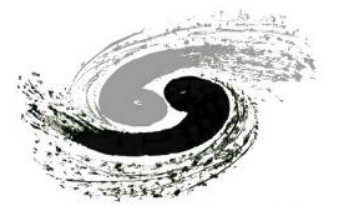
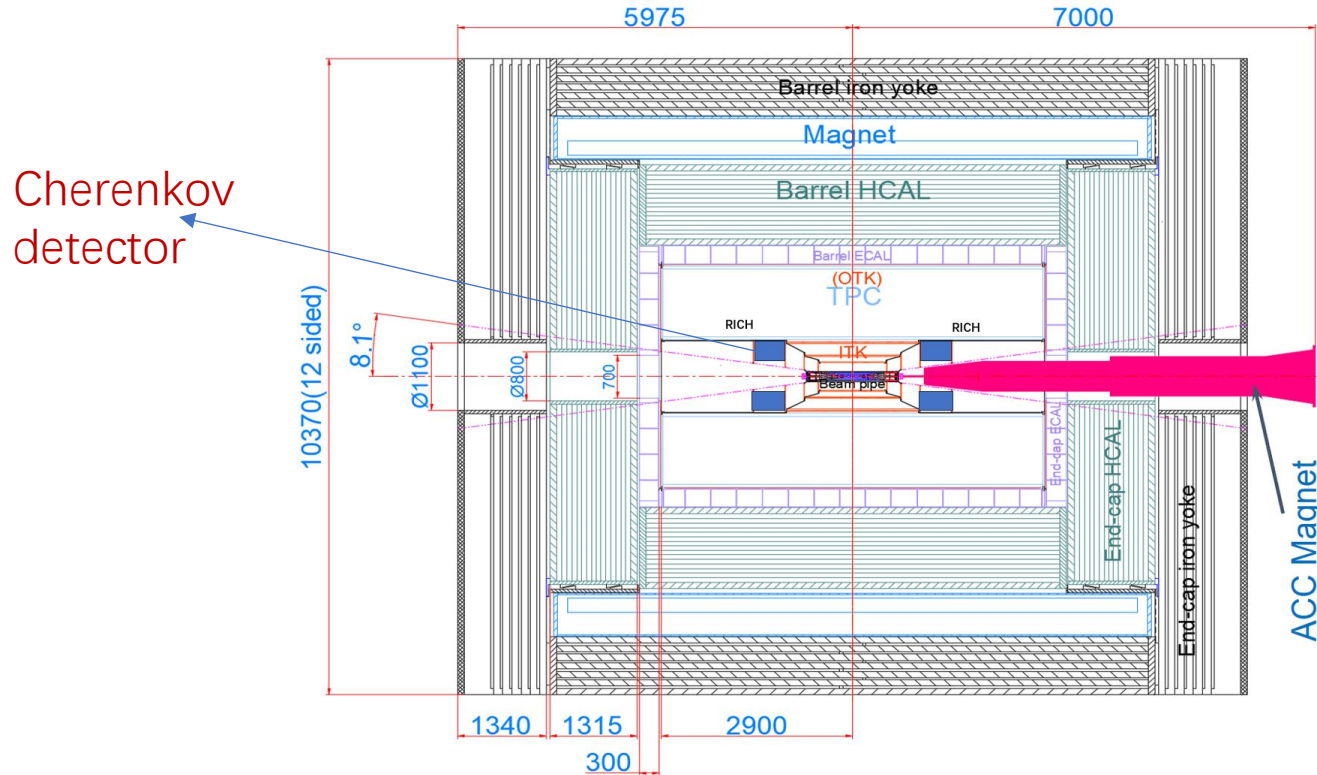




Preliminary consideration of a Cherenkov detector at CEPC



中国科学院高能物理研究所
Institute of High Energy Physics
Chinese Academy of Sciences



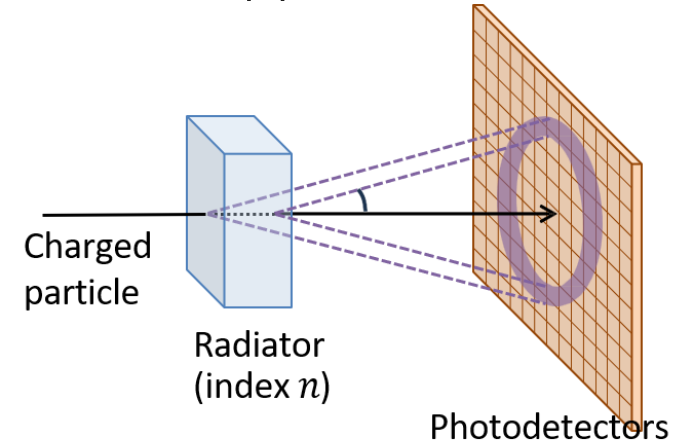
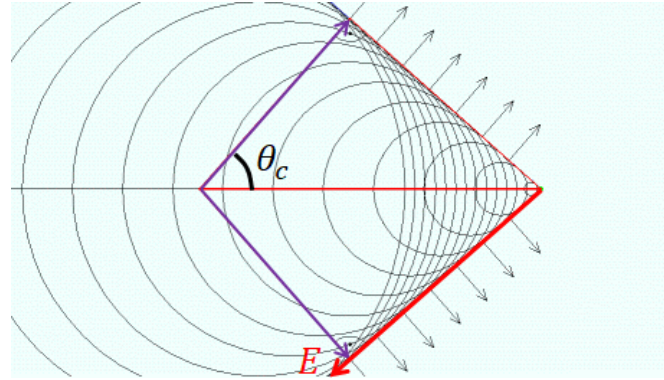
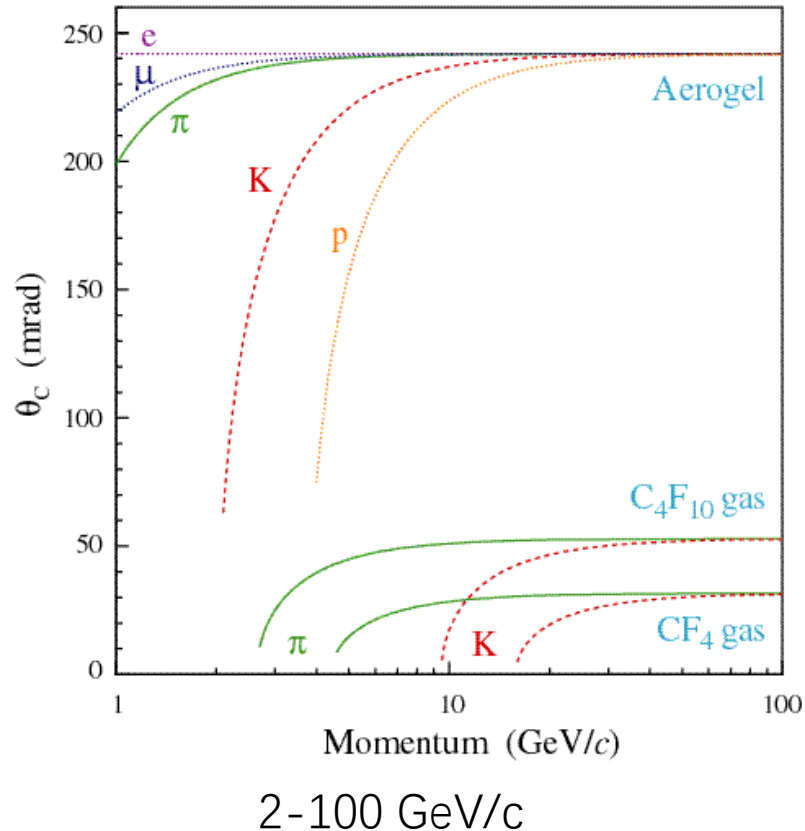
Zhonghua Qin, IHEP

CEPC physics and detector plenary meeting, Jan.7, 2026

A reminder of Cherenkov detector

- Cherenkov detector is a powerful tool for charged particle identification, especially for particles with a momentum up to several tens of GeV/c where the ToF is not applicable

LHCb RICH-1 (Aerogel+C₄F₁₀ gas radiator)
RICH-2 (CH₄ gas radiator)



RICH 2025, Kodai Matsuoka

Threshold: $\beta > 1/n$

Cherenkov angle: $\cos \theta_c = \frac{1}{n\beta}$

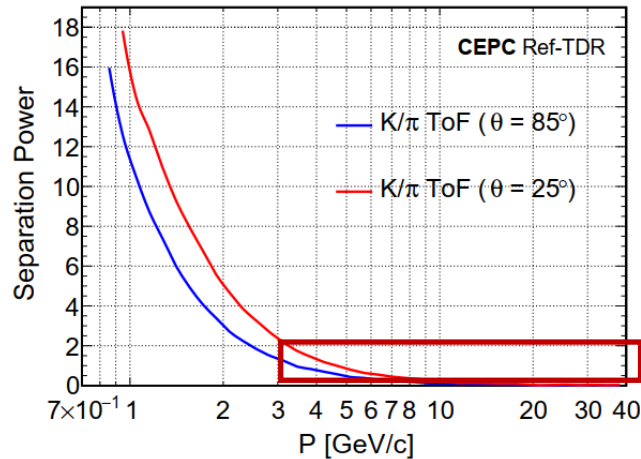
Number of photons: $\frac{dN_\gamma}{dE} = \left(\frac{\alpha}{\hbar c}\right) Z^2 L \sin^2 \theta_C$

Separation power: $N_\sigma \approx \frac{|m_1^2 - m_2^2|}{2P^2 \sigma[\theta_c(tot)] \sqrt{n^2 - 1}}$

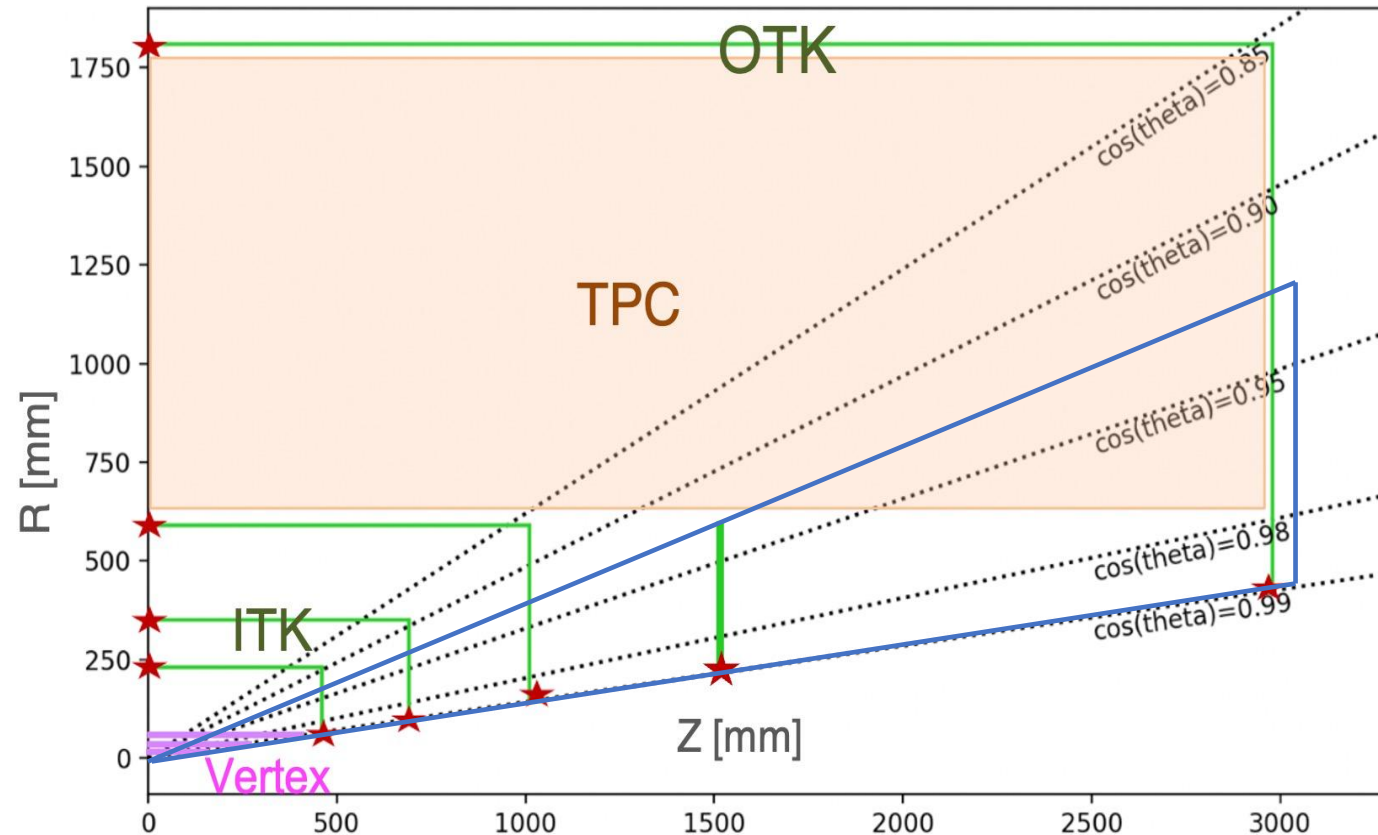
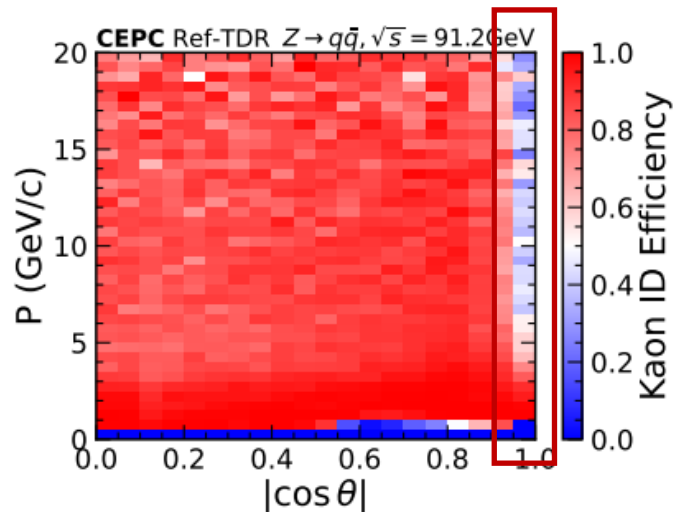
Motivation of the Cherenkov detector for CEPC

- A Cherenkov detector at CEPC is helpful, for high momentum PID(up to 20 GeV/c) at the endcap/forward region where only short tracks or even no tracks pass through TPC (so dN/dx not good)
- It's critical for flavor physics, Higgs physics (especially Higgs $\rightarrow ss$), etc.

ToF standalone
(from Ref-TDR)

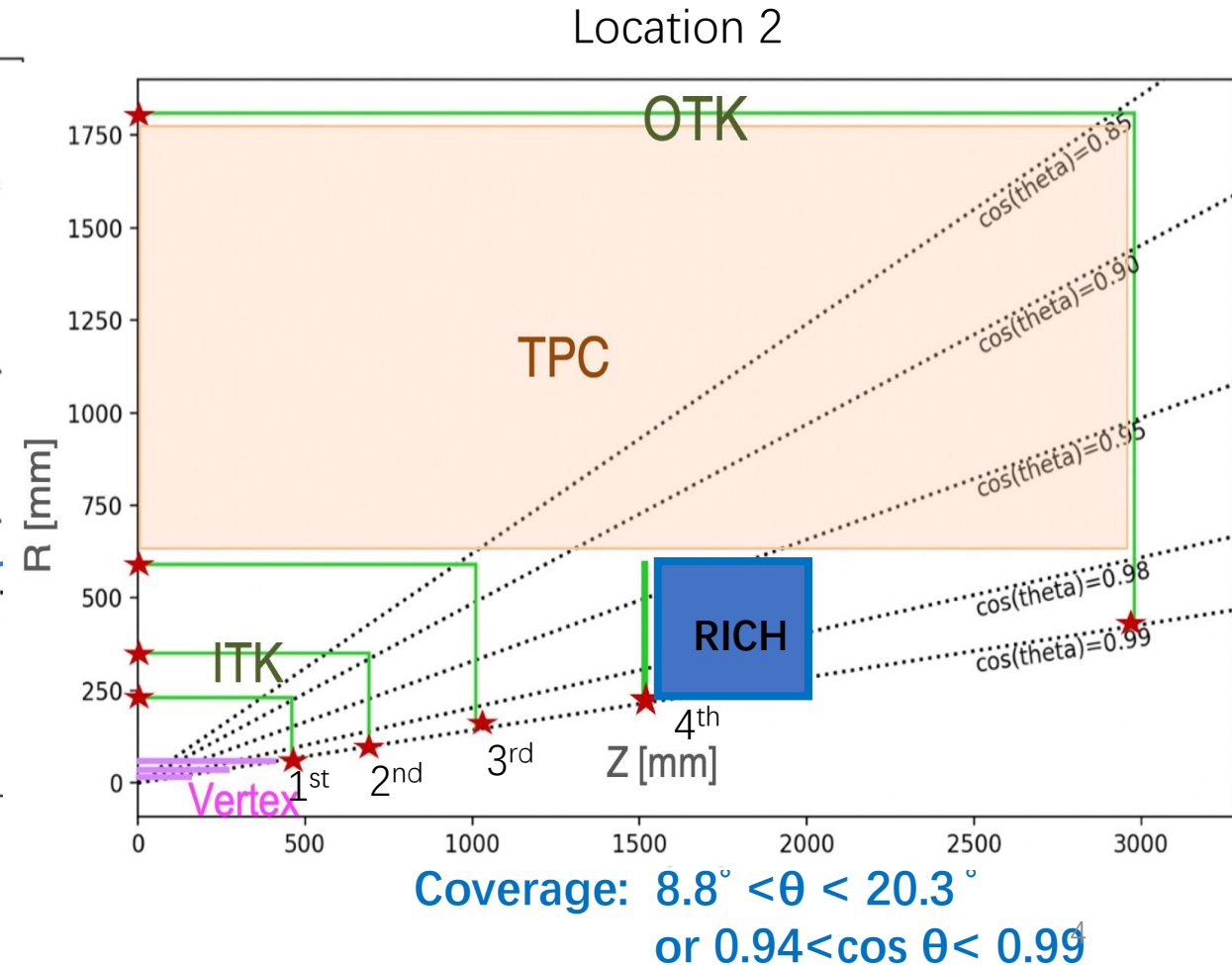
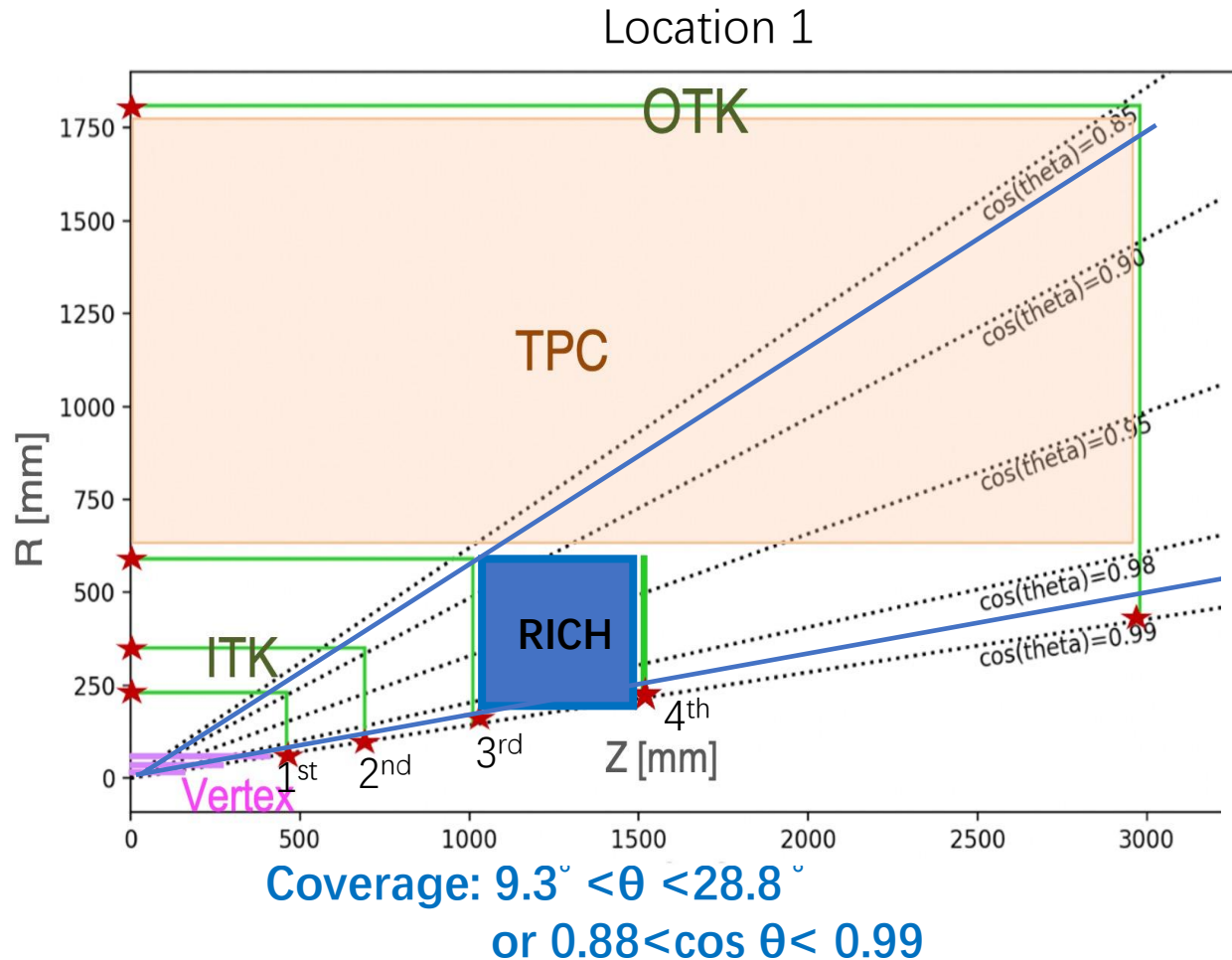


Kaon ID efficiency
(from Ref-TDR)



Possible location of the Cherenkov detector at CEPC

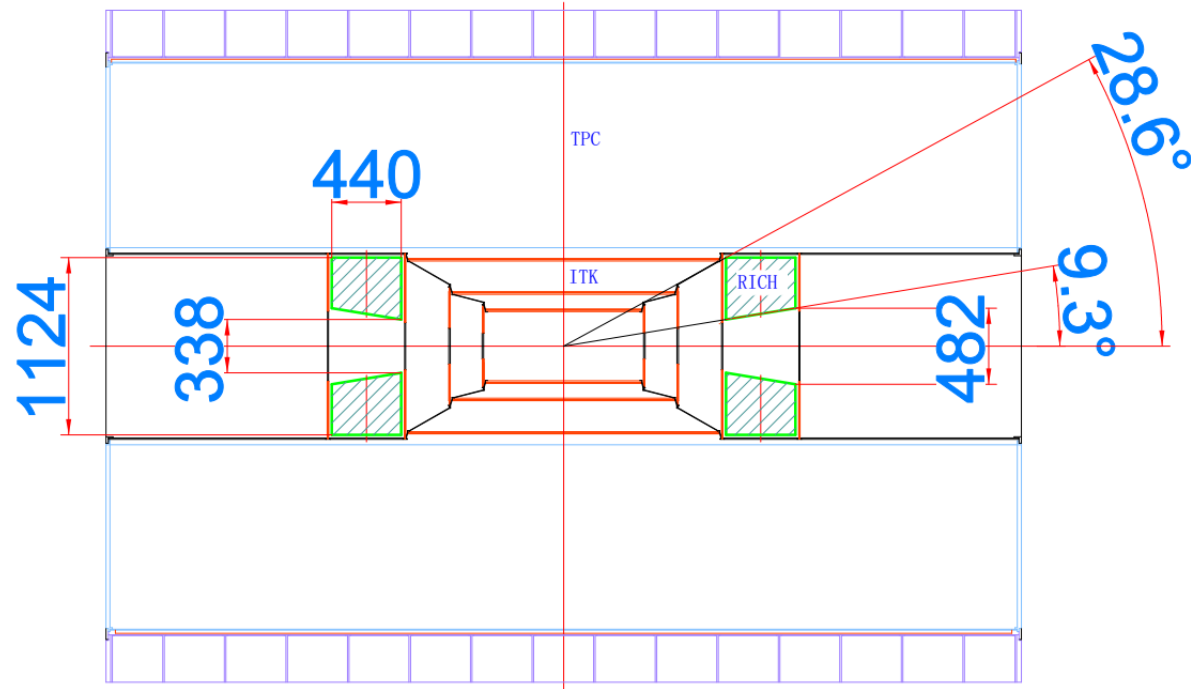
- Two possible locations without changing the other detector design in ref-TDR
- Depending on physics requirement, Cherenkov detector performance and also material budget



Drawings for the two locations

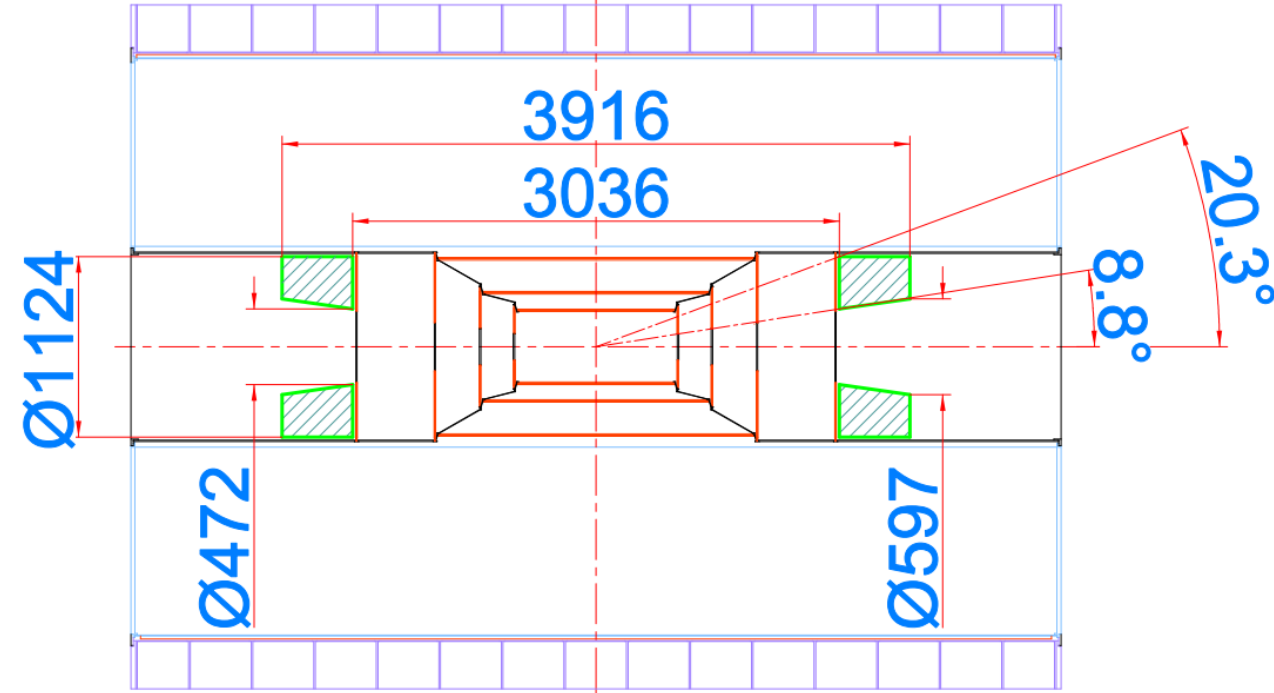
From Jian Wang,
mechanics group

Location 1 (between 3rd and 4th endcap ITK)



	Inner diameter	Outer diameter	Total area (two endcaps)	Length (single endcap)
Radiator	33.8 cm	112.4 cm	1.81 m ²	44cm
Photon detector	48.2 cm	112.4 cm	1.62 m ²	

Location 2 (outer of 4th endcap IKT)

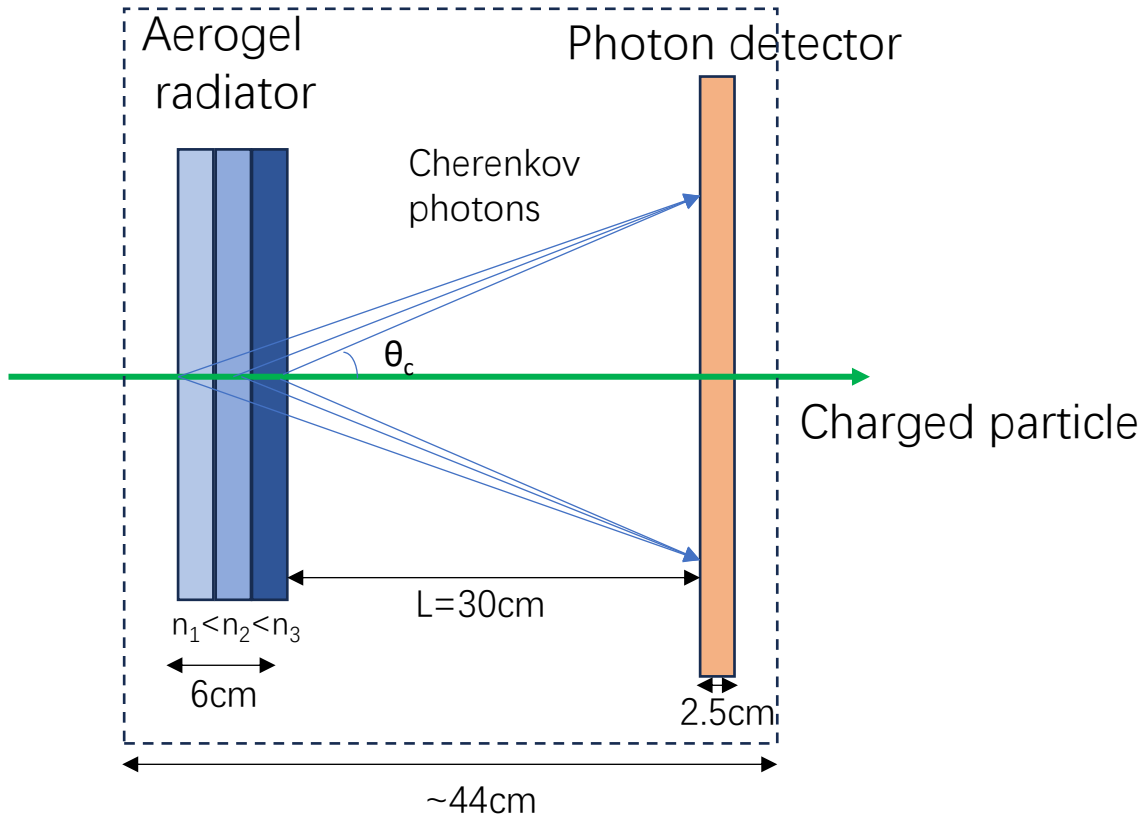


	Inner Diameter	Outer diameter	Total area (two endcaps)	Length (single endcap)
Radiator	47.2 cm	112.4 cm	1.64 m ²	44cm
Photon detector	59.7 cm	112.4 cm	1.43 m ²	

Possible design of CEPC Cherenkov detector

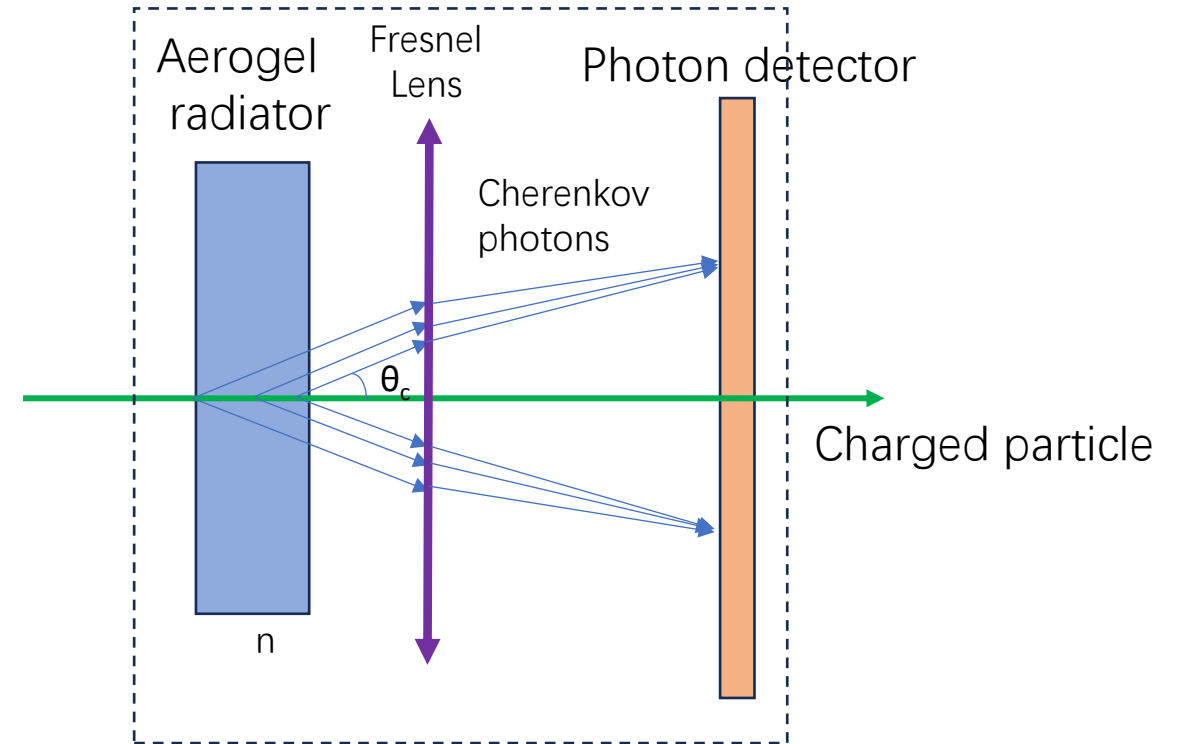
- The proximity focusing method:

Reference: T.Iijima, NIM A548 (2005) 383; A.Yu.Barnyakov, NIM A553 (2005) 70; D. Sharma, NIM A1061 (2024) 169080



Option1:

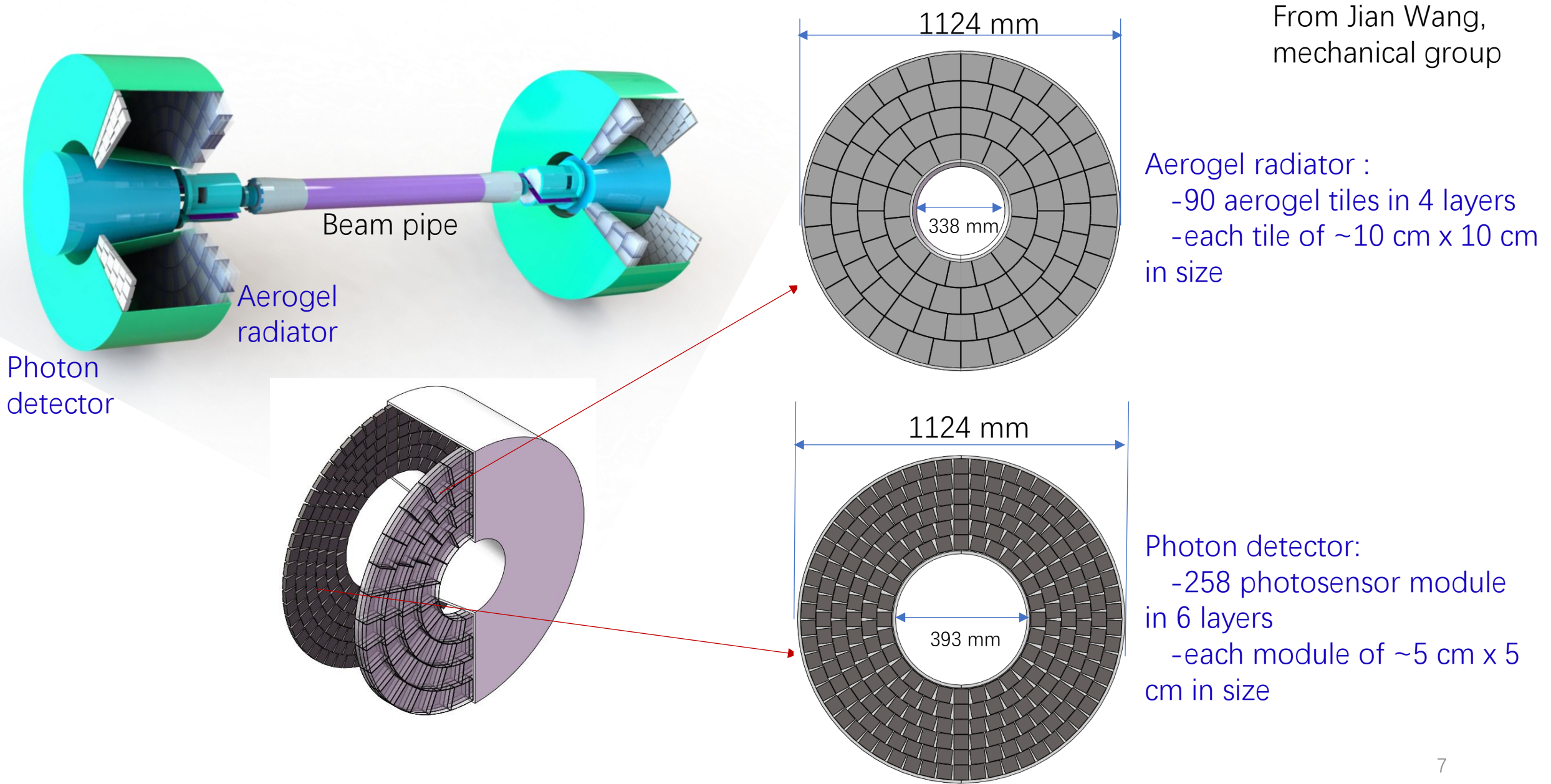
Multiple layers of aerogel with varying n , overlapped ring for different emission points



Option 2:

A single layer of aerogel, focused by a Fresnel lens.

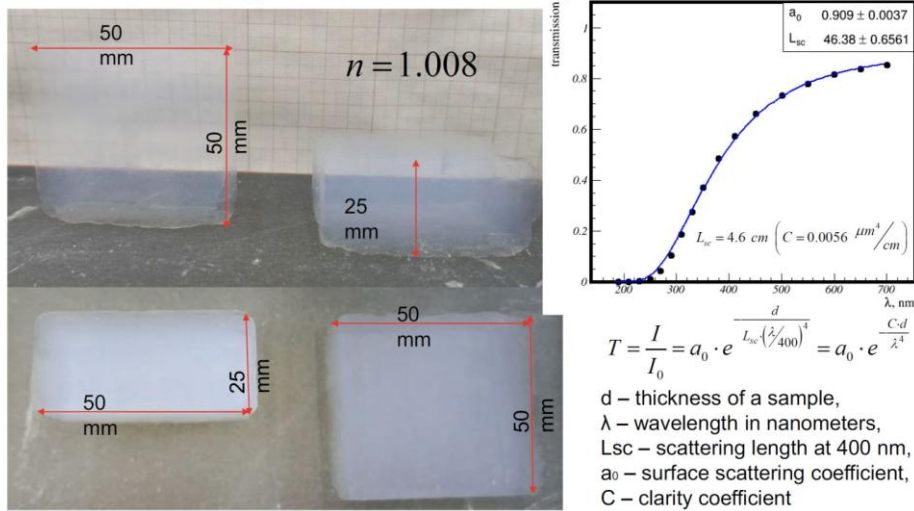
A schematics of the Cherenkov detector



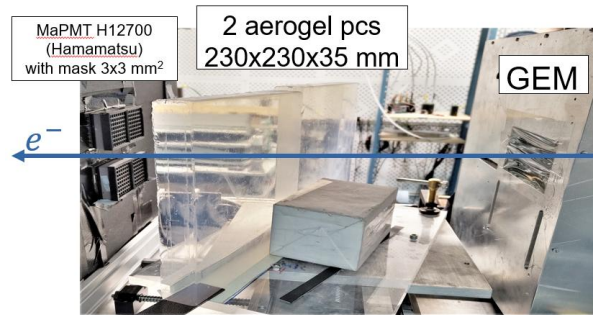
Past and ongoing R&Ds on aerogel radiator

- Led by Alexander Barnyakov from BINP

Aerogel with $n=1.008$ (Novosibirsk)

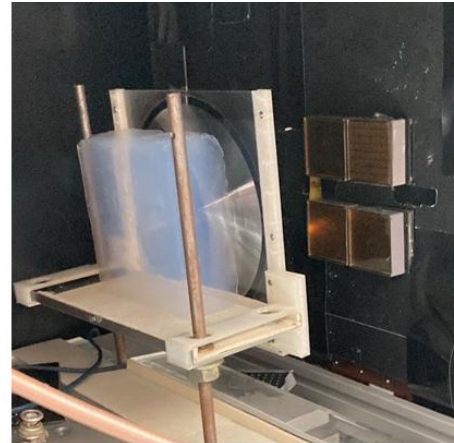


CEPC International Workshop, Haghzhou 23-27/10/2024



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

Some results of beam tests at the BINP with mRICH design



Aerogel:

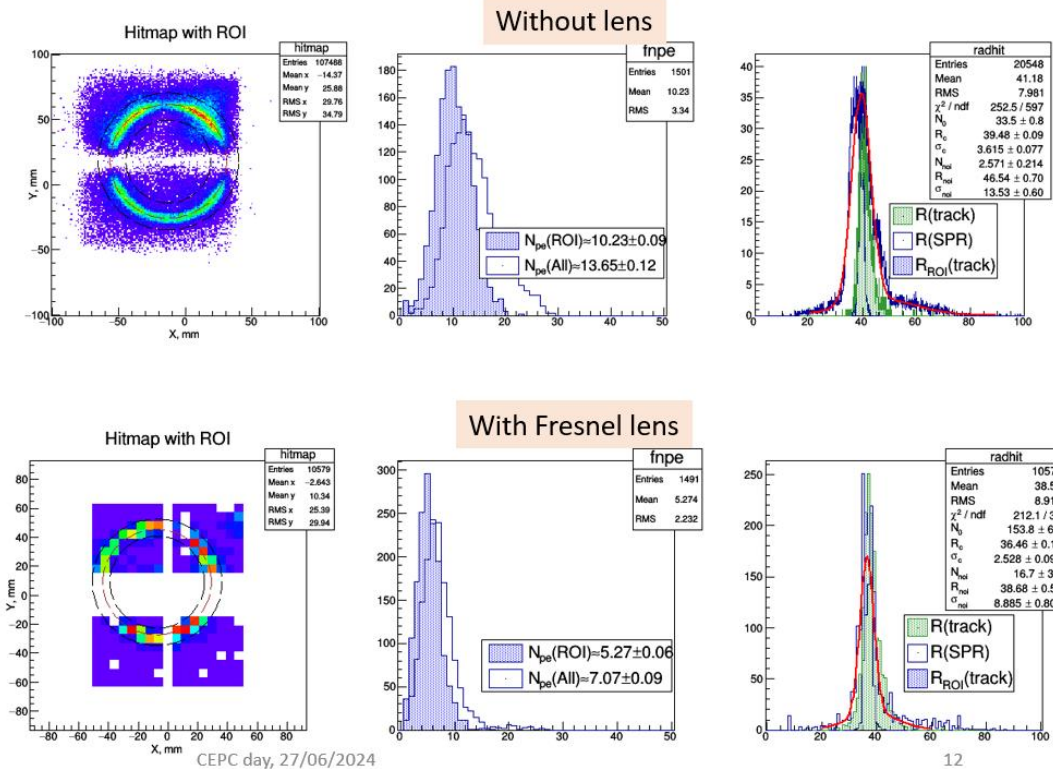
- $n=1.028$
- $L_{sc}(400nm)=48.2 \pm 0.7 \text{ mm}$
- Thickness=40mm

Fresnel lens:

- Acrylic (PMMA)
- $L_f=6''$
- Manufacturer: Edmund

PMT:

- 4 Hamamatsu H12700
- pixel 6x6 mm



Past and ongoing R&D for photon detector

- Investigation of the photon sensor (by Xiaolong, Fudan Uni.)

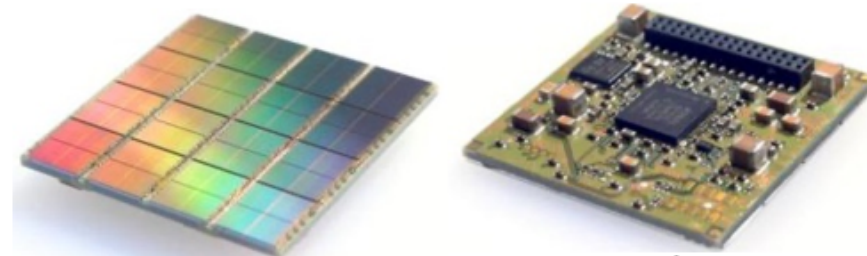
PSS-SiPM or LG-SiPM



- 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

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

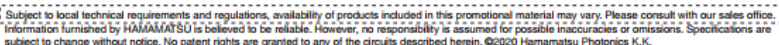
Digital PC



- DPC3200-22-44** – 3200 cells/pixel (from Philips)
- Each microcell is connected through controlled latch 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:

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

For Belle II, barrel RICH (iTOP)



10

Investigation of Multi-anode Dynode PMT

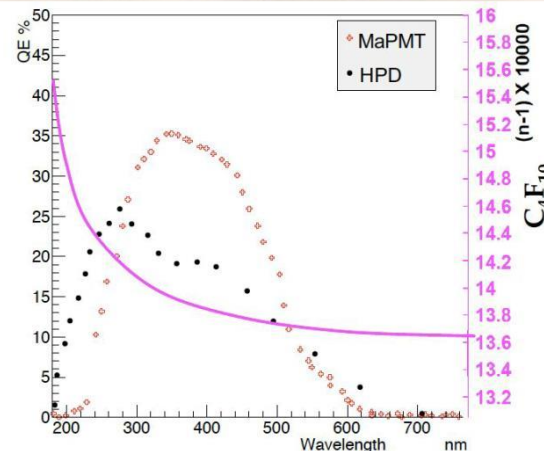
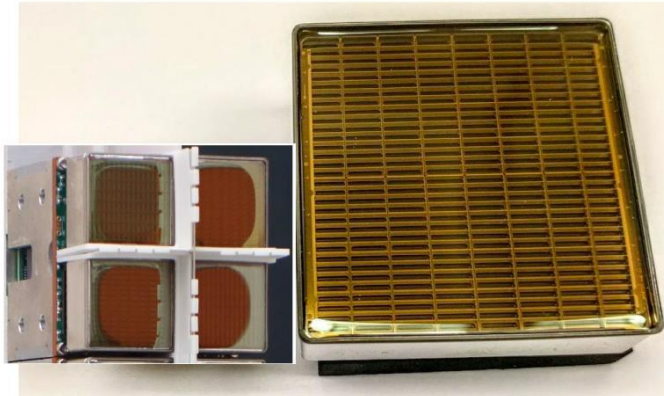
For LHCb RUN3

Sajan Easo's talk in CEPC workshop in Hangzhou, 2024
Nucl. Inst. Meth. A 876 (2017) 206-208

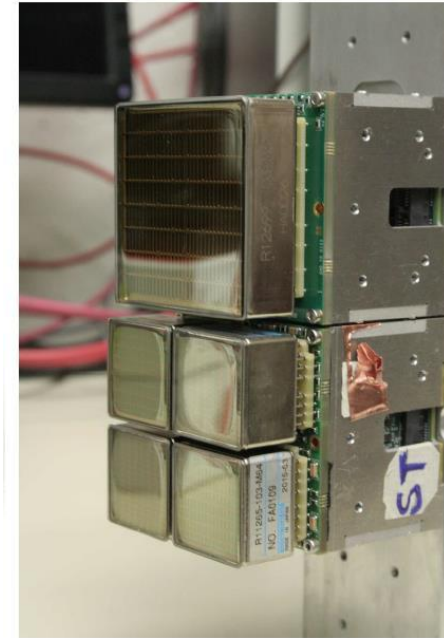
MultiAnode PhotoMultipliers

LHCb

- Hamamatsu MaPMTs
 - 3100 R13742 and 450 R13743, including spares
 - Super-bialkali photocathode
 - UV glass window
 - Minimum gain 1×10^6 at 1 kV
 - 1:4 pixel gain spread in 1" PMTs, 1:3 pixel gain spread in 2" PMTs
 - Low dark count rate
 - Single photon spectrum well separated from the noise pedestal
- Higher QE of MaPMT in the green
 - Chromatic error reduction
- Sensitive to magnetic fields
 - Shielding applied



- Effective area:
23mm x 23mm (1") or
46mm x 46 mm (2")
- Anode matrix: 8 x 8
- Anode size:
2.88mm x 2.88mm
or 5.76mmx5.76mm
- QE: 35%
- High voltage: 1.1 kV



HAMAMATSU

TENTATIVE DATA SHEET

Dec. 2015

MULTIANODE PHOTOMULTIPLIER TUBE

R13742

Exclusive for HPF-BS/ CERN and HPI/ INFN
MILANO (for LHCb/RICH)

**Super Bialkali Photocathode (SBA), UV Window, 1 Inch Square
8 x 8 Multianode and Fast Time Response**

General

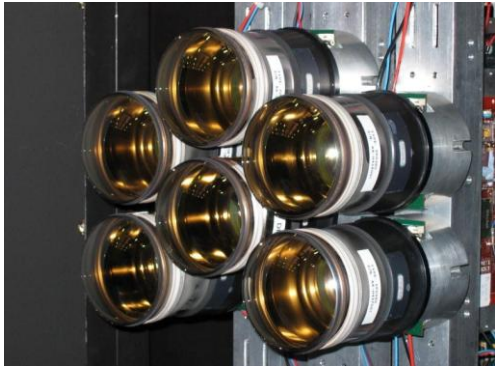
Parameter		Description	Unit
Spectral Response Range		185 to 650	nm
Peak Wavelength		350	nm
Photocathode Material		Bialkali	-
Window	Material	UV Glass	-
	Thickness	0.8	mm
Dynode	Structure	Metal Channel Dynode	-
	Number of Stage	12	-
Anode	Number of Pixels	64 (8 x 8 Matrix)	-
	Pixel Size	2.88 x 2.88	mm
Effective Area		23 x 23	mm
Dimensional Outline (W x D x H)		26.2 x 26.2 x 17.4	mm
Packing Density (Effective Area / External Size)		77	%
Weight		27	g
Operating Ambient Temperature		-30 to +50	deg C
Storage Temperature		-80 to +50	deg C

Maximum Ratings (Absolute Maximum Values)

Parameter	Value	Unit
Supply Voltage (Between Anode and Cathode)	1100	V
Average Anode Output Current in Total	0.1	mA

Investigation of HPD and HAPD

- HPD(Hybrid Photon Detector) for LHCb Run1 and Run2



Effective area: 70mm in diameter
PD size: ~2.5mm x 2.5mm
QE: 27%
High voltage: 20 kV

PRODUCT VARIATIONS

●R10467U Series

Type No.	Spectral response	Photocathode	Window material	Window type	Effective area	T.T.S.(Transit Time Spread) *1 (FWHM)
R10467U-06	220 nm to 650 nm	Bialkali	Synthetic silica	Plano-concave	φ6 mm	50 ps
R10467U-07	220 nm to 870 nm	Multialkali	Synthetic silica	Plano-concave	φ6 mm	30 ps
R10467U-40	300 nm to 740 nm	GaAsP	Borosilicate glass	Flat	φ3 mm	90 ps
R10467U-42	300 nm to 840 nm	Extended red-GaAsP	Borosilicate glass	Flat	φ3 mm	130 ps
R10467U-50	380 nm to 900 nm	GaAs	Borosilicate glass	Flat	φ3 mm	130 ps

●R11322U-40

Type No.	Spectral response	Photocathode	Window material	Window type	Effective area	T.T.S. (Transit Time Spread) *1 (FWHM)
R11322U-40	300 nm to 740 nm	GaAsP	Borosilicate glass	Flat	φ5 mm	170 ps

●R14713U-07

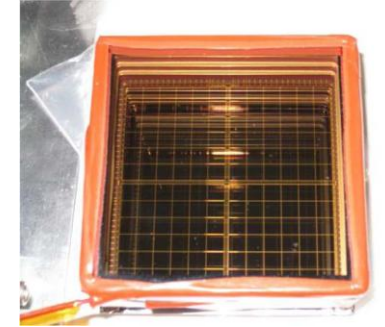
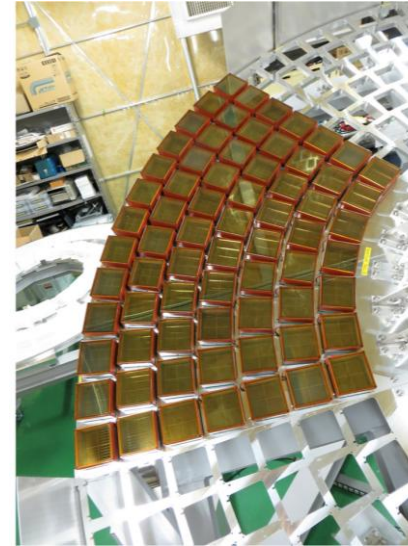
Type No.	Spectral response	Photocathode	Window material	Window type	Effective area	T.T.S. (Transit Time Spread) *1 (FWHM)
R14713U-07	220 nm to 870 nm	Multialkali	Synthetic silica	Plano-concave	φ3 mm	20 ps

●H13223-40

Type No.	Spectral response	Photocathode	Window material	Window type	Effective area	T.T.S. (Transit Time Spread) *1 (FWHM)
H13223-40	300 nm to 740 nm	GaAsP	Borosilicate glass	Flat	φ3 mm	90 ps

*1: At the single photon state and the full illumination on photocathode, specified as FWHM (Full Width at Half Maximum).
These Values include the jitter of the electronics about 30 ps.

- HAPD(Hybrid Avalanche Photon Detector) for BelleII endcap RICH (customized)



Effective area: 70mm x70mm
APD matrix: 12 x 12
APD size: ~5mm x 5mm
QE: 28%
High voltage: 8.5 kV

Table 1
Requirement for the HAPD performance.

Item	Typical	Requirement
QE ($\lambda = 400 \text{ nm}$)	28%	$\geq 24\%$
Bias Voltage	250–500 V	
High voltage	–8.5 kV	
Dark current (bias)	1–100 pA	$< 1 \mu \text{ A} / \text{channel}$
Dark current (HV)		$< 300 \text{ pA}$
Avalanche gain	40	> 30
Bombardment gain	1800	> 1500
Number of bad channels		≤ 10

General requirements for the photon detector of CEPC Cherenkov detector

Requirements	For what reasons
single photon detection capability	very small number of photons (~ 10) from aerogel radiator
low dark noise	
high detection efficiency	
high tolerance of magnetic field	3 telsa magnetic field in CEPC
high radiation tolerance	high beam background in the forward region
small material budget	inside TPC and ITK
good timing and spatial resolution	help to resolve the Cherenkov ring, improve the Cherenkov angle resolution
reasonable cost	important issues for a large project
low risk on construction and operation	

Comments on the different photon detector options

- The commercial/traditional PMTs/HPD/HAPD have a very large material budget ($> 10\% X_0$), which is not applicable for a Cherenkov detector inside the tracker (e.g. TPC, ITK.)
- The MCP-PMT (N6021 from NNVT, under developing for the other project) also has large material budget (close to $10\% X_0$) , and large anode size (5.75 mm x 5.75 mm)
- SiPM has relatively low material budget ($\sim 1\% X_0$ for SiPM +PCB), but dark noise and radiation tolerance are generally concerned, and high spatial resolution is also needed in our case

Consideration of SiPM dark noise rate

- An estimation of **fake hits from dark noise** in a readout time window in the whole photon detector plane :

$$\begin{aligned} N_{\text{false hits}} &= \text{Dark noise rate} * \text{readout time window} * \text{photon detector size} \\ &= 200 * 10^3 * 69 * 10^{-9} * 0.8 * 10^6 \\ &= 10000 \end{aligned}$$

typical dark noise rate: 200 kHz/mm²

readout time window (the same as VTX, ITK, OTK, ECal and Muon): 69 ns

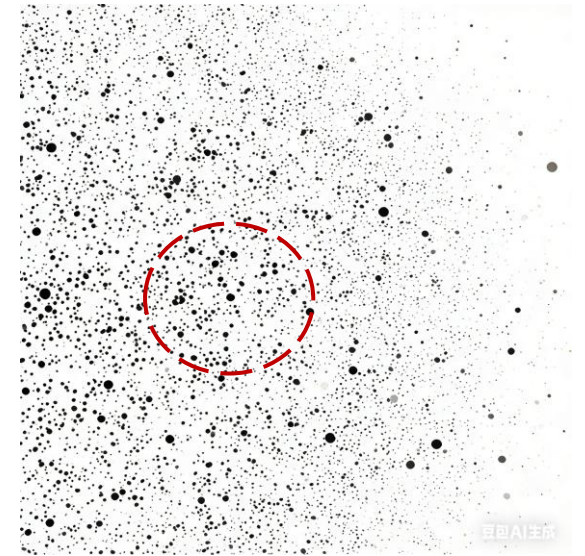
photon detector size: 0.8 m²

- Too many fake hits, any solutions then?

- reduce readout time window ? how much room?
- lower the working temperature of SiPM?

for JUNO TAO, Temp. 20 °C -> -50°C, DCR. 100kHz/mm² -> 100 Hz/mm²)

- find the ring/real hits offline by using track information from tracker systems.
- new SiPM design with lower noise: factor 10 to 100 lower?
- or a combination of all the above ?



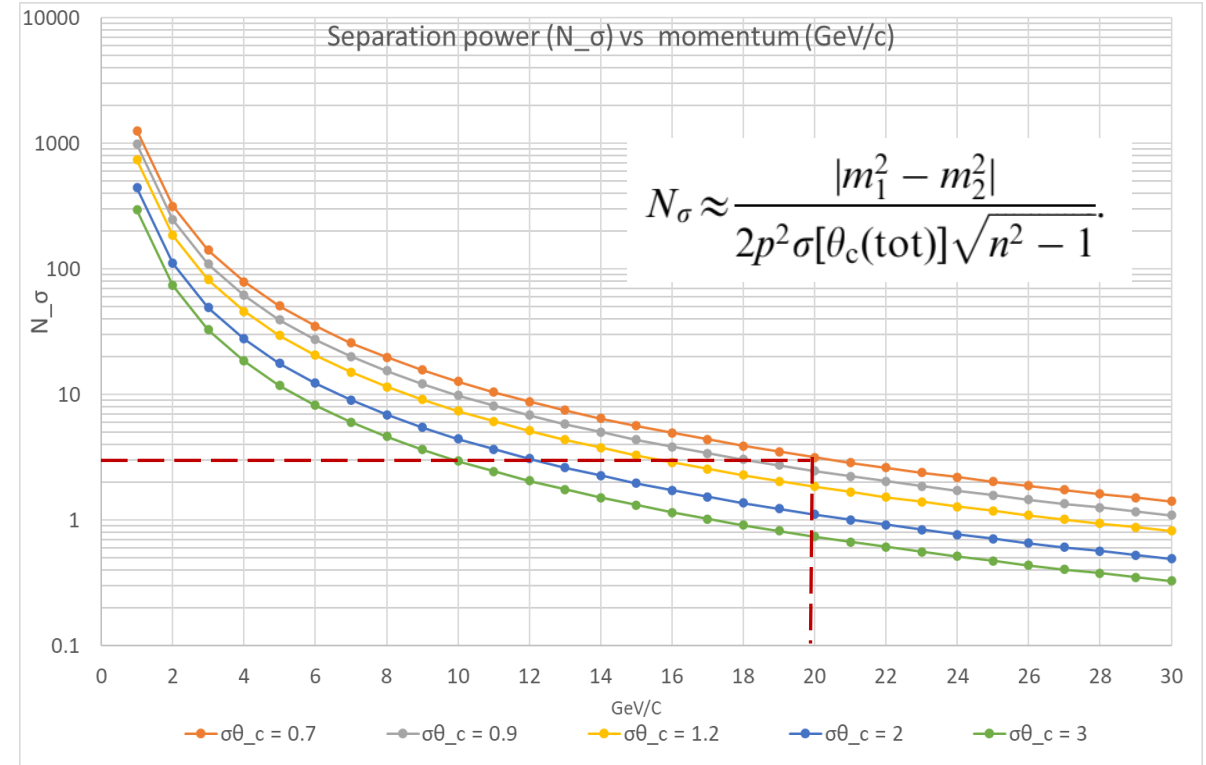
Just for illustration, a plot from AI

Consideration of SiPM spatial resolution

- To achieve 3σ K/ π separation at 20 GeV/c, a good Cherenkov angle resolution ($\sigma(\theta_c(tot))$) of **0.7 mrad** is needed;
- Resolve the spatial resolution from the Cherenkov angle resolution formula:

$$\begin{aligned}\sigma(\theta_c(tot)) &= \frac{\sigma(\theta_c(1pe))}{\sqrt{Npe}} \\ &= \frac{1}{\sqrt{Npe}} \left(\sqrt{\sigma_{spatial}^2 + \sigma_{thick}^2 + \sigma_{track}^2 + \sigma_{chromatic}^2} \right) \\ &= \frac{1}{\sqrt{Npe}} \left(\sqrt{\left(\frac{\Delta_{size}}{L\sqrt{12}}\right)^2 + \left(\frac{t \sin \theta_c}{L\sqrt{12}}\right)^2 + \sigma_{track}^2 + \left(\frac{\Delta_n}{n \tan \theta_c}\right)^2} \right)\end{aligned}$$

Assume $\Delta_{size} = 1mm$, $t = 20mm$, $\sigma_{track} = 0.5mm$, $\Delta_n = 0.0001 (n = 1.008)$, $Npe = 15$,
Then $\sigma(\theta_c(tot)) \approx 0.7 \text{ mrad}$



A SiPM with size of 1mm x 1mm, or $\sigma_{spatial} = 280 \mu m$ is desirable

Consideration of SiPM radiation tolerance

From CEPC Ref-TDR detector:

Table 3.6: Beam-induced background levels in sub-detectors at Higgs and Low-Lumi-Zoperation modes, including a safety factor of two.

Sub-Detectors	Ave. Hit Rate		Max. Hit Rate		Max. Occupancy [%]	
	Higgs	Low-Lumi-Z	Higgs	Low-Lumi-Z	Higgs	Low-Lumi-Z
VTX [MHz/ cm ²]	0.22	0.52	12	39	2.1×10^{-2}	1.3×10^{-2}
ITK-Barrel [kHz/ cm ²]	0.92	1.7	2.6	6.6	6.4×10^{-3}	1.3×10^{-2}
TPC [kHz/ cm ²]	2.4	5.2	26	24	0.15	0.14
OTK-Barrel [kHz/ cm ²]	0.74	1.3	1.2	2.2	4.2×10^{-3}	9.2×10^{-4}
ECAL-Barrel [MHz/bar]	1.4×10^{-2}	2.2×10^{-2}	1.7	0.66	1.6	0.4
HCAL-Barrel [kHz/gs cell]	4.6×10^{-3}	8.4×10^{-3}	14	24	8.0×10^{-4}	8.0×10^{-4}
ITK-Endcap [kHz/ cm ²]	3.0	5.4	24	50	2.4×10^{-3}	5.0×10^{-3}
OTK-Endcap [kHz/ cm ²]	1.9	3.1	8.2	13	7.4×10^{-2}	12×10^{-2}
ECAL-Endcap [MHz/bar]	0.062	0.10	7.2	13	7.0	1.8
HCAL-Endcap [kHz/gs cell]	0.24	0.24	640	340	8.0×10^{-2}	6.0×10^{-3}
MD-Endcap [Hz/ cm ²]	1.4	0.92	2.5	14	0.18	0.05

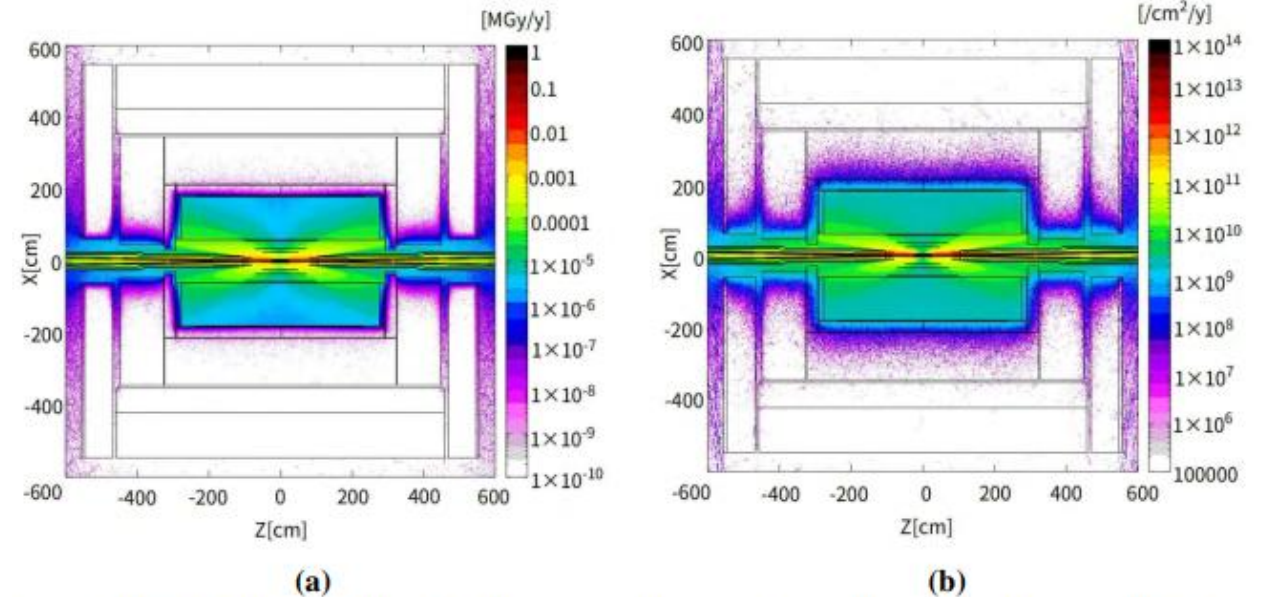


Figure 3.12: The TID and NIEL distributions at Higgs mode on the CEPC detector. The highest TID is lower than 1 MGy per year as shown in a.), while the highest level of NIEL is in the order of 10^{13} (1 MeVn_{eq}) cm^{-2} per year as shown in b.).

NIEL in the forward region where Cherenkov detector is possible put: $\sim 1 \times 10^{11}$ Neq. /cm² /year

- So the requirement for SiPM:
 1×10^{12} Neq./cm², or more conservatively 1×10^{13} Neq./cm² ?

The preliminary specifications of SiPM (still to be discussed/worked out)

Items	preliminary requirement
Wavelength	200 nm – 600 nm
Photon detection efficiency	50% at 420nm
SiPM size	1 mm x 1 mm or 3 mm x 3 mm
Time resolution	100 – 200 ps
Dark noise rate	~ 1-10 kHz/mm ² ?
Spatial resolution	~ 280 μm
Radiation tolerance	~10 ¹³ N _{eq.} /cm ² ?

A near future plan

In a couple of months:

- Work out the final specifications for the Cherenkov detector
 - overall specifications
 - specification for photon detector and aerogel radiator
- Set up a simulation/reconstruction framework in CEPCSW, finish some preliminary simulation/reconstruction
 - a student will work with software group soon
 - hopefully more students joining later
- Keep investigation and test on the photon detector for SiPM
 - SiPM of charge sharing (Fudan university)
 - SiPM with lower noise and high radiation tolerance (IHEP)
- Others?

A long-term plan

- Towards CDR in 1-2 years

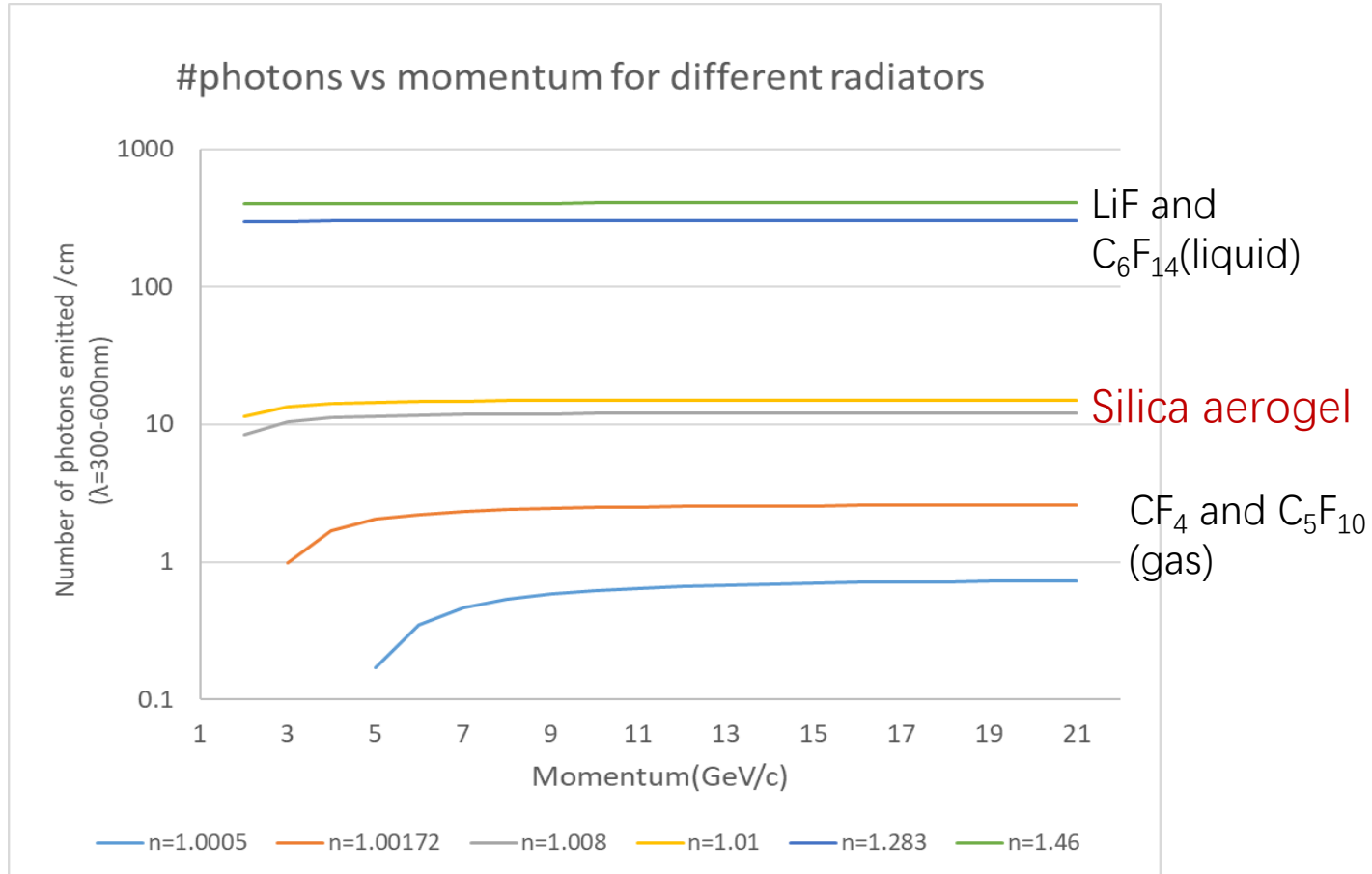
- a benchmark detector design with all components included
- a simulation/reconstruction framework for determining the detector position
- a key technology development on photon detector and related readout electronics, aerogel radiator
- a demonstrator of the benchmark detector option

- Towards TDR in 3-5 years

- a full design of all components of the detector
- a prototype of the detector and beam test
- a full simulation/reconstruction software

Thank you!

The number of photons emitted from different radiators



Radiators	Refractive index	Number of photon ($p=20\text{GeV}$, $\lambda= 300-600$ nm)
Fused silica, LiF, NaF (solid state)	1.46, 1.392, 1.334	300-400 photons /cm
C_6F_{14} (liquid)	1.283	~300 photons/cm
C_5F_{12} , C_4F_{10} , CF_4 , (gaseous)	1.0005	0.7 – 2.6 photons/cm
Silica Aerogel	1.01 – 1.001 (adjustable)	1.5 -15 photons/cm

$$\frac{dN_\gamma}{dE} = \left(\frac{\alpha}{\hbar c}\right) Z^2 L \sin^2 \theta_C$$

$$\approx 370 \sin^2 \theta_c \text{ (eV}^{-1} \text{ cm}^{-1}\text{)}$$