Аэрогелевые черенковские счетчики для современных и будущих экспериментов по физике частиц

А.Ю. Барняков от имени «Аэрогелевой группы» ИЯФ – ИК СО РАН

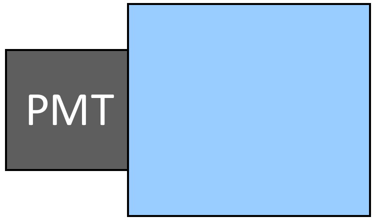
- **π/K–разделение до P=3 ГэВ/c или пороговые аэрогелевые черенковские счетчики:**
  - АШИФ для КЕДР (ВЭПП-4М) и СНД (ВЭПП-2000) в ИЯФ СО РАН
  - АШИФ для SPD (NICA, ОИЯИ)
  - АШИФ для STCF (USTC, Hefei)
- **π/K–разделение до P=6 ГэВ/c и μ/π–разделение до P=1.5 ГэВ/c:**
  - FARICH для SPD (NICA, ОИЯИ)
  - FARICH для SCTF (НЦФМ, г. Саров)
- **π/K–разделение при P≥25 ГэВ/c:**
  - RICH на аэрогеле с n=1.008 для CEPC (China) и/или FCCee (CERN)

Научная сессия-конференция СЯФ ОФН РАН 2025,

17-21 февраля 2025г., РАН, г. Москва

Threshold Cherenkov counters

Direct light collection

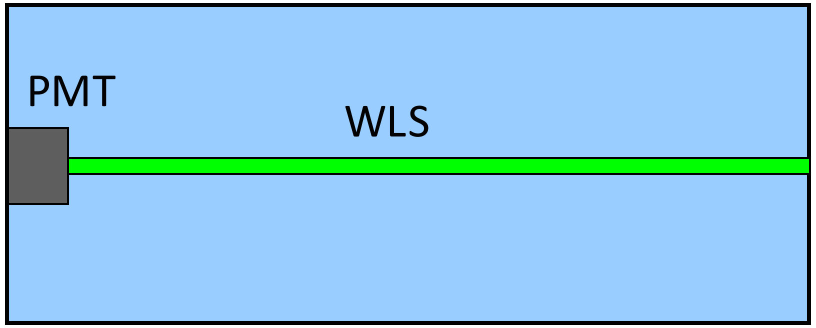


Pro: Simplicity

Con: Counter size limited → large PMT number&area → high total cost

ASHIPH – Aerogel-SHIfter-PHotomultiplier

Suggested by A.Onuchin et al. for PID of the KEDR detector [NIM A315 (1992) 517]



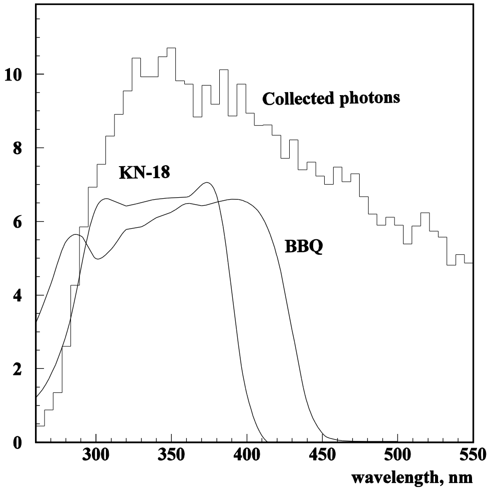
Pros:

- Large light collection area
- Small PMT (up to 10x smaller p.c. area in comparison with direct LC)
- Low cost

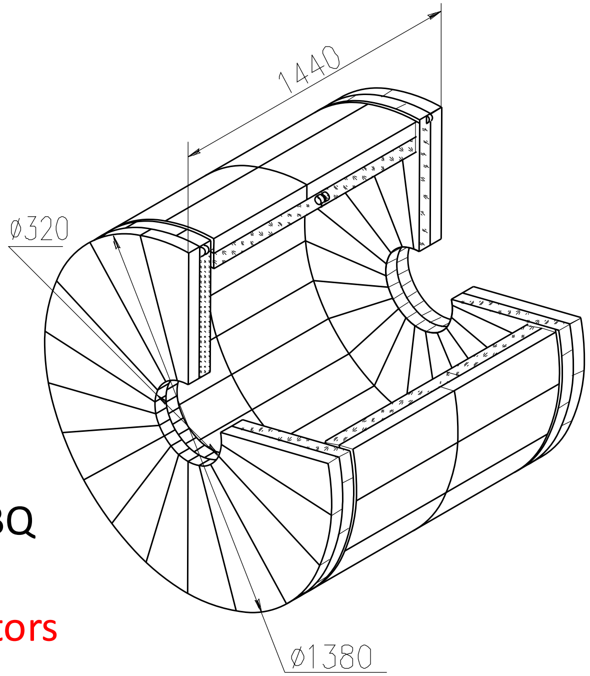
Cons:

- Particle acceptance loss due to WLS

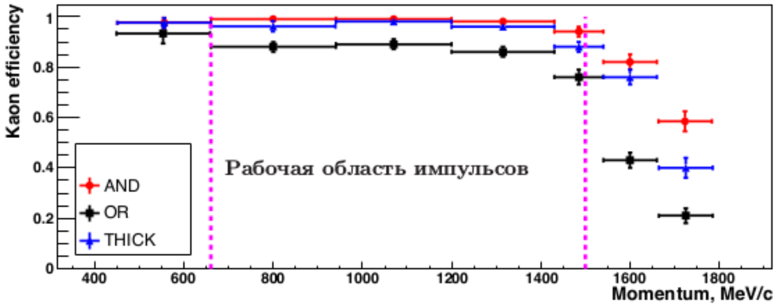
ASHIPH technique at e^+e^- collider experiments

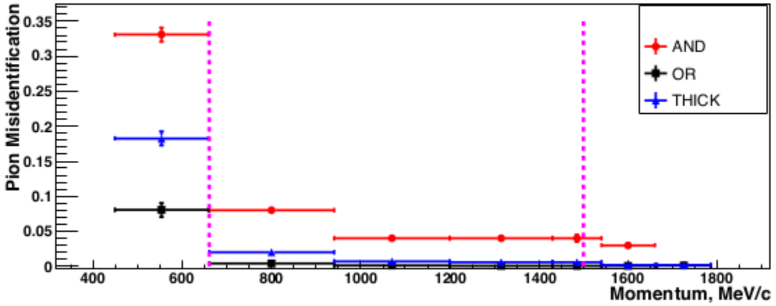


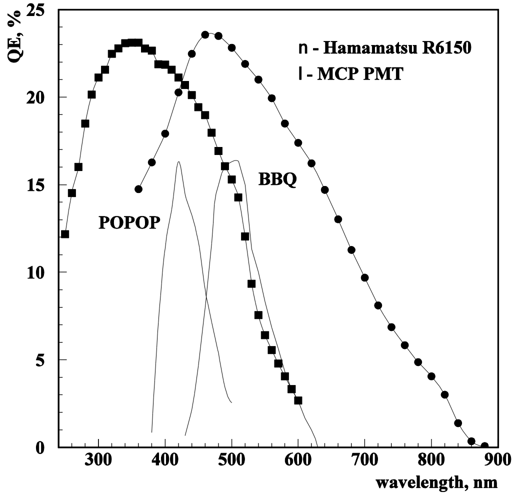
- PMMA light guide doped with BBQ dye is used as wavelength shifter
- MCP PMTs are used as Ph. detectors



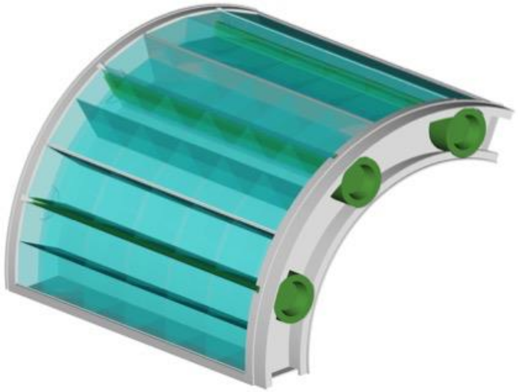
KEDR:
- 160 counters (2 layers)
- n=1.05 (1000l)
- WLS (BBQ)
- MCP PMT øPC=18 mm
- 0.97x4π
- 24% X_0

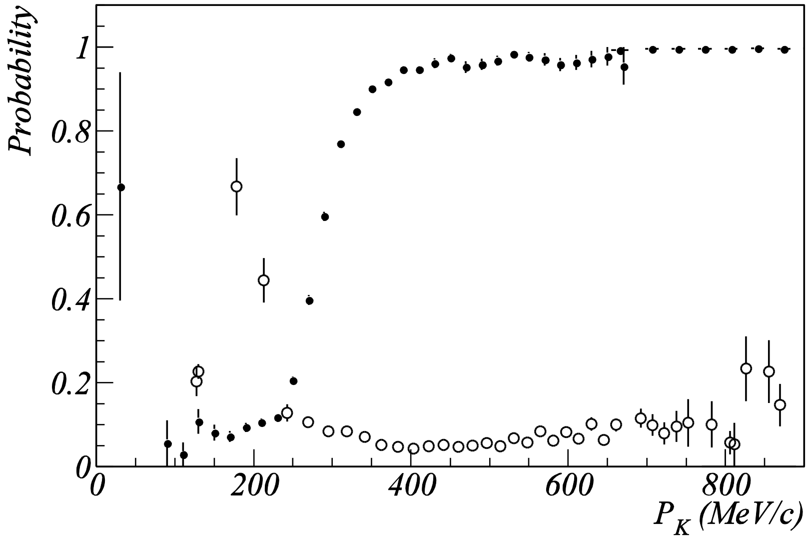






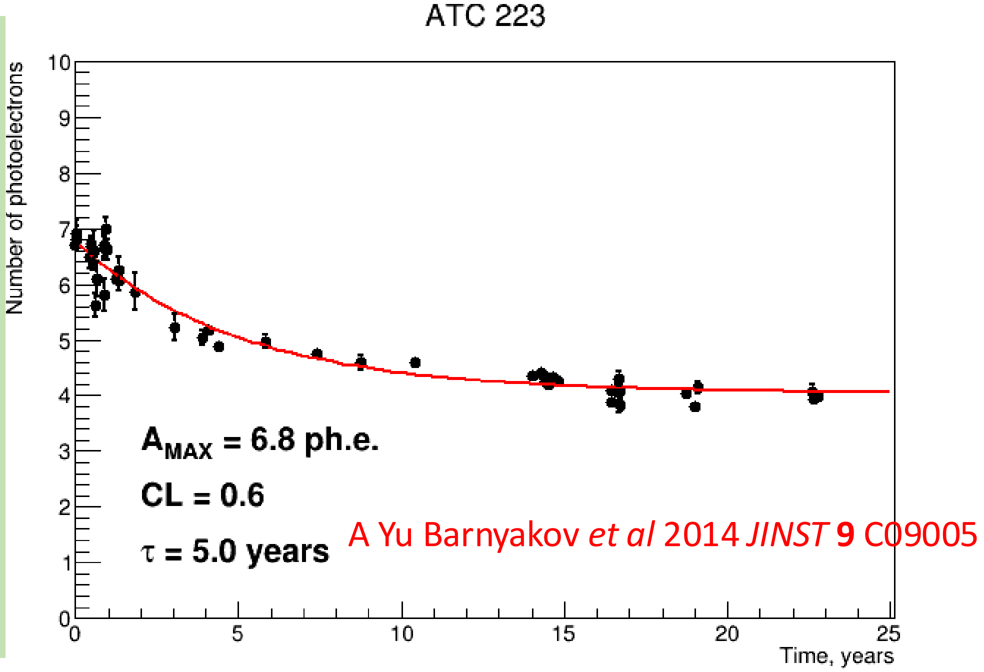
SND:
- 9 counters (1 layer)
- n=1.13 (9l)
- WLS (BBQ)
- Thickness ~ 30 mm
- MCP PMT øPC=18 mm
- 0.6x4π





Долговременная стабильность счетчиков АШИФ

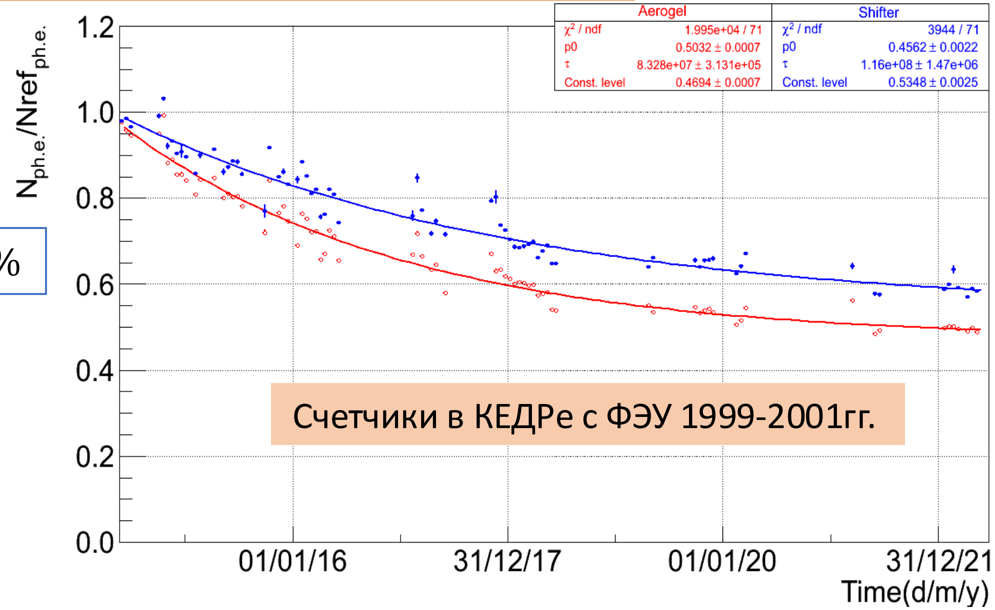
Прототип АШИФ счетчика КЕДРа, испытанные в Дубне в 2000г.



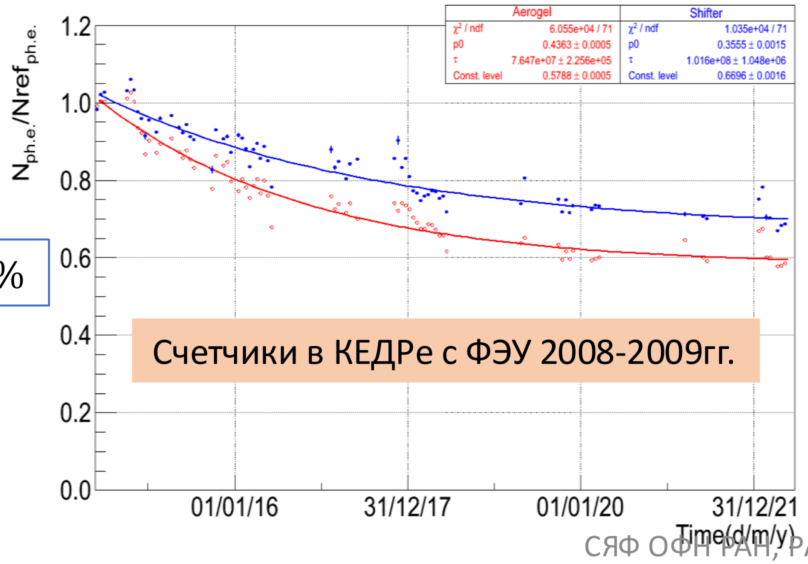
A Yu Barnyakov *et al* 2014 *JINST* **9** C09005

Счетчики АШИФ КЕДРа, в эксперименте с 2014г.

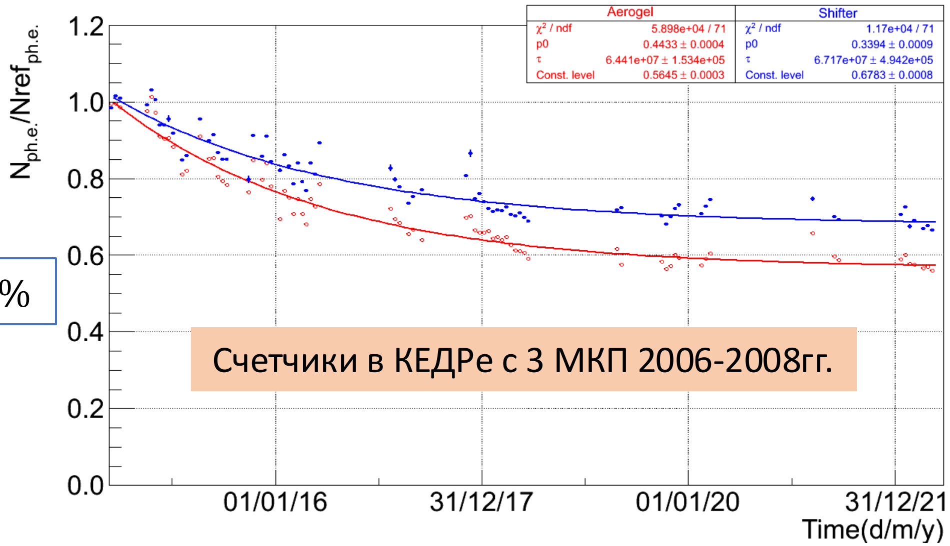
$\delta QE(500\text{нм}) \approx 40\%$



$\delta QE(500\text{нм}) \approx 32\%$



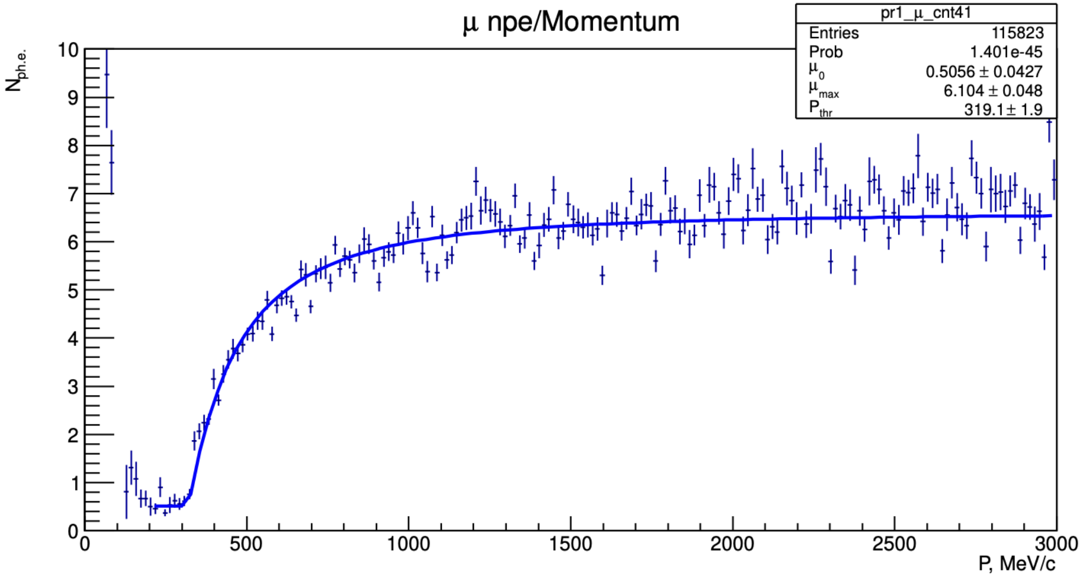
$\delta QE(500\text{нм}) \approx 33\%$



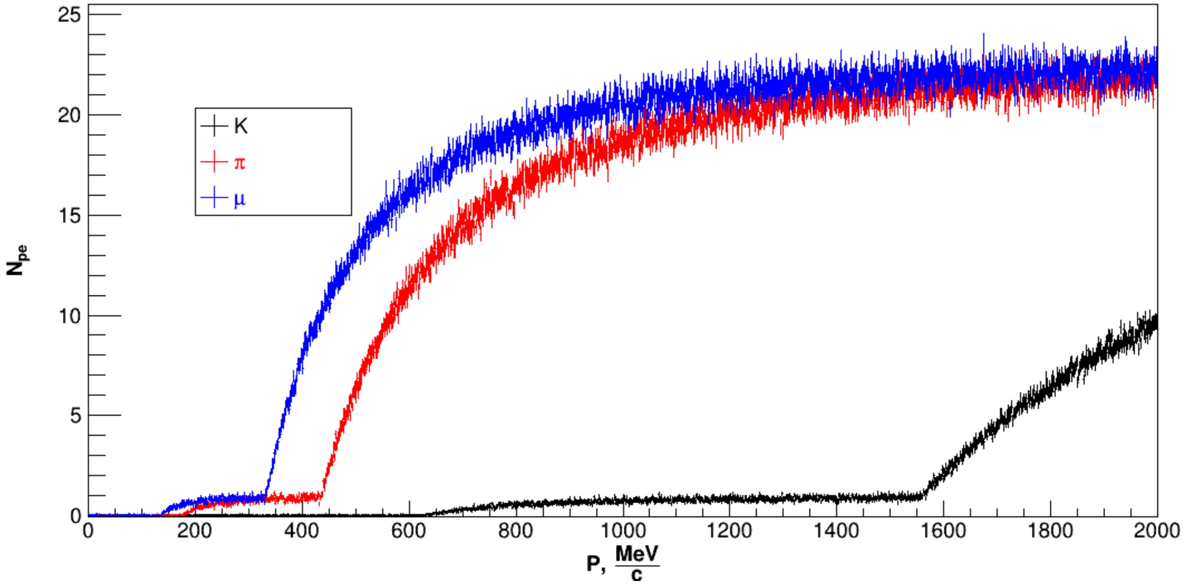
ASHIPH method upgrade: motivations and expectations

MCP PMT → SiPM
Gives increase of amp.
by 2÷2.5 times

KEDR experimental data



STCF proj. param. sim.



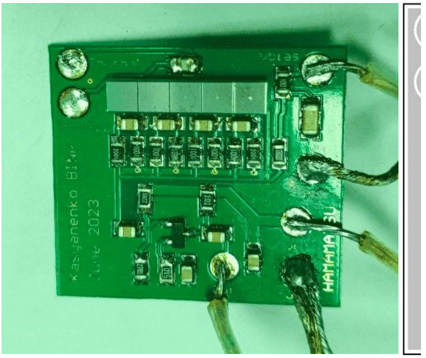
For future collidung beam experiments with high intesity interaction
high operational rate of the detector subsystems is required:
for future Super Charm-Tau factory time between two bunch-crossing about 6 ns is expected!!!

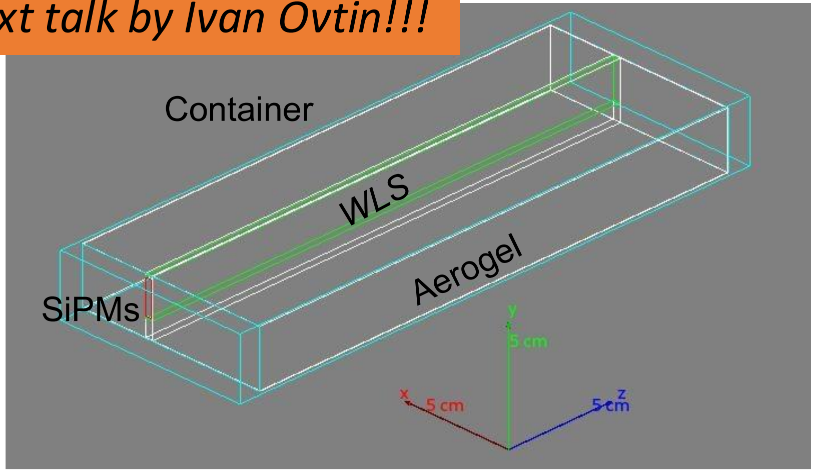
WLS(BBQ)→ WLS(NOL-1…13)

$\sigma_t(old) \approx 17ns \rightarrow \sigma_t(new) \approx 0.5 \div 1ns$ is expected!!!

Upgrade of SND-ASHIPH system

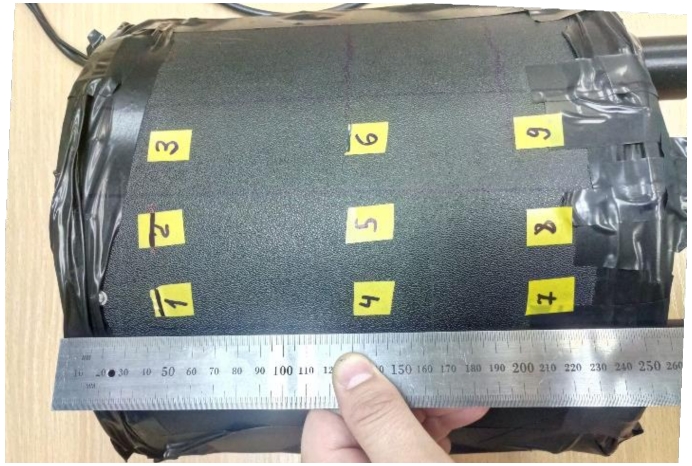
More details in next talk by Ivan Ovtin!!!



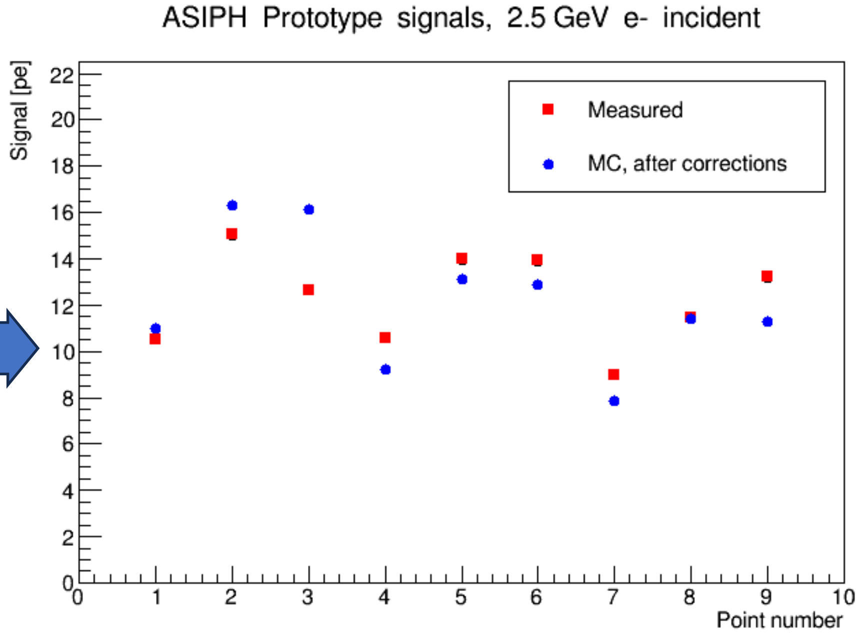


The simulated prototype:

SND ASHIPH counter was upgraded and tested with relativistic electrons (2.5 GeV) at the BINP beam test facilities.

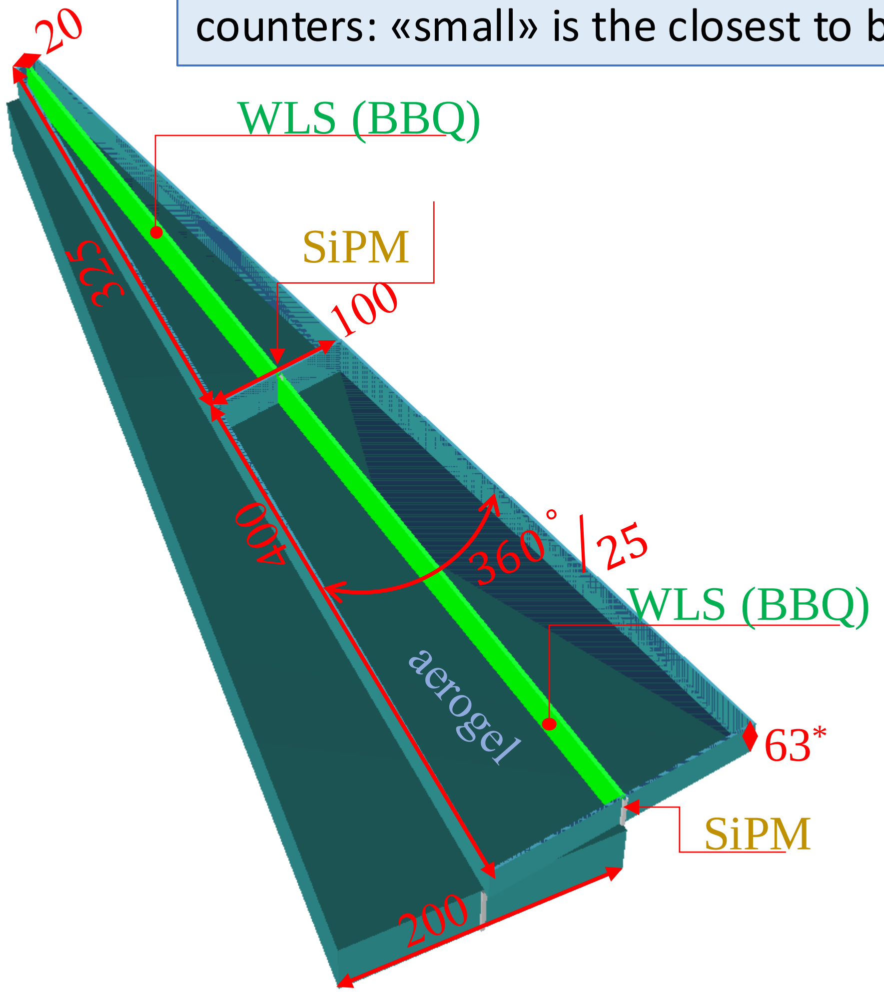


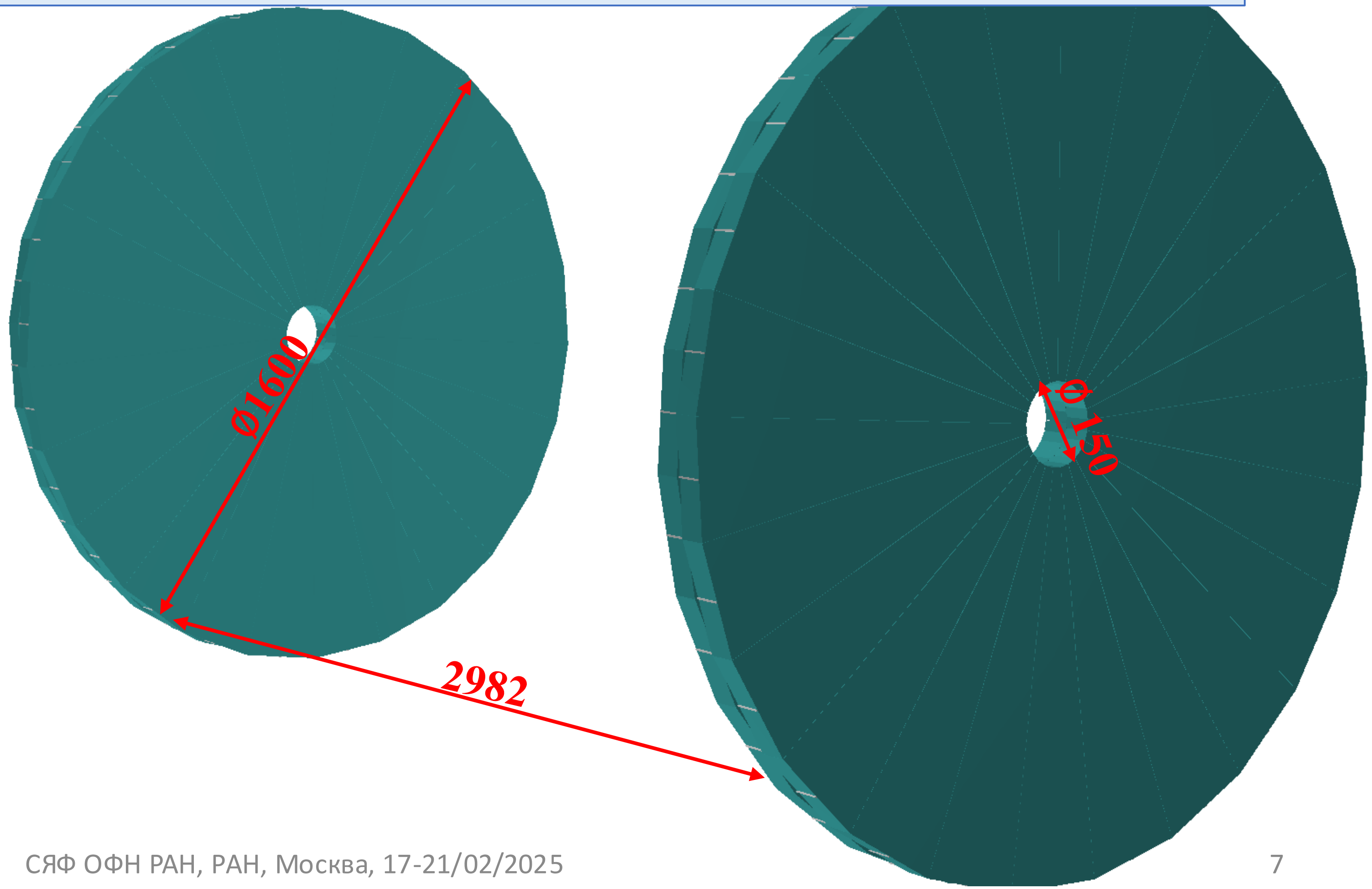
- Beam test results and GENT4 simulation are in good agreement
- Expected effect of Amp. increas is demonstrated!!!



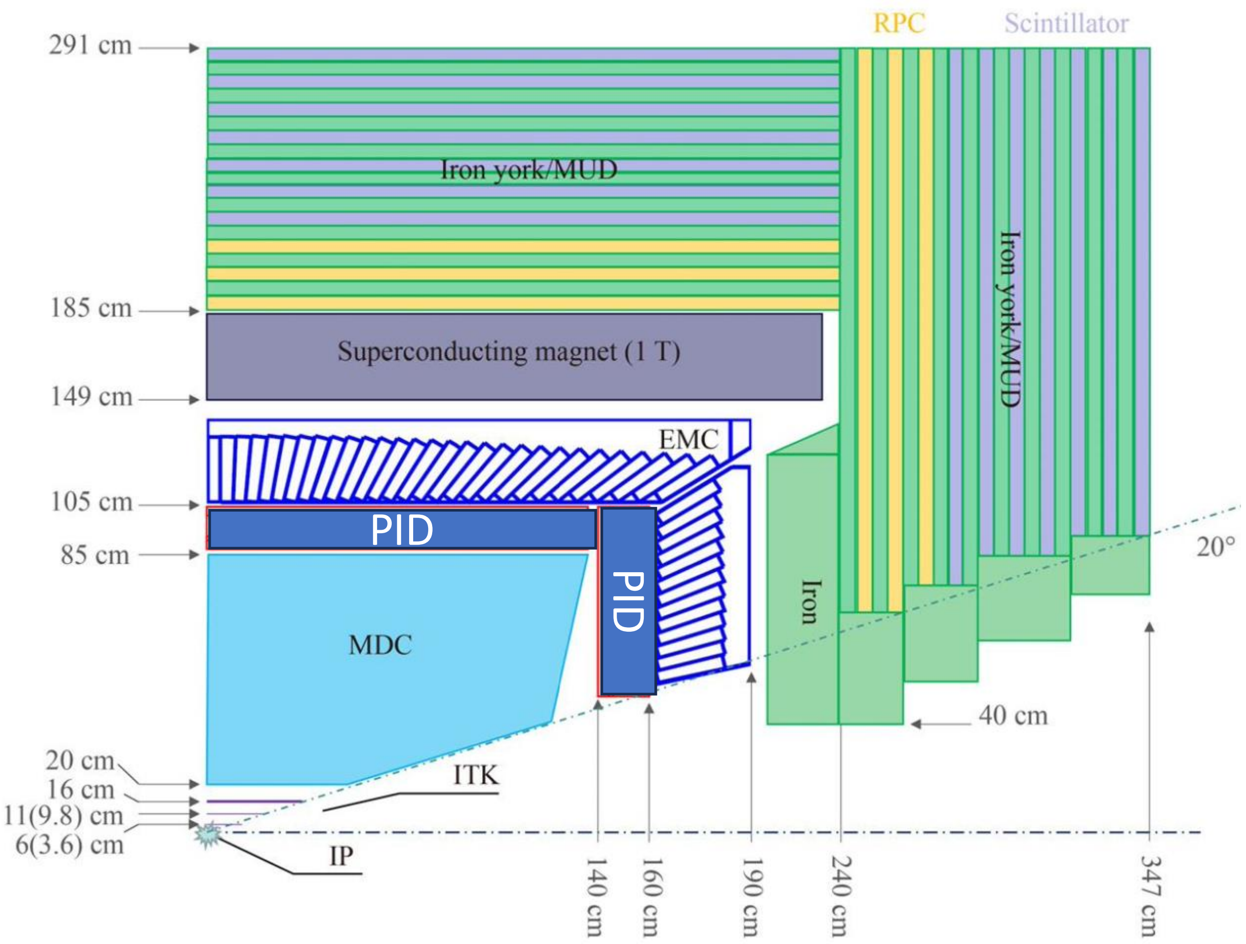
ASHIPH system proposal for SPD-NICA

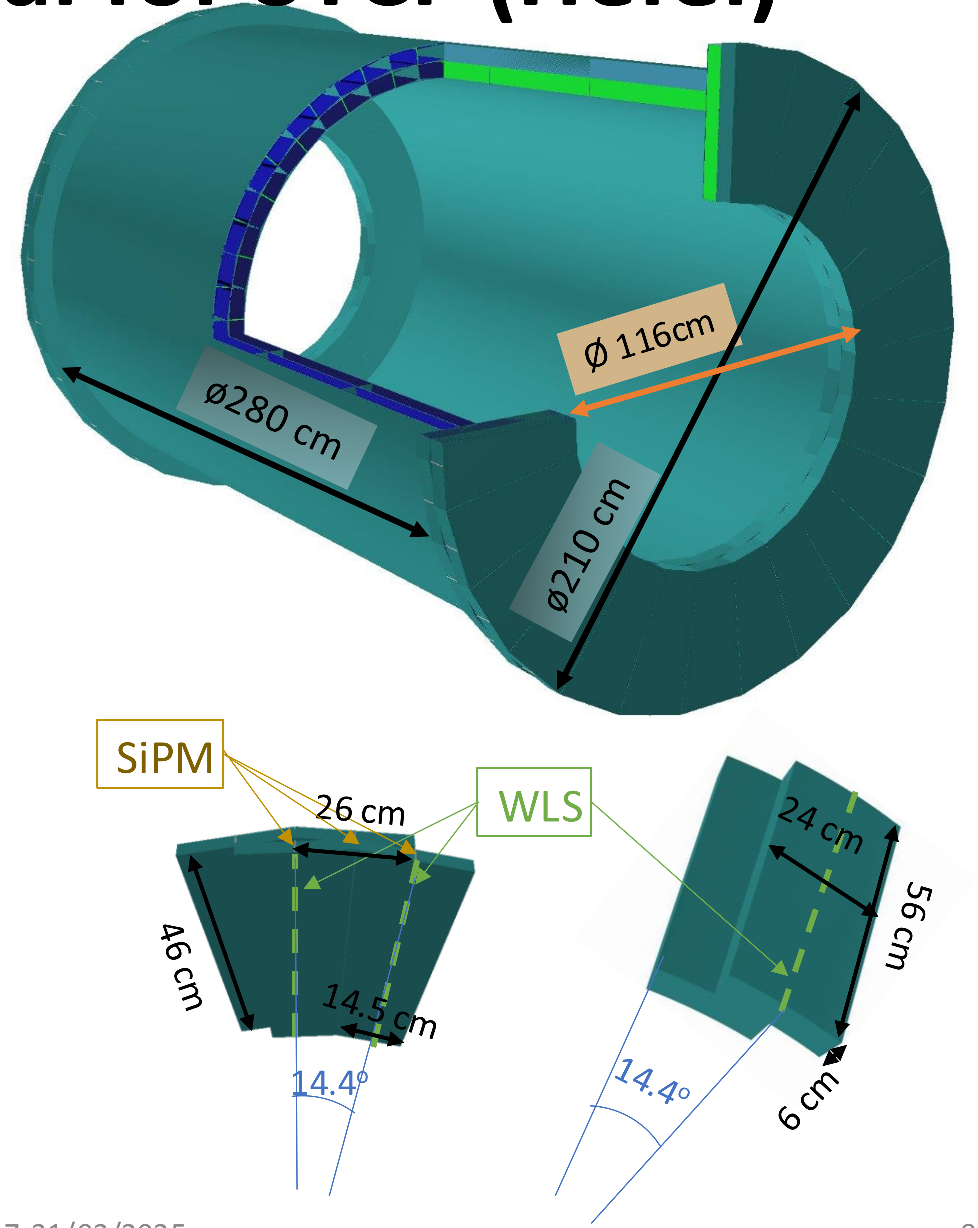
- 2 endcaps with 2 layer per each
- Each endcap formed by 25 sectors (trapezoidal shapes)
- Each layer is shifted by φ one from another at half of period: $^{360^\circ}/_{25 \bullet 2}$
- Each sector is divided by two segments along radius of the system to form two light separated counters: «small» is the closest to beam-pipe and «large» at the far distance from the beam-pipe



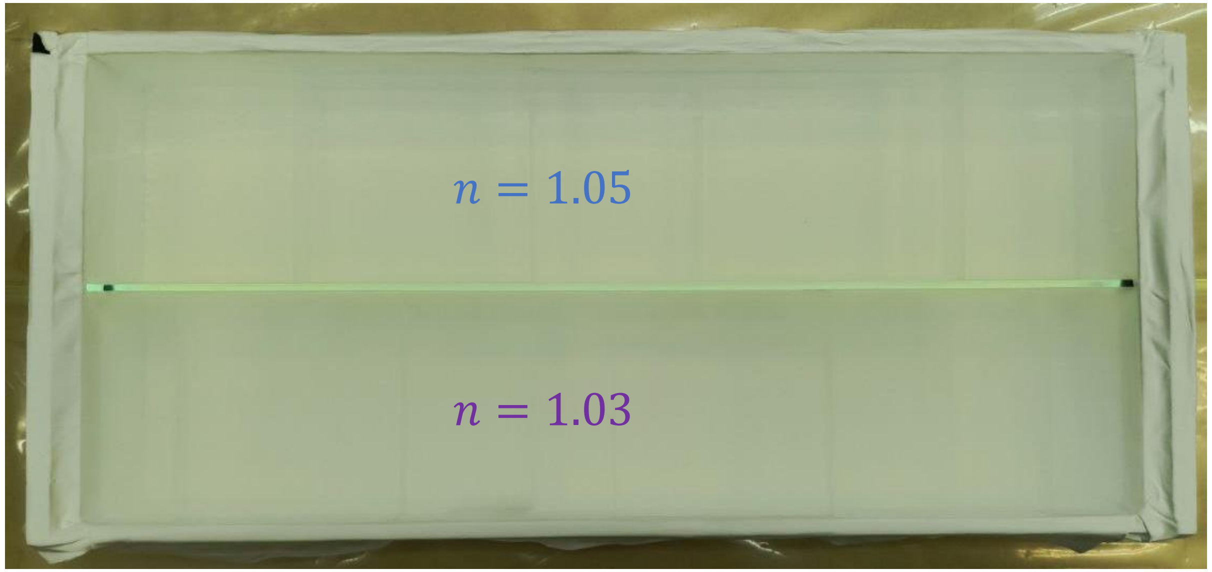


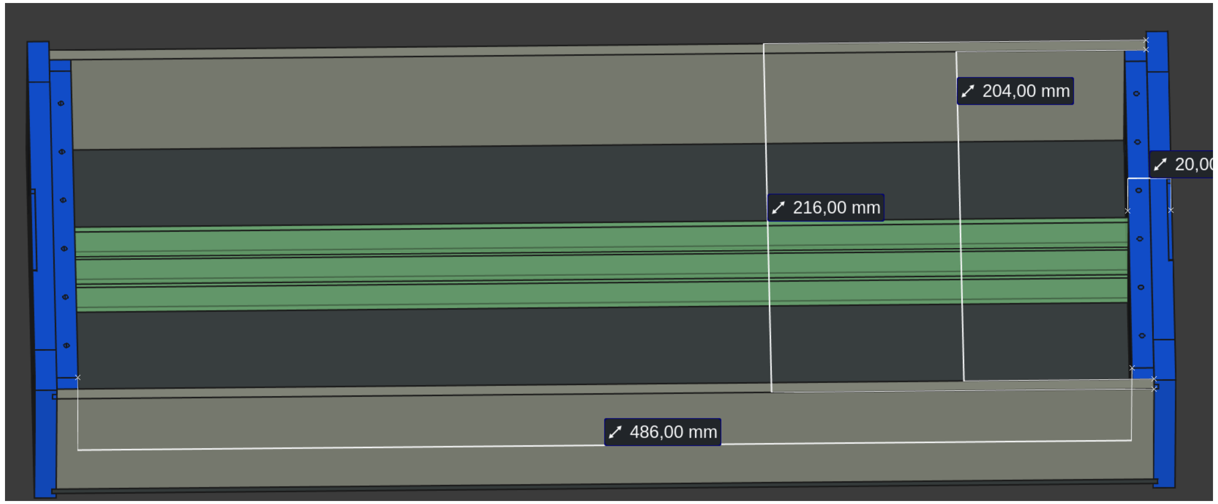
ASHIPH system proposal for STCF (Hefei)





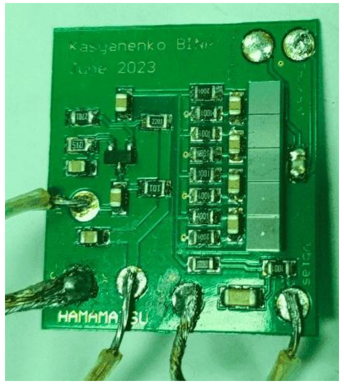
Design of ASHIPH prototype





Main goals:

- To test light collection uniformity
- To test and chose WLS dye:
  - BBQ (τ=15 ns)
  - NOL-14 (τ=0.74 ns)
- To test and chose SiPMs
  - Hamamatsu
  - NDL
  - JoinBon and …
- To test and develop FEE
- To test π/K-separation and chose aerogel



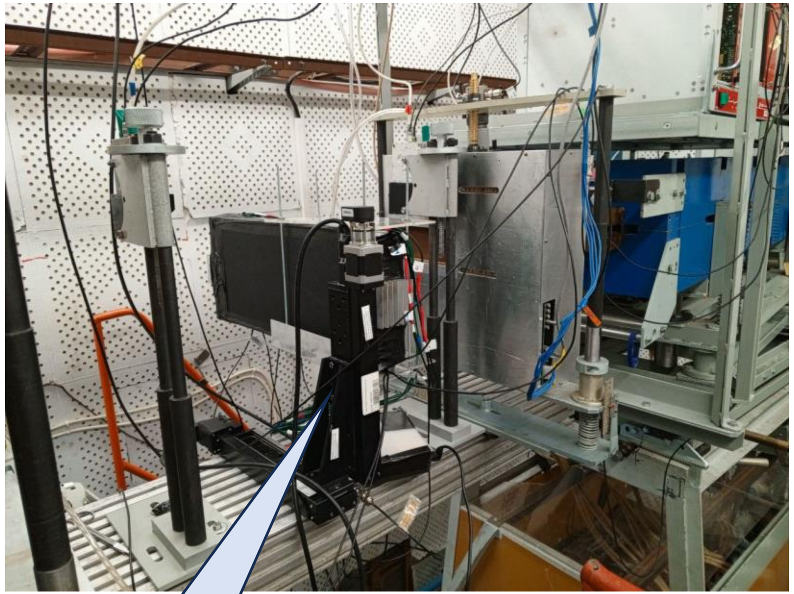
- 3 arrays 5 SiPMs each were made from MPPC S13365-3050NE-16 (Hamamtsu)
- 3 channels of V1742 (CAEN) degitizer will be used to readout

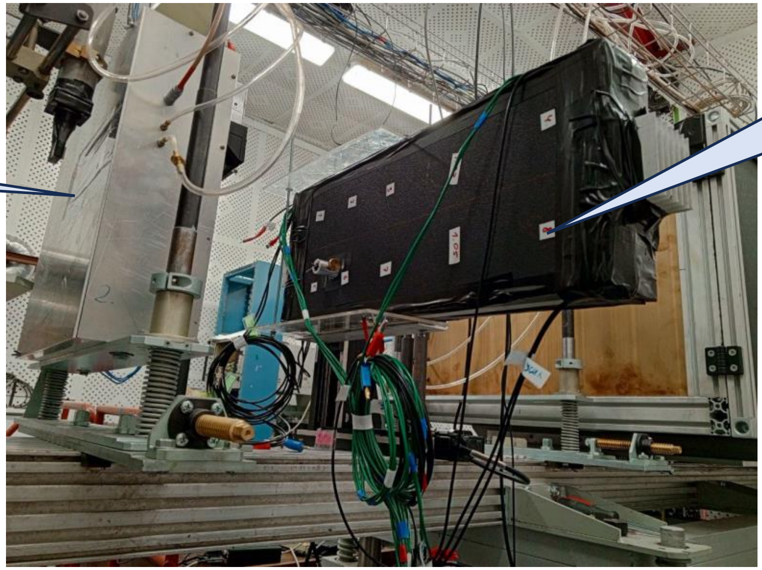
ASHIPH prototype at the BINP test beamline

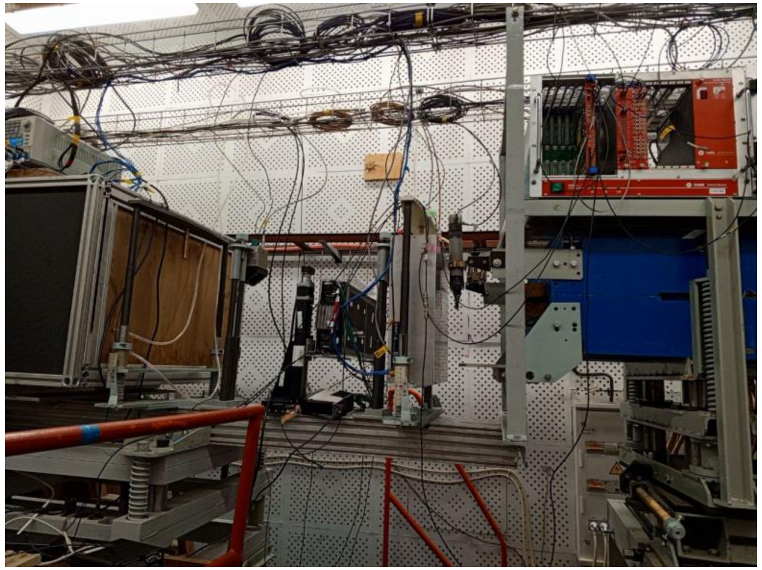
Tracker based on GEM $\sigma_{x,y} = 50\mu m$

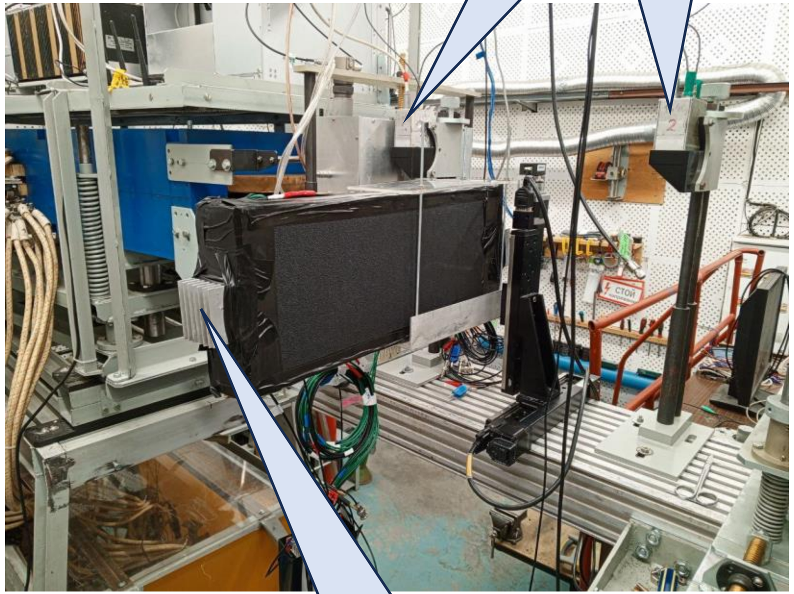
ASHIPH prototype and points for beam crossing

Trigger counters based on MCP PMT







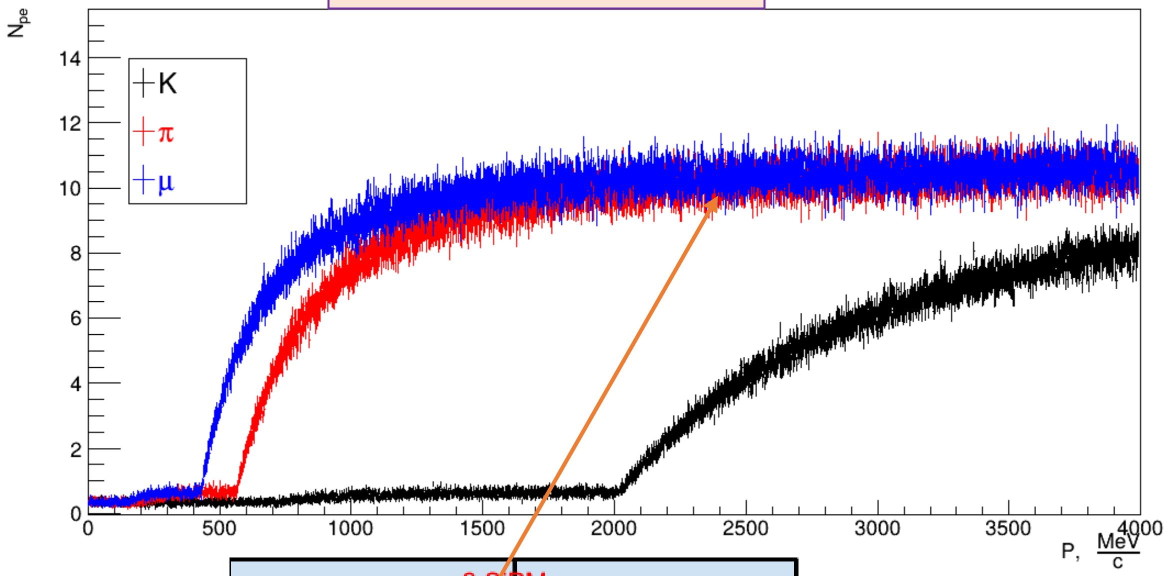


2D mover to scan Light collection uniformity

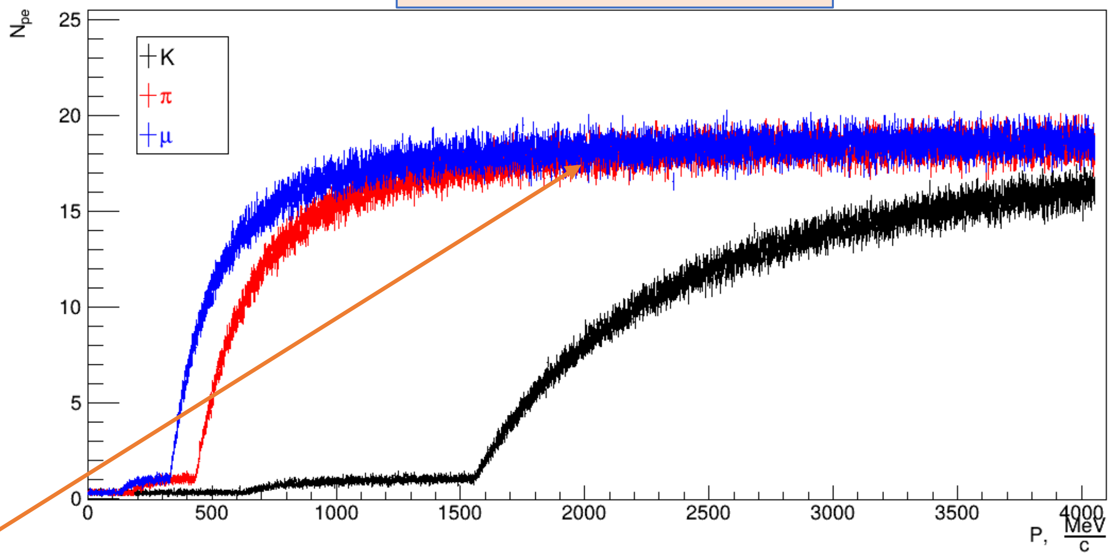
Radiator for SiPM cooling and thermostabilization

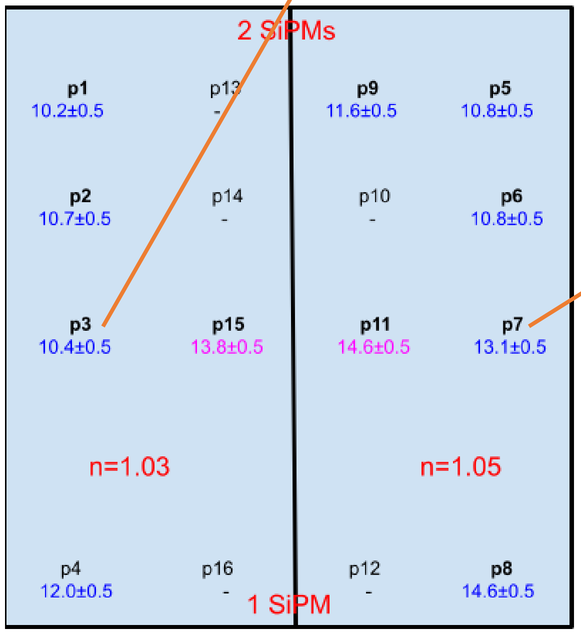
Expected and measured performances of the ASHIPH-SiPM prototype

Aerogel with n=1.03



Aerogel with n=1.05



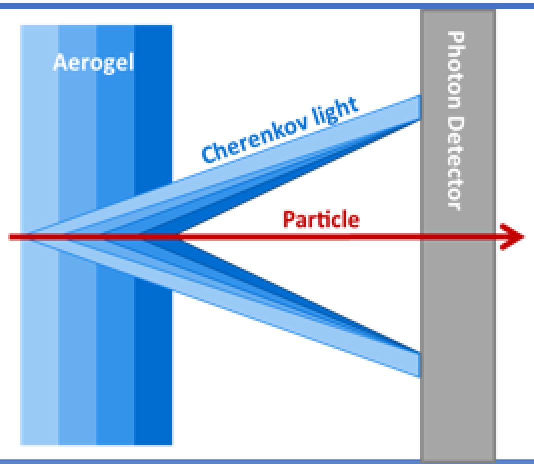


- Good agreement between measurements and estimations for relativistic particles is demonstrated with aerogel n=1.03
- Some disagreement with aerogel n=1.05 could be explained by worse aerogel optical parameters which could be improved soon

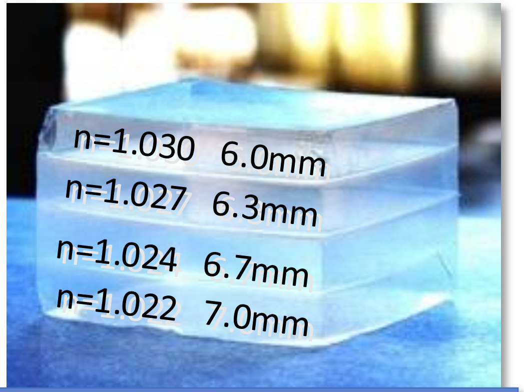
Summary:

- π/K up to P=2 GeV/c with n=1.05 & threshold ~7pe is possible
- π/K up to P=3 GeV/c with n=1.03 & threshold ~7pe is possible

FARICH technique milestones



The first 4-layer monolithic sample

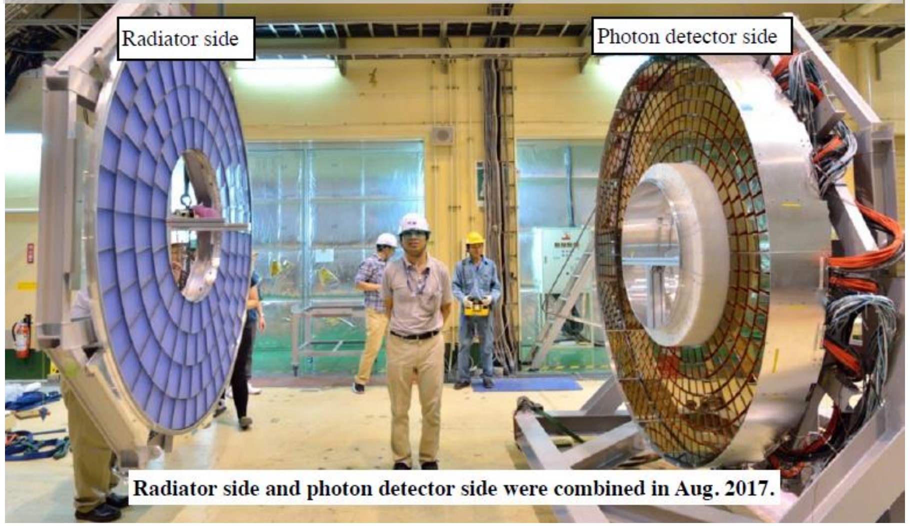


Increase N_{pe} due thickness increase without $\sigma_{\Theta c}$ degradation

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

2004÷2005

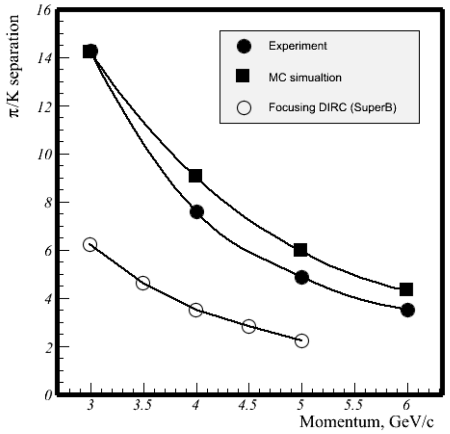
The Belle II (ARICH) is the first application of the method

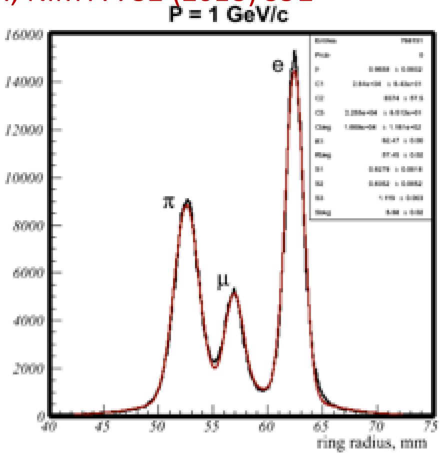


2017

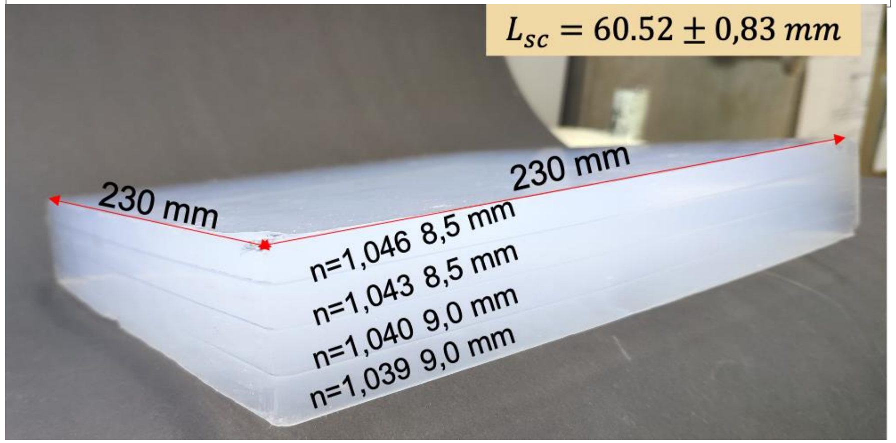
Excellent PID capability were shown at CERN beam test in 2012

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



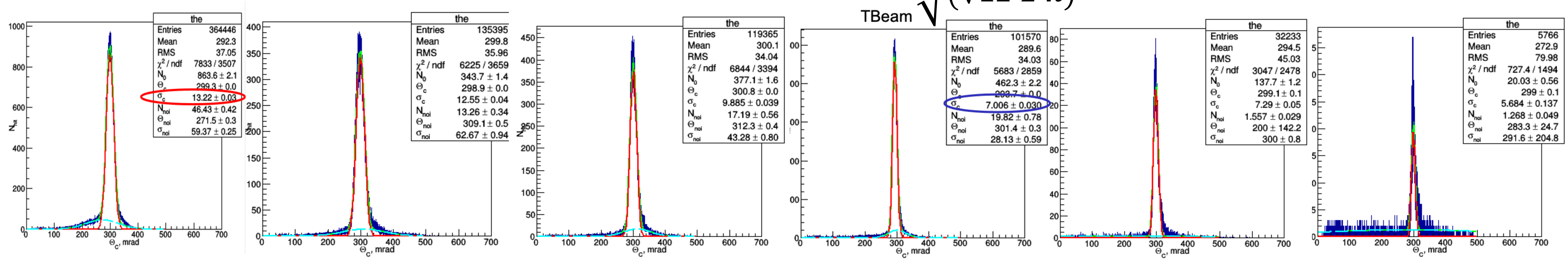


Two 4-layer focusing aerogel blocks
230x230x35 mm

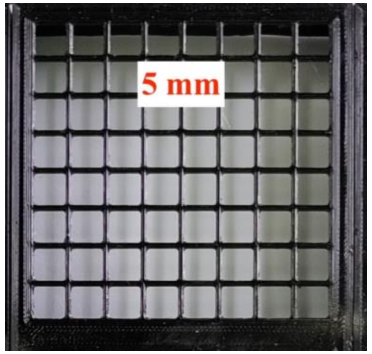


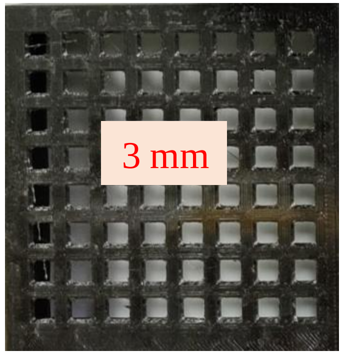
2022÷2023

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

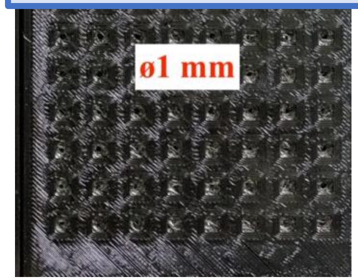


No mask: $6 \times 6\ mm$





$\sigma_{aer} \approx 5.6$ mrad

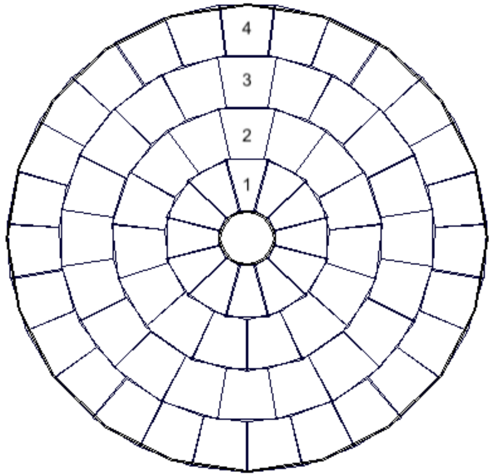


04/23: L≈200 mm	12/23: L≈180 mm	12/23: L≈180 mm	04/23: L≈200 mm	12/23: L≈180 mm	12/23: L≈180 mm
Geom.Eff. ~ 80%	Geom.Eff. ~ 56%	Geom.Eff. ~ 36%	Geom.Eff. ~ 20%	Geom.Eff. ~ 9%	Geom.Eff. ~ 2%
$N_{pe} \approx 16$	$N_{pe} \approx 12$	$N_{pe} \approx 8$	$N_{pe} \approx 4$	$N_{pe} \approx 2$	$N_{pe} \approx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

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

FARICH system concept for SPD-NICA

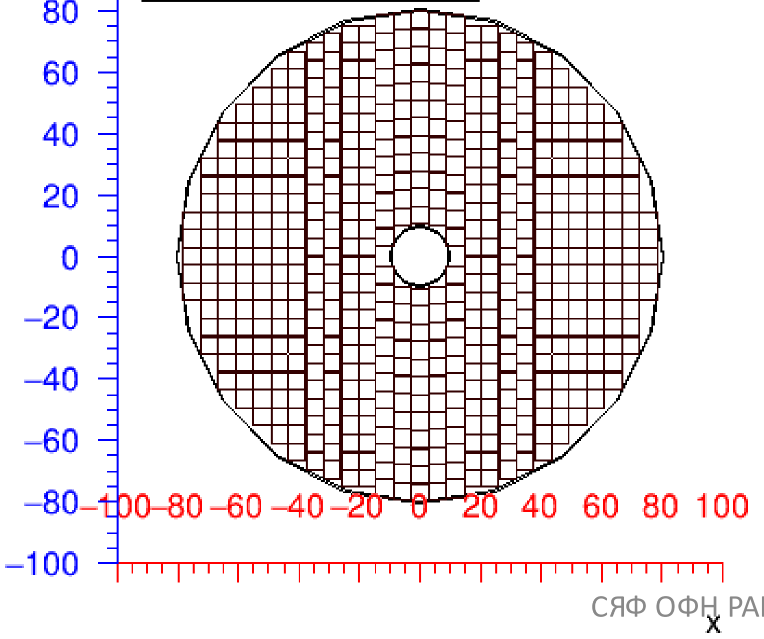
Aerogel:
74 tiles

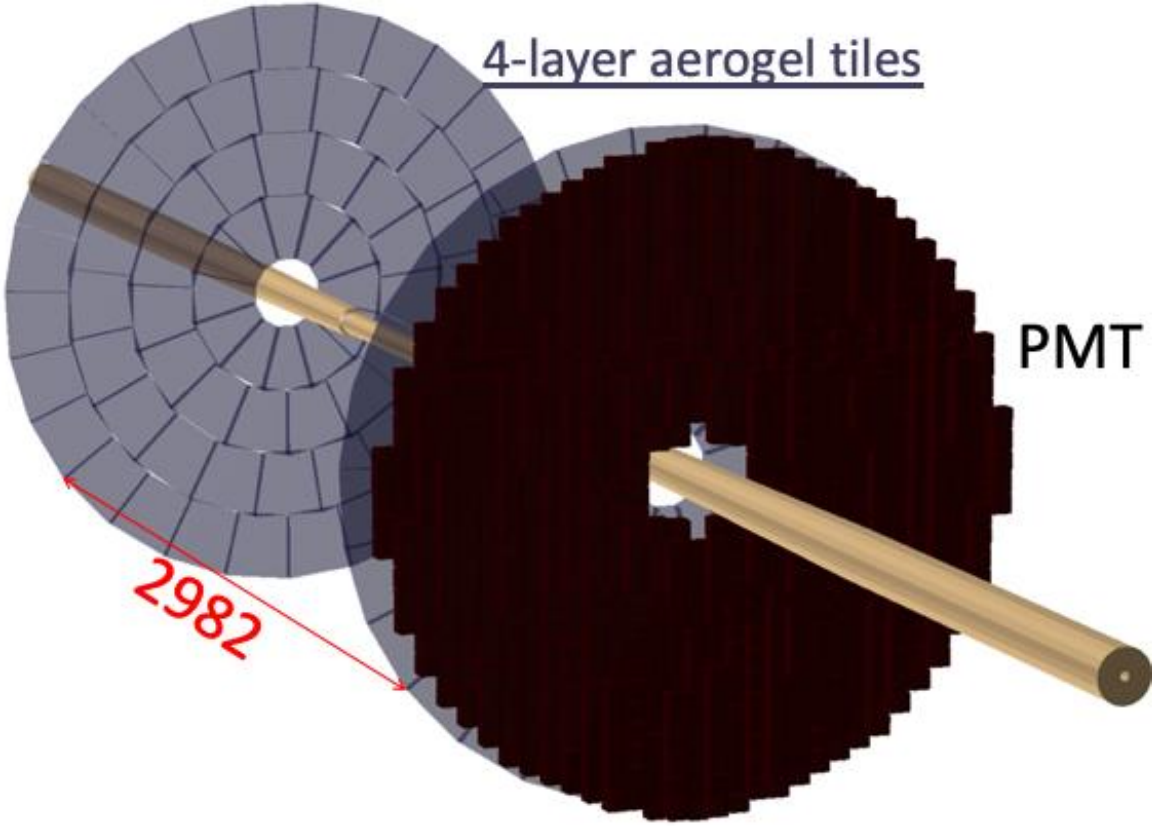


1 – 12 tiles x S=0.5•(5.6 + 15.6)•18.5 = 159.0 sq.cm
2 – 15 tiles x S=0.5•(12.2+20.2)•18.5 = 299.7 sq.cm
3 – 20 tiles x S=0.5•(15.0+20.8)•18.5 = 331.15 sq.cm
4 – 27 tiles x S=0.5•(15.2+19.6)•18.5 = 321.9 sq.cm

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

Photon detector: 548 PMT 51x51 mm





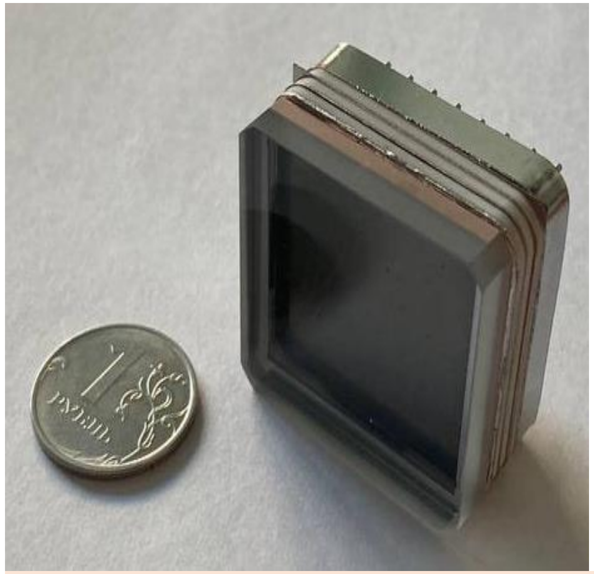
FARICH system:

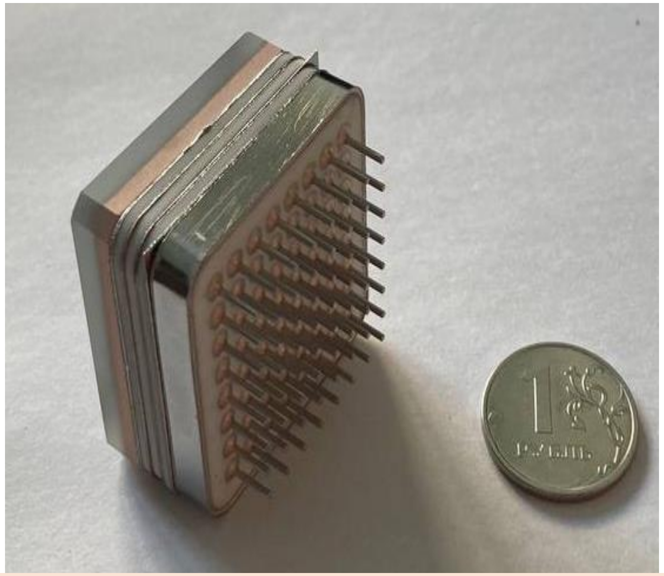
- 4-layer aerogel with n_{max}=1.05 (or less)
- Focus distance – 20 cm
- PS PD – MCP-PMT or SiPM arrays with pixel 3÷6 mm
  550 PMTs per endcap if lateral sizes ~51x51 mm
  2200 PMTs per endcap if lateral sizes ~27x27 mm

Status of MCP PMT development in Russia

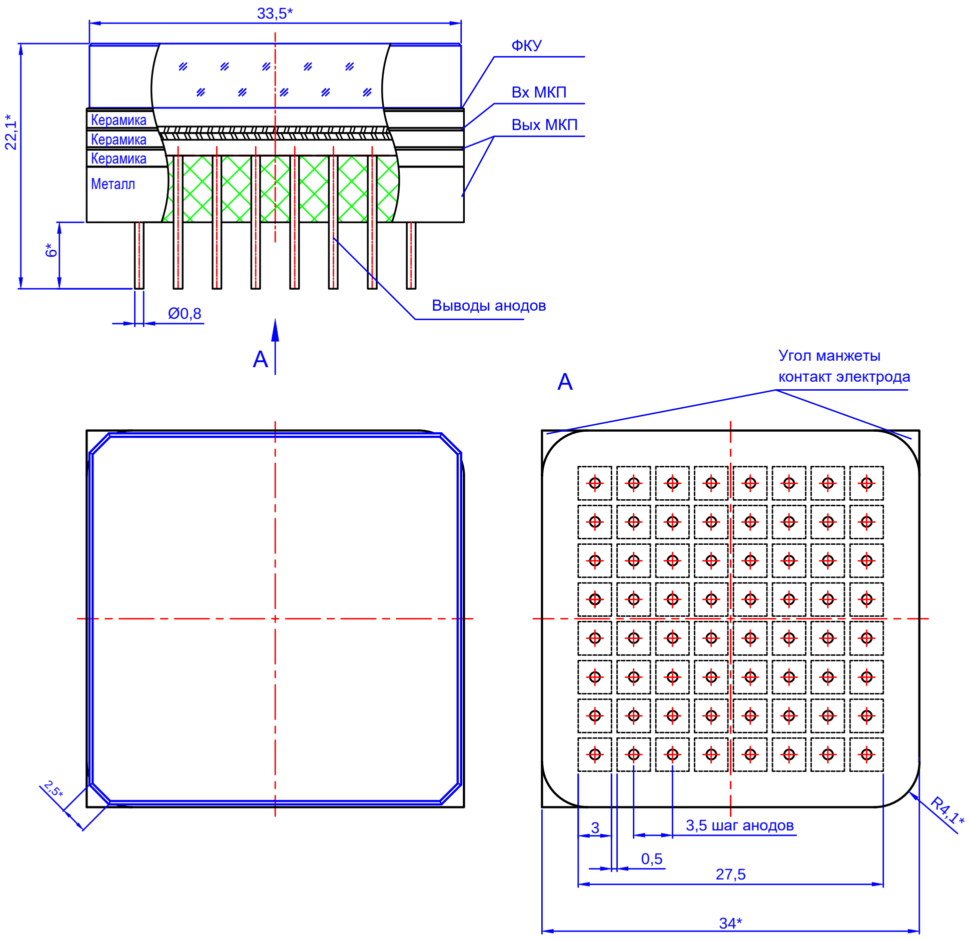
Square MCP PMT from “Ekran FEP”:

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





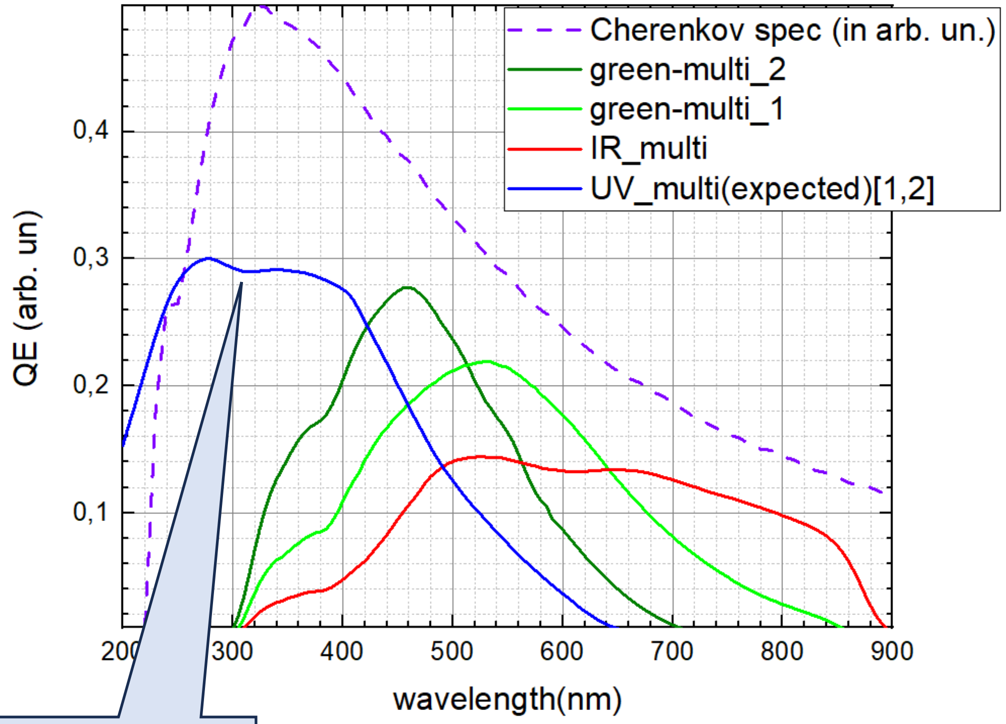
The first prototype fully asembled and vacume sealed prototype



* Размер для справок. Возможны незначительные изменения.

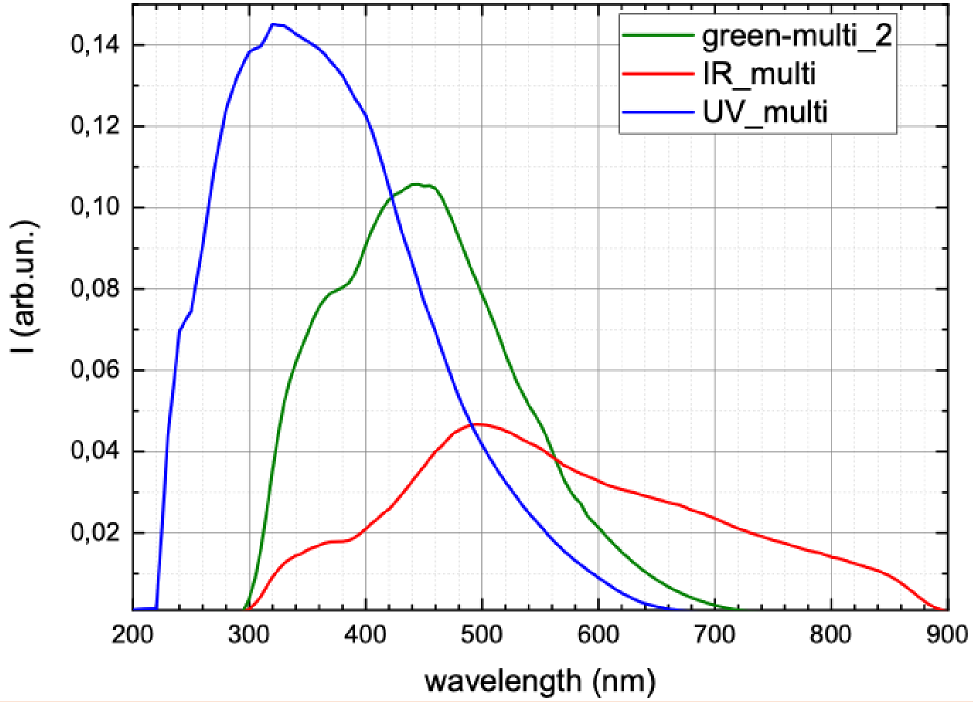
Photocathode options for “Ekran FEP” MCP PMTs

Multi-alkali PCs options and Cherenkov spectrum



It is planed to use Quartz to enhence PDE in UV region

Productions of Ch. Sp. with QE of Multi-alkali PCs



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

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

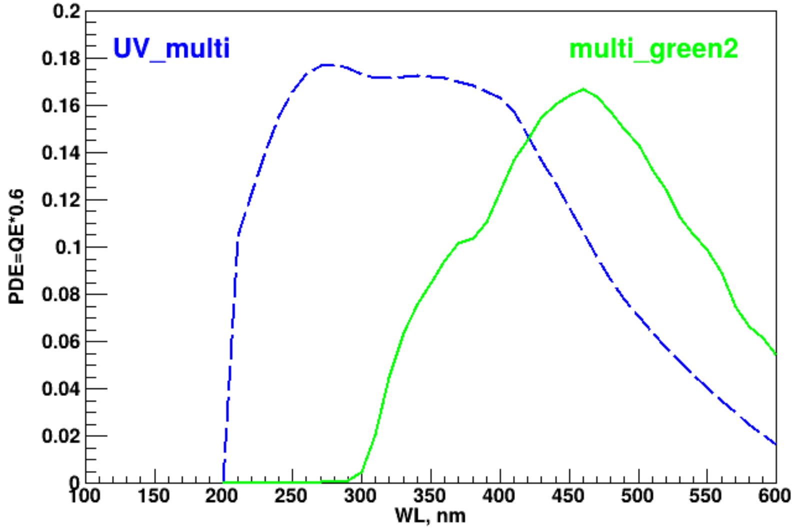
– **factor of 2** in comparison with standard “IR_multi” PC

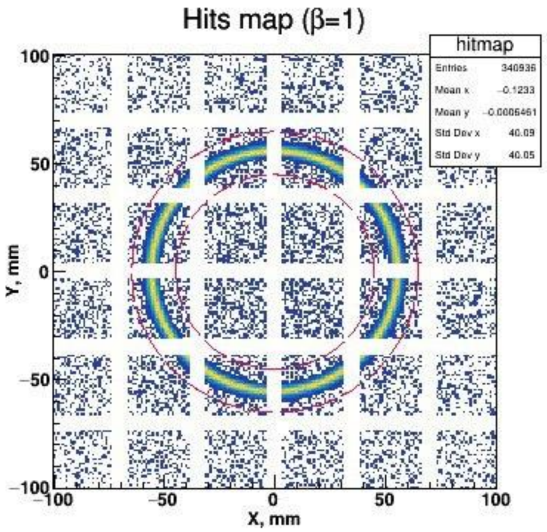
“UV_multi” QE based on data from papers:

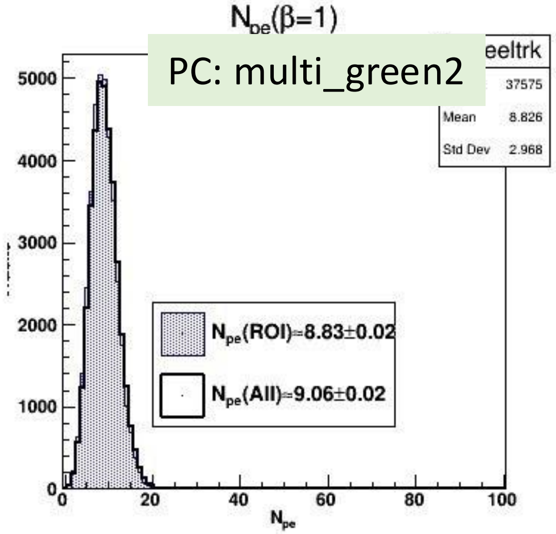
1. *Orlov, D. A., et al., High quantum efficiency S-20 photocathodes in photon counting detectors. Journal of Instrumentation, 2016 11(04), C04015–C04015*
2. *Milnes, J., et al., UV photocathodes for space detectors. Proceedings Volume 12181, Space Telescopes and Instrumentation 2022: Ultraviolet to Gamma Ray, 121813B (2022).*

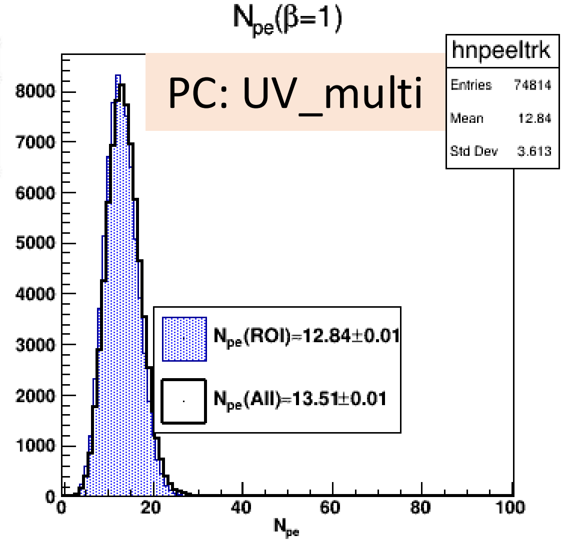
FARICH prototype based on MCP-PMT (Ekran FEP)

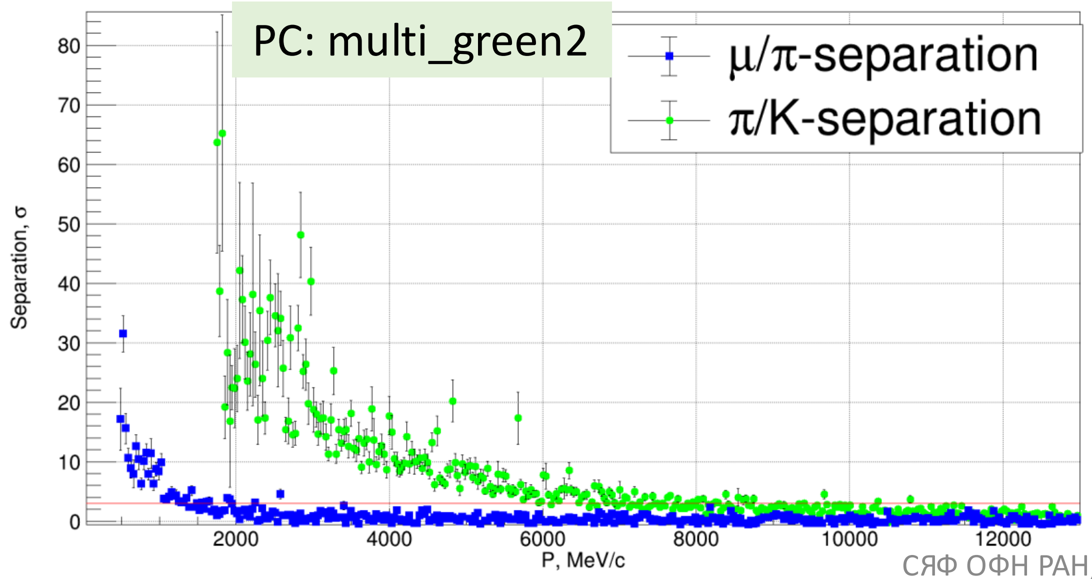
(expected performances: Geant4 simulation results)

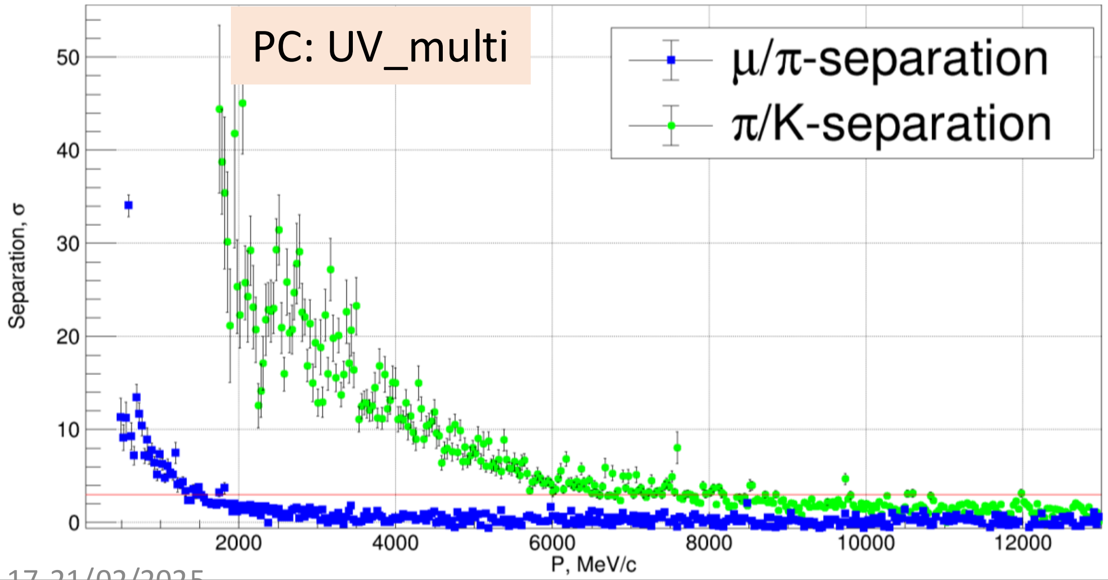






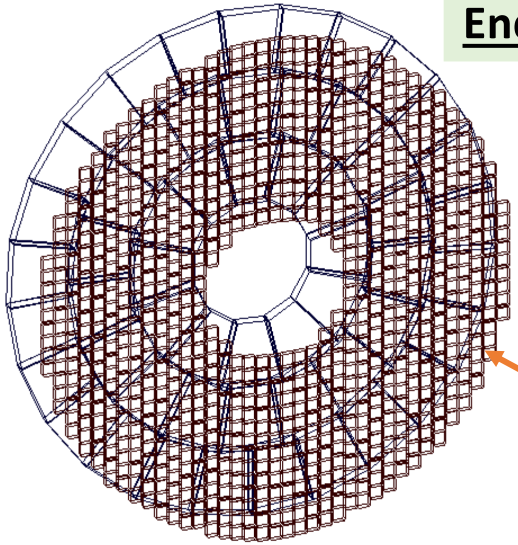




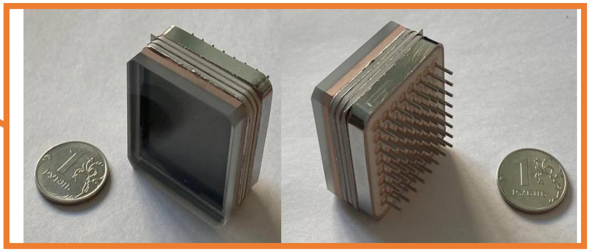


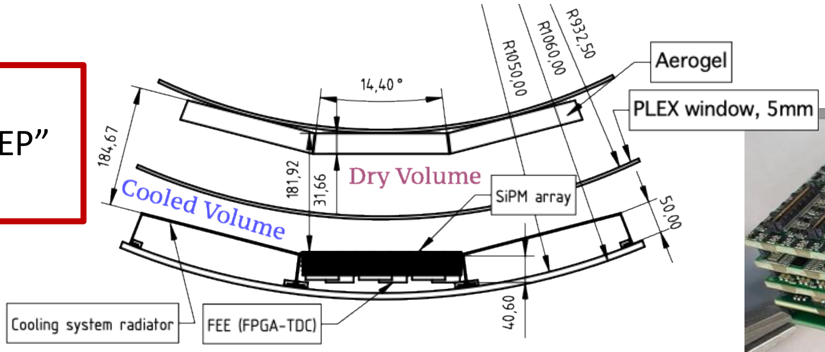
FARICH system concept for the SCTF project

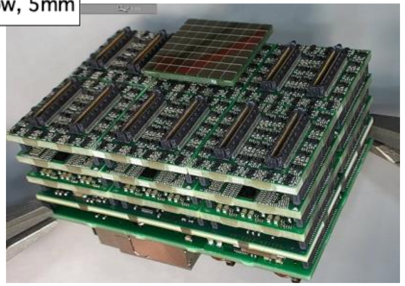
Endcap part Sketchs & key elements



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

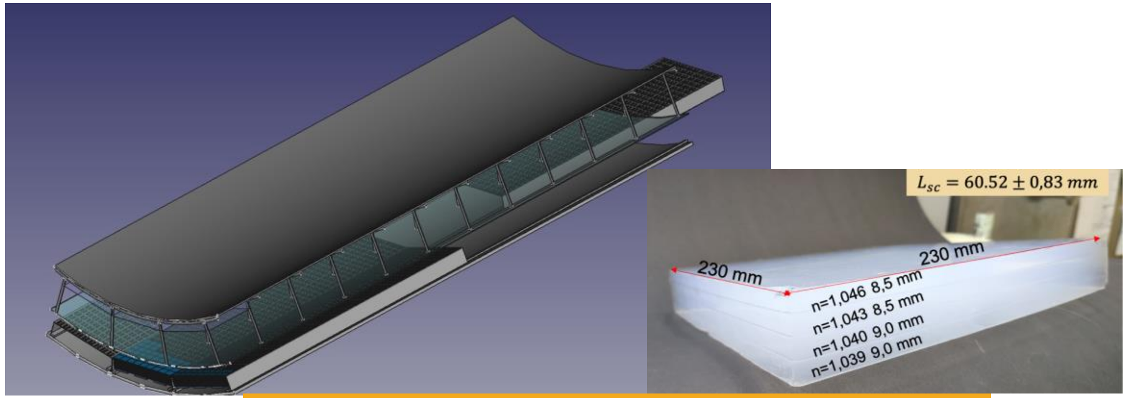




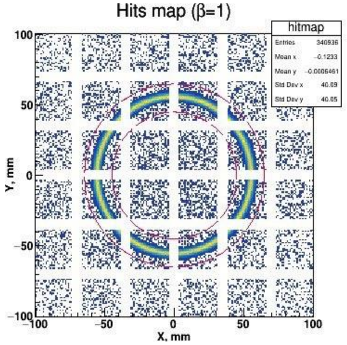


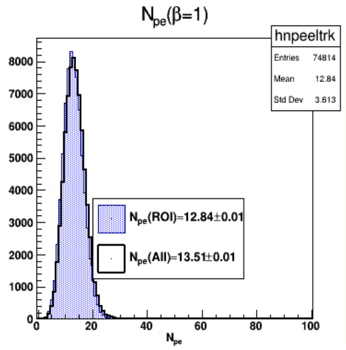
The first square MCP PMT produced in Russia:

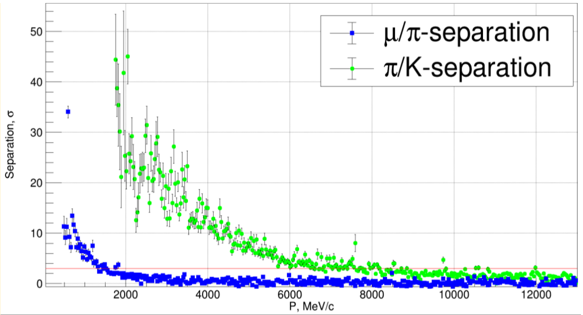
- All details and components are produced in Russia
- First samples for test will be available until the end of 2024



Expected system parameters (obtained in G4 simulation)



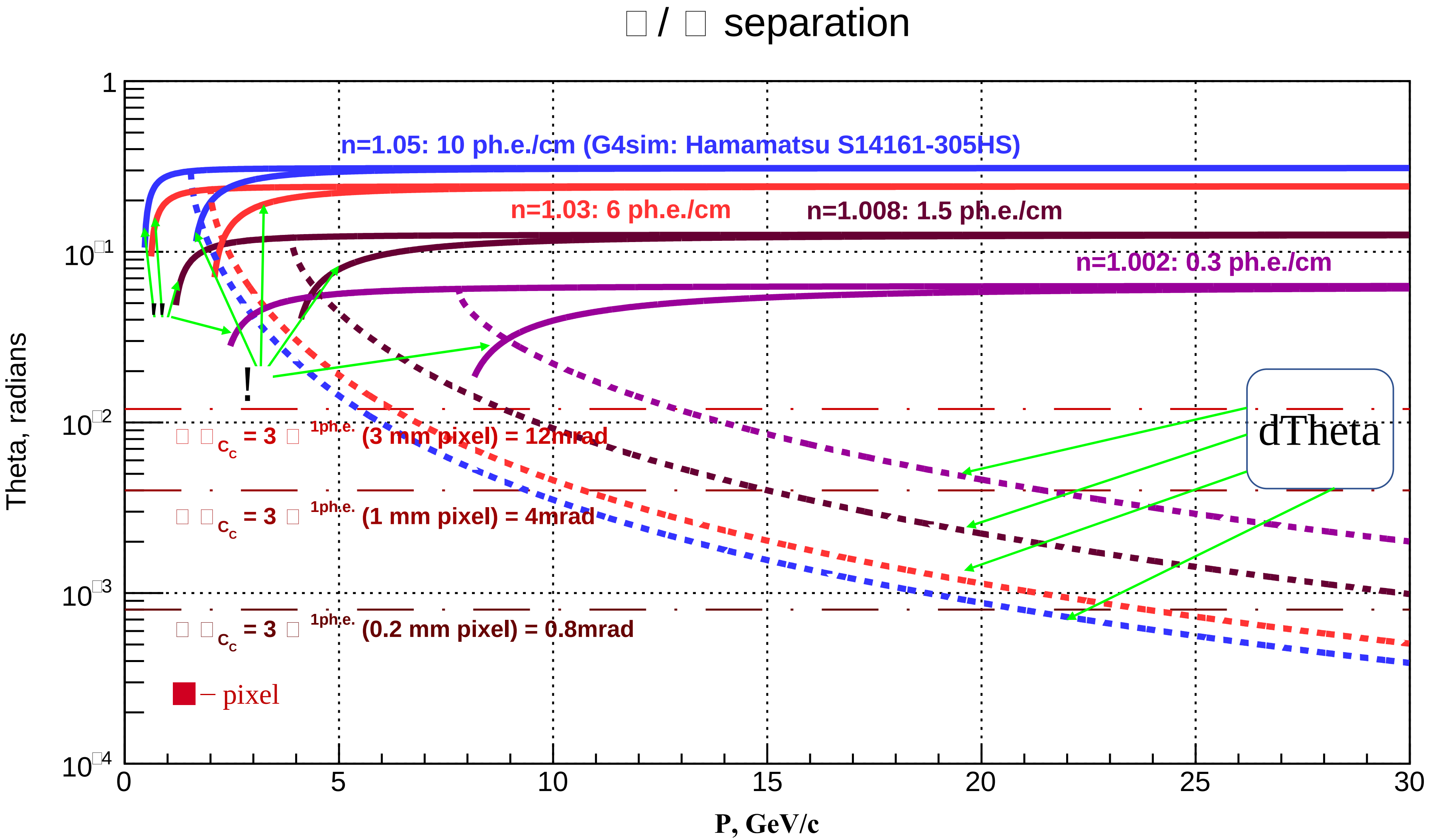




Barrel part Sketchs & key elements

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

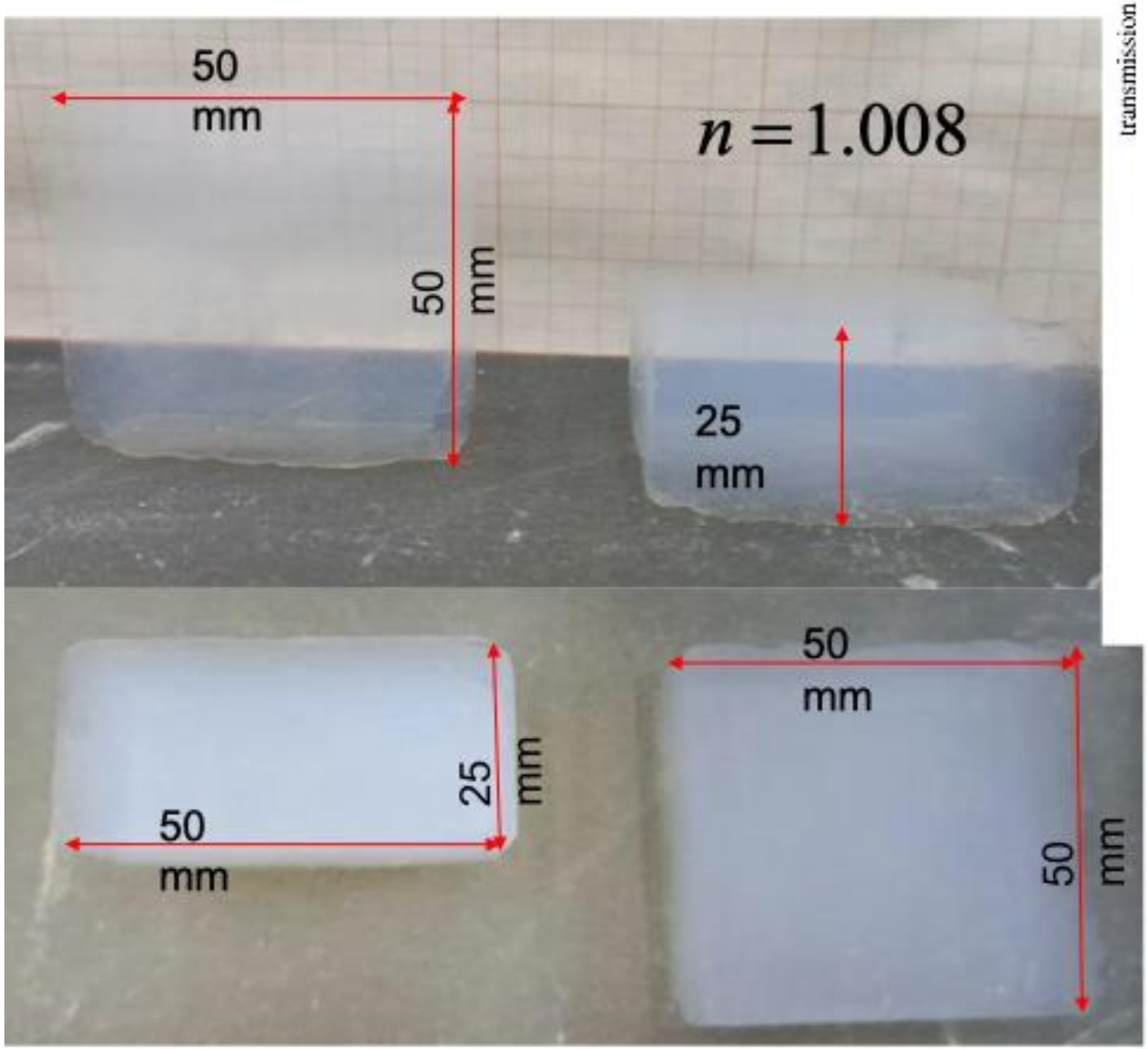
RICH detectors capability for π/K–separation

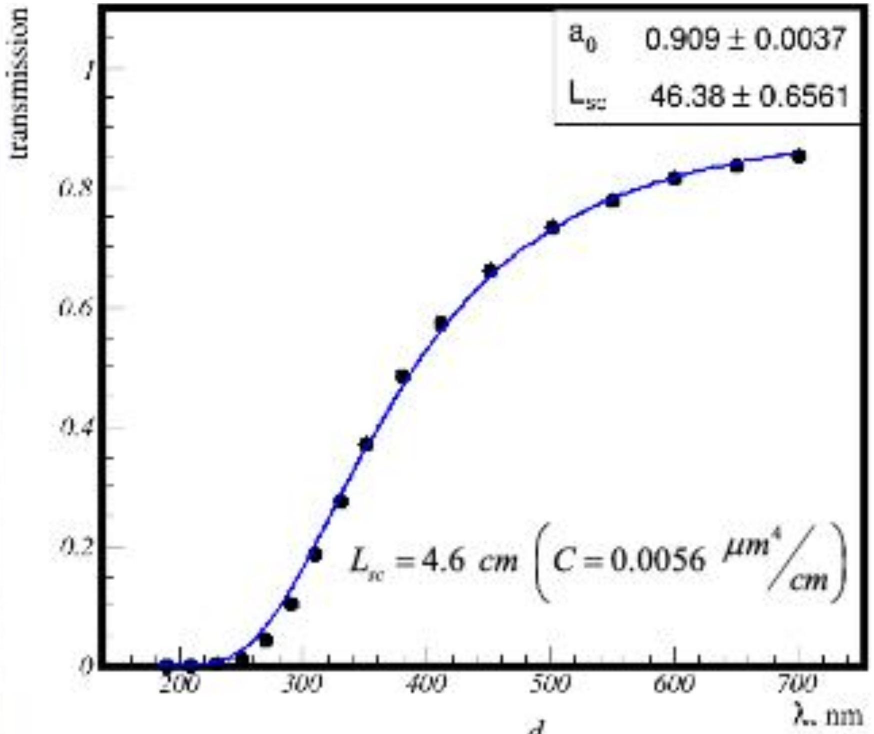


- At least 5 hits have to be detected to reconstruct Cherenkov ring.
- Thickness of Cherenkov radiator should be:
  - ≥1 cm for n=1.05 (aerogel)
  - ≥4 cm for n=1.008 (aerogel)
  - ≥15 cm for n=1.002 (C_5F_{12})
- Some focusing system is needed to provide impact from thickness at the level of few mrads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

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

Aerogel with n=1.008 (Novosibirsk)



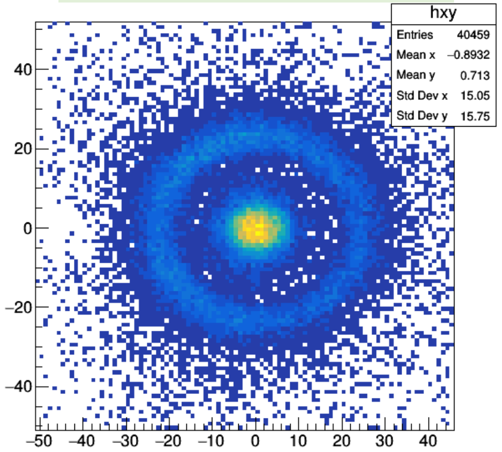


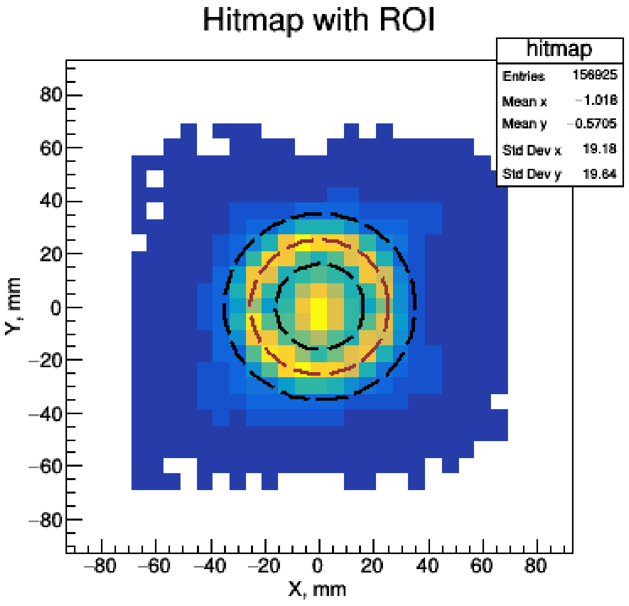
$$T = \frac{I}{I_0} = a_0 \cdot e^{-\frac{d}{L_{sc} \cdot \left(\lambda/400\right)^4}} = a_0 \cdot e^{-\frac{C \cdot d}{\lambda^4}}$$

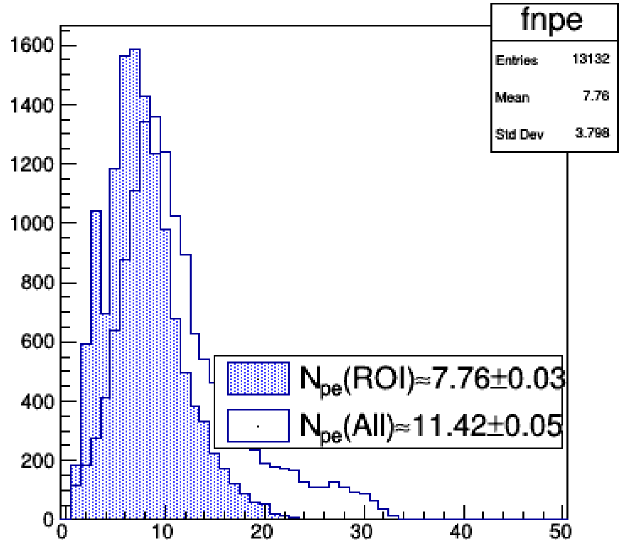
d – thickness of a sample,
λ – wavelength in nanometers,
Lsc – scattering length at 400 nm,
a_0 – surface scattering coefficient,
C – clarity coefficient

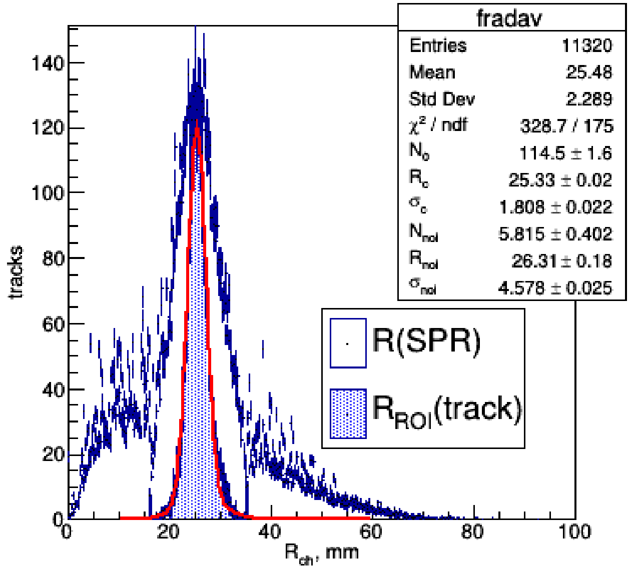
RICH based on aerogel n=1.008 at BINP beam test

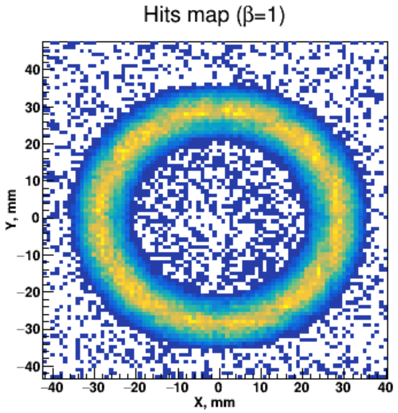
Tbeam e⁻@2.5GeV
- t_{aer}=25+25=50 mm
- L_F=200 mm











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

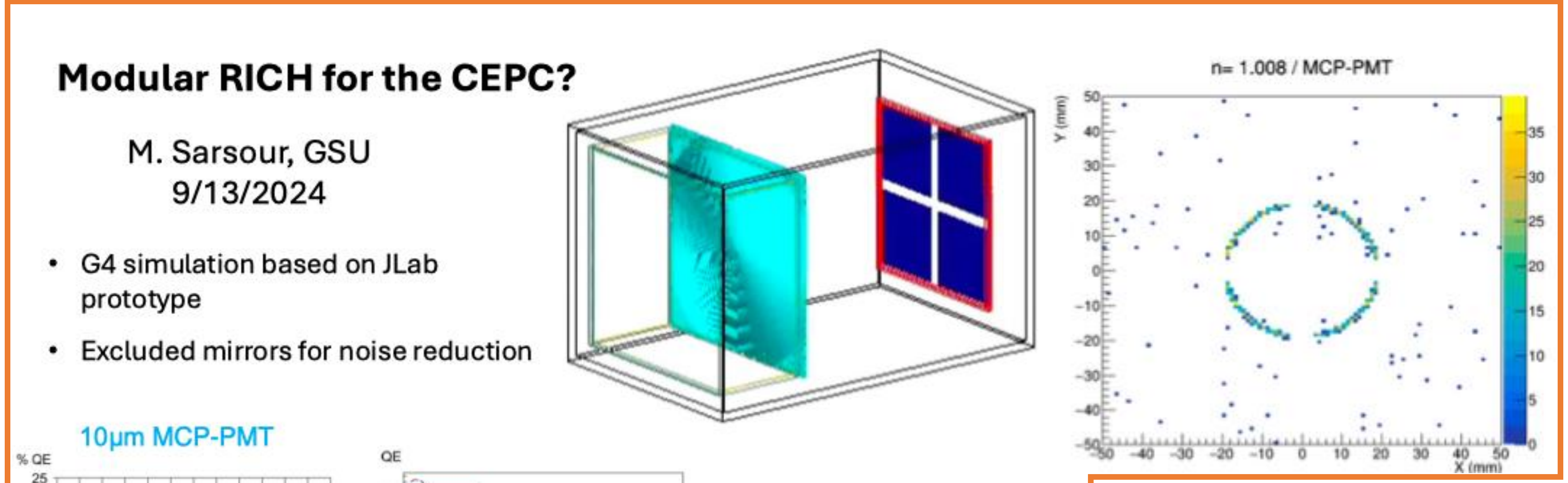
Geant4 sim.:
- t_{aer}=60 mm
- L_F=250 mm

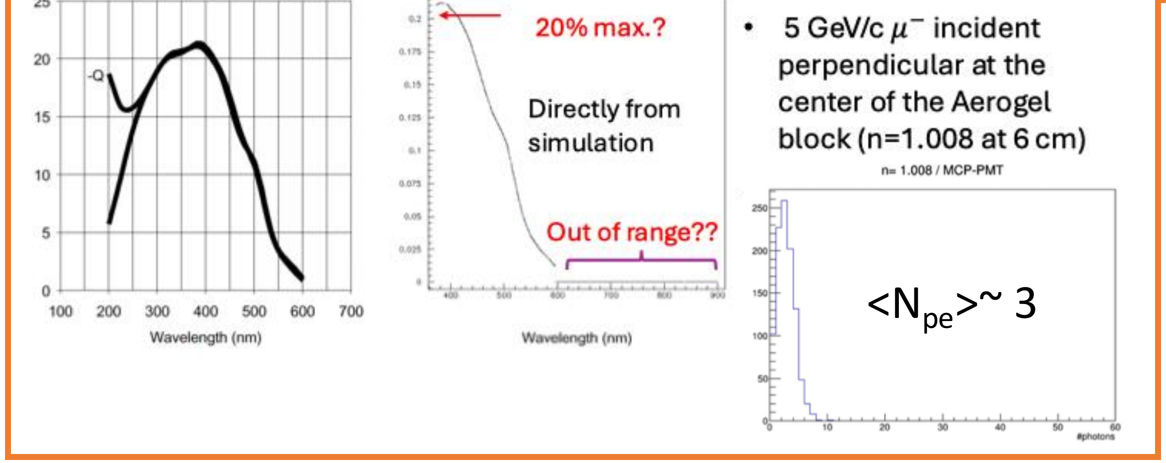
OUTPUT:
- SiPM based photon detector with PDE(400nm)=45÷50% will alow us to detect 10÷20 ph.e. for relativistic tracks
- RICH based on aerogel with n=1.008 and pixel 3x3mm is able to provide π/K-separtion at P=10 GeV/c
- ***Proximity focusing system and PD with $\sigma_x \leq 1\,mm$ is required to reach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

Proximity focusing with Fresnel Lenses

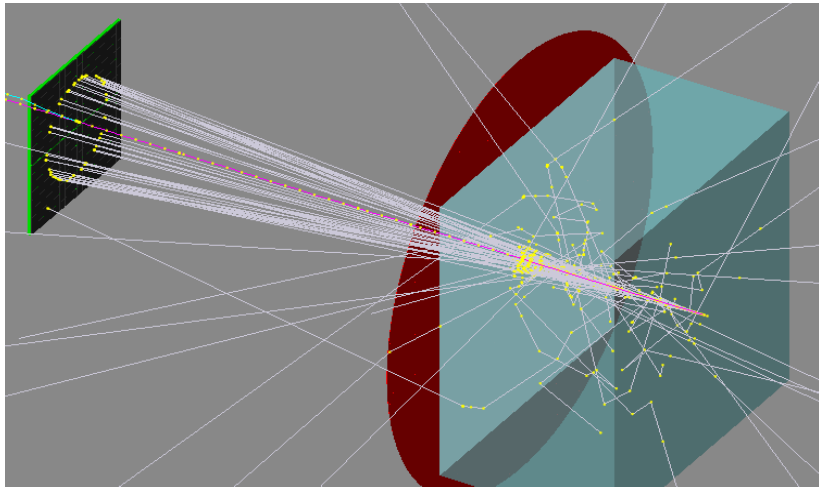
- This option was Inspired by success of mRICH R&D for EIC project [D. Sharma et al., NIM A1061 (2024) 169080]
- First steps of simulation at BINP were verified with GSU group simulation results

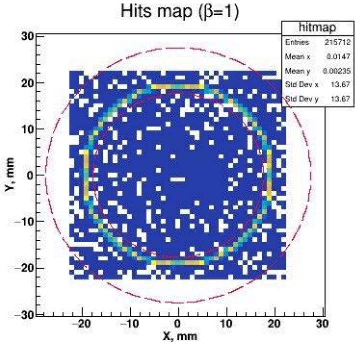
GSU sim

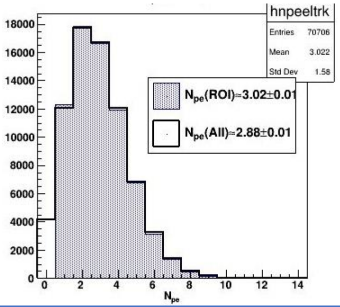


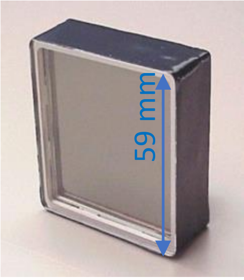


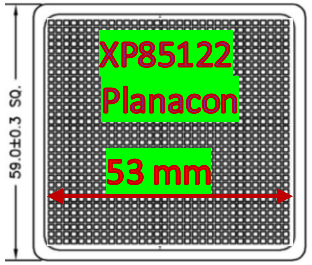
BINP sim



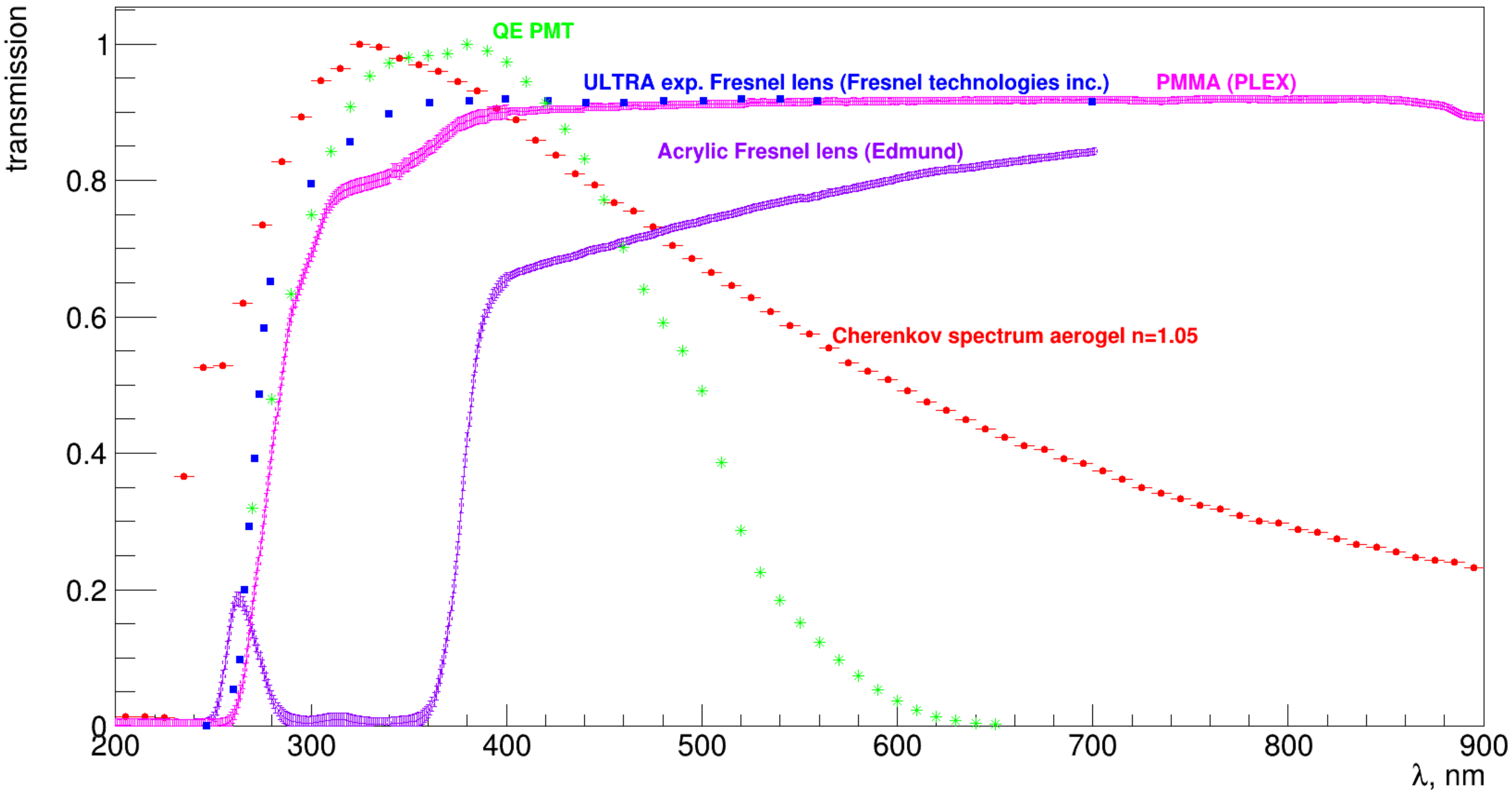






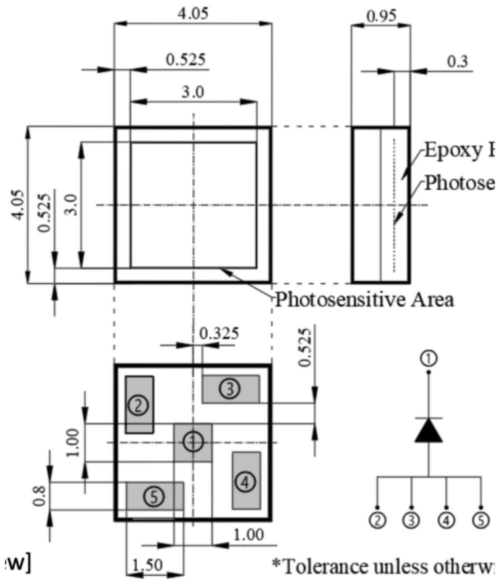


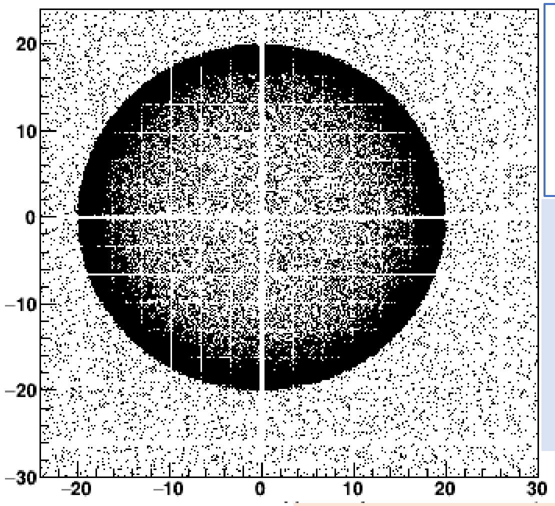
Fresnel lens transparency



- 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)

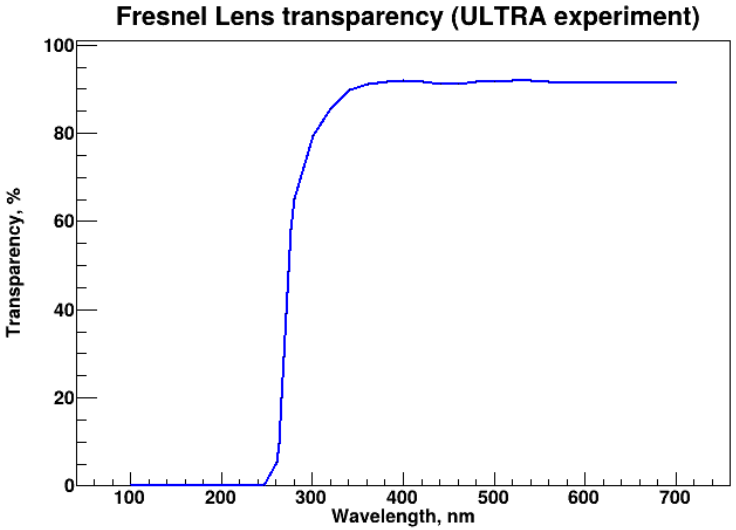


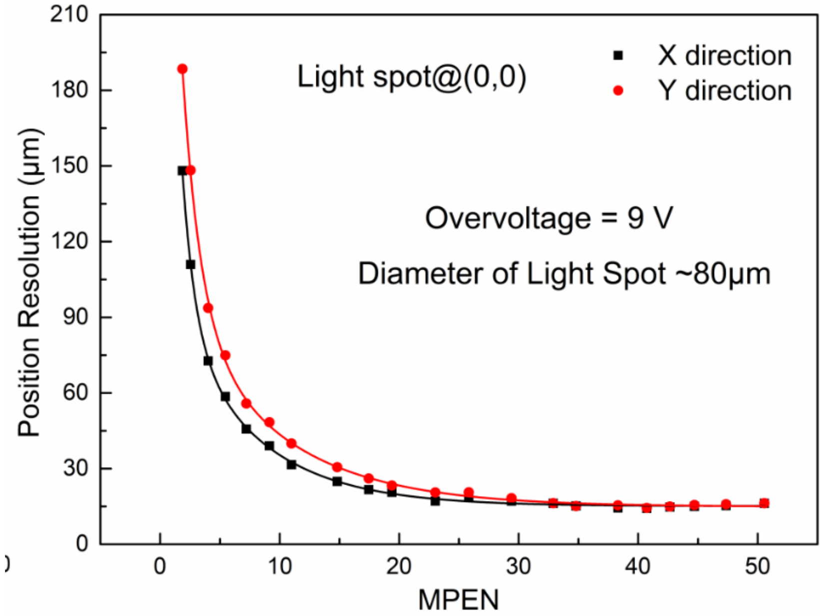


$$x_c = \frac{L}{2} \cdot k \cdot \frac{(Q_2 + Q_3) - (Q_1 + Q_4)}{(Q_1 + Q_2 + Q_3 + Q_4)}$$

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

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

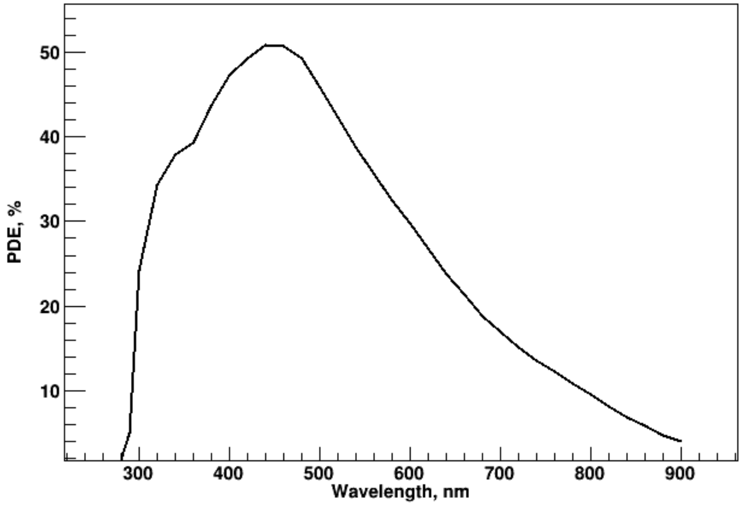




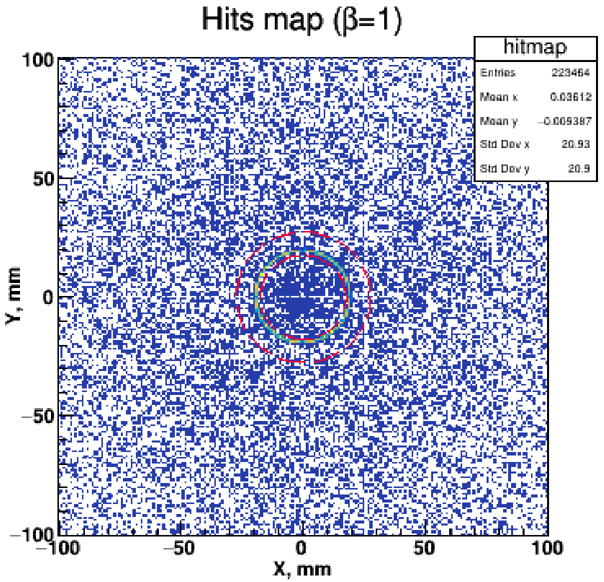
- Aerogel
  - n=1.008
  - t=6 cm
  - L_{sc}(400nm)=4.6 cm
- Position-sensitive SiPM
  - pixel 3x3 mm
  - hit position restored by charge sharing $\sigma_x = 200\mu m$
  - PDE from Hamamatsu S14161-3050HS
- Fresnel Lenses
  - **Focal length = 6” and 10”**
  - Transparency from ULTRA exp.

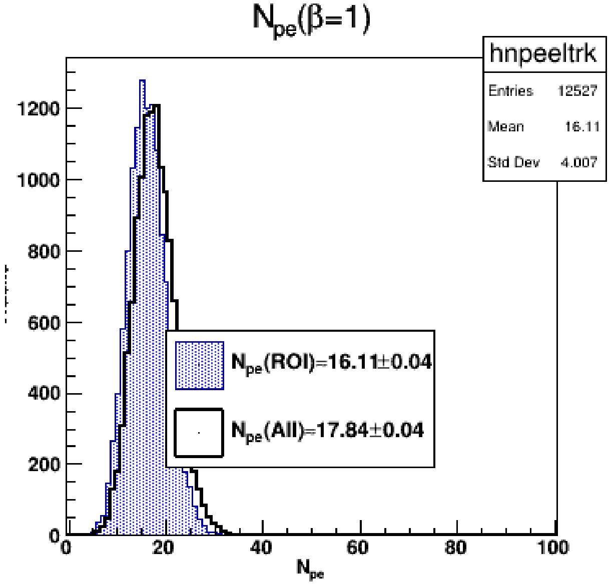
(NIM A570 (2007) 22-35)

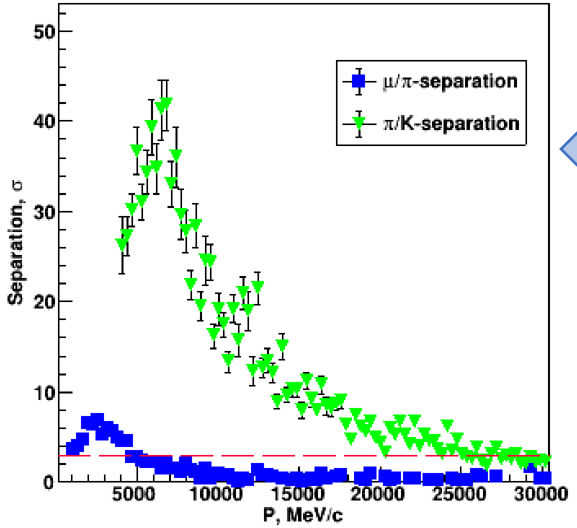
Fresnel technology inc.



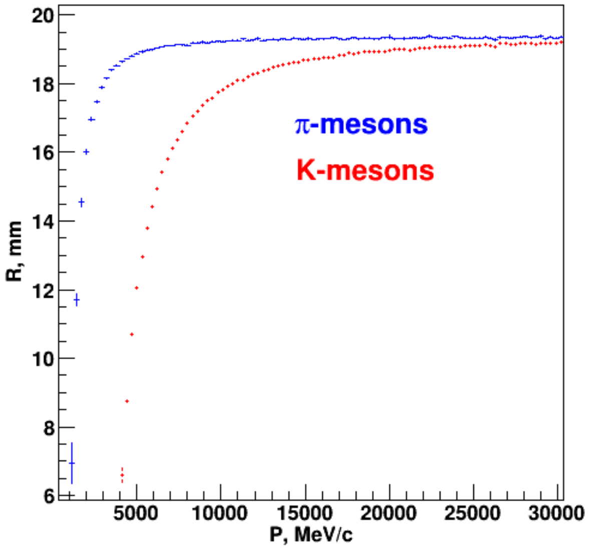
mRICH sim. results for Fresnel lens 6” and 10”

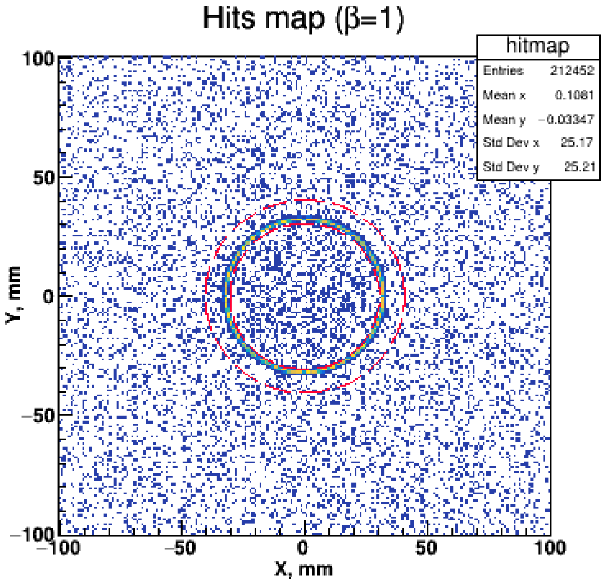


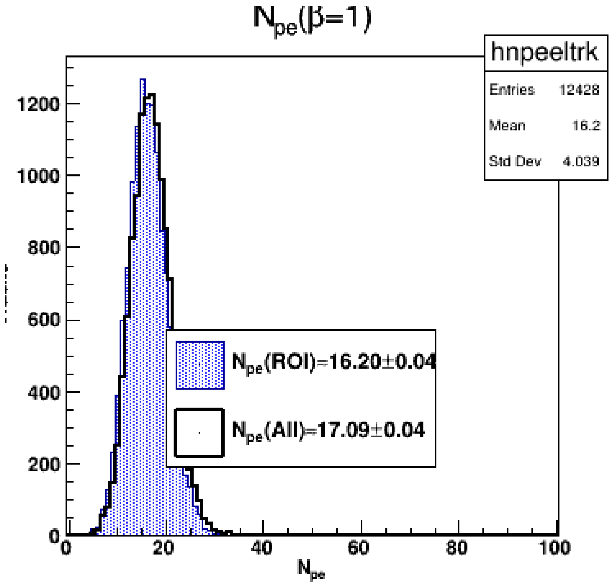


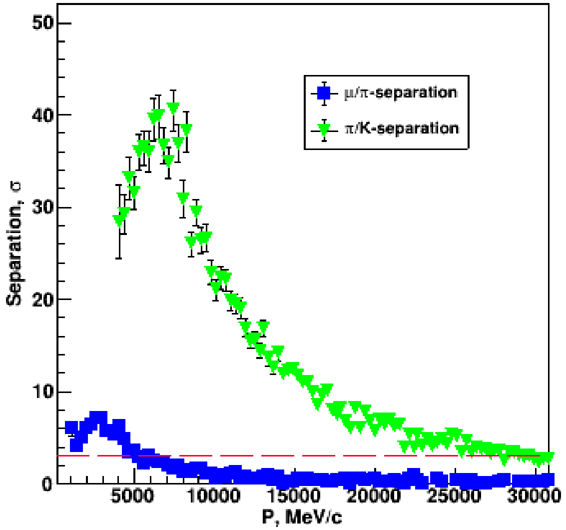


Fresnel Lens with
F=6”





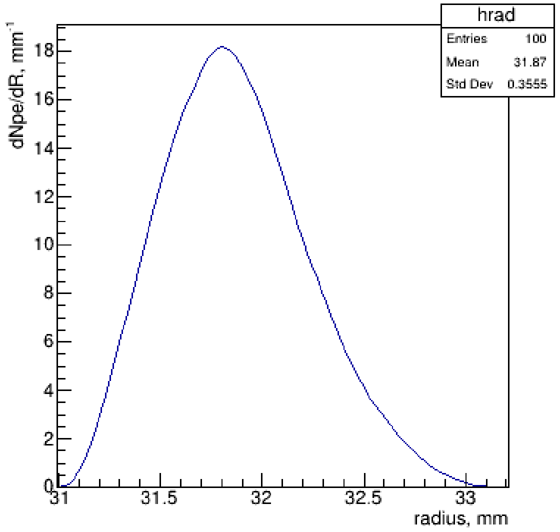


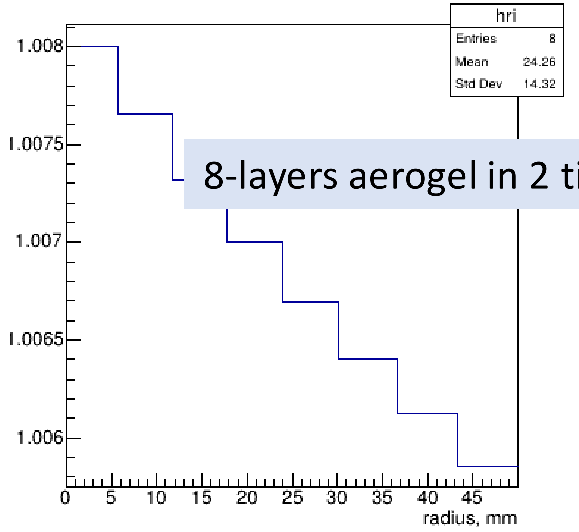


Fresnel Lens with
F=10”

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

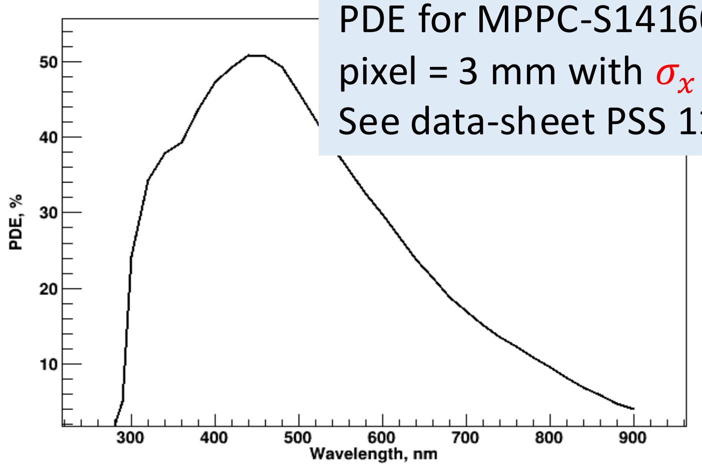
8-layer aerogel n_{max}=1.008; pixel≈0.2mm





8-layers aerogel in 2 tiles

Focal distance is 300 mm

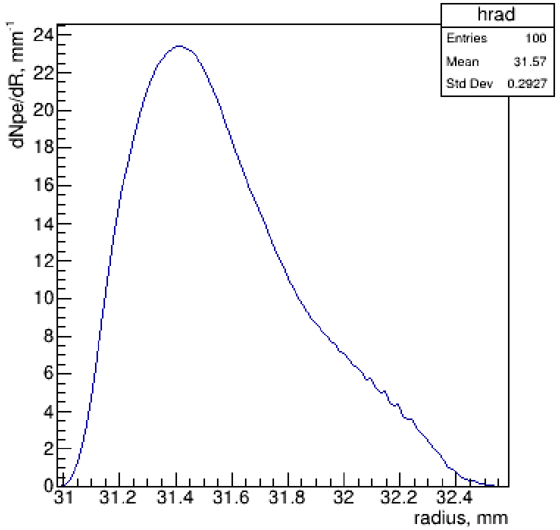


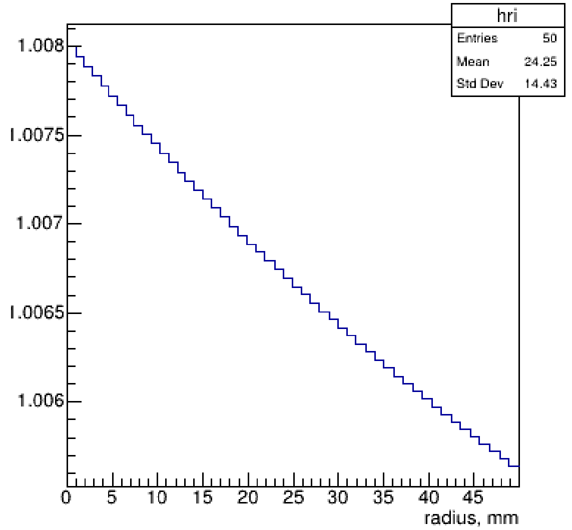
PDE for MPPC-S14160 (Hamamatsu)
pixel = 3 mm with $\sigma_x \approx 0.2mm$
See data-sheet PSS 11-3030-S (NDL)

- $N_{pe} \approx 16$

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*

- $N_{pe} \approx 16$

σ_C^{tr}≈0.33 mrad!!!

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

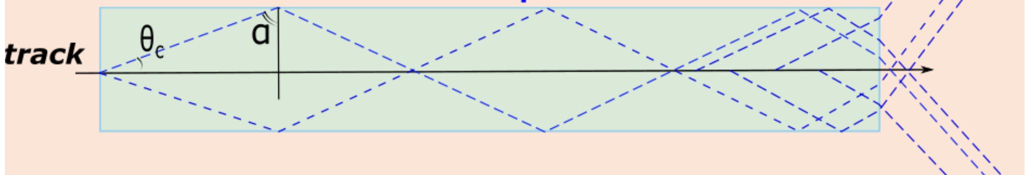
Fiber Aerogel RICH: idea & motivation

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

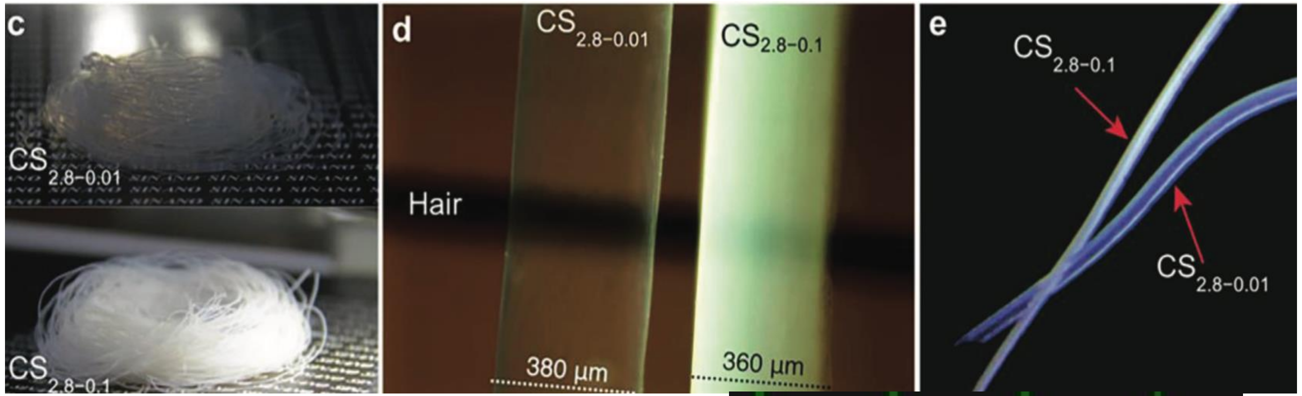
$$\cos(\theta_C)=\frac{1}{n\beta}=\sin(\alpha)$$

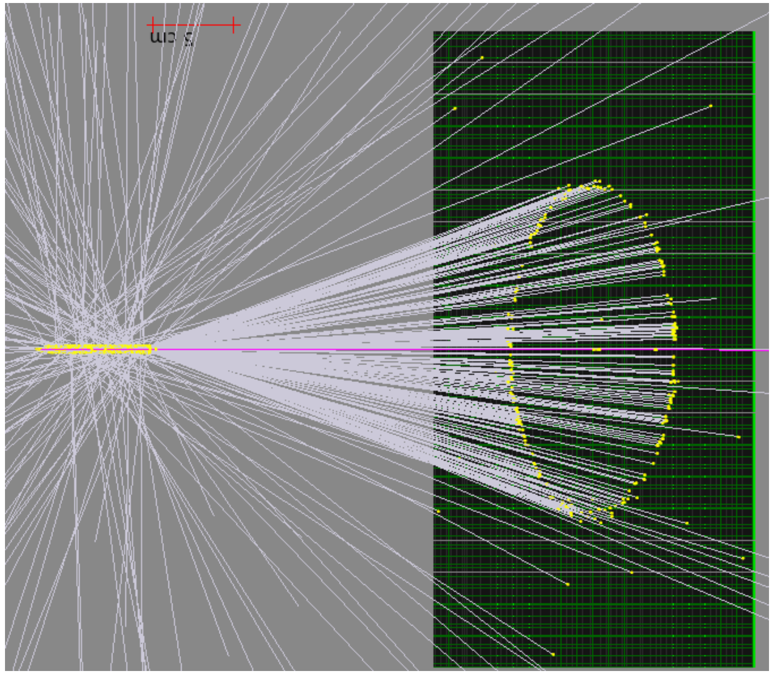


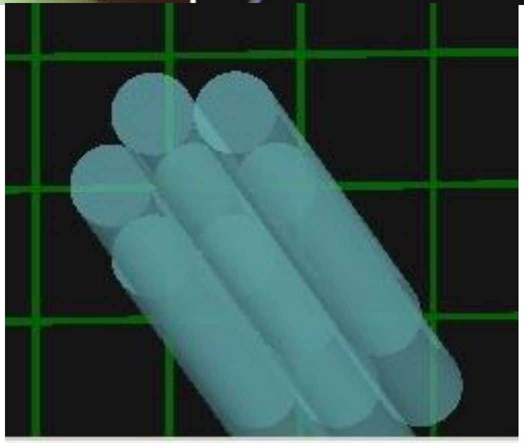
Cherenkov light ocurs in total internal reflection conditions if particle goes stright along bar or fiber axis!

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

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



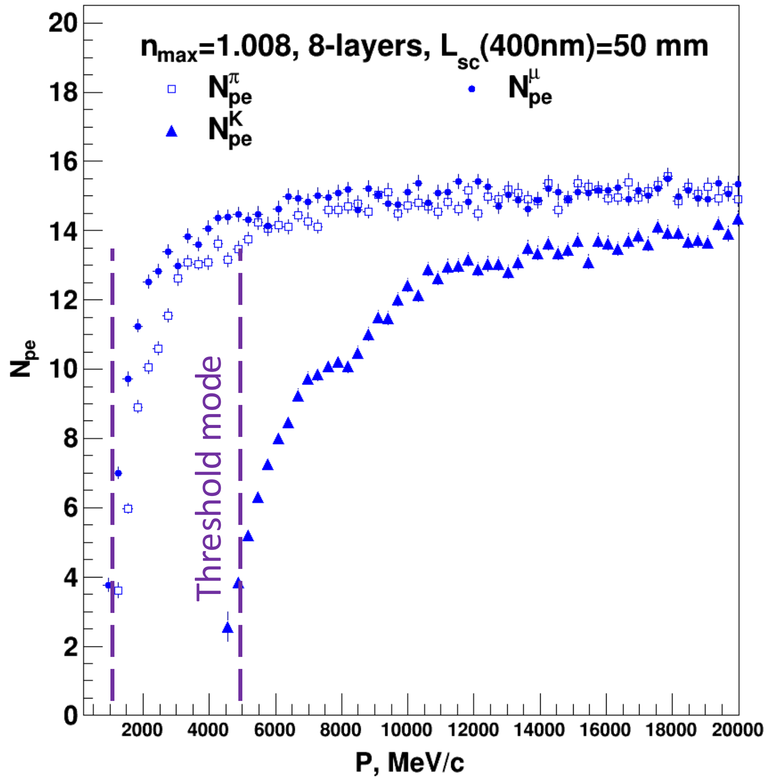


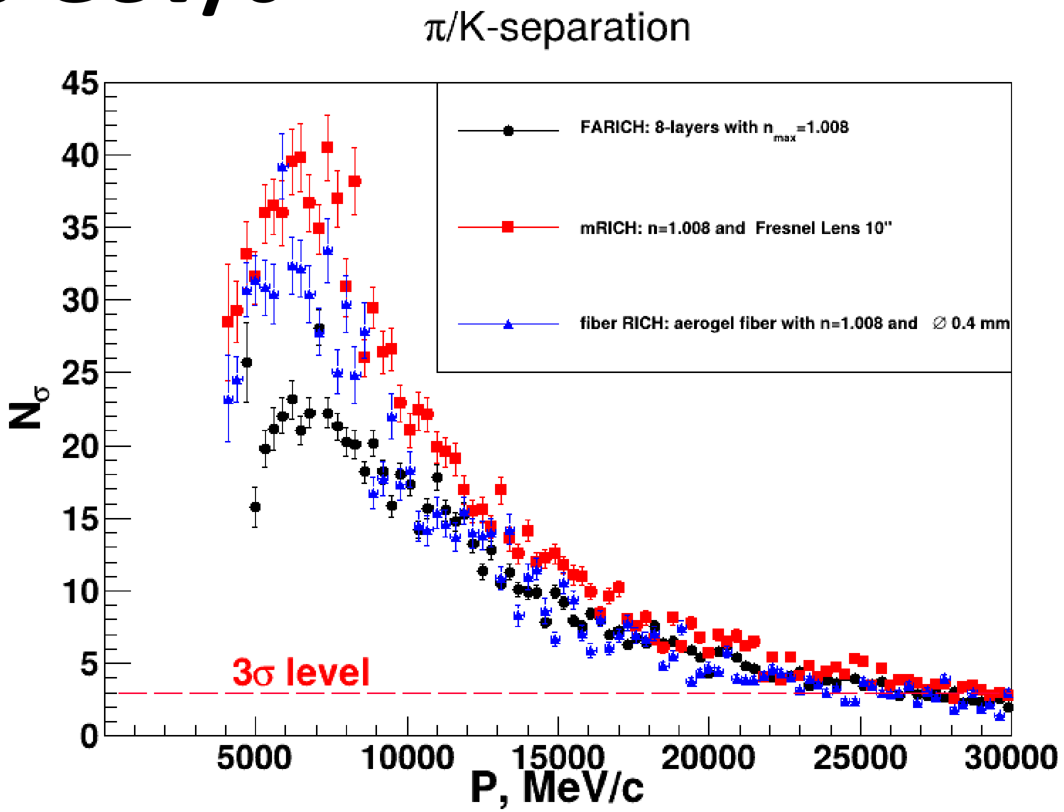


Single fiber params:

- n=1.008
- Length = 60 mm
- ø 0.4 mm

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





- 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.

Summary

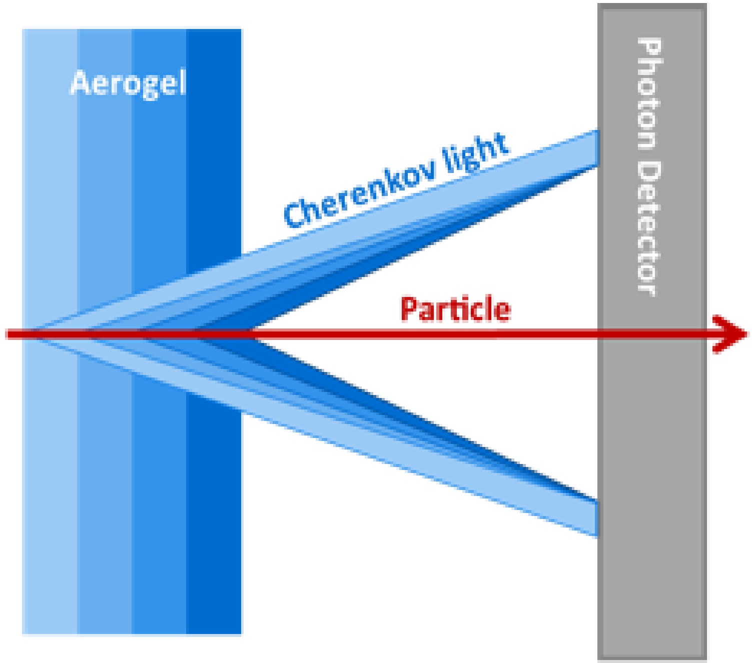
- Aerogel Cherenkov counters R&D was started in Novosibirsk in 1986.
- Since that time a lot of HEP experiments are used aerogels produced in Novosibirsk.
- The R&Ds on aerogel based Cherenkov counters for modern and future HEP experiments are carrying out at the BINP:
  - Upgrade of ASHIPH system for the SND experiment is on going now.
  - PID systems based on ASHIPH counters with SiPM were proposed for STCF (USTC, Hefei) and SPD-NICA (JINR, Dubna) projects to provide reliable π/K-separation up to 3 GeV/c. Good agreement of estimated and measured light collection in prototype was demonstrated at the beam test at the BINP.
  - Essential progress in FARICH technique development was achieved in recent years.
  - The PID system based on FARICH technique is proposed for the SPD experiment for reliable π/K-separation up to 6 GeV/c and full-scale FARICH prototype to demonstrate π/K-separation at the mixed hadron beams is under development.
  - Three approaches for reliable π/K–separation at momentum range above 20 GeV/c with help of aerogel ($n \approx 1.008$) were considered with help of GEANT4 simulation. Beam test results show us that it is possible to made a RICH detector based on such aerogel with registration of 15-20 Cherenkov photons from relativistic tracks.
- Search for suitable and available position-sensetive photon detectors and R&D on specialized FEE have to be done for succesefull realization of all mentioned projects.

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!!!

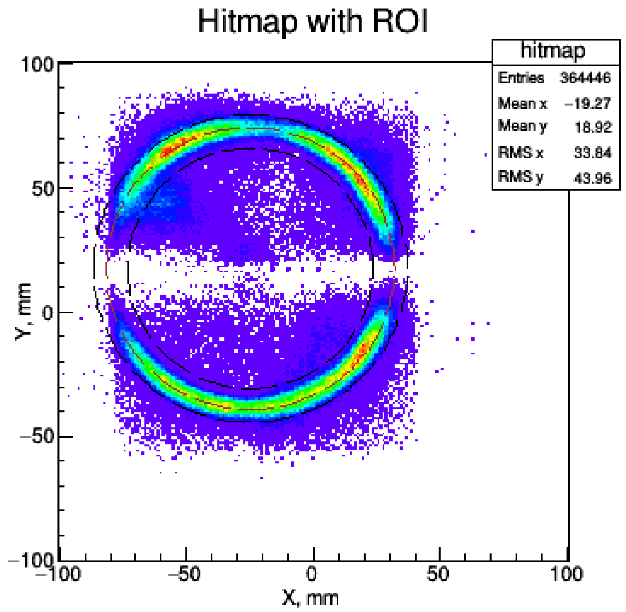


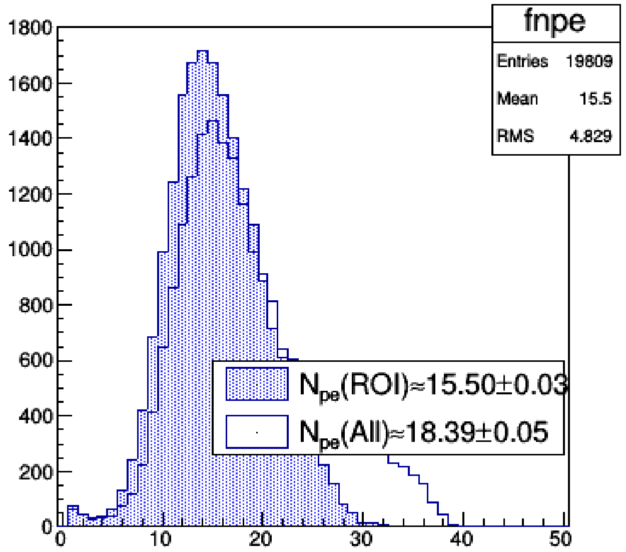
- Thicknesses and refractive indexes in each layer are adjusted in such way that Cherenkov rings from each layer overlap in the same region of the position-sensitive photon detector.
- The number of detected Cherenkov photons increases due to increase of the thickness without degradation of Cherenkov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

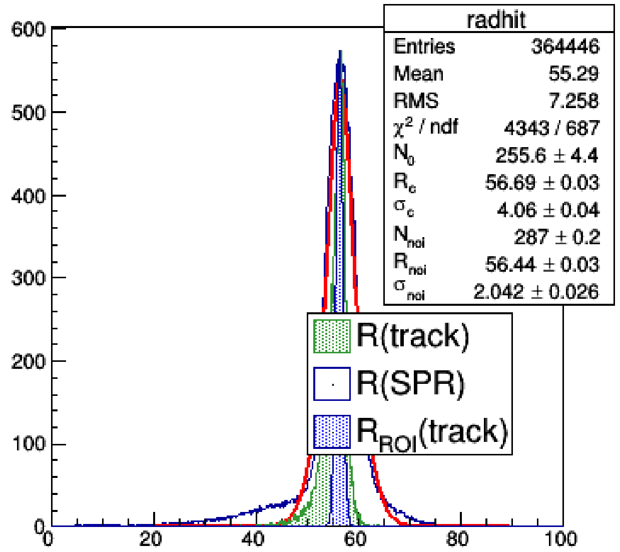
T.Iijima et al., NIM A548 (2005) 383 and A.Yu.Barnyakov et al., NIM A553 (2005) 70

Recent beam test results

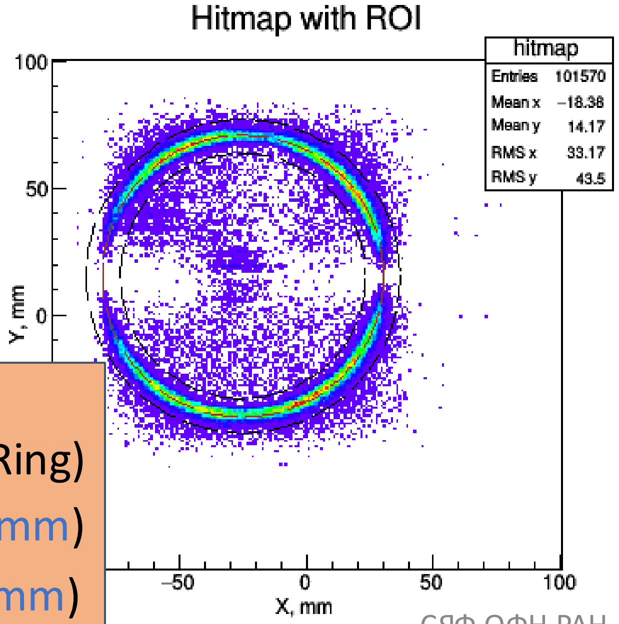
Pixel 6x6 mm
Geom.Eff. ~ 80%

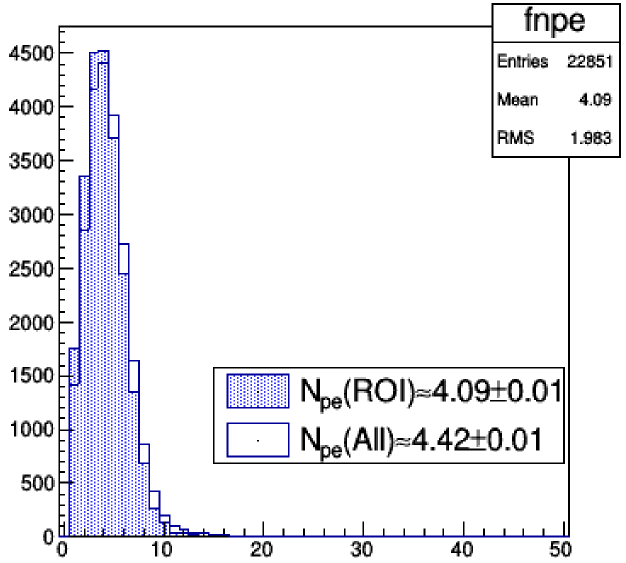


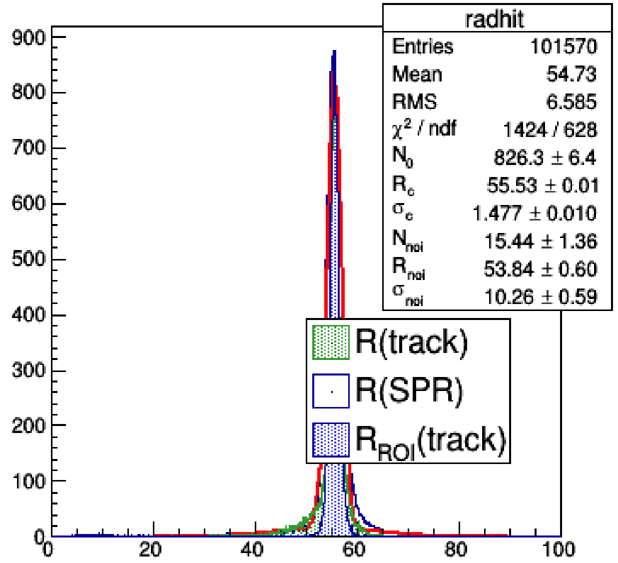




Pixel 3x3 mm
Geom.Eff. ~ 20%



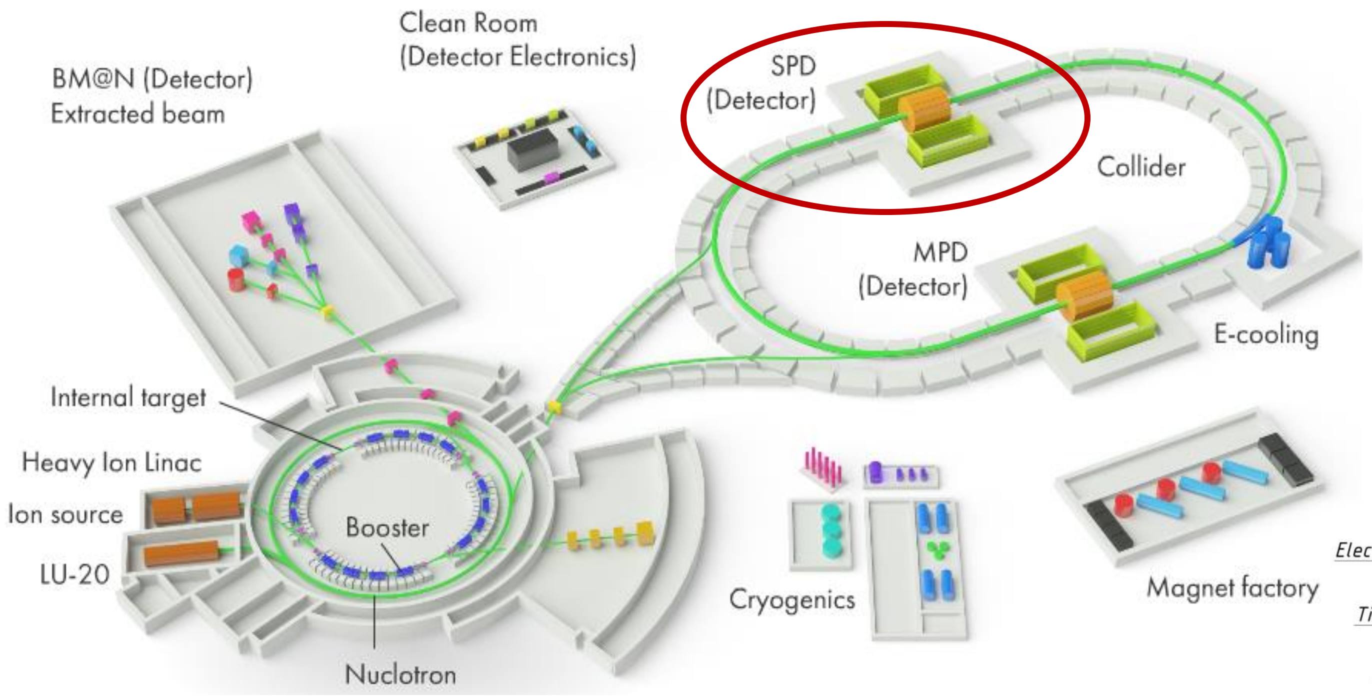




Main results:

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

SPD@NICA



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

Spin Physics Detector

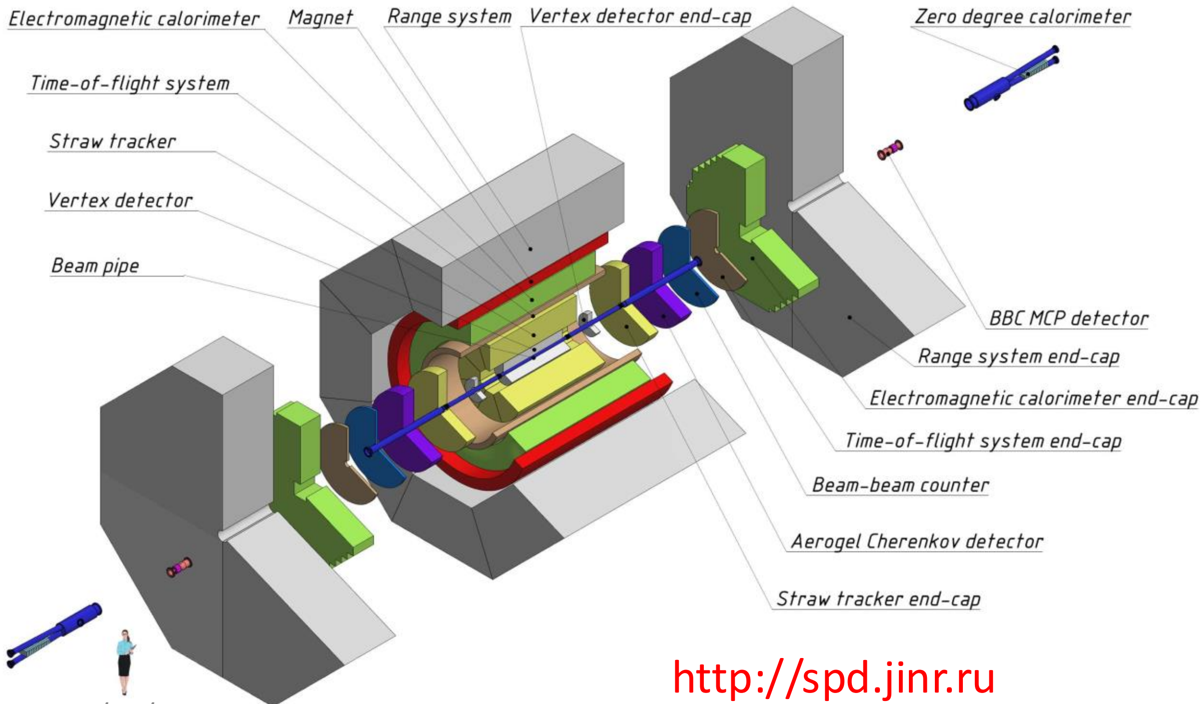
to investigate nucleon and light nuclei (p & d) spin structure with help of colliding beams at the energies up to 27 GeV.

– Polarized p and d

– $L = 10^{32} cm^{-2} s^{-1}$

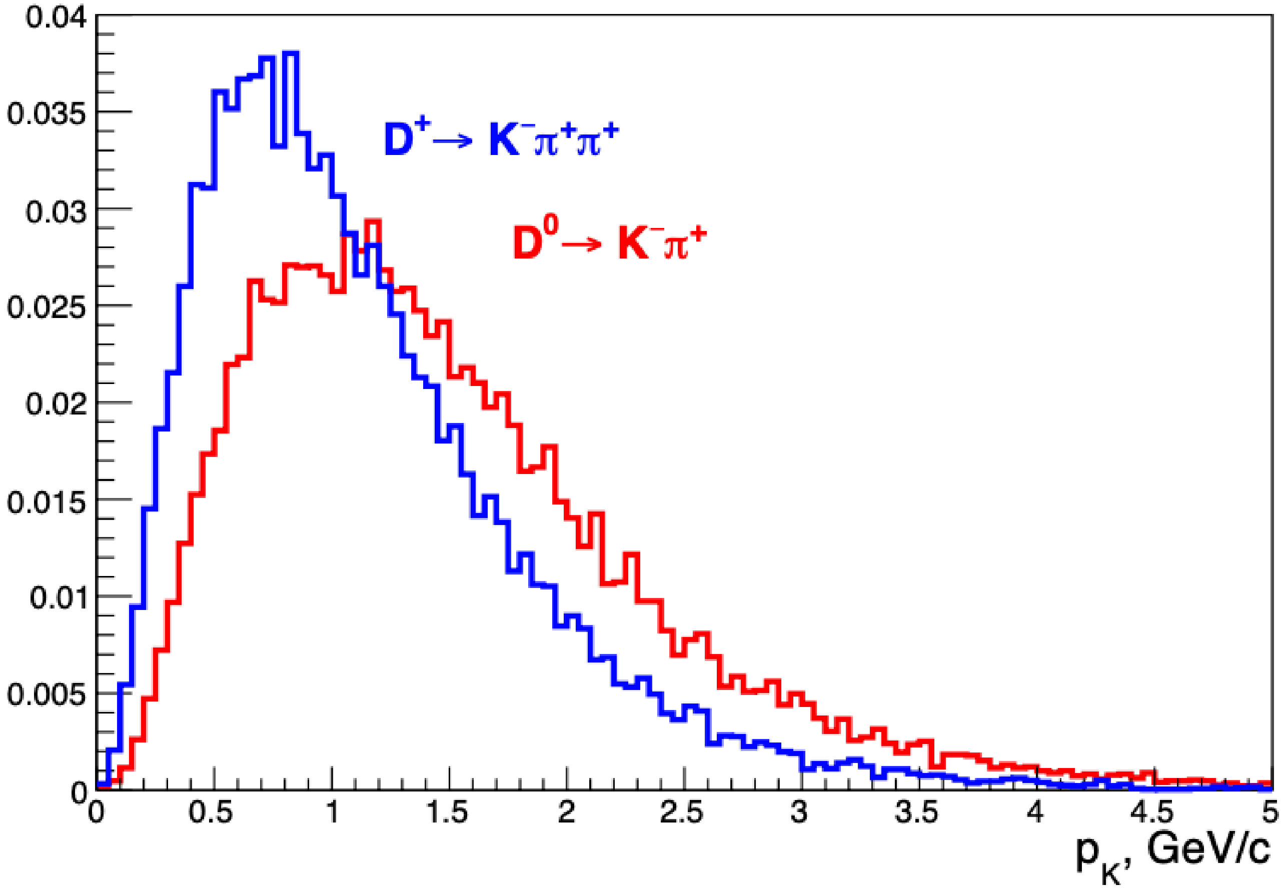
Nuclotron based Ion Colliding fAcility

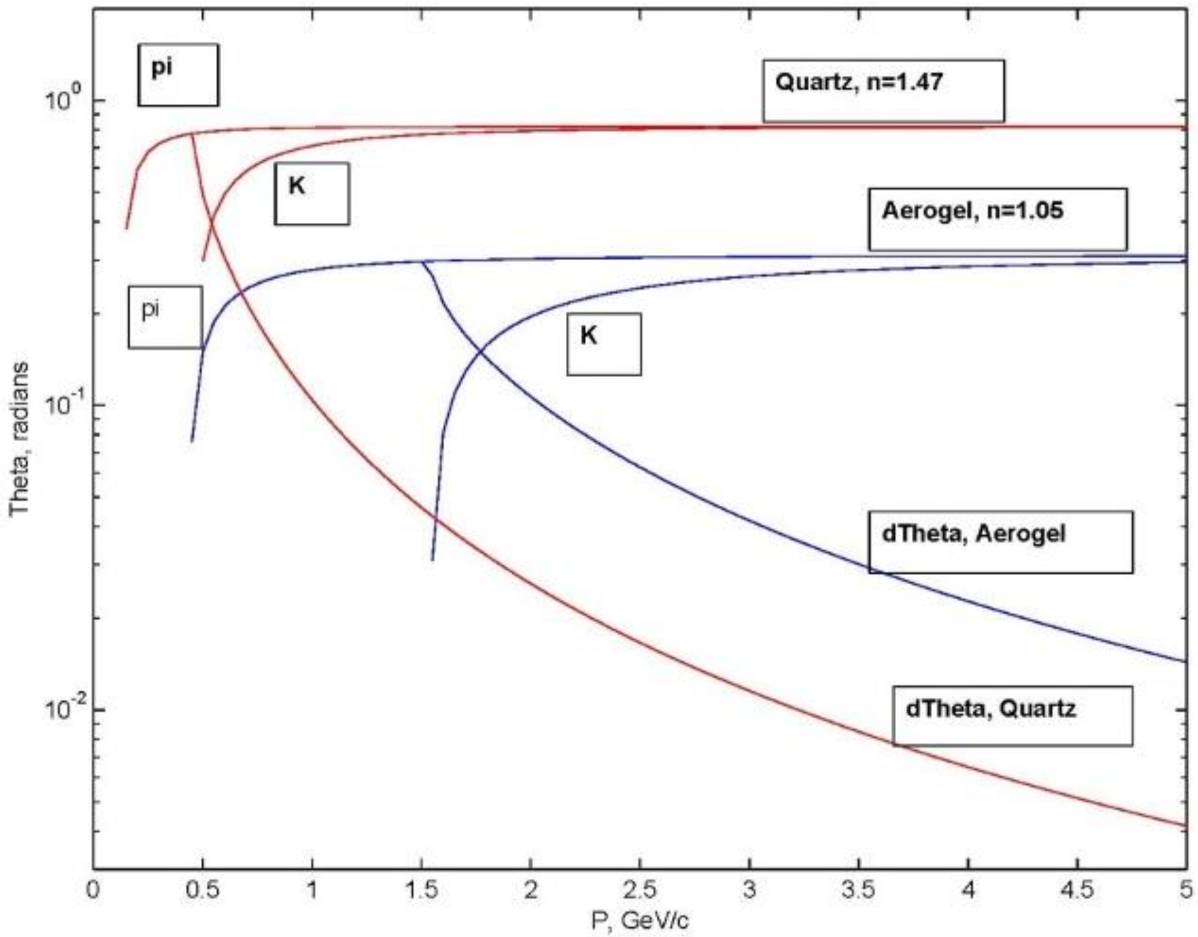
for fundamental nuclear interaction study



http://spd.jinr.ru

PID system: requirements

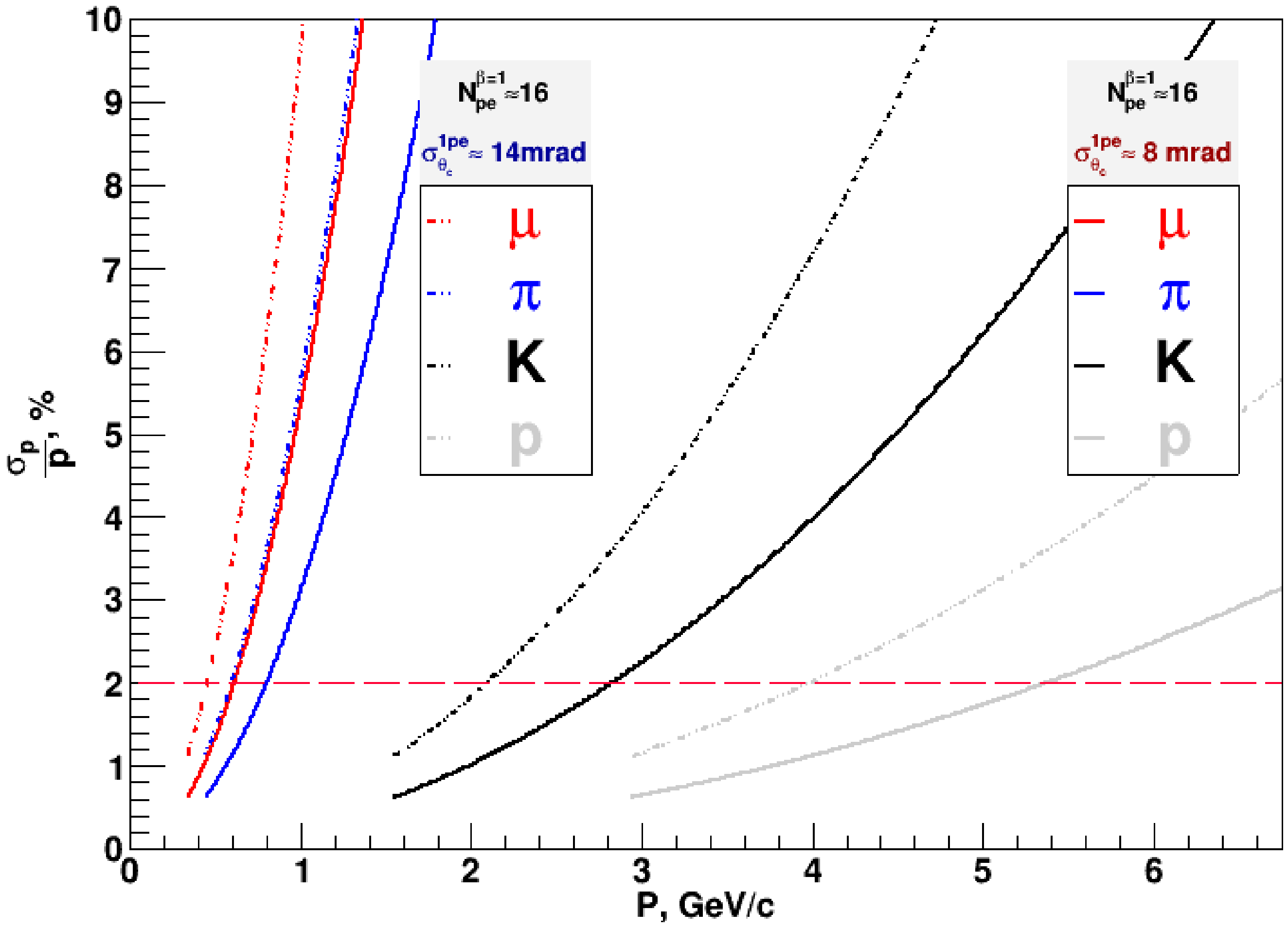




<u>The main task</u> of SPD PID system is
π/K-separation up to P=5÷6 GeV/c

For reliable π/K-separation at P=6 GeV/c the RICH detector is required:
– $n = 1.05$ (aerogel),
– $\sigma_C \sim 2.5\ mrad/track$

Momentum measurements with FARICH



$$\frac{\sigma_p}{p} = \gamma^2 \cdot \frac{\sigma_\beta}{\beta}$$

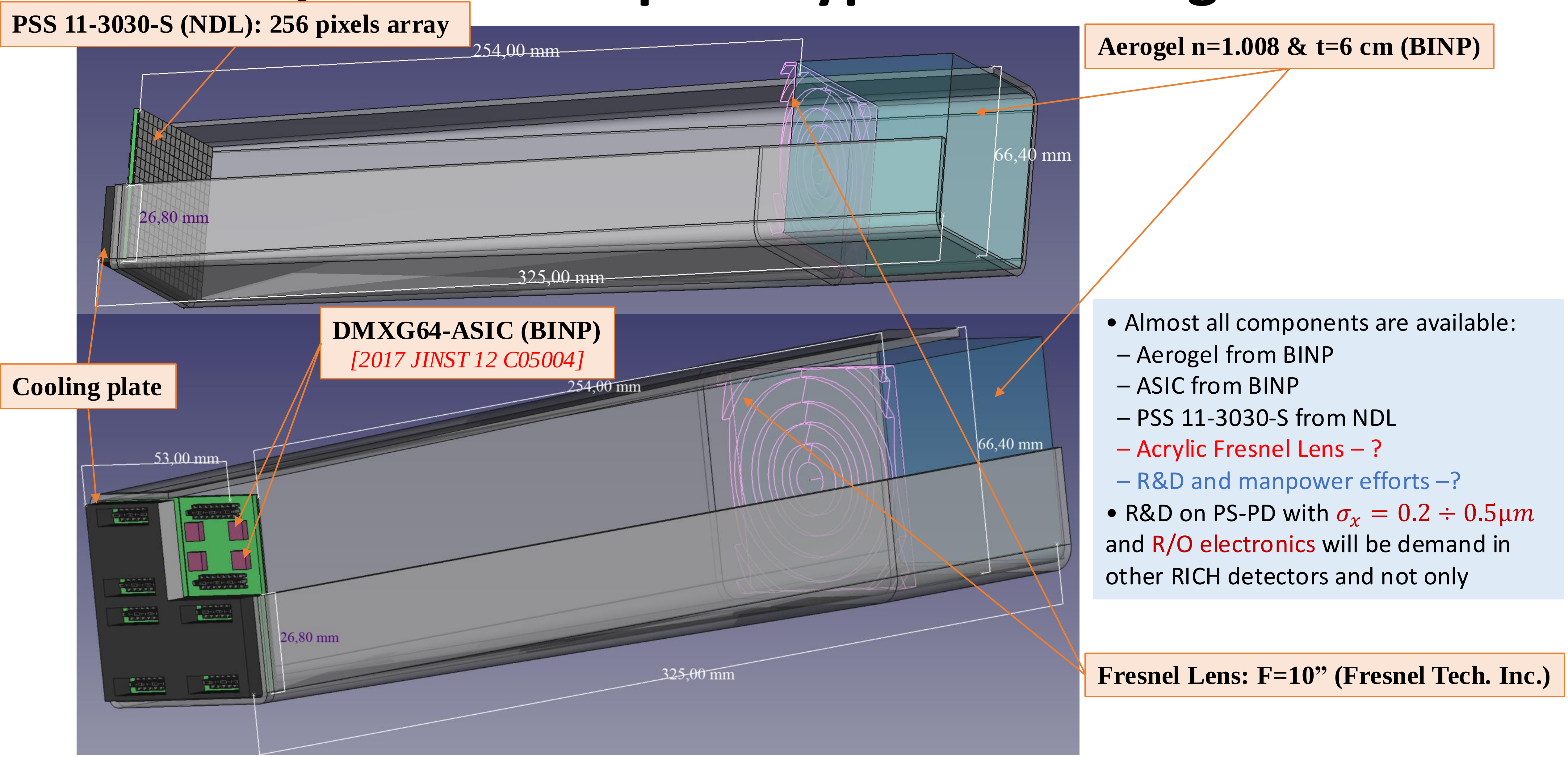
$$\frac{\sigma_p}{p} = \gamma^2 \cdot \tan\theta \cdot \sigma_\theta^{tr}$$

$$\sigma_\theta^{tr} = \frac{\sigma_\theta^{1pe}}{\sqrt{N_{pe}(p)}} = \frac{\sigma_\theta^{1pe}}{\sqrt{N_{pe}^{\beta=1}}} \cdot \frac{p\sqrt{n^2-1}}{\sqrt{p^2(n^2-1)-m^2}}$$

$$\frac{\sigma_p}{p} = \frac{p\sqrt{p^2+m^2}}{m^2}\sqrt{n^2-1} \cdot \frac{\sigma_\theta^{1pe}}{\sqrt{N_{pe}^{\beta=1}}},$$

where m – particle mass, p – particle momentum, $n = 1.05$ – refractive index of aerogel, σ_θ^{1pe} and $N_{pe}^{\beta=1}$ are single photon Cherenkov angle resolution and number of detected photons per track correspondingly measured with relativistic electron beams.

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