FTCF2024
USTC Hefei

R&D status of FARICH option for PID.

Alexander Barnyakov

on behalf of BINP PID-group of the SCT-collaboration

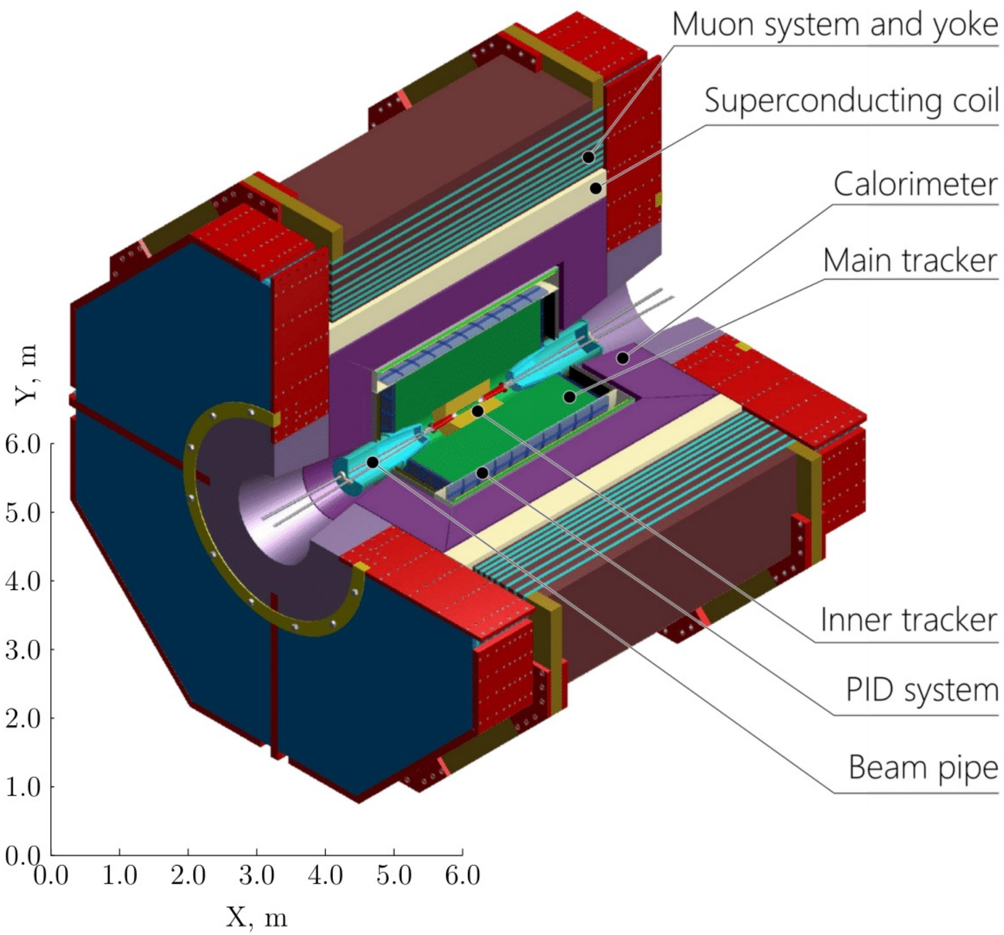
Budker Institute of Nuclear Physics, Novosibirsk, Russia

- **SCTF detector concept & Physics requirements for PID**
- **FARICH technique progress**
- **FARICH system preliminary design**
- **Summary**

14–18 January 2024

International Workshop on Future τ-charm Facilities 2024, Hefei, China

Detector concept



Momentum resolution $\sigma_p \leq 0.4\%$ at $1 GeV/c$

Very symmetric and hermetic

Able to detect soft tracks ($p_t \geq 50\ MeV/c$)

- Inner tracker should be able to handle 104 tracks/cm2s

Very good PID: $\mu/\pi/K$

- π/K up to 3.5 GeV/c, e.g. for $D\bar{D}$ mixing
- μ/π up to 1.5 GeV/c, e.g. for $\tau \rightarrow \mu\gamma$ search
- dE/dx better than 7% for PID below 0.6 GeV/c

Able to detect γ from 10 MeV to 3.5 GeV, good π^0/γ separation

- Calorimeter energy resolution $\sigma_E \leq 1.8\%$ at 1 GeV
- Calorimeter time resolution $\sigma_t \leq 1$ ns

Efficient “soft” trigger

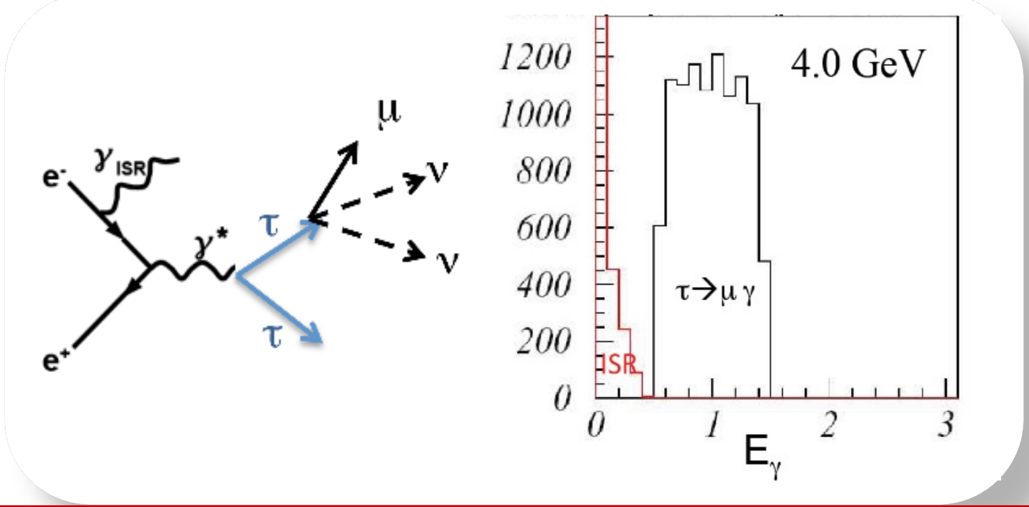
Ability to operate at high luminosity, up to 300 kHz at J/ψ

Few requirements for PID from physics program

LFV with τ

$\tau \to \mu\gamma$

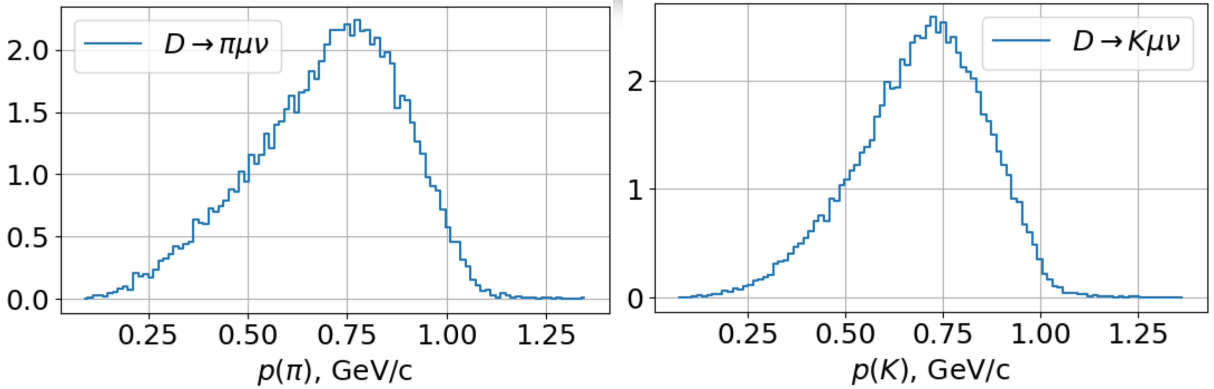
- Allowed in several BSM scenario, including SUSY, leptoquarks, technicolor, and extended Higgs models
- $\mathcal{O}(10^{-9})$ – reachable upper limit at SCT for the branching of $\tau \to \mu\gamma$
- Requires excellent π/μ separation from 0.5 to 1.5 GeV/c to suppress background $\tau \to \pi\pi^0\nu$



LU precise tests with D-mesons

$D \to \mu\pi\nu\ , D \to K\pi\nu\ \ldots$

- Excellent π/μ & π/K separation from 0.2 to 1.2 GeV/c

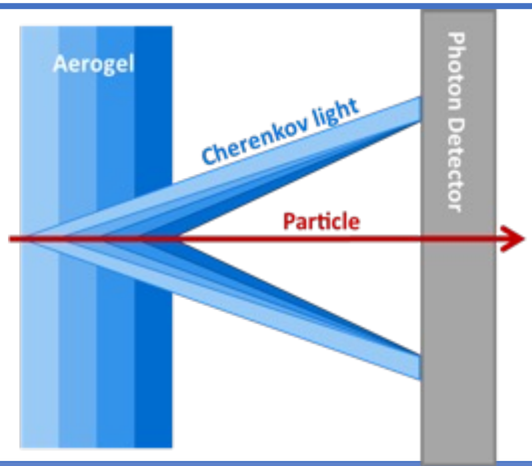


Hadron decays of D-mesons & τ -leptons

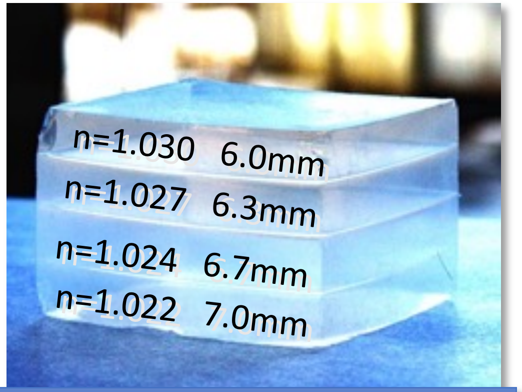
$D \to K\pi\pi\ , D^0 \to K\pi\ \ldots \tau \to \pi\pi^0\nu, \tau \to \pi\nu\ \&\ \tau \to \pi\nu\gamma?\ , \tau \to K\pi^0\nu, \tau \to K\nu\ \&\ \tau \to K\nu\gamma? \ldots$

- Excellent π/K separation from up to 3 GeV/c

FARICH technique: major MileStones



The first 4-layer monolithic sample

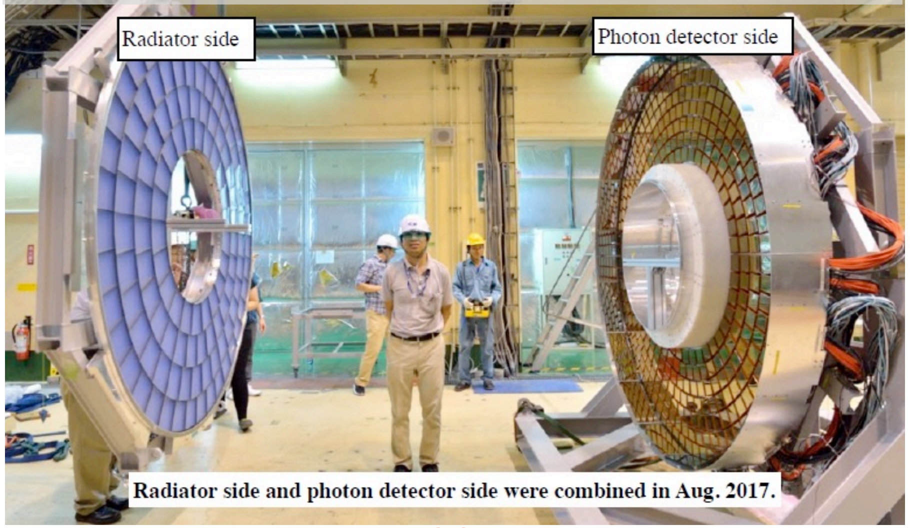


Increase N_{pe} due thickness increase without $\sigma_{\Theta c}$ degradation

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

2004÷2005

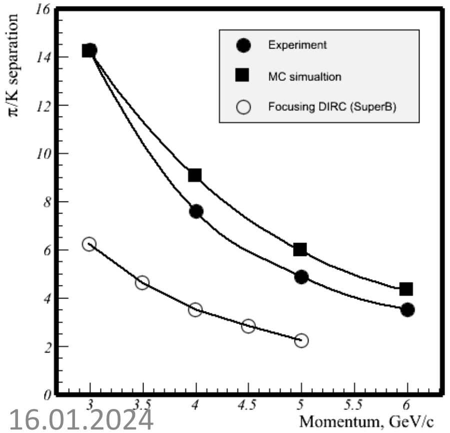
The Belle II (ARICH) is the first application of the method

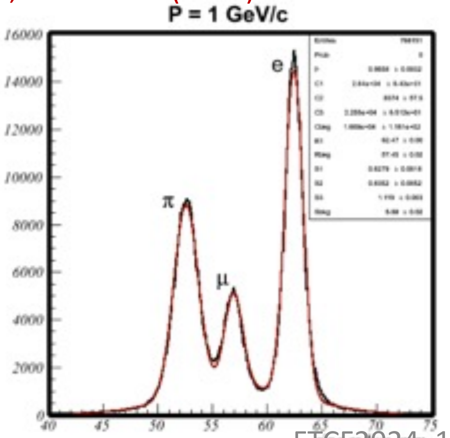


2017

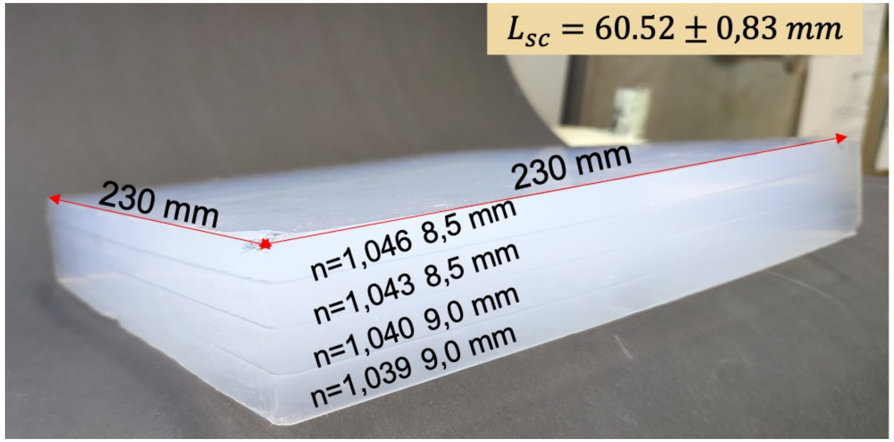
Excellent PID capability were shown at CERN beam test in 2012

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



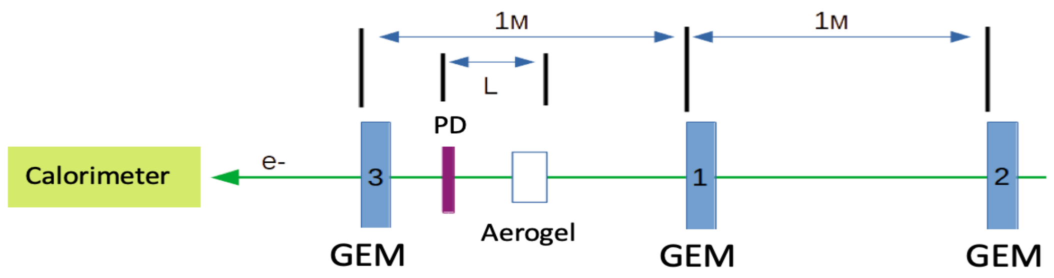


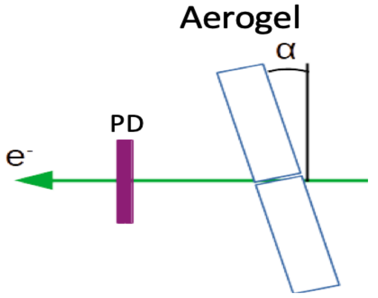
Two 4-layer focusing aerogel blocks
230x230x35 mm



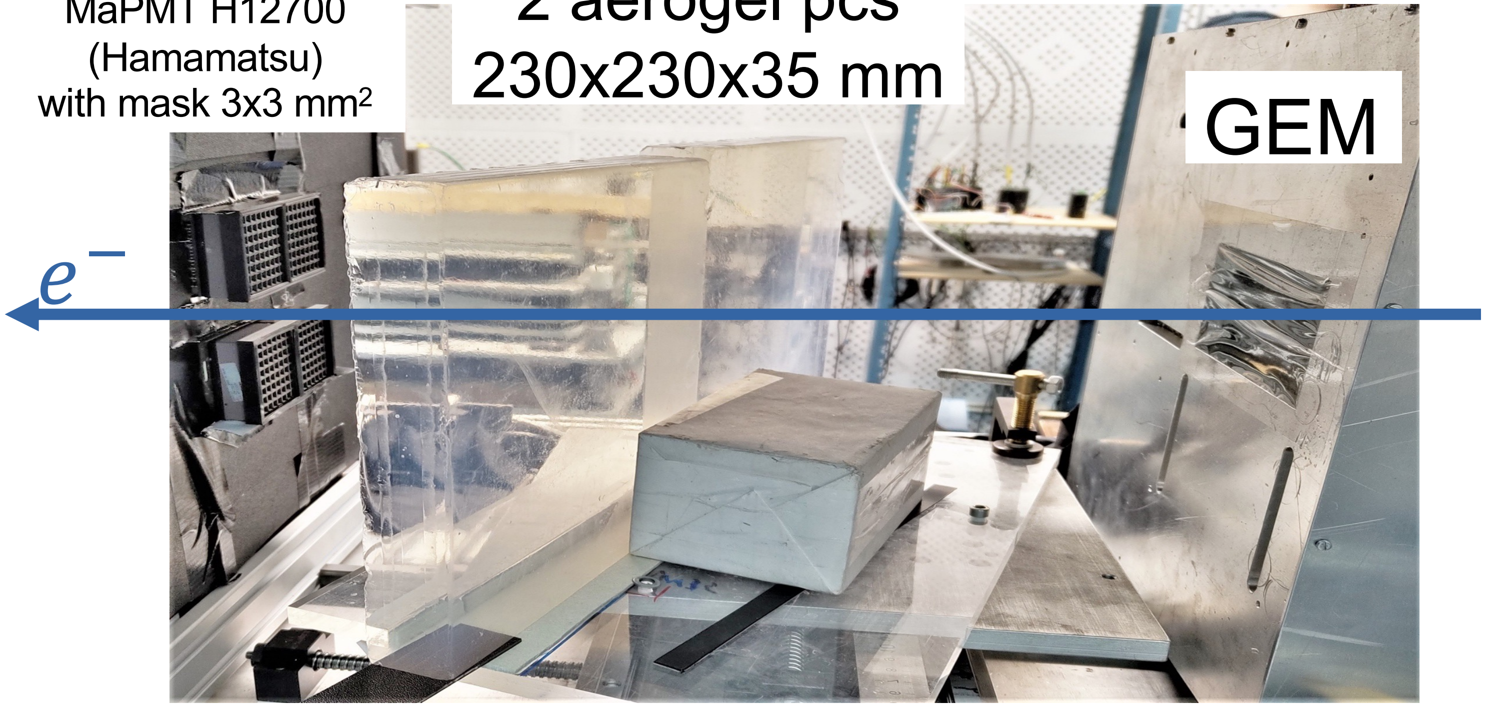
2022÷2023

The largest focusing aerogel samples produced in 2022

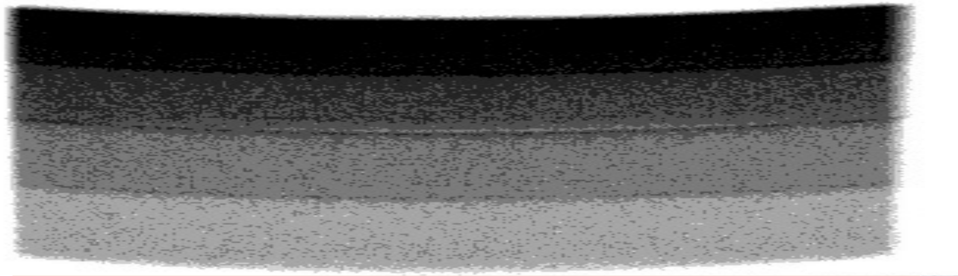




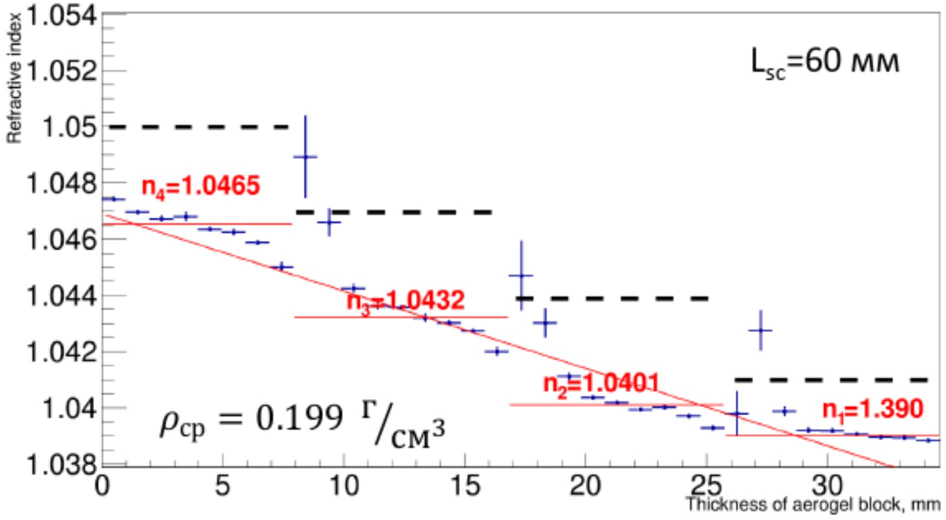
MaPMT H12700 (Hamamatsu) with mask 3x3 mm²



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



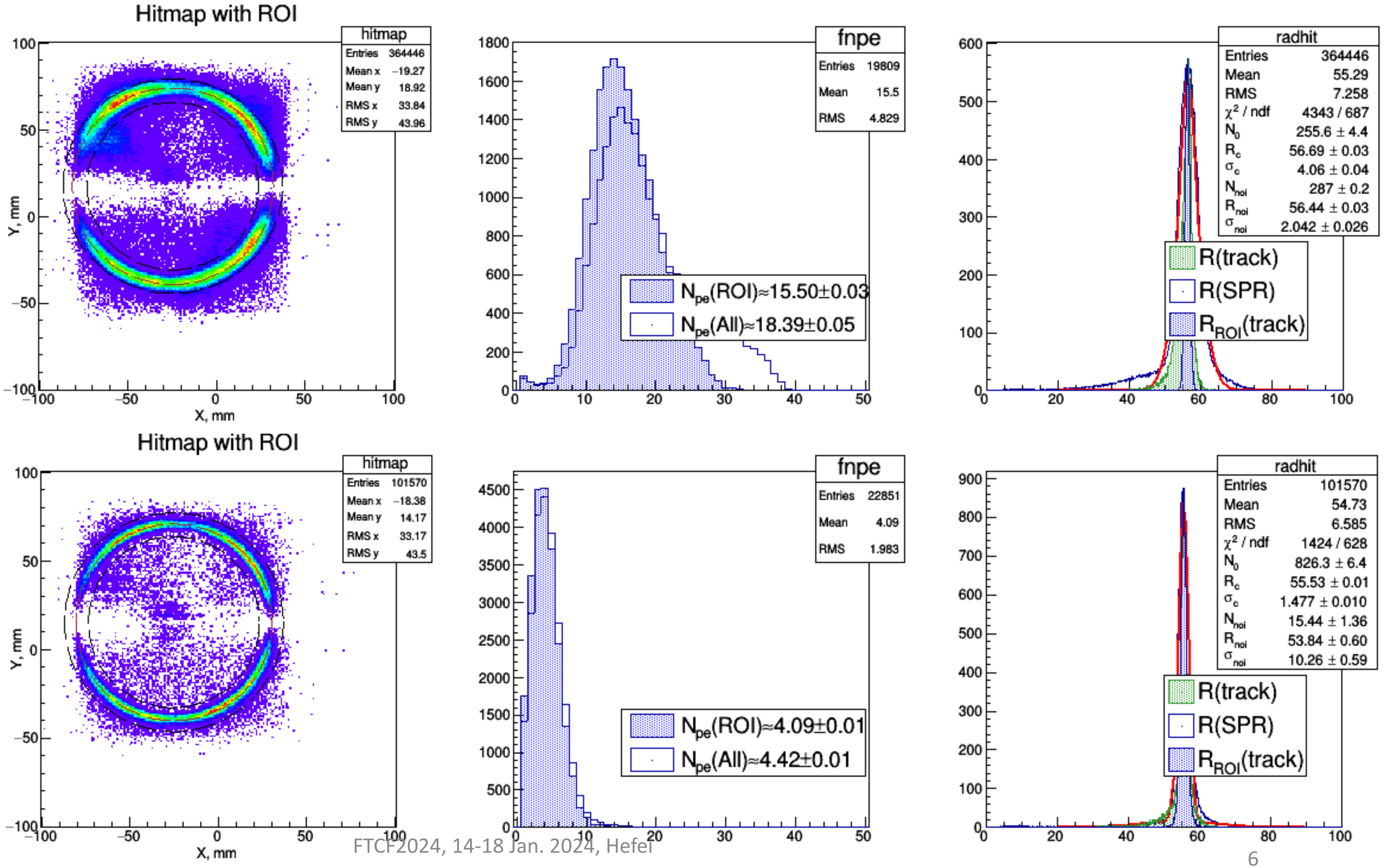
Refractive index profile is measured with help of didgital X-ray setup at the BINP.



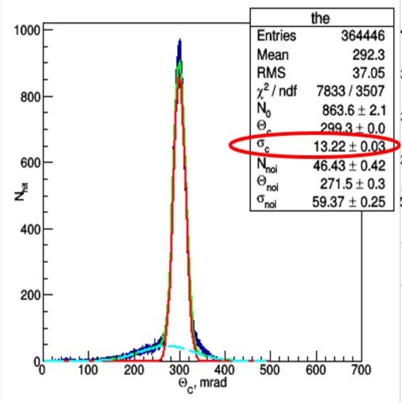
FARICH beam test 2023 results

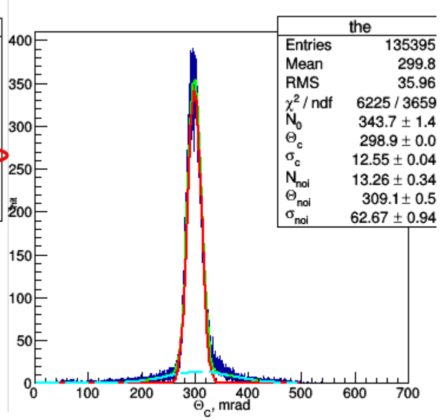
Pixel 6x6 mm
Geom.Eff. ~ 80%

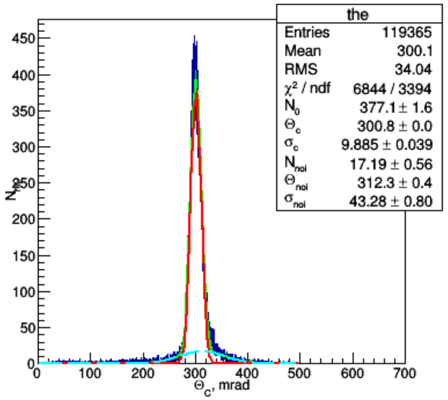
Pixel 3x3 mm
Geom.Eff. ~ 20%

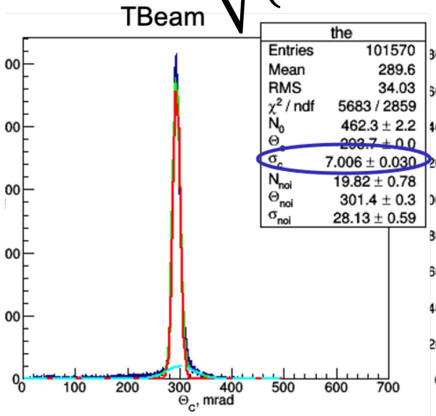


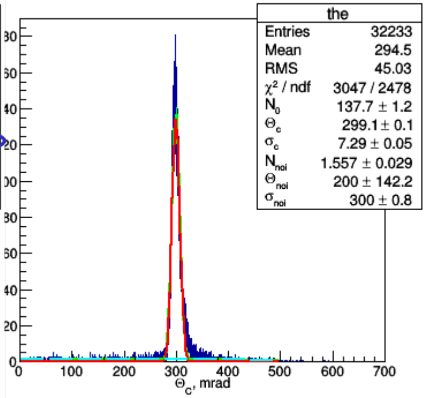
TBeam 2023 res.: $\sigma_{\theta_C}^{1pe} = \sqrt{\frac{\Delta_{pix}^2}{(\sqrt{12}\cdot L\cdot n)^2} + \sigma_{aer}^2 + \sigma_{trk}^2}$

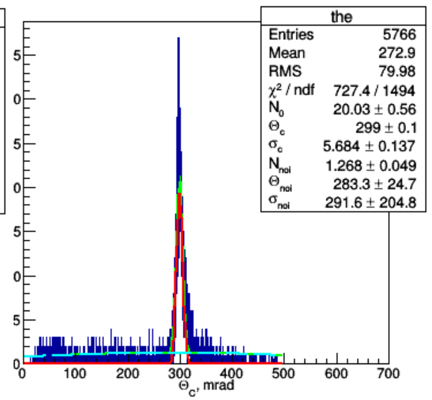




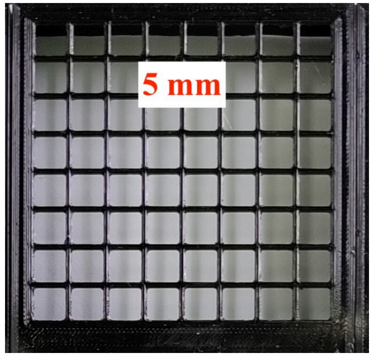


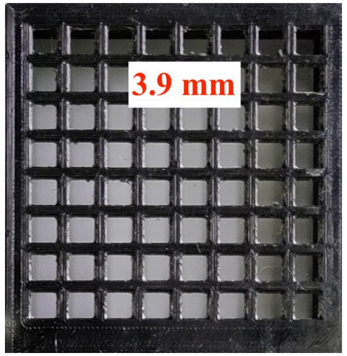


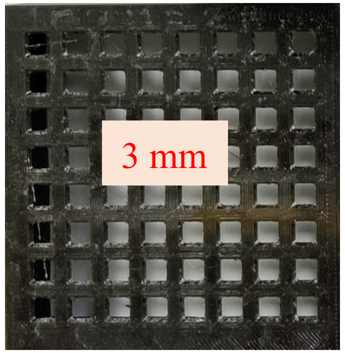


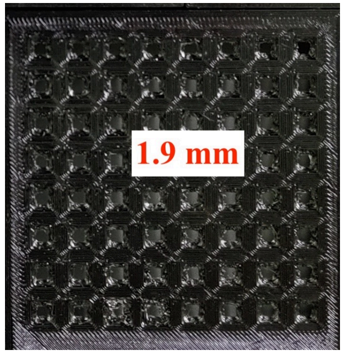


No mask: $6\times6\ mm$

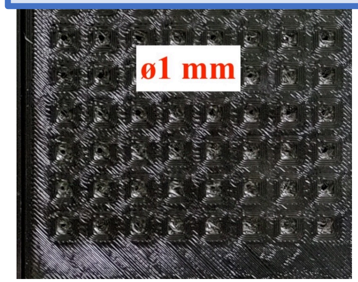








$\sigma_{aer} \approx 5.6$ mrad

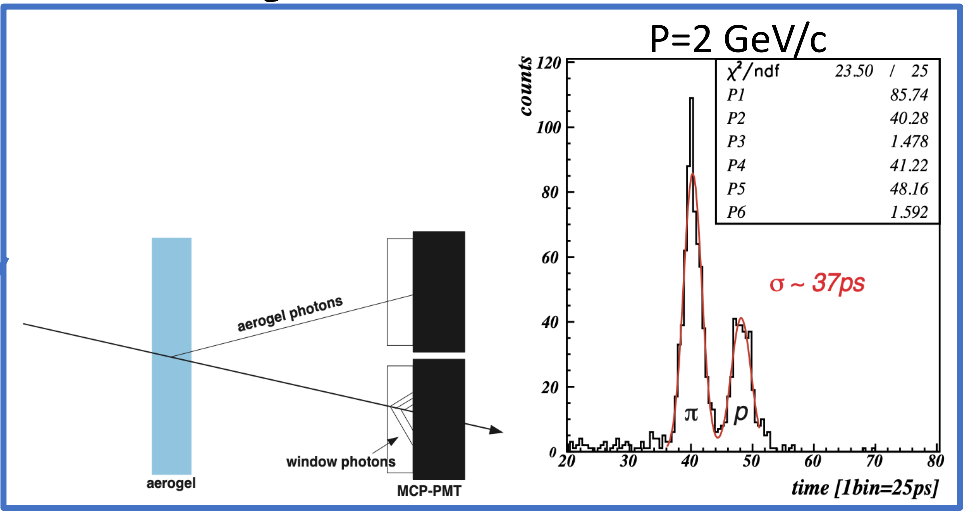


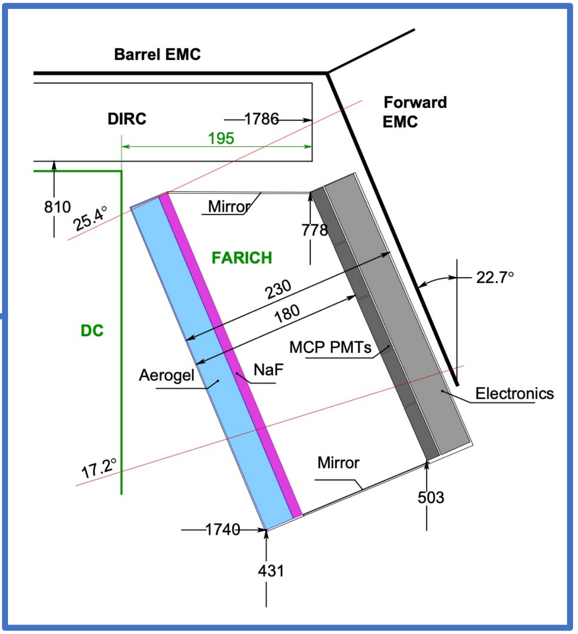
No mask	5 mm	3.9 mm	3 mm	1.9 mm	ø1 mm
04/23: L≈200 mm	12/23: L≈180 mm	12/23: L≈180 mm	04/23: L≈200 mm	12/23: L≈180 mm	12/23: L≈180 mm
Geom.Eff. ~ 80%	Geom.Eff. ~ 56%	Geom.Eff. ~ 36%	Geom.Eff. ~ 20%	Geom.Eff. ~ 9%	Geom.Eff. ~ 2%
$N_{pe} \approx 16$	$N_{pe} \approx 12$	$N_{pe} \approx 8$	$N_{pe} \approx 4$	$N_{pe} \approx 2$	$N_{pe} \approx 1$
π/K: – 5.5 GeV/c	6 GeV/c	6.5 GeV/c	8.0 GeV/c	8.0 GeV/c	8.5 GeV/c
μ/π: – 1.2 GeV/c	1.4 GeV/c	1.5 GeV/c	1.6 GeV/c	1.6 GeV/c	1.7 GeV/c

RICH with dual radiators is not very new idea!

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

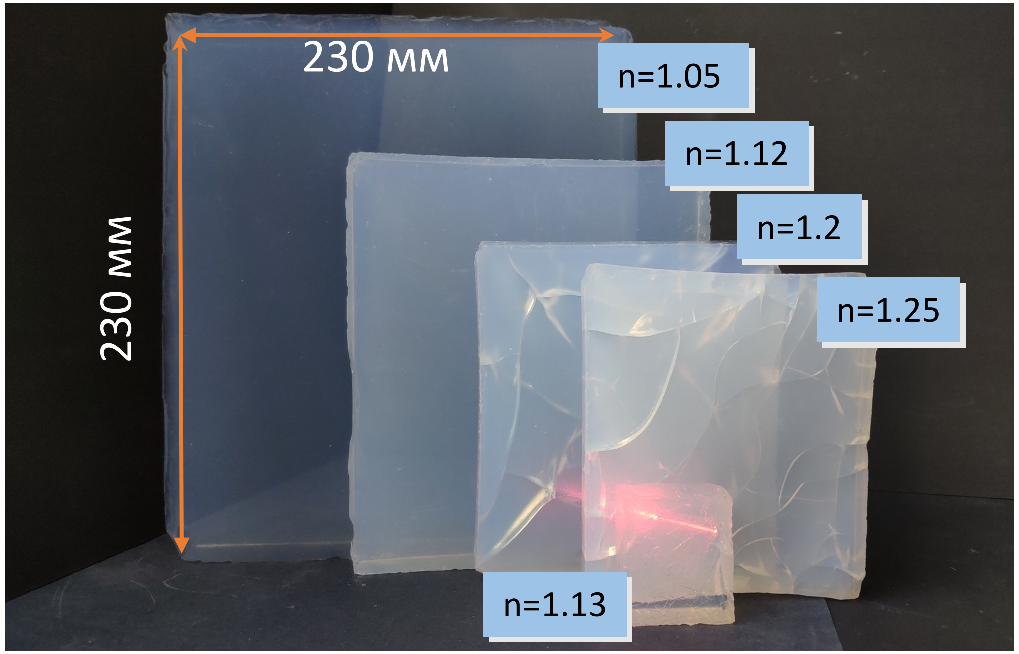
Aerogel is material with easy tunnable refractive index!

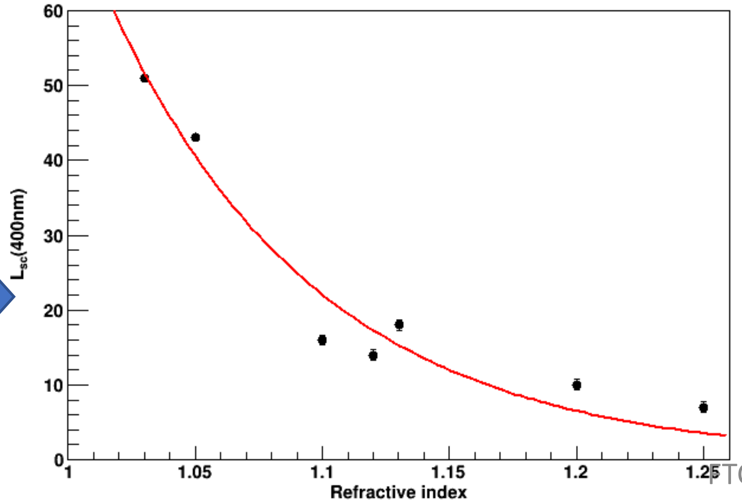




Aerogels with high optical density

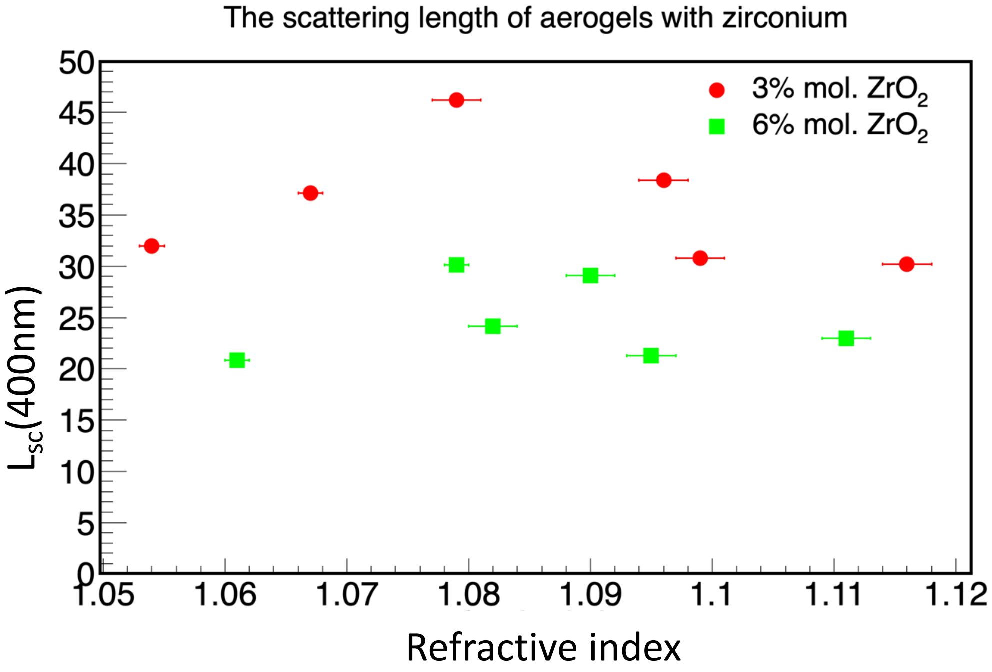
Sintering approach

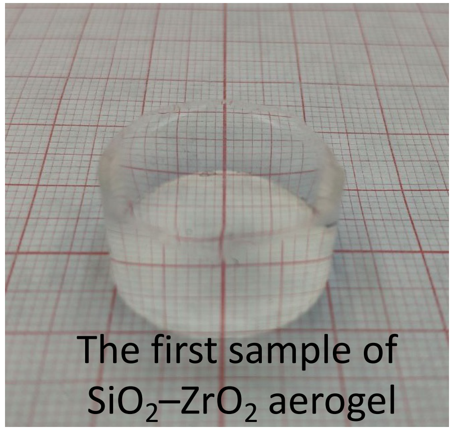




The main flaw of this approach

ZrO_2 addition approach

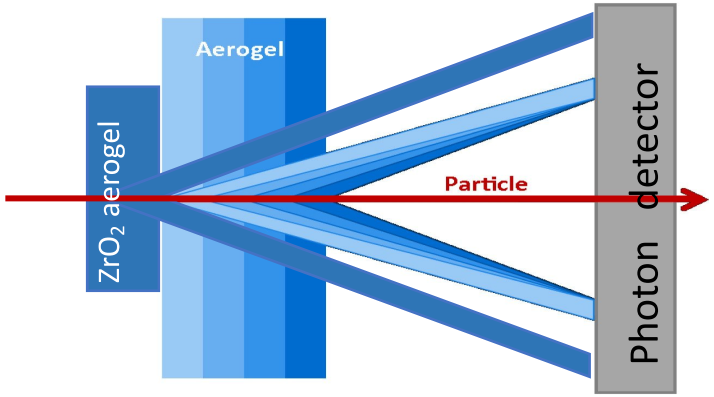


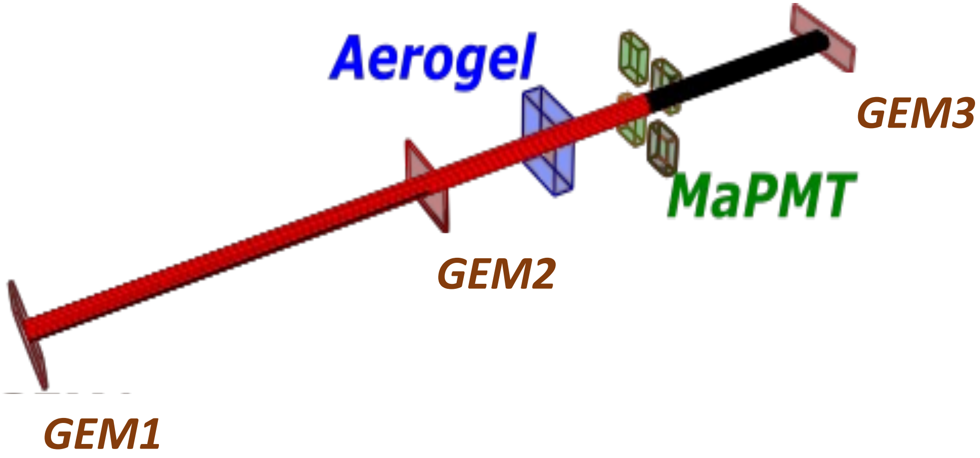


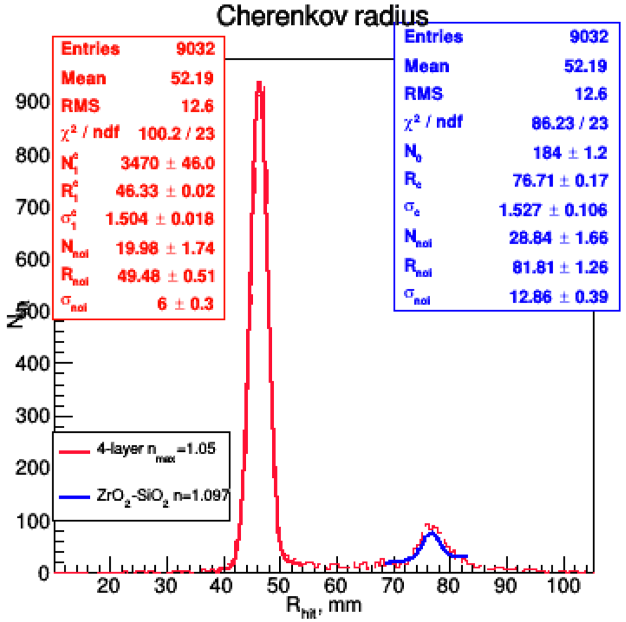
The addition of small amount (0.03÷0.06 mol) of ZrO_2 in SiO_2 based aerogel alow us to produce highly transperant aerogels with high optical density:

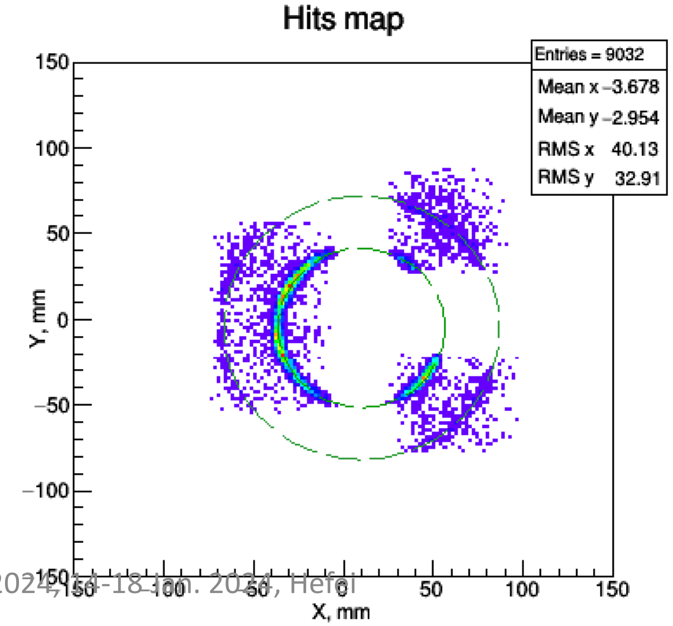
- Refractive index up to n=1.12
- Rayleigh light scattering length L_{sc}(400nm) up to 30 mm

Beam tests results of FARICH with dual radiator









ZrO_2–SiO_2 aerogel:

Thickness 12 mm & ø20 mm;

L_{sc}(400nm)=21±0.5 mm;

4-layer SiO_2 aerogel:

100x100x35 mm;

L_{sc}(400nm)=37±0.3 mm;

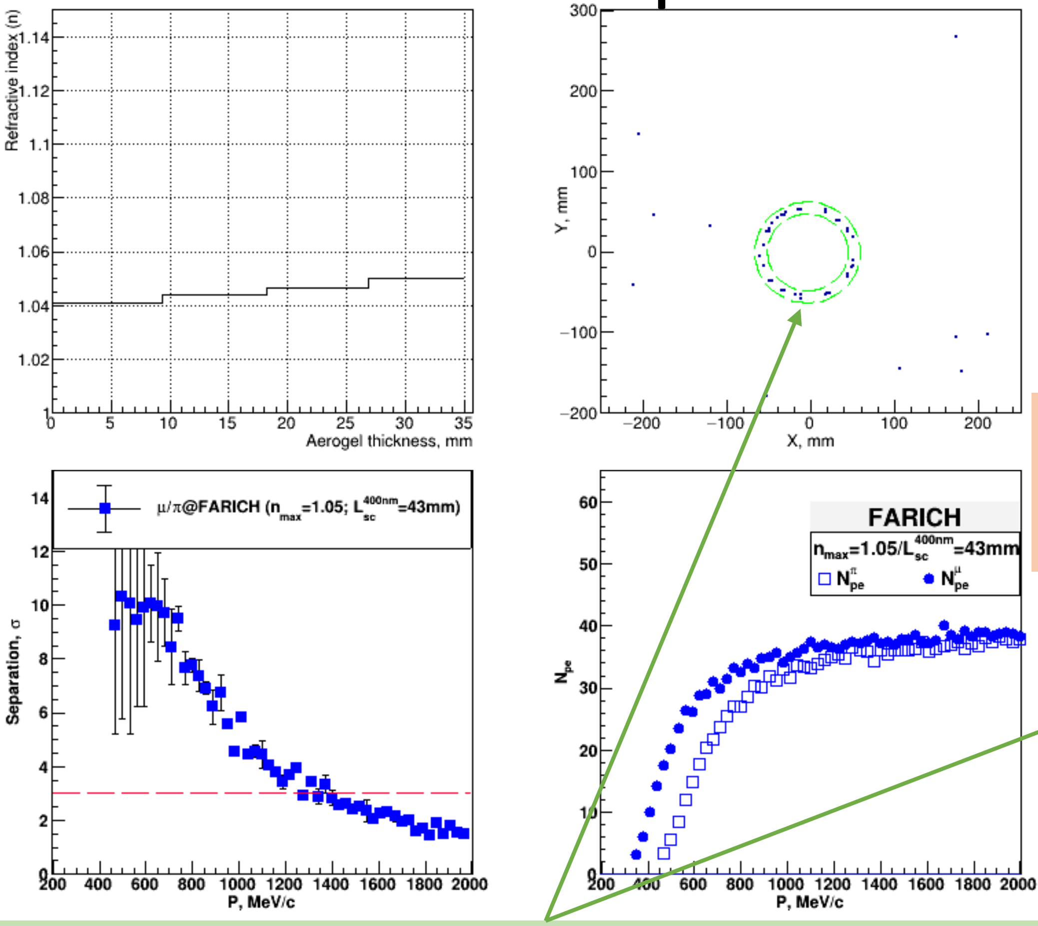
Photon detector

4 MaPMT H12700 (Hamamatsu);

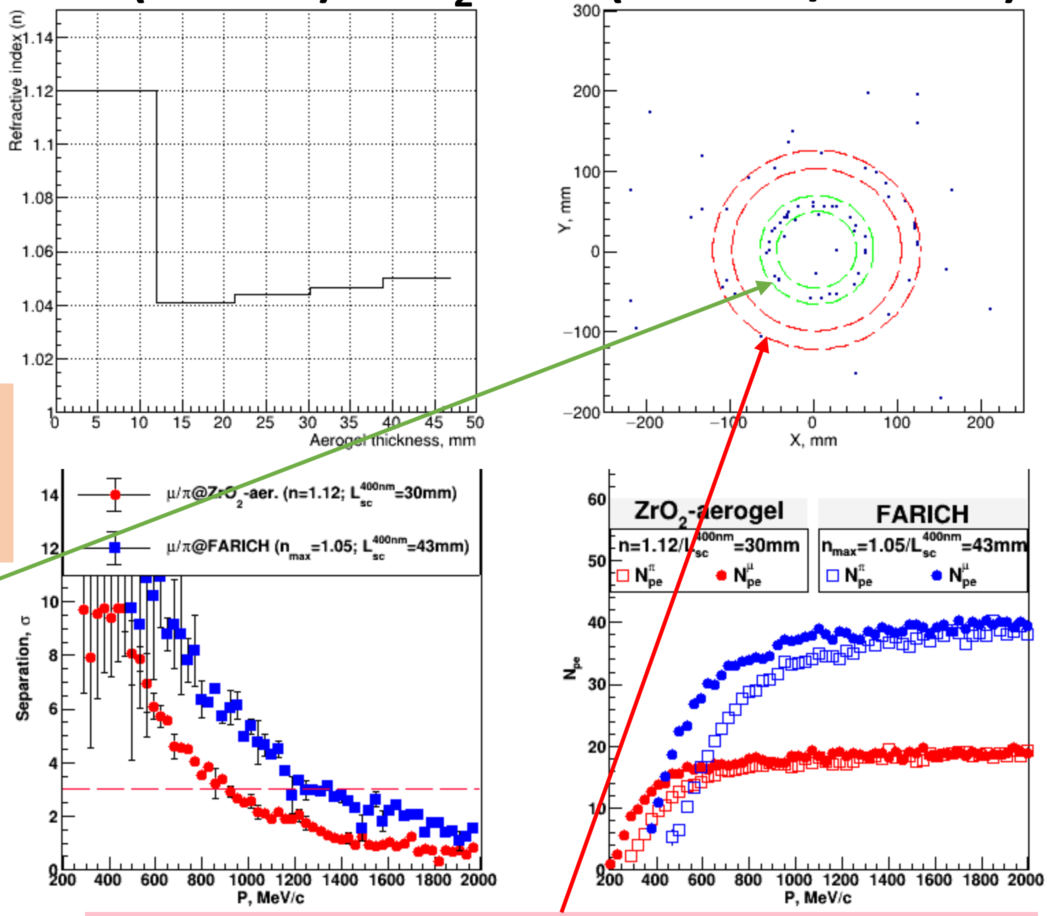
256 pixels with 3x3 mm size;

μ/π-separation via G4 simulation

FARICH: "ideal" n profile



FARICH ("ideal")+ZrO_2–aer. (n =1.12/12 mm)

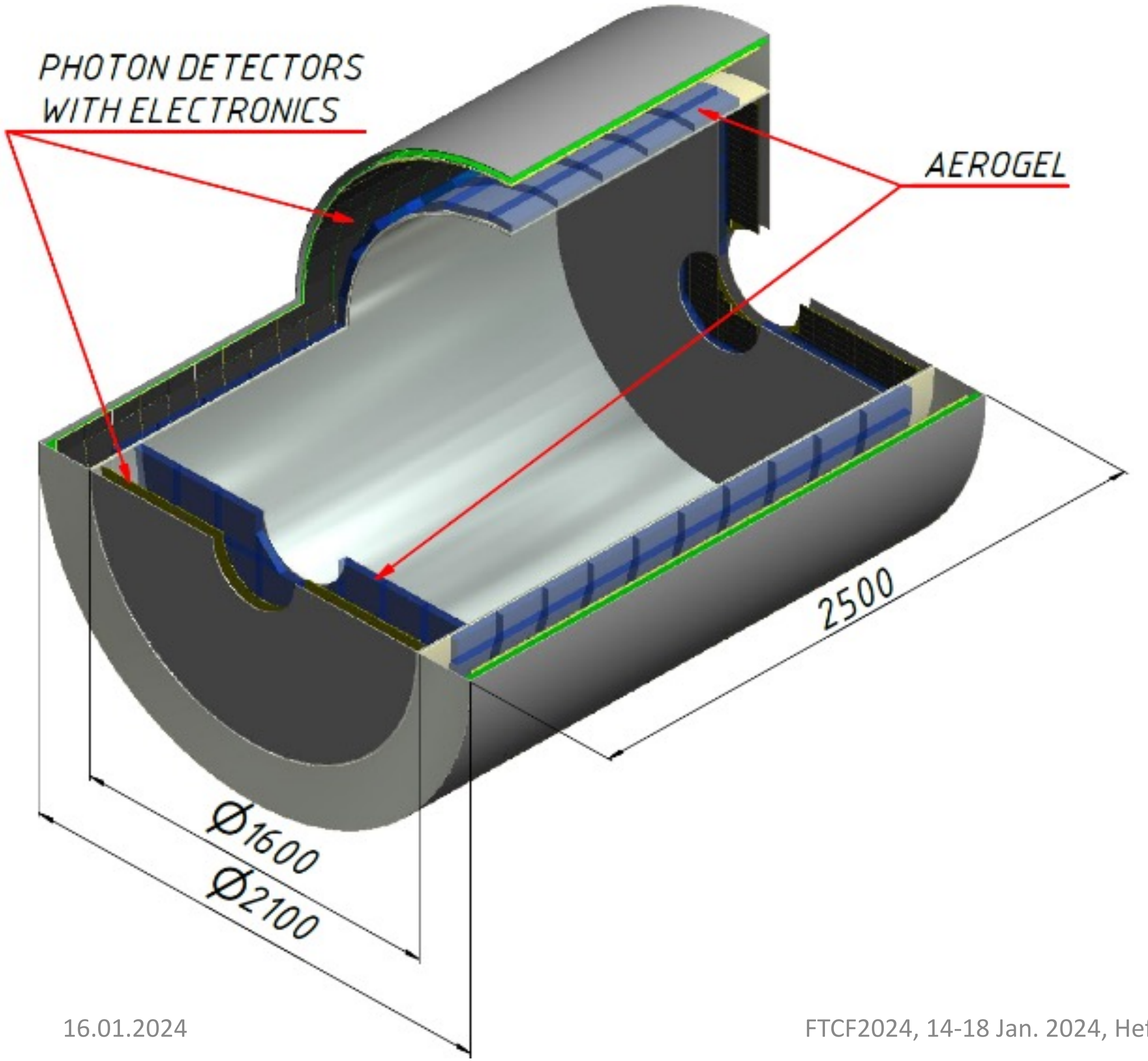


$$N_\sigma = \frac{\bar{R}_C^{\mu} - \bar{R}_C^{\pi}}{\left(\sigma_R^{\pi} + \sigma_R^{\mu}\right)/2}$$

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

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

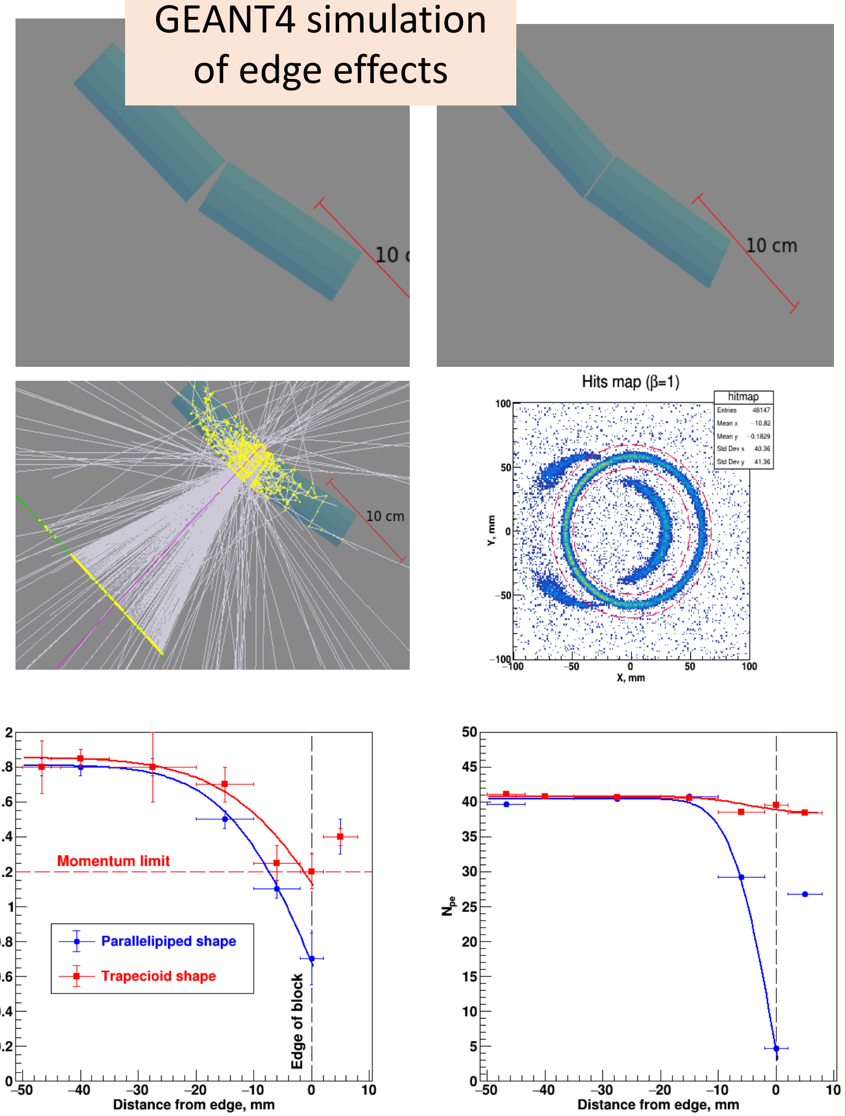
FARICH system concept for the SCTF



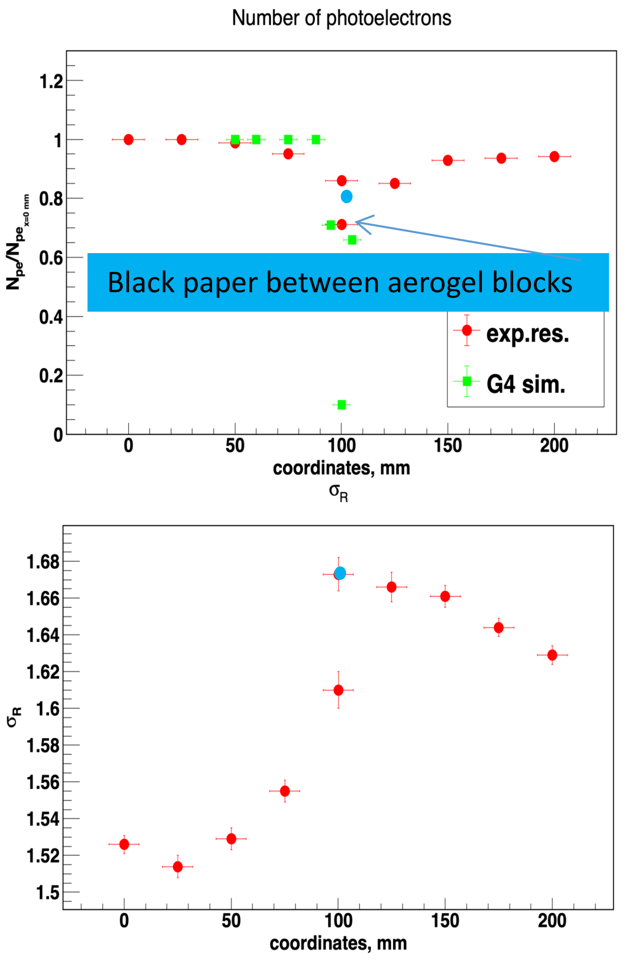
- Proximity focusing RICH
- 4-layer focusing aerogel
  - n_{max} = 1.05 (1.07?), total thickness 35 mm
  - $S_{aer} = 15\ m^2$
- 21 m^2 – total area of photon detectors
  - SiPMs – barrel part (16 m^2)
  - MCP-PMT – endcap parts (4 m^2)
- ~10^6 pixels 3x3 mm^2 with pitch 4 mm

Aerogel for SCTF-FARICH system

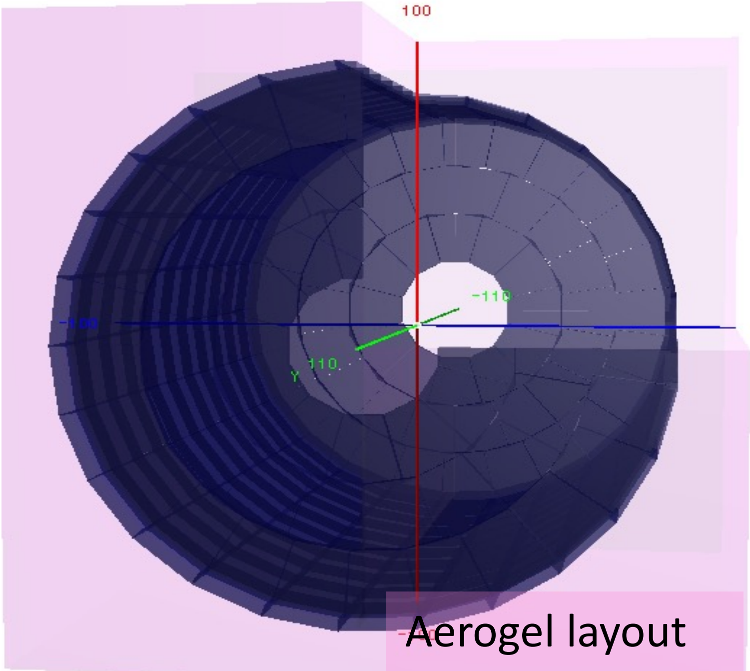
GEANT4 simulation of edge effects



TBeam & G4 res.



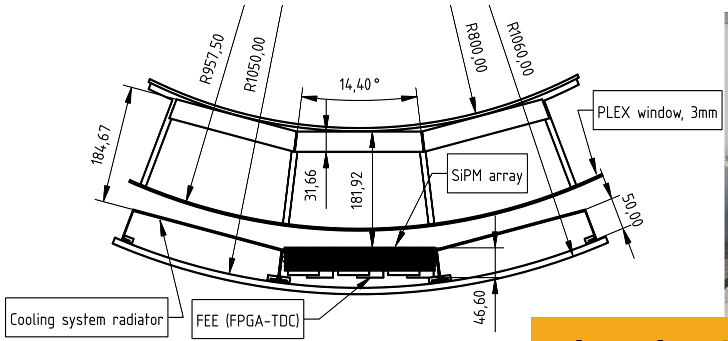
SHAPE	Δ, mm	Aerogel size, mm			
		200	100	75	50
Parall.	6	0.86	0.74	0.62	0.5
Trap.	1	0.96	0.94	0.92	0.9

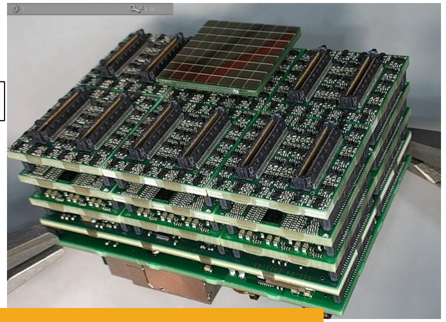


275 tiles 200x202x35 in barrel part
2x55 trapezoidal tiles in end caps:
- 2x12 – inner radius
- 2x18 – medium radius
- 2x25 – outer radius

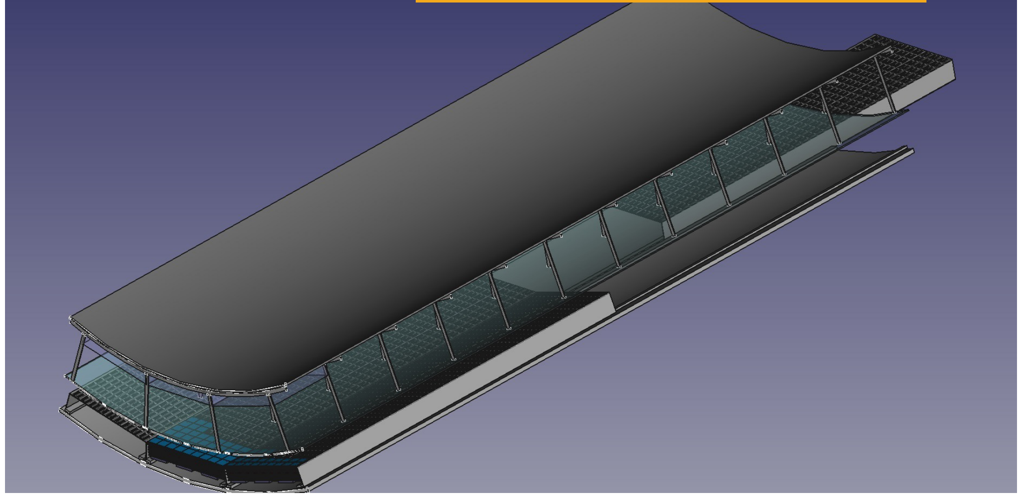
Photon sensors & R/O electronics

BARREL



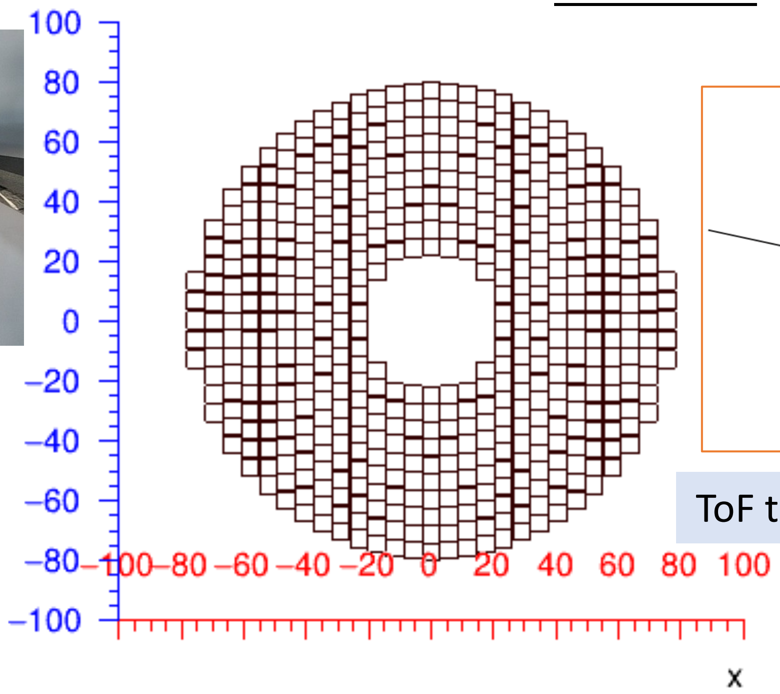


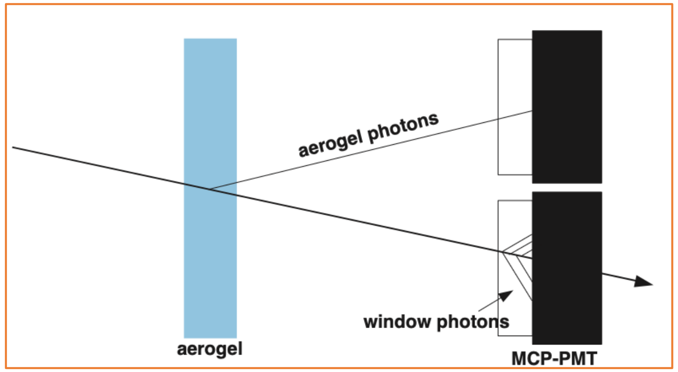
Sketchs & key elements



- Only SiPMs are able to operate in barrel FARICH
- ‘FaRICH ssytem’ R/O electronics prototype (from GSI) demonstrates ability to realised totally FPGA based approach

ENDCAP





ToF technique could be utilized as well

- 516 PMTs ■58x58 mm (PC ■ 50x50 mm) & 8x8=64 pix. 5.9x5.9 mm

$$Eff = \frac{516 \cdot 64 \cdot 0.59 \times 0.59}{S_{endcap}} = \frac{11495\ cm^2}{18850\ cm^2} \approx 0.60 \rightarrow N_{pe}^{\beta=1} \approx 10$$

- R/O system could be based on DiRICH boards (from GSI) or similar
- Expected separation:

  π/K up to ~5 GeV/c

  μ/π up to ~1 GeV/c

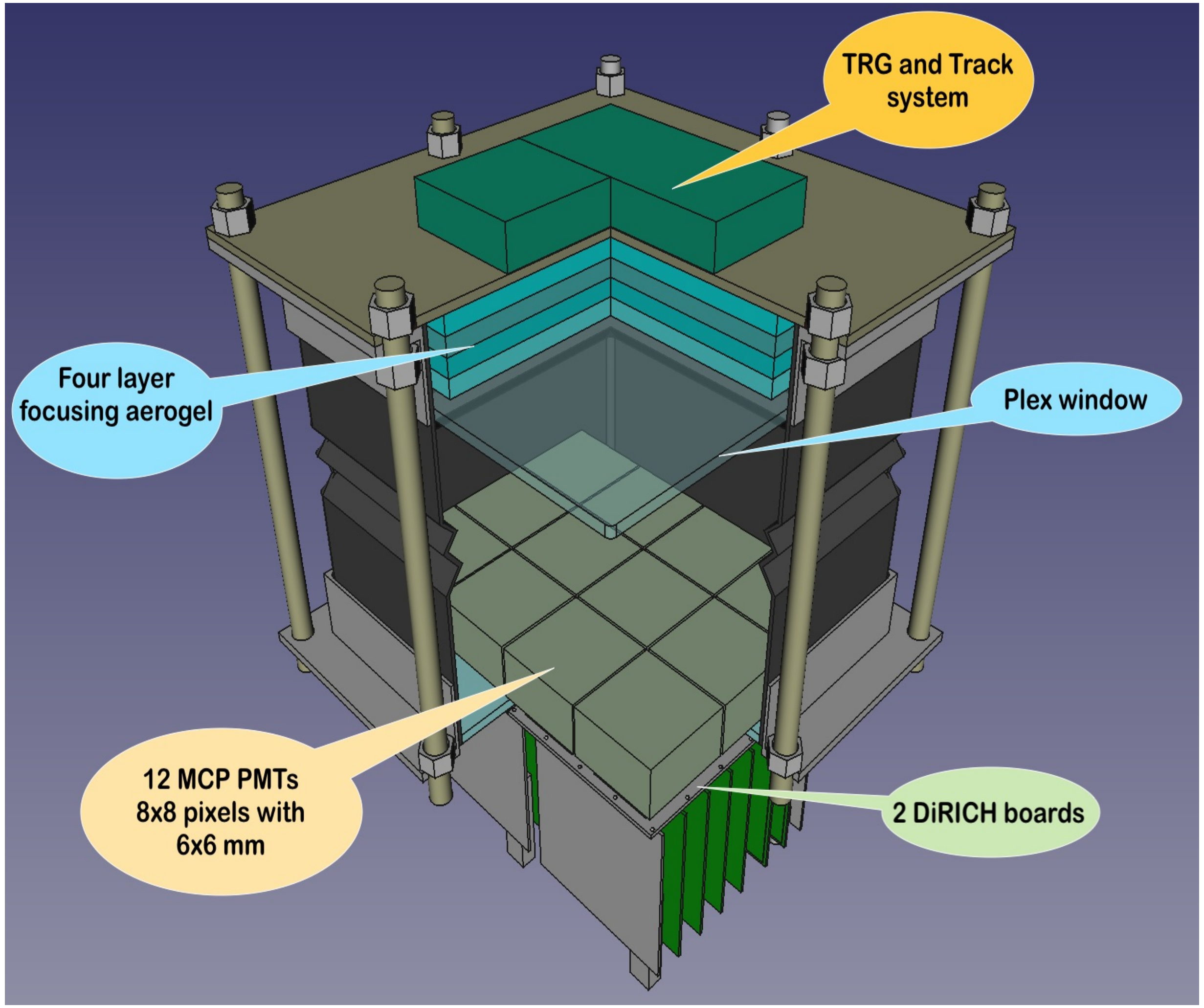
Summary

- 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 possibility to create full-scale systems based on 4-layer focusing aerogel Cherenkov radiators was demonstrated
  - The measured SPR of FARICH based on 4-layer focusing aerogel 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
  - Recent progress in high opticaly dense aerogel production with help of ZrO_2 dope allows us to consider new design of FARICH detector with dual aerogel radiator which able to provide exccelent μ/π from 0.2 GeV/c
- Further progress strongle depends on development of position-sensetive photon detectors and compatible R/O electronics. It was demonstrated that there are no any showstopers but this is an issue of coast and availability (components, manpowers, funds etc.).
- FARICH option now is also considered for several other projects: PSD-NICA (Dubna), VEPP-6 (Novosibirsk) and other.

Back up slides

FARICH prototype with full-ring detection

- To demonstrate real PID capabilities of FARICH based on modern solutions.
- We need 8÷12 MCP PMTs with size ~5x5 cm 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 cpabilities.



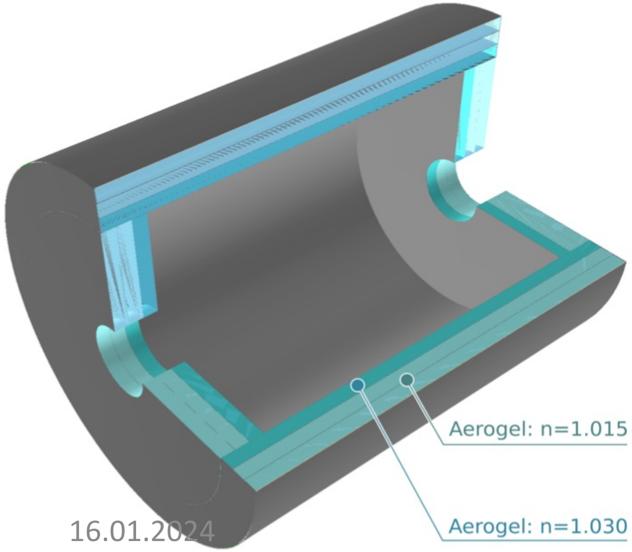
PID options for π/K – separation

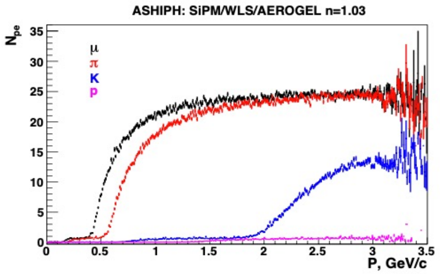
- dE/dx
  - $\frac{\sigma_{dE/dx}}{\langle dE/dx \rangle} \le 7\% \to \ge 3\sigma$ up to 0.6 GeV/c
  - $\frac{\sigma_{N_{cl}/dx}}{\langle N_{cl}/dx \rangle} \le 4\% \to \ge 3\sigma$ up to 0.9 GeV/c
- Focusing Aerogel RICH (FARICH)

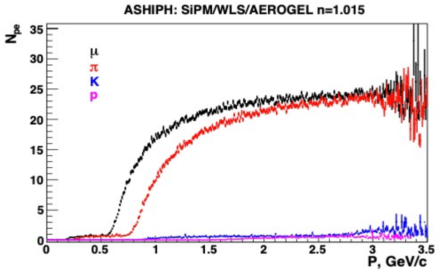
(4 layer @ n_{max}=1.05) $\to \ge 3\sigma$ from 0.5 to 6 GeV/c

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

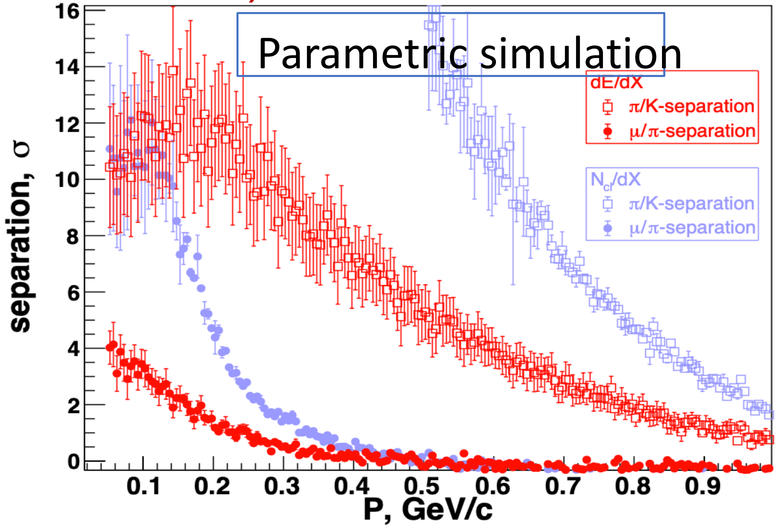
EPJ Web of Conferences **212**, 01012 (2019),
A.Yu. Barnyakov *et al* 2020 *JINST* **15** C04032



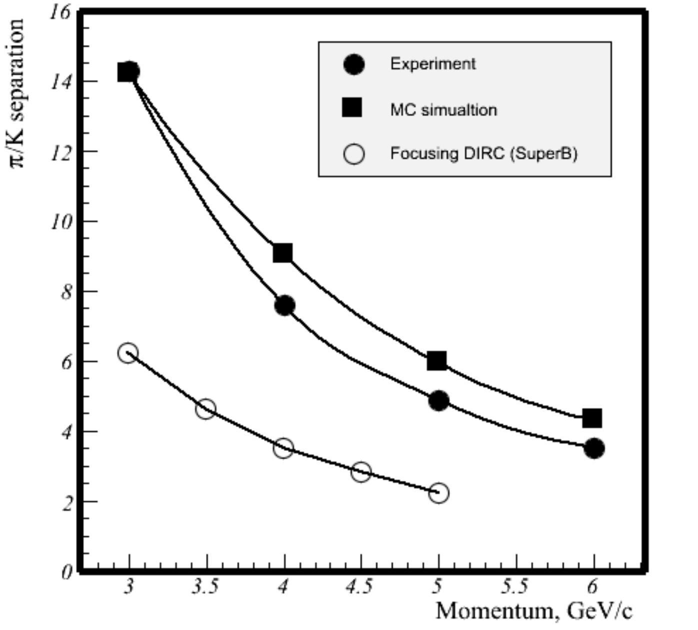




*A.Yu. Barnyakov et al 2020 JINST **15** C04032*

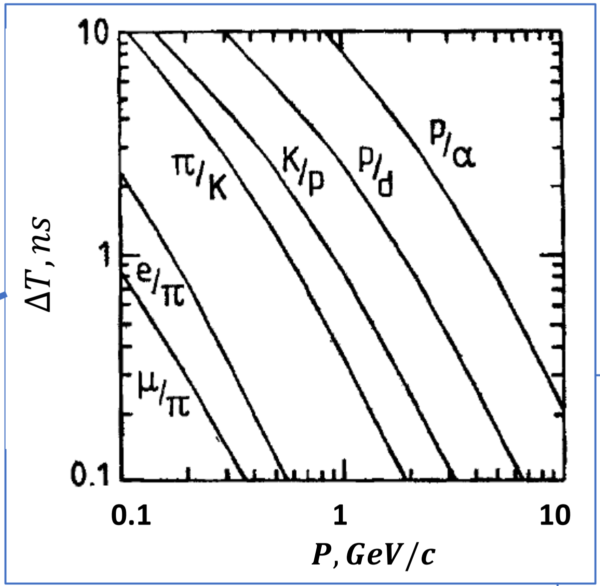


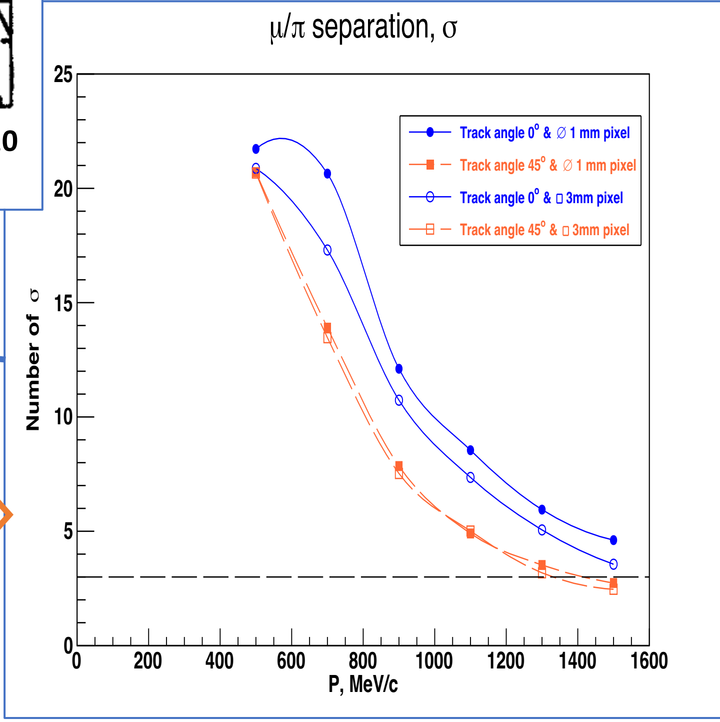
A.Yu. Barnyakov, et al., NIM A 732 (2013) 35



PID options for μ/π – separation

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





FARICH with dual aerogel radiator is proposed to extend down μ/π – separation from 0.5 to 0.2 GeV/c

Results of parametric simulation tuned with results of beam test :
– SPR(β = 1, ■3 mm)= 1.63 mm
– SPR(β = 1, ø1 mm)= 1.36 mm

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

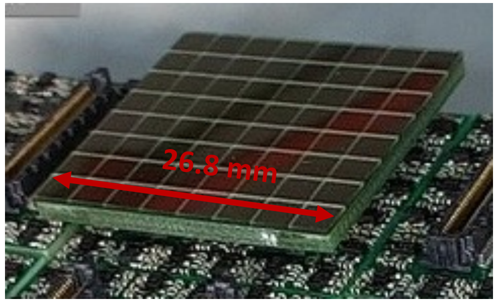
Photon detector options

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

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

SiPM arrays

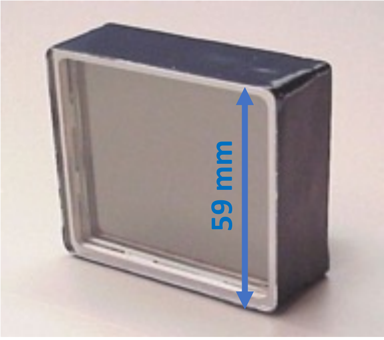
- There are several manufacturer in the world.
- It is required to develop and produce special R/O electronics and cooling system to operate with SiPMs in detector conditions



KETEK PA3325-WB-0808 (BroadCom, USA)

MCP-PMT

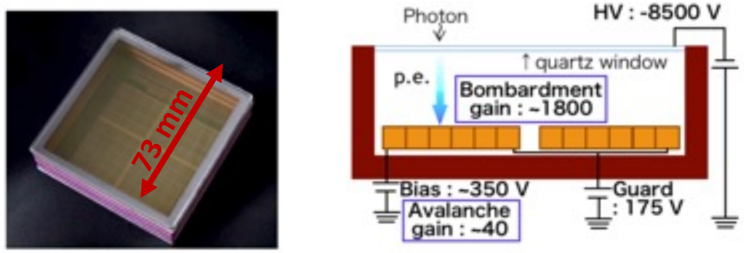
- There are several manufacturers in the world.
- PDE is not so high, it is limited by photoelectron collection efficiency (~60%) and geometrical efficiency is worse than for SiPM option. Severl vendors suggest MCP-PMT with CE=90%
- There is no such a big problem with intrinsic noise rejecion in comparison with SiPM option
- Specialised R/O elctronics is already developed for other experiments and could be adopted for the SPD experiment requirements



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!
- Expected PDE of such devices will less than for SiPM option but signficantly (1.5 times) higher than for MCP-PMT option.
- Expected gain is about $1 \div 2 \cdot 10^5$
- Development of specialised R/O elctronics is needed. It is possible to adopt some Belle II ARICH system expirience.
- The S/N-ratio is about 1000, it means that only thermostabilization system to operate at the room temperature will enough for this option.



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)

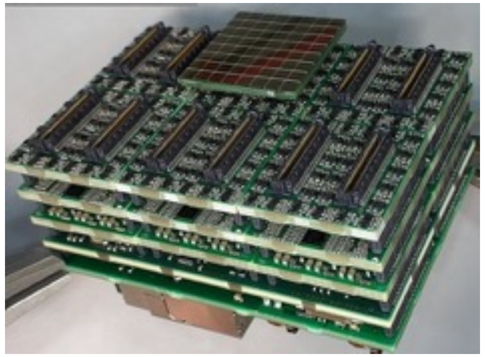
Unit	Article	Price per unit	Total price
2	DiRICH	4.917,00 €	9.834,00 €
	Additionally the export duty from Germany		150,00 €
	Total price		9.984,00 €

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

<u>A system with 30kChannel (HADES):</u>

$170k€/30k \approx 6€/chan$ (2017)

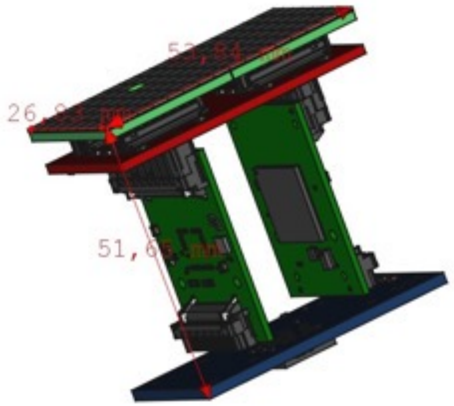
<u>Power consumption:</u> ~55mW/chan



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

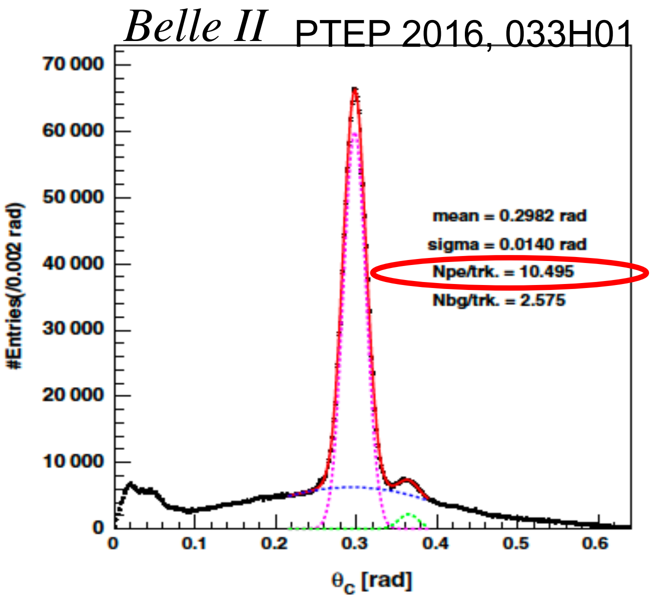
<u>A system with 100kChannel:</u>

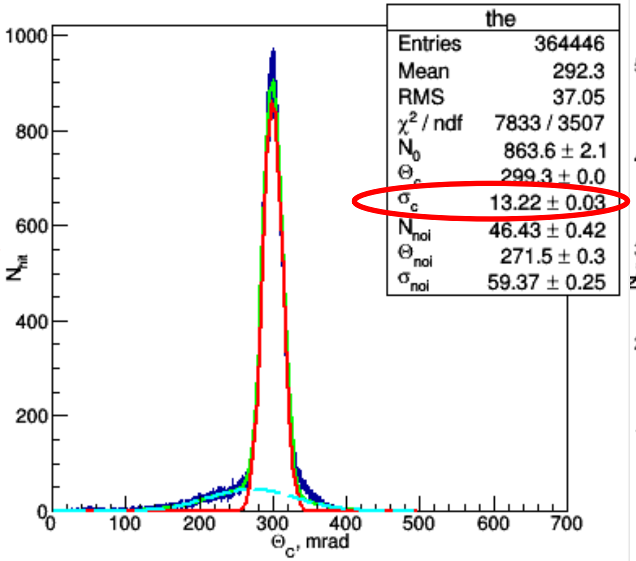
$5€/chan$ (2020)

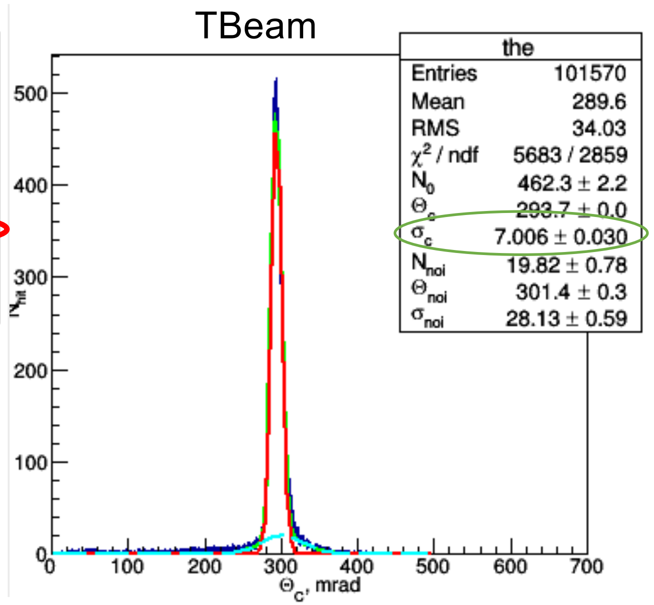
<u>Power consumption:</u>

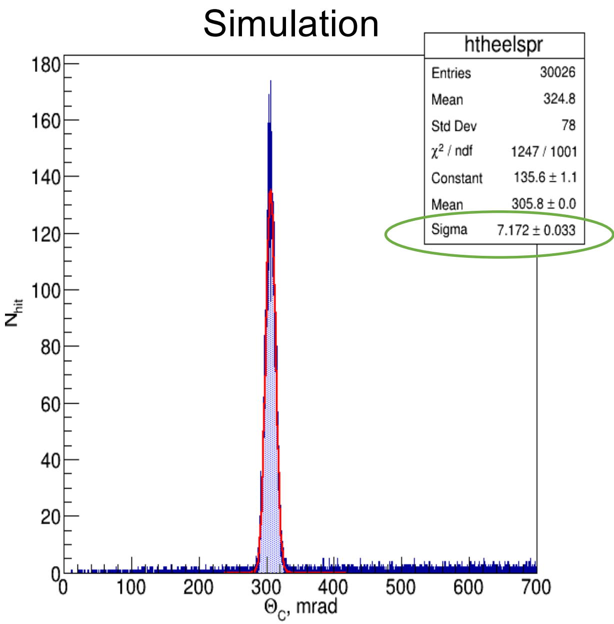
15mW/chan (ASIC) + DAQ (FPGA)~60mW/chan

TBeam results consideration









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%
$N_{pe} \approx 4$

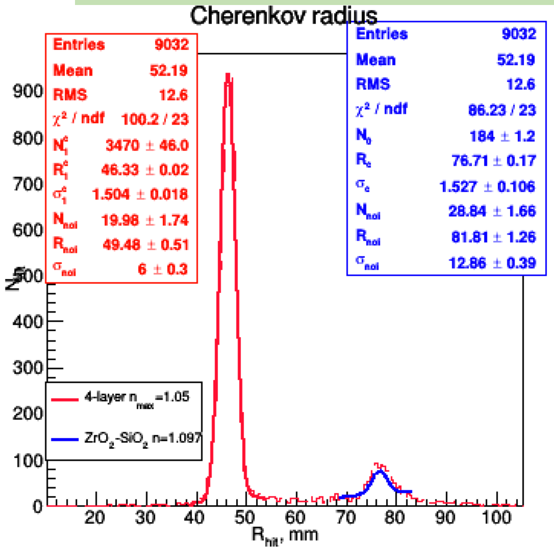
SPE resolution ~7÷8 $mrad$ is able to provide:

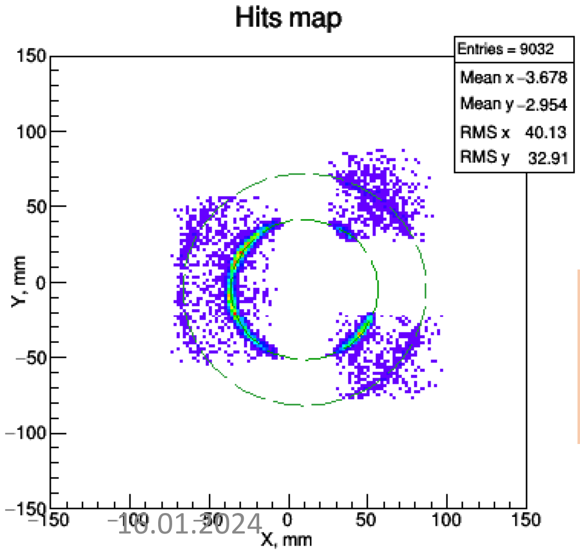
- π/K @ 8.0 GeV/c $> 3\sigma$ if ($N_{PE} = 16$) and π/K @ 6.0 GeV/c $> 3\sigma$ if ($N_{PE} = 8$)
- μ/π @ 1.5 GeV/c $> 3\sigma$ if ($N_{PE} = 16$) and μ/π @ 1.3 GeV/c $> 3\sigma$ if ($N_{PE} = 8$)

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

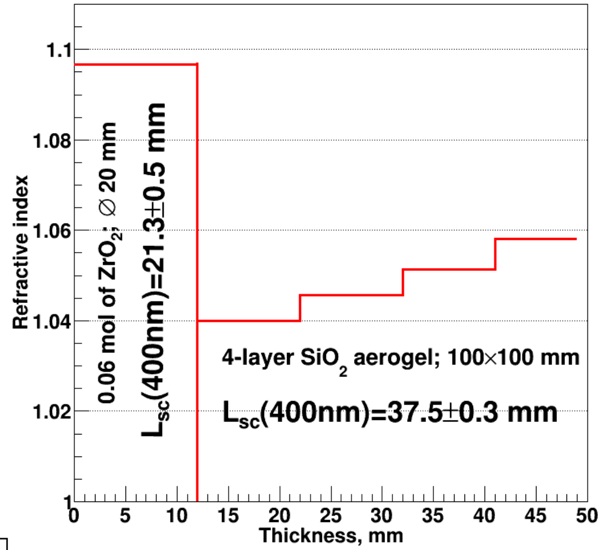
G4 simulation vs beam test results

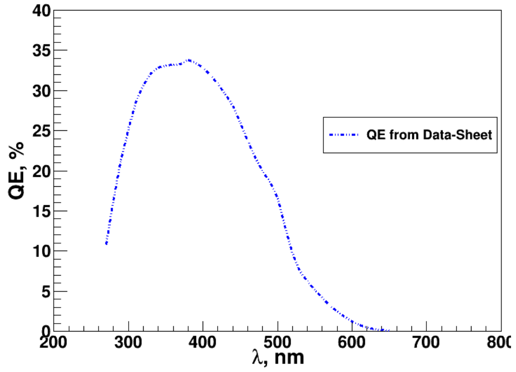
TBeam results





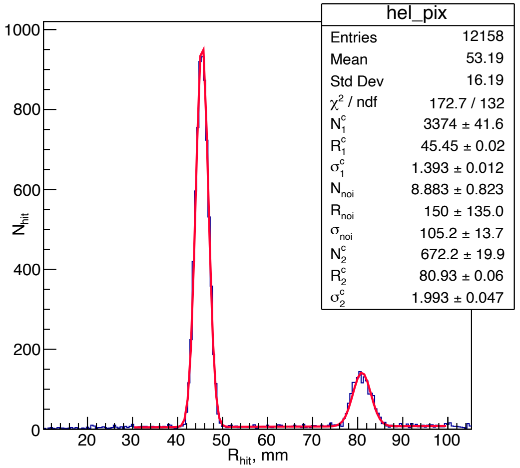
Optical parameters for G4 simultion

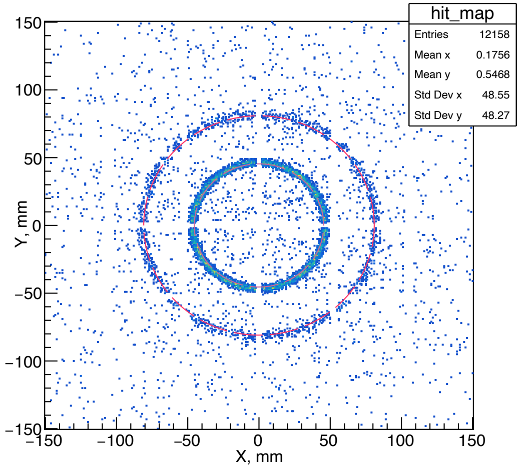




- PDE for H12700 from data-sheet
- Pixel 3x3 mm with pitch 6mm
- Focal distance L=172 mm

G4 simulation results





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