinese Academy of Sciences

Aerogel RICH in the HEP

Aerogel is a classical nanomaterial

- Aerogel was first synthesized by Samuel Stephens Kistler in 1931

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

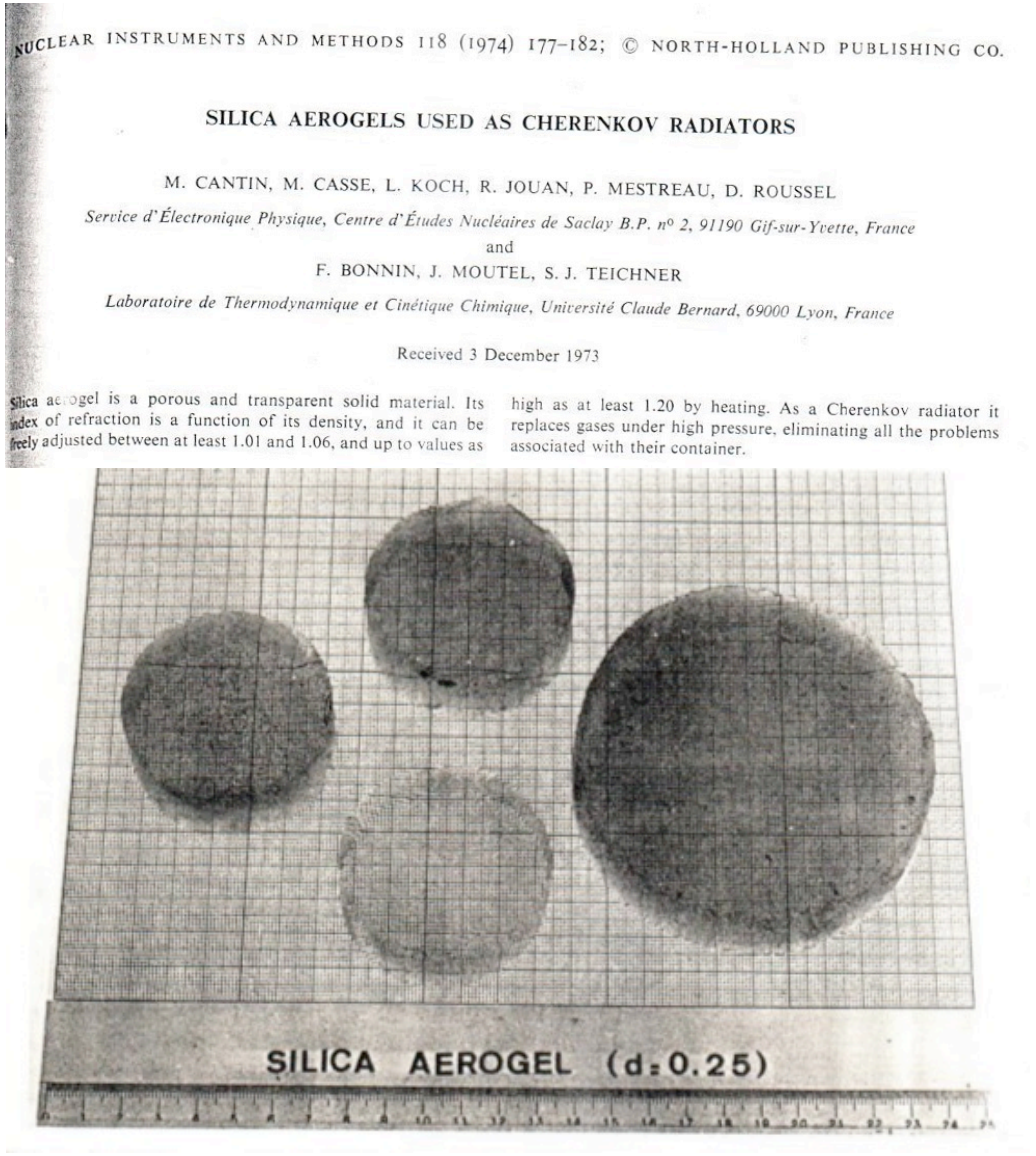


Aerogel – is a porous material with pore dimension less than visible light wavelength. It is a classical **nanomaterial**. The most interesting for physics experiments are silicon dioxide (SiO_2) based aerogels:

n	P^{μ}_{thr}, GeV/c	P^{π}_{thr}, GeV/c	P^{K}_{thr}, GeV/c	P^{p}_{thr}, GeV/c
1.008	**0.84**	**1.1**	**3.9**	**7.4**
1.03	**0.43**	**0.56**	**2.0**	**3.8**
1.05	**0.33**	**0.43**	**1.5**	**2.9**
1.13	**0.2**	**0.26**	**0.94**	**1.8**

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

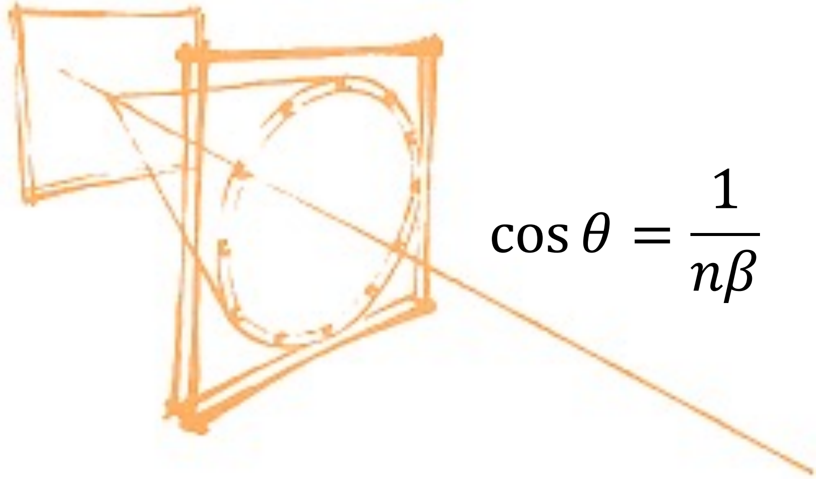
M. CANTIN, M. CASSE, L. KOCH, R. JOUAN, P. MESTREAU, D. ROUSSEL
Service d'Électronique Physique, Centre d'Études Nucléaires de Saclay B.P. nº 2, 91190 Gif-sur-Yvette, France
and
F. BONNIN, J. MOUTEL, S. J. TEICHNER
Laboratoire de Thermodynamique et Cinétique Chimique, Université Claude Bernard, 69000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

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, USA (SiO_2, n=1.47)
- Main problem – they do not provide π-K identification in the momenta range 4÷10 GeV/*c*



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

•A.Roberts, NIM 9(1960)55

•J.Seguinot and T.Ypsilantis, NIM 142(1977)377

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

Peculiarities of aerogel use in RICH detectors

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

- 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

- The first RICH with aerogel was proposed Douglas Fields in 1994

D.E.Fields et al., NIM A349(1994)431

- **1995** – Aerogel RICH for LHCb was suggested. The requirement on minimal light scattering length was elaborated. $L_{sc}(400\text{ nm}) \gtrsim 26\text{ mm}$

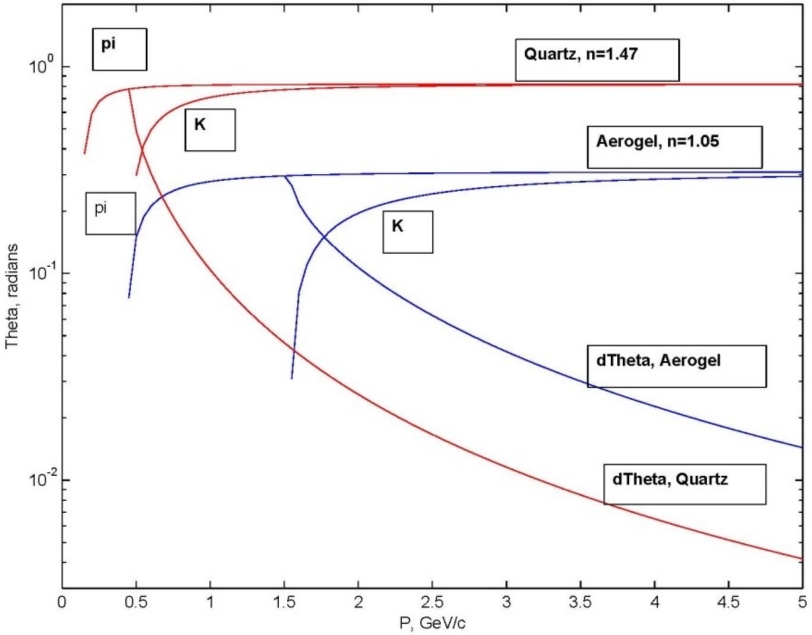
J.Seguinot, T.Ypsilantis, NIM A368(1995)229)

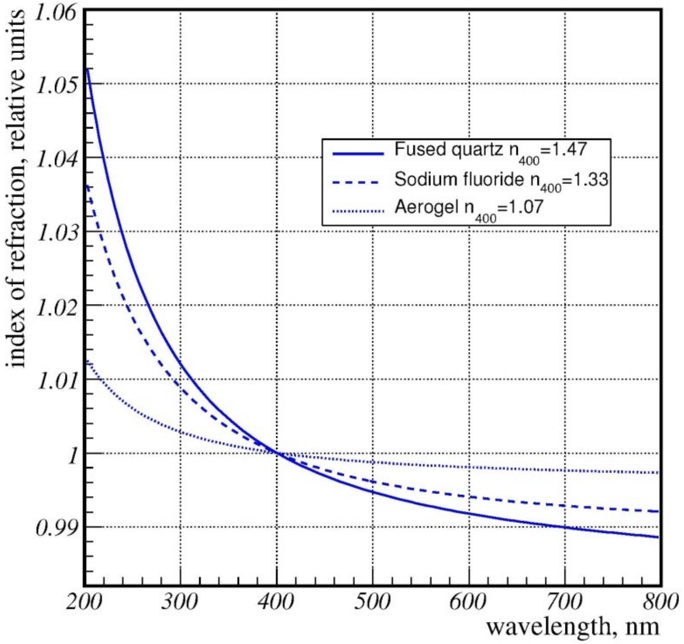
- **1995-1996** – two-step aerogel production was optimized, L_{sc}(400 mm)=40÷50 mm

A.R.Buzykaev et.al, NIM A379(1996)465)

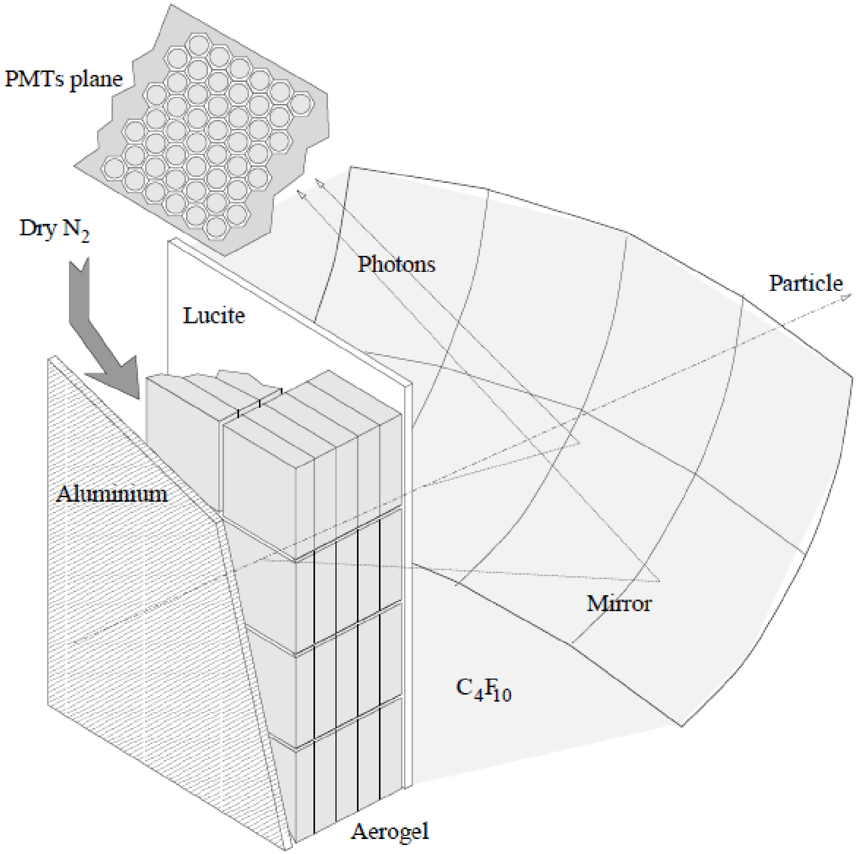
Why Aerogel RICH?

- 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 $\left(N_{pe} \sim 1 - {}^{1}/_{n^2}\right)$ can not compensate these effects $\left(\sim {}^{1}/_{\sqrt{N_{pe}}}\right)$





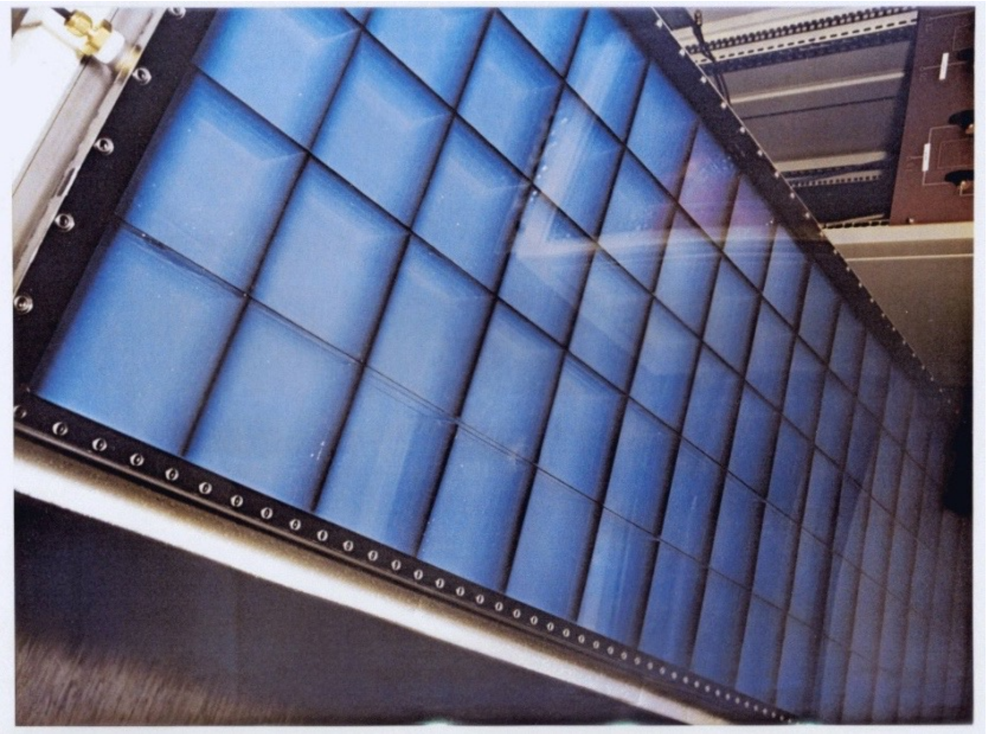
The first aerogel RICH



Start of the design – 1996
1020 aerogel tiles 114x114x11mm^3
Start of the operation -- 1998

Hermes RICH (DESY, Gamburg)

Investigate spin structure of nuclons

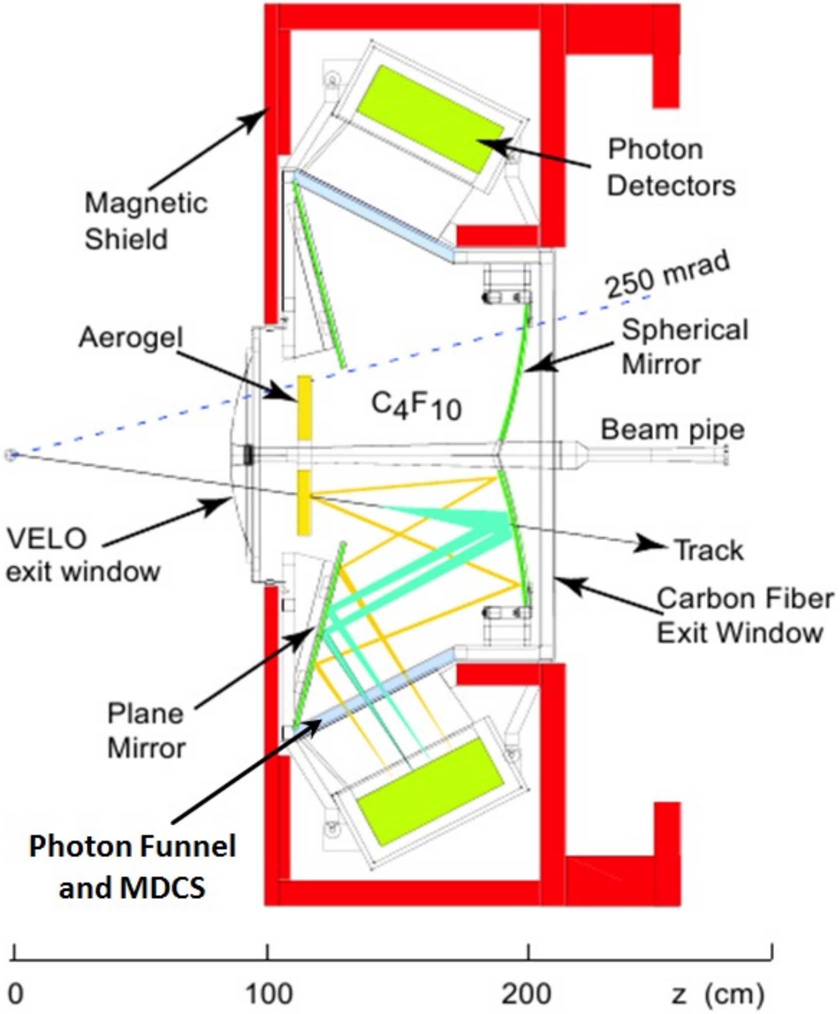


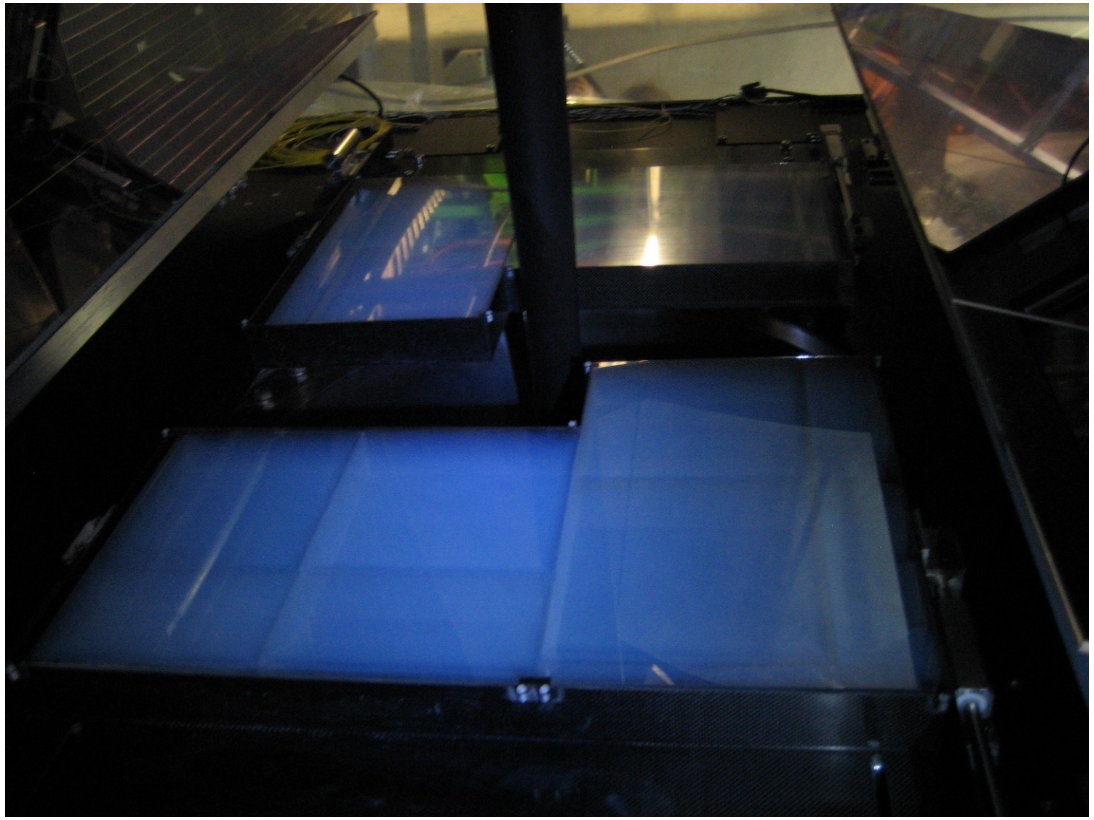
π/K/p – separation at 2÷15 GeV/c
aerogel, n=1.03 -> π/K – separation 2÷7 GeV/c
C_4F_{10}, n=1.0014 -> π/K – separation 7÷15 GeV/c

Y.Miyachi, NIM A502(2003)202

Aerogel in LHCb (LHC-CERN)

measure the parameters of CPV in the interactions of b-hadrons

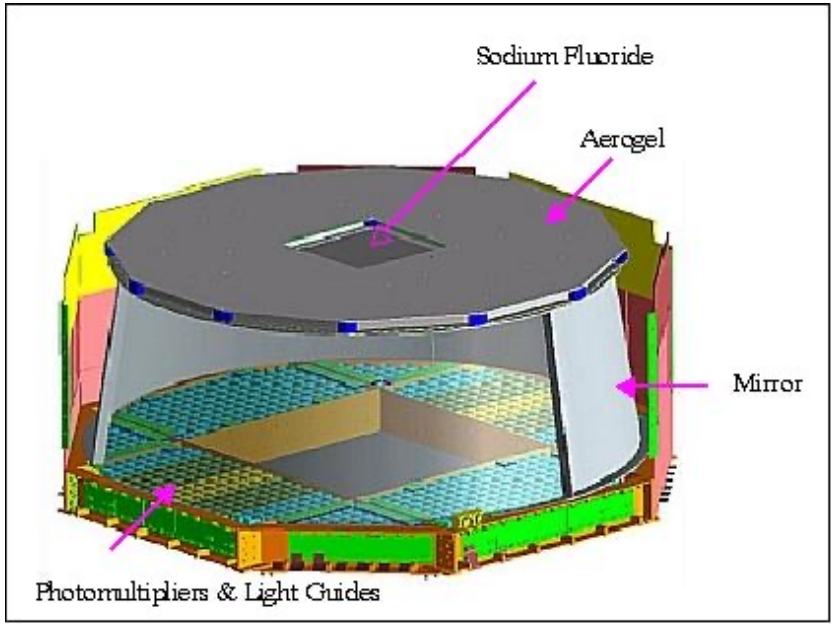


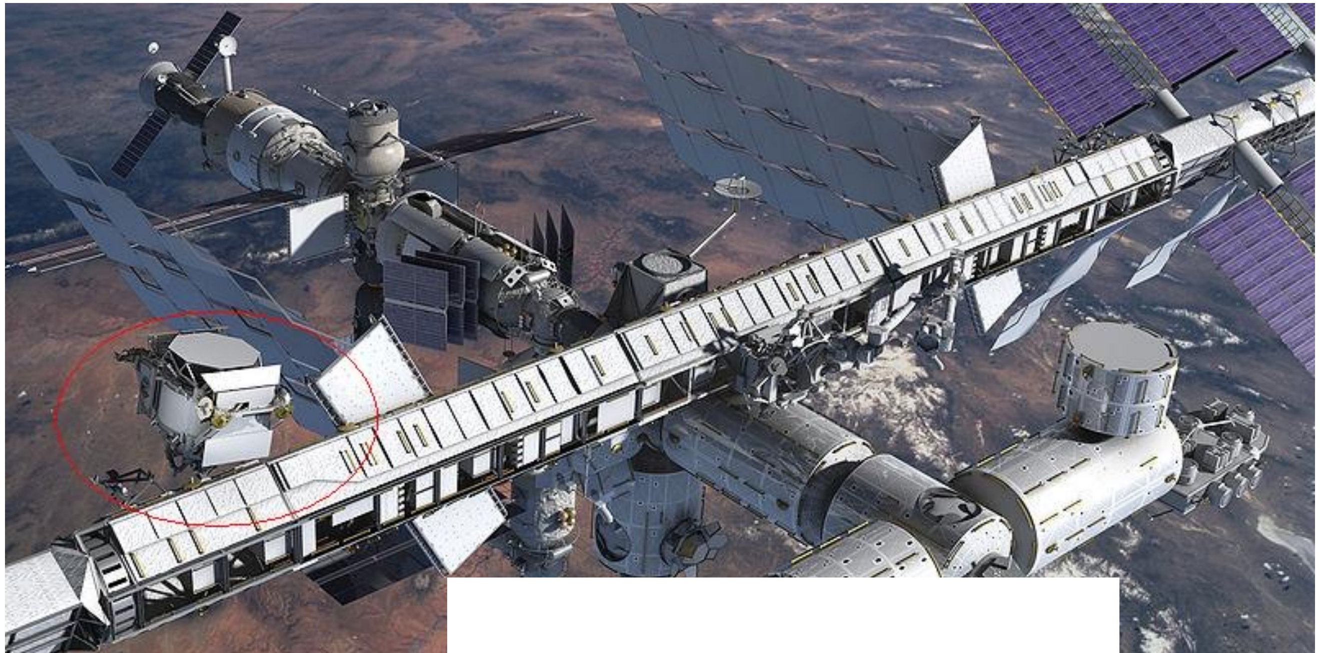


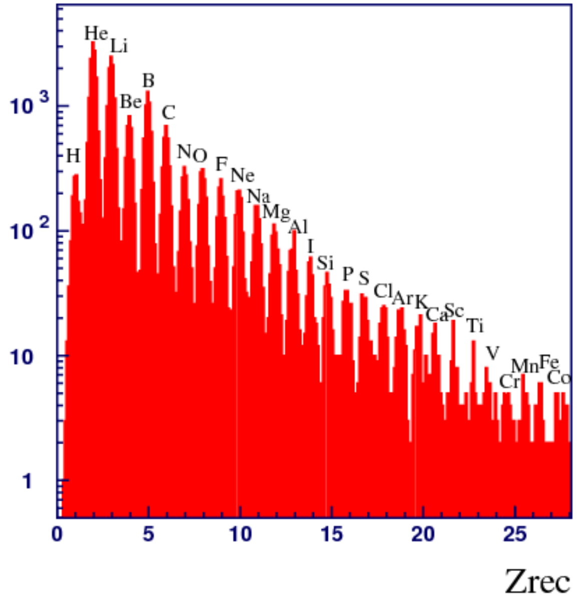
BIC/BINP production, n=1.03, 20x20x5 cm tiles
Aerogel did not work – small number of photoelectrons in the ring + strong pile-up noise

Aerogel RICH at AMS-02 at ISS

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





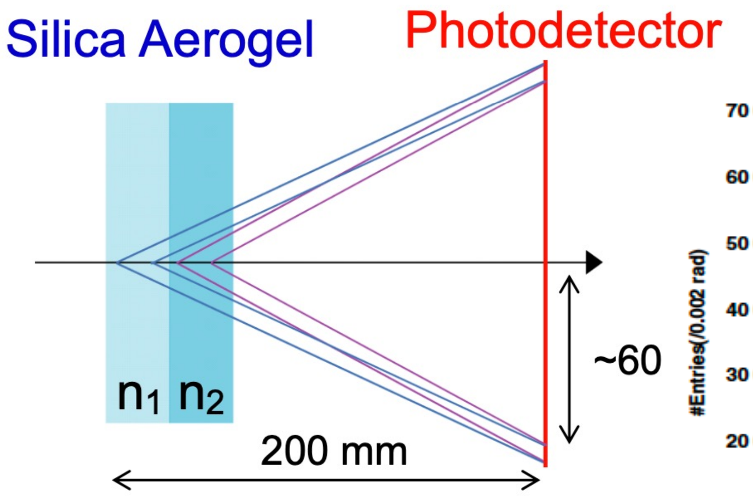


BIC/BINP production, n=1.05

- More than 10 years in operation since 2010
- Very well agreement experimental measured parameters with expected (required) in the project

F.Giovacchini et al., NIM A970 (2020) 163657

Belle II: ARICH

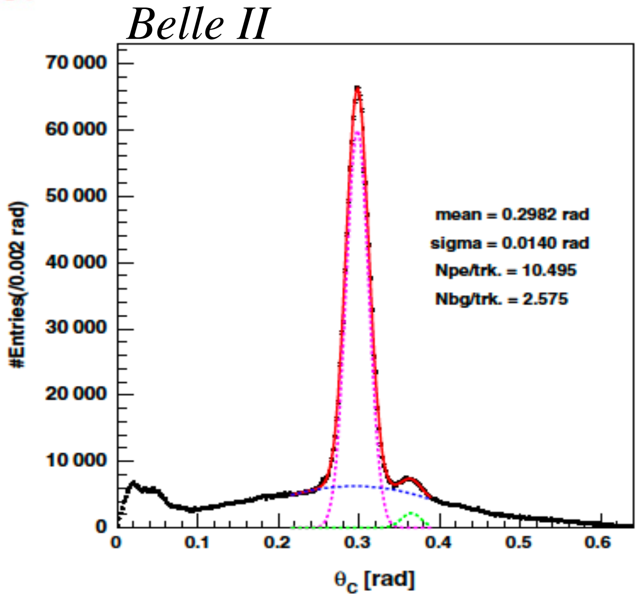


Proximity focusing aerogel RICH

- Stack of two blocks with different n:
  - n_1=1.045 / 20 mm
  - n_2=1.055 / 20 mm
- Focal distance 200 mm
- Increase N_{pe} due thickness increase without $\sigma_{\Theta c}$ degradation

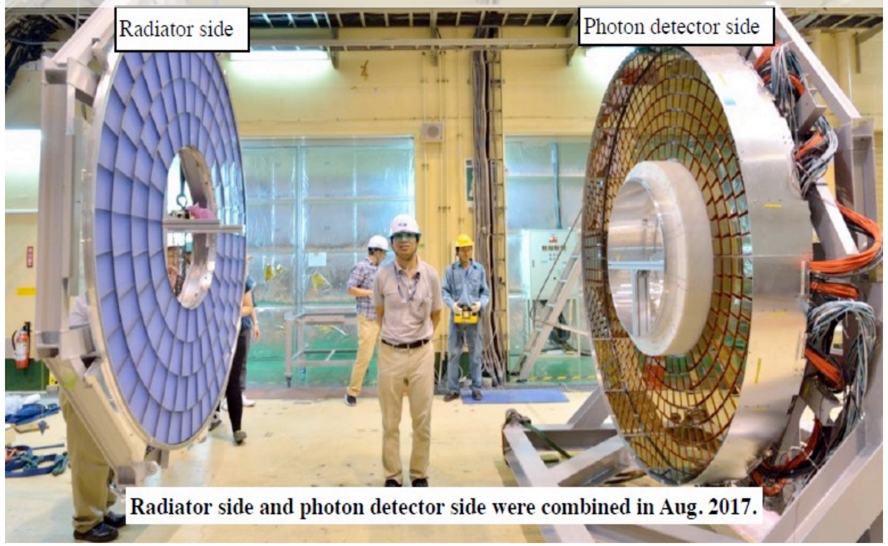
T.Iijima et al., NIM A548 (2005) 383

TBeam results



PTEP 2016, 033H01

The first application of technique in Belle2 ARICH



π/K-separation better 4σ up to 4 GeV/c

- 248 aerogel tiles in 2 layers 2+2 cm
- $n_1 = 1.045;\ n_2 = 1.055;\ S_{tot} = 3.5\ m^2$
- 420 HAPD; 144 pixels with 5x5 mm^2 per each

	ε_K	$\varepsilon_{\pi\to K}$	ε_π	$\varepsilon_{K\to\pi}$
Exper.	93.5±0.6%	10.9±0.9%	87.5±0.9%	5.6±0.3%
MC	96.7±0.2%	7.9±0.4%	91.3±0.3%	3.4±0.4%

Y.-T. Lai *et al* 2020 *JINST* **15** C07039

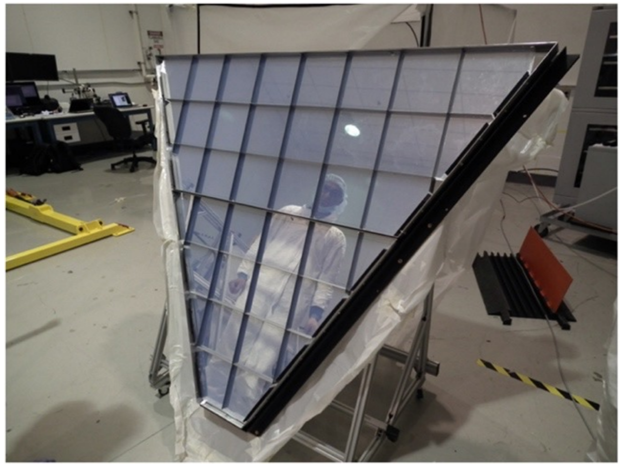
CLAS-12 RICH (J-Lab, Newport)

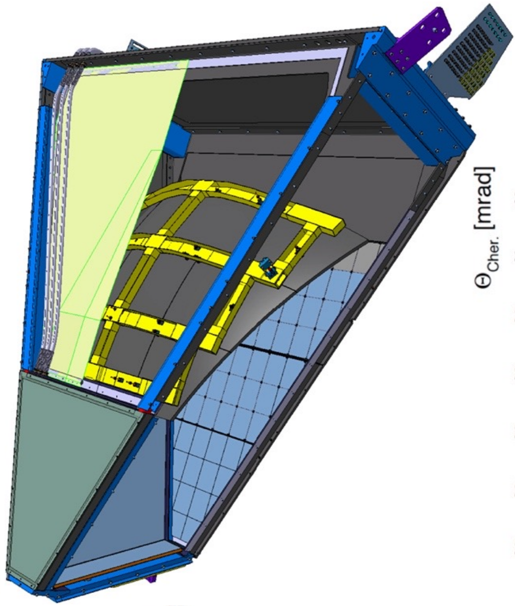
Investigate spin structure of nuclons

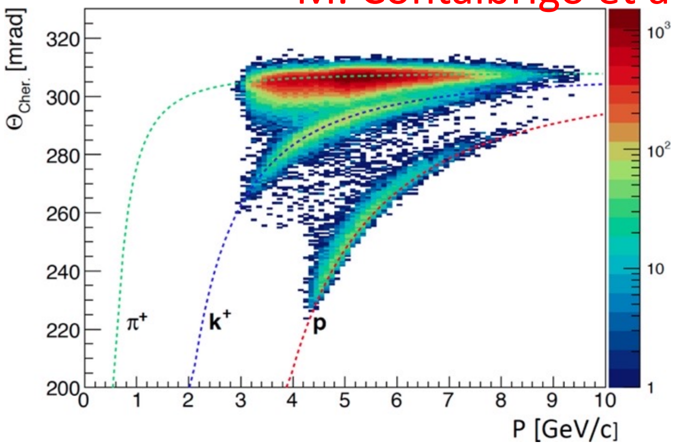
π/K/p-separation at 3÷8GeV/c

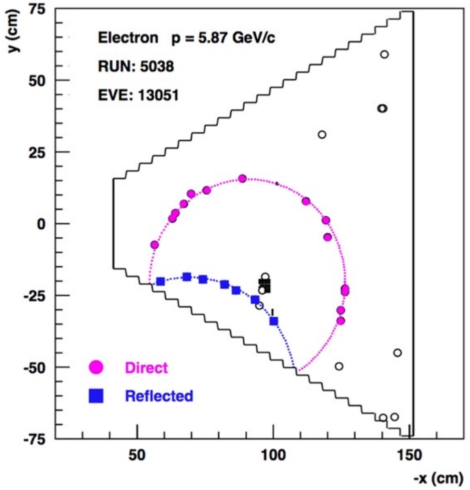
- Aerogel n=1.05
- 2 sectors with 102 tiles 20x20x3(2)cm^3/each

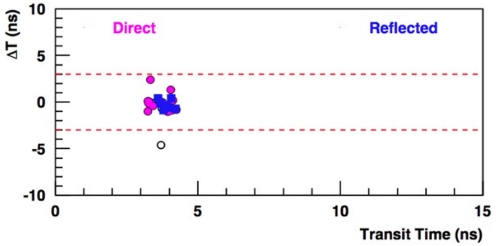
M. Contalbrigo et al., NIM A964 (2020) 163791

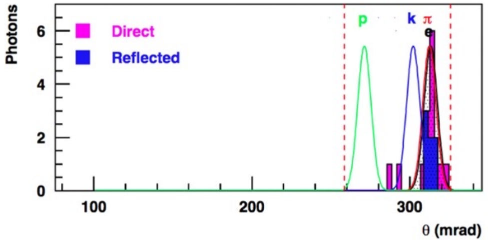


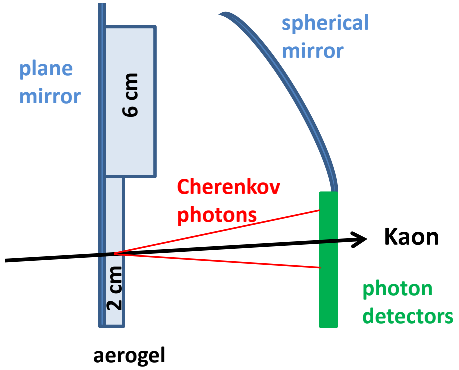


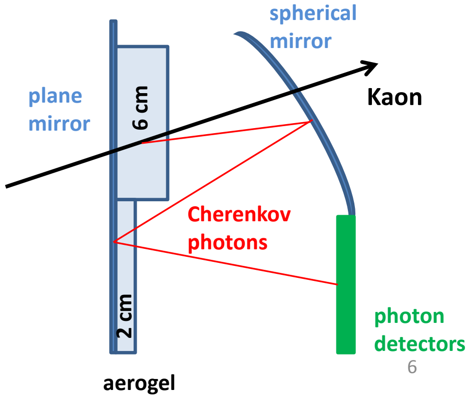








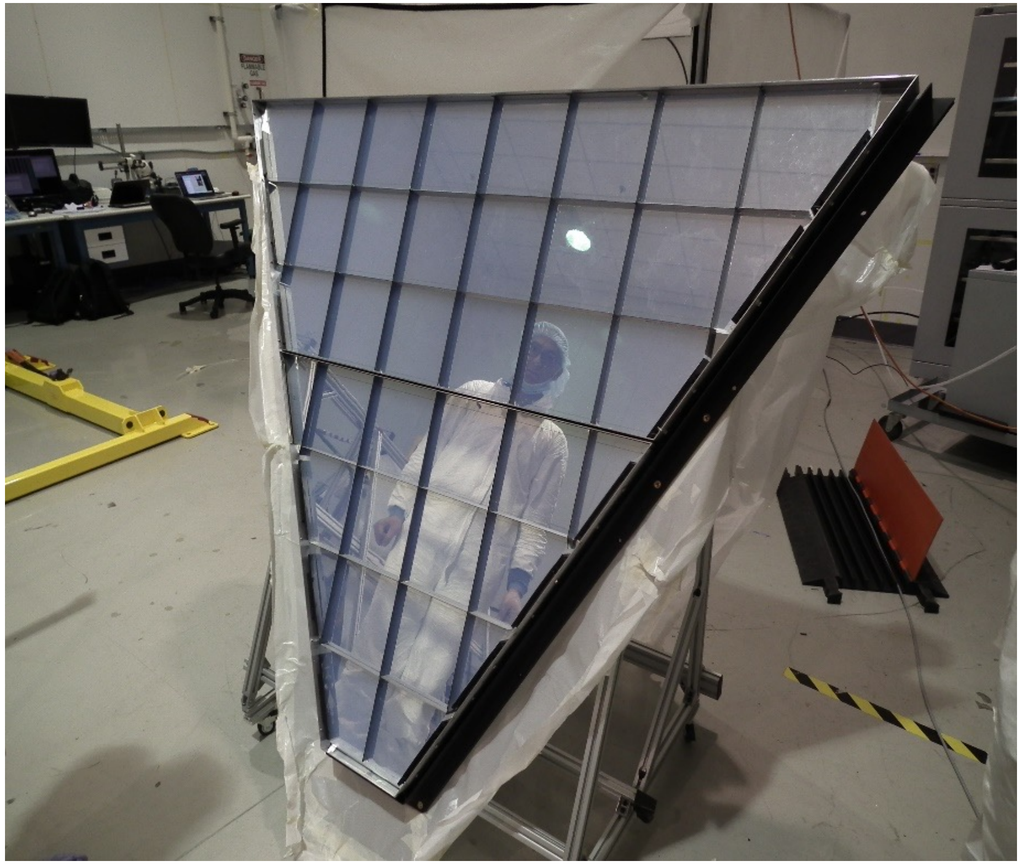




Aerogel R&Ds at the BINP

History of aerogel radiators in Novosibirsk

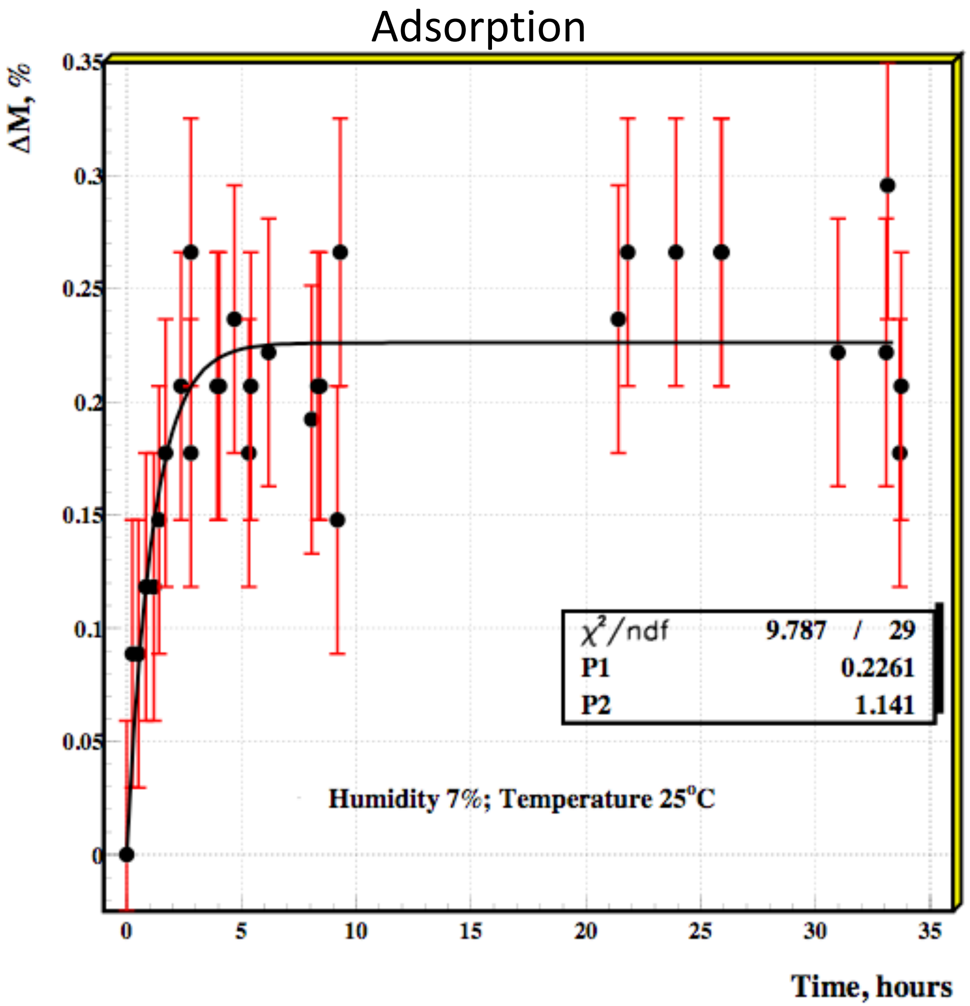
- **KEDR ASHIPH** system (VEPP-4M – BINP):
  - π/K-separation in the momentum range 0,6÷1,5 GeV/c.
  - Aerogel $n = 1{,}05$ (V~1000 L).
- **SND ASHIPH** system (VEPP-2000 – BINP):
  - π/K-separation in the momentum range 300÷870 MeV/c.
  - Aerogel $n = 1{,}13$ (V~9 L).
- **DIRAC-II** (PS – CERN):
  - 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 $см^3$.

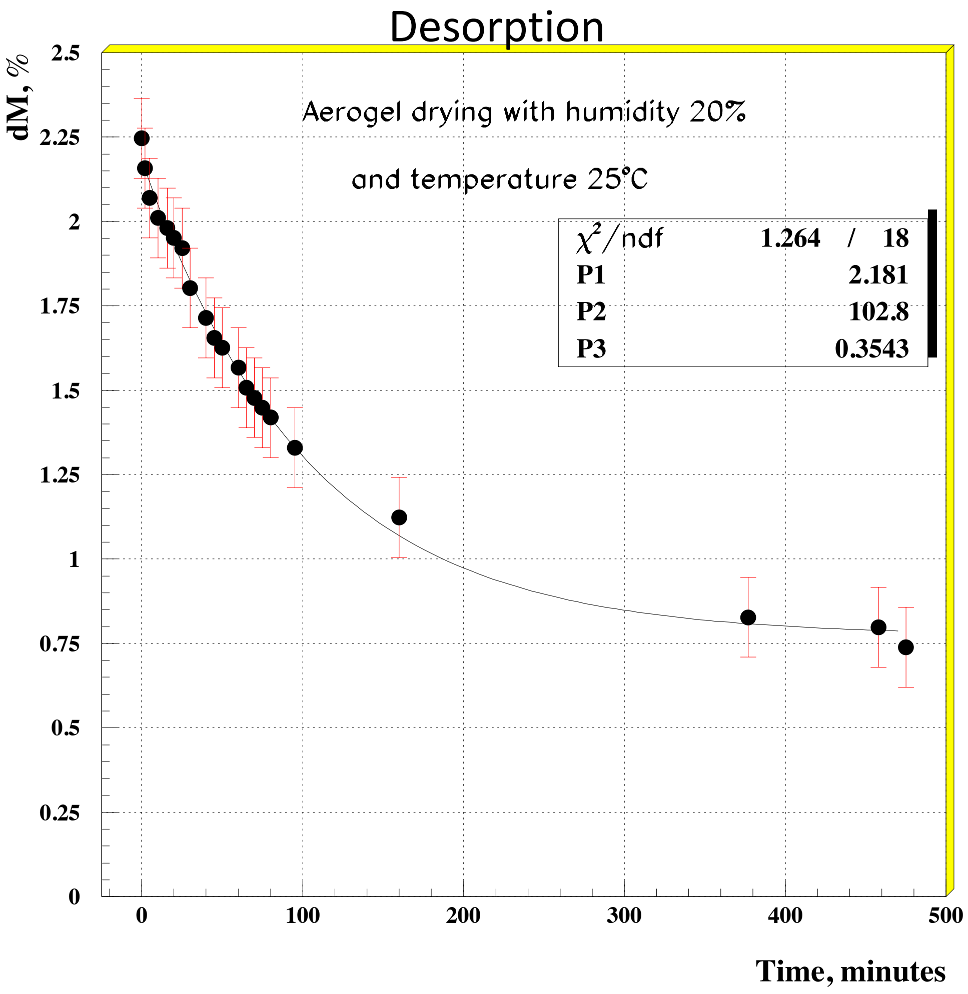


Novosibirsk aerogels is hydrophilic!

- 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 (such like WLS, hermetics or second gas/liquid Cherenkov radiators) which are going to be used in the construction on aerogel transparency.

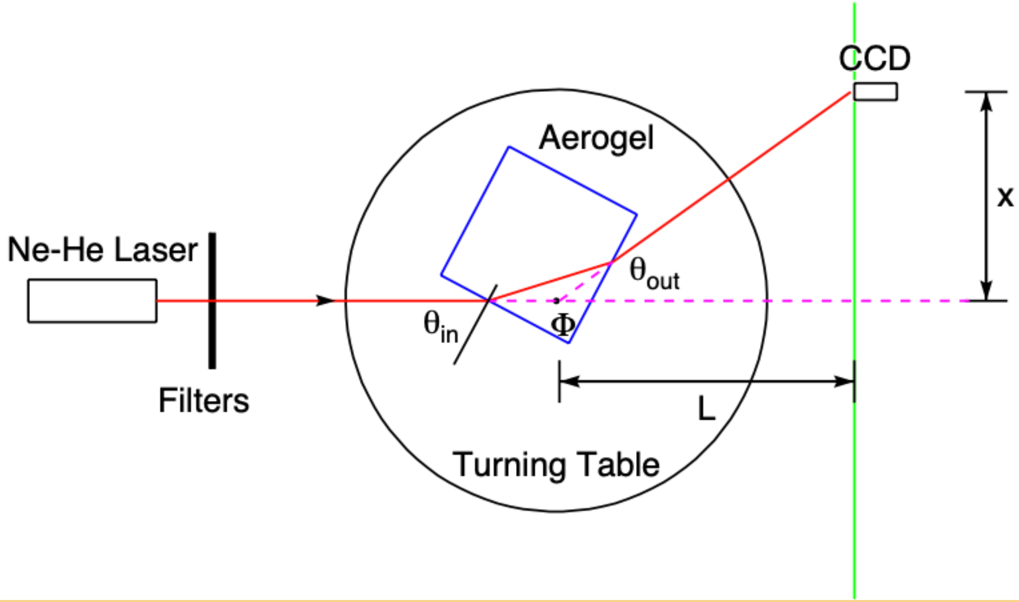
Water adsorption by aerogel





Water adsorption and desorption are the fast processes with time constant about 1 hour.
Amount of adsorbed water depends on relative humidity of invironment.

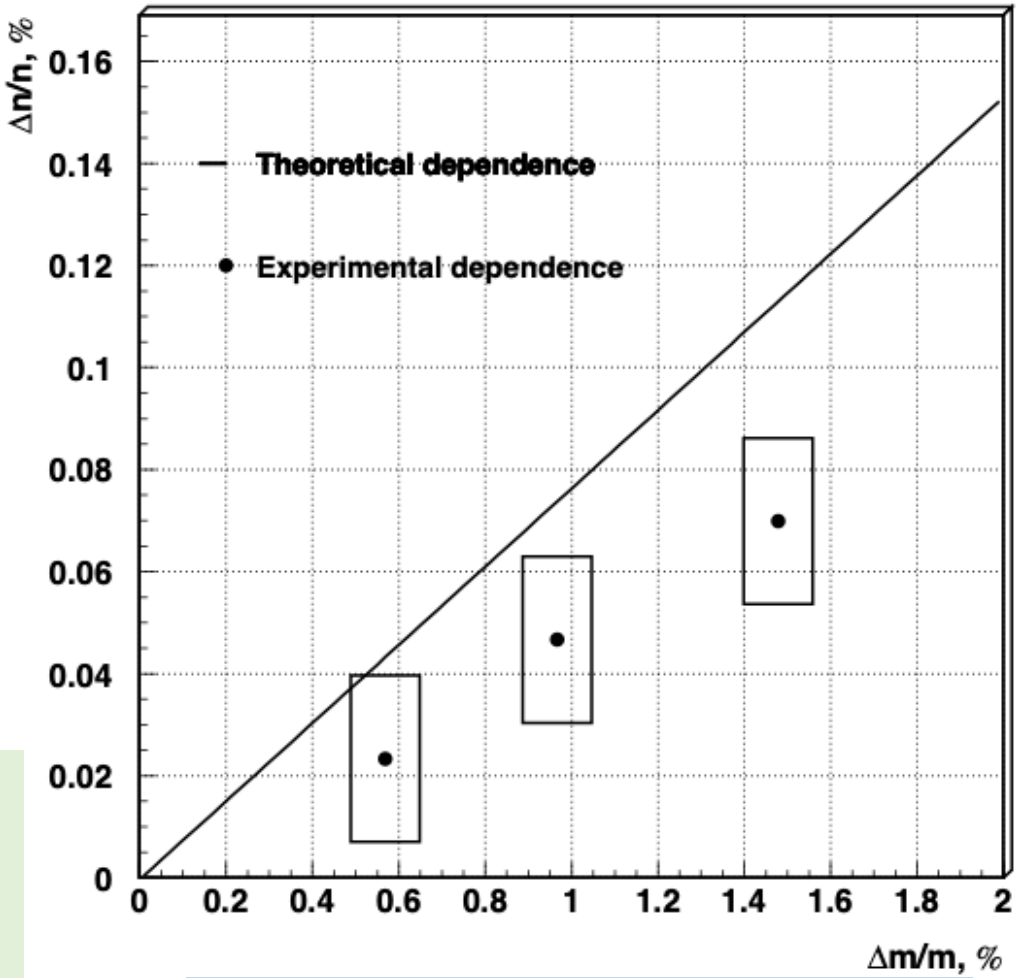
Refractive index



Impirical relation is used for fast determination of n:

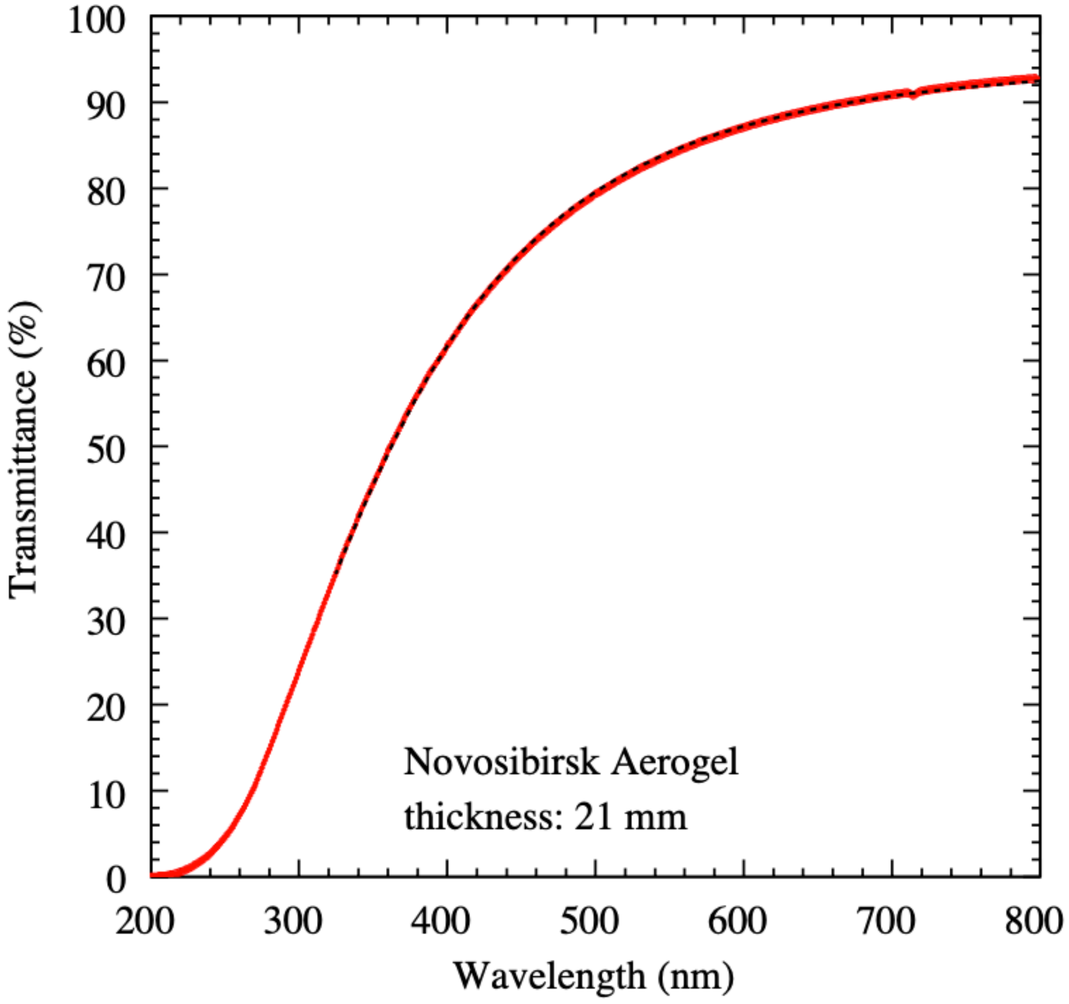
$$n^2 = 1 + 0.438 \cdot \rho \left[{}^{g}/_{cm^3}\right]$$

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.



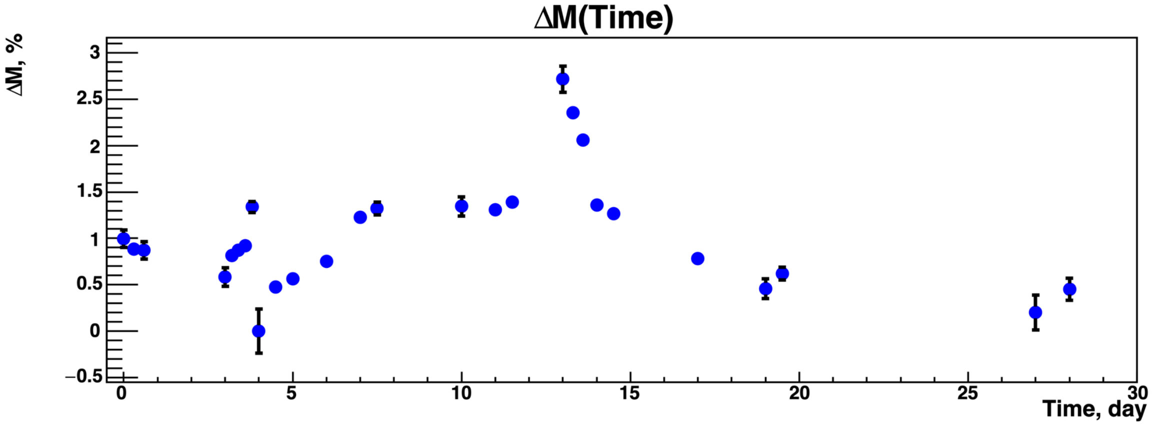
n dependence on water adsorption

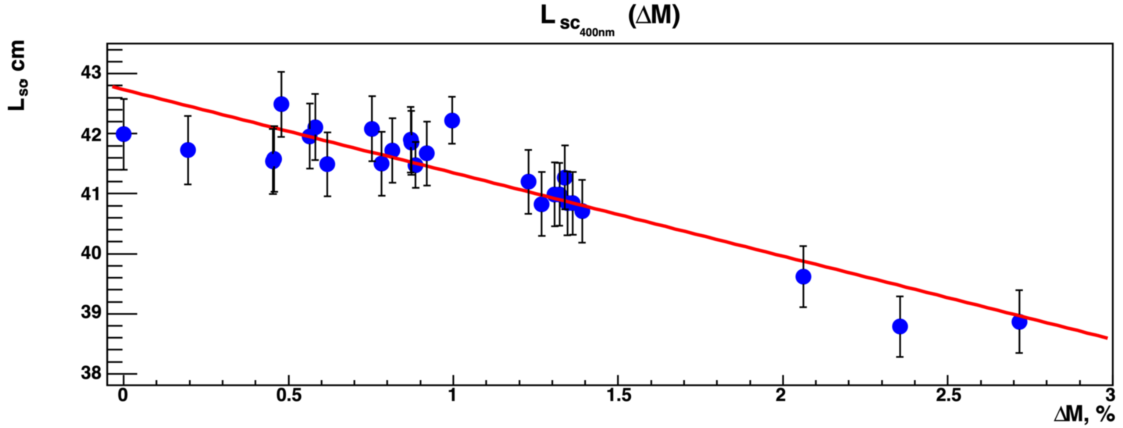
Aerogel transmittance and parameters of Rayleigh light scattering

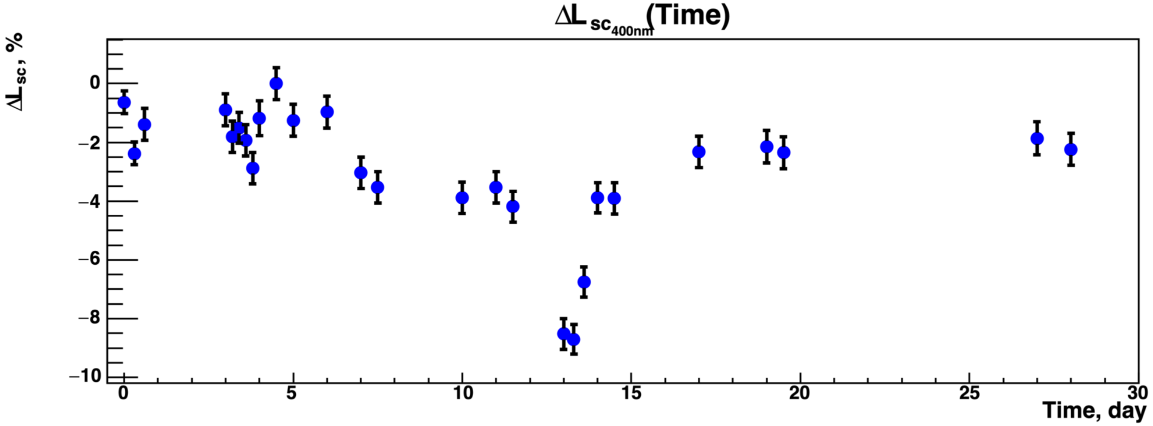


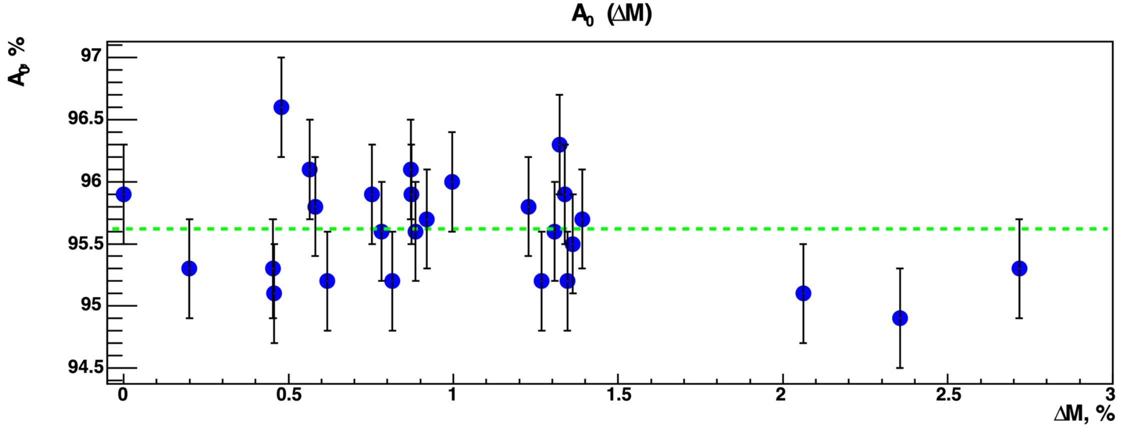
- Hunt formula to fit the transmittance (T) usually are used in two variations:
- $T(\lambda) = \frac{I}{I_0} = A_0 e^{-\left(\frac{d}{L_{sc}^{400} \times \left[\frac{\lambda}{400}\right]^4}\right)}$
- or
- $T(\lambda) = \frac{I}{I_0} = A_0 e^{-\left(C \cdot d / \lambda^4\right)}$
- where d – aerogel 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







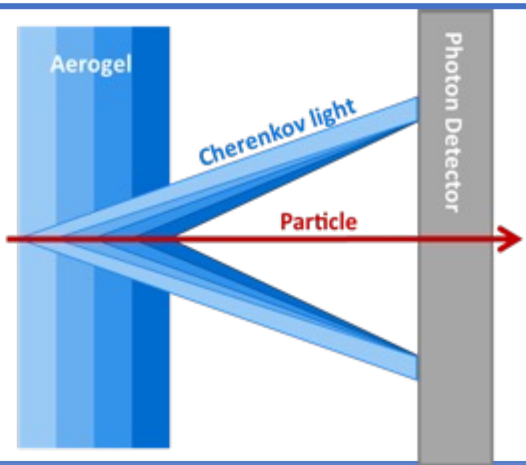


Raleigh light scattering in aerogel strongly dependce on amount of adsorbed water the effects of light scattering length decrease in normal conditions doesn’t exceed 10% (L_{sc}(400 nm) drops from 43 to 38 mm).

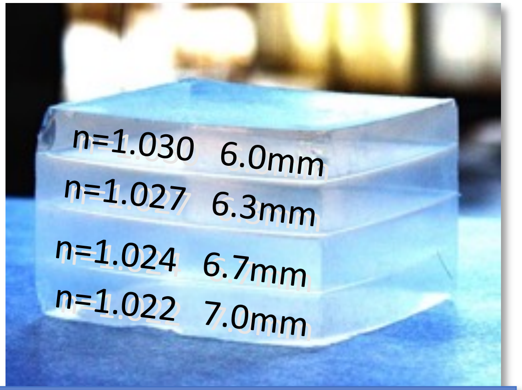
T. Bellunato, et al., NIM A 527(3) (2004) 319

FARICH – 19 years of R&Ds (since 2004)

FARICH technique



The first 4-layer monolithic sample

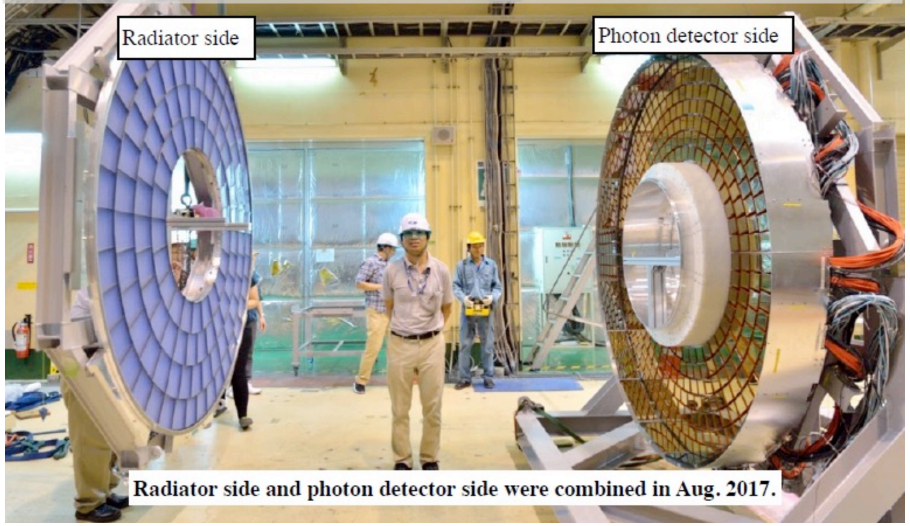


Increase N_{pe} due thickness increase without $\sigma_{\Theta c}$ degradation

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

2004÷2005

The Belle II (ARICH) is the first application of the method

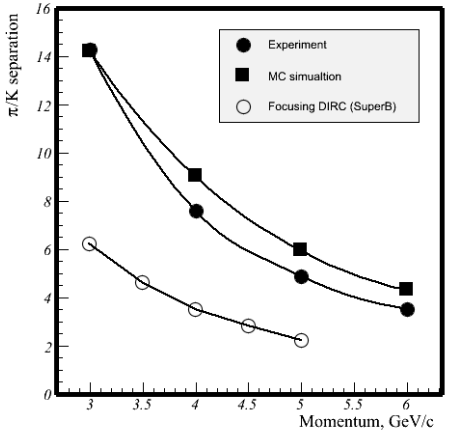


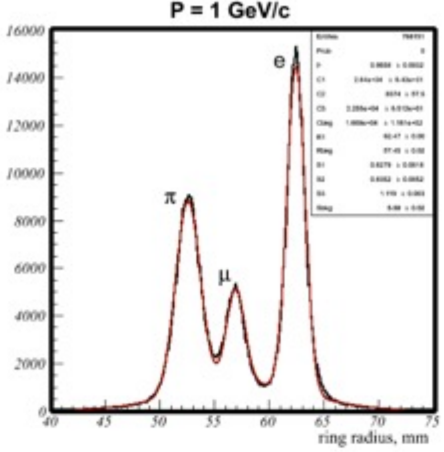
Radiator side and photon detector side were combined in Aug. 2017.

2017

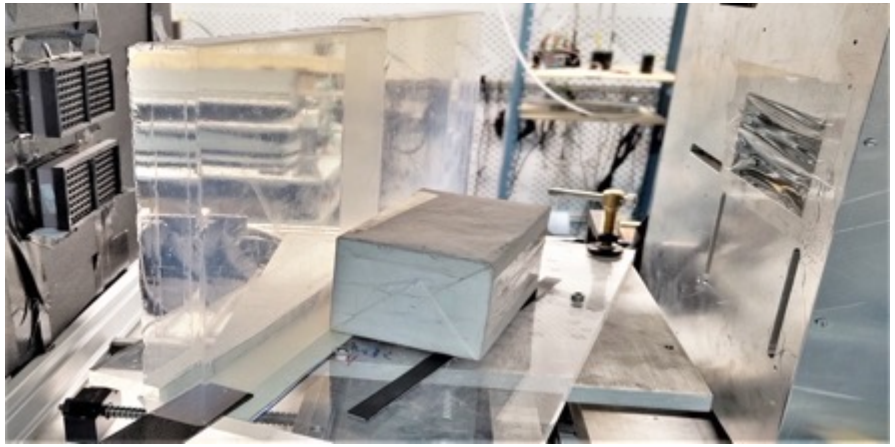
Excellent PID capability were shown at CERN beam test in 2012

A.Yu. Barnyakov, et al., NIM A 732 (2013) 352



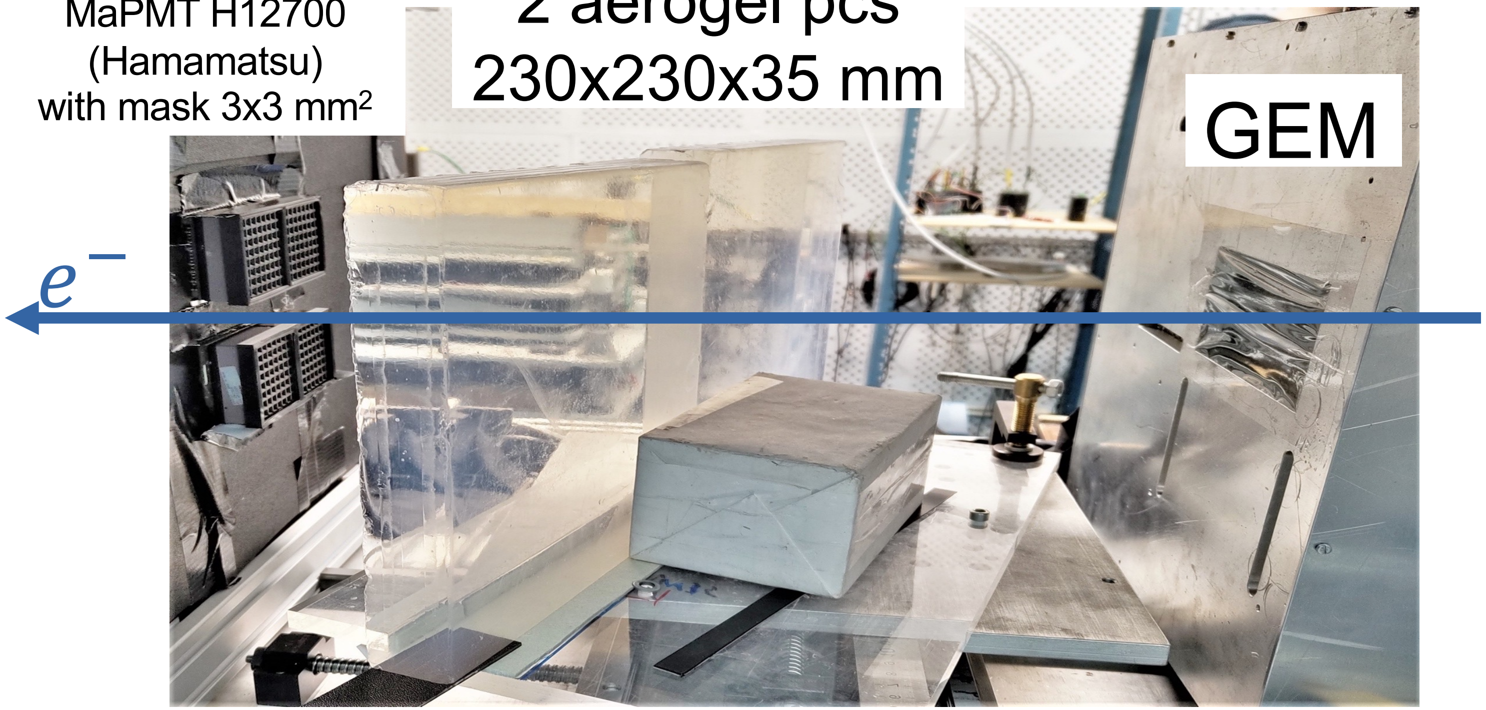


Two 4-layer focusing aerogel blocks
230x230x35 mm



2022÷2023

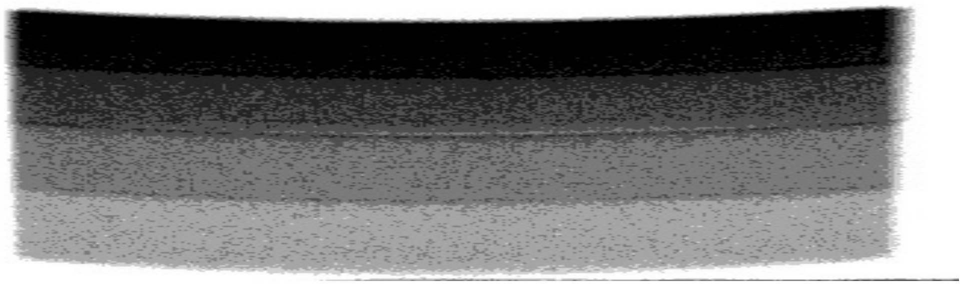
The largest 4-layers focusing aerogel samples



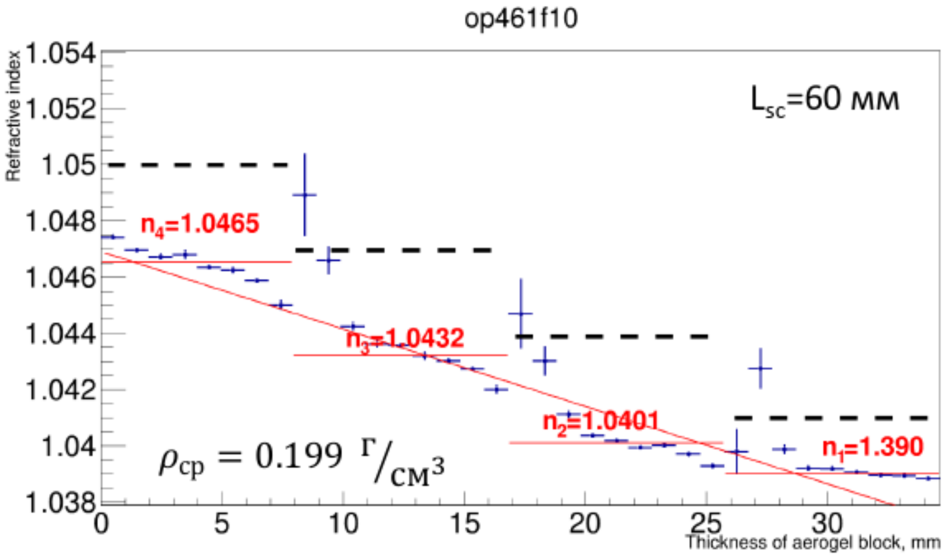
MaPMT H12700 (Hamamatsu) with mask 3x3 mm^2

2 aerogel pcs
230x230x35 mm

GEM



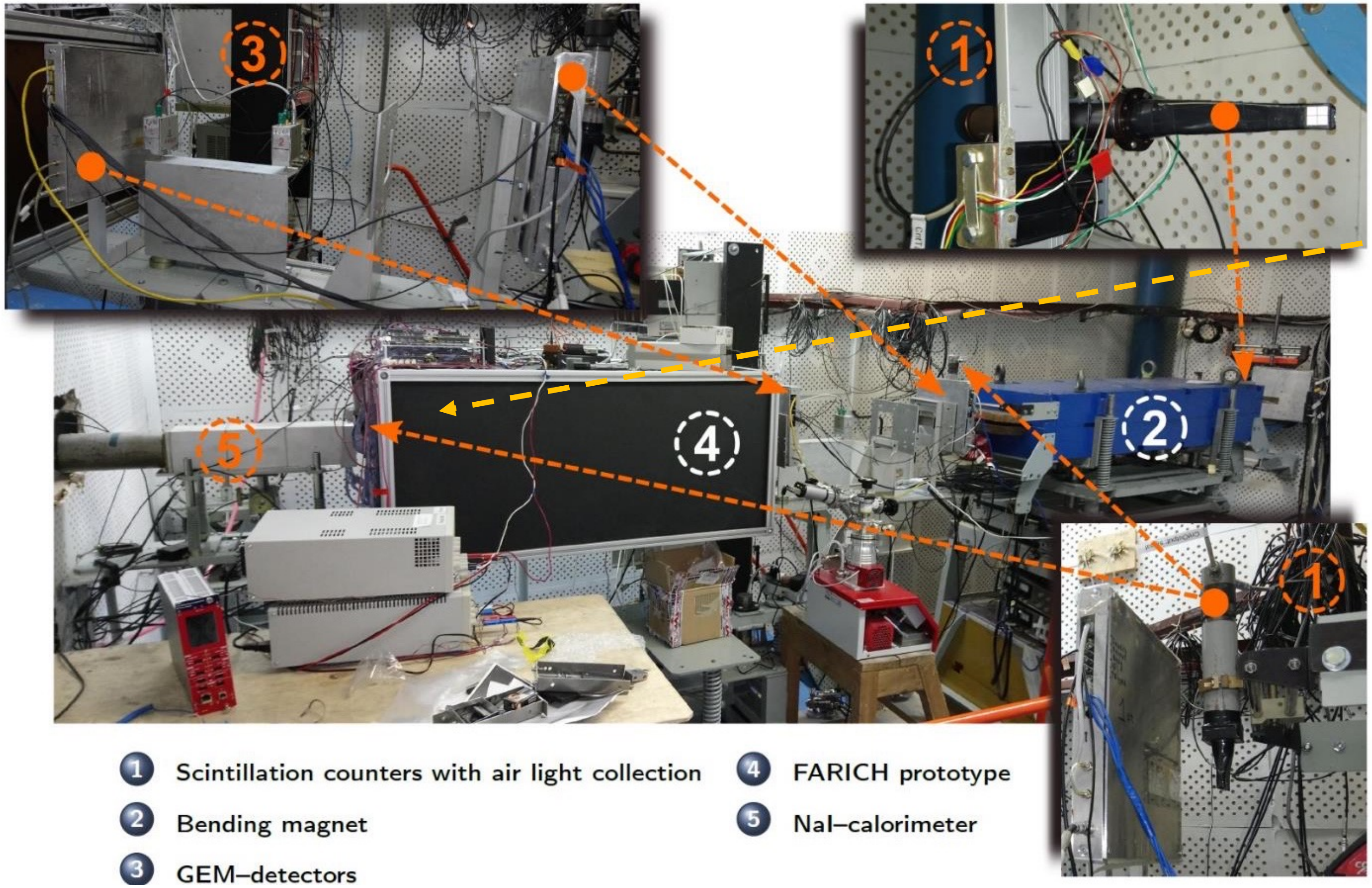
Refractive index profile is measured with help of didgital X-ray setup at the BINP.



Single photon Cherenkov angle resolution is investigated with relativistic electrons at BINP beam test facilities ”Extracted beams of VEPP-4M complex”.

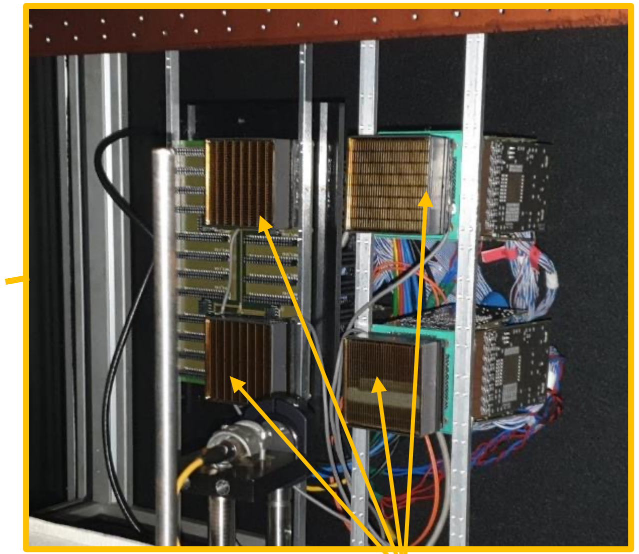
BINP beam test facility

Example disposition of equipment in experimental hall (15/03/2018)

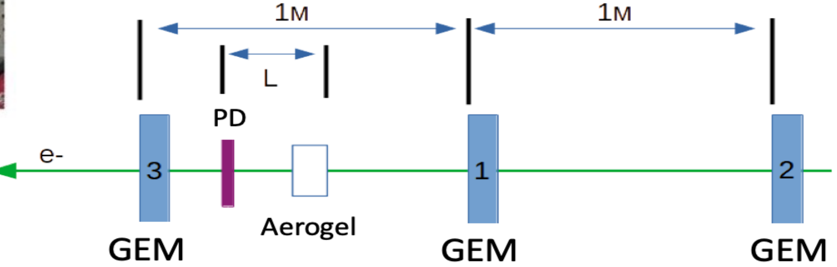


- ① Scintillation counters with air light collection
- ② Bending magnet
- ③ GEM–detectors
- ④ FARICH prototype
- ⑤ NaI–calorimeter

*G N Abramov et al 2014 JINST **9** C08022*

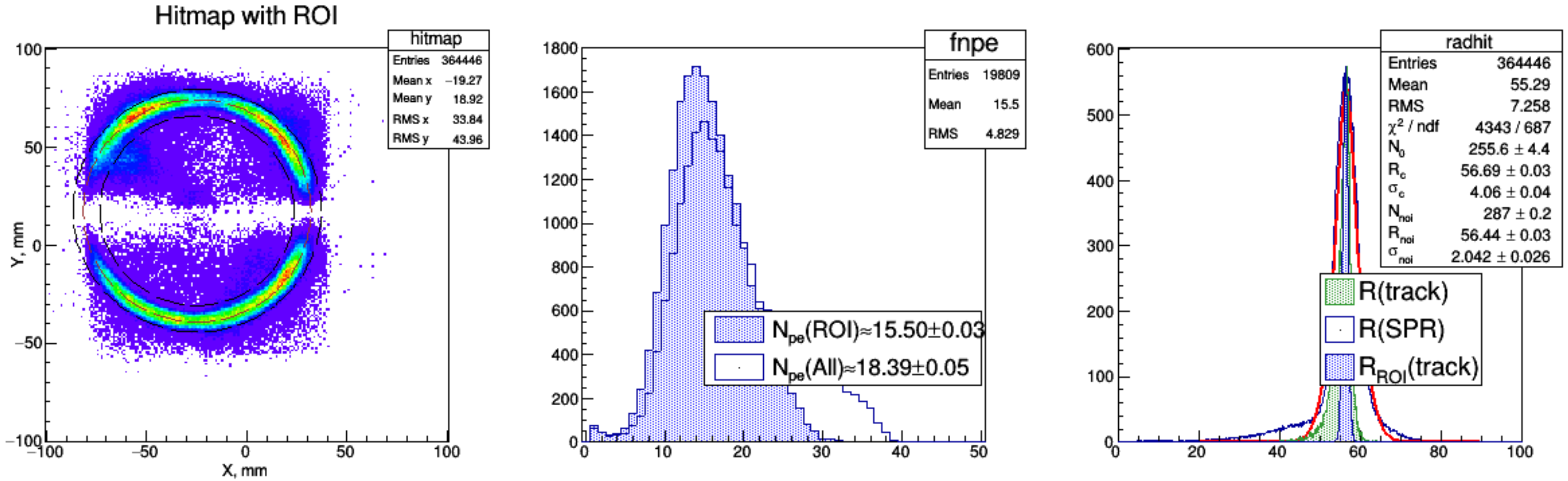


4 MaPMT H12700

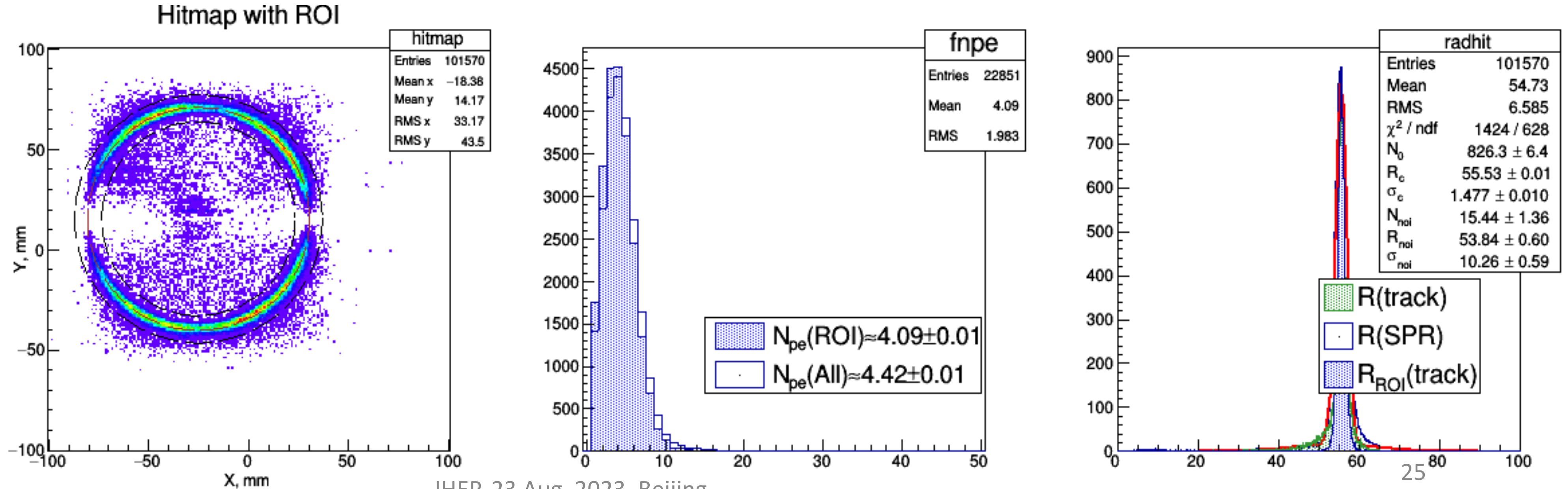


Beam test results

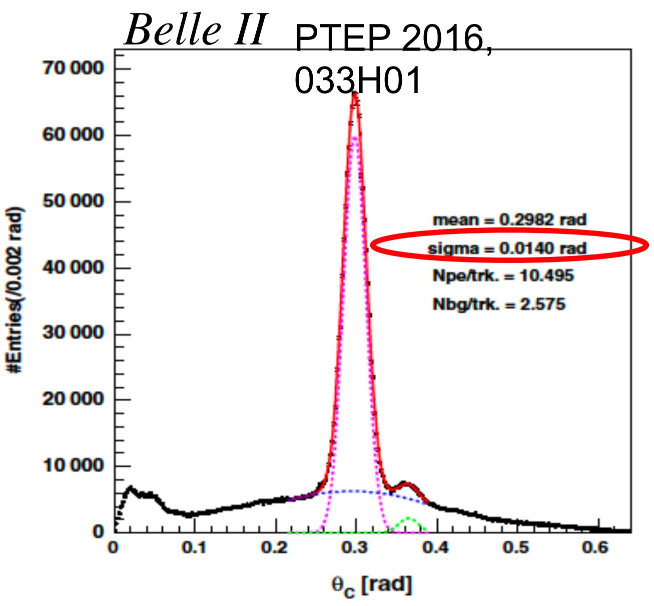
Pixel 6x6 mm
Geom.Eff. ~ 80%

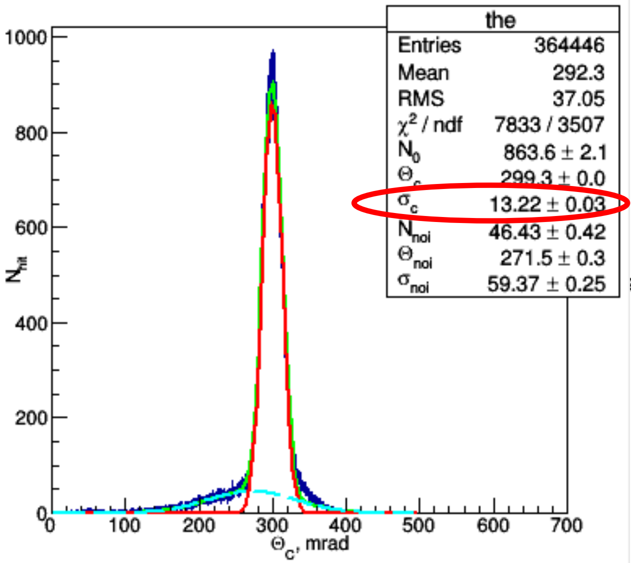


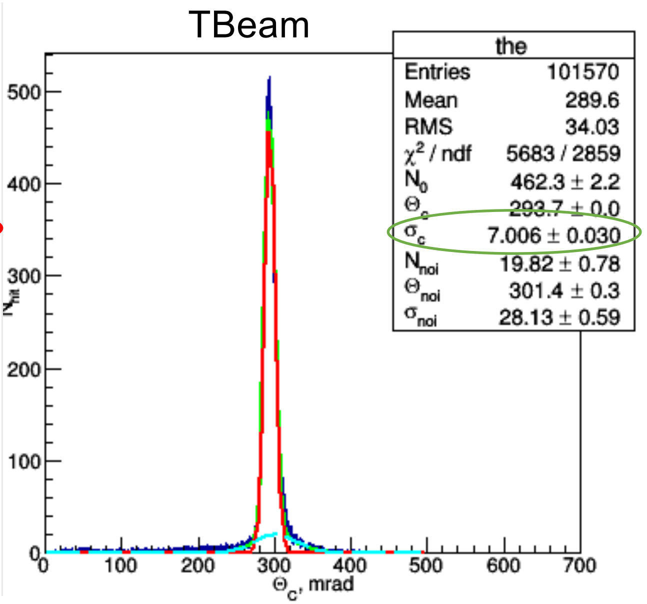
Pixel 3x3 mm
Geom.Eff. ~ 20%

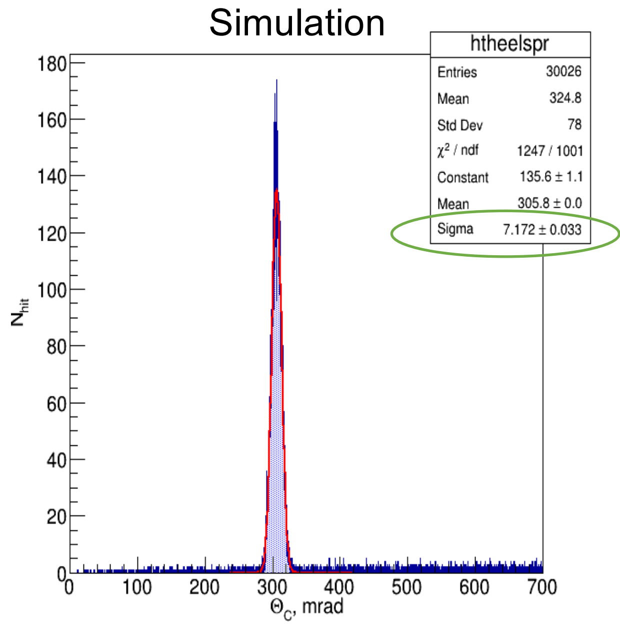


Cherenkov angle Single Photo-Electron (*SPE*) resolution







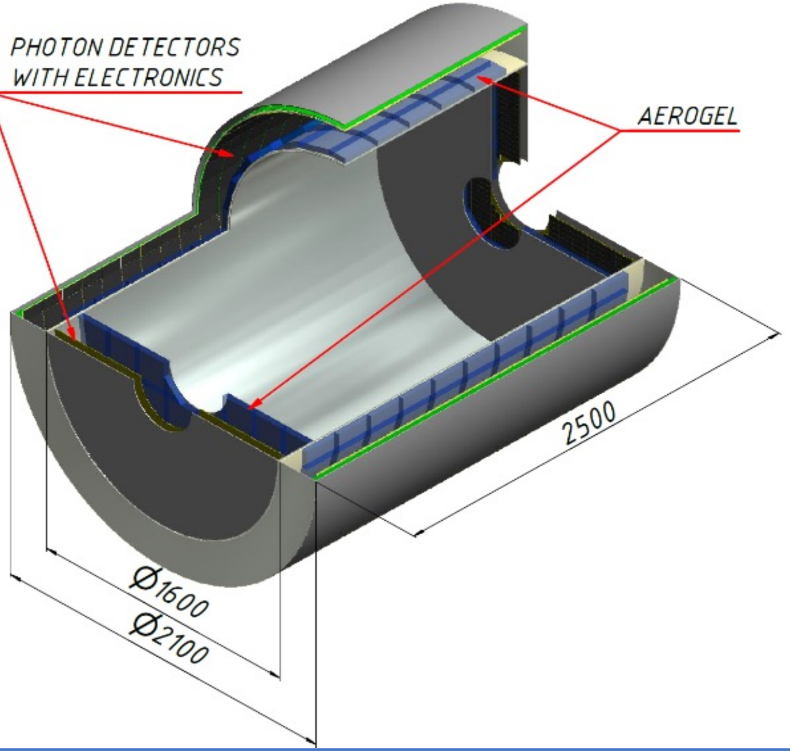


Aerogel: 20+20 mm (Chiba Univ.)	4-layers (Novosibirsk) –>	–	4-layers (ideal profile)
n(400nm): 1.045 +1.055	1.039 ÷ 1.046	–	1.041 ÷ 1.050
Pixel: 5x5 mm	6x6 mm	3x3 mm	3x3 mm
Geom.Eff. ~ 90% $N_{pe} \approx 10.5$	Geom.Eff. ~ 80% $N_{pe} \approx 16$	Geom.Eff. ~ 20% $N_{pe} \approx 4$	

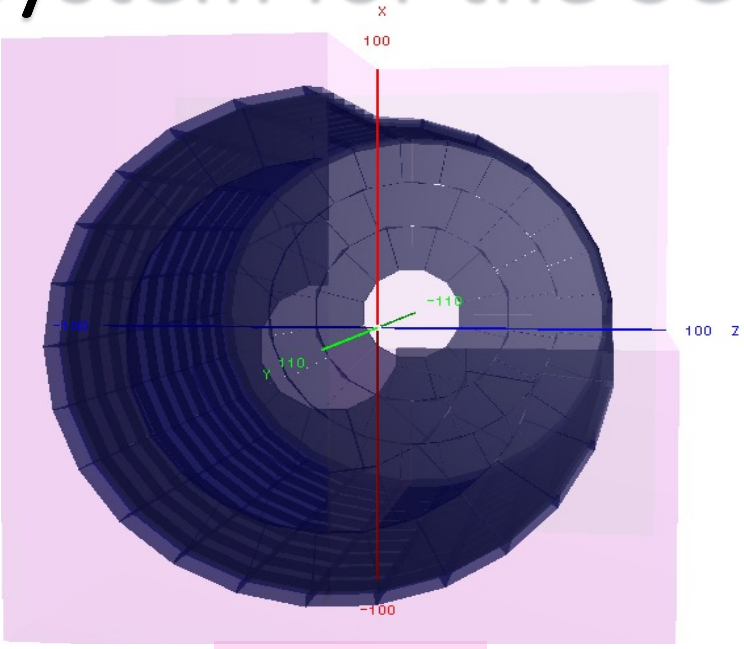
The excellent single photon Cherenkov angle resolution ~7÷8 $mrad$ was achieved with the 4-layer focusing aerogel tiles with dimensions 23x23x3.5 cm for the first time in 2022!!!

This circumstance allows us to consider the FARICH detector design based on 4-layer focusing aerogel tiles with large dimensions (23x23x3.5 cm).

FARICH system for the SCTF



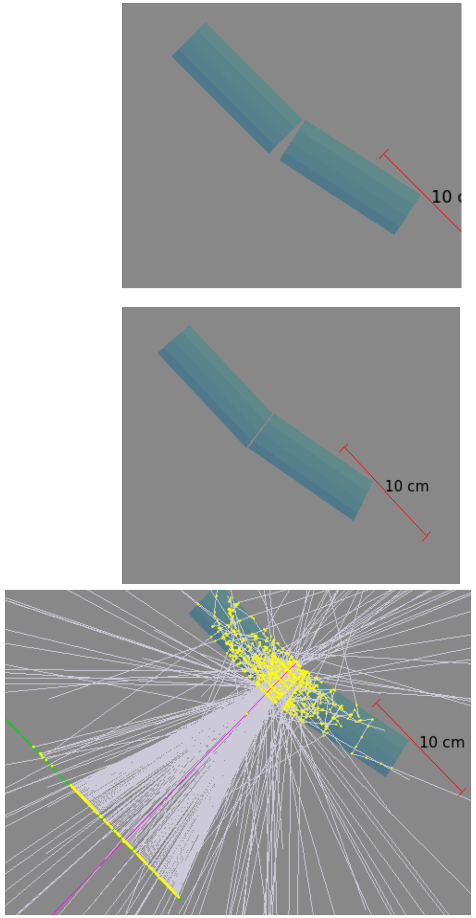
- Proximity focusing RICH
- 4-layer focusing aerogel
  - n_{max} = 1.05 (1.07?), total thickness 35 mm
  - $S_{aer} = 15\ m^2$
- 21 m^2 – total area of photon detectors
  - SiPMs – barrel part (16 m^2)
  - MCP-PMT – endcap parts (4 m^2)
- ~10^6 pixels 3x3 mm^2 with pitch 4 mm



Aerogel layout

275 tiles 200x202x35 in barrel part
2x55 trapezoidal tiles in end caps:
2x12 – inner radius
2x18 – medium radius
2x25 – outer radius

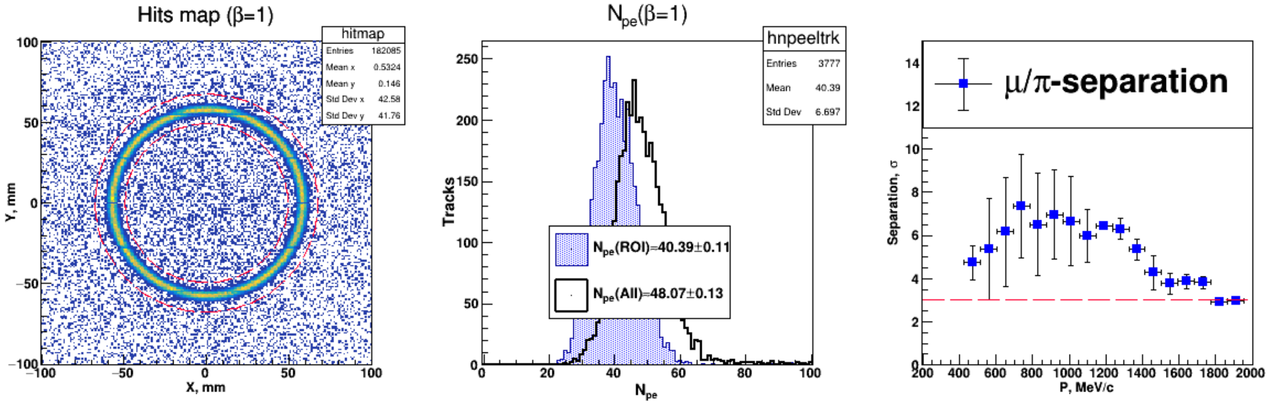
GEANT4 simulation of edge effects



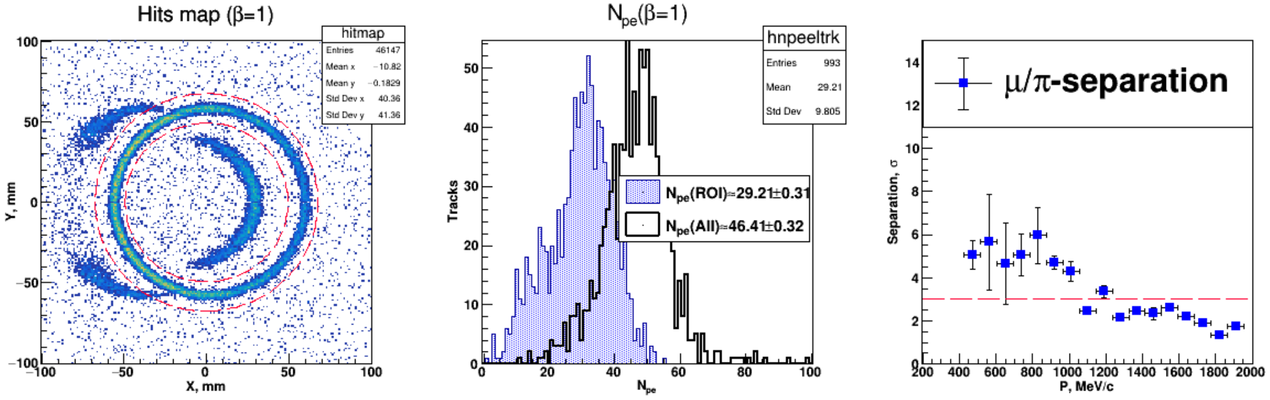
SHAPE	Δ, mm	Aerogel size, mm			
		200	100	75	50
Parallelepiped	6	0.86	0.74	0.62	0.5
Trapezoidal	1	0.96	0.94	0.92	0.9

FARICH edge effects: simulation & experiment

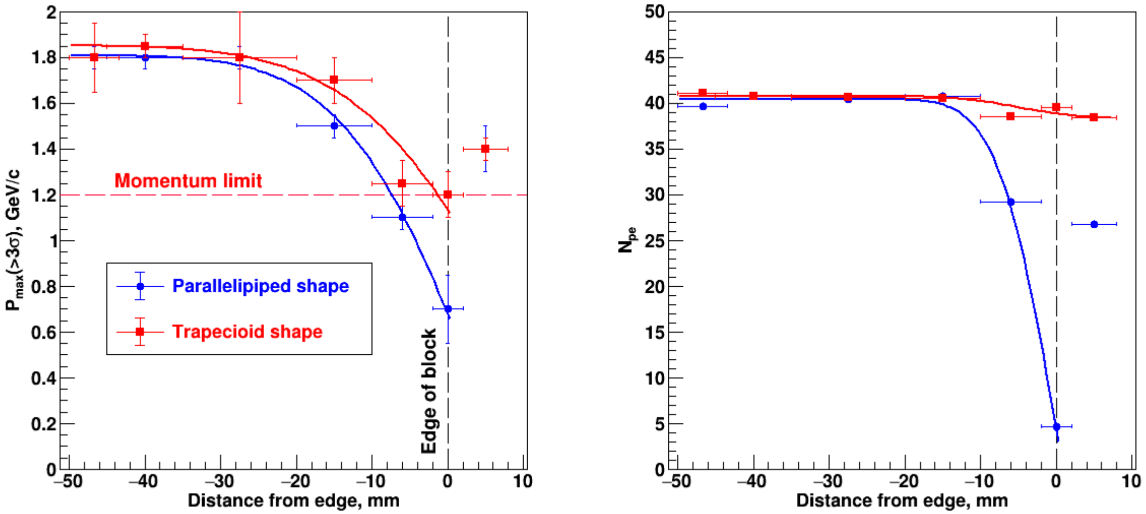
Parallelepiped shape aerogel G4sim



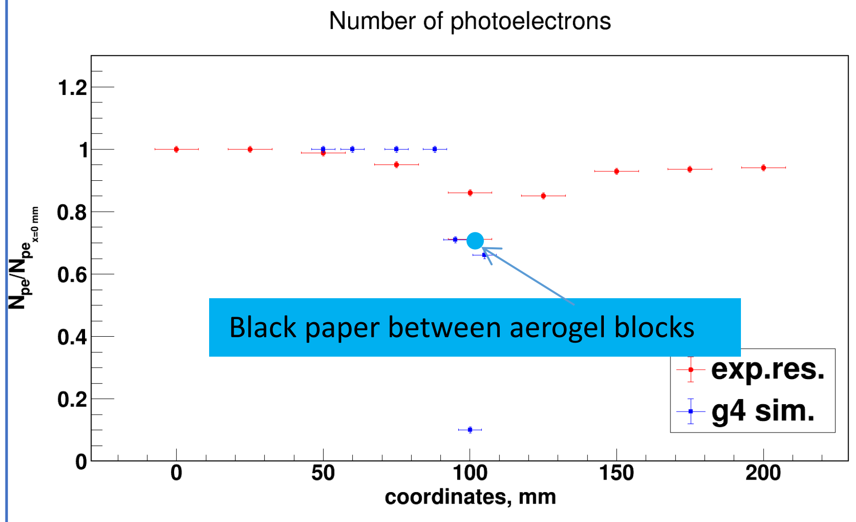
Tracks are in a midle of aerogel tile



Tracks are in 6±4 mm from aerogel tile edge



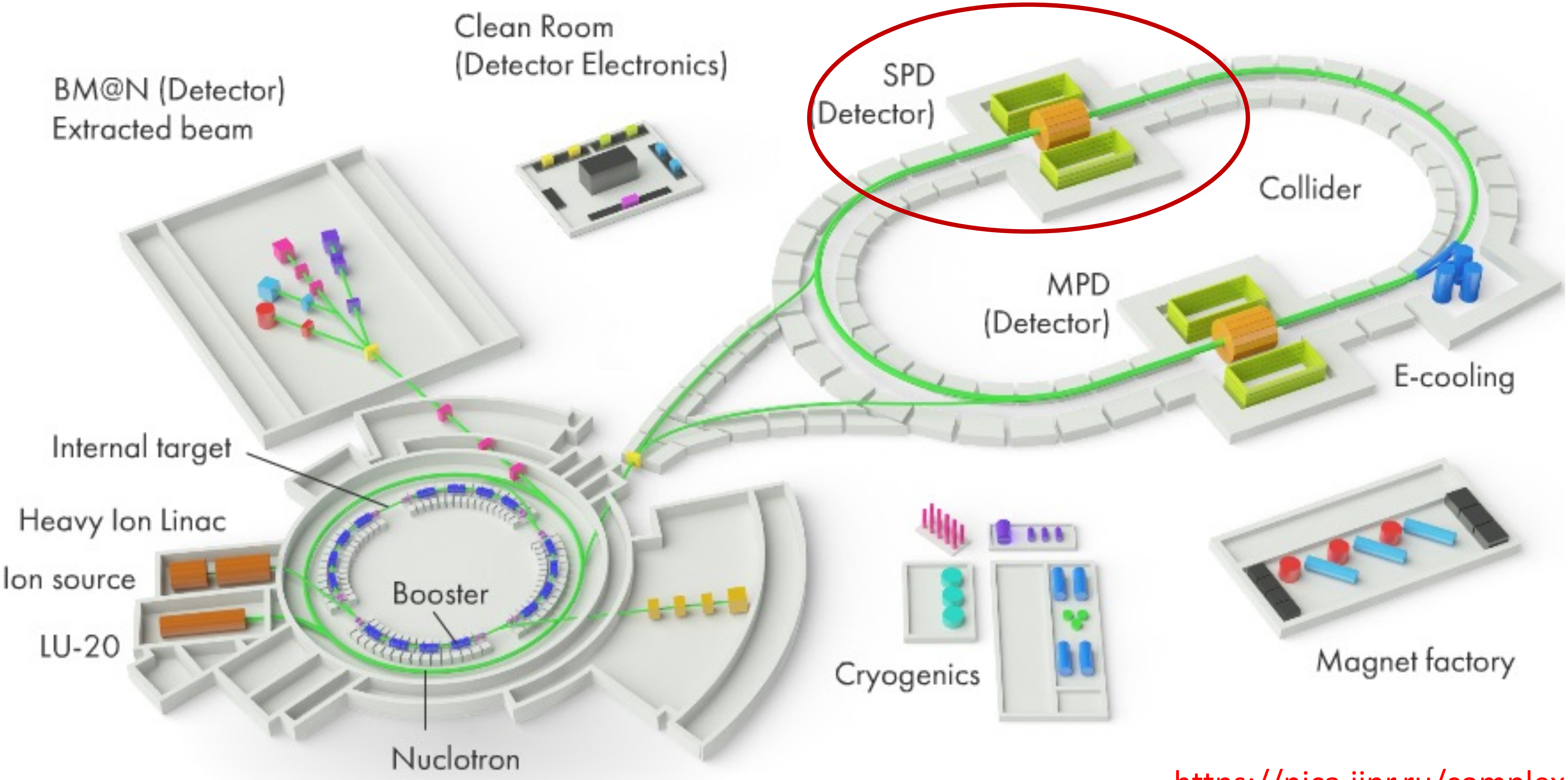
Beam test & sim. results



Black paper between aerogel blocks

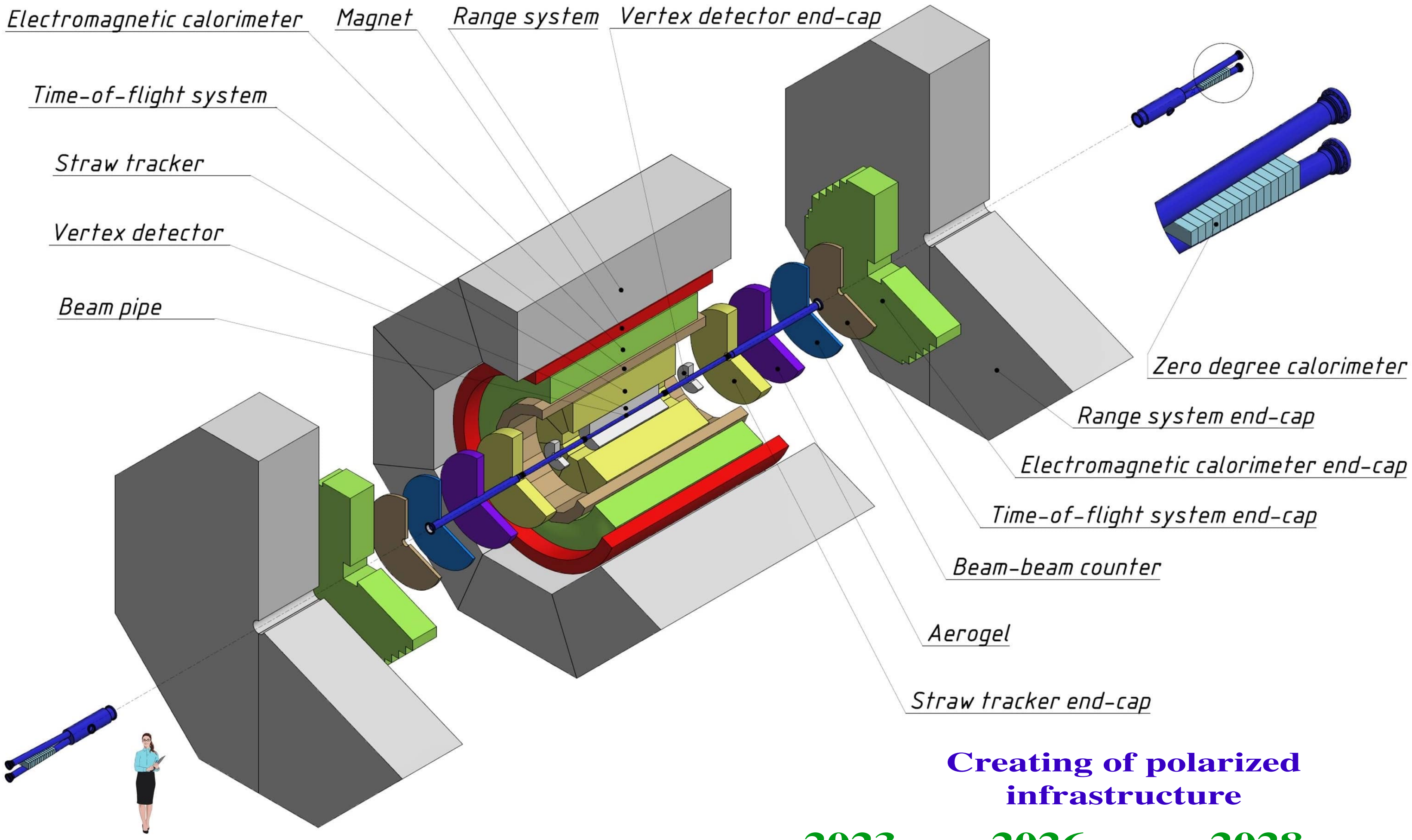
FARICH proposal for SPD-NICA experiment

NICA: Nucleon Ion Colliding fAcility



https://nica.jinr.ru/complex.php

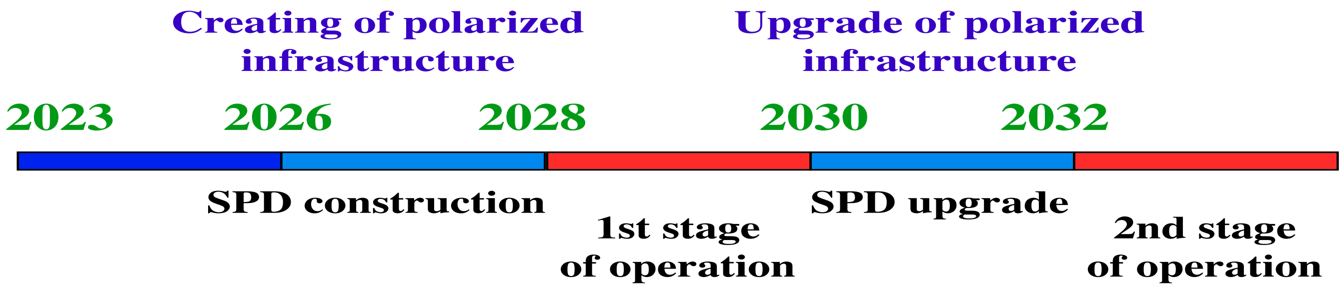
SPD: Spin Physics Detector



- Polarized p (or d)
- 2E = 27 GeV (or 13.5 GeV/nucl)
- L = 10^{32} cm^{-2}s^{-1} (or 10^{31} cm^{-2}s^{-1})

PID:

- π/K/p - separation
- ToF (60ps) + Aerogel



Creating of polarized infrastructure

Upgrade of polarized infrastructure

2023 2026 2028 2030 2032

SPD construction

1st stage of operation

SPD upgrade

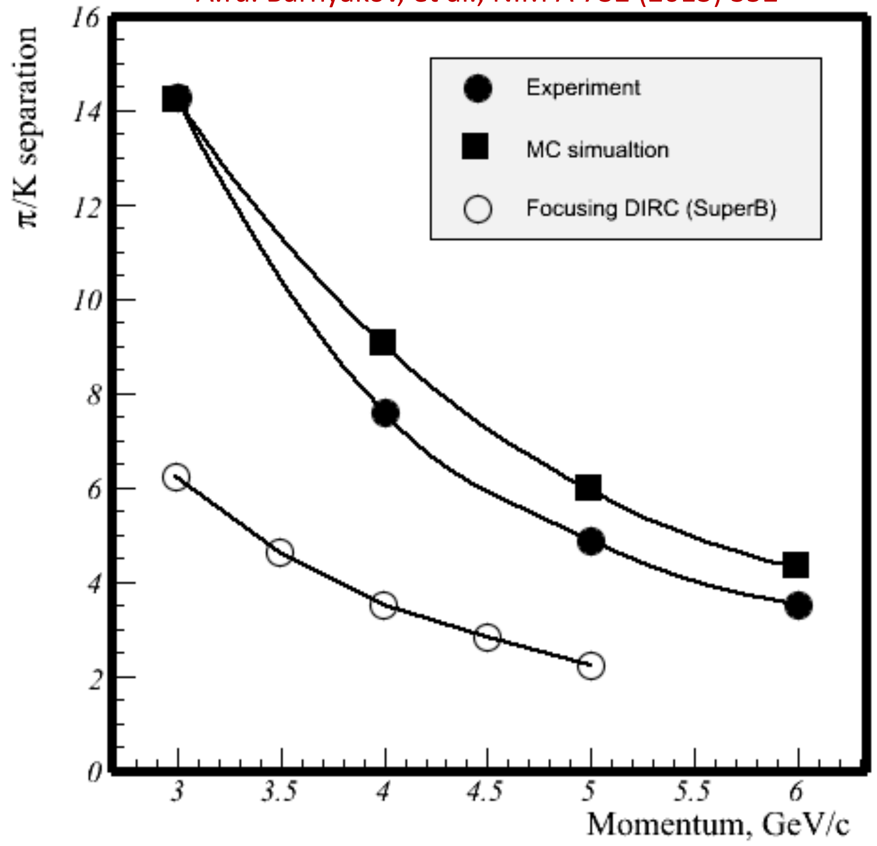
2nd stage of operation

http://spd.jinr.ru

FARICH option for SPD

π/K – separation in wide momenta range

A.Yu. Barnyakov, et al., NIM A 732 (2013) 352



Recent TBeam results:

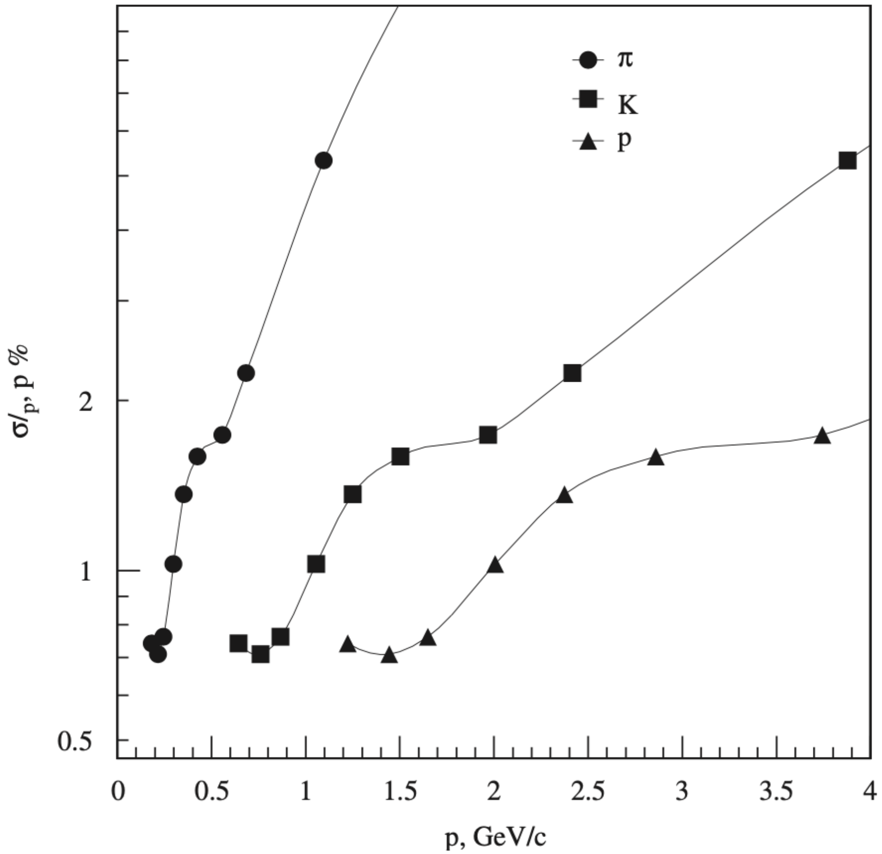
$\sigma_{SPE} = 7.5\ mrad$

$N_{PE} = 16$

π/K @ 8 GeV/c : $\frac{\theta_C^{\pi} - \theta_C^{K}}{\sigma_{SPE}/\sqrt{N_{pe}}} = \frac{309-303}{1.875} > 3\sigma$

Improve momentum resolution

A.Yu. Barnyakov, et al., NIM A 639 (2011) 290

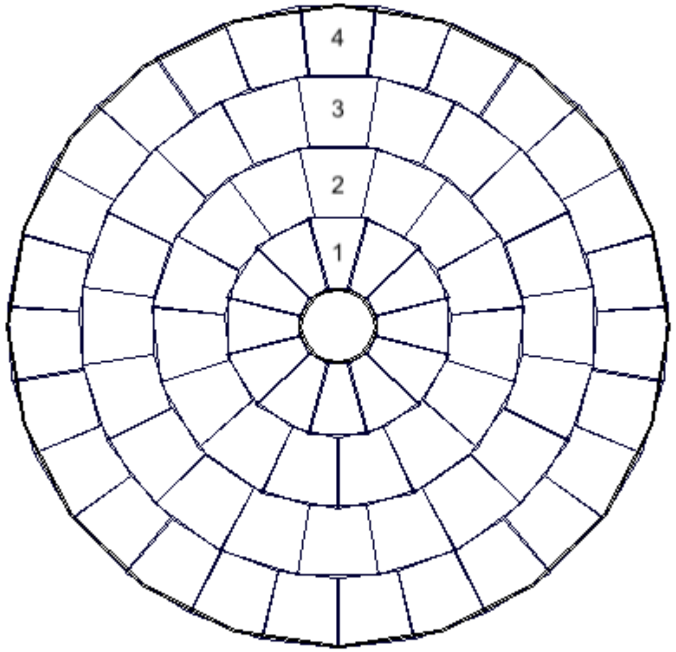


Precise mesurement of velocity with FARICH

improves momentum resolution: $\sigma_p(K)/_p = 1\%@1\ \text{GeV/c}$

DC (Straw tubes): $\sigma_p/_p = 2\%@1\ \text{GeV/c}$

Aerogel layout



1 – 12 tiles x S=0.5•(5.6 + 15.6)•18.5 = 159.0 sq.cm
2 – 15 tiles x S=0.5•(12.2+20.2)•18.5 = 299.7 sq.cm
3 – 20 tiles x S=0.5•(15.0+20.8)•18.5 = 331.15 sq.cm
4 – 27 tiles x S=0.5•(15.2+19.6)•18.5 = 321.9 sq.cm

S(aer)/S(total)=21717.8/22383.8=0.97

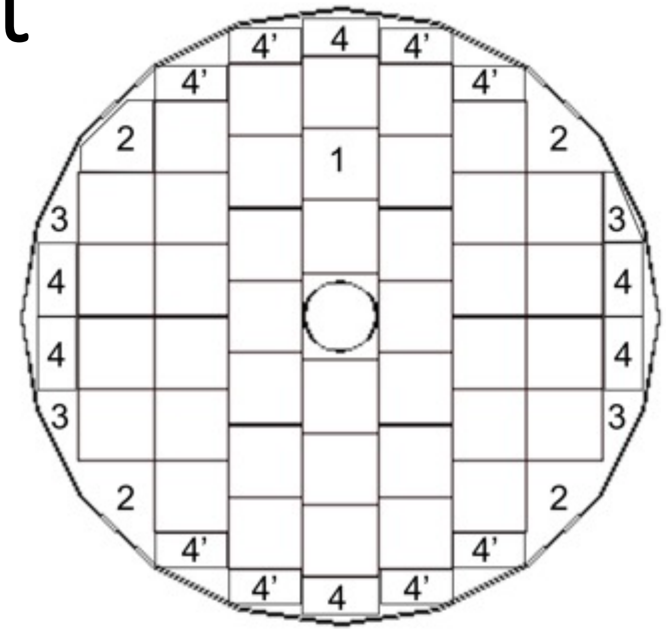
For two endcap FARICH detectors it is required:

– 136 ”good” aerogel tiles 23x23x3.5 cm (5.44 m^2);

– Produce, select and characterise ~2×136 aerogel tiles with help of digital X-ray setup and other laboratory satnds including electron beam test facilities* at BINP;

– Cutt off 136 tiles in 4 different trapziodal shapes;

2.5÷3 years for production



1 – 40 tiles x S=20•20=400 sq.cm
2 – 4 tiles x S=20•20–0.5•10•12=340 sq.cm
3 – 4 tiles x S=0.5•(12+5)•20=170 sq.cm
4 –14 tiles x S=20•10=200 sq.cm

S(aer)/S(total)=20840/22383.8=0.93

– 106 ”good” aerogel tiles 23x23x3.5 cm (4.24 m^2);

– Produce, select and characterise ~2×106 aerogel tiles with help of digital X-ray setup and other laboratory satnds including electron beam test facilities* at BINP;

– Cutt off 106 tiles in 2 rectangular and 2 trapziodal shapes;

2÷2.5 years for production

FARICH with dual aerogel radiator

PID options for π/K – separation

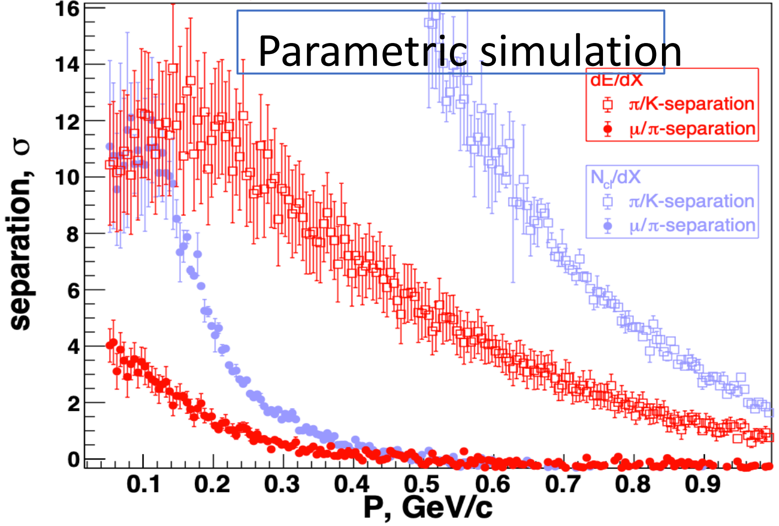
- dE/dx
  - $\frac{\sigma_{dE/dx}}{\langle dE/dx \rangle} \leq 7\% \rightarrow \geq 3\sigma$ up to 0.6 GeV/c
  - $\frac{\sigma_{N_{cl}/dx}}{\langle N_{cl}/dx \rangle} \leq 4\% \rightarrow \geq 3\sigma$ up to 0.9 GeV/c
- Focusing Aerogel RICH (FARICH)

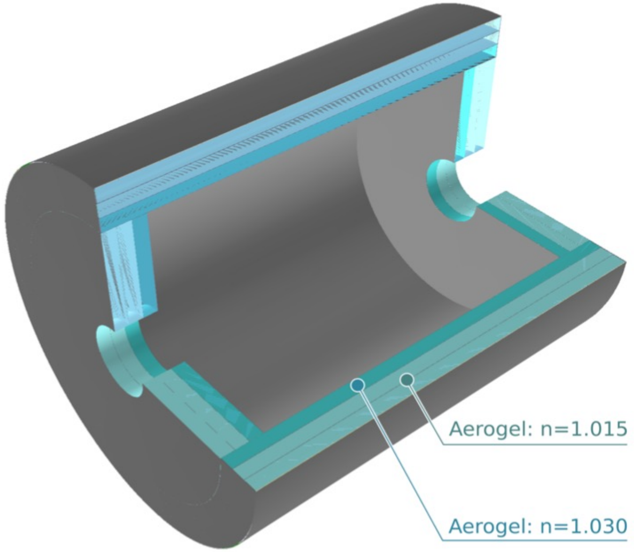
(4 layer @ n_{max}=1.05) → $\geq 3\sigma$ from 0.5 to 6 GeV/c

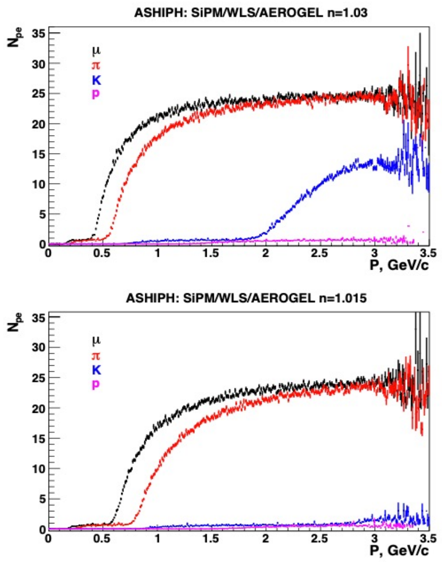
- ASHIPH@SiPM (n_1=1.03 and n_2=1.015) → $\geq 3\sigma$ from 0.6 to 3.5 GeV/c

EPJ Web of Conferences **212**, 01012 (2019),
A.Yu. Barnyakov *et al* 2020 *JINST* **15** C04032

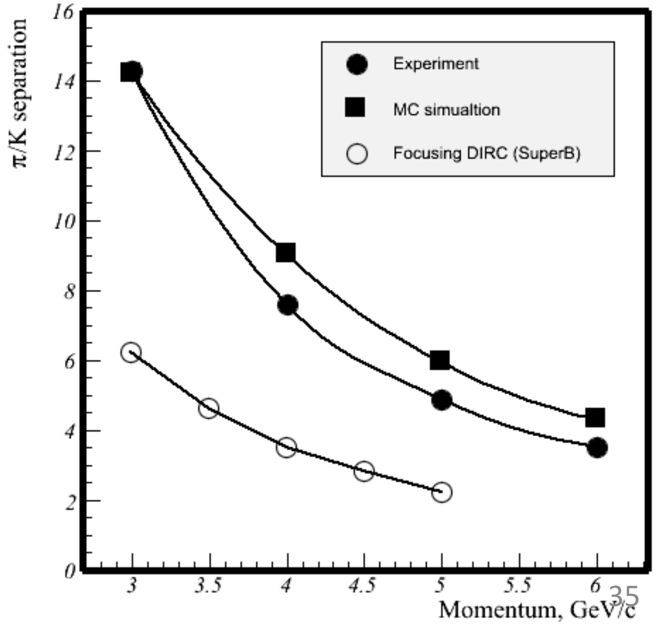
A.Yu. Barnyakov et al 2020 JINST ***15*** *C04032*





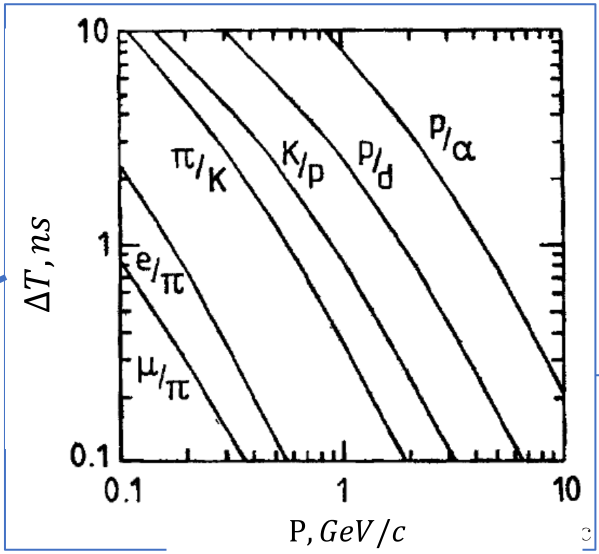


A.Yu. Barnyakov, et al., NIM A 732 (2013) 35



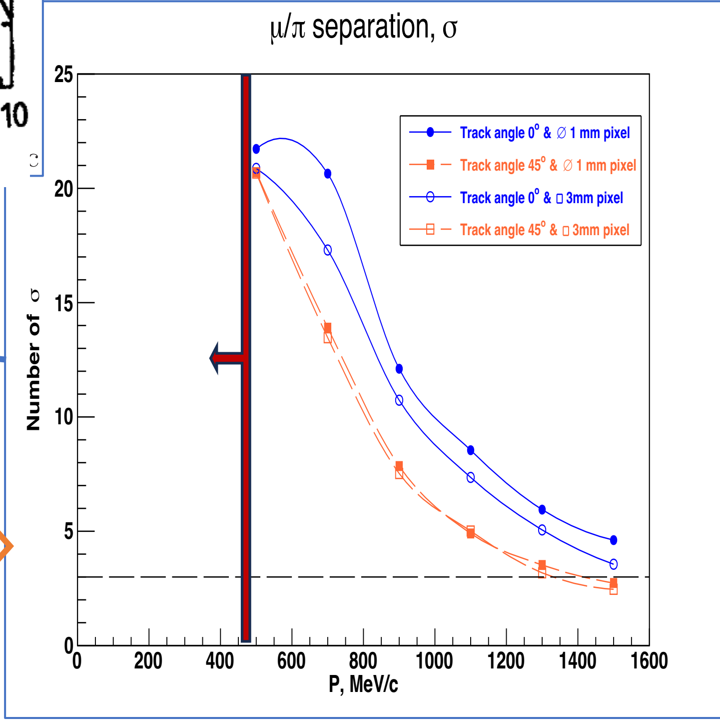
PID options for μ/$\boldsymbol{\pi}$ – separation

- $^{\boldsymbol{dE}}/_{\boldsymbol{dx}}$
  - $\frac{\sigma_{dE/dx}}{\langle dE/dx \rangle} \approx 7\% \rightarrow \geq 3\sigma$ up to 0.15 GeV/c
  - $\frac{\sigma_{N_{cl}/dx}}{\langle N_{cl}/dx \rangle} \approx 4\% \rightarrow \geq 3\sigma$ up to 0.25 GeV/c
- **TOF** with σ_t ≈100 ps $\rightarrow \geq 3\sigma$ up to 0.2 GeV/c, e.g. Chernkov light from entrance window of MCP-PMT
- **FARICH** (4-layer, n_{max}=1.05) $\rightarrow \geq 3\sigma$ from 0.5 to 1.5 GeV/c



FARICH with dual aerogel radiator is proposed to provide μ/π – separation for 0.2≤P≤0.5 GeV/c

Results of parametric simulation tuned with results of beam test campaign in 2021:
– SPR(β = 1, ■3 mm)= 1.63 mm
– SPR(β = 1, ⌀1 mm)= 1.36 mm

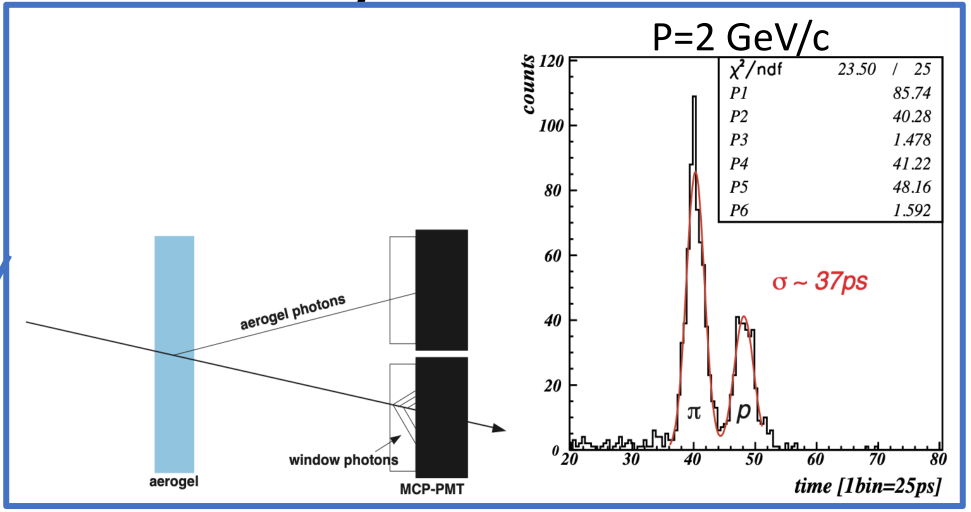


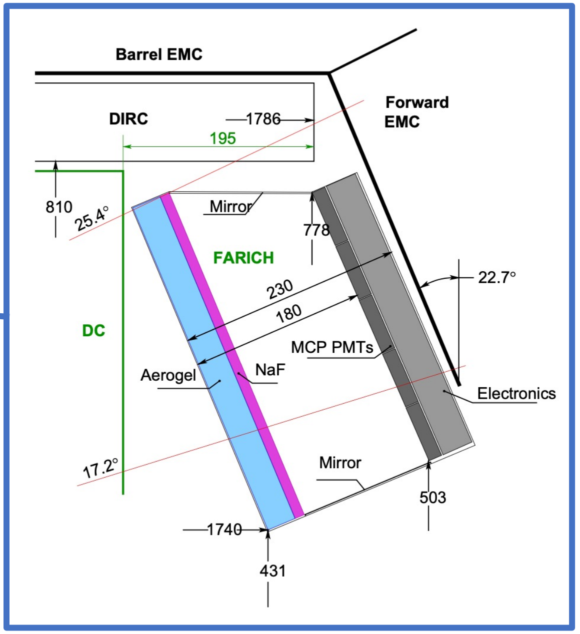
A.Yu.Barnyakov et al., NIMA 1039 (2022) 167044

RICH with dual radiators is not very new idea!

- Liquid + Gas:
  - RICH – DELPHI
  - CRID – SLD
    - C_6F_{12}(n=1.278@190nm) + C_5F_{10}(n=1.00174@190nm)
- Aerogel + Gas:
  - HERMES
  - RICH1 – LHCb
    - Aer.(n=1.03@400nm) + C_4F_{10}(n=1.00137@400nm)
- Aerogel + Crystal:
  - RICH+ToF – SuperB:
    - Aer.(n=1.05@400nm) + Quartz (n=1.47@400nm)
  - FARICH – SuperB:
    - 3-layer aer. n_{max}=1.07@400nm + NaF (n=1.33@400nm)
- Aerogel + Aerogel:
  - FARICH – SCTF:
    - 4-layer aer. n_{max}=1.05@400nm + aer (n=1.12@400nm)

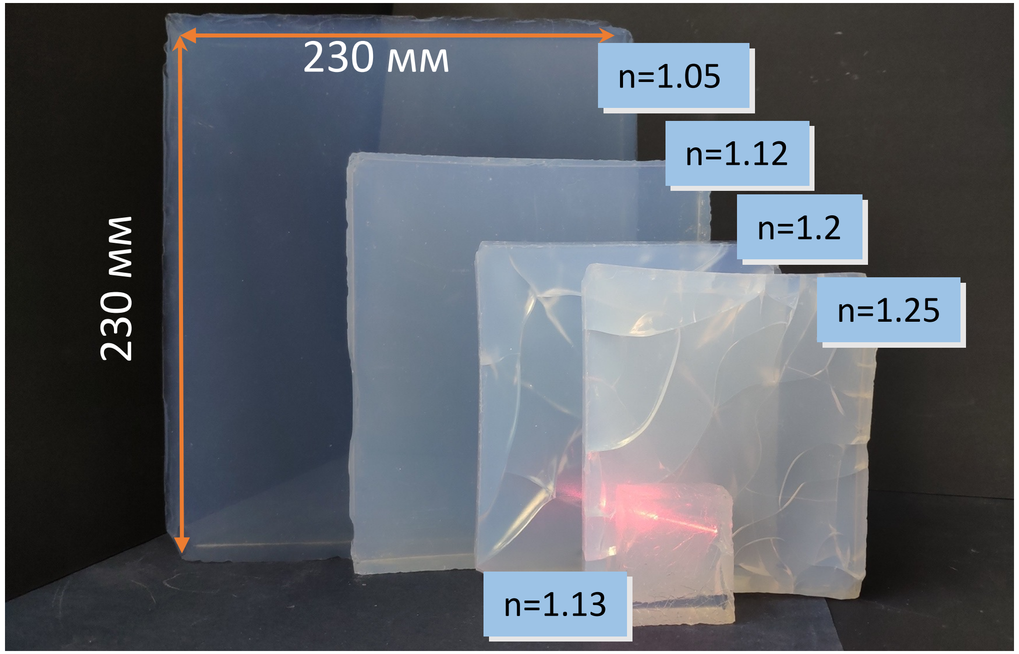
Aerogel is material with easy tunnable refractive index!

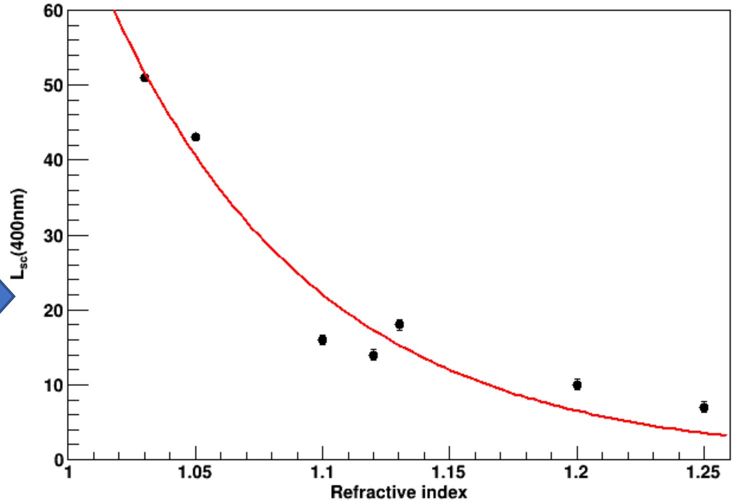




Aerogels with high optical density

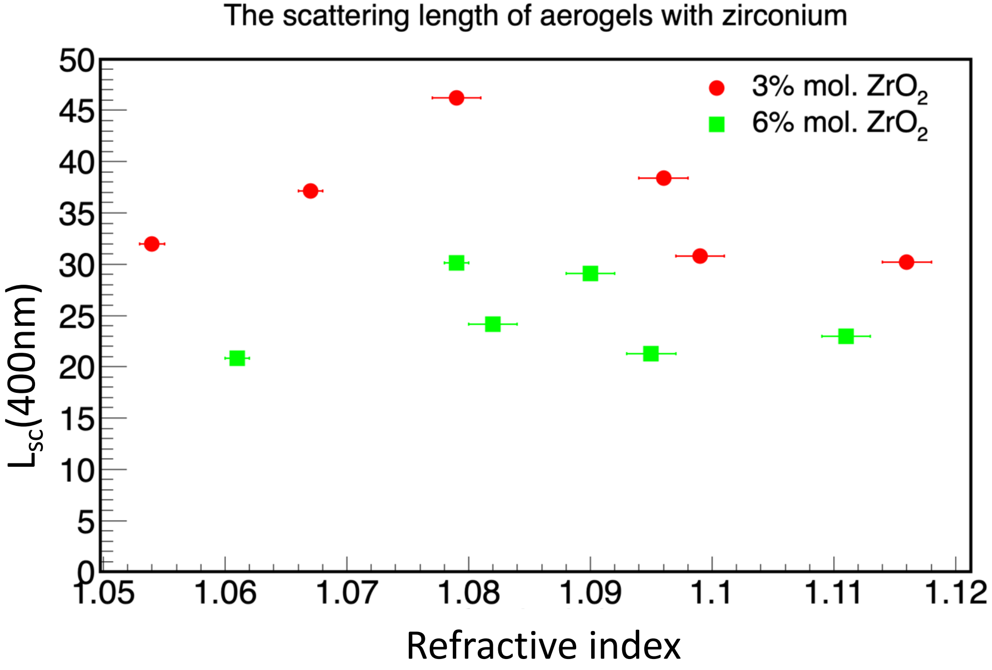
Sintering approach

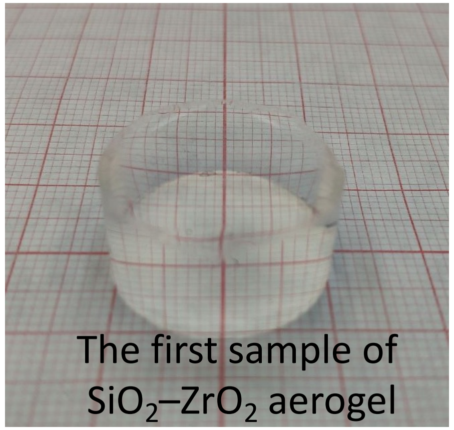




The main flaw of this approach

ZrO_2 addition approach



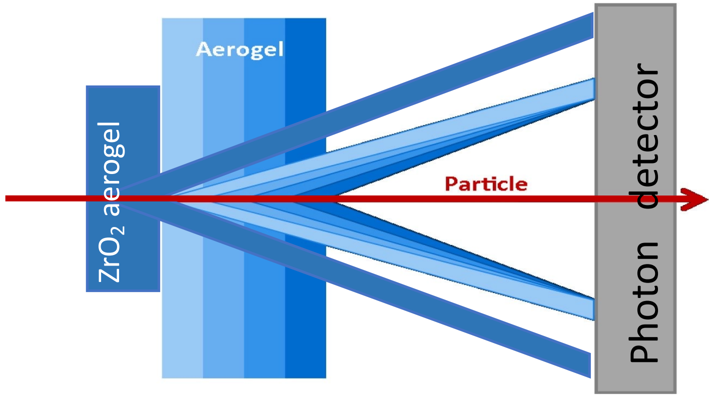


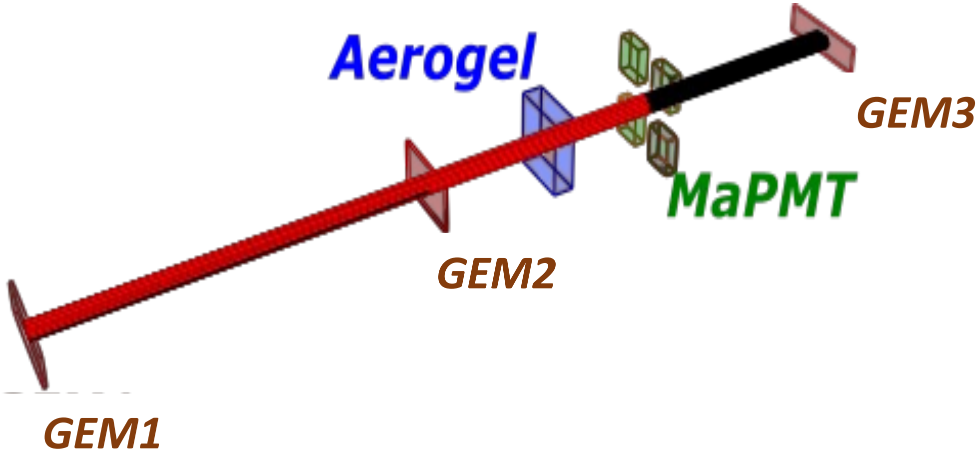
The first sample of SiO_2–ZrO_2 aerogel

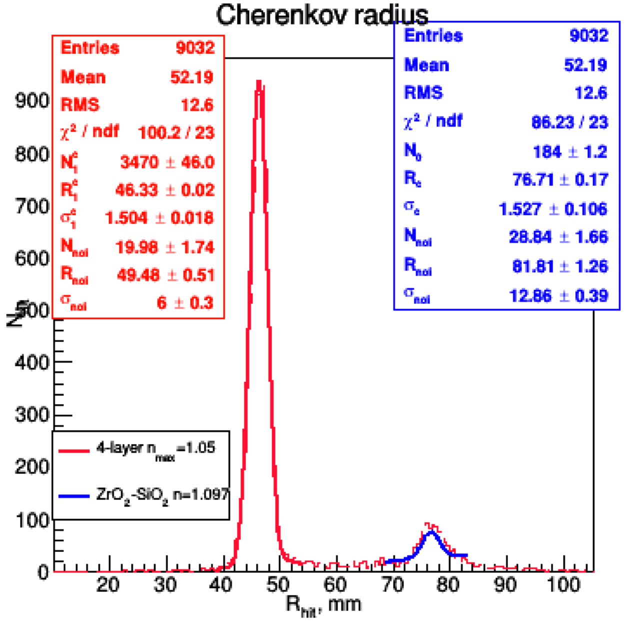
The addition of small amount (0.03÷0.06 mol) of ZrO_2 in SiO_2 based aerogel alow us to produce highly transperant aerogels with high optical density:

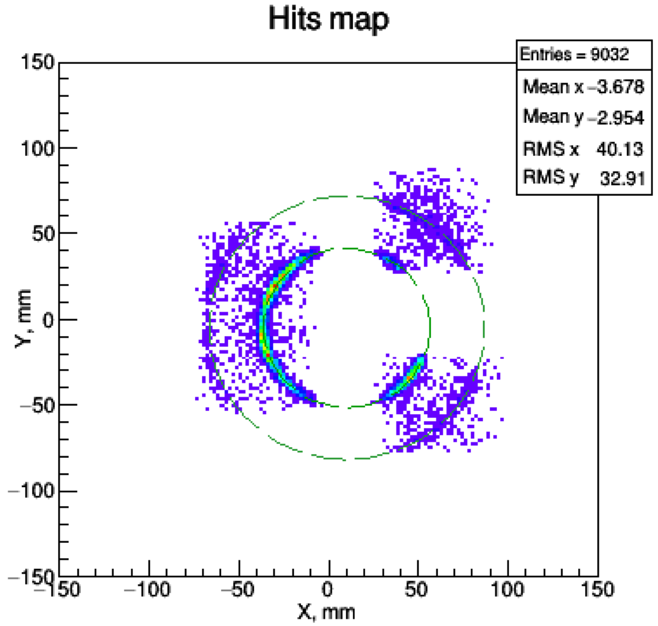
- Refractive index up to n=1.12
- Rayleigh light scattering length L_{sc}(400nm) up to 30 mm

Beam tests results of FARICH with dual radiator









ZrO_2–SiO_2 aerogel:

Thickness 12 mm & ø20 mm;

L_{sc}(400nm)=21±0.5 mm;

4-layer SiO_2 aerogel:

100x100x35 mm;

L_{sc}(400nm)=37±0.3 mm;

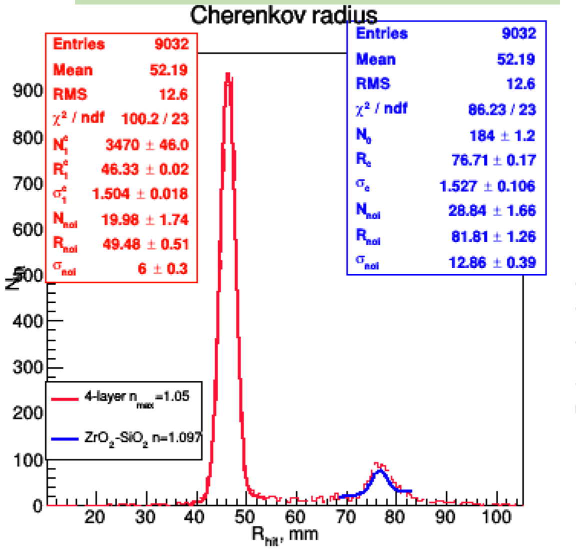
Photon detector

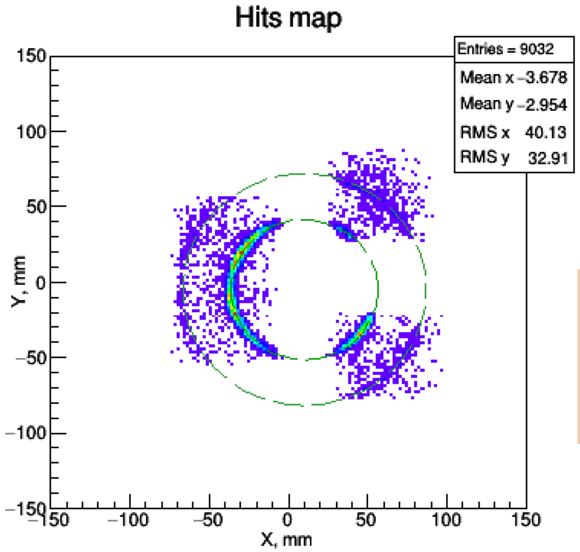
4 MaPMT H12700 (Hamamatsu);

256 pixels with 3x3 mm size;

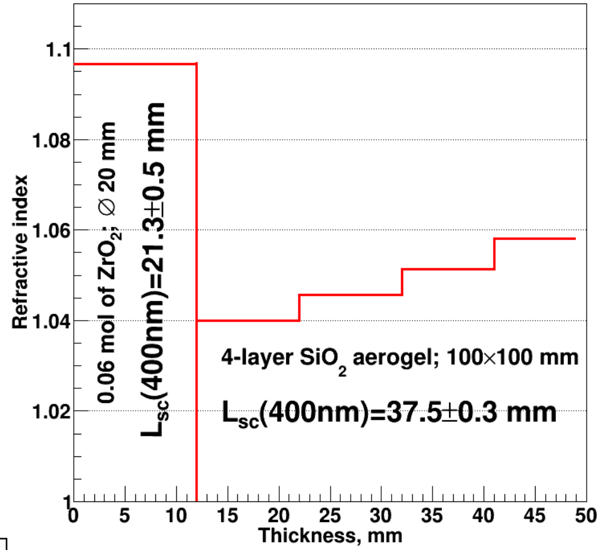
G4 simulation vs beam test results

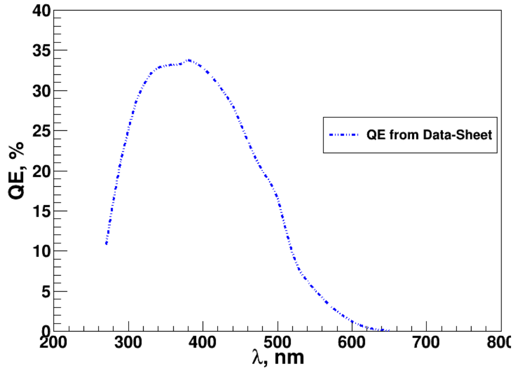
TBeam results





Optical parameters for G4 simultion

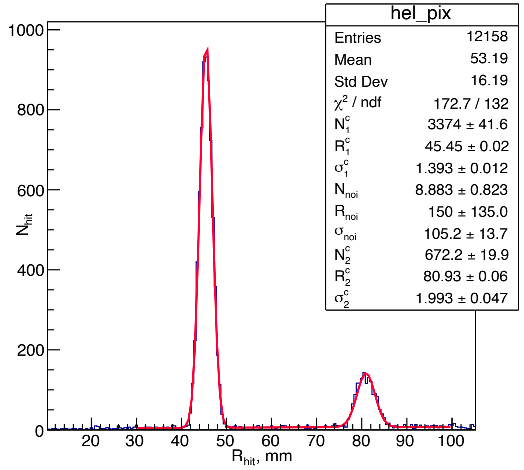


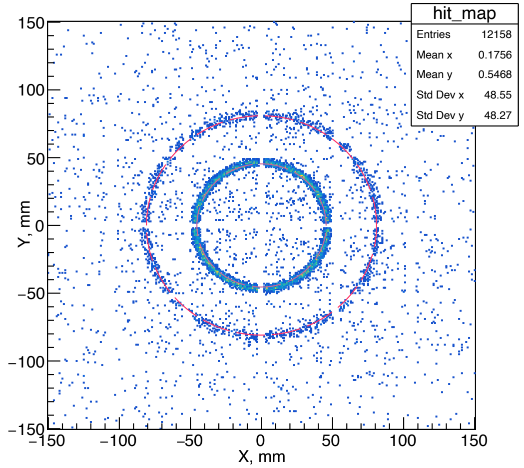


- PDE for H12700 from data-sheet
- Pixel 3x3 mm with pitch 6mm
- Focal distance L=172 mm

The main difference between G4sim and TBeam is a photon small angle scattering effect on aerogel surfaces and inside. These effects have not implemented in G4sim yet.

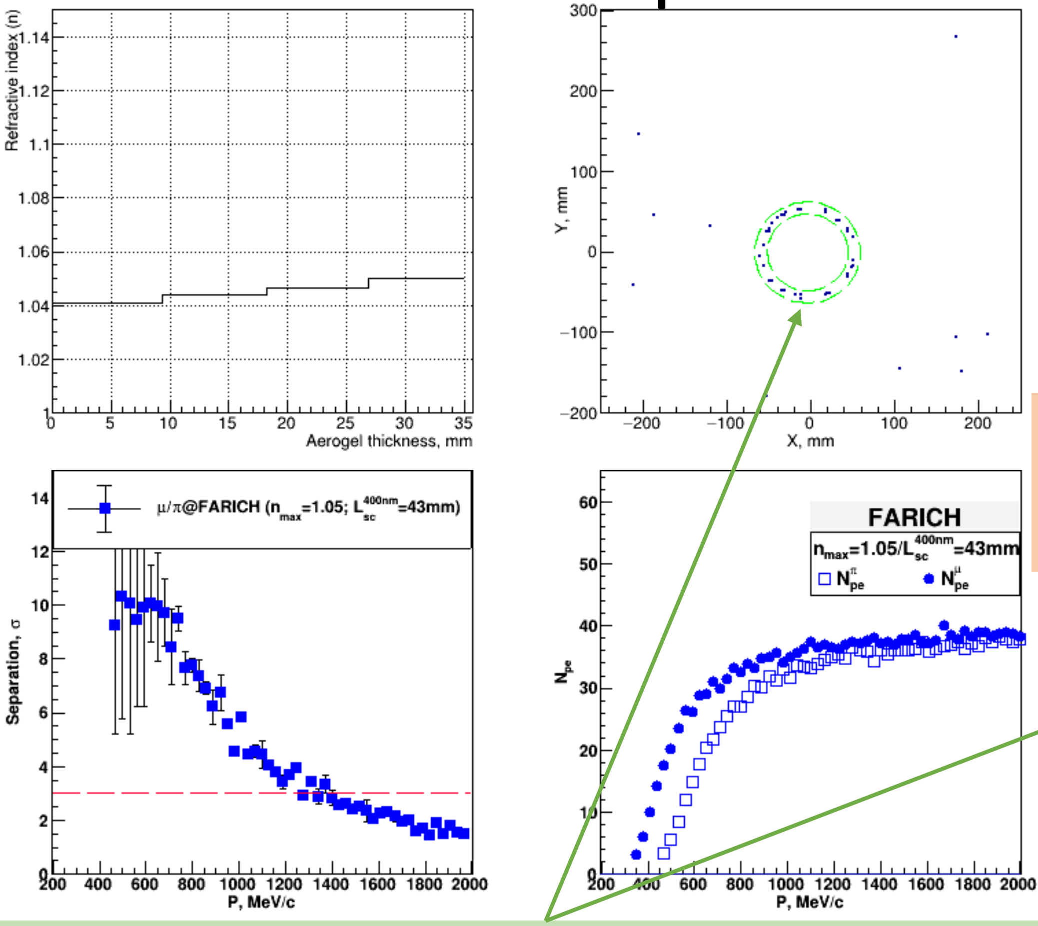
G4 simulation results



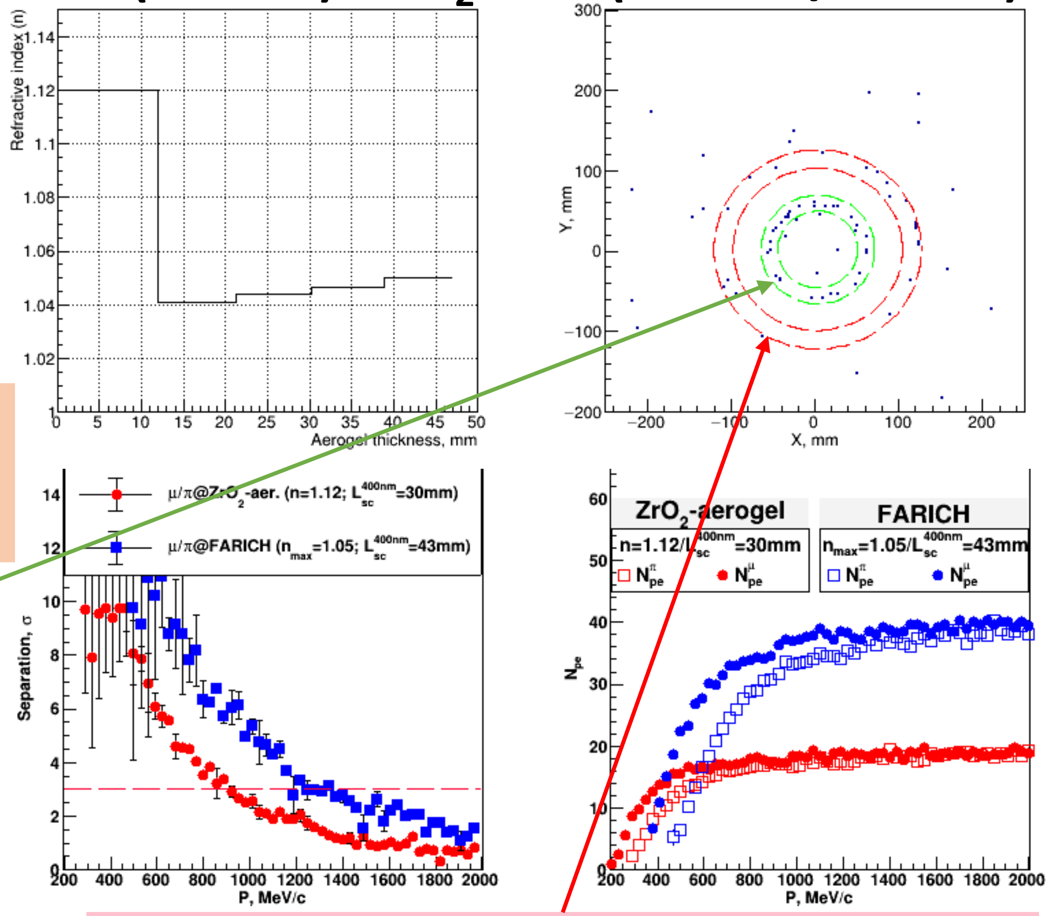


μ/π-separation via G4 simulation

FARICH: "ideal" n profile



FARICH ("ideal")+ZrO$_2$–aer. (n =1.12/12 mm)



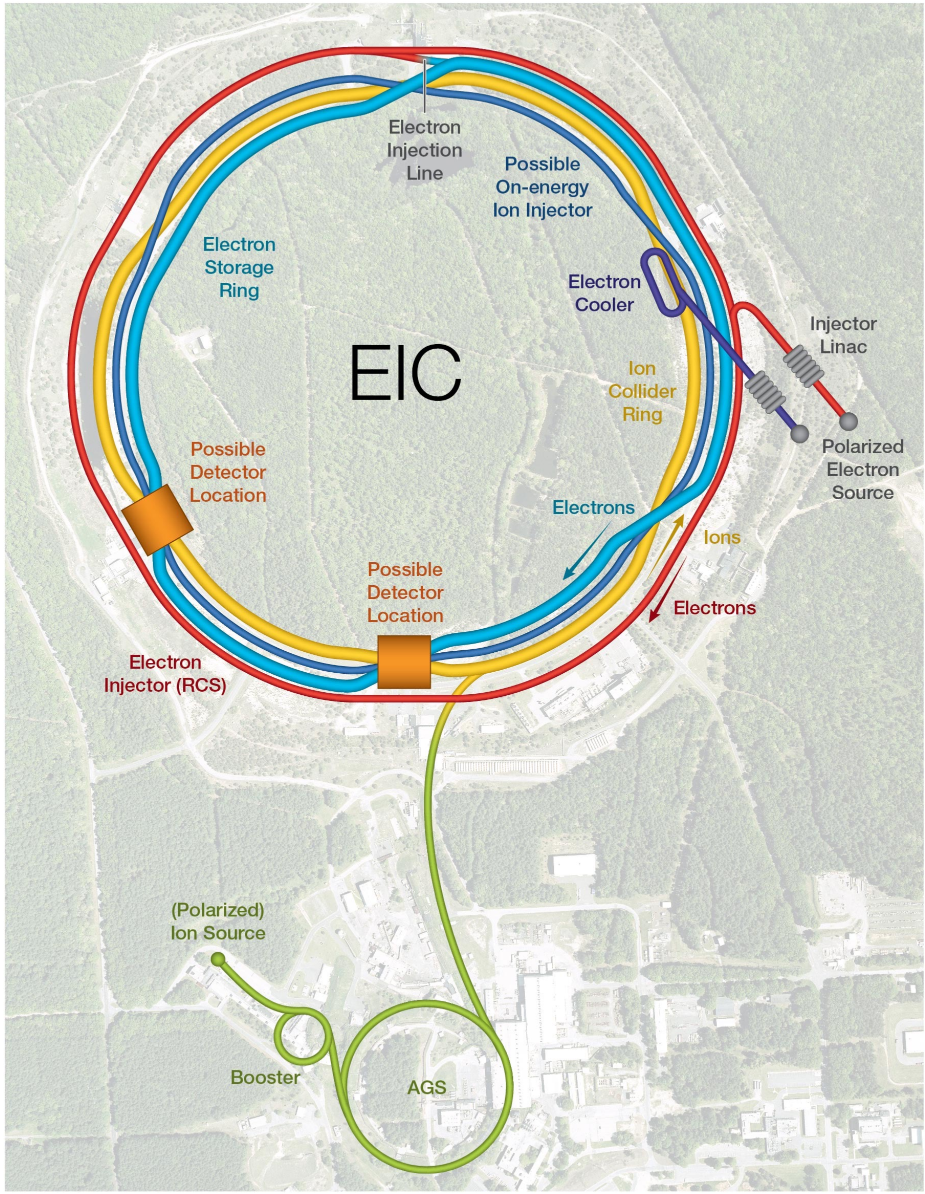
$$N_\sigma = \frac{\bar{R}_C^{\mu} - \bar{R}_C^{\pi}}{\left(\sigma_R^{\pi} + \sigma_R^{\mu}\right)/2}$$

$$(\mathbf{L_f} - \mathbf{t_{Zr}} - \mathbf{t_{Fa}}) \cdot \frac{\sqrt{\left({\mathbf{n}_{Fa}^{min}}^2 - 1\right) - \frac{m^2}{p^2}}}{\sqrt{\frac{\mathbf{m^2}}{\mathbf{p^2}} + 1}} \le \mathbf{R_{Fa}} \le (\mathbf{L_f} - \mathbf{t_{Zr}}) \cdot \frac{\sqrt{\left({\mathbf{n}_{Fa}^{max}}^2 - 1\right) - \frac{m^2}{p^2}}}{\sqrt{\left({\mathbf{n}_{Fa}^{max}}^2 - 2\right) + \frac{\mathbf{m^2}}{\mathbf{p^2}}}}$$

$$(\mathbf{L_f} - \mathbf{t_{Zr}}) \cdot \frac{\sqrt{\left({n_{Zr}}^2 - 1\right) - \frac{m^2}{p^2}}}{\sqrt{\frac{\mathbf{m^2}}{\mathbf{p^2}} + 1}} \le \mathbf{R_{Zr}} \le \mathbf{L_f} \cdot \frac{\sqrt{\left({n_{Zr}}^2 - 1\right) - \frac{m^2}{p^2}}}{\sqrt{\left({n_{Zr}}^2 - 2\right) + \frac{m^2}{\mathbf{p^2}}}}$$

RICH with Fresnel lens

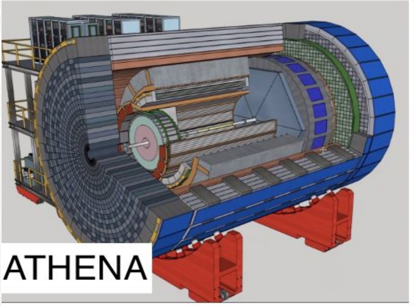
EIC project



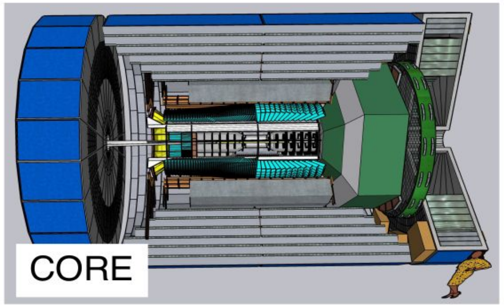
Key EIC Characteristics (parameters)

- **High particle collision rate** $L = 10^{34} cm^{-2} s^{-1}$ $\left(\int L\,dt = 100 fb^{-1}/year\right)$
- **Large center-of-mass energy range** $E_{CM} = 20 \div 140\ GeV$
  - **electrons** $2.5 \div 18\ GeV$
  - **protons** $40 \div 275\ GeV$ $(ions{:}\ Z/A \times E_p)$
- **Polarized beams** of electrons and ions $(up\ to\ 70\%)$
- **Large range of ion species** $(p \rightarrow U)$
- At least one **large-acceptance detector**
- **Projected budget:** $\approx \$2.4\ billion$ – **Start date:** ≈ 2031

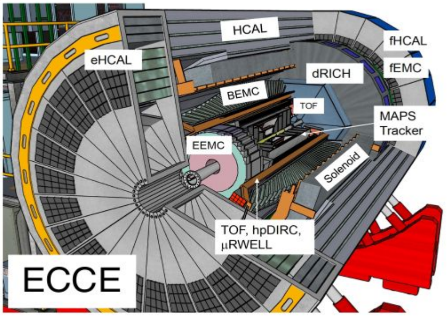
EIC detector proposals



- **backward**
  proximity-focus RICH
- **central**
  high-performance DIRC
  AC-LGAD TOF
- **forward**
  dual-radiator RICH



- **backward**
  AC-LGAD TOF
- **central**
  high-performance DIRC
- **forward**
  dual-radiator RICH

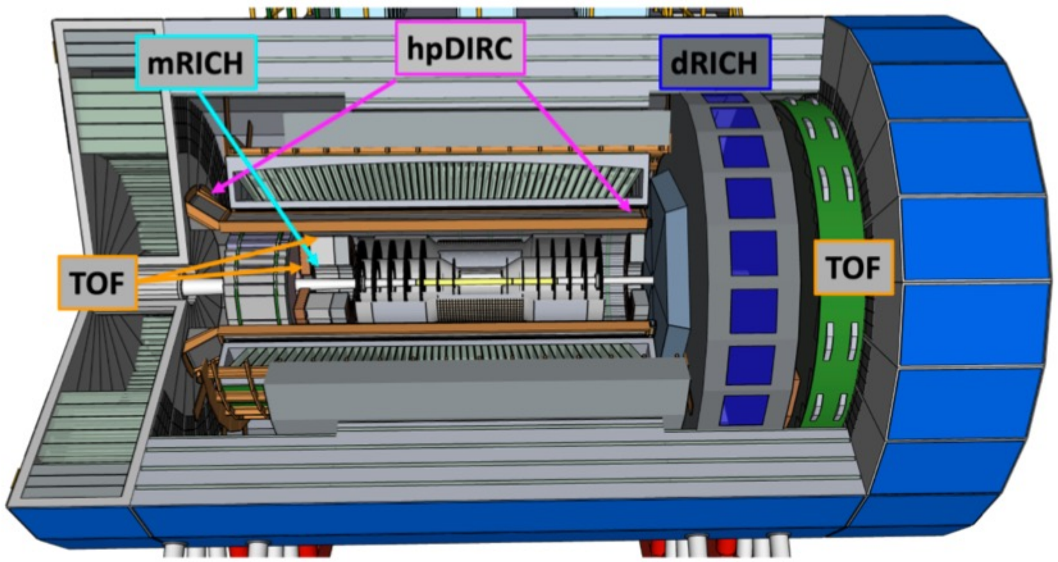


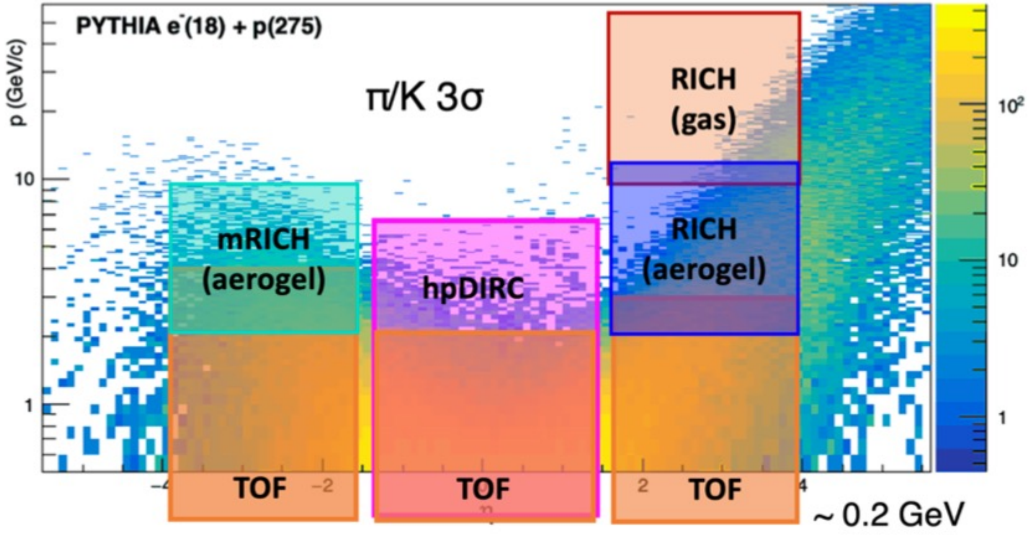
- **backward**
  modular RICH
  AC-LGAD TOF
- **central**
  high-performance DIRC
  AC-LGAD TOF
- **forward**
  dual-radiator RICH
  AC-LGAD TOF

Almost approved concept since begin of 2022

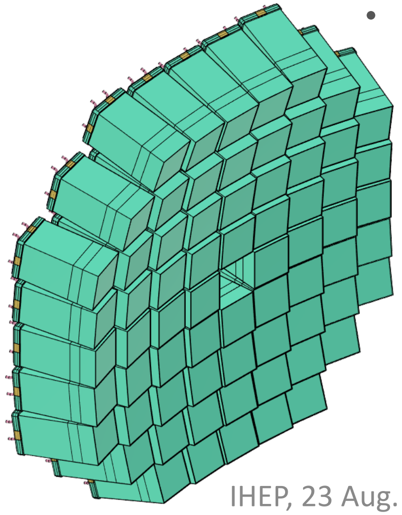
ECCE-PID & mRICH system concepts

ECCE = EIC Comprehensive Chromodynamics Experiment





- **Physics requirements**
  - pion, kaon and proton ID
  - over a wide range $|\eta| \le 3.5$
  - with better than 3σ separation
  - significant pion/electron suppression
- **Momentum-rapidity coverage**
  - forward: up to 50 GeV/c
  - central: up to 6 GeV/c
  - backward: up to 10 GeV/c
- **Demands different technologies**
- **Cherenkov detectors:**
  - dRICH = dual RICH (aerogel + gas)
  - hpDIRC = high-performance DIRC (synthetic fused silica)
  - mRICH = modular RICH (aerogel + Fresnel lens)



68 modular counters oriented to IP:

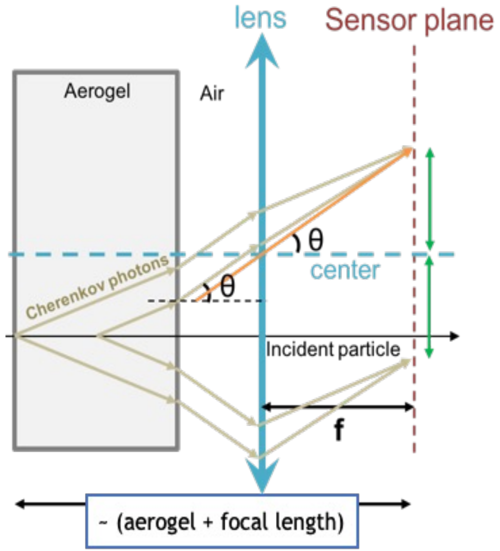
– aerogel n=1.03 100x100x40 mm^3

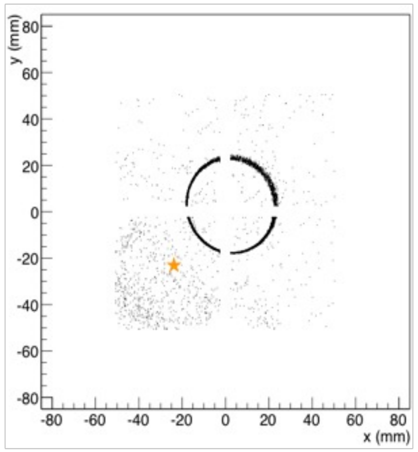
– acrylic Fresnel lens with focal distance 6”

– position sensitive photon detector HRRPD (MCP-PMT) or SiPM arrays

Aerogel RICH with Fresnel lens

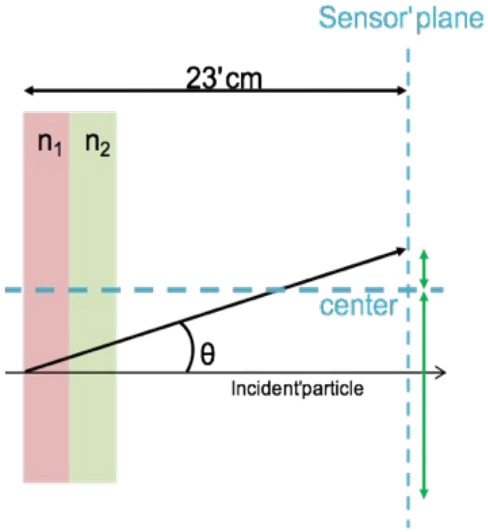
Lens-Based mRICH Design

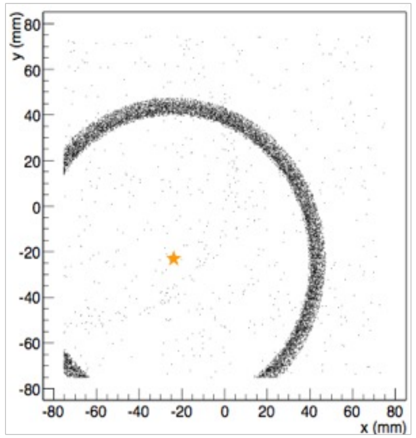




- 9 GeV/c pion beam incident at third quadrant (star) in simulation
- Ring image is **shifted toward the central region** on the sensor plane

Two-Layer Proximity Focusing Design (BELLE-2 ARICH)

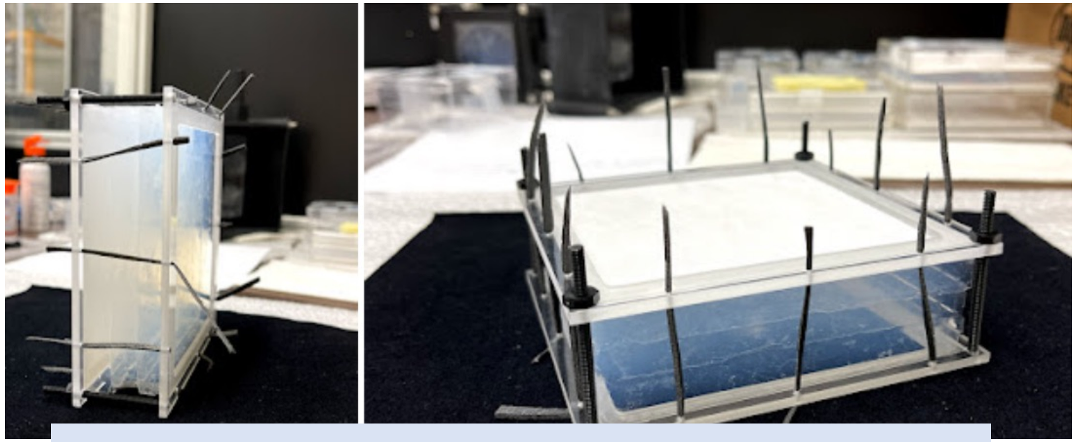




- 9 GeV/c pion beam incident at third quadrant (star) in simulation
- Ring is centered at point of incidence

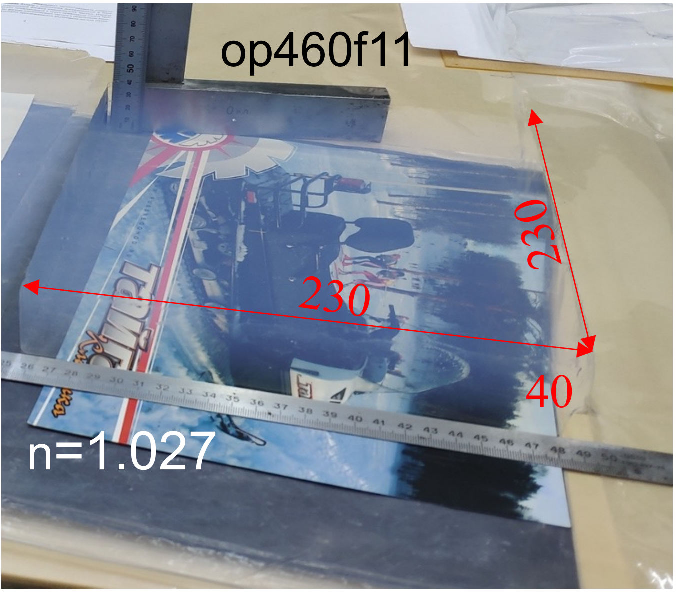
Such approach allows us to improve Cherenkov angle resolution and optimize photo detectors area!

The thick aerogel for mRICH – EIC project



FermiLAB 2021: stack of three 1 cm thickness blocks with n=1.03 from Chiba University

BINP 2022:
single block
23x23x4 cm
with n=1.027
from BIC

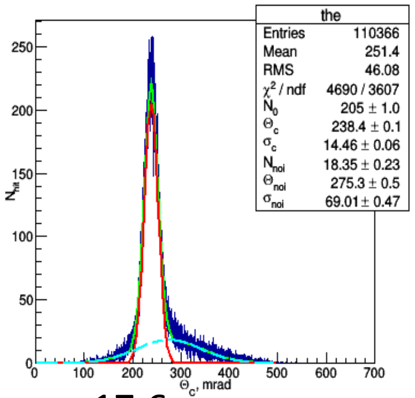


- In both cases there is no reason to make the aerogel thickness more than $(1 \div 2) \cdot L_{sc}$:

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

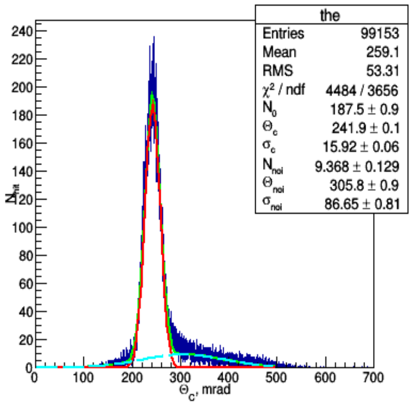
- In case of approach “stack” the additional Cherenkov photons loss is occurred due to reflectance and scattering on the additional surfaces
- There are two not cut off surfaces in aerogel
  - “Optical surface” – it contacts only with air during the production
  - “Bottom” – it contacts with metallic frame during the production processes
- Several configuration of the aerogel Cherenkov radiators were tested with relativistic electron beams at BINP beam test facilities in 2022.

Cherenkov angle single photon resolution (SPR)



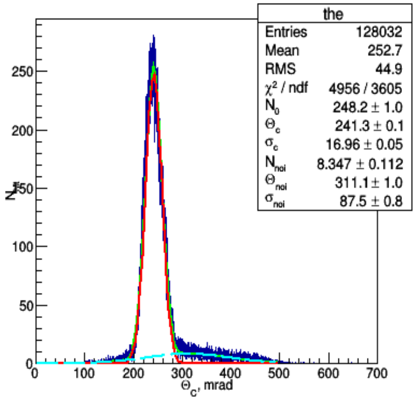
17.6 mm

457f4



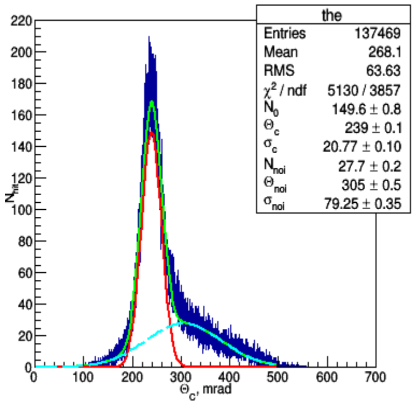
19.0 mm

457f3



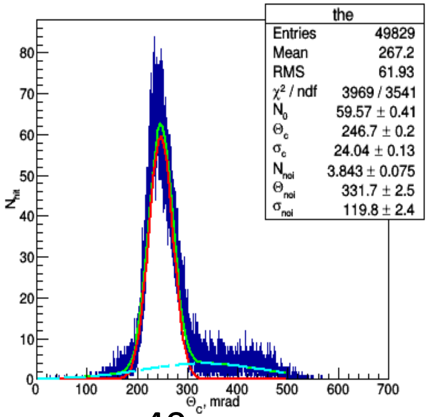
30.0 mm

460f4_3



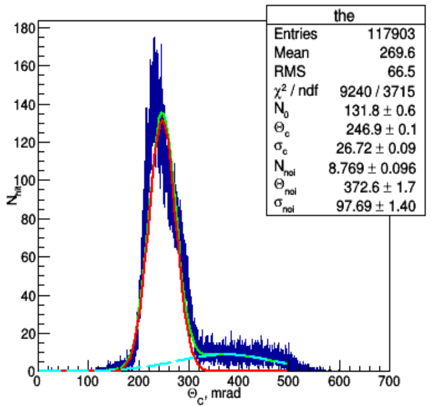
19.0+17.6 mm

457f3+457f4



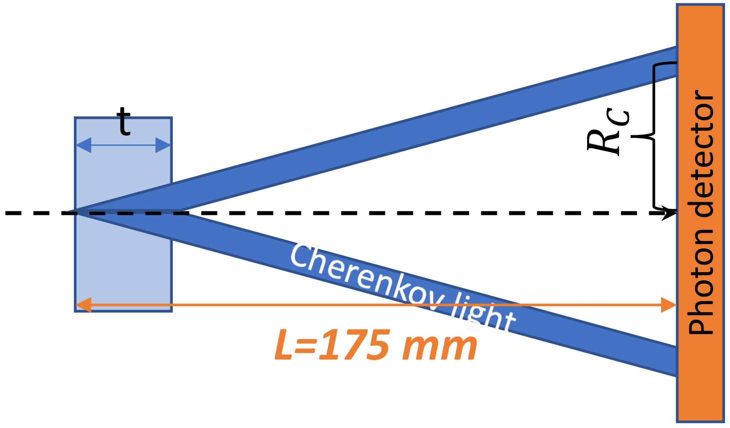
40. mm

460f11_22



50. mm

460f15_3



	457f4	457f3	460f4_3	457f3_f4	460f11_22	460f15_3
t/L, mm	17.6/185	19.0/175	30.0/185	36.6/185	40.0/185	50.0/185
$\boldsymbol{\sigma_{\theta_C}^{SPR}}$, mrad	14.46±0.06	15.92±0.06	16.96±0.05	20.8±0.1	24.0±0.1	26.7±0.1
N$_{pe}$* – 60% of the ring	4.01±0.01	4.16±0.01	7.69±0.02	5.51±0.02	8.22±0.03	8.05±0.02
$\boldsymbol{\sigma_{\theta_C}^{trk}} = \frac{\sigma_{\theta_C}^{SPR}}{\sqrt{N_{pe}}}$,mrad	7.2	7.8	6.1	8.9	8.4	9.4
$\boldsymbol{\sigma_{R_C}^{ROI}}$, mm	1.11±0.03	1.08±0.04	1.20±0.02	1.33±0.06	1.35±0.04	1.37±0.07
$\boldsymbol{\sigma_{\theta_C}^{R}} \approx \frac{1}{n^2}\frac{\sigma_{R_C}}{L-{}^{t}/_{2}}$	5.9	6.15	6.65	7.5	7.7	8.1

$$\boldsymbol{\theta_C^R} = arctan\left(\frac{R_C}{L-{}^{t}/_{2}}\right),$$

$$\boldsymbol{\sigma_{\theta_C}^R} = \cos^2\theta_C\left(\frac{1}{L-{}^{t}/_{2}}\right)\cdot\sqrt{\sigma_{R_C}{}^2 + \tan^2\theta_C\cdot(\sigma_L^2+\sigma_t^2)} \approx \frac{1}{n^2}\frac{\sigma_{R_C}}{L-{}^{t}/_{2}},$$

How much effect from Fresnel lens is expected?!

Position-sensitive photon detectors

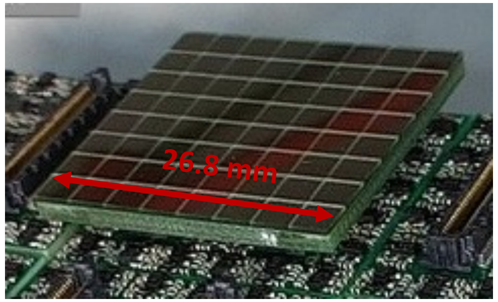
Photon detector options

Due to axial magnetic field the SiPM is only one possible candidate for the cylindrical part of the FARICH system!!!

For the endacp regions there are three options of photon detectors.

SiPM arrays

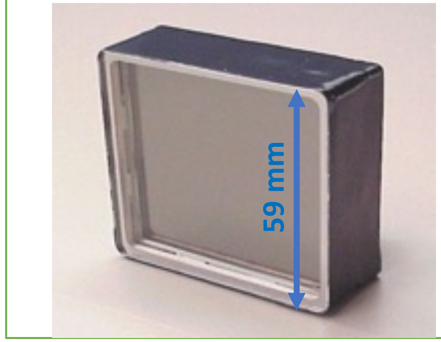
- There are several manufacturer in the world including China.
- There is no comercially available SiPM arrays produced in Russia for the moment, but some R&Ds are going now.
- Estimated cost of such detector option is about 100$/cm^2
- It is required to develop and produce special R/O electronics and cooling system to operate with SiPMs in SPD detector conditions



KETEK PA3325-WB-0808
(BroadCom, USA)

MCP-PMT

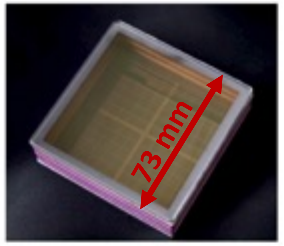
- There are several manufacturer in the world including China.
- There is no comercially available position-sensitive MCP-PMTs produced in Russia for the moment, but R&Ds are going now in (Baspik&Ekran FEP).
- There is a very large spread of prices for rectangular position-sensitive MCP-PMT. The best price is about 200$/cm^2
- PDE is not so high, it is limited by photoelectron collection efficiency (~60%) and geometrical efficiency is worse than for SiPM option.
- Specialised R/O elctronics is already developed for other experiments and could be adopted for the SPD experiment requirements
- There is no such a big problem with intrinsic noise rejecion in comparison with SiPM option

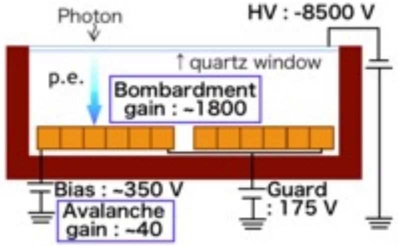


Planacon XP85112
8x8 pixels with 6x6 mm
Cost: 15 $k$$

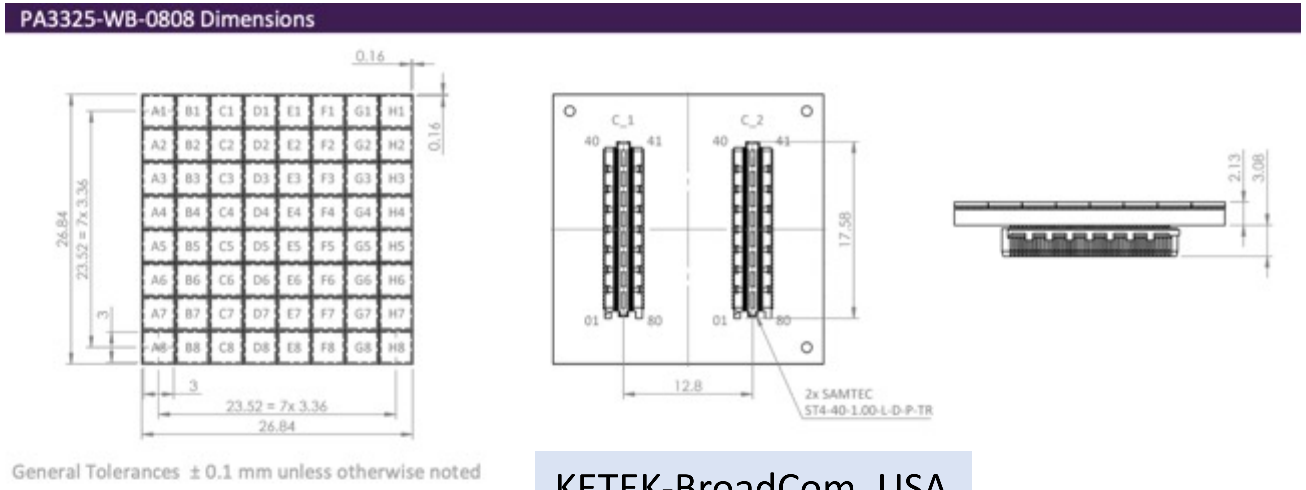
HAPD

- Only Hamamtsu produced such devices for the Belle II experiment and now it doesn't produced anymore!
- There is no comercially available HAPDs in Russia for the moment, but R&Ds are going now in ISP SB RAS.
- Price – ???
- Expected PDE of such devices will less than for SiPM option but signficantly (1.5 times) higher than for MCP-PMT option.
- Expected gain is about $1 \div 2 \cdot 10^5$
- Development of specialised R/O elctronics is needed. It is possible to adopt some Belle II ARICH system expirience.





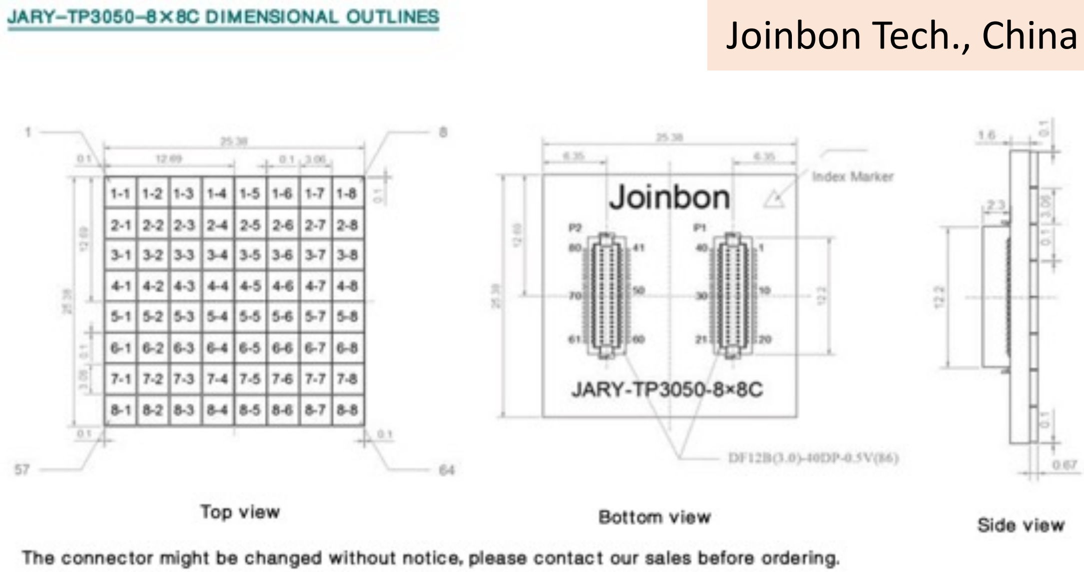
SiPM array option



PA3325-WB-0808 Dimensions

General Tolerances ± 0.1 mm unless otherwise noted

KETEK-BroadCom, USA



JARY-TP3050-8×8C DIMENSIONAL OUTLINES

Joinbon Tech., China

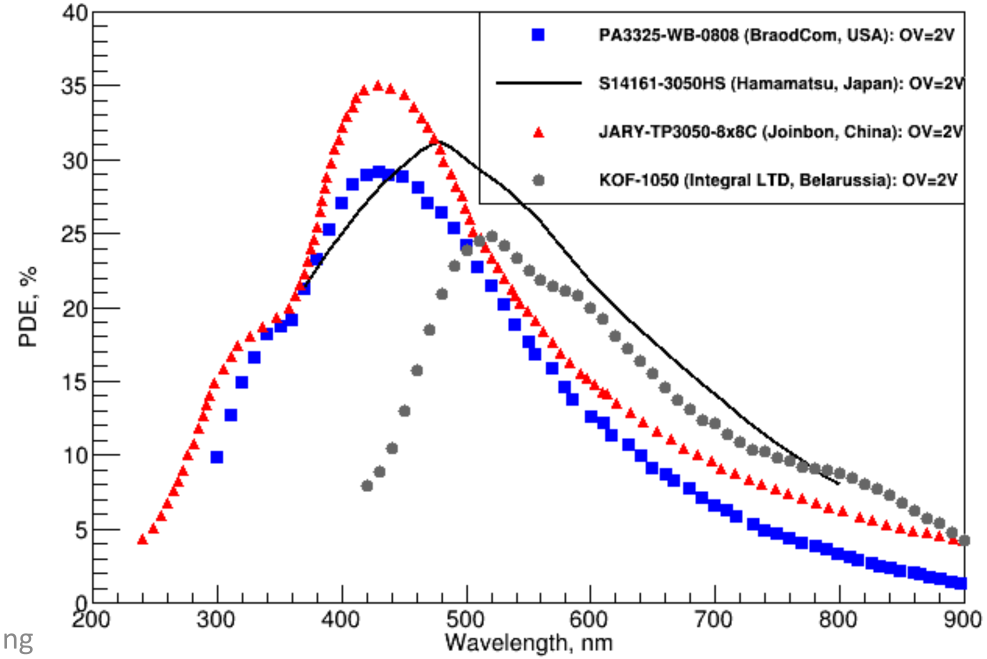
Top view

Bottom view

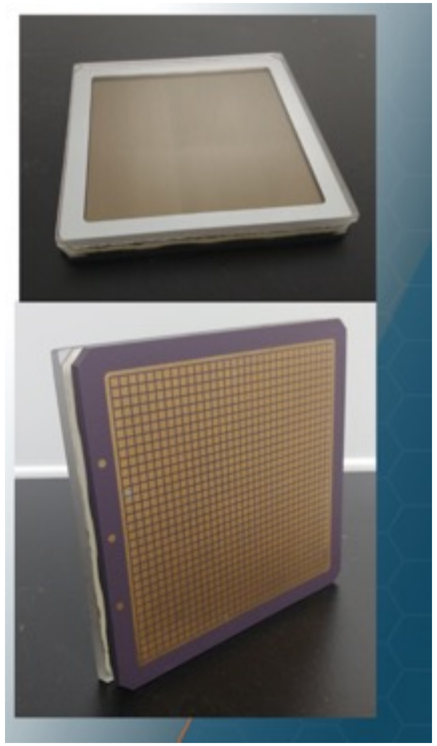
Side view

The connector might be changed without notice, please contact our sales before ordering.

- Endcaps: 2x2490 SiPM arrays 2.7x2.7 cm^2
- Barrel: 18 000 SiPM arrays 2.7x2.7 cm^2
- 1 470.7k pixels with 3x3 mm^2
- Geometrical Efficiency $\frac{S_{detect}}{S_{total}} \approx 76 \div 80\%$
- Highly effective cooling sysytem is required!

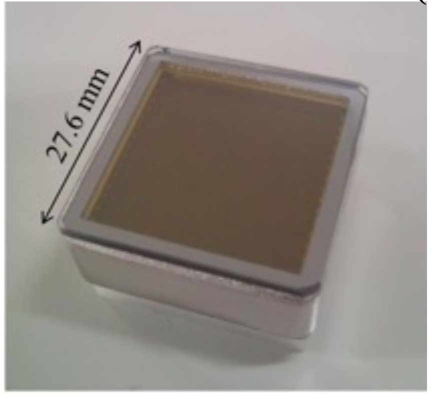


Position-sensitive MCP-PMT

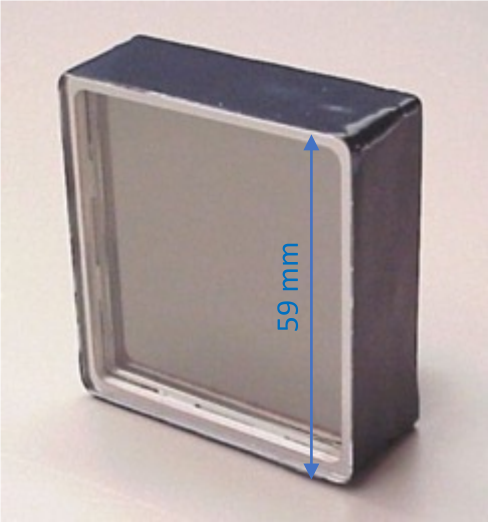


HRPPD (Income)
10x10 cm; pixel 2.5x2.5 mm

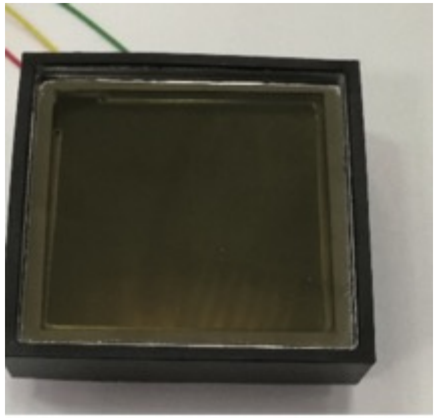
Hamamtsu R10754-016-M16(N)

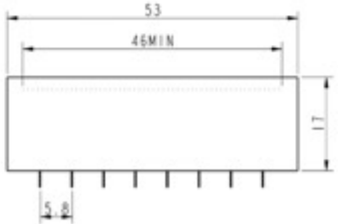


4x4 pixels with 5x5 mm

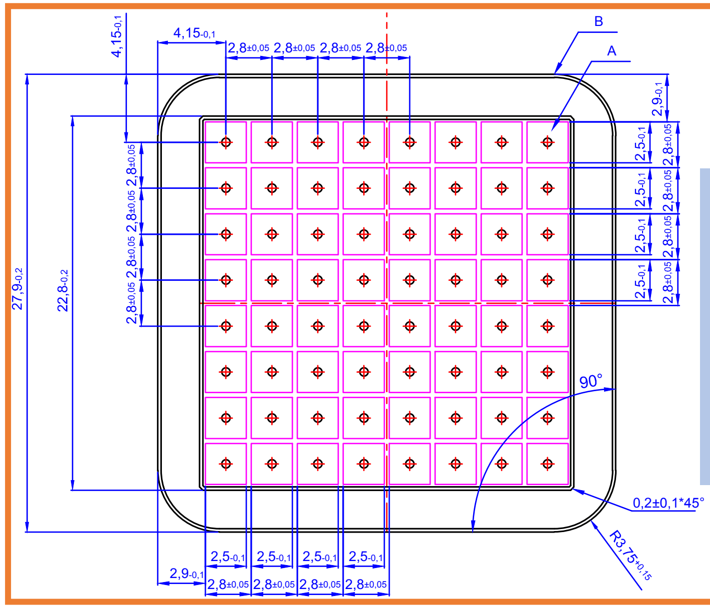


Planacon XP85112
8x8 pixels with 6x6 mm





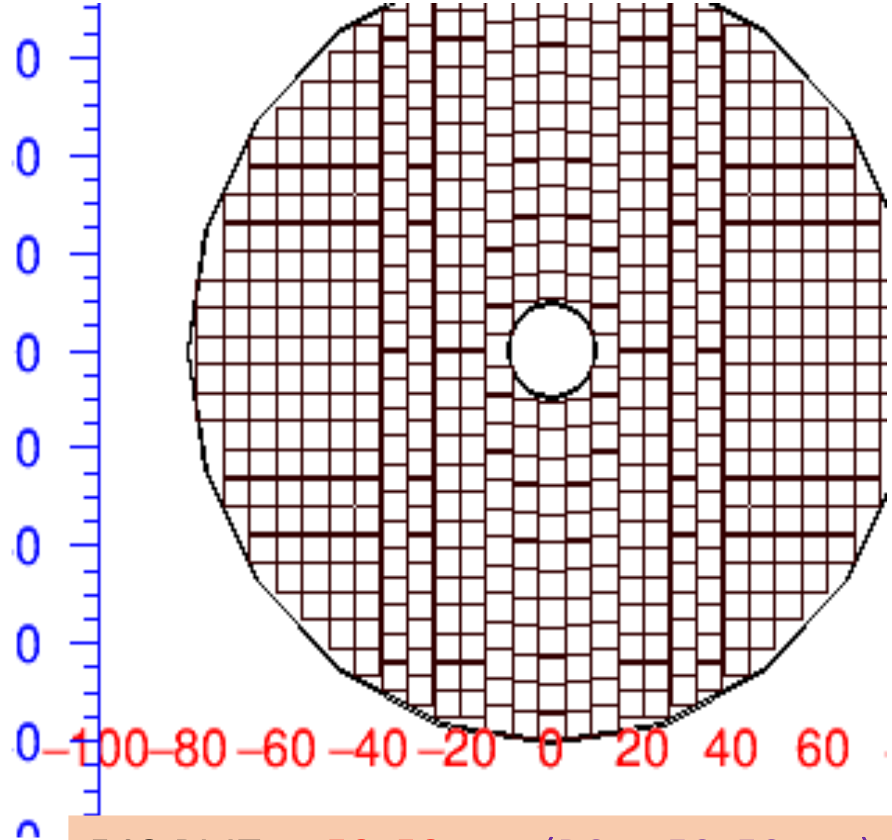
NNVT (China)

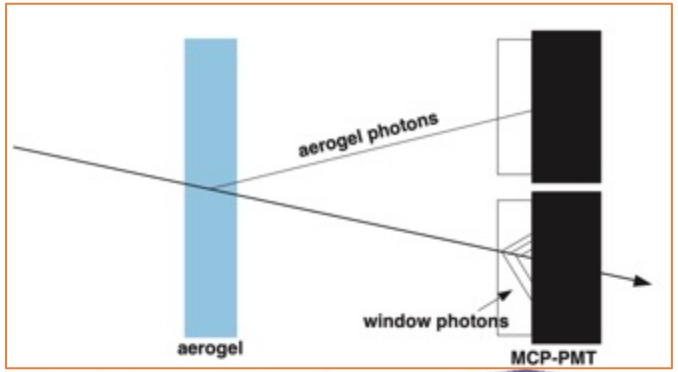


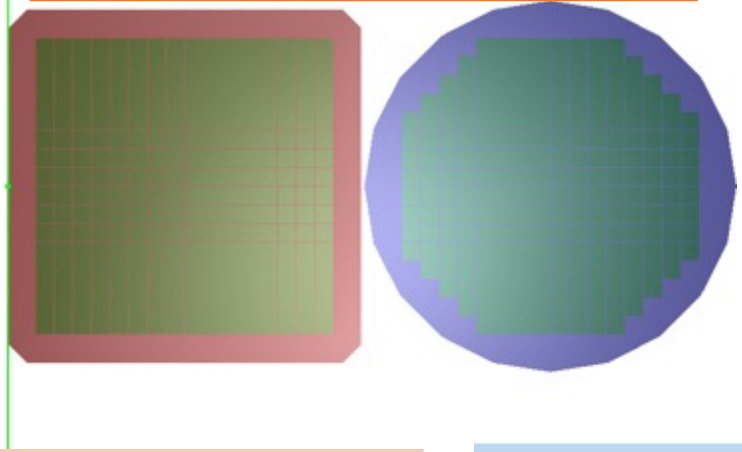
Collector plane of MCP-PMT
Concept of Ekran FEP
(Summer 2022)

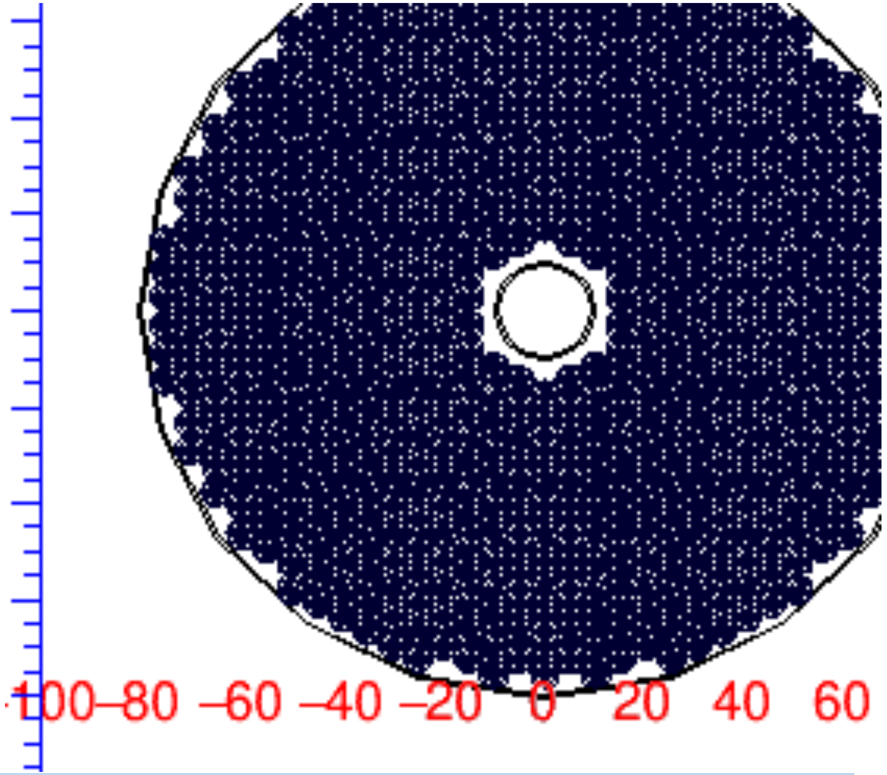
Availabilty: until end of 2023?!
Price: until end of 2023?!

Round vs Square MCP-PMT for the RICH









548 PMTs 🟥58x58 mm (PC 🟪 50x50 мм) –>

$$Eff = \frac{548 \cdot 5{\times}5}{S_{endcap}} = \frac{13700\ cm^2}{19792\ cm^2} \approx 0.69$$

16x16=256 pixels 2.9x2.9 mm

$$Eff = \frac{548 \cdot 256 \cdot 0.29{\times}0.29}{S_{endcap}} = \frac{11798\ cm^2}{19792\ cm^2} \approx 0.596$$

630 PMTs Ø58 mm (PC Ø50 mm) –>

$$Eff = \frac{630 \cdot \pi \cdot 2.5^2}{S_{endcap}} = \frac{12370\ cm^2}{19792\ cm^2} \approx 0.625$$

216 pixels 2.9x2.9 мм

$$Eff = \frac{630 \cdot 216 \cdot 0.29{\times}0.29}{S_{endcap}} = \frac{11444\ cm^2}{19792\ cm^2} \approx 0.58$$

Round vs Square MCP-PMT for the RICH (2)

expected FARICH performance

To evaluate expected performance we can use recent FARICH beam test data:

- $N_{pe}^{H12700} \approx 16$
- $CE^{H12700} \approx 0.8$ – photoelectron collection efficiency ($CE^{MCP} \approx 0.6$)
- $GE^{TB} \approx 0.8$ – Geometrical Efficiency of Test Beam setup (GE^{exp} is determined by fill factor of photon detectors for the experimental setup)

$$N_{pe}^{expect} = \frac{N_{pe}^{H12700} \cdot CE^{MCP} \cdot GE^{exp}}{CE^{H12700} \cdot GE^{TB}}$$

Square shape MCP-PMT

- $GE^{exp} \approx 0.59$
- $N_{pe}^{expect} = \frac{16 \cdot 0.6 \cdot 0.59}{0.8 \cdot 0.8} \approx 8.8pe$ (for $\beta = 1$)
- $\sigma_{tr}^{\theta} = \frac{\sigma_{SPE}^{\theta}}{\sqrt{N_{pe}}} = \frac{7 \div 8\ mrad}{\sqrt{8.8}} = 2.3 \div 2.7\ mrad$

Round shape MCP-PMT

- $GE^{exp} \approx 0.57$
- $N_{pe}^{expect} = \frac{16 \cdot 0.6 \cdot 0.57}{0.8 \cdot 0.8} \approx 8.5pe$ (for $\beta = 1$)
- $\sigma_{tr}^{\theta} = \frac{\sigma_{SPE}^{\theta}}{\sqrt{N_{pe}}} = \frac{7 \div 8\ mrad}{\sqrt{8.5}} = 2.4 \div 2.7\ mrad$

μ/π @ 1 GeV/c: $\frac{\theta_C^{\mu} - \theta_C^{\pi}}{\sigma_{tr}^{\theta}} = \frac{292 - 278}{2.5} = 5.6\sigma$

π/K @ 6 GeV/c: $\frac{\theta_C^{\pi} - \theta_C^{K}}{\sigma_{tr}^{\theta}} = \frac{309 - 299}{2.5} = 3.9\sigma$

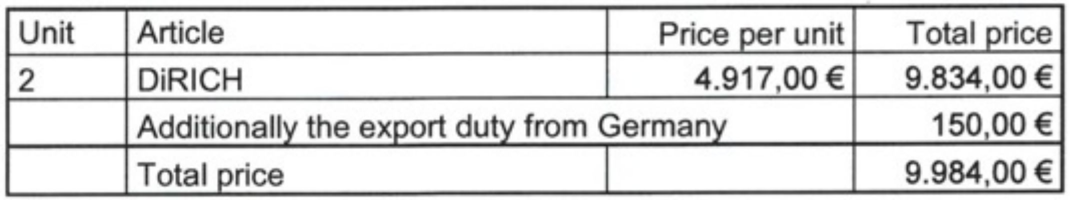
R/O electronics cost estimation

There are two modern approaches in development of specialised R/O electronics:

- ASIC (Application Specialised Integrated Circuits)
- FPGA (Field Programable Gate Arrays)

The differences in performance, power consumption and costs are not sufficient today!!!

FPG-TDC (GSI)



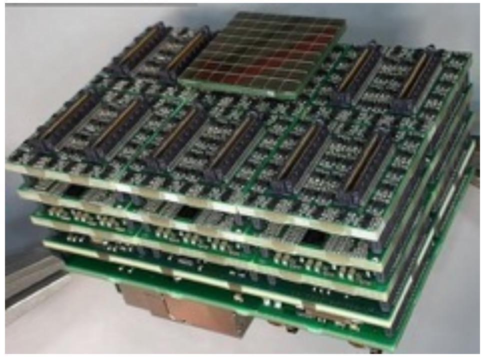
Unit	Article	Price per unit	Total price
2	DiRICH	4.917,00 €	9.834,00 €
	Additionally the export duty from Germany		150,00 €
	Total price		9.984,00 €

$\frac{9\,834€}{2\times384} \approx 13€/chan$ if N_{ch}<1000 (2019)

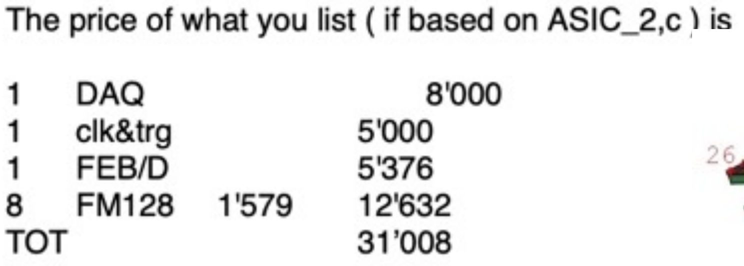
A system with 30kChannel (HADES):

$170k€/30k \approx 6€/chan$ (2017)

Power consumption: ~55mW/chan

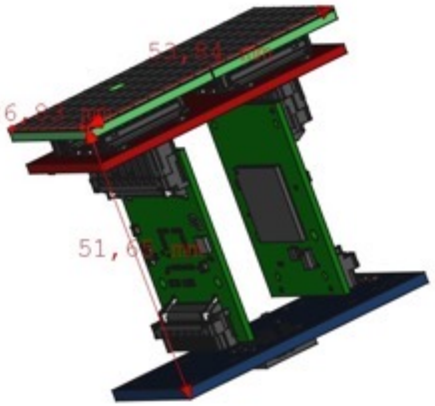


TOFPET-II (PetSys)



The price of what you list (if based on ASIC_2,c) is

1	DAQ		8'000
1	clk&trg		5'000
1	FEB/D		5'376
8	FM128	1'579	12'632
TOT			31'008



$\frac{31\,008€}{8\times128} \approx 30€/chan$ if N_{ch}≤1000

A system with 100kChannel:

$5€/chan$ (2020)

Power consumption:

15mW/chan (ASIC) + DAQ (FPGA)~60mW/chan

Both options are not available for us, we are looking for new solution!

Summary

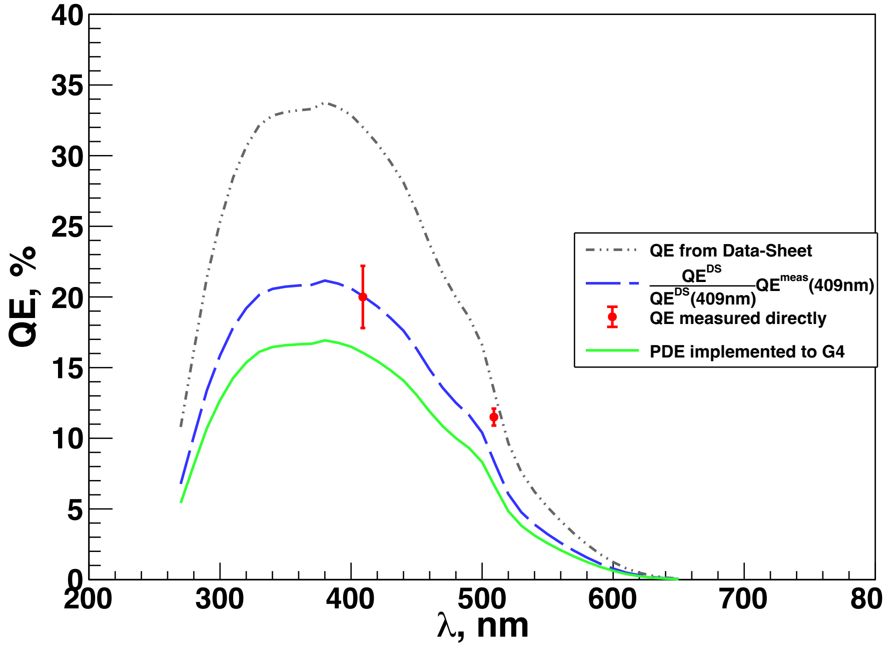
- The PID systems based on aerogel Chernkov counters hve been developeing at the BINP since 1986 and huge experience is already accumulated
- Aerogel based RICH detectors are very demand technique for some future colliding beam experiments
- In 2020-2023 the essential progress in aerogel RICH development was achieved in Novosibirsk (BINP/BIC):
  - Large (23x23x4 or 5 cm with n=1.03 or 1.05) and higly transperant aerogel blocks were produced and tested
  - The 4-layer focusing aerogel sample with 20x20x3.5 cm size were produced for the first time in the world –> the possibility to create full-scale systems based on 4-layer focusing aerogel Cherenkov radiators was demonstrated
  - The measured SPR (~7 mrad) of FARICH based on 4-layer focusing aerogel is in good agreement with simulation and expectation
  - Recent progress in high opticaly dense aerogel production with help of ZrO_2 dope allows us to consider new design of FARICH detector with dual aerogel radiator which able to provide exccelent μ/π – separation from 0.2 up to 1.5 GeV/c
- For further progress of the aerogel RICH detectors development of photon detectors and compatible R/O electronics are highly required

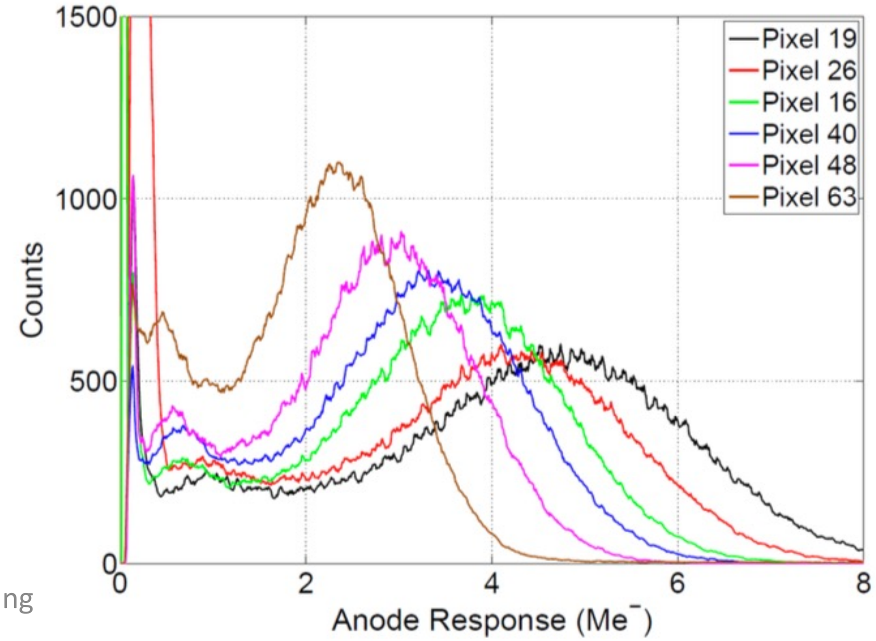
Back up slides

TBeam simulation with G4: input data.

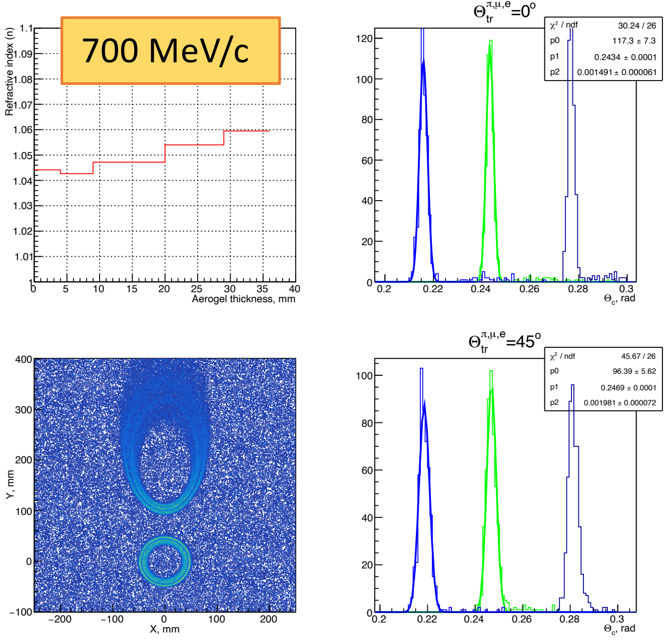
- To perform quntitively comparison TBeam results with G4 simulation it is necessary to implement in simulation very correct data on aerogel parameters (n, L_{sc}, thick) and also about photon detector parameters such like Geometry and PDE.
- As a QE(λ) we will use data for MaPMT H12700 from manufacturier (Hamamatsu) data-sheet (DS) normalized on our own direct measurement QE(λ=409nm) performed with laser light sourse(see the pictures below: left).
- Also it is necessary to take into account that flat-pannel MaPMTs have non 100% photoelectron collection efficiency (CE). According to invetigations (Ref. *arXiv:1506.04302v2 [physics.ins-det] 5 Oct 2015*) about 20% of photoelectrons are able to give by 5 times smaller amplitude than a single photoelectron peak due to skip of the first dynode stage (see the pictures below: right). It means that if the read out electronics discriminator threshold is set ~0.1-0.2pe we will lose about 20% of photoelectrons.
- In the G4 simulation is implemented recalculated photon detection efficiency (PDE):

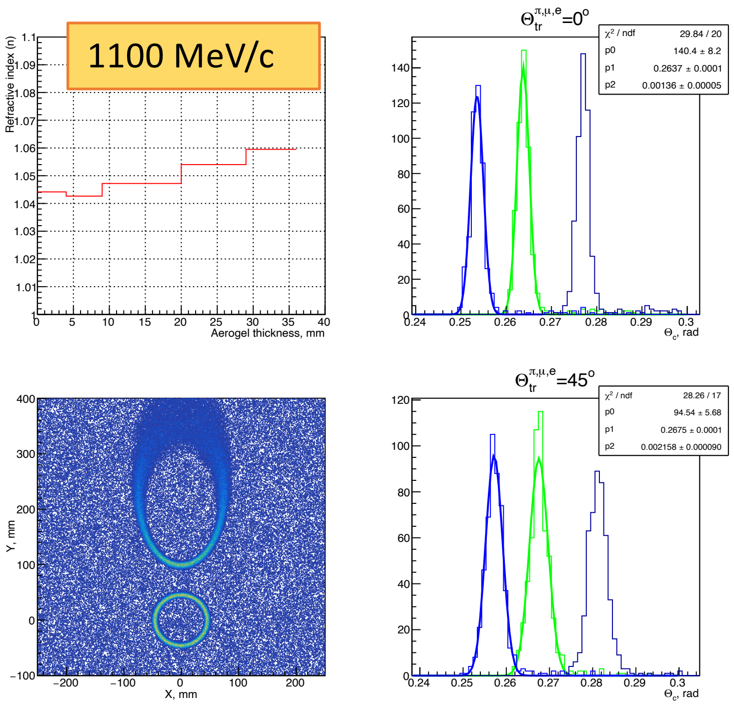
$$PDE(\lambda) = \frac{QE(\lambda)^{\mathrm{DS}}}{QE(409nm)^{\mathrm{DS}}} QE(409nm)^{\mathrm{Meas}} \cdot CE = \frac{QE(\lambda)^{\mathrm{DS}}}{32\%} 20\% \cdot 0.8$$

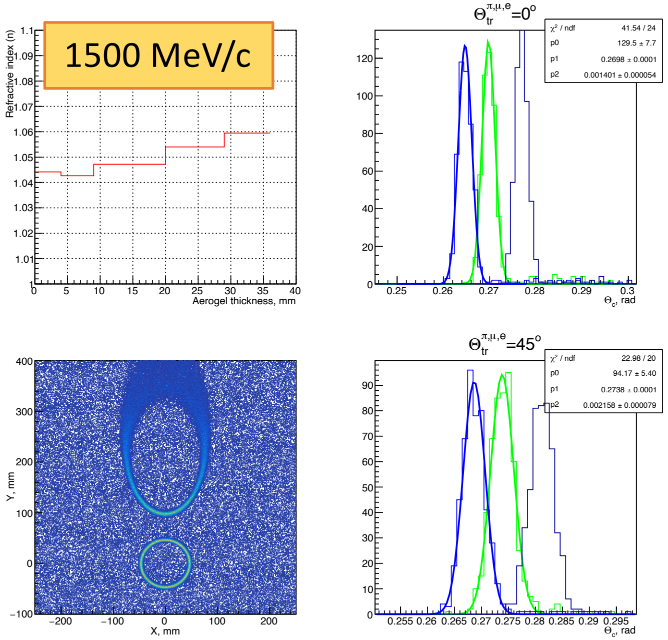


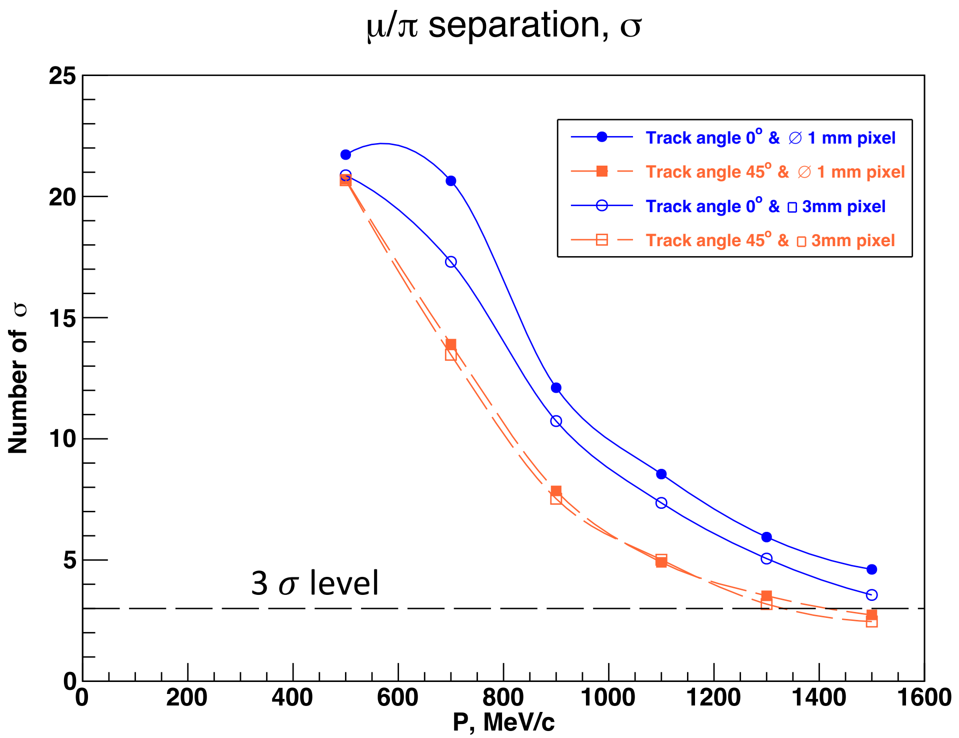


Expected e/μ/π – separation with FARICH up to 1.5 GeV/c









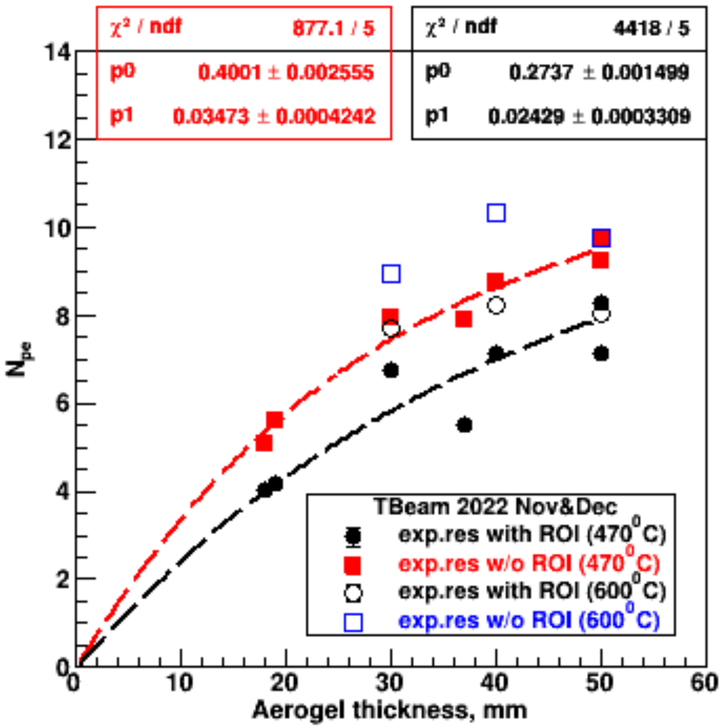
To estimate μ/π-separation capability in wide momentum range results of parametric simulation were used:

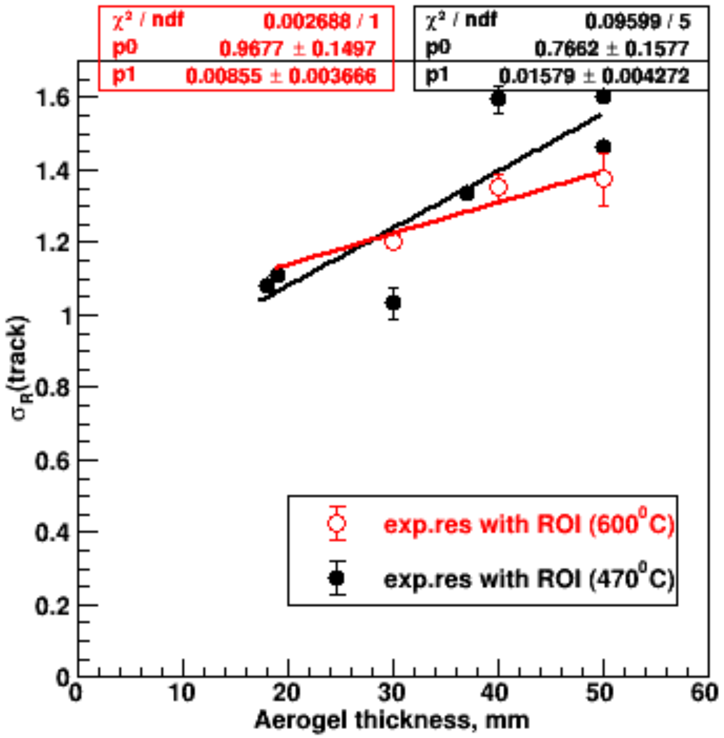
- Refractive index profile approximation for aerogel sample *453f4* and its focusing distance *L=160 mm*
- Simulation was performed for track angles *0°* and *45°*.
- Number of photoelectrons for relativistic particles (beta=1) is equal to 39 (was taken from G4 simulation).
- Single Photon Resolution (SPR) for relativistic particles SPR(■3 mm) =1.63 mm and SPR(ø1 mm)=1.36 mm (was taken from beam test results).

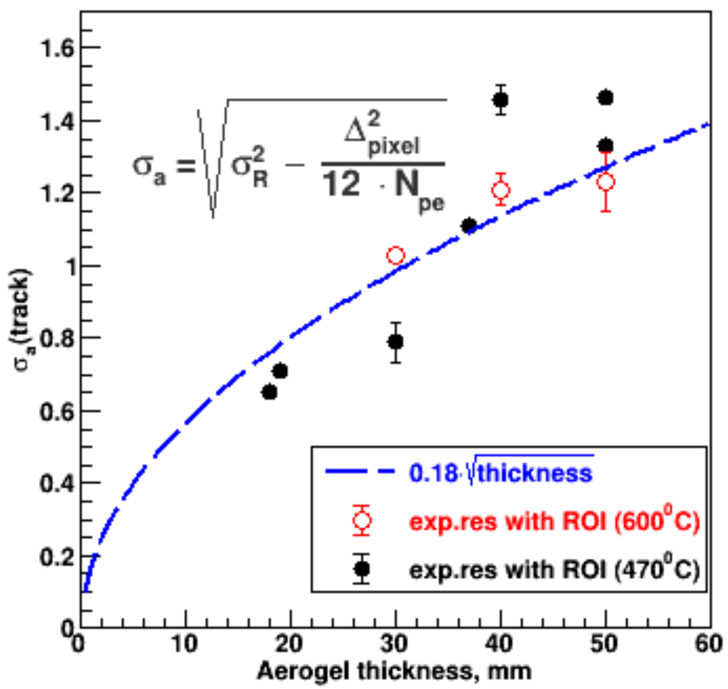
Quality of particles separation is determined as:

$$N_\sigma = \frac{\bar{\theta}_1 - \bar{\theta}_2}{(\sigma_1+\sigma_2)/2}.$$

Dependence of N_{pe} and $\boldsymbol{\sigma_R}$ on aerogel thickness

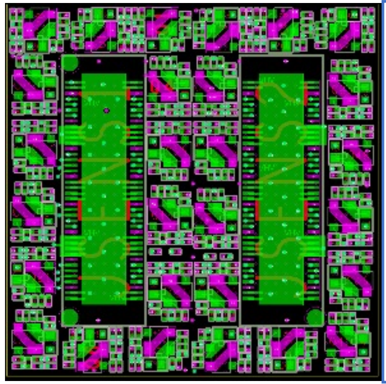




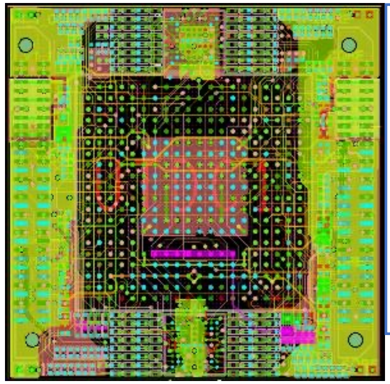


- N_{pe} dependes on the aerogel thickness as expected and limitted by the Releigh light scattering law.
- Some ssytematical increase of N_{pe} (~13÷15%) are observed in new thick aerogels after increase of backing temperature (470˚C –> 600˚C). This effect could not be quantatively explained by increase of refractive indexes (1.027 –> 1.029) and it is contra to N_{pe} decrease (~5÷6%) expected due to Releigh light scattering decrease ($L_{sc}(400nm, 1.027) \approx 47mm \ \rightarrow L_{sc}(400nm, 1.029) \approx 41mm$)
- $\sigma_R \sim \sqrt{thickness}$ (as expected), while for several aerogel samples some deviations σ_R from the dependence are observed. The reason of this effect could be in some impurites inside the aerogel which are able to give additional small angle forward scattering.

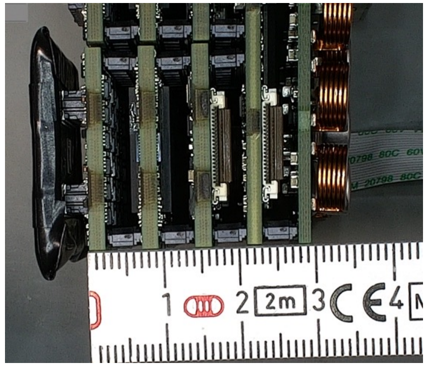
FEE based on FPGA-TDC



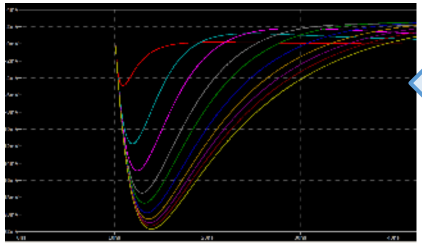
Amplifier board
- 27×27 mm^2 size
- 14-layer PCB
- 30x gain, 64 channels
- couples to KETEK 8×8 SiPM array



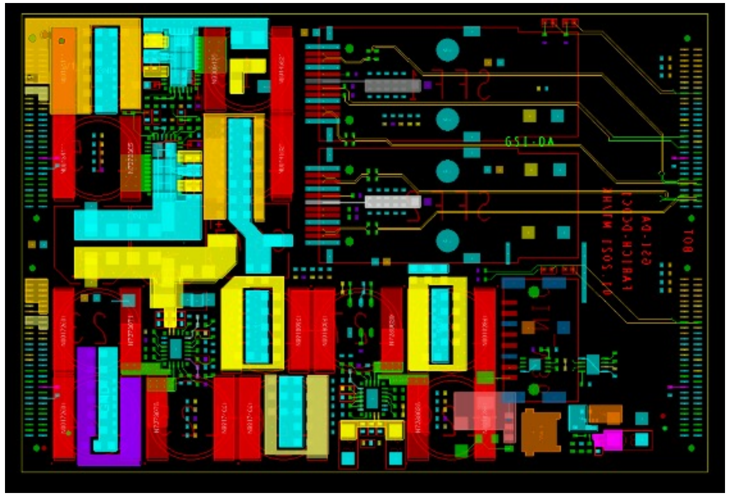
TDC board
- 64 channels
- 2 TDC + 4 threshold FPGAs
- 10ps precision



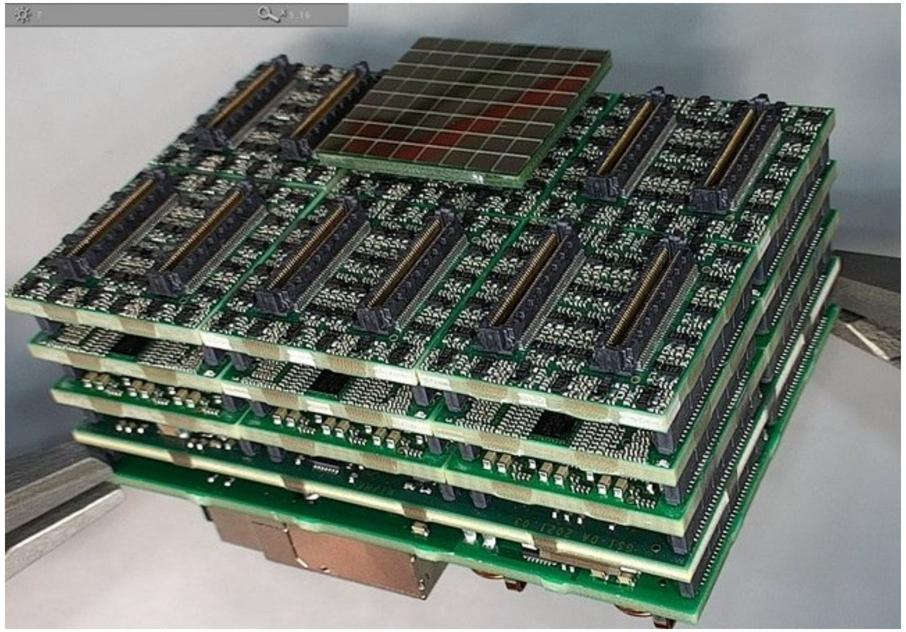
- Each module readouts 6 arrays 8x8 pixels and equipped with optical transceiver.
- Thickness of 5-layer design is less than 5 cm.



Simulated single photon pulse shapes from amplifier for different input resistance. ~ 22mV amplitude can be achieved.

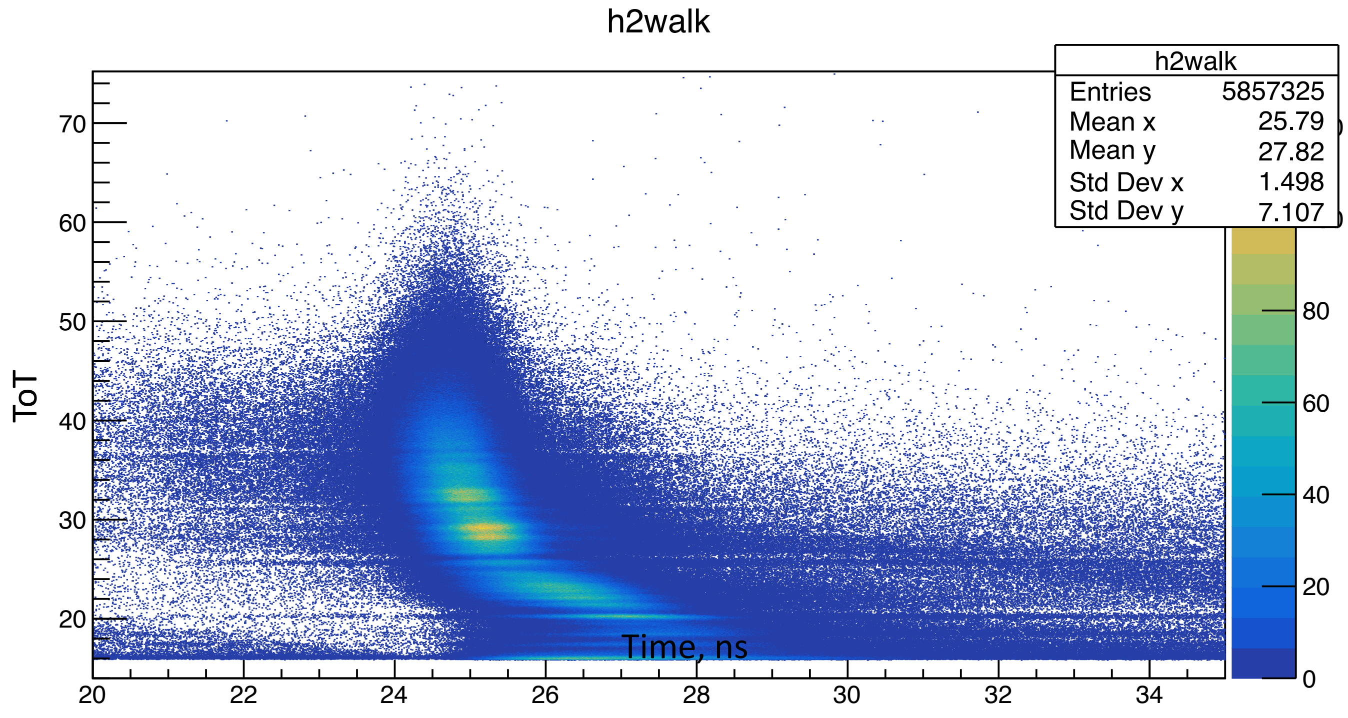


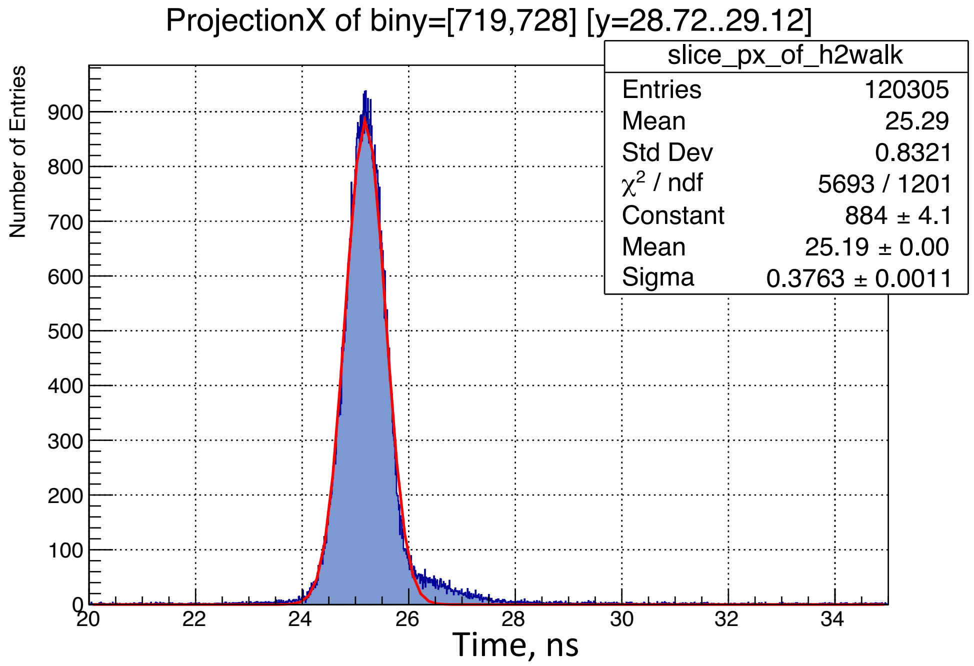
DC-DC convertor board
- goes behind the backplane
- 51×84 mm^2 size
- provides power to SiPMs, amplifiers, FPGA
- uses air inductive coils to operate in the detector magnetic field
- power, trigger & clock connectors



The first tests of *FaRICH-Auslese-System*

FPGA-TDC (FaRICH-Auslese-System) to readout 2304 SiPMs developed and produced in GSI.





The tests performed bu Mechael Traxler, Matthias Hoek and Merlin Böhm at HIM-Institute in Mainz.

- Everything works as expected: ToT(Time) is as expected for single photon distribution.
- Single photon detection time resolution without any corrections and proper TDC calibration is about 380ps (it is good enough value for FARICH), while intrinsic resolution of TDC is about 8÷12 ps.
- A lot of dark counts are in the data (every 3rd hit is noise). Thermostabilization or cooling is needed for future tests.