Applicability of digital silicon photomultipliers in RICH detectors

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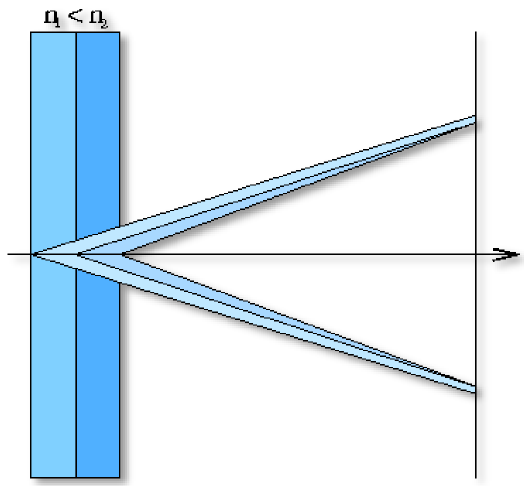
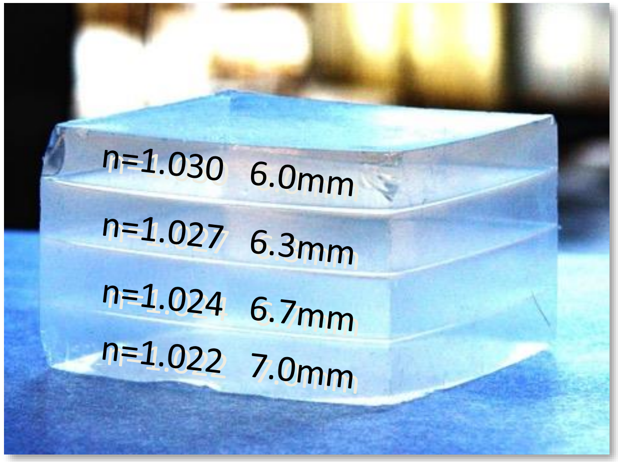
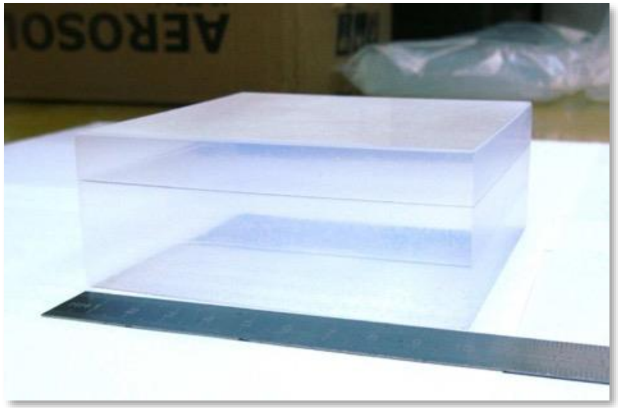
Focusing Aerogel RICH (FARICH)



First sample of 4-layer aerogel



3-layer aerogel 115x115x41 mm^3

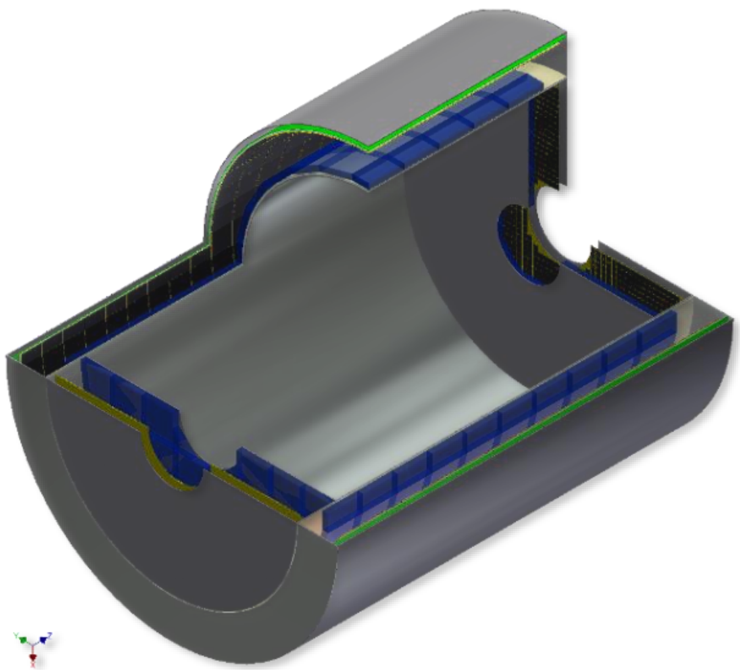


Focusing aerogel improves proximity focusing design by reducing the contribution of radiator thickness into the Cherenkov angle resolution

Multi-layer monolith aerogels have been being 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

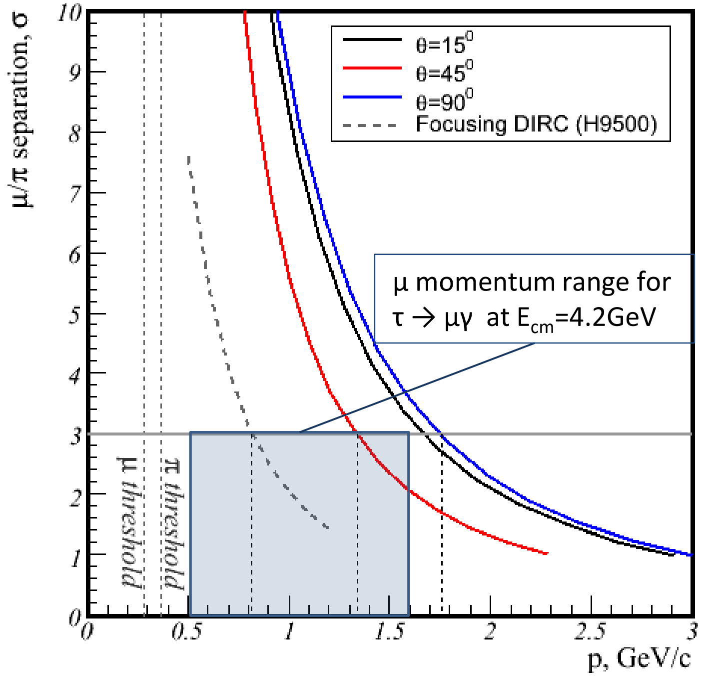
FARICH for Super Charm-Tau Factory



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

μ/π: MC simulation

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



μ/π is required for LFV search in τ→μγ.
Target sensitivity on Br(τ→μγ) ~10^{-9}

SiPMs in RICH application (single photons)

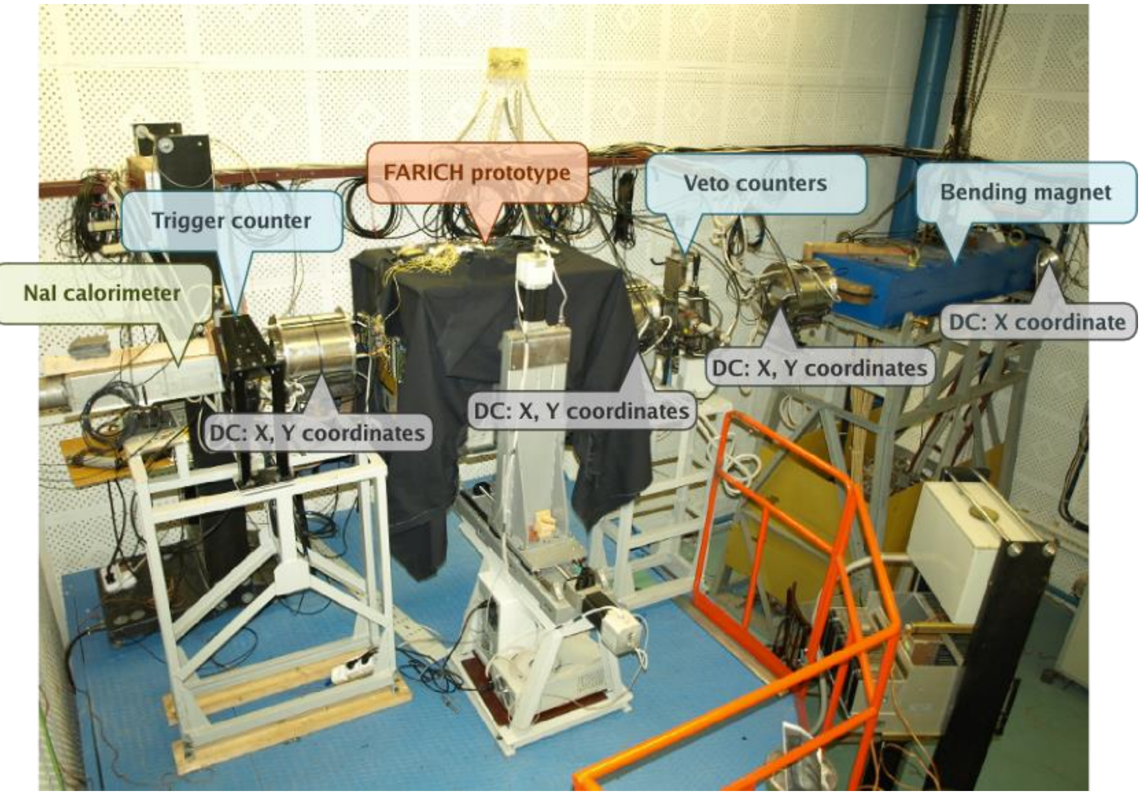
Pros

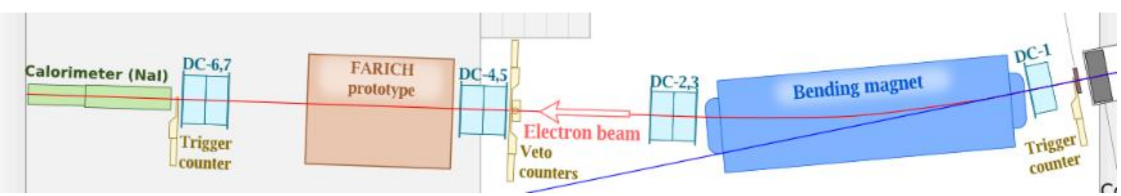
- High PDE
- Sub-ns timing resolution
- Immune to magnetic field
- Active/Total area ratio
- Very compact with low material budget

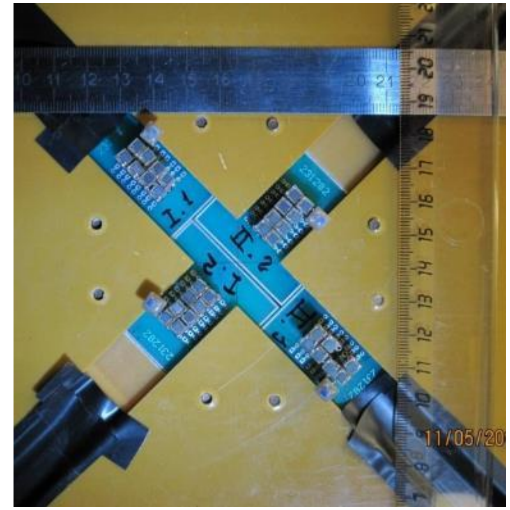
Cons

- High dark count rate (10-100 kHz/mm^2)
- Radiation induced damage (~10^{10} n_{1MeV}/cm^2)
  - 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





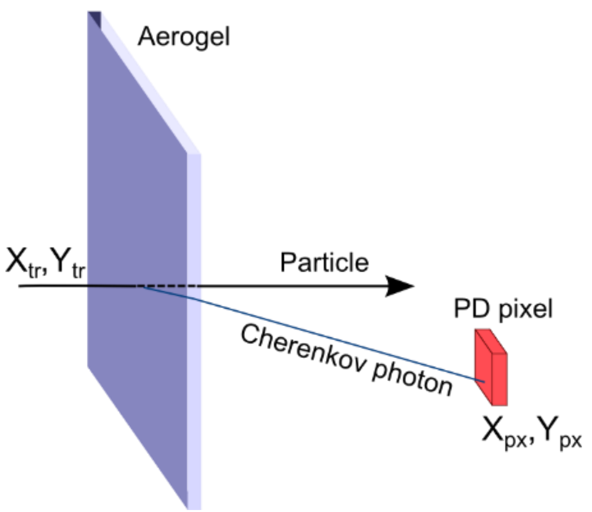


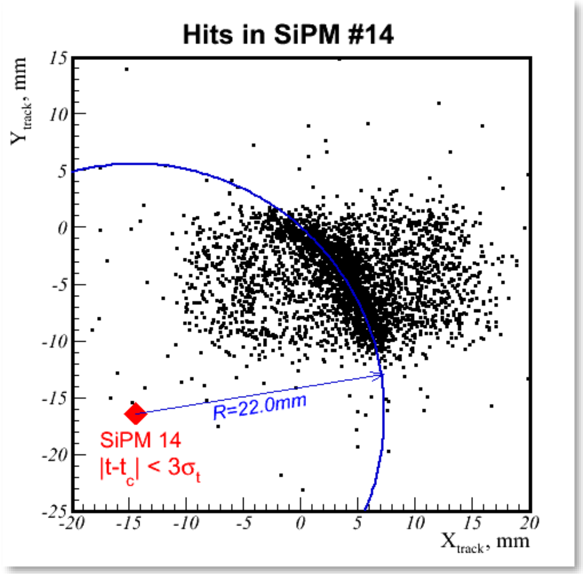
32 CPTA MRS APDs with active pixel size 2.1x2.1mm^2

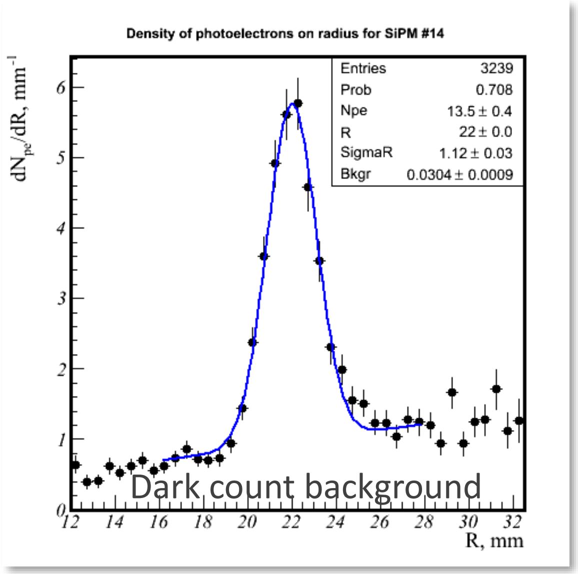
DCR ~ 5 MHz/device

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_{sc}(400nm) = 43mm

Cherenkov ring observation with single pixels

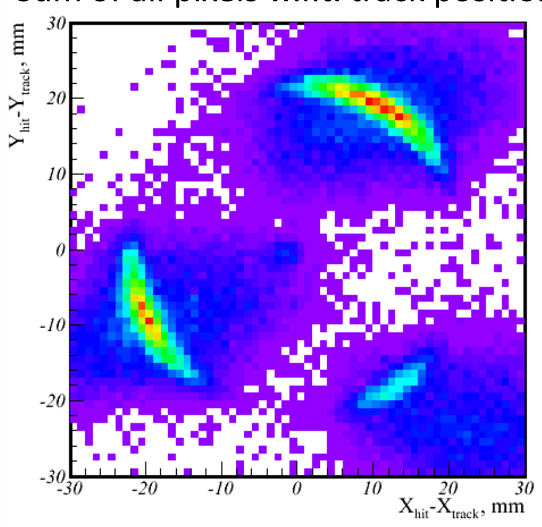






Given a tracking system, wide beam and enough particle statistics, a single PD pixel is enough to build the distribution of Cherenkov photons on R_{ch} (θ_{ch}).

Sum of all pixels w.r.t. track position



Many pixels can be combined to improve accuracy and align the tracking system with the photon detector

Analog SiPM vs Digital SiPM

Analog

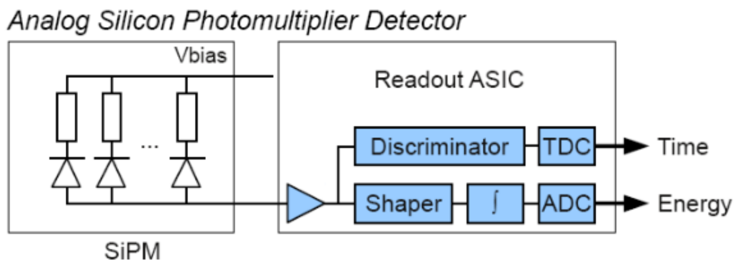
- Established technology
- Great progress in improving parameters: PDE, DCR, RadHard
- High active/total area ratio
- Availability from different vendors
- Need for external analog-to-digital readout electronics – bulky detector, higher power consumption
- No control of individual SPADs

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

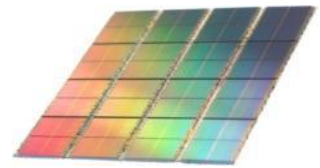
DPC is an Integrated, Scalable Solution

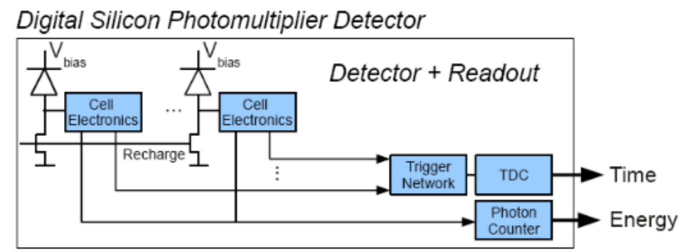
Analog SiPM



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

Digital SiPM



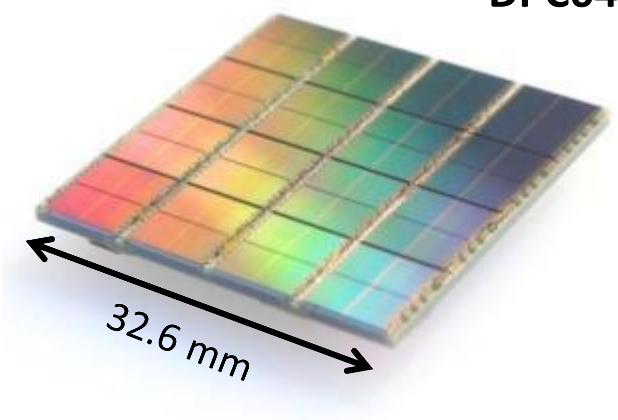


- fully integrated thanks to CMOS
- fully digital signals
- no ASIC needed
- fully scalable

Courtesy of Philips Digital Photon Counting

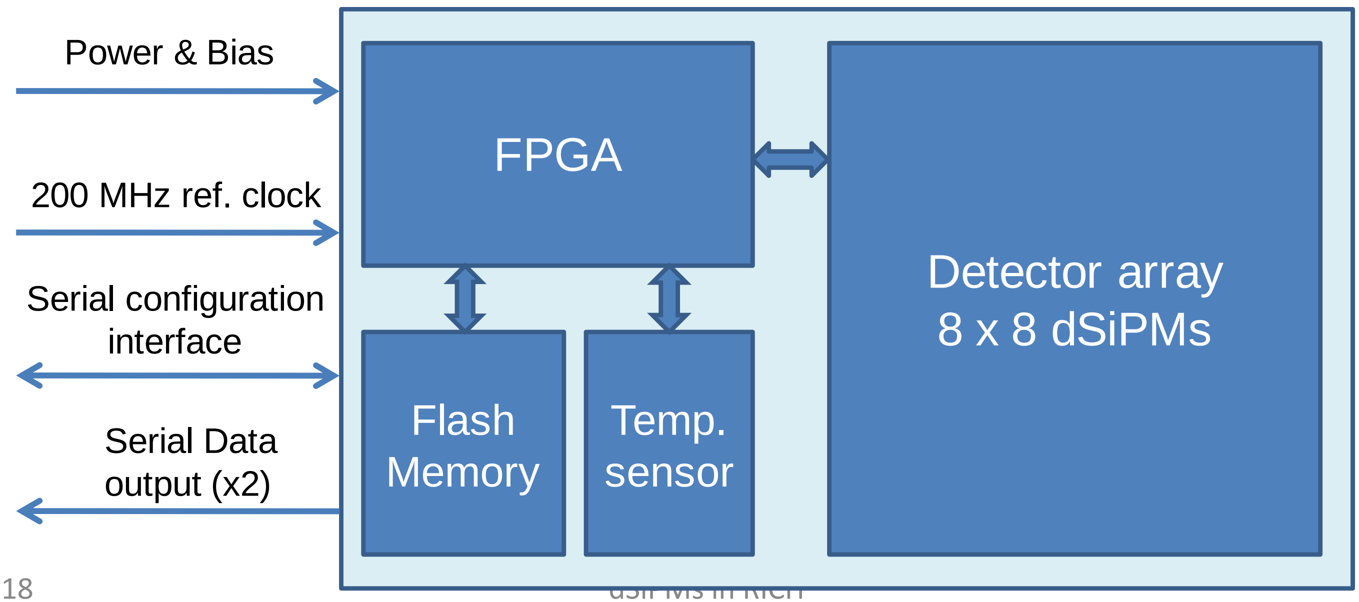
DPC is an Integrated "Intelligent" Sensor by Philips Digital Photon Counting

DPC3200-22-44 – 3200 cells/pixel
DPC6400-22-44 – 6396 cells/pixel



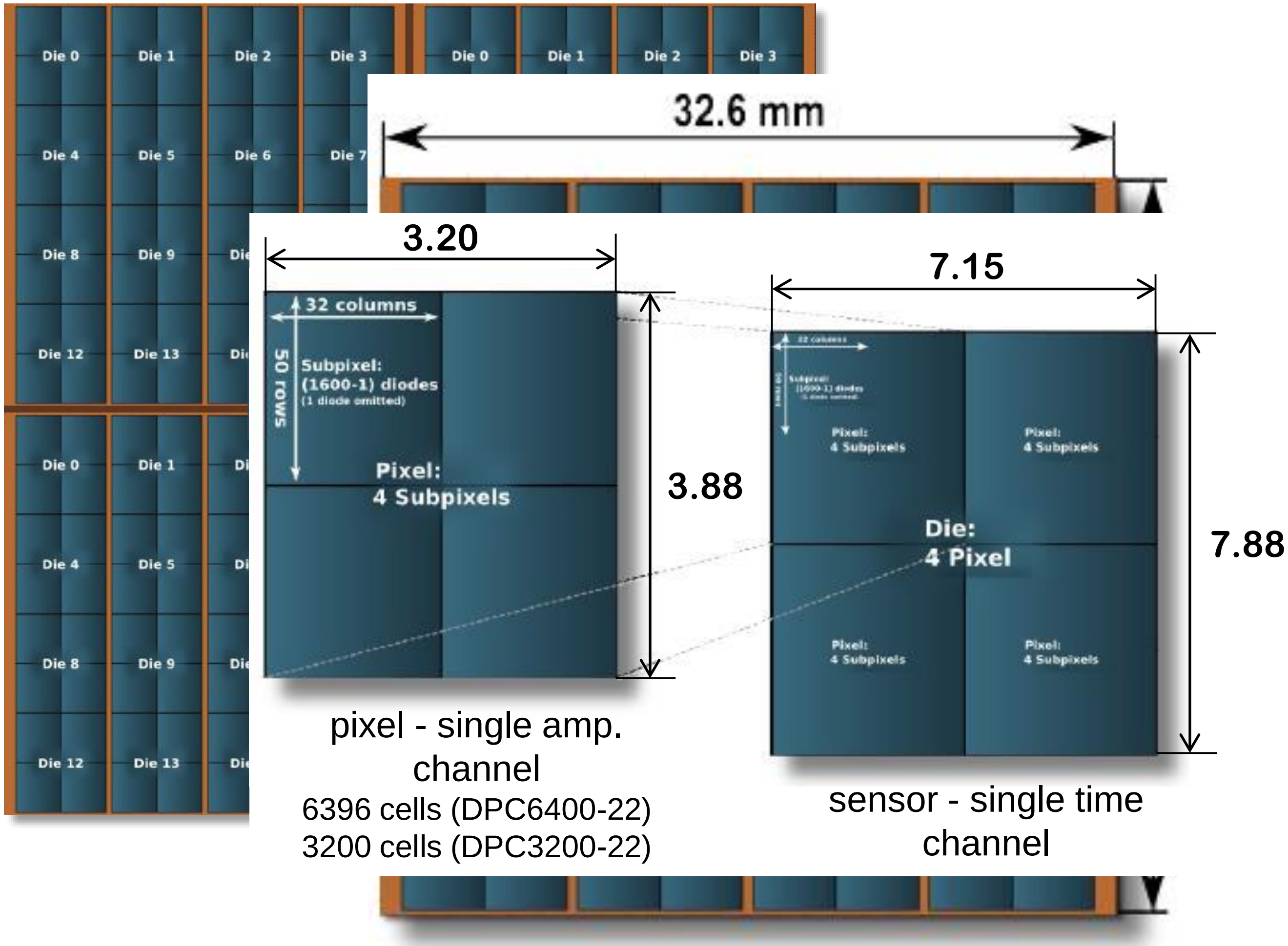
FPGA
- Clock distribution
- Data collection/concentration
- TDC linearization
- Saturation correction
- Skew correction

Flash
- FPGA firmware
- Configuration
- Inhibit memory maps



Courtesy of Philips Digital Photon Counting

DPC readout units



Geometrical efficiency ≈70%

FARICH prototype with DPC

4-layer aerogel

- n_{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

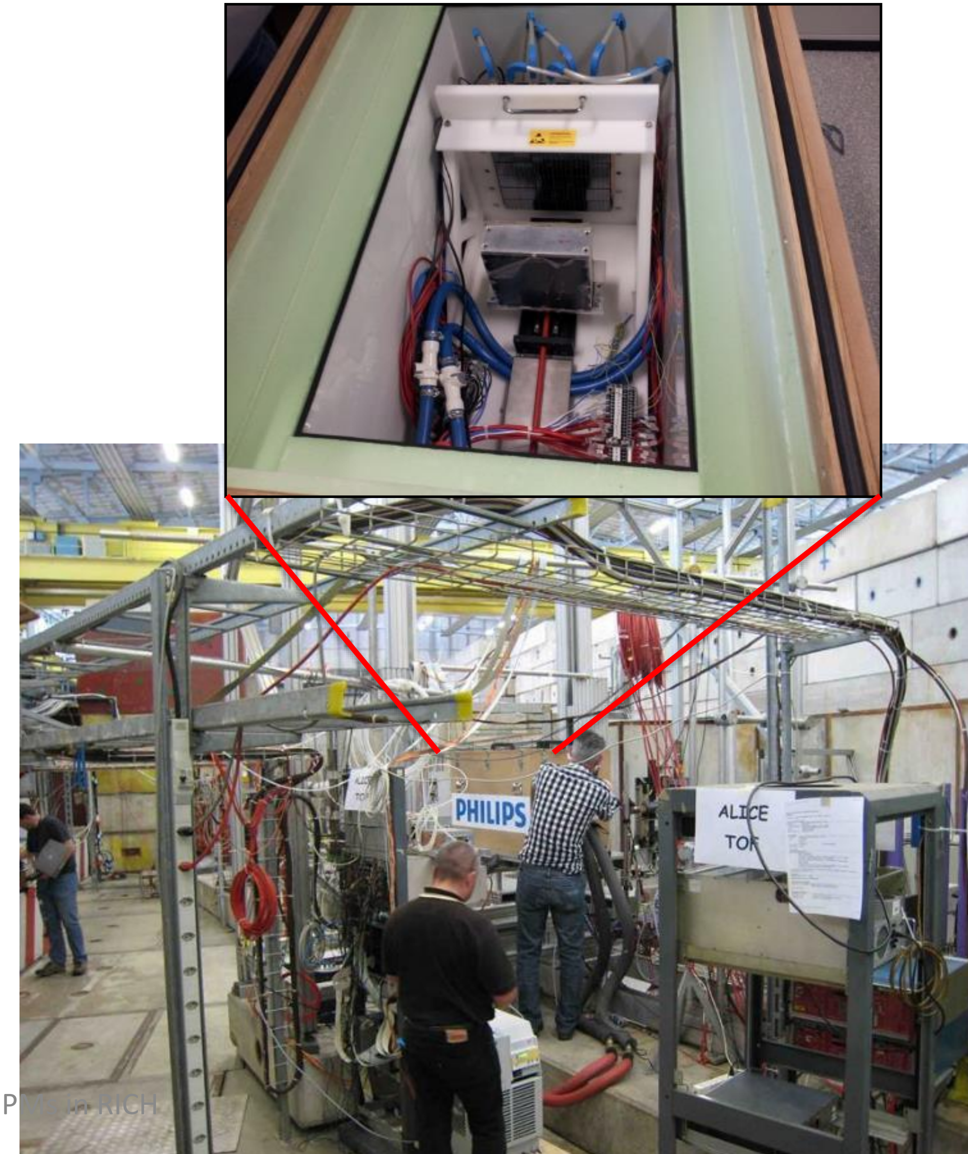
PDPC-FARICH prototype beam test
CERN PS/T10, 2012

Main objective:

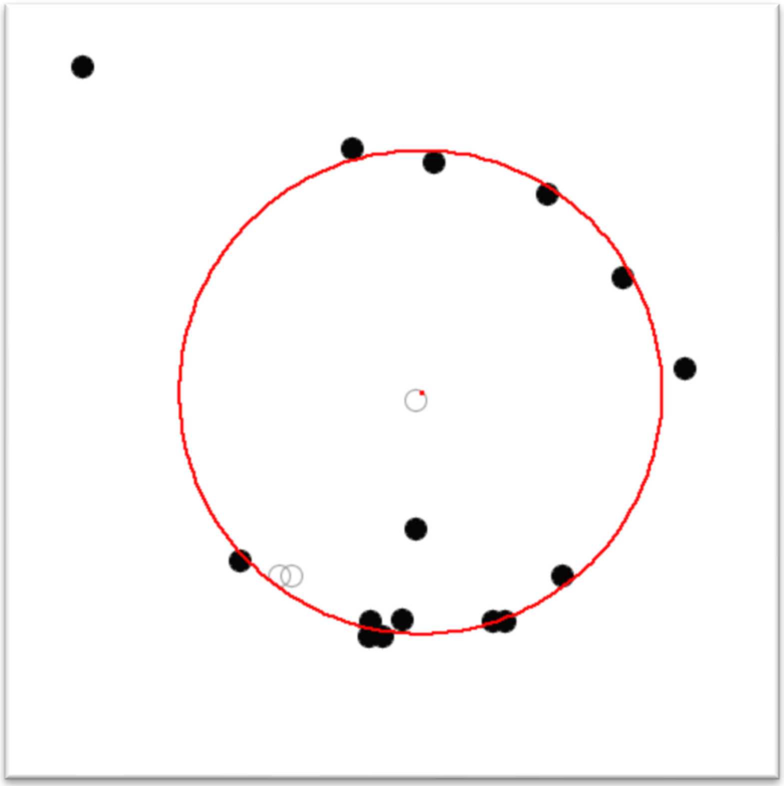
Proof of concept: full Cherenkov ring detection with a DPC array

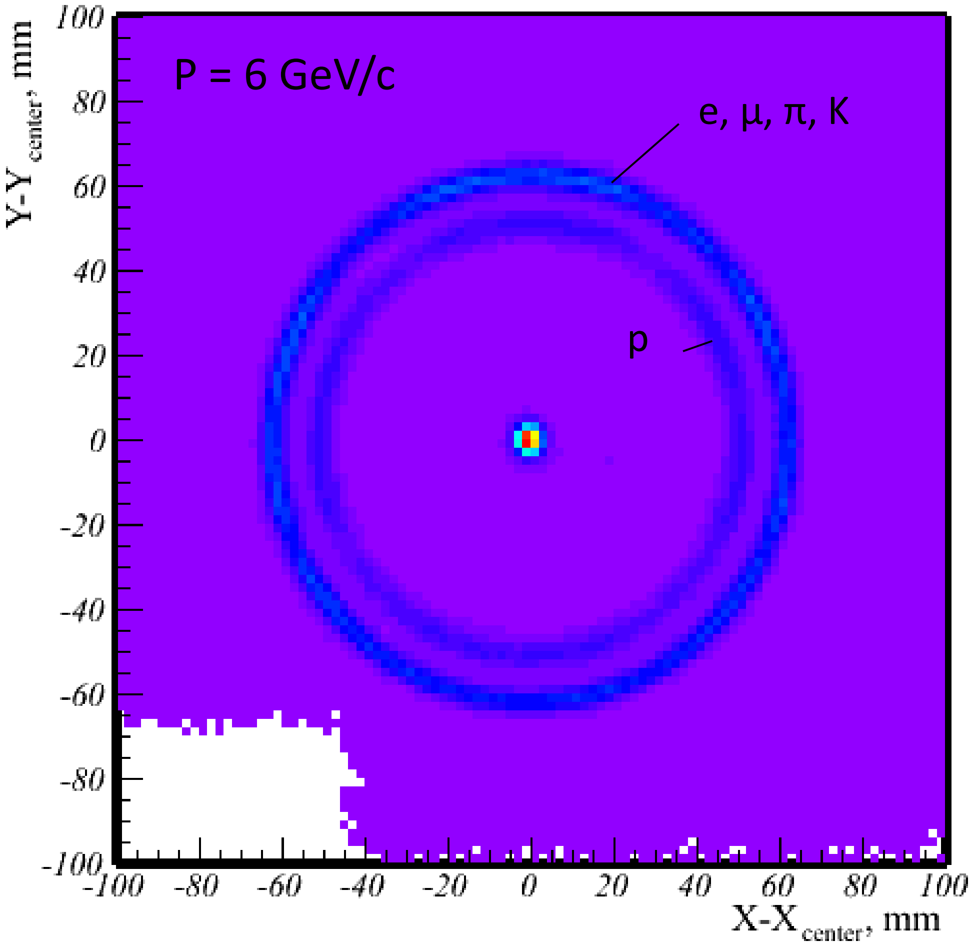
Details:

- Operation temperature is −40°C to suppress dark count rate
  - Dead time is 720 ns.
  - DCR(+25°C) ≈ 10 Mcps/sensor single photon detection is not feasible!
  - DCR(-40°C) ≈ 100 kcps/sensor inefficiency is 7% .
- 2 stage cooling: LAUDA process thermostat + Peltiers.
- Dry N_2 constant flow to avoid condensation.



PDPC-FARICH: Cherenkov ring





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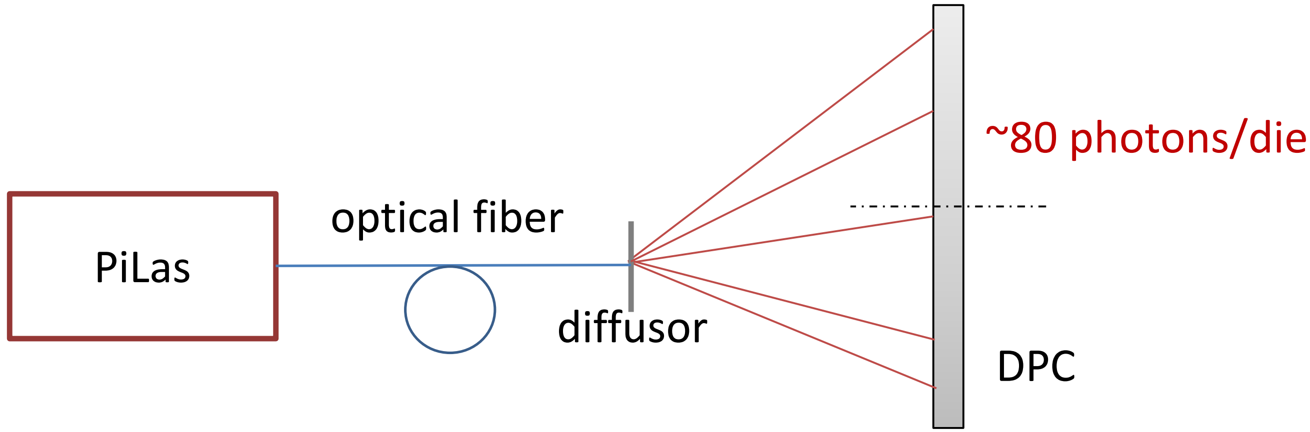
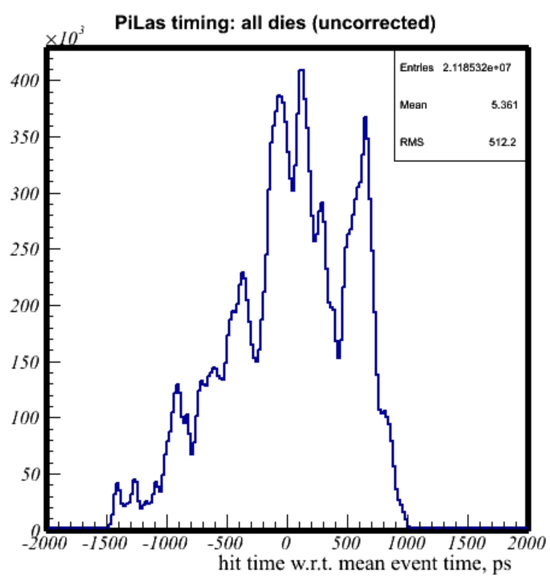
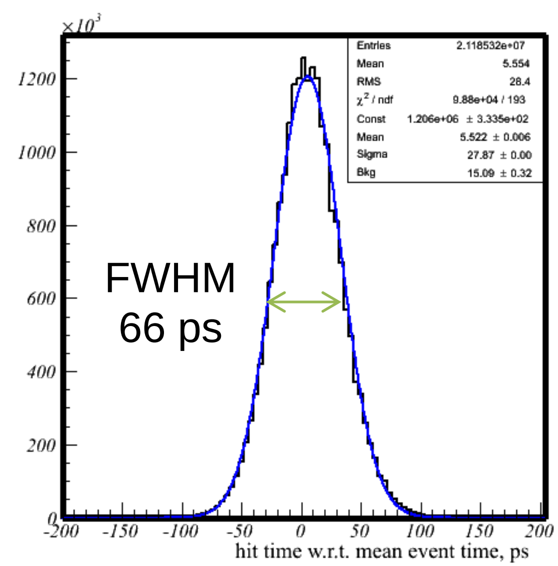
Clock skew correction between dies



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

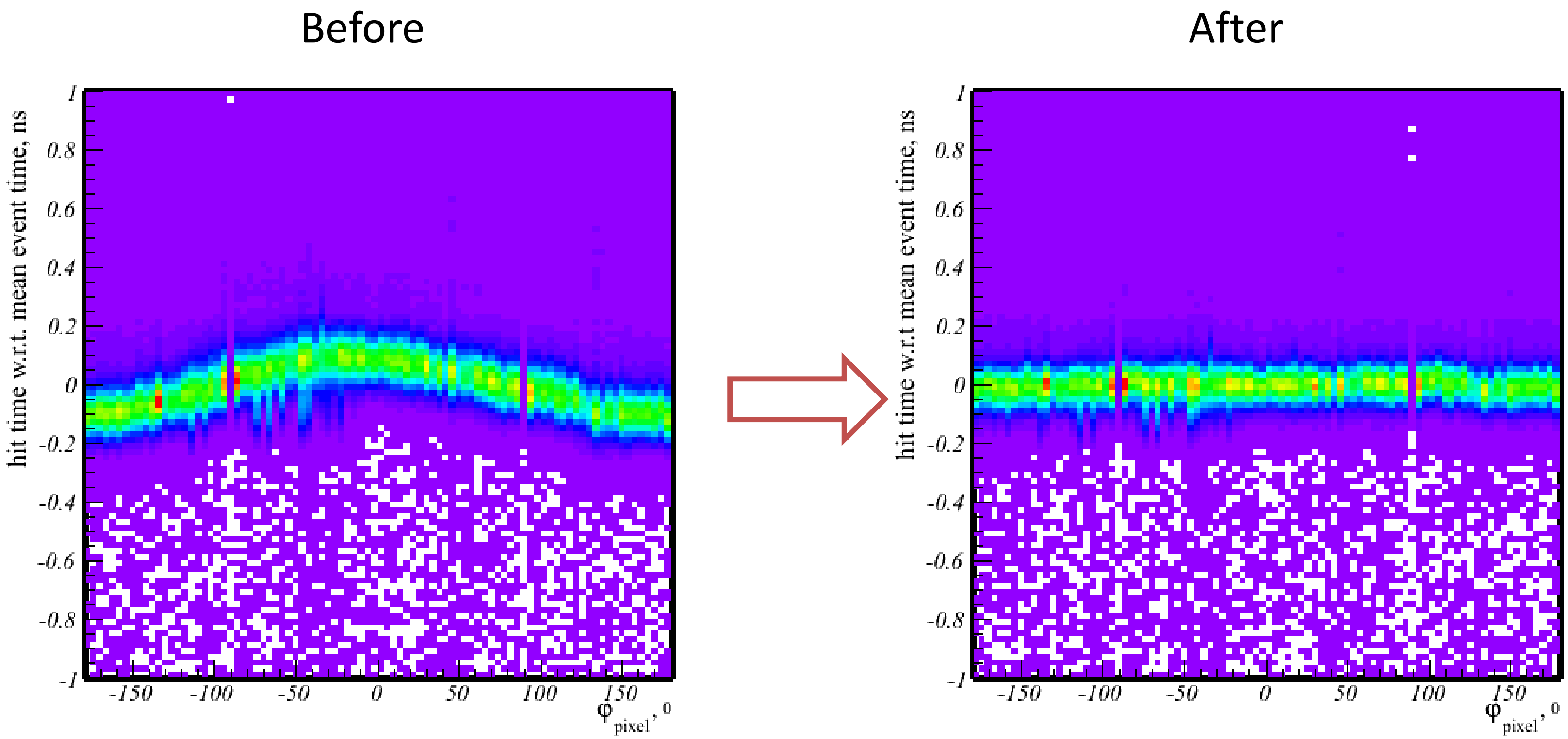


Clock skew correction between dies

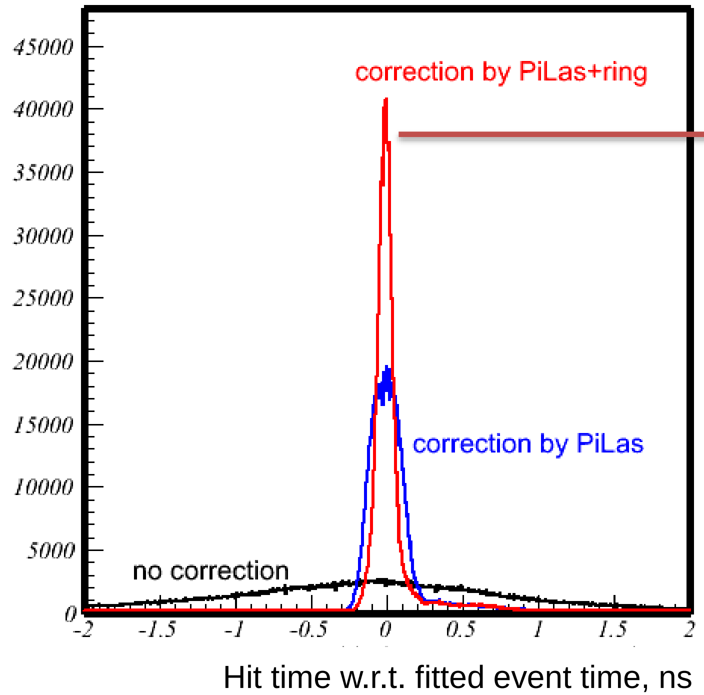


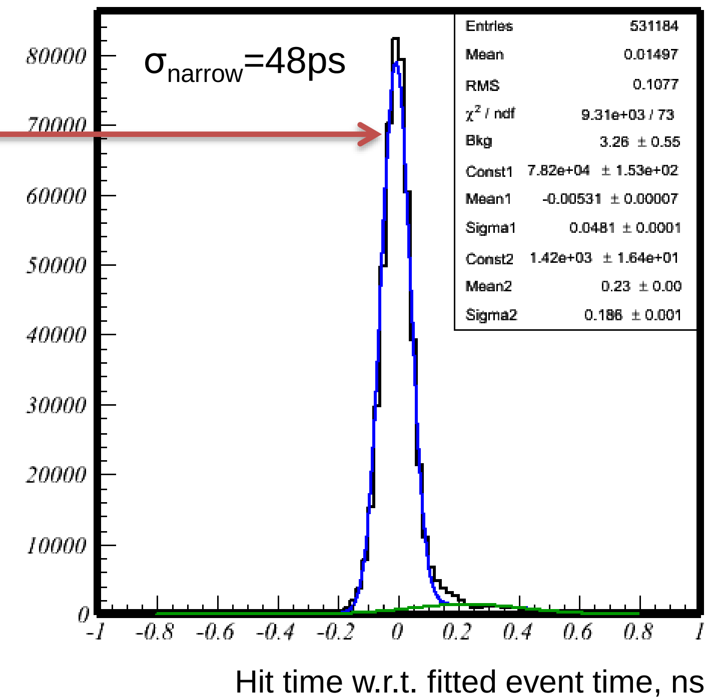
Timing correction by Cherenkov ring data

Hit timing vs φ-position



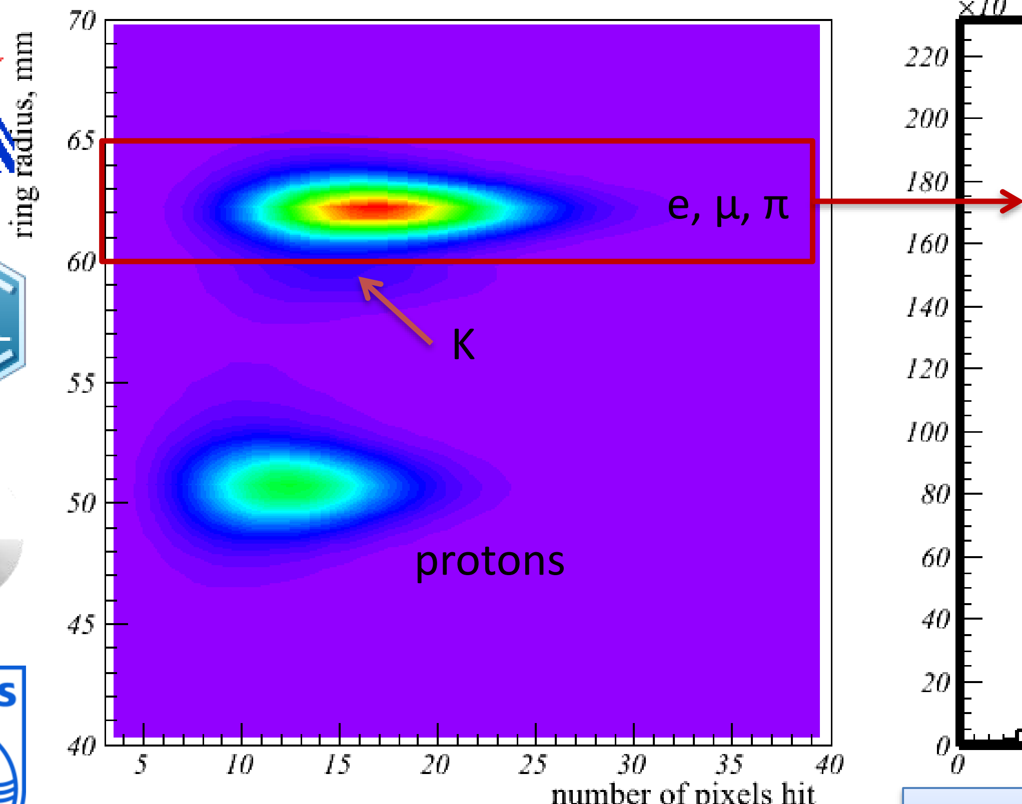
Single photon timing resolution for Cherenkov light

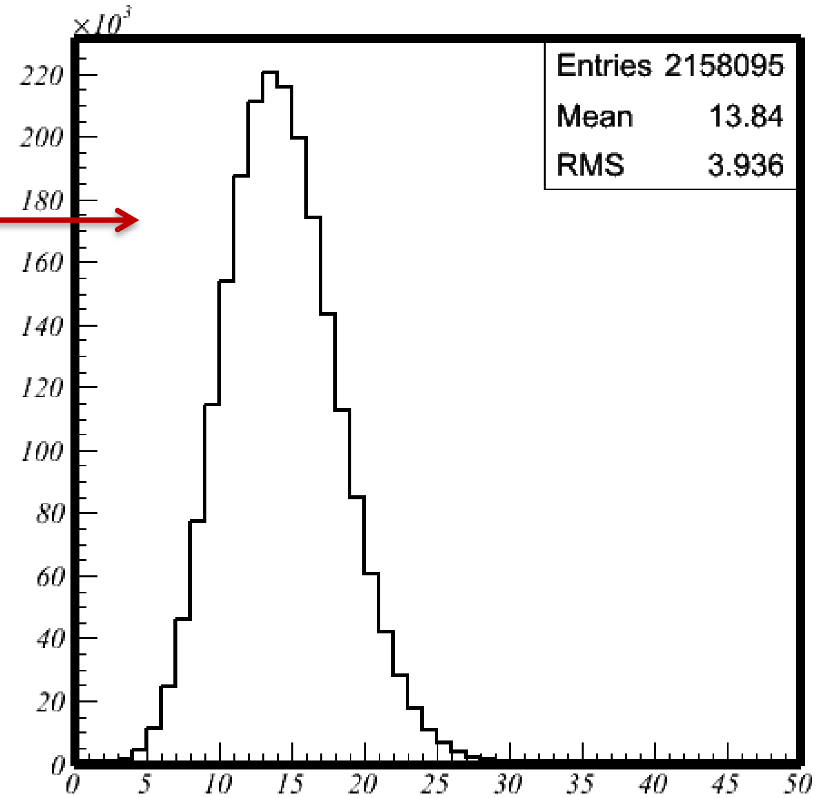




Fit two gaussians plus constant. 90% of area is contained in the narrow gaussian.

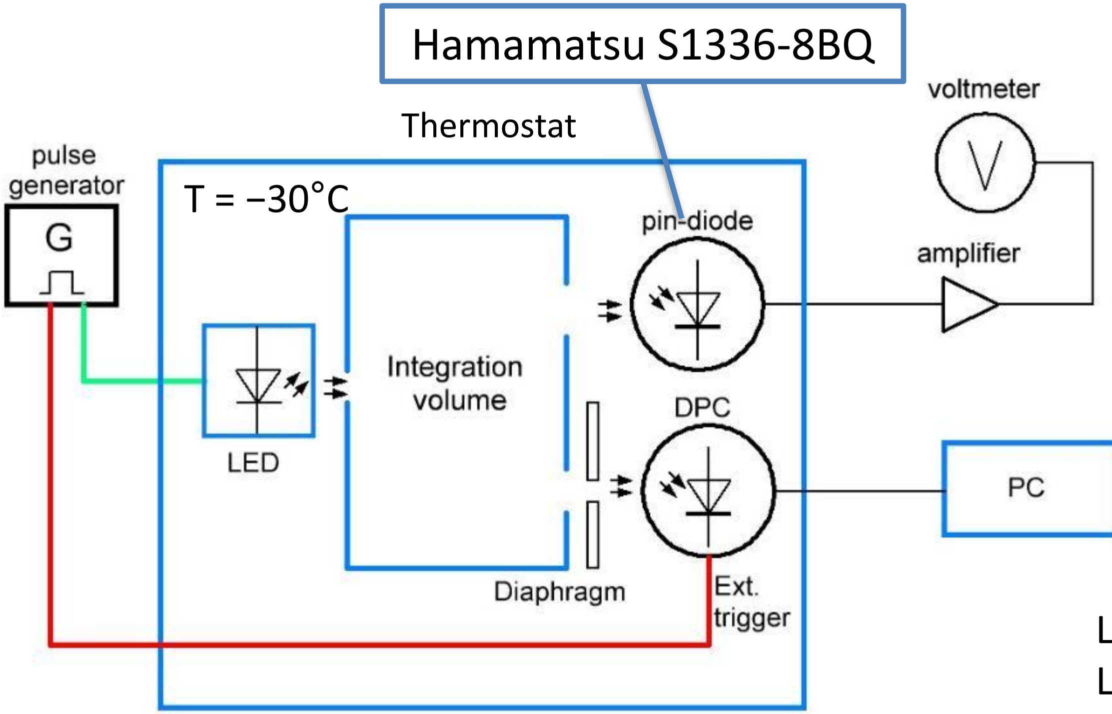
Number of photoelectrons



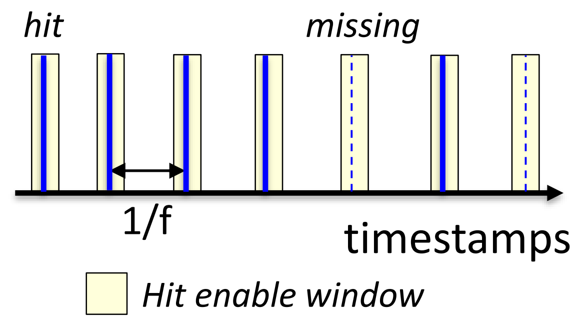


N_{pe} = 12 after taking into account crosstalks. ~2x lower then expected.

Absolute PDE measurement of DPC



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



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

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

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

Dark count rate and dead time taken into account:

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

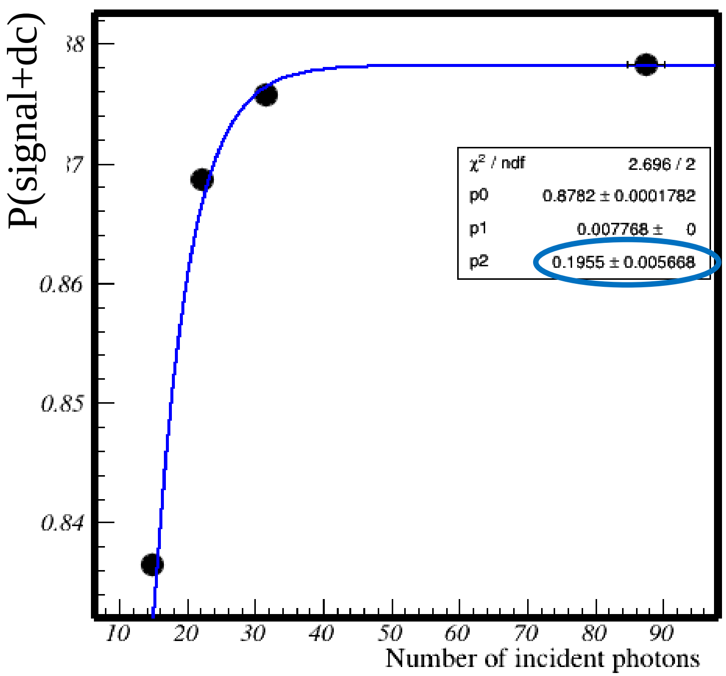
LTR – live time ratio, determined **only** by dark counts coming before LED pulse.

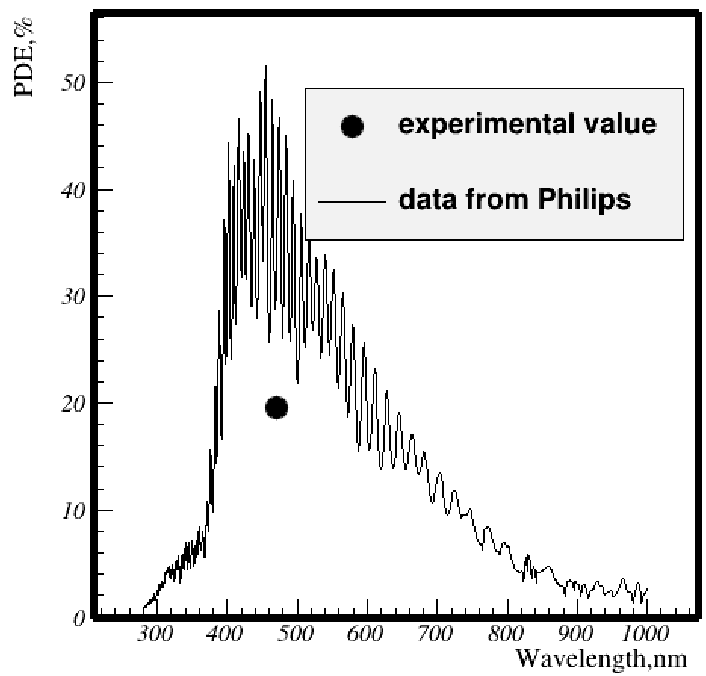
$$P(\text{signal+dc}) = \\ = \text{LTF} - \left(\text{LTF} - P(\text{dc})\right) e^{-\text{PDE} \cdot N_\gamma}$$

N_γ per pulse is determined from photocurrent of PIN diode and calibrated ratio of test/monitor channels

Absolute PDE of DPC

Fit P(signal+dc) as function of N_γ and extract PDE





PDE(470 nm)

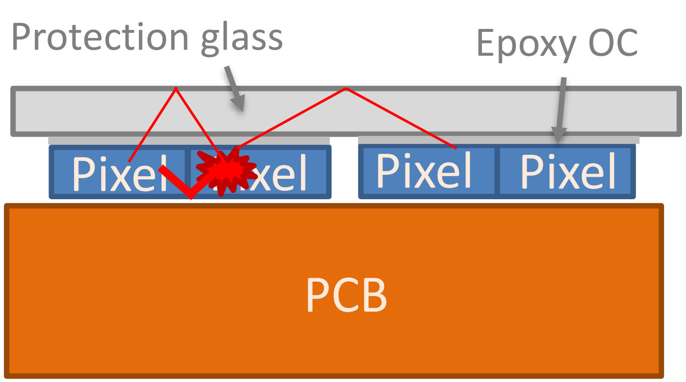
19±1% in our measurement vs 36% by PDPC measurement

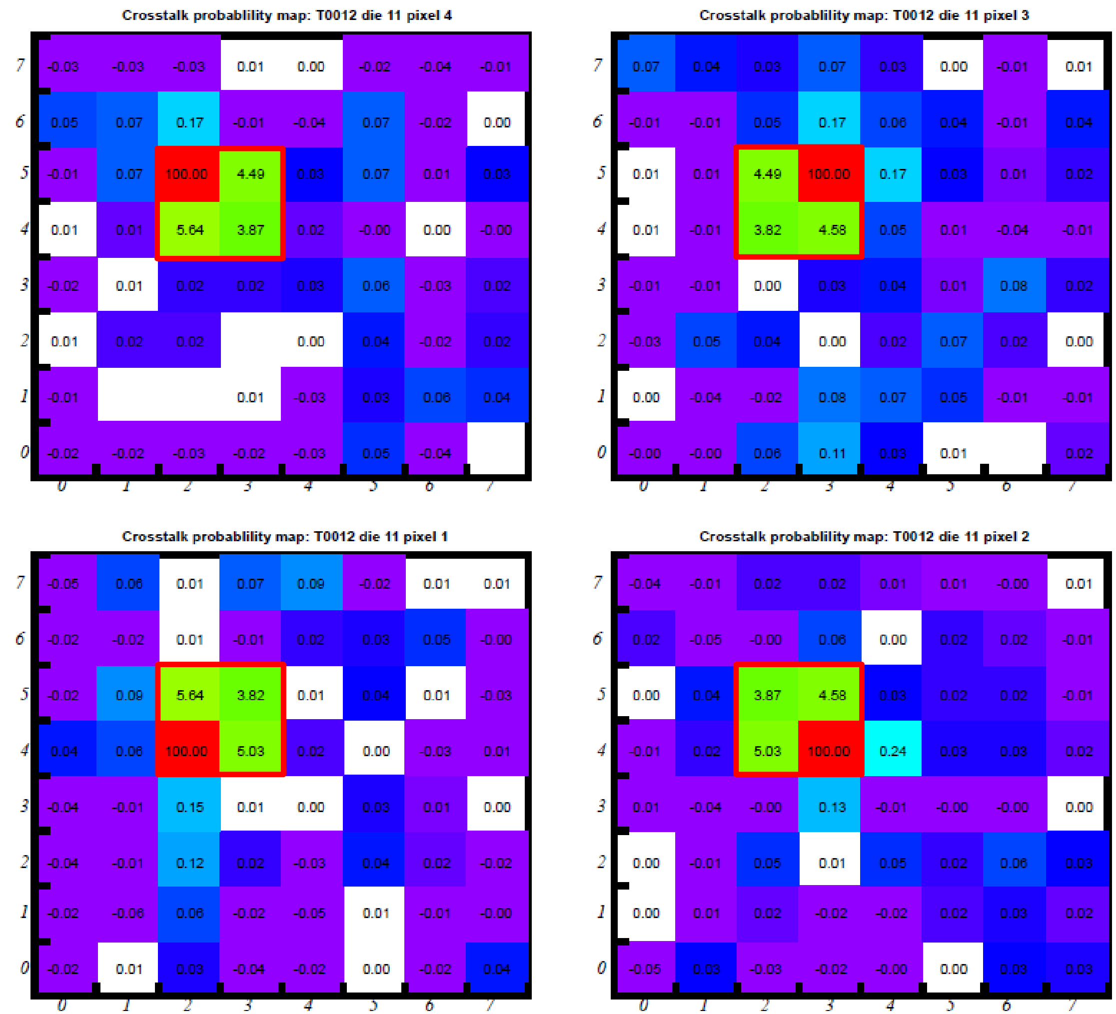
Optical crosstalks in DPC

X-talks between pixels deteriorate position resolution

Crosstalk ways:

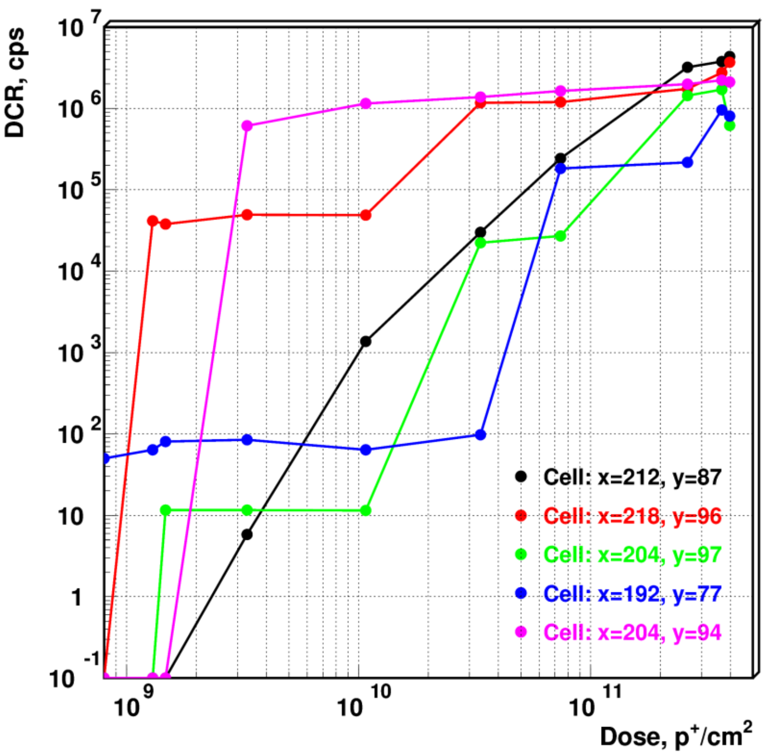
- ❑ between pixels of the same die (3-4%) go likely via Si substrate
- ❑ between neighboring dies (0.1-0.2%) go via protection glass



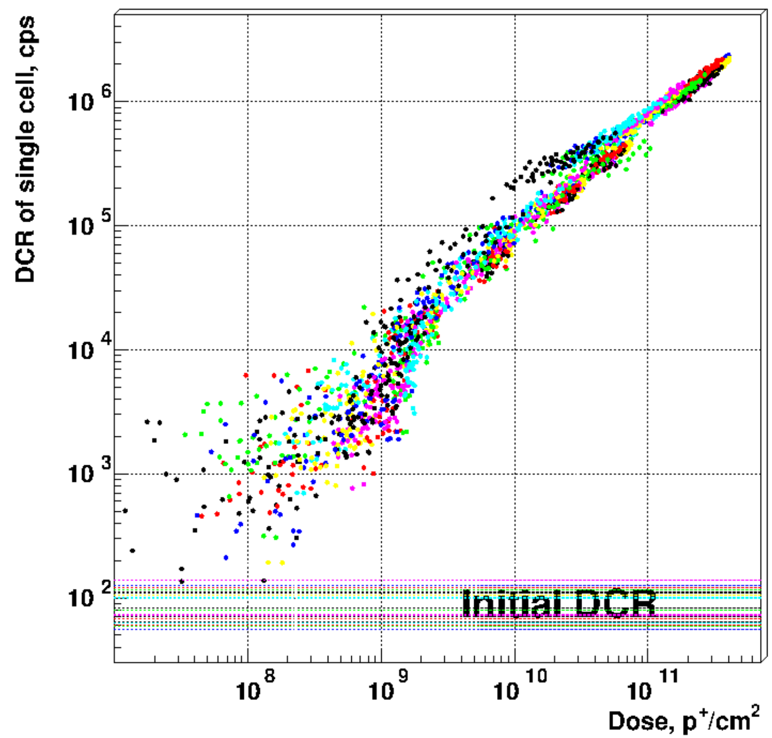


Irradiation of DPC tiles

proton beam (800 Mev/c) at COSY PS in FZ Jülich



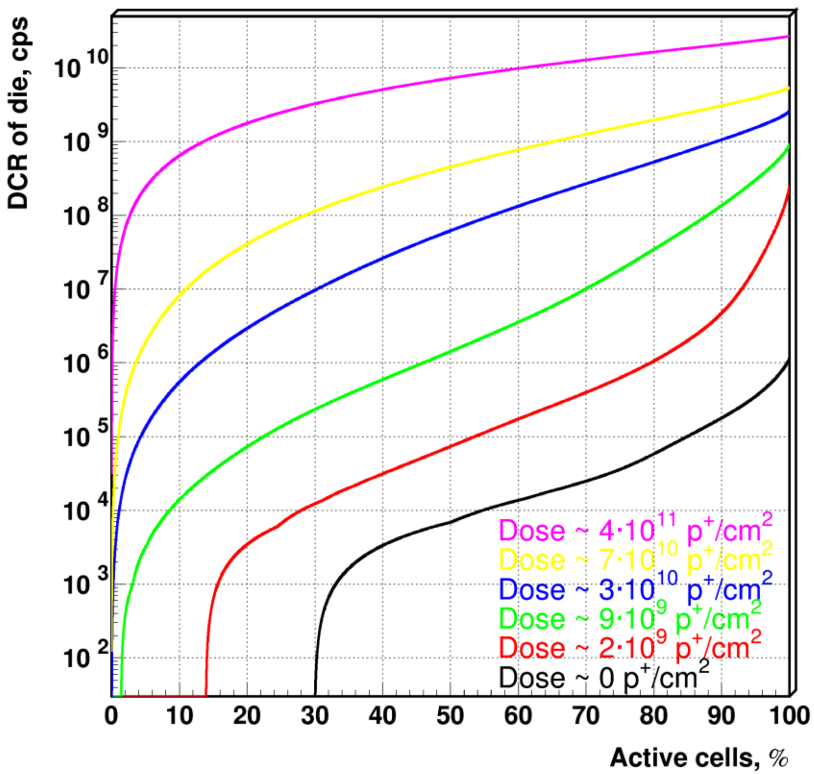
Die-averaged cell DCR vs fluence



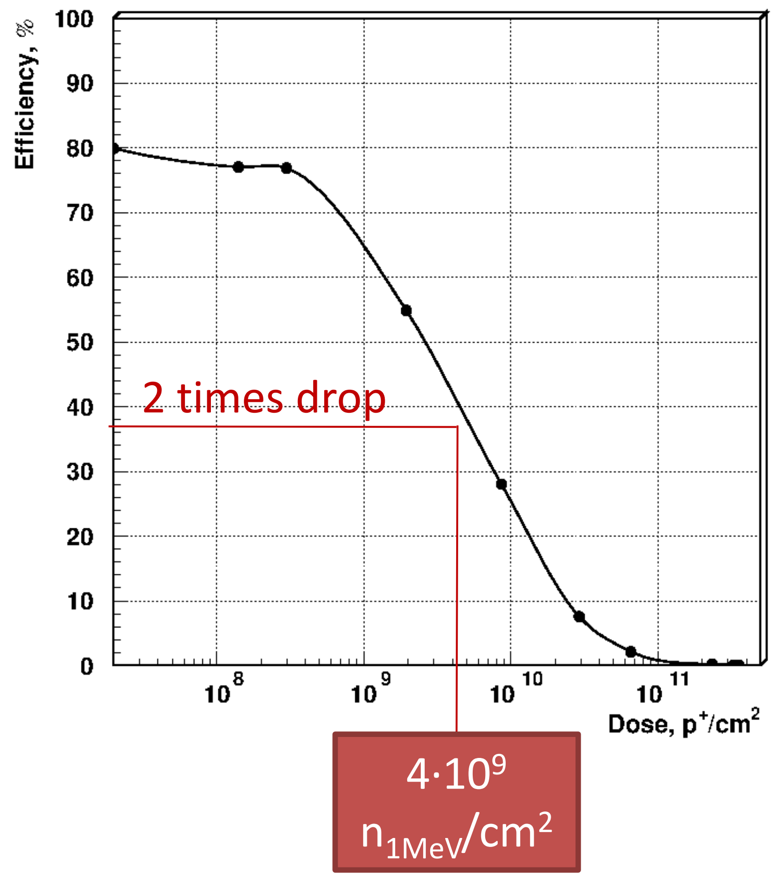
DPC tiles cooled to −18°C. Maximum fluence accumulated: $4{\cdot}10^{11}$ p/cm^2

Radiation hardness study of DPC

Estimated die DCR vs active cell fraction



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



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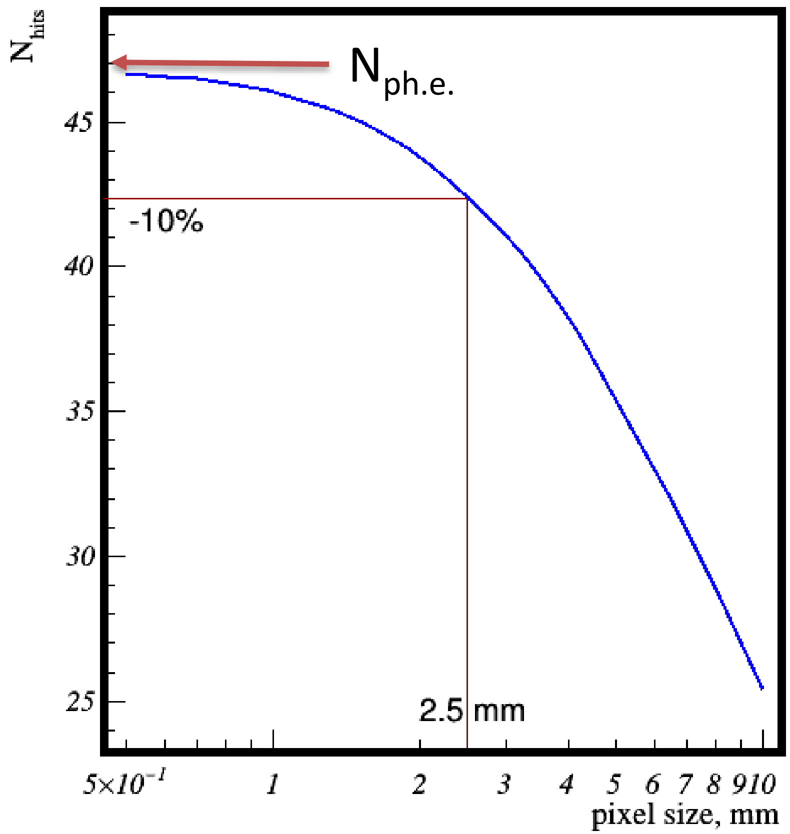
Desired characteristics of digital SiPMs for aerogel RICH

- 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/mm^2
- Dead time ratio ≤ 1%
- Position resolution σ_x ≤ 1 mm: may be realized by determining position of a fired SPAD in an array of size ~3x3 mm^2
- SPTR ≤ 100 ps would be useful for DIRC-like detectors or suppressing uncorrelated background
- Radiation hard ≥10^{11} n_{1MeV}/cm^2, 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

Number of fired pixels vs pixel size



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

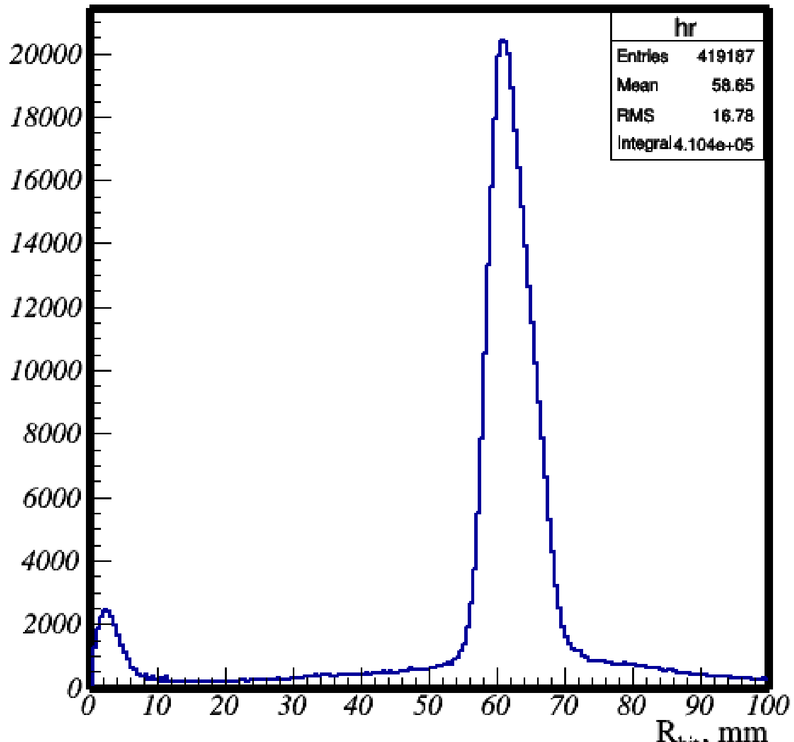
→ 10% loss of photons for pixel size 2.5 mm

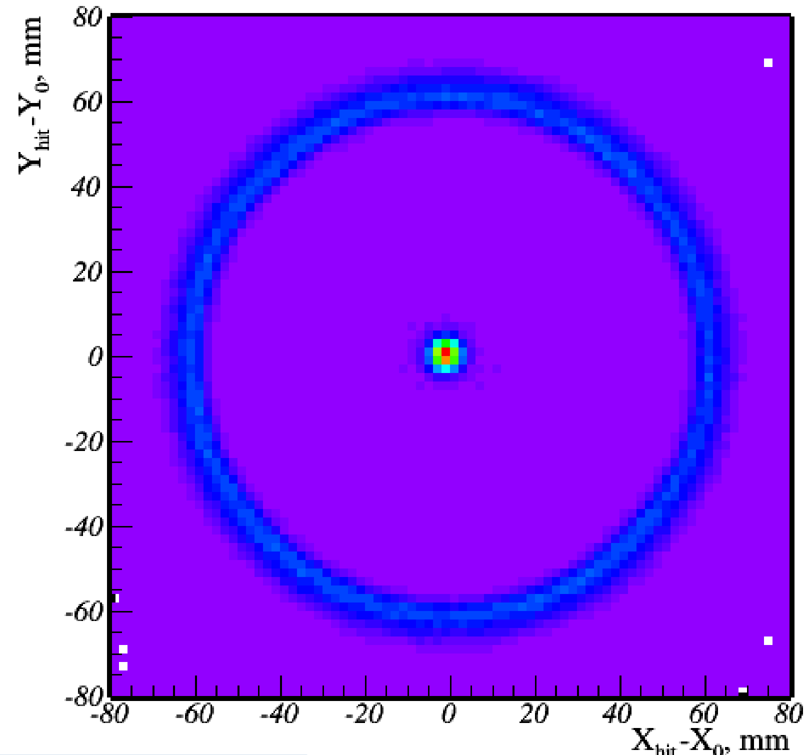
Summary & conclusion

- 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