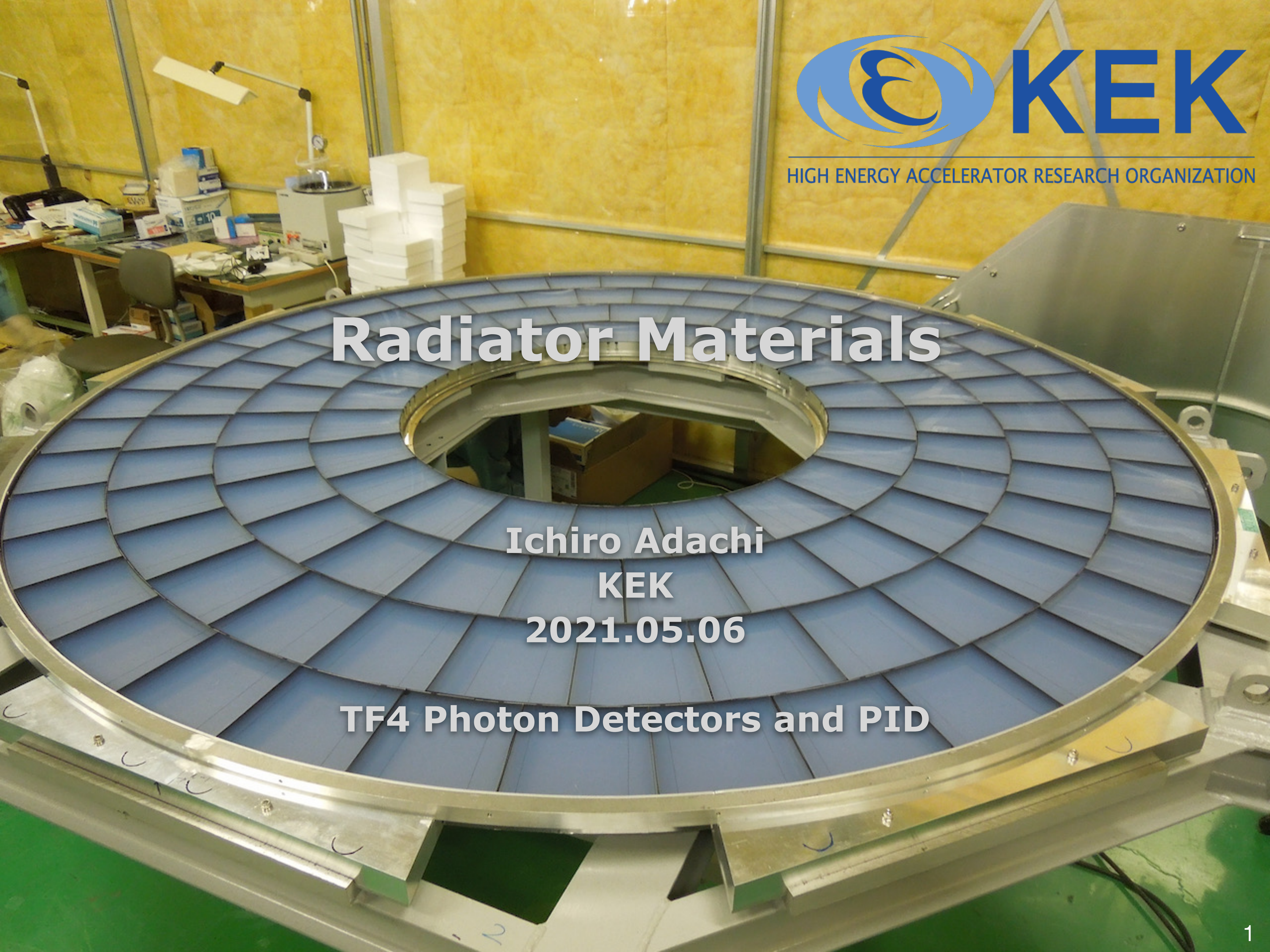


KEK
HIGH ENERGY ACCELERATOR RESEARCH ORGANIZATION

Radiator Materials

Ichiro Adachi
KEK
2021.05.06

TF4 Photon Detectors and PID

Radiator Requirements

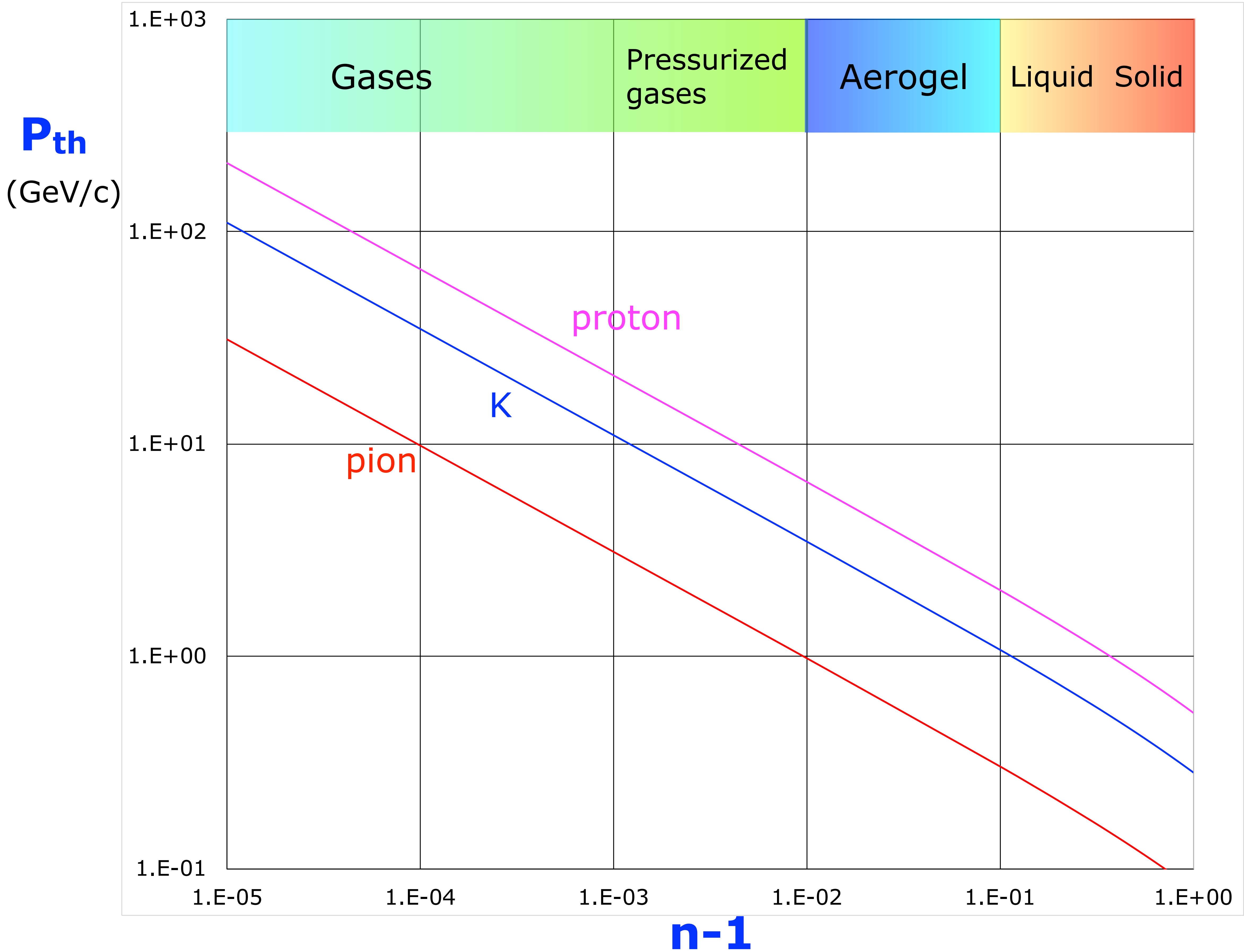
- RICH radiator material is selected to match your requirements:
  - Momentum range
  - Particle species

Cherenkov radiation

Threshold momentum P_{th} is related to refractive index (n) of radiator medium and incident particle mass (m) .

$$P_{th} = \frac{m}{\sqrt{n^2 - 1}}$$

Radiator defines refractive index, giving us threshold momentum


Gases
Pressurized gases
Aerogel
Liquid
Solid
Pth
(GeV/c)
1.E+03
1.E+02
1.E+01
1.E+00
1.E-01
proton
K
pion
1.E-05
1.E-04
1.E-03
1.E-02
1.E-01
1.E+00
n-1

Radiator Requirements

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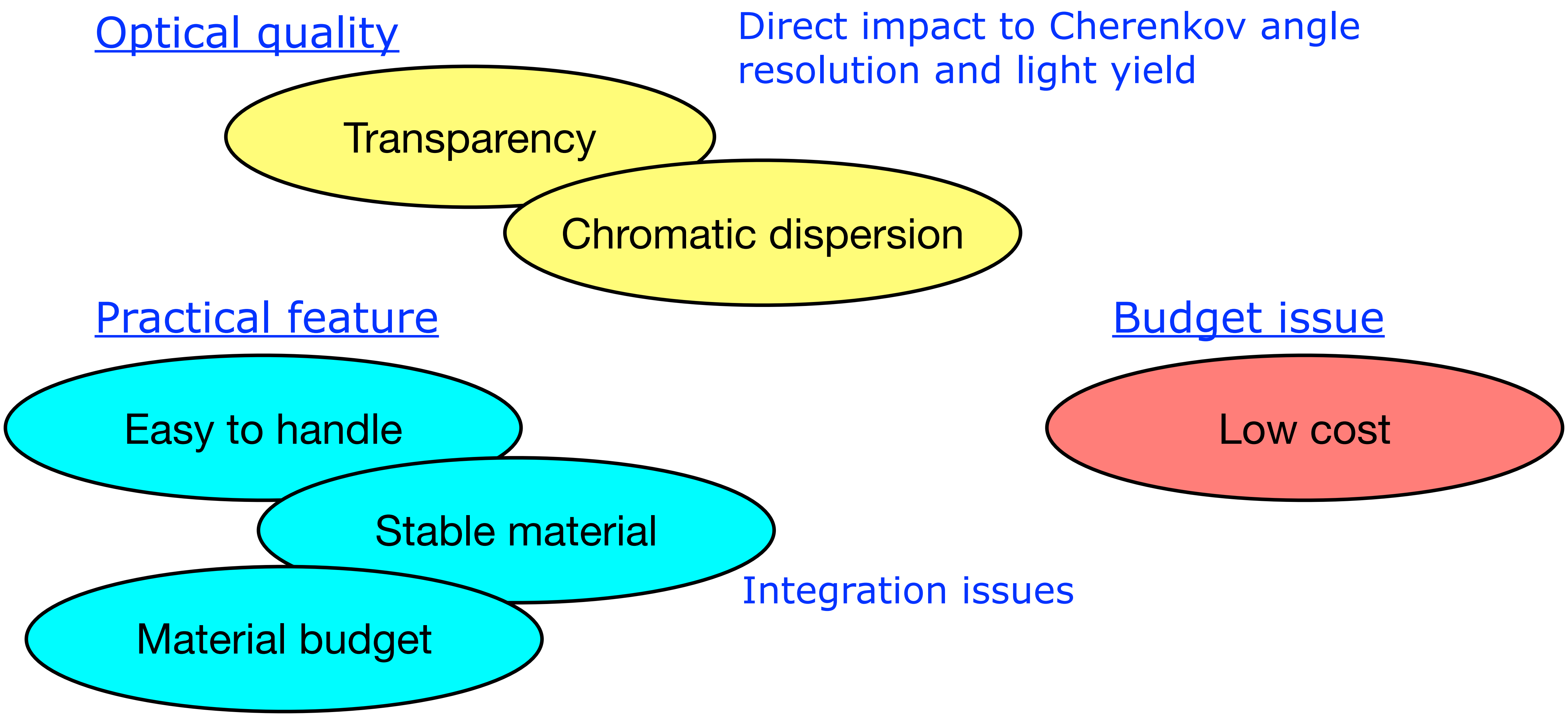
  - Particle species

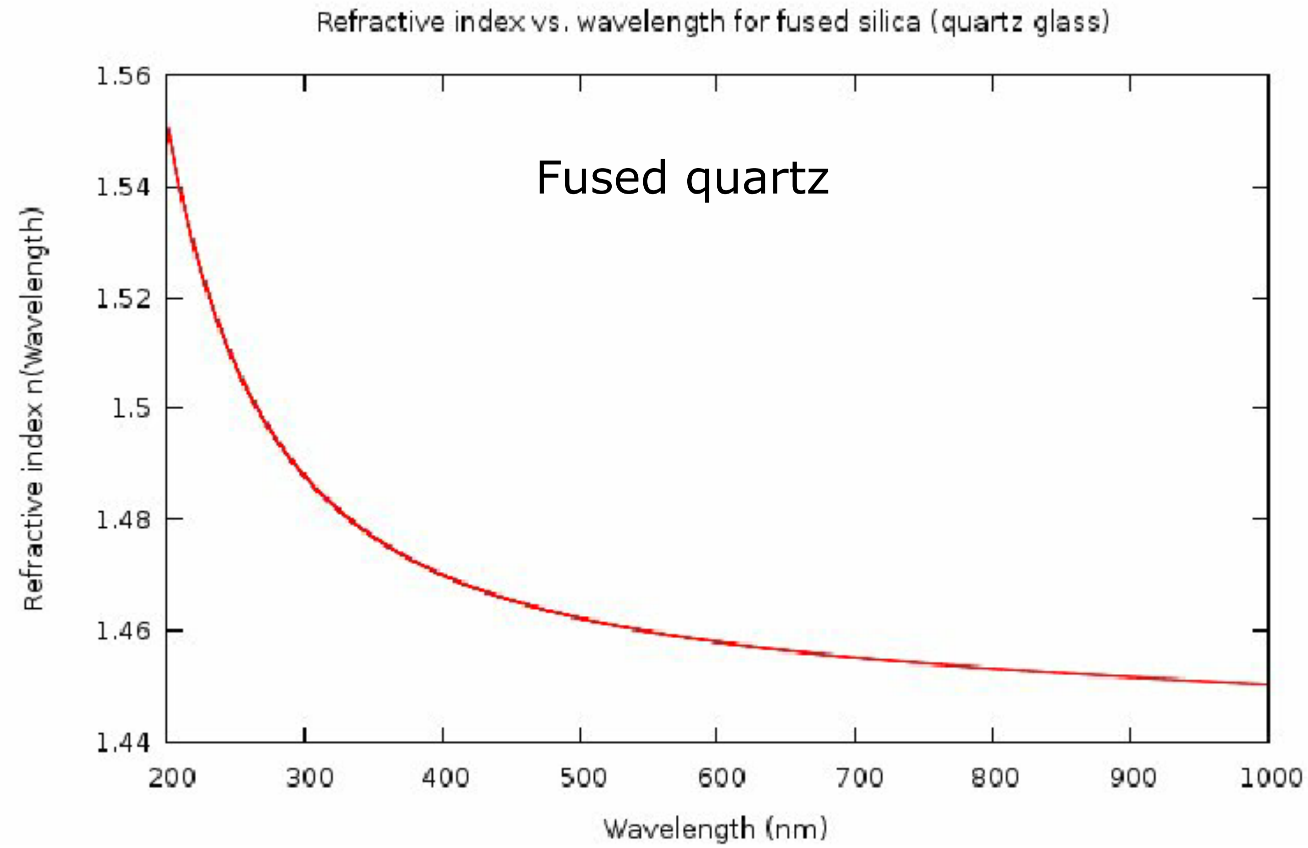


Chromatic Dispersion

Chromatic dispersion : approximated Cauchy's equation

$$n(\lambda) \simeq A + \frac{B}{\lambda^2}$$

n : refractive index of medium
λ : photon wave length
A and B : constants



In case of $\delta n = n - 1 \ll 1$

$$\frac{dn}{dE} \propto (n-1)^2 \cdot E$$
$$= \delta n^2 \cdot E$$

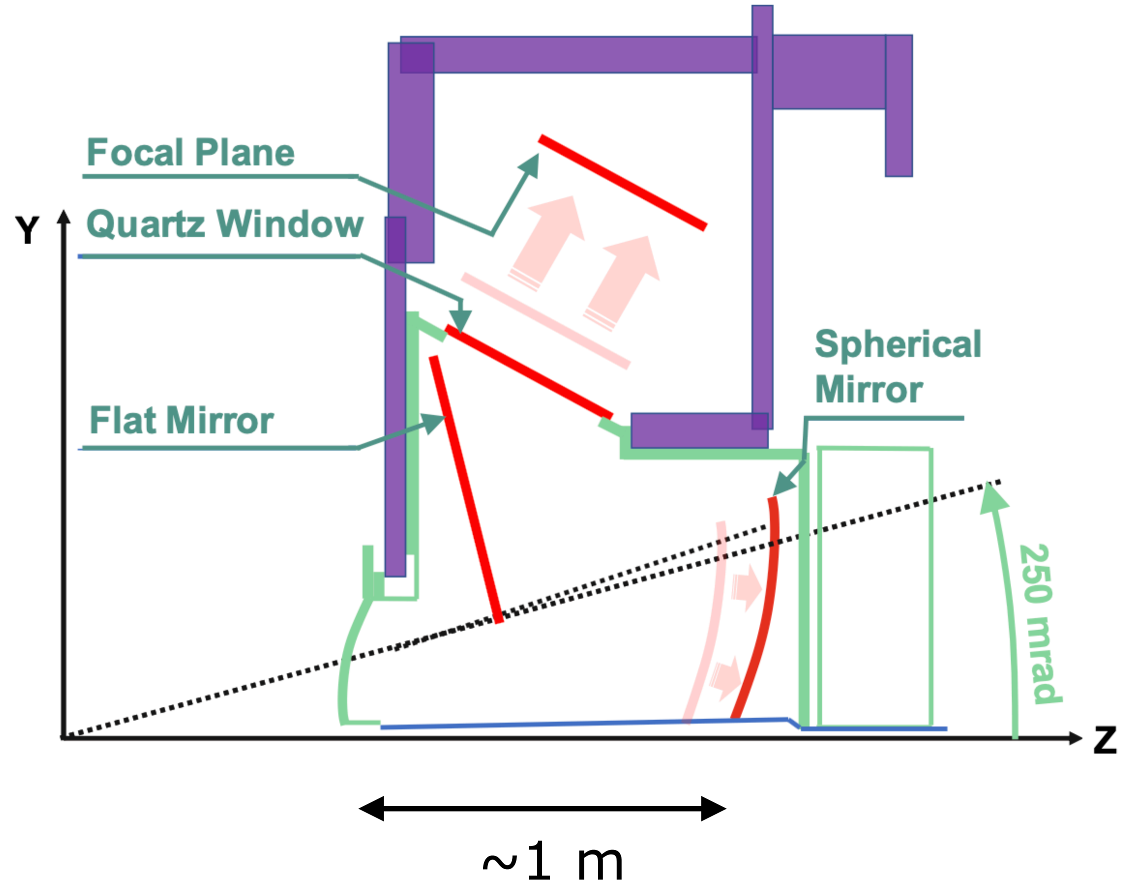
E : photon energy

Limit wavelength range ->
Good balance between light yield
and chromatic error

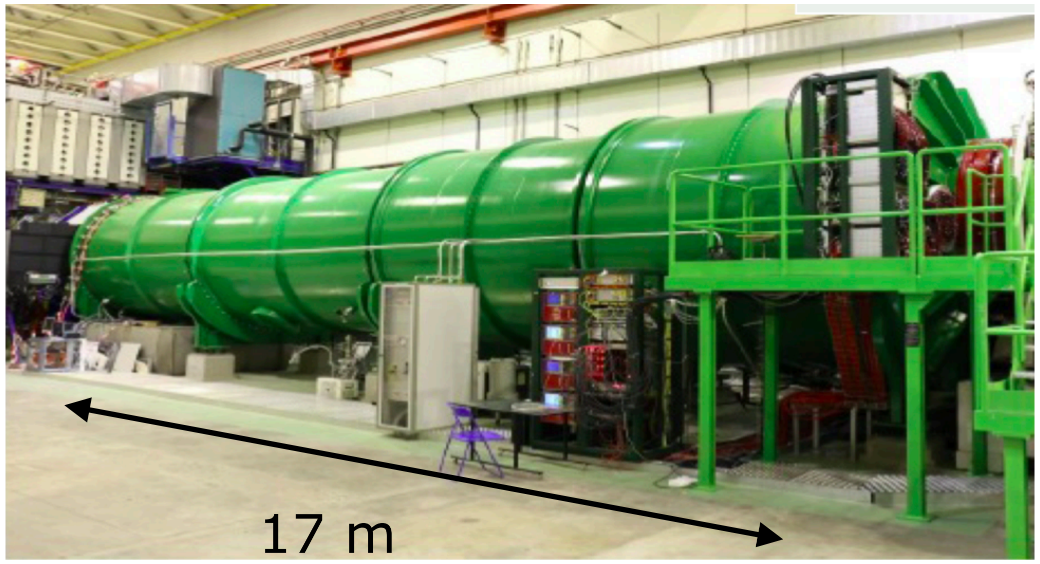
Gas Radiator

- PID for wide momentum range with small chromatic dispersion.
- Gas radiator requires big volume O(10-100m^3) to get Cherenkov light yield enough to show good PID performance.
  - Mirrors are used to guide the emitted photons to the photon sensor plan in a proper way.
  - Gas-tight enclosure has to be produced. An exit window is usually is equipped, depending on optics.

LHCb RICH1



Radiator vessel at NA62



Typical Gas Radiators

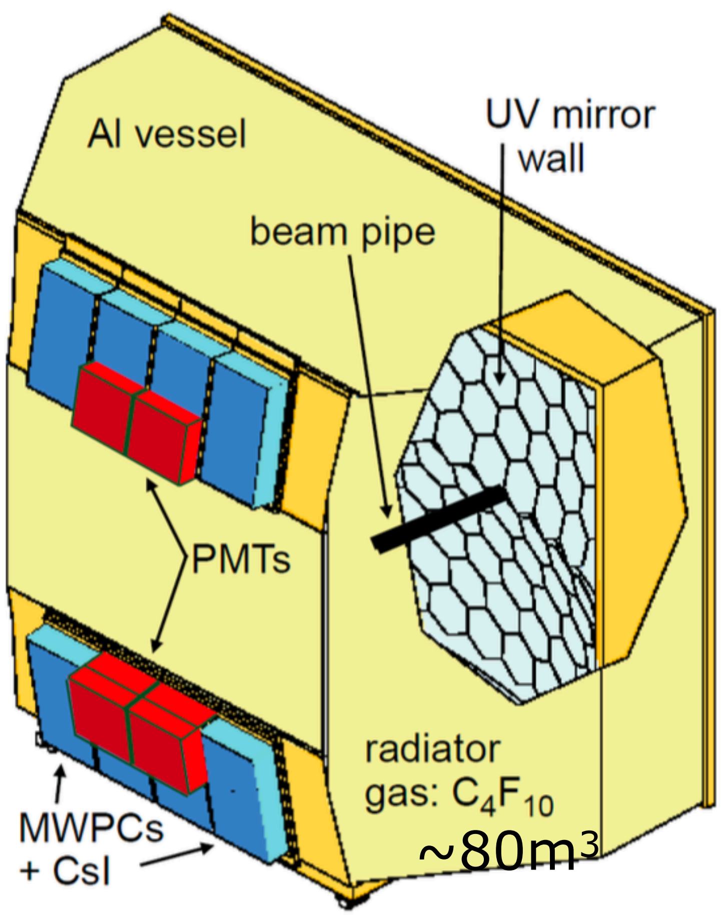
Gas	Refractive index	P_{th}(pion)	P_{th}(kaon)	P_{th}(proton)	Experiment
C_4F_{10} Perflourobutane	1.0014	2.6 GeV/c	9.3 GeV/c	17.7 GeV/c	LHCb RICH1 COMPASS RICH1
CF_4 Carbon Tetrafluoride	1.0005	4.4 GeV/c	15.6 GeV/c	29.7 GeV/c	LHCb RICH2
C_2F_6 Hexafluoro-ethane	1.0008	1.1 GeV/c	3.9 GeV/c	7.4 GeV/c	Dual RICH at EIC
Neon	1.000063	12.4 GeV/c	44.0 GeV/c	83.6 GeV/c	NA62

Radiator Transparency

The COMPASS RICH1 radiator gas C_4F_{10} should be kept transparent for UVU range (160-220 nm) because of CsI photocathode sensitivity

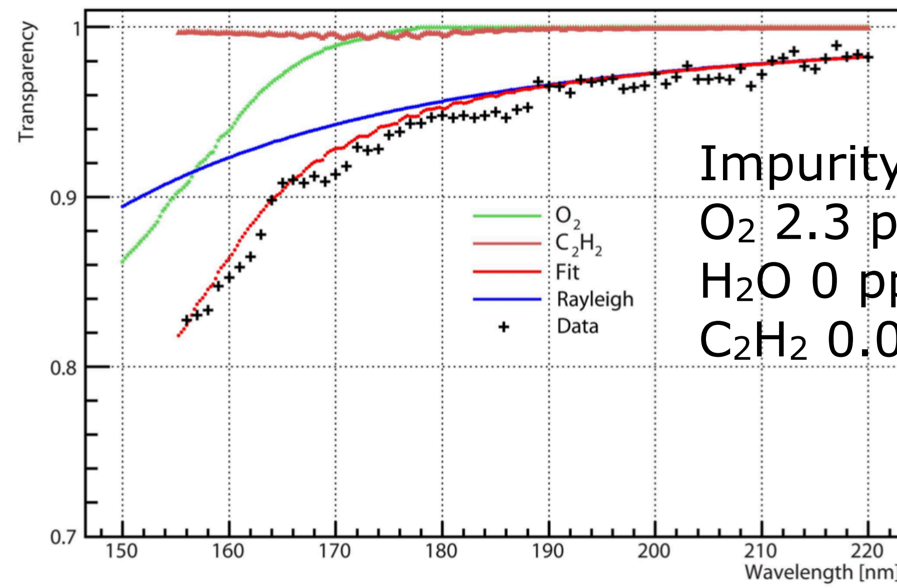
Gas is circulated in a closed loop (at a rate of $2m^3/h$) with Cu catalyst filter and 5A molecular sieves, achieving H_2O < 1 ppm O_2 < 3 ppm

2014 JINST9 C09011
NIM A502(2003)266

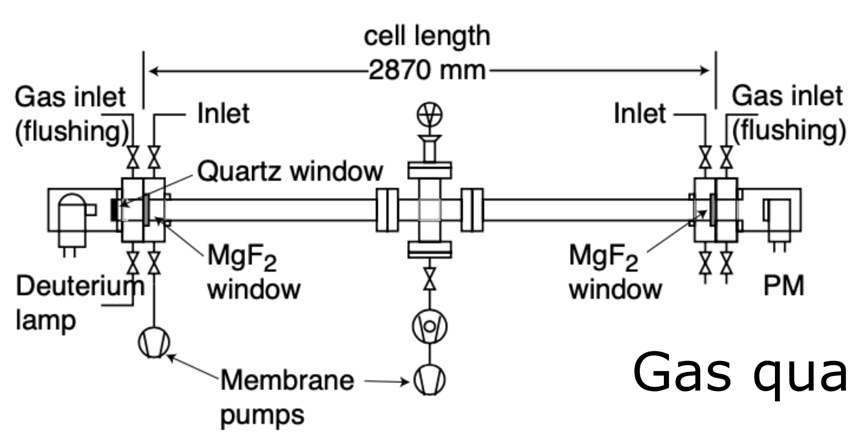


COPASS RICH1

C_4F_{10} transparency monitored



Impurity level
O_2 2.3 ppm
H_2O 0 ppm
C_2H_2 0.03 ppm



Gas quality set-up for VUV light

Radiator Transparency

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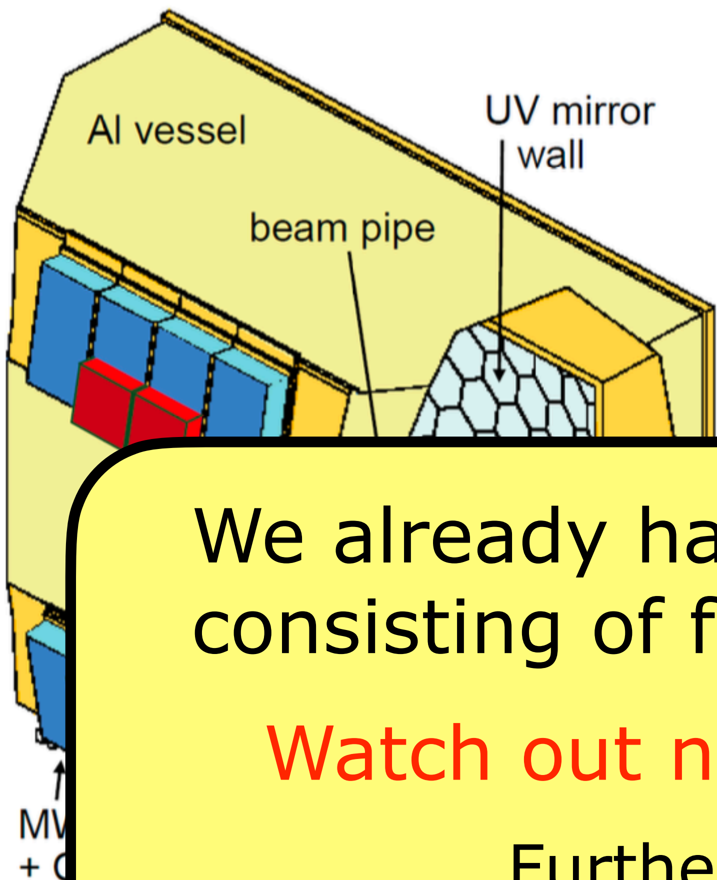
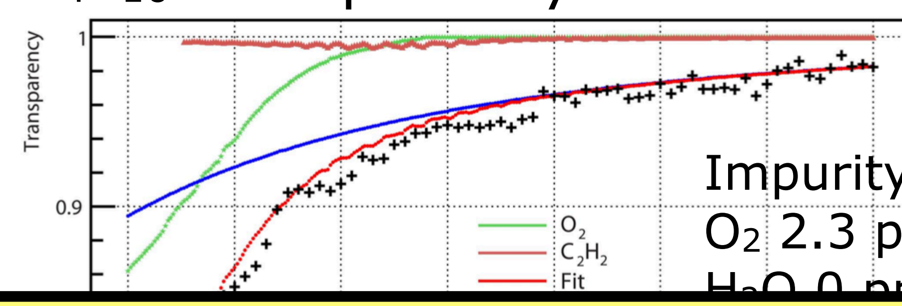


C_4F_{10} transparency monitored

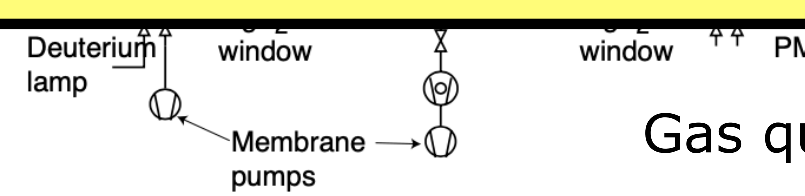


Impurity level
O_2 2.3 ppm

We already have good peripheral systems consisting of filter, oil-free compressor etc…

Watch out new products from industry

Further better performance
Compactness…



Gas quality set-up for VUV light

Refractive Index Monitoring

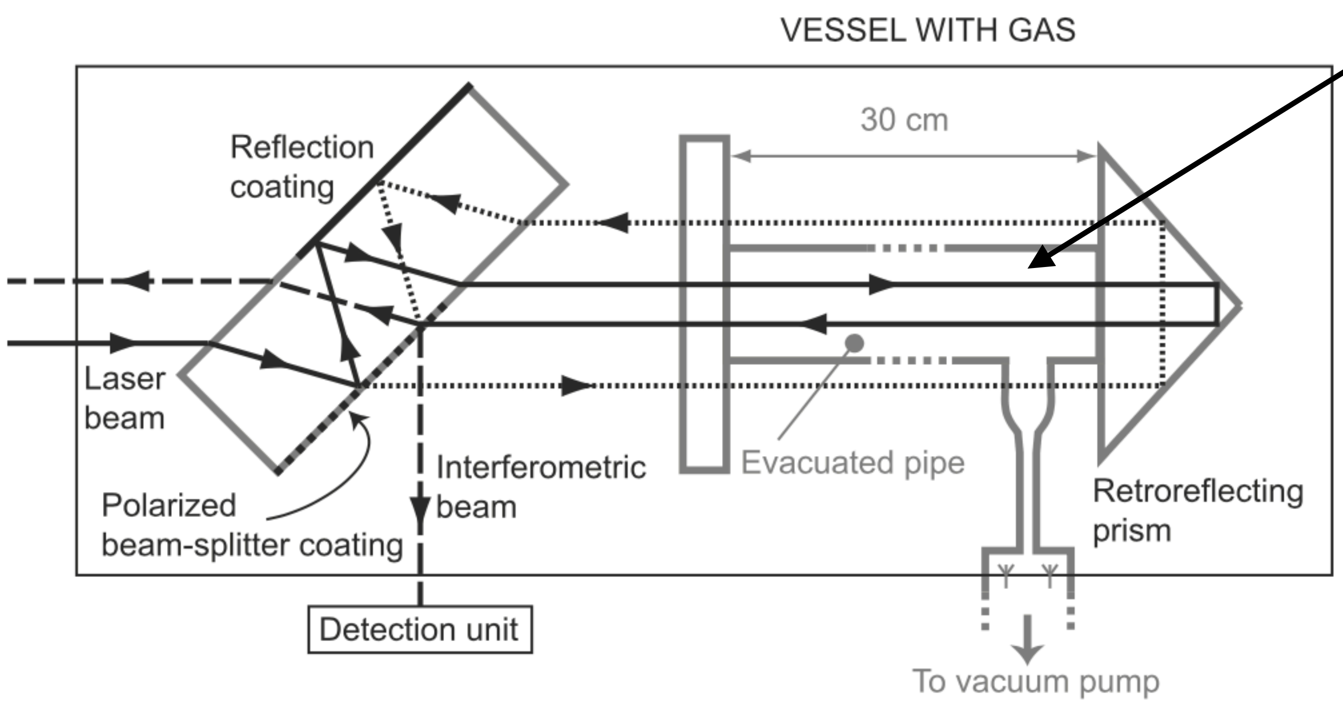
- Refractive index of gas depends on pressure(p), temperature(T), and impurities level(c) and it can be expressed by:

NIM A639(2011)271

$$n(\lambda, p, T, c) - 1 = K(\lambda) \cdot \rho(p, T, c)$$

- Monitoring refractive index (n) by the Jamin interferometer at COMPASS RICH1. Measurement of n can be done with accuracy of 10^{-6}

C_4F_{10} or vacuum

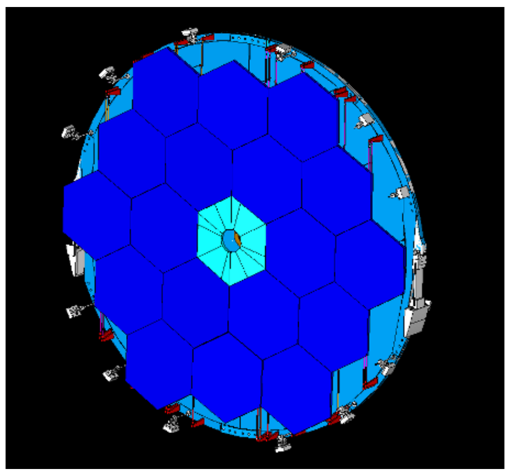


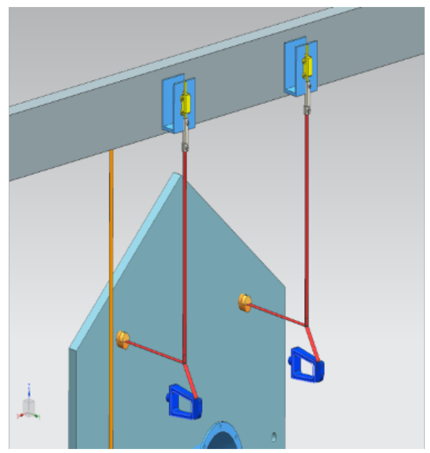
Mirror Alignment

NA62

NIM A952(2020)162005

20 spherical mirrors supported by a dowel.
Piezo motors control their orientation remotely
Alignment in offline analysis

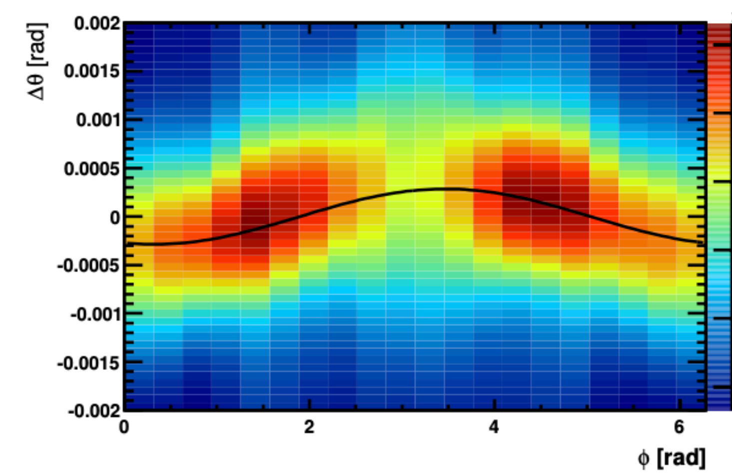




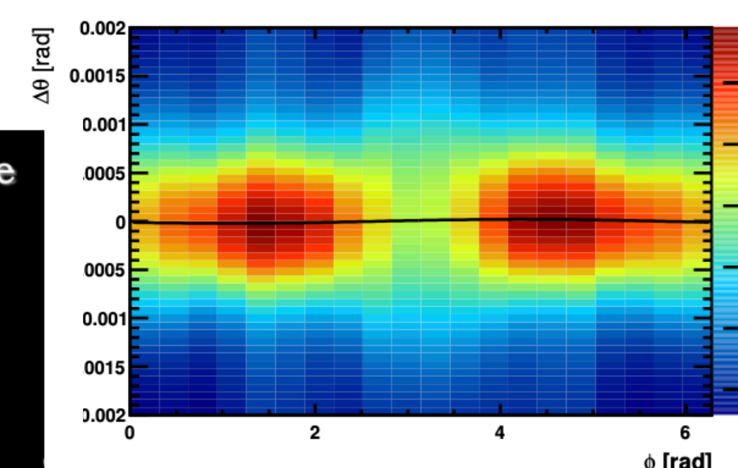
LHCb RICH1

NIM A952(2020)161882

Alignment study in offline data



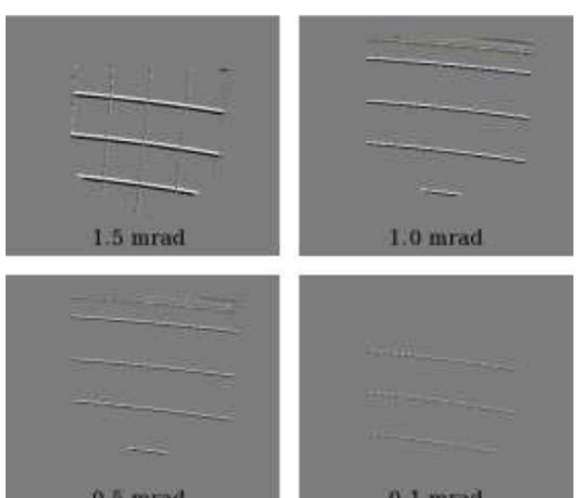
Before

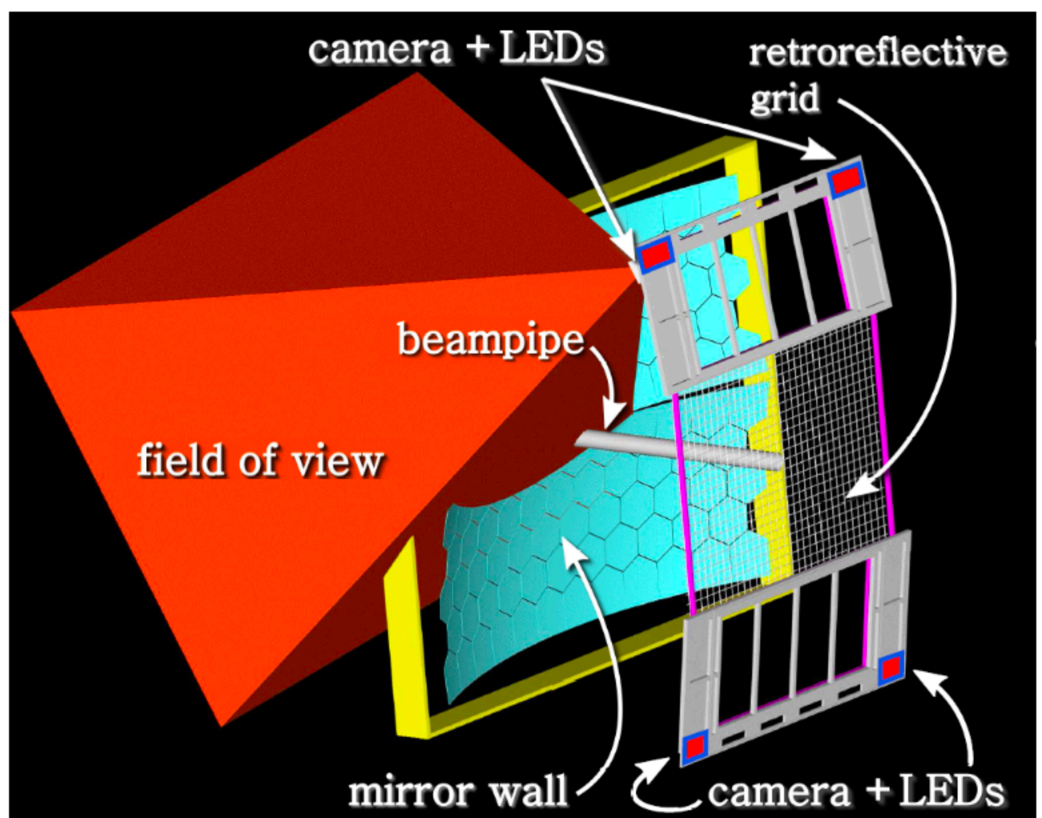


After

COMPASS RICH1

CLAM (Continuous line alignment) introduced.





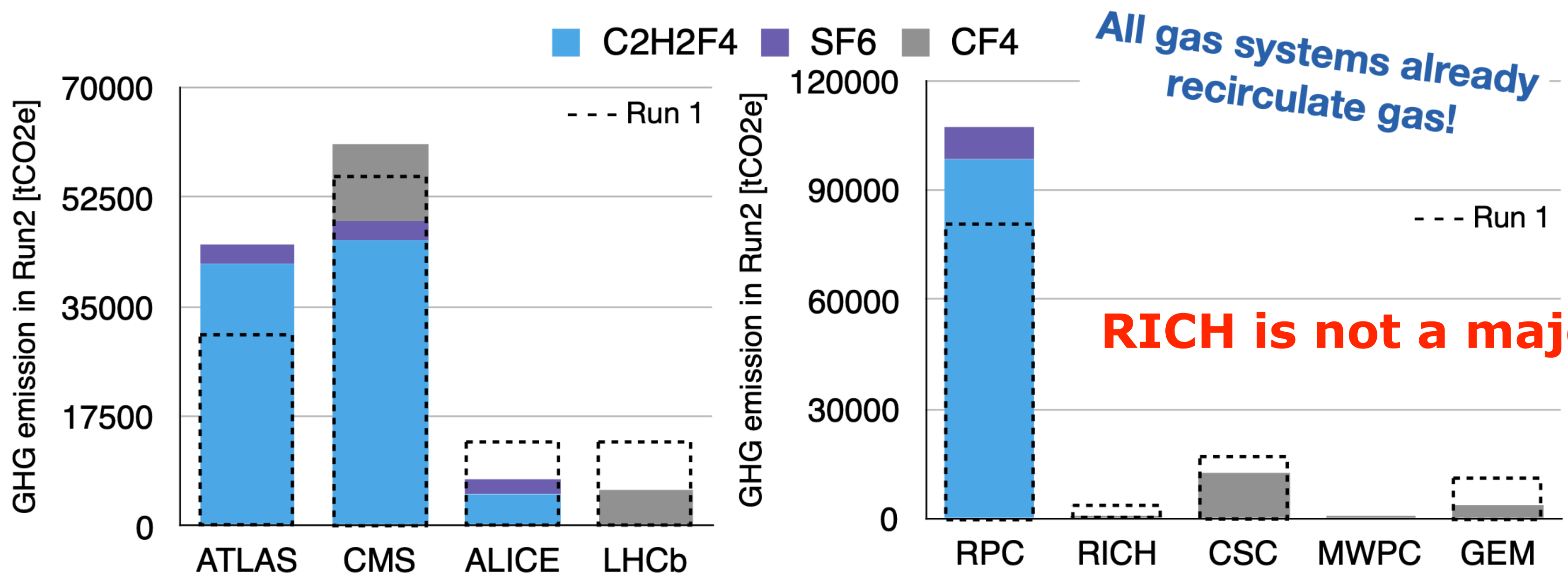
NIM A553(2005)135

Greenhouse Gas Issue

GHG at LHC Run 2

B. Mandelli report on TF1 symposium

GHGs are used in CERN experiments
mainly due to their properties necessary for good detector operation



RICH is not a major contributor

- Fluoride gases listed here have no impact on ozone depletion. However, they are potent (and long-lived) greenhouse gases.

Gas	Ozone depletion potential	Global warming potential
C_4F_{10}	0	4800
CF_4	0	6500
C_2F_6	0	9200

$CO_2 = 1$

Greenhouse Gas Issue

Some studies have been done. For instance, A.H.Harvey et al. NIM B425(2018)28

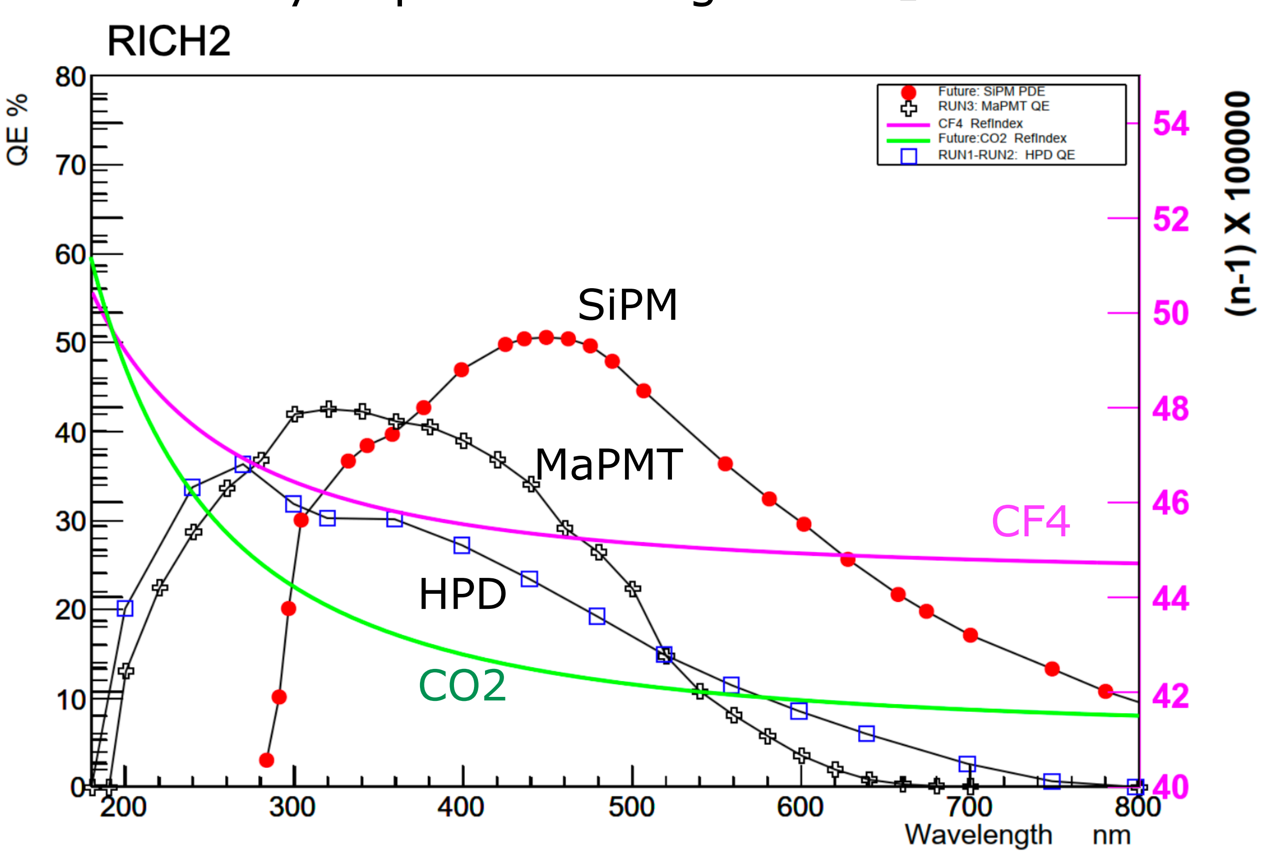
Gas	Ozone depletion potential	Global warming potential	Refractive index(λ=633nm)	Remarks
R-1234yf	0	<1	1.001015	Slightly flammable
R-1234ze(E)	0	<1	1.001964	Slightly flammable Lower volatility

1.03MPa and~20 deg

Flammable gas -> double wall tank ? Material issue.

Negative pressure <1 atm?

Study of possible usage of CO_2 for LHCb



S.Easo report at mini-workshop April 22, 2021

CO_2 chromatic dispersion is worse than CF_4.
It can be improved to optimize sensitive region in wave length.

Possibility of SiPM in future

Dark rate issue and/or cooling environment ?

RICH2: RUN3 — Preliminary

Nominal single photon resolution (in mrad)	MaPMT; CF_4	MaPMT: CO_2
Chromatic	0.34	0.53
Overall	0.50	0.66
Yield	34	33

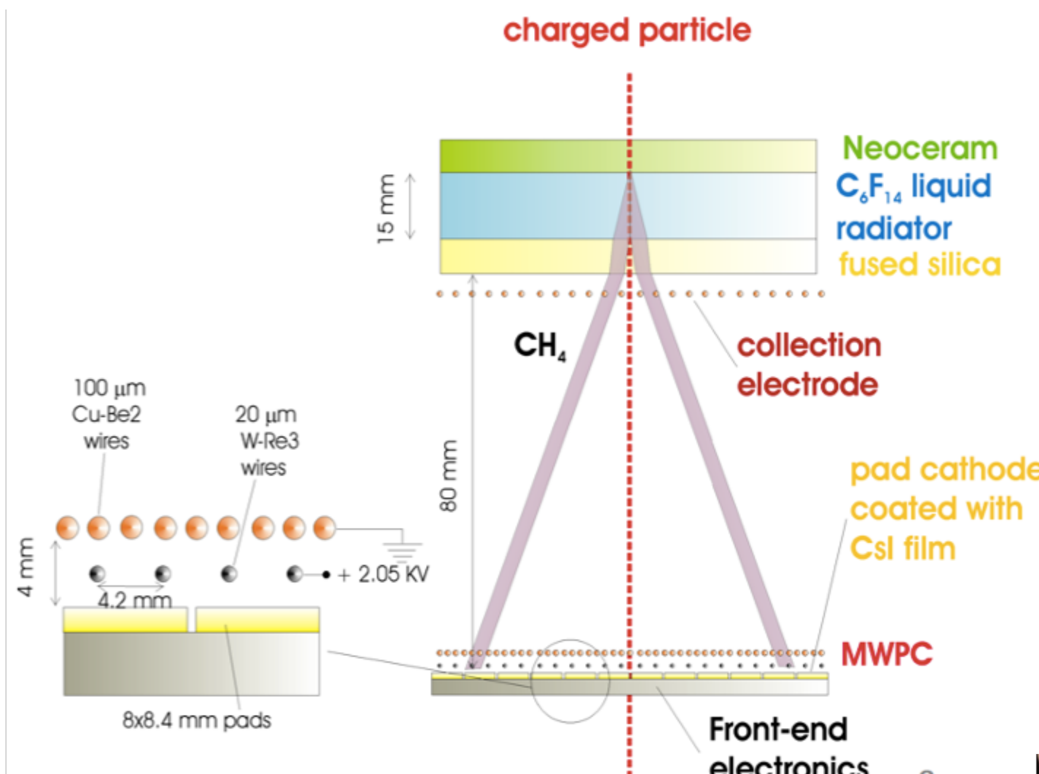
- CO_2 expected to have a worse chromatic error contribution than CF_4

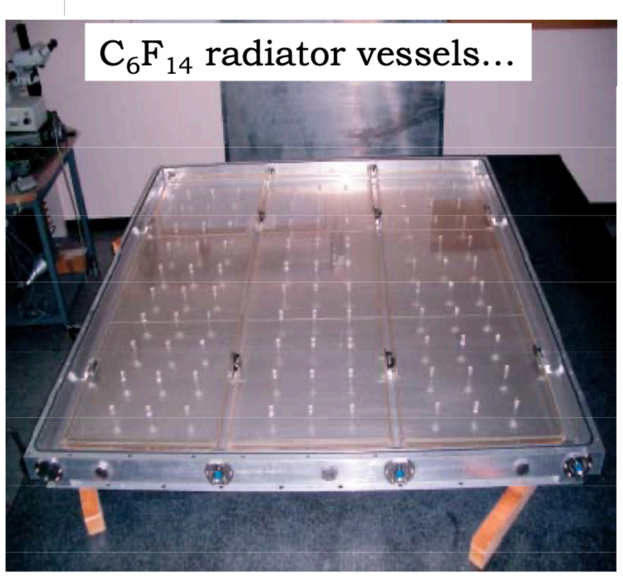
Liquid Radiator: ALICE RICH

NIM A595(2008)27
NIM A876(2017)65

15 mm liquid C_6F_{14}

n=1.2989 at λ=175nm

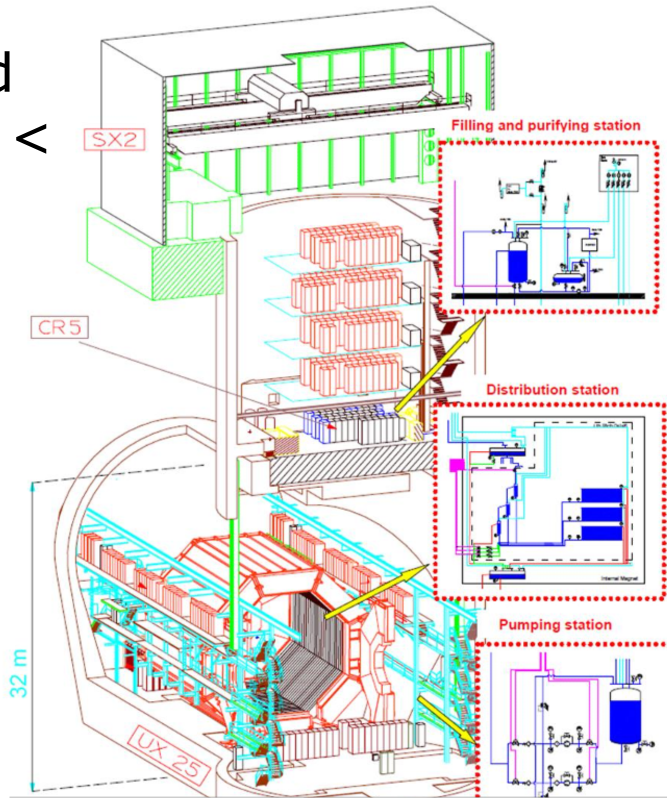


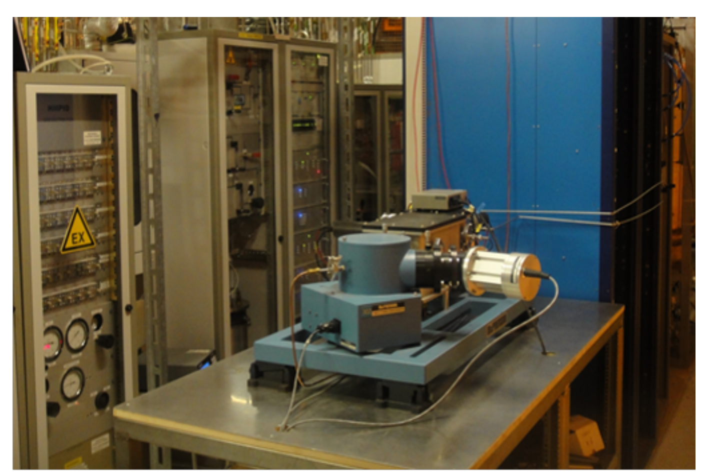


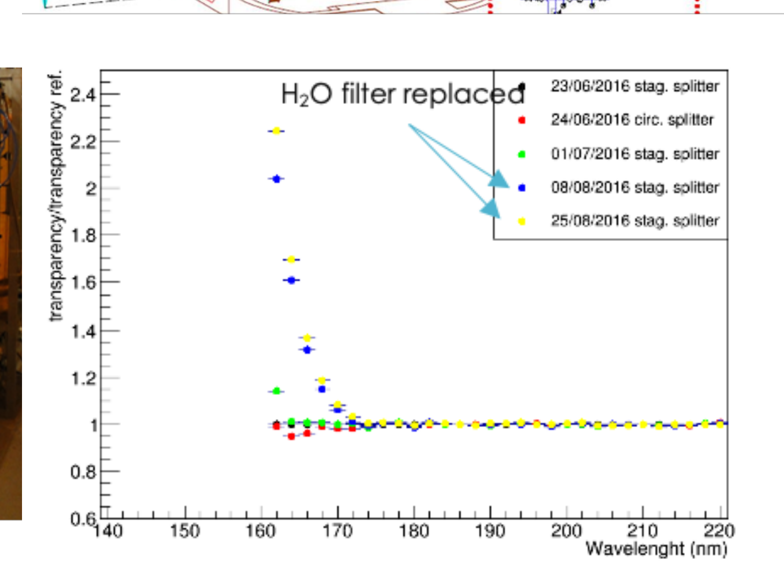
3 radiator vessels/module

liquid C_6F_{14} circulation by the gravity flow principle

Filters to remove O_2 and water equipped to keep < 5 ppm







C_6F_{14} transparency monitoring

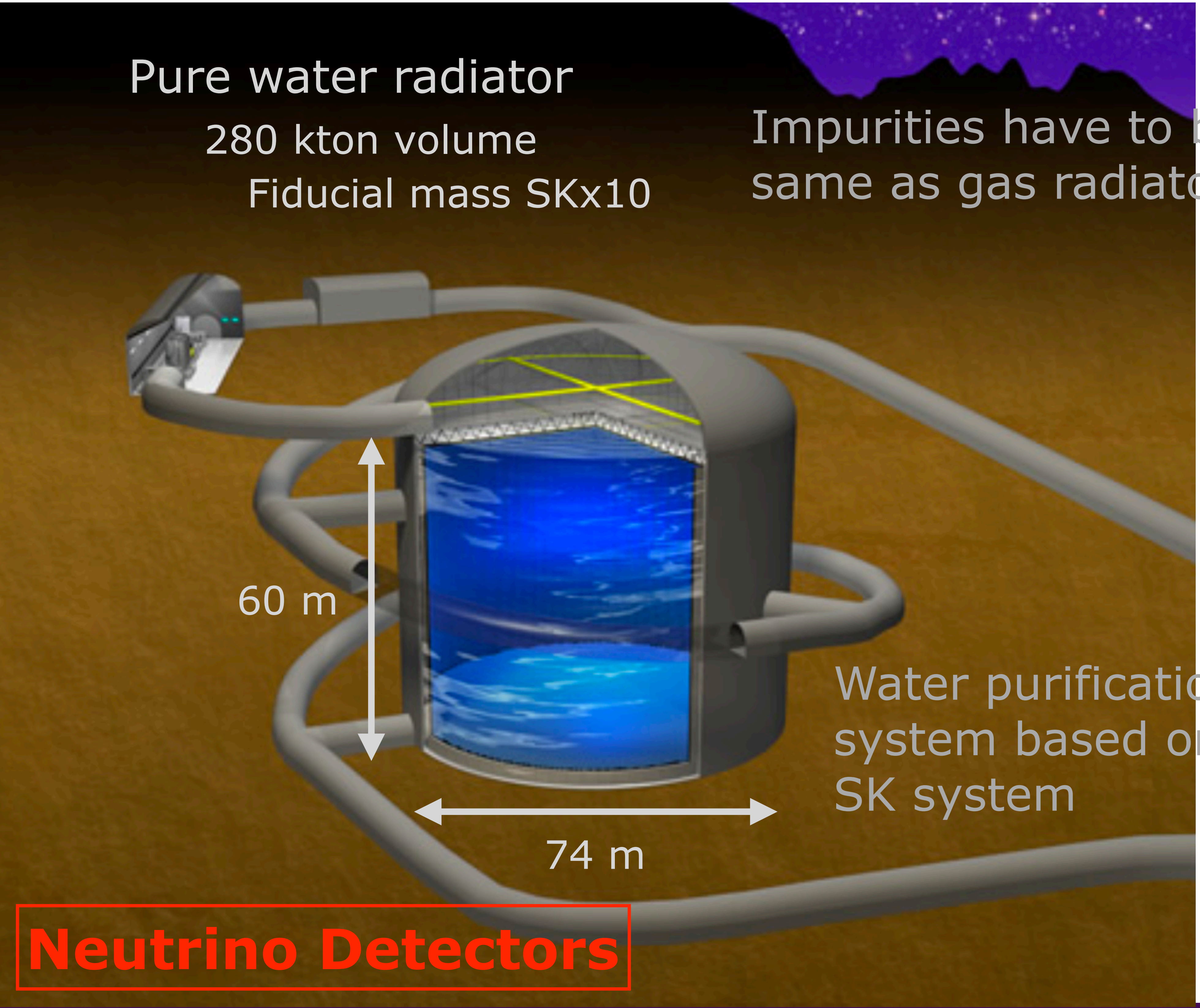
Hyper Kamiokande

Pure water radiator

280 kton volume

Fiducial mass SKx10

Impurities have to be removed (the same as gas radiator case).

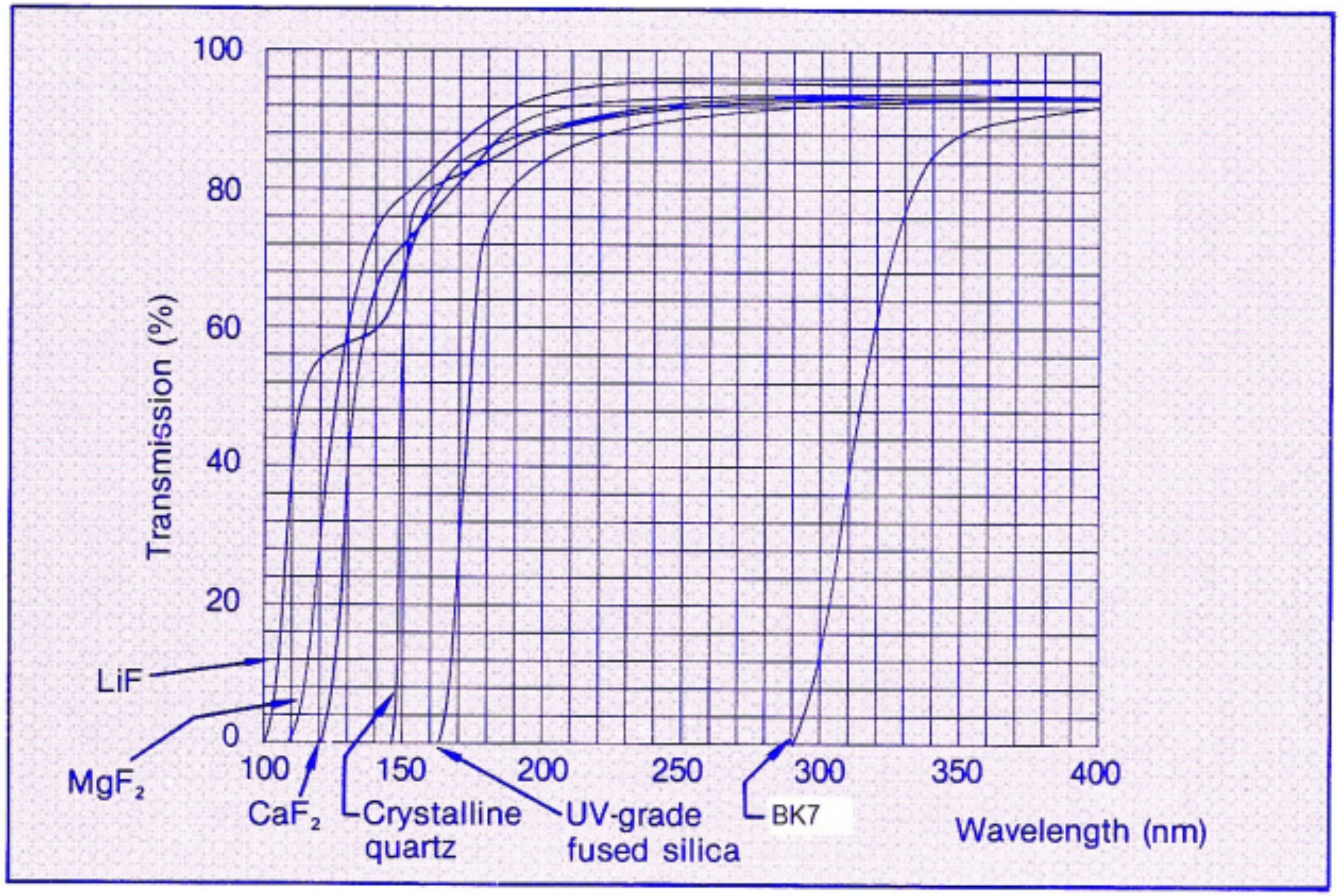


Water purification and circulation system based on experience at the SK system

Neutrino Detectors

Solid Radiator

- Crystal radiator
  - Wavelength cutoff at VUV region
    - Quartz ~ 160 nm
  - Chromatic dispersion
    - n depends on wavelength
  - Machining possible
  - Usually expensive



Quartz Bar

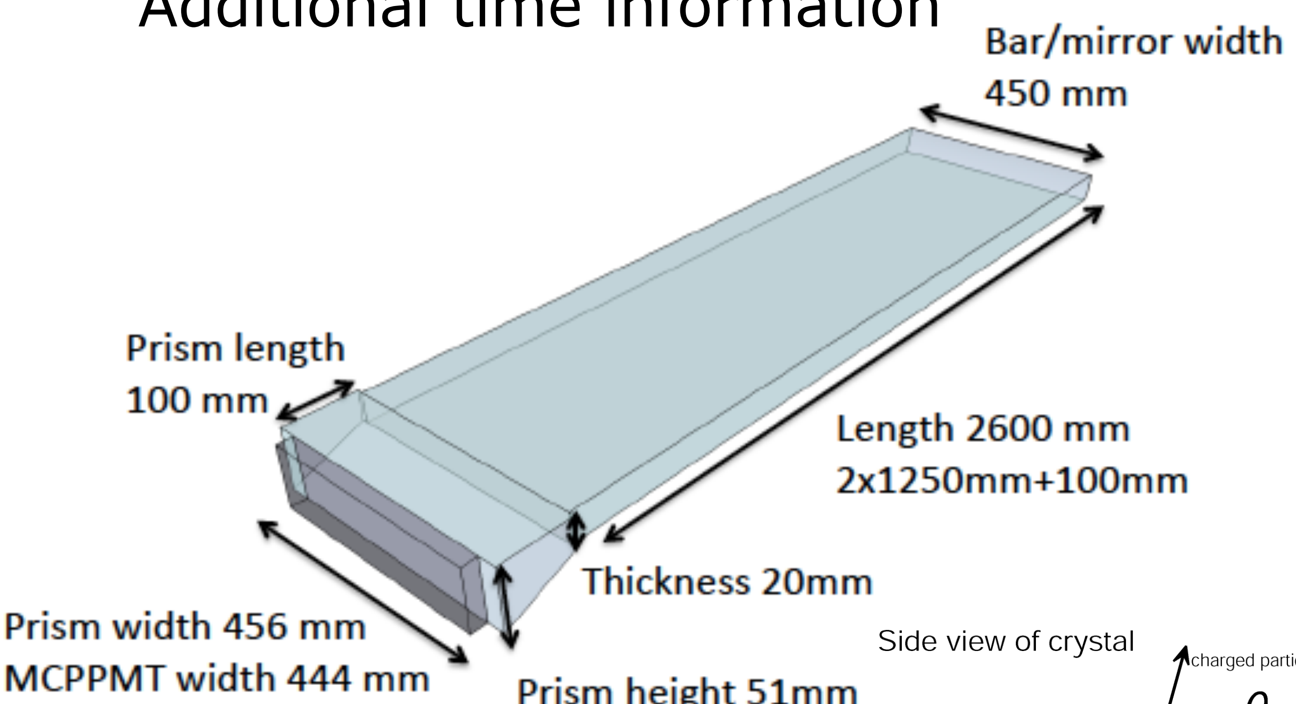
1st generation

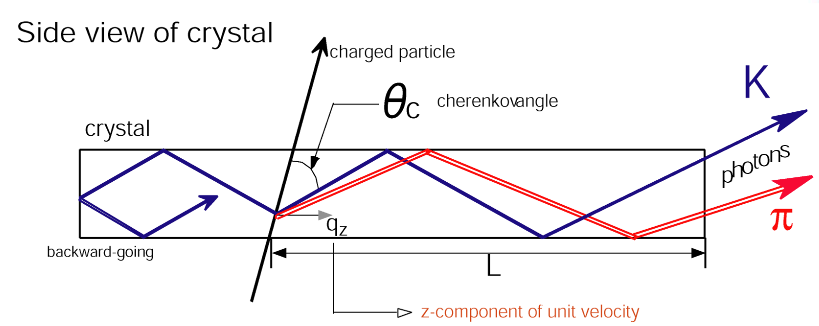
BaBar DIRC

2D imaging of internally reflected Cherenkov photons using narrow bar

Belle II TOP (time-of-propagation) counter

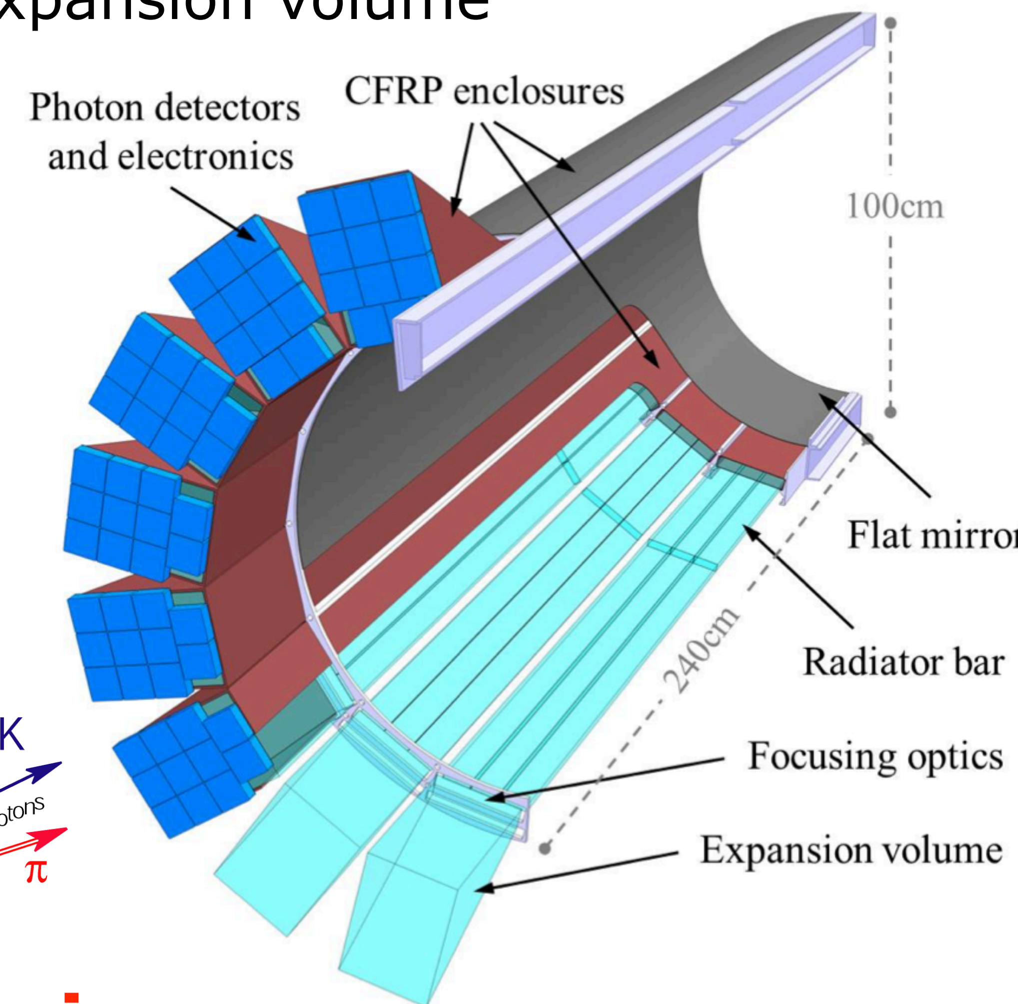
Additional time information





PANDA Barrel DIRC

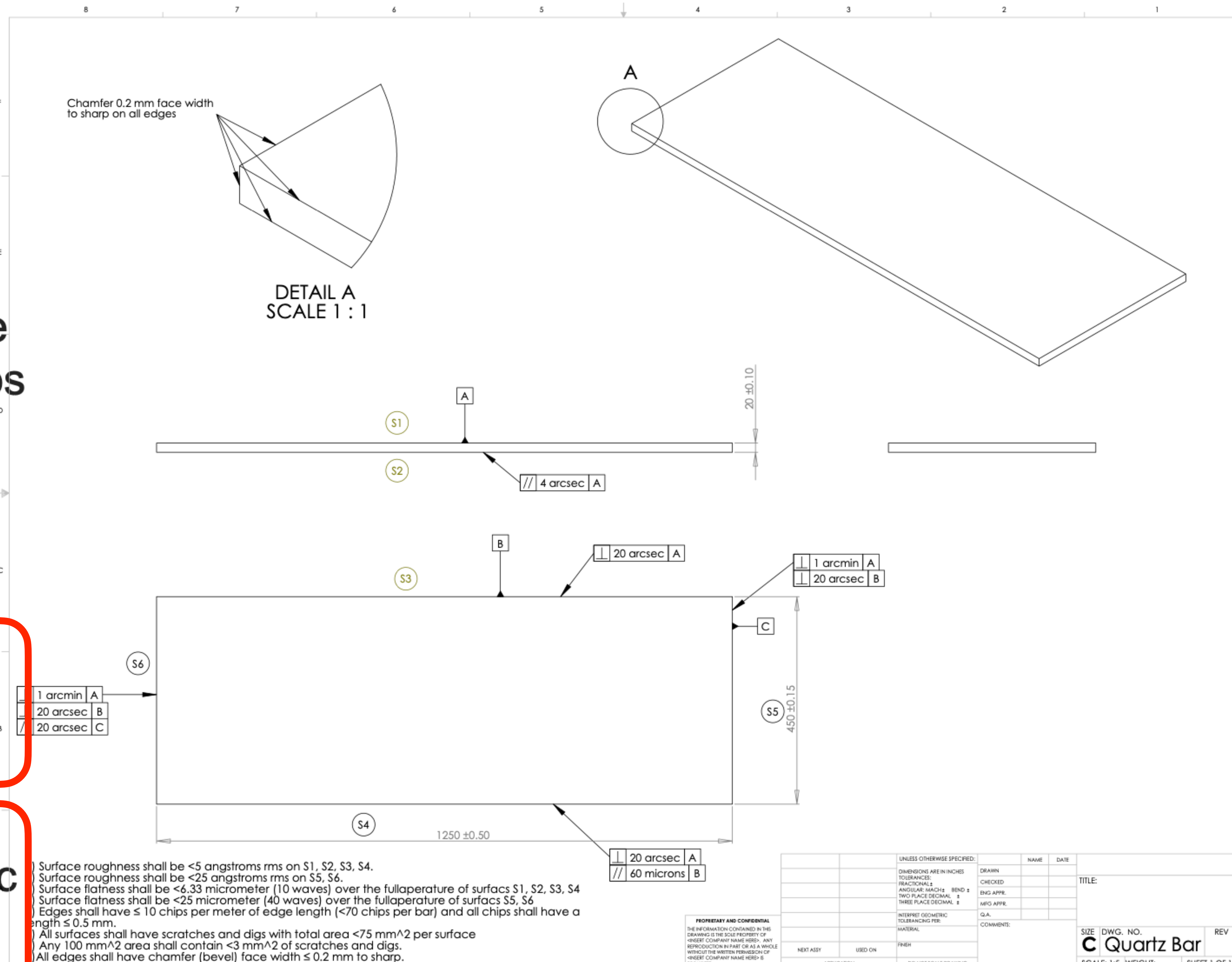
Excellent focusing optics with compact expansion volume



Challenge for ultra-precise machining

TOP Q-bar Specifications

- All chamfers (bevels) of edges shall have face width ≤ 0.2 mm to sharp.
- Each bar shall have total area of all chips ≤ 25 mm2. Bars should have ≤ 20 chips total on all edges.
- Large surfaces flat to <6.3 microns (10 waves).
- Large surfaces parallel to <4 arcsec (24 micron runout over 1.25 meter)



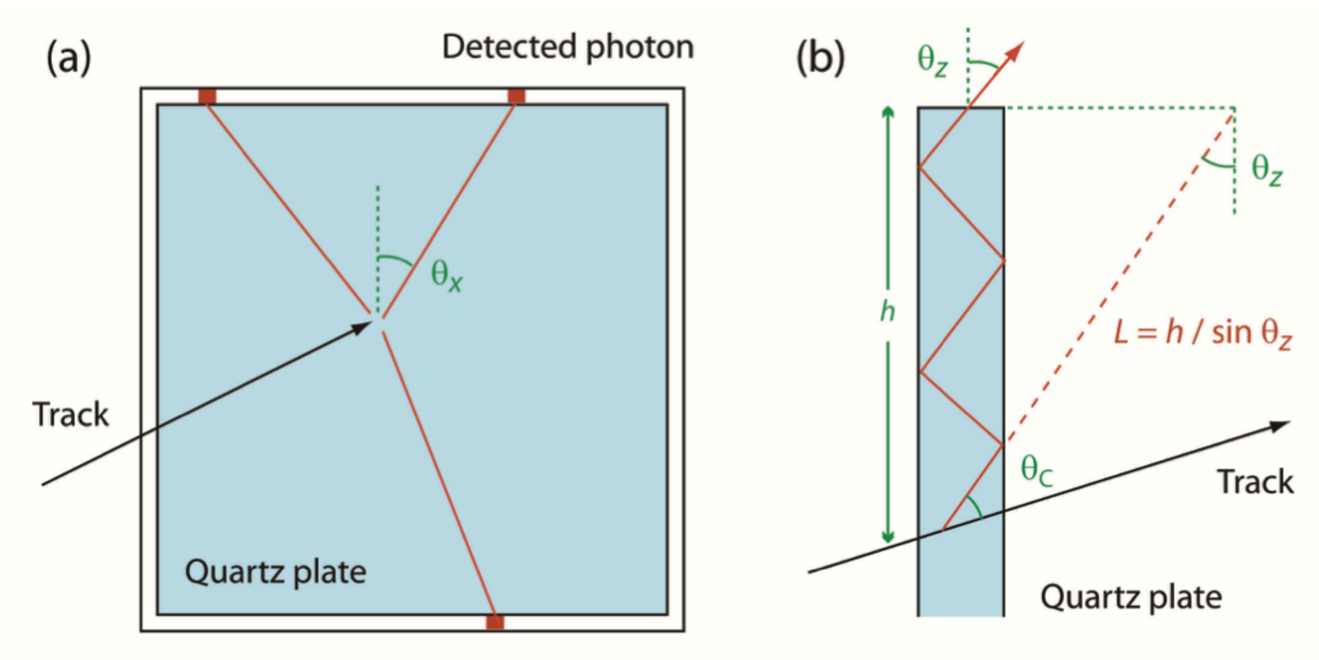
DIRC technology report by J. Schwiening

Q-Planar Radiator

TORCH detector

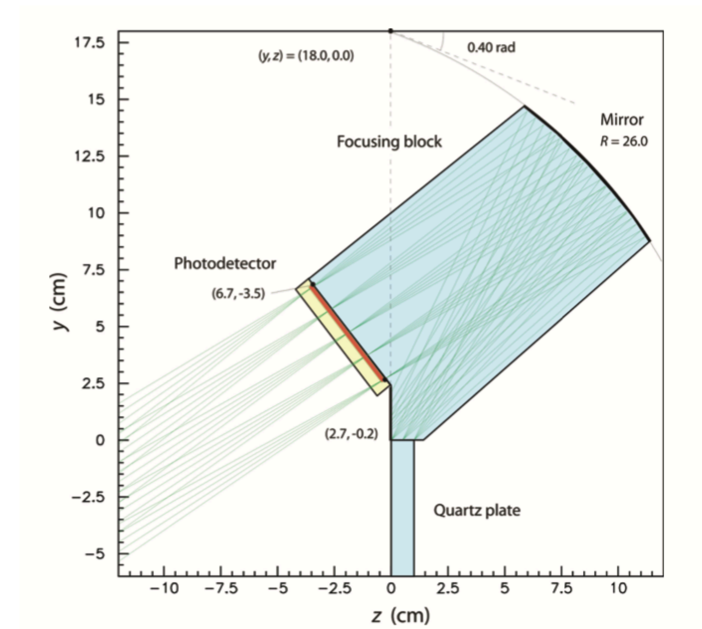
Physics Procedia 37(2012)626

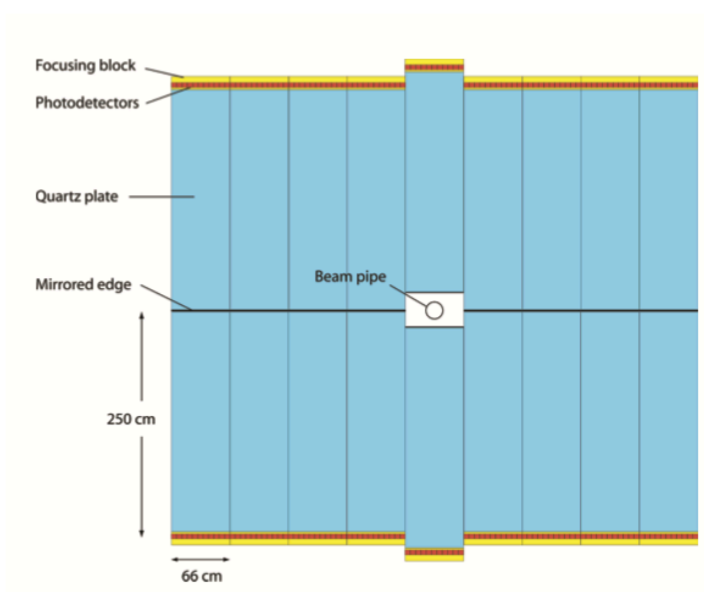
Time of flight and photon angle are measured.

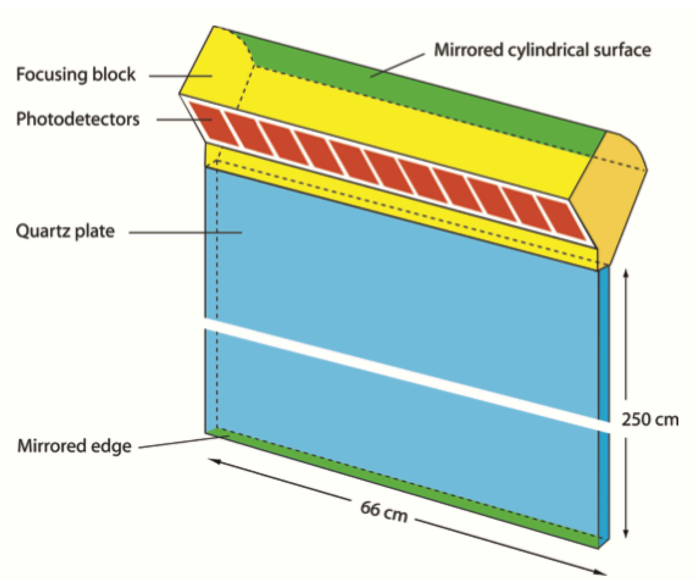


Photon angle are preserved because of internal reflections in the planar bar

Measurement of angle can be done by pixel position of photon detector



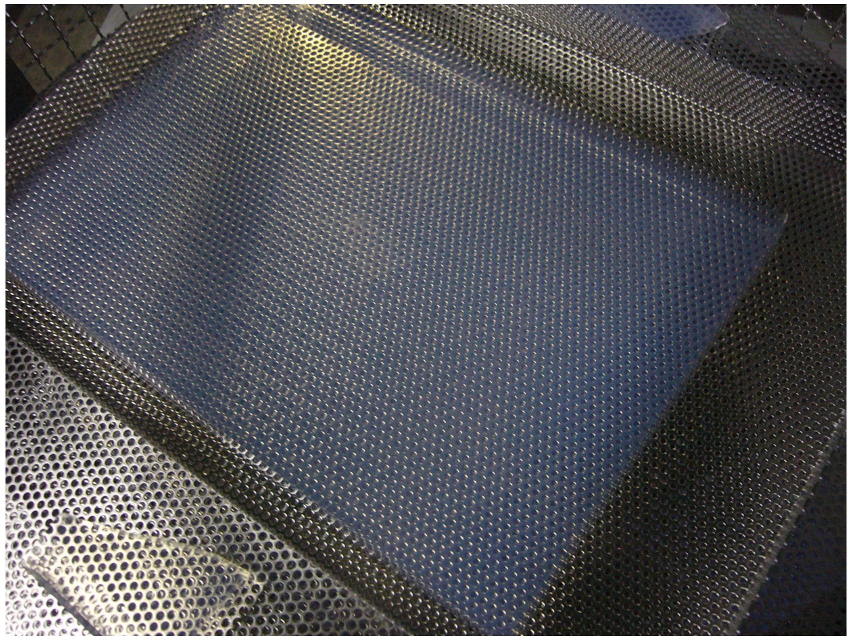


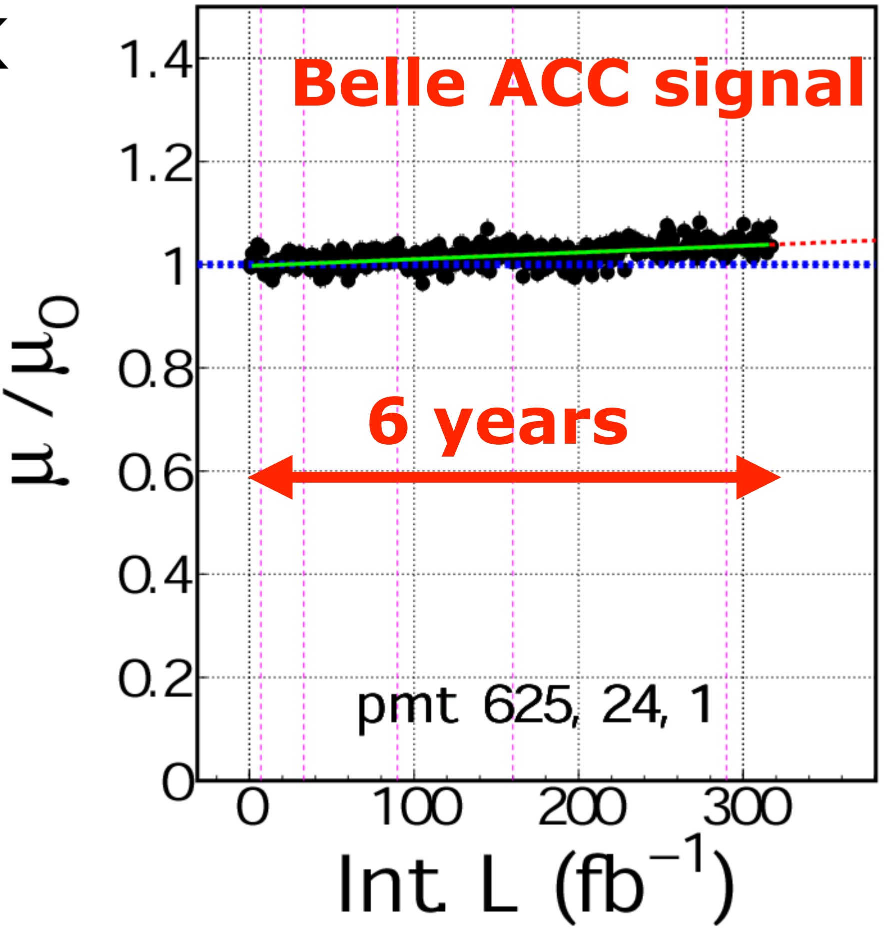


TOF technology report by R. Forty

Silica Aerogel

- Silica aerogel possesses refractive index of 1.01 - 1.2, which fills up index gap between gas and liquid.
- Aerogel samples in 1990's were transparent enough to use RICH Cherenkov radiator.
  - HERMES RICH for the 1st time.
- Hydrophobic feature from Chiba/KEK
  - Long term stability





Aerogel Production Facility

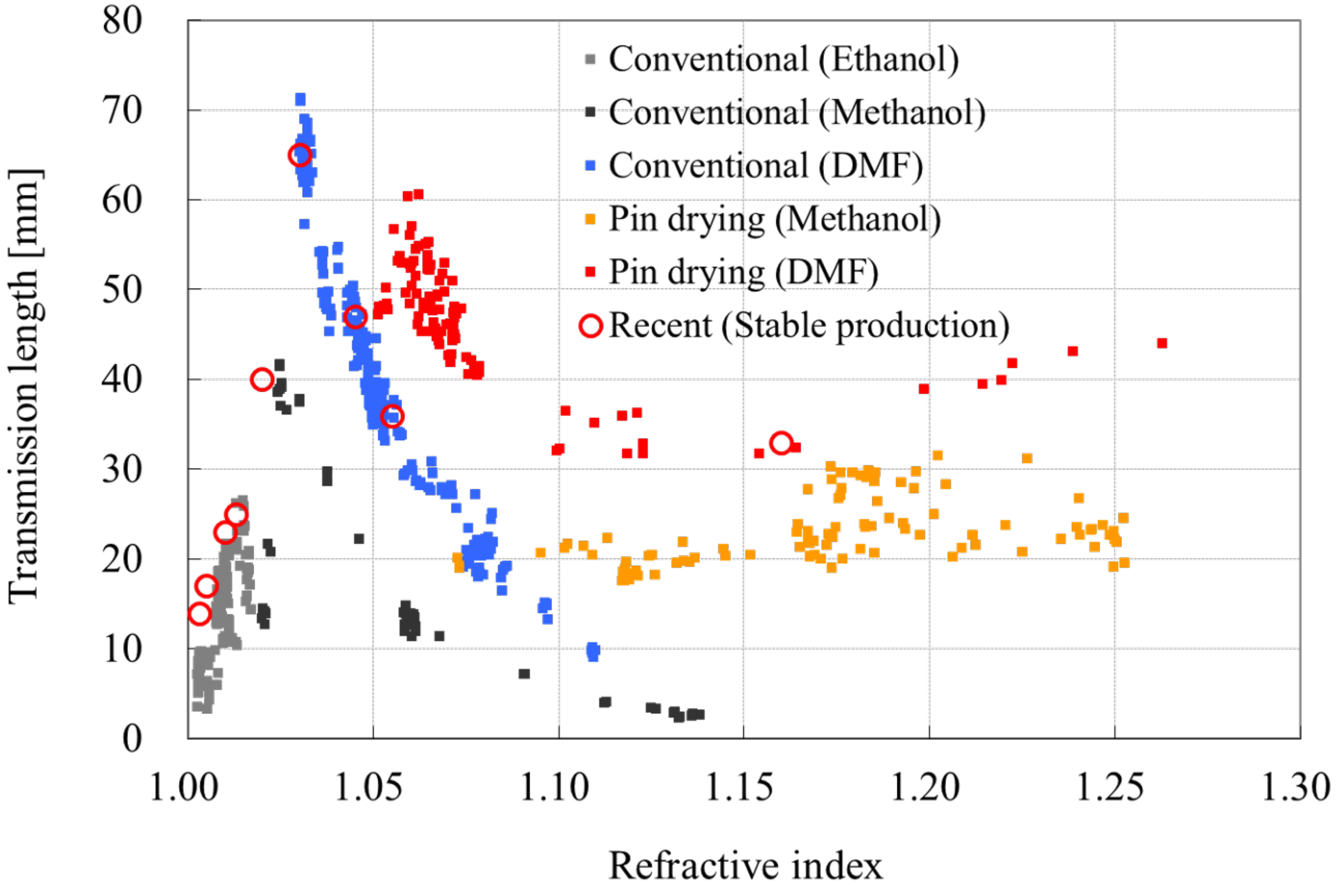
- Two major production facilities which provide aerogels for high energy physics.

Chiba university in Japan

Hydrophobic sample
Pin-drying (PD) method to get n > 1.1

Novosibirsk in Russia

No hydrophobic, but recoverable by baking



We can not obtain transparent aerogel with n > 1.1 in the conventional method because of too many silica particles.

Chemical synthesis targeting n~1.06, then alco-gel partially evaporated in the controlled environment to get target density.

NIM A952(2020)161879

Human resource to investigate a recipe seriously limited.

Aerogel Production Facility

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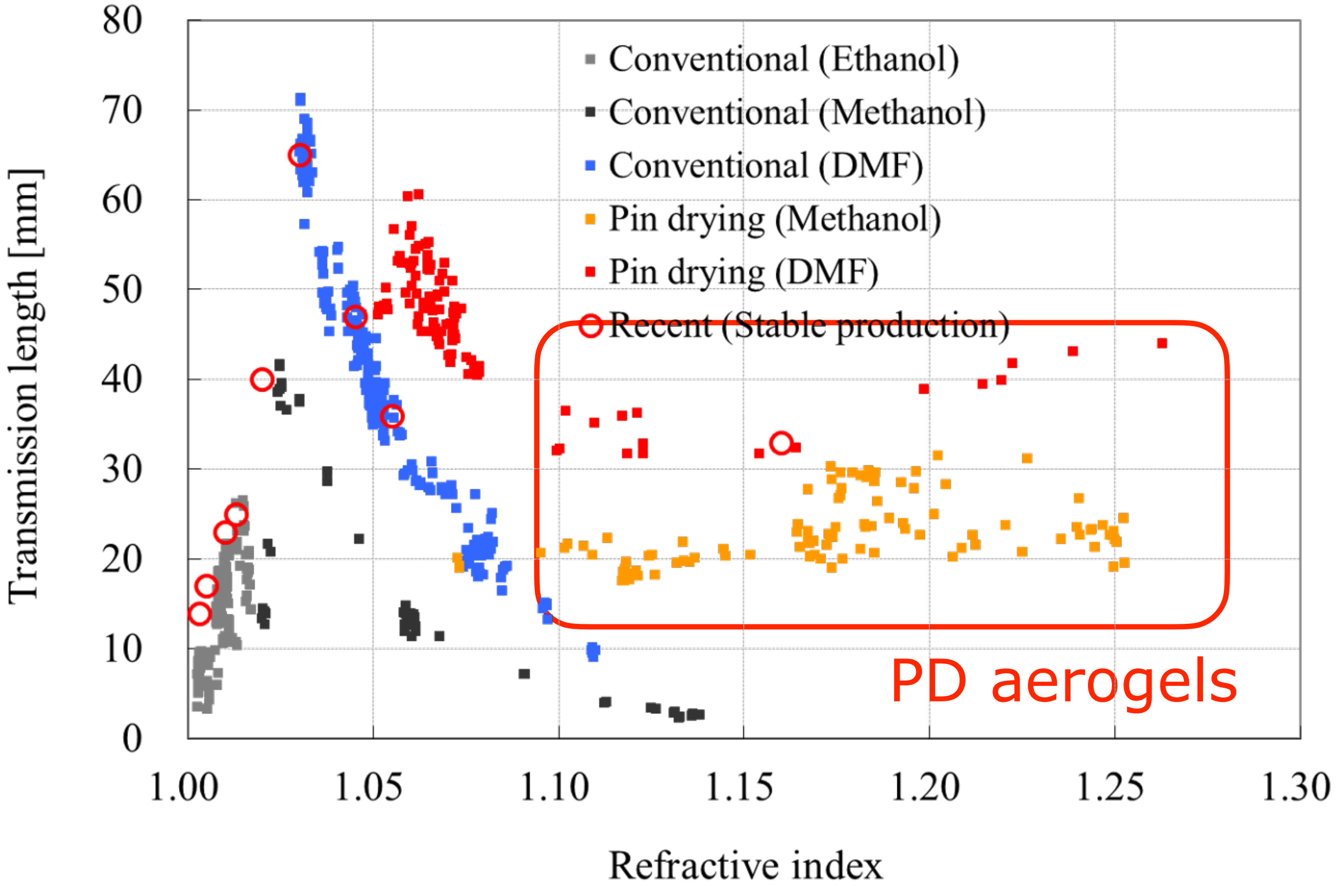
Hydrophobic sample
Pin-drying (PD) method to get n > 1.1



NIM A952(2020)161879

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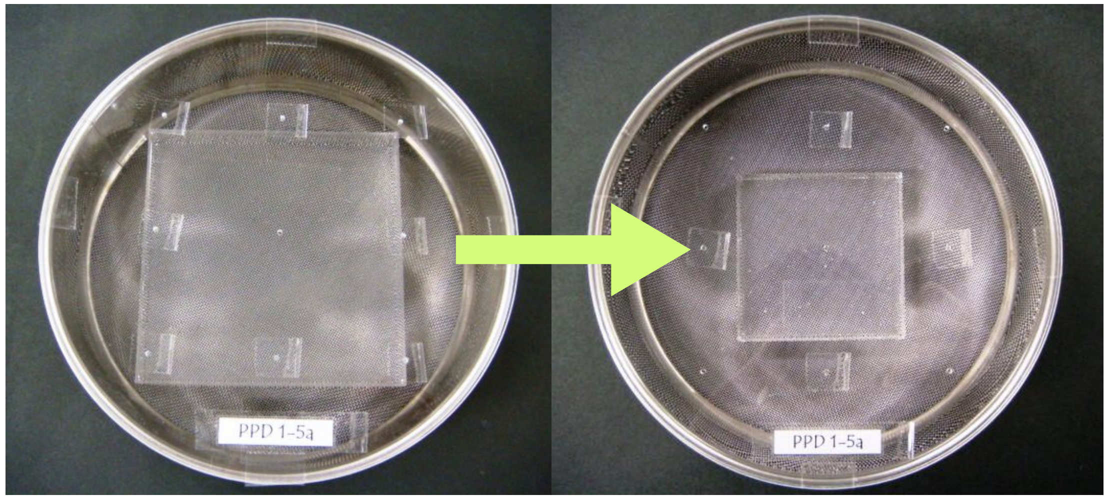


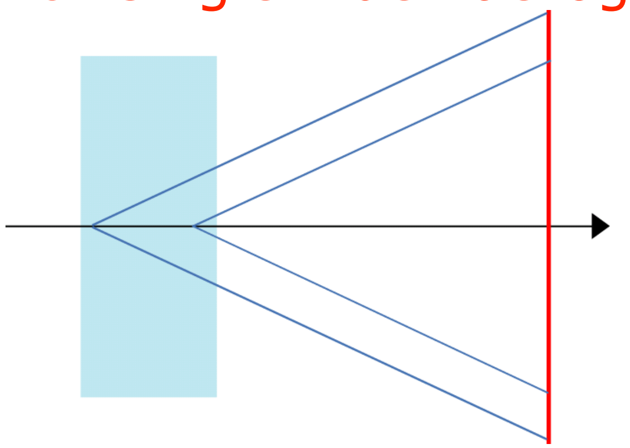
Dual Aerogel Layers

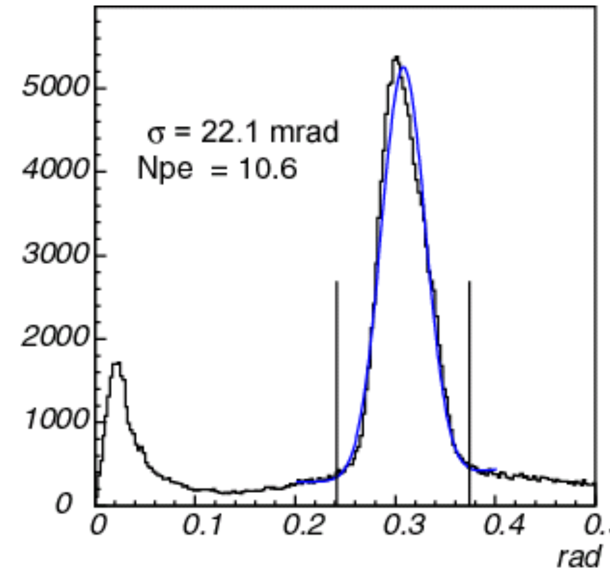
NIM A548(2005)383

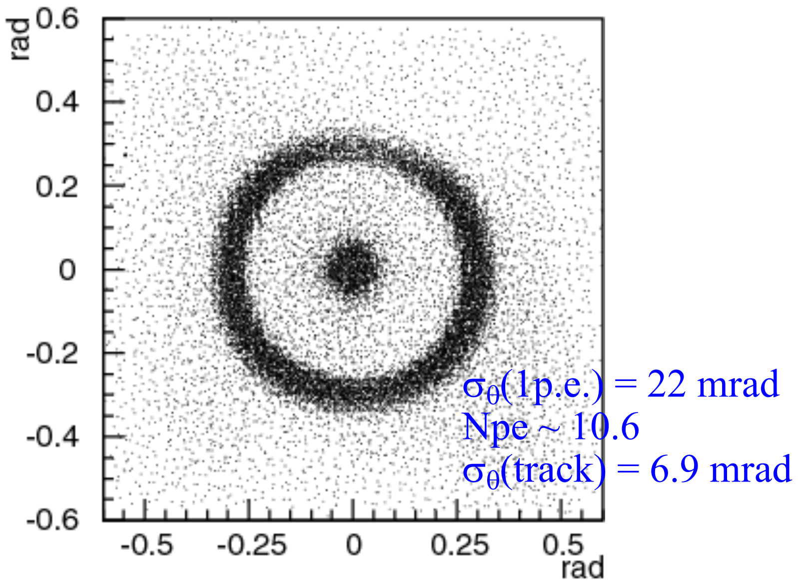
- Highly transparent tile with n>1.03
- Dual layers consists of 1.045 (upstream) and 1.055(downstream)
- Refractive index can be adjusted so as to organize the overlapped image.

Increase light yield w/ suppressing emission point uncertainty

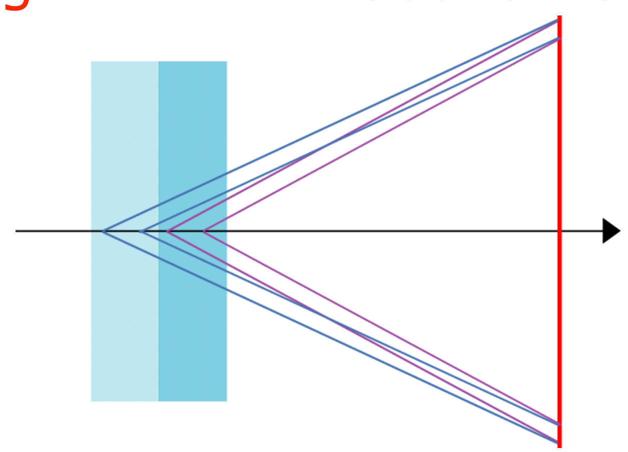
4cm thick single index aerogel

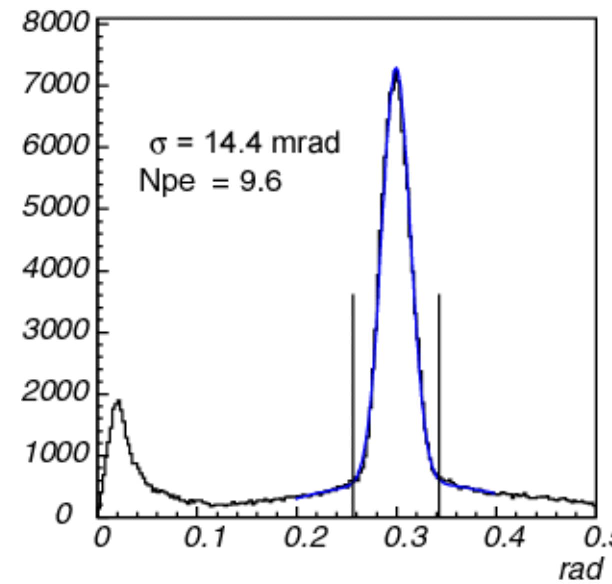


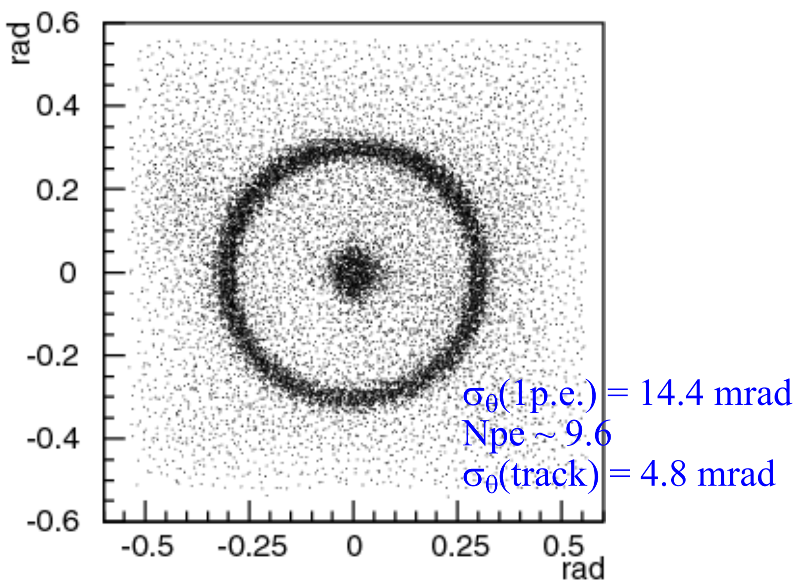




Focusing 2cm+2cm dual aerogel







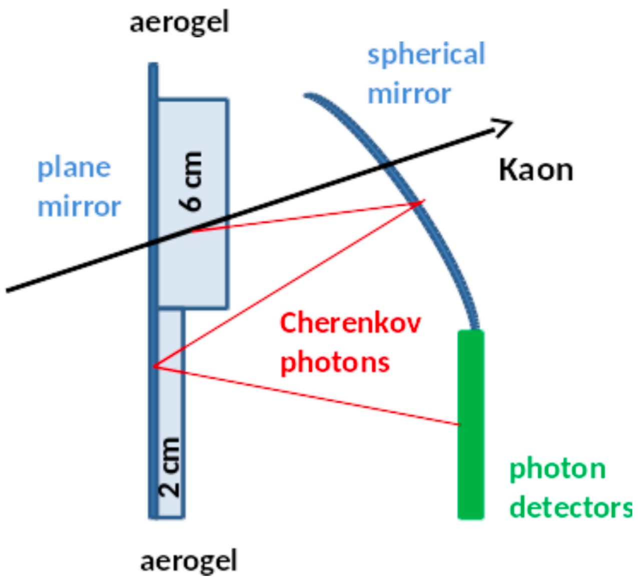
Radiator Applications

NIM A952(2020)162123

EIC Yellow Report

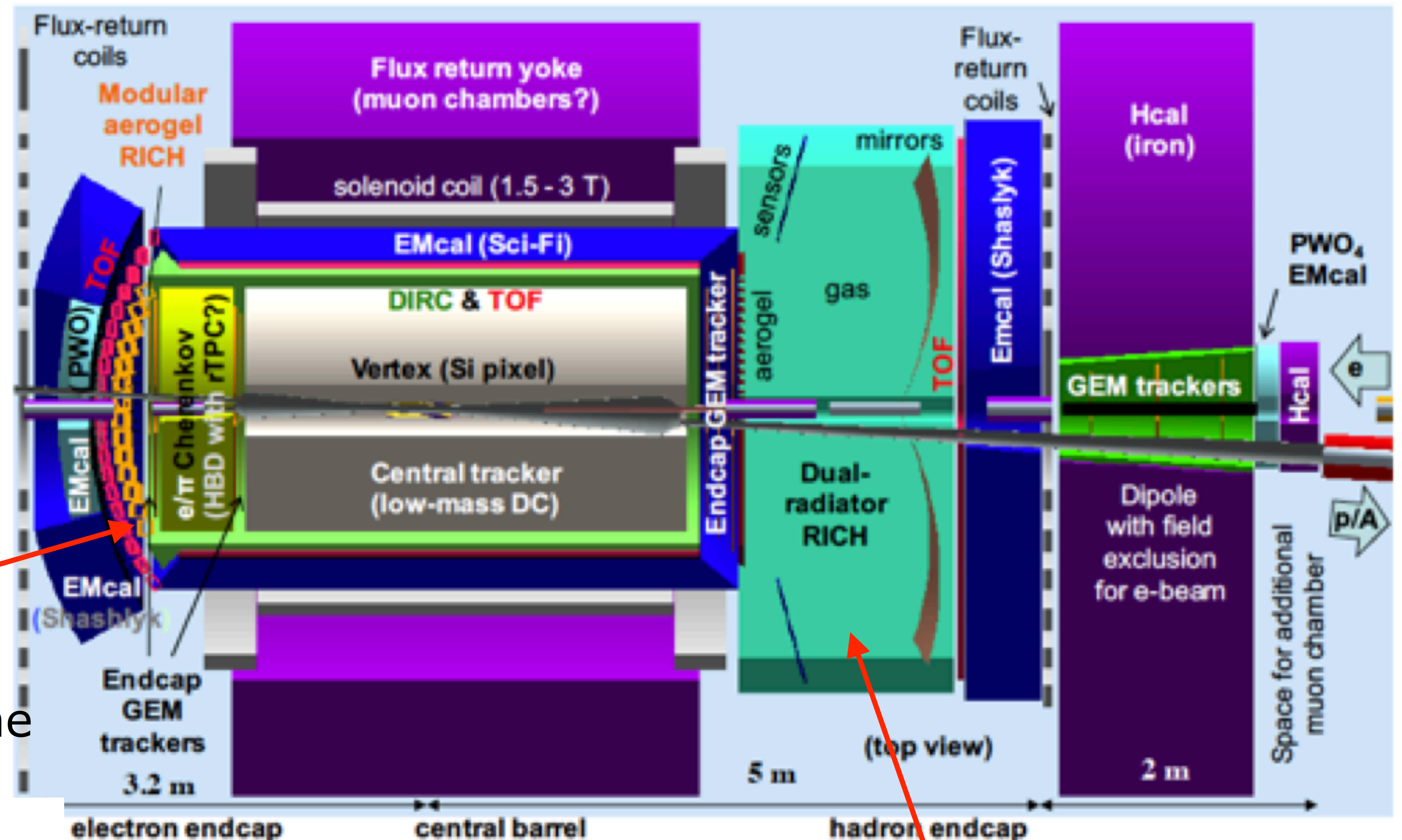
CLAS12 RICH

Challenging optics.
2 layers of 30 mm thick (n=1.05)



Electron Ion Collider experiment

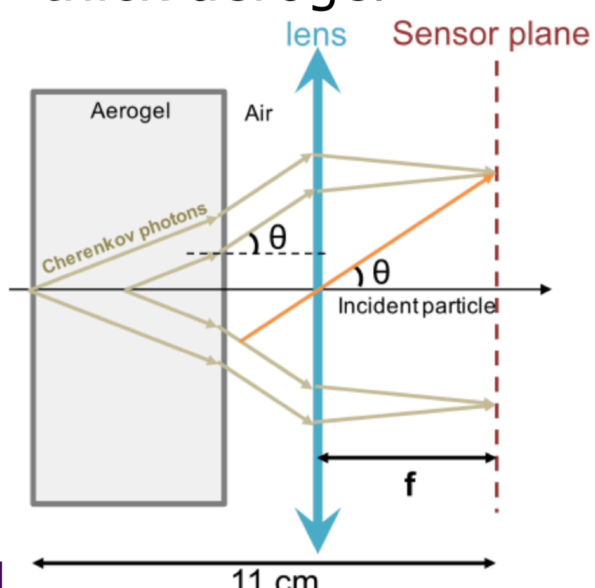
JLab Version

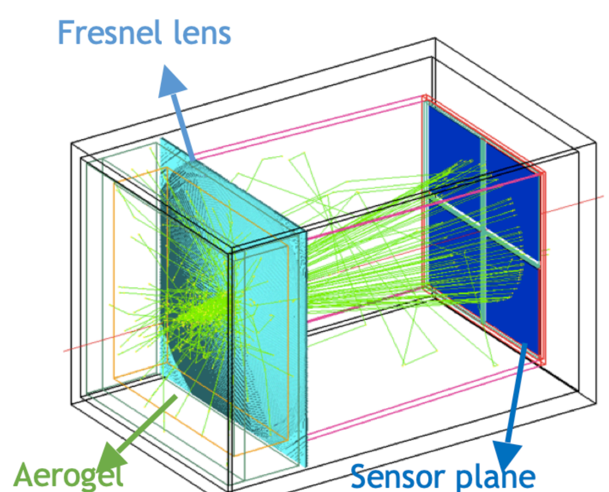


Modular RICH

Fresnel lens focusing scheme makes compact system

n=1.03 3cm thick aerogel





Geant4 Simulation

Dual radiator RICH

n=1.02 aerogel & C_2F_6

Pion/K separation up to 50 GeV/c

New Radiators

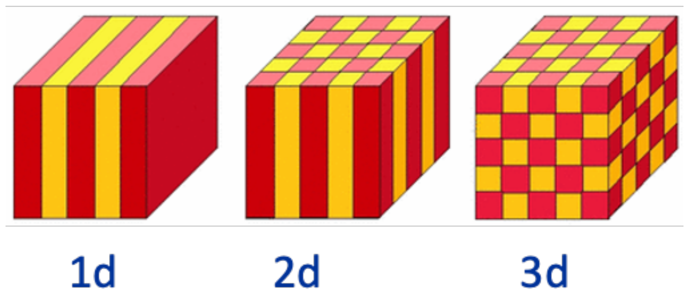
S.Easo report at RICH2018
M. Blago report
Nature Physics Vol14(2018)816

- Radiator limitations
  - In low momentum region below threshold, one can not detect Cherenkov photons. Only “veto mode” can be used for particle separation.
  - In high momentum region, (long) gas radiator is (almost) a unique choice.

Can we produce new crystal radiator with refractive index which we want to have ?

Photonic crystals could be one of the candidates.

Made from two materials with different n
Layer thickness ~ photon wavelength
Feasible in recent years



Meta material

- Layer thickness smaller than the wavelengths considered
- Particles ‘see’ an ‘effective medium’ instead of the atoms
- Normally made from resonant structure of metallic wires or nanomaterials
- They can also have positive refractive index.

Phys.Rev.Lett. 113(2014)167402

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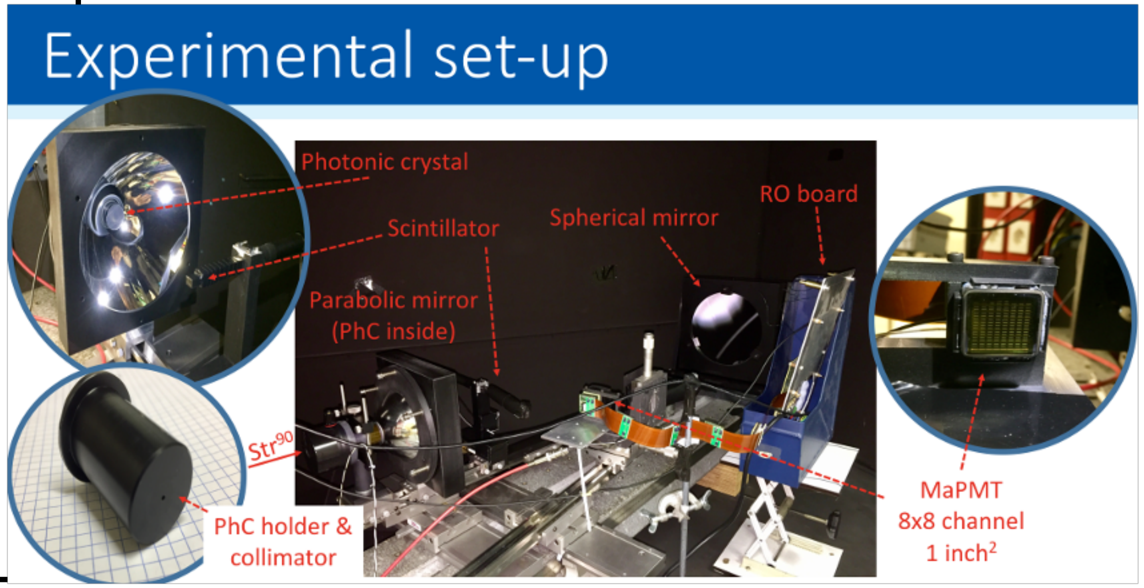
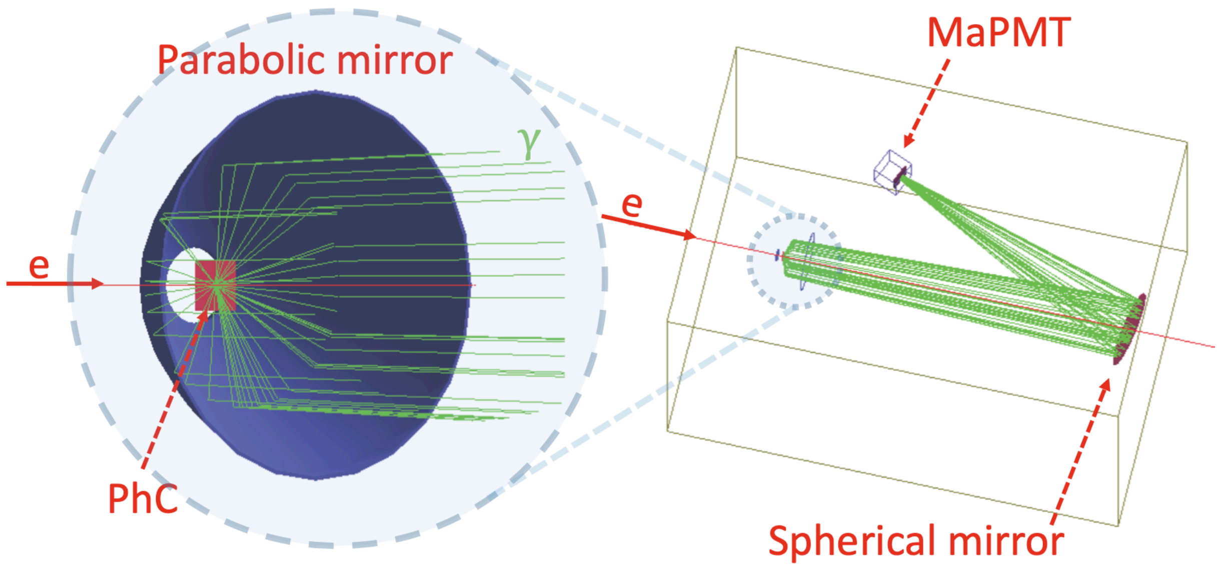
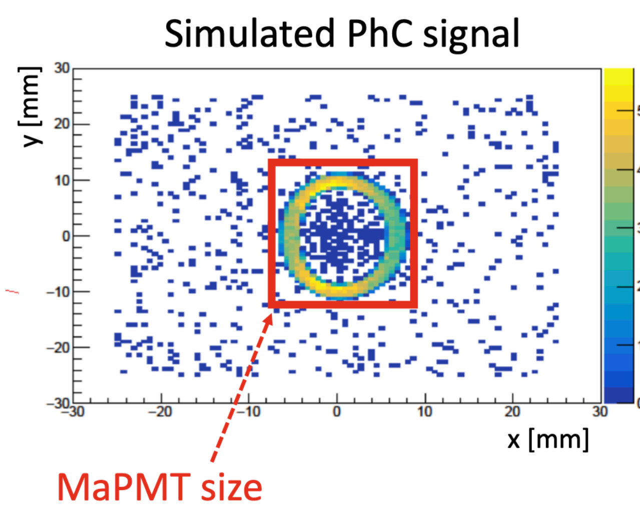
1d photonic crystal from industry

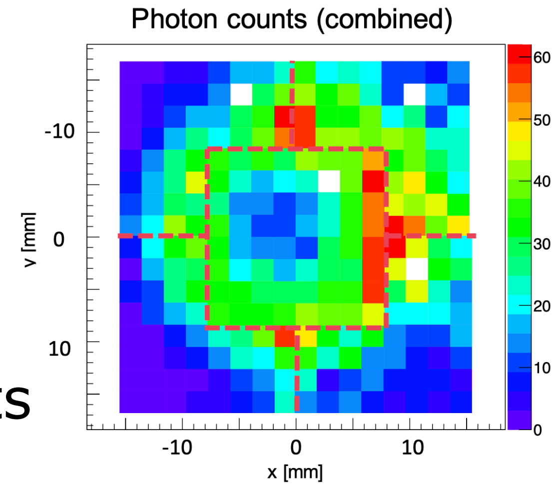
- PVDF (n1=1.414) + PET (n2=1.567)
  1024 layers, each with 250 nm thickness
- This sample has negligible chromatic error
- Sensitive to low momentum particles
  from a radio active source



Geant4 simulations







Preliminary results

Summary

A variety of Cherenkov radiators has been used, so far.

Peripheral systems (circulation/purification/monitoring) established.
Keep close eyes on new products

Choice of photon sensor

Sensitive to VUV : gas or liquid

Usage of Cherenkov photons

Imaging : gas or liquid or aerogel
Timing : quartz (internal reflected)

Momentum range of your interests

Wide range p>10GeV/c : gas or gas combined with solid

Volume available

Large volume : gas or gas combined with solid

More conditions...

Radiation?

Effort to investigate new materials ongoing

- https://www.nikon.com/products/components/lineup/materials/i-line/