Options of the RICH detectors based on silica aerogels for high momenta range

Alexander Barnyakov on behalf of "Aerogel team" BINP&BIC (Novosibirsk)

- **Requirements to RICH for π/K–separation above P=20 GeV/c**
- **RICH based on aerogel with n=1.008**
  - **Focusing Aerogel RICH**
  - **Aerogel RICH with Fresnel Lens**
  - **RICH based on aerogel fibers**
- **Summary**

International Workshop on **De**tector **Sy**stem and **T**echniques for fundamental and applied physics,

24-26 February **2025**, LNS-INFN, Catania

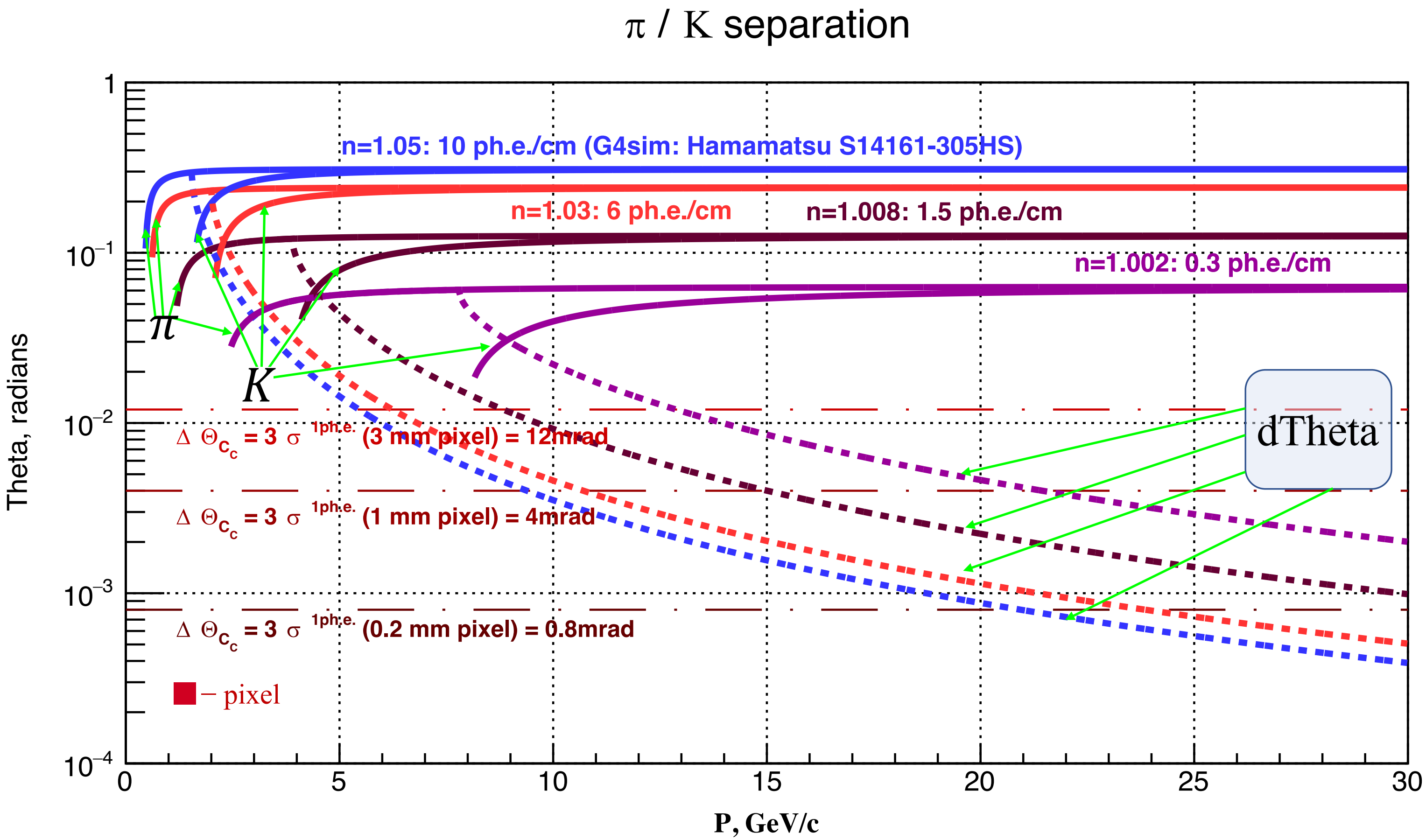
Motivations for π/K–separation above 20 GeV/c

- Future e^+e^- H-factories such like FCCee (CERN) and CEPC (China) have extensive physics programe at Z-pole $\left(\sqrt{s} = 91.2\ GeV\right)$.
- Expected $4{\times}10^{12}$ Z-bozons $\left(\int Ldt \approx 100ab^{-1}\right)$ will provide extensive statistic of $b\bar{b}$, $c\bar{c}$ and $\tau^+\tau^-$ for precise flavor physics investigations. *[arXiv:2412.19743v2 [hep-ex] 31 Dec 2024]*
- π/K– separation is needed not only to supress combinatorial background and to separate similar topology of final states like:

$B^0_{(s)} \rightarrow \pi^+\pi^-, B^0_{(s)} \rightarrow K^+K^-, B^0_{(s)} \rightarrow K^\pm\pi^\mp$ and so on.

- Baseline option of the CEPC detector is able to provide π/K– separation at the level of 2σ up to 20 GeV/c by combining ${}^{dE}/_{dx}$ and ToF techniques. *[Y.Zhu et al., NIM A 1047 (2023) 167835]*
- π/K–separation at the level $\geq 3\sigma$ in wider momentum range is highly desirable for such experiments.

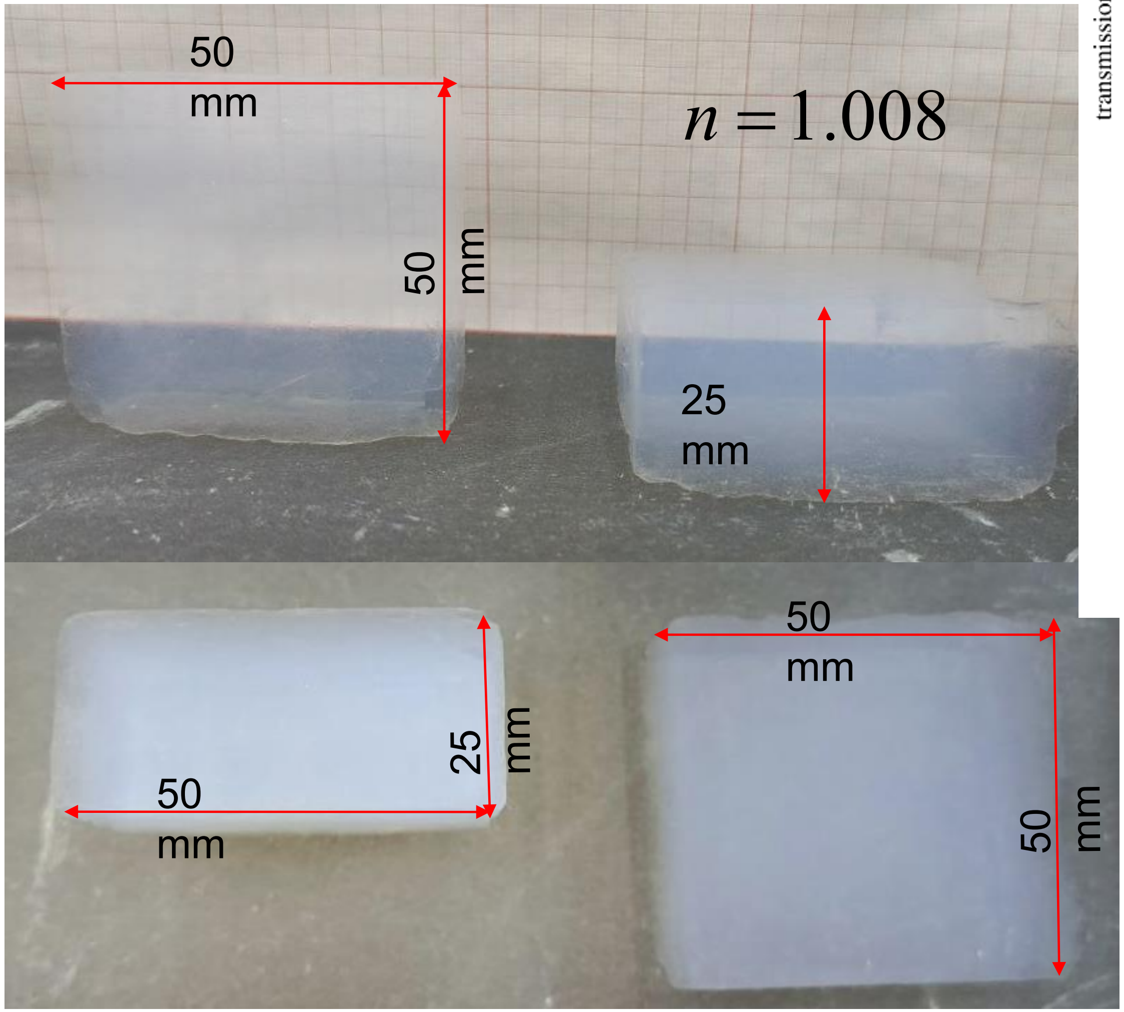
RICH detectors capability for π/K–separation

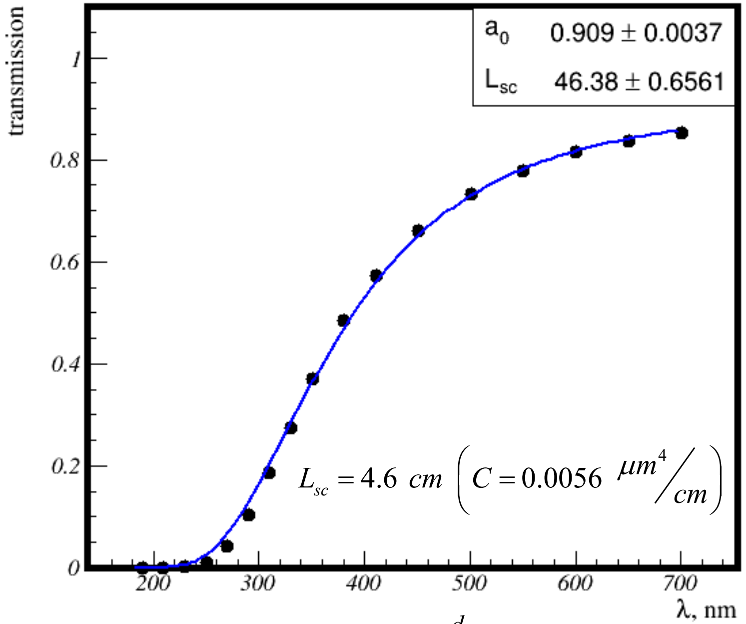


- $\sigma_C^{tr} = {}^{1}/_{\sqrt{N_{pe}}} \cdot \sqrt{\left(\frac{\Delta_{pix} \cdot \cos\theta_C}{L \cdot \sqrt{12}}\right)^2 + \left(\frac{\sigma_n}{n \cdot \tan\theta_C}\right)^2 + \left(\frac{t \cdot \sin\theta_C}{L \cdot \sqrt{12}}\right)^2 + \sigma_{tr}^2} \sim \sqrt{t}$
- $N_{pe}(\beta = 1) \sim 500 \cdot \frac{n^2 - 1}{n^2} \cdot t \cdot QE$

- At least 5 hits have to be detected to reconstruct Cherenkov ring.
- Thickness of Cherenkov radiator should be:
  - ≥1 cm for n=1.05 (aerogel)
  - ≥4 cm for n=1.008 (aerogel)
  - ≥15 cm for n=1.002 (C_5F_{12})
- Some focusing system is needed to provide impact from thickness at the level of few mrads for base 200÷300 mm!!!

Aerogel with n=1.008 (Novosibirsk)



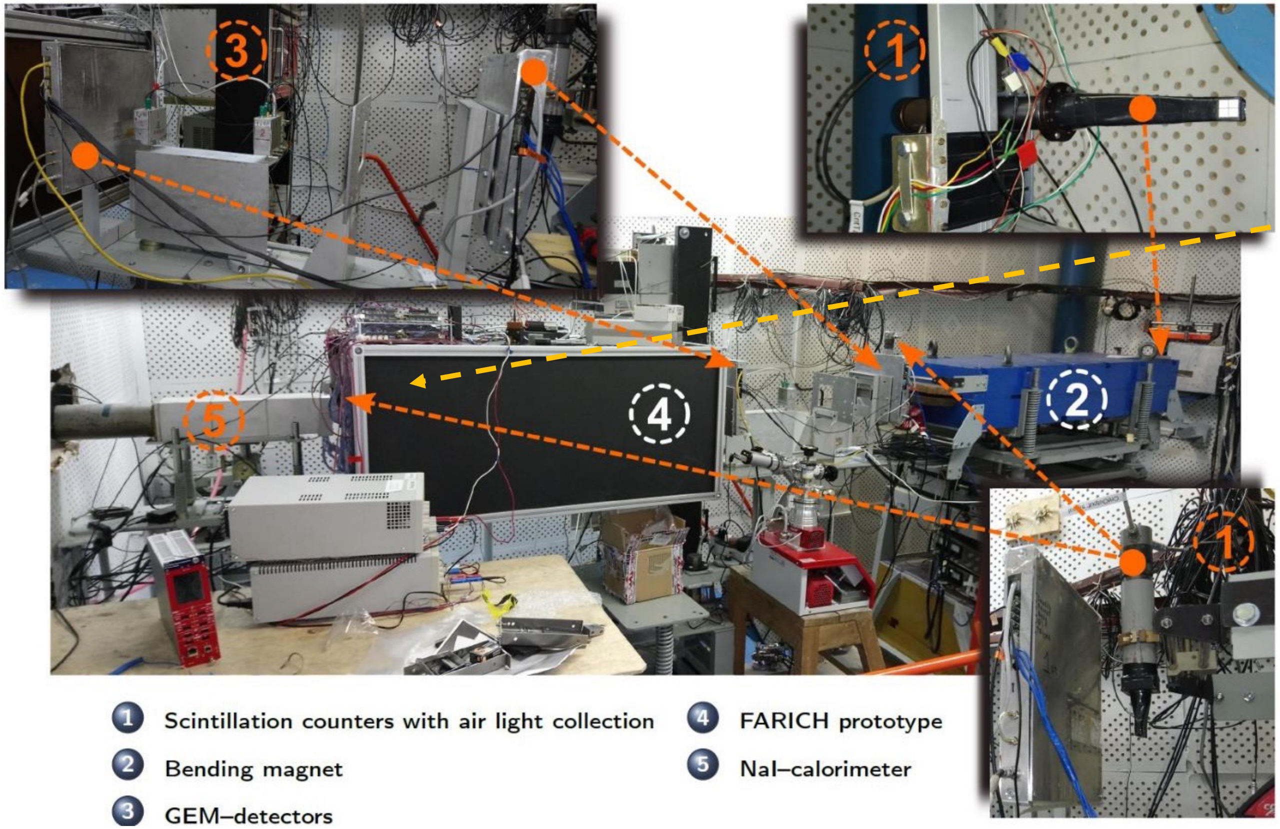


$$T = \frac{I}{I_0} = a_0 \cdot e^{-\frac{d}{L_{sc} \cdot (\lambda / 400)^4}} = a_0 \cdot e^{-\frac{C \cdot d}{\lambda^4}}$$

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

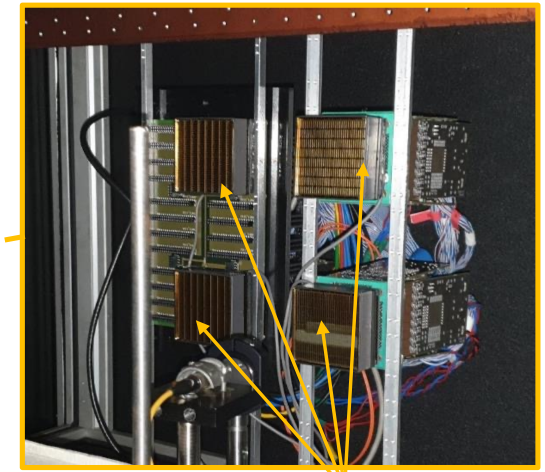
BINP beam test facility

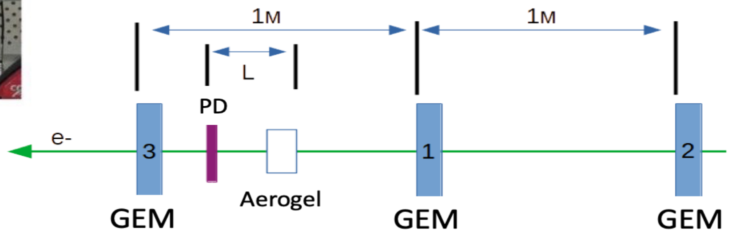
Example disposition of equipment in experimental hall (15/03/2018)



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

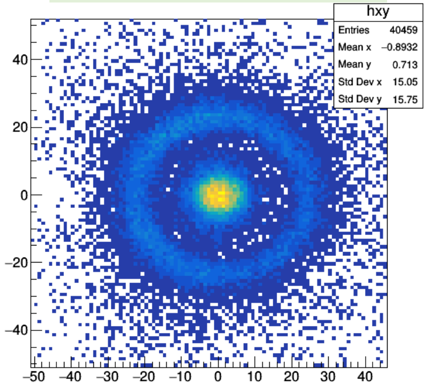
*G N Abramov et al 2014 JINST **9** C08022*

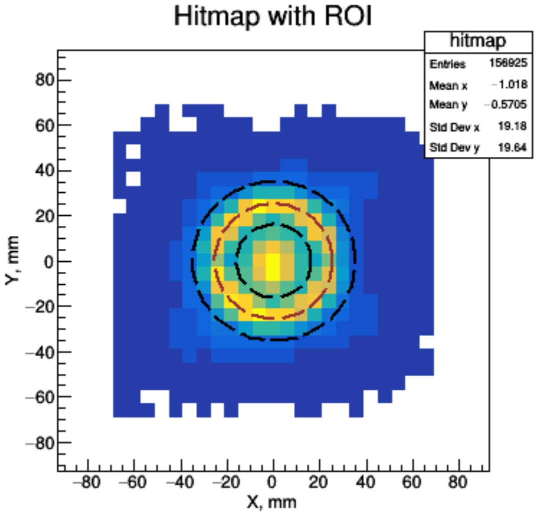


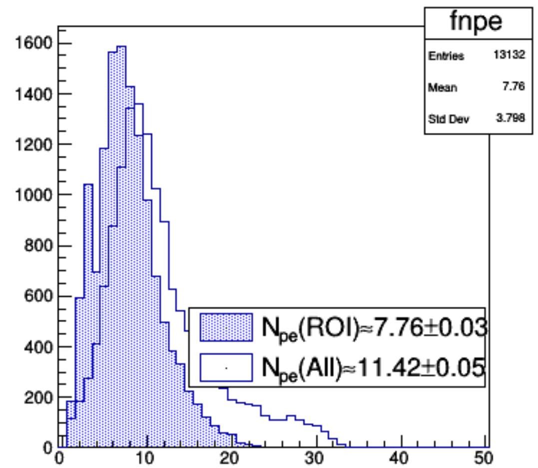


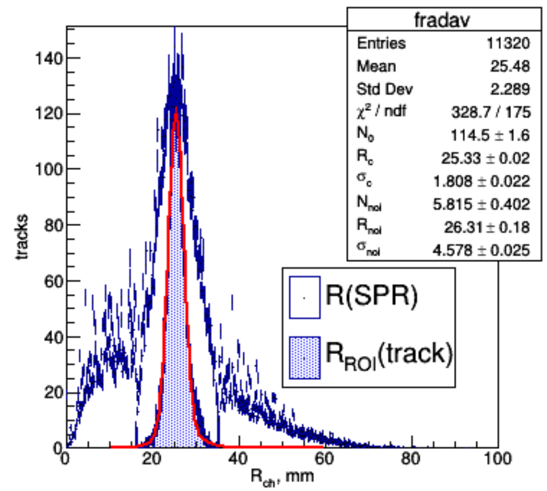
RICH based on aerogel n=1.008: some beam test results

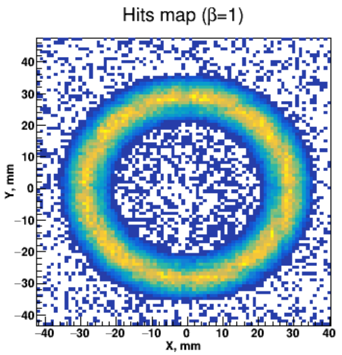
Tbeam e⁻@2.5GeV
- t_{aer}=25+25=50 mm
- L_F=200 mm











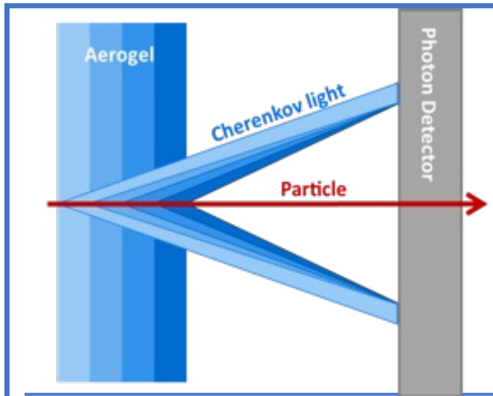
Geant4 sim.:
- t_{aer}=60 mm
- L_F=250 mm

TBeam results reconstructed w/o track information:
- MaPMT H12700 with QE(400nm) ≈ 20%
- Pixel 6x6 mm
- Aerogel:
  - stack of 3 tiles 25+25+25=75 mm
  - refractive index n≈1.008
- L_F=235 mm

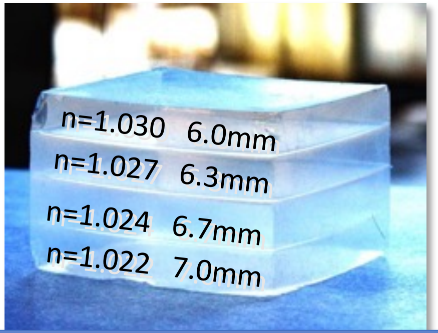
OUTPUT:
- SiPM based photon detector with PDE(400nm)=45÷50% will alow us to detect 10÷20 ph.e. for relativistic tracks
- RICH based on aerogel with n=1.008 and pixel 3x3mm is able to provide π/K-separtion at P=10 GeV/c
- ***Proximity focusing system and PD with $\sigma_x \leq 1\ mm$ is required to reach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

FARICH with n_{max}=*1.008* option

FARICH technique milestones



The first 4-layer monolithic sample

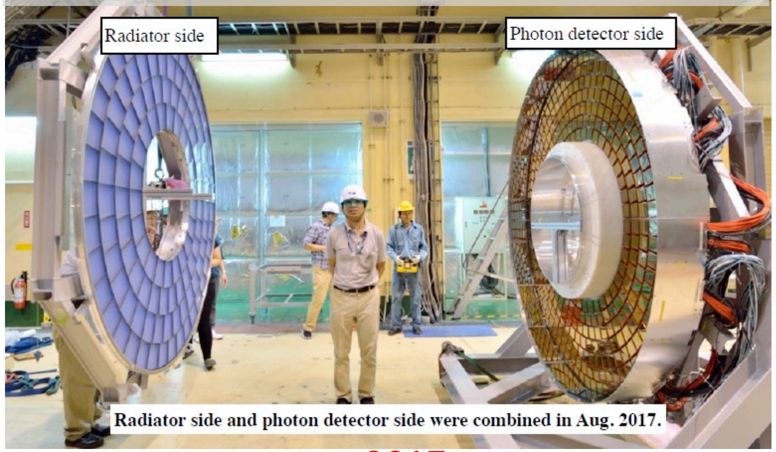


Increase N_{pe} due thickness increase without $\sigma_{\Theta c}$ degradation

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

2004÷2005

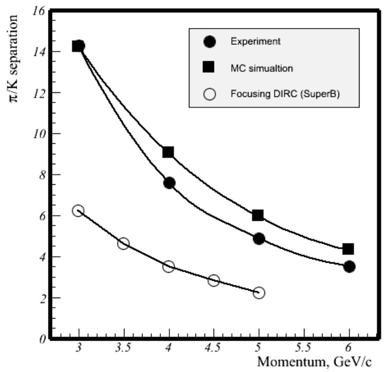
The Belle II (ARICH) is the first application of the method

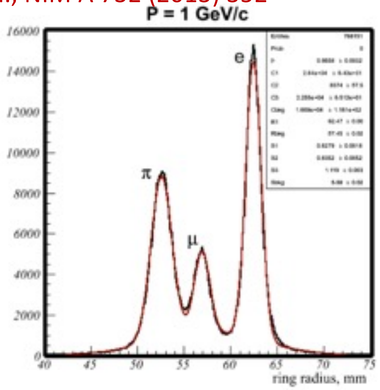


2017

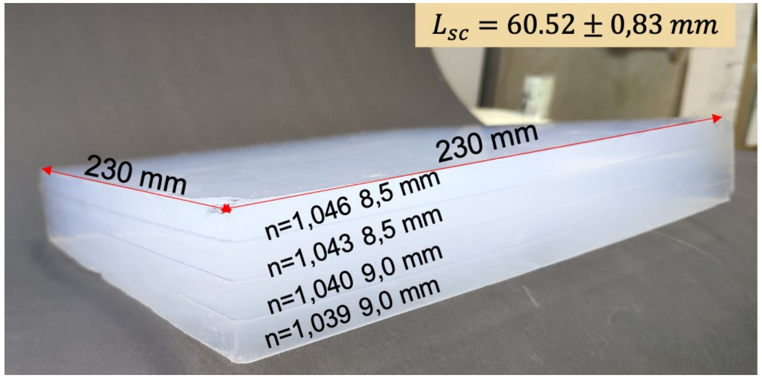
Excellent PID capability were shown at CERN beam test in 2012

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





Two 4-layer focusing aerogel blocks
230x230x35 mm

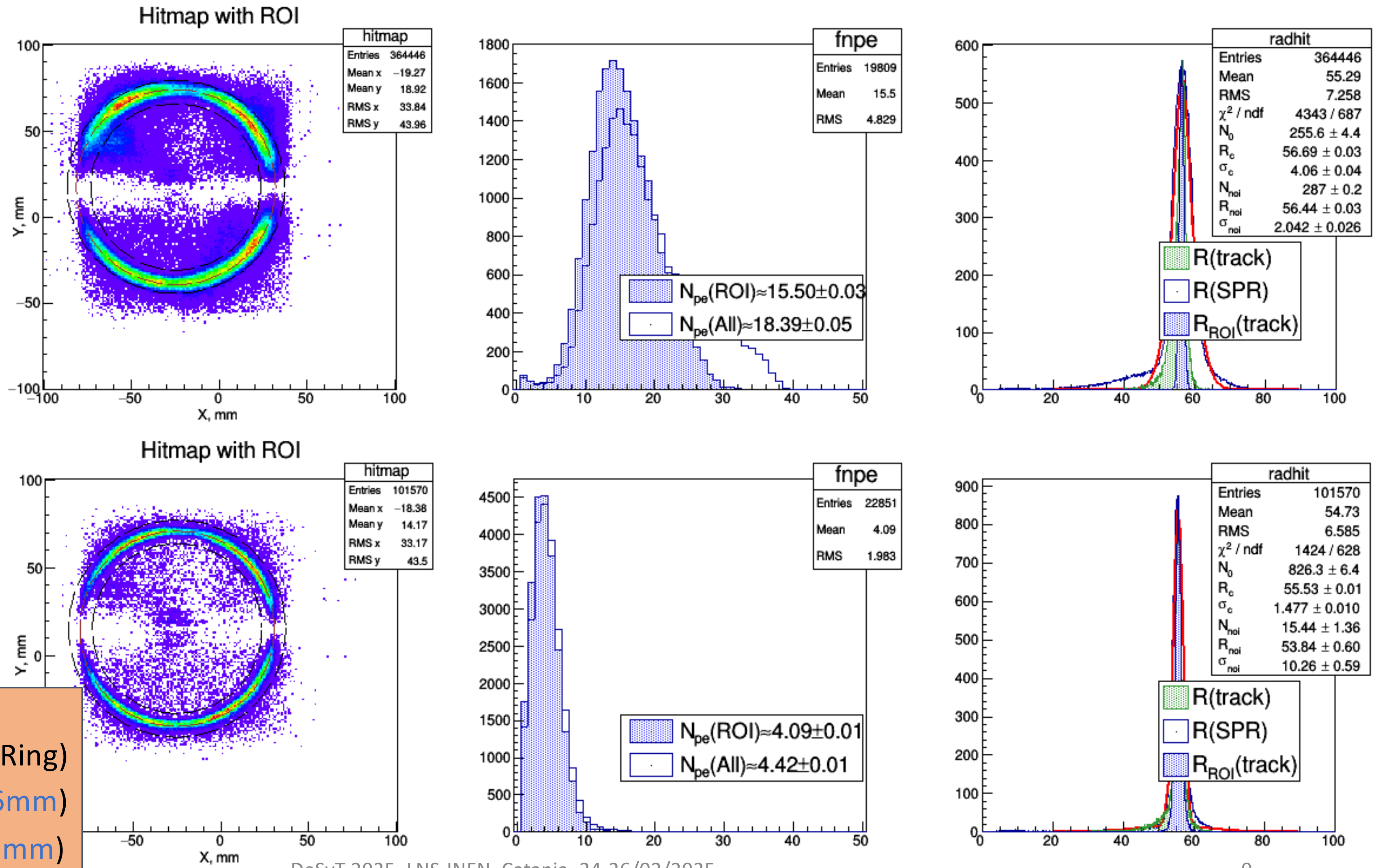


2022÷2023

Recent beam test results

Pixel 6x6 mm
Geom.Eff. ~ 80%

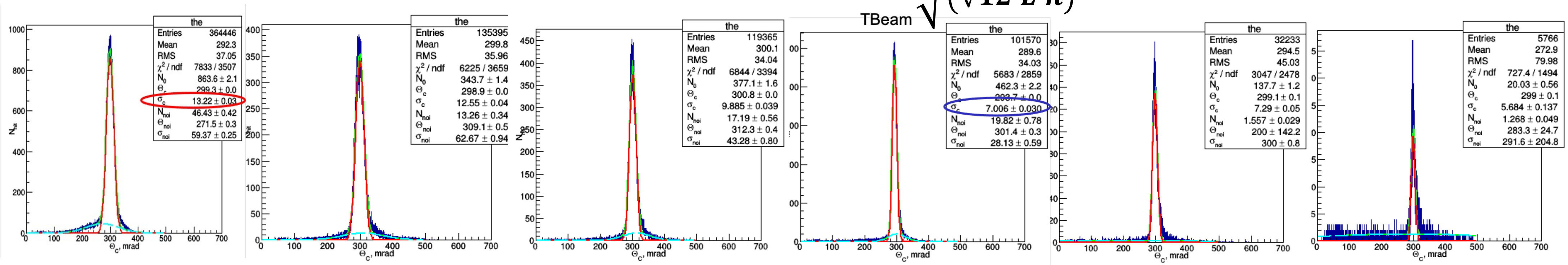
Pixel 3x3 mm
Geom.Eff. ~ 20%



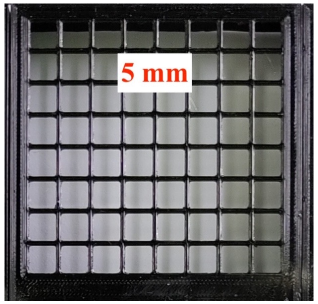
Main results:

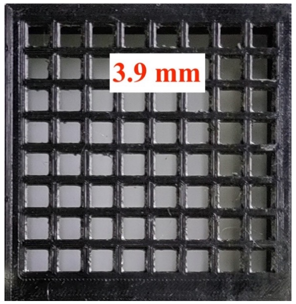
- $N_{pe} \approx 16$ (~ 0.8 of Ring)
- $\sigma_\theta^{1pe} \approx 13.5\ mrad$ (■ 6mm)
- $\sigma_\theta^{1pe} \approx 7.5\ mrad$ (■ 3mm)

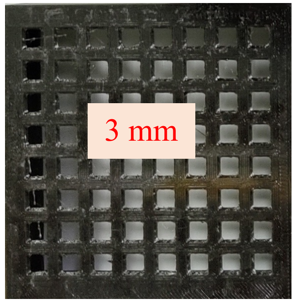
TBeam 2023 res.: $\sigma_{\theta_C}^{1pe} = \sqrt{\frac{\Delta_{pix}^2}{(\sqrt{12}\cdot L\cdot n)^2} + \sigma_{aer}^2 + \sigma_{trk}^2}$

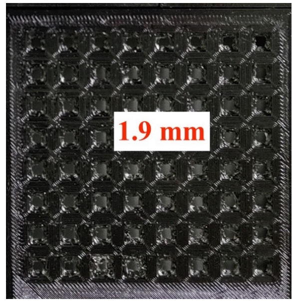


No mask: $6{\times}6\ mm$

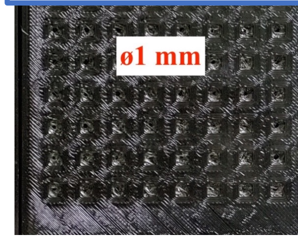








$\sigma_{aer} \approx 5.6$ mrad



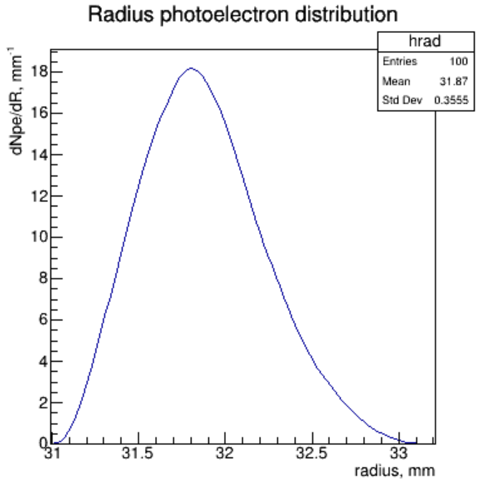
04/23: L≈200 mm	12/23: L≈180 mm	12/23: L≈180 mm	04/23: L≈200 mm	12/23: L≈180 mm	12/23: L≈180 mm
Geom.Eff. ~ 80%	Geom.Eff. ~ 56%	Geom.Eff. ~ 36%	Geom.Eff. ~ 20%	Geom.Eff. ~ 9%	Geom.Eff. ~ 2%
$N_{pe} \approx 16$	$N_{pe} \approx 12$	$N_{pe} \approx 8$	$N_{pe} \approx 4$	$N_{pe} \approx 2$	$N_{pe} \approx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

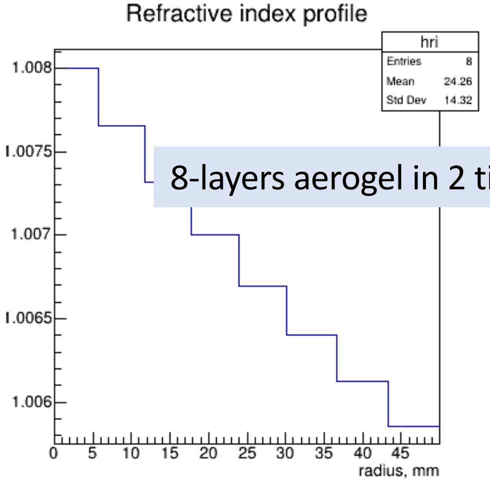
π/K: – 5.5 GeV/c 6 GeV/c 6.5 GeV/c 8.0 GeV/c 8.5 GeV/c

μ/π: – 1.2 GeV/c. 1.4 GeV/c 1.5 GeV/c 1.6 GeV/c 1.7 GeV/c

FARICH option for π/K–separation above 20 GeV/c

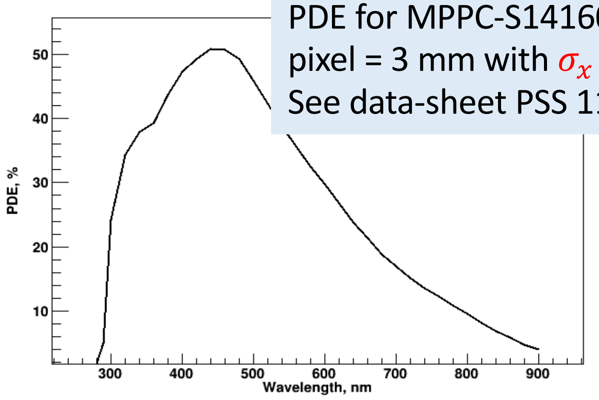
8-layer aerogel n_{max}=1.008; pixel≈0.2mm





8-layers aerogel in 2 tiles

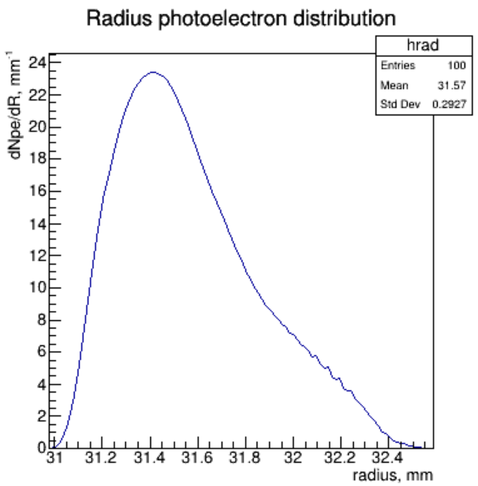
Focal distance is 300 mm

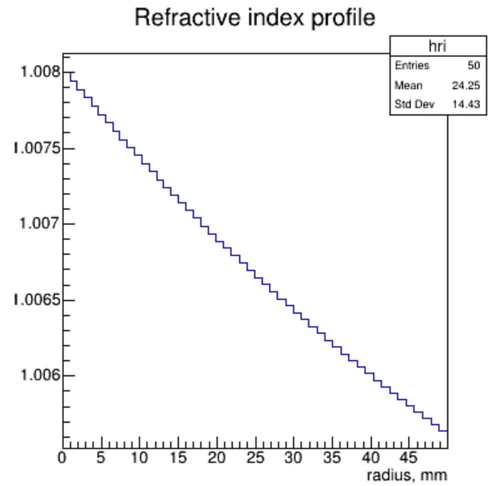


PDE for MPPC-S14160 (Hamamatsu)
pixel = 3 mm with $\sigma_x \approx 0.2mm$
See data-sheet PSS 11-3030-S (NDL)

- N_{pe}≈16
σ_C^{tr}≈0.33 mrad!!!

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



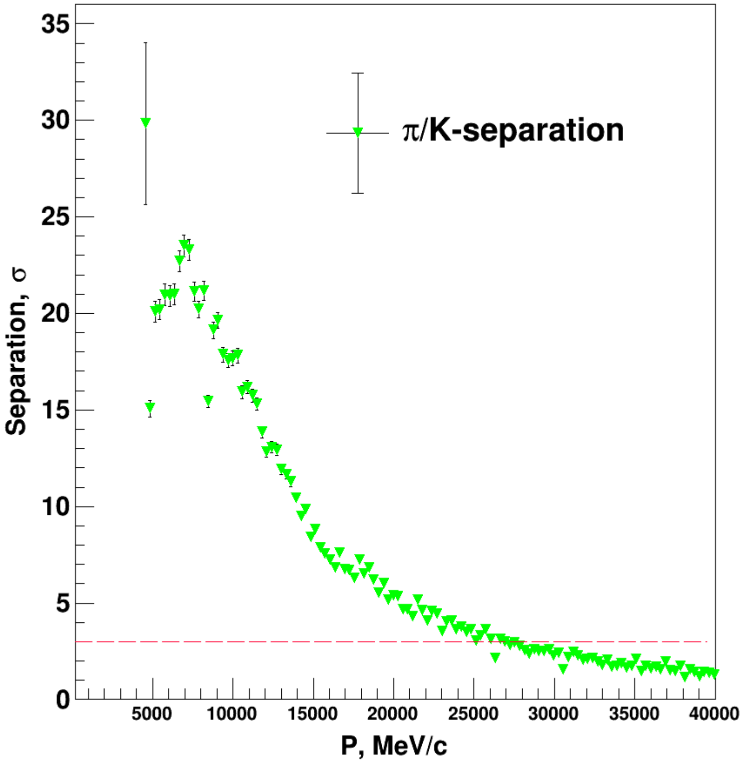


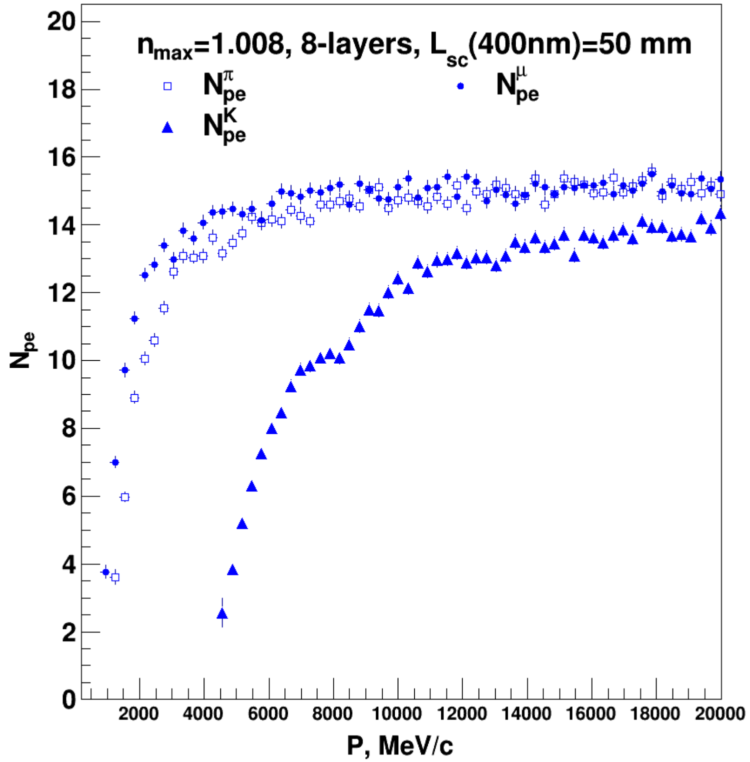
The possibility to produce of gradient aerogel was demonstrated in
NIM A766 (2014) 88-91 and NIM A766 (2014) 235-236

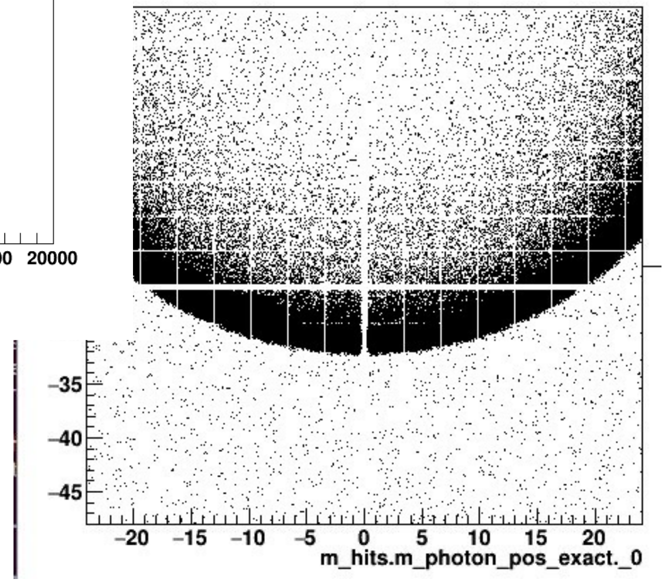
- N_{pe}≈16
σ_C^{tr}≈0.33 mrad!!!

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

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







Aerogel RICH with Fresnel Lens

n=1.008

Proximity focusing with Fresnel Lenses

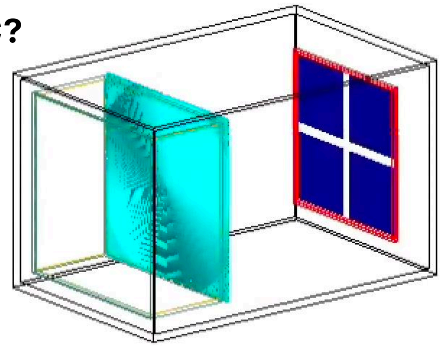
- This option was Inspired by success of mRICH R&D for EIC project [D. Sharma et al., NIM A1061 (2024) 169080]
- First steps of simulation at BINP were verified with GSU group simulation results

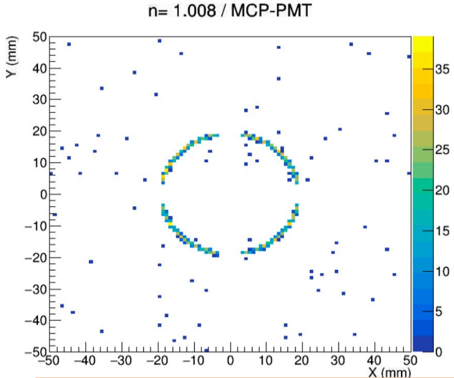
GSU sim

Modular RICH for the CEPC?

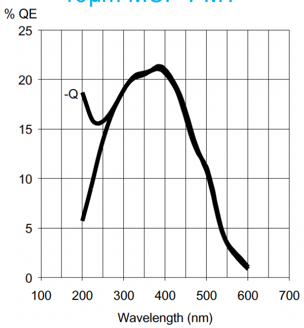
M. Sarsour, GSU
9/13/2024

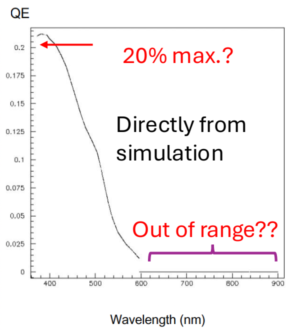
- G4 simulation based on JLab prototype
- Excluded mirrors for noise reduction



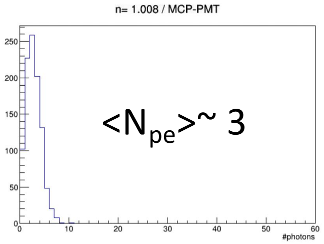


10μm MCP-PMT

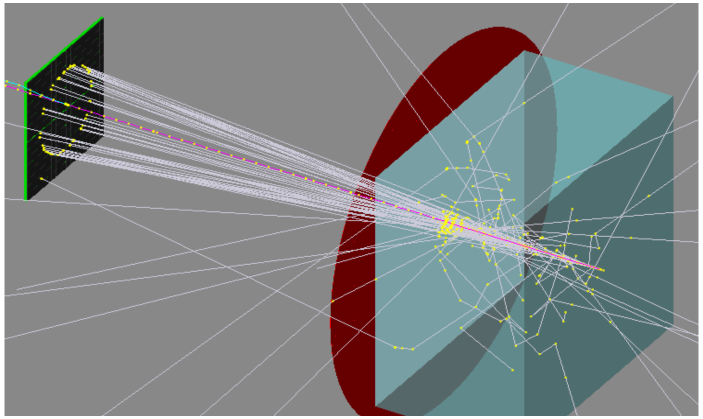


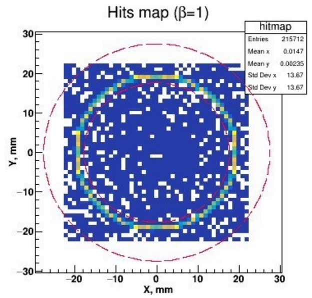


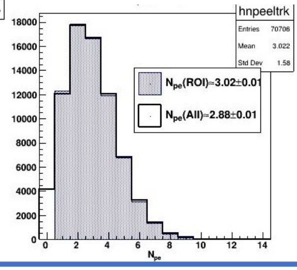
- 5 GeV/c μ^- incident perpendicular at the center of the Aerogel block (n=1.008 at 6 cm)

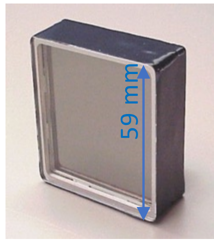


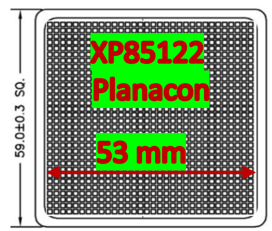
BINP sim



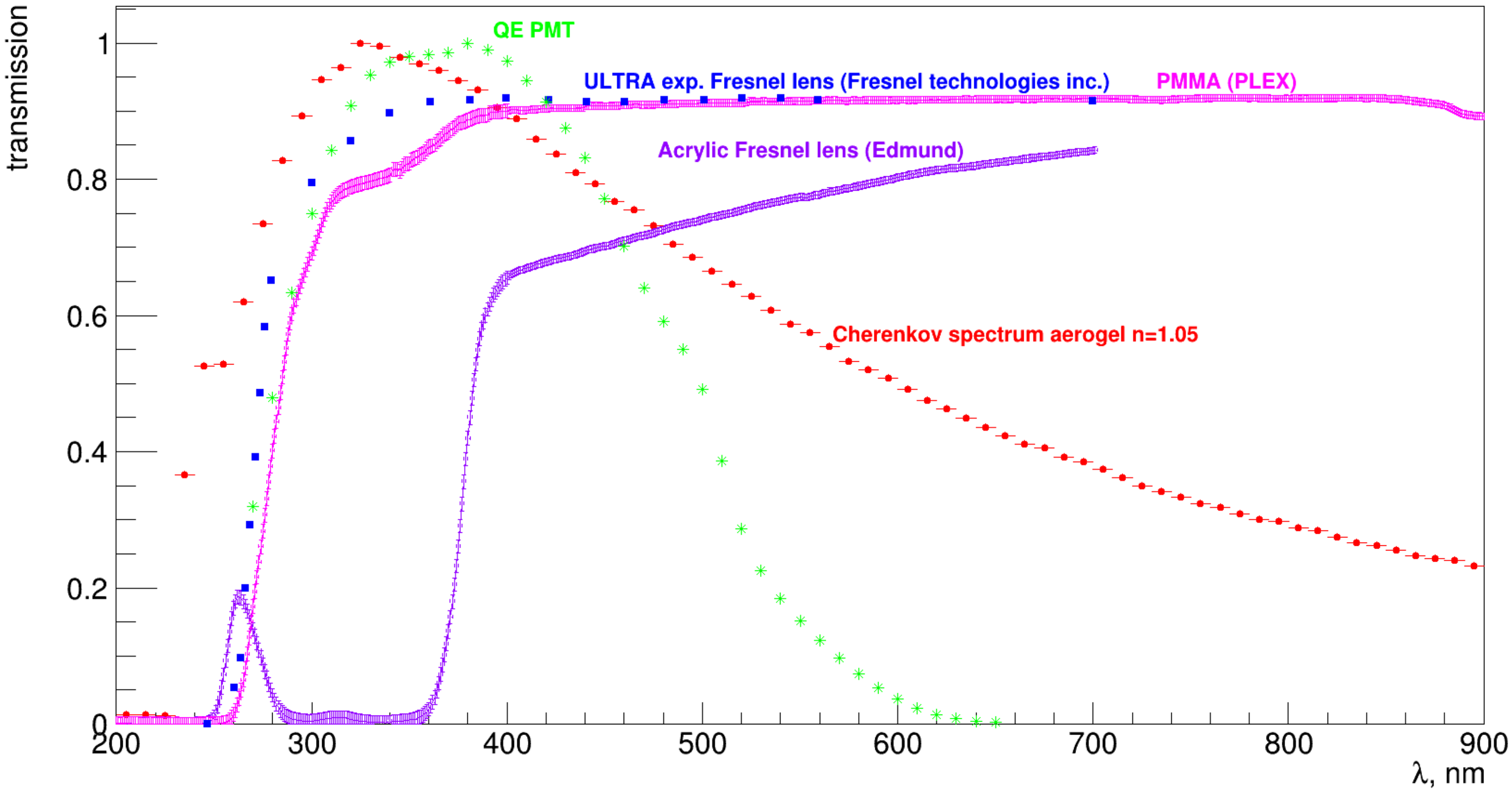






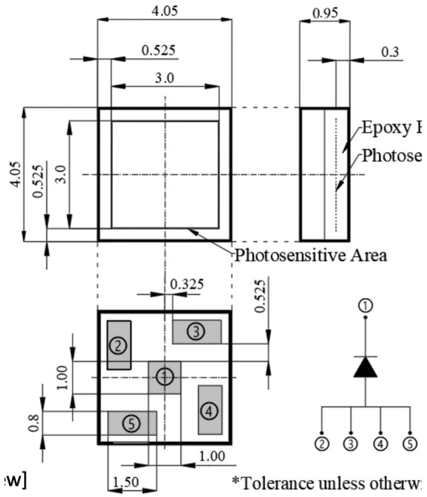


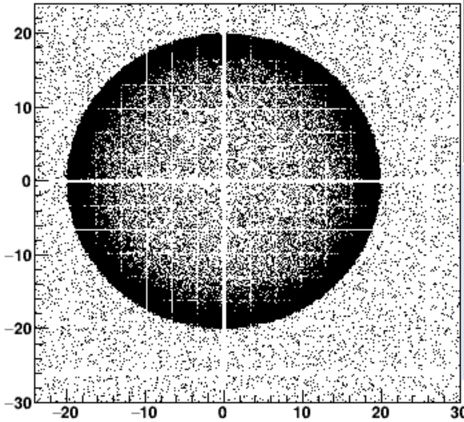
Fresnel lens transparency



- About half of Cherenkov photons from aerogel is absorbed by material of Edmund lens
- There are another option of application of Acrylic lenses from Fresnel Technology Inc. of special production of UV-transparent lens for ULTRA experiment *(NIM A570 (2007) 22-35)*

mRICH GEANT4 sim. with SiPM like PSS 11-3030-S (NDL)

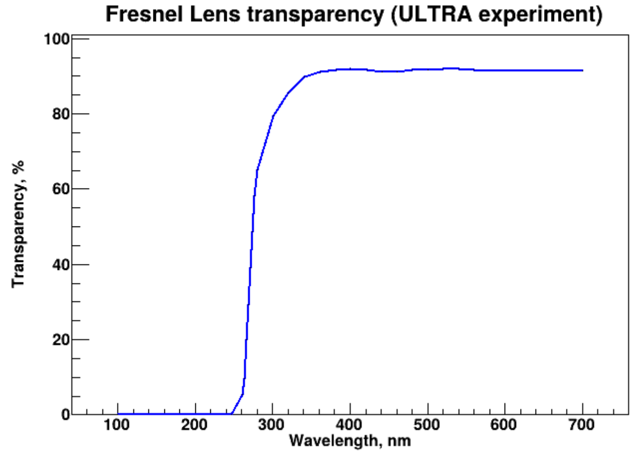


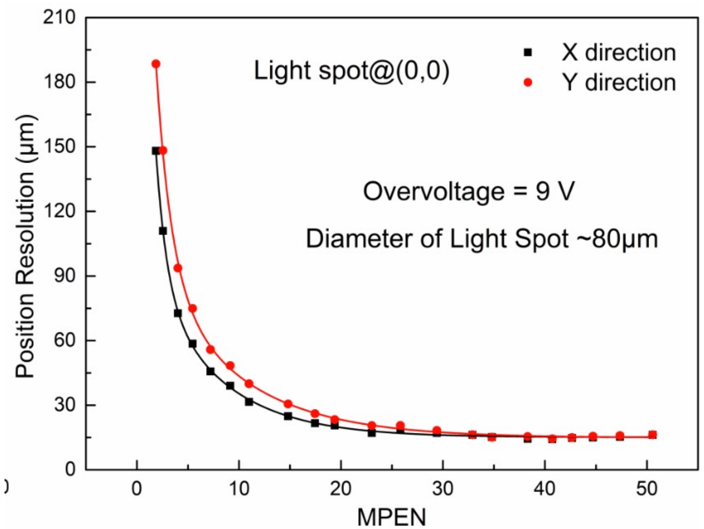


$$x_c = \frac{L}{2} \cdot k \cdot \frac{(Q_2+Q_3)-(Q_1+Q_4)}{(Q_1+Q_2+Q_3+Q_4)}$$

$$y_c = \frac{L}{2} \cdot k \cdot \frac{(Q_3+Q_4)-(Q_1+Q_2)}{(Q_1+Q_2+Q_3+Q_4)}$$

Exact hit positions from G4sim are smeared by Gaussian with $\sigma_x = 200\mu m$

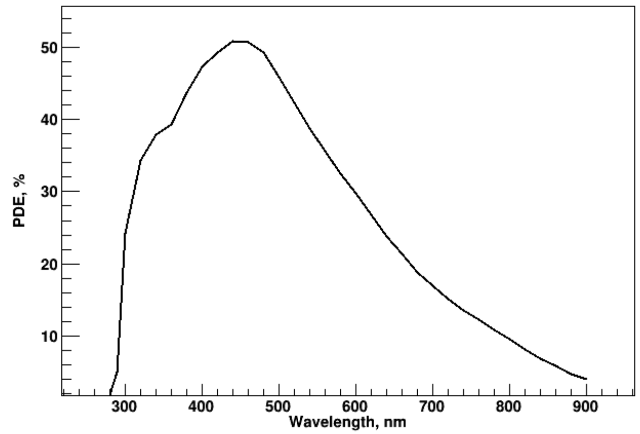




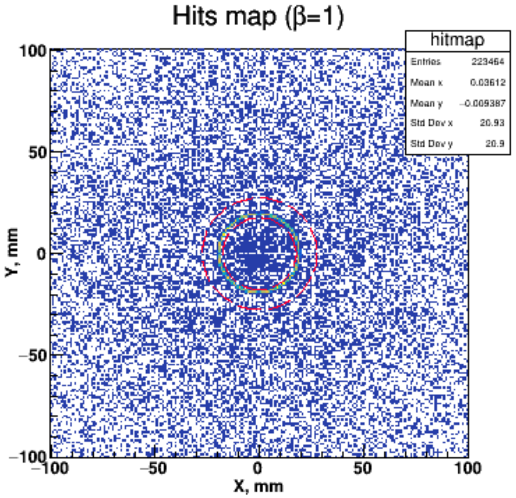
- Aerogel
  - n=1.008
  - t=6 cm
  - L_{sc}(400nm)=4.6 cm
- Position-sensitive SiPM
  - pixel 3x3 mm
  - hit position restored by charge sharing $\sigma_x = 200\mu m$
  - PDE from Hamamatsu S14161-3050HS
- Fresnel Lenses
  - **Focal length = 6” and 10”**
  - Transparency from ULTRA exp.

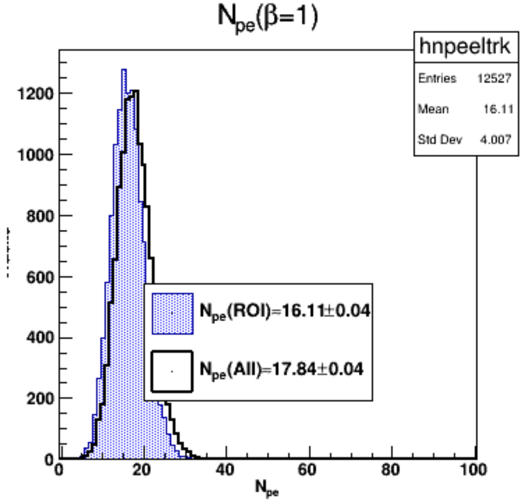
(NIM A570 (2007) 22-35)

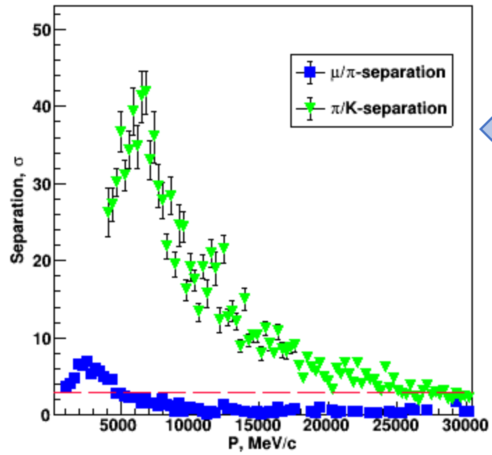
Fresnel technology inc.



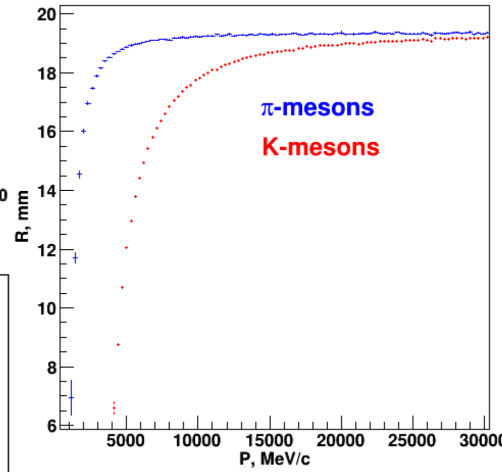
mRICH sim. results for Fresnel lens 6” and 10”

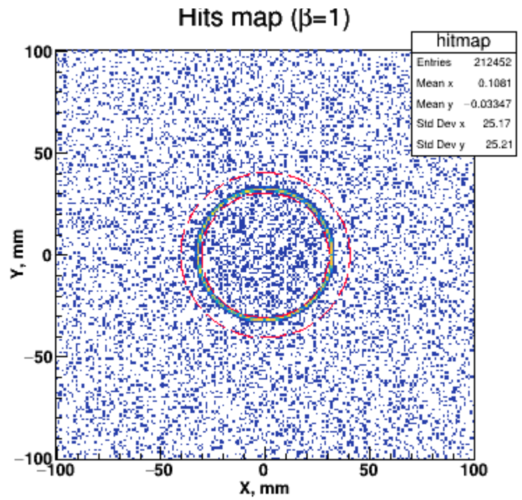


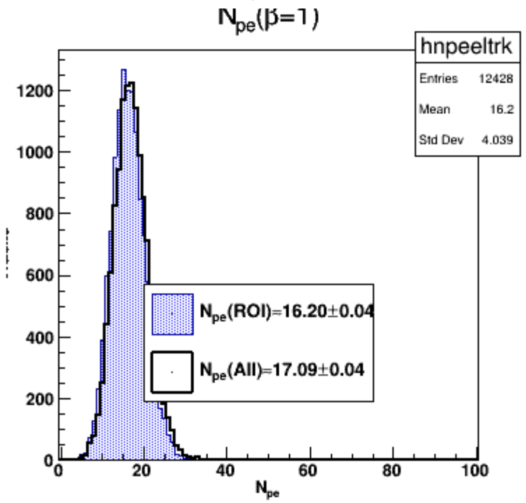


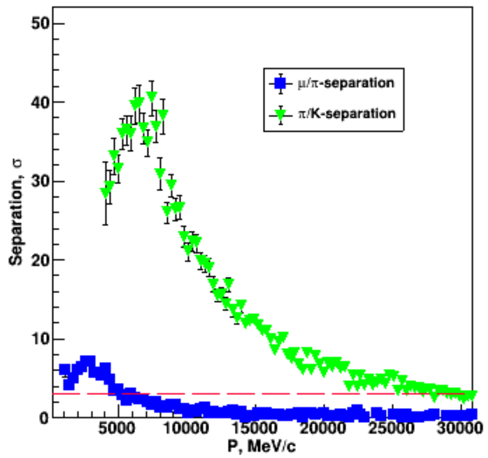


Fresnel Lens with F=6”









Fresnel Lens with F=10”

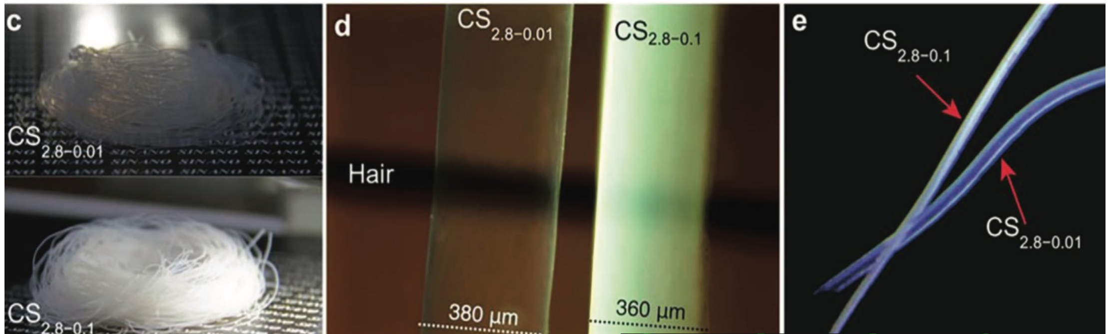
RICH based on aerogel fibers

Fiber Aerogel RICH: idea & motivation

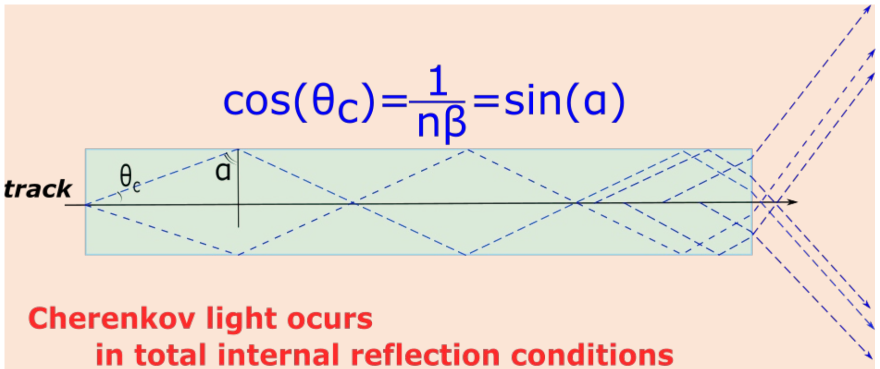
For π/K-separation above 20 GeV/c we need $n \leq 1.008$ consequently N_{pe} decreases significantly. We consider approach how to compensate N_{pe} by means of aerogel fibers without segnificant angle resolution degradation.

- It was inspired by discussion at SINANO (Sughou) with prof. Xeutong Zhang and Co. in August 2023.
- The possibility of aerogel fiber production is decribed in article:

Adv. Sci. **2023**, *10*, 2205762



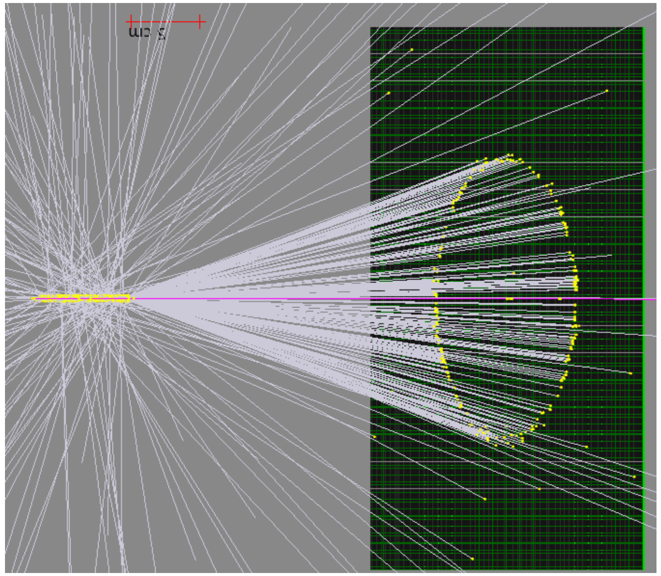
$$\cos(\theta_C) = \frac{1}{n\beta} = \sin(\alpha)$$



Cherenkov light ocurs in total internal reflection conditions if particle goes stright along bar or fiber axis!

Chernkov photon emmision point is determined by transverse size of fiber.

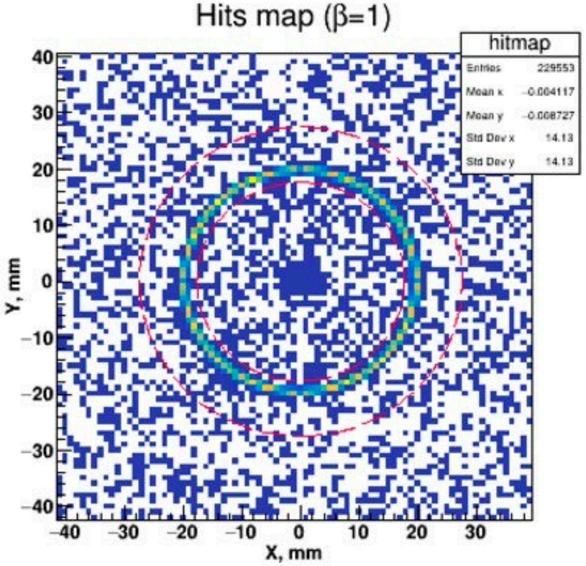
Chernkov photon number is determined by length, refractive index and transparency of fiber.

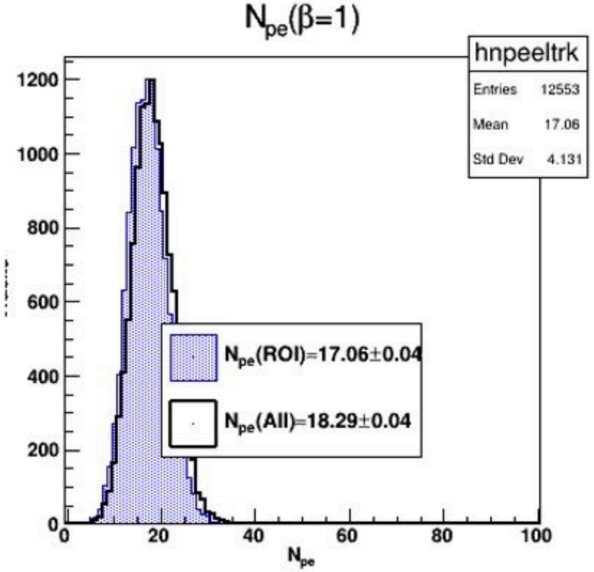


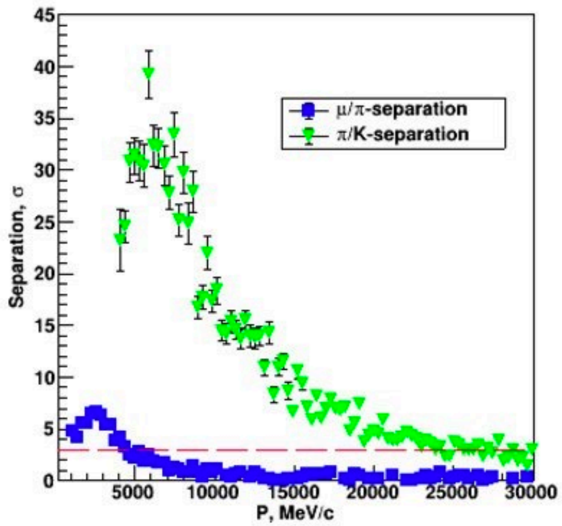
Single fiber params:

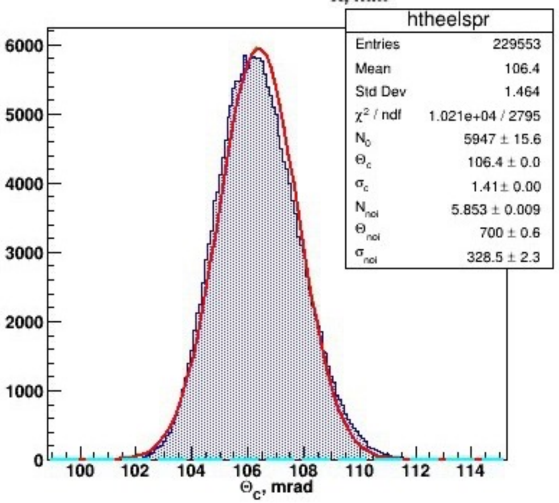
- n=1.008
- Length = 60 mm
- ø 0.4 mm

GEANT-4 results for aerogel fiber based RICH







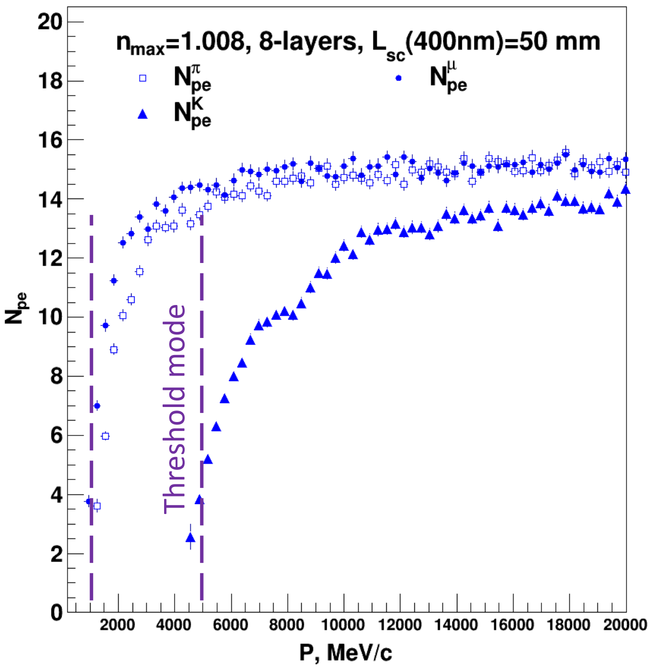


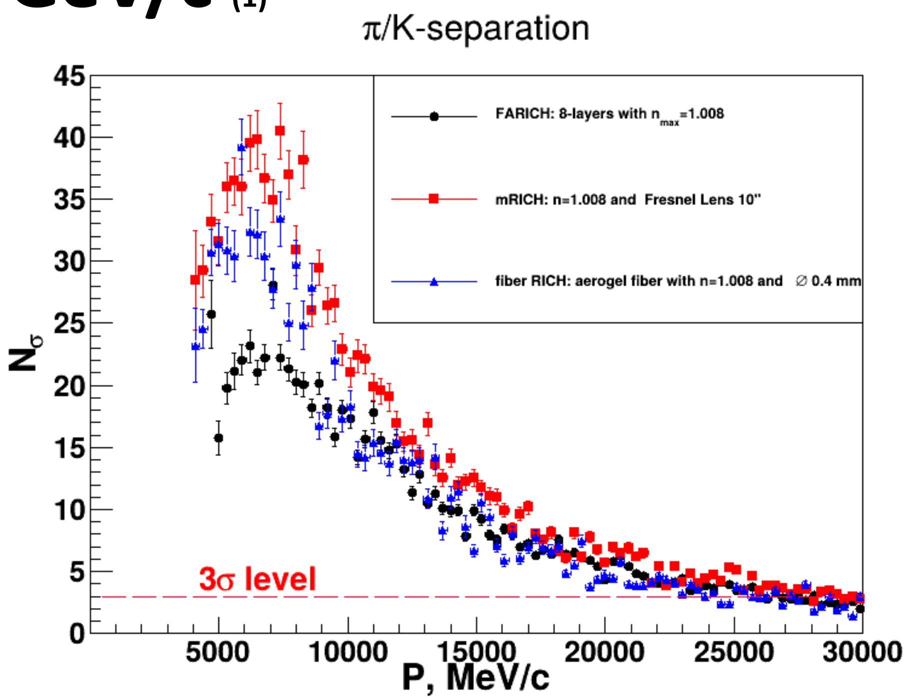
Phton Detector: σ_x ≈200µm; PDE(400nm)≈45% (Hamamtsu S14160)

Aerogel Fibra: $t = 6cm$; $n = 1.008$; $ø400µm$ (SINANO)

Summary

Comparison of three approaches for π/K–separation above 20 GeV/c (1)





- From 1 to 5 GeV/c $^{\pi}/_{K}$–separation in the aerogel counters with n=1.008 could be performed in ”Threshold” mode, above 5 GeV/c in “RICH” mode.
- Fine focusing of the Cherenkov light should be realized in the ssytem
- Spatial resolution of photn detector should be better than 0.3 mm

All three cnsidered options show us very attractive results.

Comparison of three approaches for π/K–separation above 20 GeV/c (2)

Three approaches to provide excelent π/K-separation at momentum range above 20 GeV/c are considered now. There are several common isuues like a position-sensetive photon detection and readout electronics and some specific issues in the future R&D.

R&D	mRICH	FARICH	Fiber RICH
AEROGEL	Simplest	Medium	Complex
Pos.-sens. PD	For all three options $\sigma_x \leq 0.3mm$, PDE(400nm) as high as possible, intrinsic noises as low as possible and good tolerance to magnetic field are required		
	$S_{PD} \leq S_{aer}$	$S_{PD} > S_{aer}$	$S_{PD} > S_{aer}$
R/O electronics	For all options FEE and DAQ could be the same, but number of channels for mRICH option is less than for other		
Additional optical elements	Acrylic FL	NO	NO
Tilted track	Orientation to IP	It works	Need to be stydied

Summary

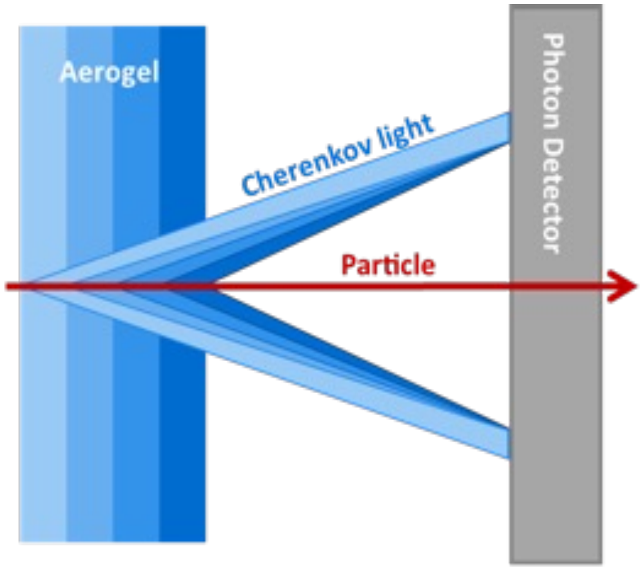
- It is not easy task to make RICH detector based on aerogel for π/K@30 GeV/c in colliding beam experiment, but it seems it is possible!!!
  - Three approaches were evaluated with help of GEANT4 simulation and exciting promising results were demonstrated:
    - FARICH approach: 8-layer focusing aerogel with n_{max}=1.008 –> 3 STDEV π/K@27 GeV/c
    - mRICH approach: thick (~6cm) aerogel with n=1.008 and FL(10”) –> 3 STDEV π/K@30 GeV/c
    - fibre RICH: aerogel fibres with n=1.008, L=6÷8 cm; ø200÷400μm –> 3 STDEV π/K@25 GeV/c
  - There are several approaches how to do photon detectors with spatial resolution better than several hundreds microns:
    - MCP PMTs which could be readout with help of delay lines or charge distribution lines
    - Position Sensitive SiPMs, where hit positions are reconstructed by calculation of charge shared among 4 readout pads
- The most expensive and important task is R&D for photon sensors and compatible R/O electronics.
- Some interesting R&D on aerogel fabrication (especially connected with aerogel fibres production and assemblage) are foreseen as well.

BACK UP SLIDES

FARICH motivation

- $\sigma_C^{tr} = {}^{1}/_{\sqrt{N_{pe}}} \cdot \sqrt{\left(\frac{\Delta_{pix} \cdot \cos\theta_C}{L \cdot \sqrt{12}}\right)^2 + \left(\frac{\sigma_n}{n \cdot \tan\theta_C}\right)^2 + \left(\frac{t \cdot \sin\theta_C}{L \cdot \sqrt{12}}\right)^2} \sim \sqrt{t}$
- $N_{pe}(\beta = 1) \sim 500 \cdot \frac{n^2 - 1}{n^2} \cdot t \cdot QE$

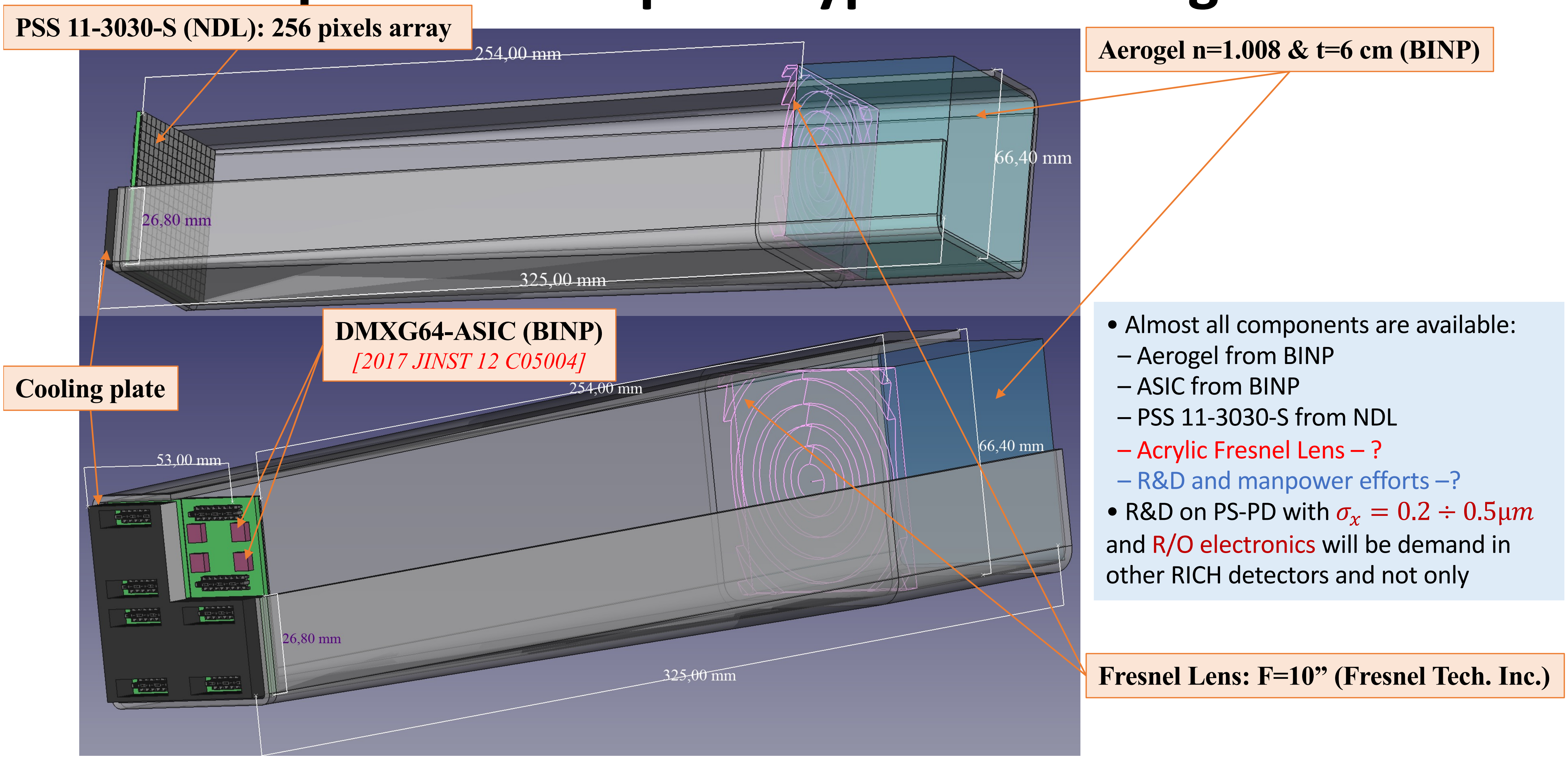
To get $\langle N_{pe} \rangle \gg 5$ from aerogel with n=1.05 & thickness 1 cm is too hard practice task!!!



- Thicknesses and refractive indexes in each layer are adjusted in such way that Cherenkov rings from each layer overlap in the same region of the position-sensitive photon detector.
- The number of detected Cherenkov photons increases due to increase of the thickness without degradation of Cherenkov angle resolution due to uncertainties of photon emission point.

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

Concept of mRICH prototype with aerogel n=1.008

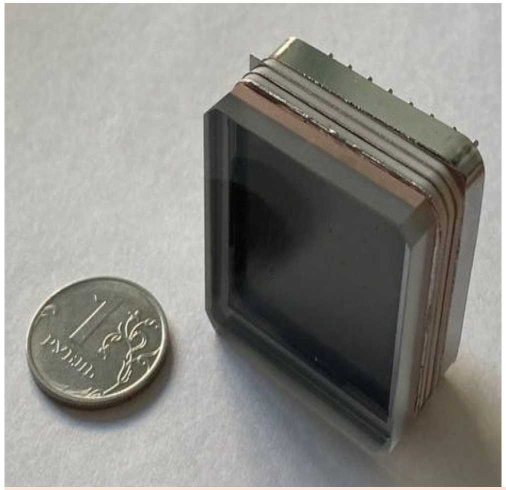


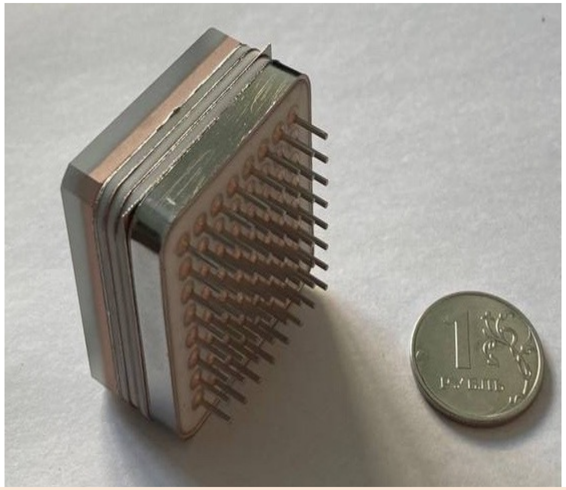
- Almost all components are available:
  - Aerogel from BINP
  - ASIC from BINP
  - PSS 11-3030-S from NDL
  - Acrylic Fresnel Lens – ?
  - R&D and manpower efforts –?
- R&D on PS-PD with $\sigma_x = 0.2 \div 0.5 \mu m$ and R/O electronics will be demand in other RICH detectors and not only

Status of MCP PMT development in Russia

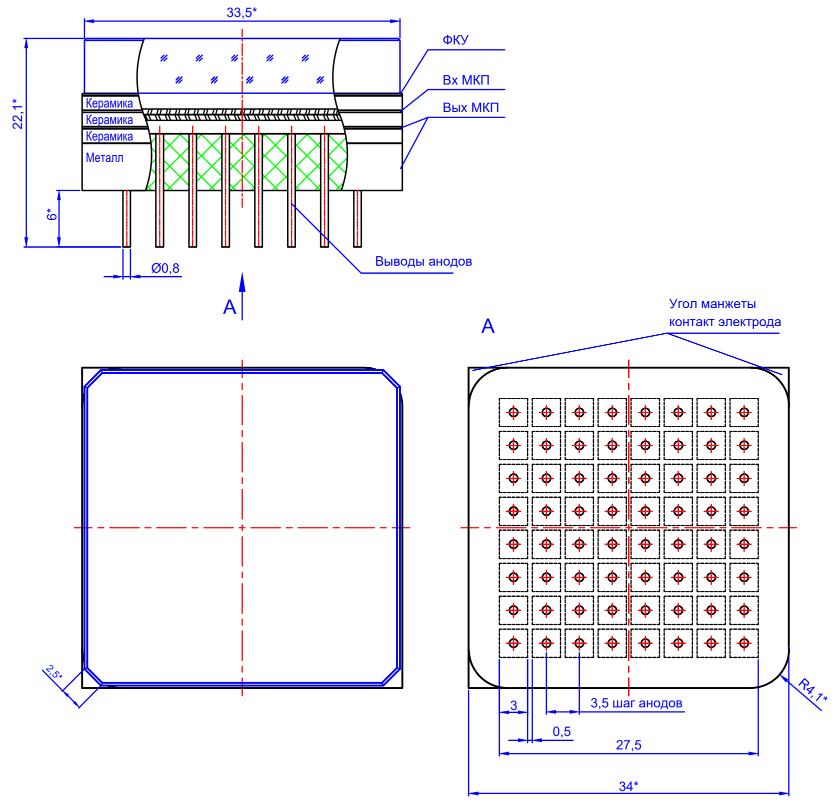
Square MCP PMT from “Ekran FEP”:

- Construction and design is developed
- All details and components are produced in Russia
- All technological processes are developed and realized





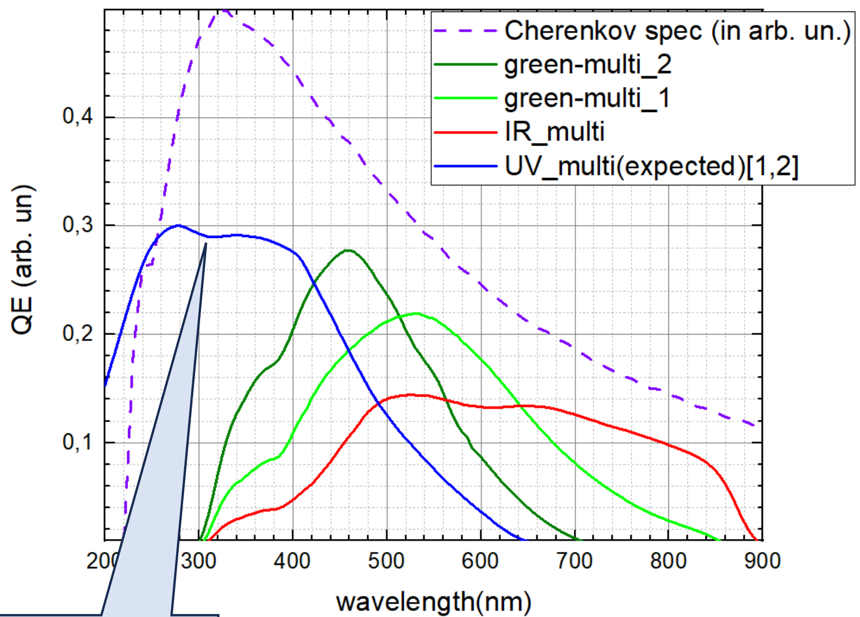
The first prototype fully asembled and vacume sealed prototype



* Размер для справок. Возможны незначительные изменения.

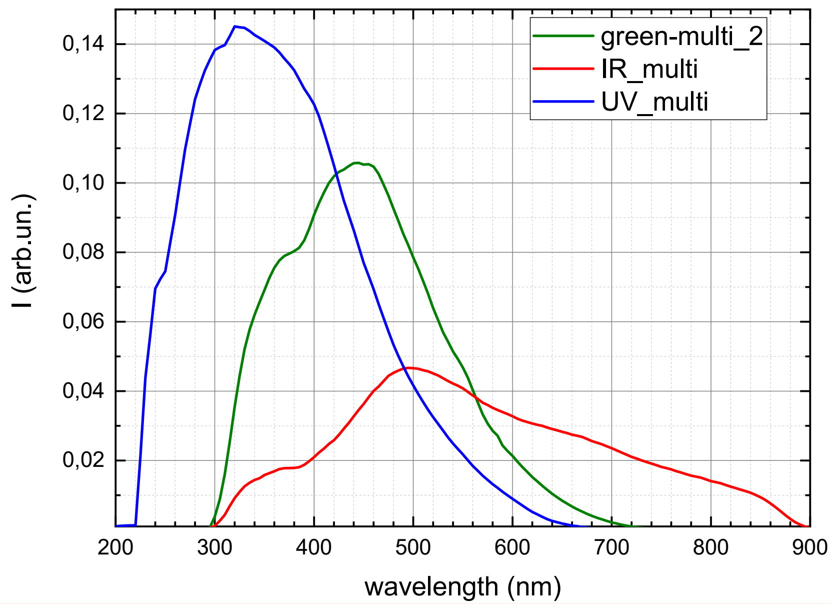
Photocathode options for “Ekran FEP” MCP PMTs

<u>Multi-alkali PCs</u> options and Cherenkov spectrum



It is planed to use <u>Quartz</u> to enhence PDE in UV region

<u>Productions</u> of Ch. Sp. with QE of Multi-alkali PCs



The advantages of use **<u>“UV_multi” PC (Quartz)</u>** are expected as following:

– **factor of 1.5** more detcted Cherenkov photonsin in comparison with standard “green-multi2” PC

– **factor of 2** in comparison with standard “IR_multi” PC

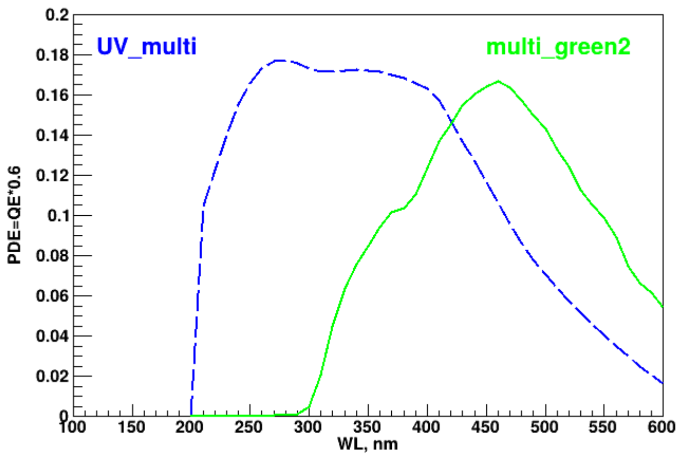
<u>“UV_multi” QE based on data from papers:</u>

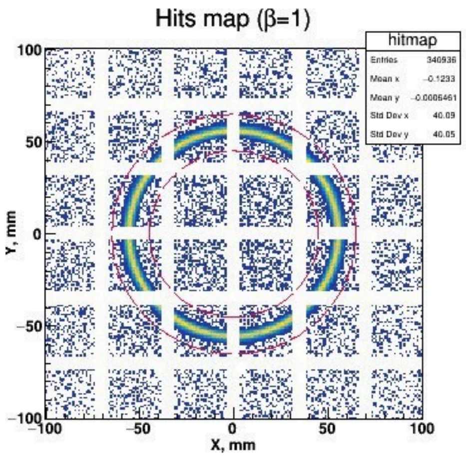
1. Orlov, D. A., et al., High quantum efficiency S-20 photocathodes in photon counting detectors. Journal of Instrumentation, 2016 11(04), C04015–C04015

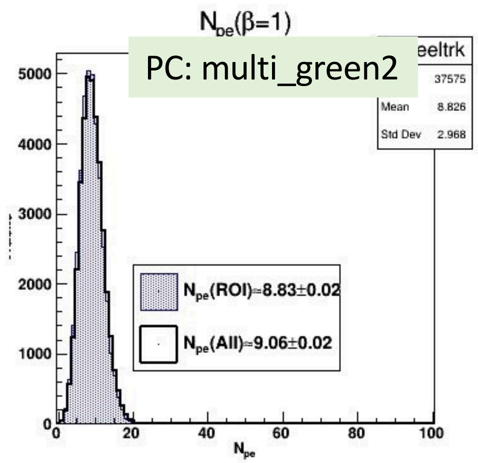
2. Milnes, J., et al., UV photocathodes for space detectors. Proceedings Volume 12181, Space Telescopes and Instrumentation 2022: Ultraviolet to Gamma Ray, 121813B (2022).

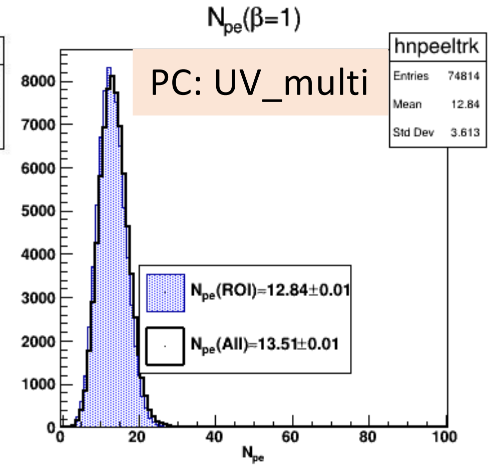
FARICH prototype based on MCP-PMT (Ekran FEP)

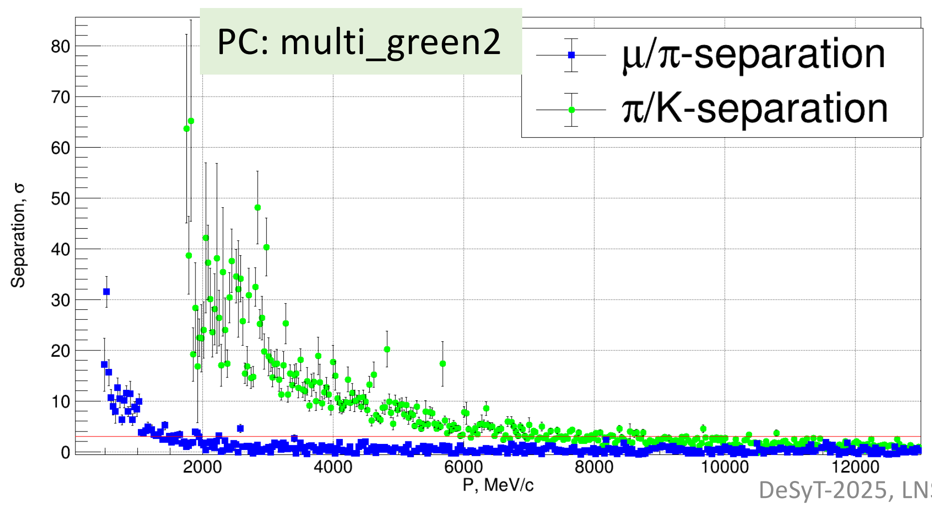
(expected performances: Geant4 simulation results)

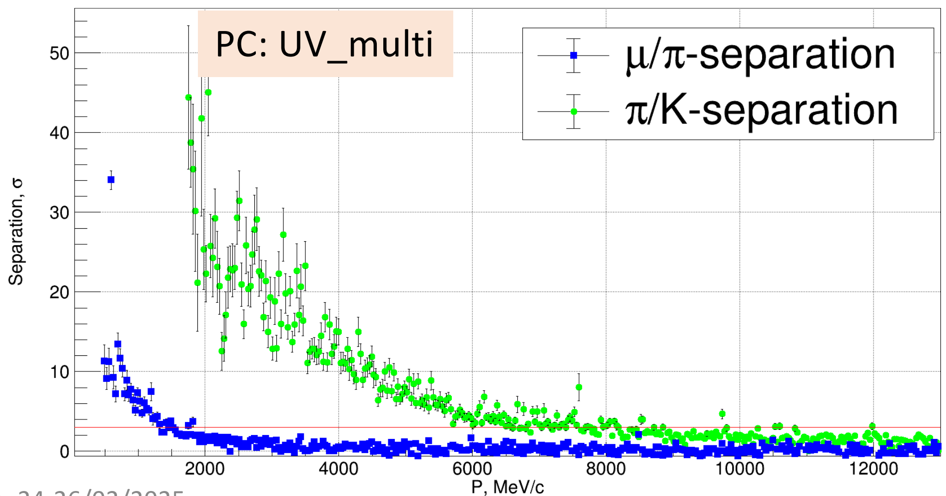






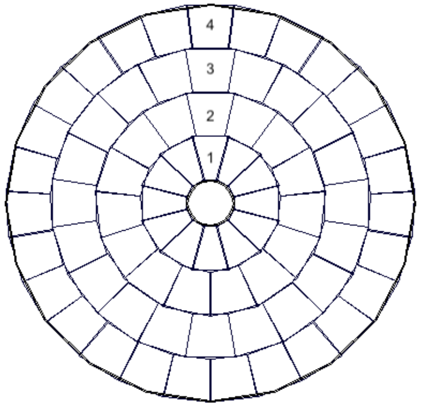






FARICH system concept for SPD-NICA

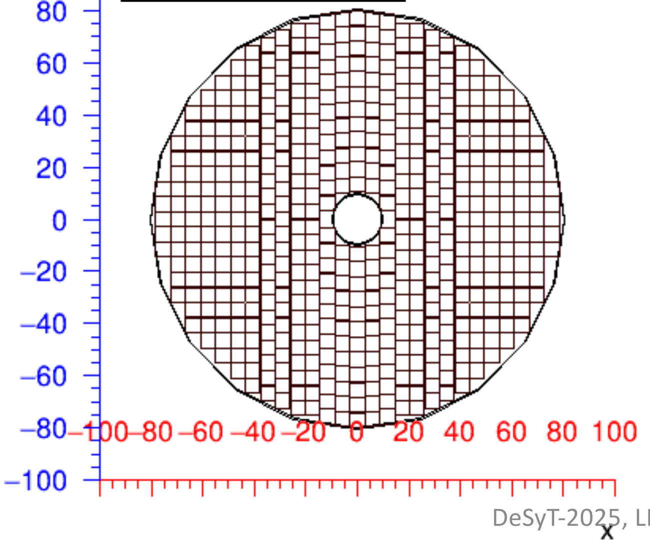
Aerogel:
74 tiles

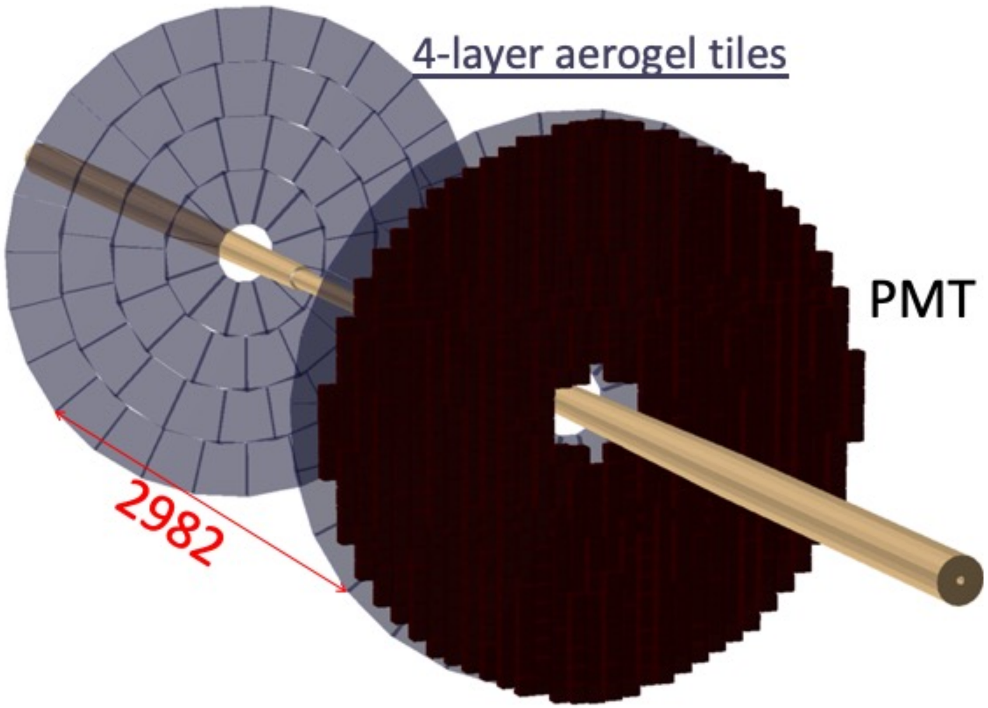


1 – 12 tiles x S=0.5•(5.6 + 15.6)•18.5 = 159.0 sq.cm
2 – 15 tiles x S=0.5•(12.2+20.2)•18.5 = 299.7 sq.cm
3 – 20 tiles x S=0.5•(15.0+20.8)•18.5 = 331.15 sq.cm
4 – 27 tiles x S=0.5•(15.2+19.6)•18.5 = 321.9 sq.cm

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

Photon detector: 548 PMT 51x51 mm



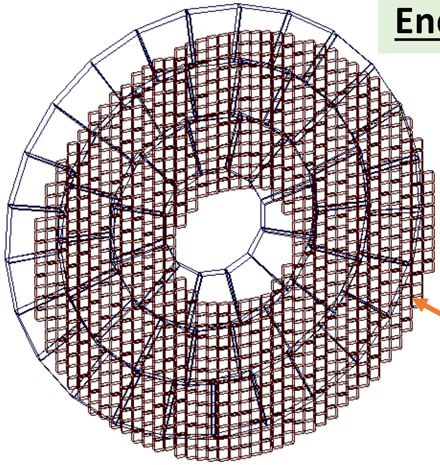


FARICH system:

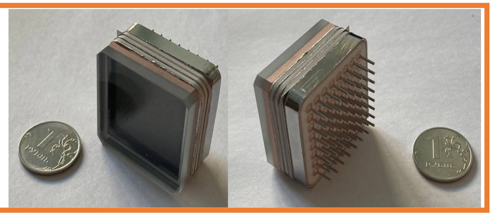
- 4-layer aerogel with n_{max}=1.05 (or less)
- Focus distance – 20 cm
- PS PD – MCP-PMT or SiPM arrays with pixel 3÷6 mm
  550 PMTs per endcap if lateral sizes ~51x51 mm
  2200 PMTs per endcap if lateral sizes ~27x27 mm

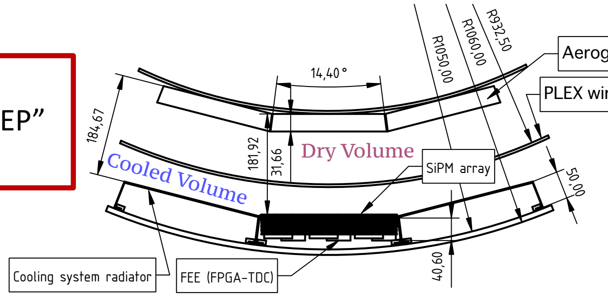
FARICH system concept for the SCTF project

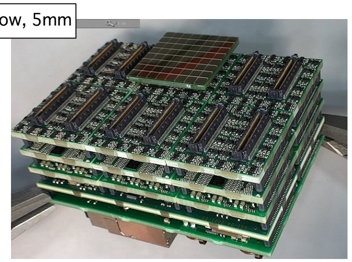
Endcap part Sketchs & key elements



- 2x55 trapezoidal aerogel tiles in end caps:
- 2x1000 MCP PMTs 34x34mm^2 from “Ekran FEP”
- MCP PMTs can operate without cooling

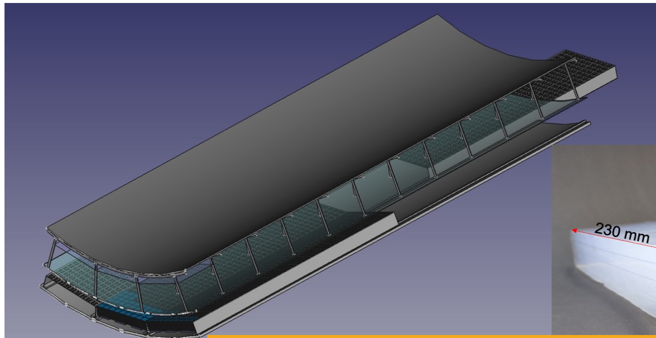


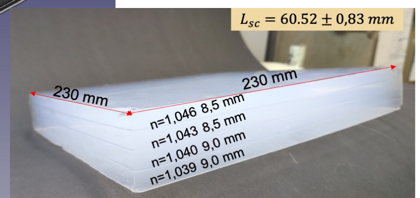




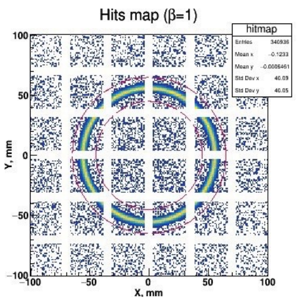
The first square MCP PMT produced in Russia:

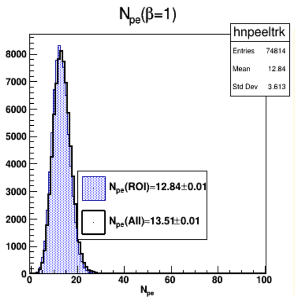
- All details and components are produced in Russia
- First samples for test will be available until the end of 2024

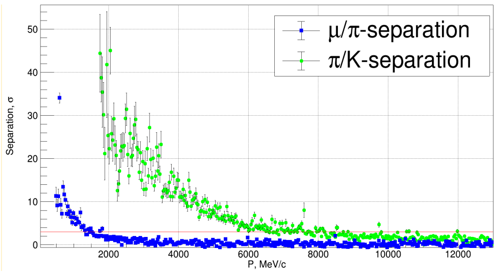




Expected system parameters (obtained in G4 simulation)







Barrel part Sketchs & key elements

- 275 aerogel tiles 200x202x35 in barrel part
- only SiPM will operate in magnetic field
- effective cooling system is required