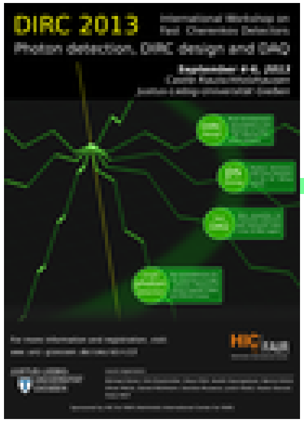
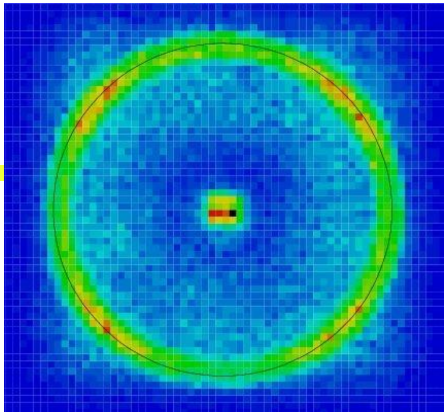


DIRC 2013, September 4-6, 2013



Photon detectors for fast single photon detection

Peter Križan

University of Ljubljana and J. Stefan Institute

University of Ljubljana

"Jožef Stefan" Institute

Contents

Why fast single photon detection?

Multianode PMTs

MCP PMTs

HPDs, HAPDs

SiPMs

Summary

Parameters of photosensors

Photon detection efficiency (PDE)

- quantum efficiency
- collection efficiency / Geiger discharge probability

Granularity

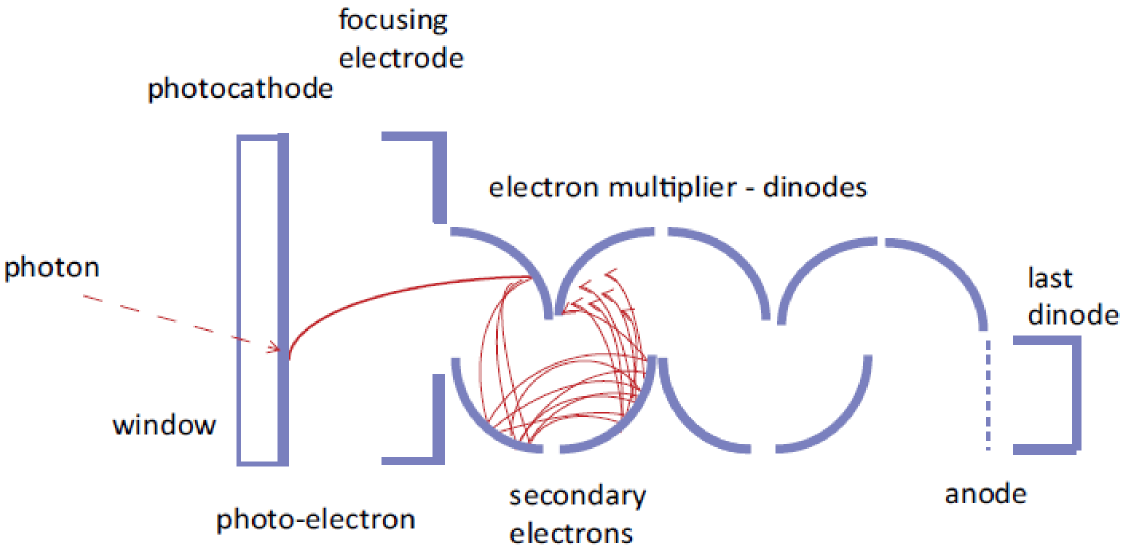
Time resolution (transient time spread – TTS)

Long term stability

Operation in magnetic field

Dark count rate

+ …

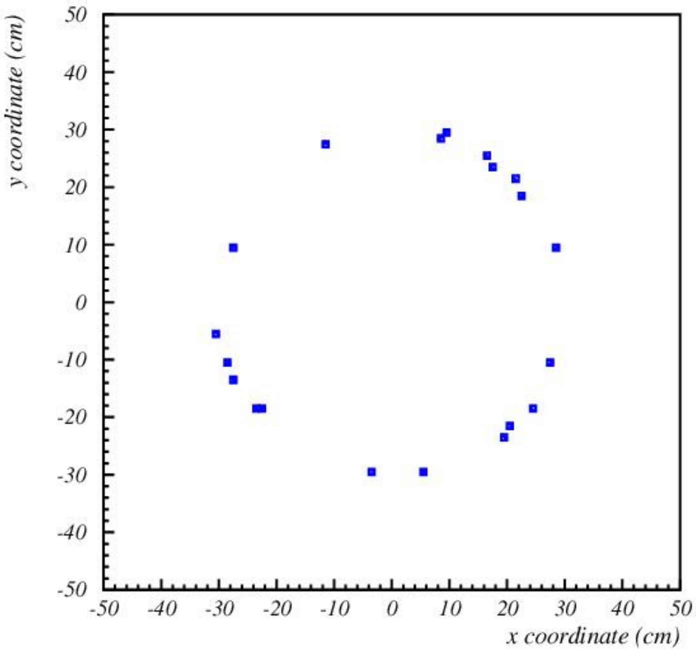


Photon detection in RICH counters

RICH counter: measure photon impact point on the photon detector surface

→ detection of single photons with

- sufficient spatial resolution
- high efficiency and good signal-to-noise ratio
- over a large area (square meters)



Special requirements:

- Operation in magnetic field
- High rate capability
- Very high spatial resolution
- Excellent timing (time-of-arrival information)

Fast photon detection

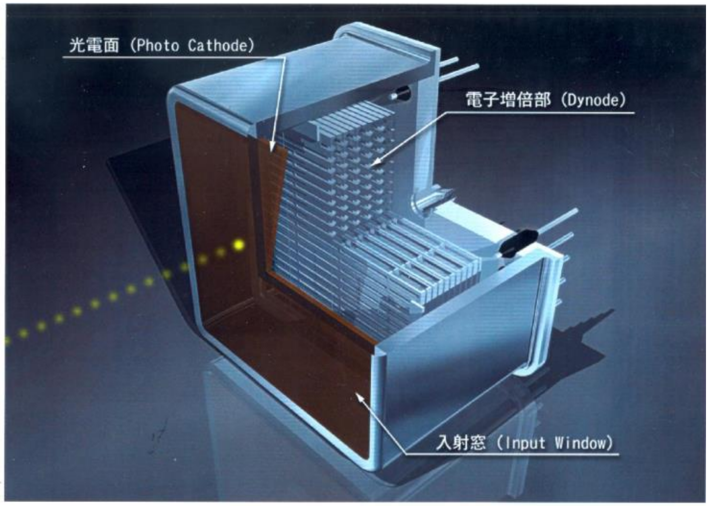
New generation of RICH counters: precise time information needed to further improve performance:

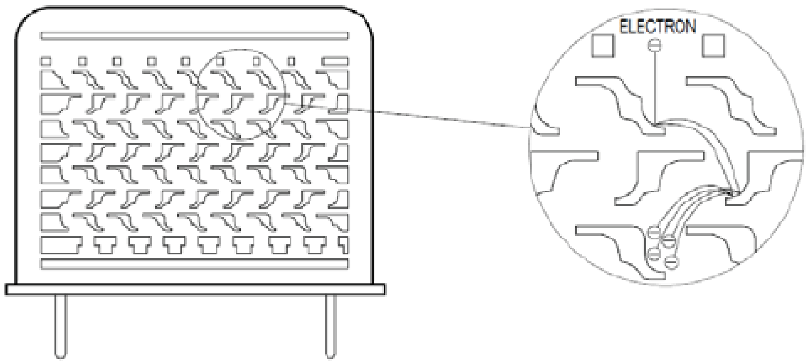
- Reduce chromatic abberation (group velocity): Focusing DIRC
- Combine TOF and RICH techniques: TOP (Time-of-propagation counter), TORCH

→ Need photo sensors with excellent timing

First fast multianode sensor for single photons: MA PMT

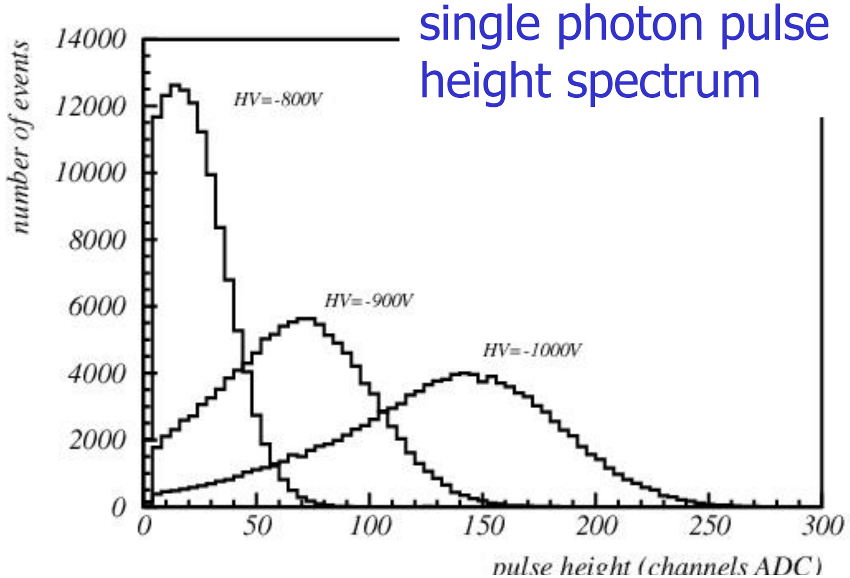
Multianode PMT Hamamatsu R5900 with metal foil dynodes





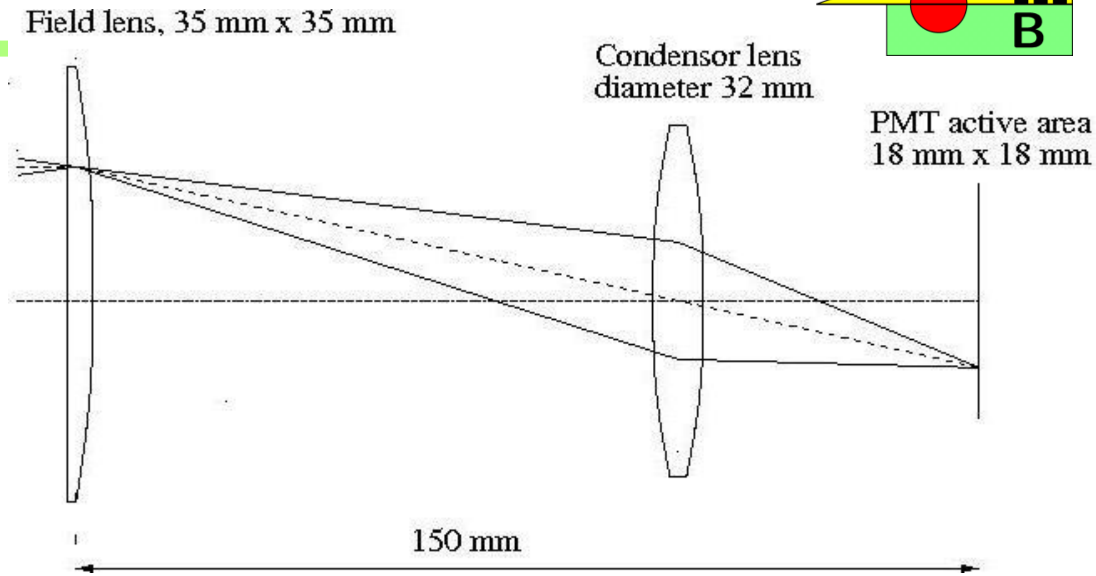
- Excellent single photon pulse height spectrum
- Low noise (few Hz/ch)
- Low cross-talk (<1%)

single photon pulse height spectrum



NIM A394 (1997) 27

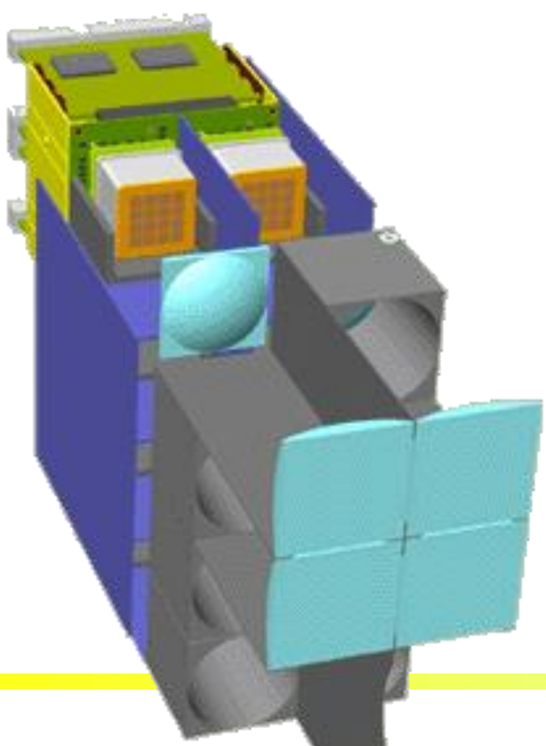
First major application: HERA-B RICH

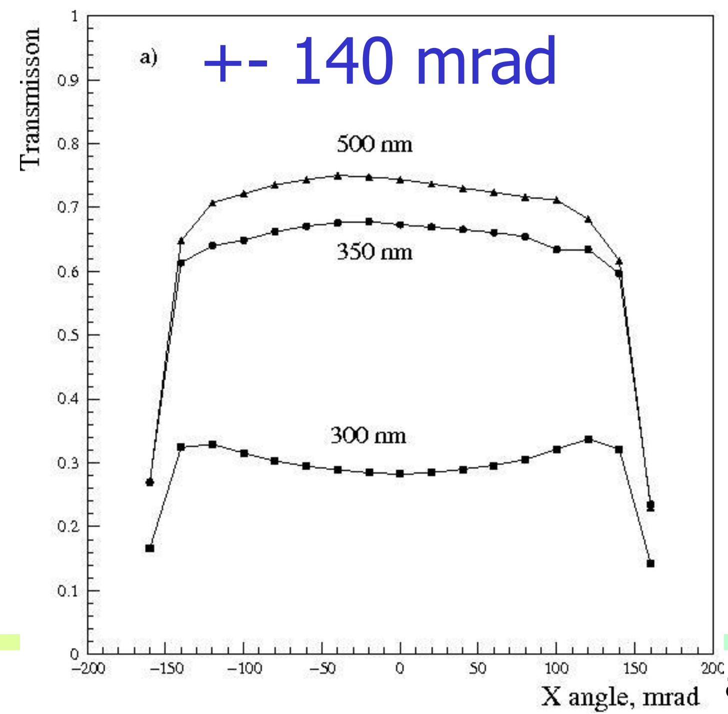


Light collection system (imaging!) to:

-Eliminate dead areas

-Adapt the pad size





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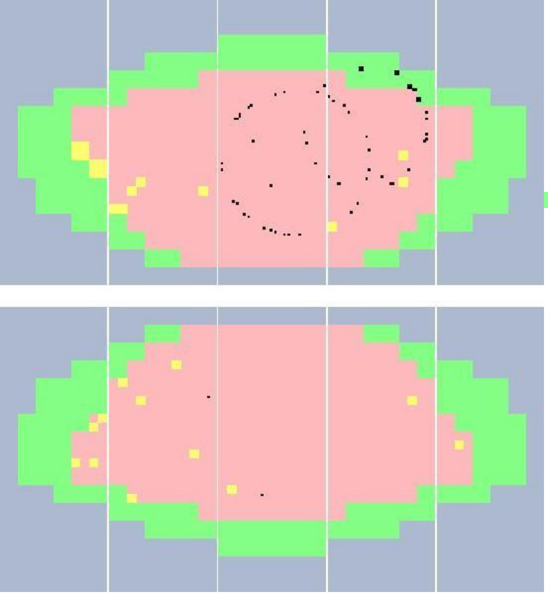
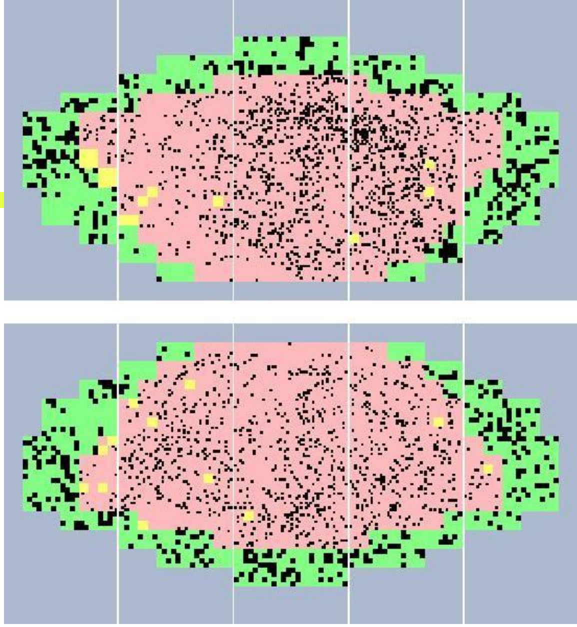
HERA-B RICH

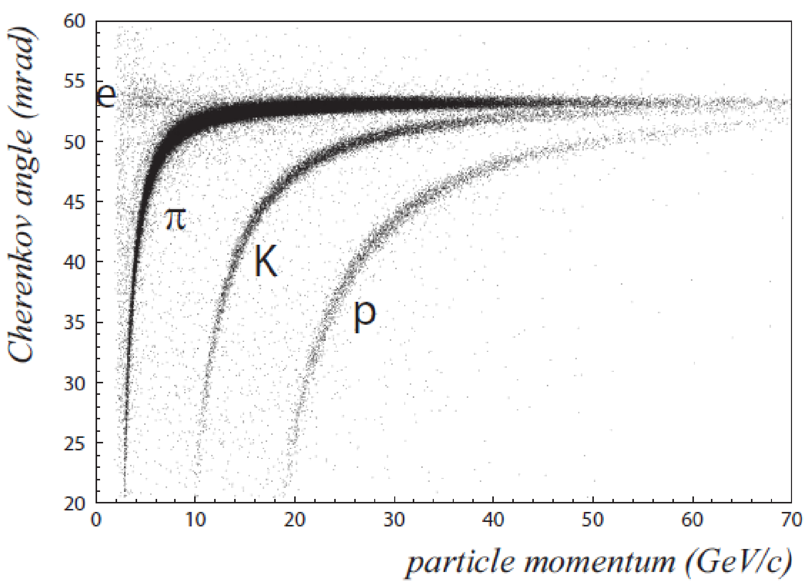


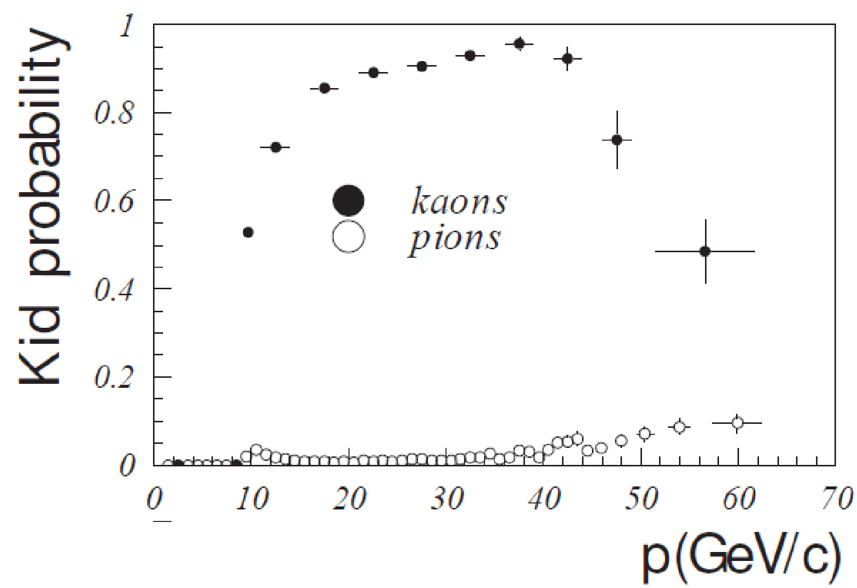
← Little noise, ~30 photons per ring



Typical event

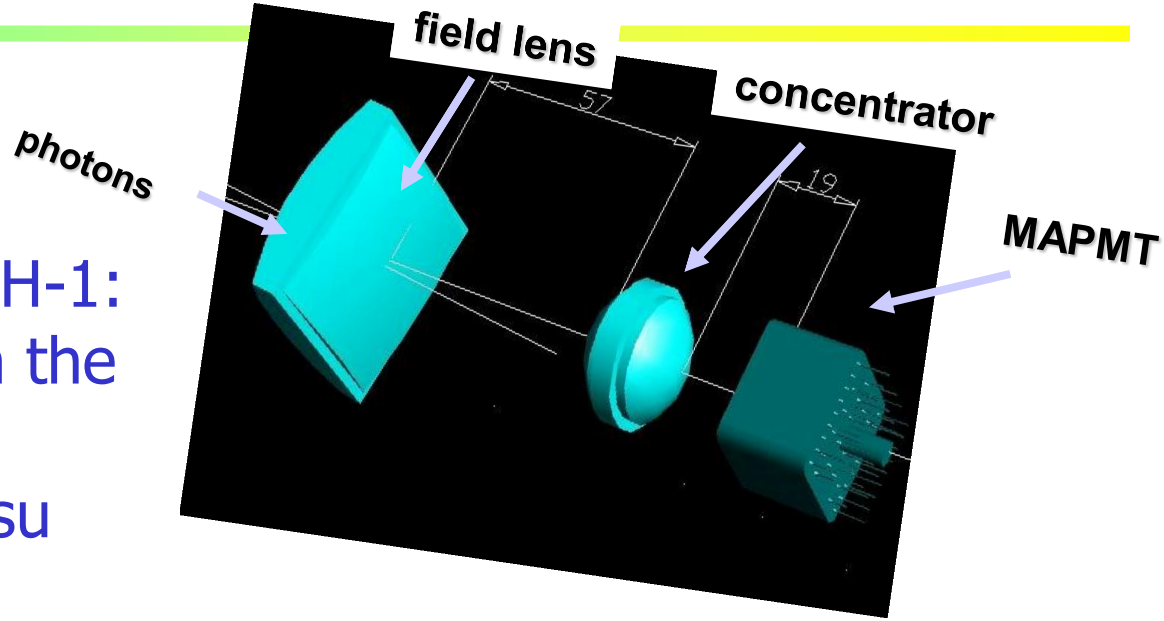
Very good performance:





Kaon efficiency and pion fake probability

Photon detector for the COMPASS RICH-1



Upgraded COMPASS RICH-1:
similar concept as in the HERA-B RICH, lens system + Hamamatsu MAPMTs

New features:

- UV extended PMTs & lenses (down to 200 nm)
- surface ratio = (telescope entrance surface) / (photocathode surface) = 7
- fast electronics with <120 ps time resolution

COMPASS RICH-1 upgrade

Performance:

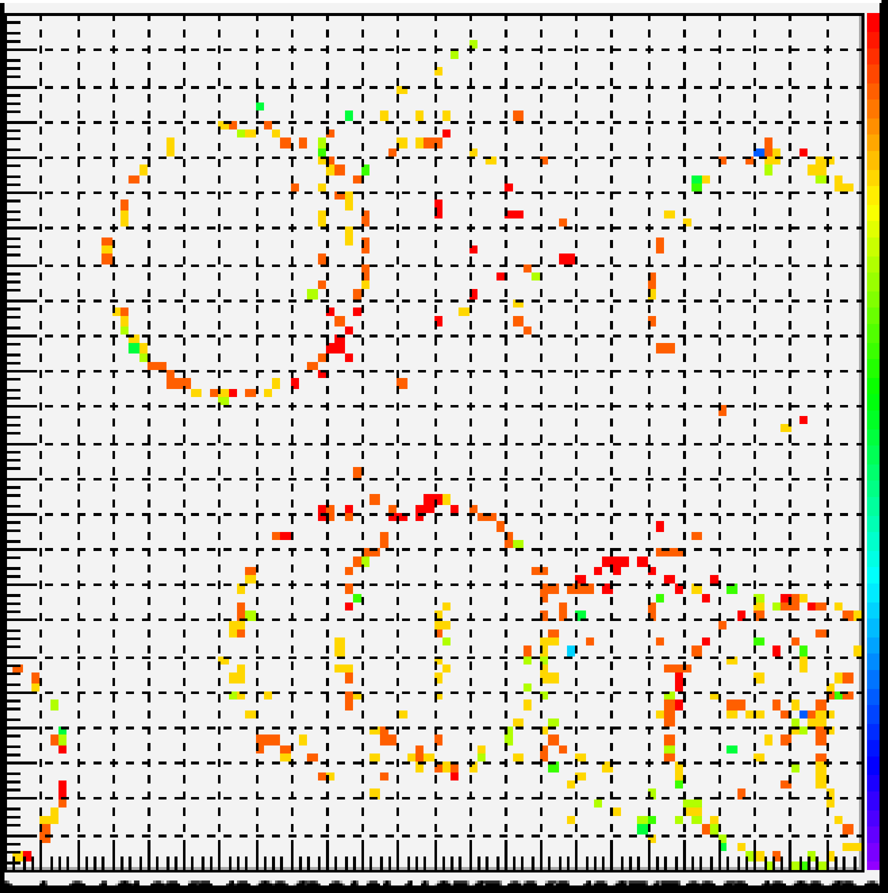
~ 60 detected photons per ring at saturation (β = 1) → N_0 ~66 cm^{-1}

σ_θ ~ 0.3 mrad → 2 σ π-K separation at ~ 60 GeV/c

K-ID efficiency ($K^\pm$ from Φ decay) > 90%

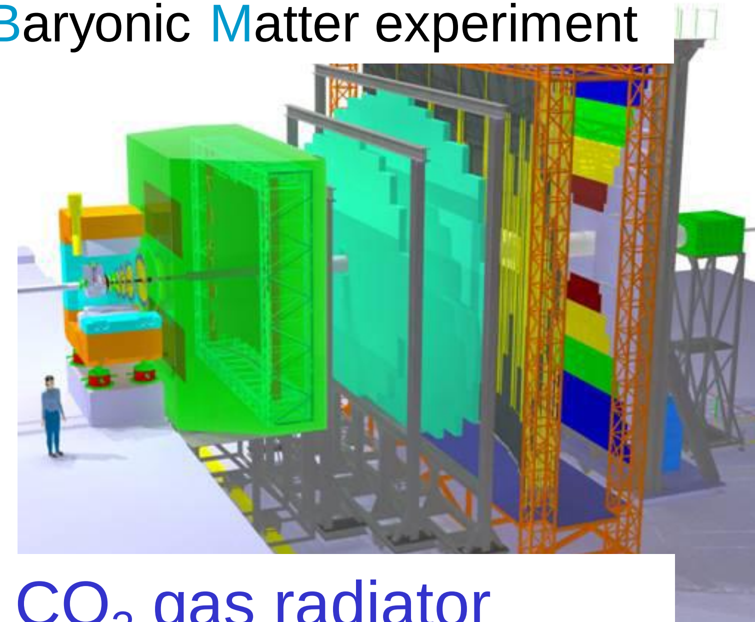
π → K misidentification ($\pi^\pm$ from K_s decay) ~ 1 %

IMAGE FROM THE ON-LINE EVENT DISPLAY



RICH for CBM at FAIR (GSI)

Compressed Baryonic Matter experiment



RICH: electron ID (= strong π suppression) and hadron ID

- 2.25 m long CO_2 gas radiator
- photon detector: 2 MA PMT planes
- need sensitivity down to 180nm

One of the sensor candidates: a recent version of the R5900

Hamamatsu R11265-103-M16:
78% effective coverage
SBA cathode, 35% max q.e.

Flat pannel multianode PMTs

Problem: active area fraction

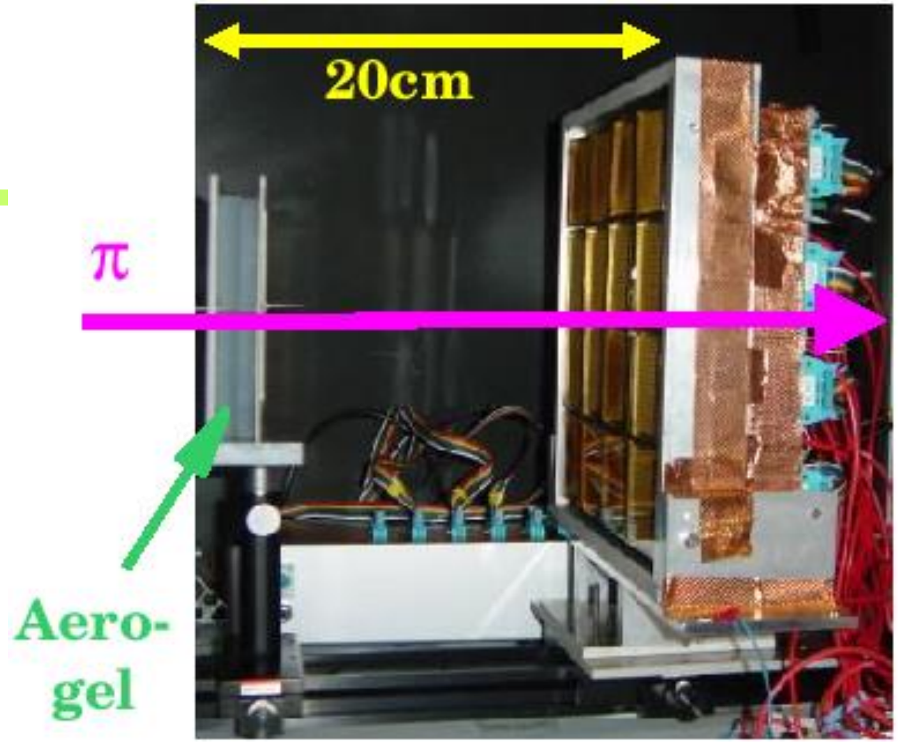
One possible solution: make a larger sensor

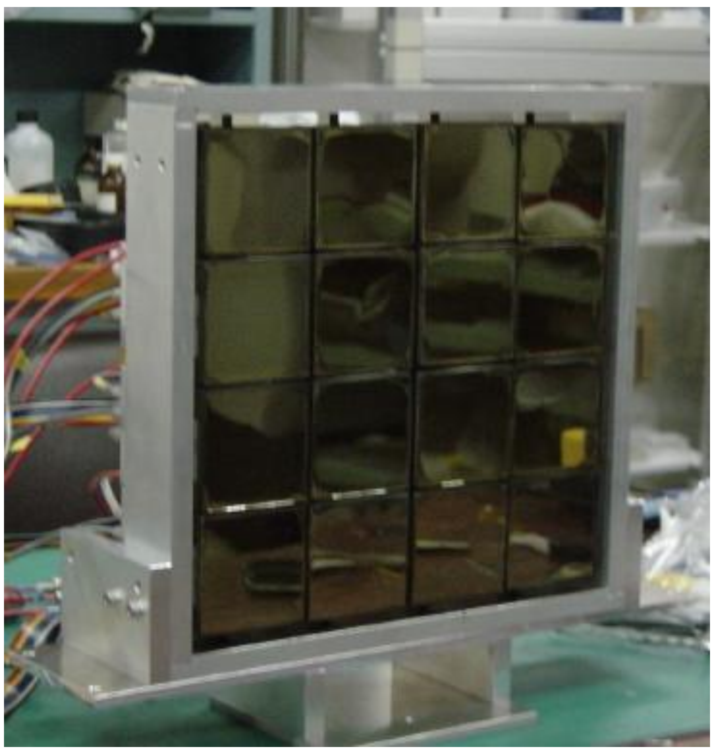
Hamamatsu: flat pannel PMT H8500

- 52 x 52mm², 89% effective coverage
- 64 channels, pixel size 5.8 x 5.8 mm2
- 12 dynodes, metal foil type
- Bialkali cathode, max 25% quantum efficiency
- single photon pulse height distribution not as good as in the smaller R5900 (and related tubes like 7600)

Flat pannel MA PMTs

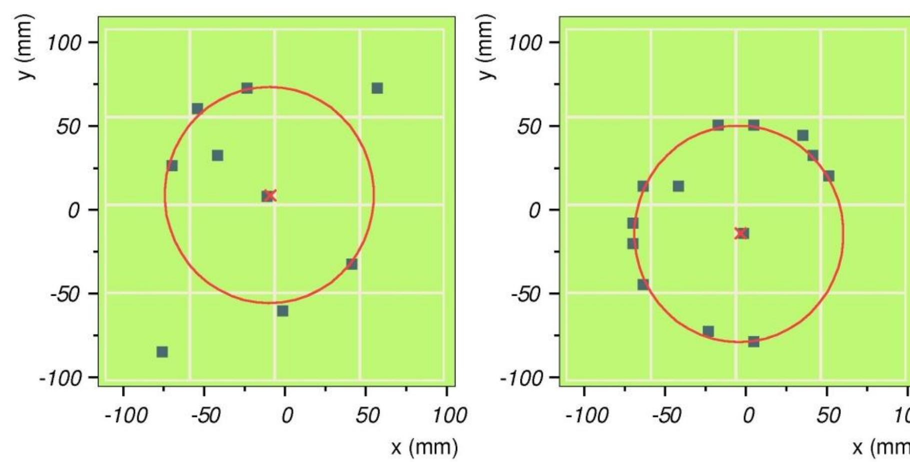
First used in a prototype RICH
for Belle II, with aerogel radiator.





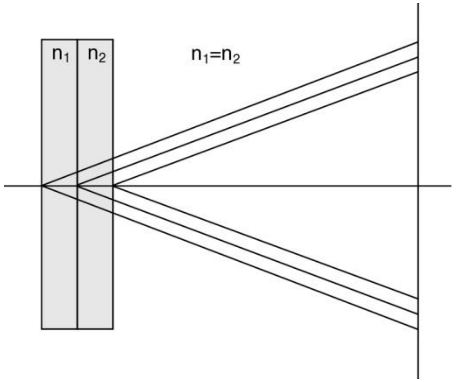
array of 16 H8500 PMTs

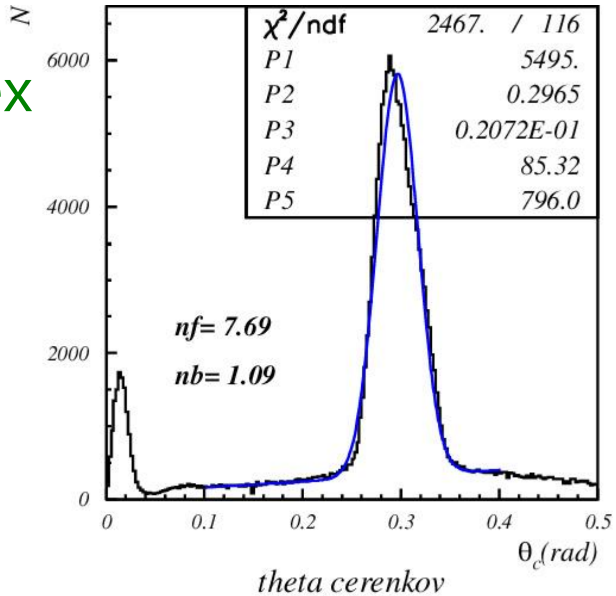
Clear rings, little background

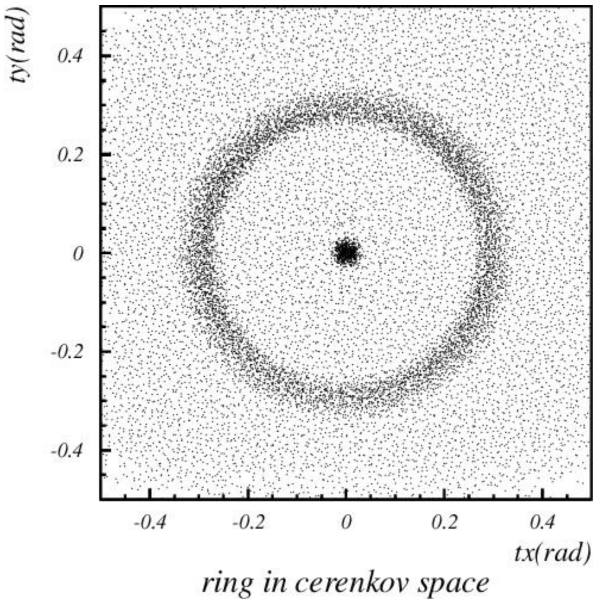


Used for the proof-of-principle test of the focusing radiator configuration

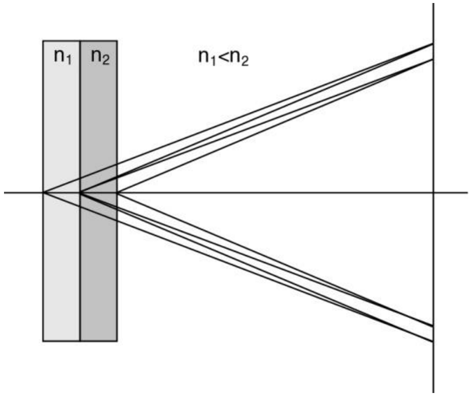
4cm aerogel single index

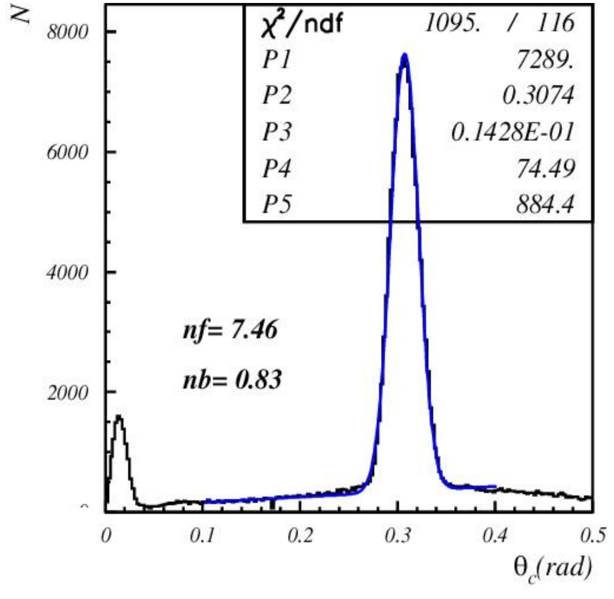


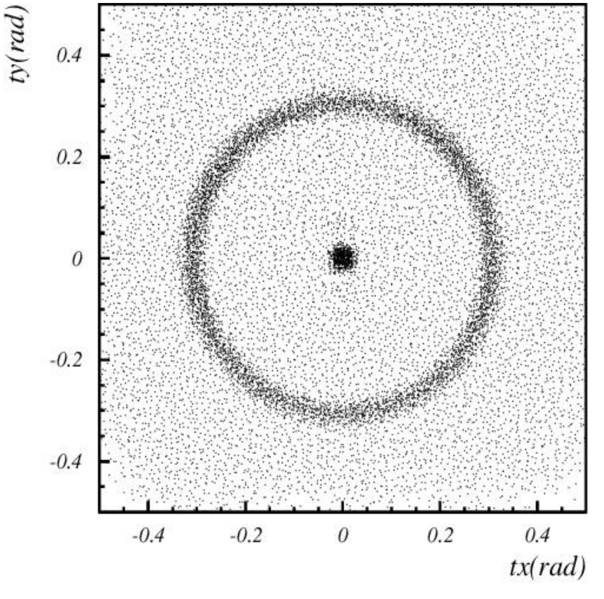




2+2cm aerogel



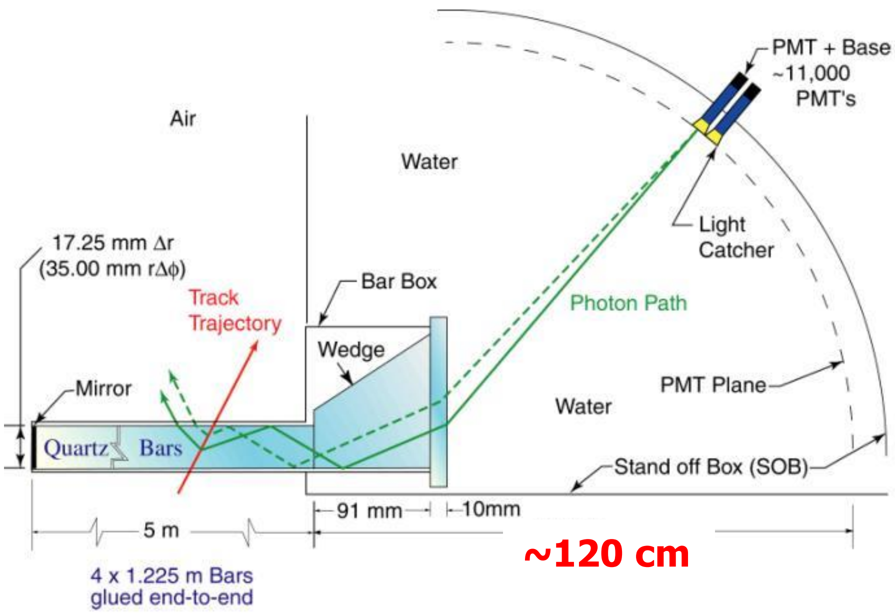


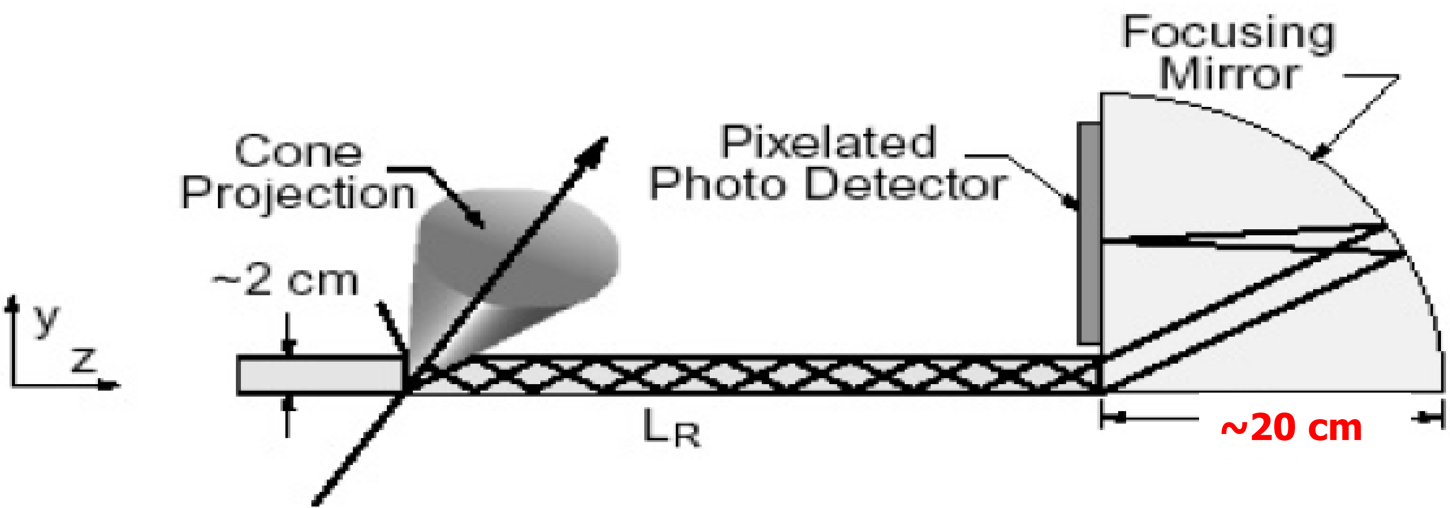


→NIM A548 (2005) 383

Flat pannel MA PMTs: Focusing DIRC

Next step in the DIRCdevelopment, remove the stand-off box →





Focusing DIRC

Super-B factory: 100x higher luminosity => DIRC needs to be smaller and faster

Focusing and smaller pixels can reduce the expansion volume by a factor of 7-10 !

Timing resolution improvement: σ ~1.7ns (BaBar DIRC) → $\sigma \leq$150-200ps (~10x better) allows a measurement of the photon group velocity $c_g(\lambda)$ to correct the chromatic error of θ_c.

Photon detector requirements:

- Pad size <5mm
- Time resolution ~50-100ps

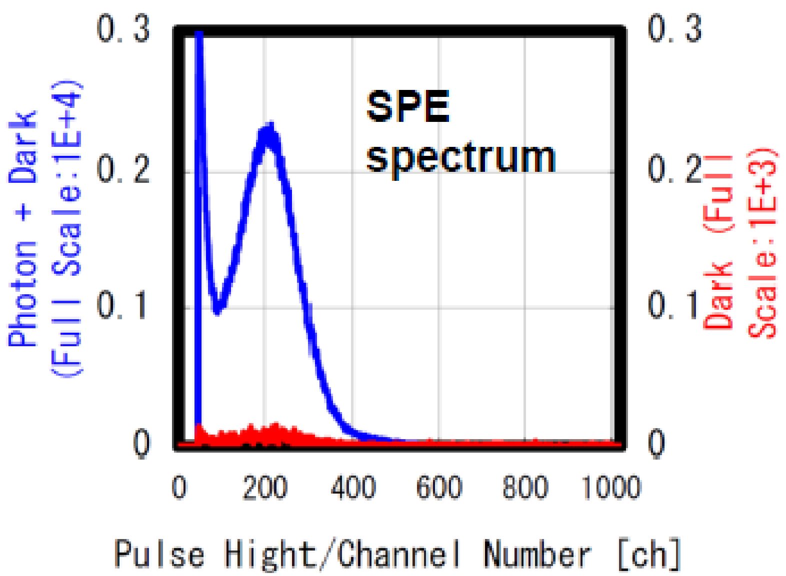
One of the two options: Hamamatsu flat pannel PMTs.

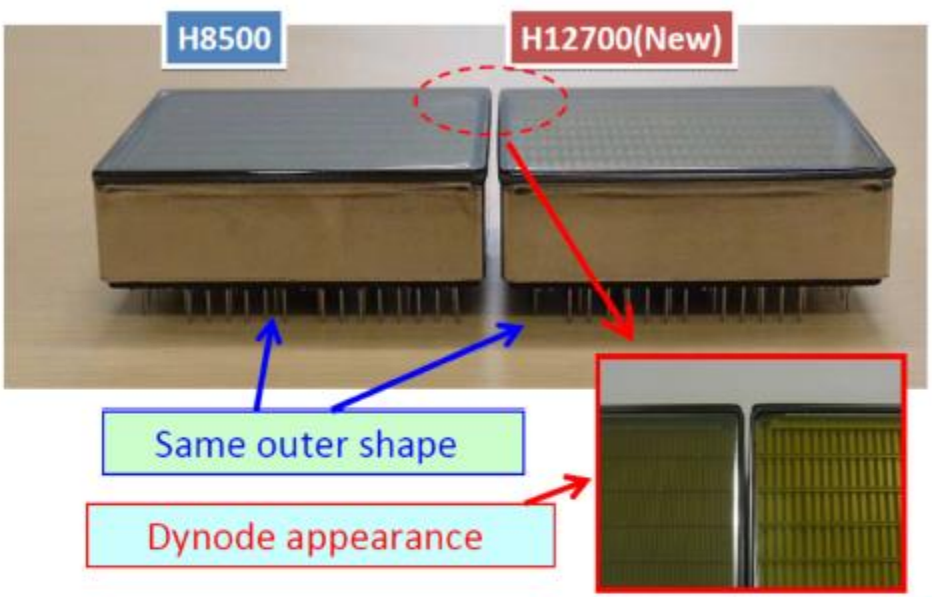
Flat pannel MA PMTs: CBM RICH

Baseline option for the CBM RICH

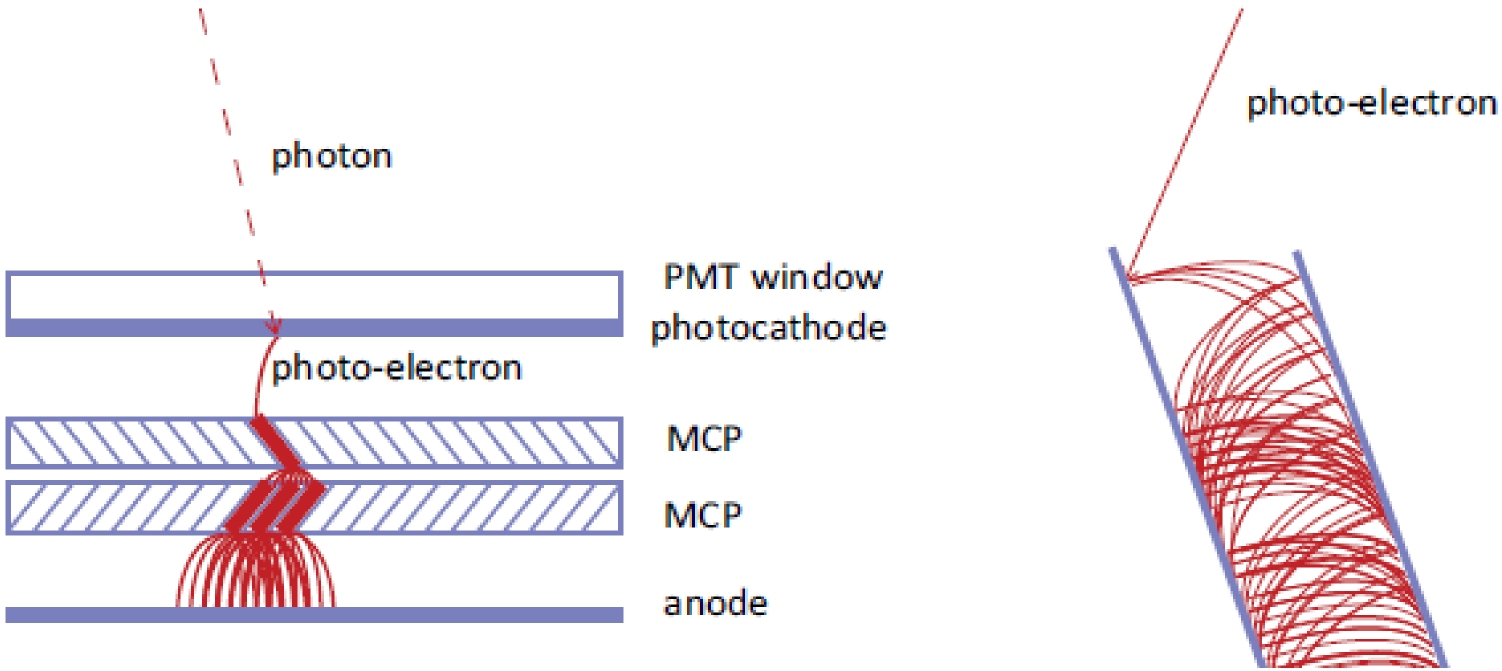
News: a novel version of H8500 available, with a considerably better single photon pulse height distribution

Same sensor also considered for the CLASS12 RICH





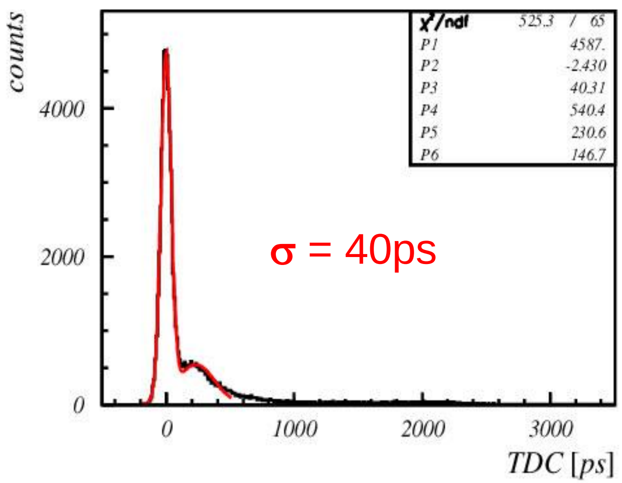
Micro-channel plate PMTs

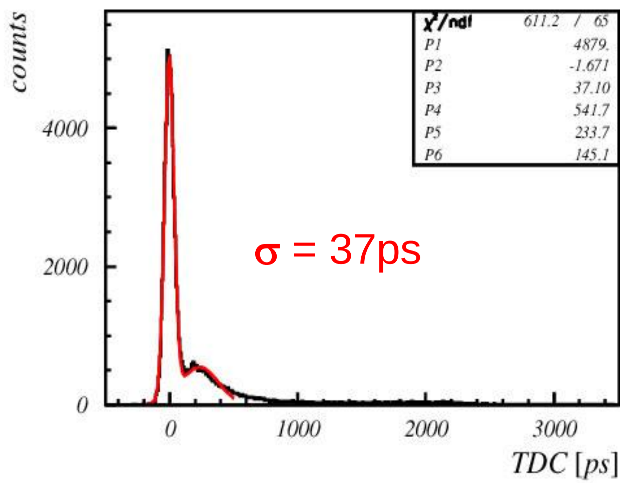


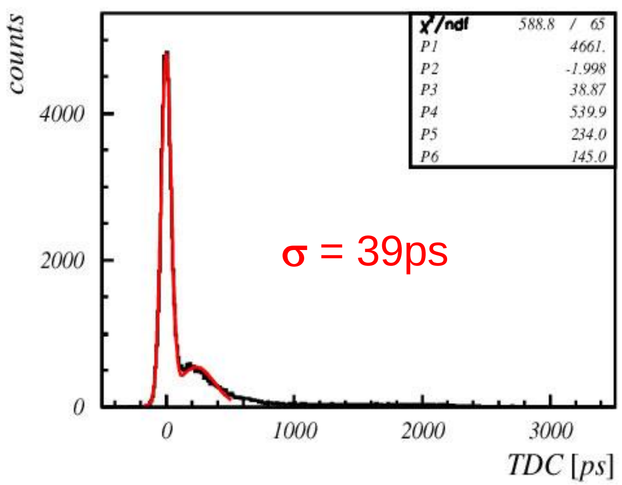
- Fast
- Immune to an axial magnetic field

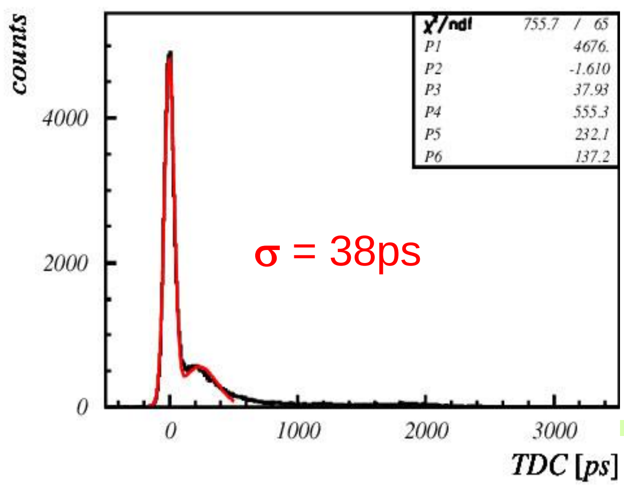
BURLE/Photonis MCP-PMT

BURLE 85011 microchannel plate (MCP) PMT: time resolution after time walk correction



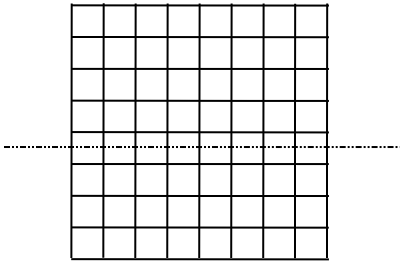




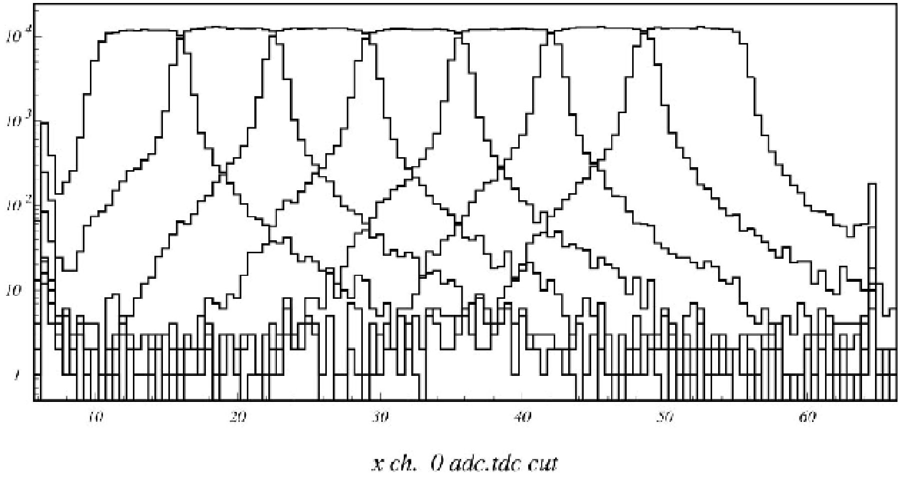


Tails understood, can be significantly reduced by:

- decreased photocathode-MCP distance and
- increased voltage difference

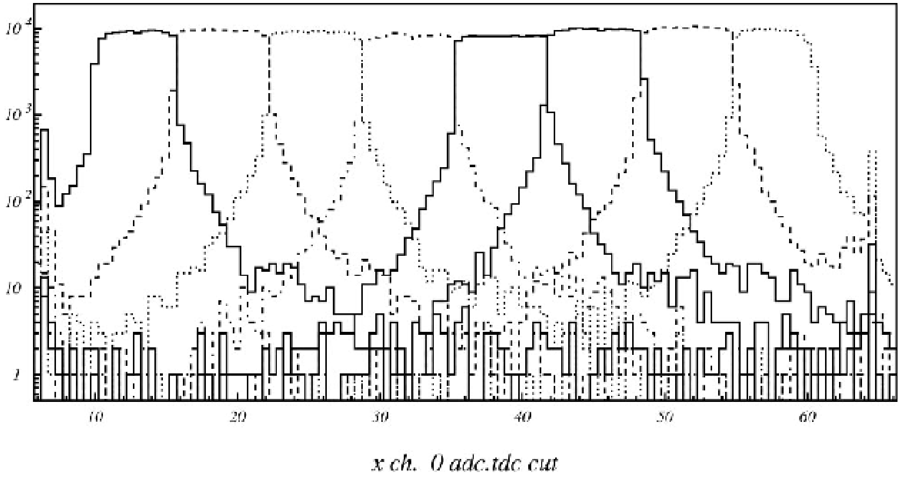


MCP PMT: sensitivity to magnetic field



Number of detected hits on individual channels as a function of light spot position.

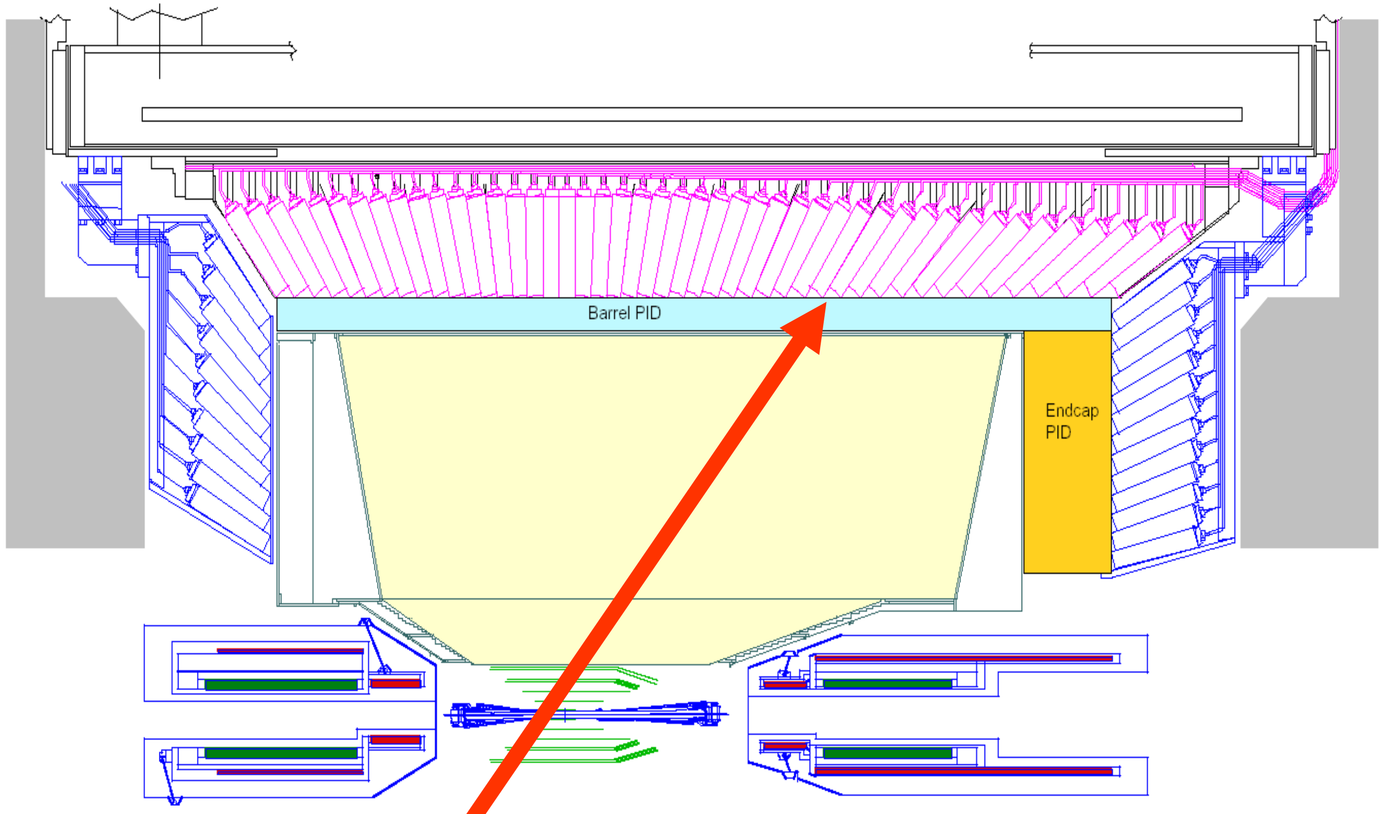
B = 0 T,
HV = 2400 V



B = 1.5 T,
HV = 2500 V

In the presence of magnetic field, charge sharing and cross talk due to long range photoelectron back-scattering are considerably reduced.

Belle upgrade – side view

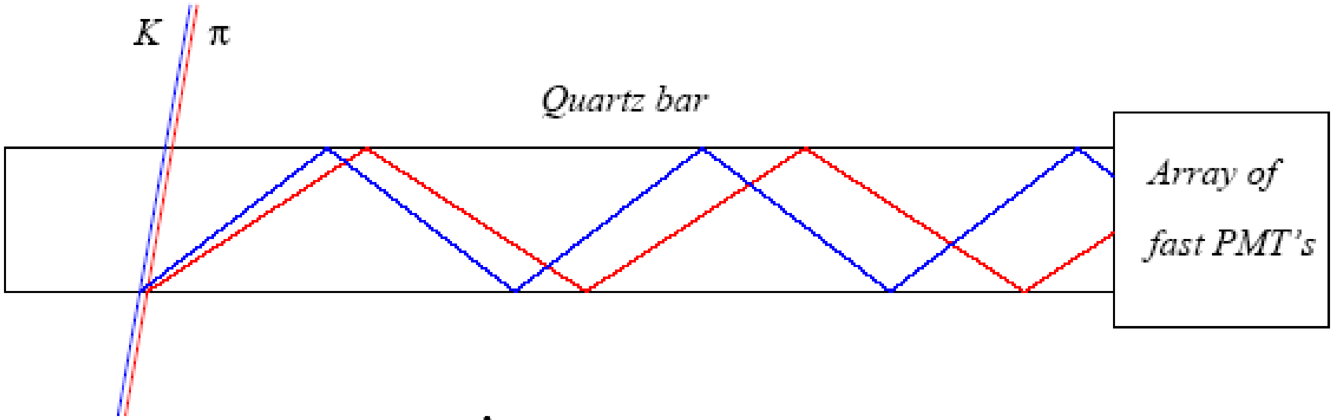


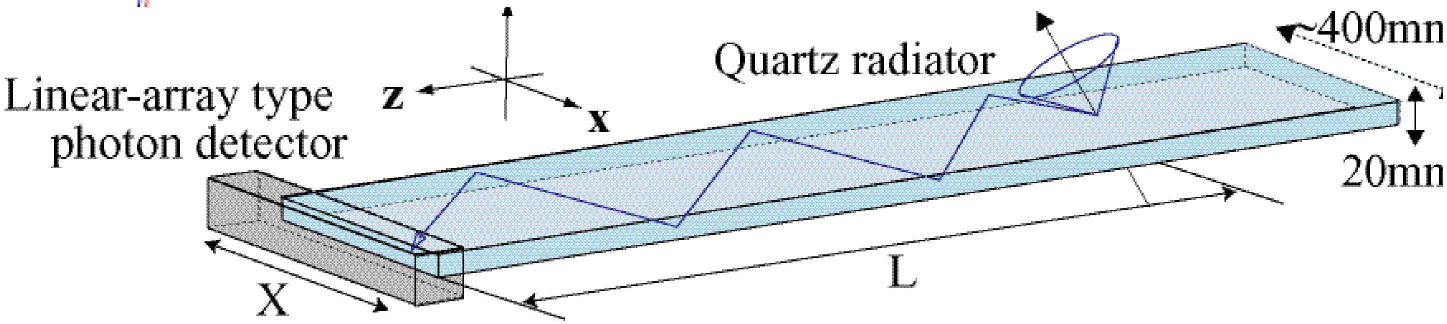
Two new particle ID devices, both RICHes:

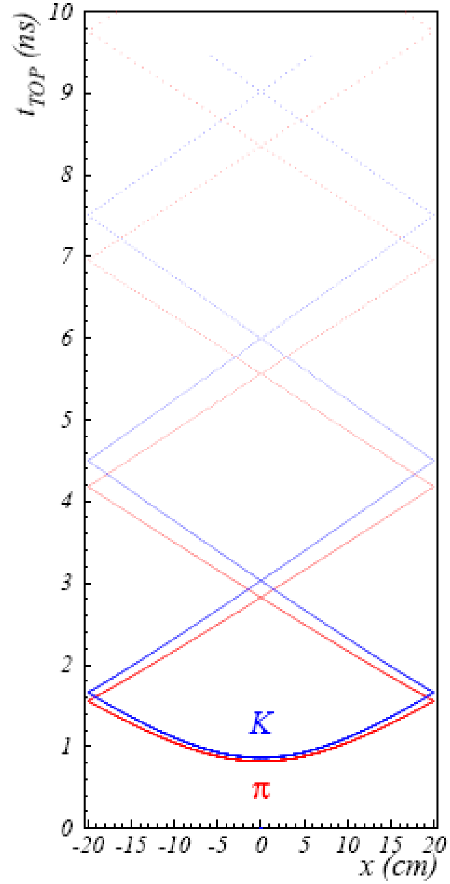
Barrel: Time-of-propagation counter (TOP) counter

Endcap: proximity focusing RICH

Time-Of-Propagation (TOP) counter



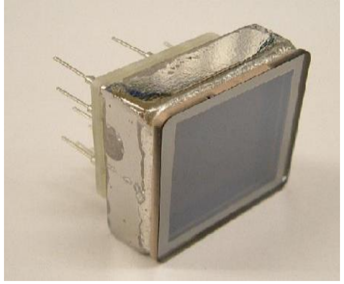




Similar to DIRC, but instead of two coordinates measure:

- One (or two coordinates) with a few mm precision
- Time-of-arrival

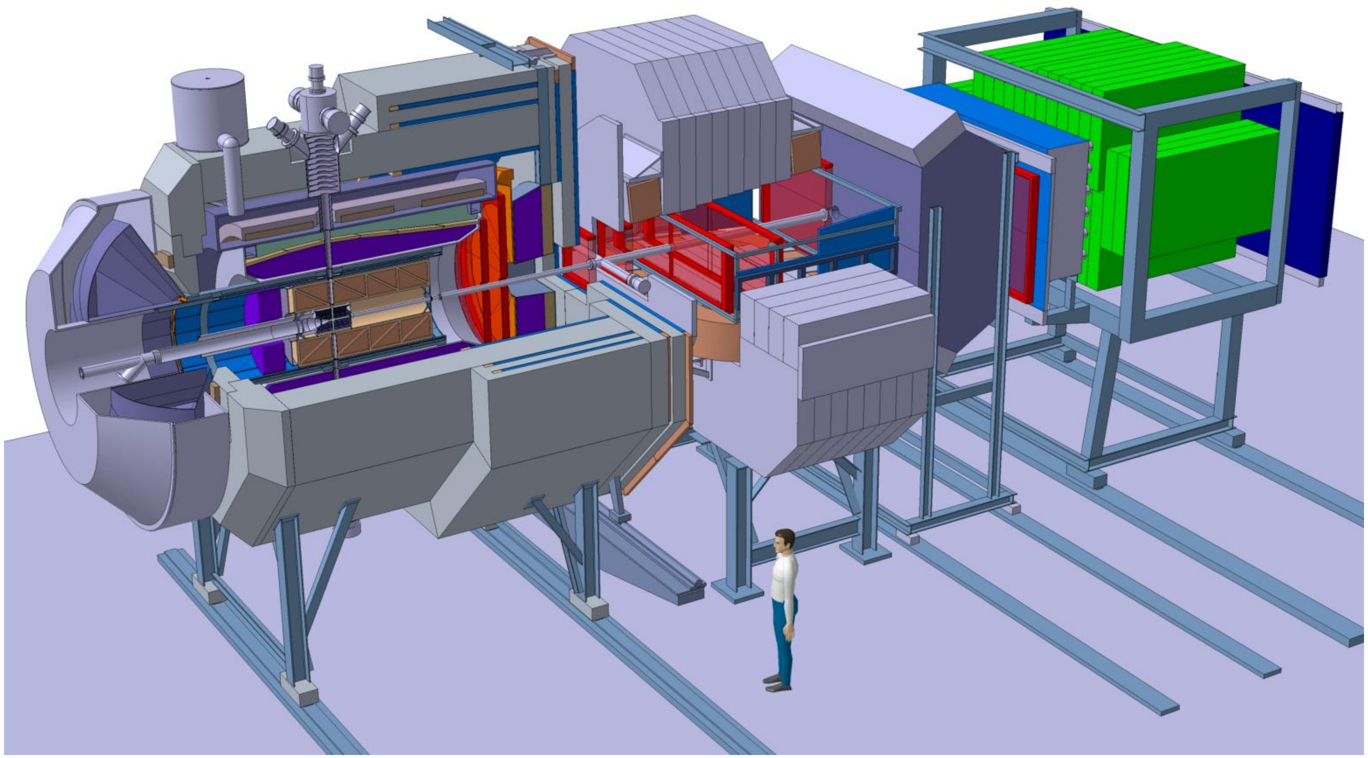
→ Excellent time resolution < ~40ps
required for single photons in 1.5T B field



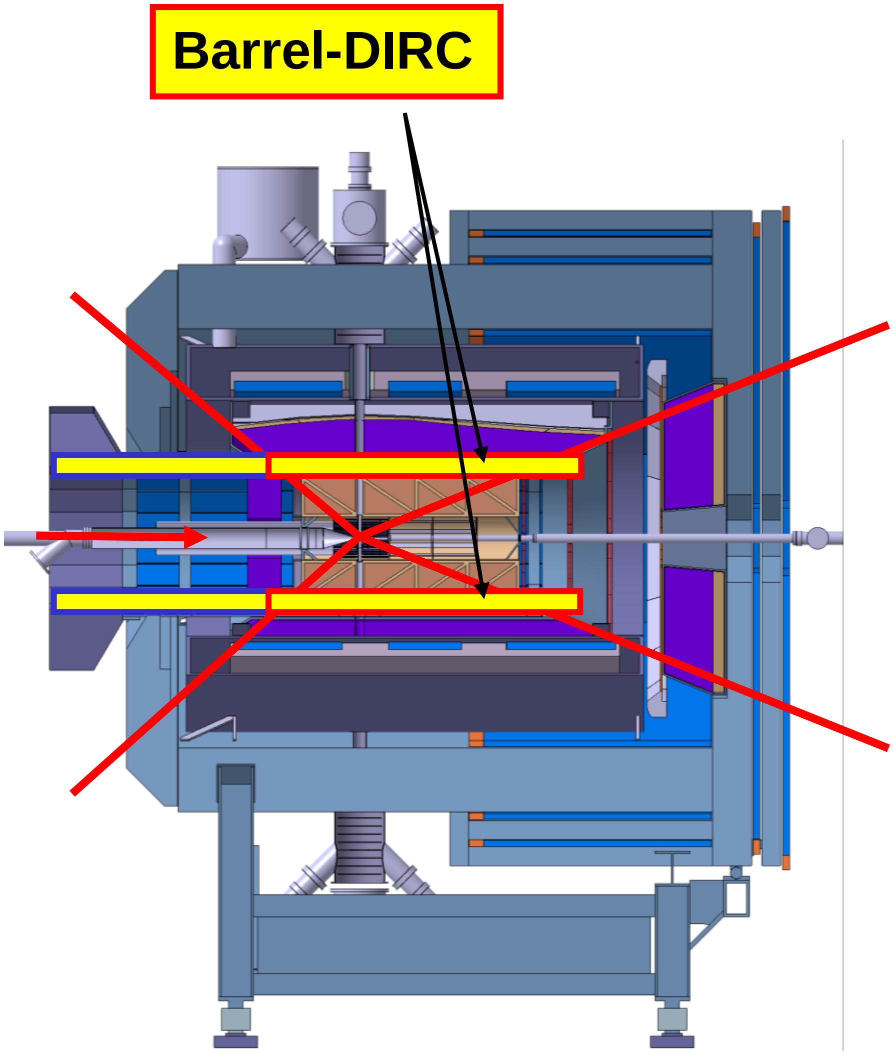
Hamamatsu
SL10 MCP-PMT

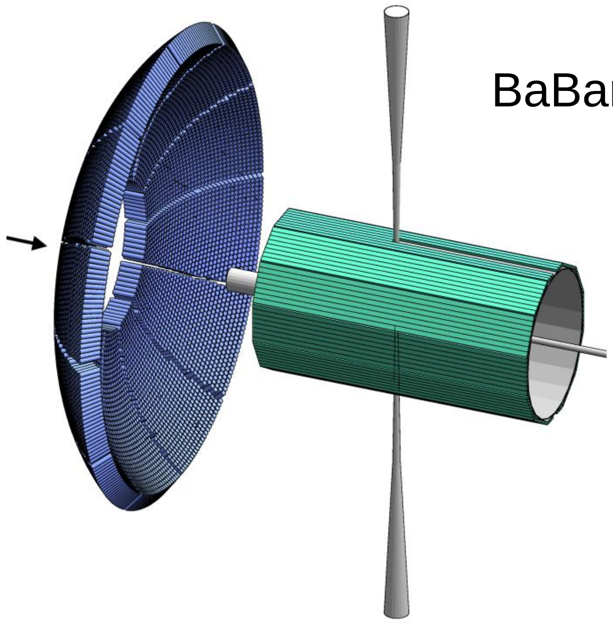
DIRC counters for PANDA (FAIR, GSI)

Two DIRC-like counters are considered for the PANDA experiment



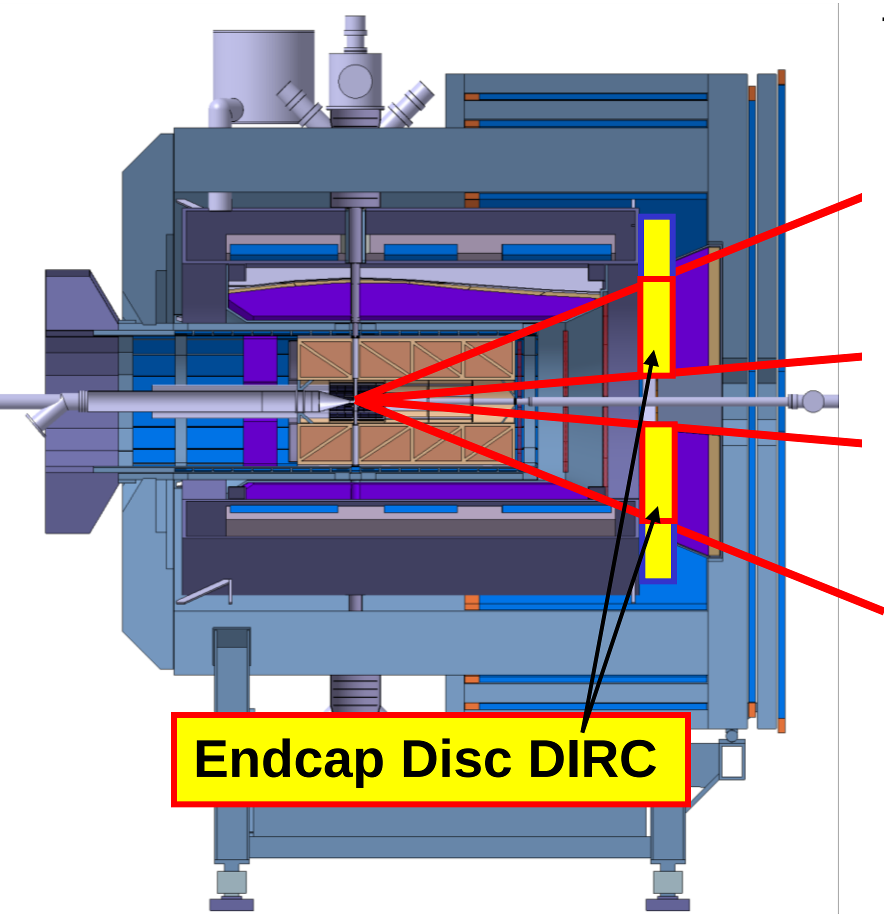
PANDA barrel DIRC





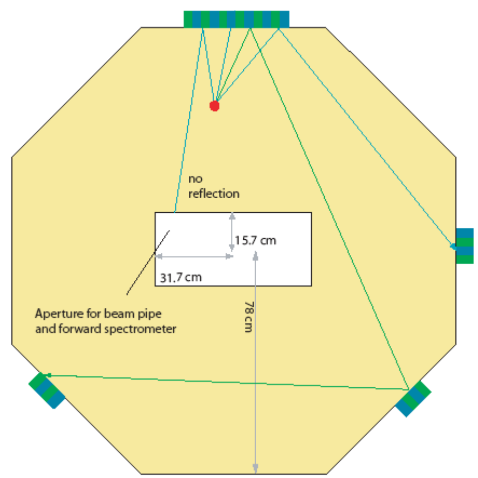
→ Talk by Mathias Hoek

PANDA endcap DIRC

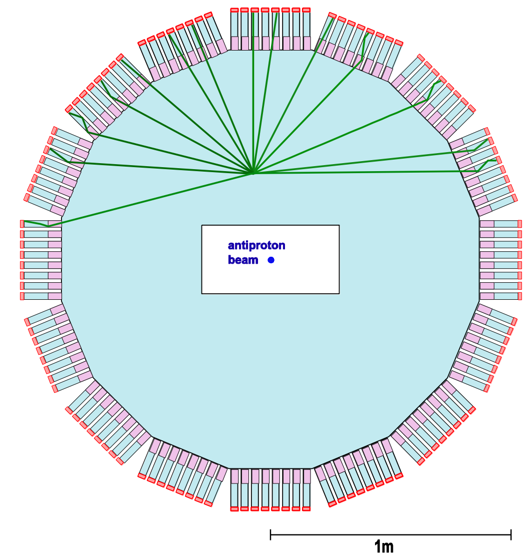


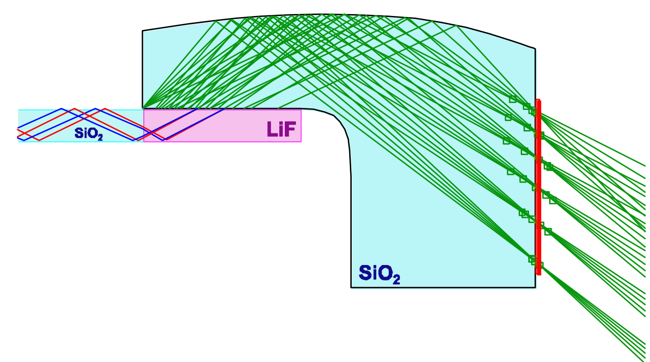
Two different readout designs:

Time-of-Propagation



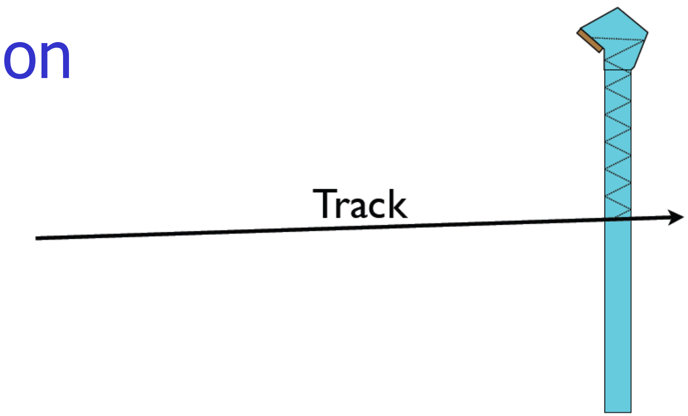
Focussing light guide

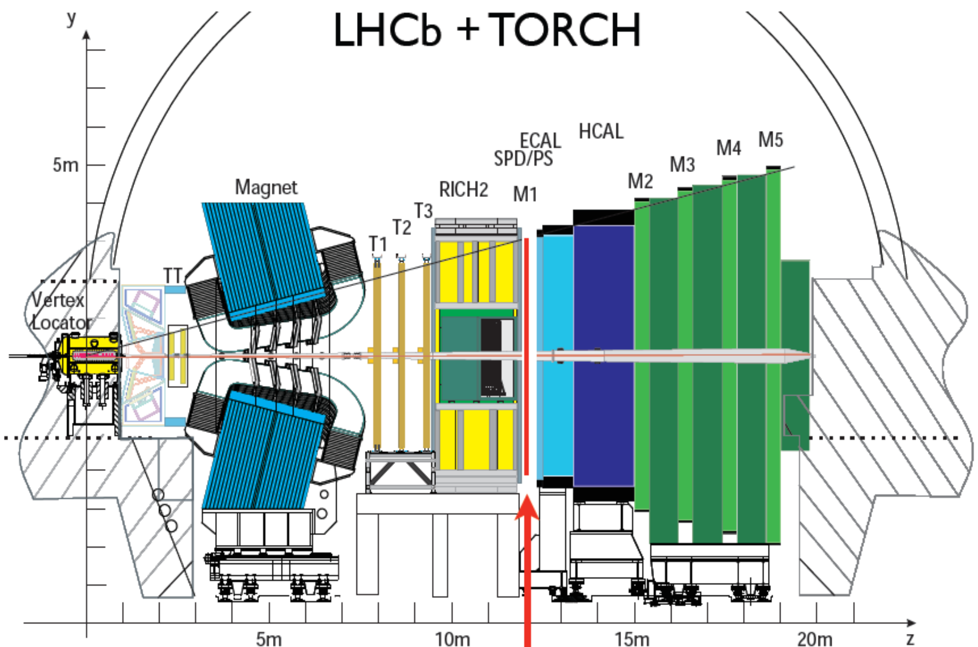




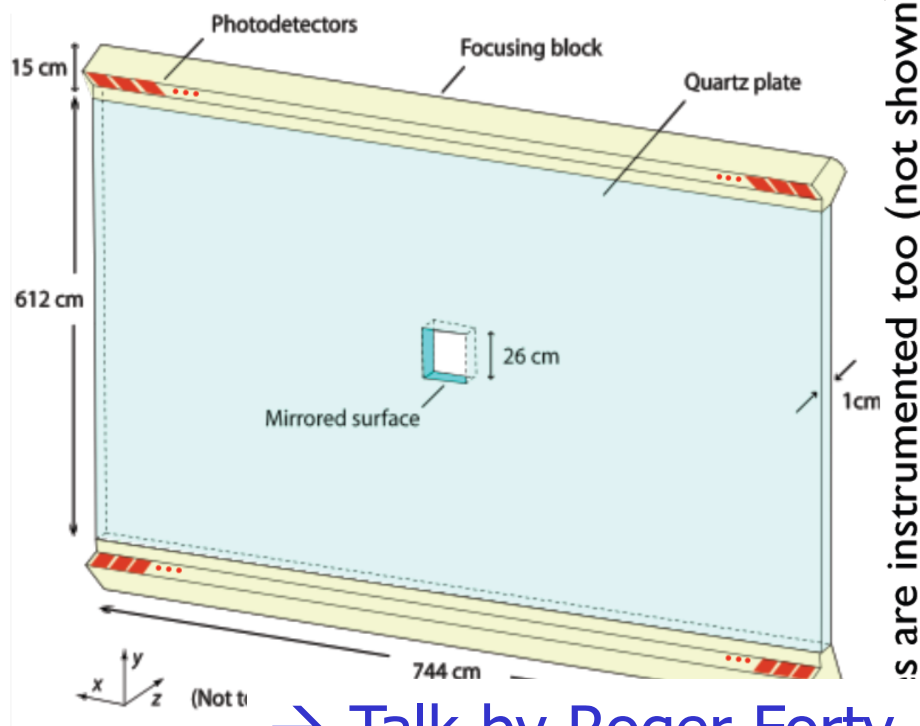
LHCb PID upgrade: TORCH

A special type of Time-of-Propagation counter for the LHCb upgrade





1cm-thick quartz plate at z=12m



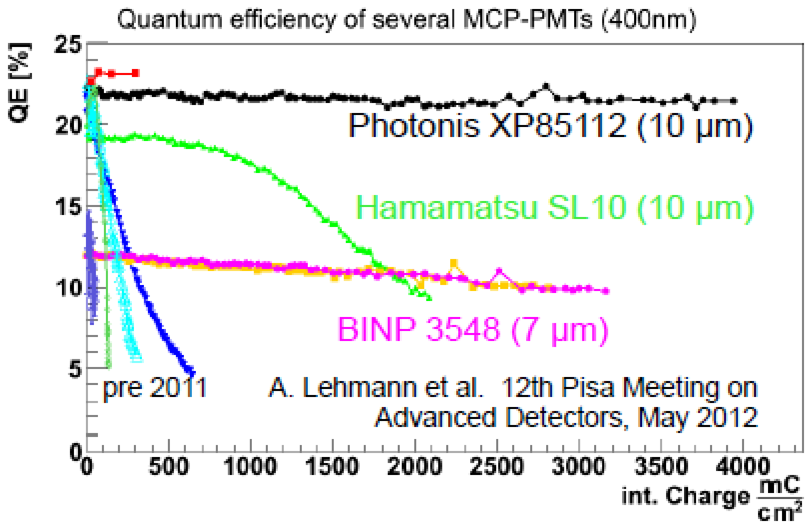
→ Talk by Roger Forty

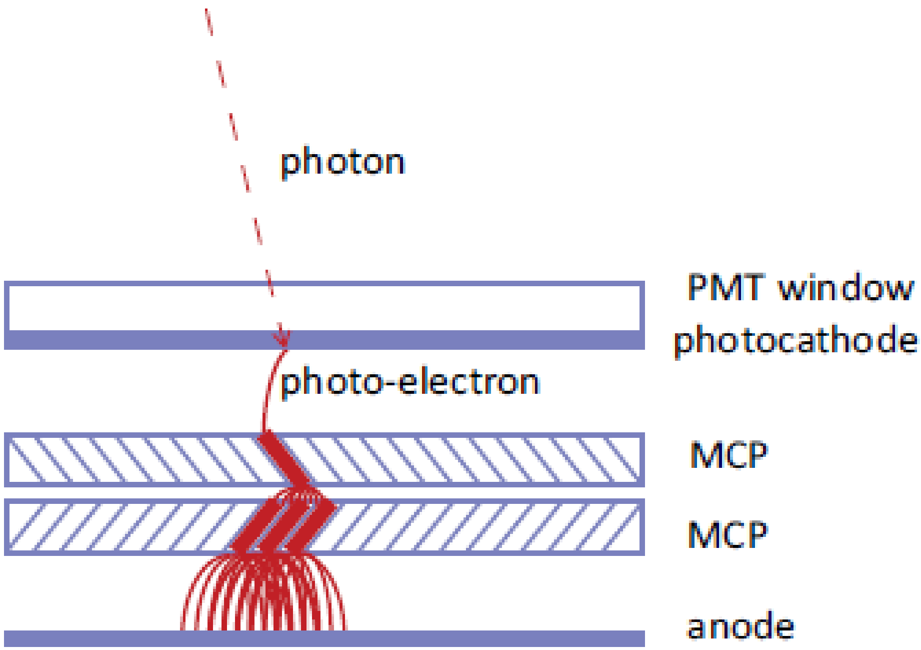
MCP PMTs ageing

MCP PMT ageing: a serious problem in most of the planned aplications.

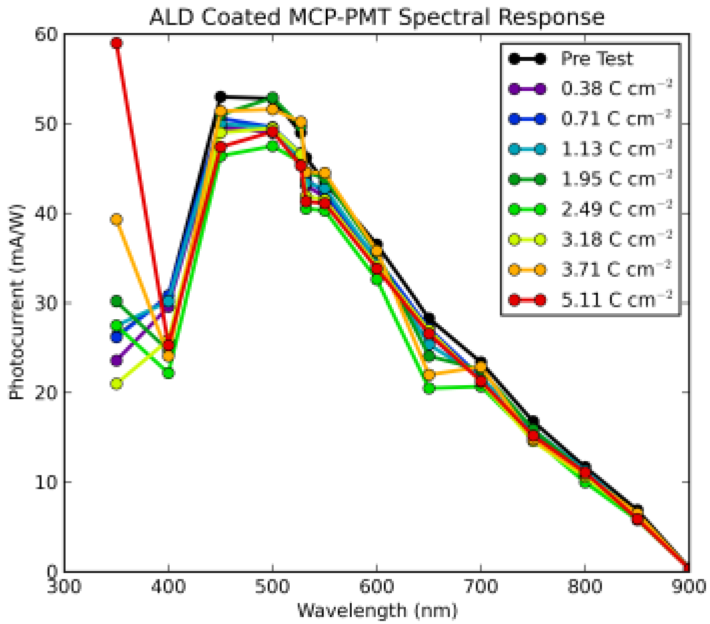
Cures:

- Better cleaning of the MCPs, better vacuum
- Al foil between PC and first MCP
- Al foil between two MPC stages
- Atomic layer deposition (ALD)





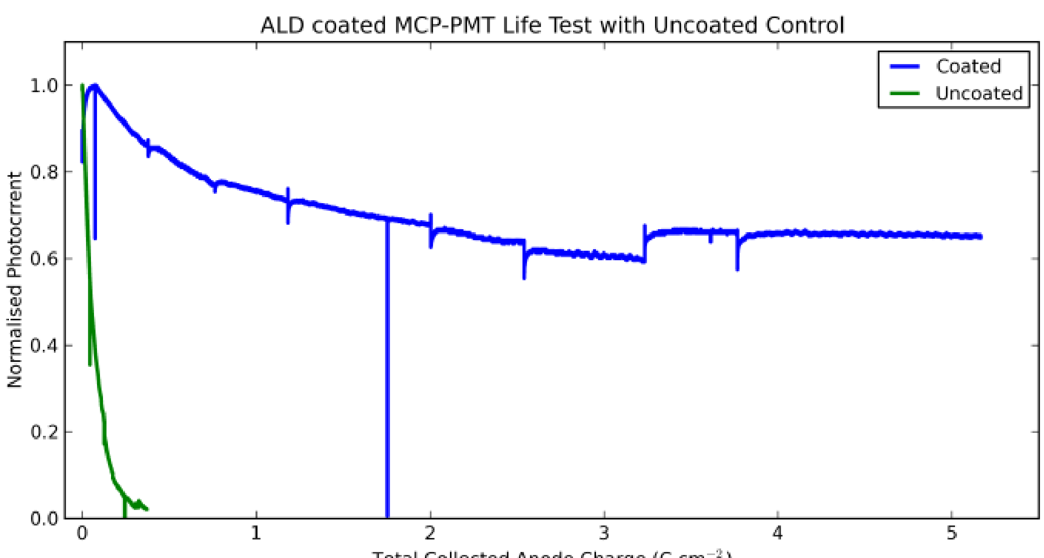
MCP PMTs ageing, cure

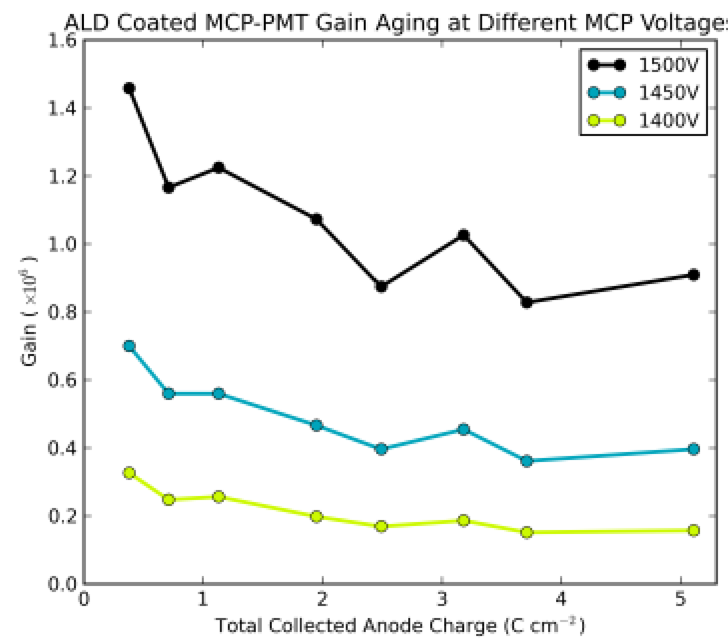


Photek, ALD deposition

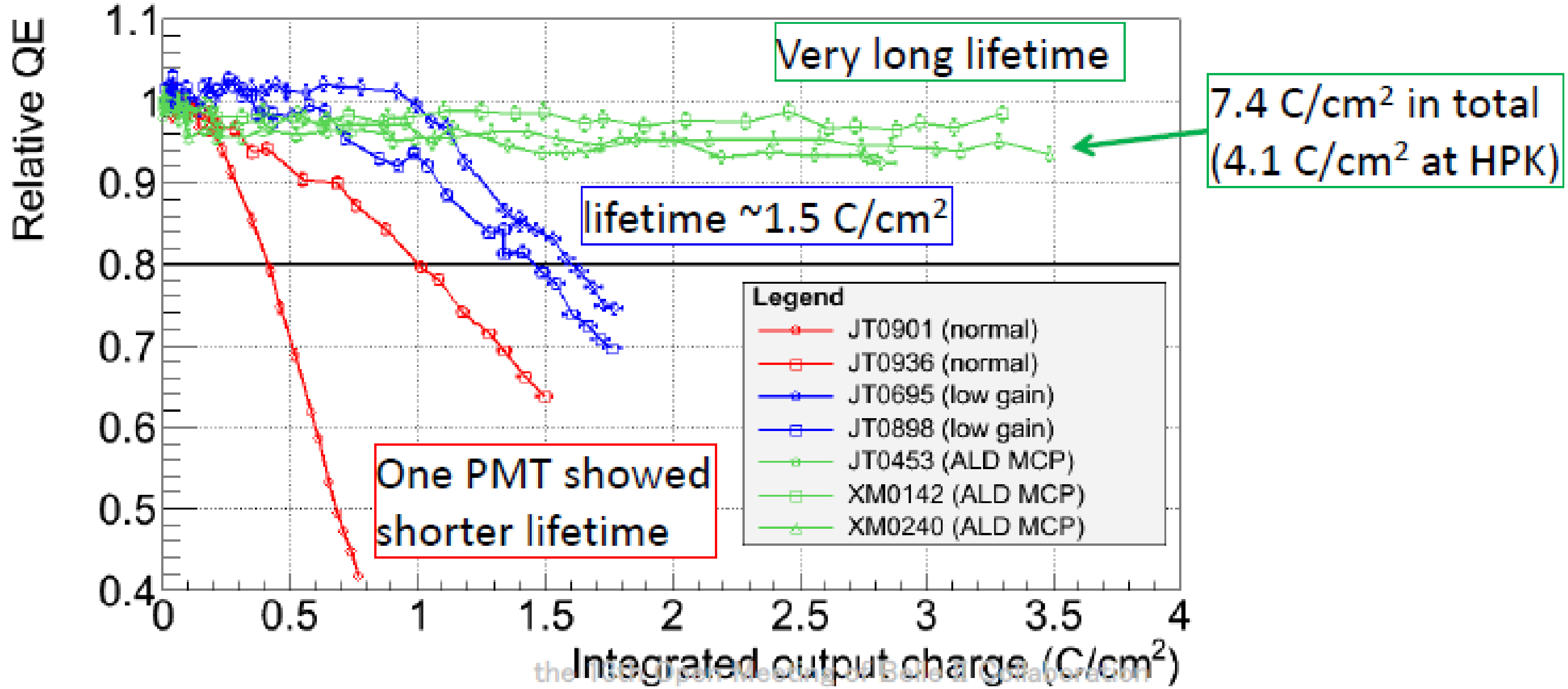
No drop in QE after 5 C/cm^2

Photo current drop due to a reduced gain (microchannel plate ageing)





MCP PMTs ageing, cure



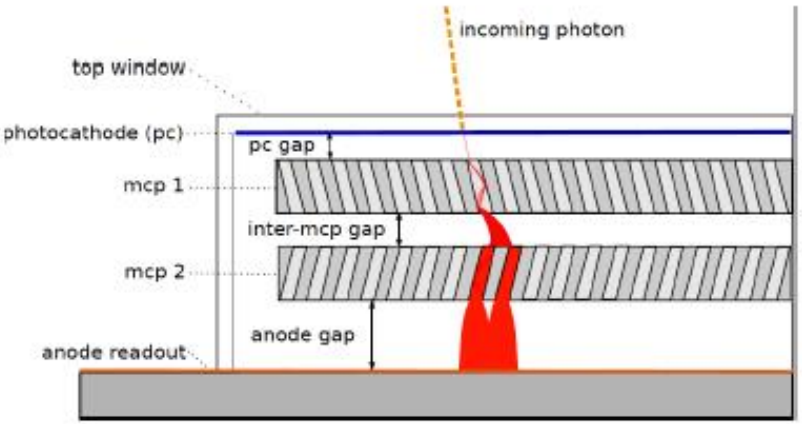
Hamamatsu, ALD deposition

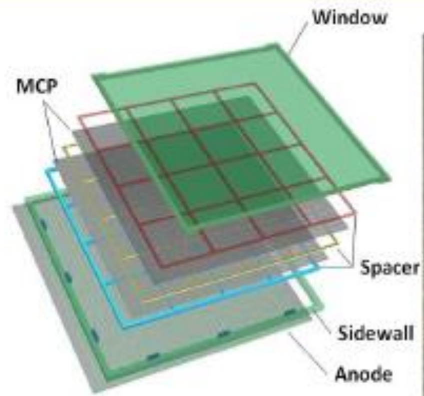
No drop in QE after 7.4 C/cm^2

LAPPD – Large Area Picosecond Photon Detector

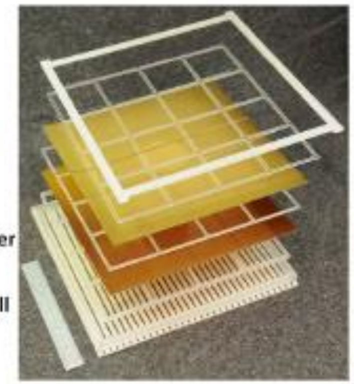
Glass Package (20x20cm^2)

University of Chicago



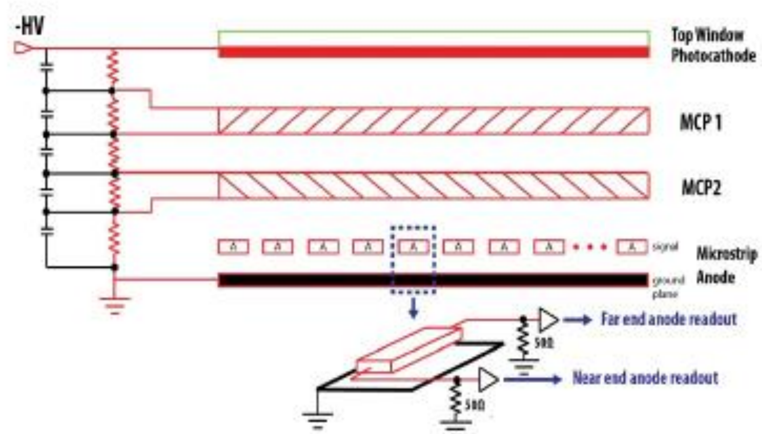


Design Drawing - September 2010



Actual Glass Parts - April 2012

The Frugal Tile

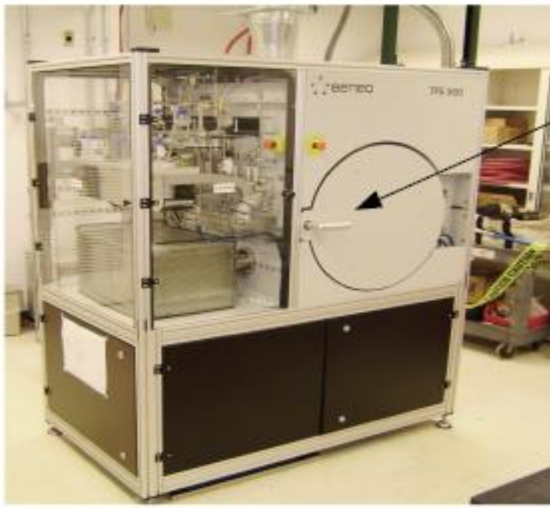


- Cheap, widely available float glass
- Anode is made by silk-screening
- Flat panel
- No pins, single HV cable
- Modular design
- High bandwidth 50 Ω object
  - designed for fast timing

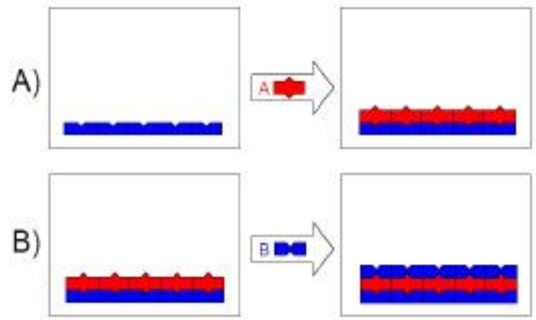
LAPPD – Large Area Picosecond Photon Detector

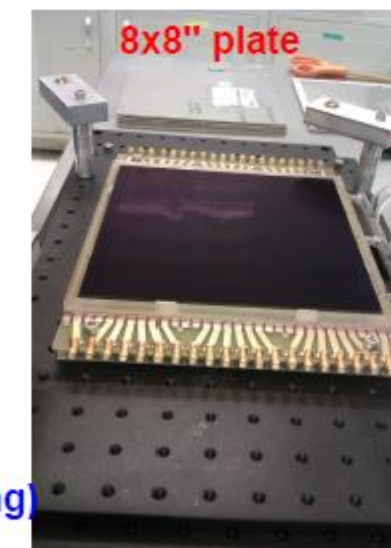
MCP by Atomic Layer Deposition (ALD)

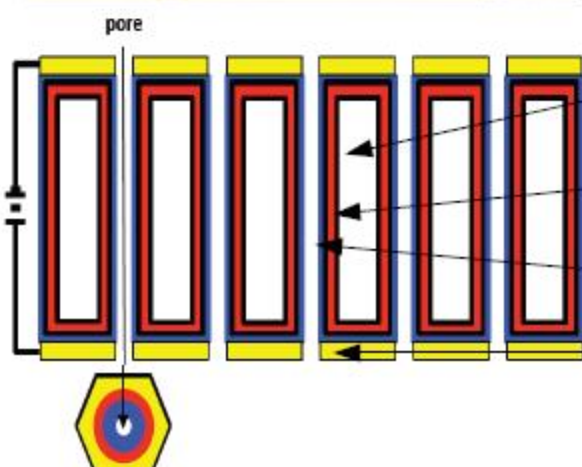
University of Chicago



Beneq reactor for ALD
@Argonne National Laboratory
A.Mane, J.Elam







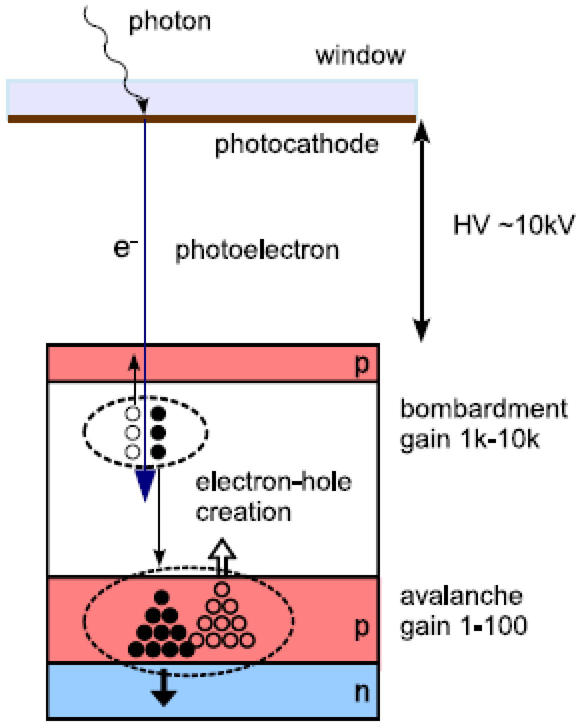
Porous glass

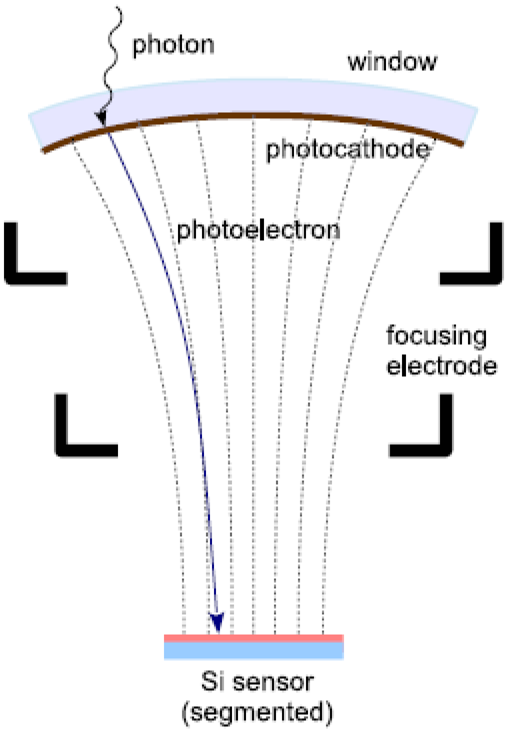
Resistive coating ~100nm (ALD)

Emissive coating ~ 20nm (ALD)

Conductive coating
(thermal evaporation or sputtering)

Hybrid photodetectors

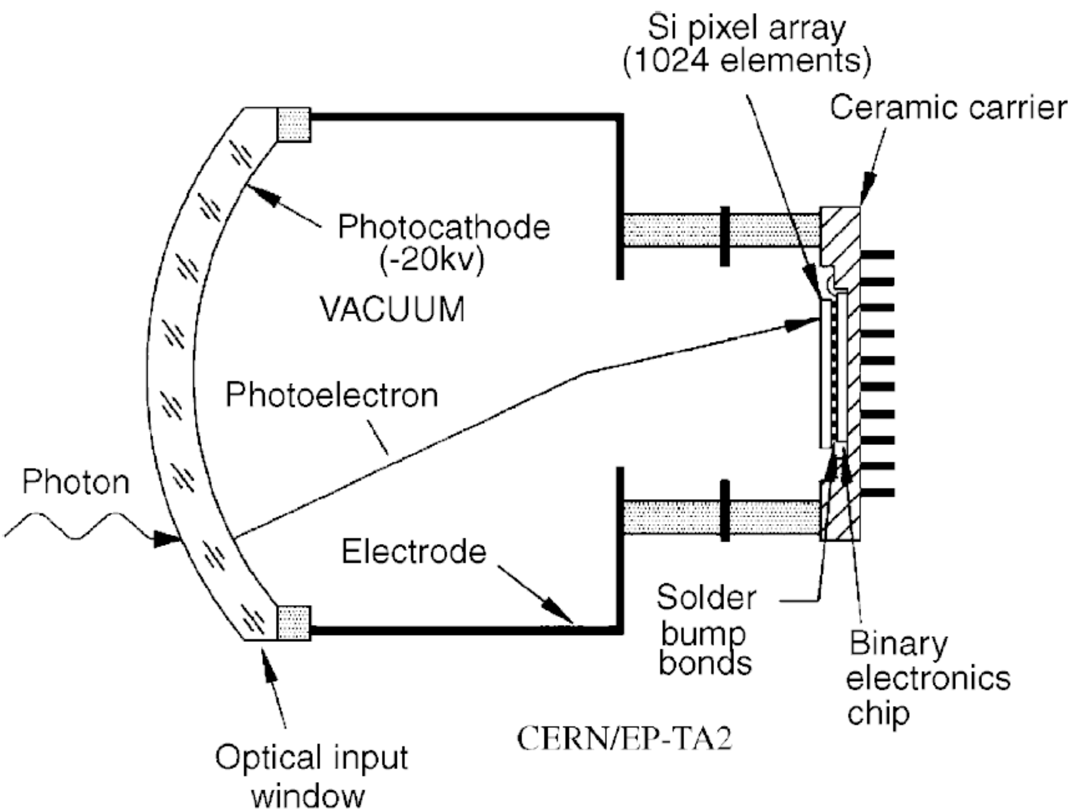




Hybrid photodetector: LHCb RICHes

Photon detector: hybrid PMT (R+D with DEP) with 5x demagnification (electrostatic focusing).

Hybrid PMT: accelerate photoelectrons in electric field (~20kV), detect it in a pixelated silicon detector.



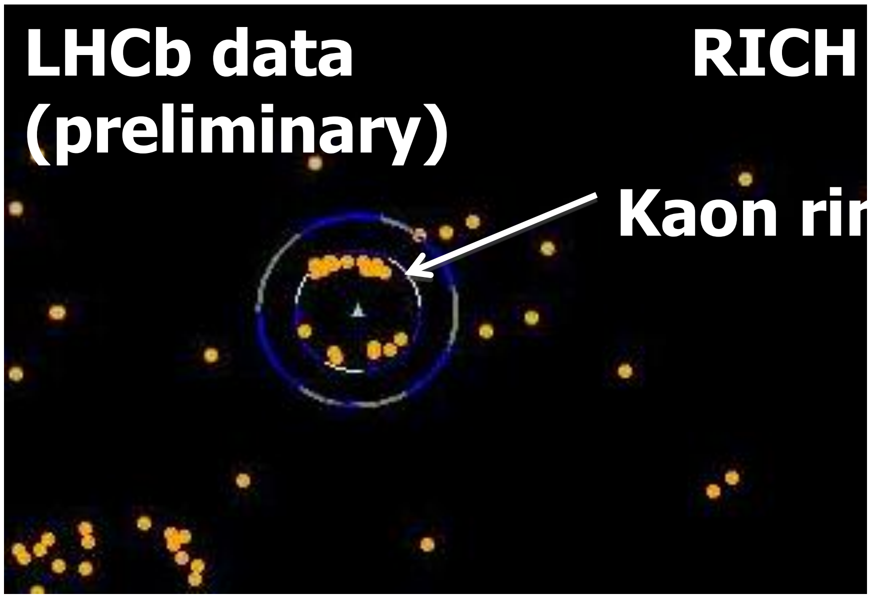
NIM A553 (2005) 333

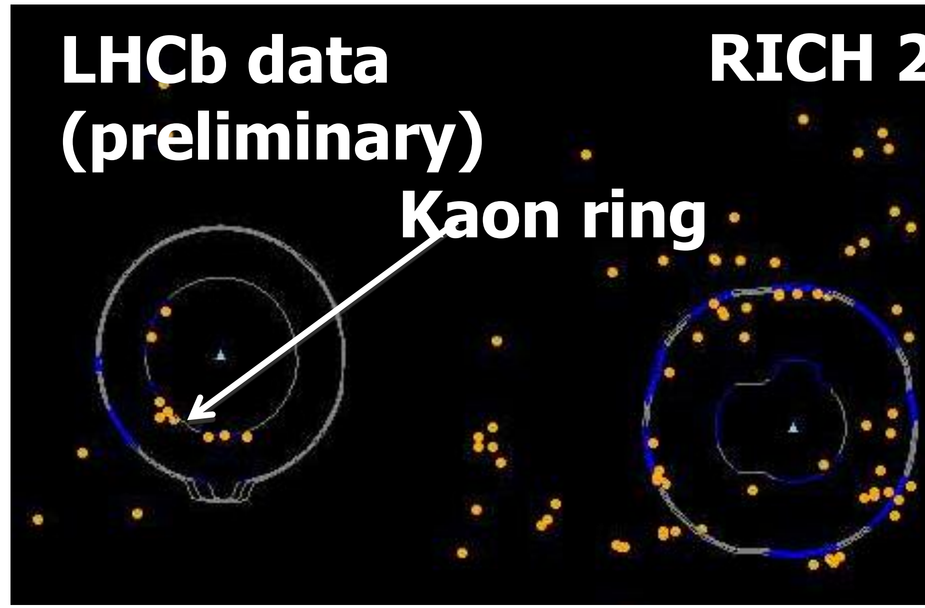
LHCb Event Display

RICH1

Early data, Nov/Dec 2009
LHC beams √s = 900 GeV

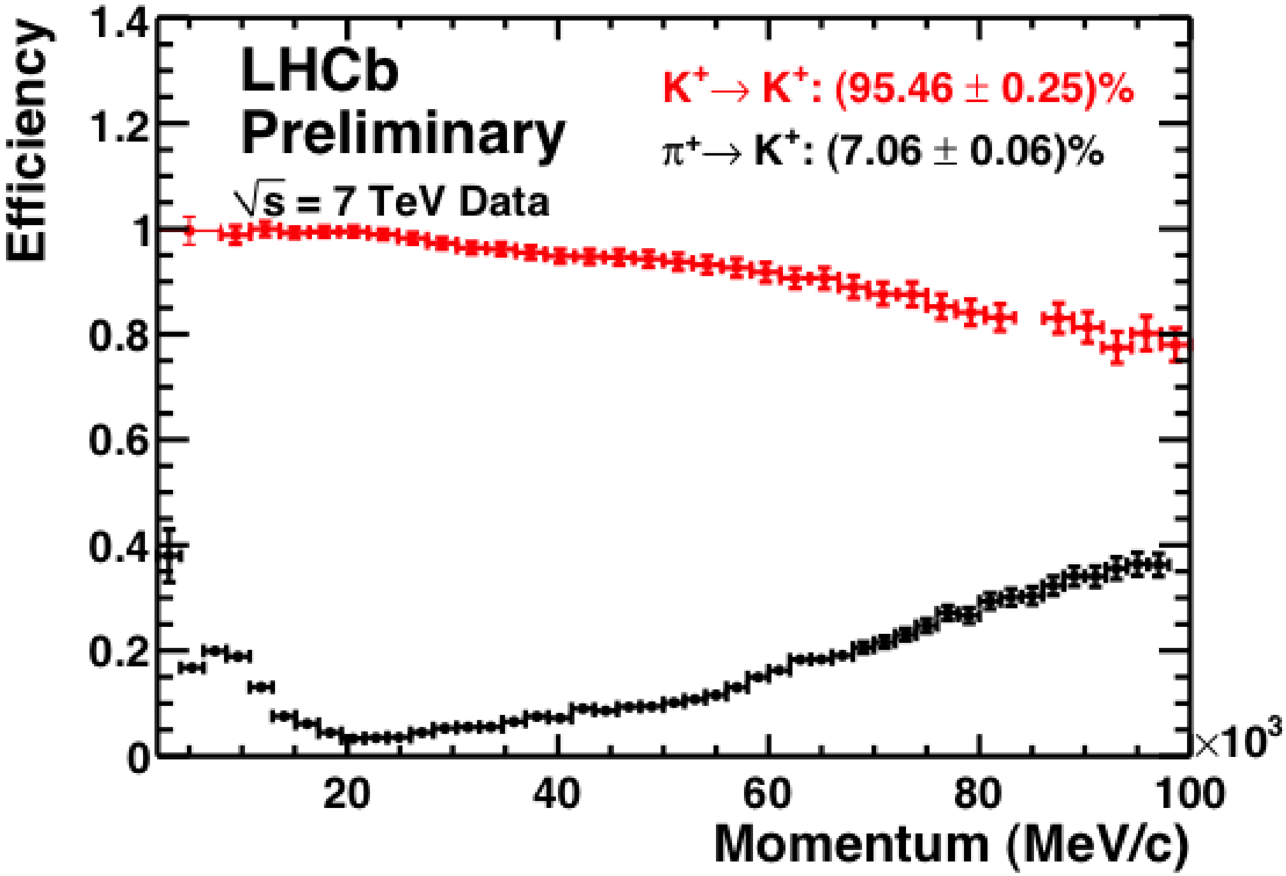
RICH2



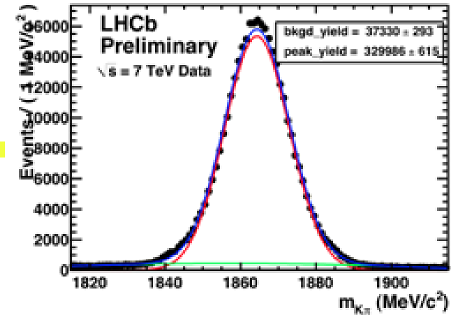


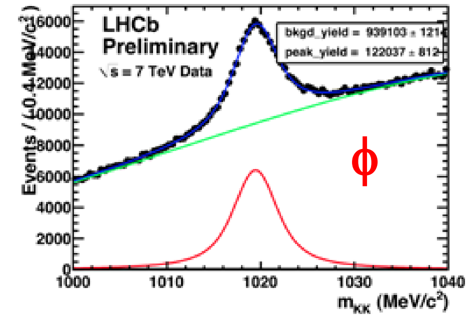
- Orange points → photon hits
- Continuous lines → expected distribution for each particle hypothesis

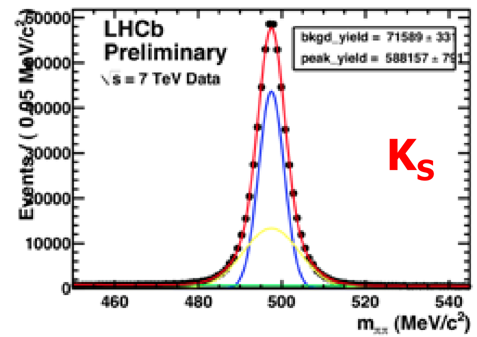
LHCb RICHes: performance

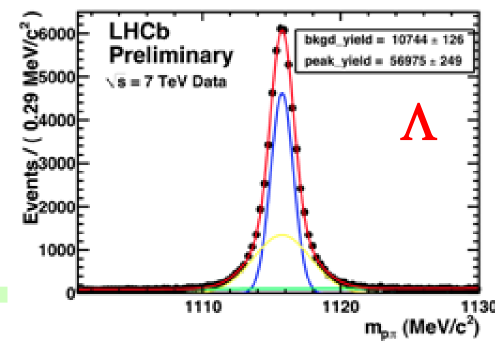


D from D*



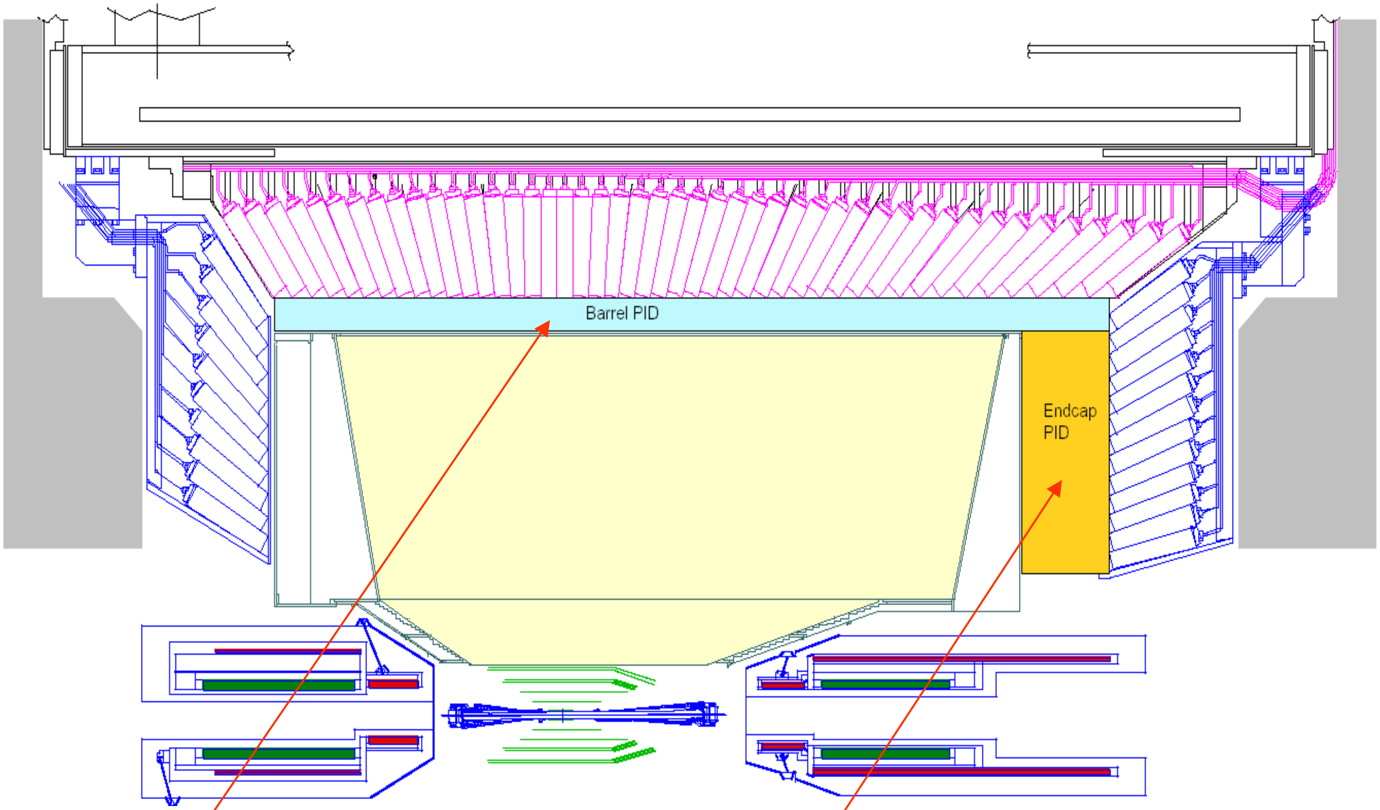






Efficiency and purity from data → excellent agreement with MC

Belle upgrade – side view



Two new particle ID devices, both RICHes:

Barrel: time-of-propagation (TOP) counter

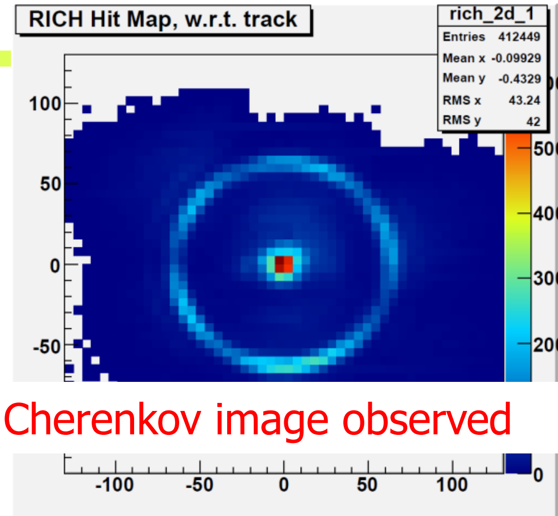
Endcap: proximity focusing RICH

→Talk by T. Iijima

Aerogel RICH photon detectors

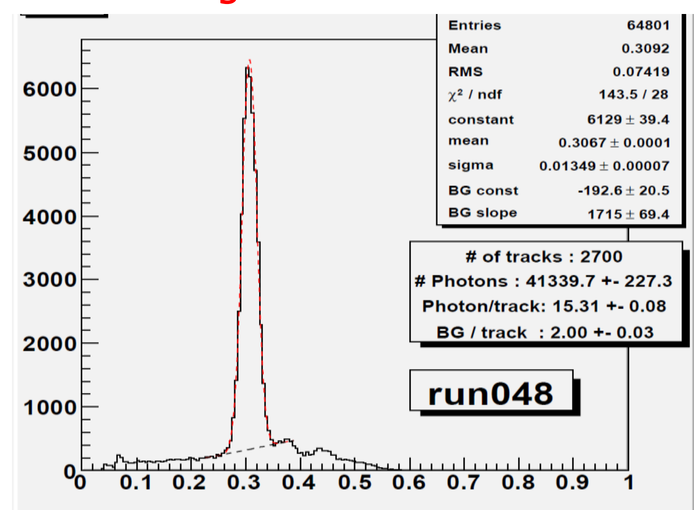
Need:
Operation in 1.5 T magnetic field
Pad size ~5-6mm

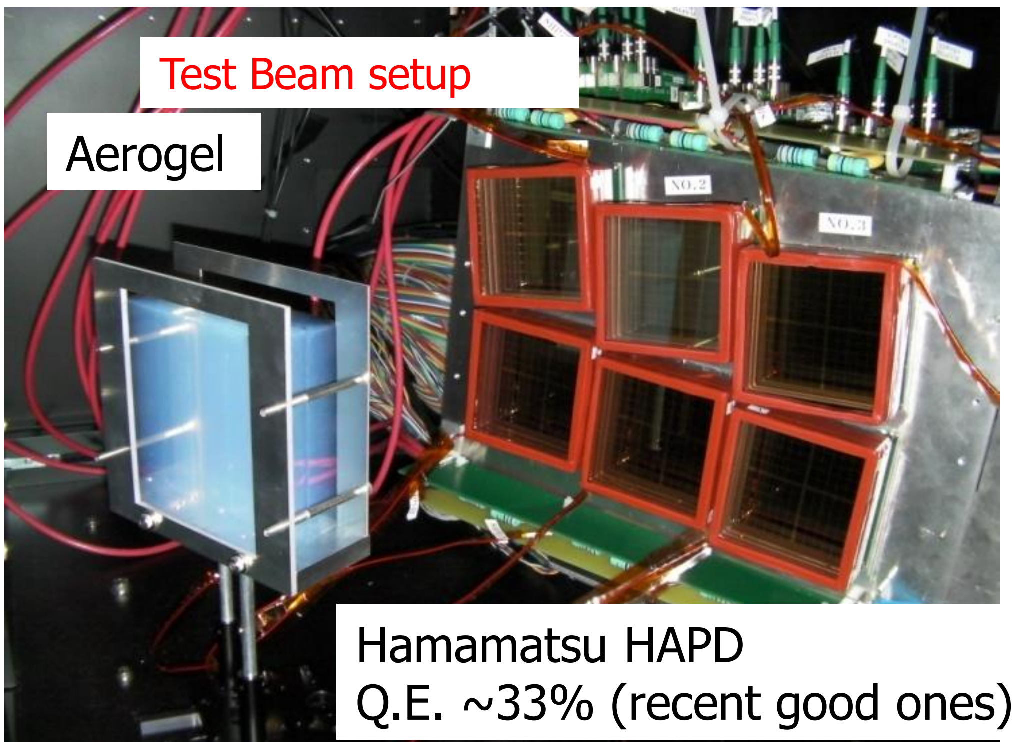
Baseline option: large active area HAPD of the proximity focusing type



Clear Cherenkov image observed

Cherenkov angle distribution





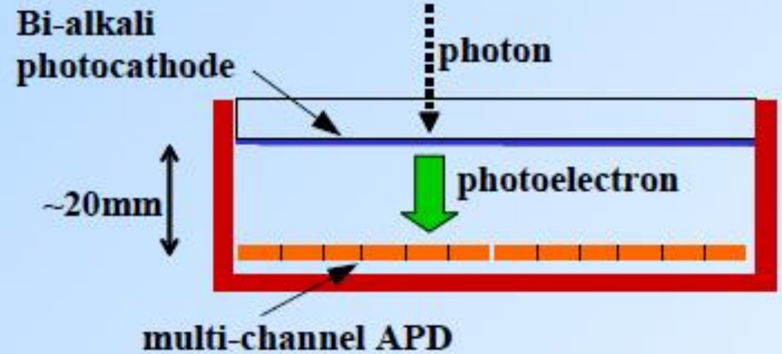
6.6 σ p/K at 4GeV/c !

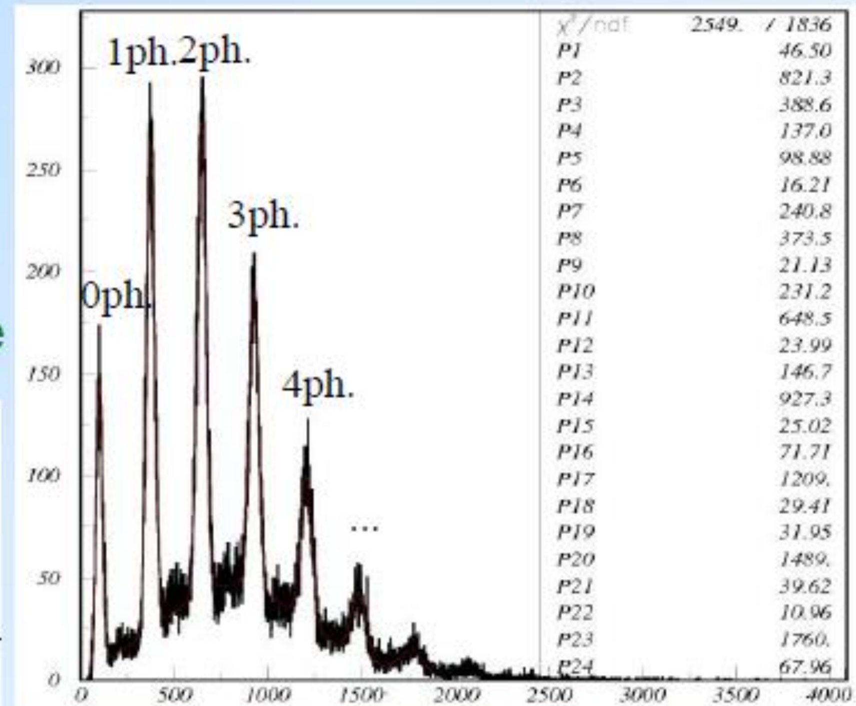
→ NIM A595 (2008) 180

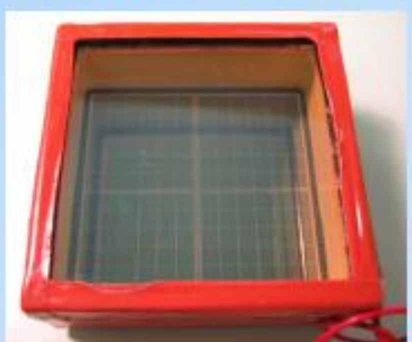
ARICH photon detector: HAPD

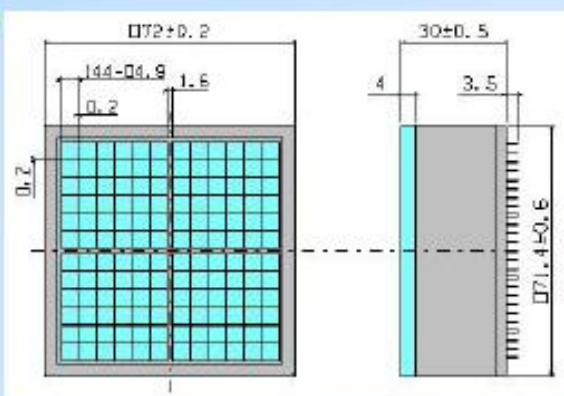
Hybrid avalanche photo-detector developed in cooperation with Hamamatsu (proximity focusing configuration):

- 12x12 channels (~5x5 mm^2)
- size ~ 72mm x 72mm
- ~ 65% effective area
- total gain ~ 10^4 – 10^5 (bombardment ~1500, avalanche ~40)
- detector capacitance ~ 80pF/ch.
- typical peak QE ~ 30%
- works in mag. field (~perpendicular to the entrance window)





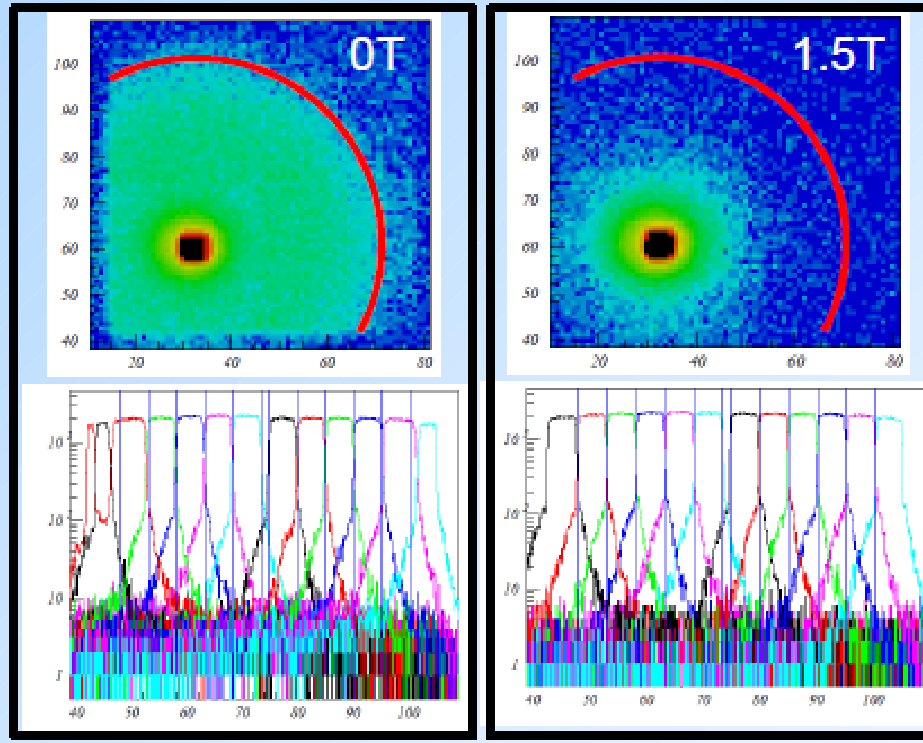




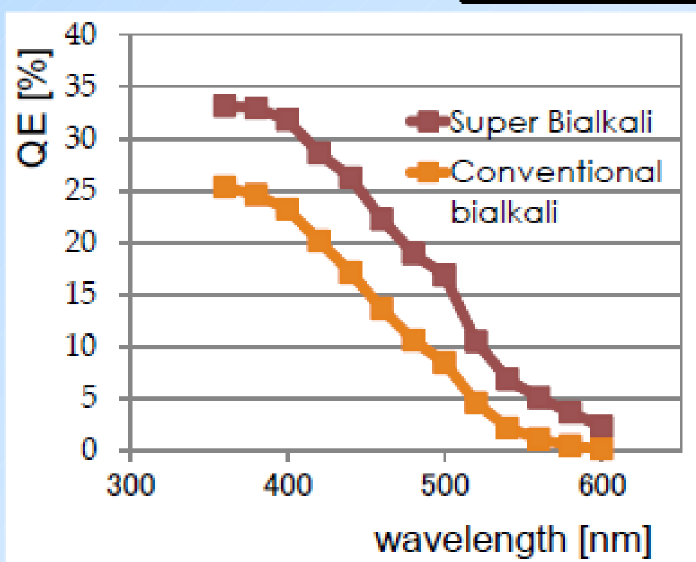
ARICH photon detector: HAPD

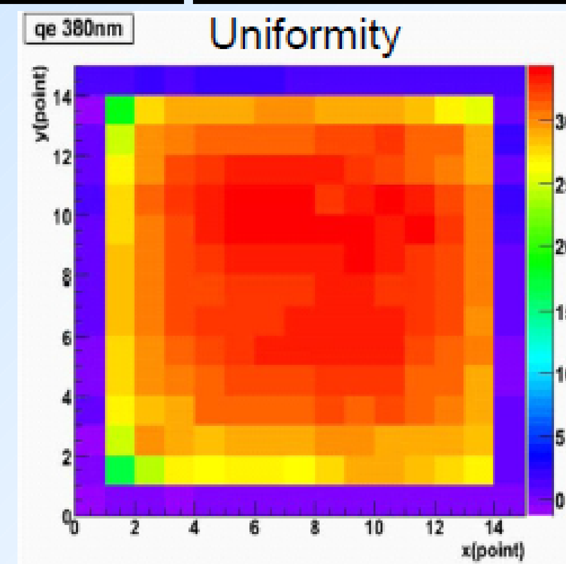
Tests in 1.5 T magnetic field show improved performance:

- no photoelectron back-scattering cross-talk
- Effect of non-uniformity of electric field disappears



QE improved by Hamamatsu with super bialkali photocathode: 25% → 32% peak





SiPM as photon detector?

Can we use SiPM (Geiger mode APD) as the photon detector in a RICH counter?

+immune to magnetic field

+high photon detection efficiency, single photon sensitivity

+easy to handle (thin, can be mounted on a PCB)

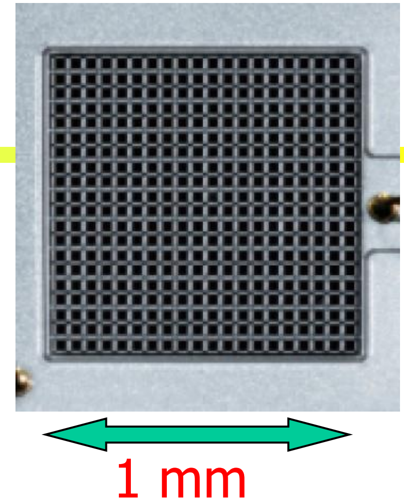
+potentially cheap (not yet...) silicon technology

+no high voltage

-very high dark count rate (100kHz – 1MHz) with single photon pulse height

-radiation hardness

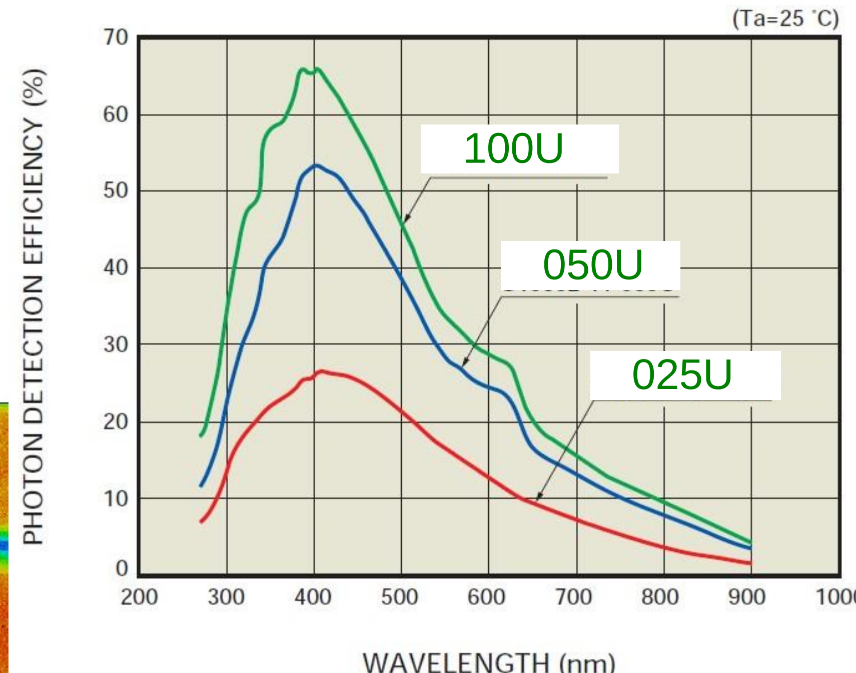
SiPMs as photon detectors?

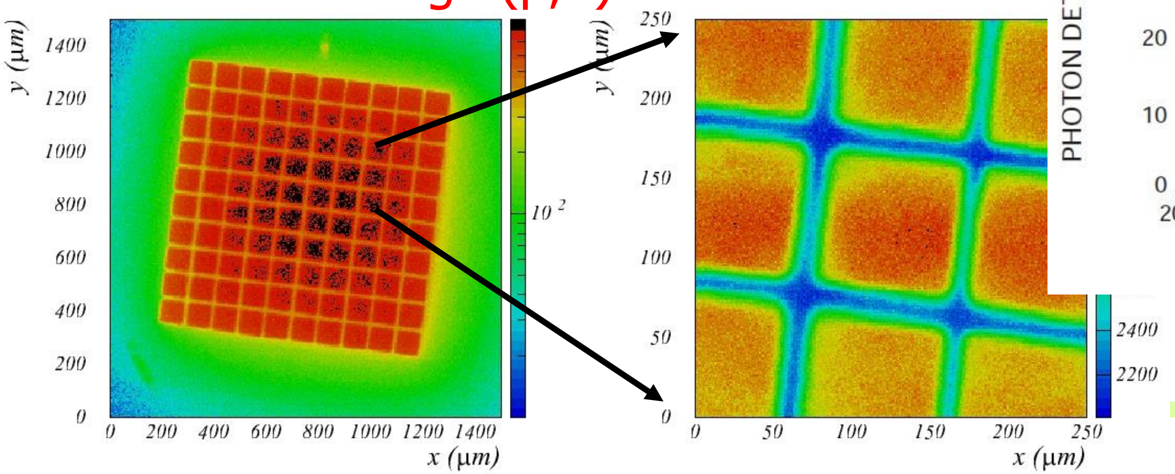


SiPM is an array of APDs operating in Geiger mode. Characteristics:

- low operation voltage ~ 10-100 V
- gain ~ 10^6
- peak PDE up to 65%(@400nm)

  $PDE = QE \times \varepsilon_{geiger} \times \varepsilon_{geo}$
- ε_{geo} – dead space between the cells
- time resolution ~ 100 ps
- works in high magnetic field
- dark counts ~ few 100 kHz/mm^2
- radiation damage (p,n)





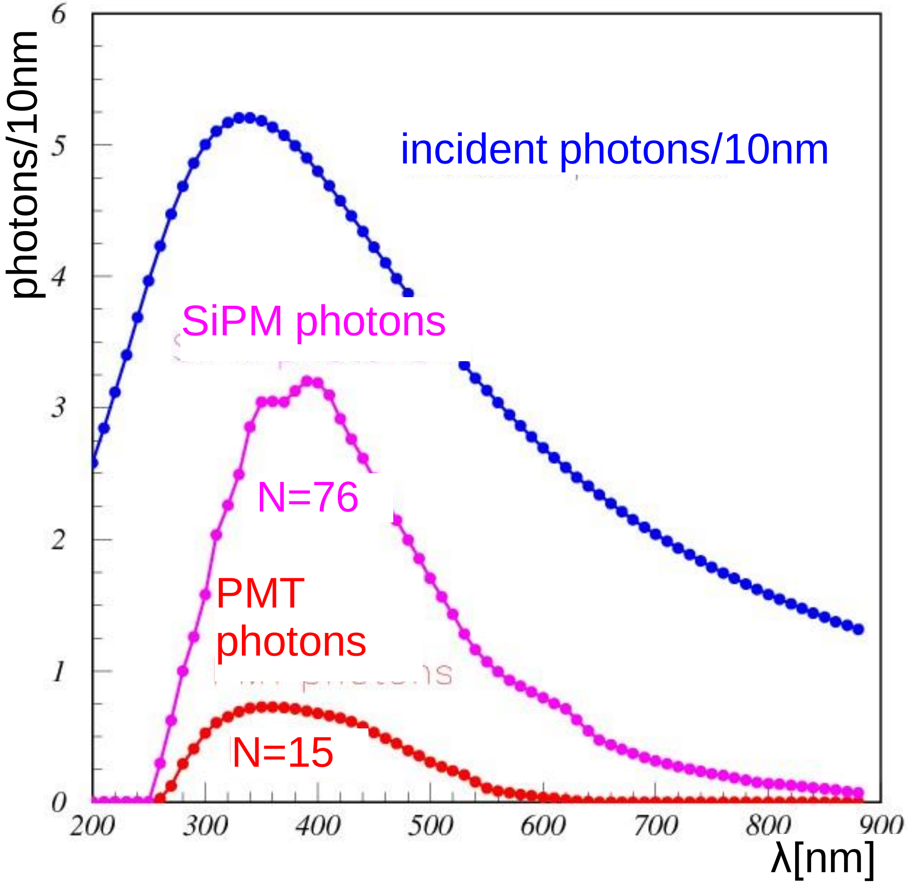
Hamamatsu MPPC: S10362-11

Expected number of photons for aerogel RICH

with multianode PMTs or SiPMs(100U), and
aerogel radiator: thickness 2.5 cm, n = 1.045
and transmission length (@400nm) 4 cm.

N_{SiPM}/N_{PMT}~5

Assuming 100% detector active area



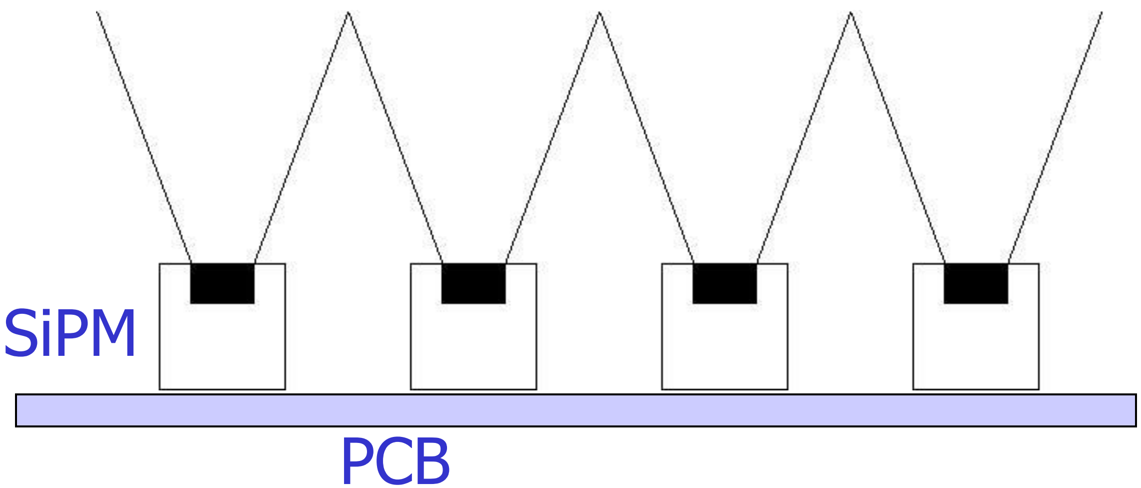
But: Dark counts have single photon pulse heights (rate 0.1-1 MHz)

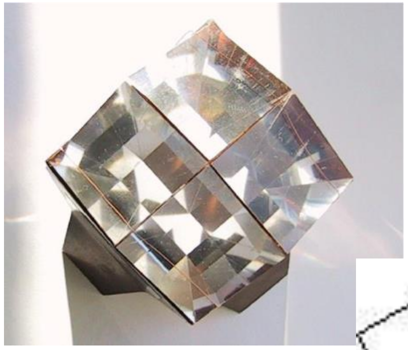
Can such a detector work?

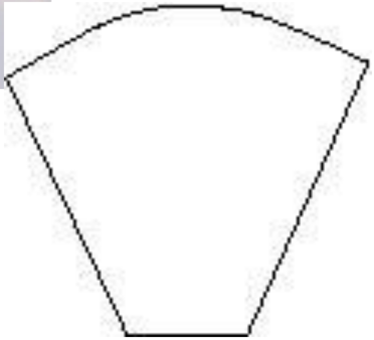
Improve the signal to noise ratio:

- Reduce the noise by a narrow (<10ns) time window
- Increase the number of signal hits per single sensor by using light collectors and by adjusting the pad size to the ring thickness

E.g. light collector with reflective walls

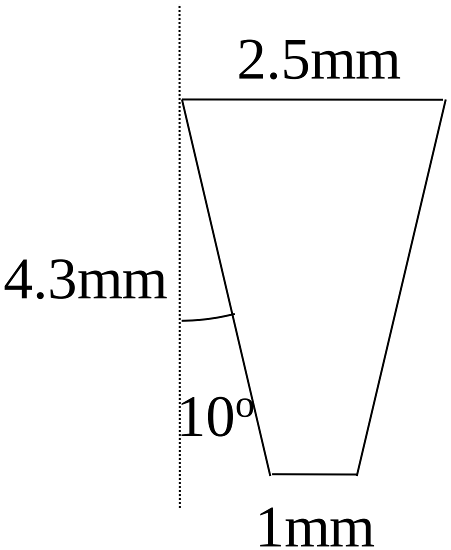


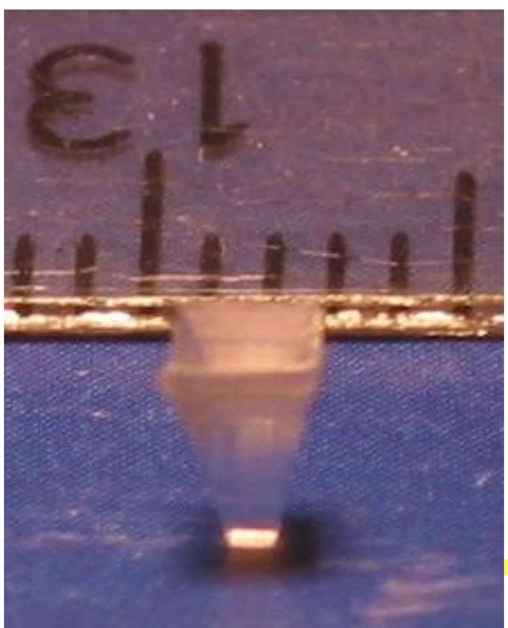




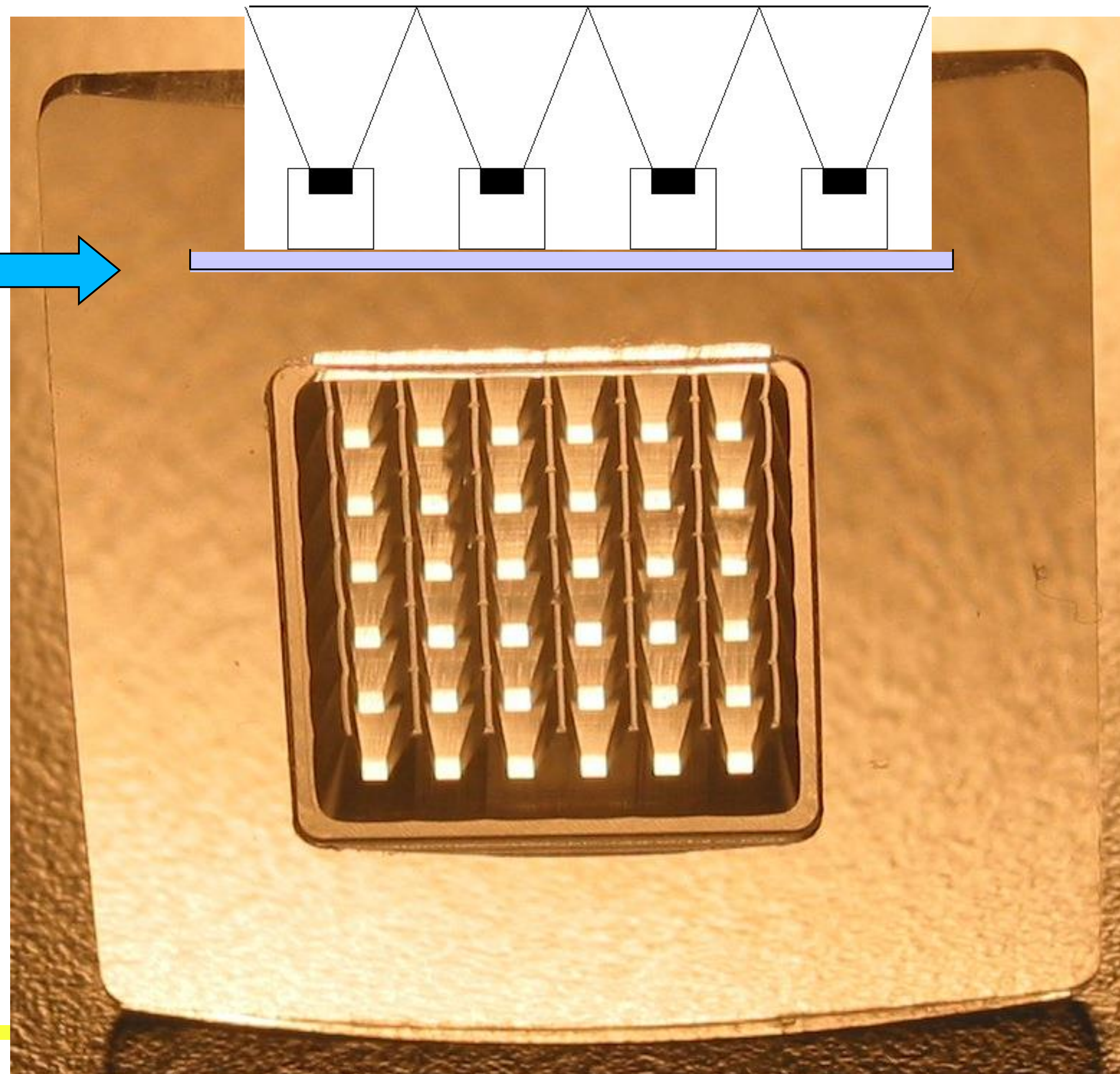
or combine a lens and mirror walls

Detector module design



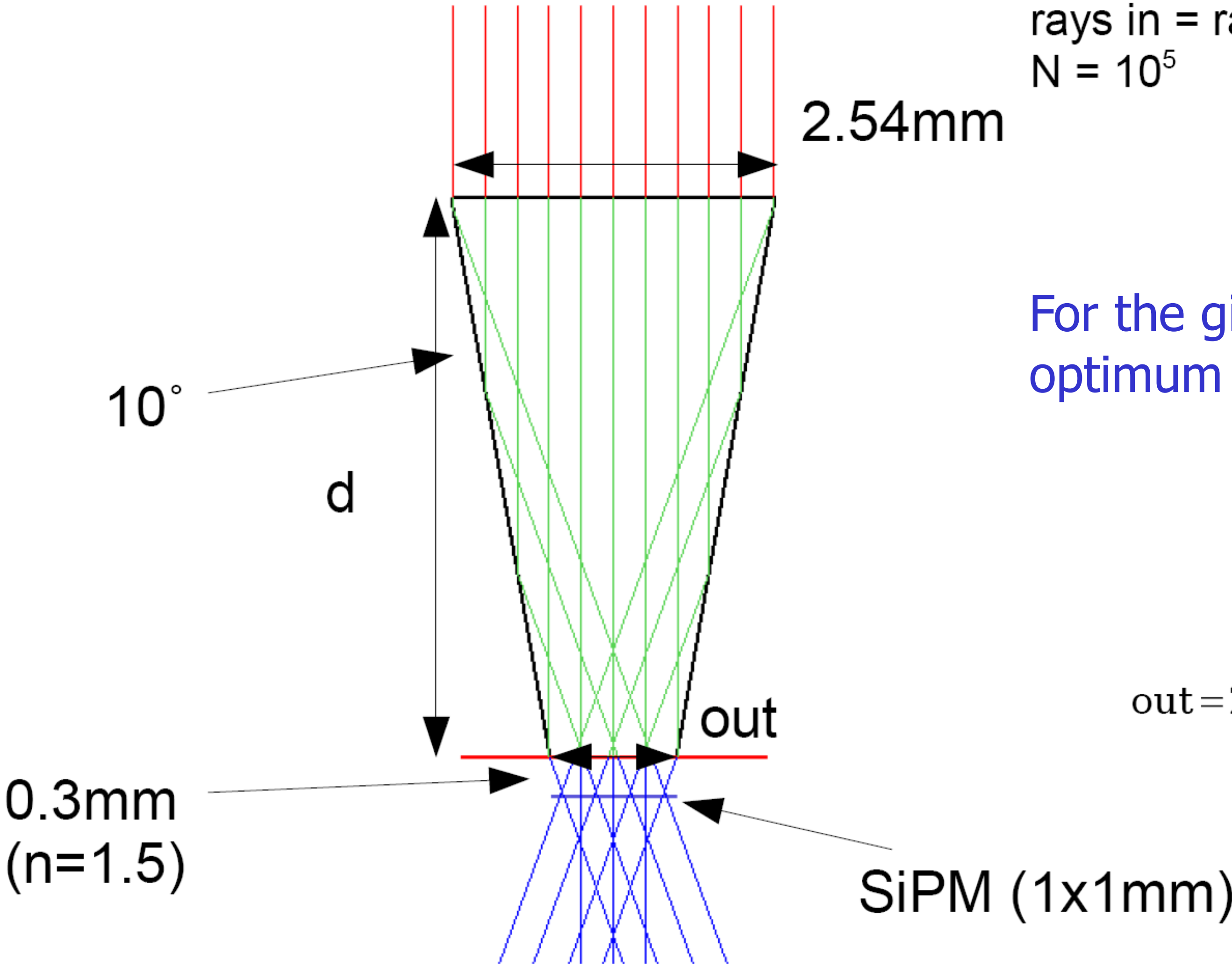


SiPM array with light guides



Light guide geometry optimisation

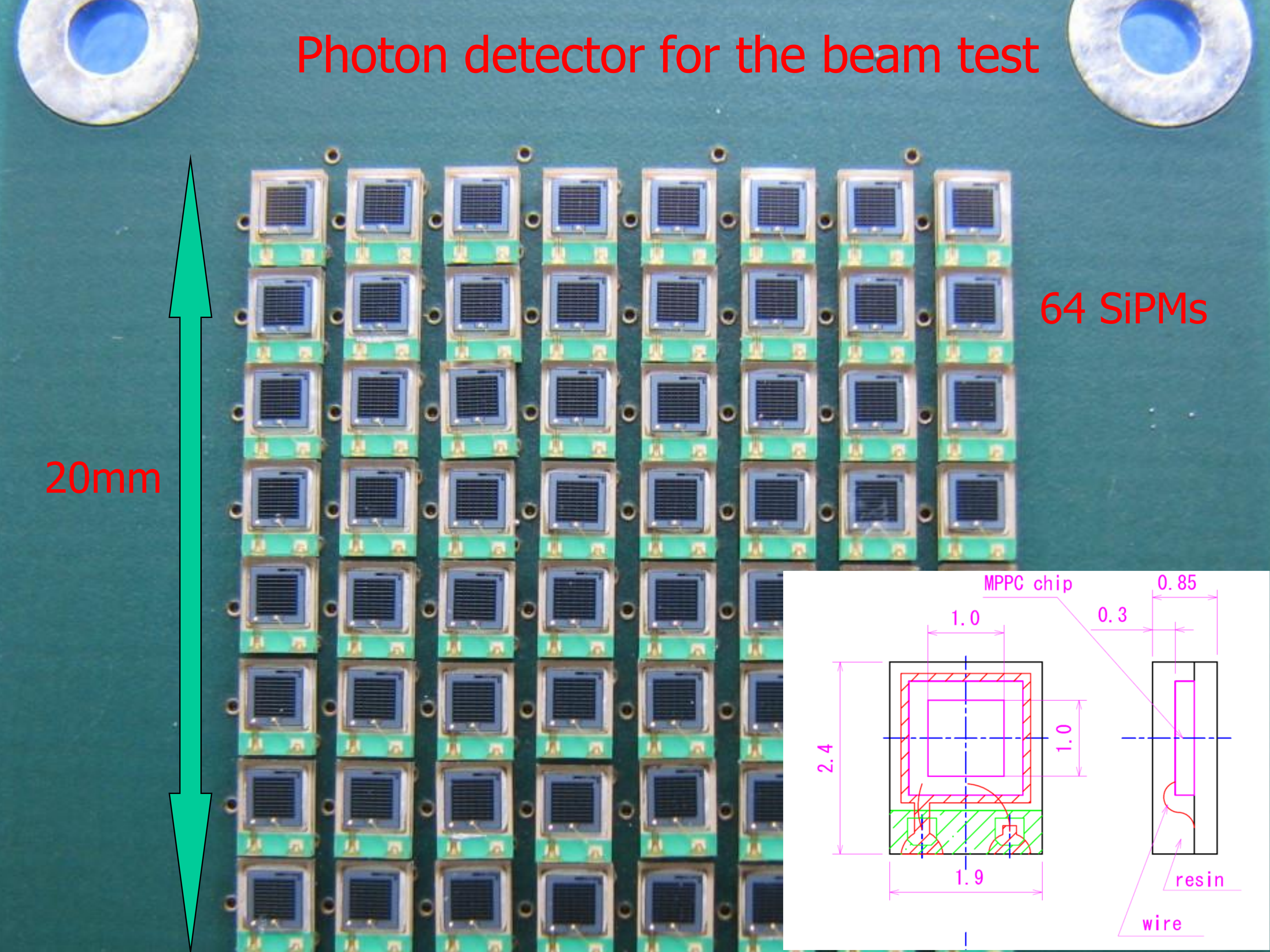
Light Guide Acceptance / (d and out)



rays in = random isotropic 0-30°
N = 10^5

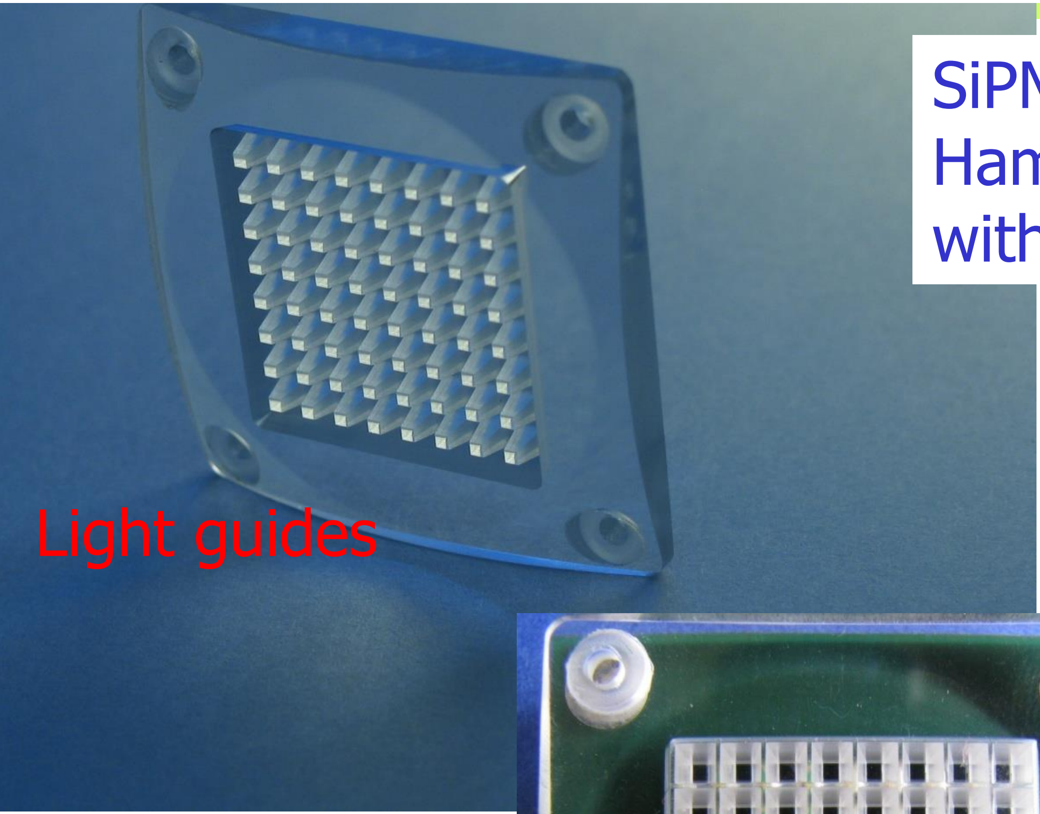
For the given geometry → optimum length 4mm

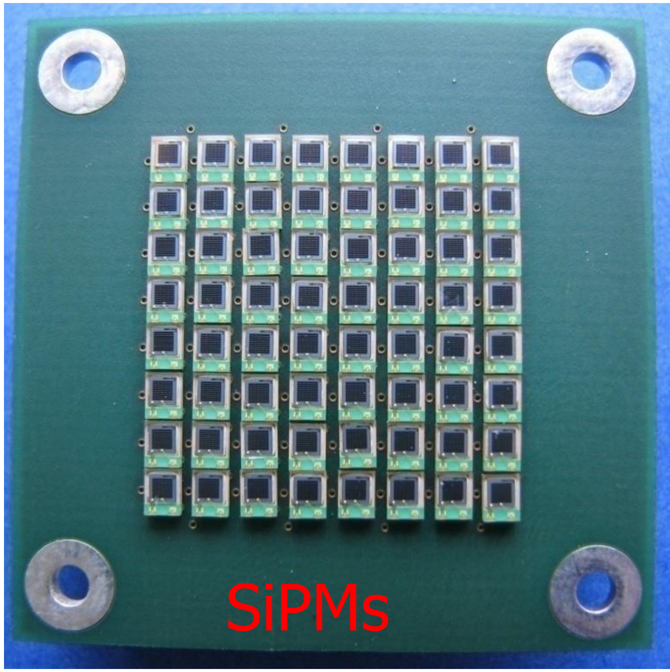
$$out = 2.54mm - 2 * d * \tan(10°)$$


Photon detector for the beam test
20mm
64 SiPMs
MPPC chip
0.85
0.3
1.0
1.0
2.4
1.9
resin
wire

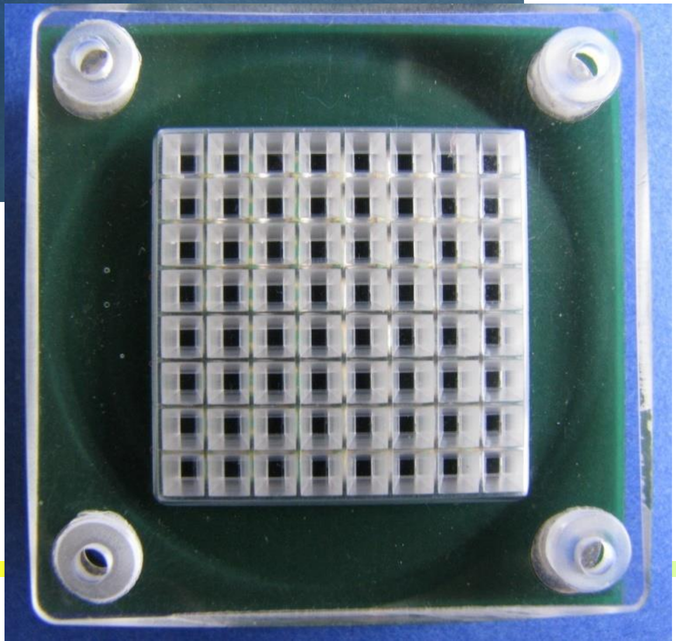
Detector module

SiPMs: array of 8x8 SMD mount Hamamatsu S10362-11-100P with 0.3mm protective layer





2cm

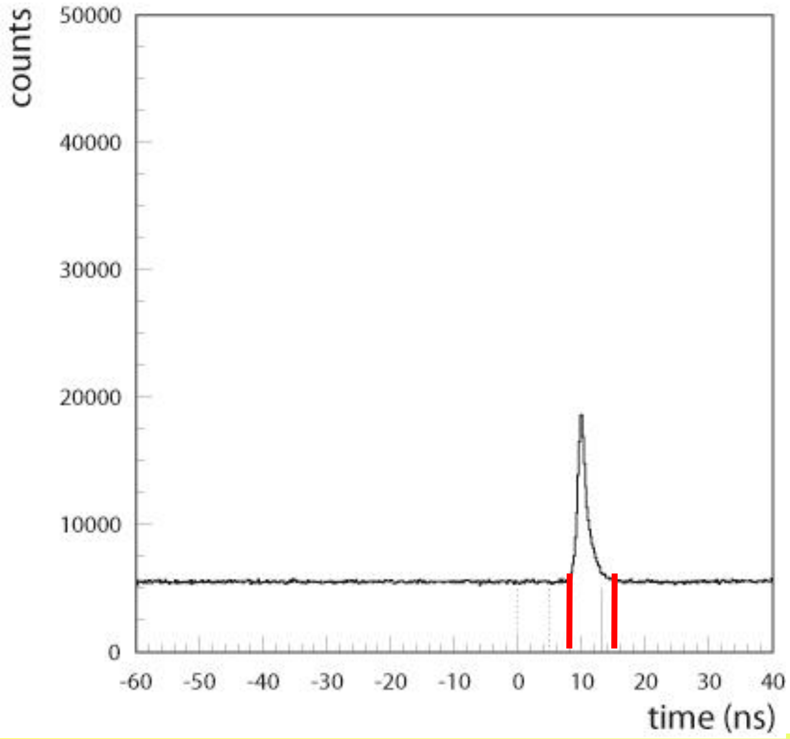


SiPMs + light guides

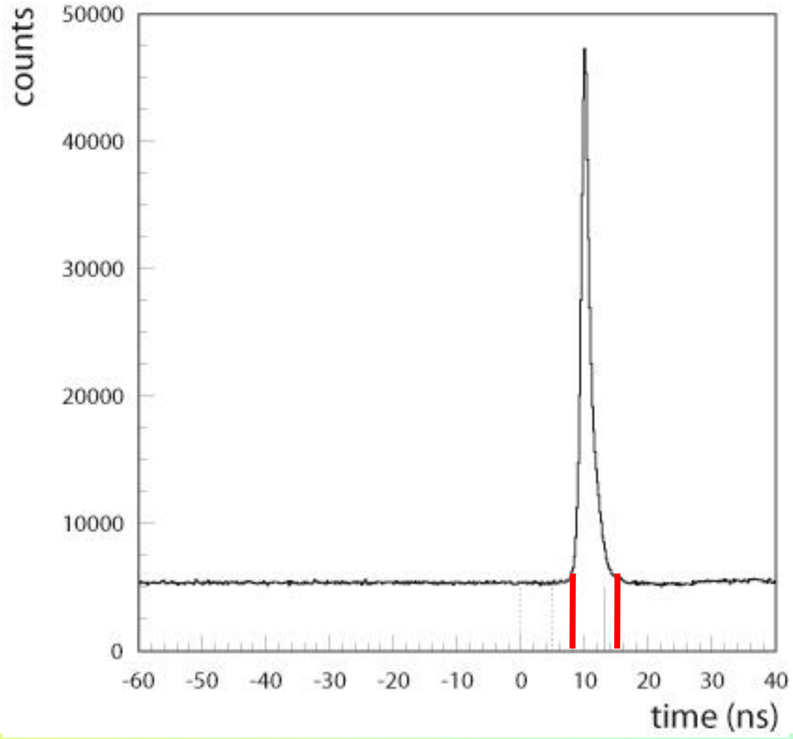
SiPM beam test: TDC distributions

- Total noise rate ~35 MHz (~600 kHz/MPPC)
- Hits in the time window of 5ns around the peak are selected for the Cherenkov angle analysis

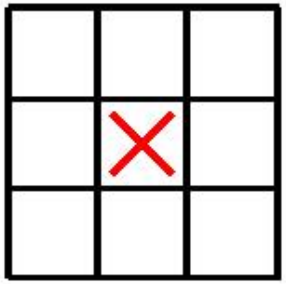
without light guides



with light guides

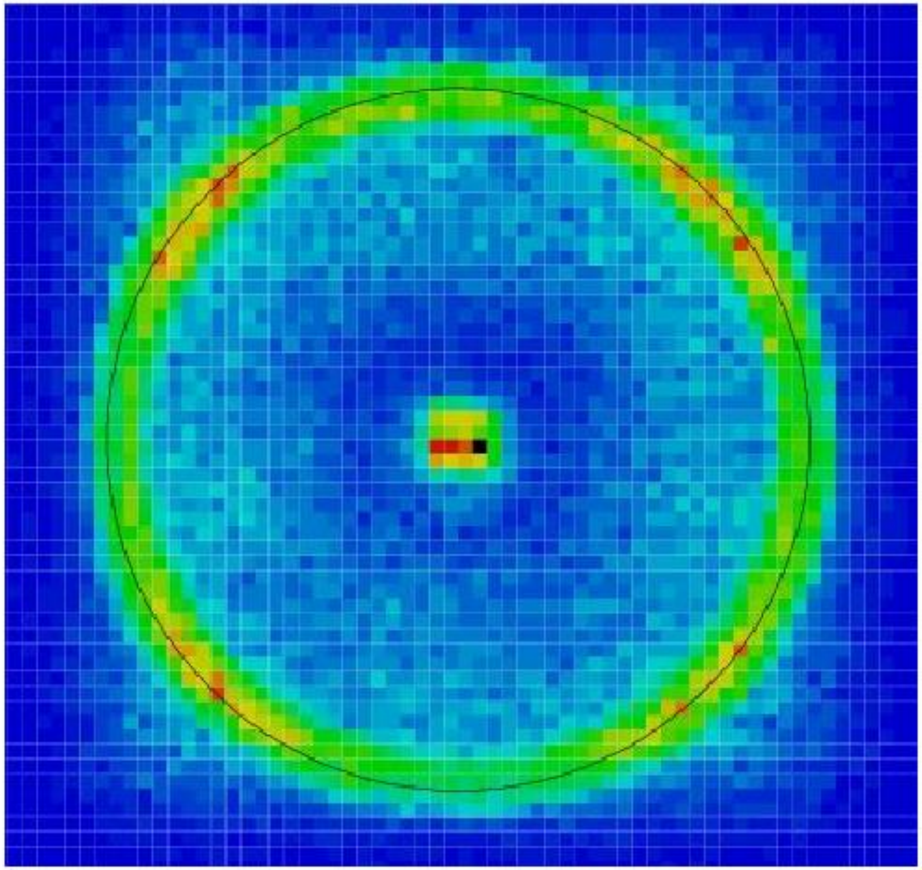


Ring images

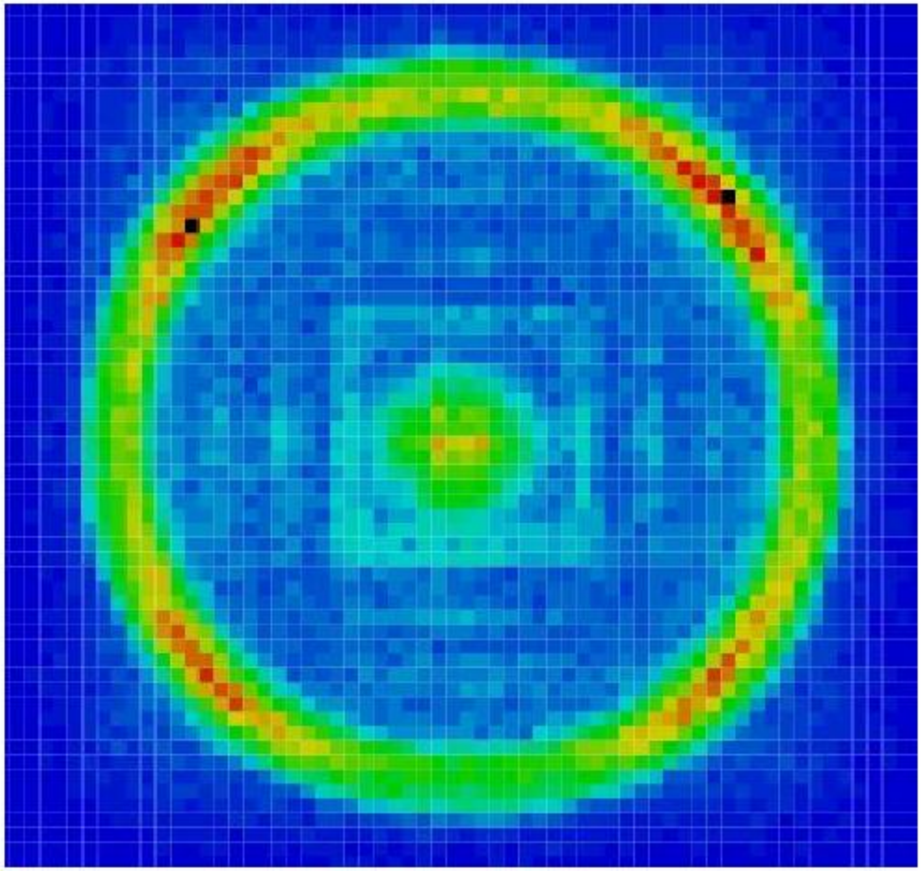


- module was moved to 9 positions to cover the ring area
- these plots show only superposition of 8 positions (central position is not included)

w/o light guides

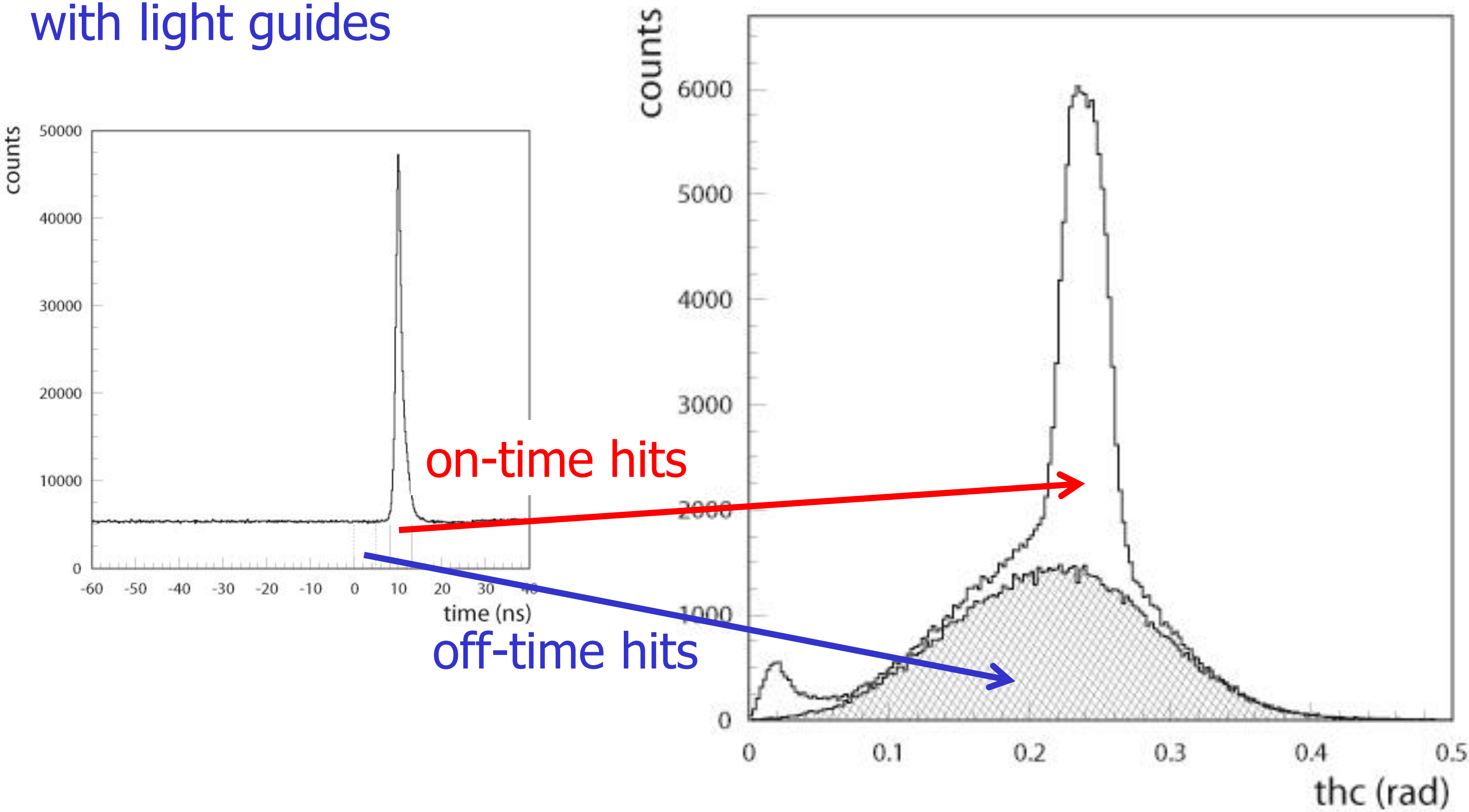


w/ light guides

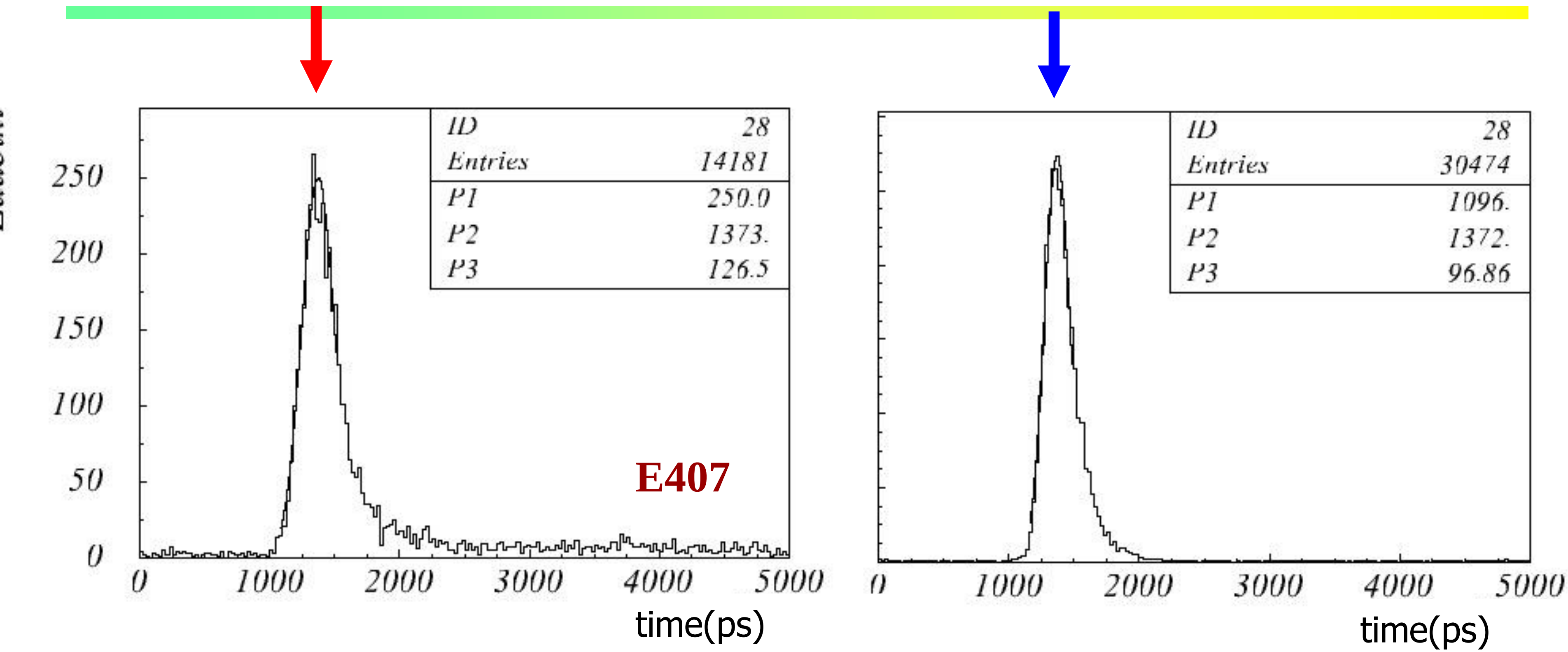


SiPM beam test: Cherenkov angle distributions

with light guides



Time resolution: blue vs red



	E407	S137	H100C	H050C	H025C
σ_{red} (ps)	**127**	**182**	**145**	**212**	**154**
σ_{blue} (ps)	**97**	**151**	**136**	**358**	**135**

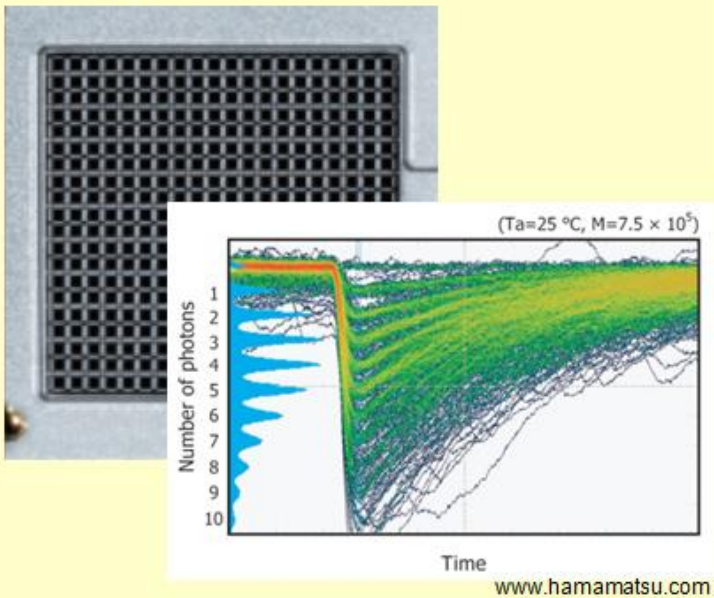
- $\sigma \approx 100$ ps

- $\sigma_{red} > \sigma_{blue}$

New player: digital dSiPM

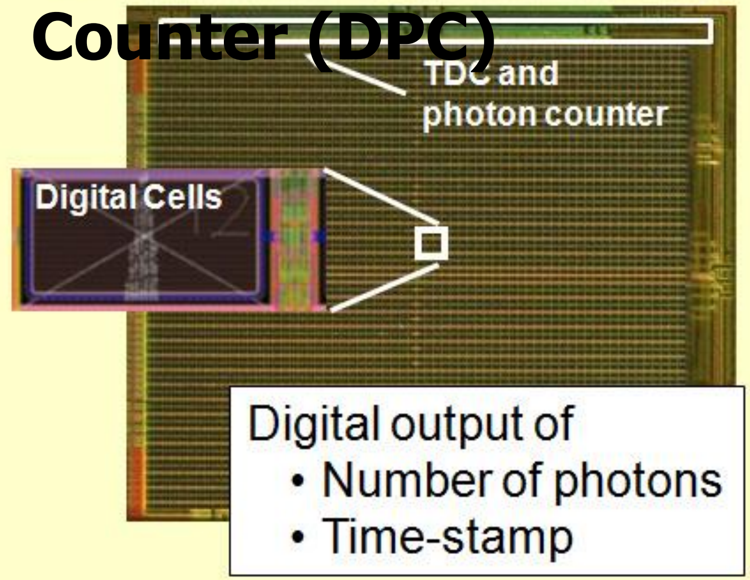
DPC: Front-end Digitization by Integration of SPAD & CMOS Electronics

analog SiPM



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

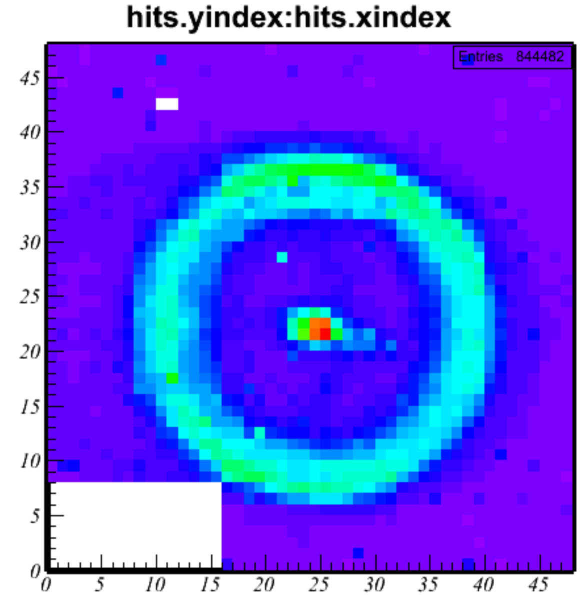
Digital Photon Counter (DPC)

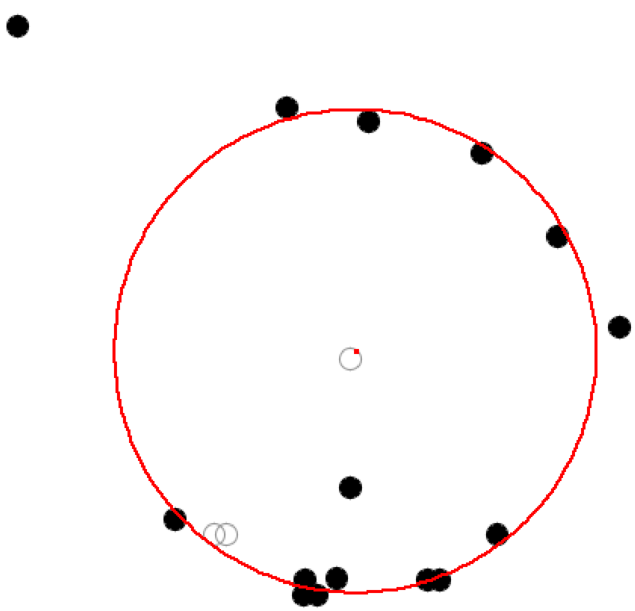


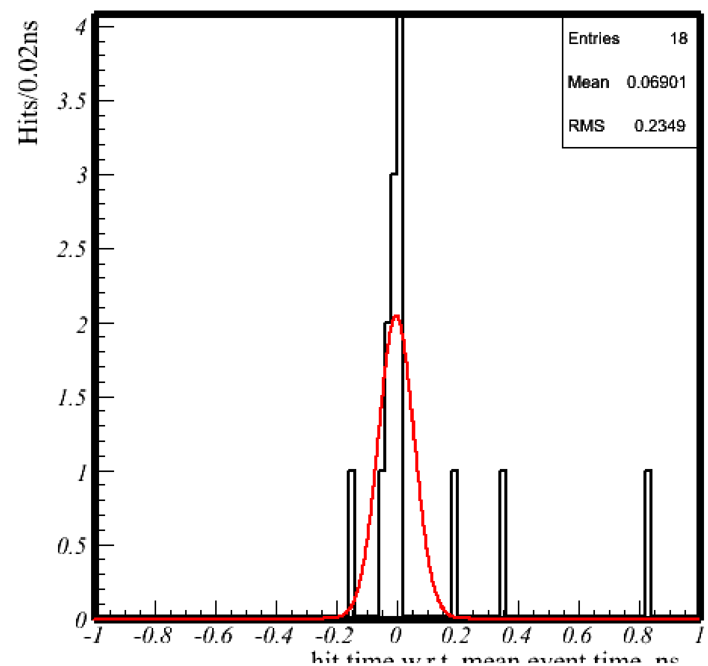
Integrated readout electronics is the key element to superior detector performance

T. Frach, G. Prescher, C. Degenhardt, B. Zwaans, IEEE NSS/MIC (2010) pp.1722-1727
C. Degenhardt, T. Frach, B. Zwaans, R. de Gruyter, IEEE NSS/MIC (2010) pp.1954-1956

dSiPM in beam tests

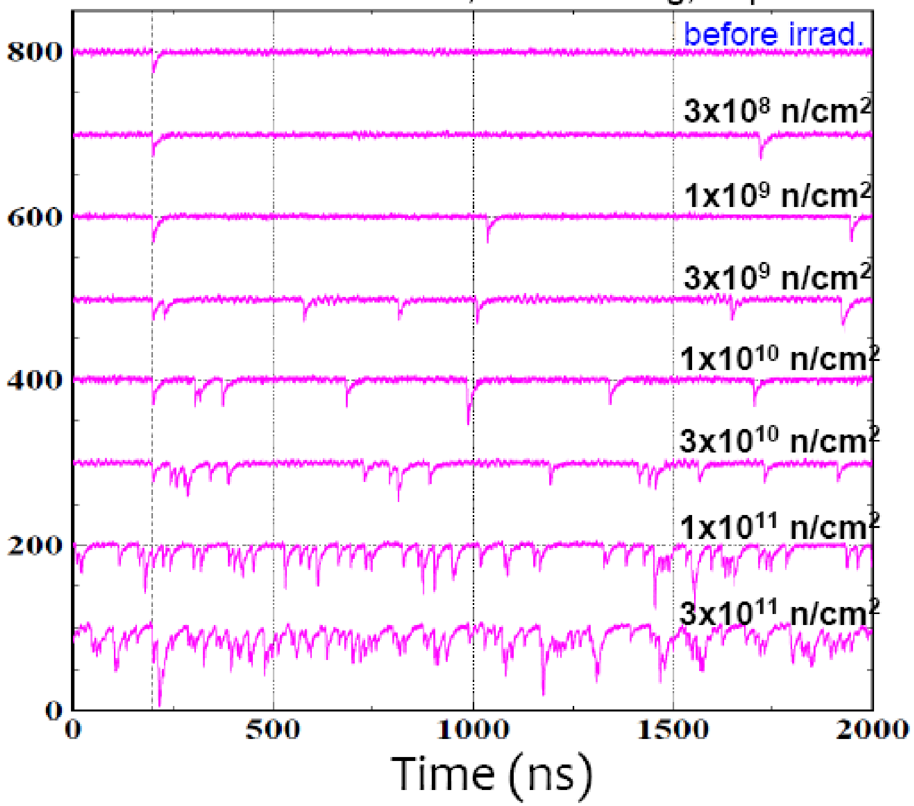






Radiation damage

I.Nakamura, JPS meeting, Sep. 2008



Expected fluence at 50/ab at Belle II: 2-20 10^{11} n cm^{-2}

→ Worst than the lowest line

→Very hard to use present SiPMs as single photon detectors in many applications (including Belle II) because of radiation damage by neutrons

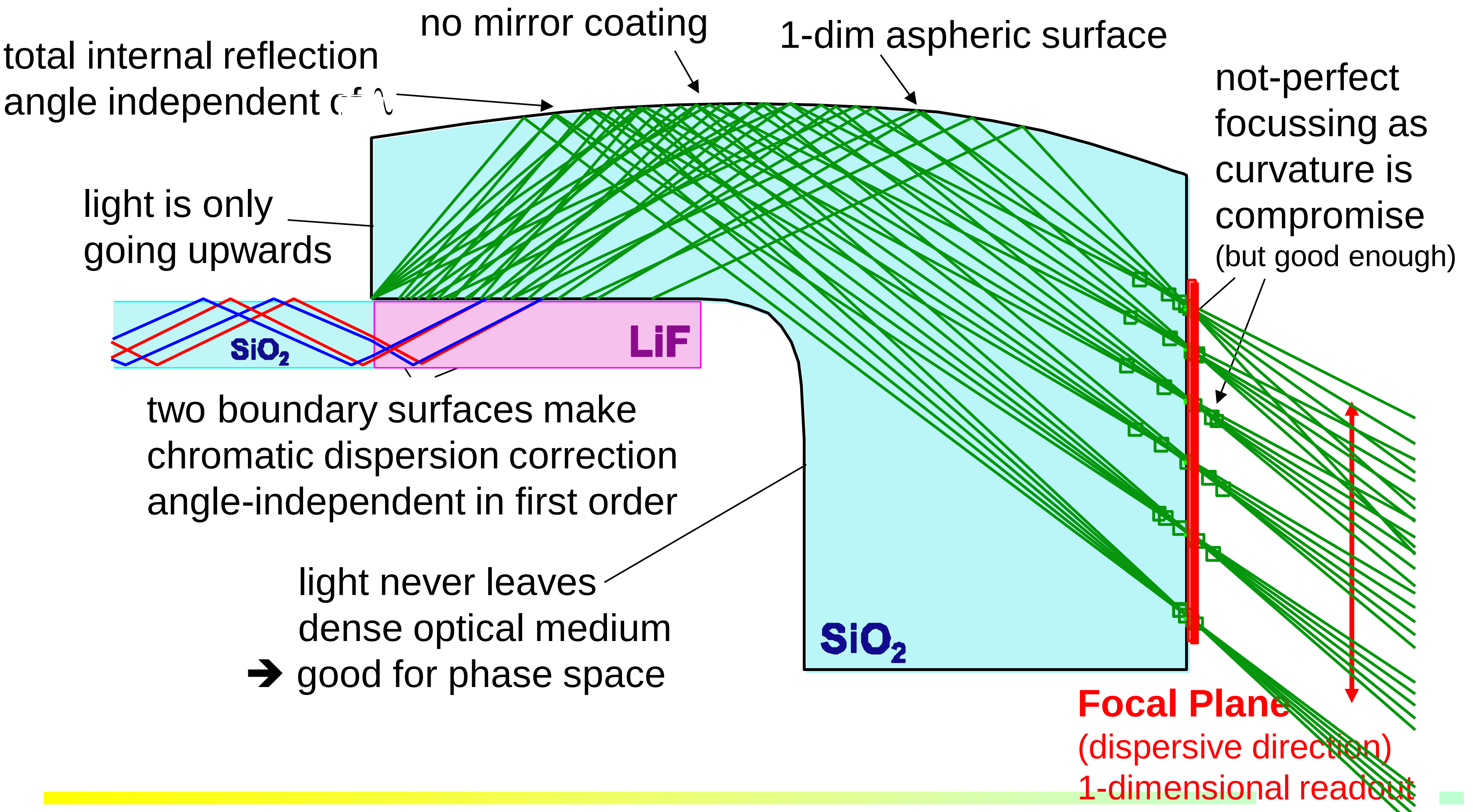
→ Also: could only be used with a sofisticated electronics – wave-form sampling

Summary

- Single photon detection is at the hearth of the RICH detectors
- New methods require very fast timing in radiation harsh environments
- A number of new detectors has been developed recently to cope with these requirements
- A very active field!
- My talk can only be seen as a warming up – there will be several very interesting presentation on recent results!

Back-up slides

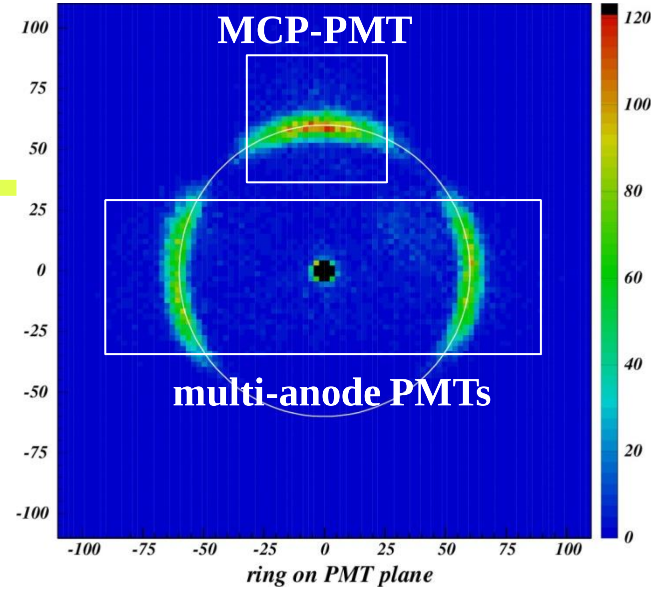
PANDA endcap DIRC focussing & chromatic correction



Photon detector candidate: MCP-PMT

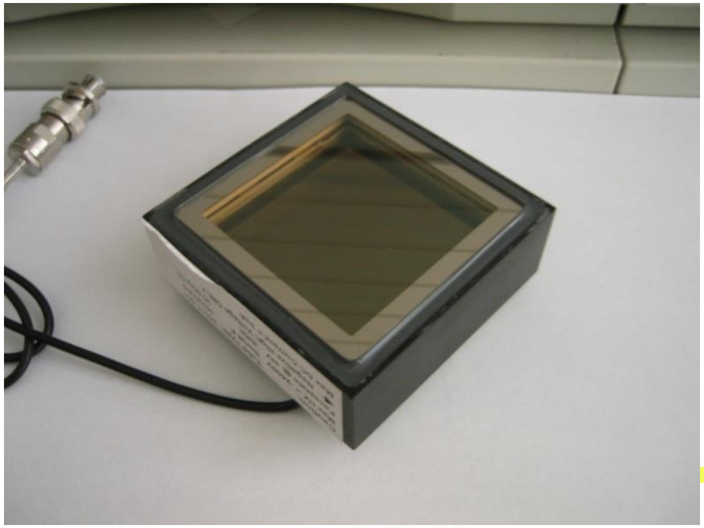
BURLE 85011 MCP-PMT:

- multi-anode PMT with two MCP steps
- 25 μm pores
- bialkali photocathode
- gain ~ 0.6 x 10^6
- collection efficiency ~ 60%
- box dimensions ~ 71mm square
- 64(8x8) anode pads
- pitch ~ 6.45mm, gap ~ 0.5mm
- active area fraction ~ 52%



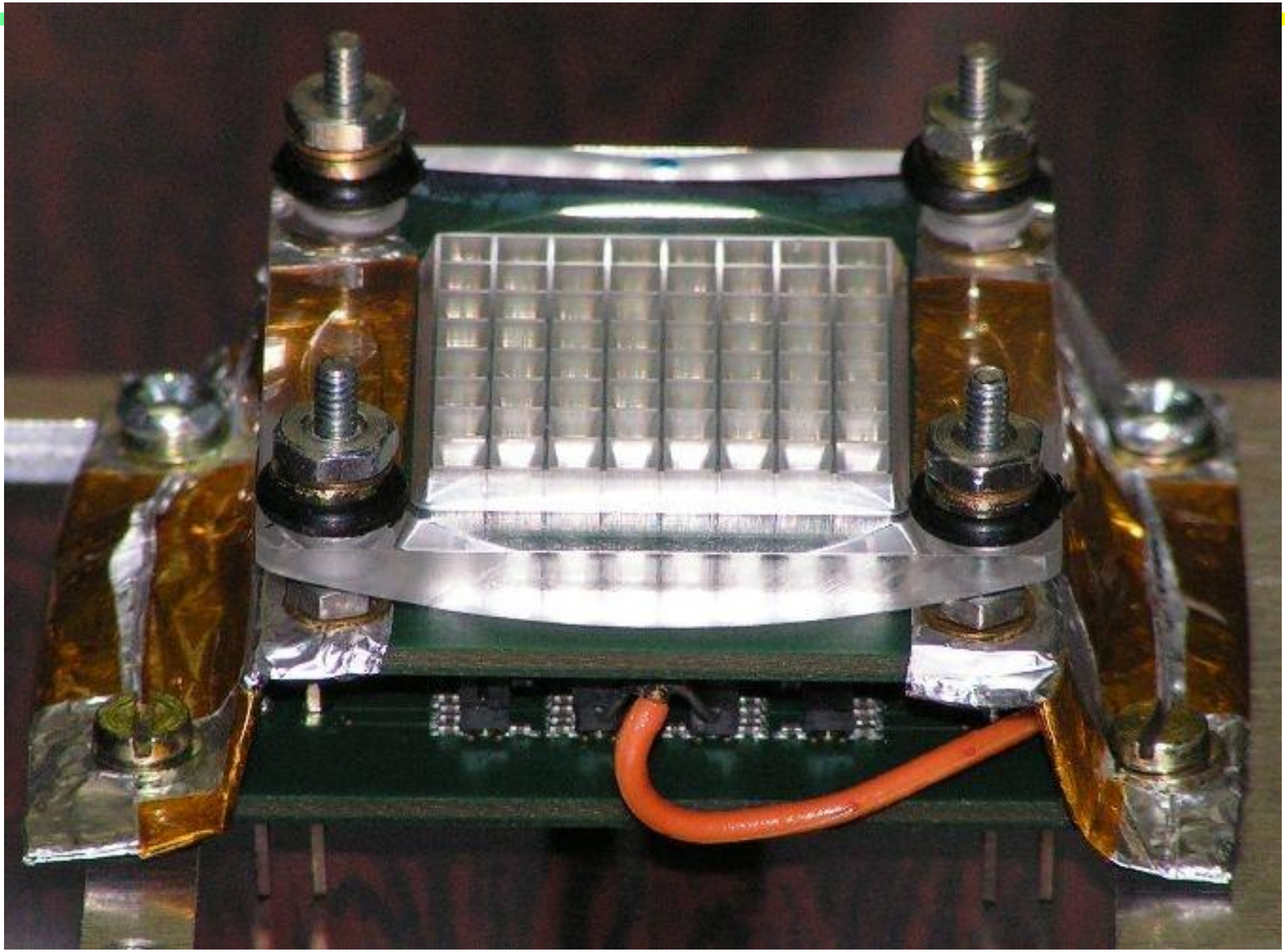
- Tested in combination with multi-anode PMTs

- σ_ϑ~13 mrad (single cluster)
- number of clusters per track N ~ 4.5
- σ_ϑ~ 6 mrad (per track)
- -> ~ **4 σ π/K separation at 4 GeV/c**



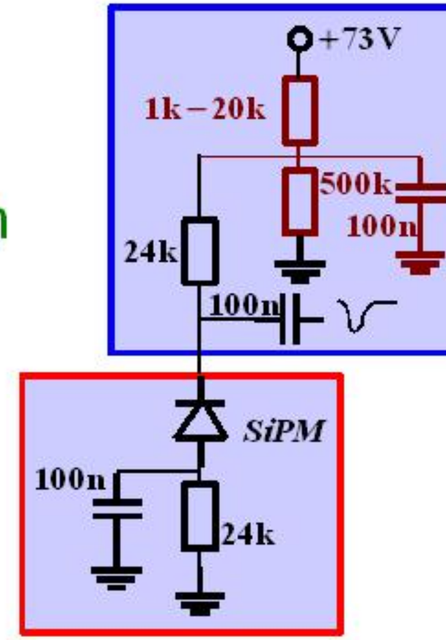
- 10 μm pores required for 1.5T
- collection eff. and active area fraction should be improved
- aging study should be carried out

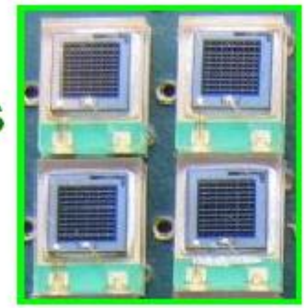
Fully assembled detector module

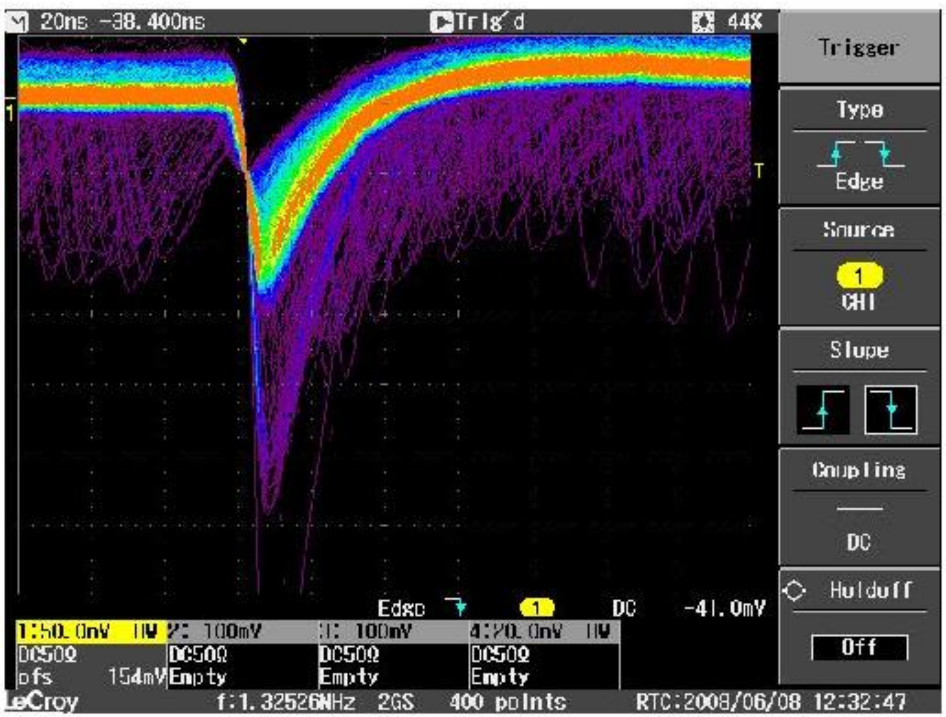


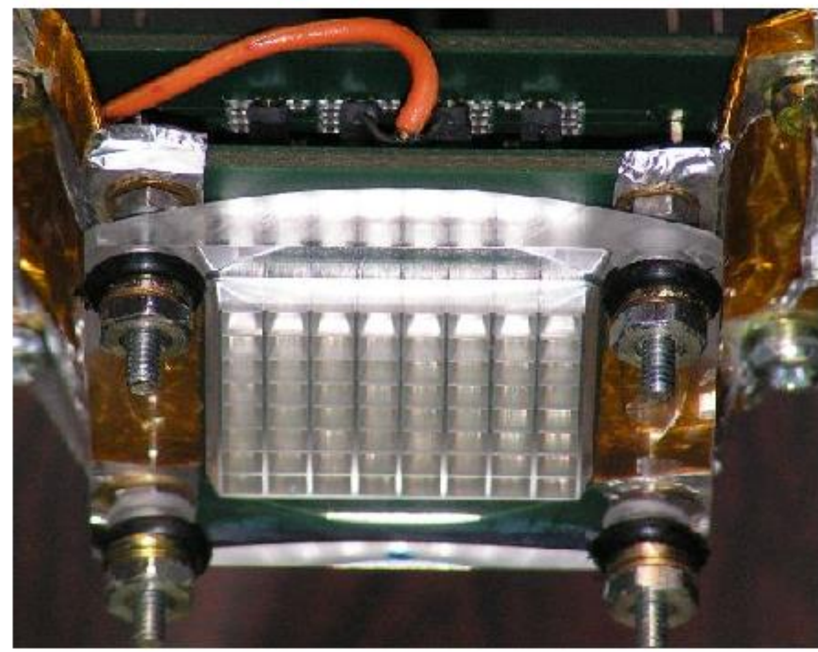
MPPC module

- main board with dividers, bias and signal connectors
- piggy back board with MPPCs (8x8 array of HC100 in SMD package; background ~ 400kHz/MPPC)
- light guides
- 16 electronics channels (4x4) - 4 MPPCs connected to single channel





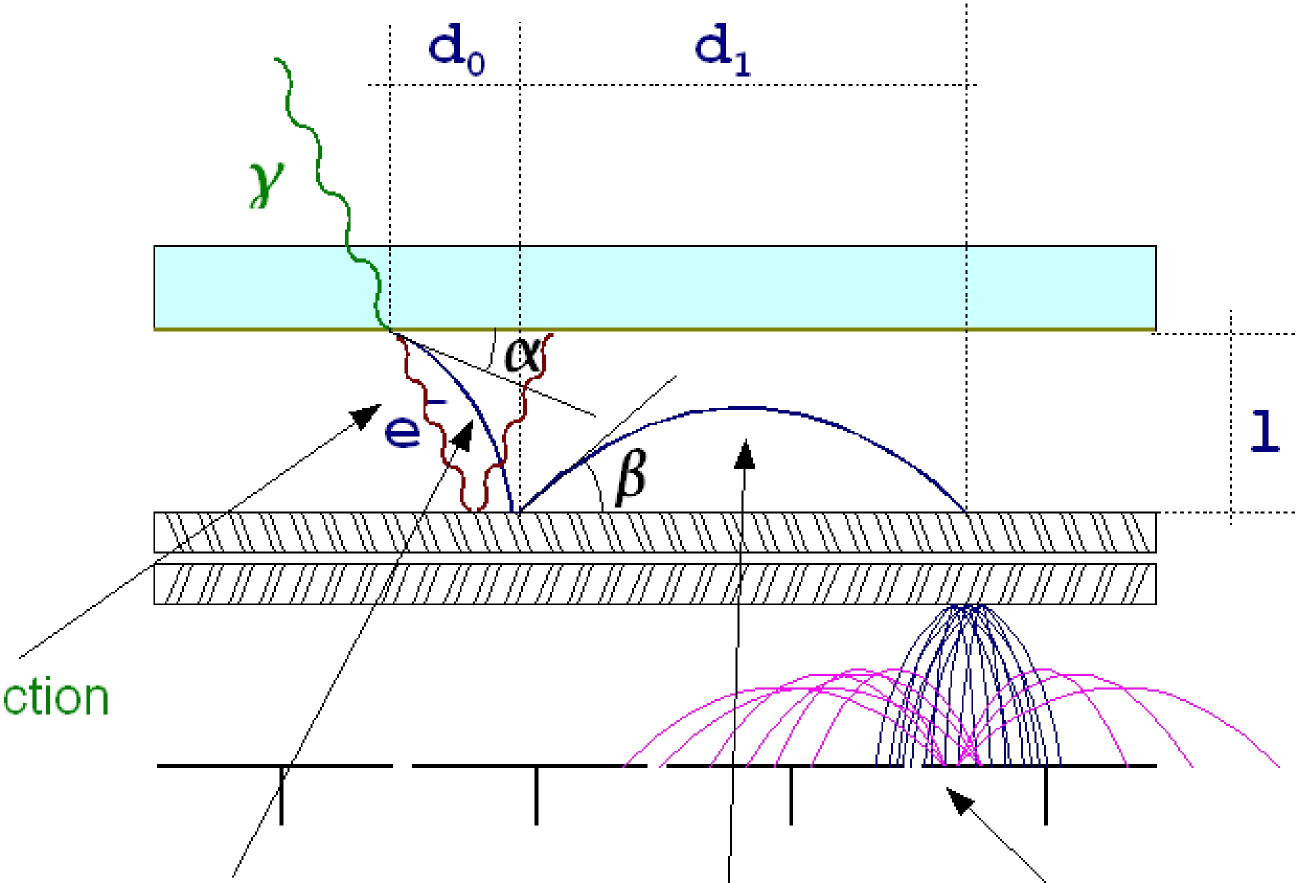




MCP PMT: processes involved in photon detection

Parameters used:

- U = 200 V
- l = 6 mm (K-MCP)
- E_0 = 1 eV
- m_e = 511 keV/c²
- $e_0 = 1.6\ 10^{-19}$ As



Internal-reflection

Photo-electron:

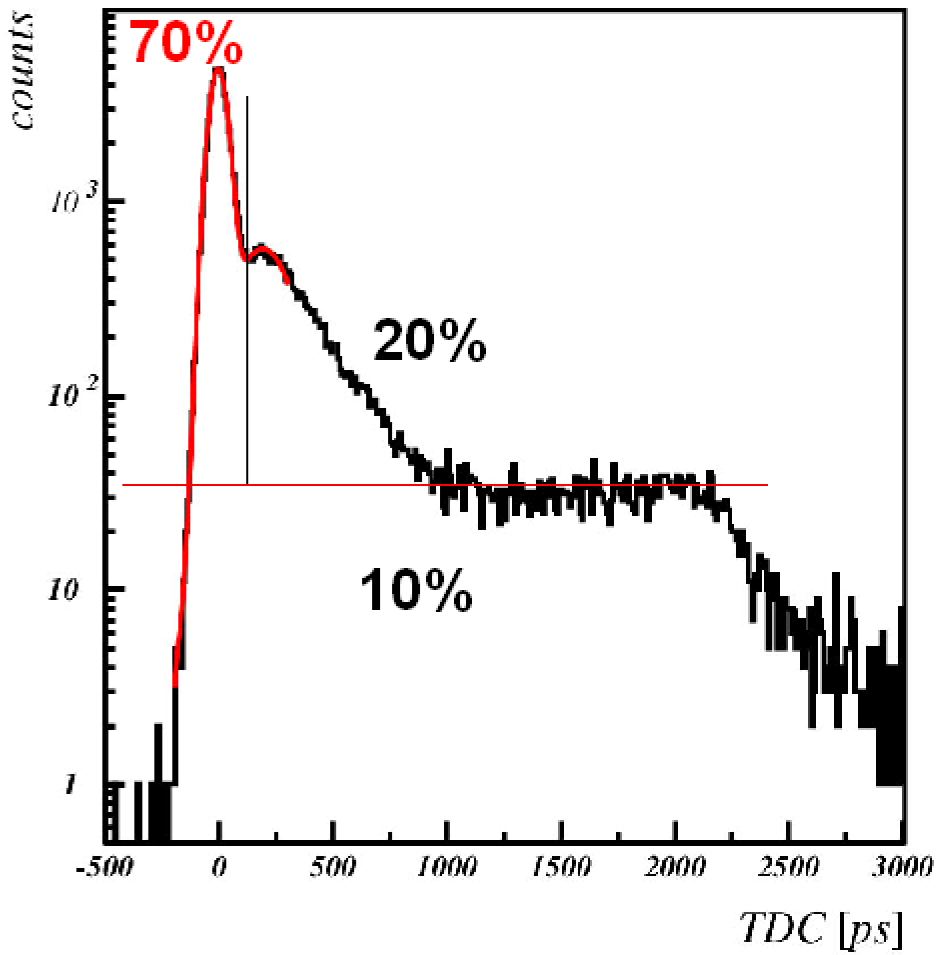
- $d_{0,max}$ ~ 0.8 mm
- t_0 ~ 1.4 ns
- Δt_0 ~ 100 ps

Backscattering:

- $d_{1,max}$ ~ 12 mm
- $t_{1,max}$ ~ 2.8 ns

Charge sharing

MCP PMT timing

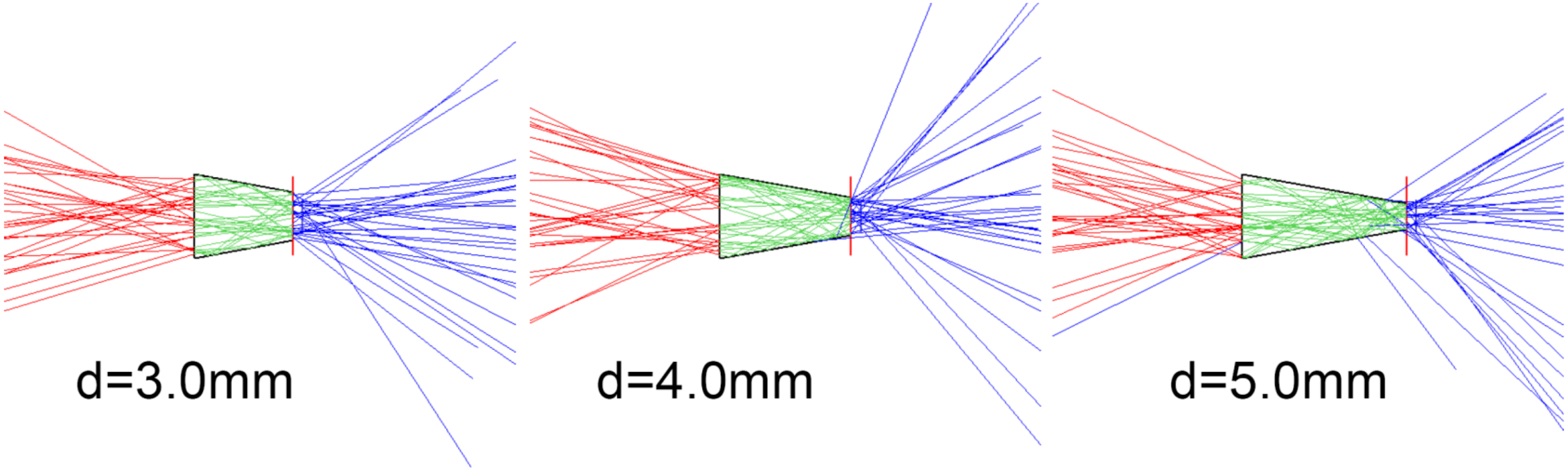


Tails understood (scattering of photoelectrons off the MCP), can be significantly reduced by:

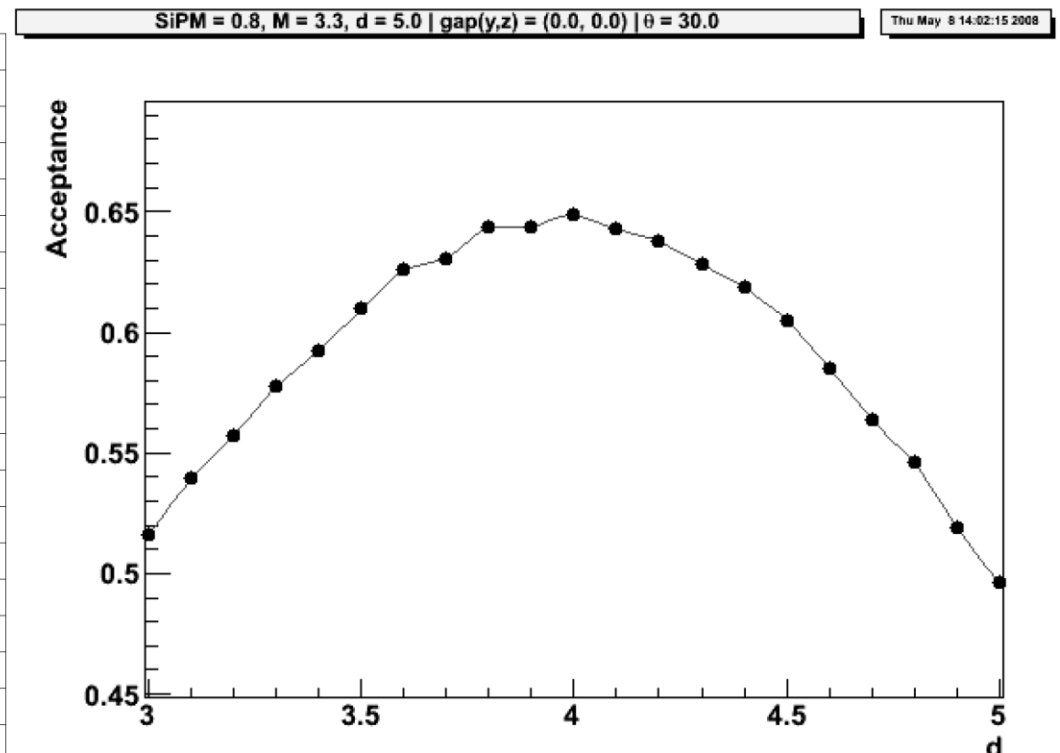
- decreased photocathode-MCP distance and
- increased voltage difference

- prompt signal ~ 70%
- short delay ~ 20%
- ~ 10% uniform distribution

Light guide geometry optimisation



d (mm)	out (mm)	accept. (%)
3.0	1.48	51.6
3.1	1.45	54.0
3.2	1.41	55.7
3.3	1.38	57.8
3.4	1.34	59.2
3.5	1.31	61.0
3.6	1.27	62.6
3.7	1.24	63.1
3.8	1.20	64.4
3.9	1.16	64.4
4.0	**1.13**	**64.9**
4.1	1.09	64.3
4.2	1.06	63.8
4.3	1.02	62.8
4.4	0.99	61.8
4.5	0.95	60.5
4.6	0.92	58.5
4.7	0.88	56.4
4.8	0.85	54.6
4.9	0.81	51.9



MCP PMT: Gain in magnetic field

Gain as a function of magnetic field for different operation voltages and as a function of applied voltage for different magnetic fields.

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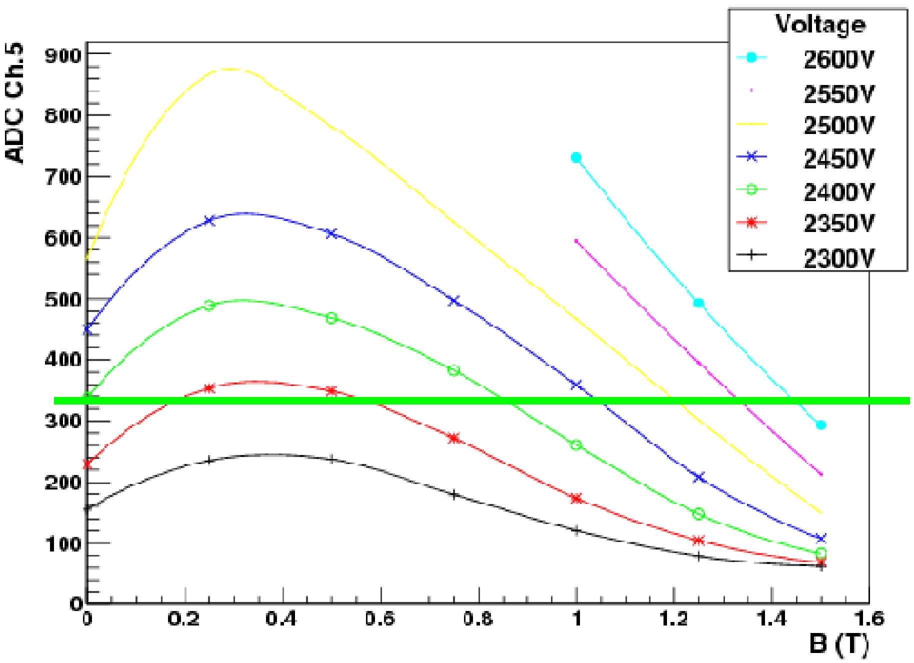
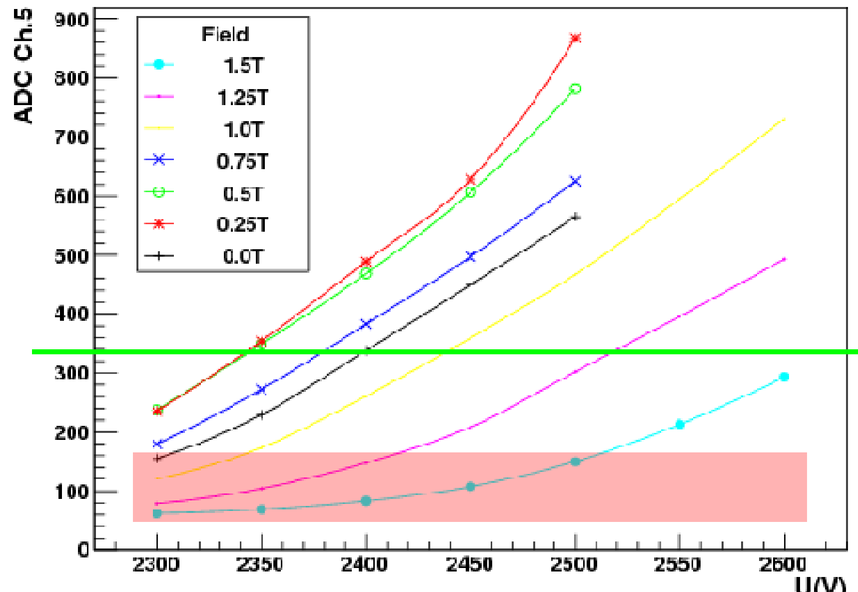




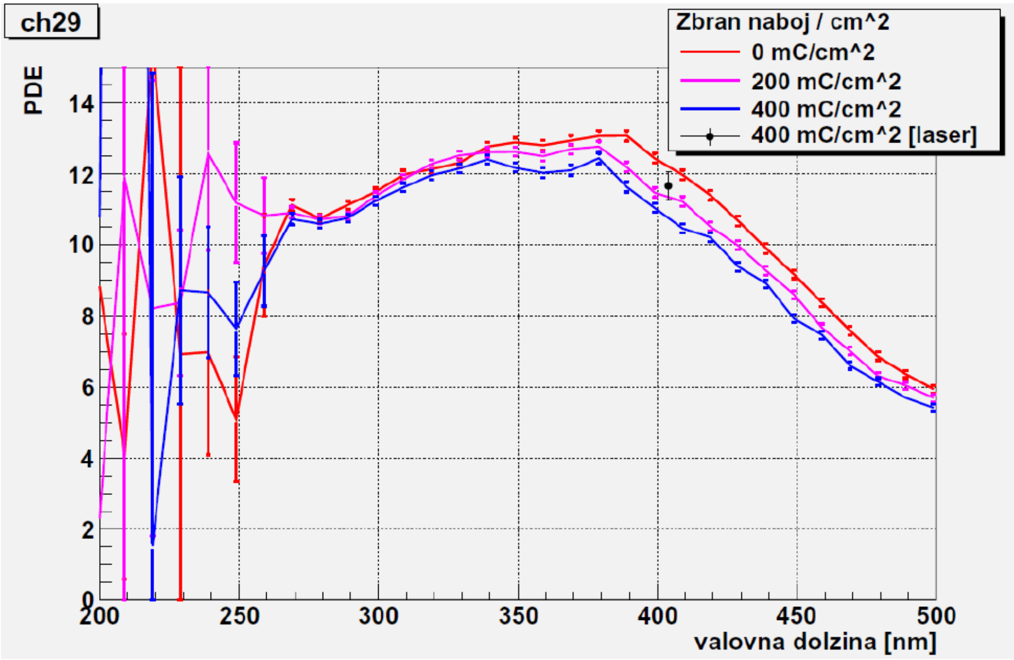
High B field: no problem, to run at the same gain HV → +200V

In the presence of magnetic field, charge sharing and cross talk due to long range photoelectron back-scattering are considerably reduced.

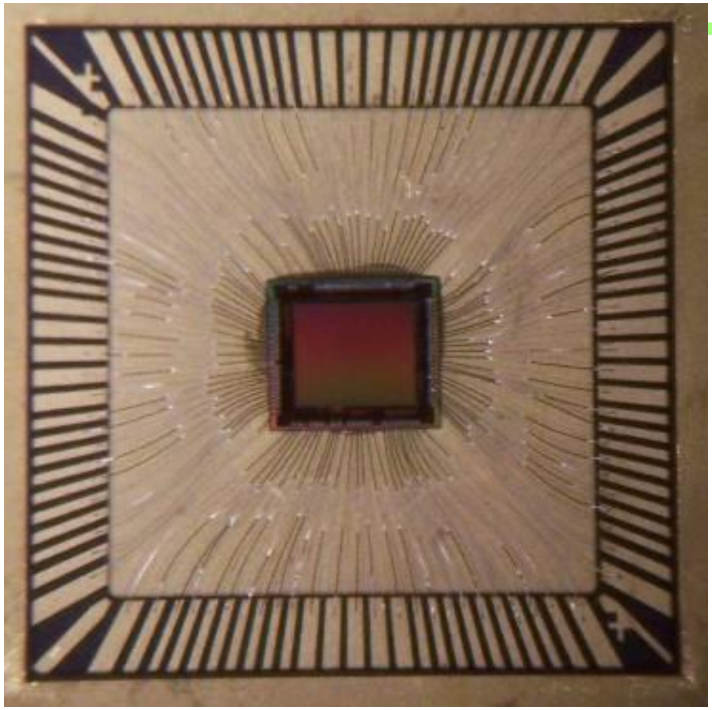
MCP PMT - ageing

Ageing test: high rate illumination of the whole photosensitive surface by LED, pulsed laser monitoring of the amplification. Reference PMT is used for periodic QE measuemnets with a monochromator in the same set-up.

Results:
after 400 mC/cm^2 (= Belle II lifetime for the aerogel RICH counter) the efficiency drops by about 10% → no problem for operation.



Read out: Buffered LABRADOR (BLAB1) ASIC



3mm x 2.8mm, TSMC 0.25um

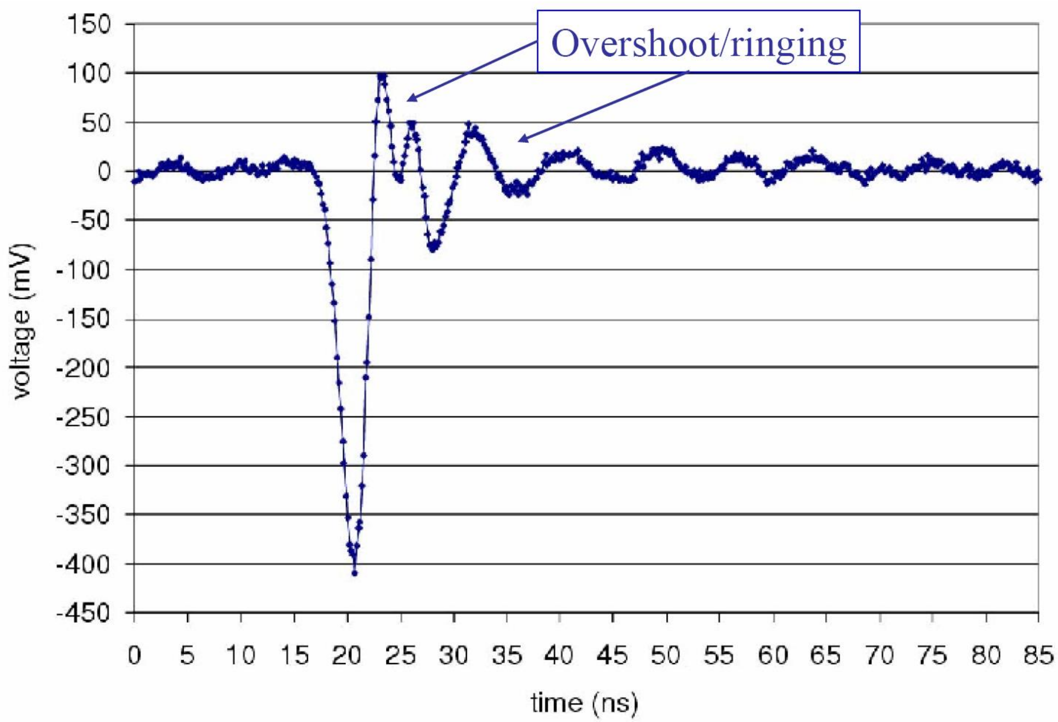
- 64k samples deep
- Multi-MSa/s to Multi-GSa/s

Gary Varner, Larry Ruckman (Hawaii)

Variant of the LABRADOR 3

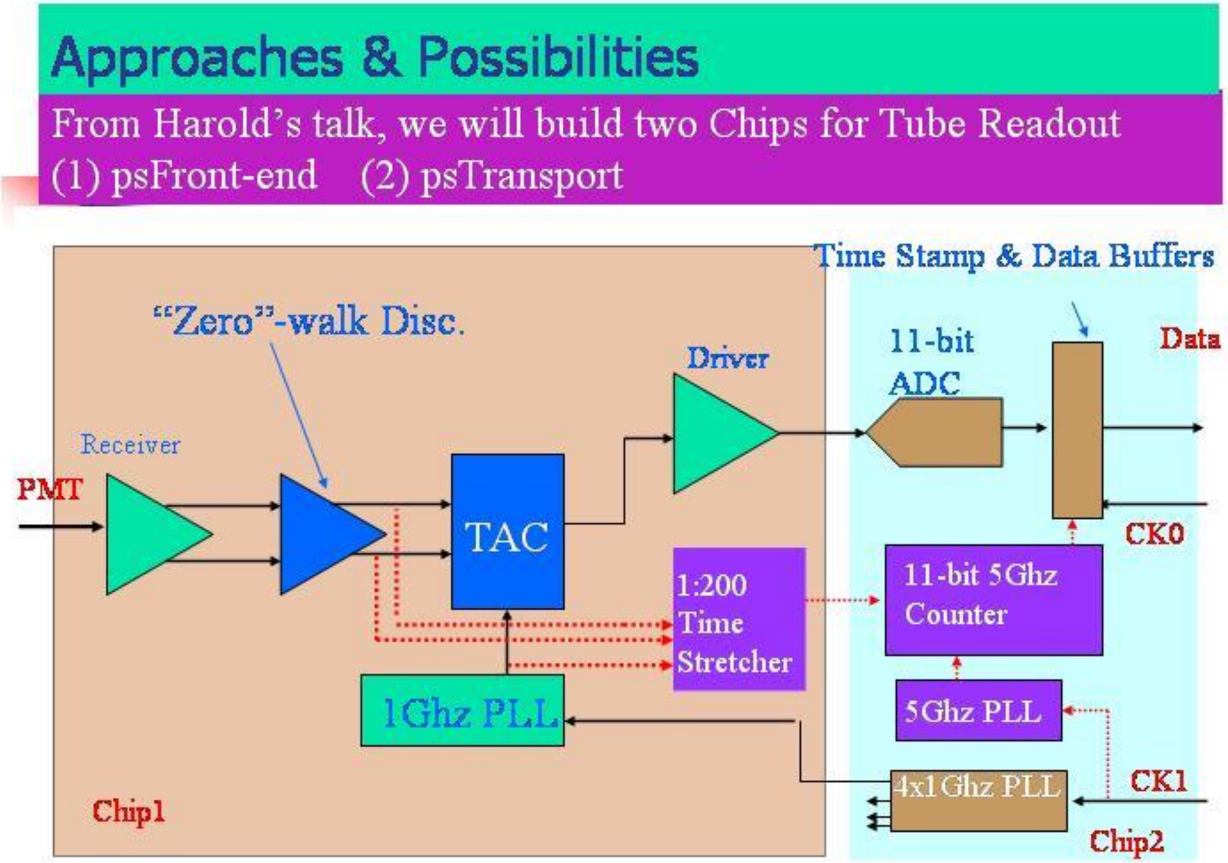
Successfully flew on ANITA in Dec 06/Jan 07 (<= 50ps timing)

Typical single p.e. signal [Burle]



Effort to develop ps TOF counter

H. Frisch & H. Sanders, Univ. of Chicago, K. Byrum, G. Drake, Argonne lab

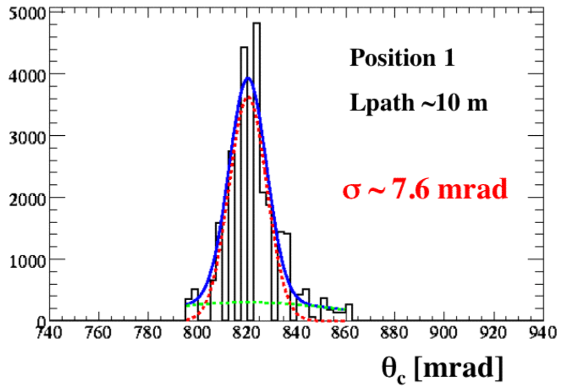


- ASIC-based technology for a new CFD & TDC

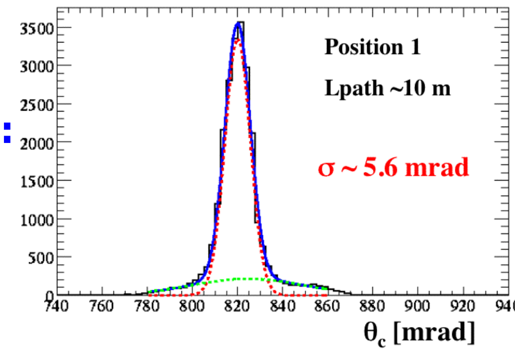
Focusing DIRC- the chromatic correction

Beam test results with BURLE/Photonis MCP PMT

Correction off:



Correction on:



θ_C resolution and chromatic correction for 3mm pixels:

Expected PID performance: