Опция ФАРИЧ детектора для эксперимента SPD

А.Ю. Барняков от имени группы ИЯФ СО РАН
для коллаборации SPD

Для эксперимента SPD (Spin Physics Detector) на коллайдере NICA (Nuclotron-based Ion Collider fAcility) ведется разработка универсального детектора элементарных частиц. В качестве специализированной системы идентификации предложено разработать счетчик ФАРИЧ (Фокусирующий Аэрогелевый РИЧ). Представлена концепция счетчика ФАРИЧ для детектора SPD, обсуждаются современные результаты расчетов и испытаний прототипа, а так же достижения в производстве черенковских аэрогелевых радиаторов в Новосибирске.

Научная сессия-конференция СЯФ ОФН РАН 2024,
1-5 апреля 2024г., ОИЯИ, г. Дубна

FARICH option for the SPD experiment

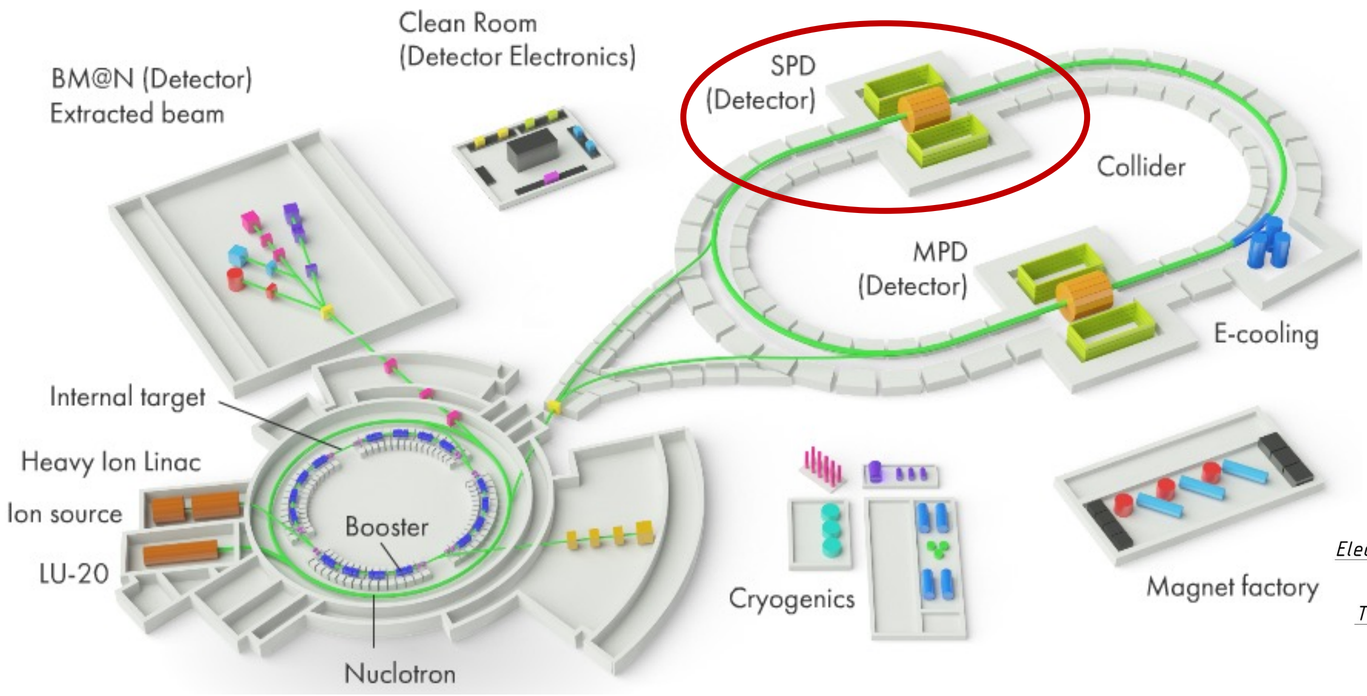
A.Yu.Barnyakov on behalf of BINP team

for the SPD collaboration

Scientific session-conference of Section of Nuclear Physics Physics Science Branch of RAS 2024,

1-5 April 2024, JINR, Dubna

SPD@NICA



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

Nuclotron based Ion Colliding fAcility

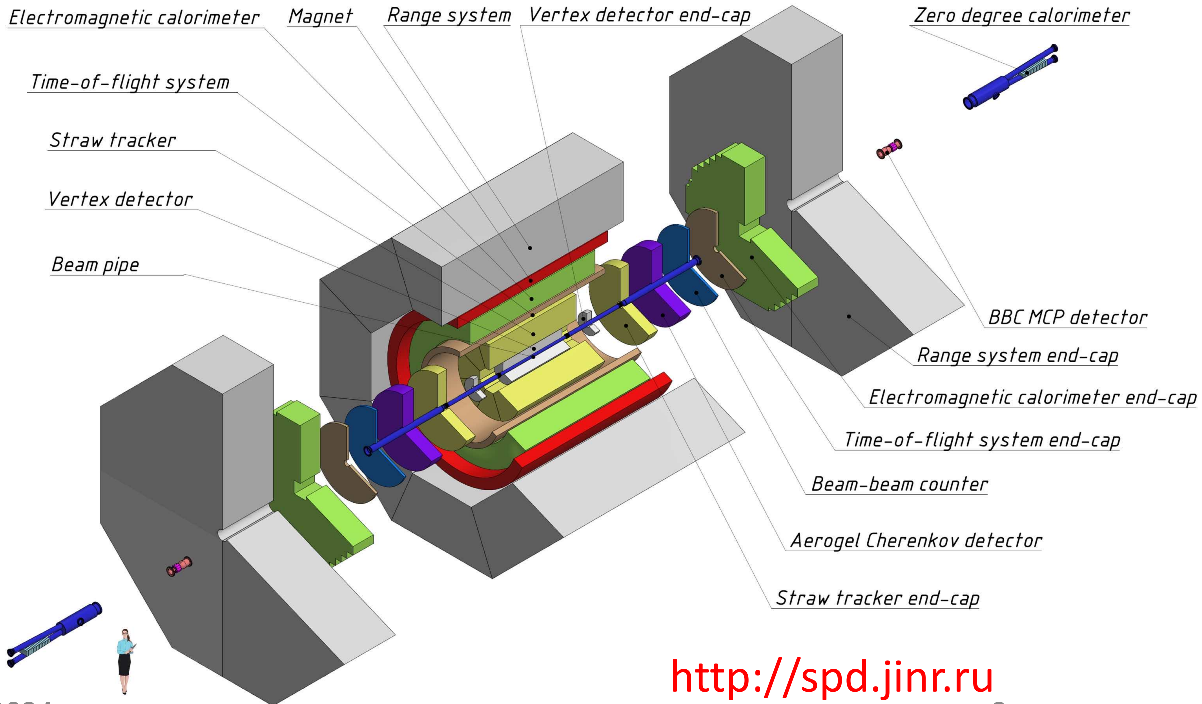
for fundamental nuclear interaction study

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.

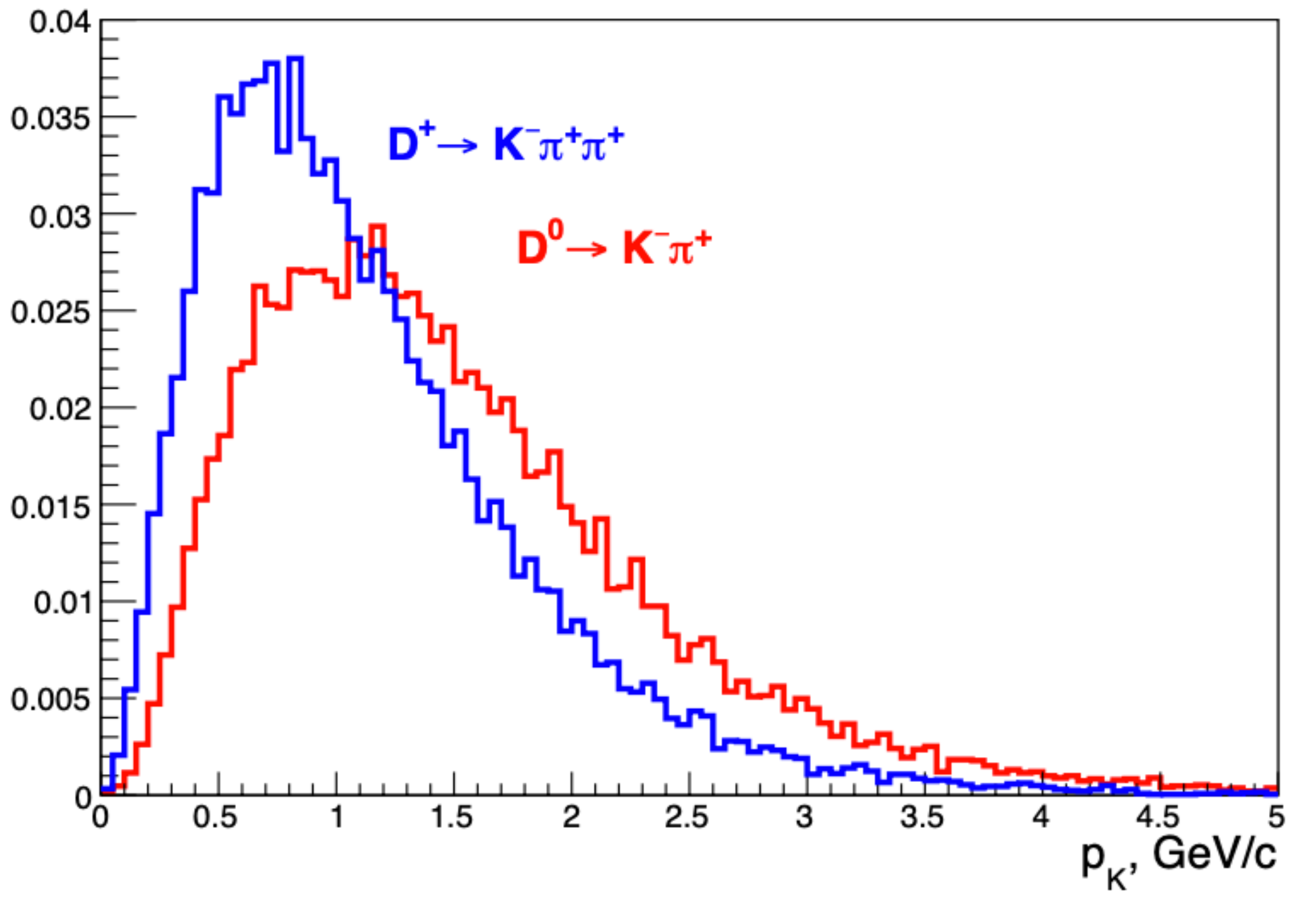
– Polarized p and d

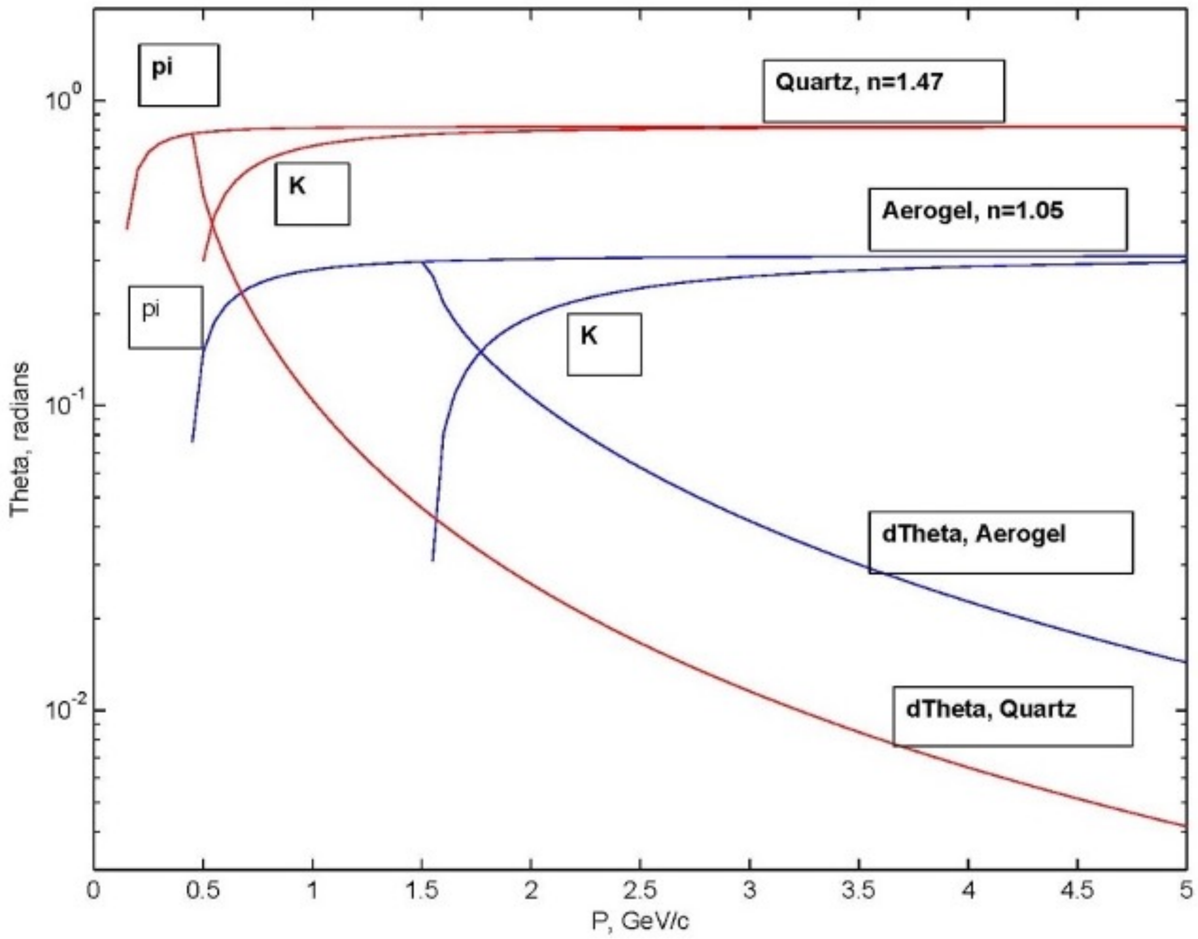
– $L = 10^{32} cm^{-2} s^{-1}$



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:

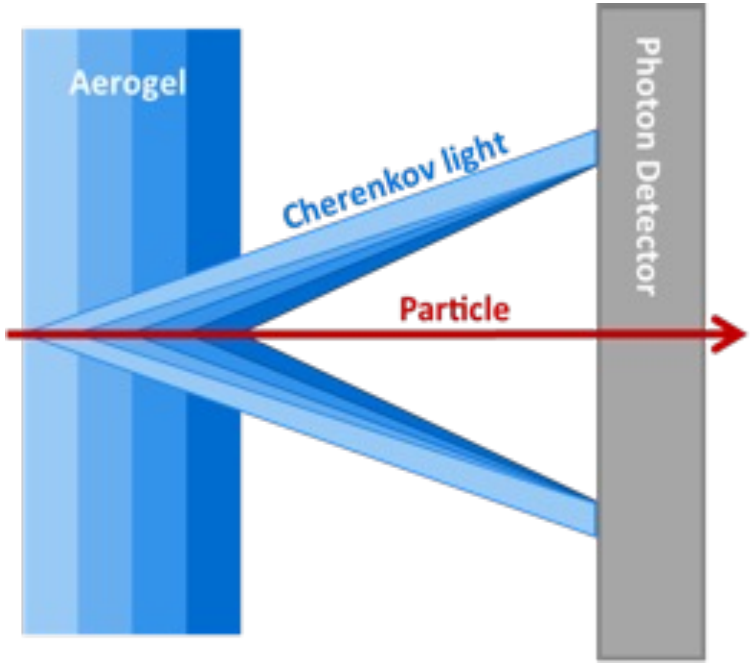
– $n = 1.05$ (aerogel),

– $\sigma_C \sim 2.5\ mrad/track$

FARICH motivation

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

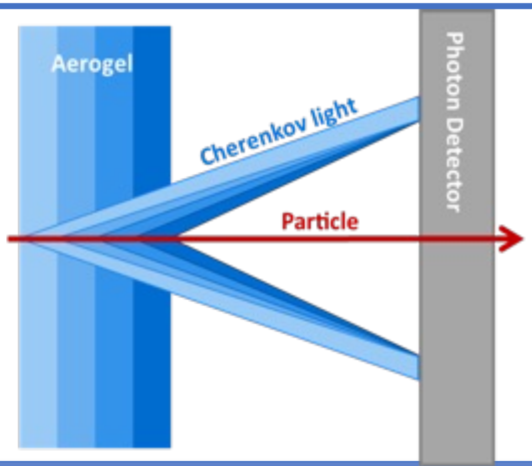
To get $\langle N_{pe}\rangle \gg 5$ from aerogel with n=1.05 & thickness 1 cm is too hard practice task!!!



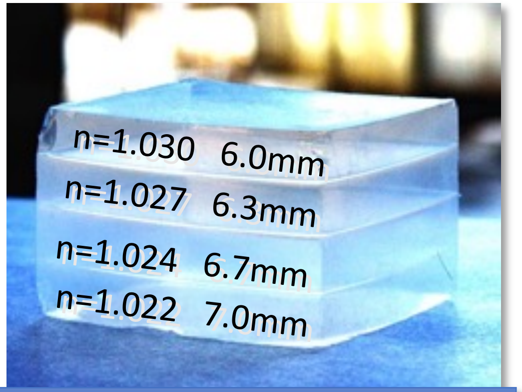
- Thicknesses and refractive indexes in each layer are adjusted in such way that Cherenkov rings from each layer overlap in the same region of the position-sensitive photon detector.
- The number of detected Cherenkov photons increases due to increase of the thickness without degradation of Cherenkov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

FARICH technique milestones



The first 4-layer monolithic sample

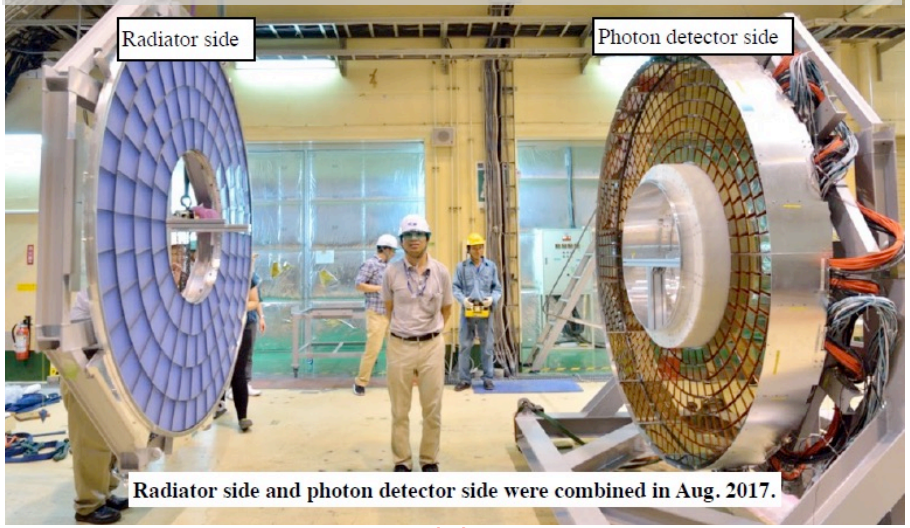


Increase N_{pe} due thickness increase without $\sigma_{\Theta c}$ degradation

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

2004÷2005

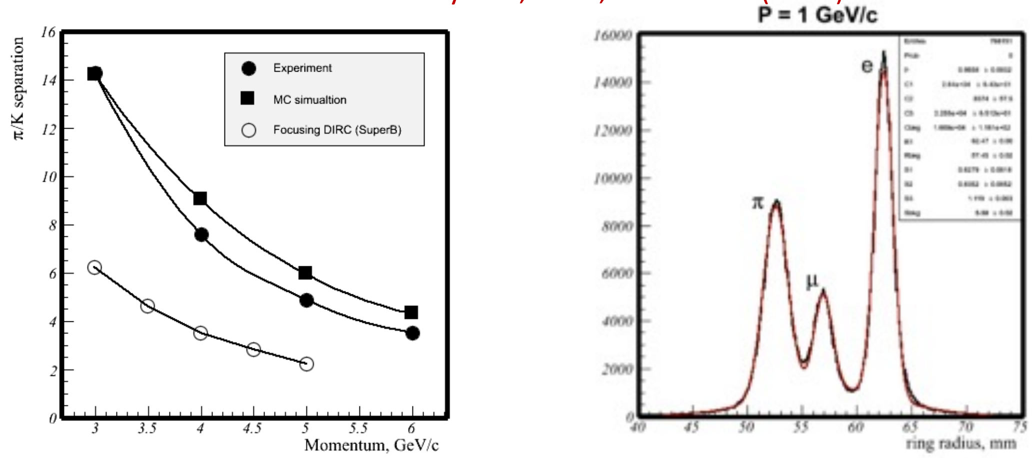
The Belle II (ARICH) is the first application of the method



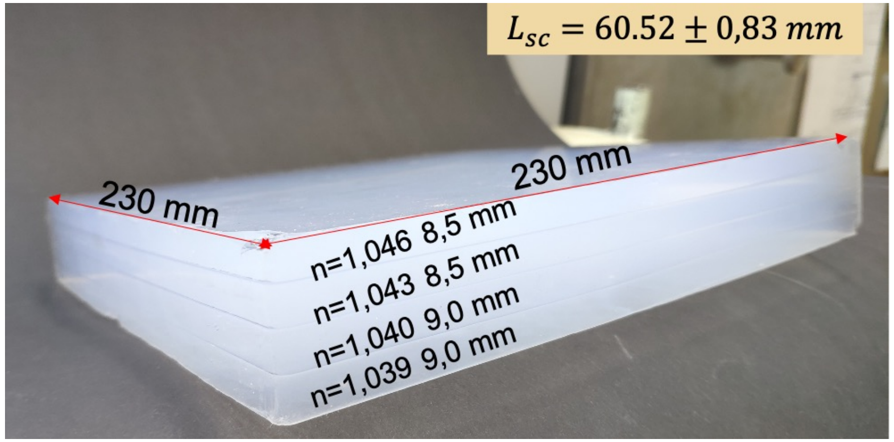
2017

Excellent PID capability were shown at CERN beam test in 2012

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

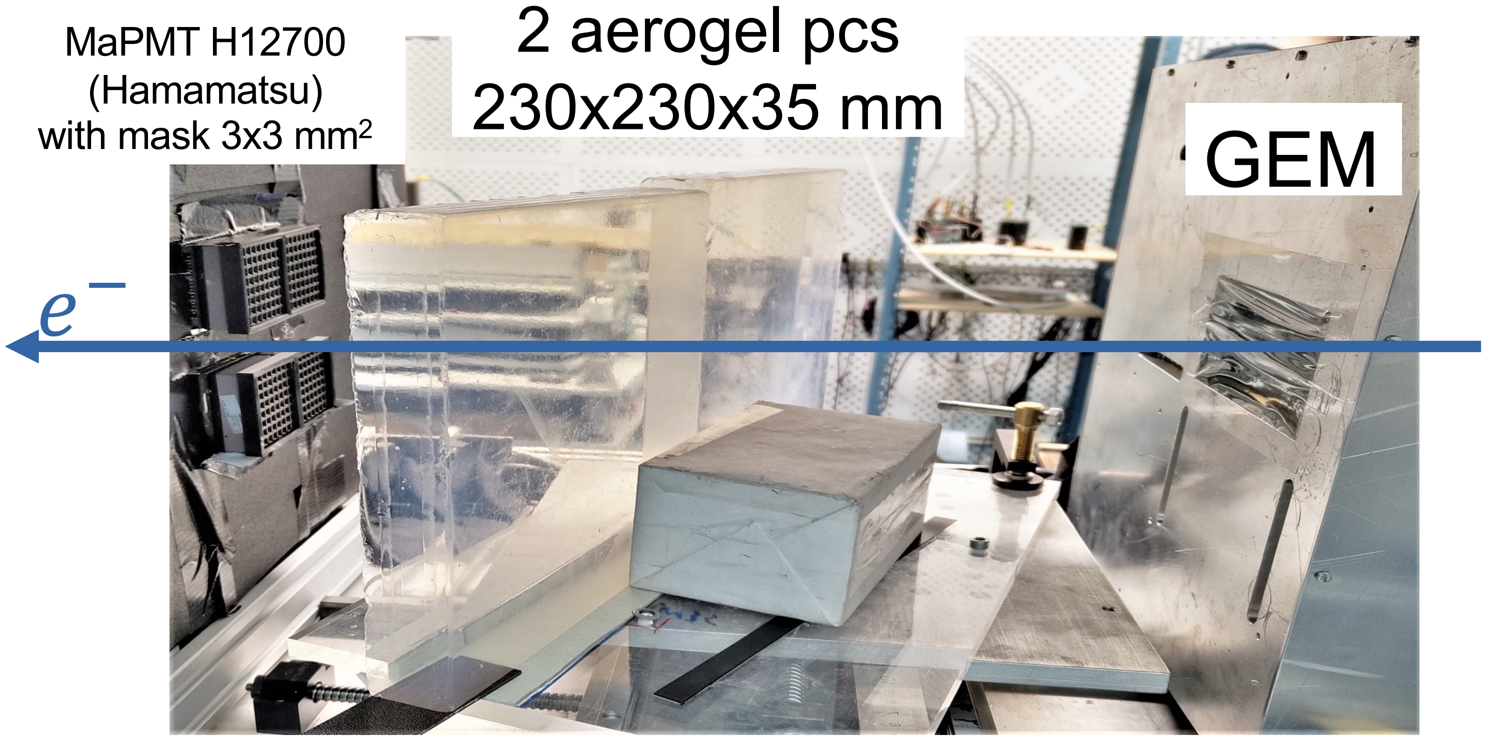


Two 4-layer focusing aerogel blocks 230x230x35 mm

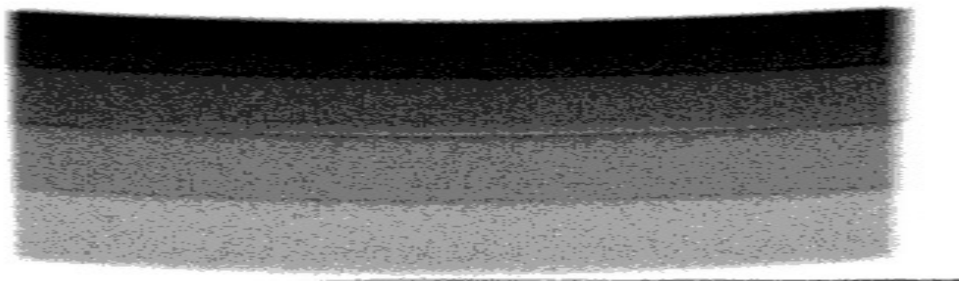


2022÷2023

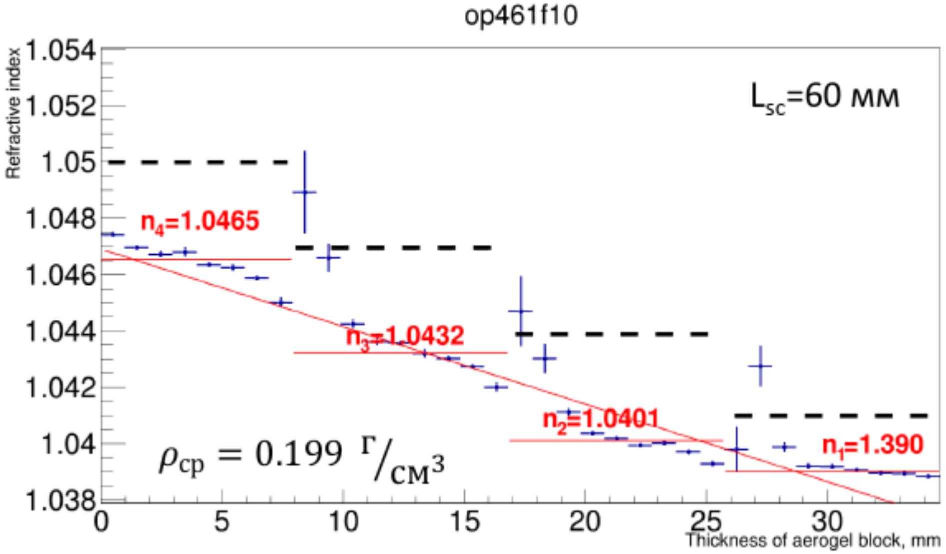
The largest 4-layer focusing aerogel samples were produced in Novosibirsk and tested at BINP in 2022-2023



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

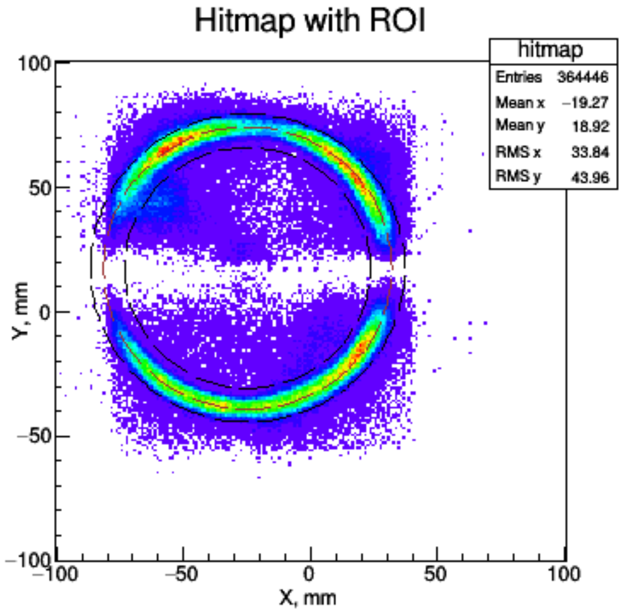


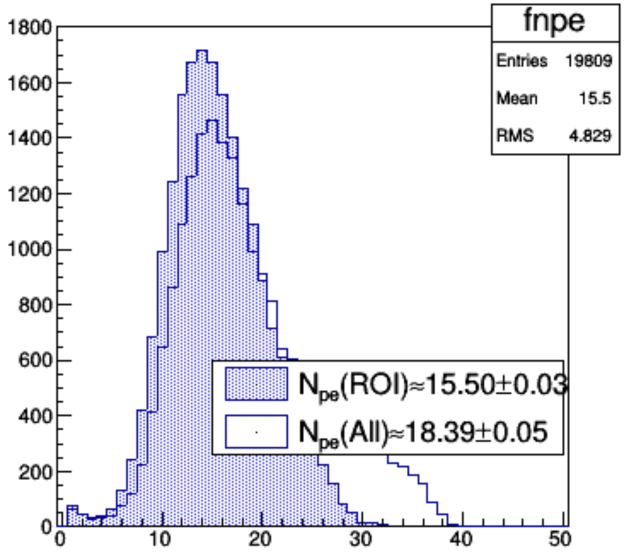
Refractive index profile is measured with help of digital X-ray setup at the BINP.

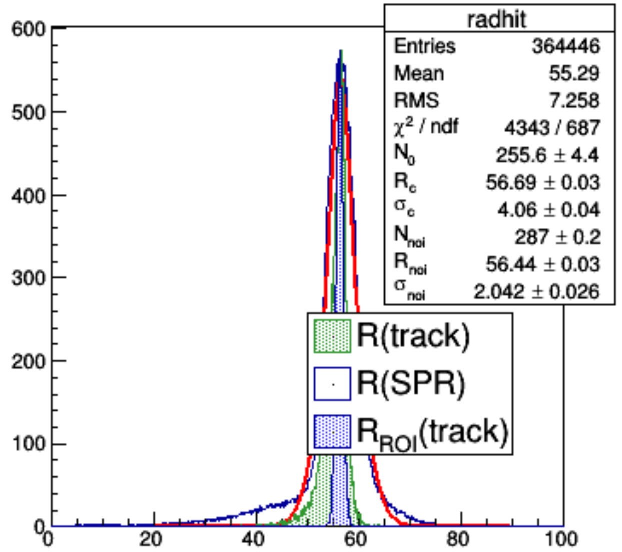


Recent beam test results

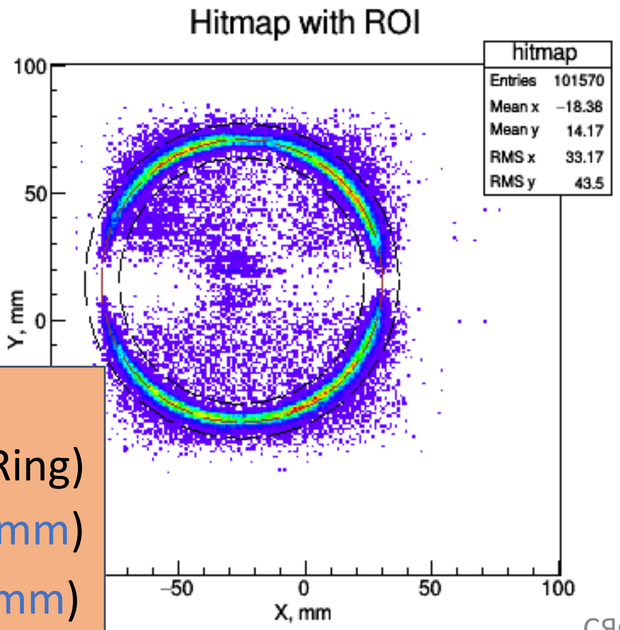
Pixel 6x6 mm
Geom.Eff. ~ 80%

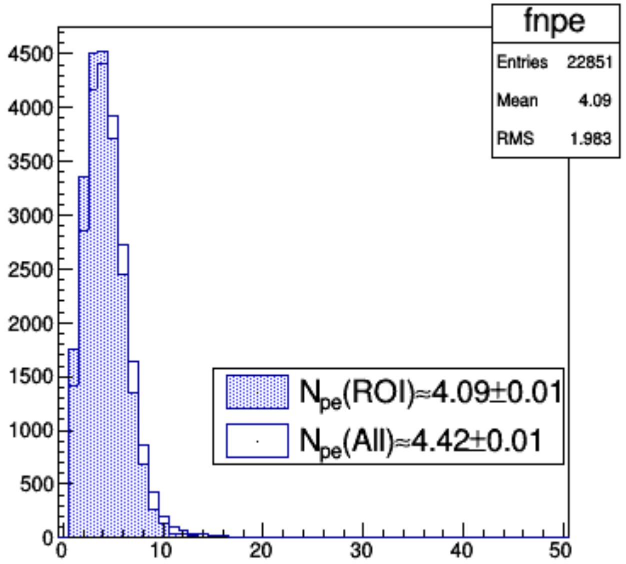


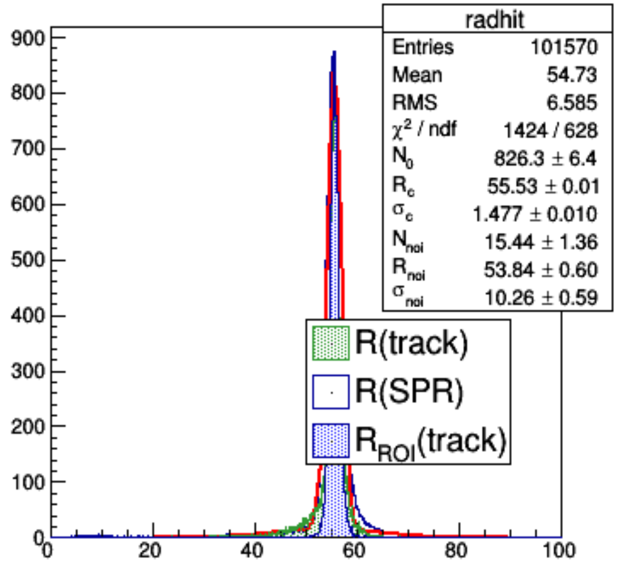




Pixel 3x3 mm
Geom.Eff. ~ 20%



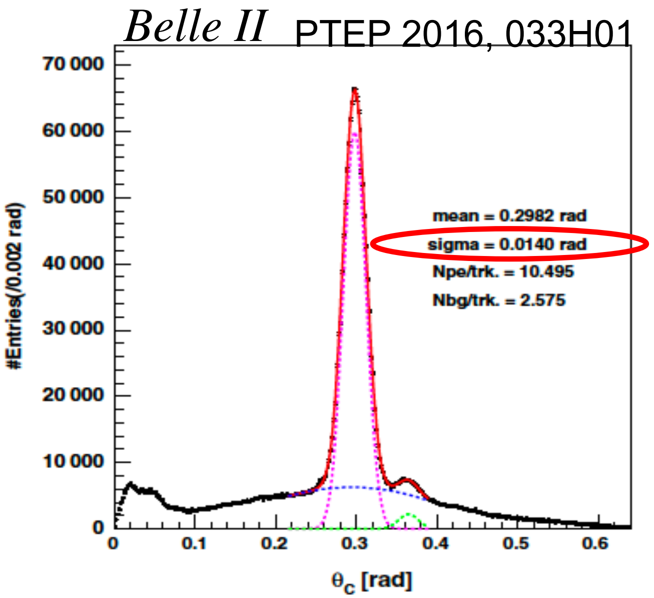


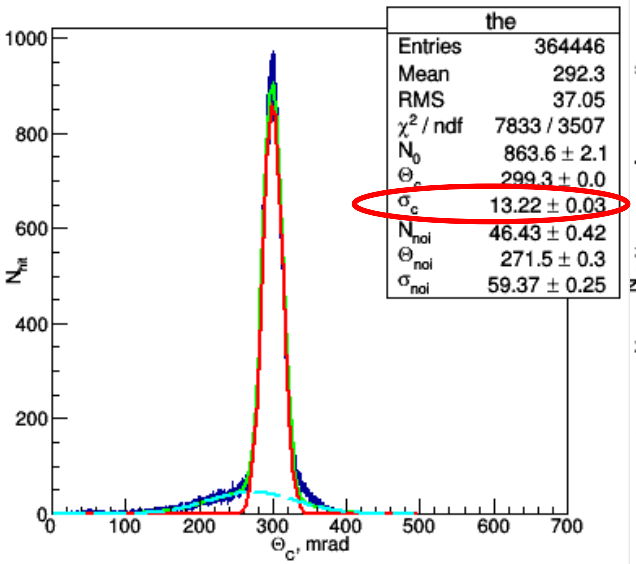


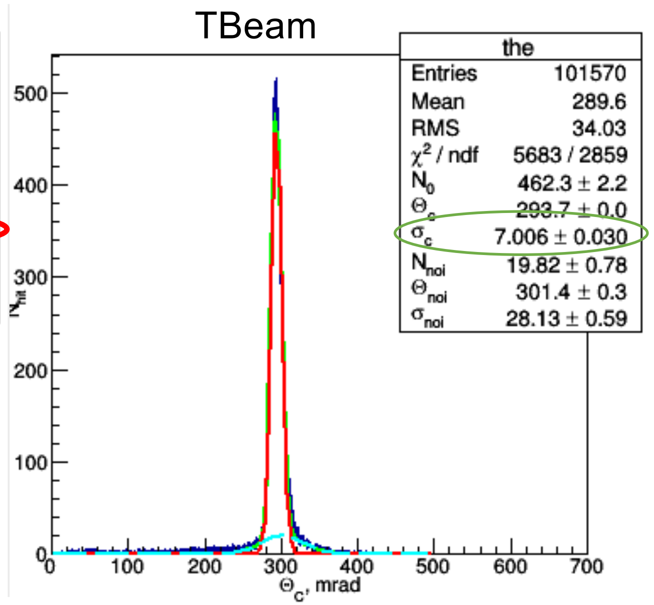
Main results:

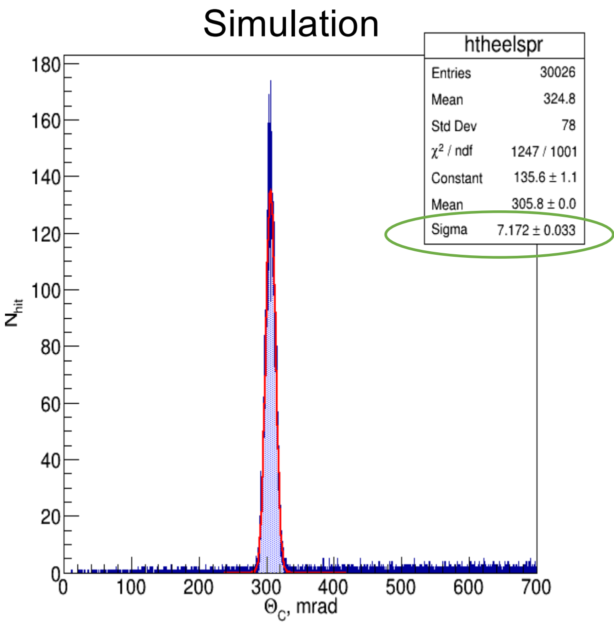
- $N_{pe} \approx 16$ (~ 0.8 of Ring)
- $\sigma_\theta^{1pe} \approx 13.5\ mrad$ (■ 6mm)
- $\sigma_\theta^{1pe} \approx 7.5\ mrad$ (■ 3mm)

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







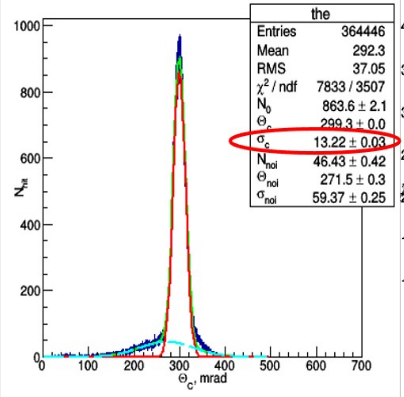


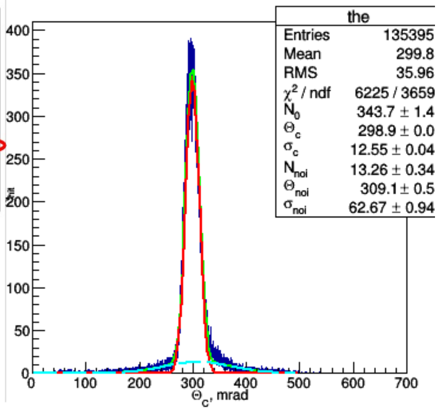
	Belle II	Novosibirsk	TBeam	Simulation
Aerogel:	20+20 mm (Chiba Univ.)	4-layers (Novosibirsk) –>	–	4-layers (ideal profile)
n(400nm):	1.045 +1.055	1.039 ÷ 1.046	–	1.041 ÷ 1.050
Pixel:	5x5 mm	6x6 mm	3x3 mm	3x3 mm
	Geom.Eff. ~ 90% $N_{pe} \approx 10.5$	Geom.Eff. ~ 80% $N_{pe} \approx 16$	Geom.Eff. ~ 20%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

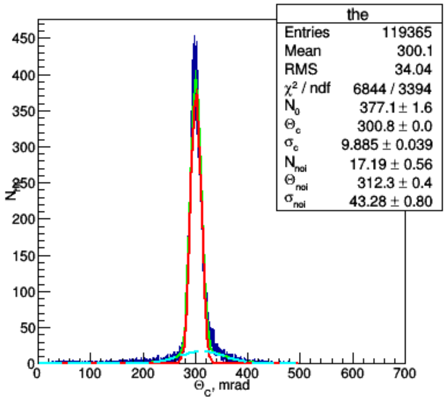
Beam test results are in good agreement with MC simulation and corresponds to:
π/K–separation at level of 3σ up to P=4.5 GeV/c for 6x6 mm pixel
π/K–separation at level of 3σ up to P=8.5 GeV/c for 3x3 mm pixel

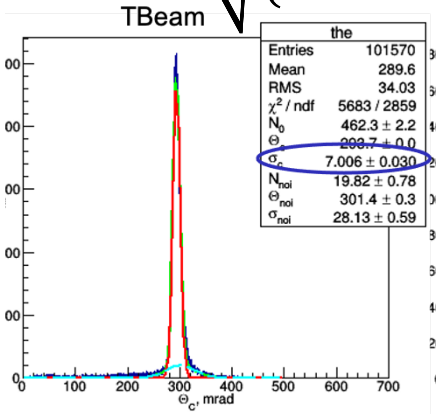
Dimensions of focusing aerogels 23x23x3.5 cm allow us to design the full-scale FARICH systems for the future particle physics experiments.

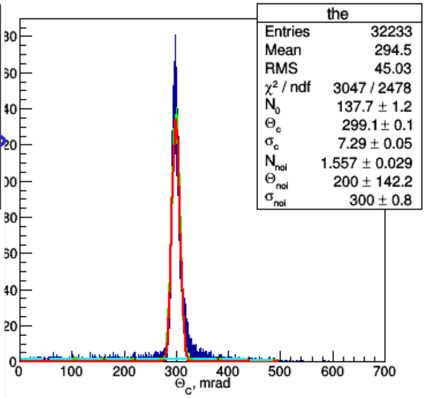
TBeam 2023 res.: $\sigma_{\theta_C}^{1pe} = \sqrt{\frac{\Delta_{pix}^2}{(\sqrt{12}\cdot L\cdot n)^2} + \sigma_{aer}^2 + \sigma_{trk}^2}$

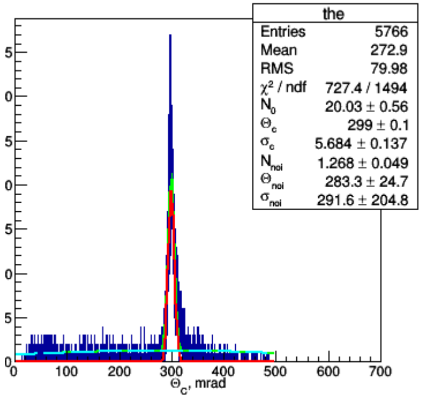




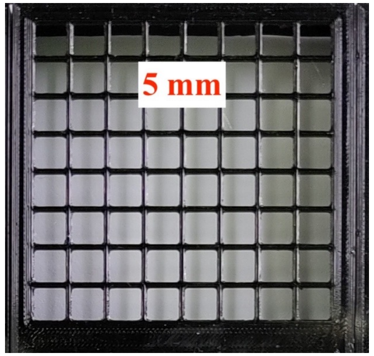


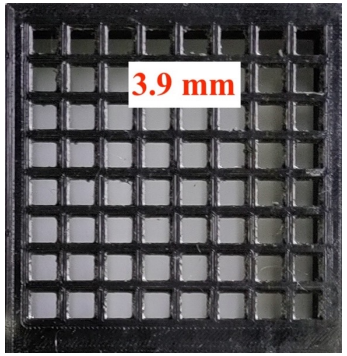


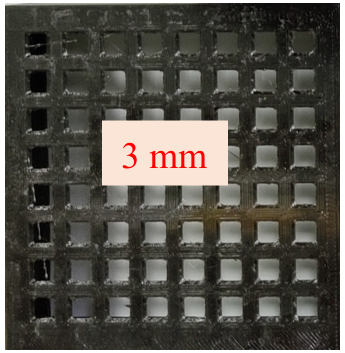


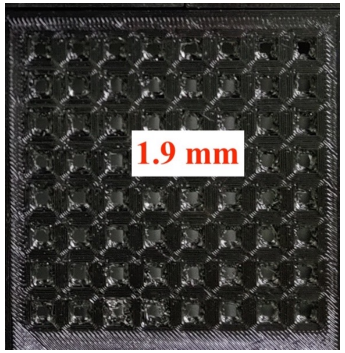


No mask: $6\times6\ mm$

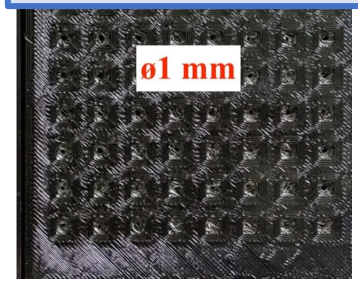








$\sigma_{aer} \approx 5.6$ mrad

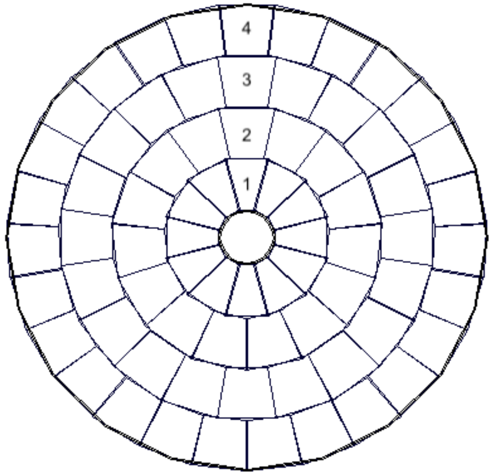


04/23: L≈200 mm	12/23: L≈180 mm	12/23: L≈180 mm	04/23: L≈200 mm	12/23: L≈180 mm	12/23: L≈180 mm
Geom.Eff. ~ 80%	Geom.Eff. ~ 56%	Geom.Eff. ~ 36%	Geom.Eff. ~ 20%	Geom.Eff. ~ 9%	Geom.Eff. ~ 2%
$N_{pe} \approx 16$	$N_{pe} \approx 12$	$N_{pe} \approx 8$	$N_{pe} \approx 4$	$N_{pe} \approx 2$	$N_{pe} \approx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

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 conceptual design

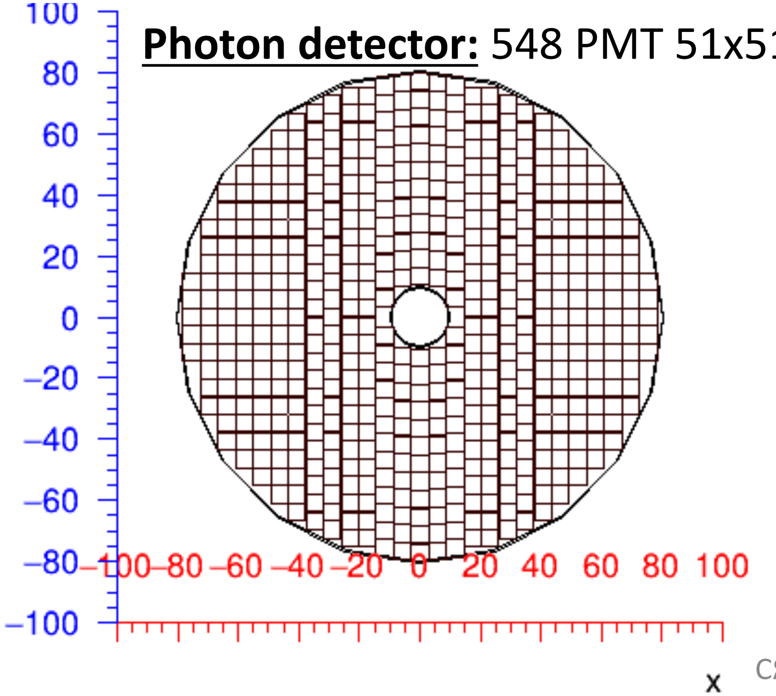
Aerogel:
74 tiles

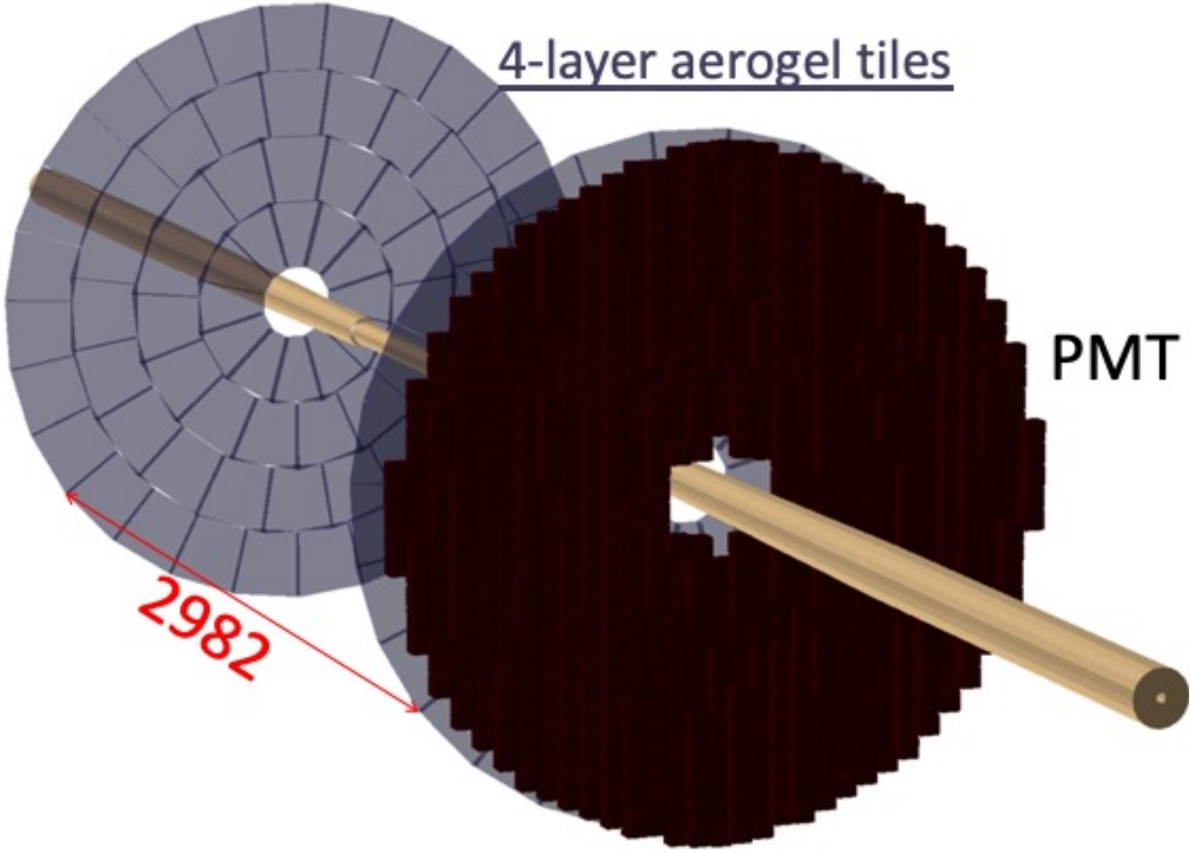


1 – 12 tiles x S=0.5•(5.6 + 15.6)•18.5 = 159.0 sq.cm
2 – 15 tiles x S=0.5•(12.2+20.2)•18.5 = 299.7 sq.cm
3 – 20 tiles x S=0.5•(15.0+20.8)•18.5 = 331.15 sq.cm
4 – 27 tiles x S=0.5•(15.2+19.6)•18.5 = 321.9 sq.cm

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

Photon detector: 548 PMT 51x51 mm





FARICH system:

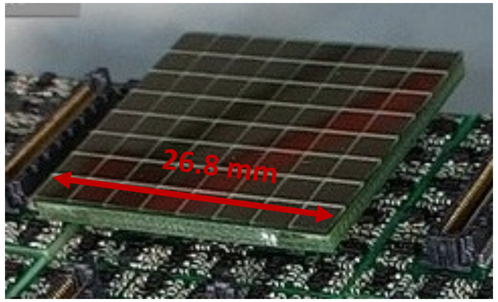
- 4-layer aerogel with n_{max}=1.05
- Focus distance – 20 см
- PS PD – MCP-PMT or SiPM arrays with pixel 3÷5 mm
  550 PMTs per endcap if lateral sizes ~51x51 mm
  2200 PMTs per endcap if lateral sizes ~27x27 mm

Photon detector options

Due to axial magnetic field in endcap region of the detector only limited opations of the photon detectors are able to detect very low intensity Cherenkov radiation produced in aerogel

SiPM arrays

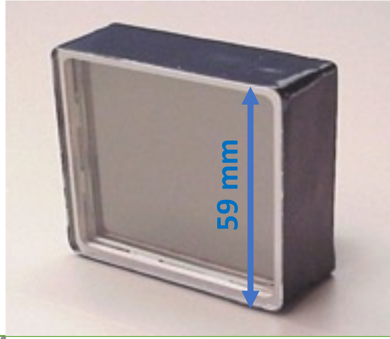
- There are several manufacturer in the world including China.
- There is no comercially available SiPM arrays produced in Russia for the moment, but some R&Ds are going now.
- Estimated cost of such detector option is about 100$/cm^2
- It is required to develop and produce special R/O electronics and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



KETEK PA3325-WB-0808
(BroadCom, USA)

MCP-PMT

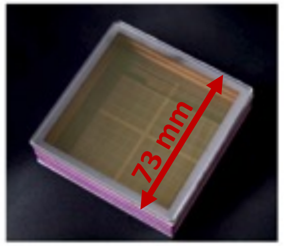
- There are several manufacturer in the world including China.
- There is no comercially available position-sensitive MCP-PMTs produced in Russia for the moment, but R&Ds are going now in (Baspik&Ekran FEP).
- There is a very large spread of prices for rectangular position-sensitive MCP-PMT. The best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

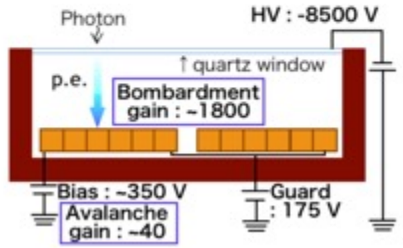


Planacon XP85112
8x8 pixels with 6x6 mm
Cost: 15 $k$$

HAPD

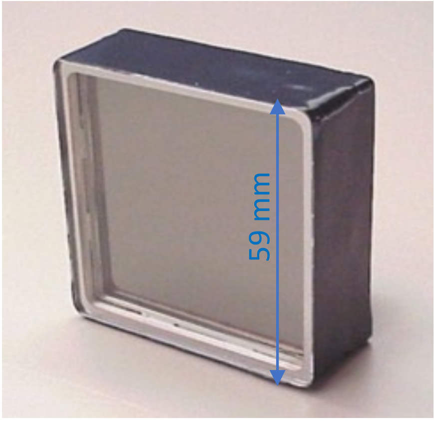
- Only Hamamtsu produced such devices for the Belle II experiment and now it doesn't produced anymore!
- There is no comercially available HAPDs in Russia for the moment, but R&Ds are going now in ISP SB RAS.
- Price – ???
- Expected PDE of such devices will be less than for SiPM option but signficantly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



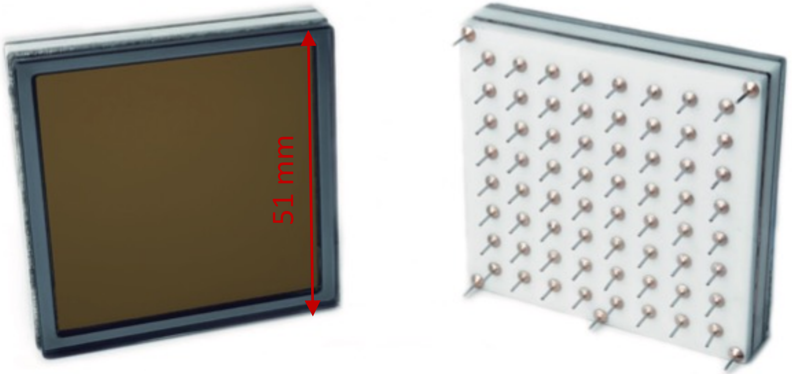


FARICH based on existing solutions

MCP PMT available from vendors:



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

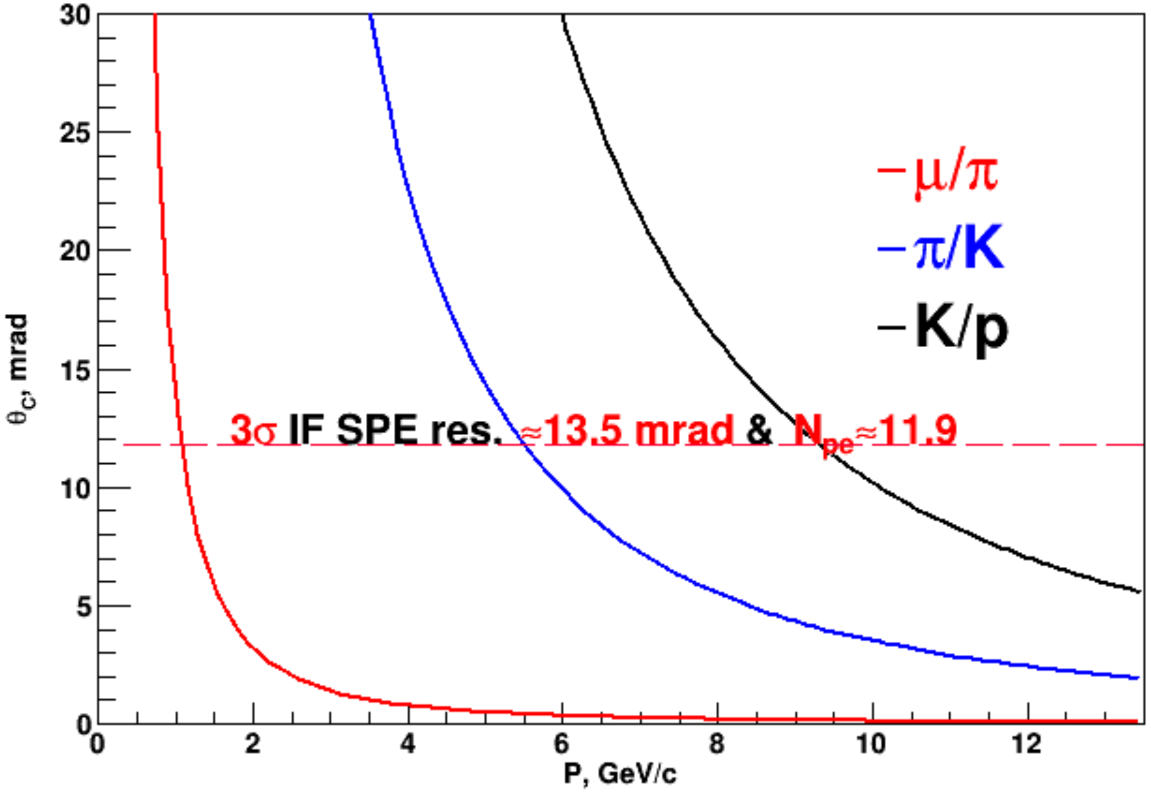


NNVT N6021 (China)
8x8 pixels with 5.9x5.9 mm

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

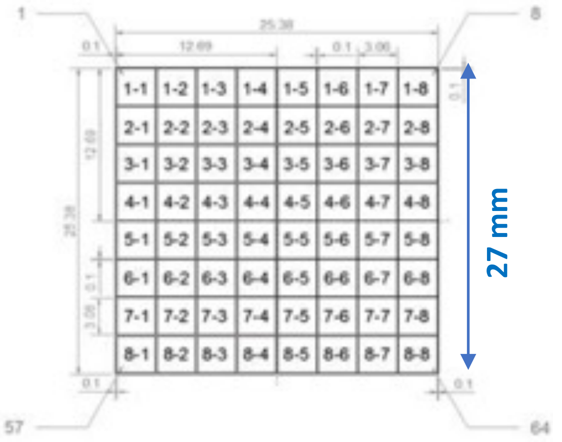
Expected performance:



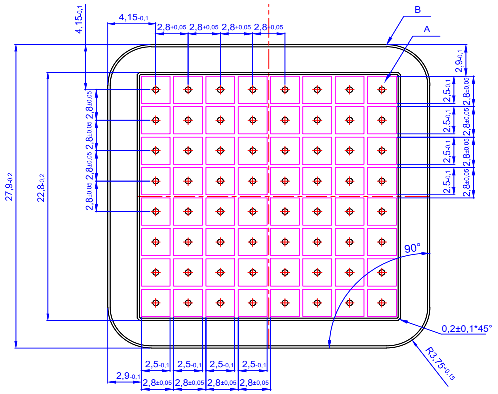
- π/K–separation up to 5 GeV/c
- μ/π–separation up to 1.1 GeV/c
- K/p–separation from 3 to 9 GeV/c

FARICH based on 3x3mm pixels

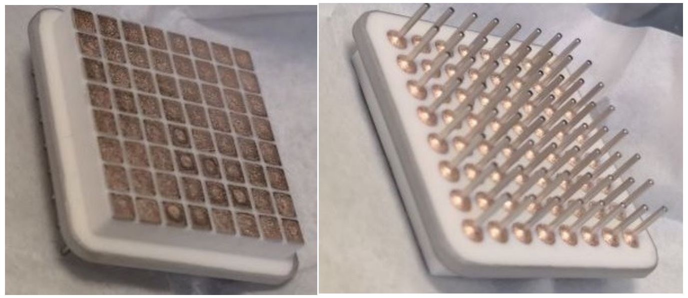
Suitable PDs with 3x3mm pixels



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

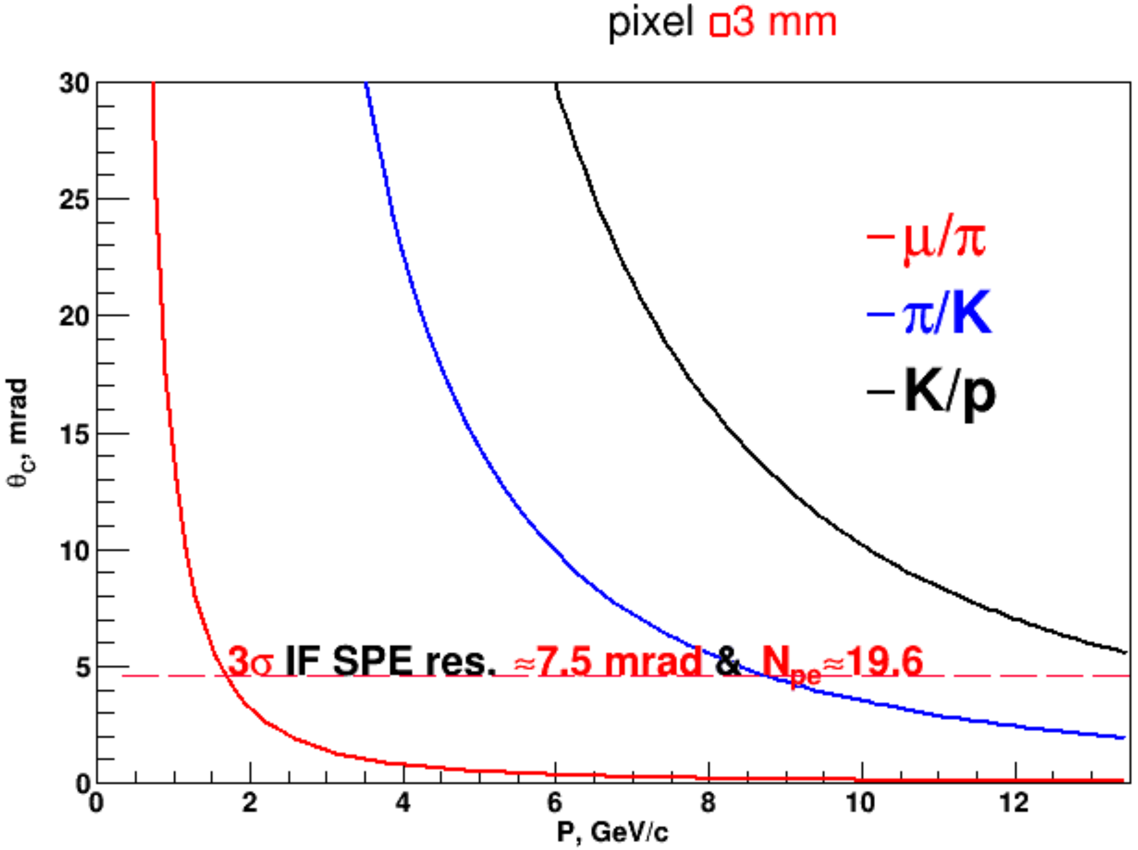


2x2600 PMTs:
- 2x166.4kPixels
- Pixel 3x3 mm

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

R/O electronics cost estimation

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

– ASIC (Application Specialised Integrated Circuits)

– FPGA (Field Programable Gate Arrays)

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

FPG-TDC (GSI)

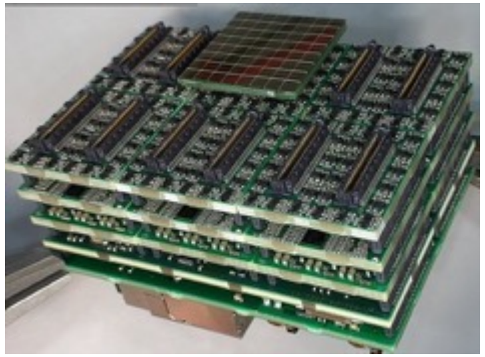
Unit	Article	Price per unit	Total price
2	DiRICH	4.917,00 €	9.834,00 €
	Additionally the export duty from Germany		150,00 €
	Total price		9.984,00 €

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

A system with 30kChannel (HADES):

$170k€/30k \approx 6€/chan$ (2017)

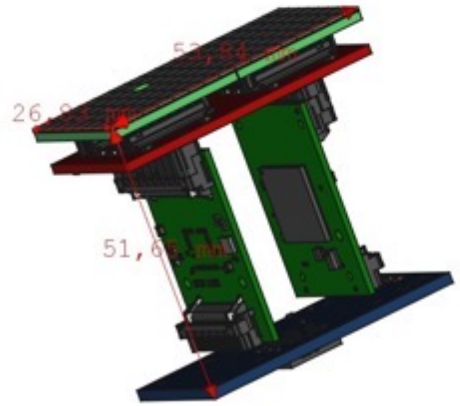
Power consumption: ~55mW/chan



TOFPET-II (PetSys)

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

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



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

A system with 100kChannel:

$5€/chan$ (2020)

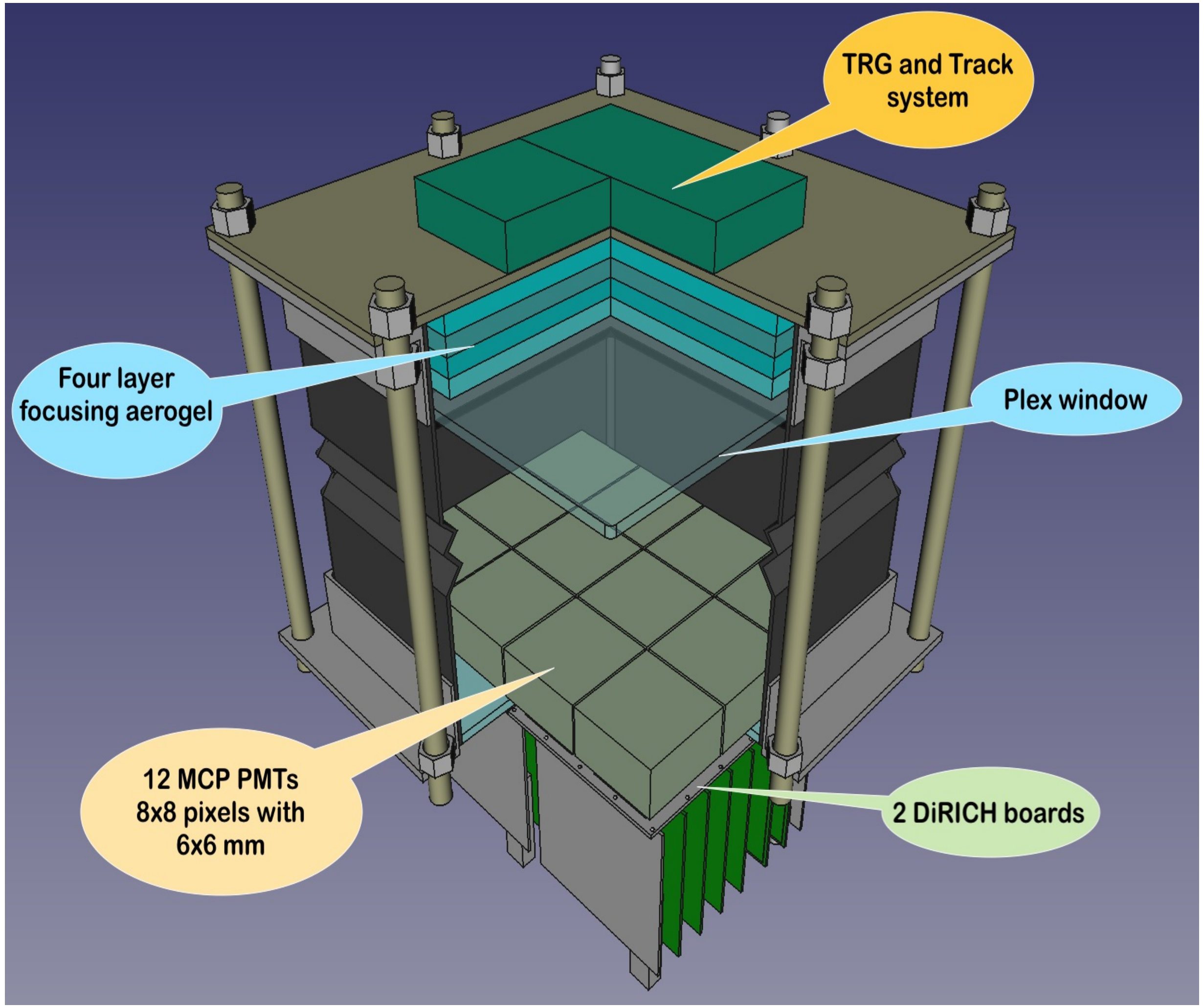
Power consumption:

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

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

FARICH prototype with full-ring detection

- To demonstrate real PID capabilities of the FARICH based on modern solutions.
- 8÷12 MCP PMTs with size ~5x5 cm (like N6021 from NNVT, China) to provide photon detection area S≈15x15 cm.
- We have at BINP FEE to readout up to 18 MCP PMTs (18•64=1152 pixels) by means of DiRICH boards and TRB-3 interface.
- Time performances and ToF approaches should be tested too. Jitter of this FPGA-TDC from GSI declared better than 40 ps.
- This FARICH prototype could be tested with mixed hadron beams or with cosmic rays to demonstrate PID capabilities.

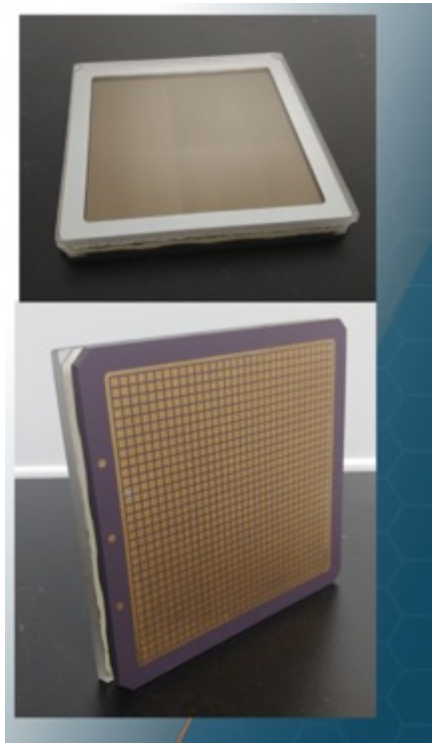


Summary

- In 2020-2023 the essential progress in FARICH technique was achieved:
  - The 4-layer focusing aerogel sample with 20x20x3.5 cm size were produced for the first time in the world
  - The measured SPR of these samples is in good agreement with simulation and could provide π/K up to 8.5 GeV/c and μ/π up to 1.7 GeV/c in combination with 3 mm pixel size based photon detectors
- The PID system based on FARICH technique is proposed for SPD experiment for reliable π/K-separation
- Full-scale FARICH prototype to demonstrate π/K-separation up to 6 GeV/c is under development
- Search for suitable and available position-sensetive photon detectors and R&D on specialized FEE have to be done for succesefull realization of the FARICH system in SPD project.

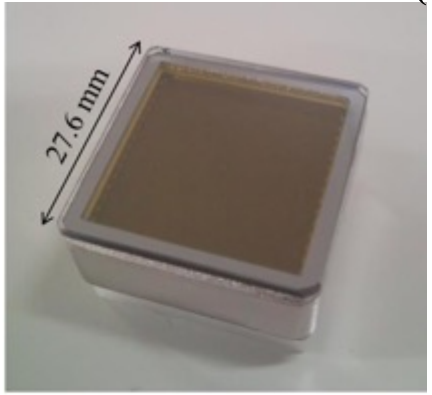
BACK UP SLIDES

Position-sensitive MCP-PMT

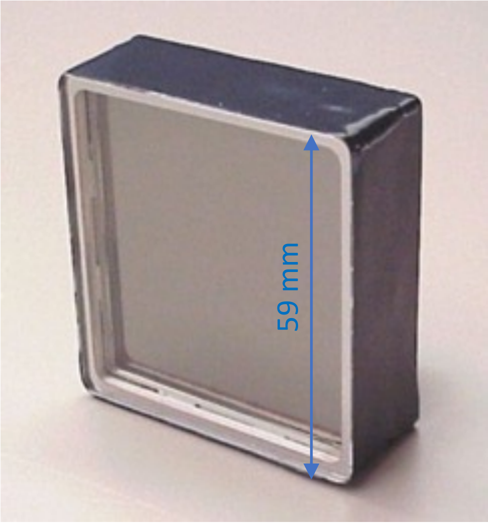


HRPPD (Income)
10x10 cm; pixel 2.5x2.5 mm

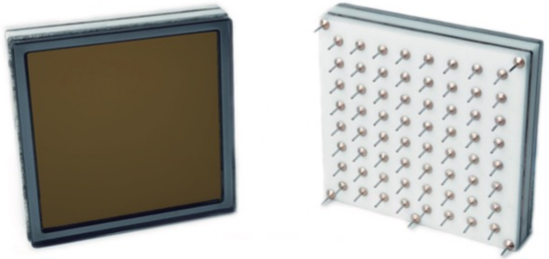
Hamamtsu R10754-016-M16(N)

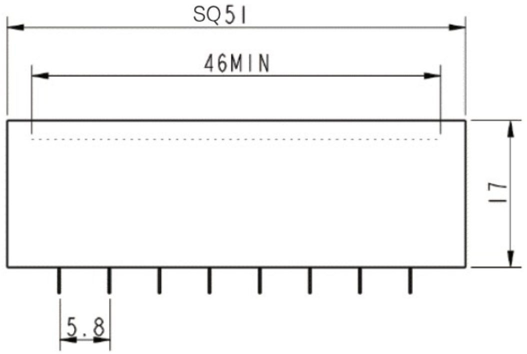


4x4 pixels with 5x5 mm

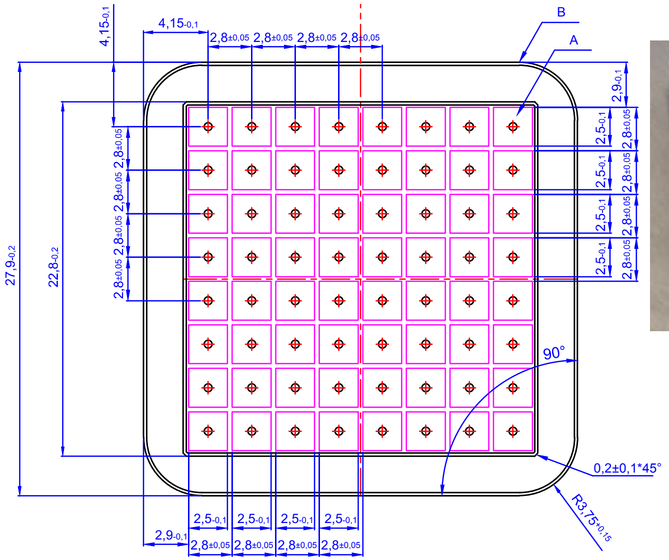


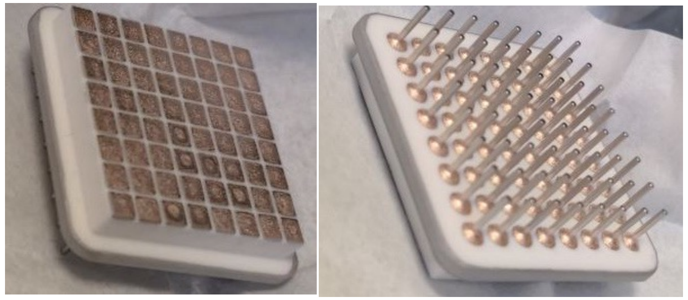
Planacon XP85112
8x8 pixels with 6x6 mm





NNVT (China)





Collector plane of MCP-PMT
Ekran FEP: until the end of 2024

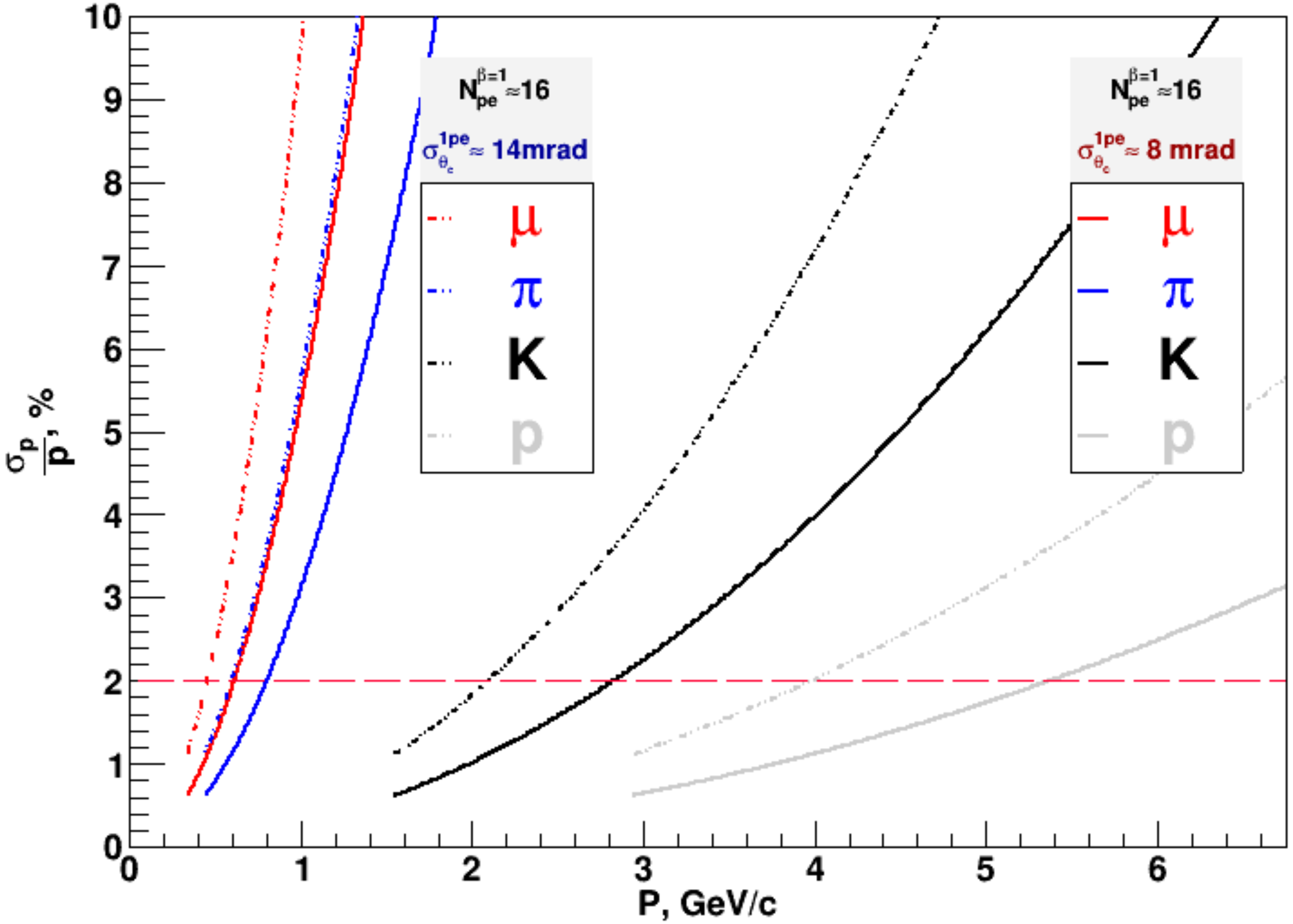
Momentum measurements with FARICH

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

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

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

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



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.