Beam test of FARICH prototype with DPC (dSiPM)

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FARICH concept

Focusing Aerogel RICH – FARICH

Improves proximity focusing design by reducing radiator thickness contribution into the Cherenkov angle resolution

Single ring option

Multi-ring option

T. Iijima et al., NIM A548 (2005) 383
A. Yu. Barnyakov et al., NIM A553 (2005) 70
Multi-layer ‘focusing’ aerogels

- Produced by Boreskov Institute of Catalysis (Novosibirsk) in cooperation with Budker Institute since 2004

First 4-layer sample produced in 2004
A.Yu.Barnyakov et al., NIM A553 (2005) 70
FARICH projects and proposals

FARICH for Super Charm-Tau Factory (Novosibirsk)
Particle ID: $\mu/\pi$ up to 1.7 GeV/c
$21\,m^2$ detector area (SiPMs)
~1M channels

FARICH for ALICE HMPID upgrade
Particle ID: $\pi/K$ up to 10 GeV/c, $K/p$ up to 15 GeV/c
$3m^2$ detector area (SiPMs)

Forward Spectrometer RICH for PANDA
Particle ID: $\pi/K/p$ up to 10 GeV/c
$3m^2$ detector area (MaPMTs or SiPMs)
Philips Digital Photon Counting (PDPC)

Philips Digital Photon Counting is designing and manufacturing scalable detectors based on digital Silicon Photomultiplier (dSiPM) technology – a new type of advanced solid state light detector, now called Digital Photon Counter (DPC).

Potential Applications

• Medical Imaging
• Life Sciences
• High Energy Physics
• Material Testing/Detection
• Process Control
DPC: Front-end Digitization by Integration of SPAD & CMOS Electronics

analog SiPM

Summing all cell outputs leads to an analog output signal and limited performance

Digital Photon Counter (DPC)

TDC and photon counter

Digital Cells

Digital output of
- Number of photons
- Time-stamp

Integrated readout electronics is the key element to superior detector performance

DPC hierarchy for FARICH prototype

Pixel = 1 amplitude ch
6396 cells (DPC6400-22-44)
3200 cells (DPC3200-22-44)

Die = 1 timing ch

Pixels in module packing density ~70%
First test of DPC in High Energy Physics: FARICH Detector @ CERN, June 2012

Main objective:
Proof of concept: full Cherenkov ring detection with DPC array

Timeline:
- Started to envisage: 28/02/12
- Requirements for the FARICH prototype test setup fixed: 30/04/12
- Prototype operational @ Aachen Labs: 03/06/12
- Installed @ CERN: 12/06/12
- Subsequent beam runs for 12 days until 25/06/12 with smooth setup operation

Fast prototyping!
FARICH prototype with DPC: engineered and made by PDPC

- DPC detector 20x20 cm²
- Aerogel sample container on movable table
- Operation at -40°C to suppress dark counts: DCR ~ 100 kcps/die. Blow dry N₂ to avoid condensation.

Process thermostat
LAUDA Integral XT

Thermal insulation:
10 cm styrofoam
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 $20 \times 20 \text{ cm}^2$
- Sensors: DPC3200-22-44
- 3x3 modules = 6x6 tiles = 24x24 dies = 48x48 pixels in total
- 576 time channels
- 2304 amplitude (position) channels
- 4 levels of FPGA readout: tiles, modules, bus boards, test board
FARICH prototype at CERN PS T10 beam channel

Inventor of DPC
Thomas Frach
Observation of Cherenkov ring

**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 of trigger
- Hardware hit selection in a programmable time window to fit in data bandwidth

**Pixel hit map**

$\text{hits.yindex:hits.xindex}$
Event-by-event ring fit

Hit selection and ring fit:
- Reject central hits
- Select hits in 4 ns time window
- More than 3 selected hits per event
- 4 parameters fitted: $X_{\text{center}}$, $Y_{\text{center}}$, R, $\tau_0$

![Diagram of hits and fit parameters](image)

<table>
<thead>
<tr>
<th>Statistics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries</td>
<td>18</td>
</tr>
<tr>
<td>Mean</td>
<td>0.06901</td>
</tr>
<tr>
<td>RMS</td>
<td>0.2349</td>
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</table>
Die-to-die clock skew correction

All dies hit times w.r.t. mean event time

~80 photons/die

Clock skew correction between dies

FWHM 66 ps
Timing correction by ring data

Hit timing vs $\phi$-position

Before

After
Timing resolution for Cherenkov photons

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

\[ \sigma_{\text{narrow}} = 48 \text{ps} \]
Ring center adjusted distributions
P=6 GeV/c, L=200mm

Ring center position in detector plane

Hit positions
Number of photoelectrons

The graph shows the distribution of photoelectrons with the number of pixels hit on the x-axis and the number of photoelectrons on the y-axis. The data includes measurements for protons, electrons (e), muons (μ), and pions (π). The histogram indicates that the mean number of photoelectrons is 13.84 with a RMS of 3.936. The total number of entries is 2158095.
Radial distributions
P=6 GeV/c, L=200mm

Hit distribution on radius

Event distribution on radius

entries: 1152798

entries: 63940
Ring radius distribution fit

**Fit function**
sum of three gaussians for each particle type with distinct radius plus gaussian background (to account for non-monochromatic particles in the beam)

**Free parameters:**
- Particle momentum
- Ring radius of rightmost gaussian (other radii derived from Cherenkov law)
- Constants and sigmas of all gaussians

**Fixed parameter:**
- Effective refractive index \( n_{\text{eff}} = 1.038 \)
Aerogel-detector distance dependence “pions” at P=6 GeV/c

\[ R = p_0 + p_1 L \]

\[ \sigma_t \approx 0.8\text{mm} \]
Momentum dependence

6 points on momentum

Not more than 3 particle peaks are fit in each point
Momentum dependence...

Ring radius vs $\beta\gamma = p/M$

Ring radius $\sigma$ vs $\beta\gamma$

Cherenkov law fit

$$R = L \tan \theta'_c$$
Rather idealized simulation for 
P=6 GeV/c gives 
N_{pe} (π) = 24 
π/K separation = 9 σ 

Experimental results are far from simulated values, but there are reasons: 
• Seems to be lower PDE than measured by PDPC previously (needs to be checked) 
• Resolution deterioration due to pixel crosstalk 
• No tracking (simulation relies on it) 
• Probably: focusing aerogel tested gives wider ring than expected

\[ S = 2 \frac{R_π - R_K}{(σ_π + σ_K)} \]

\[ π/K: \ 3.8σ \ @ \ 6\text{GeV/c} \]
\[ μ/π: \ 4.5σ \ @ \ 1\text{GeV/c} \]
Crosstalk between pixels

Crosstalk probability (%) on a tile pixel map
Special run with random trigger

Crosstalk is significant only between pixels of one die
Crosstalk between pixels...

Crosstalk distribution of pixel pairs

~4% crosstalk probability between pixels of one die → ring radius resolution deterioration
**Radiation damage:** Dark count rate changing

- **5th day of beam**

Partial recovery is observed after annealing for 2 days at 30°C

**Breakage:** only 4 of 36 tiles failed after 2 weeks and several thermal cycles. DPC modules and tiles was not designed to work routinely at low temperature with frequent thermal cycles. It was just a first test.

**Note:** radiation dose was not monitored during the experiment.
Conclusion

- Beam test of FARICH prototype with Philips DPC was prepared and successfully realized in a short time scale.
- Cherenkov rings are detected from focusing aerogel with ~14 photoelectrons for relativistic particles.
- Timing resolution of $\sigma_t=48$ ps is achieved for single Cherenkov photons.
- $\pi/K$ separation obtained for $P=6$ GeV/c is $3.8\sigma$, $\mu/\pi$ separation is $4.5\sigma$ for $P=1$ GeV/c.
- Signs of radiation damage are observed that partially recovered by annealing at room temperature.
- Very positive experience of 2 weeks operation of the large and complex setup.
- Tests were continued at electron test beam in BINP in January 2013. Results are coming up.
Thank you for attention!
Die trigger
- 1st photon trigger
- no validation
- TDC timestamp

Die readout
- Number of photons
- Recharge
- Die is ready to detect next photons after 720ns

Hit selection
- Hits are selected in a programmable time window generated from ext. sync signal by tile FPGA

FPGA chain readout
- No additional data reduction
- Bottleneck is data transfer to PC by USB 1.1 link @ 12 Mbit/s

Most significant data loss happen at the die level:
- Dead time 720 ns
- DCR = 100 kcps @ -40°C
- Photon detection efficiency loss of ~7%
DPC is an Integrated “Intelligent” Sensor

DPC3200-22-44
DPC6400-22-44

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)

Detector array
8 x 8 dSiPMs
DPC: Front End Digitization Significantly Reduces Temperature Sensitivity

- 24 ps full-width at half-maximum timing resolution of ps-laser
- Photopeak changes 0.33% per degree C due to changing PDE (values of analog SiPM’s are ranging from 2-8%)
- Time changes 15.3 ps per degree C (TDC + trigger network drift)

0.33% / K
Without bias correction!
DPC: CMOS Integration Enables Active Quenching

Figure 11. Generic schematics of a passive (left) and an active (right) quenching circuit employed at the micro-cell level (the micro-cell is represented by the diode symbol).

Cell layout of Digital SiPM cells: Digital electronics take up only 3-6% of active area.

Digital SiPMs show reduced afterpulsing (0.3%) and crosstalk.

Graphics from Spanoudaki & Levin, Stanford, in: Sensors (10), 2010
DPC: CMOS Integration Allows Active Control of Dark Count Rate (DCR)

- Silicon based light sensors have background noise (dark counts), varying with temperature.
- In digital SiPMs every cell can be addressed individually.
- Cells with high dark counts can be switched off.
- A few cells switched off (1-5%) reduces dark count levels by orders of magnitude.
DPC PDE vs wavelength

DPC3200-22-44
Ring fit LH function

- PDF = gaussian on radius x gaussian on time + background
  \[ f(X_i, Y_i, t_i; X_0, Y_0, t_0, R) = \]
  \[ \frac{N_{\text{pe}} S_{\text{px}}}{2\pi R} G \left( \sqrt{(X_i - X_0)^2 + (Y_i - Y_0)^2}; R, \sigma_R \right) \times G(t_i; t_0, \sigma_t) + B, \]
  where
  - \( X_i, Y_i, t_i \) – pixel hit position and time
  - \( X_0, Y_0 \) – ring center position,
    \( t_0 \) – mean event time,
    \( R \) – ring radius,
  - \( N_{\text{pe}} \) – mean number of photoelectrons in a ring,
  - \( S_{\text{px}} \) – pixel area,
  - \( \sigma_R, \sigma_t \) – sigmas on radius and time,
  - \( B \) – noise hit probability per pixel and time unit.

- The following function is minimized to fit the ring
  \[ -\log \text{LH} = - \sum_{i=1}^{N_h} \log f(X_i, Y_i, t_i; X_0, Y_0, t_0, R) \]
Crosstalk treatment

Let’s assume there are two channels (1 and 2) with independent probabilities to fire $P_i^0$ and dependent probabilities to fire determined by $P_x$ (crosstalk probability), then:

\[
P_{12} = P_1^0 P_2^0 + (1 - P_1^0) P_2^0 P_x + (1 - P_2^0) P_1^0 P_x \quad \text{– probability that both pixels fire}
\]

\[
P_{\overline{1}2} = (1 - P_1^0) P_2^0 (1 - P_x) \quad \text{– probability that 1^{st} pixel does not fire and 2^{nd} fires}
\]

\[
P_{1\overline{2}} = (1 - P_2^0) P_1^0 (1 - P_x) \quad \text{– probability that 1^{st} pixel fires and 2^{nd} does not fire}
\]

\[
P_{\overline{1}\overline{2}} = (1 - P_1^0)(1 - P_2^0) \quad \text{– probability that both pixels do not fire}
\]

As $P_{12} + P_{\overline{1}2} + P_{1\overline{2}} + P_{\overline{1}\overline{2}} = 1$, there are 3 independent equations and all unknowns ($P_1^0, P_2^0, P_x$) can be determined from observables ($P_{12}, P_{\overline{1}2}, P_{1\overline{2}}$).

The only pre-assumption that crosstalk probabilities are symmetric, i.e.:

\[
P_{1\rightarrow 2} = P_{2\rightarrow 1} \equiv P_x
\]
Timing resolution (log y-scale)

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

- Entries: 531184
- Mean: 0.01497
- RMS: 0.1077
- χ² / ndf: 9.31e+03 / 73
- Bkg: 3.28 ± 0.55
- Const1: 7.82e+04 ± 1.53e+02
- Mean1: -0.00531 ± 0.00007
- Sigma1: 0.0481 ± 0.0001
- Const2: 1.42e+03 ± 1.64e+01
- Mean2: 0.23 ± 0.00
- Sigma2: 0.186 ± 0.001