Particle Identification system based on aerogel in BINP


Budker Institute of Nuclear Physics, Novosibirsk, Russia

A.F.Danilyuk, V.Kirilov, A.Pridein

Boreskov Institute of Catalysis, Novosibirsk, Russia

D.A.Finogeev, A.B.Kurepin, A.I.Reshetin, E.A.Usenko

Institute of Nuclear Research RAS, Moscow, Russia

C.Degenhardt, R.Dorscheid, T.Frach, O.Muelhens, R.Schulze, B.Zwaans

Philips Digital Photon Counting, Aachen, Germany

Alexander Barnyakov
Outline:

• Aerogel
• Threshold counters
  – ASHIPH method
  – The ASHIPH system of the KEDR detector
  – The ASHIPH system of the SND detector
• FARICH
  – Concept
  – Forward RICH for PANDA detector
  – FARICH for Super CTF
• Aerogel production: status and perspectives
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 ($n-1 \lesssim 10^{-3}$) 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)$_4$
Threshold Cherenkov counters

Direct light collection

Pros: Simplicity

Cons: Counter size limited → large PMT number & area → high total cost
Threshold Cherenkov counters

Direct light collection

Pros: Simplicity
Cons: Counter size limited → large PMT number & area → high total cost

ASHIPH – Aerogel-SHIfter-PHotomultiplier

Suggested by A. Onuchin et al. for PID of the KEDR detector [NIM A315 (1992) 517]

Pros:
- Large light collection area
- Small PMT (up to 10x smaller p.c. area in comparison with direct LC)
- Low cost

Cons:
- Particle acceptance loss due to WLS
The ASHIPH system of the KEDR detector

- 160 counters (2 layers)
- $n=1.05$ (1000l)
- WLS (BBQ)
- MCP PMT $\phi_{PC}=18$ mm
- Diffusive LC (PTFE)
- $0.97 \times 4\pi$
- 24% $X_0$

Since 2014 is under operation in the KEDR experiment at VEPP-4M collider.
Figure 6. The amplitude dependence of “Thick counter” on the momentum of cosmic muons which cross the aerogel in the KEDR ASHIPH system.

Acknowledgments
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References

Good agreement MC simulation with experimental data is obtained

Under-threshold efficiency:
- \( P_\mu < 110 \text{ MeV/c} \) – PTFE scintillation
- \( P_\mu > 110 \text{ MeV/c} \) – PTFE Cher. light
- \( P_\mu > 130 \text{ MeV/c} \) – Cher. light from \( \delta \)-electrons in aerogel.

A.Yu. Barnyakov et al 2017 JINST 12 C07041
AND: relativistic particle have to give a signal in both layers of the system
OR: relativistic particle have to give a signal at least in one layer
THICK: sum of the amplitudes in both layers have to be more than threshold

- $\pi/K = 4.3\sigma$ at 1.2GeV/c
- $e^+e^-\rightarrow e^+e^-$ supp. $>600$ times


Study in progress (collected data):
- $Br(J/\psi \rightarrow pp, \pi\pi, KK, p\gamma, \pi\pi\gamma, KK\gamma, pp\pi^0, \pi\pi\pi^0, KK\pi^0)$
- D-meson masses measurement
Long term ASHIPH stability

- Since 2000 the stability of ASHIPH counters has been studied.
- 80 counters of the system were under operation in detector from 2003 to 2011.
- The main sources of amplitude decrease were studied:
  - QE PMT – 18%
  - LC(Aerogel) – 22%

Dynamic of the amplitude dependence on time is explained by slow aerogel degradation which goes to some stable level.
SND at VEPP-2000

Symmetric $e^+e^-$ collider with round beams
$2E_{\text{max}}=2000\text{ MeV}$
$L=10^{31}\text{cm}^{-2}\text{s}^{-1}$ at $E=510\text{ MeV}$
$L=10^{32}\text{cm}^{-2}\text{s}^{-1}$ at $E=1000\text{ MeV}$

1. VEPP-2000 beam pipe
2. Tracking system
3. Aerogel Cherenkov counters
4. NaI(Tl) crystals
5. Vacuum phototriodes
6. Fe absorber
7. 
8. Muon system
9. 
10. VEPP-2000 s.c. focusing solenoids
The ASHIPH system of the SND detector

- 9 counters (1 layer)
- 9 liters of aerogel:
  - $n=1.13$ for $\pi/K$ (300÷870 MeV/c)
  - $n=1.05$ for $e/\pi$ (up to 450 MeV/c)
- WLS (BBQ)
- MCP PMT $\varnothing_{PC}=18$ mm
- Diffusive LC (PTFE)
- Thickness $\sim 30$ mm
- $0.6 \times 4\pi$
SND counters assembling & installation

Segment case

Filled with aerogel

MCP PMT with voltage divider

Installed in the SND

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The status of SND detector ASHIPH system

The Born cross section for $e^+e^- \rightarrow K^+K^-$ process

A. Y. Barnyakov et al., JINST 9 C09023 (2014)

ASHIPH upgrade

MCP PMT → SiPM

Pros:

<table>
<thead>
<tr>
<th></th>
<th>MCP PMT</th>
<th>SiPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>PDE=QE*CE</td>
<td>25*0.6≈15%</td>
<td>30-45%</td>
</tr>
<tr>
<td>Magnetic field imm.</td>
<td>Axial</td>
<td>Any direction</td>
</tr>
<tr>
<td>Power supply</td>
<td>2÷4 kV</td>
<td>&lt;100V</td>
</tr>
</tbody>
</table>

Cons:

- High level of noise → New specific FEE → Cooling system
- Radiation tolerance is still low.

In case of existing experiments such upgrade are possible right now. For Super Cτ (B)- Factories SiPM R&D is needed.
Ring Imaging Cherenkov detectors with aerogel radiators

- If the Cherenkov radiation angle is measured, the identification quality will be higher than in threshold counters.
- In the 1980s and 1990s, a whole series of RICH detectors were constructed:
  - CRID, SLD detector, SLAC(C_6F_{14} n=1.277, C_5F_{12}/N_2 n=1.0017)
  - RICH, Delphi detector, CERN, (C_5F_{12}|C_6F_{14}, C_4F_{10})
  - RICH, CLEOIII detector, Cornell, (LiF, n=1.50)
  - DIRC, detector BaBar, SLAC, США (SiO_2, n=1.47)
- Main problem – they do not provide π and K identification with 4÷10 GeV/c momenta
- **Material with \( n=1.03÷1.05 \) is needed. Aerogel!**
Focusing Aerogel RICH for PID system

(Motivation)

Dependence of Cherenkov threshold momentum on refractive index

Dependence of $\Delta \Theta_c$ on refractive index

Aerogel threshold counters for reliable $K/\pi$ separation up to 2GeV/c could be used.

For reliable $\mu/\pi$ separation we need aerogel RICH with $\sigma_{\text{track}}(\Theta_c) < 2.5$ mrad
Focusing aerogel improves proximity focusing design by reducing the contribution of radiator thickness into the Cherenkov angle resolution.

**Single ring option**

\( n_1 < n_2 \)

**Multi-ring option**

\( n_1 > n_2 \)

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*T. Iijima et al., NIM A548 (2005) 383*

*A. Yu. Barnyakov et al., NIM A553 (2005) 70*
Single ring option: two approaches

<table>
<thead>
<tr>
<th>Two blocks</th>
<th>Two layer block</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Aerogel RICH for Belle-II:</strong></td>
<td><strong>Aerogel from BINF&amp;BIC:</strong></td>
</tr>
<tr>
<td>– $n_1=1.045$, $n_2=1.055$</td>
<td>– $n_1=1.045$, $n_2=1.053$</td>
</tr>
<tr>
<td>– Thickness – 20 + 20 mm</td>
<td>– Thickness – 15 + 15 mm</td>
</tr>
<tr>
<td>– Distance – 200 mm</td>
<td>– Distance – 200 mm</td>
</tr>
<tr>
<td>• HAPD with 5x5 mm pixel</td>
<td>• Philips DPC3200 – 4x4 mm pixel</td>
</tr>
<tr>
<td>• $\sigma_{\Theta}=15.8$ mrad and $N_{pe}=8.6$</td>
<td>• $\sigma_{\Theta}=11.2$ mrad and $N_{pe}=6.6$</td>
</tr>
<tr>
<td>$\sigma_{\Theta}(\text{track})=\sigma_{\Theta}/\sqrt{N_{pe}} \approx 5.4$ mrad</td>
<td>$\sigma_{\Theta}(\text{track})=\sigma_{\Theta}/\sqrt{N_{pe}} \approx 4.4$ mrad</td>
</tr>
</tbody>
</table>

*S. Nishida et al., NIM A 766 (2014) 28*

Preliminary results of BINF testbeam 2016
Beam test of FARICH at CERN PS T10, June 2012

4-layer aerogel
- $n_{\text{max}} = 1.046$
- Thickness 37.5 mm
- Focal distance 200 mm

Test conditions
- Positive polarity: $e^+, \mu^+, \pi^+, K^+, p$
- Momentum: 1–6 GeV/c
- Trigger: a pair of sc. counters 1.5x1.5 cm$^2$ in coincidence separated by ~3 m
- No external tracking, particle ID, precise timing

DPC matrix 20x20 cm$^2$
- Sensors: DPC3200-22-44
- 3x3 modules = 6x6 tiles = 24x24 dies = 48x48 pixels
- 576 time channels
- 2304 amplitude (position) channels
- Operation at −40°C to reduce dark counts
Beam test results at CERN PS T10, June 2012

Hit positions

Ring radius distributions

σ = 48 ps

P = 6 GeV/c

S(π/K) = \( \frac{R_{\pi} - R_{K}}{\sigma_{\pi}} \)

π / K : 7.6σ @ 4 GeV/c

µ / π : 5.3σ @ 1 GeV/c

Forward RICH for PANDA

Particle ID: $\pi/K/p$ up to 10 GeV/c 3m$^2$ detector area (MaPMTs)

**Mirrors**
- Flat segments
- Float glass substrate 2 mm thick
- Al+SiO$_2$ coating, R$\geq$90%

**Radiator**
- Focusing 2- or 3-layer aerogel
- 40 mm thick

**Photon Detector**
Hamamatsu H12700 MaPMT
- flat panel,
- 8x8 anode pixels of 6mm size
- 87% active area ratio
- Bialkali photocathode
- Gain: $1.5 \cdot 10^6$
Forward RICH for PANDA (prototype)

- MaPMT
- Mirror
- Aerogel
- MaPMT H12700
- MCP PMT (Planacone)

Graphs showing the relationship between the thickness of the aerogel block and the refractive index.
Super Charm-Tau Factory project

Factory outline:
- Double ring symmetric $e^+e^-$ collider with Crab Waist scheme
- $E_{\text{c.m.}} = 2\div5$ GeV
- $L = 10^{35}$ cm$^{-2}$s$^{-1}$ (100 times more than existing c-$\tau$ factories)
- Longitudinal polarization of $e^-$ - beams in IP
Detector for Super $\tau$-factory

**Physical program:**
- Rare decays of D-mesons, $\tau$-lepton;
- D-meson oscillations;
- Searches for lepton-flavor-violating decays of $\tau$ \textit{(for instance $\tau \rightarrow \mu \gamma$)};
- ...

**Detector requirements**
- An excellent momentum resolution for charged particles and a good energy resolution for photons;
- $K/\pi$ separation higher than 3\(\sigma\);
- $\mu/\pi$ separation up to 1.5 GeV/c;
- DAQ system, which is able to read events at a rate of 300÷400kHz with 30kB event length;
- ...

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1 – Vertex Detector
2 – Drift Chamber
3 – PID => FARICH
4 – EMC
5 – Superconducting Solenoid
6 – Yoke + MU system

See CTF CDR (https://ctd.inp.nsk.su/docs/ScTau_CDR_en/CDR_en_ScTau.pdf)
FARICH system

Main parameters

- Focusing aerogel radiator, $n_{\text{max}} = 1.07$, 4 layers
- Proximity focusing at distance 200 mm
- Photon detector: $\sim 3 \times 3 \text{mm}^2$, pitch $3.5 \div 4 \text{ mm}$
  
  \textit{DPC (Philips), MPPC (Hamamatsu), NUV-HD (FBK-IRIS), ArrayJ (SensL), MA MCCP PMT (Planacon)}

- Area of the photon detector: 20 m²
- Area of the aerogel radiator: 14 m²
- $\sim 1 \div 2 \cdot 10^6$ channels
- Readout electronics based on ASIC
  
  \textit{TOFPET-2 or similar}

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Production of aerogel in Novosibirsk

• Started in 1986 by the Boreskov Institute of Catalysis SB RAS in cooperation with the Budker Institute of Nuclear Physics SB RAS
• Hydrophilic
• Refraction indices 1.006 – 1.08 (1.08-1.13 produced by sintering)
• Block dimensions up to 200x200x50 mm³ (n=1.03) & 200x200x30 mm (n=1.05)
• Inner surface 800 m²/g
• Remarkable optical quality has been achieved:
  \[ L_{\text{abs}} (400\text{nm}) = 5 \text{ – 7 m} \]
  \[ L_{\text{sc}} (400\text{nm}) = 4 \text{ – 6 cm} \]
  (Clarity = 0.0043 – 0.0064 μm⁴/cm)
Refractive index

\[ n^2 = 1 + 0.438 \cdot \rho \]

\( n = 1.006 \ldots 1.070 \) – synthesis
\( n = 1.070 \ldots 1.130 \) – sintering

\( \text{SiO}_2 + \text{H}_2\text{O}(1\pm5\%) \)
Light scattering

Rayleigh scattering on aerogel structure elements

Transmittance:

\[
T = \frac{I}{I_0} = A \cdot \exp \left( -\frac{d}{L_{sc} \cdot (\lambda/400)^4} \right) = A \cdot \exp \left( -\frac{C \cdot d}{\lambda^4} \right)
\]

A – surface scattering coefficient
~0.95 for intrinsic surface
~0.70 for polished surface

\(L_{sc}\) – scattering length at \(\lambda=400\text{nm}\)
> 4.5 cm

C – clarity \((0.4^4 / L_{sc})\)
< 0.0057 \(\mu\text{m}^4/\text{cm}\)
Light absorption

Light is absorbed by impurities.

Contamination of metals (Fe, Co, Cu, Mn, etc.) is determined by raw material quality and synthesis technology.
Water adsorption

\[ 1 \text{ cm}^3 \Rightarrow S_{\text{inner}} \sim 100 \text{ m}^2 \]

Water adsorption

RLC degradation

\[ \tau \sim \text{hours} \]

\[ \tau \sim \text{weeks} \]

A.Yu.Barnyakov et al., NIM A598 (2009) 166

Aerogel study with digital X-ray setup

<table>
<thead>
<tr>
<th>Layer</th>
<th>n</th>
<th>h, mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Layer 1</td>
<td>1.050</td>
<td>6.2</td>
</tr>
<tr>
<td>Layer 2</td>
<td>1.041</td>
<td>7.0</td>
</tr>
<tr>
<td>Layer 3</td>
<td>1.035</td>
<td>7.7</td>
</tr>
<tr>
<td>Layer 4</td>
<td>1.030</td>
<td>9.7</td>
</tr>
</tbody>
</table>

- 100x100x31 mm$^3$
- $L_{sc}(400\text{nm})=43$ mm
- $n^2=1+0.438\rho$
Application of aerogel produced in Novosibirsk

Produced in Novosibirsk:
- >1000 l of aerogel for threshold ACC
Application of aerogel produced in Novosibirsk

Produced in Novosibirsk:
- >1000 l of aerogel for threshold ACC
- >6 m² of aerogel radiators for RICH counters

SND ASHIPH system
- π/K at 300-870 MeV/c
- Aerogel \( n=1.13 \)
- V~9 liters

KEDR ASHIPH system
- π/K 0.6-1.5 GeV/c
- Aerogel \( n=1.05 \)
- V~1000 liters

RICH1 LHCb (LHC-CERN)
- π/K 5.5-8.0 GeV/c
- Aerogel \( n=1.03 \); size 20x20x5 cm³
- S ~ 0.5 m²

RICH of AMS-02 (ISS)
- Antimatter search & Cosmic rays study
- Aerogel \( n=1.05 \); S ~ 1 m²

DIRAC-II (PS-CERN)
- Aerogel \( n=1.008 \)
- π/K 5.5-8 GeV/c
- V~ 12 liters

RICH CLAS-12 (J-Lab)
- π/K/p at 4σ level up to few GeV/c
- Aerogel \( n=1.05 \)
- S ~ 6 m²

The RICH concept
- aerogel plane
- mirror
- spherical mirror
- photon detectors
- 6 cm
- 2 cm
- Kaon
- Cherenkov photons

Hybrid solution:
- proximity gap and mirror focusing
- Small polar angle, up to 8 GeV/c
- 1m gap
- thin aerogel
- direct imaging of the Cherenkov photons

The RICH in CLAS12
- The RICH will replace the existing Low Threshold Cherenkov detectors
- first sector for the beginning of the CLAS12 operation (October 2017)
- second sector for operation with transverse target
- Challenging project because of the geometry of the detector
- large size
- no free space out of the acceptance

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Application of aerogel produced in Novosibirsk

Produced in Novosibirsk:
- >1000 l of aerogel for threshold ACC
- >6 m² of aerogel radiators for RICH counters

Future projects:
- ~20 m² for FARICH are needed
Addendum
Continuous density gradient aerogel

To produce aerogel tiles with designed profile of gradient we modernized the method suggested by [S.M. Jones “A method for producing gradient density aerogel”, J Sol-Gel Sci Technol. 44 (2007) 255]

- We mix two pre-prepared mixtures with different content of TEOS fed by peristaltic pumps from vessels A and B.
- The mixture with designed concentration of TEOS seeps through the filter to the mould where gelation takes place.
- The mould is positioned on the vertically moving table. The peristaltic pumps and moving table are controlled by a computer.

Refractive index profile along thickness
FARICH perspectives

For the proximity focusing RICH detectors there are 3 main contributions to the resolution: $\sigma_{\Theta}^2 = \sigma_{\text{chr}}^2 + \sigma_{\text{geom}}^2 + \sigma_{\text{phot}}^2$

- Suggested technology of gradient aerogel tile production could give us radiators with $\sigma_{\text{geom}} \ll \sigma_{\text{chr}}$
- Philips Digital Photon Counting are working on the next version of the sensor which could read out the time and micro-cell number (instead of the number of fired cells) of the hit, $\sigma_{\text{phot}} \approx 20 \mu m \ll \sigma_{\text{chr}}$
- Could we build RICH with $\sigma_{\Theta}^2 \approx \sigma_{\text{chr}}^2$?
Summary

• Development of aerogel Cherenkov counters for HEP experiments have been carrying out in Novosibirsk since 1986 by BINP and BIC in close cooperation.

• The ASHIPH method for threshold Cherenkov counters was developed. Good π/K-separation was achieved in ASHIPH system of the KEDR detector and the SND detector.

• Aerogel radiators for RICH detector of the AMS02 experiment were produced in Novosibirsk. Experimental number of photoelectrons and Cherenkov angle resolution are in good agreement with MC simulation. The AMS02 experiment has been operating since 2010 at ISS.

• Production of aerogel radiators with 200x200 transvers dimensions and high transparency for RICH of CLAS12 project is organized in Novosibirsk.

• Two projects of FARICH detectors for PANDA experiment and SCTF experiment are under development now.
Aerogel RICH of AMS-02 at ISS

• Antimatter search
• Dark matter
• Cosmic rays
• Strangelets search
• ...

Measurement of $Z$ of the nucleon, $N_{pe} \sim Z^2$
BIC/BINP production, $n=1.05$
It has working at ISS since 2011
RICH detector for the CLAS12

- $K/\pi$ and $K/\rho$ separation at $>4\sigma$ level in few GeV/c region;
- The RICH will replace the existing LTC detectors;
- Installation in CLAS12 by September 2017;

*RICH 2016, September 9th 2016, Bled: talks by M.Marazita, M.Contralbrigo, E.Kravchenko*
KEDR experiment at VEPP-4M

Physics program
- Precise particle mass measurements: $J/\psi$, $\psi(2S)$, $\psi(3770)$, $\tau$ lepton, $D$ mesons, $Y$ mesons
- Measurements of $\psi$ and $Y$ mesons lepton width
- $R$ measurement in 2-10 GeV c.m. energy range
- $\gamma\gamma \rightarrow$ hadrons and other $2\gamma$ processes
- Branching fractions measurements in charm and bottom quark systems (above $10^{-4}$)

VEPP-4M
- Symmetric $e^+e^-$ collider
- $E_{c.m.} = 2$–10 GeV
- $L = (1÷80) \times 10^{30}$ cm$^{-2}$s$^{-1}$
- Precise energy calibration:
  RD: $(5÷15) \times 10^{-6}$
  CBS: $3 \times 10^{-5}$
KEDR ASHIPH counters

End-cap counter

Barrel counter

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Aerogel Cherenkov counters for SND

Outline

• π/K separation from 300 to 870 MeV/c
• Cylindrical shape: R=105±141 mm
• Case material: 1mm of Al
• 3 segments of 3 counters in each
• Solid angle: ~60% of 4π
• Thickness: 0.09 $X_0$

Counter Design

• Scheme: ASCHIPH
• WLS position: displaced by ~5° from counter center
• Aerogel thickness: ~30 mm

Aerogel parameters

• Refraction index: $n=1.13\pm0.01$
• Density: $\rho=0.65$ g/cm$^3$
• $L_{sc}=19$ mm at $\lambda=400$ nm
• $L_{abs}=100$ cm at $\lambda=400$ nm
What it is -- Aerogel?(2)

• Production method:
• Synthesis of the alcogel:
• \( \text{Si(OR)}_4 + 2\text{H}_2\text{O} \rightarrow \text{SiO}_2 + 4\text{HOR} \)
• alkoxide water silica alcohol
• Supercritical drying in the autoclave to remove alcohol \( P_{\text{max}} = 100 \text{ atm}, \quad T_{\text{max}} = 260^\circ\text{C} \)
  • methanol -- \( P_{\text{cr}} = 81 \text{ atm}, \quad T_{\text{cr}} = 230^\circ\text{C} \)
  • isopropanol -- \( P_{\text{cr}} = 53 \text{ atm}, \quad T_{\text{cr}} = 235^\circ\text{C} \)
  • carbon dioxide -- \( P_{\text{cr}} = 73 \text{ atm}, \quad T_{\text{cr}} = 31^\circ\text{C} \)

• Aerogel parameters:
• Density \( 0.003 \div 1.0 \text{ g/cm}^3 \)
  \( (\text{fused silica} \quad \rho = 2.2 \text{ g/cm}^3) \)
• Refractive index
  • \( n \approx 1 + 0.2 \cdot \rho [\text{g/cm}^3] \rightarrow \)
  • \( (n = 1.0006 \div 1.2) \)
• Porosity 99.8%
• Inner surface 800 m\(^2\)/g
Era of high transparency aerogel

- One-step technology
- Direct alcogel synthesis
  \[ \text{Si(OR)}_4 + 2\text{H}_2\text{O} \rightarrow \text{SiO}_2 + 4\text{HOR} \]
- alkoxide water silica alcohol
  \[ L_{sc}(400) \sim 20 \text{ mm} \]

- Two-step technology
- A mixture of oligomers preparation
  \[ \text{Si}_k\text{O}_l(\text{OR})_m(\text{OH})_n \rightarrow \text{SiO}_2 + \text{alcohol} \]
- \[ L_{sc}(400) > 35 \text{ mm} \]

Two-step technology was implemented at BIC in 1992
Quartz vs Aerogel radiators

Difference in Cherenkov angle $\theta_c$ for $\pi$ and $K$
Bands – chromatic dispersion in 350-700 nm

\[ \Delta \theta_c \text{ [mrad]} \]

Fused silica

Aerogel $n=1.05$
DPC: Front-end Digitization by Integration of SPAD & CMOS Electronics

Philips Digital Photon Counting (PDPC)