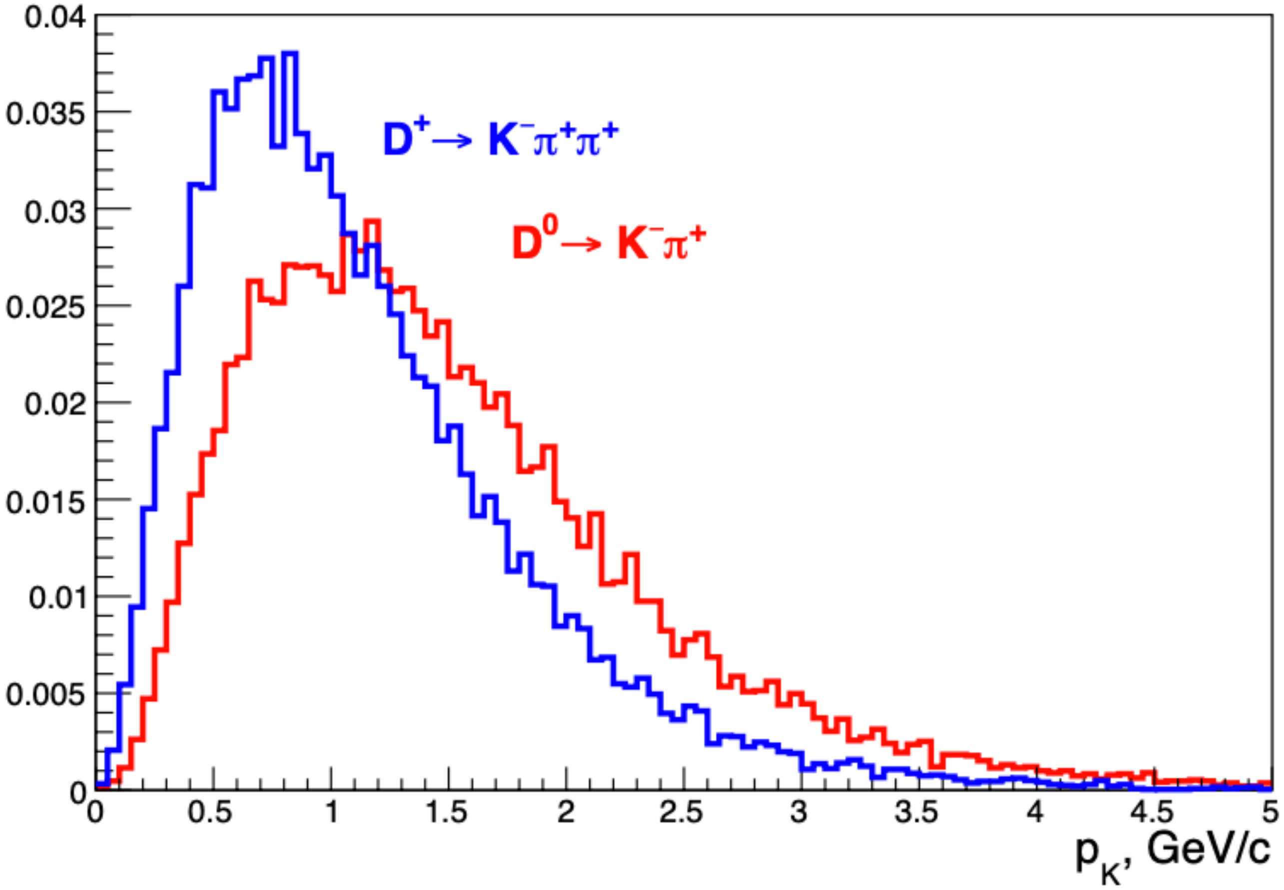
Development of FARICH detector for the SPD experiment: status and prospects

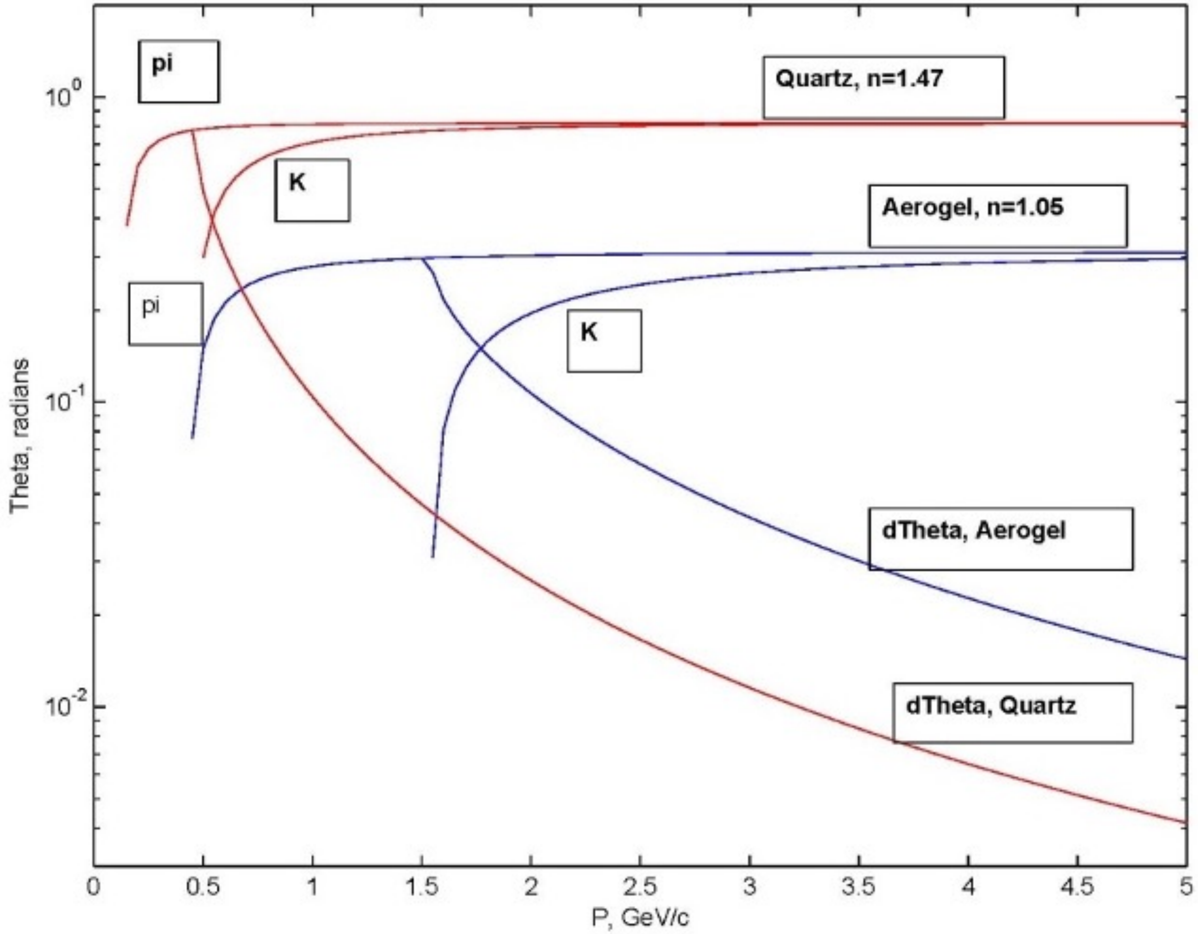
A.Yu.Barnyakov on behalf of PID group

SPD Collaboration Meeting

20-24 May 2024, KBTU, Almaty, Kazkhstan

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:

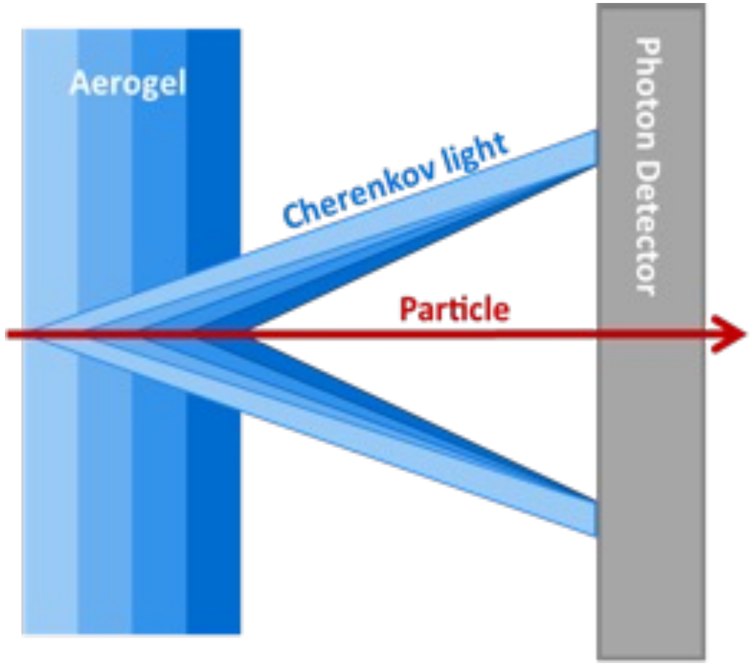
– $n = 1.05$ (aerogel),

– $\sigma_C \sim 2.5\ mrad/track$

FARICH motivation

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

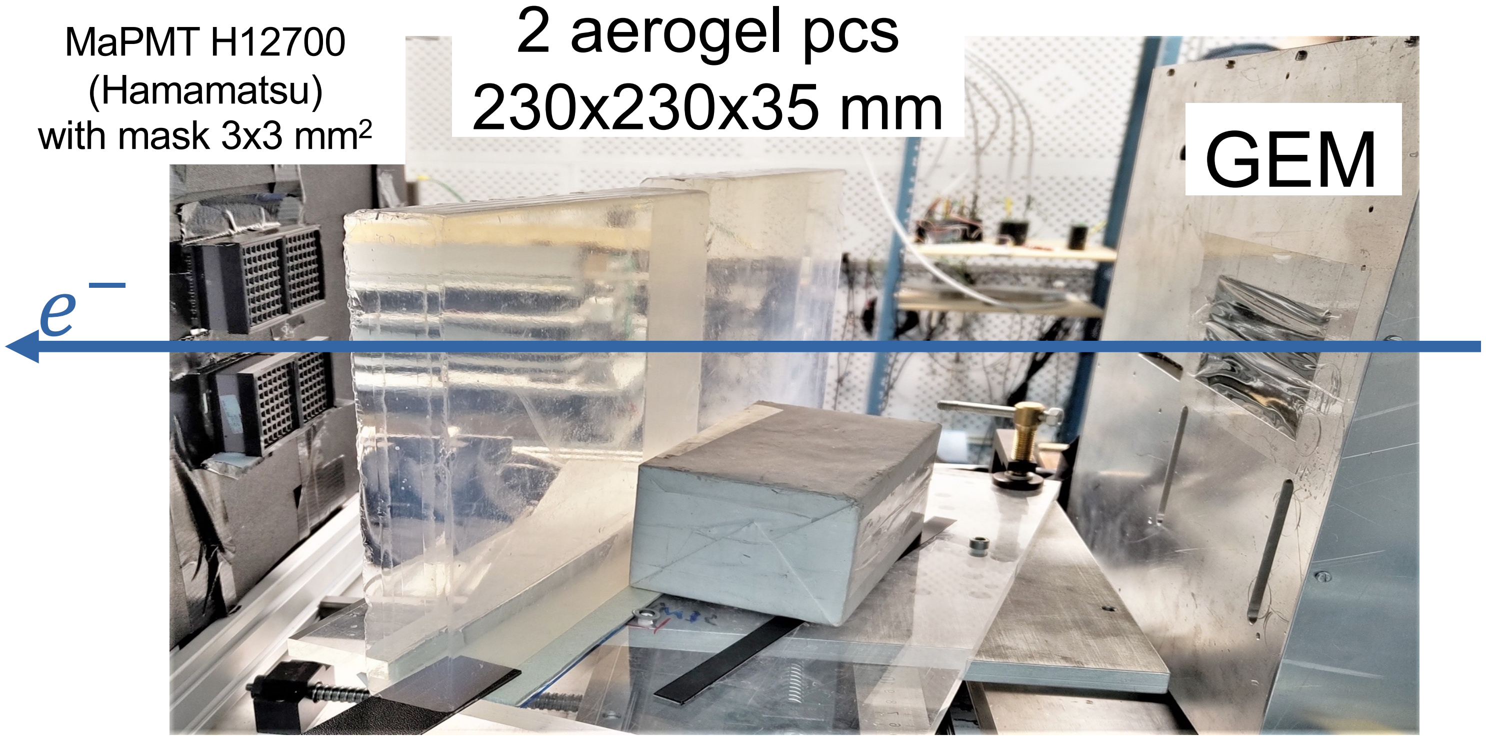
To get $\langle N_{pe} \rangle \gg 5$ from aerogel with n=1.05 & thickness 1 cm is too hard practice task!!!



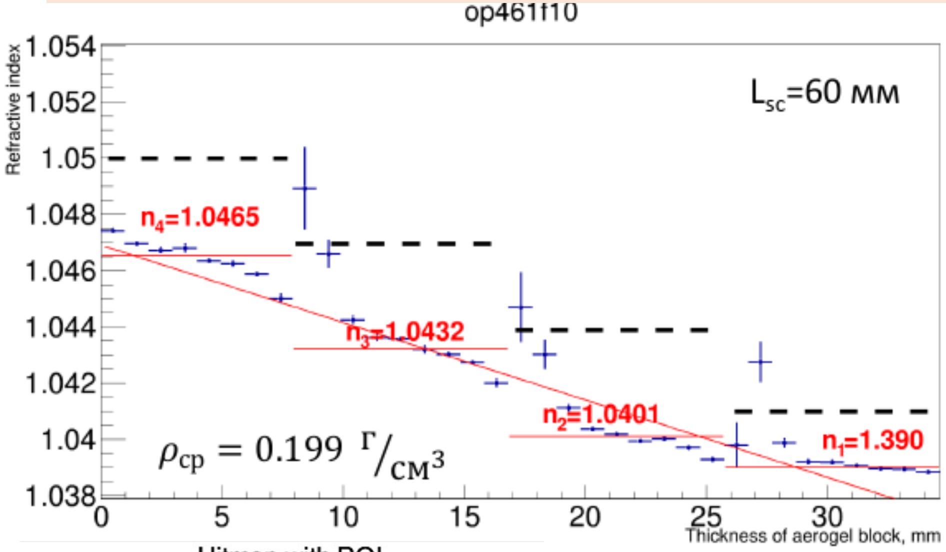
- Thicknesses and refractive indexes in each layer are adjusted in such way that Cherenkov rings from each layer overlap in the same region of the position-sensitive photon detector.
- The number of detected Cherenkov photons increases due to increase of the thickness without degradation of Cherenkov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

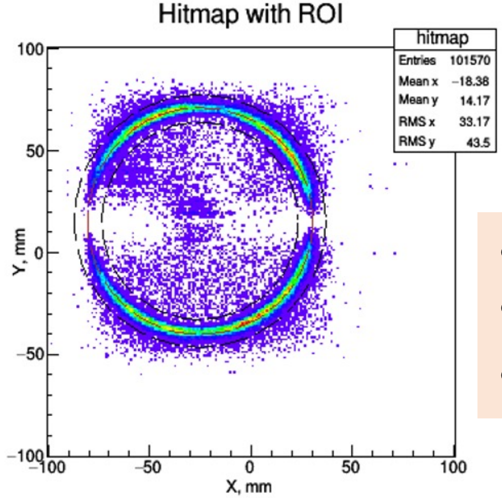
T.Iijima et al., NIM A548 (2005) 383 and A.Yu.Barnyakov et al., NIM A553 (2005) 70

The largest 4-layer focusing aerogel samples were produced in Novosibirsk and tested at BINP in 2022-2023



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

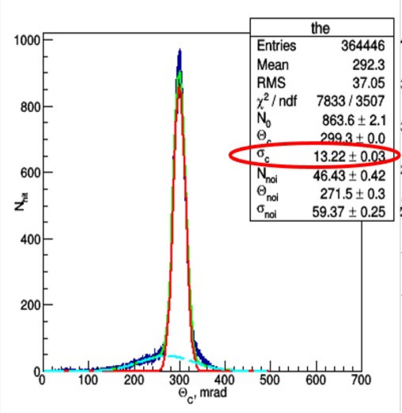


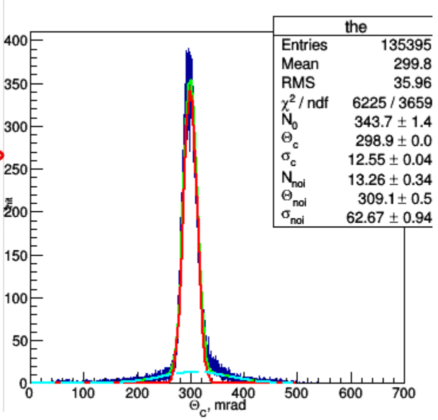


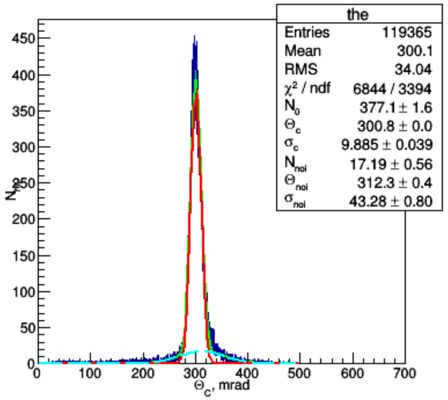
Single photon Cherenkov angle resolution is investigated with relativistic electrons at BINP beam test facilities "Extracted beams of VEPP-4M complex".

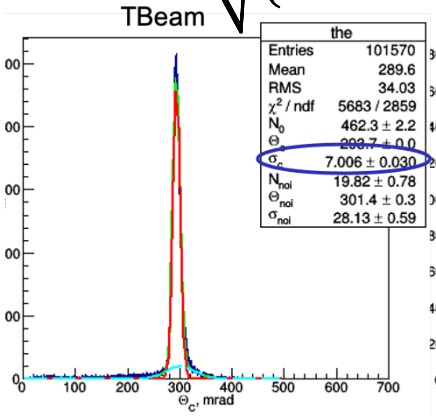
- Pixel ■ 3x3 mm
- Geom.Eff. ~ 20%
- $\sigma_\theta^{1pe} \approx 7\ mrad$

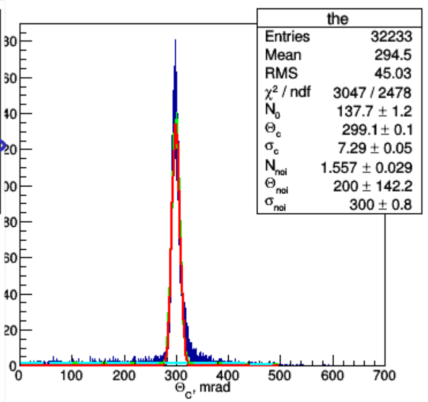
TBeam 2023 res.: $\sigma^{1pe}_{\theta_C} = \sqrt{\frac{\Delta^2_{pix}}{(\sqrt{12}\cdot L\cdot n)^2} + \sigma^2_{aer} + \sigma^2_{trk}}$

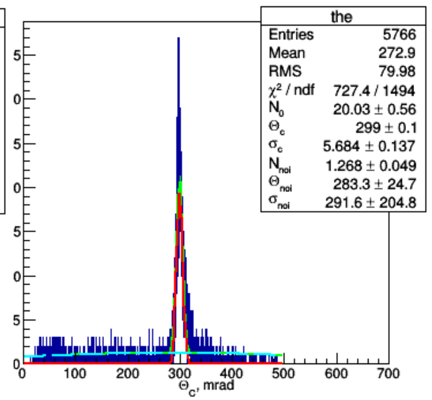




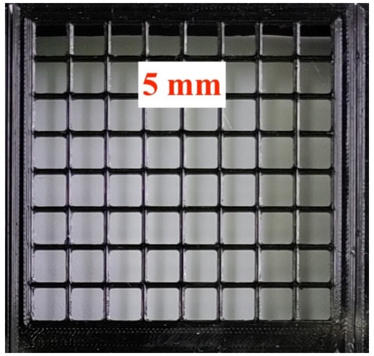


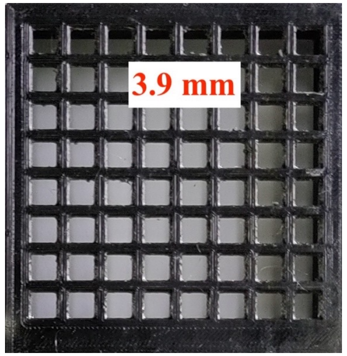


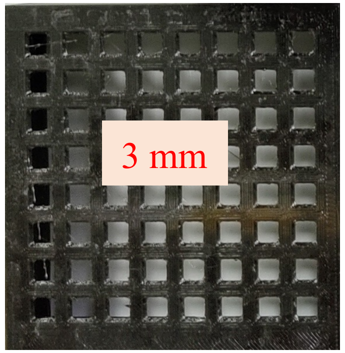


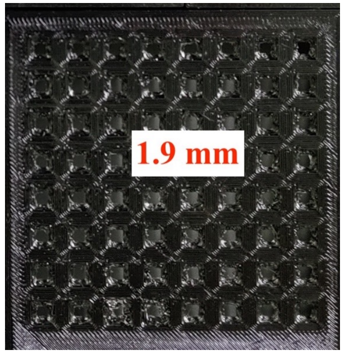


No mask:
$6\times6\ mm$

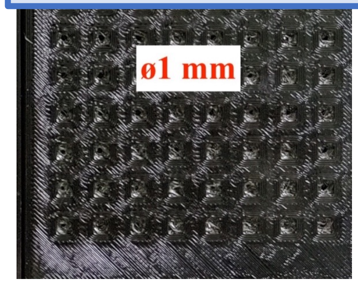








$\sigma_{aer} \approx 5.7$ mrad



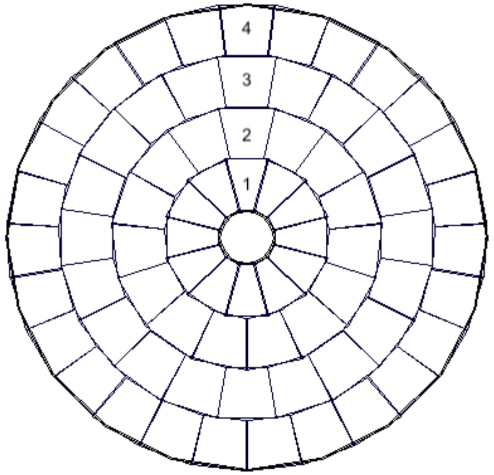
04/23: L≈200 mm	12/23: L≈180 mm	12/23: L≈180 mm	04/23: L≈200 mm	12/23: L≈180 mm	12/23: L≈180 mm
Geom.Eff. ~ 80%	Geom.Eff. ~ 56%	Geom.Eff. ~ 36%	Geom.Eff. ~ 20%	Geom.Eff. ~ 9%	Geom.Eff. ~ 2%
$N_{pe} \approx 16$	$N_{pe} \approx 12$	$N_{pe} \approx 8$	$N_{pe} \approx 4$	$N_{pe} \approx 2$	$N_{pe} \approx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

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 conceptual design

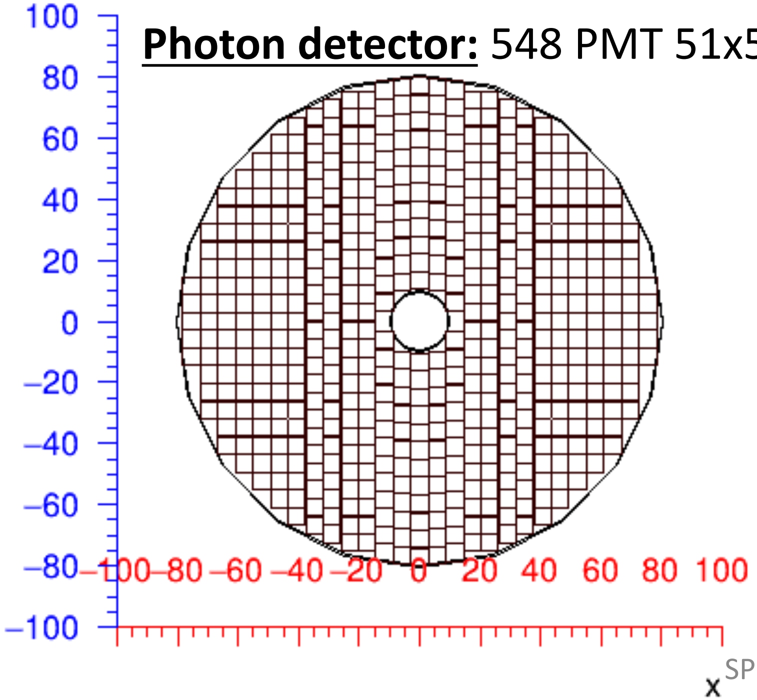
Aerogel:
74 tiles

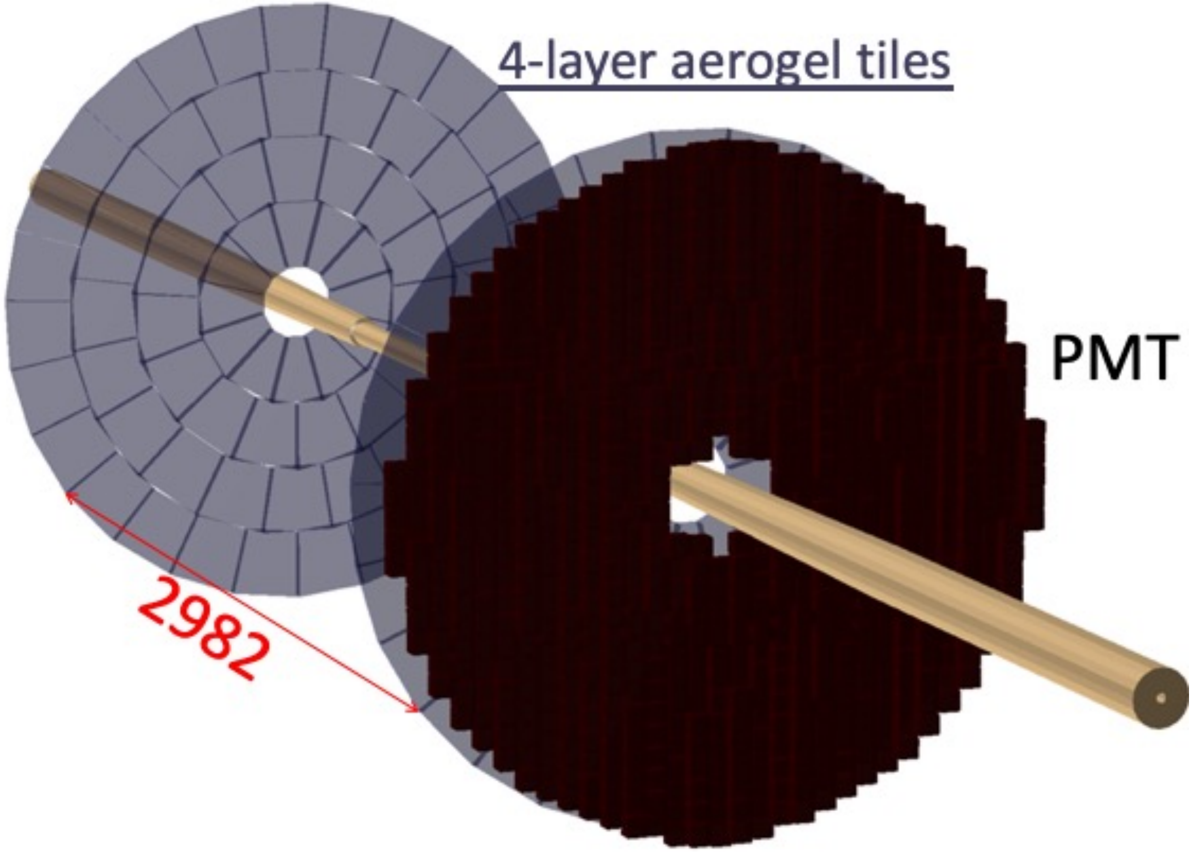


1 – 12 tiles x S=0.5•(5.6 + 15.6)•18.5 = 159.0 sq.cm
2 – 15 tiles x S=0.5•(12.2+20.2)•18.5 = 299.7 sq.cm
3 – 20 tiles x S=0.5•(15.0+20.8)•18.5 = 331.15 sq.cm
4 – 27 tiles x S=0.5•(15.2+19.6)•18.5 = 321.9 sq.cm

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

Photon detector: 548 PMT 51x51 mm



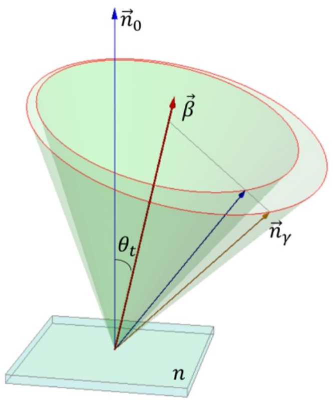


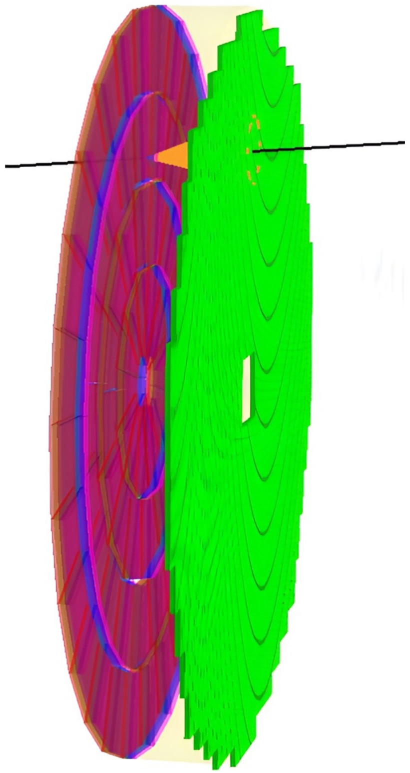
FARICH system:

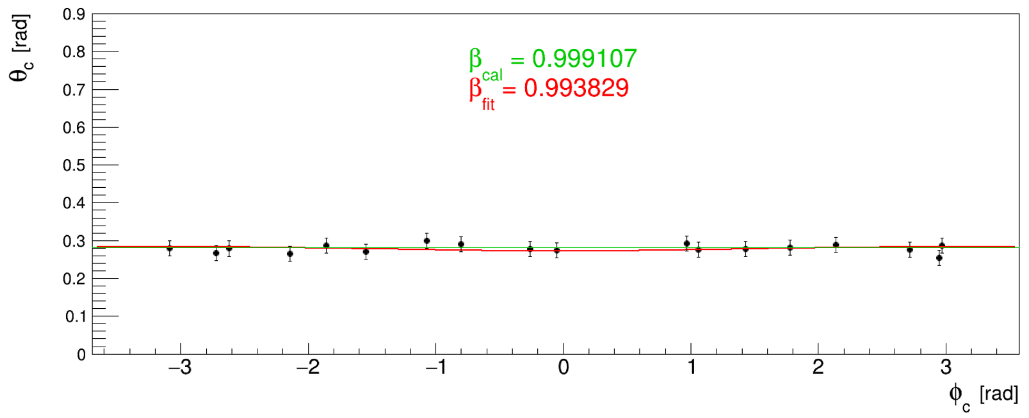
- 4-layer aerogel with n_{max}=1.05 (or less)
- Focus distance – 20 cm
- PS PD – MCP-PMT or SiPM arrays with pixel 3÷6 mm
  550 PMTs per endcap if lateral sizes ~51x51 mm
  2200 PMTs per endcap if lateral sizes ~27x27 mm

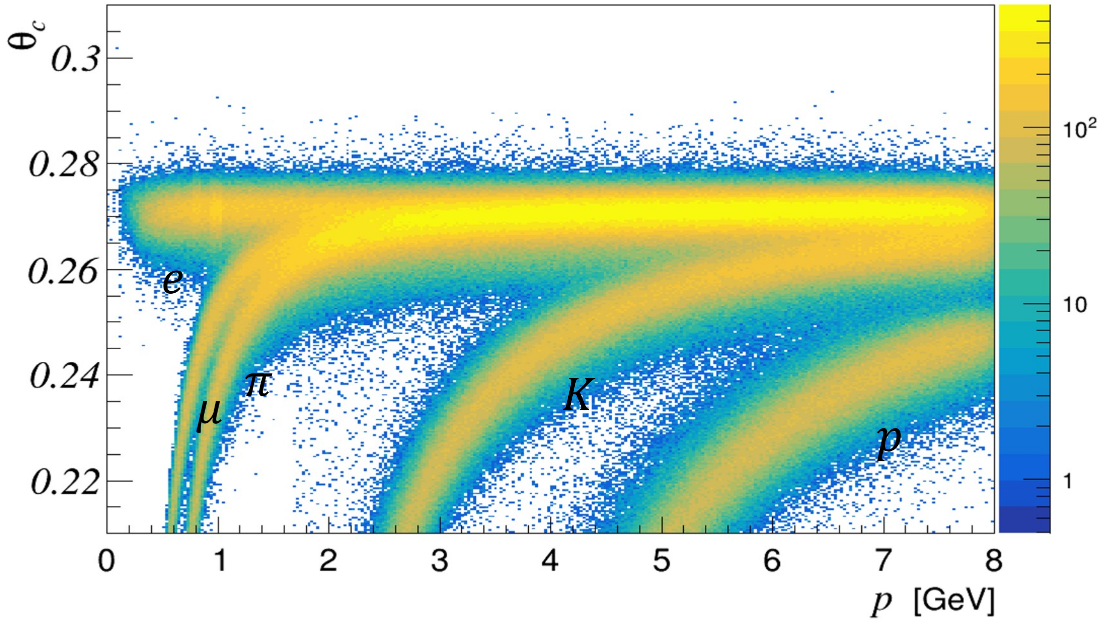
Simulation FARICH in SPD

Reconstruction: fit analytical formula to (θ_{c},φ_{c}) distribution to obtain β

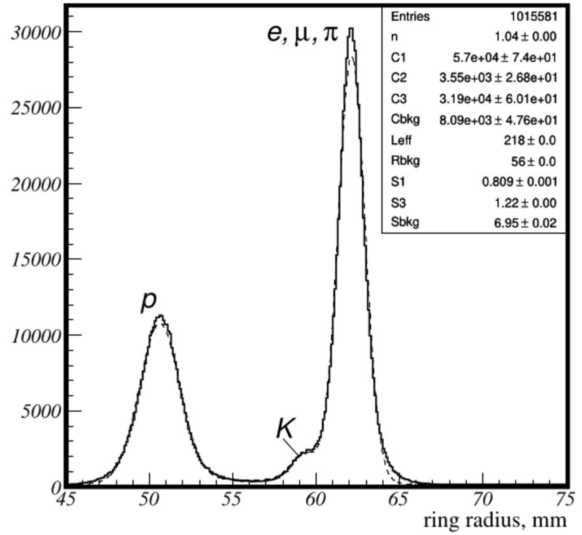




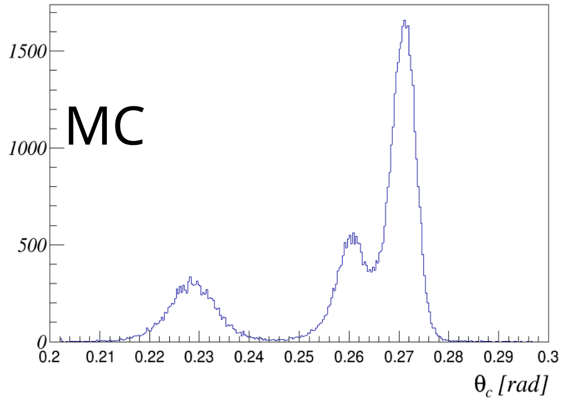




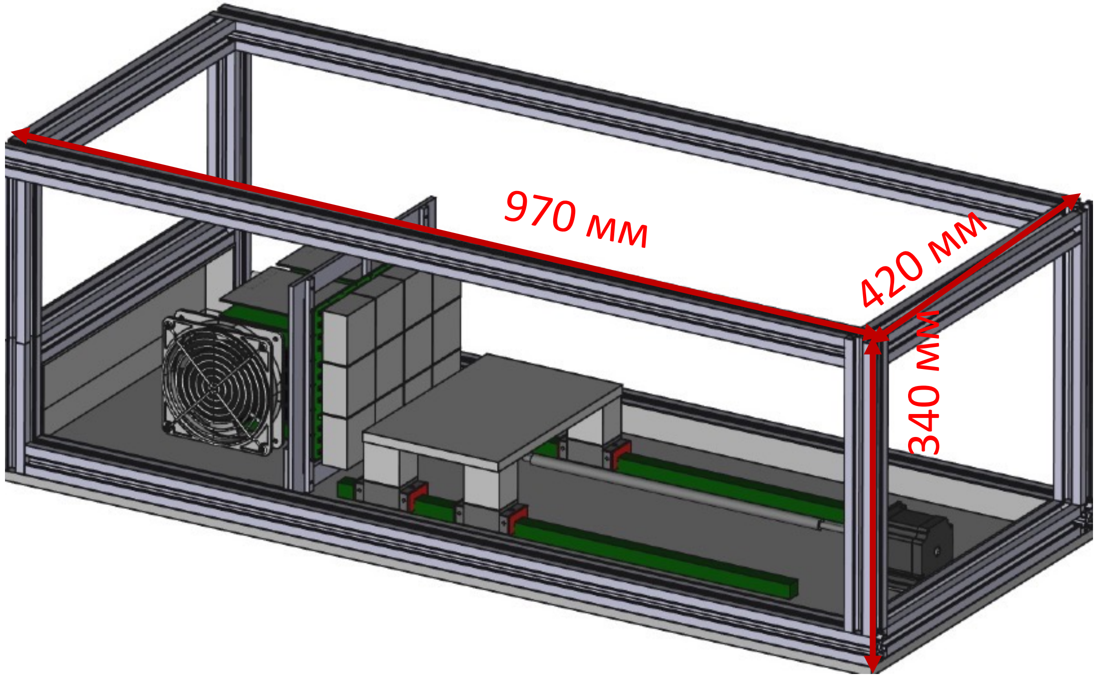
Nucl. Instrum. Meth. A, 732:352–356, 2013

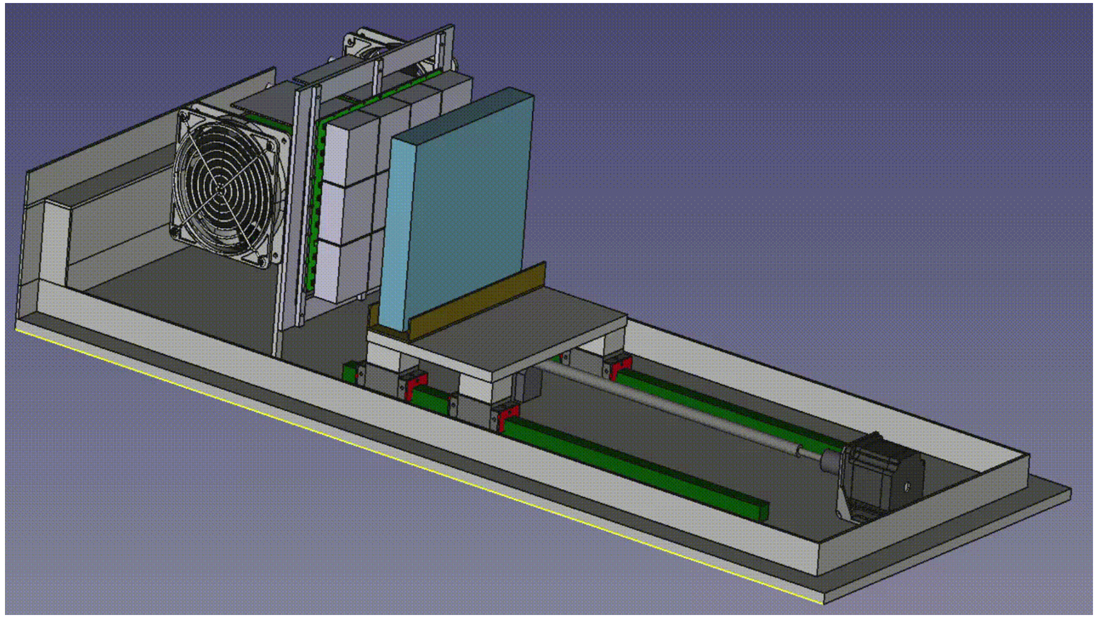


particles momentum 6 GeV/c



FARICH prototype with full ring detection

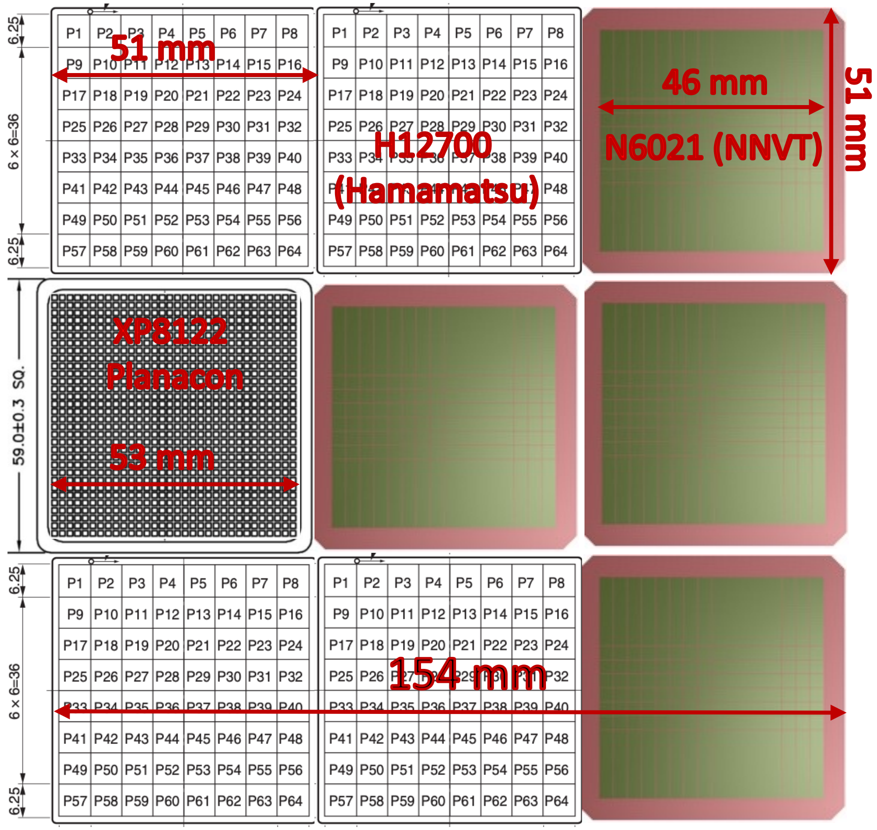


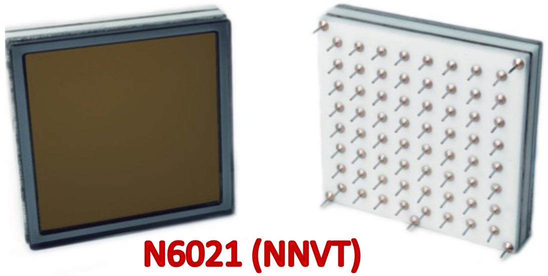


- Tunable focal distance from 5 to 60 cm
- Aerogel tiles with lateral dimensions up to 200x200 mm^2
- 2 DiRICH boards (GSI) to readout up to 12 multi-anode PMTS with 768 pixels *in total* – option #1
- 6 DiRICH boards (GSI) to readout up to 36 multi-anode PMTS with 2304 pixels *in total* –option #2

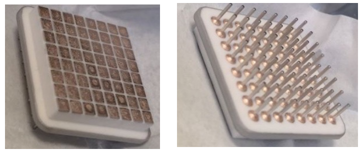
FARICH prototypes

Step #1 (2024/25): 6x6mm





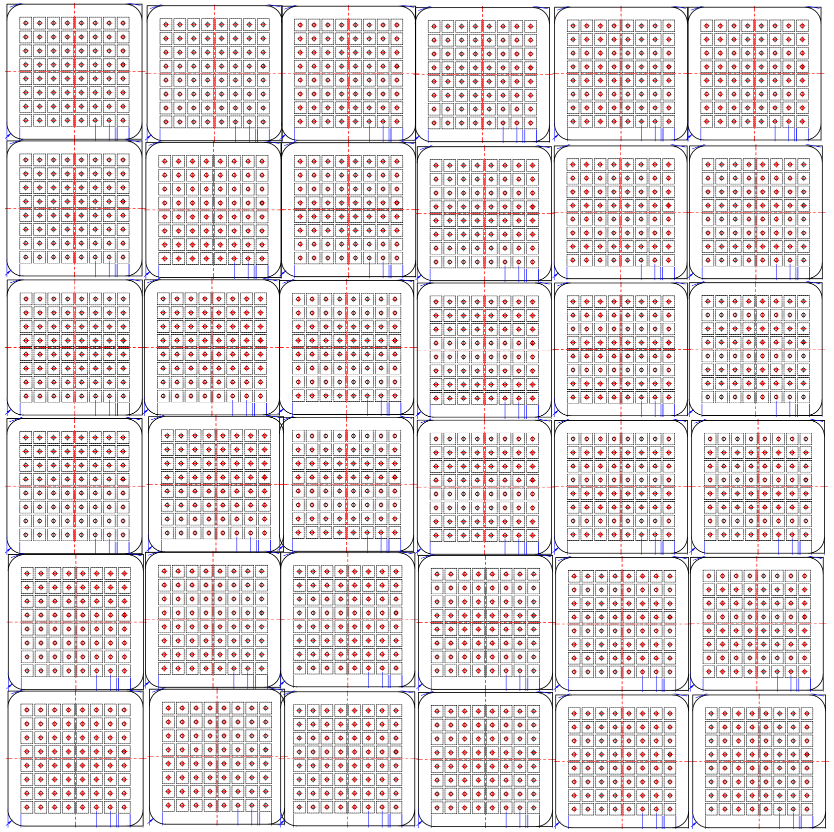
N6021 (NNVT)



Ekran FEP

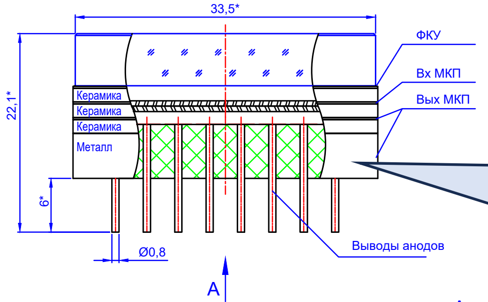
$6{\times}6\ mm$ {
- 4 MCP PMTs N6021 from NNVT
- 4 MaPMTs H12700 from Hamamtsu
- 1 XP85122 Planacon MCP PMT from from Photonis
- $S_{sens}/S_{tot} \approx 0.8$
- 2 DiRICH boards (GSI) to readout chan.

Step #2 (2025/26): 3x3mm

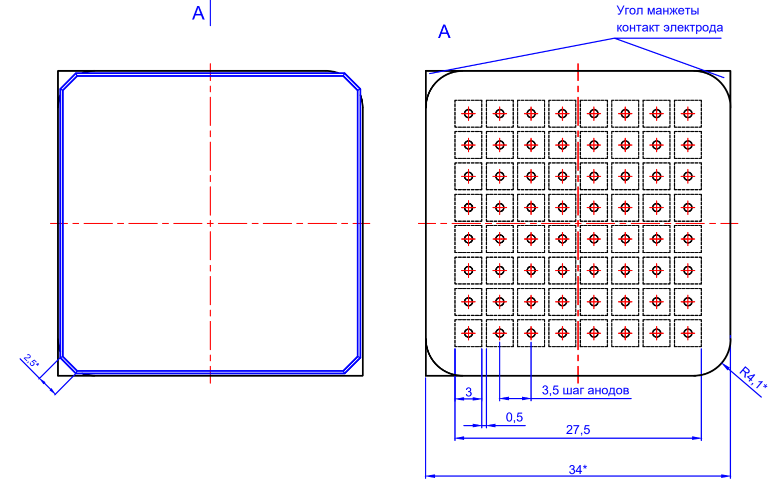


- 6x6=36 MCP PMTs from Ekran FEP
- 3x3mm pixel
- $S_{sens}/S_{tot} \approx 0.5$
- 6 DiRICH boards (GSI) to readout 2304 chan.

MCP PMT rectangular shape from Ekran FEP



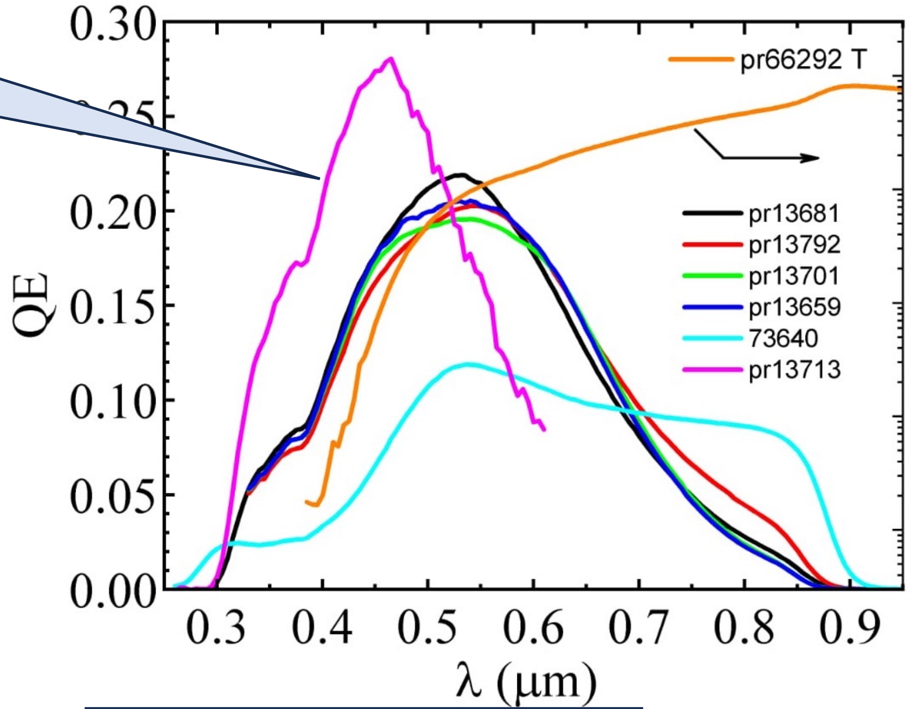
Ekran FEP design of MCP PMT with 8x8 3x3 mm pixels



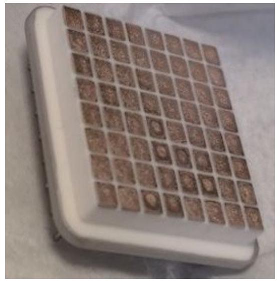
* Размер для справок. Возможны незначительные изменения.

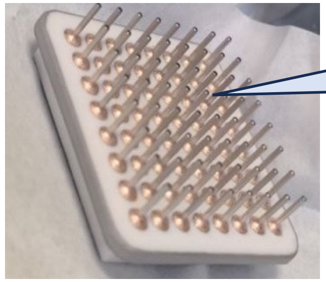
It is planed to use <u>UV-glass</u> to enhence PDE in blue region

<u>Multi-alkali PCs</u> sputtered on ordinary glass



- Until the Autumn the first Russian rectangular-shape multi-anode MCP PMTs partially based on Chinese components are expected
- Until the end of year MCP PMTs totally based on Russian components are expected



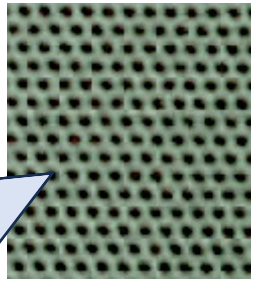


<u>Ceramic components</u> from China (NNVT) deliverd to Ekran FEP

Ekran FEP also works with vendors from Saratov to produce ceramic components inside the Russia

<u>MCPs:</u>

- For the first rectangular PMTs usage of MCPs made by Ekran FEP is planed
- For the first serial batch implementation of MCPs from VTC Baspik is planed



On aerogel optimization for the SPD project

- 4-layer aerogel with $n_{max} = 1.05$ and thickness $35\,mm$ was optimized for SCTF to provide reliable μ/π–separation at $1\ GeV/c$
- For SPD aerogel lower index looks more suitable to provide π/K– and μ/π–separation at higher momenta. Lower n means:
  - Larger difference in π– and K–mesons Cherenkov angles;
  - lower impact from dispersion;
  - but lower number of Cherenkov photons which could be compensted by increase of aerogel thickness especially if the pixel size is about $6\ mm$.
- More optimal aerogel for SPD looks like:

  > Maximal refractive index ~ 1.04

  > Aerogel thikness is about $40\ mm$

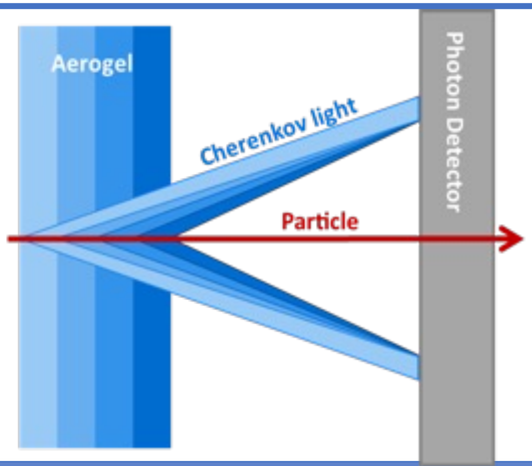
  > 3 or 4 number of layers with 15 or 10 mm thick each
- There is a room for optimization with help of simulation or even ML approaches
- There is a room for optimization with help of simulation or even ML approaches
- R&Ds on production of optimal SPD aerogel and test its performances are required.

Summary & Plans for 2024/2025

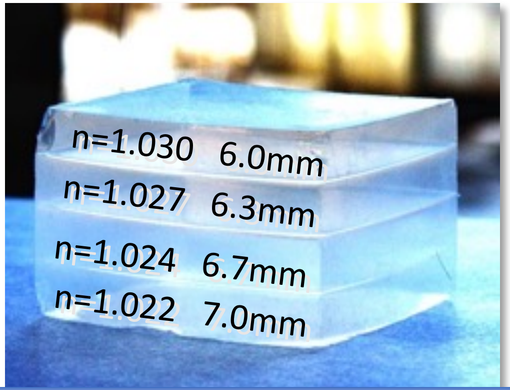
- We are going (and almost ready) to prepare and carry out tests with FARICH prototype based on available components at hadron beams to demonstrate its current PID capabilities:
  - 4-layer aerogel tiles with n_{max}=1.05 and t=35mm (*optimized for SCTF project*)
  - Multi-anode PMTs (from Hamamatsu, NNVT, Photonis) with $6\times6\ mm$ pixels
  - DiRICH (GSI) based readout system
- Optimize (with help of simulation) and produce first aerogel tiles for the SPD experiment requirements (n_{max}=1.04 and t=40mm)
- Test and compare performances of position-sensetive MCP PMTs with rectangular shapes:
  - N6021 from NNVT (China) – $6\times6\ mm$ pixels
  - For the first time produced in Russia from Ekran FEP – $3\times3\ mm$ pixels
- Start developmant of FARICH prototype based on Russian position-sensetive MCP PMTs

BACK UP SLIDES

FARICH technique milestones



The first 4-layer monolithic sample

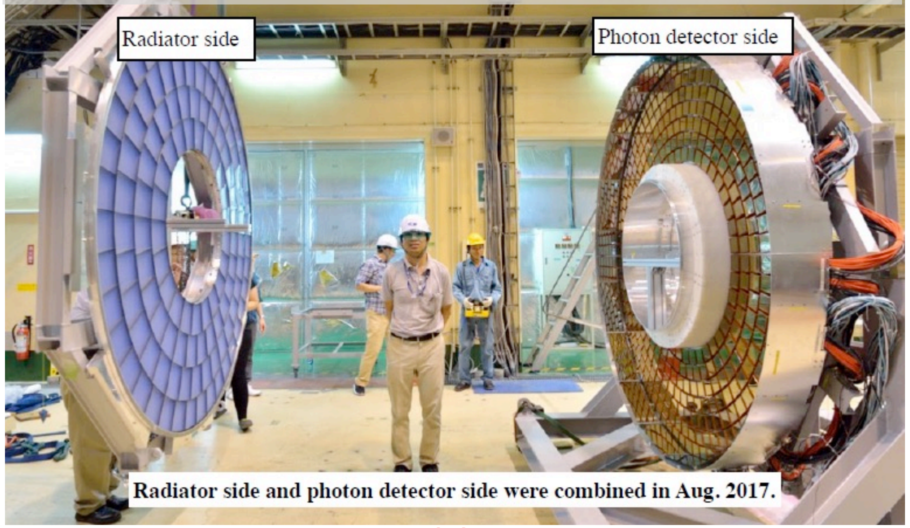


Increase N_{pe} due thickness increase without $\sigma_{\Theta c}$ degradation

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

2004÷2005

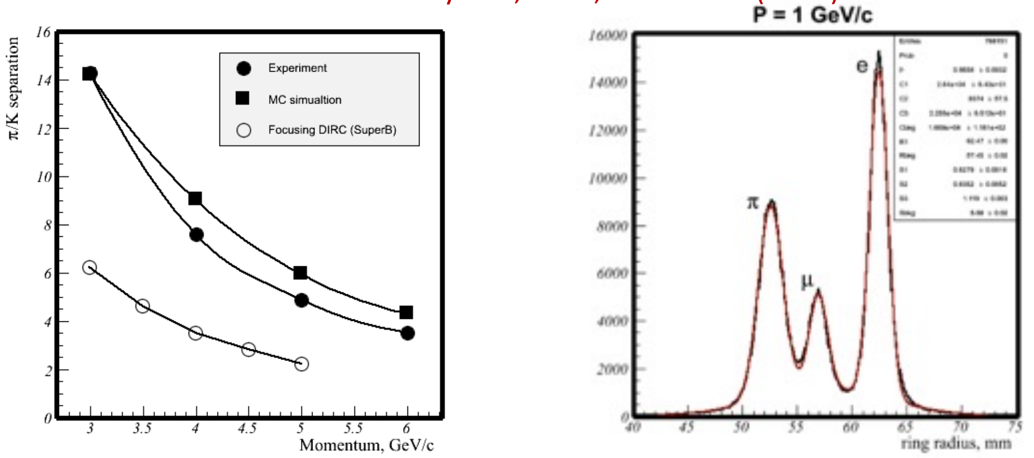
The Belle II (ARICH) is the first application of the method



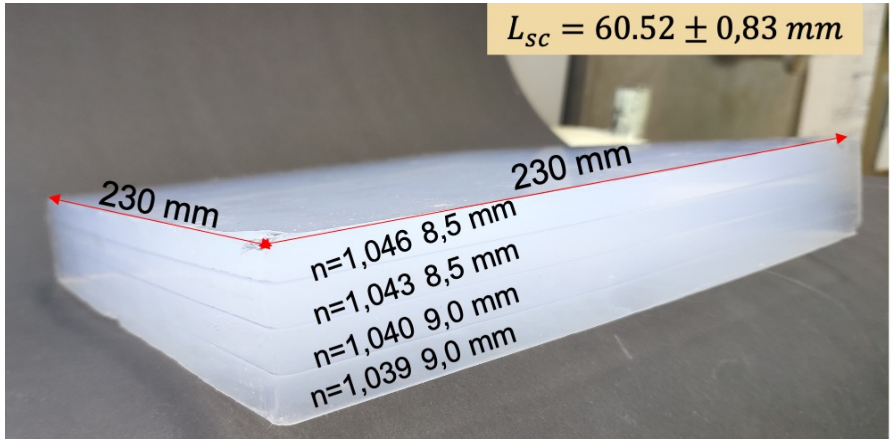
2017

Excellent PID capability were shown at CERN beam test in 2012

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



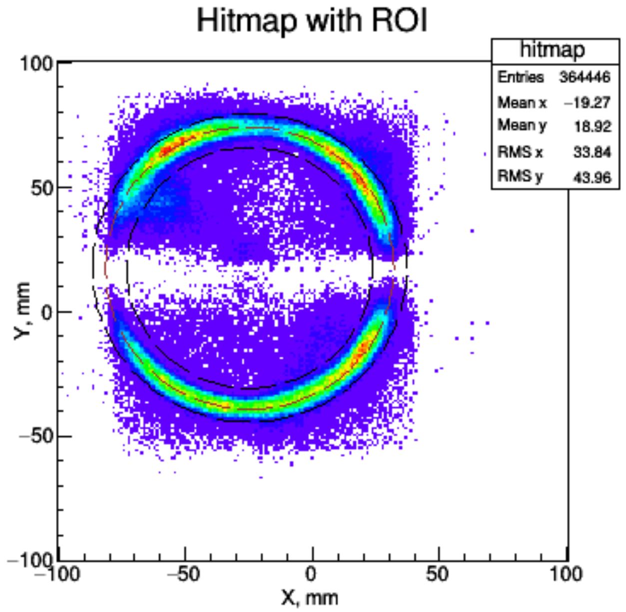
Two 4-layer focusing aerogel blocks
230x230x35 mm

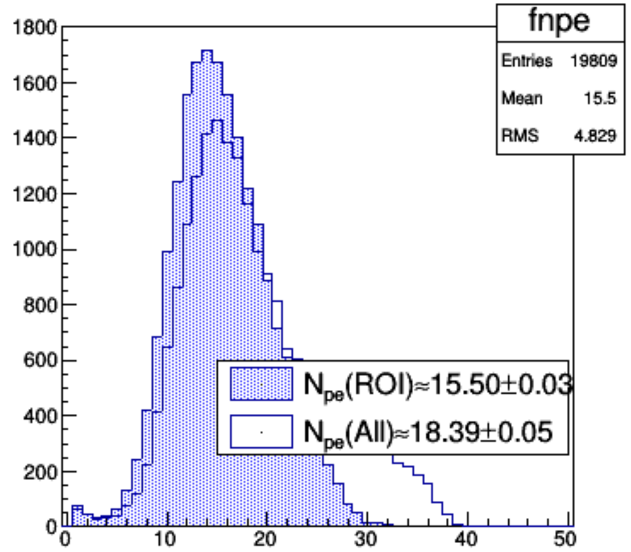


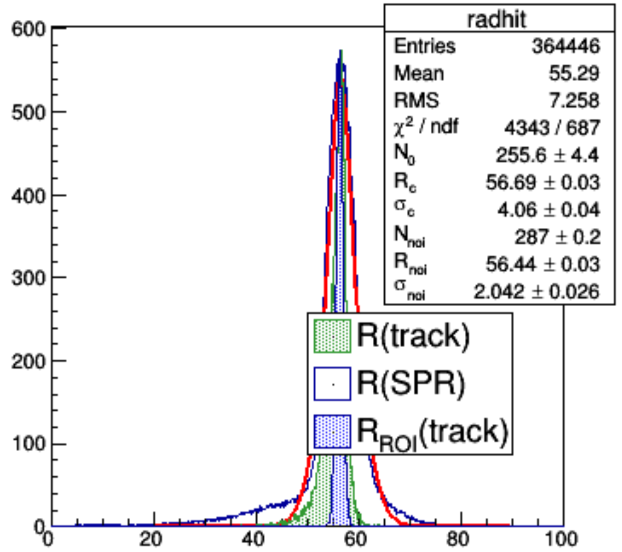
2022÷2023

Recent beam test results

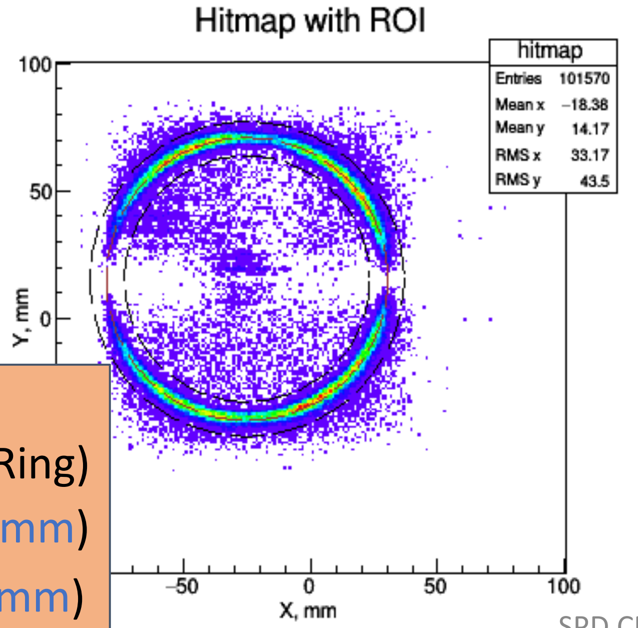
Pixel 6x6 mm
Geom.Eff. ~ 80%

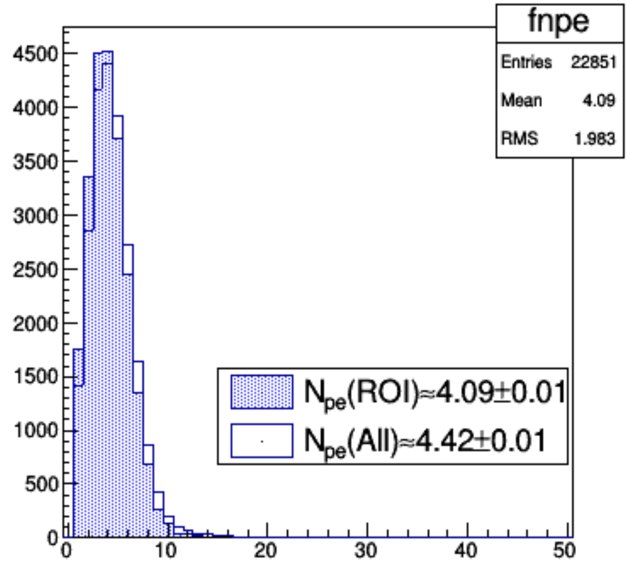


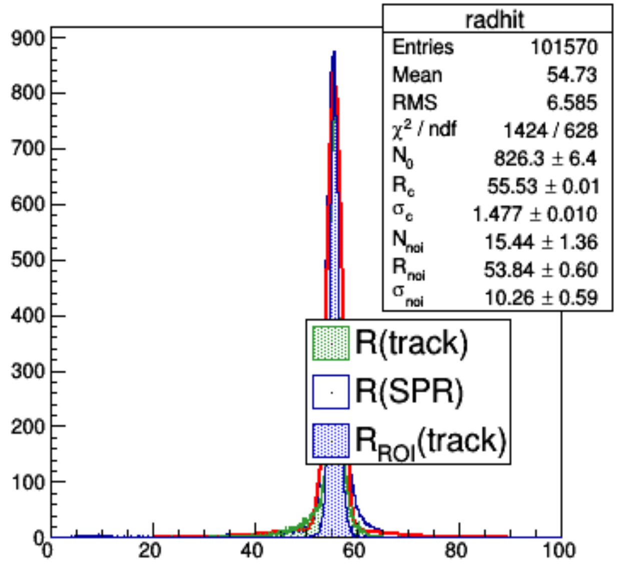




Pixel 3x3 mm
Geom.Eff. ~ 20%



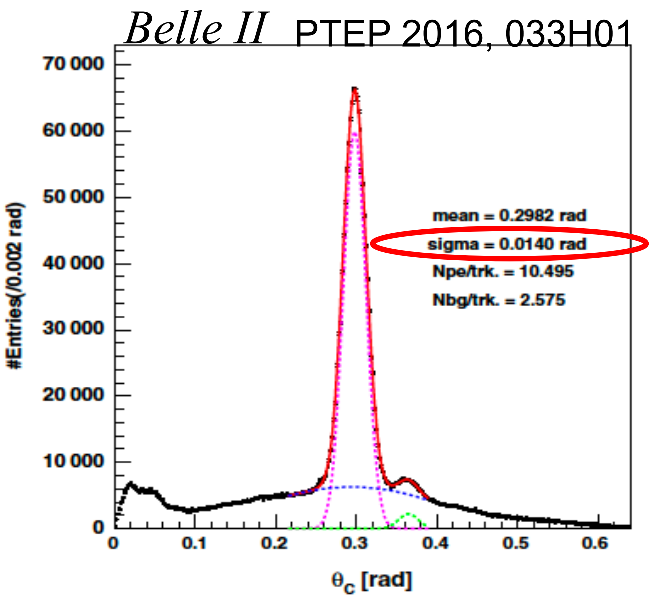


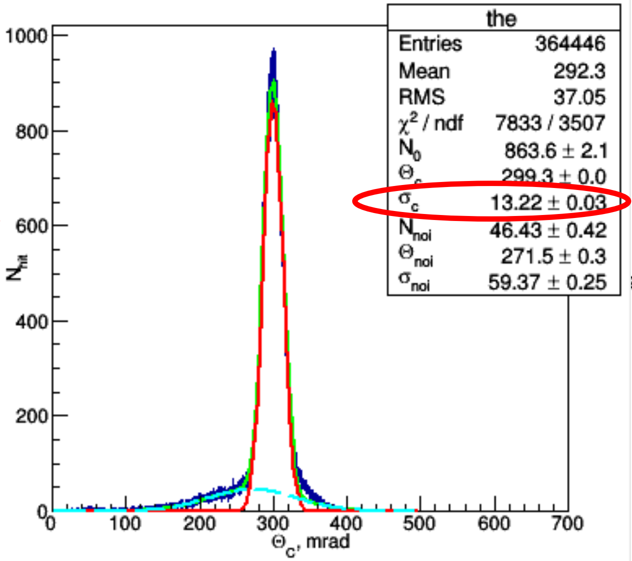


Main results:

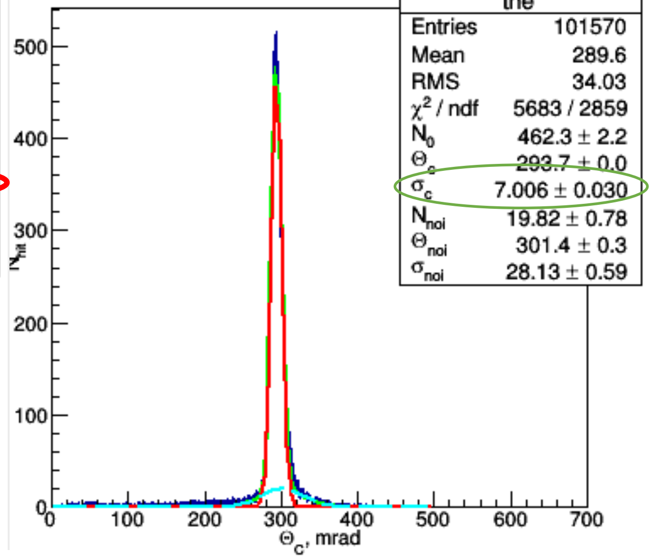
- N_{pe} ≈ 16 (~ 0.8 of Ring)
- $\sigma_\theta^{1pe} \approx 13.5\ mrad$ (■ 6mm)
- $\sigma_\theta^{1pe} \approx 7.5\ mrad$ (■ 3mm)

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

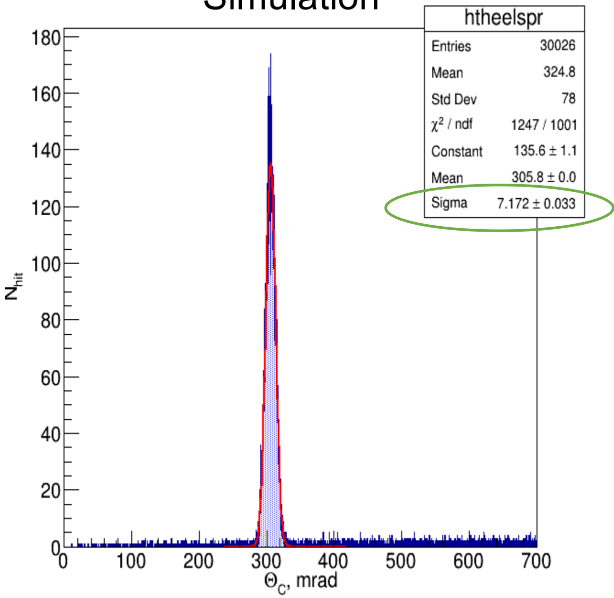




TBeam



Simulation



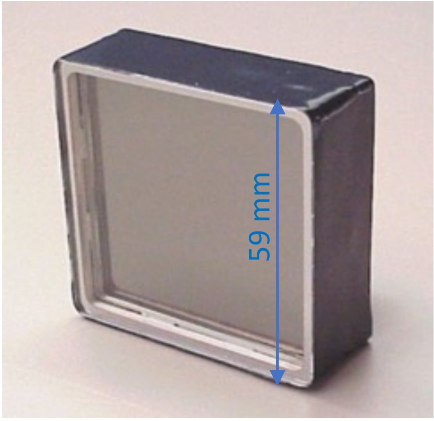
	Belle II		TBeam	Simulation
Aerogel:	20+20 mm (Chiba Univ.)	4-layers (Novosibirsk) –>	–	4-layers (ideal profile)
n(400nm):	1.045 +1.055	1.039 ÷ 1.046	–	1.041 ÷ 1.050
Pixel:	5x5 mm	6x6 mm	3x3 mm	3x3 mm
	Geom.Eff. ~ 90% $N_{pe} \approx 10.5$	Geom.Eff. ~ 80% $N_{pe} \approx 16$	Geom.Eff. ~ 20% $N_{pe} \approx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

Beam test results are in good agreement with MC simulation and corresponds to:
π/K–separation at level of 3σ up to P=4.5 GeV/c for 6x6 mm pixel
π/K–separation at level of 3σ up to P=8.5 GeV/c for 3x3 mm pixel

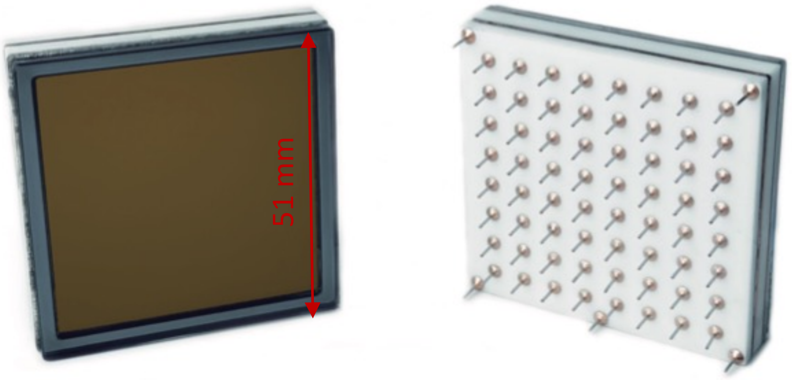
Dimensions of focusing aerogels 23x23x3.5 cm allow us to design the full-scale FARICH systems for the future particle physics experiments.

FARICH based on existing solutions

MCP PMT available from vendors:



Planacon XP85112 (USA)
8x8 pixels with 6x6 mm

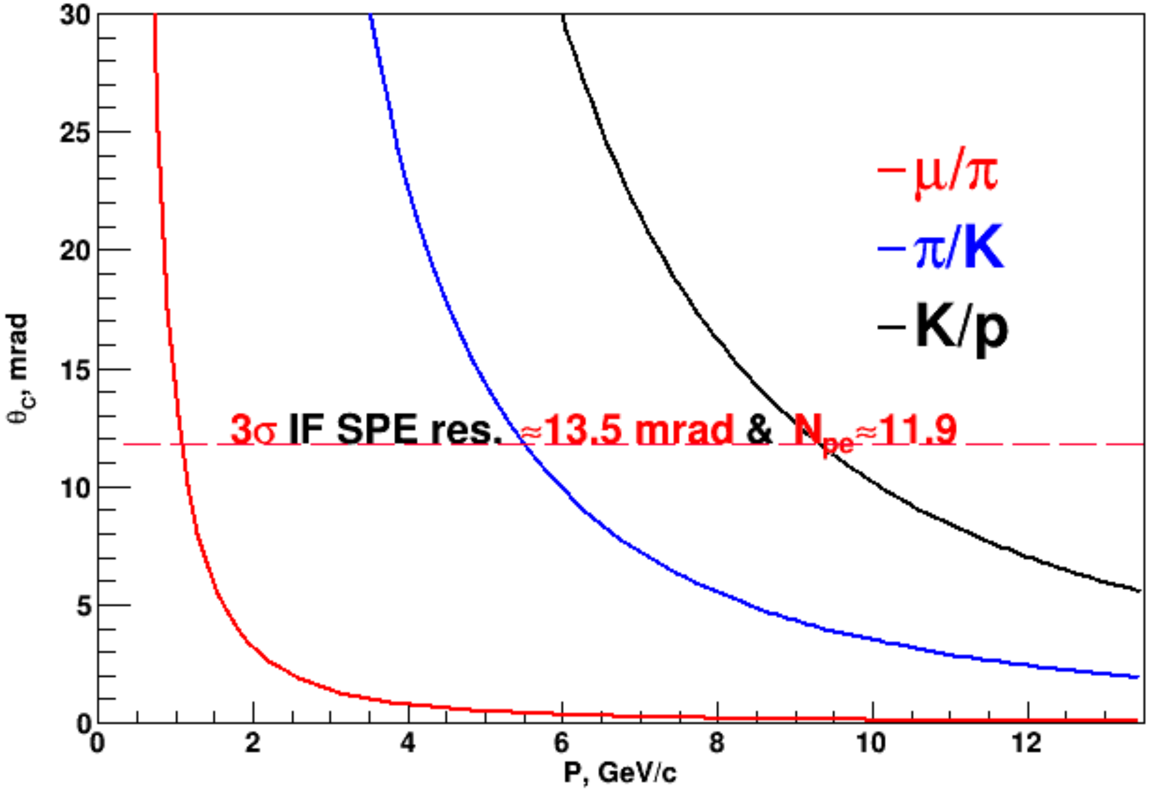


NNVT N6021 (China)
8x8 pixels with 5.9x5.9 mm

2x548 PMTs:
- 2x35kPixels
- Pixel ~6x6 mm

Existing FEE aka DiRICH (GSI):
- 1 DiRICH board per each 6 PMTs
- 2x100 DiRICHs per 2 end-caps
- 2x100 optical links to DAQ sys.
- 10÷20 TRB3 interfaces

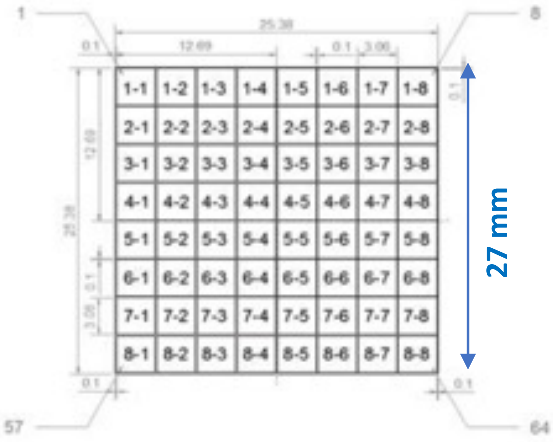
Expected performance:



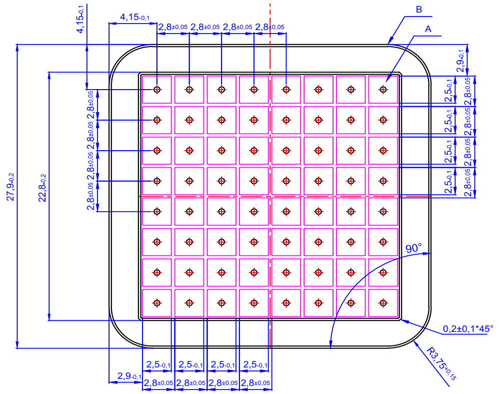
- π/K–separation up to 5 GeV/c
- μ/π–separation up to 1.1 GeV/c
- K/p–separation from 3 to 9 GeV/c

FARICH based on 3x3mm pixels

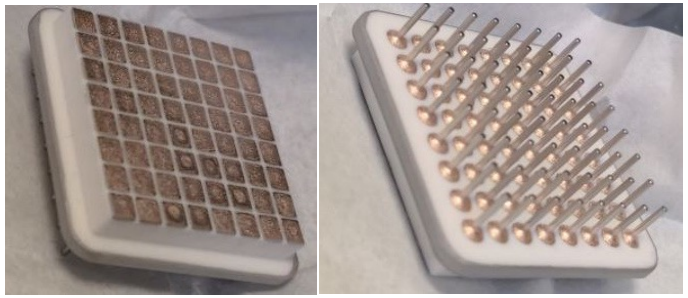
Suitable PDs with 3x3mm pixels



SiPM arrays, Joinbon (China)
64 3x3mm pixels, PDE~40%
DCR ~1÷2·10^6cps/ch.@300°K



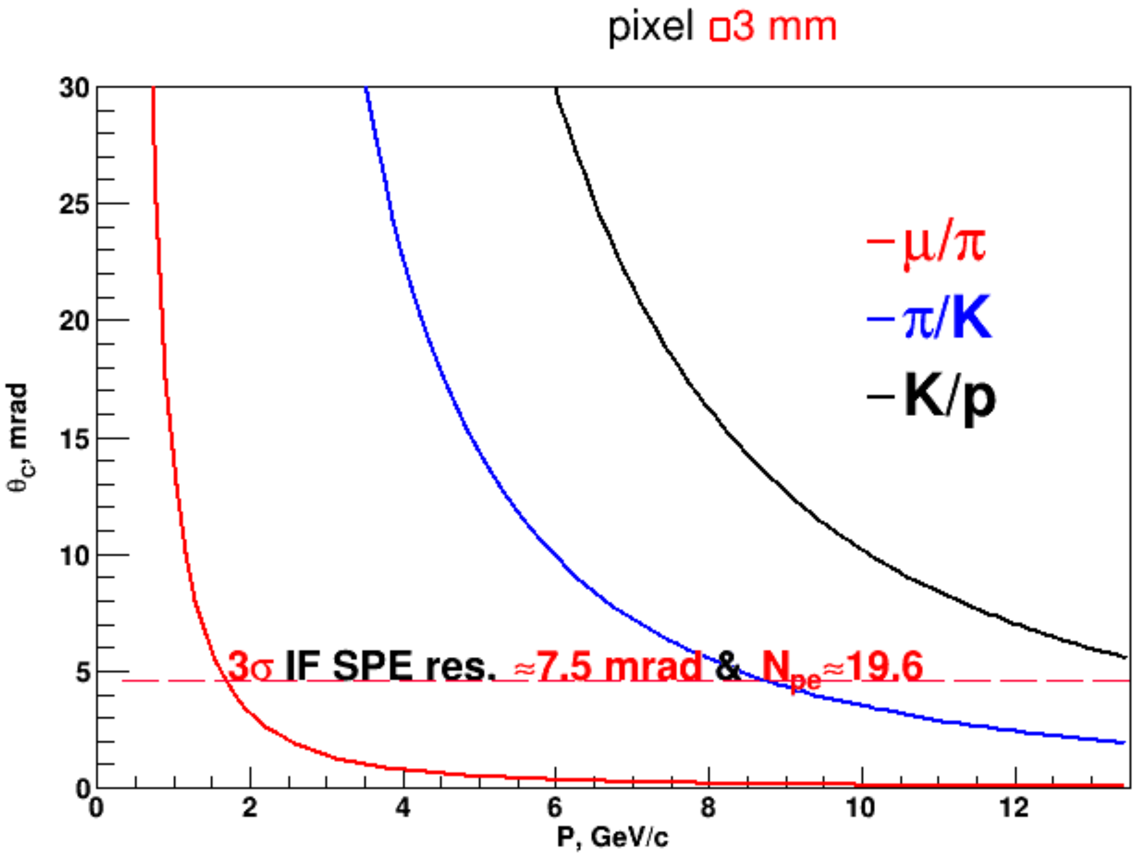
MCP PMT, Ekran FEP (RU)
64 2.5x2.5mm pixels
Still under R&D



2x2600 PMTs:
- 2x166.4kPixels
- Pixel 3x3 mm

Specialazed FEE is required!!!
- FaRICH-Auslese-System (GSI) – design inspired by DiRICH approach to readout of SiPM arrays or MCP PMTs with 3x3mm pixels?!
- ASICs developed at BINP for SR detector to readout Hybrid Photo Detectors?!

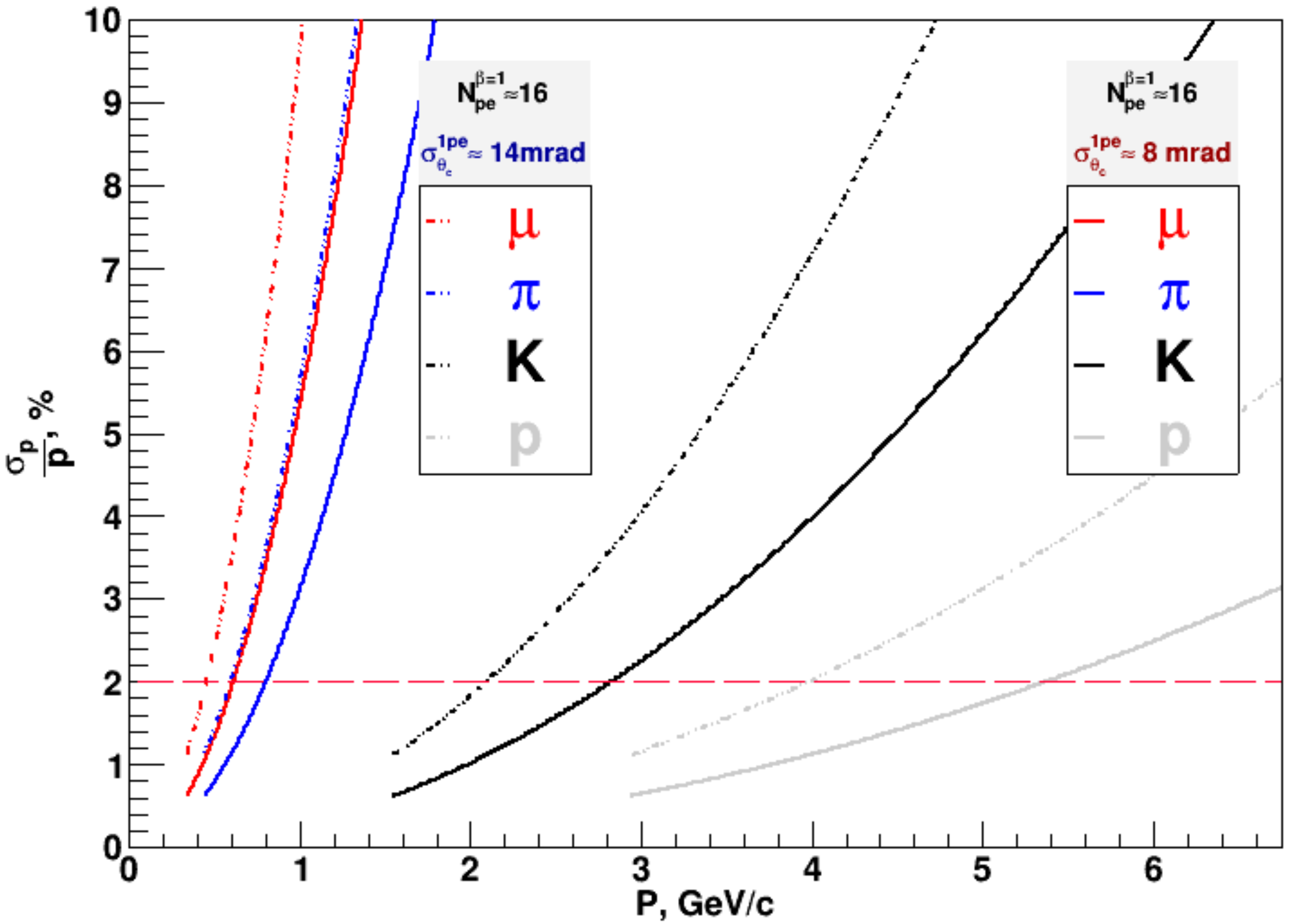
Expected performance:



- π/K–separation up to 8.5 GeV/c
- μ/π–separation up to 1.7 GeV/c
- K/p–separation from 3 to 14 GeV/c

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.