Preliminary consideration of a Cherenkov detector at CEPC

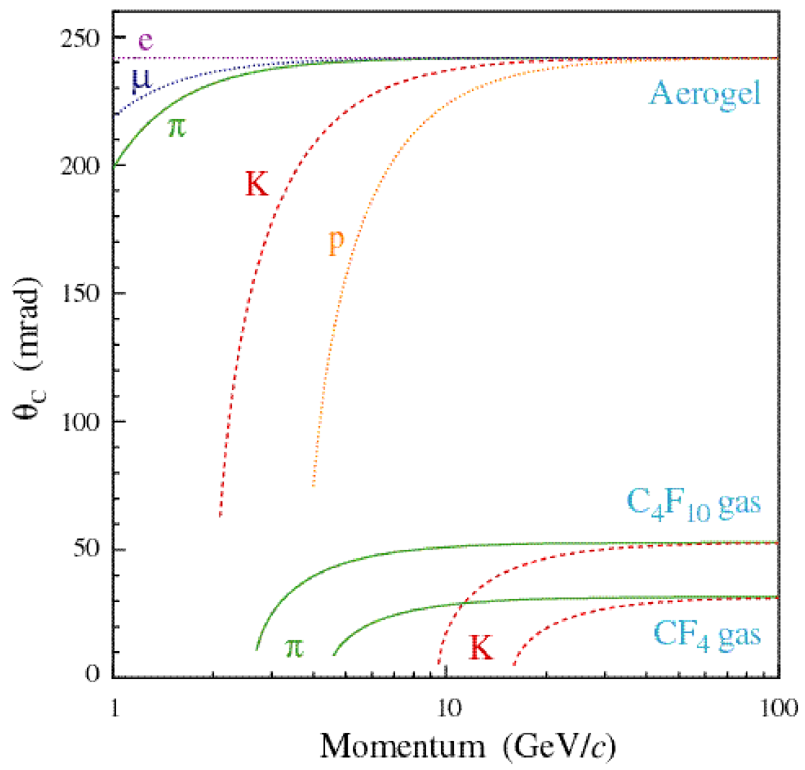
Zhonghua Qin, IHEP

CEPC Day, 2025.10.16

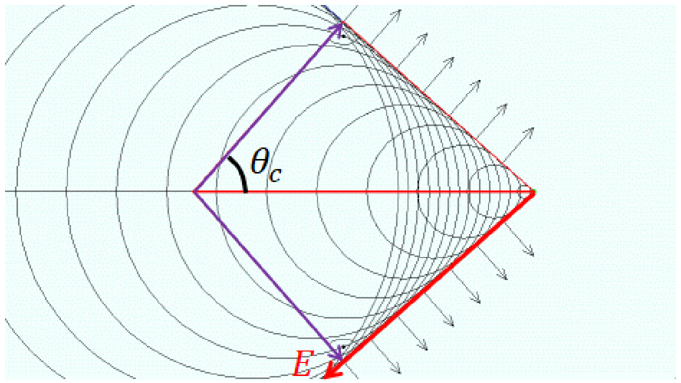
A reminder of Cherenkov detector

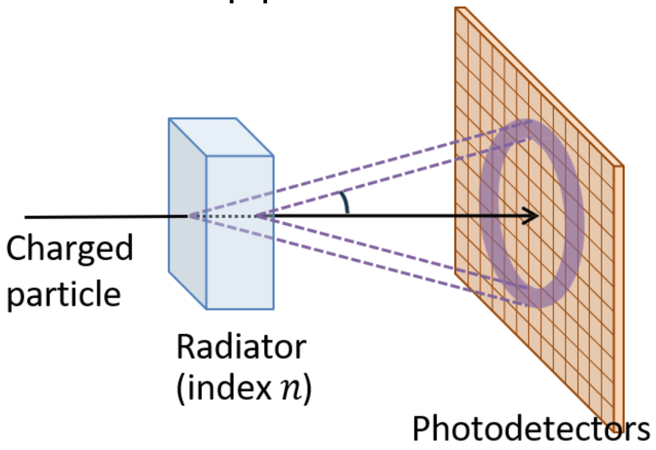
- Cherenkov detector is a powerful tool for charged particle identification, especially for particles with a momentum up to several tens of GeV/c where the ToF is not applicable

LHCb RICH-1 (Aerogel+C_4F_{10} gas radiator)
RICH-2 (CH_4 gas radiator)



2-100 GeV/c





RICH 2025, Kodai Matsuoka

Threshold: $\beta > 1/n$

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

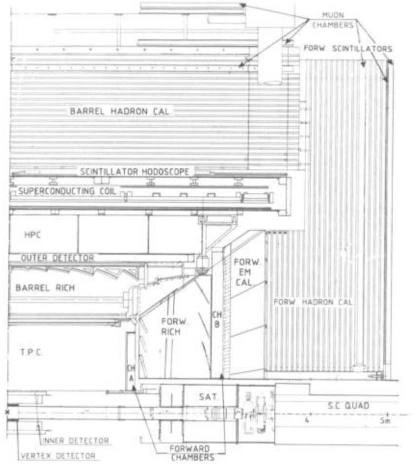
Number of photons: $\frac{dN_\gamma}{dE} = \left(\frac{\alpha}{\hbar c}\right) Z^2 L \sin^2\theta_C \approx 370 \sin^2\theta_c$ ($eV^{-1}\,cm^{-1}$)

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

Cherenkov detector widely used by many experiments

- A lot of high energy particle /nuclear/astrophysics/neutrino physics experiments around the world

 -DELPHI, CLEOIII, BABAR, BELLE I & BELLE II, LHCb, ALICE, COMPASS, STAR, NA62, CLAS12 , AMS02... (and many neutrino experiments not listed)



DELPHI

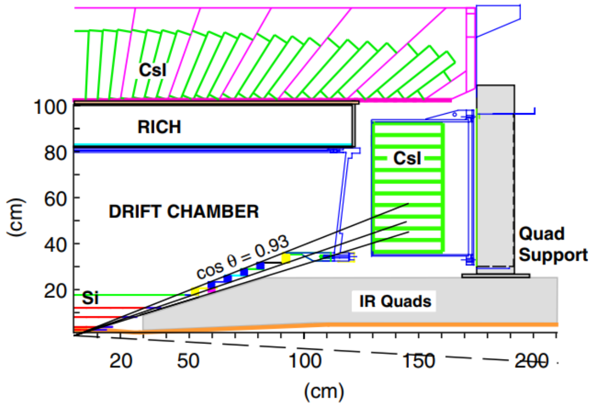
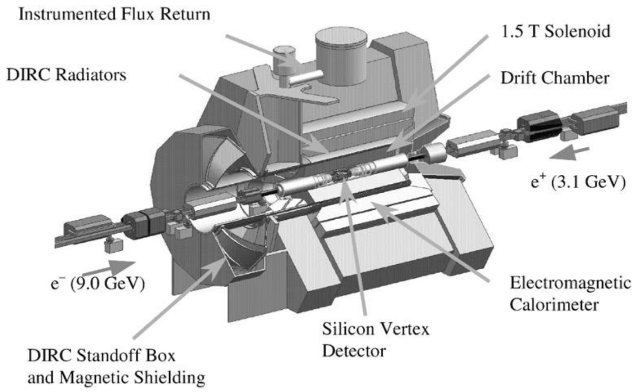


Fig. 3. The CLEO RICH, shown in CLEO-III configuration.

CELOIII



BABAR

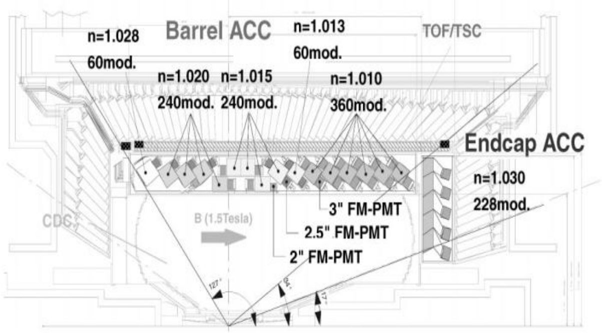
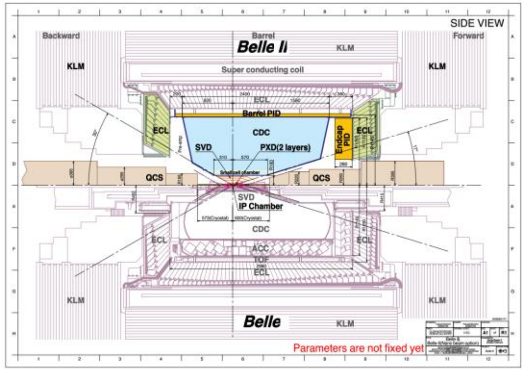


Fig. 1. Schematic drawing of the BELLE-ACC system.

BELLE I



BELLE II

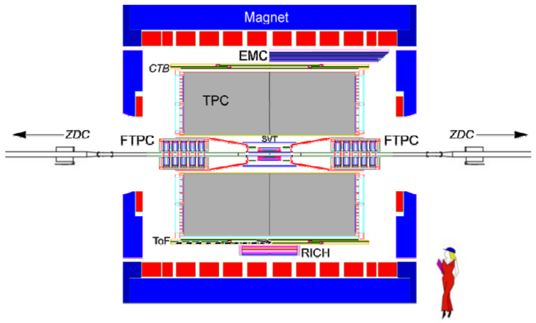
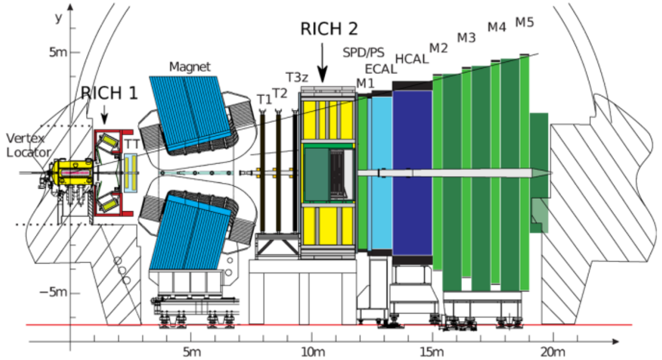
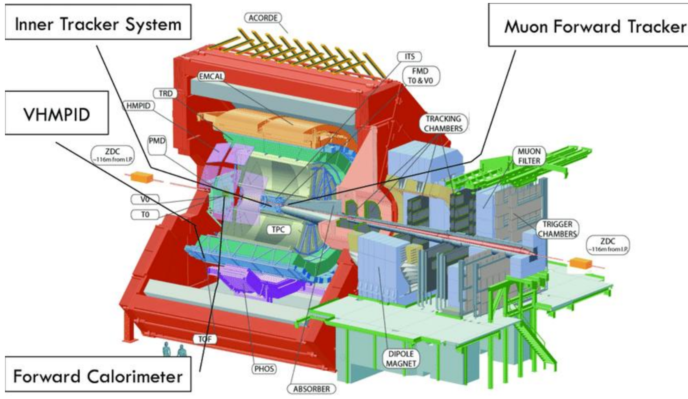


Fig. 2. Cutaway side view of the STAR detector as configured in 2001.

STAR



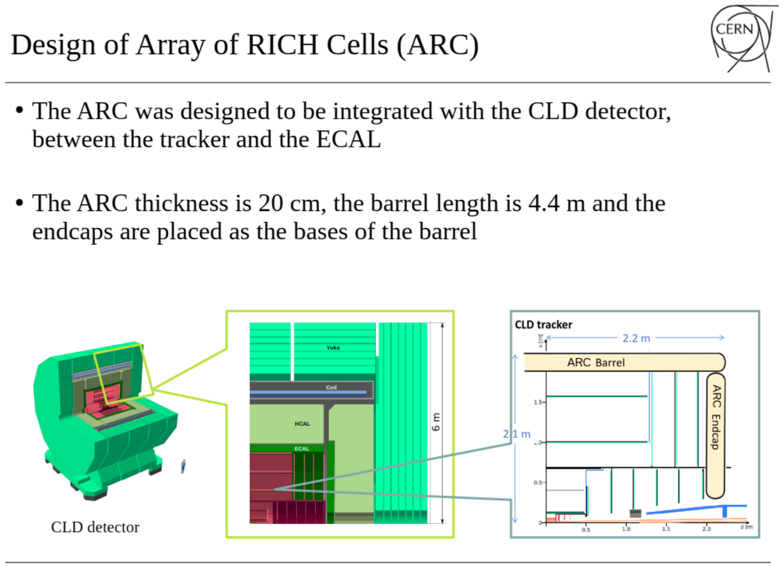
LHCb



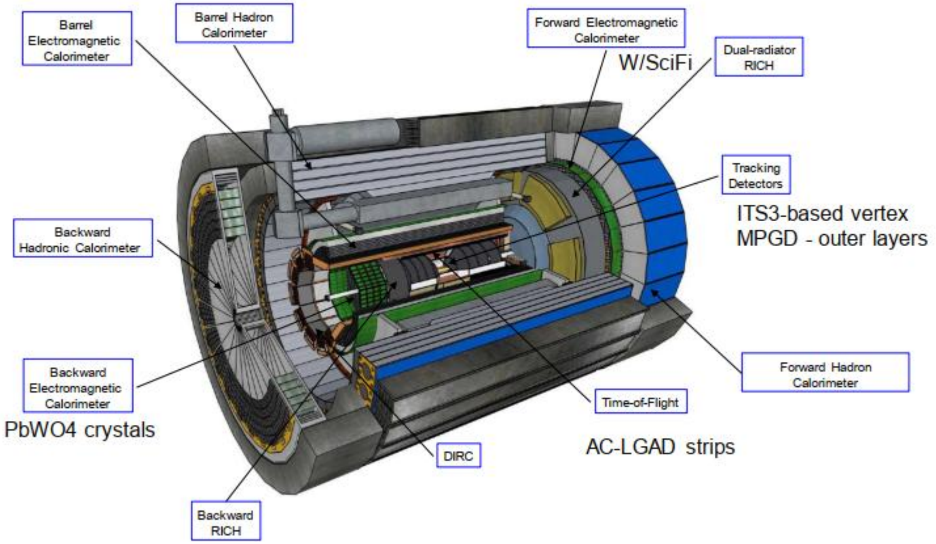
ALICE

Proposed also by the future experiments

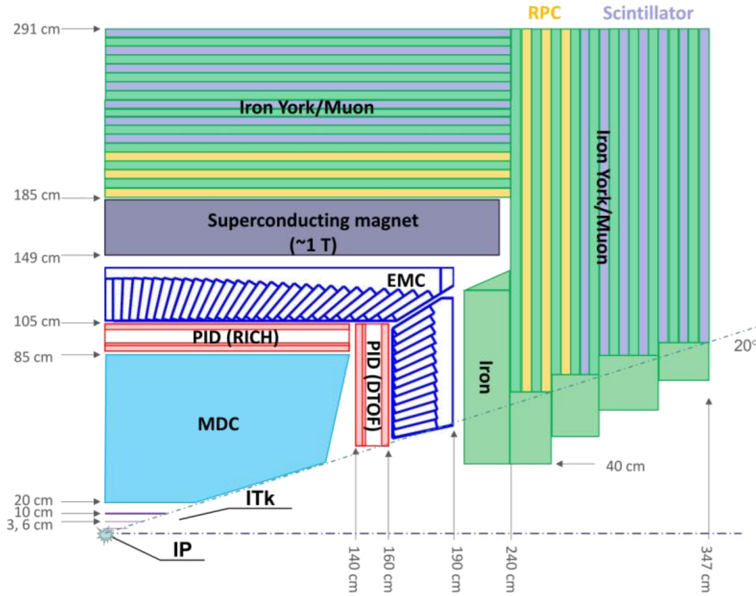
- Such as FCC-ee, EIC, STCF …



FCC-ee (CLD detector concept)



ePIC detector at EIC

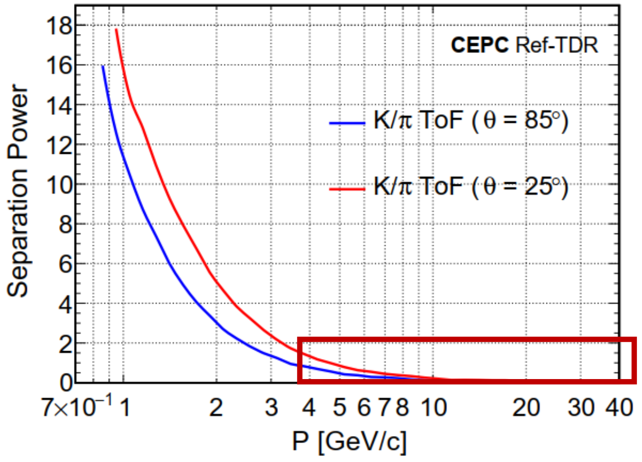


STCF

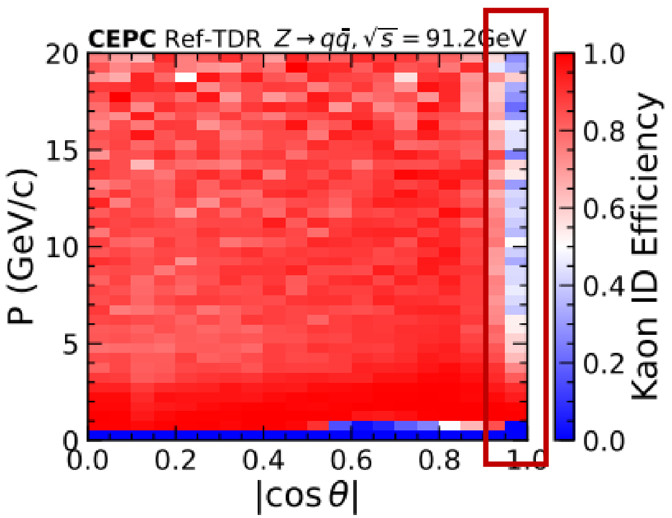
Motivation of the Cherenkov detector for CEPC

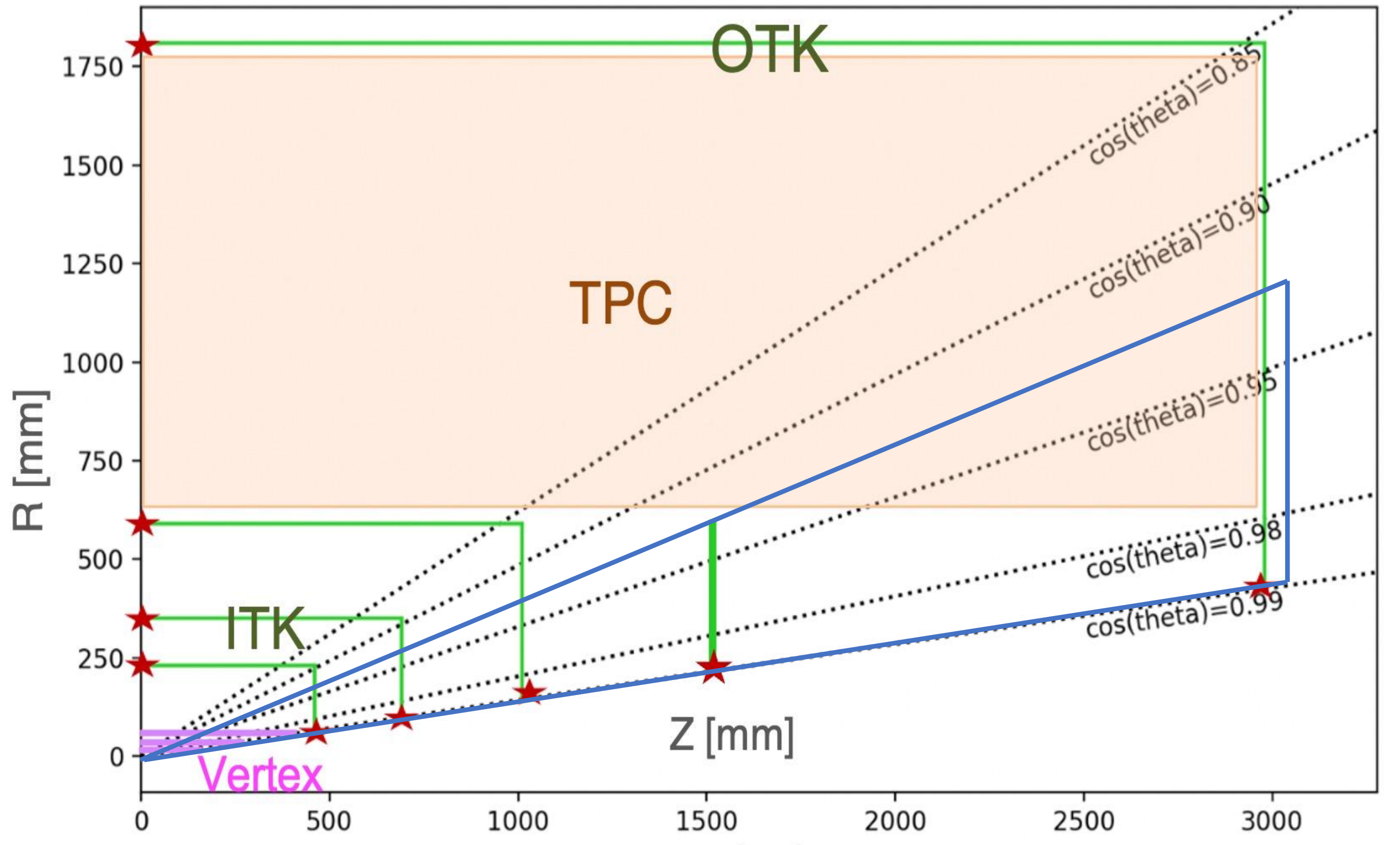
- A Cherenkov detector at CEPC is helpful, for high momentum PID(up to 20 GeV/c) at the endcap or forward region where there is only a short track or even no track in TPC (dN/dx not good)

ToF standalone
Ref-TDR



Kaon ID efficiency
Ref-TDR

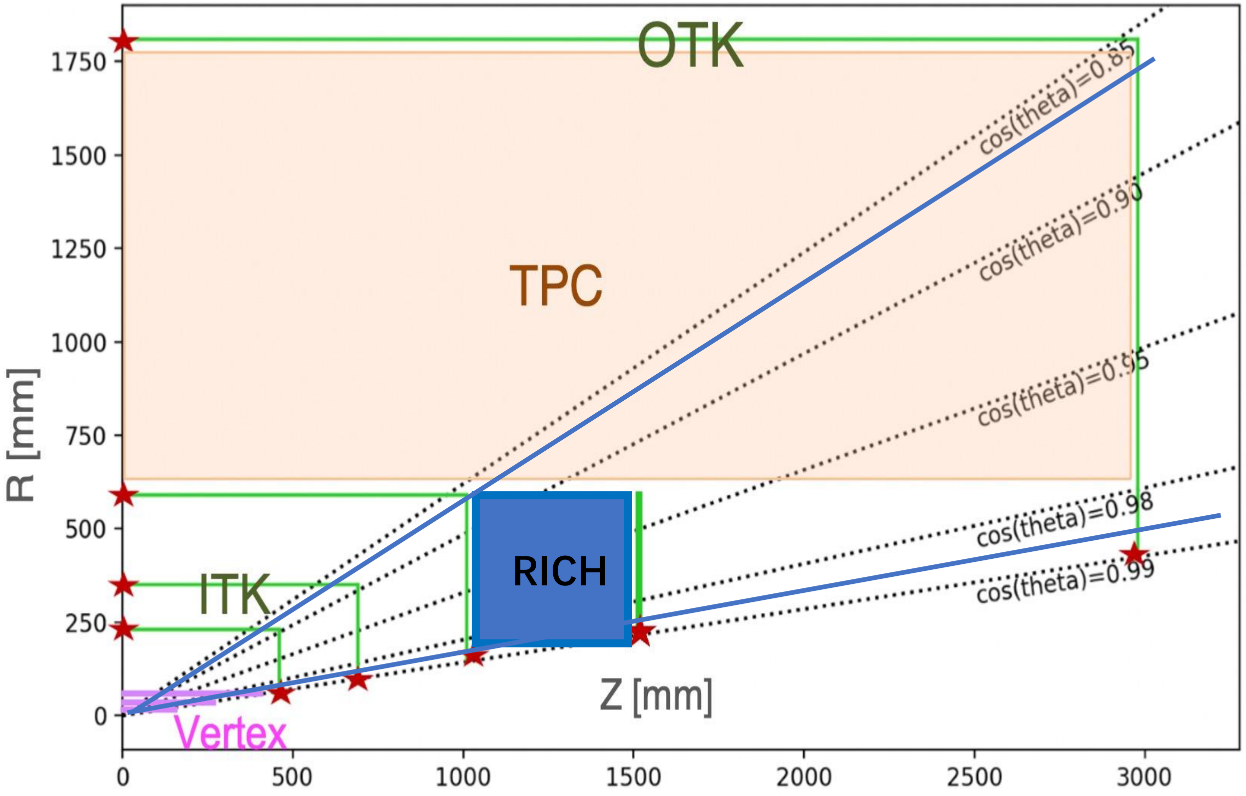




Possible location of the Cherenkov detector at CEPC

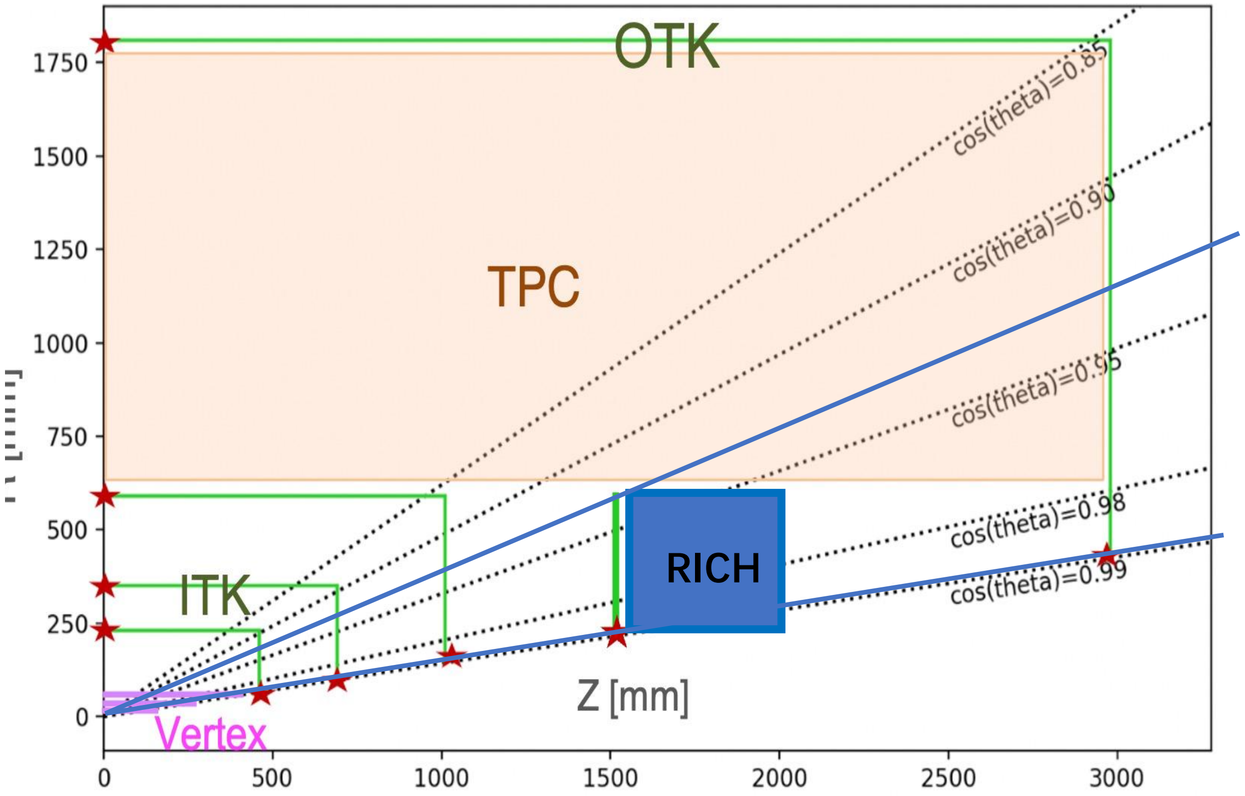
- Two possible locations without changing the other detector design in ref-TDR
- Depending on physics requirement, Cherenkov detector performance and also material budget

Location 1



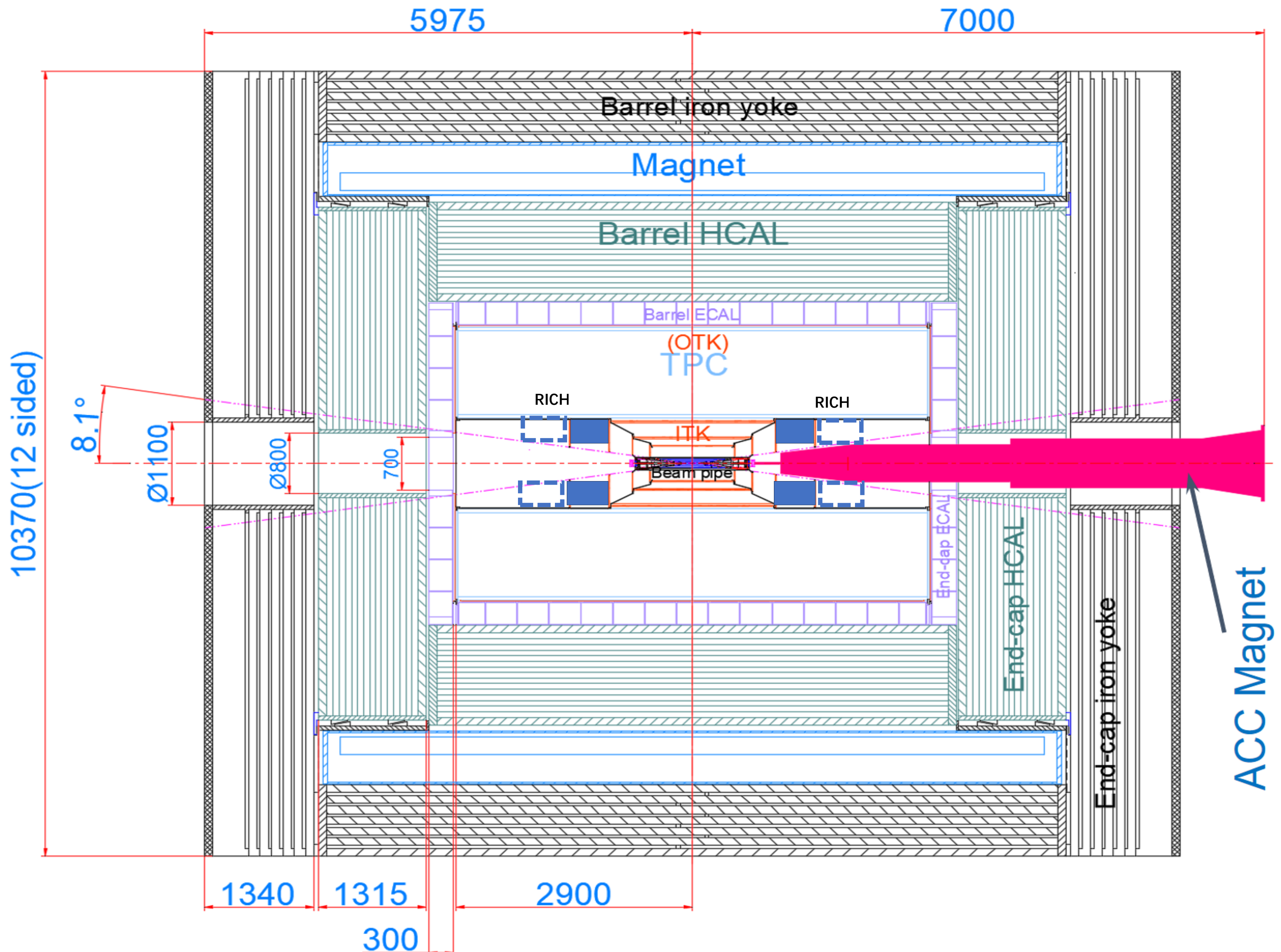
Coverage: 9.3° <θ <28.8°
or 0.99<cos θ< 0.88

Location 2



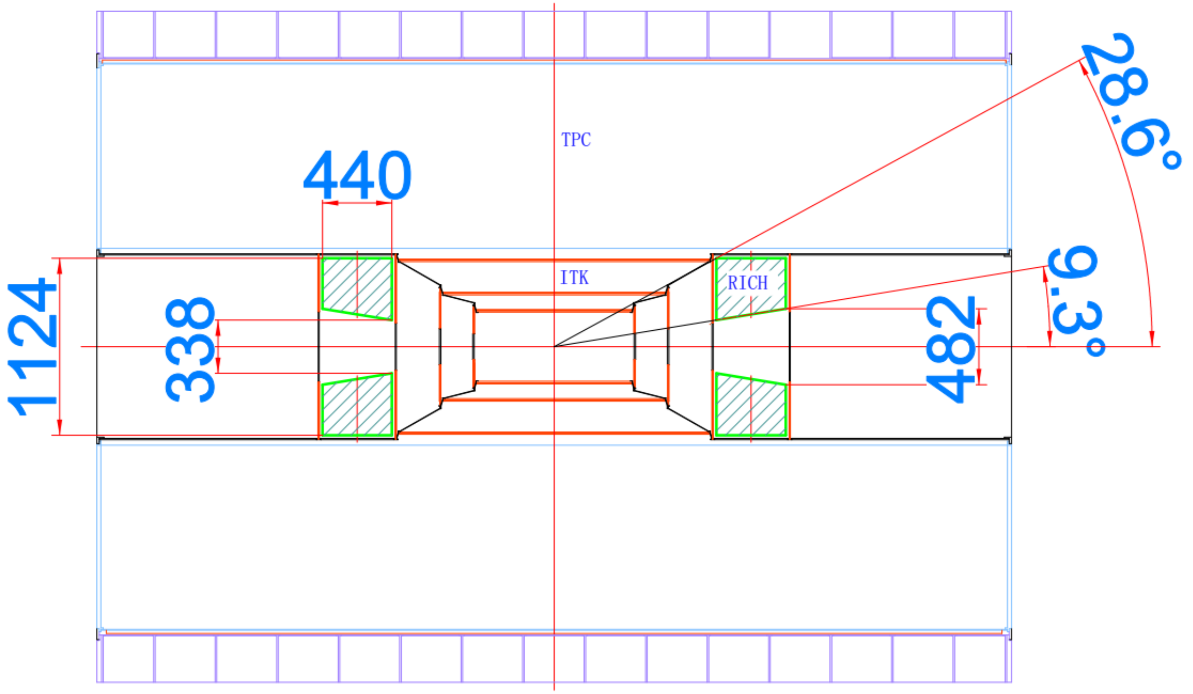
Coverage: 8.8° <θ < 20.3°
or 0.99<cos θ< 0.94

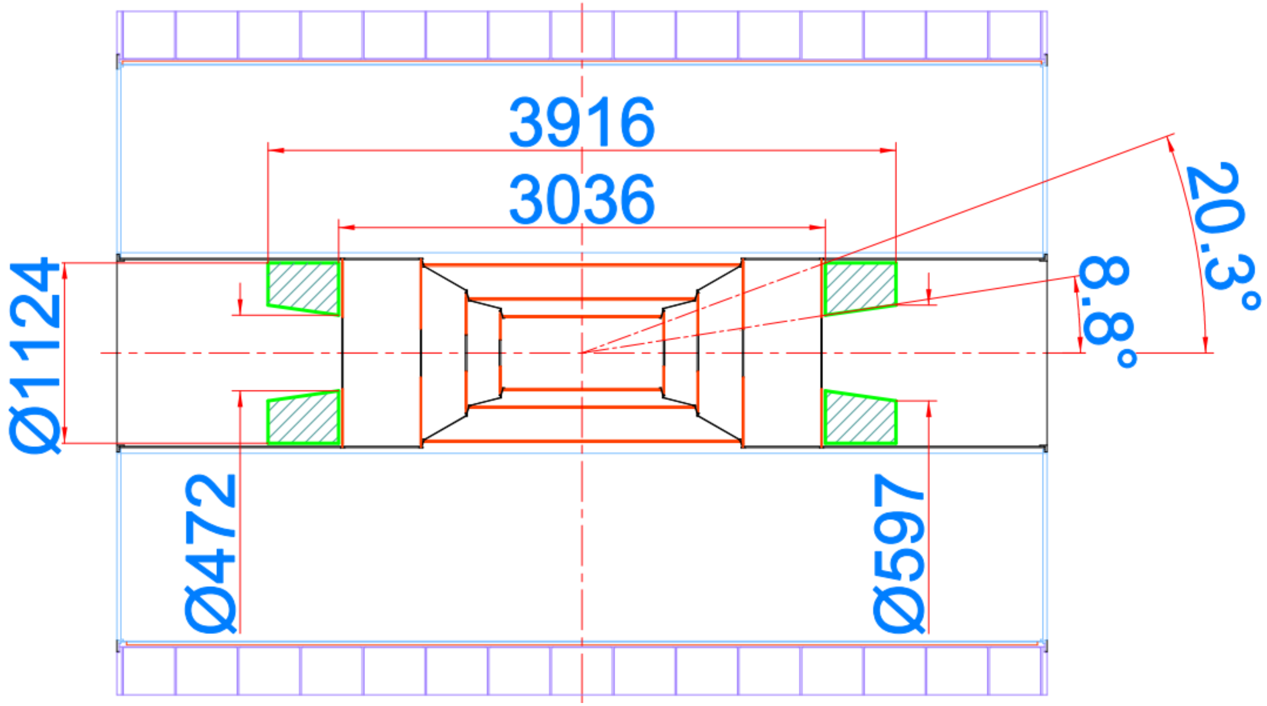
An overall view for the locations



The drawing of the two locations

From Jian Wang, mechanics group



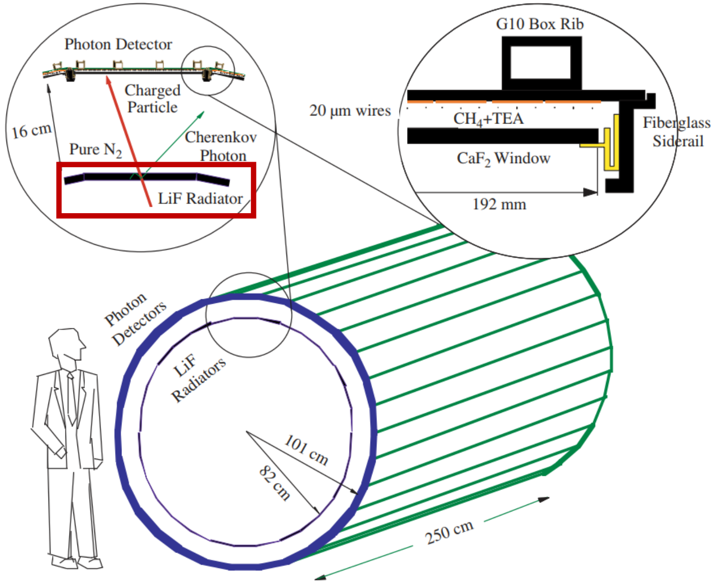


	Inner diameter	Outer diameter	Total area (two endcaps)
Radiator	33.8 cm	112.4 cm	1.81 m^2
Photon detector	48.2 cm	112.4 cm	1.62 m^2

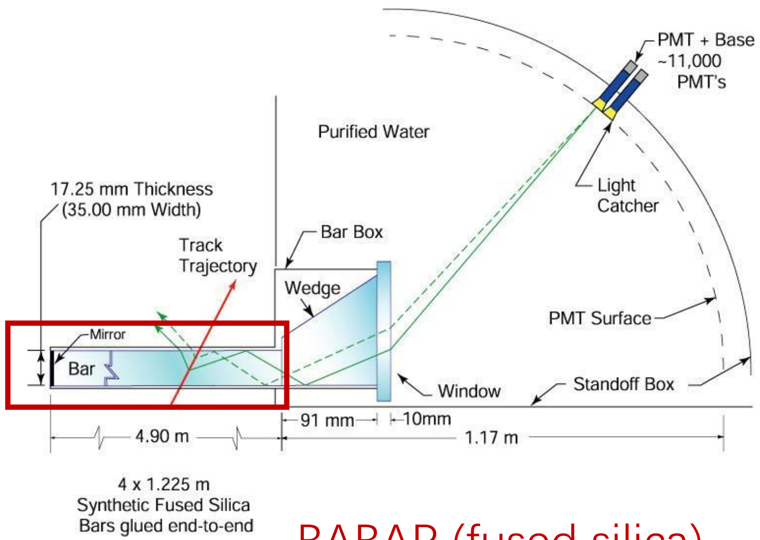
	Inner Diameter	Outer diameter	Total area (two endcaps)
Radiator	47.2 cm	112.4 cm	1.64 m^2
Photon detector	59.7 cm	112.4 cm	1.43 m^2

Investigation of technologies used for Cherenkov detector

- Radiator
  - Solid-state or liquid: LiF, NaF, fused Silica, C_6F_{14}(liquid)
  - Gaseous: CF_4, C_4F_{10}, C_5F_{12}
  - Aerogel (silica aerogel)
  - Hybrid: aerogel + gas

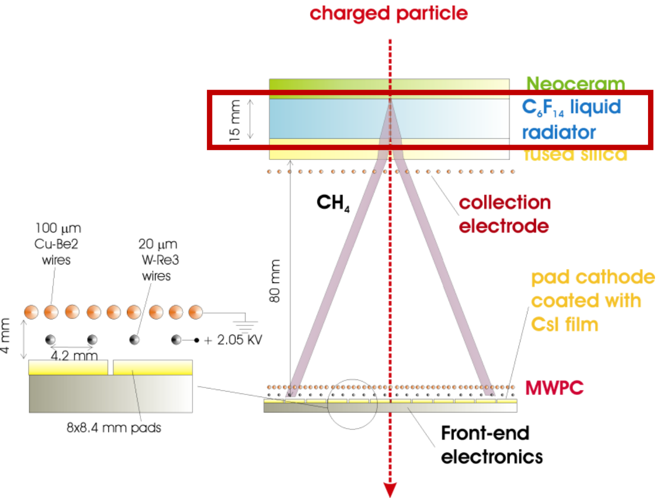


CLEOIII (LiF crystal)

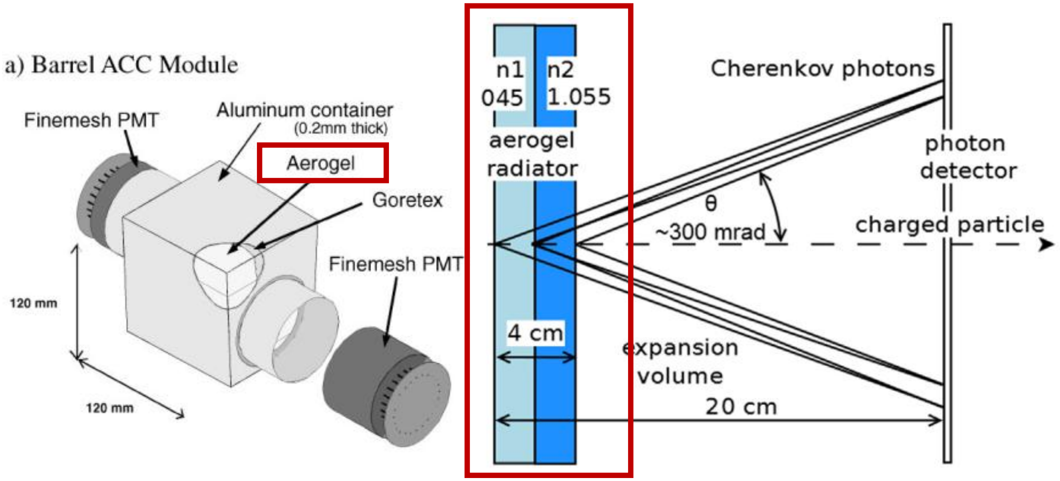


BABAR (fused silica)

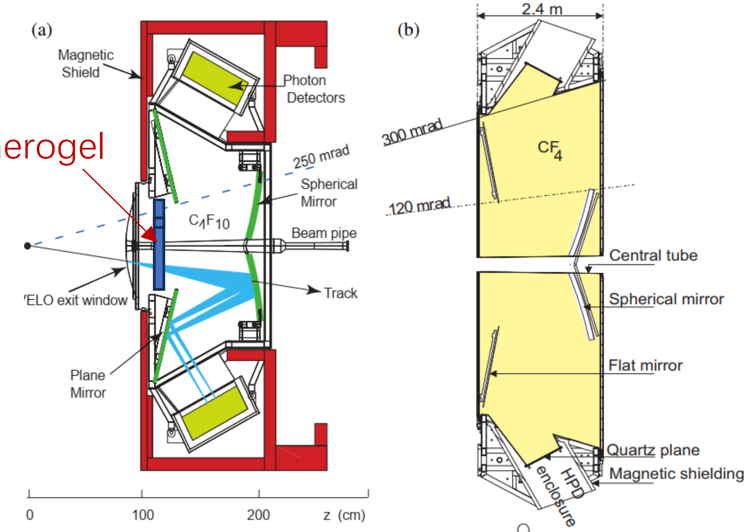
NIM A 554 (2005) 147–194



ALICE (liquid C_6F_{14})



Belle I & Belle II (silica aerogel)



LHCb (Aerogel + C_4F_{10}+ CF_4)

Investigation of technologies used for Cherenkov detector

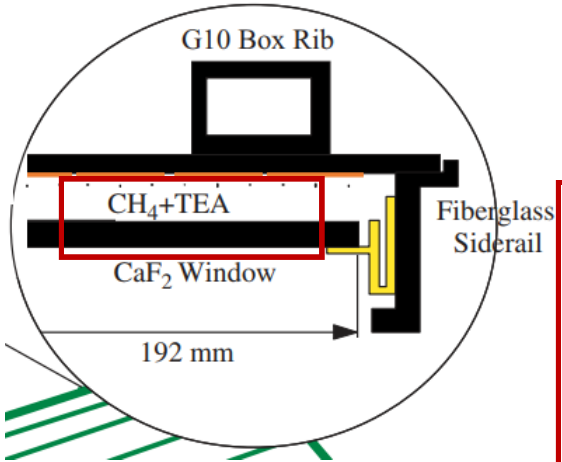
- Photon detector

  - Gaseous chamber: TPC-like / MWPC filled with photoionizing gas (TEA) or photocathode coating (CsI)

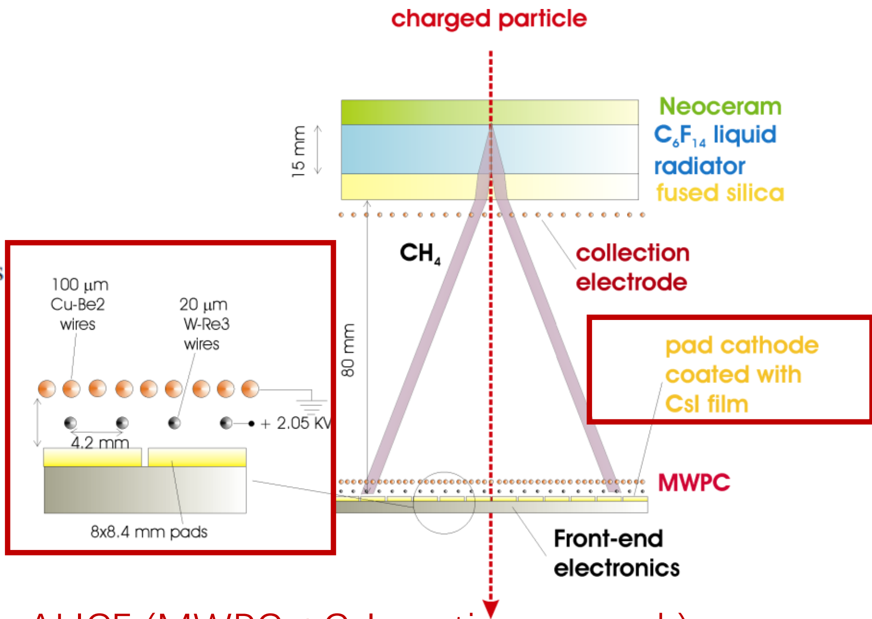
  - PMT: dynode PMT (fine-mesh, metal channel), MCP PMT

  - Hybrid detector: HPD(hybrid photon detector) and HAPD(hybrid avalanche photon detector)

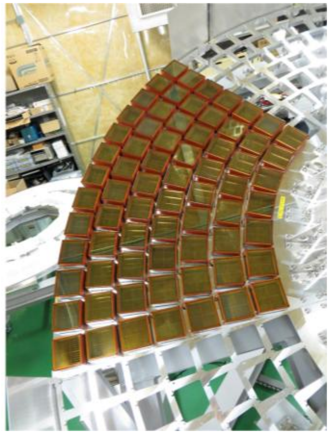
  - SiPM (proposed but not yet used)



CLEO III (MWPC with CH_4 +TEA(triethylamine)

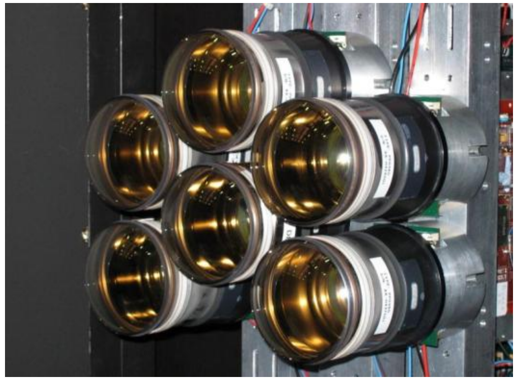


ALICE (MWPC +CsI coating on pad)



Multi-anode HAPD (Belle II endcap)

MCP PMT (Hamamatsu R10754-07-M16), Belle II barrel(iTOP)



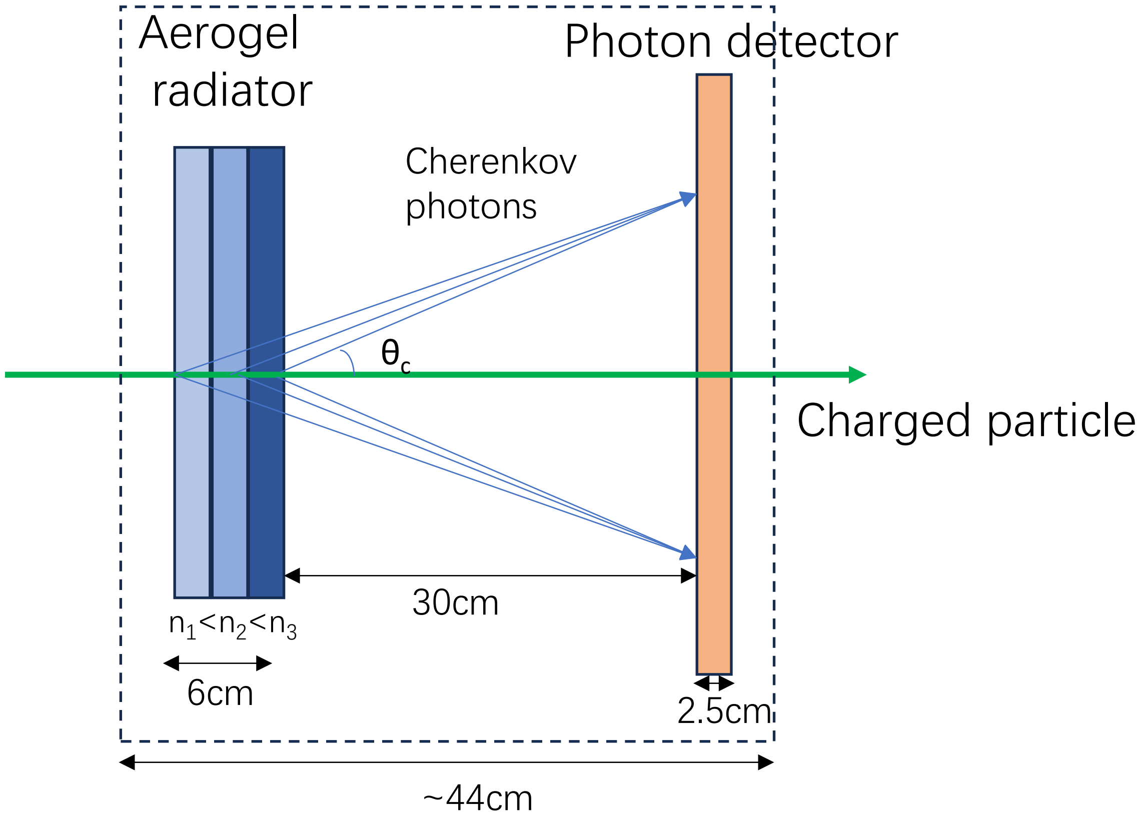
HPD (LHCb RUN1&2)

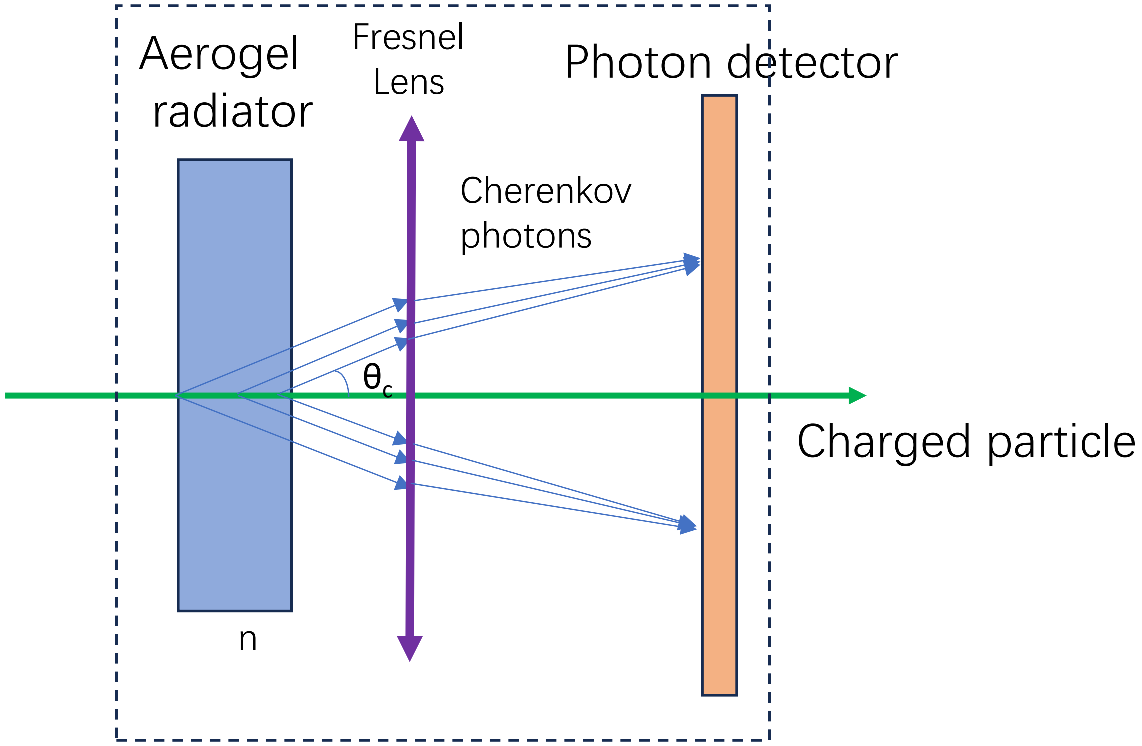
Multi-anode metal-channel dynode PMT (LHCb RUN3)

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

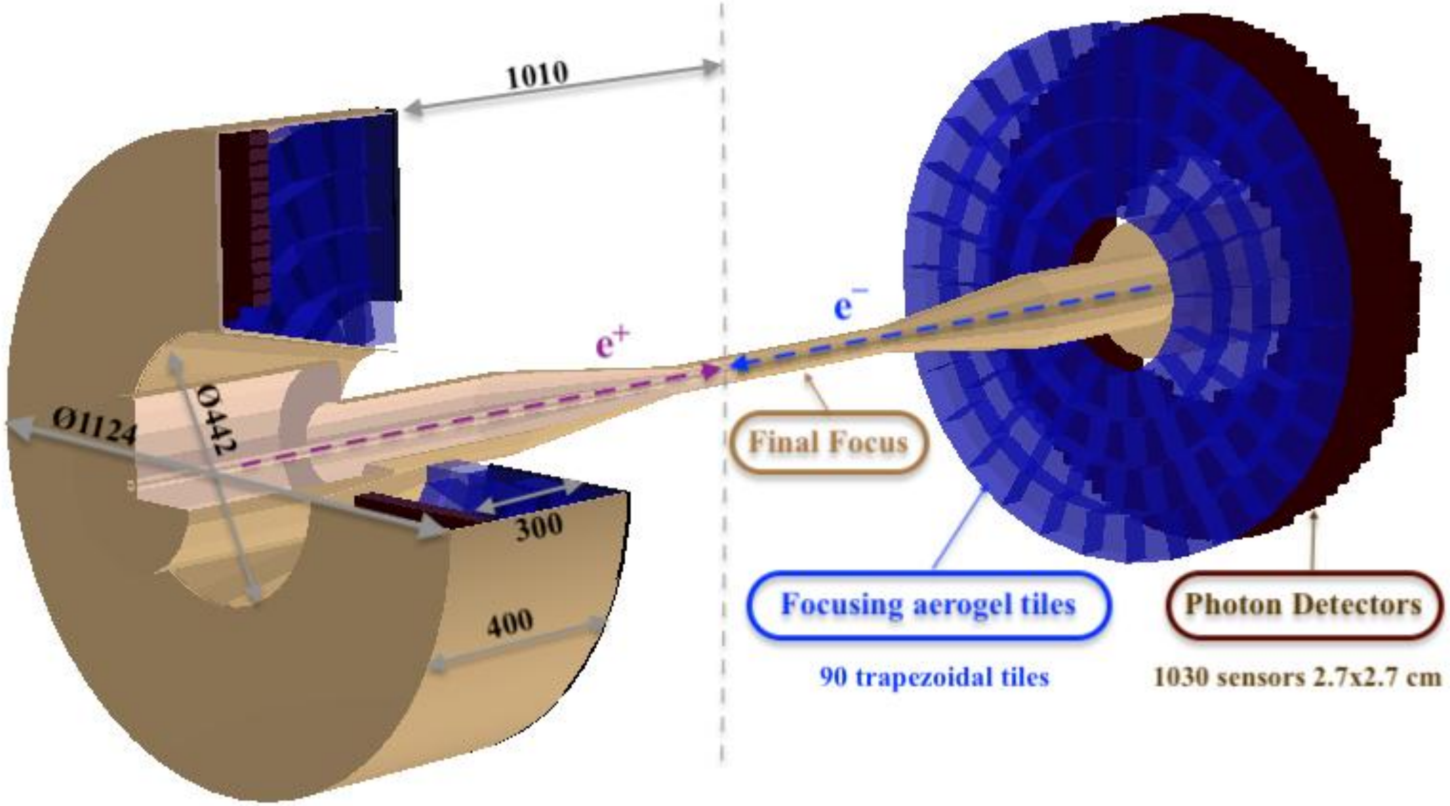


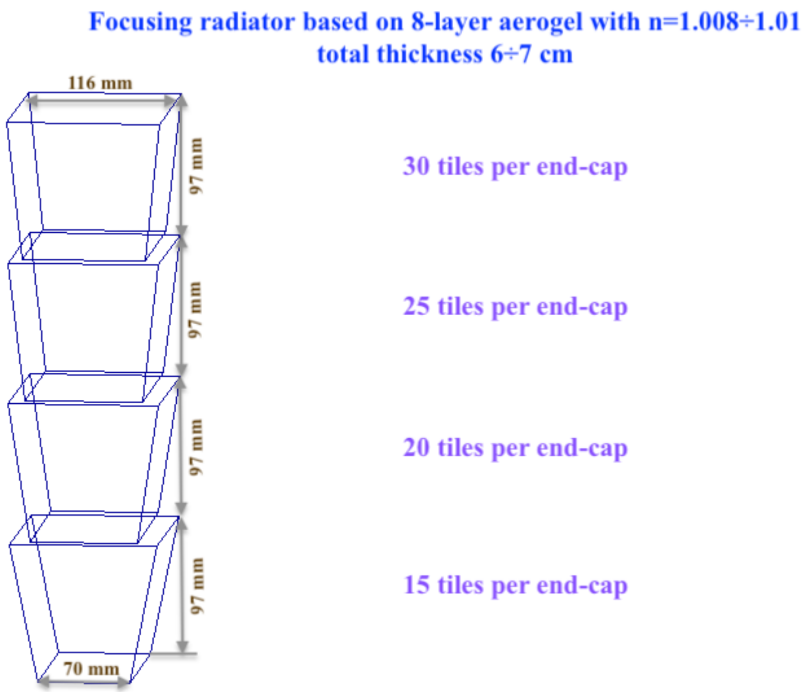


Option1:
Multiple layers of aerogel with varying n, overlapped ring for different emission points

Option 2:
A single layer of aerogel, focused by a Fresnel lens.

A 3D sketch of the Cherenkov detector





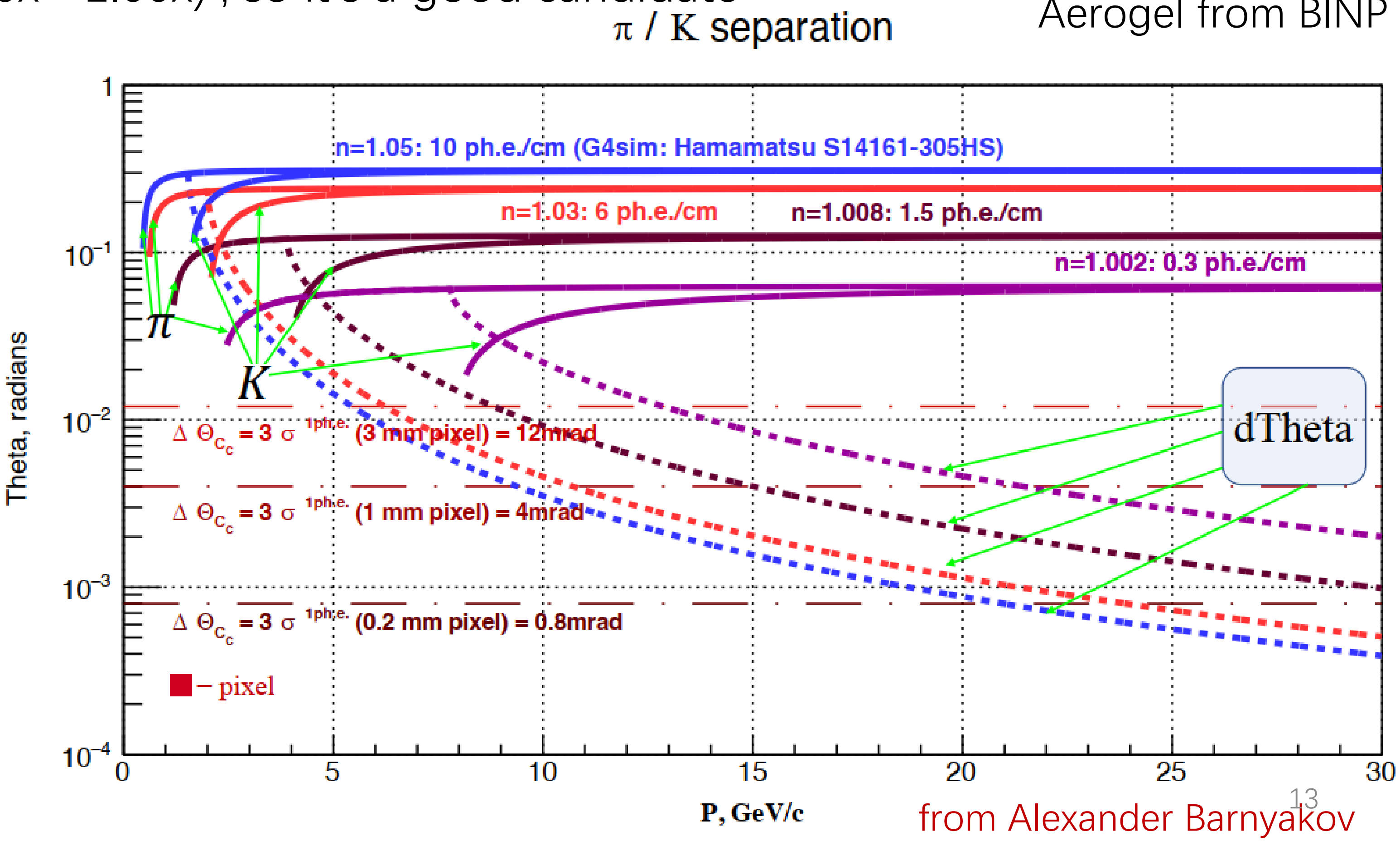
from Alexander Barnyakov, BINP

Why uses aerogel as the radiator

- Generally, to have PID for 3-20 GeV/c:
  - Solid-state/liquid radiator are excluded, due to very large n (1.3 or larger)
  - Gaseous radiator is also not applicable, due to very small n (1.001 or smaller)
  - Aerogel can have adjustable n (1.0x ~1.00x) , so it's a good candidate

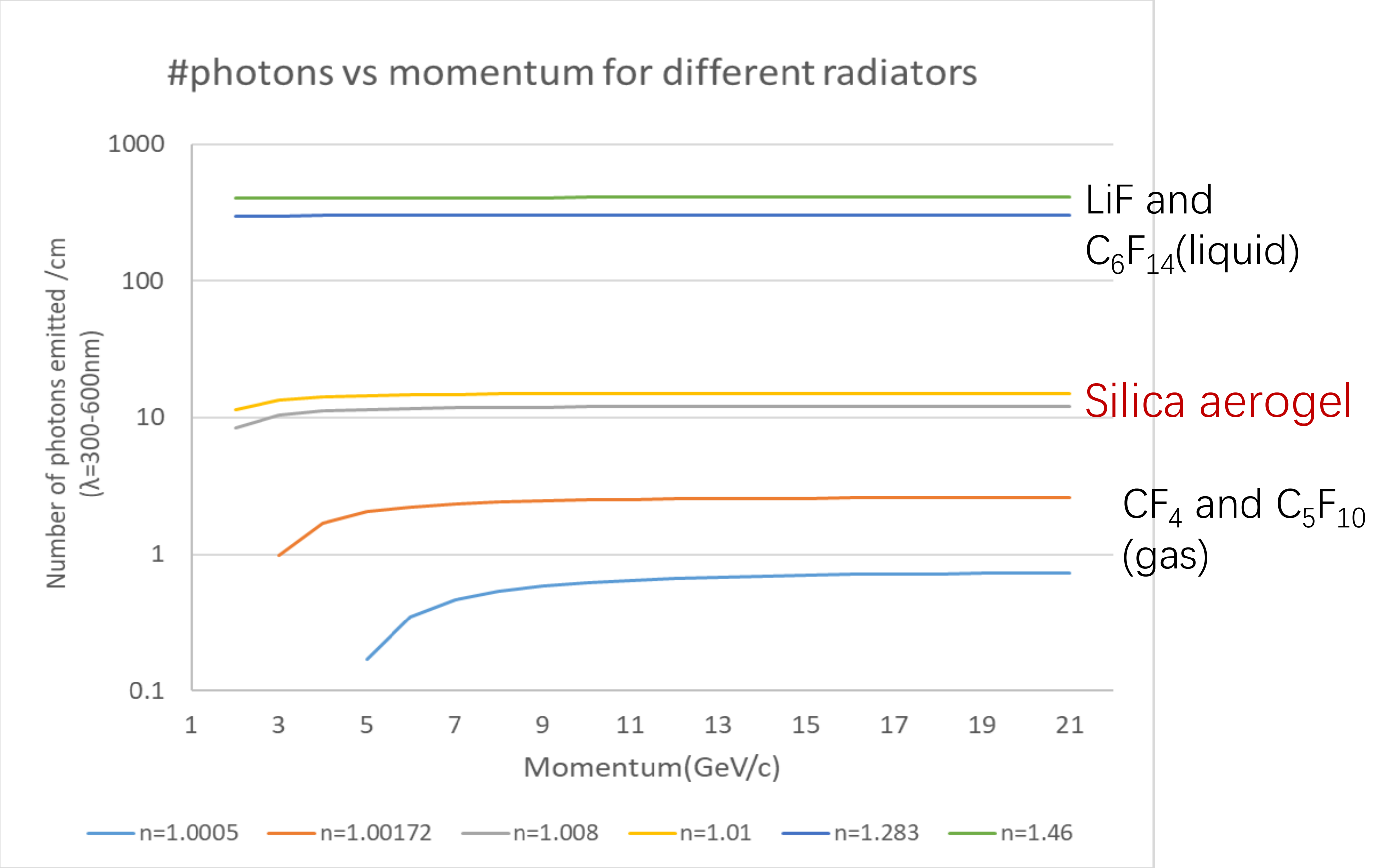
Aerogel from BINP

With aerogel (**n=1.008**) π/K can be separated better than 3σ up to 20GeV/c (if σ_θ^{1pe}< 4mrad)



from Alexander Barnyakov

Some calculation on the number of photons emitted from different radiators



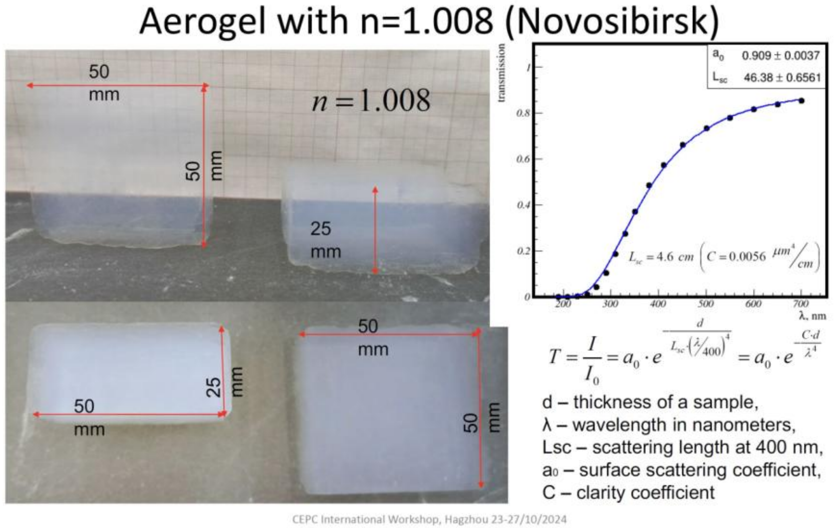
Radiators	Refractive index	Number of photon (p=20GeV, λ= 300-600 nm)
Fused silica, LiF, NaF (solid state)	1.46, 1.392, 1.334	300-400 photons /cm
C_6F_{14} (liquid)	1.283	~300 photons/cm
C_5F_{12}, C_4F_{10}, CF_4, (gaseous)	1.00172, 1.0014, 1.0005,	0.7 – 2.6 photons/cm
Silica Aerogel	1.01 – 1.001 (adjustable)	1.5 -15 photons/cm

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

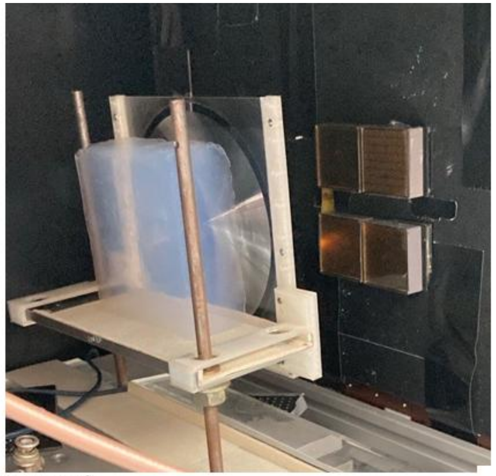
$$\approx 370 \sin^2\theta_c \ (\mathrm{eV}^{-1}\,\mathrm{cm}^{-1})$$

Past and ongoing R&Ds on aerogel

- By Alexander Barnyakov from BINP



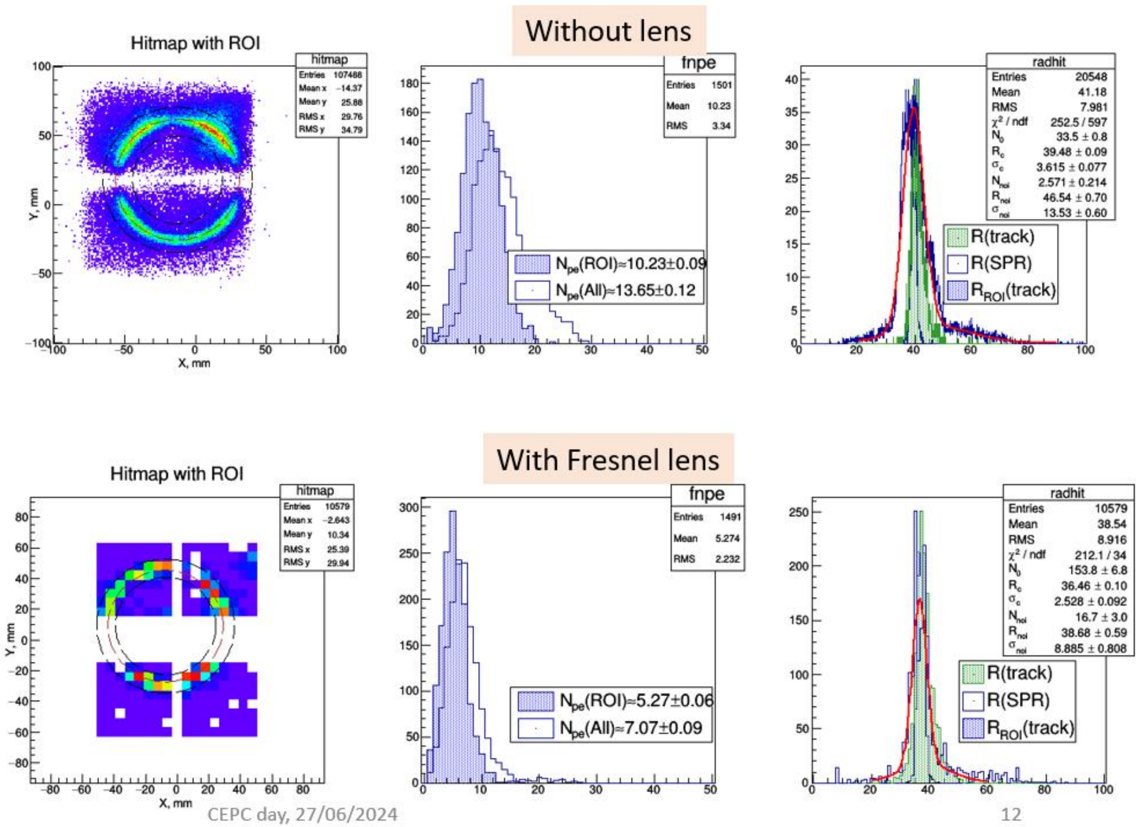
Some results of beam tests at the BINP with mRICH design

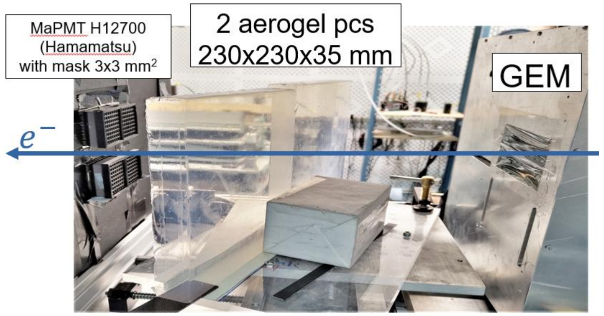


Aerogel:
- n=1.028
- L_{sc}(400nm)=48.2±0.7 mm
- Thickness=40mm

Fresnel lens:
- Acrilic (PMMA)
- L_f=6''
- Manufacturer: Edmund

PMT:
- 4 Hamamatsu H12700
- pixel 6x6 mm





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

Consideration of the photon detector

- General requirements

  -low dark noise/single photon detection capability

  -high detection efficiency

  -high magnetic field tolerance (3 Tesla)

  - small material budget (location inside TPC and ITK)

  - good time resolution (time resolved Cherenkov detector?)

  - relatively good position resolution

  - reasonable cost

  - low risk on construction and operation

- Possible photon sensors

  -Gaseous detector (MWPC, MPGD)

  -PMT(dynode/MCP PMT)

  -HPD/HAPD

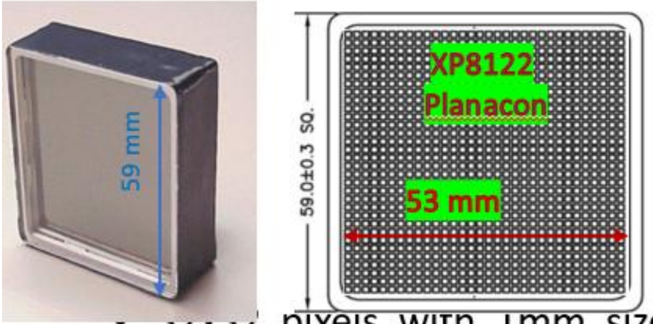
  -SiPM

Past and ongoing R&D for photon detector

- Investigation of the photon sensor (by Xiaolong)

MCP PMT

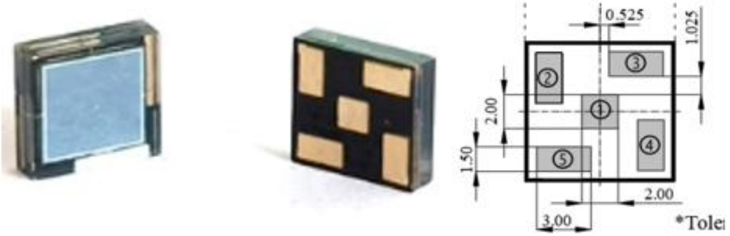
- Planacone XP8122



- 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

$$\sigma_x \approx \frac{1}{\sqrt{12}} \approx 0.3\mu m$$

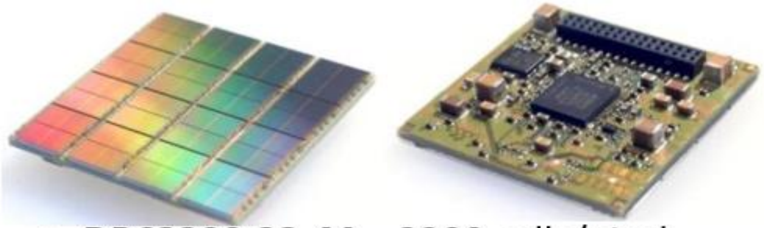
PSS-SiPM or LG-SiPM



- 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:

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

Investigation of MCP PMT as photon sensor

For Belle II, barrel RICH (iTOP)

HAMAMATSU
PHOTON IS OUR BUSINESS

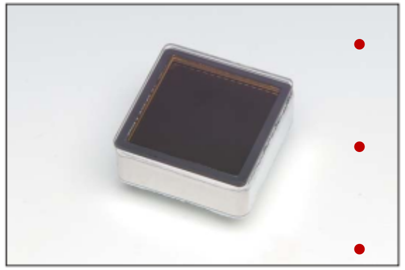
MICROCHANNEL PLATE PHOTOMULTIPLIER TUBE
R10754-07-M16

FEATURES

- 16 matrix multianode
- Small dead space
- Fast time response
- High magnetic field immunity
- Long life time

APPLICATIONS

- High energy physics
- Multichannel time resolved fluorescence detection measurement
- Light detection and ranging



SPECIFICATIONS

GENERAL

Parameter		Description / Value	Unit
Spectral response		160 to 850	nm
Wavelength of maximum response		380	nm
Window material		Synthetic silica	—
Photocathode	Material	Multialkali	—
	Minimum effective area	23 × 23	mm
Dynode	Dynode structure	2 stages Microchannel plate	—
	Channel diameter	10	μm
Number of anode pixels		16 (4 × 4 matrix)	—
Anode pixel size		5.28 × 5.28	mm
Operating ambient temperature Ⓐ		-30 to +45	°C
Storage temperature Ⓐ		-30 to +50	°C

MAXIMUM RATINGS (Absolute maximum values)

Parameter		Value	Unit
Supply voltage	Between anode and cathode	2700	V
Average anode current		2	μA

CHARACTERISTICS (at 25 °C, 2200 V)

Parameter		Min.	Typ.	Max.	Unit
Cathode sensitivity	Luminous (2856 K)	80	110	—	μA/lm
	Blue sensitivity index	—	7.5	—	—
Anode luminous sensitivity		22	110	—	A/lm
Gain		—	1×10^6	—	—
Dark current (After 30 minutes storage in darkness)		—	5	30	nA
Time response	Rise time	—	195	—	ps
	Fall time	—	310	—	ps
	Width	—	400	—	ps
	T.T.S. (FWHM) Ⓑ	—	75	—	ps

Ⓐ No condensation
Ⓑ Transit-time spread (T.T.S.) is the fluctuation in transit time between individual pulse and specified as an FWHM (full width at half maximum) with the incident light having a single photoelectron state. This value includes the jitter of the electronics about 30 ps.

VOLTAGE DISTRIBUTION RATIO AND SUPPLY VOLTAGE

Electrode	K		1st MCP-in		1st MCP-out		2nd MCP-in		2nd MCP-out		P
Distribution ratio		1		5		5		5		3	

Supply voltage: 2200 V, K: Cathode, P: Anode

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- Effective area: 23mm x 23mm
- Anode matrix: 4 x 4
- Anode size: 5.28mmx5.28mm
- QE: ~20%
- TTS（FWHM): 75ps
- HV: 2.7kV

N6021光电倍增管 N6021 MCP−PMT

“FPMT”，NNVT&IHEP

应用领域 Application

医学影像/Specialized Medical Imaging
Cherenkov – RICH, TOF, TOP, DIRC
高能物理/High Energy Physics
国土安全/Security

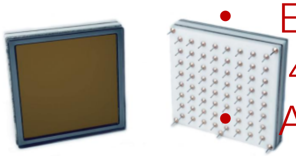
产品特点 Features

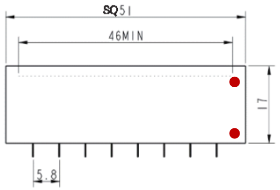
响应快 High Speed
增益高 High Gain
噪声低 Low Noise

技术参数 Specifications

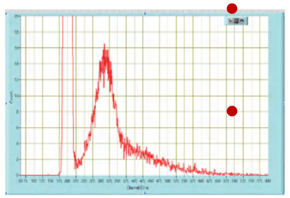
玻璃材料/Window material	AVG glass
光电阴极/Photocathode material	双碱/Bialkali
倍增结构/Multiplier structure	2片微通道板型/2 MCP
阳极结构/Anode structure	8 ×8

N6021		Min.	Typ.	Max.	Unit
阴极参数 Cathode parameters	光谱范围/Spectral response		280−650		nm
	量子效率峰值波长/Quantum efficiency peak wavelength		380		nm
	积分灵敏度/Luminous sensitivity		60		μ A/lm
	量子效率@410nm/QE @410nm		21		%
	辐射灵敏度/Radiant sensitivity@410nm		72		mA/W
阳极参数 Anode parameters	工作电压/Supply voltage		2000	2500	V
	增益/Gain		2×10^6		
	暗计数/Dark count rate@0.2pe(单阳极)		500	5000	Hz
	能量分辨率/Charge resolution		35		%
	单光电子谱峰谷比/Peak to valley ratio		3		
时间参数 Time response	上升时间/Rise time		300		ps
	脉冲宽度/Pulse width		650		ps
	下降时间/Fall time		800		ps
	渡越时间弥散/TTS@ σ (SPE)		50		ps
	渡越时间弥散/TTS@ σ (MPE)		15		ps
工作环境温度/Operating ambient temperature			−30~+50		℃
储藏温度/Storage temperature			−50~+50		℃

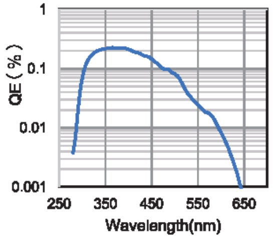




N6021 光电倍增管外型结构
N6021 PMT dimentional outline



典型单光电子谱
Typical single photoelectron spectrum



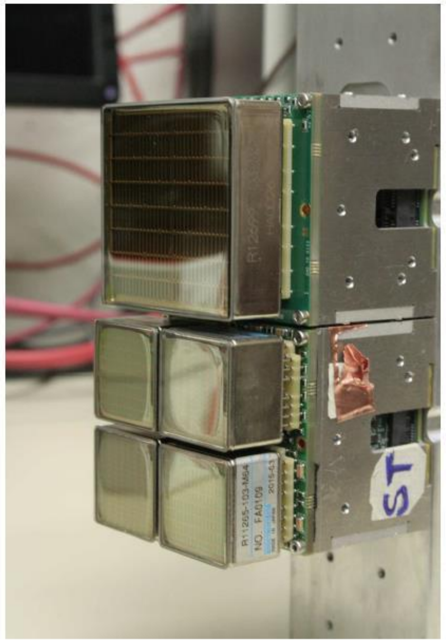
典型光谱响应曲线
Typical spectral response chara

- Effective area: 46mm x 46mm
- Anode matrix: 8 x 8
- Anode size: 5.75mmx5.75mm
- QE: 21%
- TTS (σ) : 15ps(MPE) 50ps(SPE)
- dark noise rate: 500 Hz/anode
- HV: 2 kV

Investigation of Multi-anode Dynode PMT

For LHCb RUN3

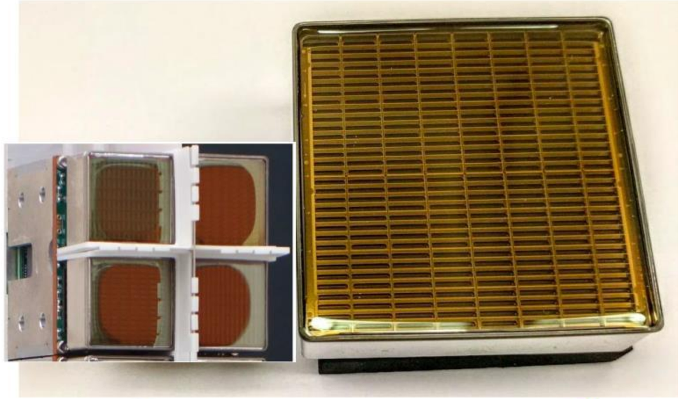
- Effective area:
  23mm x 23mm (1”) or
  46mm x 46 mm (2”)
- Anode matrix: 8 x 8
- Anode size:
  2.88mm x 2.88mm
  or 5.76mmx5.76mm
- QE: 35%
- High voltage: 1.1 kV

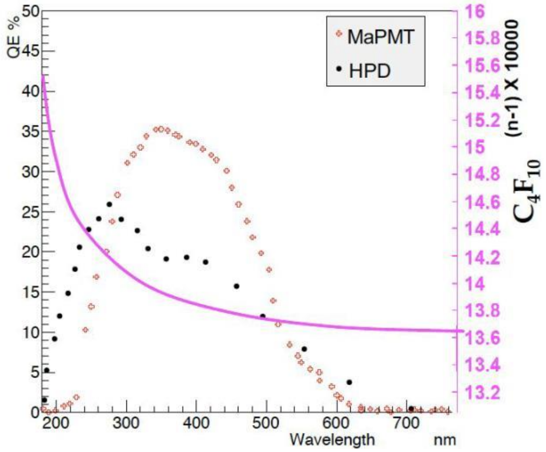


MultiAnode PhotoMultipliers

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





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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

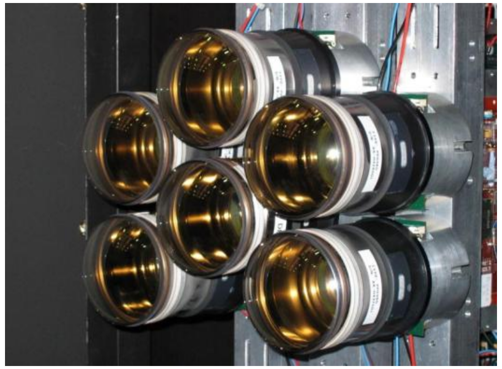
Parameter		Description	Unit
Spectral Response Range		185 to 650	nm
Peak Wavelength		350	nm
Photocathode Material		Bialkali	-
Window	Material	UV Glass	-
	Thickness	0.8	mm
Dynode	Structure	Metal Channel Dynode	-
	Number of Stage	12	-
Anode	Number of Pixels	64 (8 x 8 Matrix)	-
	Pixel Size	2.88 x 2.88	mm
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

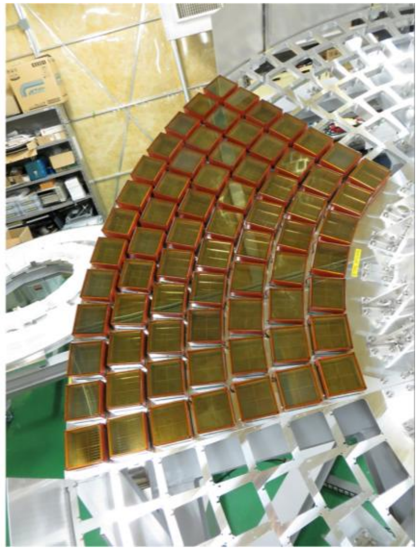
Type No.	Spectral response	Photocathode	Window material	Window type	Effective area	T.T.S. (Transit Time Spread) *1 (FWHM)
R14713U-07	220 nm to 870 nm	Multialkali	Synthetic silica	Plano-concave	ϕ3 mm	20 ps

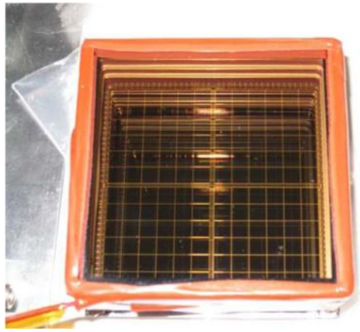
●H13223-40

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 (λ = 400 nm)	28%	≥24%
Bias Voltage	250–500 V	
High voltage	−8.5 kV	
Dark current (bias)	1–100 pA	<1 μ A / channel
Dark current (HV)		<300 pA
Avalanche gain	40	>30
Bombardment gain	1800	>1500
Number of bad channels		≤10

A preliminary summary of photon detector

Photon detector types	Quantum efficiency	Spatial resolution	Dark noise rate	Time resolution	Magnetic field tolerance	Radiation tolerance	Material budget	Cost estimation	Risk on construction &operation
Gaseous chamber (MWPC, MPGD)	poor (~28% at VUV region, 160-170nm)	good (~1-2 mm, charge centroid method)	good (~1 Hz/cm^2)	poor (~1-50 ns)	poor (due to charged particles drifting)	good (no silicon)	good (~4% X0)	Good (several 10 RMB/cm^2)	poor (complex with gas, high voltage, pho-tocathode)
PMT (dynode or MCP PMT)	medium (~20-35% at 400nm)	medium (~3-5 mm with multi-anode)	good (~5-100 Hz/cm^2)	medium for dynode(~200-500ps); good for MCP(<50ps)	medium (specially designed dynode or MCP)	good (no silicon)	poor (~10% X0)	poor (~1000 RMB/cm^2)	good (simple for construction and running)
HPD and HAPD	medium (~25-30 % at 400 nm)	medium (~2.8-6 mm with multi-anode)	medium (~2.5-5 KHz/cm^2)	medium (~50-200ps)	medium (with high voltage)	medium (partially silicon)	poor (~10% X0)	poor (~1000 RMB/cm^2)	medium (high voltage 8-20kV needed)
SiPM	good (~45-50% at 400nm)	medium (~3-6 mm depending on the size)	poor (~10 MHz /cm^2, room temperature)	medium (~50-100ps)	good (small thickness)	poor (atom displace-ment)	good if no cooling (~4% X0); poor if with cooling (~10% X0)	medium if no cooling (~100 RMB/cm^2); poor with cooling	good (simple for construction and running)

- No clear conclusion, need more investigation

Summary and next step

- A Cherenkov detector for CEPC will be beneficial even though it's challenging
- Some consideration and design for the Cherenkov detector have been done but at early stage.
- R&D on aerogel from Russia group is helpful
- More investigation on photon detector is needed
- A lot of things (mechanical supporting, cooling, cabling, readout electronics, etc.) need to be considered

Thanks a lot to Xiaolong, Jianchun and Alexander Barnyakov for useful discussion and input !