Applicability of digital silicon photomultipliers in RICH detectors


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Focusing aerogel improves proximity focusing design by reducing the contribution of radiator thickness into the Cherenkov angle resolution.

Multi-layer monolith aerogels have been produced by the Boreskov Institute of Catalysis in cooperation with the Budker INP since 2004.

T. Iijima et al., NIM A548 (2005) 383
A. Yu. Barnyakov et al., NIM A553 (2005) 70
FARICH for Super Charm-Tau Factory

$\mu/\pi$: MC simulation

MPPC S10362 3x3mm, D=200mm, 4-layer aerogel

- Proximity focusing RICH
- 21 m$^2$ photon detector area
- Use SiPMs due to 1T magnetic field
- $\sim 10^6$ pixels with 4 mm pitch
- 4-layer or gradient aerogel radiator

$\mu/\pi$ is required for LFV search in $\tau \rightarrow \mu \gamma$. Target sensitivity on $\text{Br}(\tau \rightarrow \mu \gamma) \sim 10^{-9}$

$\mu$ momentum range for $\tau \rightarrow \mu \gamma$ at $E_{cm}=4.2$GeV
SiPMs in RICH application
(single photons)

Pros
• High PDE
• Sub-ns timing resolution
• Immune to magnetic field
• Active/Total area ratio
• Very compact with low material budget

Cons
• High dark count rate (10-100 kHz/mm²)
• Radiation induced damage (∼10¹⁰ n₁MeV/cm²)

• S. Korpar et al., NIM A 594 (2008) 13
• A.Y. Barnyakov et al., NIM A 732 (2013) 352
• S. Korpar et al., NIM A 766 (2014) 107
• M. Contalbrigo, NIM A 787 (2014) 224
• I. Balossino et al., NIM A 876 (2017) 89
FARICH detector prototype with CPTA MRS APDs
BINP e\(^-\) test beam in 2011

32 CPTA MRS APDs with active pixel size 2.1x2.1mm\(^2\)
DCR ~ 5 MHz/device

4-layer aerogel focusing at 62 mm
n\(_1\)=1,050  t\(_1\)=6,2mm
n\(_2\)=1,041  t\(_2\)=7,0mm
n\(_3\)=1,035  t\(_3\)=7,7mm
n\(_4\)=1,030  t\(_4\)=9,7mm
Size: 100x100x31mm\(^3\)
L\(_{\text{sc}}\)(400nm) = 43mm
Given a tracking system, wide beam and enough particle statistics, a single PD pixel is enough to build the distribution of Cherenkov photons on $R_{ch} (\theta_{ch})$.

Many pixels can be combined to improve accuracy and align the tracking system with the photon detector.
Analog SiPM vs Digital SiPM

**Analog**
- Established technology
- Great progress in improving parameters: PDE, DCR, RadHard
- High active/total area ratio
- Availability from different vendors
- Need for external analog-to-digital readout electronics – bulky detector, higher power consumption
- No control of individual SPADs

**Digital**
- On-chip integration of readout electronics – no need for ASICs
- Possibility to locate firing SPAD in low light applications – ~10 um resolution
- Better timing resolution
- Control of individual SPADs for inhibiting noisy ones
- Different designs for different applications – cost issue
- Limited possibilities for custom modifications due to CMOS production process
DPC is an Integrated, Scalable Solution

Analog SiPM

- discrete, limited integration
- analog signals to be digitized
- dedicated ASIC needed
- difficult to scale

Digital SiPM

- fully integrated thanks to CMOS
- fully digital signals
- no ASIC needed
- fully scalable

Courtesy of Philips Digital Photon Counting
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

Power & Bias
200 MHz ref. clock
Serial configuration interface
Serial Data output (x2)

Flash Memory
Temp. sensor
Detector array 8 x 8 dSiPMs

13 June 2018  
Courtesy of Philips Digital Photon Counting
DPC readout units

Geometrical efficiency ≈70%

Module
- Geometrical efficiency ≈70%

Tile
- Single amp. channel
- 6396 cells (DPC6400-22)
- 3200 cells (DPC3200-22)

Pixel - single amp. channel
- 32 columns
- 32 rows

Sensor - single time channel
- 4 Pixel
- 4 Subpixels

32.6 mm

3.20

7.15

7.88

3.88
FARICH prototype with DPC

4-layer aerogel
- $n_{\text{max}} = 1.046$
- Thickness 37.5 mm
- Calculated focal distance 200 mm
- Hermetic container with plexiglass window to avoid moisture condensation on aerogel

Square matrix 20x20 cm$^2$
- Sensors: DPC3200-22-44
- 3x3 modules = 6x6 tiles = 24x24 dies = 48x48 pixels in total
- 576 timing channels
- 2304 amplitude channels (pixels 3.2x3.9 mm$^2$)
- 4 levels of FPGA readout: tiles, modules, bus boards, test board
Main objective:
Proof of concept: full Cherenkov ring detection with a DPC array

Details:
• Operation temperature is $-40^\circ C$ to suppress dark count rate
  – Dead time is 720 ns.
  – $DCR(+25^\circ C) \approx 10 \text{ Mcps/sensor}$
    single photon detection is not feasible!
  – $DCR(-40^\circ C) \approx 100 \text{ kcps/sensor}$
    inefficiency is 7% .
• 2 stage cooling: LAUDA process thermostat + Peltiers.
• Dry $N_2$ constant flow to avoid condensation.
PDPC-FARICH: Cherenkov ring

Clock skew correction between dies

~80 photons/die

Hit times w.r.t. mean hit time in event

Clock skew correction between dies

FWHM 66 ps
Timing correction by Cherenkov ring data

Hit timing vs $\varphi$-position

Before

After
Single photon timing resolution for Cherenkov light

Fit two gaussians plus constant. 90% of area is contained in the narrow gaussian.

$\sigma_{\text{narrow}} = 48 \text{ps}$

Hit time w.r.t. fitted event time, ns

Hit time w.r.t. fitted event time, ns

Correction by PiLas+ring

Correction by PiLas

no correction

Hit time w.r.t. fitted event time, ns
Number of photoelectrons

Protons, e, μ, π

N_{pe} = 12 after taking into account crosstalks. ~2x lower than expected.
Absolute PDE measurement of DPC

Hamamatsu S1336-8BQ

Thermostat

T = -30°C

Integration volume

Diaphragm

Ext. trigger

voltmeter

ampifier

PC

G

LED

pulse generator

P(0) = e^{-\mu}, \mu = \text{PDE} \cdot N_\gamma

Dark count rate and dead time taken into account:

P(0) = \frac{1 - P(\text{signal+dc})/\text{LTR}}{1 - P(\text{dc})/\text{LTR}}

LTR – live time ratio, determined only by dark counts coming before LED pulse.

P(hit) = \frac{N_{hit}}{f \cdot T_{run}}

LED ON: P(hit) = P(\text{signal+dc})

LED OFF: P(hit) = P(\text{noise})

P(\text{signal+dc}) = LTF - (LTF - P(\text{dc})) e^{-\text{PDE} \cdot N_\gamma}

N_\gamma per pulse is determined from photocurrent of PIN diode and calibrated ratio of test/monitor channels.
Absolute PDE of DPC

Fit $P(\text{signal+dc})$ as function of $N_\gamma$ and extract PDE

![Graph of PDE vs Number of incident photons]

- $P(\text{signal+dc})$ as a function of $N_\gamma$

**Summary:**

- PDE(470 nm) 19±1% in our measurement vs 36% by PDPC measurement
Optical crosstalks in DPC

X-talks between pixels deteriorate position resolution

Crosstalk ways:

- between pixels of the same die (3-4%) go likely via Si substrate
- between neighboring dies (0.1-0.2%) go via protection glass

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dSiPMs in RICH

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Irradiation of DPC tiles
proton beam (800 Mev/c) at COSY PS in FZ Jülich

DPC tiles cooled to −18°C. Maximum fluence accumulated: 4·10^{11} p/cm^2
Radiation hardness study of DPC

Estimated die DCR vs active cell fraction

Dose ~ $4 \times 10^{11}$ p$^+/cm^2$
Dose ~ $7 \times 10^{10}$ p$^+/cm^2$
Dose ~ $3 \times 10^{10}$ p$^+/cm^2$
Dose ~ $9 \times 10^{9}$ p$^+/cm^2$
Dose ~ $2 \times 10^{9}$ p$^+/cm^2$
Dose ~ $0$ p$^+/cm^2$

Efficiency, %

Active cells, %

Estimated PDE degradation due to DCR increase with inhibiting most noisy cells

2 times drop

M.Yu. Barnyakov et al, NIM A 824 (2016) 83

$4 \times 10^9 n_{1MeV/cm^2}$
Desired characteristics of digital SiPMs for aerogel RICH

- PDE as high as possible: high active area ratio → amplitude dynamic range does not matter → large SPAD
- Room temperature operation → dark count rate at room temperature ≤ 10 kHz/mm²
- Dead time ratio ≤ 1%
- Position resolution $\sigma_x \leq 1$ mm: may be realized by determining position of a fired SPAD in an array of size ~3x3 mm²
- SPTR ≤ 100 ps would be useful for DIRC-like detectors or suppressing uncorrelated background
- Radiation hard $\geq 10^{11}$ n$_{1\text{MeV}}$/cm², dead time ratio after irradiation ≤ 10-20%, or cheap enough to be replaced after degradation
- Fast analog output for generating trigger from rings
Density of photoelectrons in aerogel RICH

- PDE of MPPC S13361-3050
- Pixel packing factor - 80%
- Ring radius ~ 55 mm
- Ring width FWHM ~ 3mm

→ 10% loss of photons for pixel size 2.5 mm
Summary & conclusion

- Digital SiPMs are promising sensor candidates for RICH applications in visible & NUV range and only one in strong magnetic fields
- DPC parameters were studied: not quite suitable for aerogel RICH due to large dead time
- Looking for other dSiPM solutions for application in Super Char-Tau Factory (Novosibirsk)
- Welcome to collaboration!
Thank you for your attention!
Nice Cherenkov rings from aerogel detected by DPC at the $e^-$ beam at BINP

2-layer aerogel of 40mm thick
D=160 mm