Aerogel based Cherenkov counters for momenta above 20 GeV/c

Alexander Barnyakov

CEPC International Workshop, 23-27/10/2024, Hangzhou

OUTLINE:

Aerogel is unique material

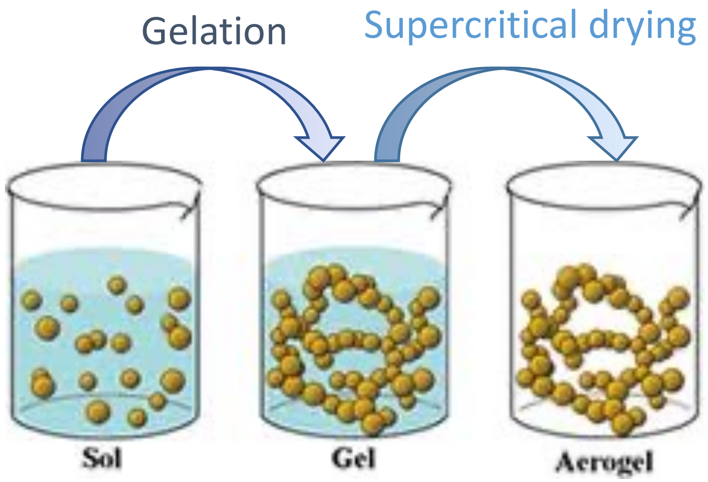
Aerogel RICH with focusing effects:

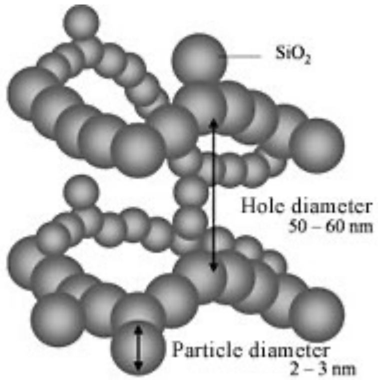
- *ARC-FCC*
- *FARICH technique*
- *mRICH technique (RICH with Fresnel lens)*
- *aerogel fibers*
- *precise position sensetive photon detectors*

Summary

Silica aerogel

- Silica aerogel was first produced in 1931 by Samuel S. Kistler
- Lightest solids. Close the nature's gap in refractive index between gases @ STP ($n-1 \lesssim 10^{-3}$) and liquids/solids ($n \gtrsim 1.3$).
- 3D network of SiO_2 nanometer sized pellets and 50-100 nm pores
- Now produced by sol-gel method out of silicon alkoxide $Si(OR)_4$

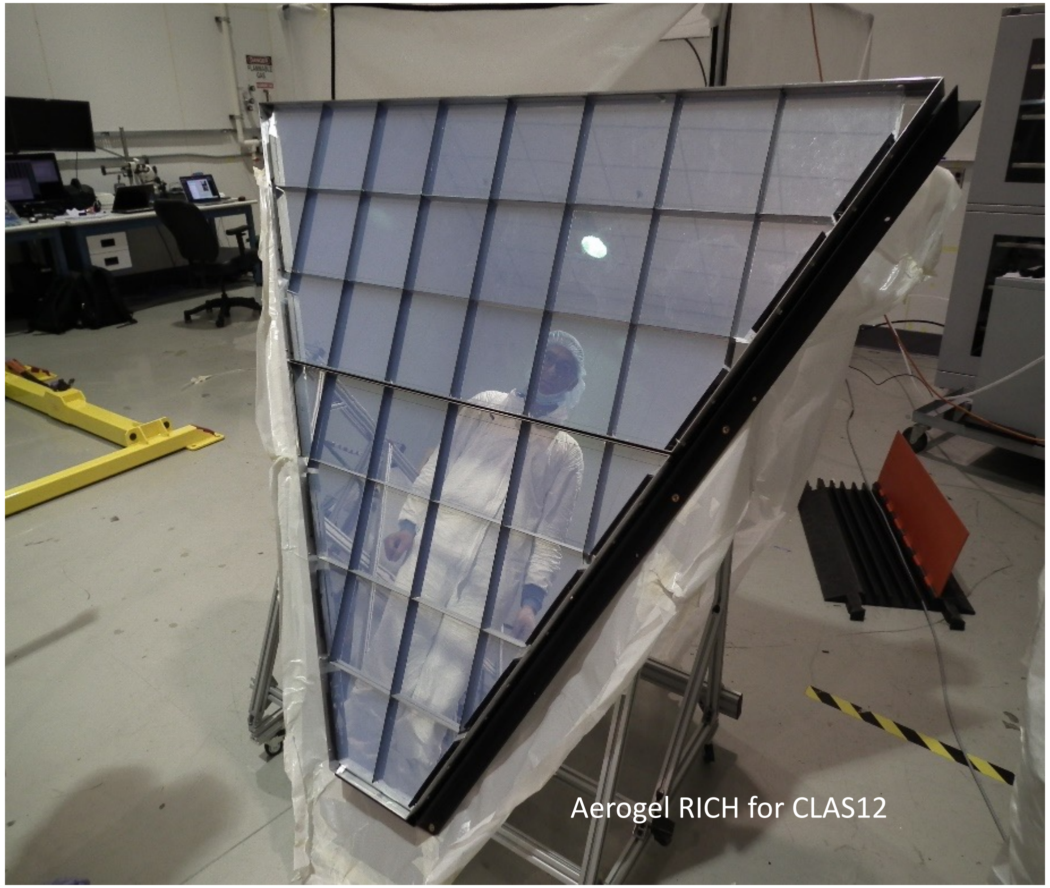




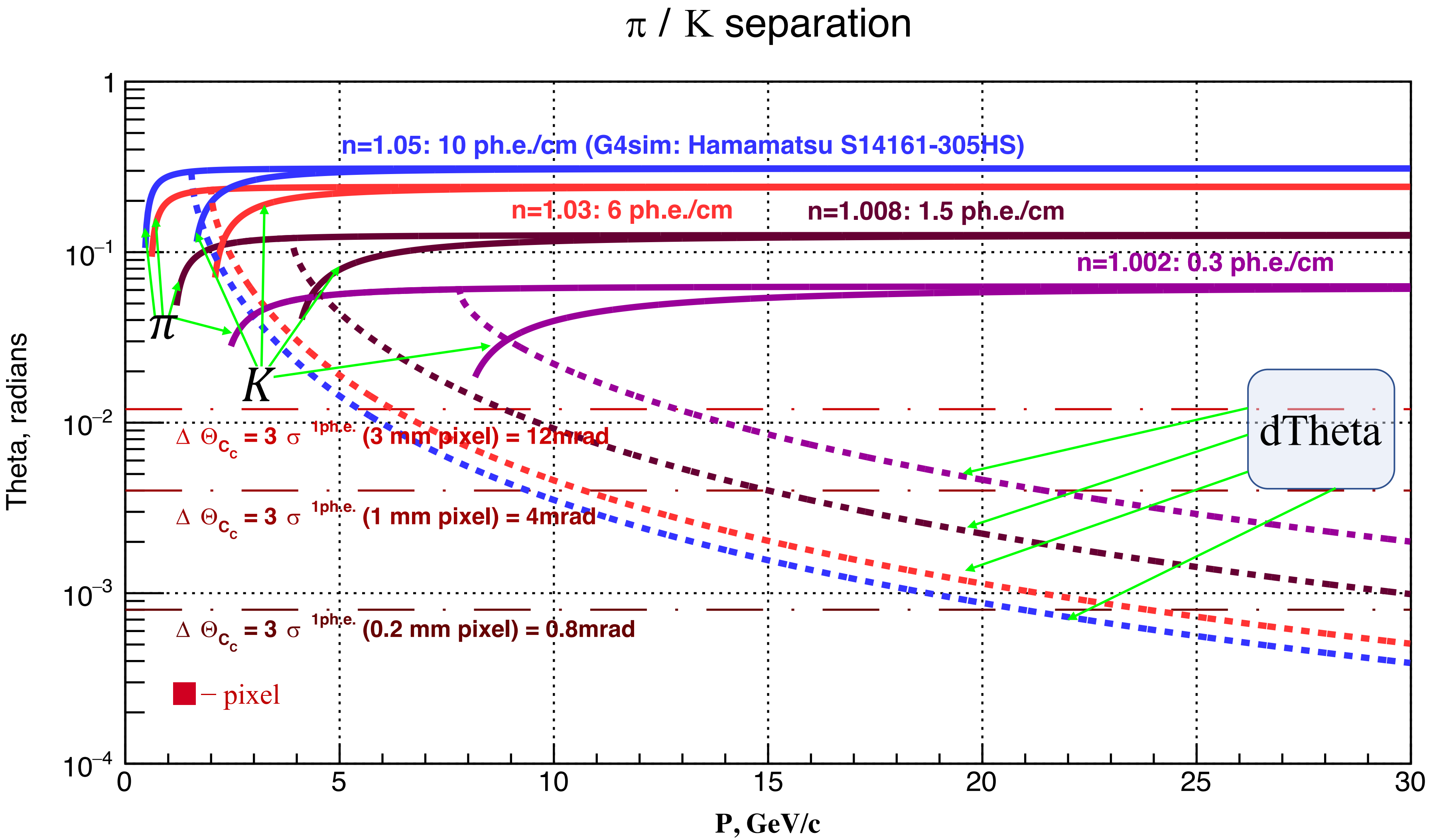
HEP projects based on aerogel from Novosibirsk

The history of the Novosibirsk aerogels began in 1986.

- KEDR ASHIPH system (VEPP-4M – BINP):
  - π/K-separation in the momentum range 0,6÷1,5 GeV/c.
  - Aerogel $n = 1{,}05$ (V~1000 L).
- SND ASHIPH system (VEPP-2000 – BINP):
  - π/K-separation in the momentum range 300÷870 MeV/c.
  - Aerogel $n = 1{,}13$ (V~9 L).
- DIRAC-II (PS – CERN):
  - π/K-separation in the momentum range 5,5÷8,0 GeV/c.
  - Aerogel $n = 1{,}008$ (V~9 L).
- AMS-02 aerogel RICH (ISS):
  - Search for antimatter, study of cosmic rays.
  - Aerogel $n = 1{,}05$ (S~1 m^2).
- LHCb aerogel RICH (LHC – CERN):
  - π/K-separation in the momentum range 5,5÷8,0 GeV/c.
  - Aerogel $n = 1{,}03$ (S~0,5 m^2), aerogel tile 20x20x5 $см^3$.
- CLAS-12 aerogel RICH (J-Lab):
  - π/K- & K/p-separation at level 4σ with several momentum GeV/c.
  - Aerogel $n = 1{,}05$ (S~6 m^2), aerogel tile 20x20x2-3 $см^3$.


Aerogel RICH for CLAS12

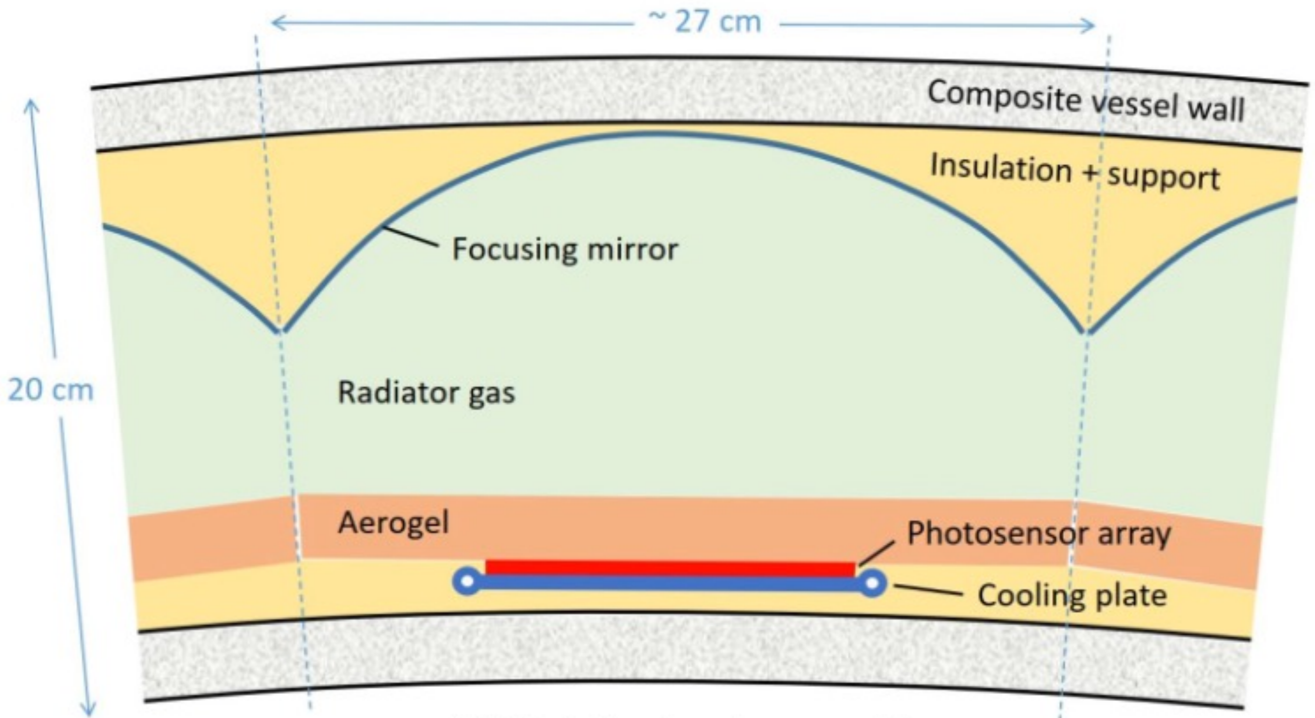
RICH detectors capability for π/K–separation



- 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!!!

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

ARC-FCC: few remarks

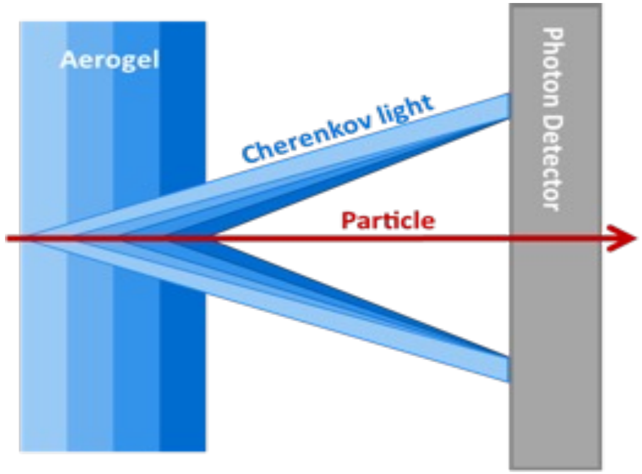


ARC detector (one cell)

Design inspired by succes of DELPHI and LHCb experiments

- **Light collection through aerogel**
  - Cherenkv light produced in aerogel will pass through aerogel twice
  - Cherenkov light from gas will pass the aerogel too
  - Therefore aerogel transperancy has to be better than for proximity focusing RICH approach preliminary by factor of two
- **Connection of Aerogel with perfluoride gases** (C_4F_{10}, C_5F_{12},…). This issue has to be investigated very carefully
  - Refractive index of aerogel will be changed due to replacement of air (n=1.0003) to gas (n=1.004) inside the aerogel pores, as well as light scattering parameters
  - Mechanical destroy of aerogel is possible due to condensation of pressurised C_4F_{10} inside pores [NIM A421 (1999) 249-255]
- To combine aerogel and gas Cherenkov radiators the **system design** has to become **more complex**

Proximity focusing approaches of Cherenkov light from aerogel

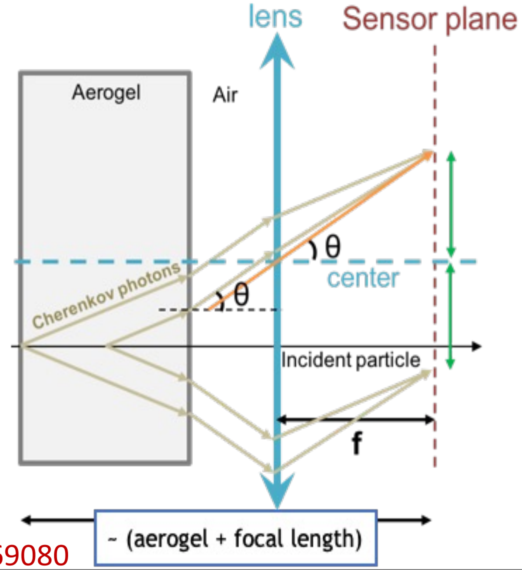


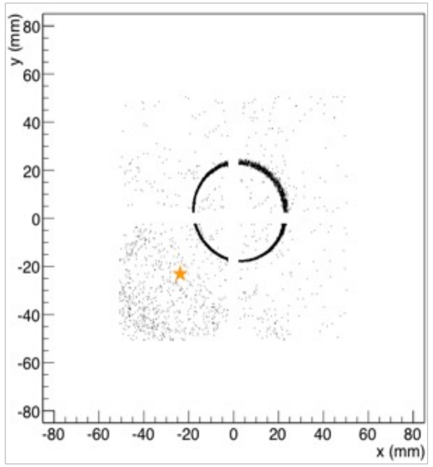
- Thicknesses and refractive indexes in each layer are adjusted in such way that Cherenkov rings from each layer overlap in the same region of the position-sensitive photon detector.
- The number of detected Cherenkov photons increases due to increase of the thickness without degradation of Cherenkov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

Focusing Aerogel RICH (FARICH)

Lens-Based mRICH Design





- 9 GeV/c pion beam incident at third quadrant (star) in simulation
- Ring image is **shifted toward the central region** on the sensor plane

D. Sharma et al., NIM A1061 (2024) 169080

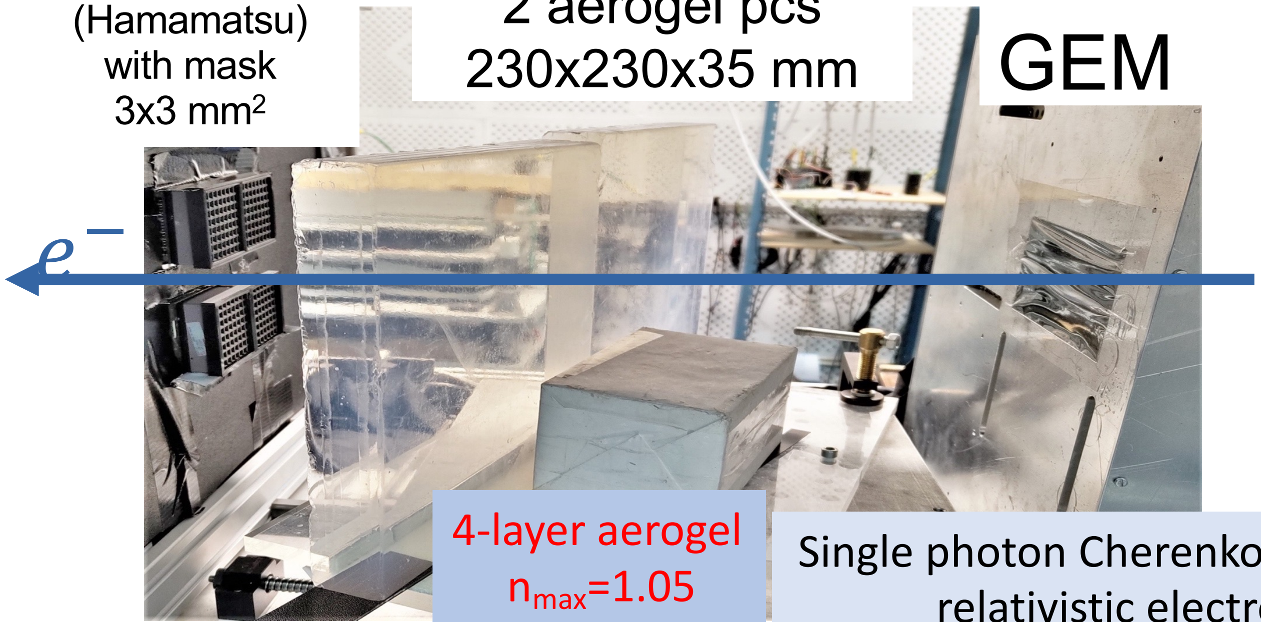
Aerogel RICH with Fresnel lens = modular RICH

Both approaches (mRICH and FARICH) based on the large aerogel samples produced in Novosibirsk were tested at the BINP

MaPMT H12700 (Hamamatsu) with mask 3x3 mm^2

2 aerogel pcs 230x230x35 mm

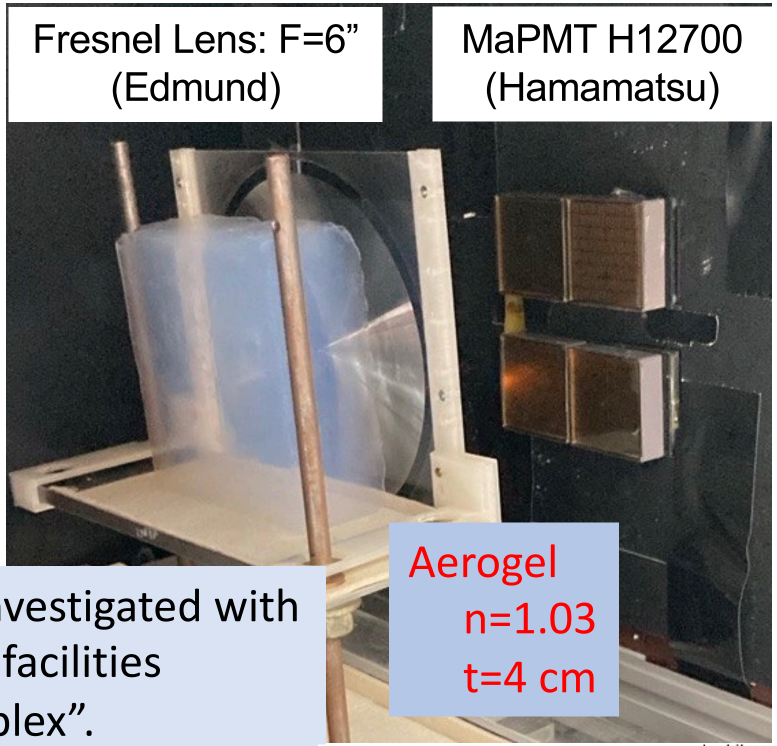
GEM



4-layer aerogel
n_{max}=1.05
t=3.5 cm

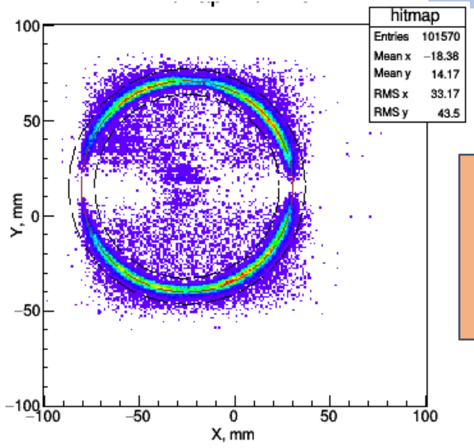
Fresnel Lens: F=6" (Edmund)

MaPMT H12700 (Hamamatsu)



Aerogel
n=1.03
t=4 cm

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

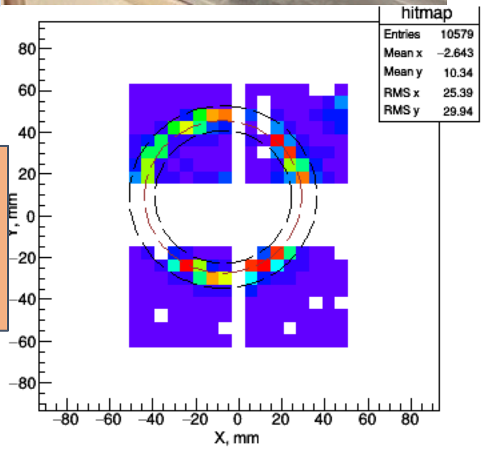


Main results:

- $N_{pe} \approx$ 16 (~ 0.8 of Ring)
- $\sigma_\theta^{1pe} \approx 7.0\ mrad$ (■ 3mm)

Main results:

- $N_{pe} \approx$ 5.3 (~ 0.6 of Ring)
- $\sigma_\theta^{1pe} \approx 10\ mrad$ (■ 6mm)

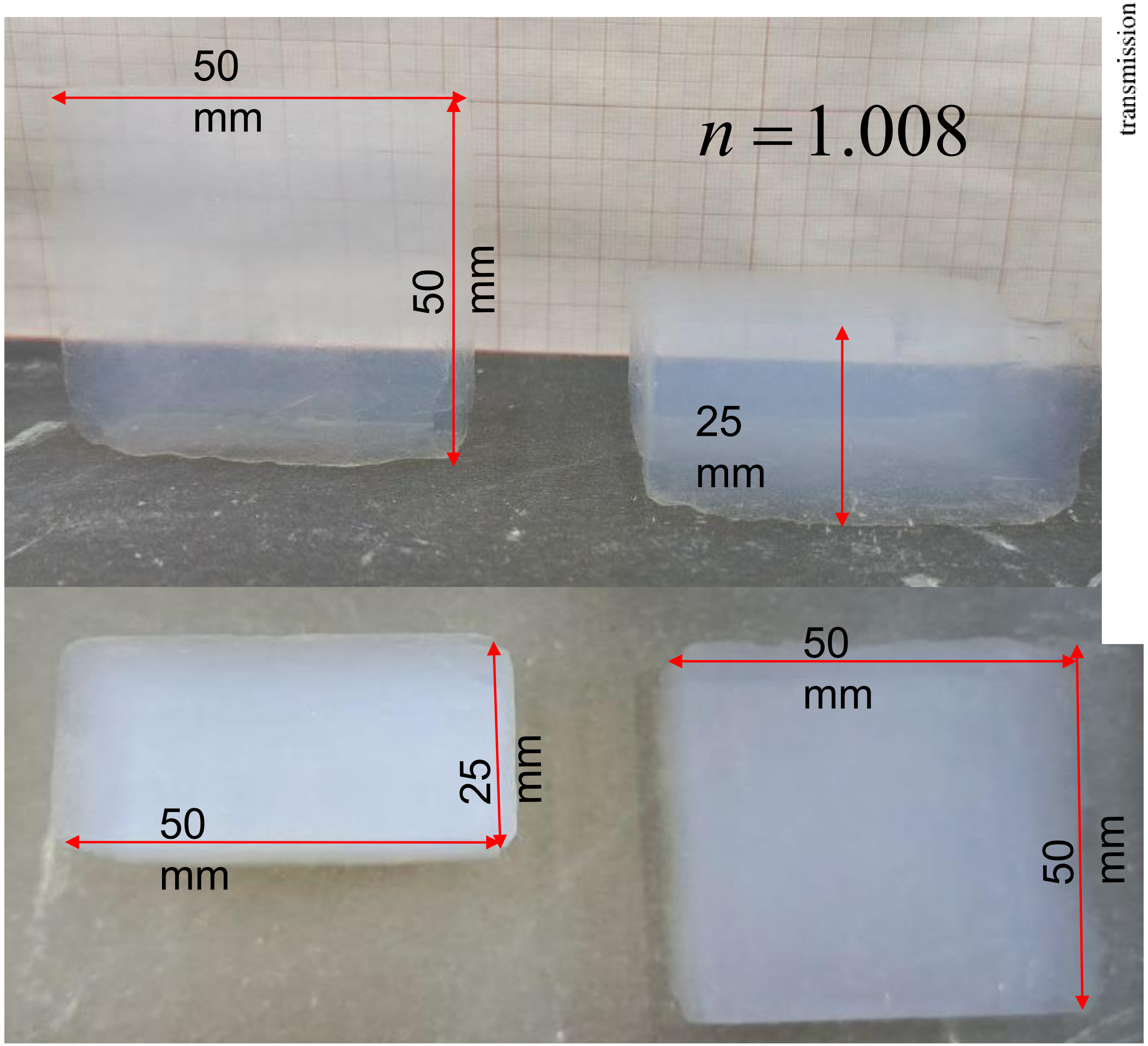


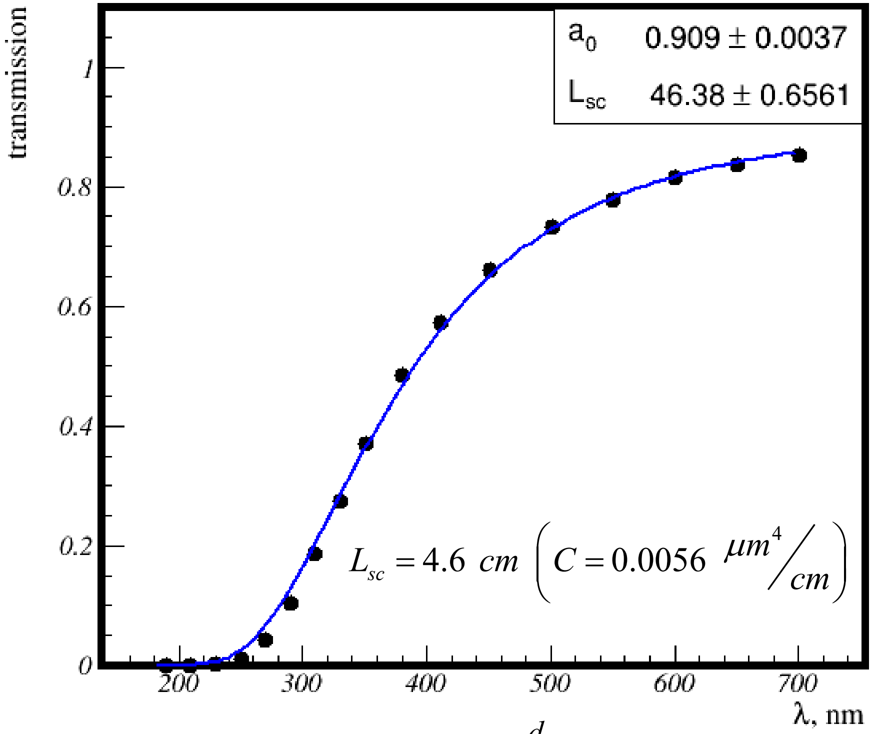
In both cases TB results are in good agreement with simulation

Main RICH components for PID@20GeV/c:

- ***Aerogel***
- ***Photon detectors***

Aerogel with n=1.008 (Novosibirsk)





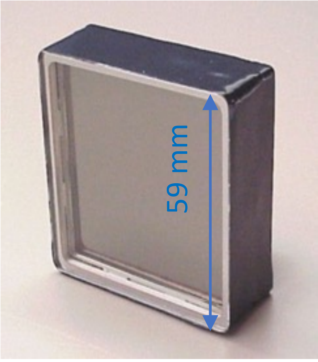
$$T = \frac{I}{I_0} = a_0 \cdot e^{-\frac{d}{L_{sc}\cdot\left(\lambda/400\right)^4}} = a_0 \cdot e^{-\frac{C\cdot d}{\lambda^4}}$$

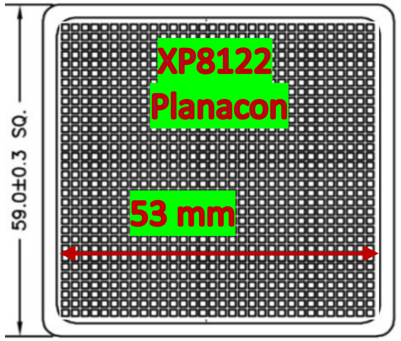
d – thickness of a sample,
λ – wavelength in nanometers,
Lsc – scattering length at 400 nm,
a_0 – surface scattering coefficient,
C – clarity coefficient

Several PMTs with submillimeter position sensetivity

MCP PMT

- Planacone XP85122

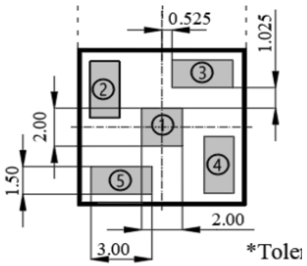




- 32x32 pixels with 1mm size and pithch ~2mm
- To decreas readout electronics channels it is possible to develop *‘spread delay lines’* or ‘*chrge sharing’* approaches
- Expected spatial resolution as small as

$$\sigma_x \approx \frac{1}{\sqrt{12}} \approx 300\mu m$$

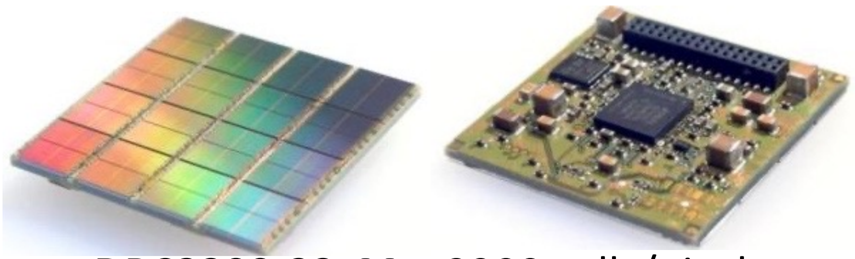
PSS-SiPM or LG-SiPM



- PSS 11-3030-S (from NDL, China)
- 3x3 or 6x6mm SiPM is read out by 4 digitizers
- Position is reconstructed by charge sharing among 4 pads connected to resistive plane of the SiPM
- Declared resolution for single photon hit is about

$$\sigma_x \approx 200\mu m$$

Digital PC

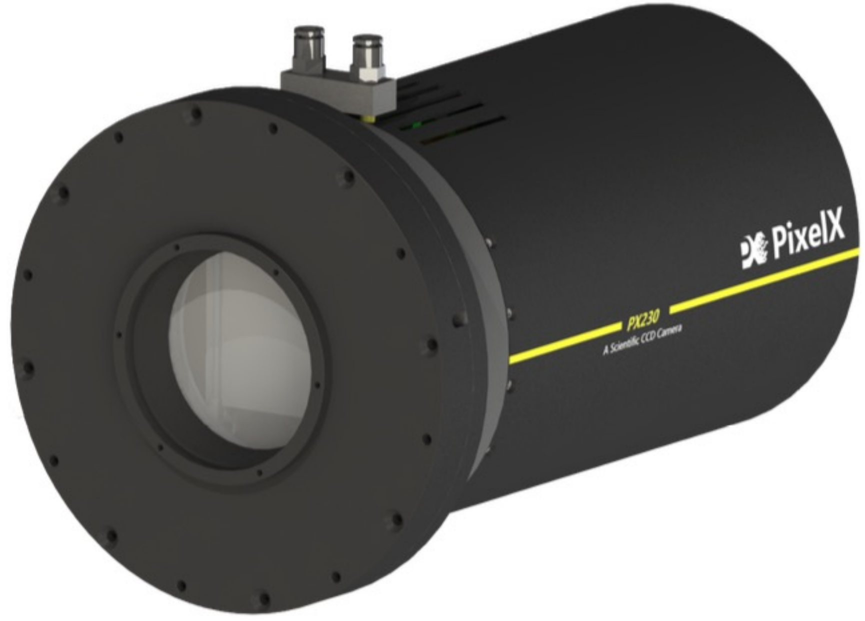


- **DPC3200-22-44 –** 3200 cells/pixel (from Philips)
- Each microcell is connected through controled lattch and could be switched On or Off for readout
- Output data are *‘timestamp‘* of the first fired microcells and total *‘number‘* of fired microcells
- Output data could be changed to *‘timestamp‘* and *‘serial number‘* of fired microcell and then spatial resolution will be determined microcell sizes:

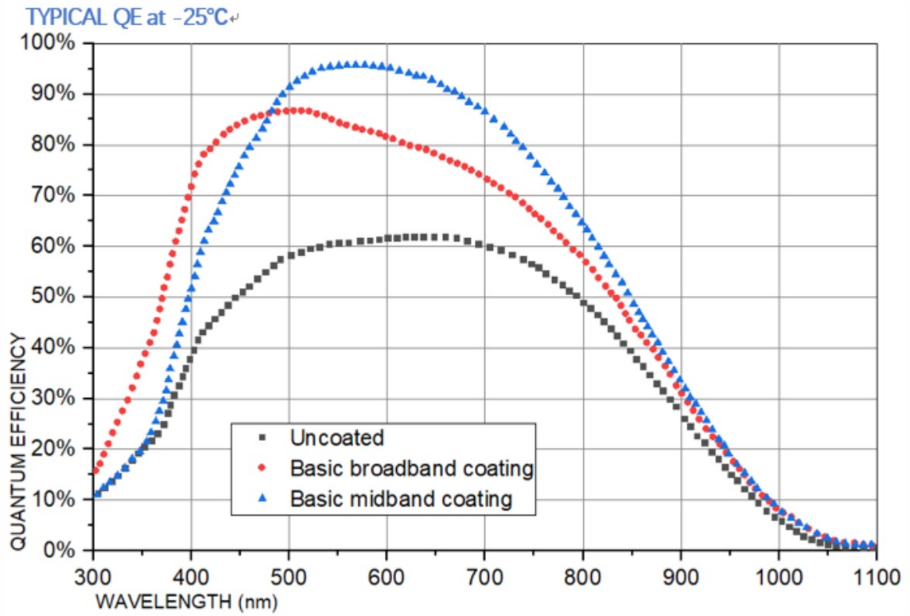
$$\sigma_x \leq 50{,}25{,}12\mu m$$

Scientific CCD with high rate readout?!

PXE230



Technical parameters

Camera category	Scientific CCD
Typical size	61.44mm(H) × 61.44mm(V)
Effective pixel area	4096(H) × 4096(V)
Pixel size	15μm × 15μm
Full well capacity	150Ke⁻
Quantum efficiency	
Readout speed	100KHz、500KHz(@ 4channels)

– Very high readout rate for CCD!!!
–Does it work with external trigger?!
– Perhaps it could be a good option for prototype tests.

mRICH for CEPC

n=1.008

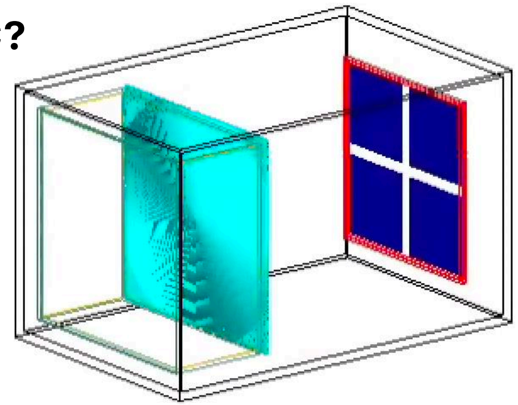
- This option was Inspired by success of mRICH R&D for EIC project [D. Sharma et al., NIM A1061 (2024) 169080]
- First steps of simulation at BINP were verified with GSU group simulation results
- Good agreement between two simulations was achieved

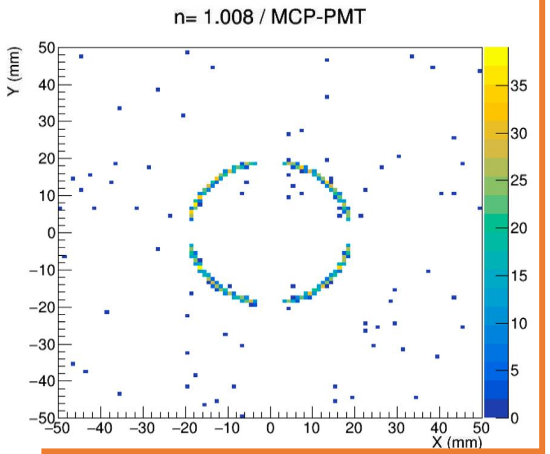
GSU sim

Modular RICH for the CEPC?

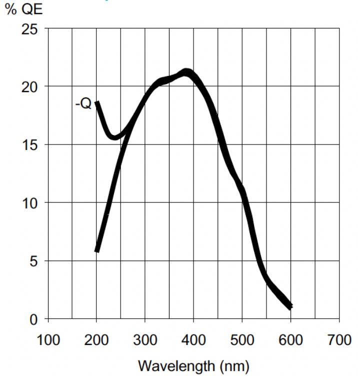
M. Sarsour, GSU
9/13/2024

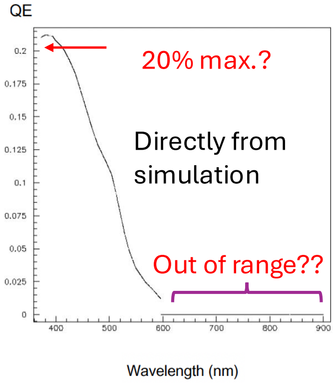
- G4 simulation based on JLab prototype
- Excluded mirrors for noise reduction



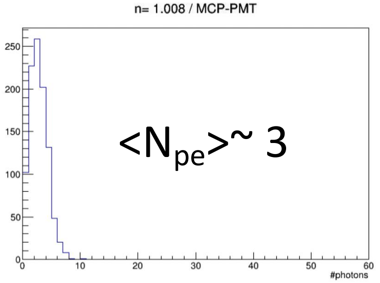


10μm MCP-PMT

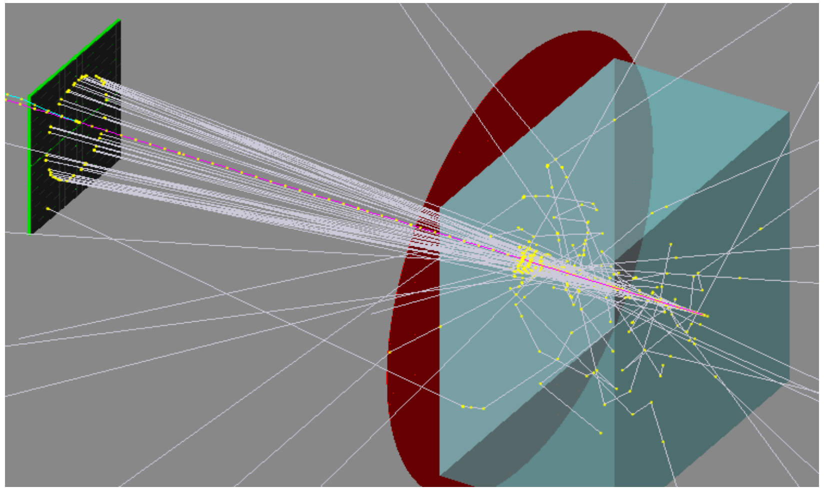


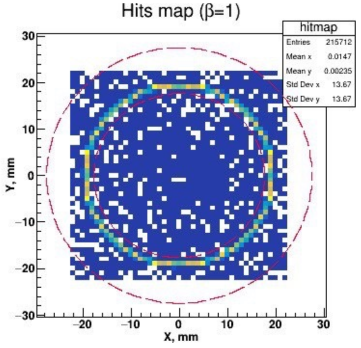


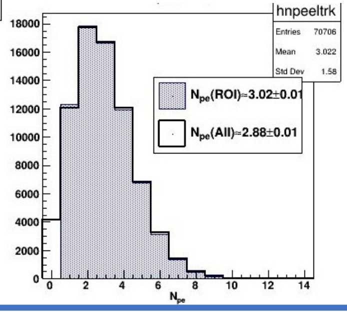
- 5 GeV/c μ^- incident perpendicular at the center of the Aerogel block (n=1.008 at 6 cm)

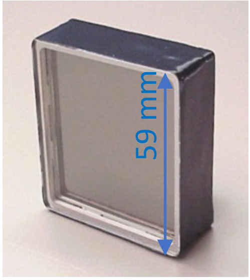


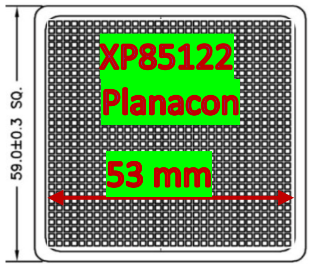
BINP sim



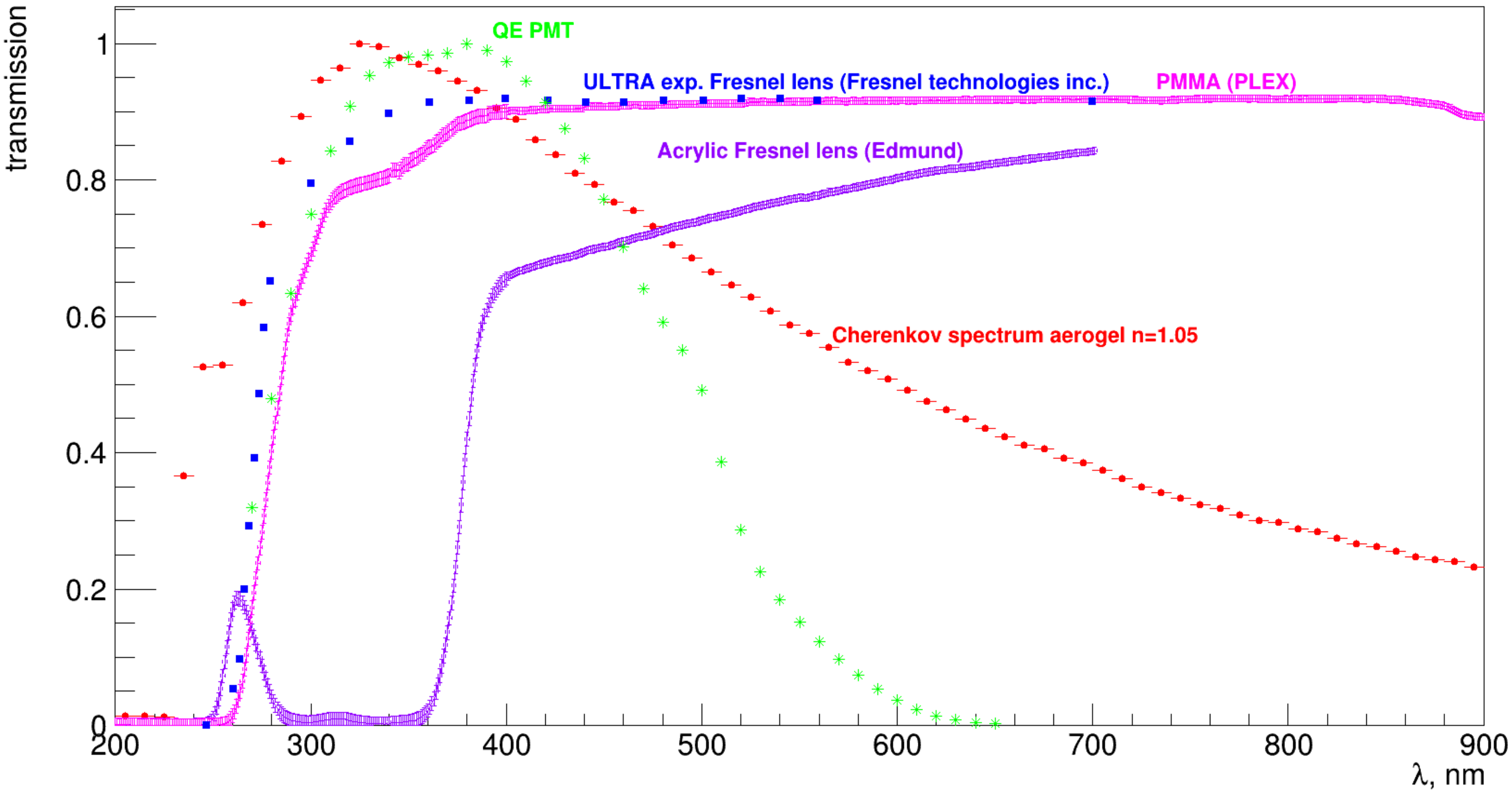






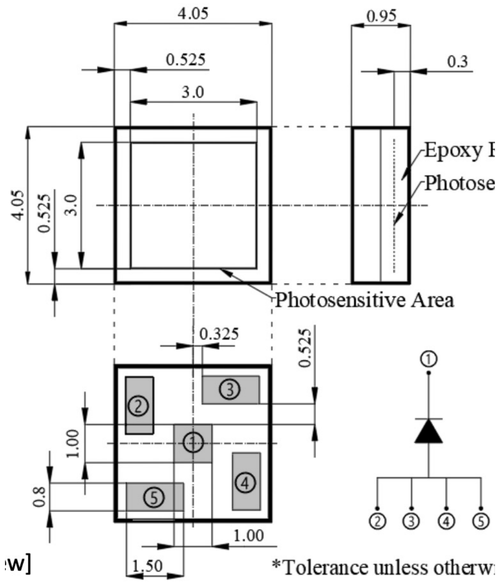


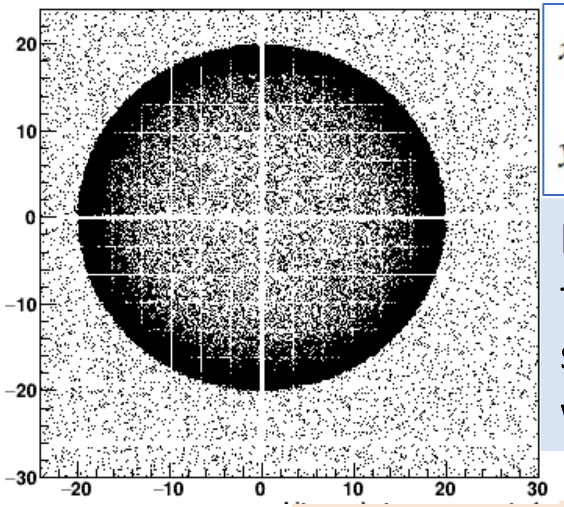
Fresnel lens transparency



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

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

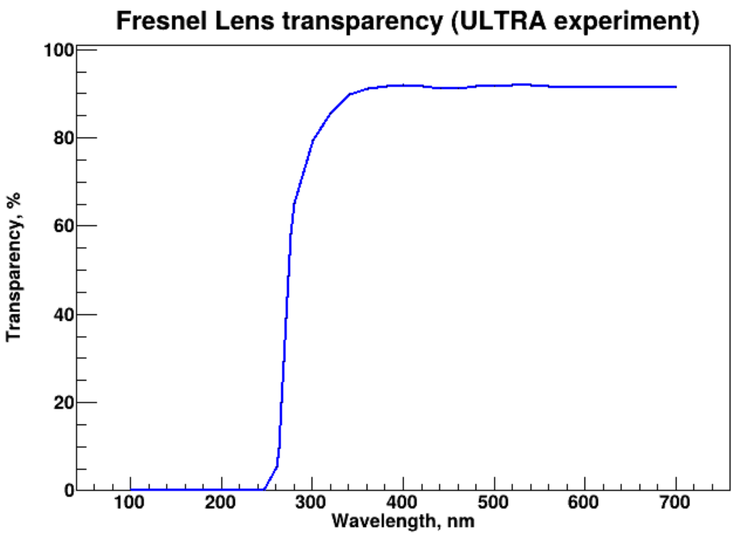


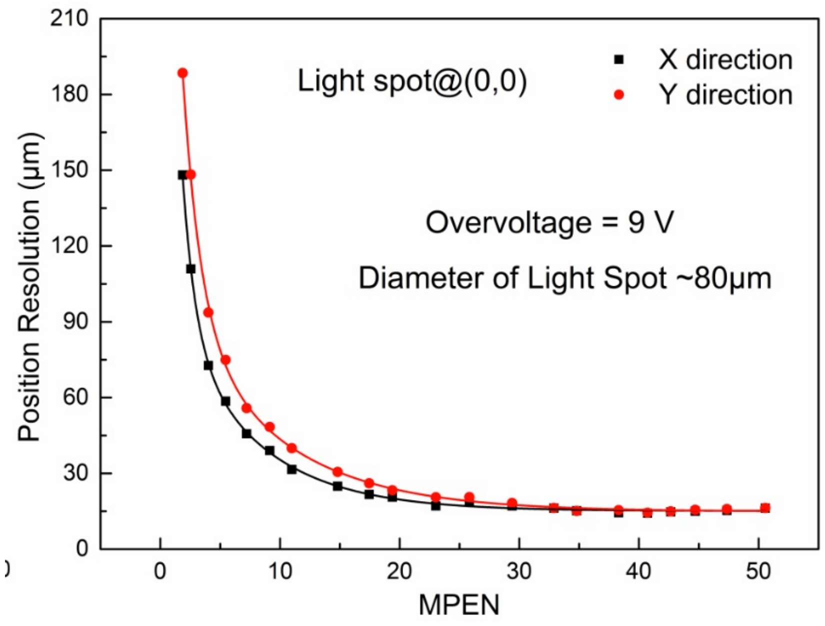


$$x_c = \frac{L}{2} \cdot k \cdot \frac{(Q_2+Q_3)-(Q_1+Q_4)}{(Q_1+Q_2+Q_3+Q_4)}$$

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

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

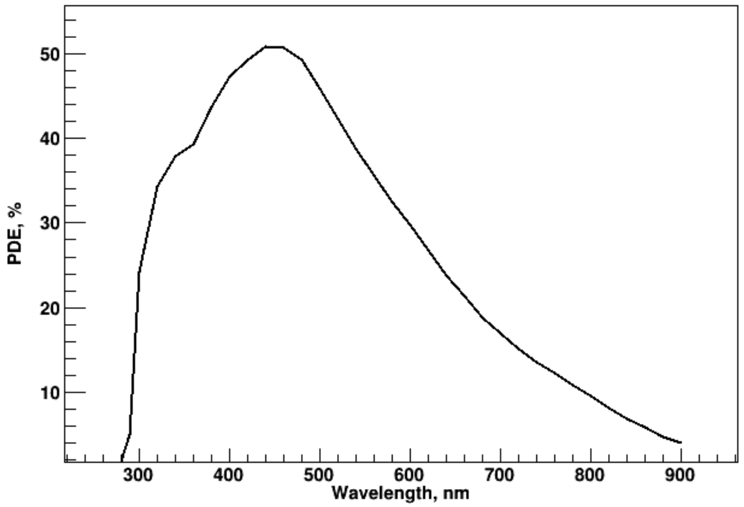




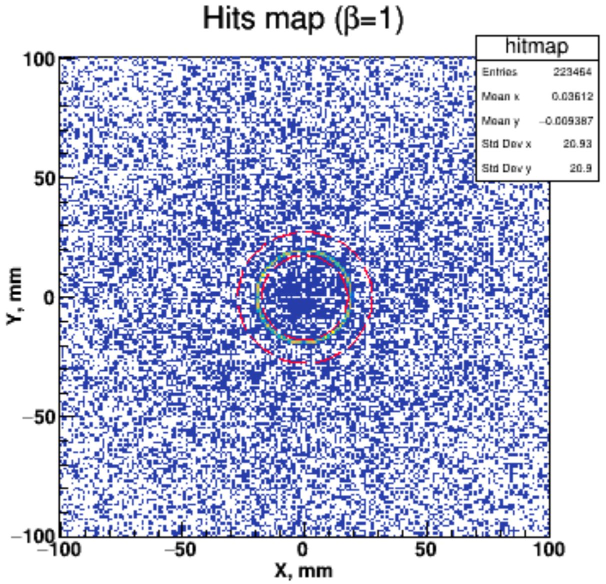
- Aerogel
  - n=1.008
  - t=6 cm
  - L_{sc}(400nm)=4.6 cm
- Position-sensitive SiPM
  - pixel 3x3 mm
  - hit position restored by charge sharing $\sigma_x = 200\mu m$
  - PDE from Hamamatsu S14161-3050HS
- Fresnel Lenses
  - **Focal length = 6” and 10”**
  - Transparency from ULTRA exp.

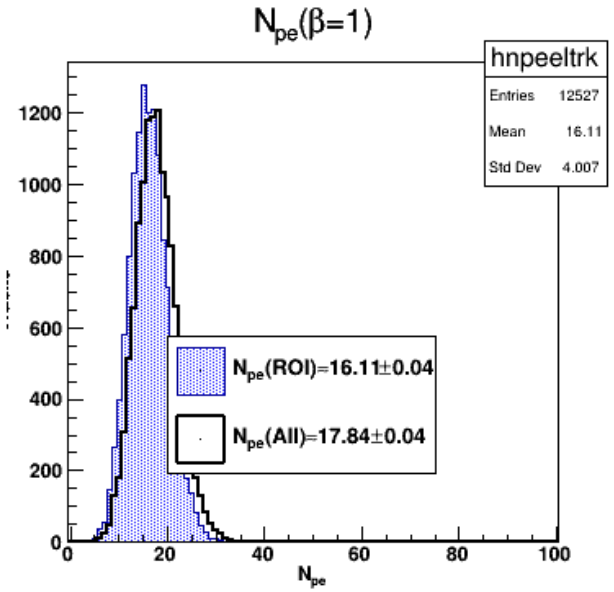
(NIM A570 (2007) 22-35)

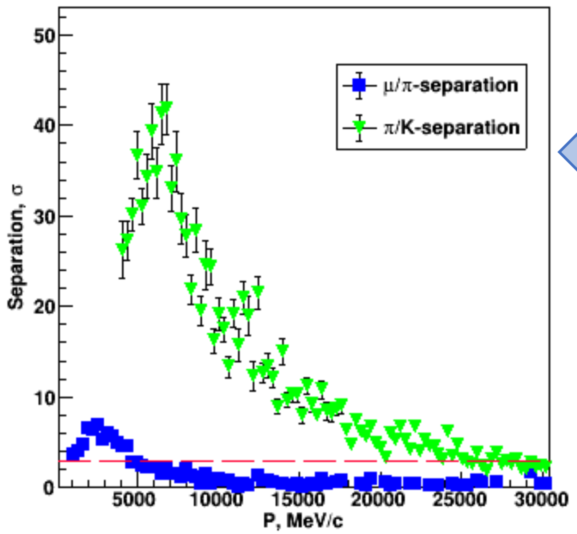
Fresnel technology inc.



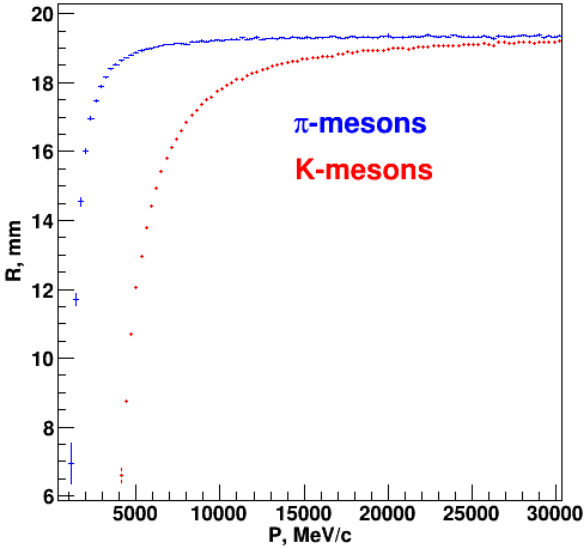
mRICH sim. results for Fresnel lens 6” and 10”

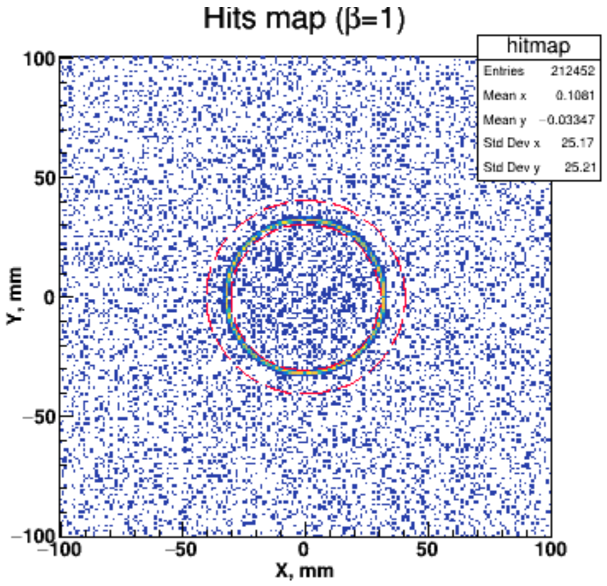


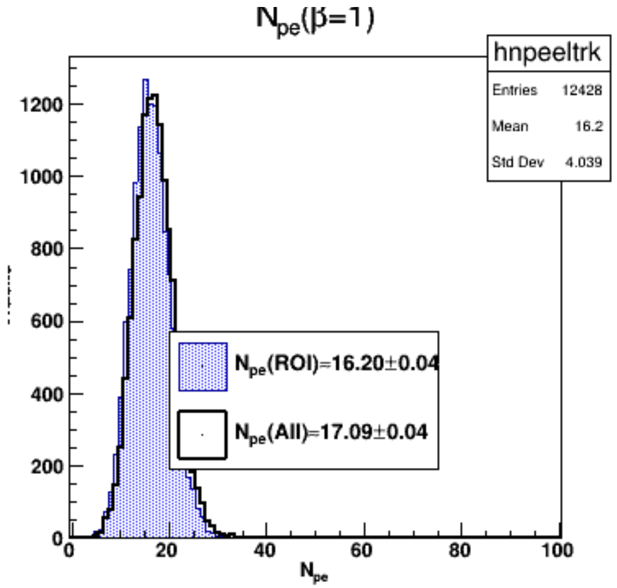


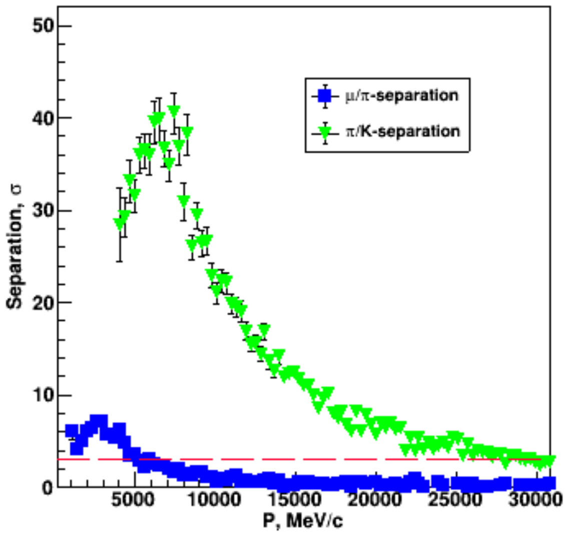


Fresnel Lens with F=6”









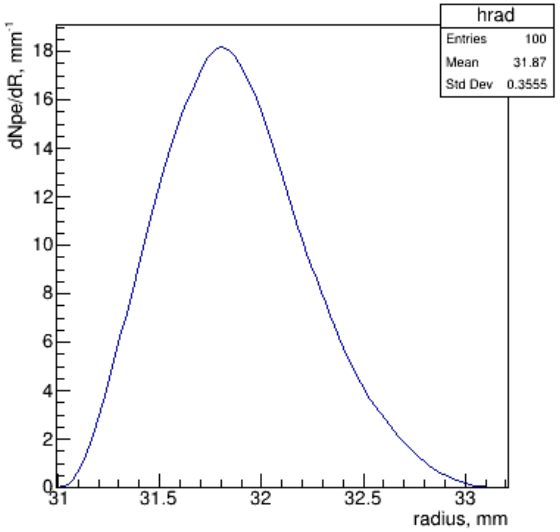
Fresnel Lens with F=10”

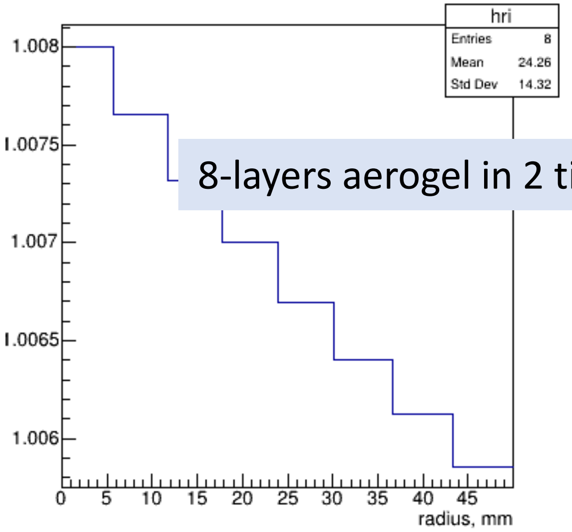
FARICH for CEPC

n_{max}=*1.008*

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

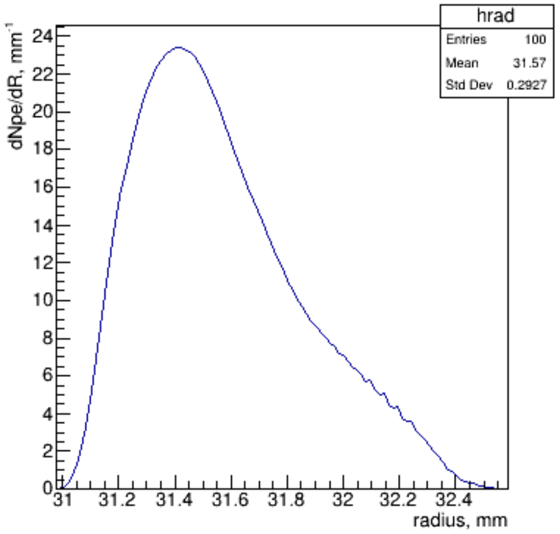
8-layer aerogel n_{max}=1.008; pixel≈0.2mm

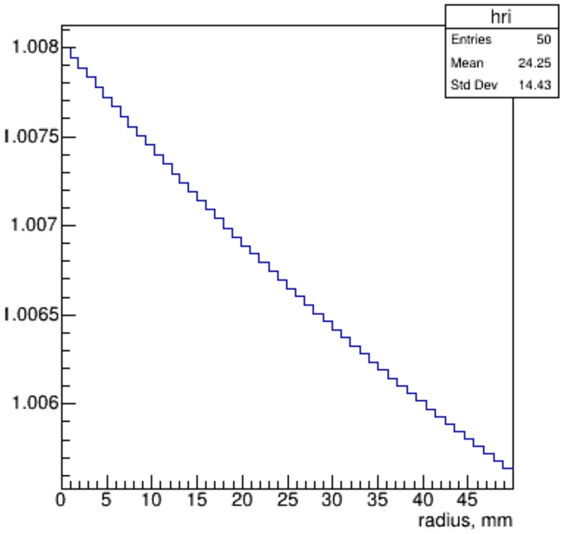




8-layers aerogel in 2 tiles

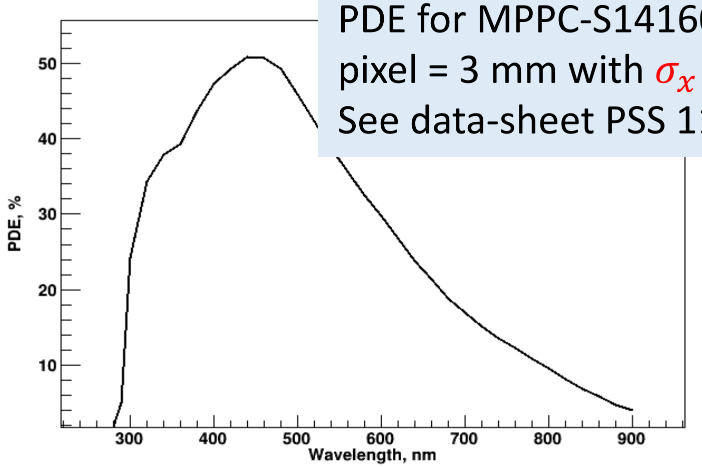
Gradient aerogel n_{max}=1.008; pixel≈0.7mm





Focal distance is 300 mm

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



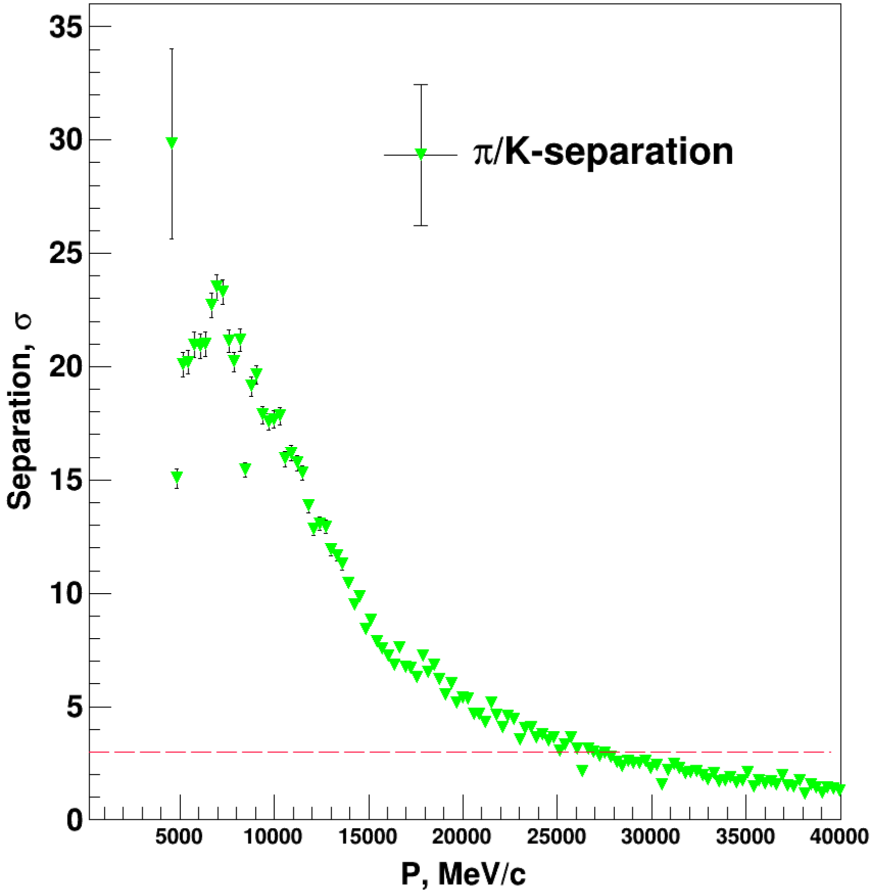
PDE for MPPC-S14160 (Hamamatsu)
pixel = 3 mm with $\sigma_x \approx 0.2mm$
See data-sheet PSS 11-3030-S (NDL)

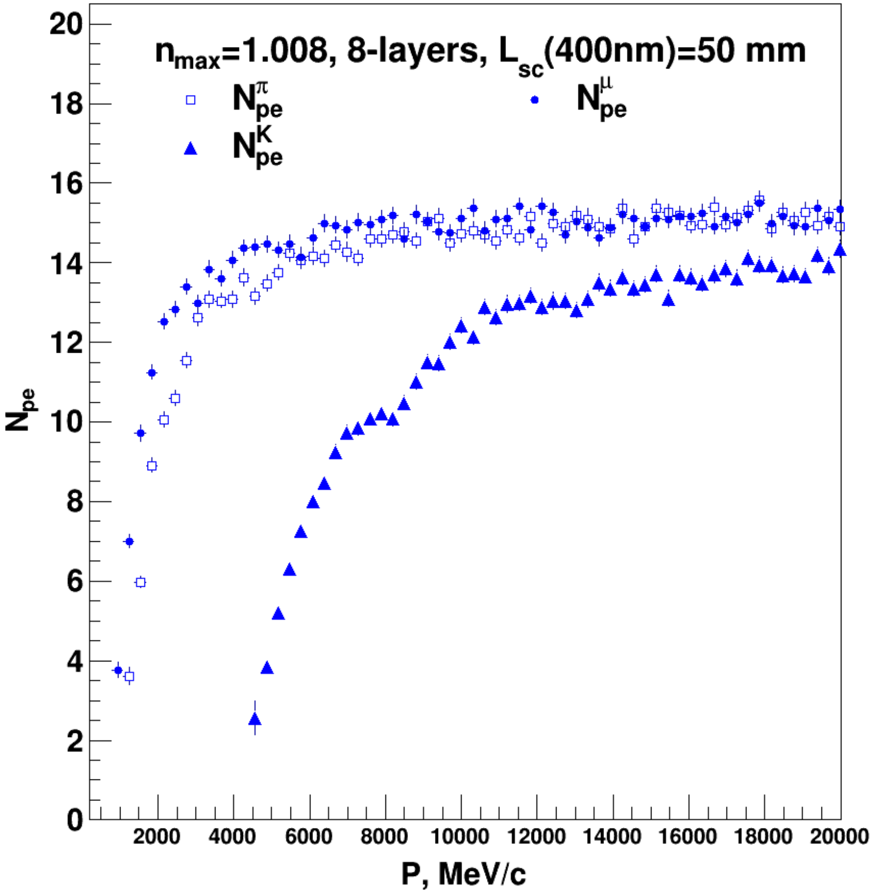
- $N_{pe} \approx 16$
σ_C^{tr} ≈0.33 mrad!!!

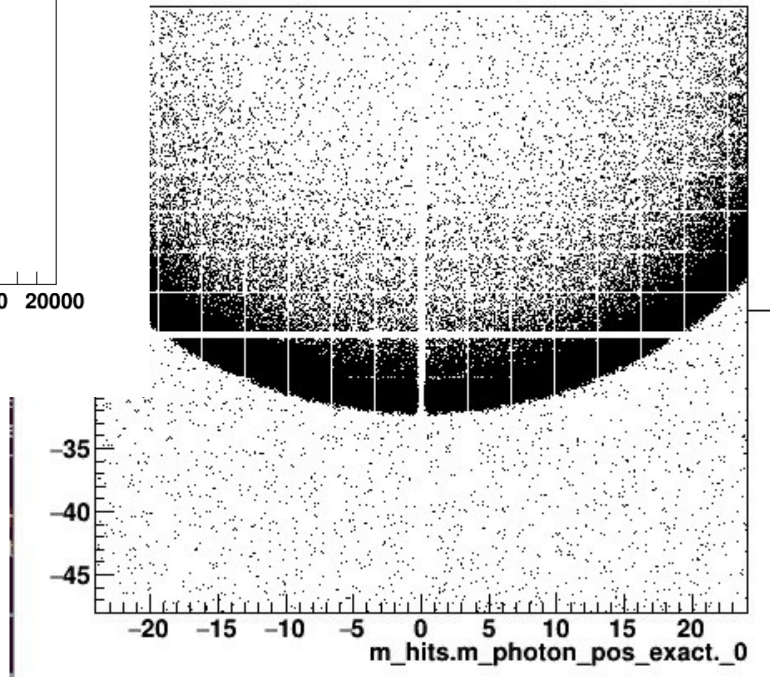
- $N_{pe} \approx 16$
σ_C^{tr} ≈0.33 mrad!!!

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

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







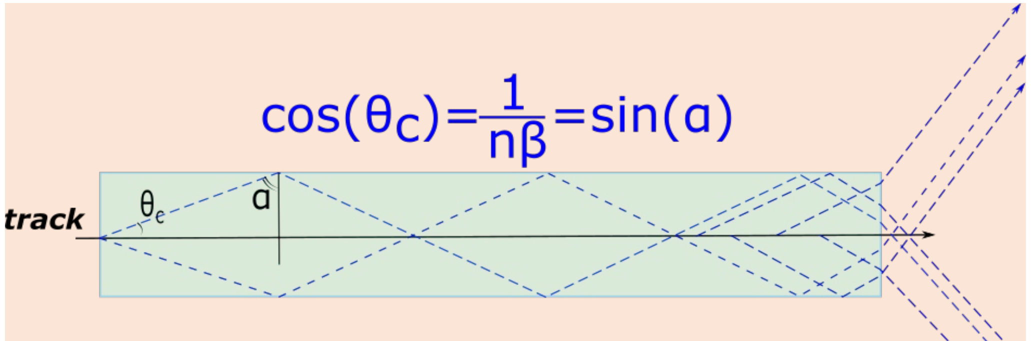
Fiber RICH for CEPC
n=1.008

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:

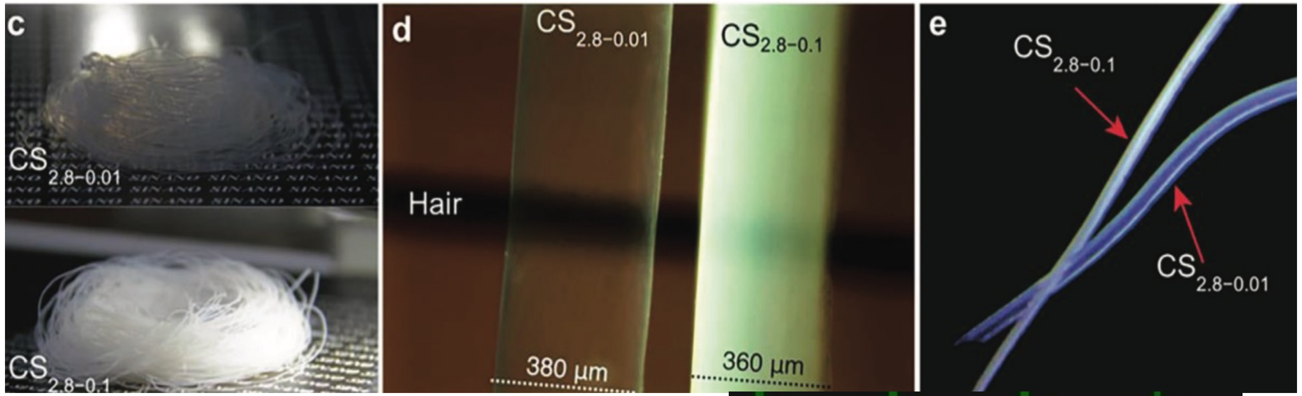
Adv. Sci. **2023**, *10*, 2205762

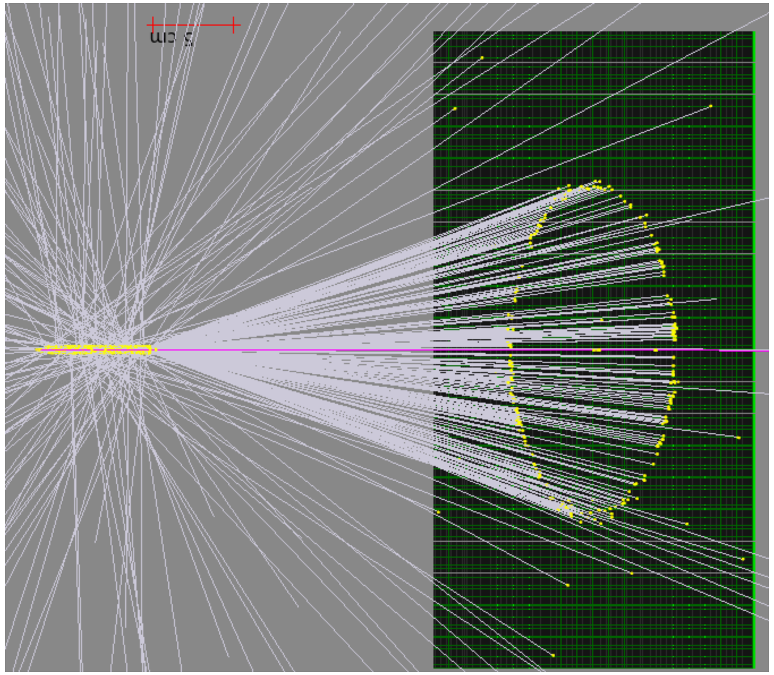


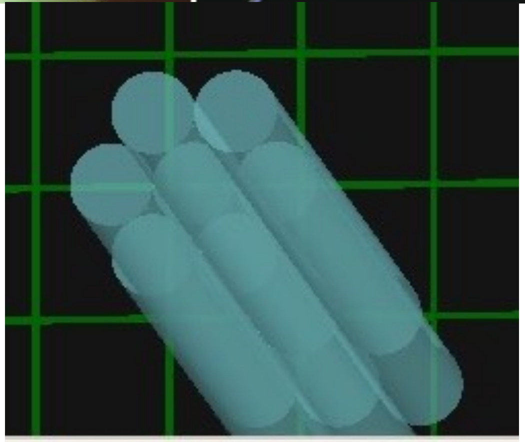
Cherenkov light ocurs in total internal reflection conditions if particle goes stright along bar or fiber axis!

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

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

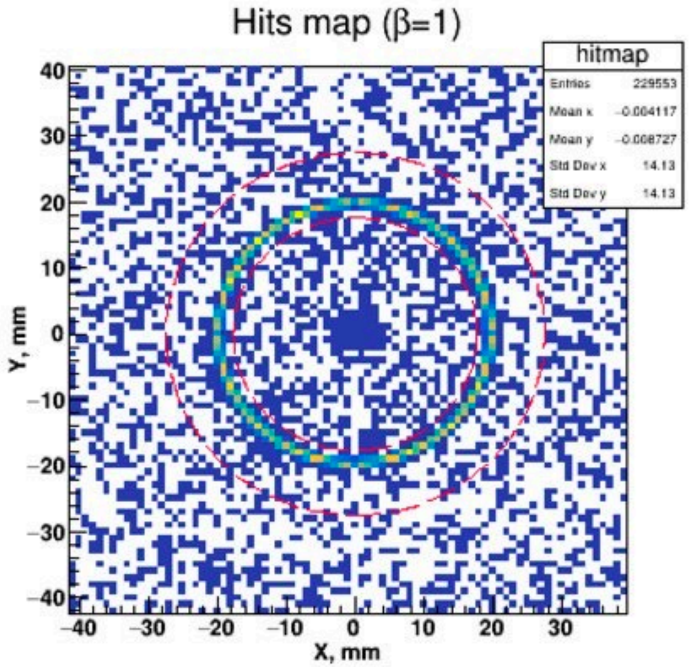


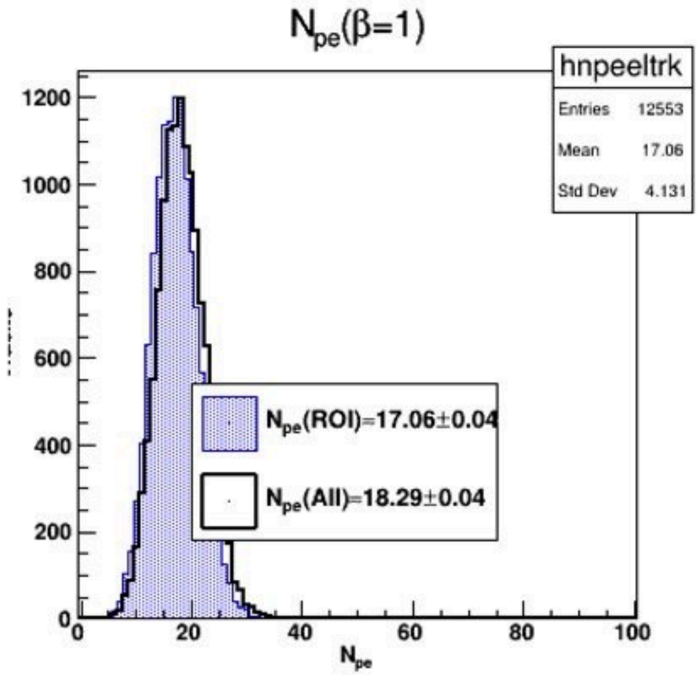


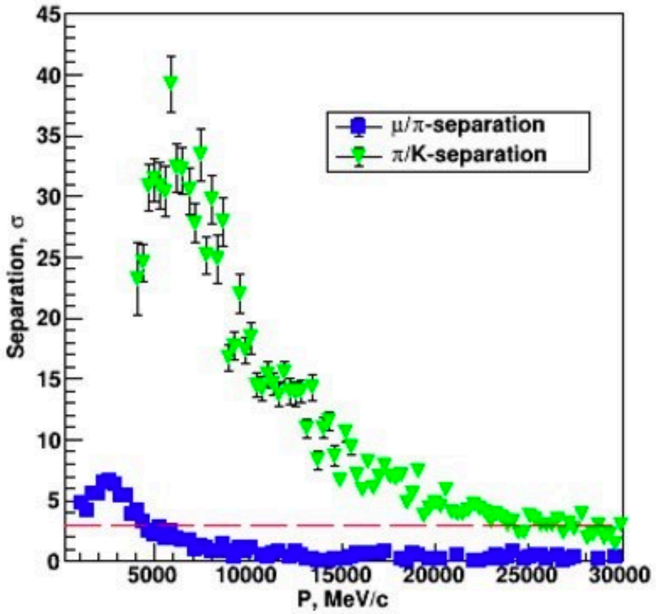


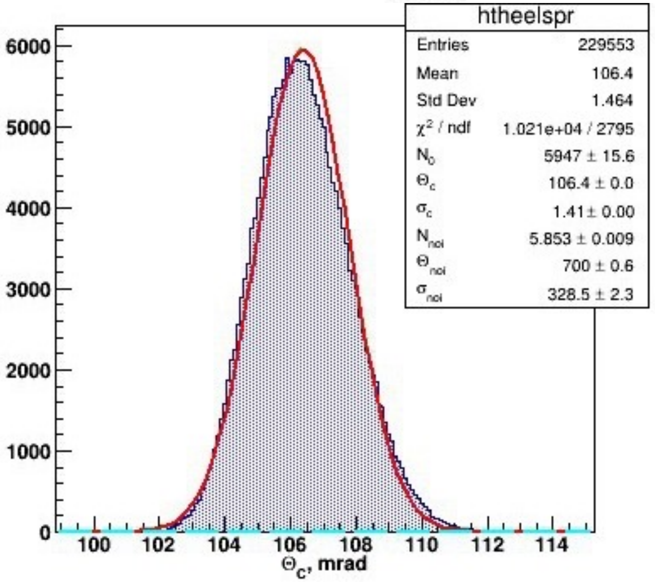
Single fiber params:
- n=1.008
- Length = 60 mm
- ø 0.4 mm

GEANT-4 results for aerogel fiber based RICH









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

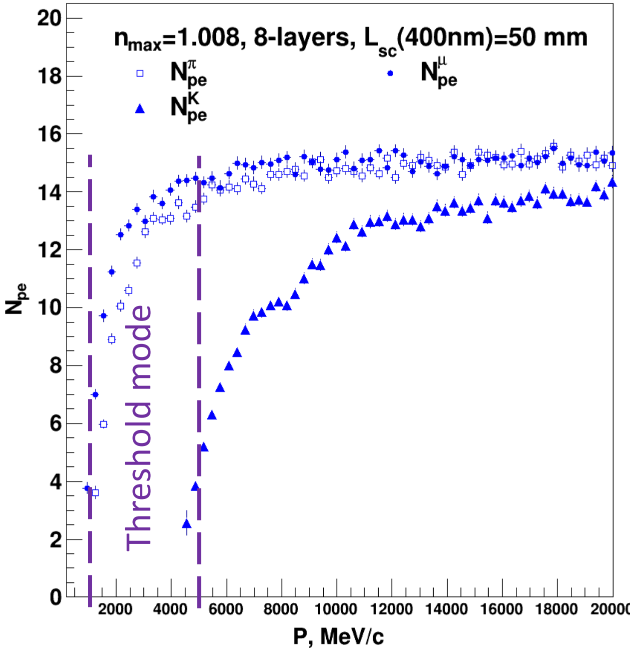
Aerogel Fibra: $t = 6cm$; $n = 1.008$; $ø400\mu m$ (SINANO)

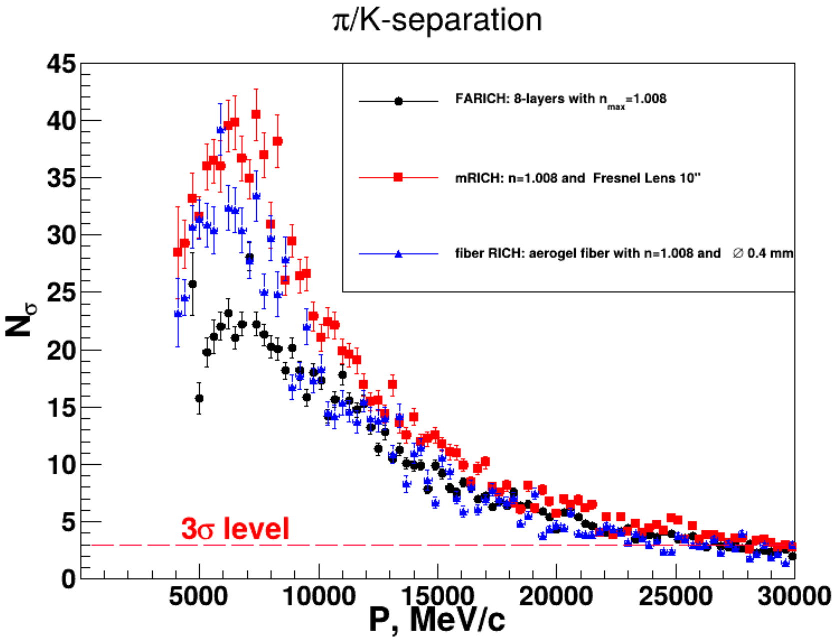
Conclusion #1

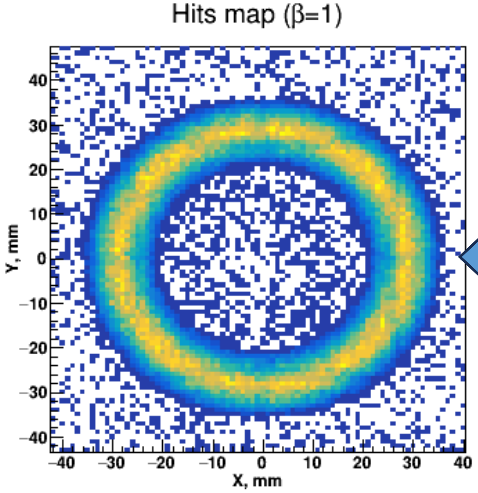
To provide reliable $\pi/_K$ –separation above 20 GeV/c:

- Detect at least 14÷15 ph.e. per track with $\beta = 1$
- From 1 to 5 GeV/c $\pi/_K$ – separation in the aerogel counters with n=1.008 could be performed in ”Threshold” mode, above 5 GeV/c in “RICH” mode.
- Fine focusing of the Cherenkov light should be realized in the ssytem
- Spatial resolution of photn detector should be better than 0.3 mm

All three considered options show us very attractive results.

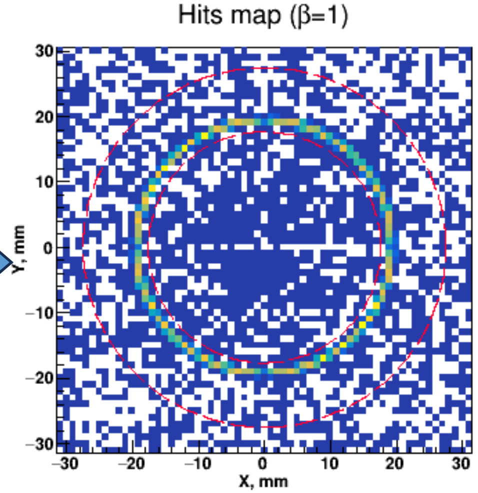






W/O focusing
6cm aerogel n=1.008

With Fresnel Lens
6cm aerogel n=1.008

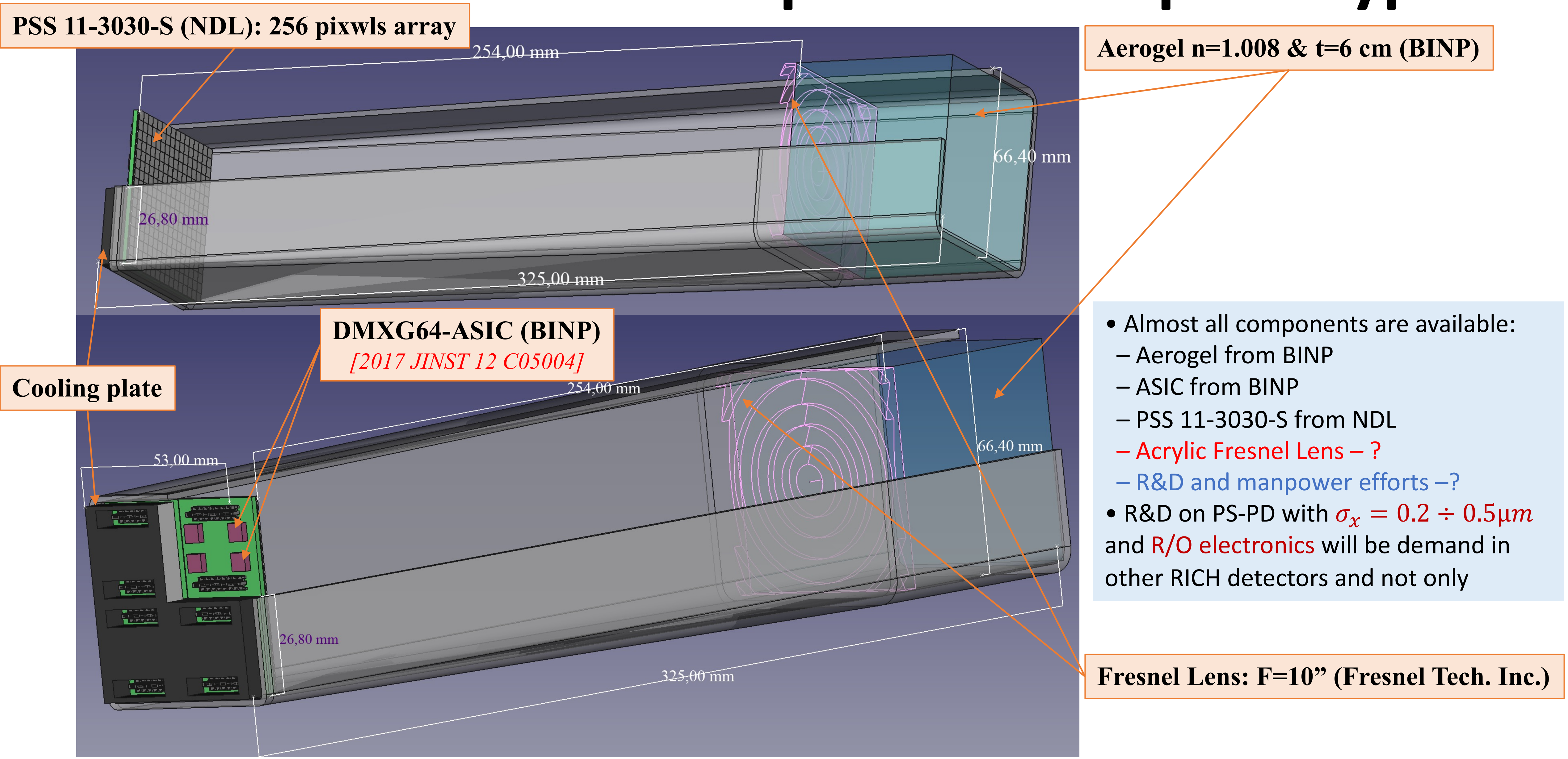


Conclusion #2

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

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

Conclusion #3: Concept of mRICH prototype



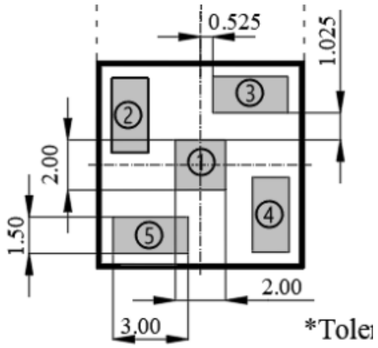
- Almost all components are available:
  - Aerogel from BINP
  - ASIC from BINP
  - PSS 11-3030-S from NDL
  - Acrylic Fresnel Lens – ?
  - R&D and manpower efforts –?
- R&D on PS-PD with $\sigma_x = 0.2 \div 0.5\mu m$ and R/O electronics will be demand in other RICH detectors and not only

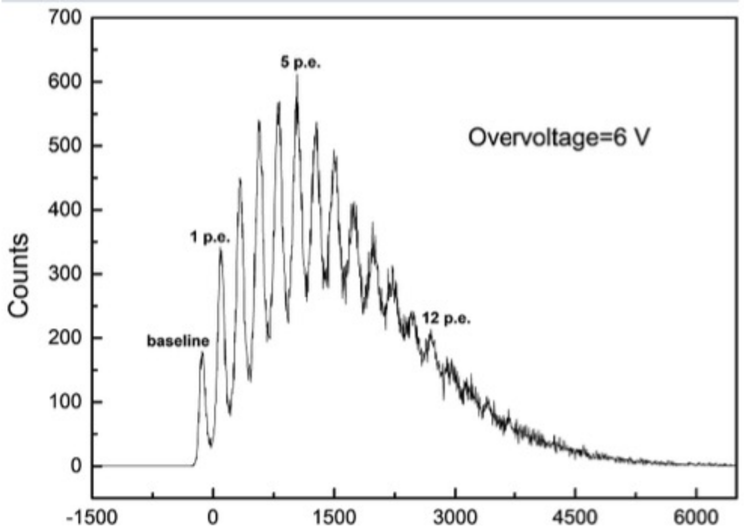
Summary

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

Photon detector option for Fibra RICH

Position Sensetive SiPM or PSS 11-3030-S (from NDL, China) or LG-SiPM (from FBK, Italy) are able to provide spatial resolution $\sigma_x \approx 200\mu m$ per single photon detected.



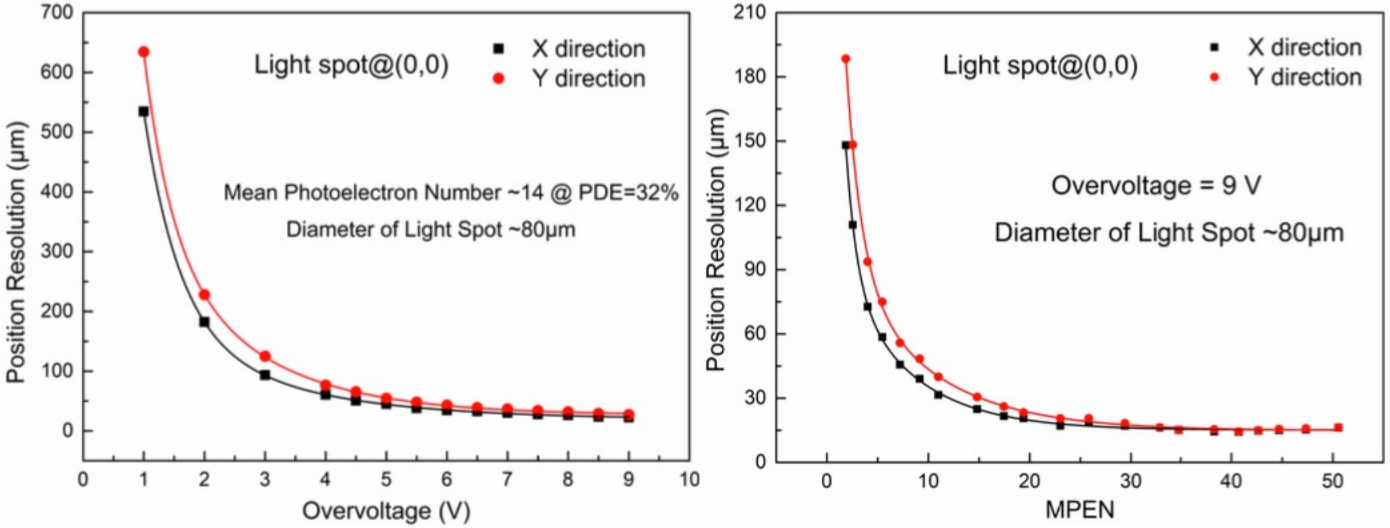


Position Algorithm

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

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

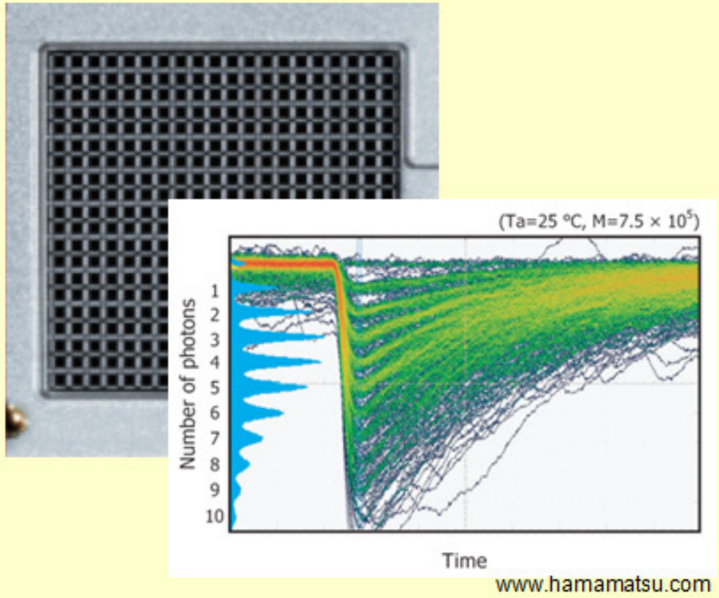
L is the length of the active area. Q_i ($i = 1, 2, 3, 4$) is the shared charge of the corresponding anode. k is the calibration factor.



Test Conditions: OV=9 V if not specified, Temp.=20 °C, Load Impedance = 50 Ω.

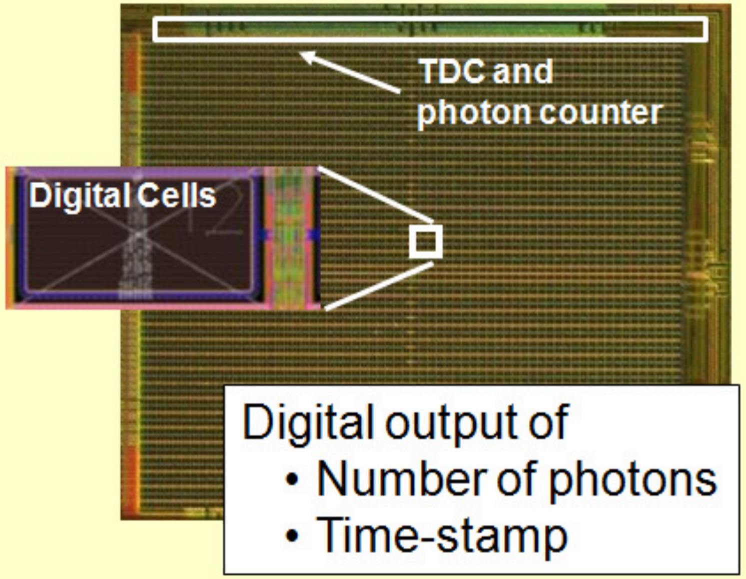
DPC: Front-end Digitization by Integration of SPAD & CMOS Electronics

analog SiPM



Summing all cell outputs leads to an analog output signal and limited performance

Digital Photon Counter (DPC)

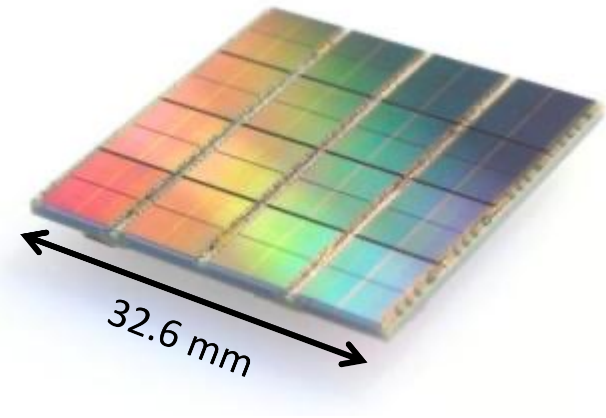


Integrated readout electronics is the key element to superior detector performance

T. Frach, G. Prescher, C. Degenhardt, B. Zwaans, IEEE NSS/MIC (2010) pp.1722-1727
C. Degenhardt, T. Frach, B. Zwaans, R. de Gruyter, IEEE NSS/MIC (2010) pp.1954-1956

DPC is an Integrated "Intelligent" Sensor by Philips Digital Photon Counting

DPC3200-22-44 – 3200 cells/pixel
DPC6400-22-44 – 6396 cells/pixel



FPGA
- Clock distribution
- Data collection/concentration
- TDC linearization
- Saturation correction
- Skew correction

Flash
- FPGA firmware
- Configuration
- Inhibit memory maps