DECEMBER • 2nd - 4th • 2014

MCP based detectors, ANL

Overview and status of photodetectors

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Why (fast) single photon detection?

Multianode PMTs

MCP PMTs

HPDs, HAPDs

SiPMs

Summary

Parameters of photo-sensors

Photon detection efficiency (PDE)

- quantum efficiency
- collection efficiency / Geiger discharge probability

Granularity

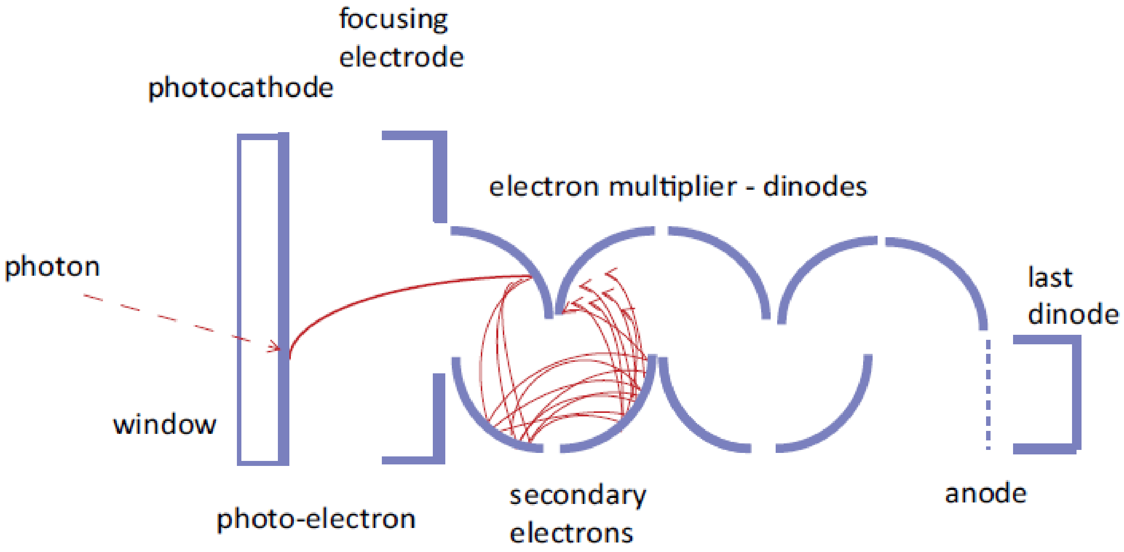
Time resolution (transient time spread – TTS)

Long term stability

Operation in magnetic field

Dark count rate

+ …

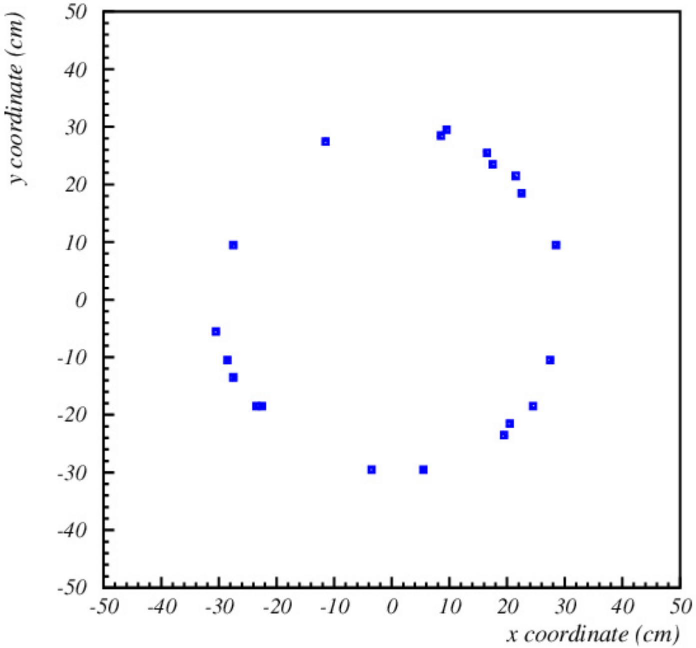


Photon detection in RICH counters

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 Cherenkov counters: precise time information needed to further improve performance:

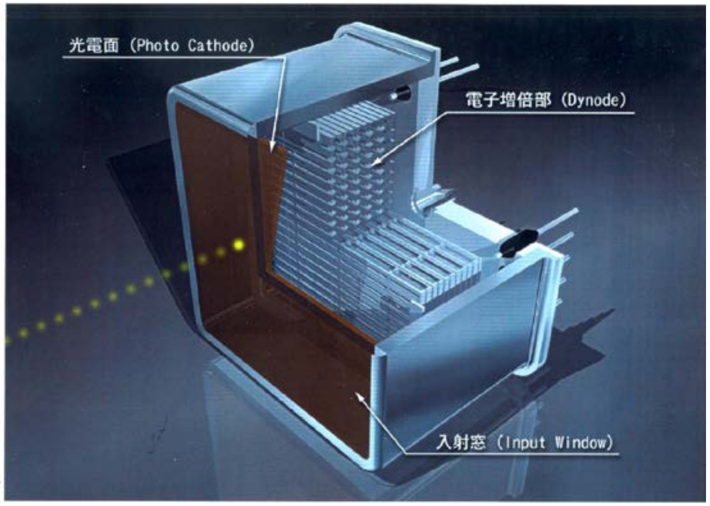
- Reduce chromatic abberation in a RICH detector (measure group velocity): Focusing DIRC
- Combine TOF and RICH techniques: TOP (Time-of-propagation counter), TORCH
- Dedicated TOF

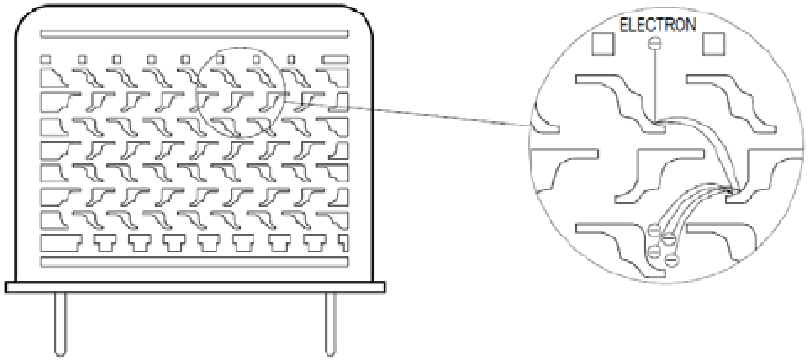
New possibilities in medical imaging: TOFPET with Cherenkov light

→ Need photo sensors with excellent timing

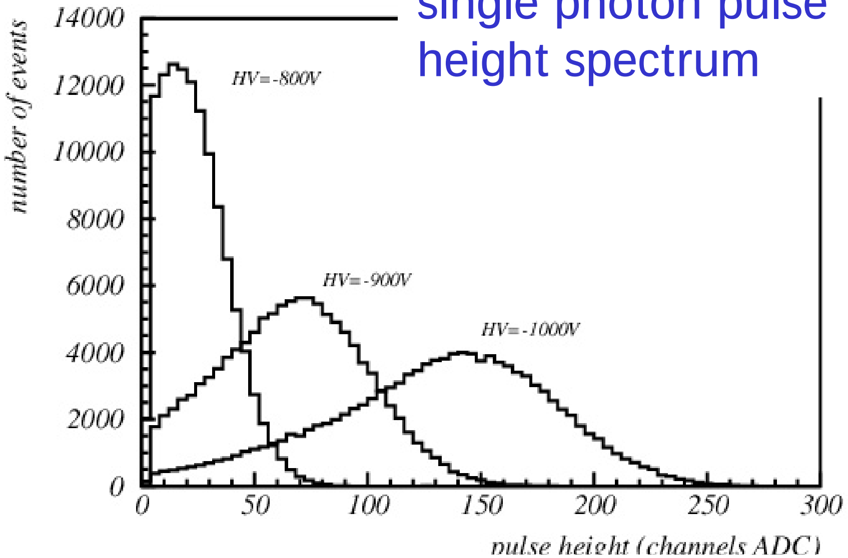
First fast multianode sensor for single photons: MA PMT

Multianode PMT Hamamatsu R5900 with metal foil dynodes





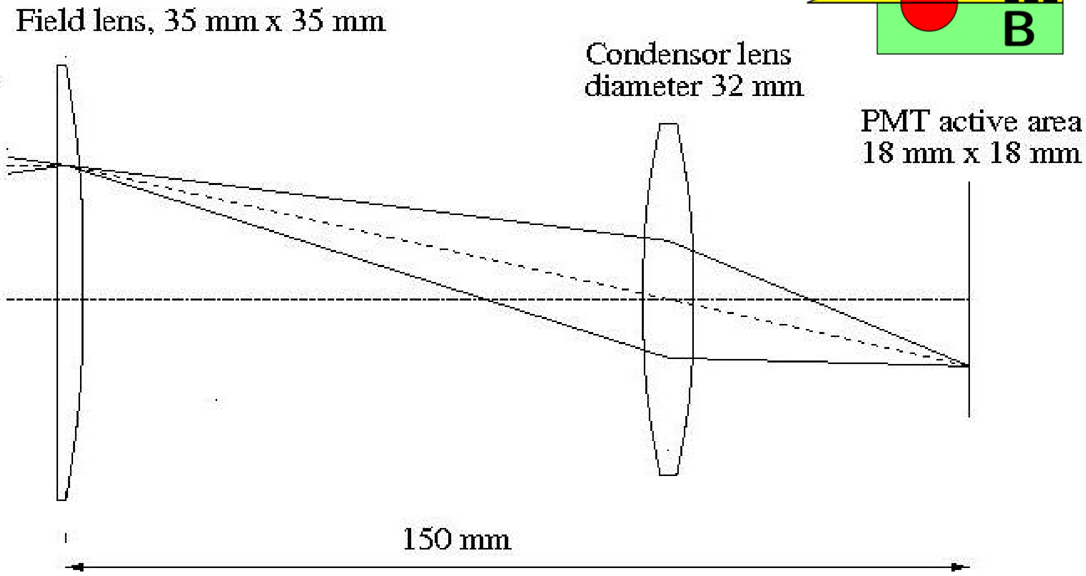
- Excellent single photon pulse height spectrum
- Low noise (few Hz/ch)
- Low cross-talk (<1%)



single photon pulse height spectrum

NIM A394 (1997) 27

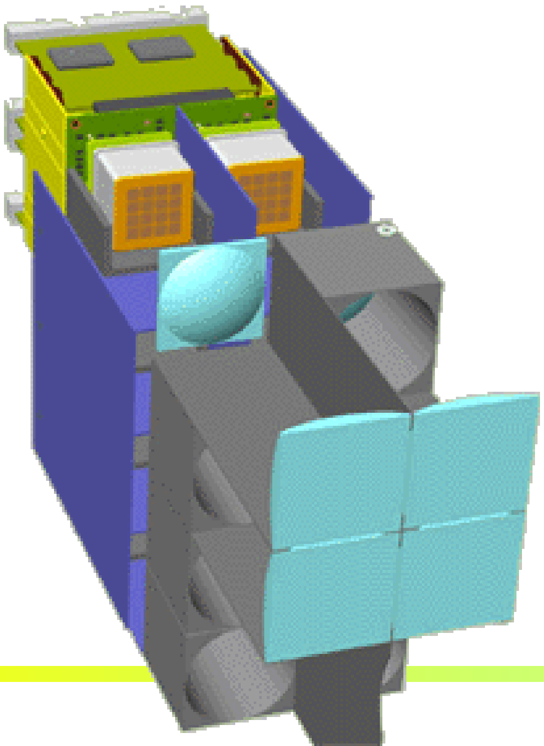
First major application: HERA-B RICH

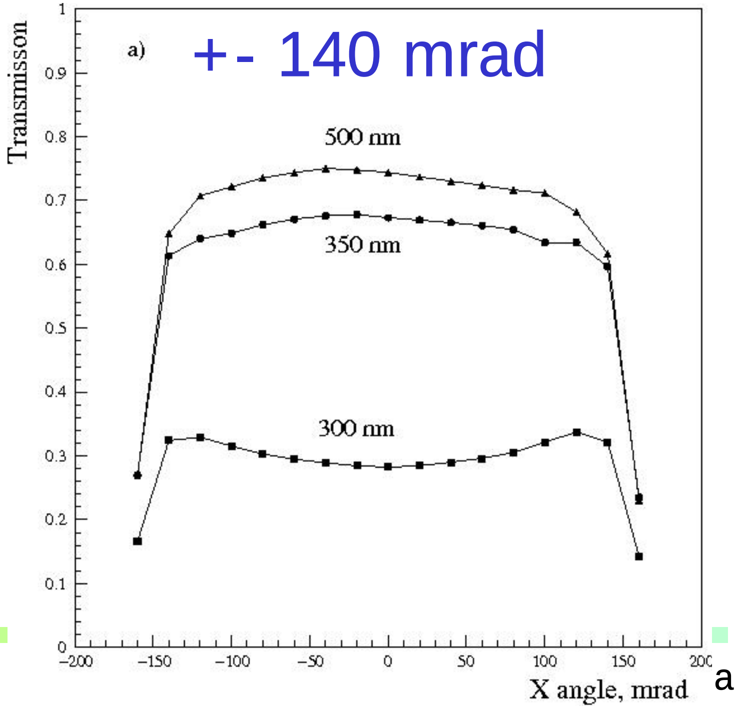


Light collection system (imaging!) to:

-Eliminate dead areas

-Adapt the pad size

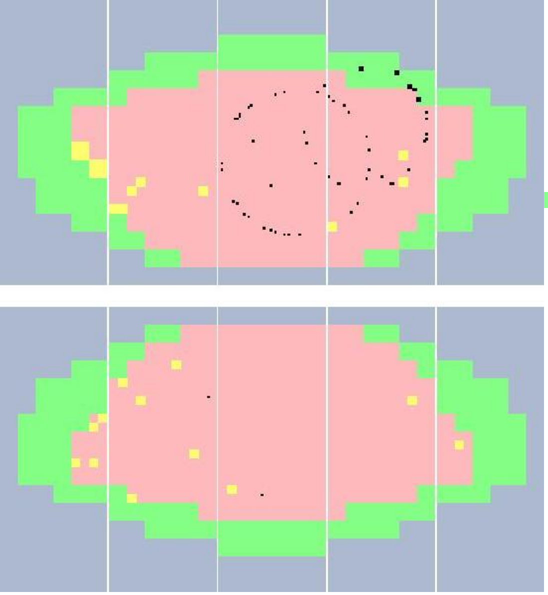




+- 140 mrad

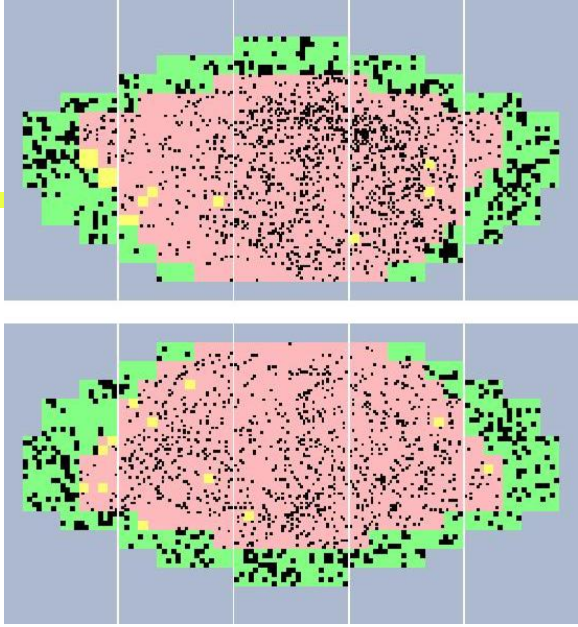
a

HERA-B RICH

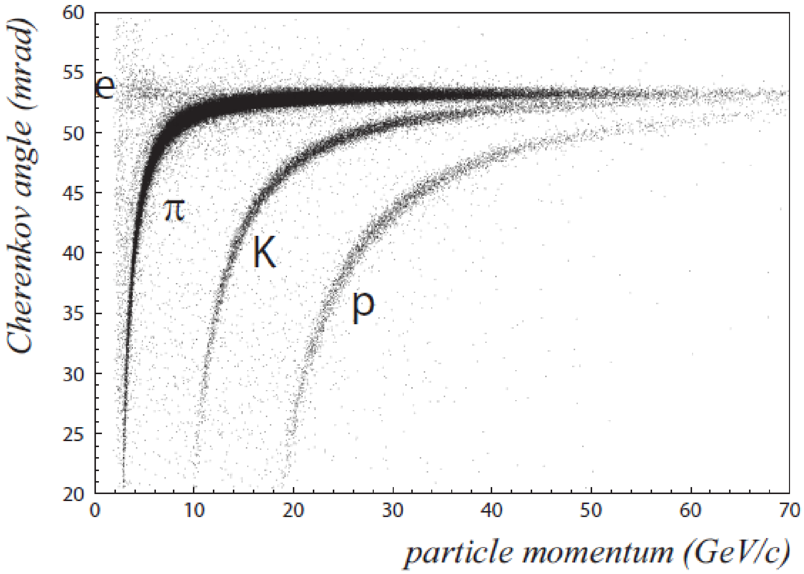


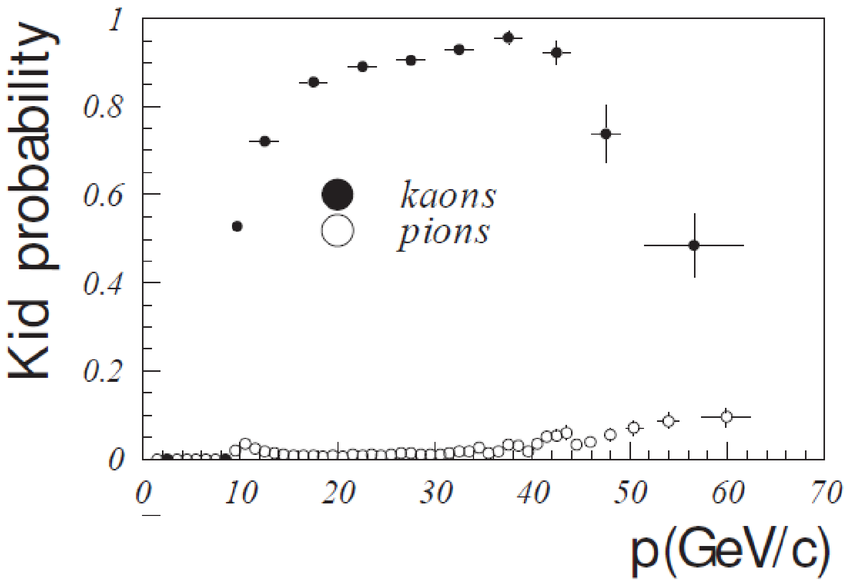
← Little noise, ~30 photons per ring

Typical event →



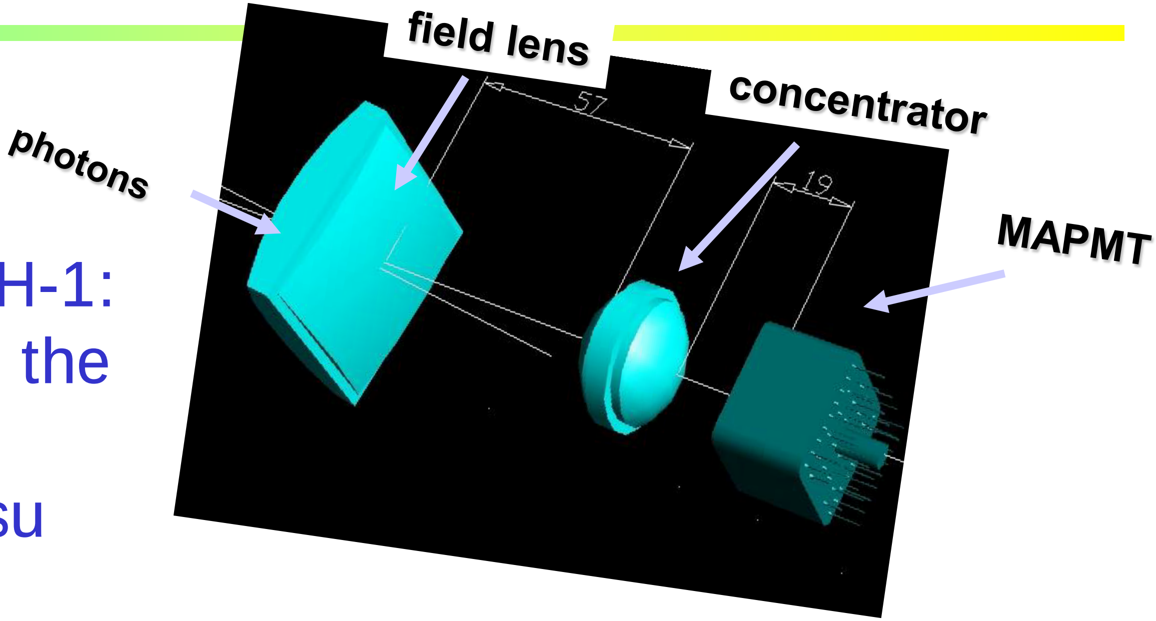
Very good performance:





Kaon efficiency and pion fake probability

Photon detector for the COMPASS RICH-1 upgrade



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

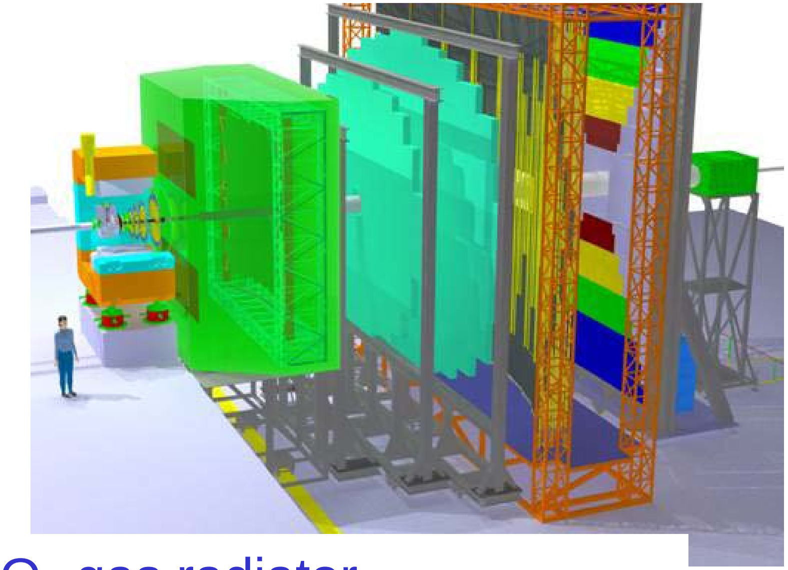
New features:

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

RICH for CBM at FAIR (GSI)

Compressed Baryonic Matter experiment

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



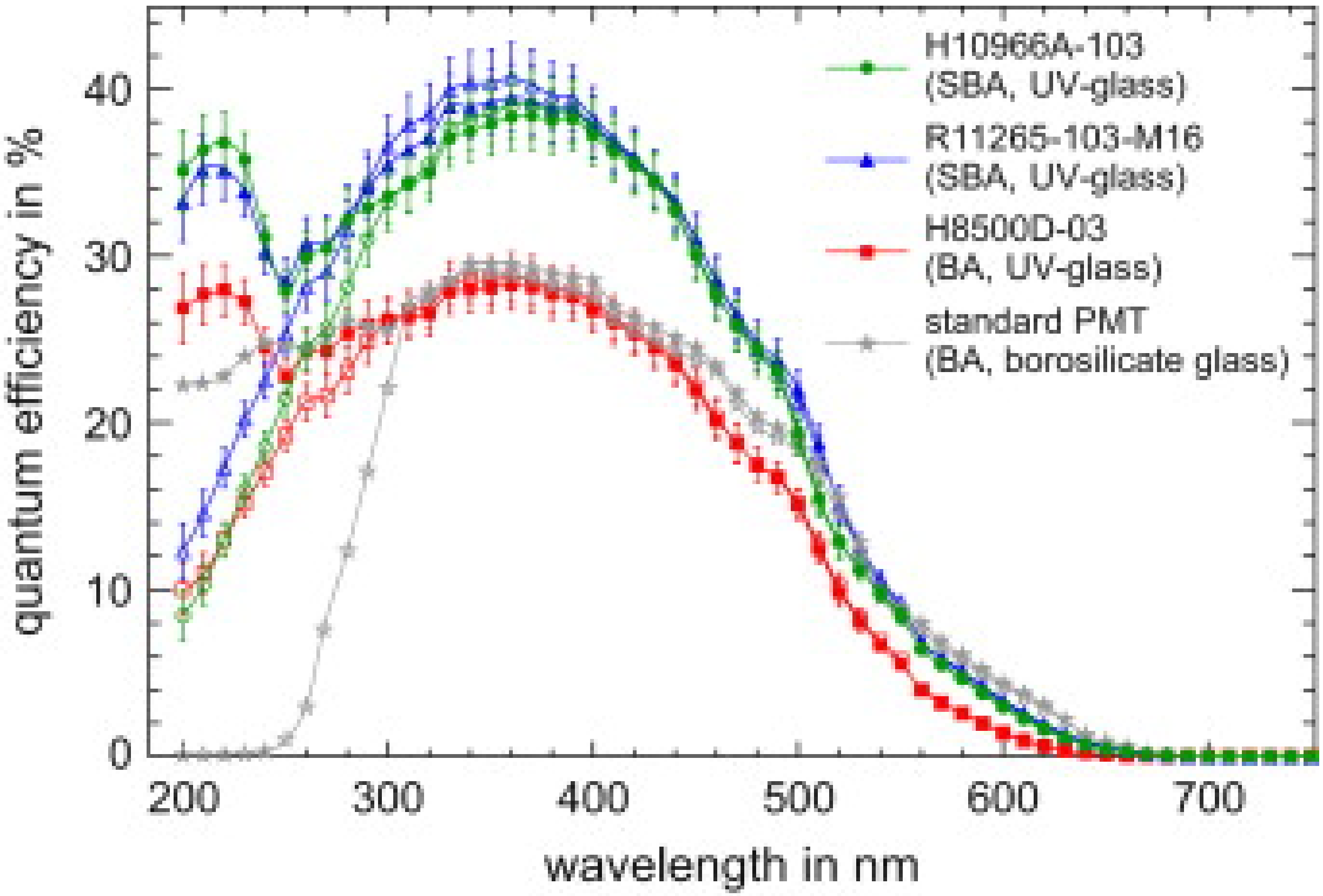
- 2.25 m long CO_2 gas radiator
- photon detector: 2 MA PMT planes
- need sensitivity down to 180nm

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

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

Extending PMT sensitivity to lower wavelengths

CBM RICH R+D: Wavelength-shifter coating of the PMT window



→NIM A766 (2014) 180

Flat pannel multianode PMTs

Problem of vacuum based sensors: active area fraction

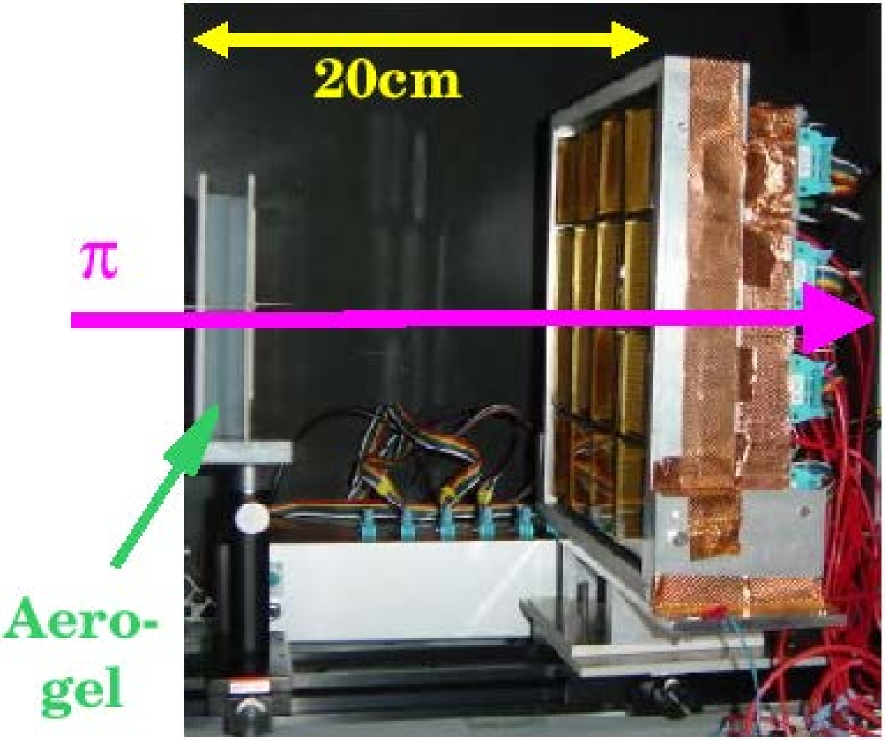
One possible solution: make a larger sensor

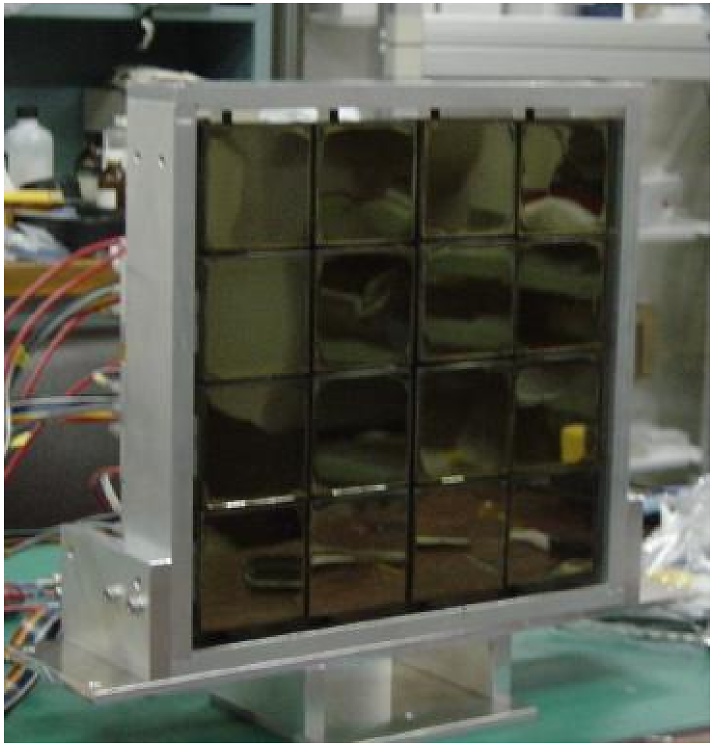
Hamamatsu: flat pannel PMT H8500

- 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

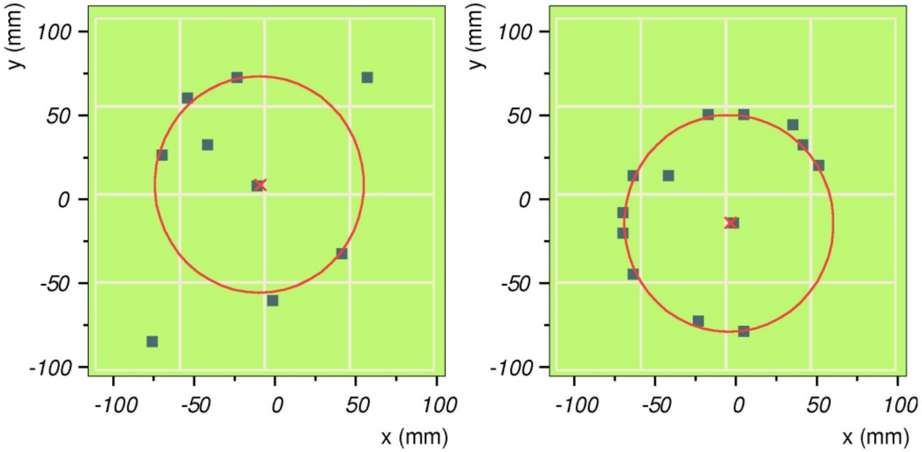
First used in a prototype RICH
for Belle II, with aerogel radiator.





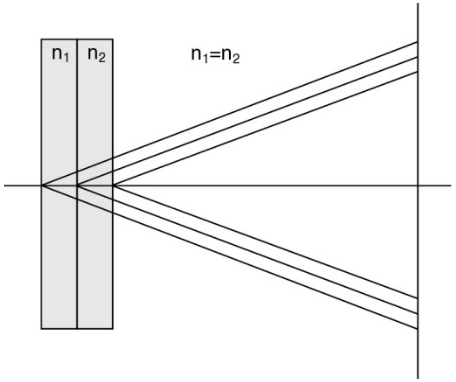
array of 16 H8500 PMTs

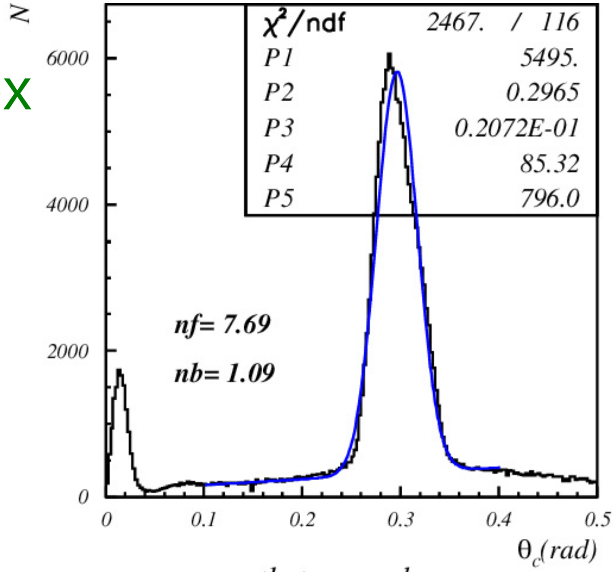
Clear rings, little background



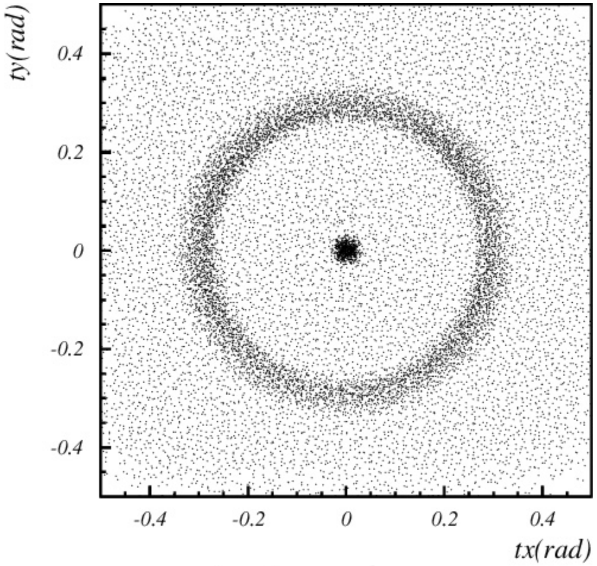
Used for the proof-of-principle test of the focusing radiator configuration

4cm aerogel single index



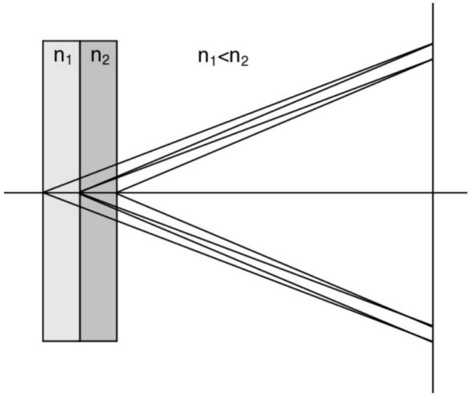


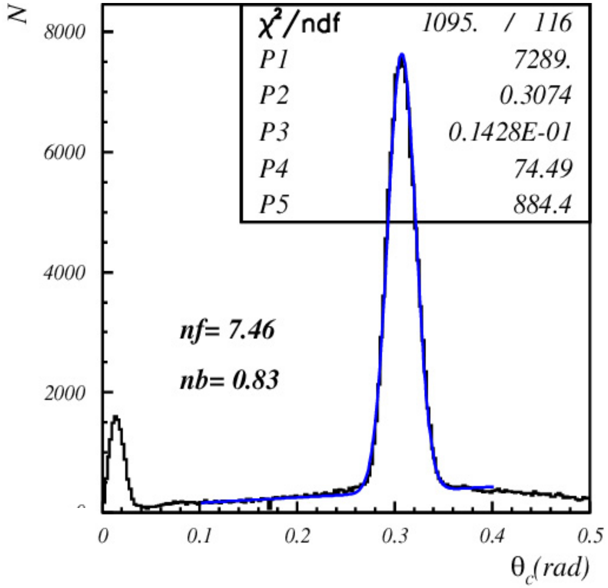
theta cerenkov

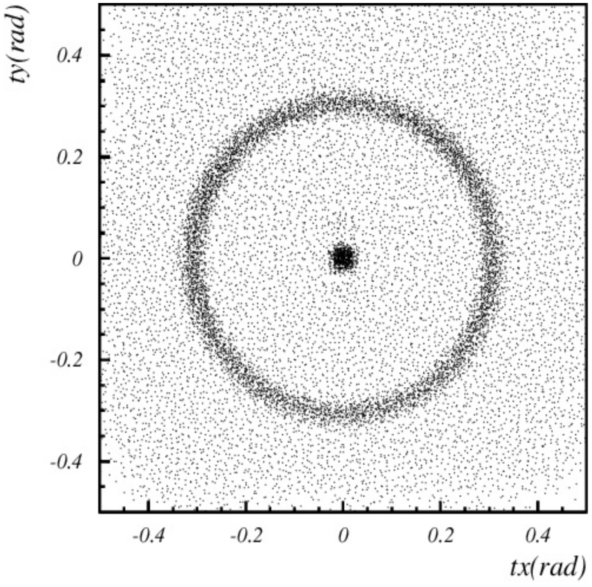


ring in cerenkov space

2+2cm aerogel



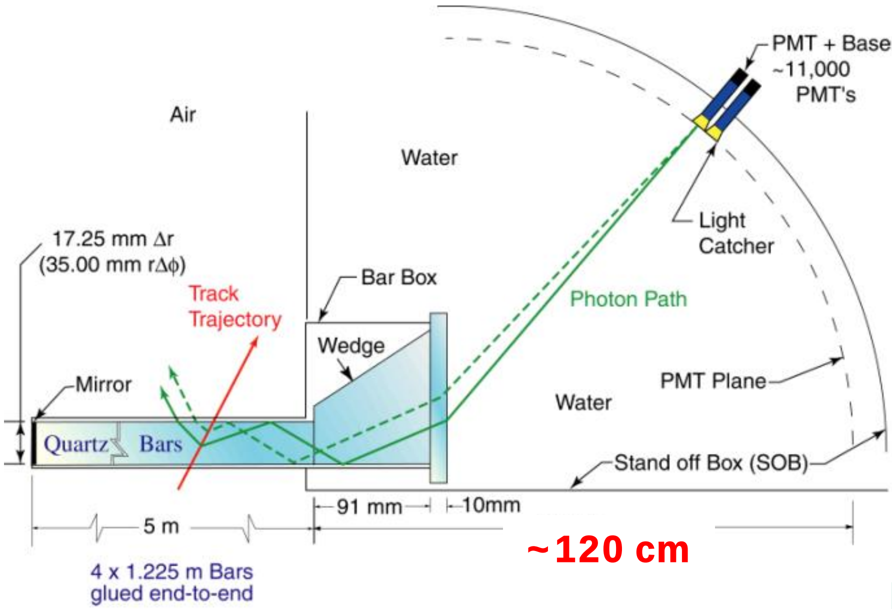




→NIM A548 (2005) 383

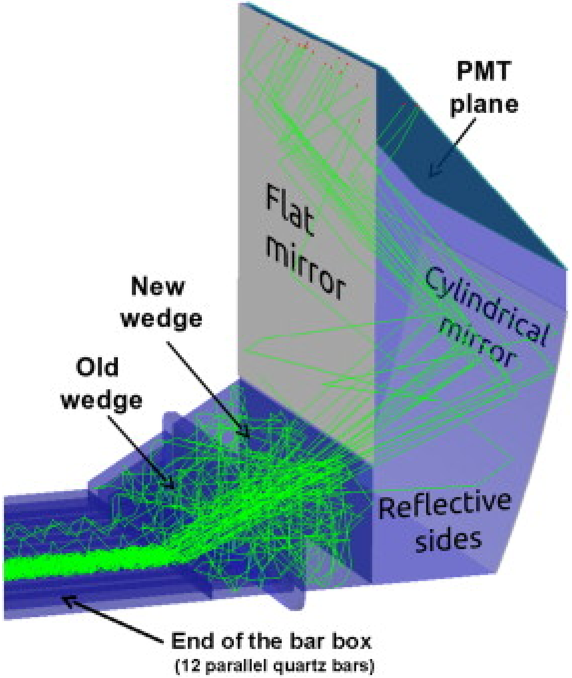
Flat pannel MA PMTs: Focusing DIRC

Next step in the DIRC development, remove the stand-off box →



~120 cm

→ add a focusing element and use fast pixelated photo-sensors



~20 cm

→NIM A766 (2014) 114

Focusing DIRC

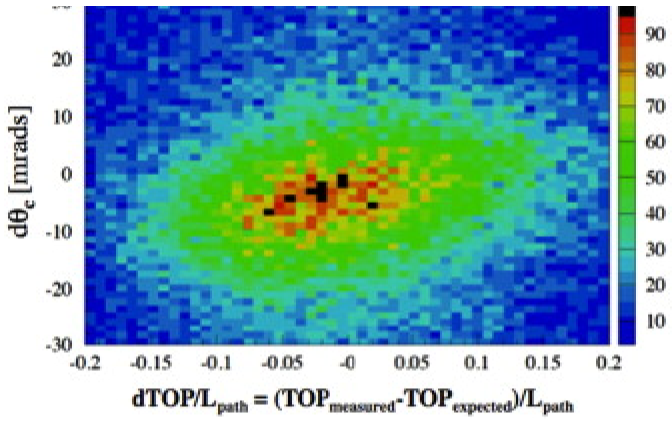
Super-B factory: 100x higher luminosity => DIRC needs to be smaller and faster

Focusing and smaller pixels can reduce the expansion volume (source of background hits) 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.

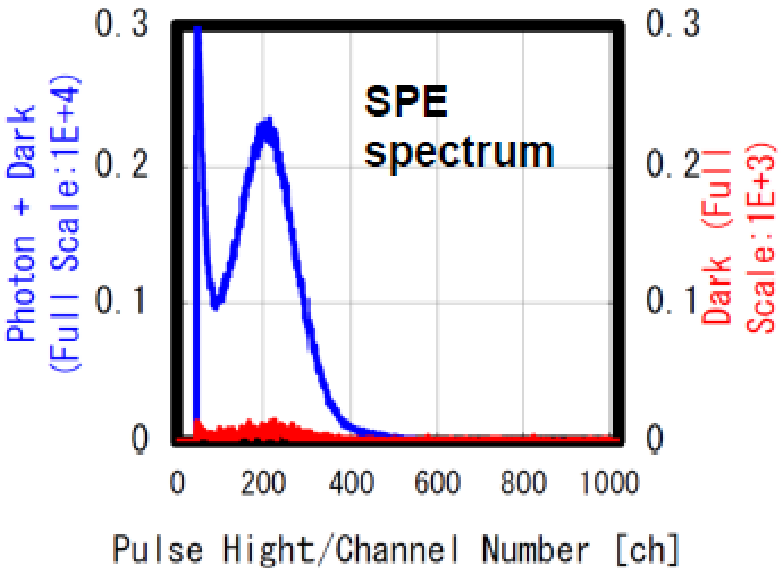
Prototype beam test: Cherenkov angle correction vs. TOP
→ NIM A766 (2014) 114

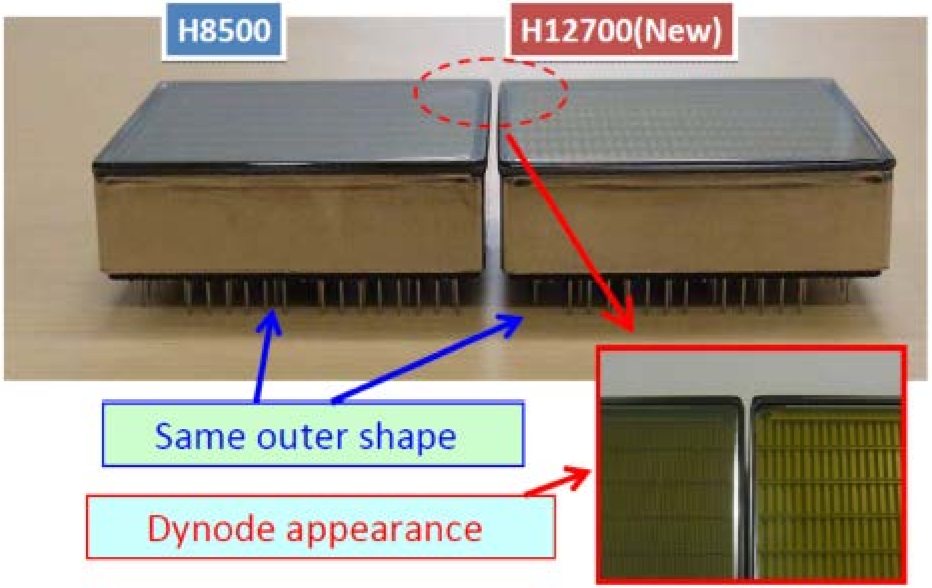
Flat pannel MA PMTs: CBM RICH

Baseline option for the CBM RICH

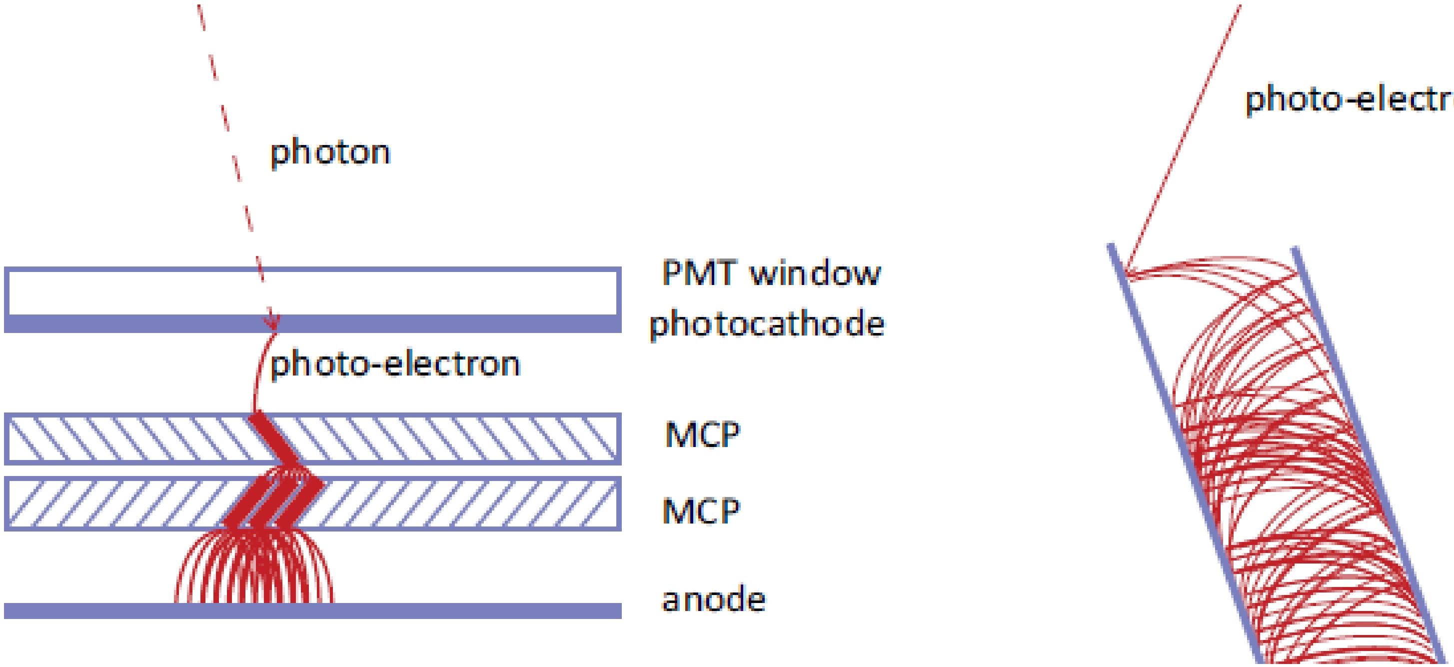
News: a novel version of H8500 available, with a considerably better single photon pulse height distribution

Same sensor also considered for the CLASS12 RICH





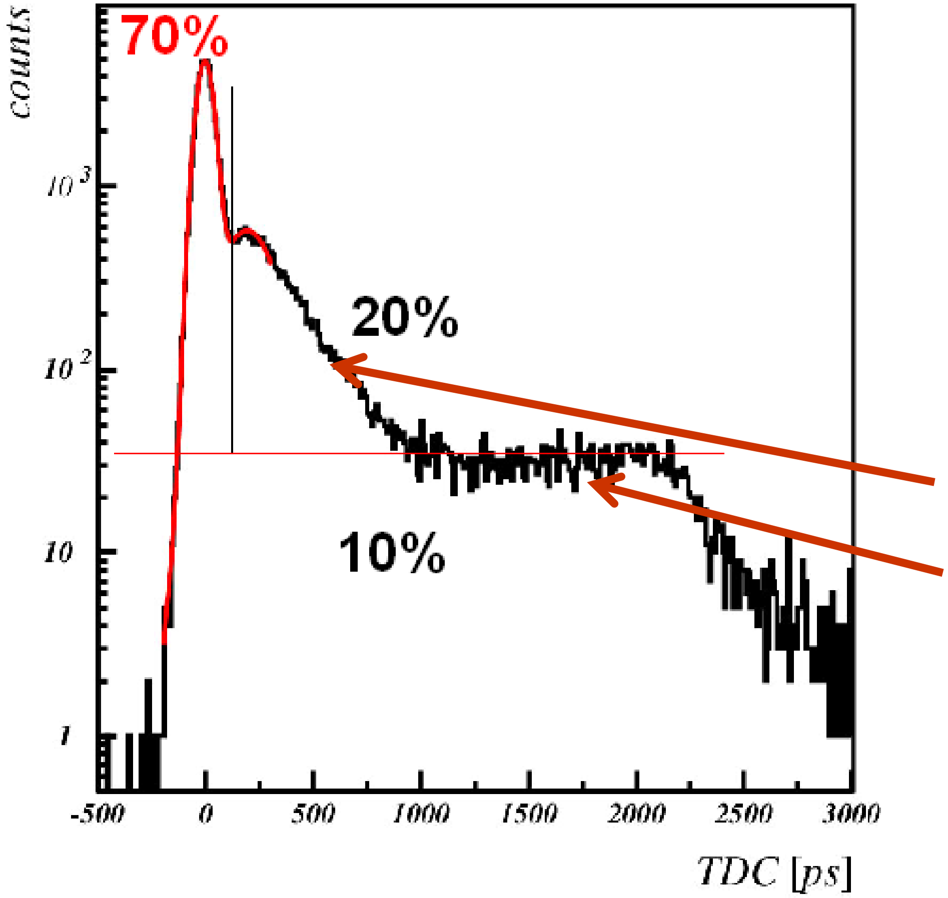
Micro-channel plate PMTs

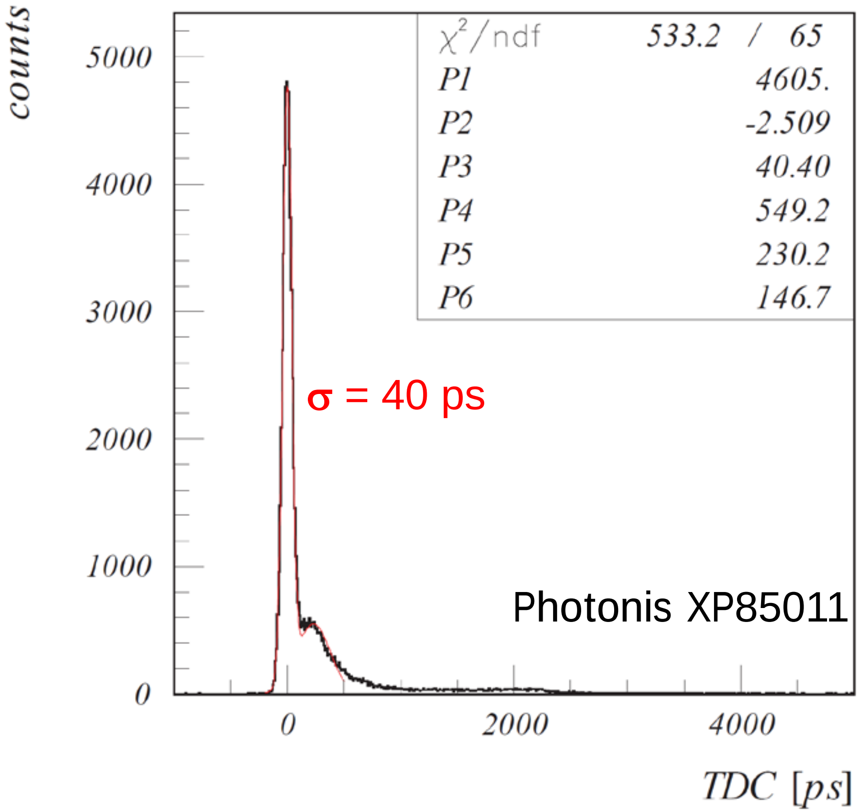


- Fast
- Immune to an axial magnetic field

MCP PMT timing

MCP PMTs: main peak with excellent timing accompanied with a tail





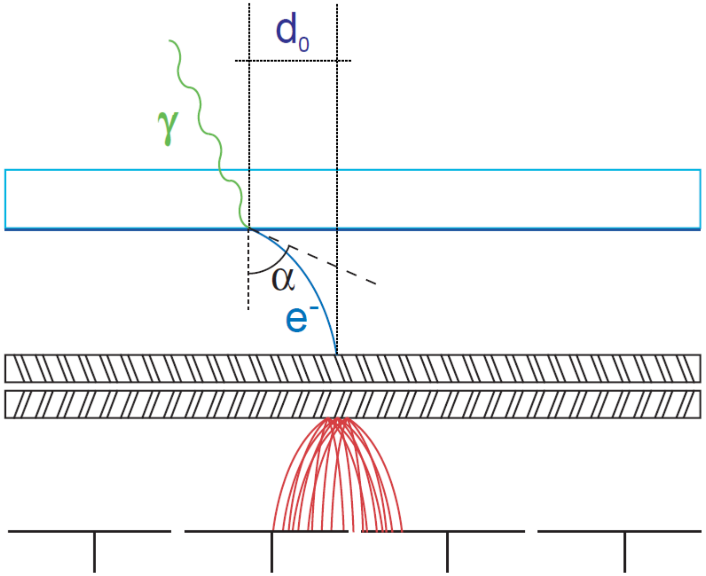
- Inelastic back-scattering
- Elastic back-scattering

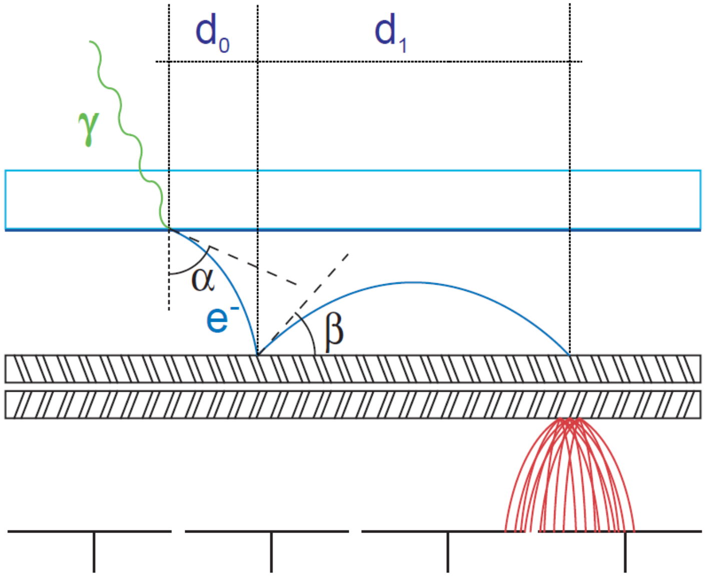
→good agreement with a simple model →

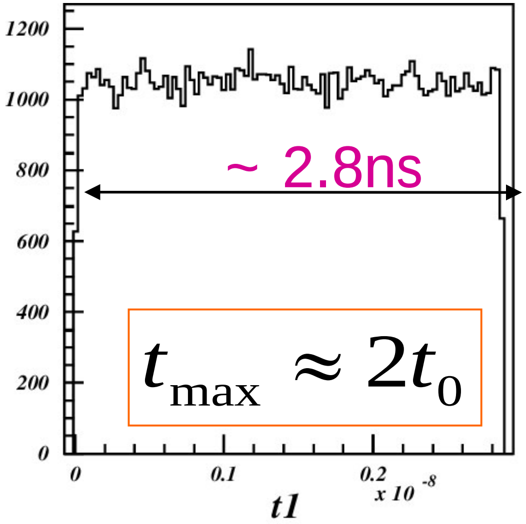
→ NIMA 595 (2008) 169

→ JINST 4 (2009) P11017

Elastically backscattered photoelectrons

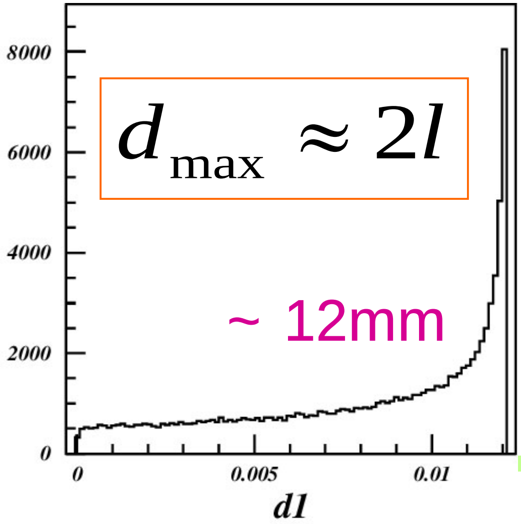






~ 2.8ns

$$t_{\max} \approx 2t_0$$



$$d_{\max} \approx 2l$$

~ 12mm

Results of a simple modeling: we assume that the photoelectron back-scattering by the angle **β** is uniform over the solid angle.

→ NIMA 595 (2008) 169
JINST 4 (2009) P11017

MCP PMT: processes involved in photon detection

MCP PMT parameters used: Photonis XP85011

Parameters used:

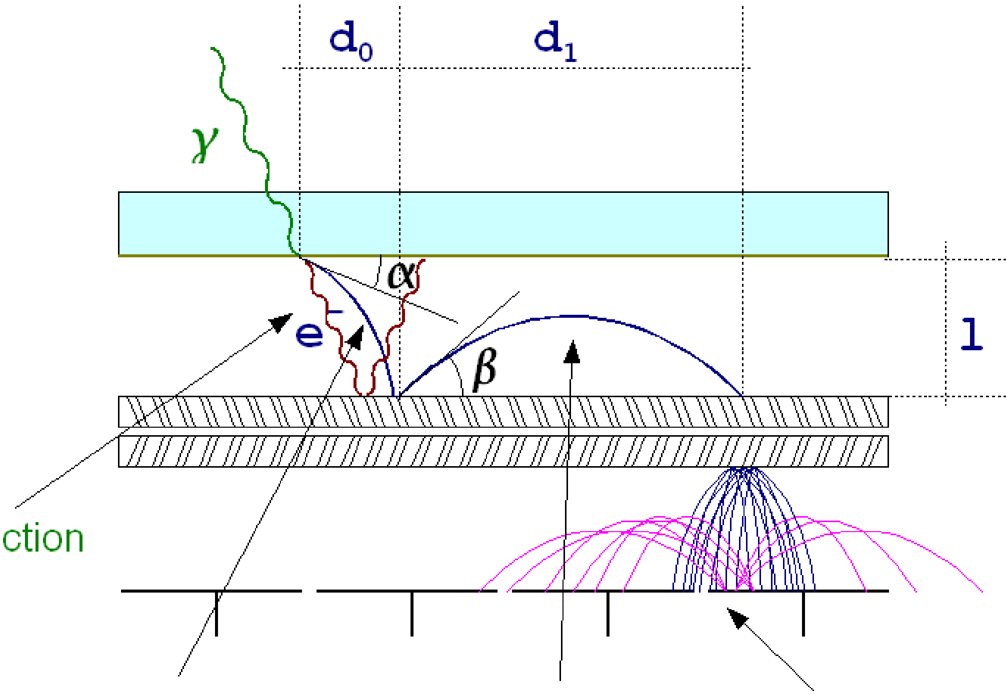
- $U = 200$ V
- $l = 6$ mm (K-MCP)
- $E_0 = 1$ eV
- $m_e = 511$ keV/c^2
- $e_0 = 1.6\ 10^{-19}$ As

$$\boxed{t_{\max} \approx 2t_0}$$

$$\boxed{d_{\max} \approx 2l}$$

Tails can be significantly reduced by:

- decreased photocathode-MCP distance and
- increased voltage difference



Internal-reflection

Photo-electron:

- $d_{0,max} \sim 0.8$ mm
- $t_0 \sim 1.4$ ns
- $\Delta t_0 \sim 100$ ps

Backscattering:

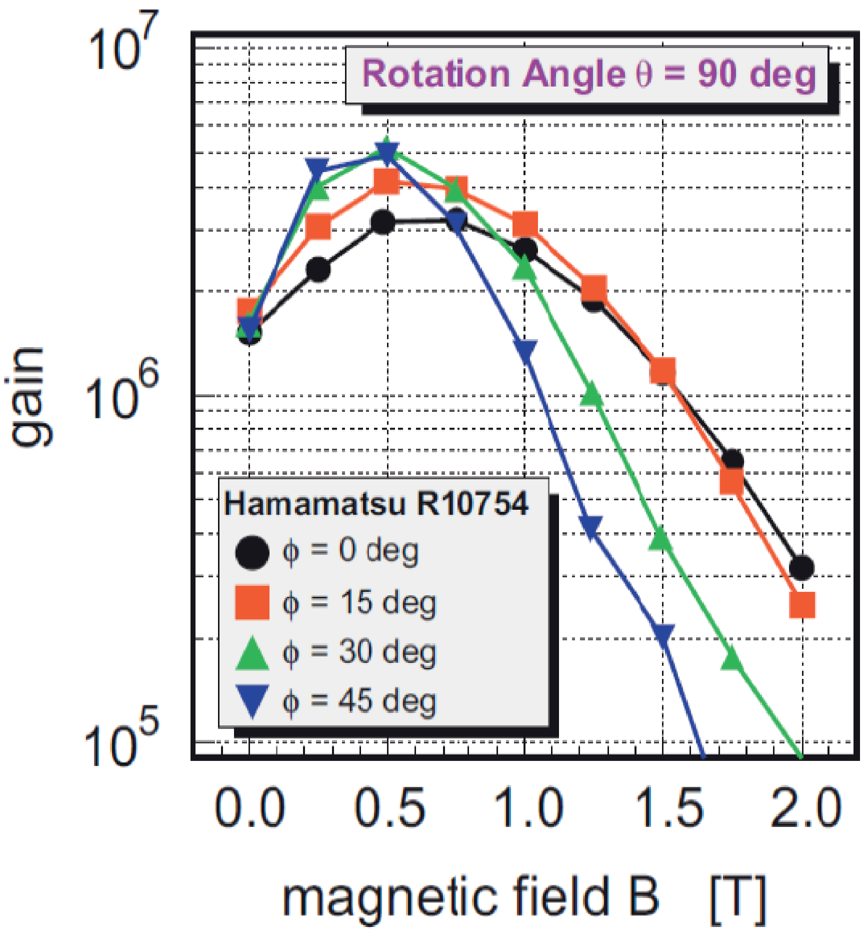
- $d_{1,max} \sim 12$ mm
- $t_{1,max} \sim 2.8$ ns

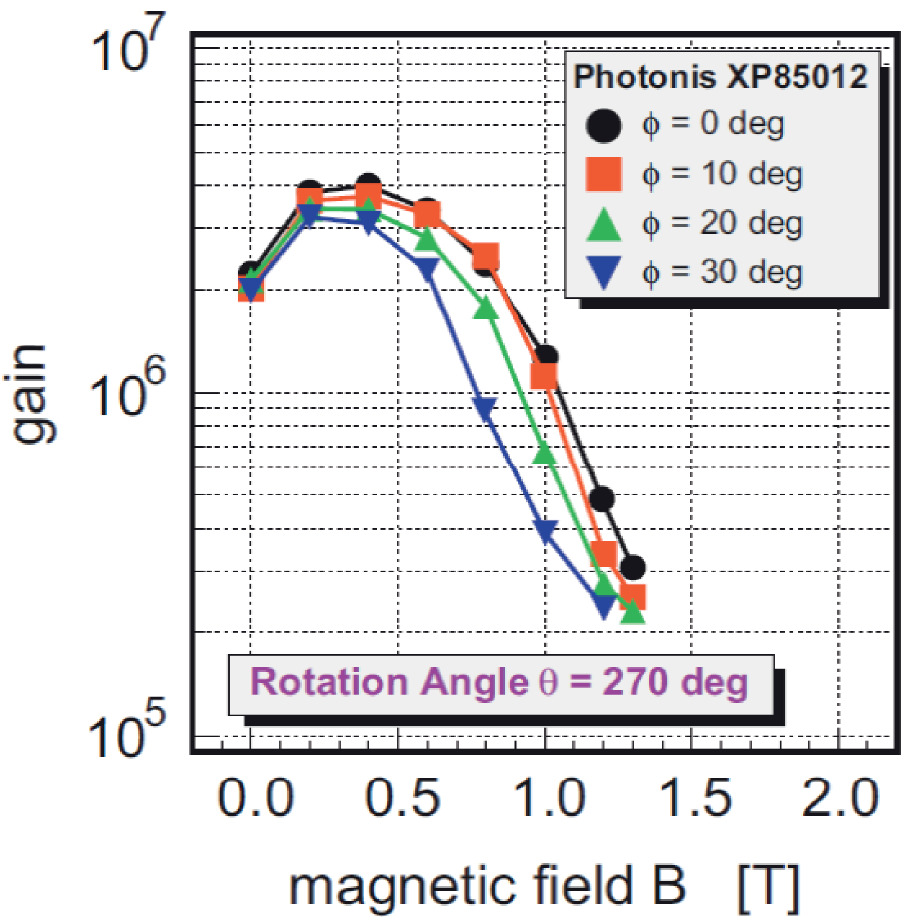
Charge sharing

→ NIMA 595 (2008) 169
JINST 4 (2009) P11017

MCP PMTs in magnetic field

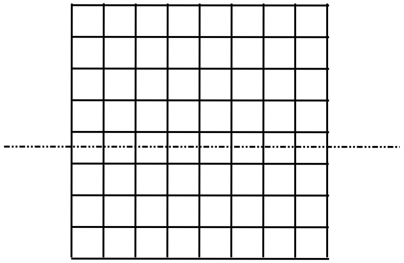
Gain vs B field for different tilt angles



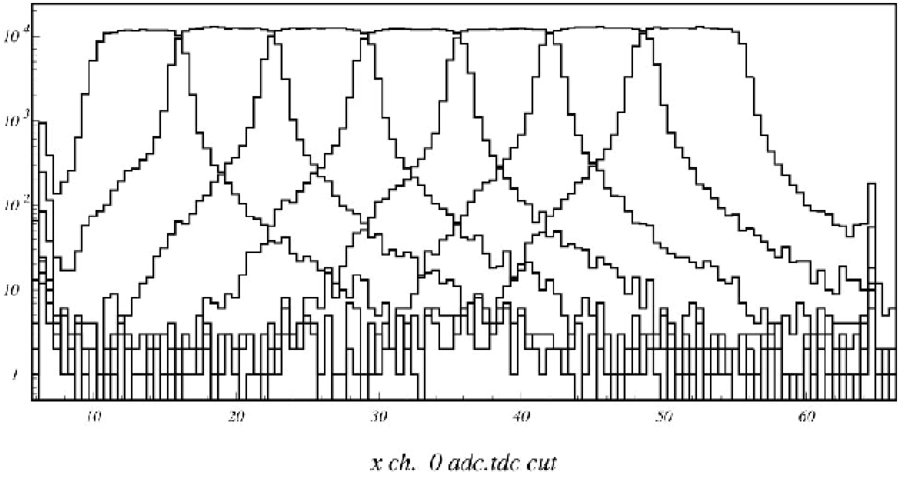


→ NIMA 639 (2011) 144

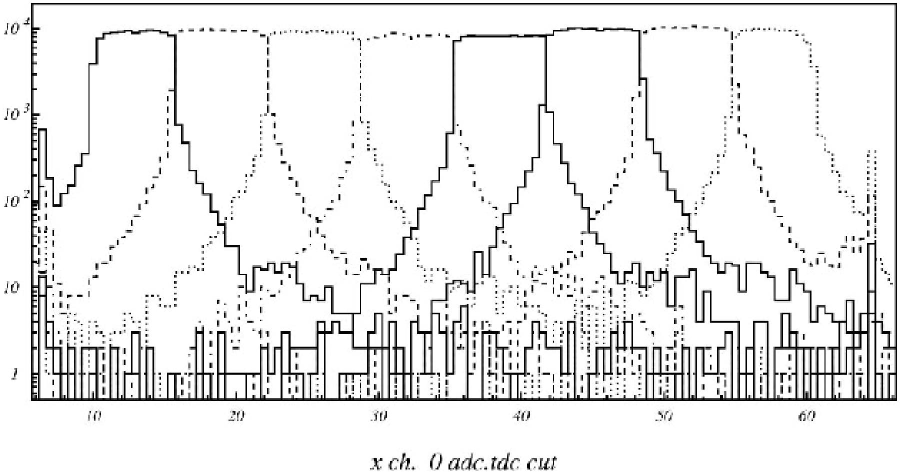
MCP PMT: improved performance in magnetic field



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



B = 0 T,
HV = 2400 V



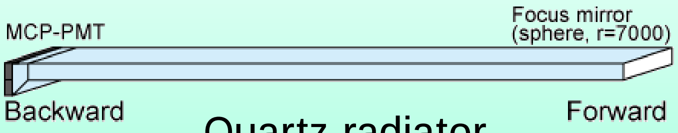
B = 1.5 T,
HV = 2500 V

Backscattered photoelectrons get ˝locked˝ to the B field lines

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

Belle II Cherenkov detectors

Barrel PID: Time of Propagation Counter (TOP)



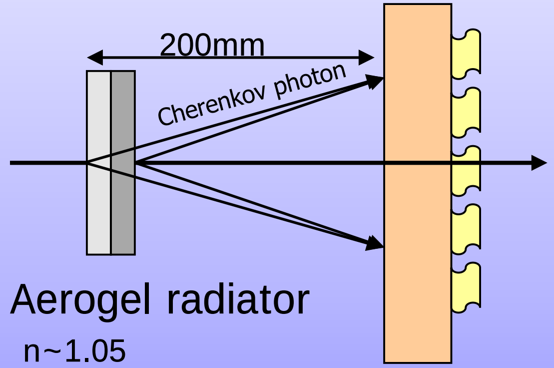
Quartz radiator

Focusing mirror

Small expansion block

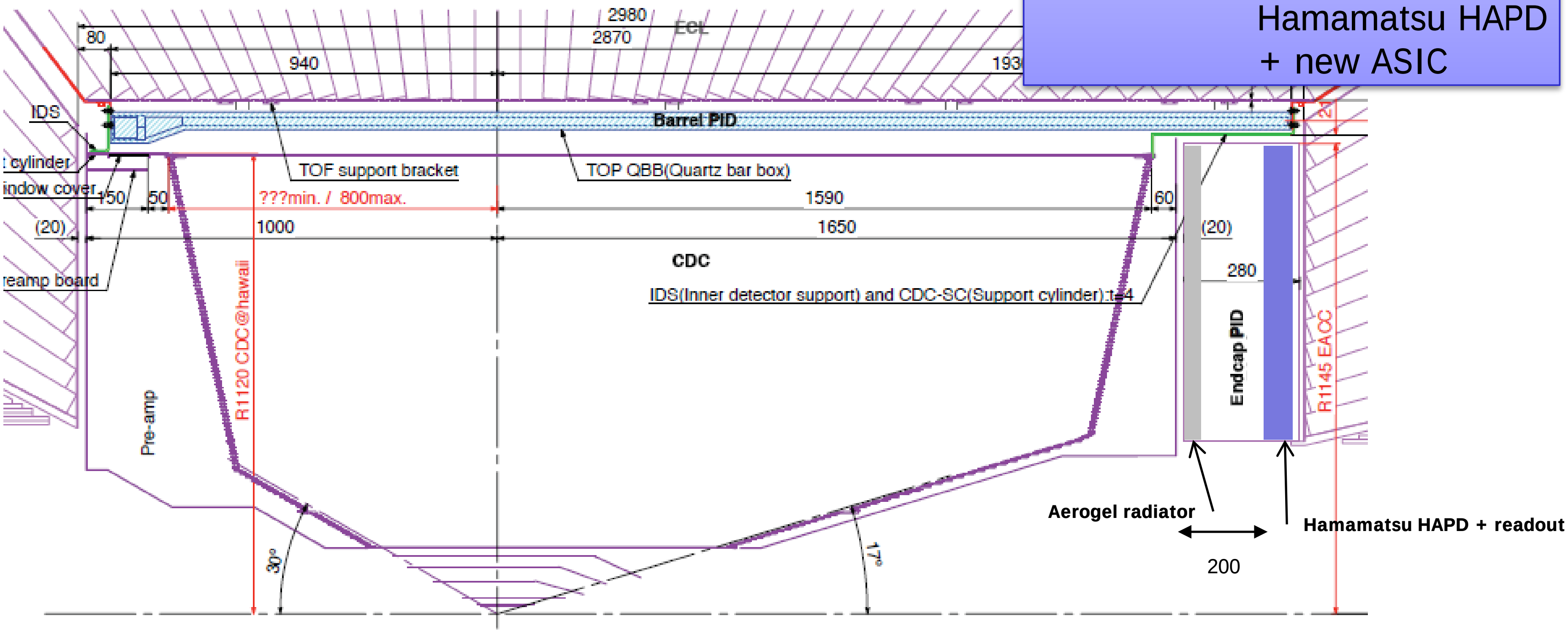
Hamamatsu MCP-PMT (measure t, x and y)

Endcap PID: Aerogel RICH (ARICH)



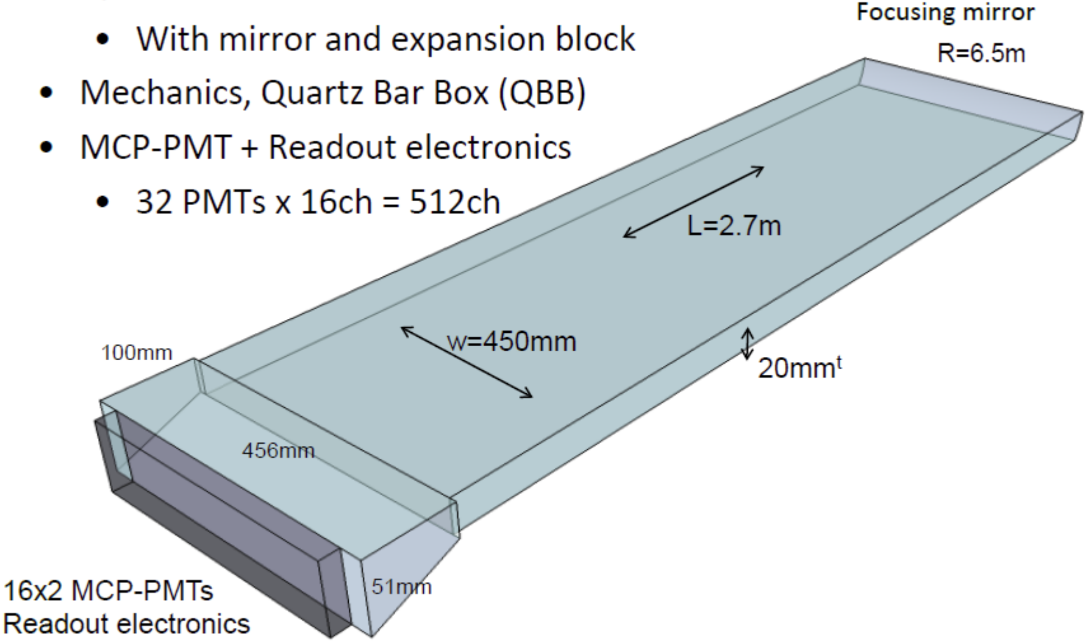
Aerogel radiator
n~1.05

Hamamatsu HAPD
+ new ASIC

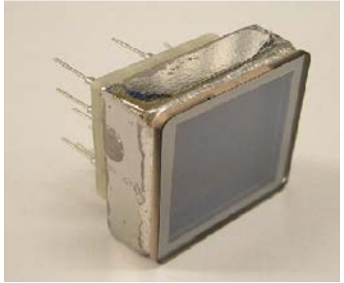


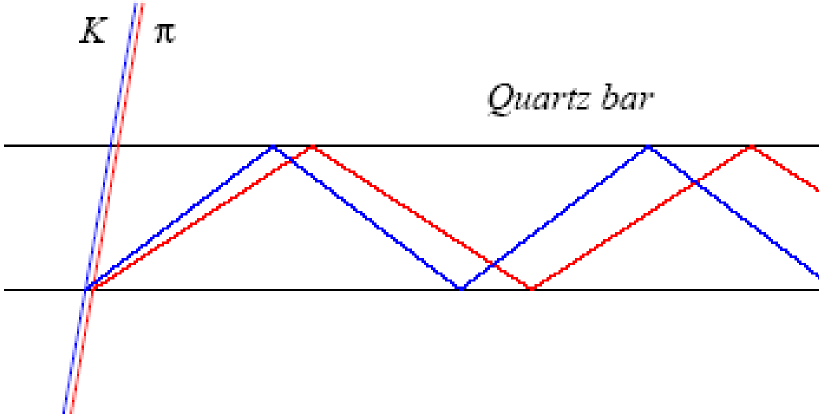
Time-Of-Propagation (TOP) counter

- Quartz radiator
  - With mirror and expansion block
- Mechanics, Quartz Bar Box (QBB)
- MCP-PMT + Readout electronics
  - 32 PMTs x 16ch = 512ch



Hamamatsu
SL10 MCP-PMT





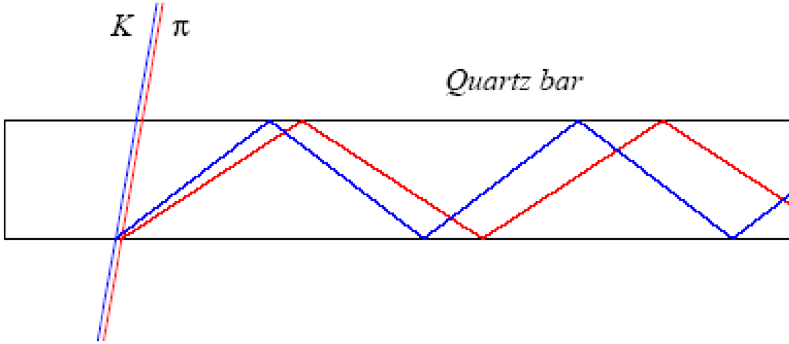
Similar to DIRC, but instead of two coordinates measure:

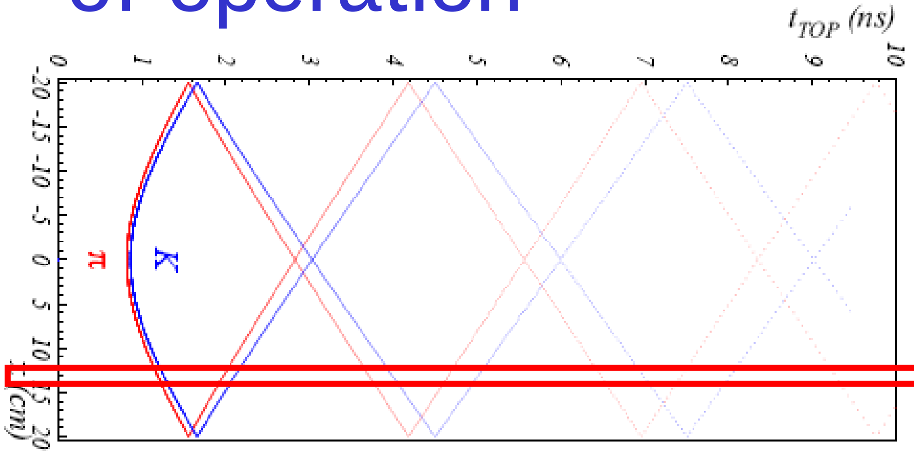
- – One (or two coordinates) with a few mm precision
- – Time-of-arrival

→ Excellent time resolution < 100ps (incl. read-out)
required for single photons in 1.5T B field

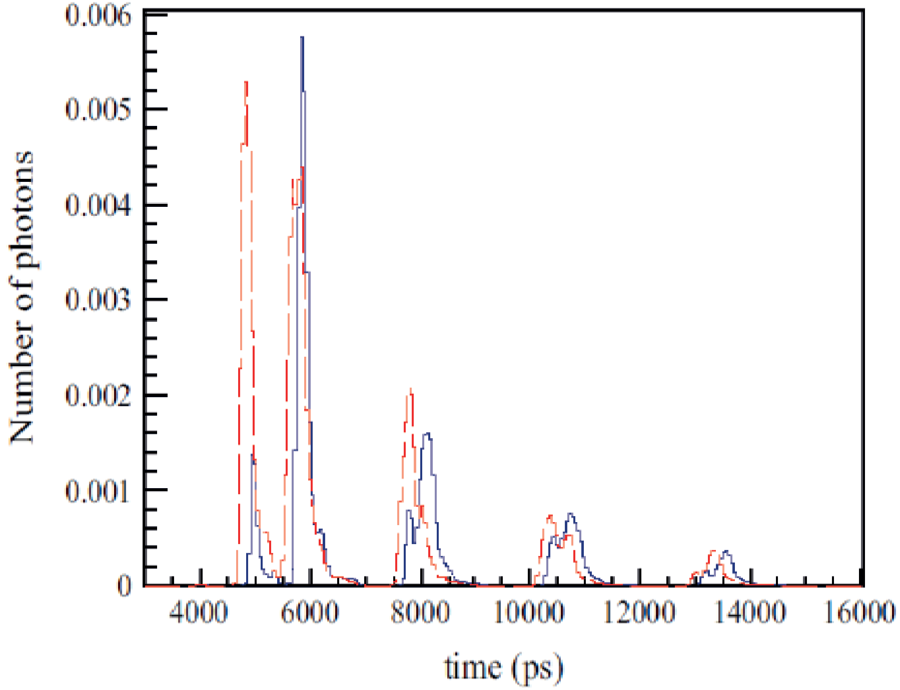
→ talks by K. Matsuoka, K. Inami, G. Varner

TOP counter: principle of operation





Pattern in the coordinate-time space (‘ring’) of a pion and a kaon hitting a quartz bar

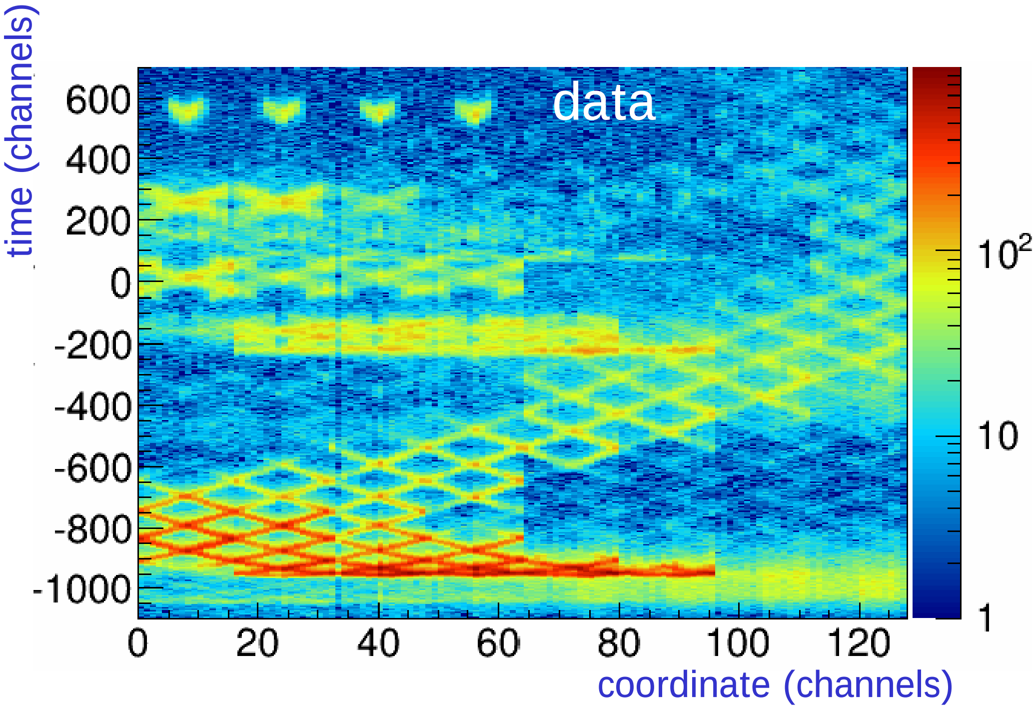


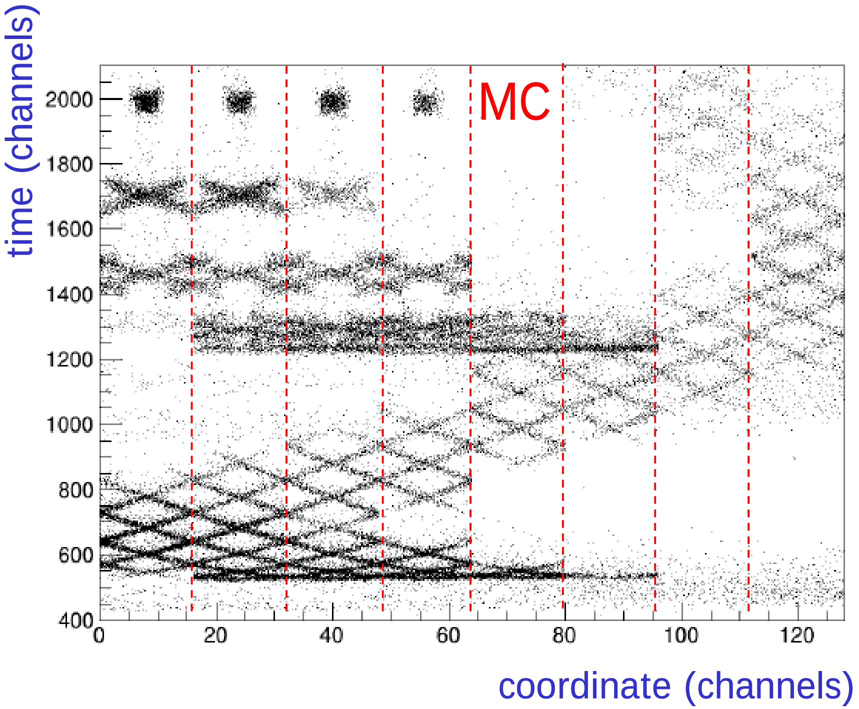
Time distribution of signals recorded by one of the PMT channels: different for π and K (~shifted in time)

TOP beam test vs MC

Pattern in the coordinate-time space (‘ring’): eight replicas of the time vs channel coordinate pattern, one of each pixel row.

Very good agreement between beam test data and MC simulated patterns.

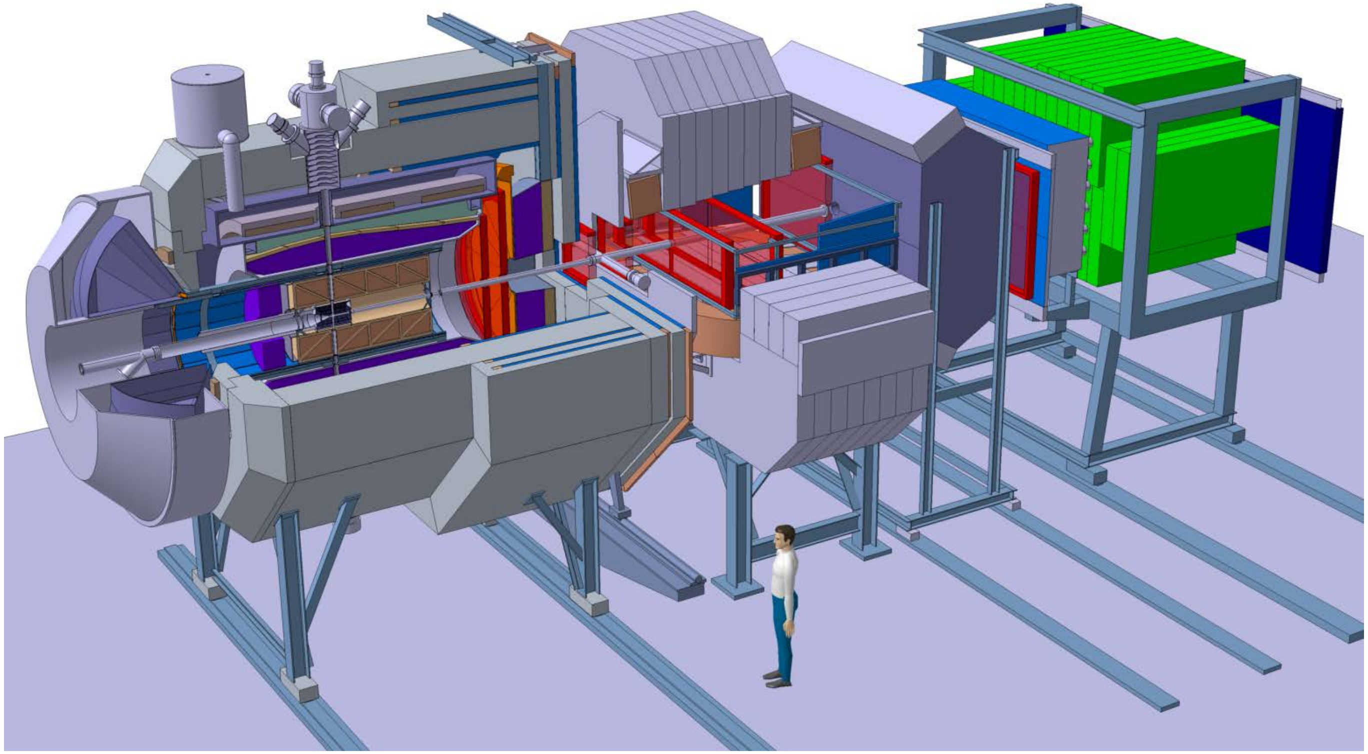




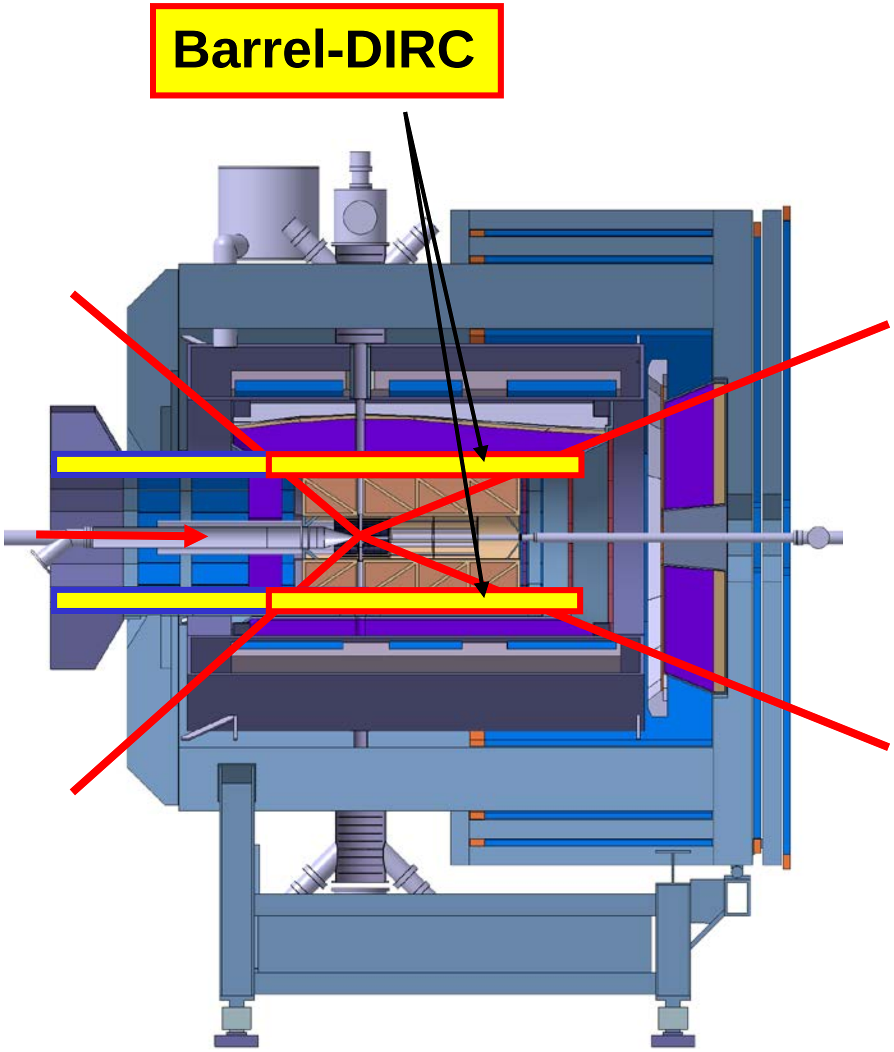
Recorded by the CFD-based read-out.

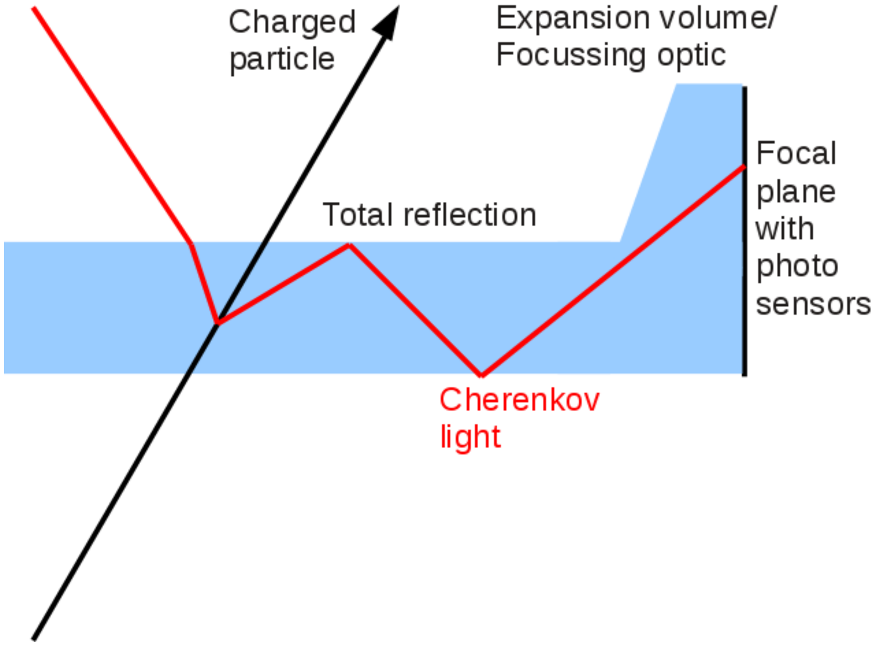
DIRC counters for PANDA (FAIR, GSI)

Two DIRC-like counters are under preparation for the PANDA experiment



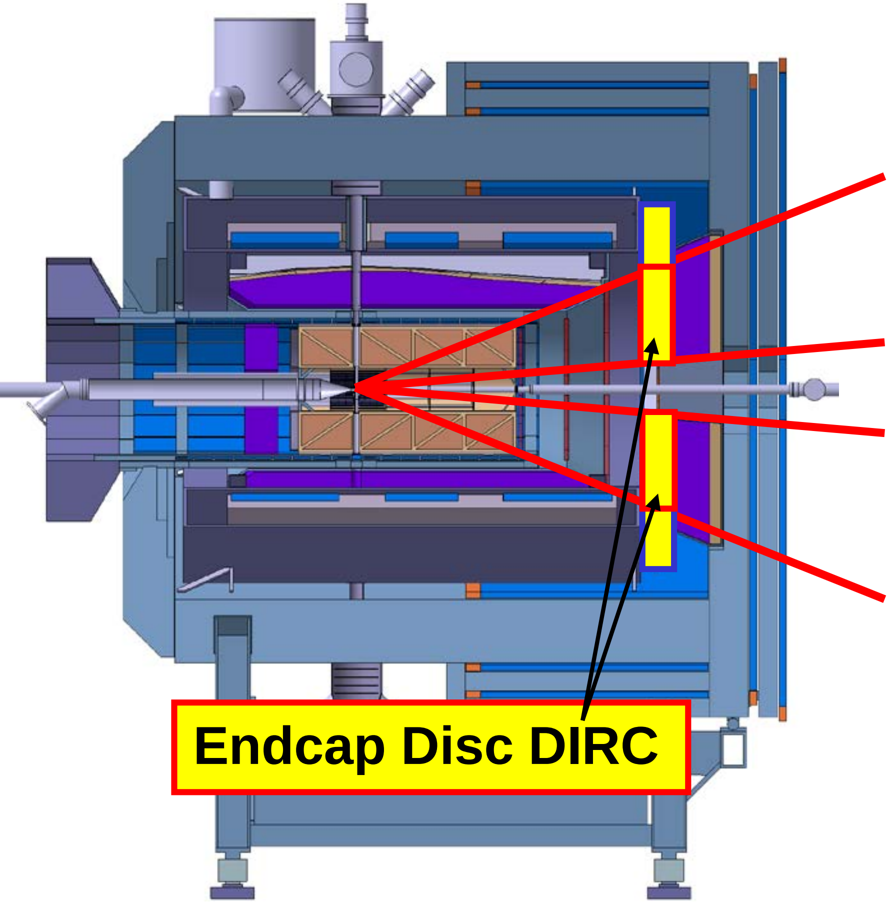
PANDA barrel DIRC

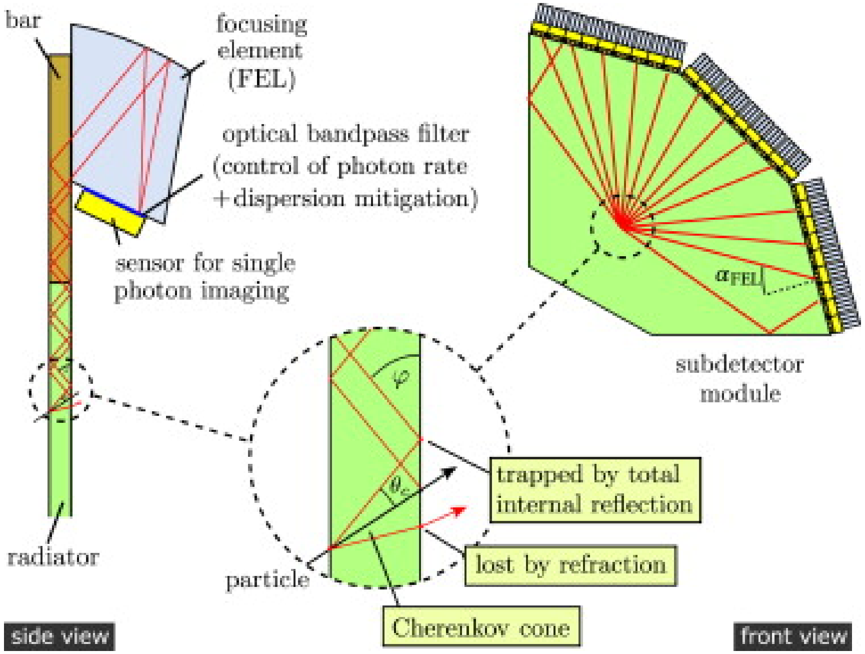




→ Talk by J. Schwiening

PANDA endcap DIRC

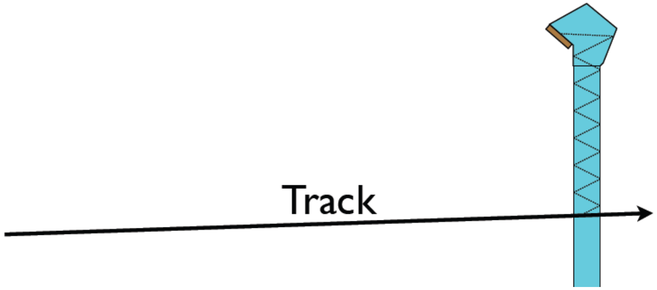


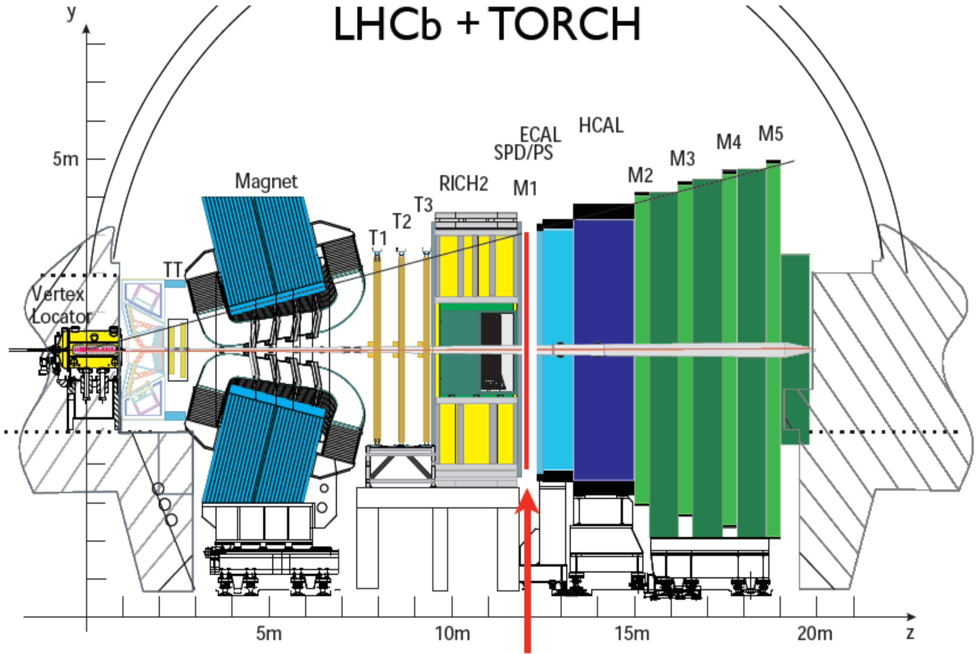


→ Talk by J. Schwiening

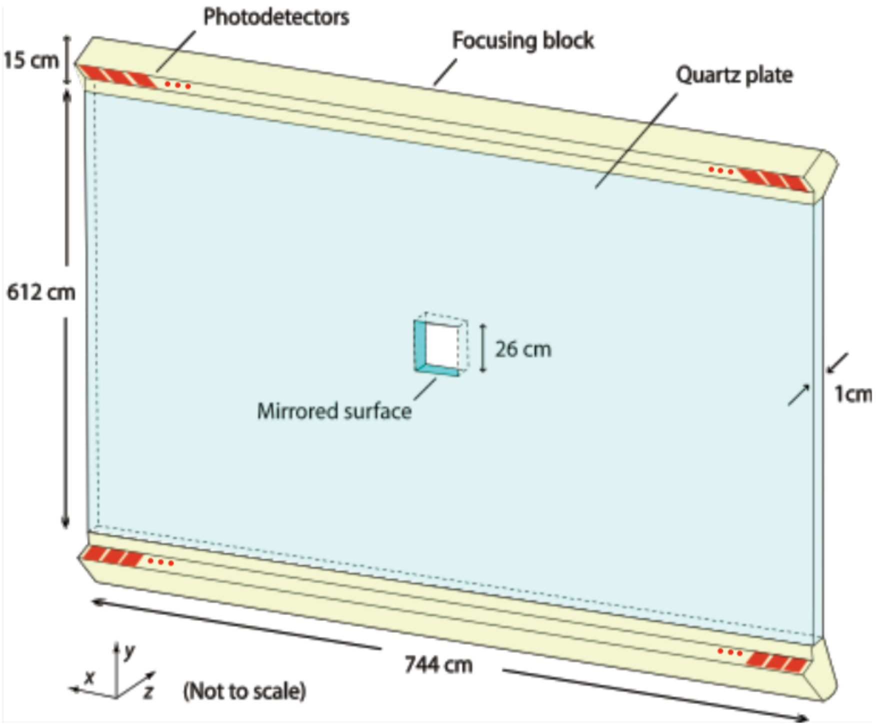
LHCb PID upgrade: TORCH

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





1cm-thick quartz plate at z=12m



Sides are instrumented too (not shown)

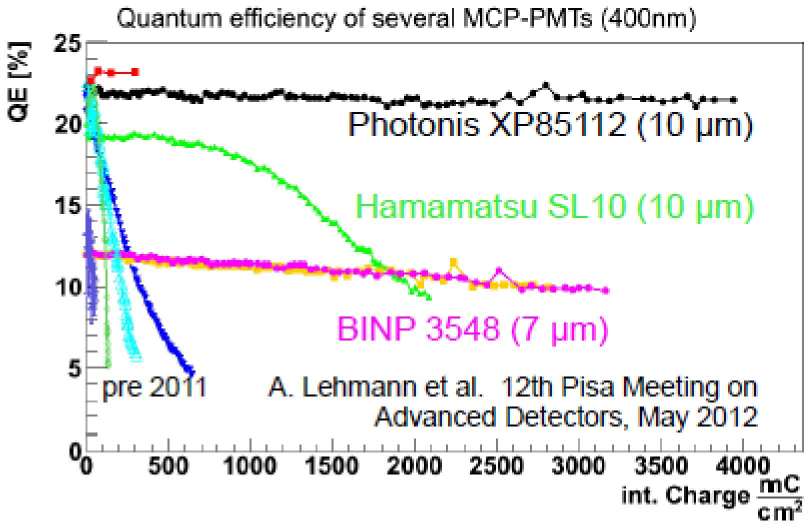
→ talk on photosensor R+D by P. Kapetanopoulos

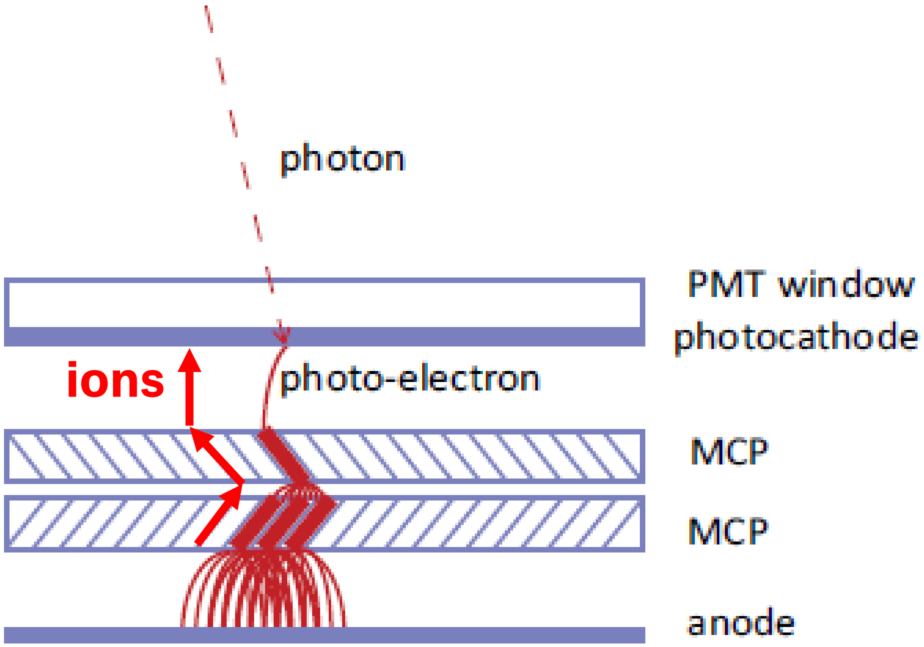
MCP PMTs ageing

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

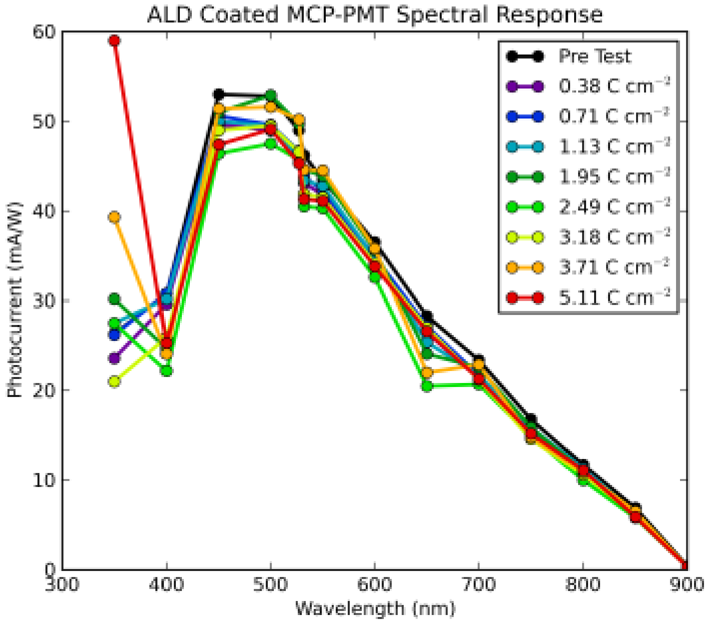
Cures:

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





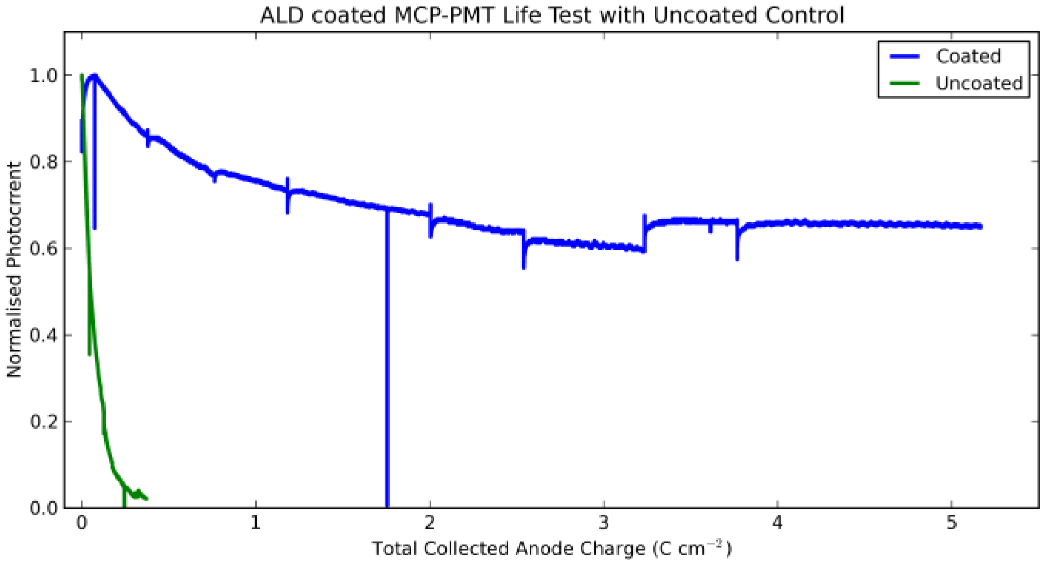
MCP PMTs ageing, cure

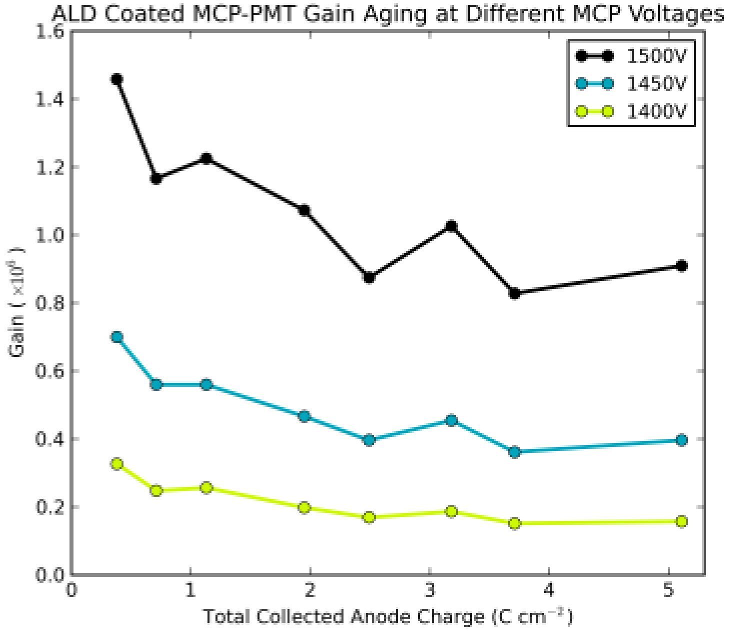


Photek, ALD deposition

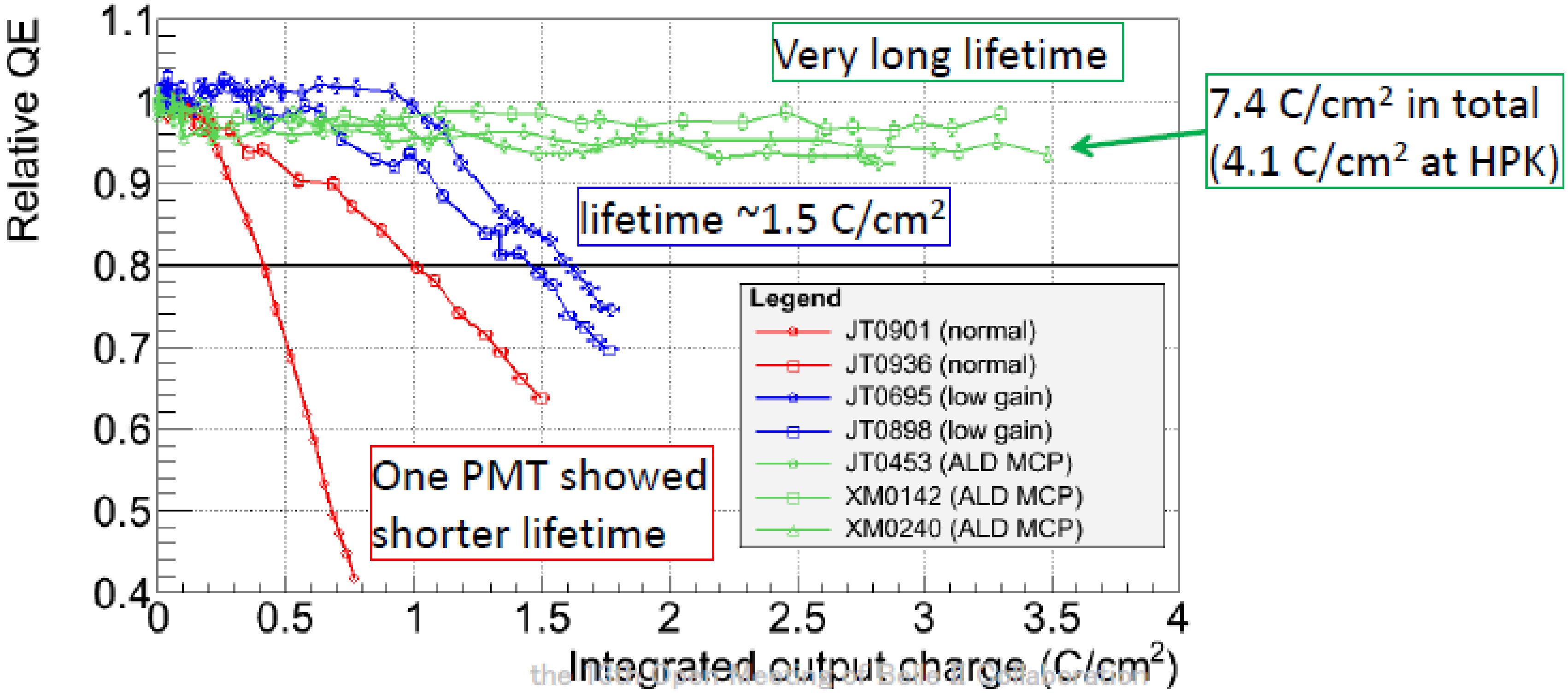
No drop in QE after 5 C/cm^2

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





MCP PMTs ageing, cure



Very long lifetime

7.4 C/cm² in total
(4.1 C/cm² at HPK)

lifetime ~1.5 C/cm²

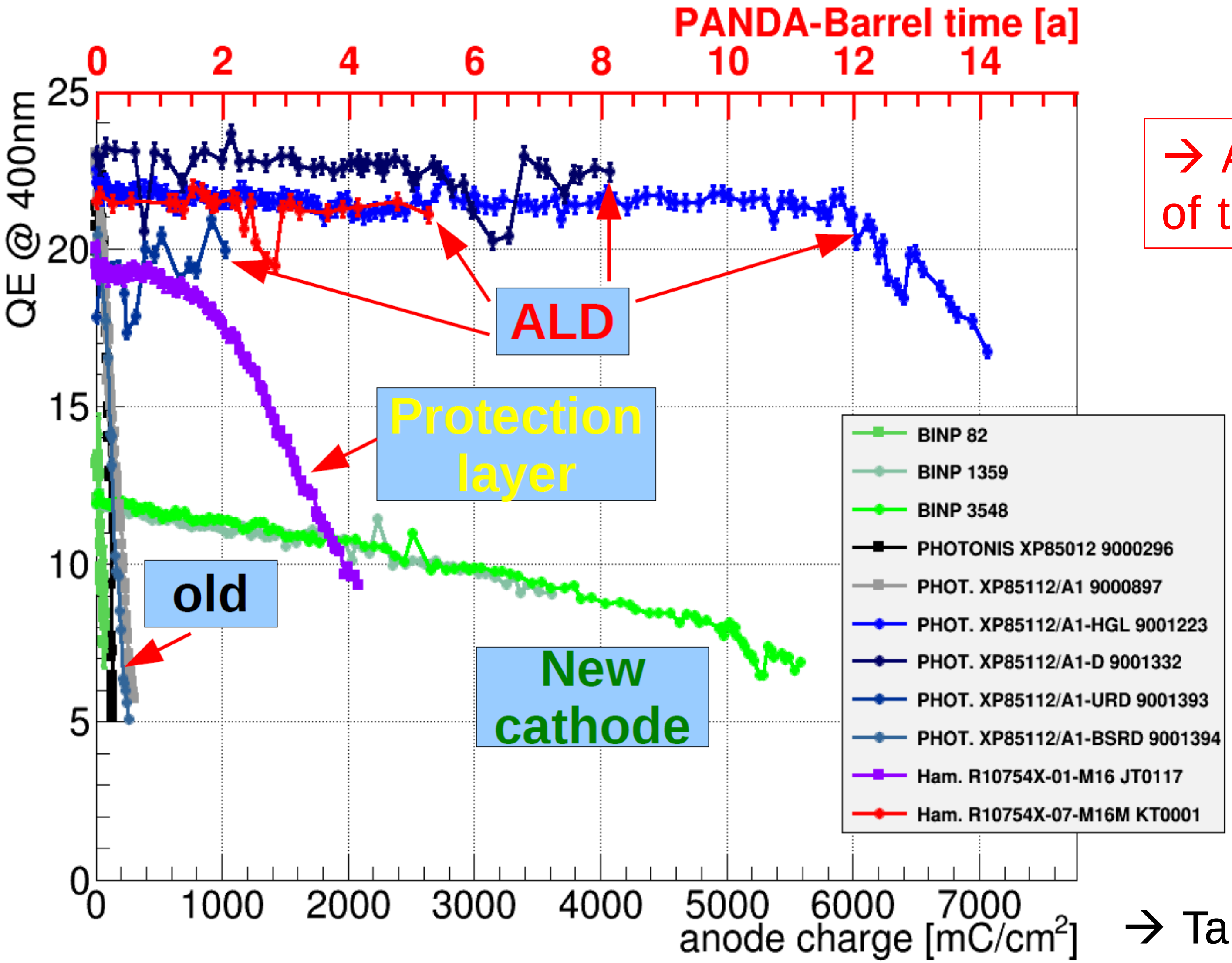
One PMT showed
shorter lifetime

Hamamatsu, ALD deposition

No drop in QE after 7.4 C/cm^2

Aging study by A. Lehmann et al (for the Panda DIRC)

Lifetime of various MCP-PMTs (400nm)



ALD

Protection layer

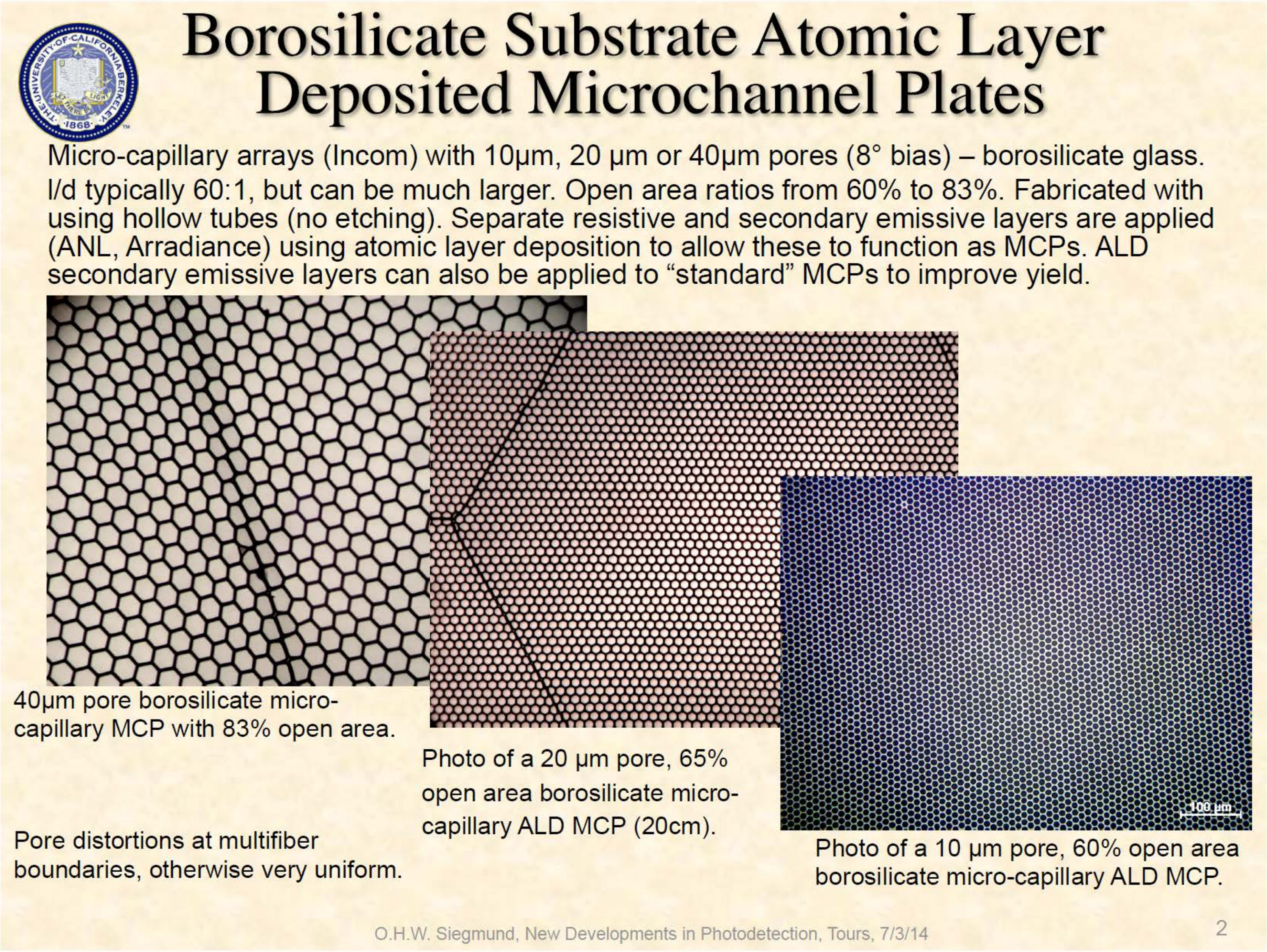
old

New cathode

→ ALD is the name of the game

→ Talk by J. Schwiening

ALD for MCP PMTs: born in Chicago area.
ALD can turn a borosilicate glass substrate into an MCP



Borosilicate Substrate Atomic Layer Deposited Microchannel Plates

Micro-capillary arrays (Incom) with 10µm, 20 µm or 40µm pores (8° bias) – borosilicate glass. l/d typically 60:1, but can be much larger. Open area ratios from 60% to 83%. Fabricated with using hollow tubes (no etching). Separate resistive and secondary emissive layers are applied (ANL, Arradiance) using atomic layer deposition to allow these to function as MCPs. ALD secondary emissive layers can also be applied to "standard" MCPs to improve yield.

40µm pore borosilicate micro-capillary MCP with 83% open area.

Pore distortions at multifiber boundaries, otherwise very uniform.

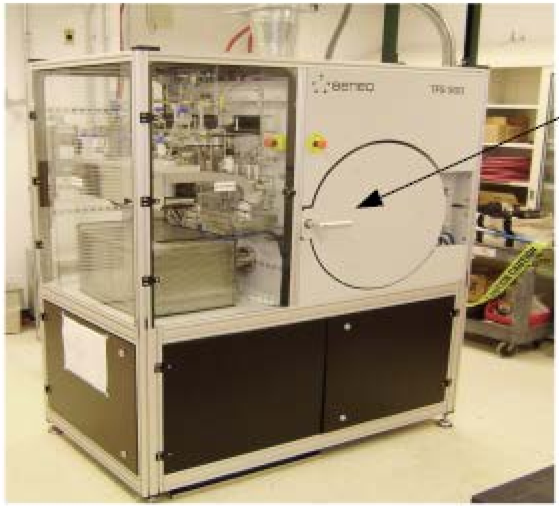
Photo of a 20 µm pore, 65% open area borosilicate micro-capillary ALD MCP (20cm).

Photo of a 10 µm pore, 60% open area borosilicate micro-capillary ALD MCP.

O.H.W. Siegmund, New Developments in Photodetection, Tours, 7/3/14

LAPPD – Large Area Picosecond Photon Detector

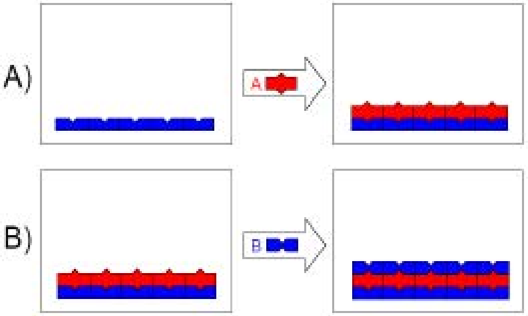
MCP by Atomic Layer Deposition (ALD)

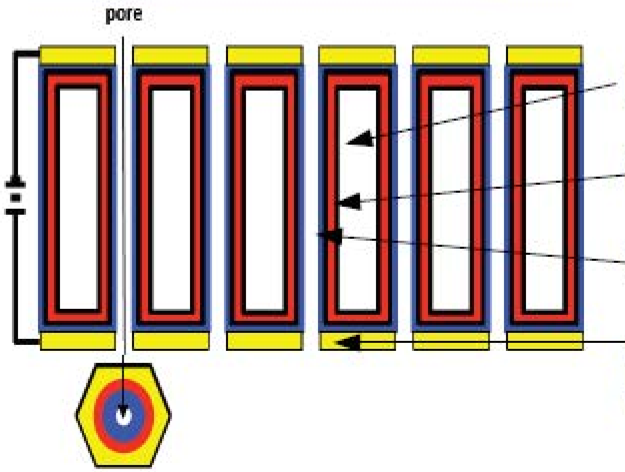


Beneq reactor for ALD

@Argonne National Laboratory

A.Mane, J.Elam



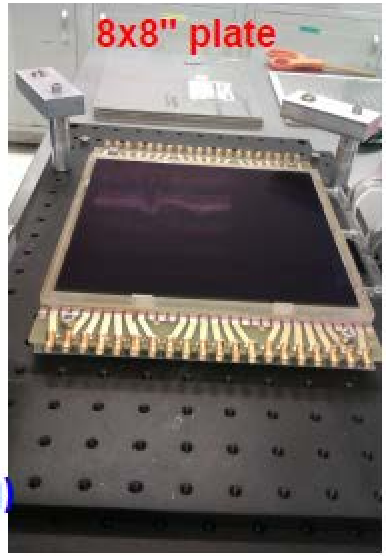


Porous glass

Resistive coating ~100nm (ALD)

Emissive coating ~ 20nm (ALD)

Conductive coating
(thermal evaporation or sputtering)



Key Issues for ALD Borosilicate MCPs

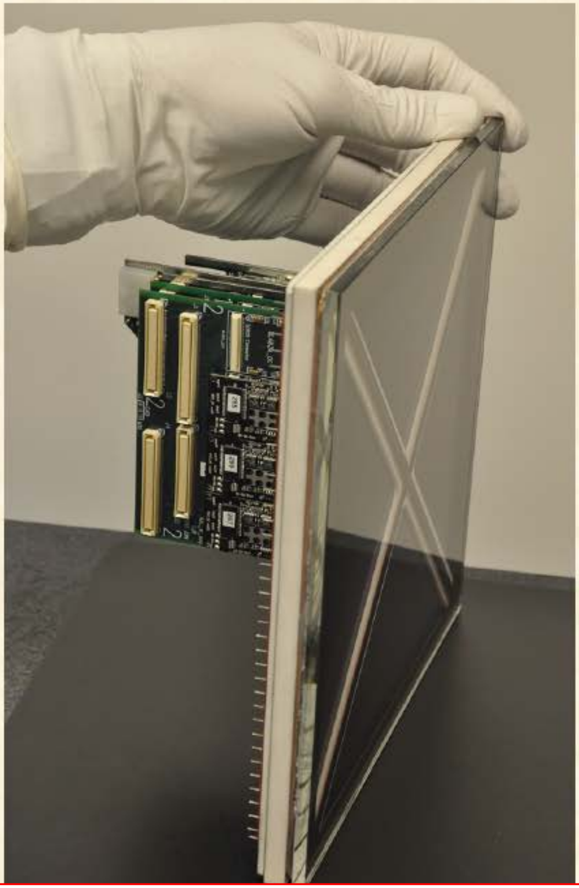
Current MCP devices have specific limitations due to the nature of the structure and processing of conventional MCPs. Atomic layer deposited (ALD) MCPs made on borosilicate substrates provide a unique way to improve on current devices or make new device types.

Borosilicate substrate:-	Strong & clean compared with standard MCP glass
Large areas can be made	large detectors for security applications
Larger open area ratios	– higher photon /electron/ion detection efficiency
Low/no radioactive content	lower background for security applications
Low outgassing	longer device lifetimes, shorter process/fab times
High temperatures	deposit materials & cathodes not otherwise possible

Atomic layer deposition:-	Decoupled from substrate, many materials possible
Resistance tailored to suit	can make a wider range than standard MCPs allowing high local counting rates
High secondary emissive layer	better pulse height at low gain, better gain
Stable secondary emissive layer	faster gain burn-in, or none needed – very long lifetime & durability – compatibility with alkali cathodes

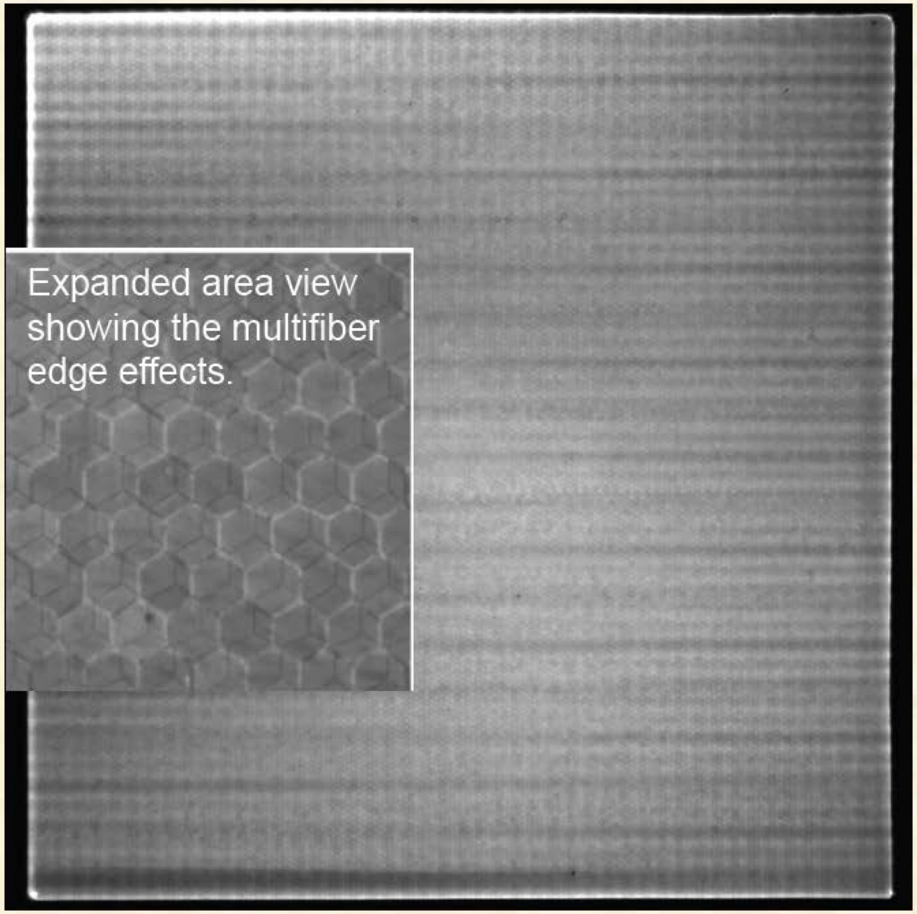
20cm ALD-MCP & Sealed Tube Development

LAPPD collaboration development of 20cm ALD MCPs and sealed tube with bialkali cathode and stripline anode for 2D imaging and <10ps timing.



Also see Incom poster.

First tube did not seal, making new tubes this summer

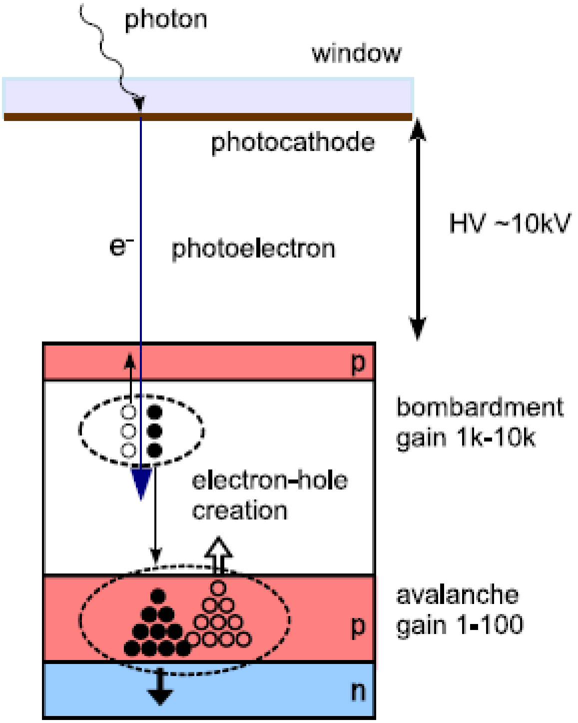


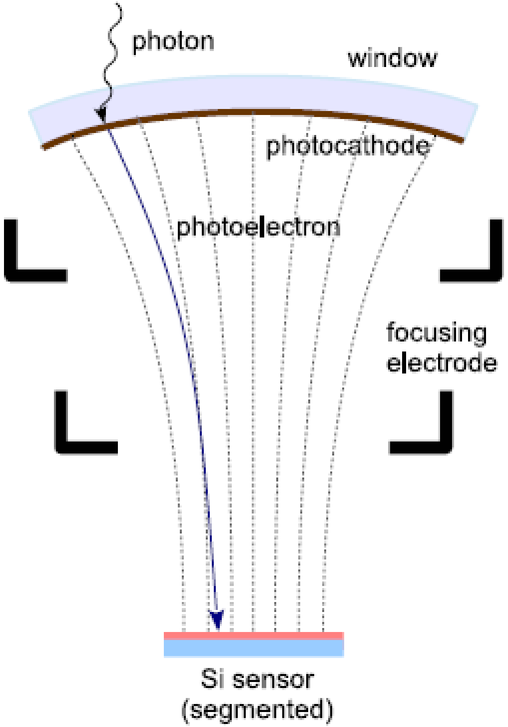
Expanded area view showing the multifiber edge effects.

20cm, 20µm pore, Al_2O_3 SEY, MCP pair image with 185nm non-uniform UV illumination. Cross delay line photon counting anode. Image striping is due to the anode period/charge cloud size modulation.

→ Extremely important development, many talks in this workshop

Hybrid photodetectors

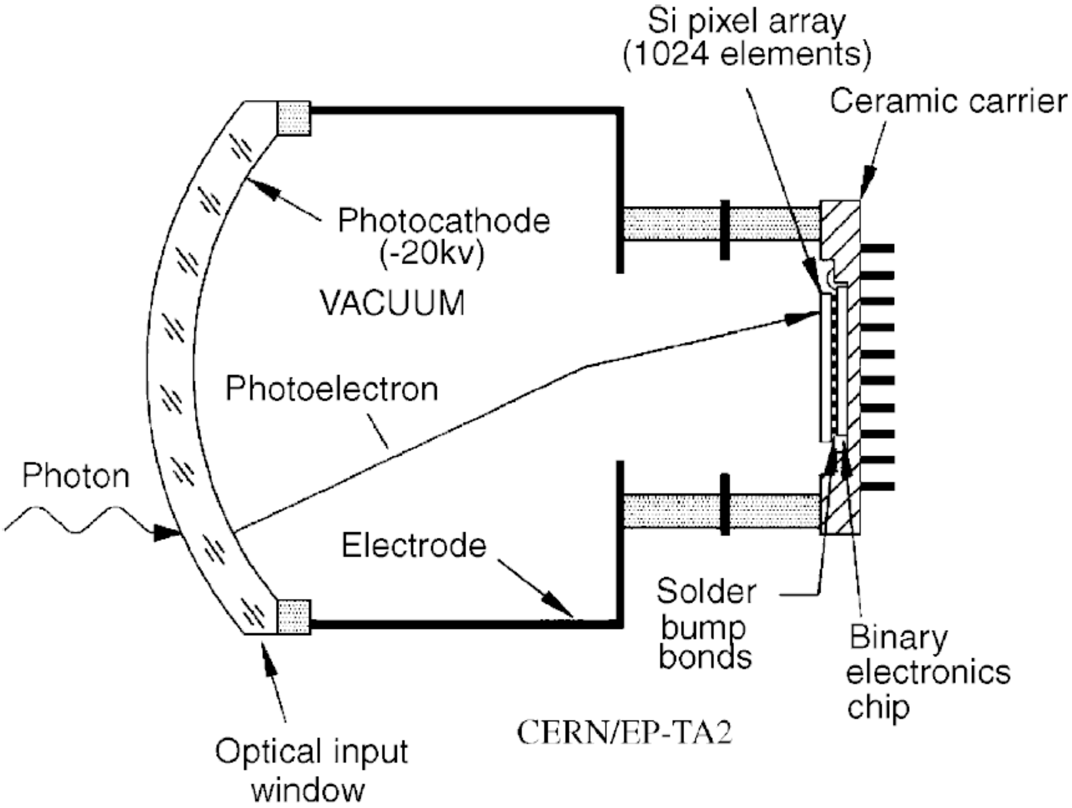




Hybrid photodetector: LHCb RICHes

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.



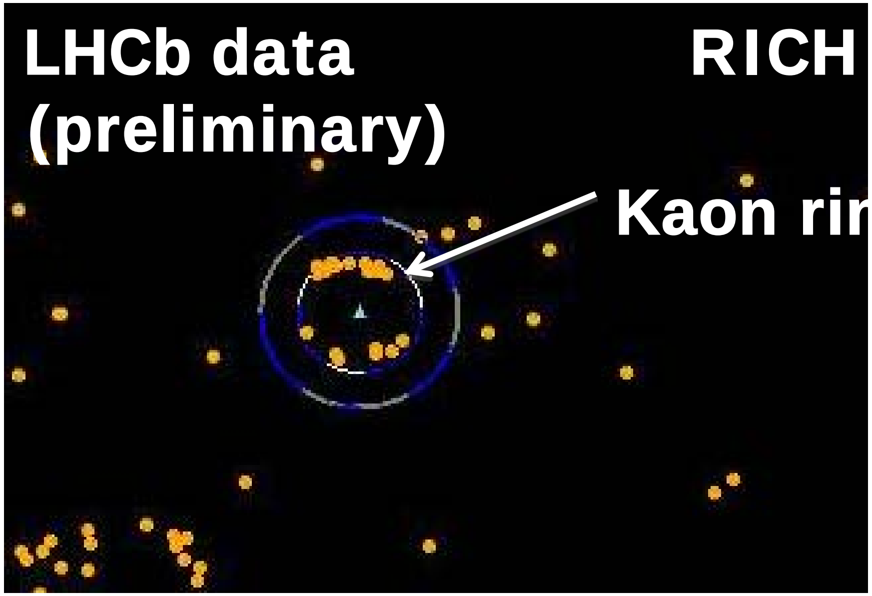
NIM A553 (2005) 333

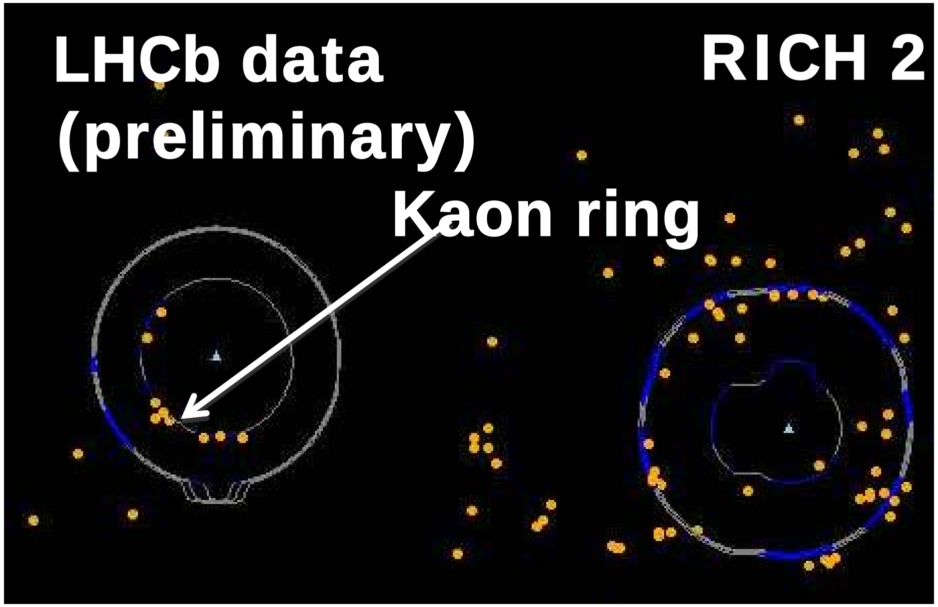
LHCb Event Display

RICH1

Early data, Nov/Dec 2009
LHC beams $\sqrt{s} = 900$ GeV

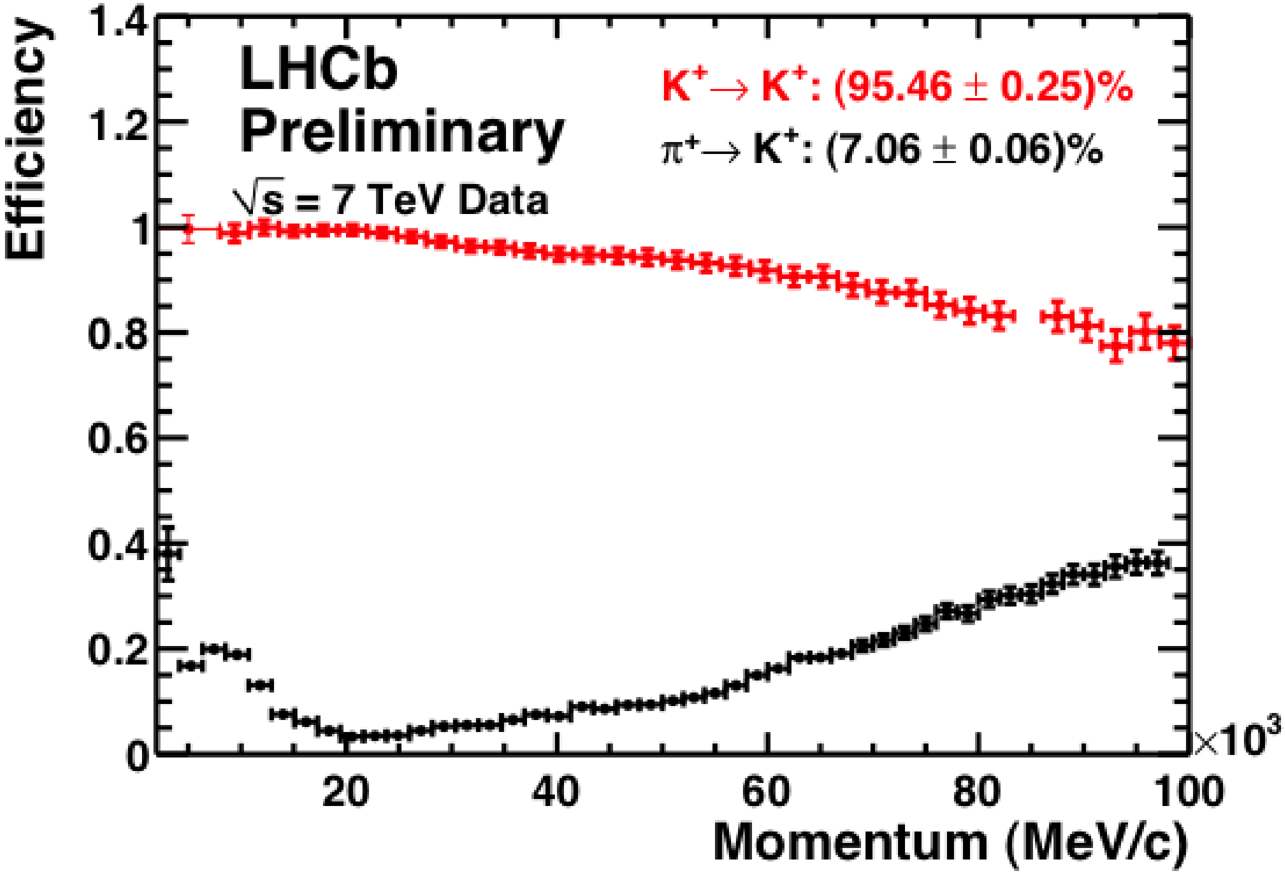
RICH2

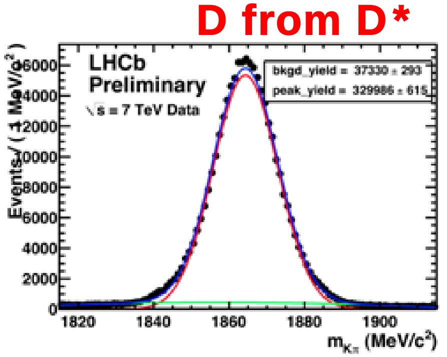


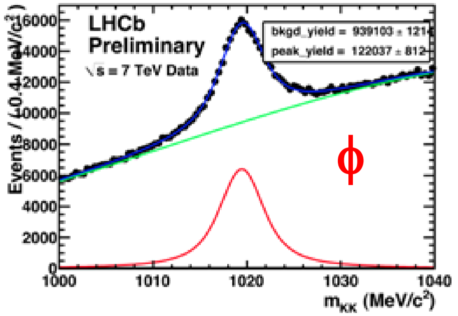


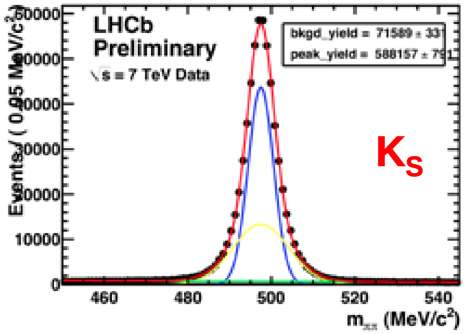
- Orange points → photon hits
- Continuous lines → expected distribution for each particle hypothesis

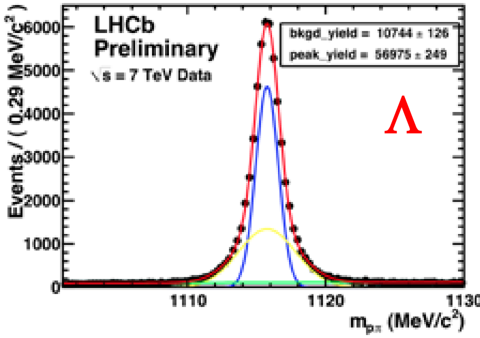
LHCb RICHes: performance







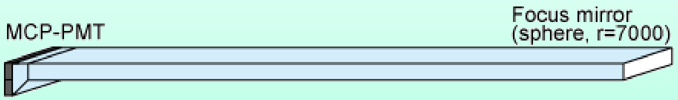




Efficiency and purity from data →
excellent agreement with MC

Belle II Cherenkov detectors

Barrel PID: Time of Propagation Counter (TOP)



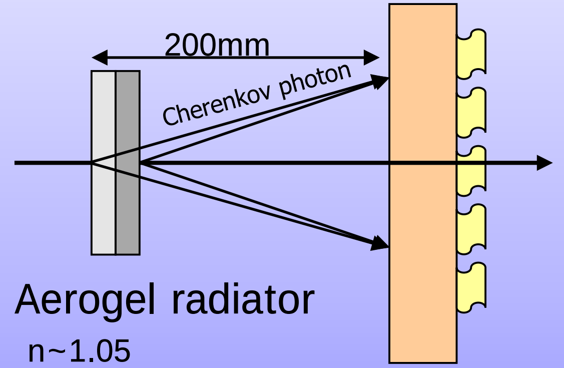
Quartz radiator

Focusing mirror

Small expansion block

Hamamatsu MCP-PMT (measure t, x and y)

Endcap PID: Aerogel RICH (ARICH)

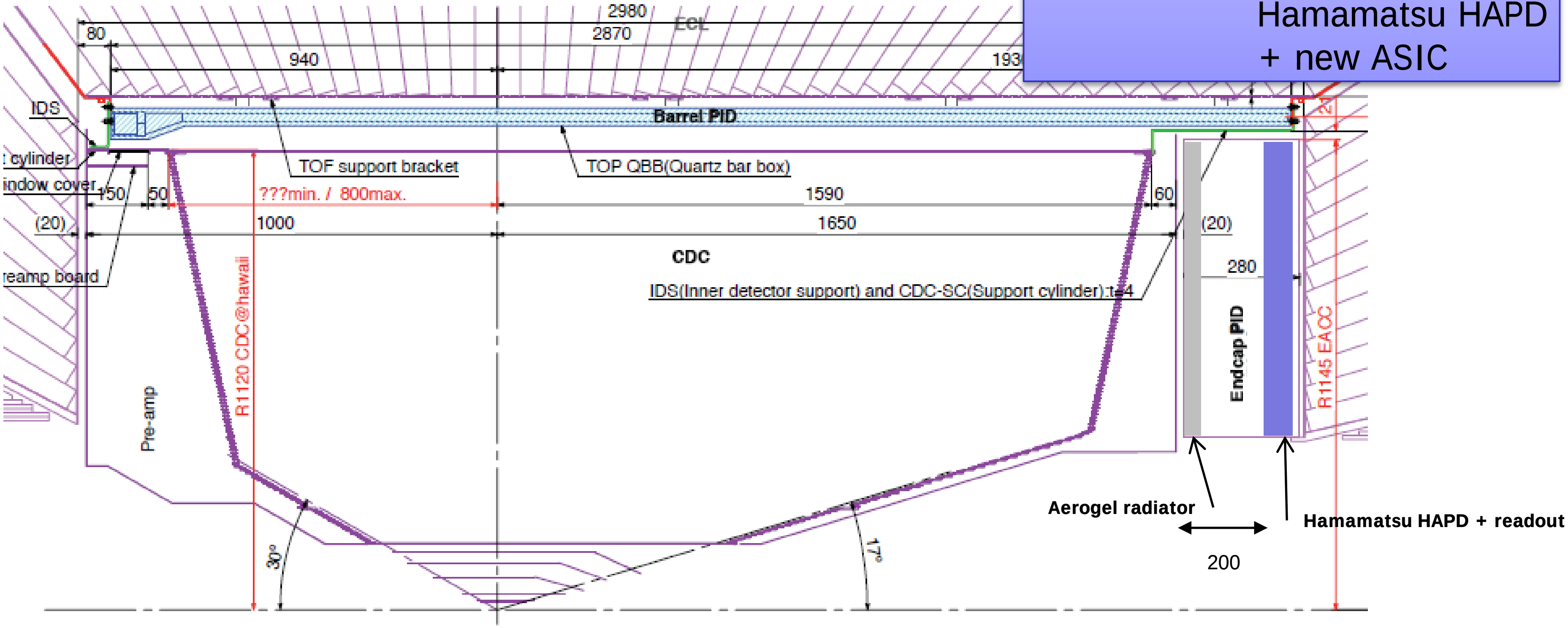


Aerogel radiator

n~1.05

Hamamatsu HAPD

+ new ASIC

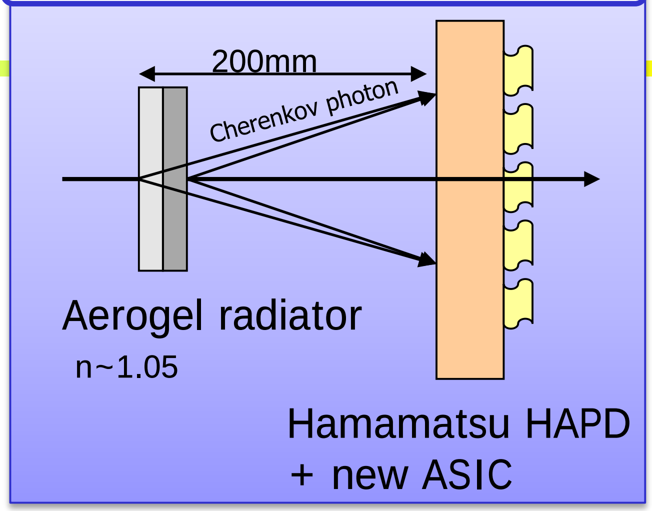


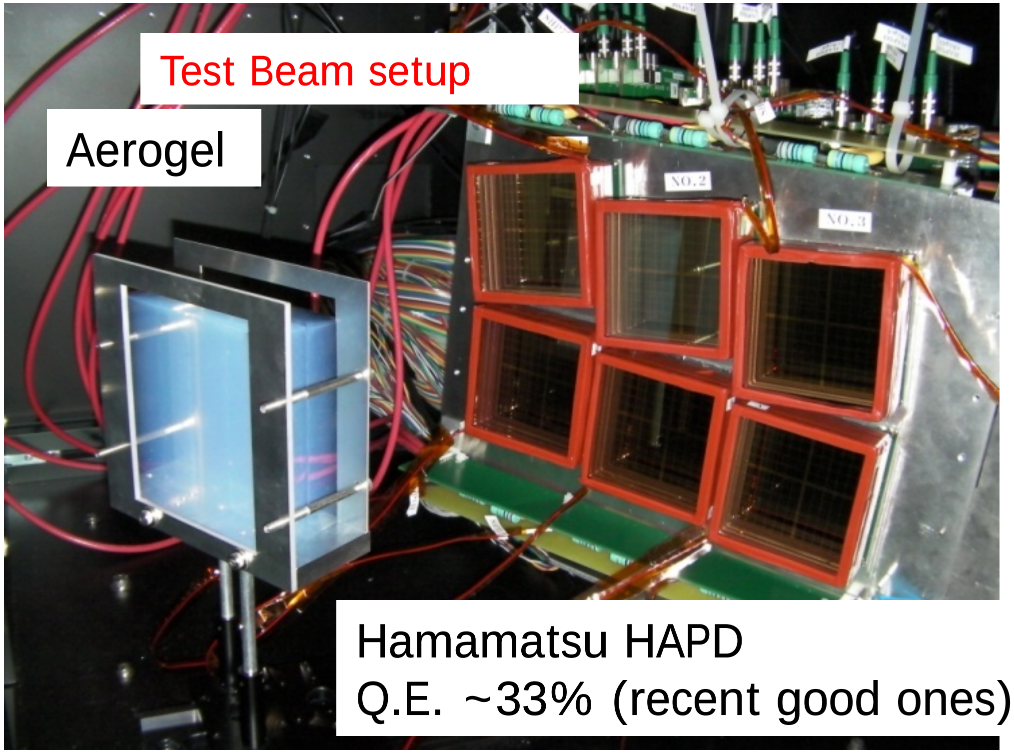
Aerogel RICH

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

Photosensor: large active area HAPD of the proximity focusing type

Endcap PID: Aerogel RICH (ARICH)

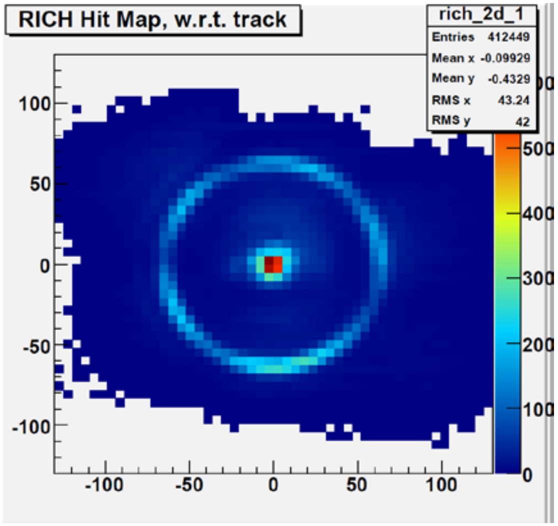



Test Beam setup

Aerogel

Hamamatsu HAPD
Q.E. ~33% (recent good ones)

Clear Cherenkov image observed



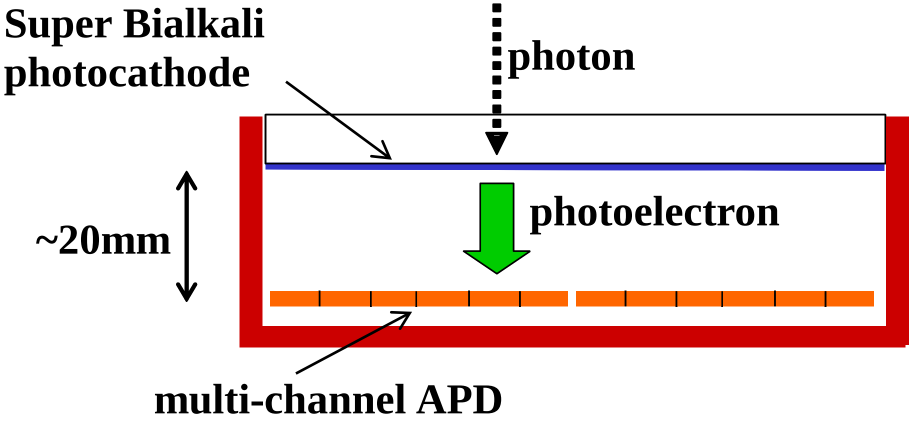
6.6 σ p/K at 4GeV/c !

→ NIM A595 (2008) 180

ARICH photon detector: HAPD

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

- 12 x12 channels (~ 5 x 5 mm^2)
- size ~ 72 mm x 72 mm
- ~ 65% effective area
- total gain > 4.5x10^4 (two steps: bombardment > 1500, avalanche > 30)
- detector capacitance ~ 80pF/ch.
- super bialkali photocatode, typical peak QE ~ 28% (> 24%)
- works in mag. field (~ perpendicular to the entrance window)



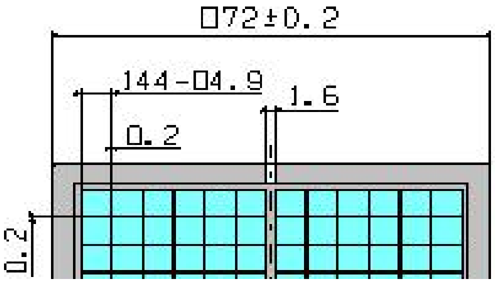
Super Bialkali photocathode

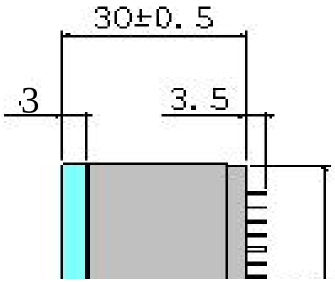
photon

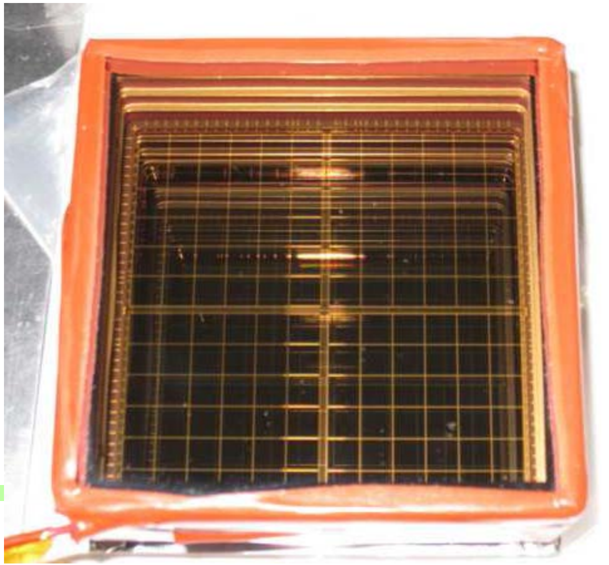
photoelectron

~20mm

multi-channel APD

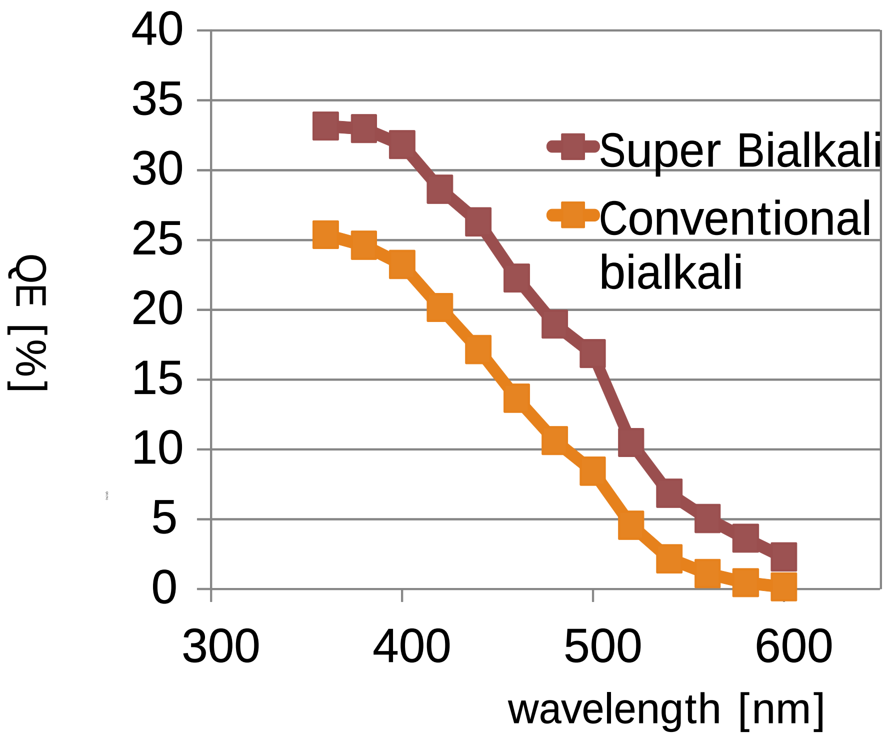


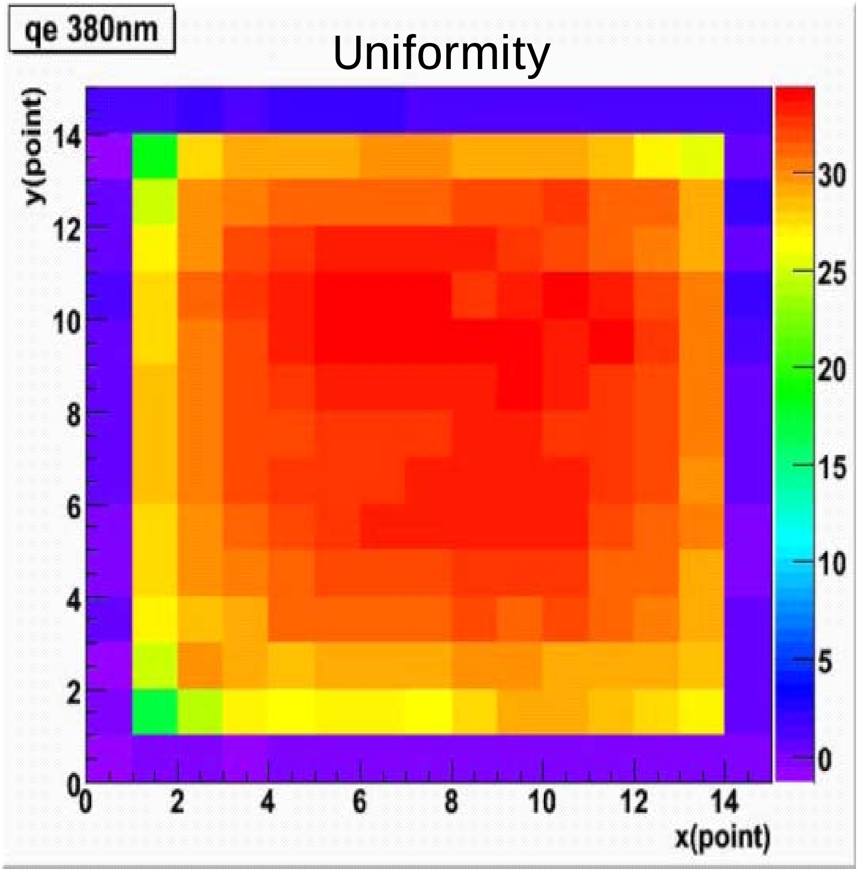




HAPD QE

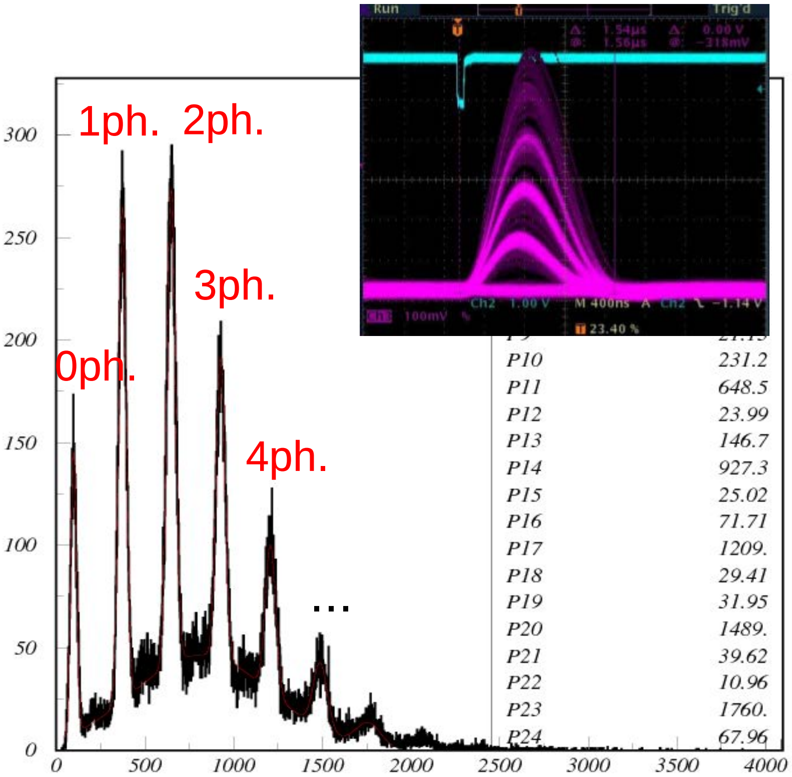
- peak QE improved by Hamamatsu with super bialkali photocathode: 25% → >30%
- typically QE is somewhat lower at the edges of the HAPD

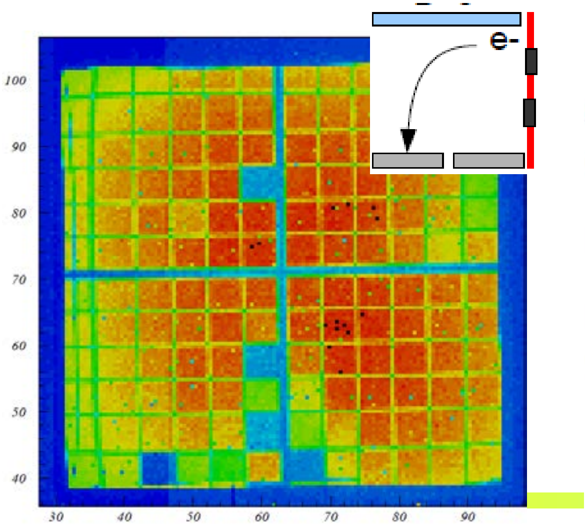


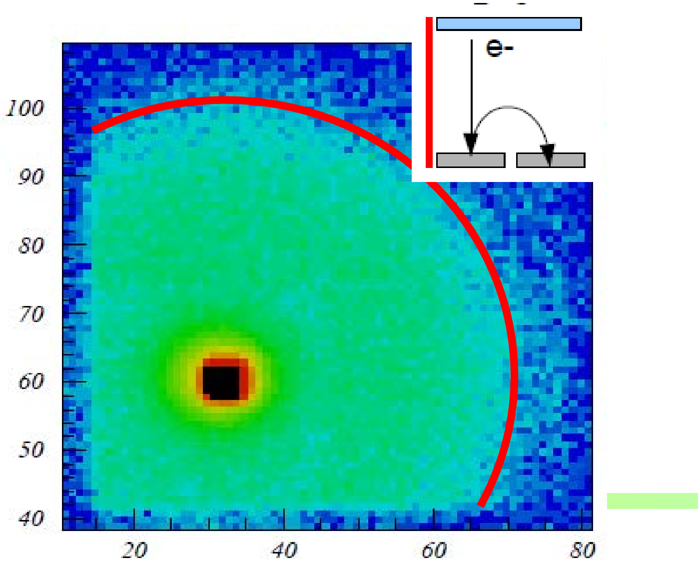


HAPD performance @ B=0T

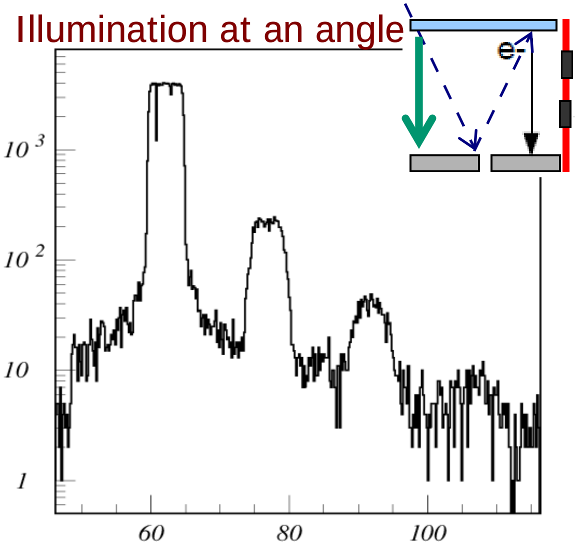
- excellent photon counting affected only by photo-electron back-scattering → high single photon counting efficiency
- sharp transition between channels
- image distortion due to a non-uniform electric field at the edges
- back-scattering induced cross-talk
- optical cross-talk by reflection from APD surface → weak echo ring



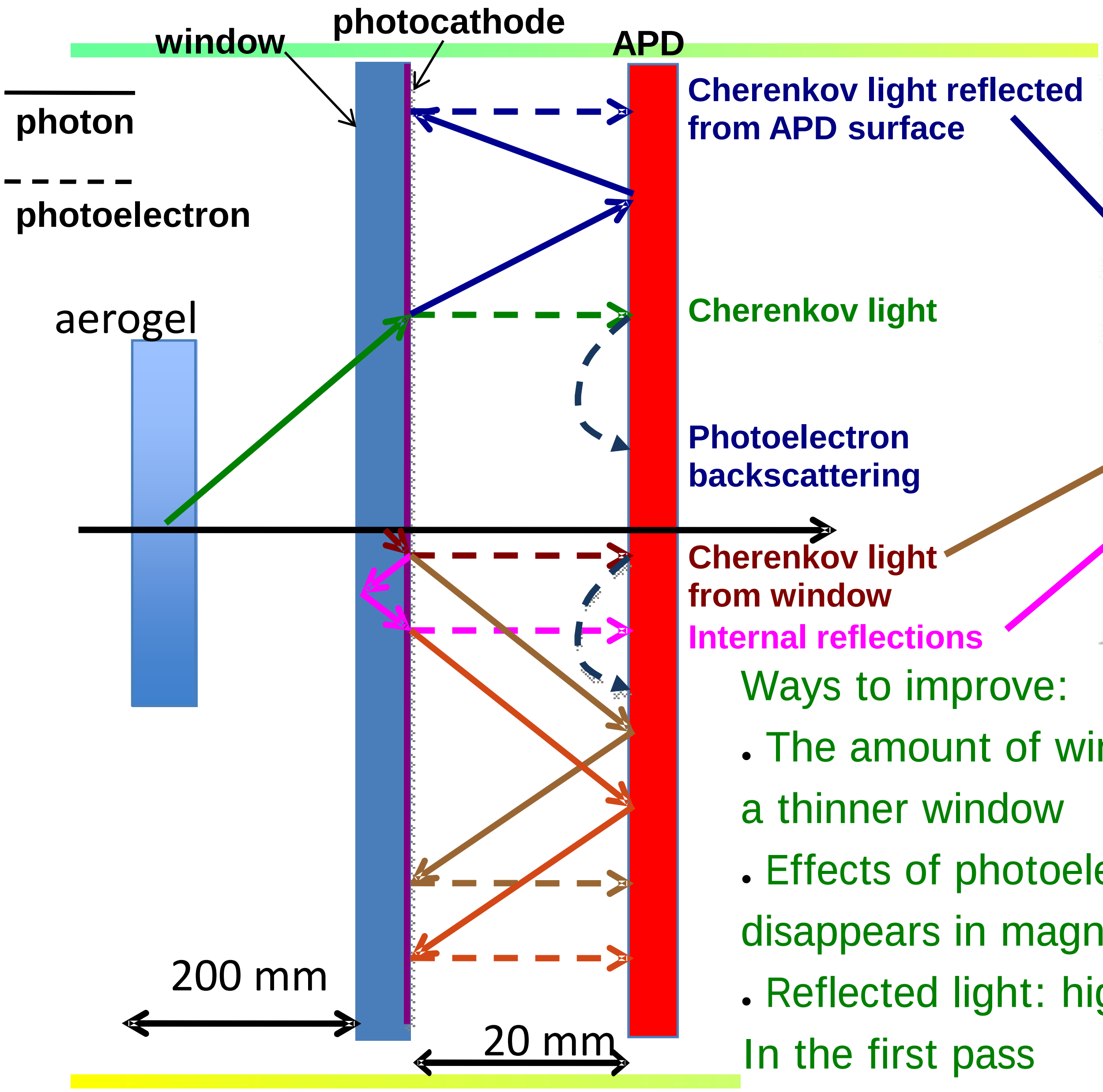




Illumination at an angle



Ring image, background contributions (B=0T)



window

photocathode

APD

photon

photoelectron

aerogel

Cherenkov light reflected from APD surface

Cherenkov light

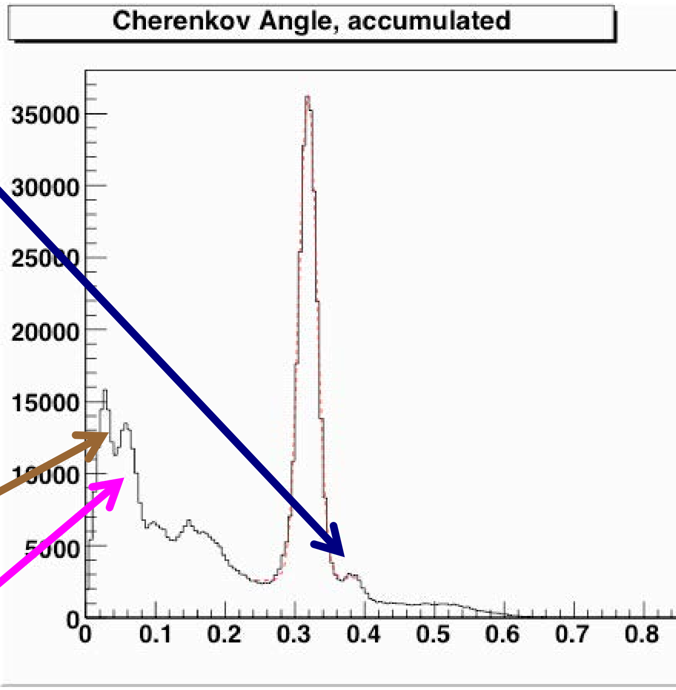
Photoelectron backscattering

Cherenkov light from window

Internal reflections

200 mm

20 mm



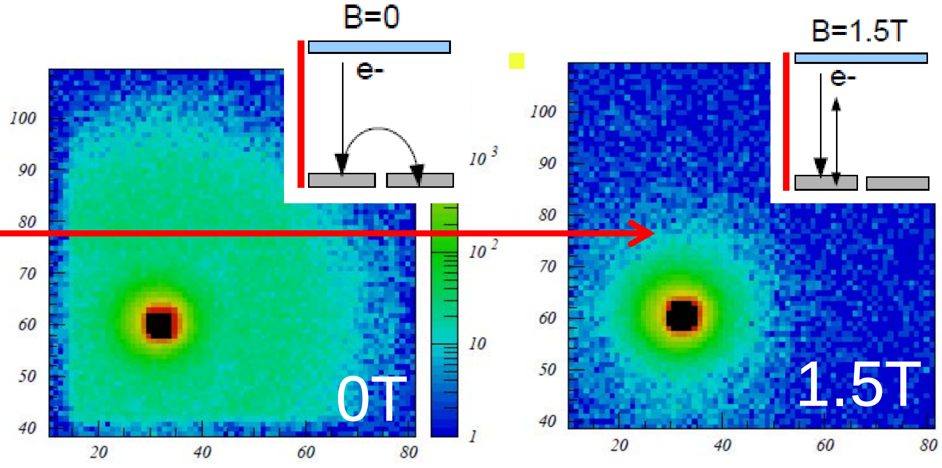
Ways to improve:

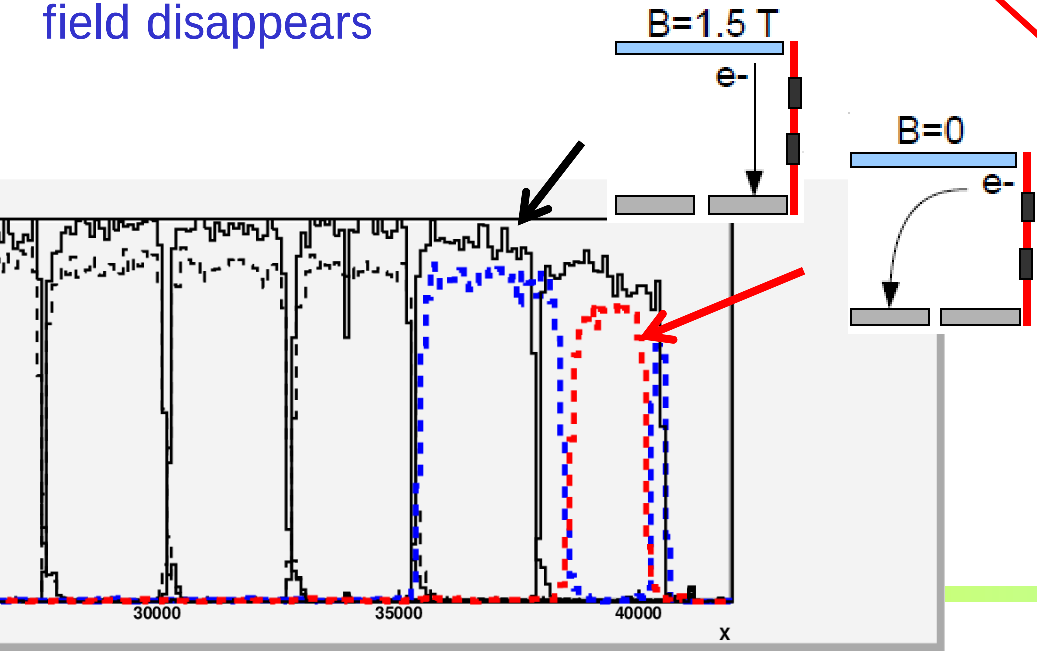
- The amount of window light can be reduced by a thinner window
- Effects of photoelectron backscattering disappears in magnetic field
- Reflected light: higher QE, more absorption In the first pass
- Anti-reflective coating?

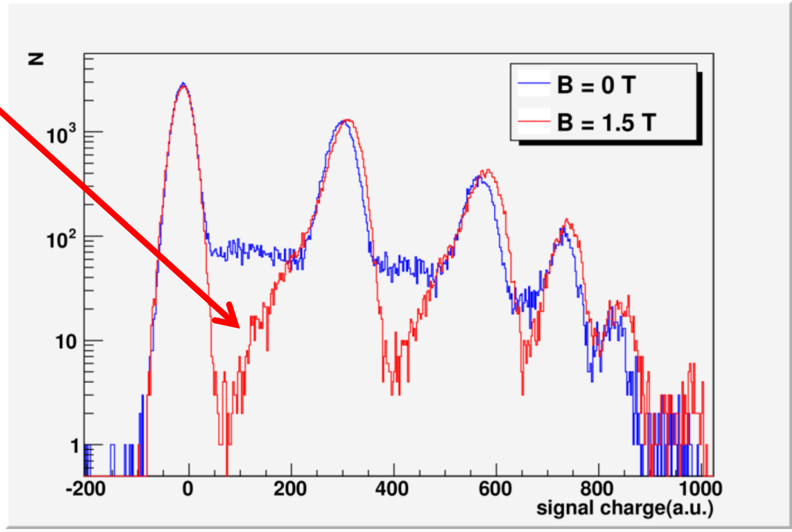
HAPD: operation in 1.5 T

Tests in 1.5 T magnetic field show improved HAPD performance:

- no photoelectron back-scattering cross-talk
- increase of detection efficiency – photoelectron energy deposited at one place
- effect of non-uniformity of electric field disappears

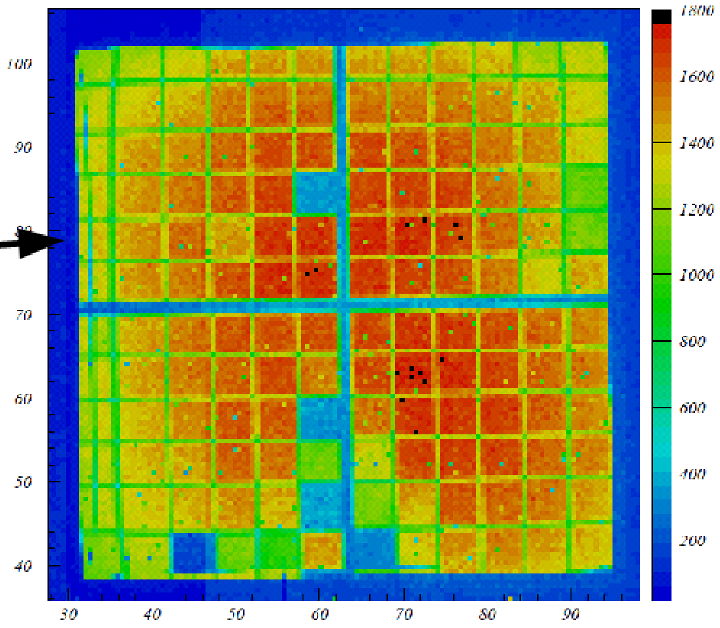




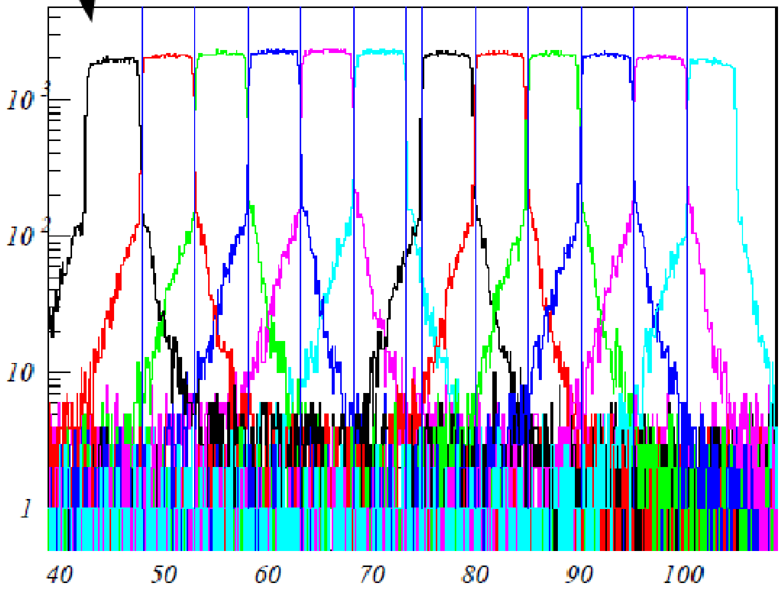


Test in magnetic field 1.5 T

- distortion of electric field lines at HAPD edge produces irregular shapes of areas covered by each channel
- in magnetic field photoelectrons circulate along the magnetic field lines and distortion disappears



magnetic field 1.5 T



no magnetic field

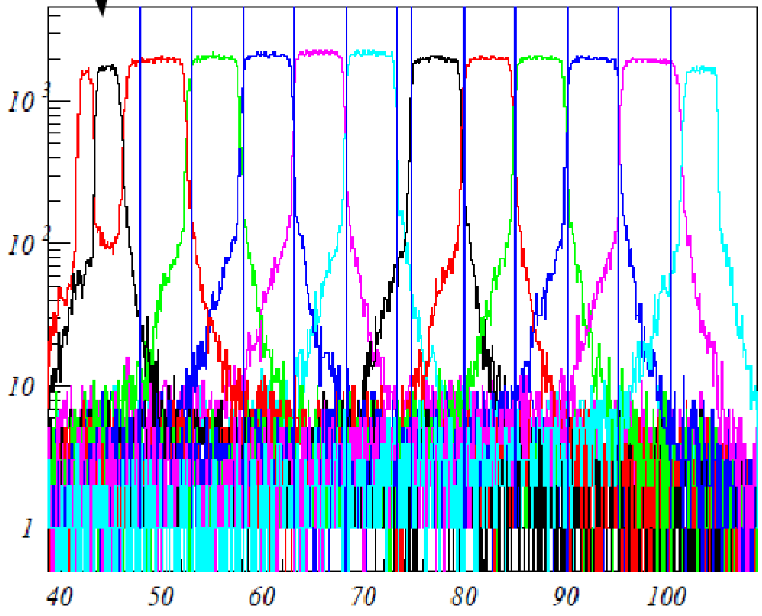
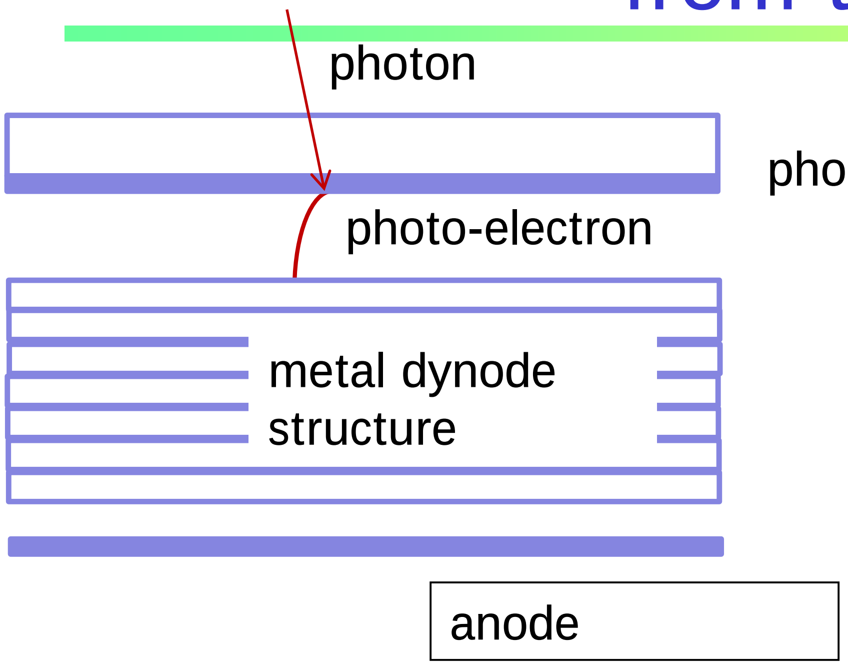


Photo-electron backscattering, light reflection from the APD etc


photon

photocathode

photo-electron

metal dynode structure

anode

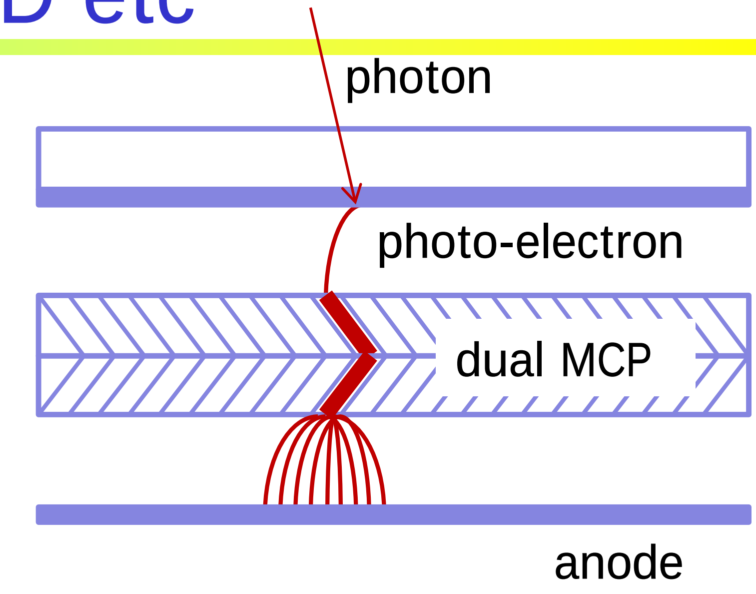
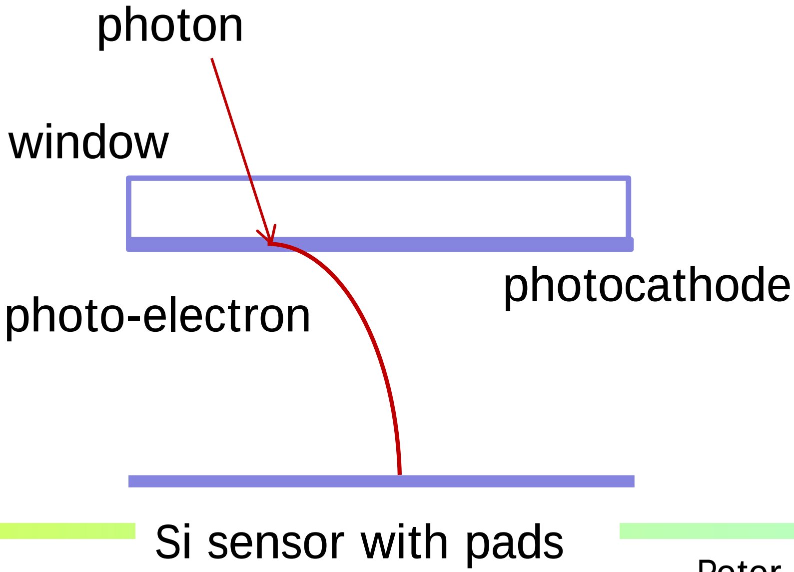

photon

photo-electron

dual MCP

anode

Similar geometries in the photo-electron step
→ A lot of similarities between prox. focusing HAPD, MCP PMTs and MA-PMTs


photon

window

photocathode

photo-electron

Si sensor with pads

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)

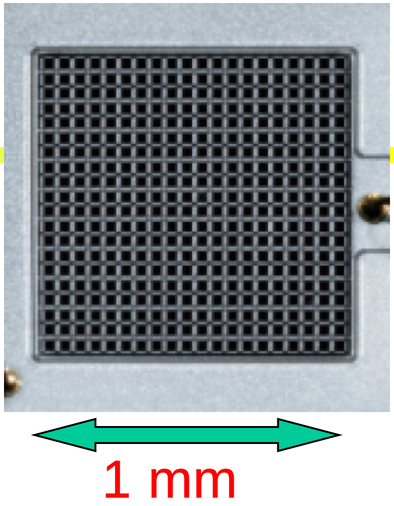
+potentially cheap (not yet…) silicon technology

+no high voltage

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

-radiation hardness

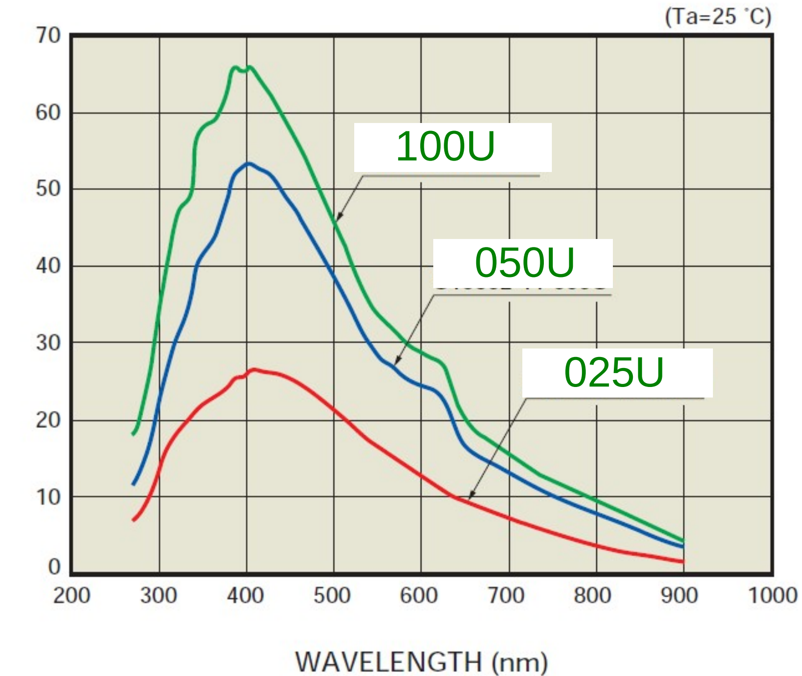
SiPMs as photon detectors?

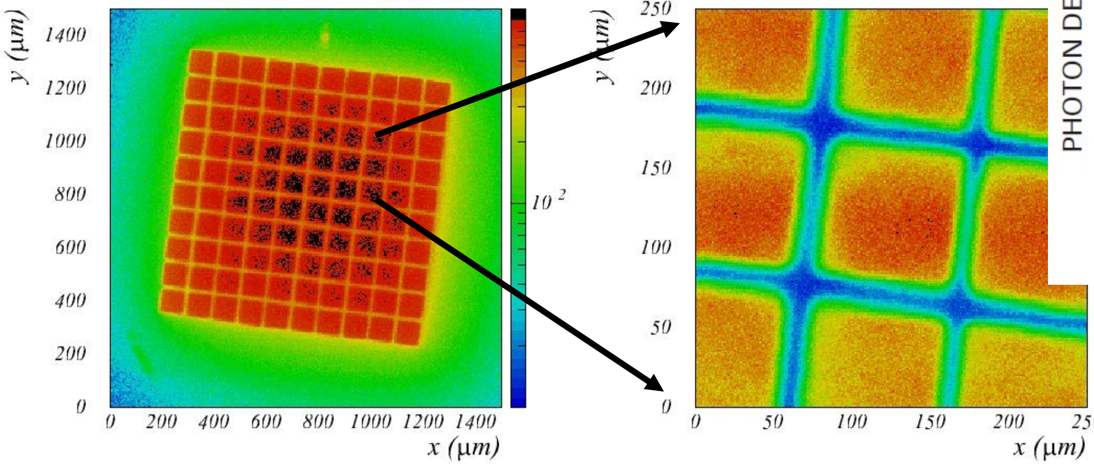


SiPM is an array of APDs operating in Geiger mode. Characteristics:

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

  PDE = QE x ε_{geiger} x ε_{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)





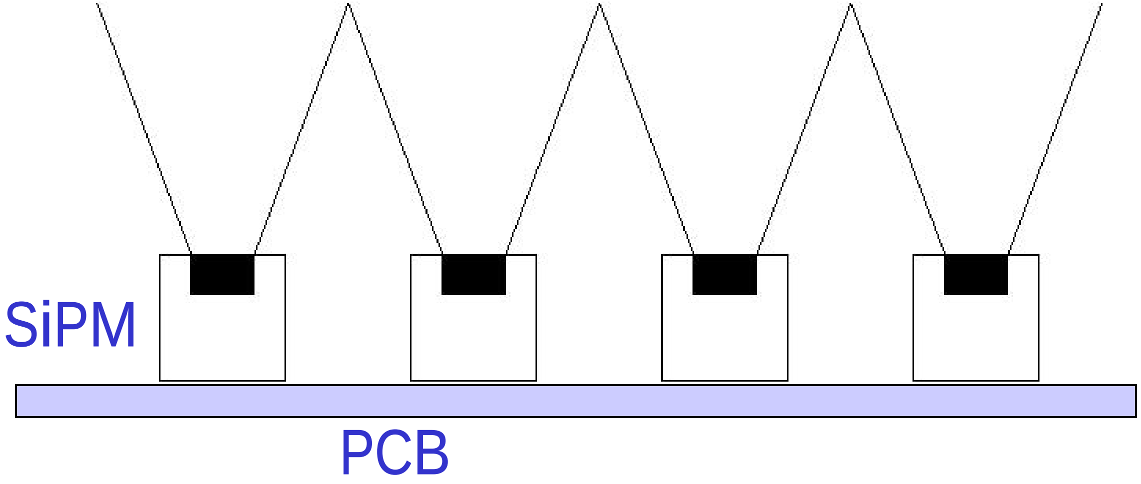
Hamamatsu MPPC: S10362-11

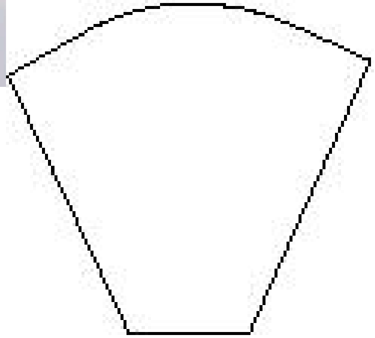
Can such a detector work?

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

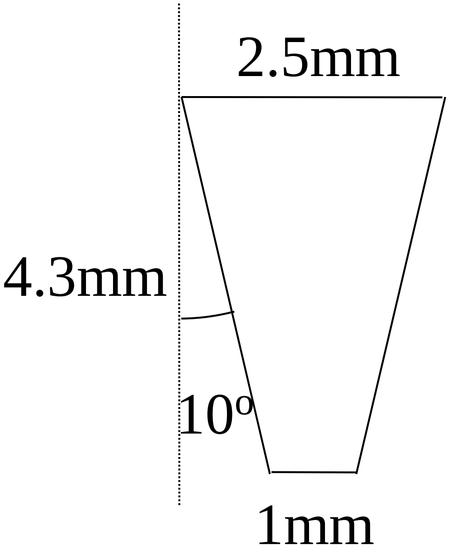
E.g. light collector with reflective walls

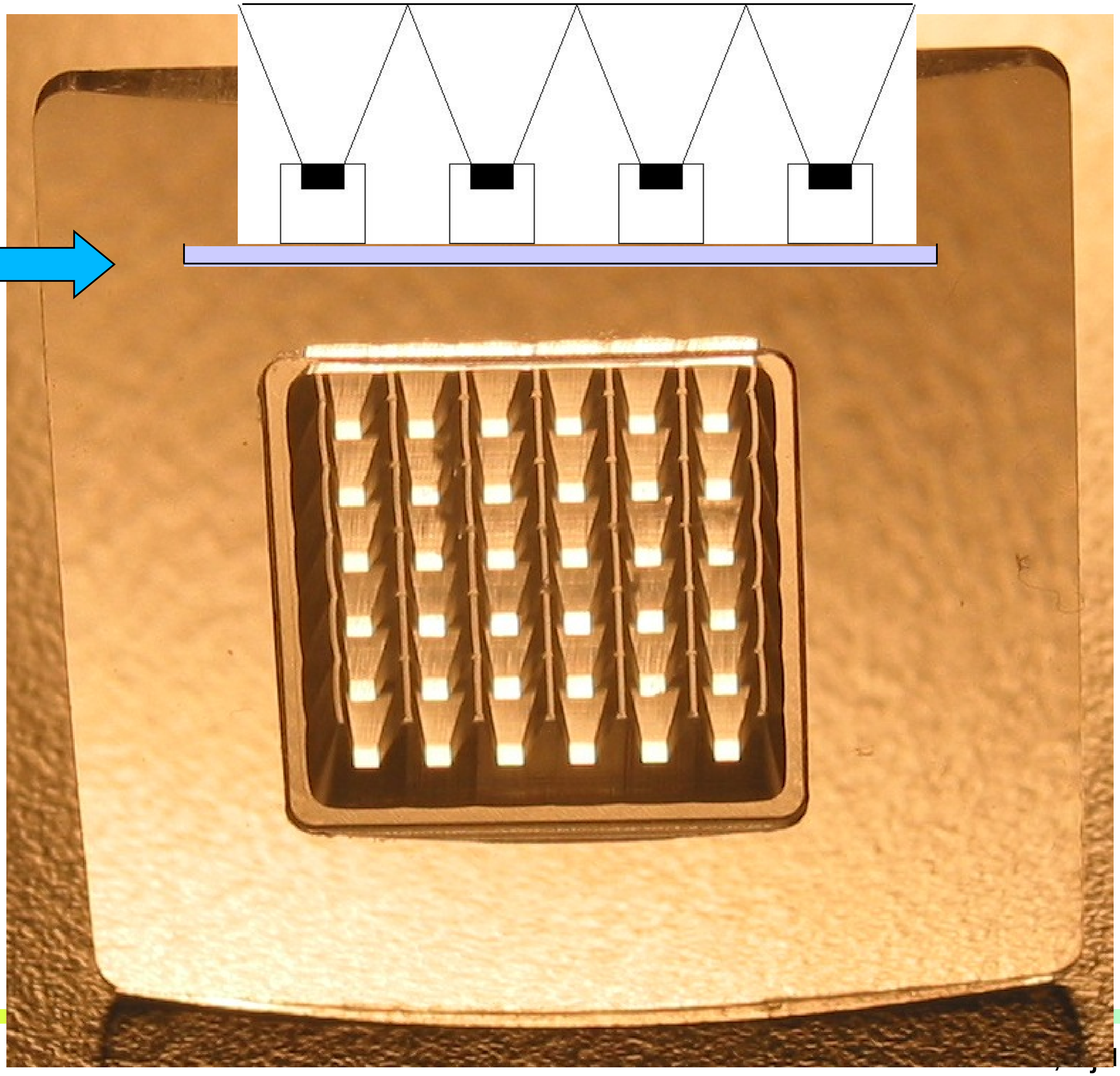


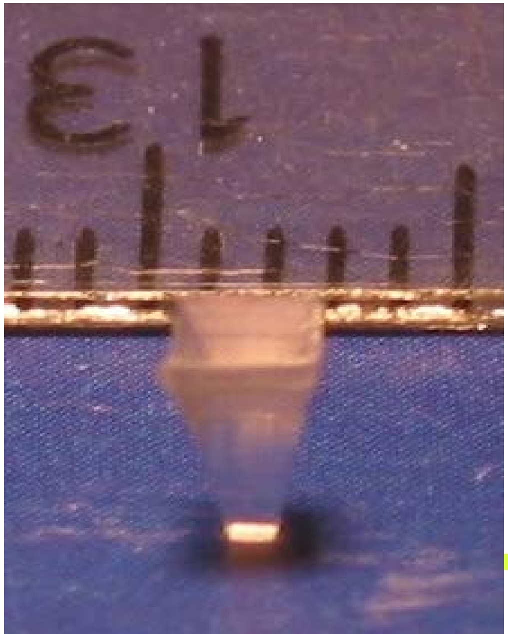


or combine a lens and mirror walls

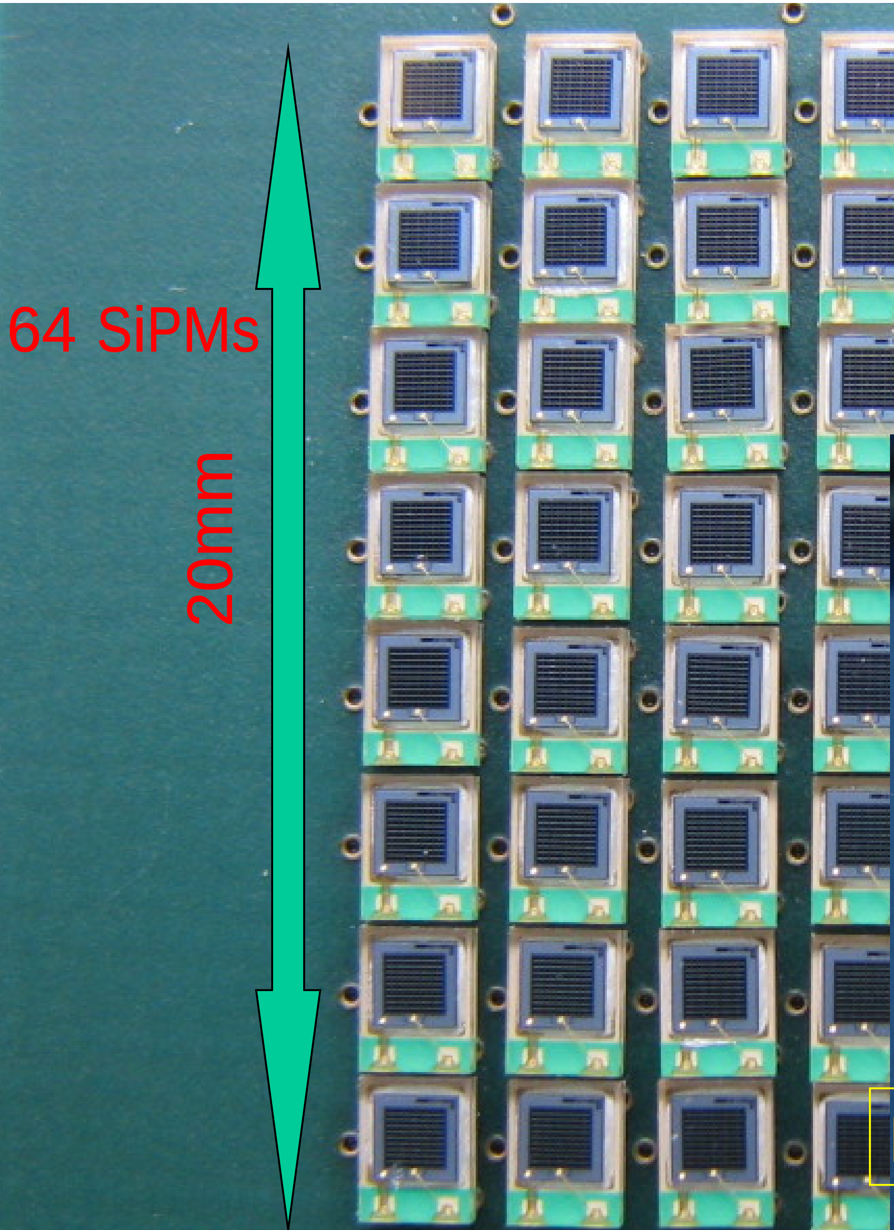
Detector module design

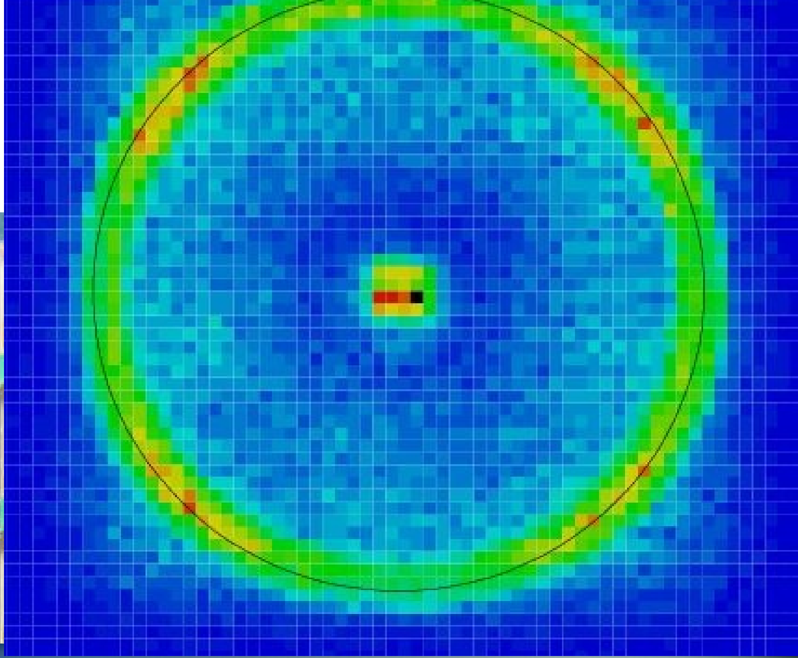



SiPM array with light guides



Photon detector with SiPMs and light guides





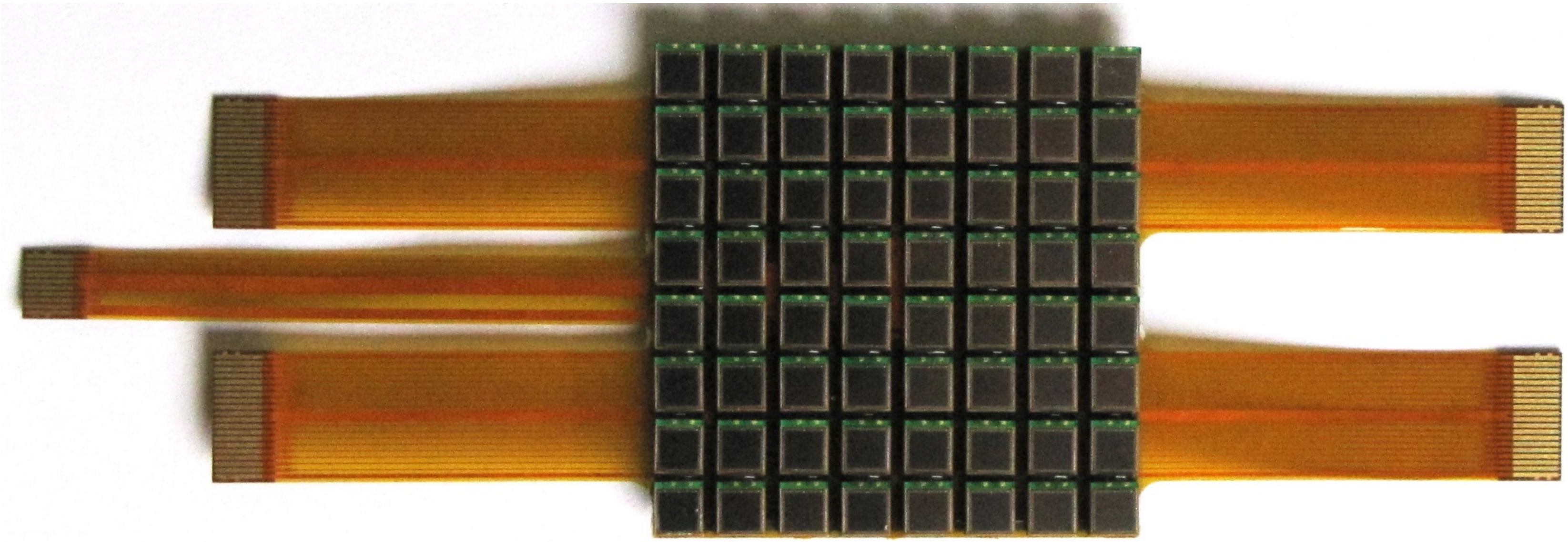
Full ring in a pion beam

Korpar et al., NIM A613 (2010) 195

A new SiPM device

Array of SiPMs: Hamamatsu MPPC S11834-3388DF

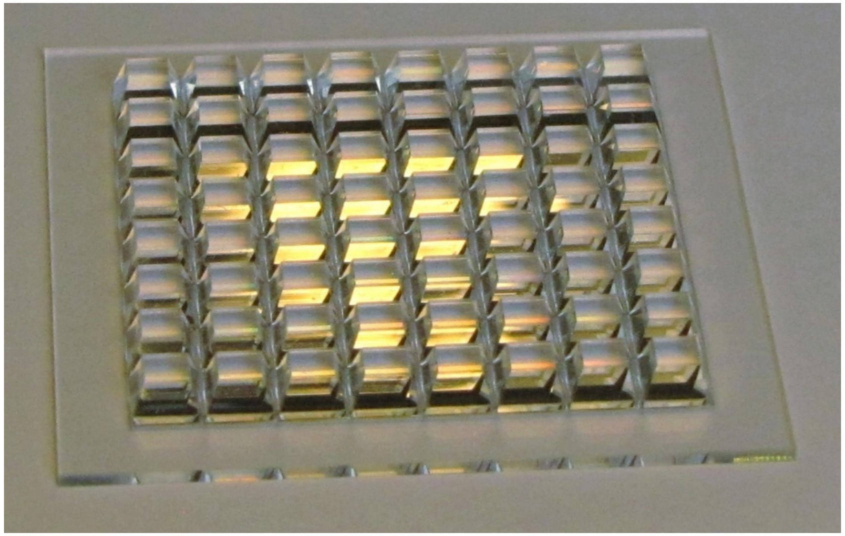
- A novel type of a multi-pixel Photon Counter (MPPC)
- 8x8 SiPM array, with 5x5 mm^2 SiPM channels
- Active area 3x3 mm^2
- Cell size: 50 µm
- Rather low dark count rate (~100 kHz/mm^2)
- Operating voltage: (70 ± 10) V

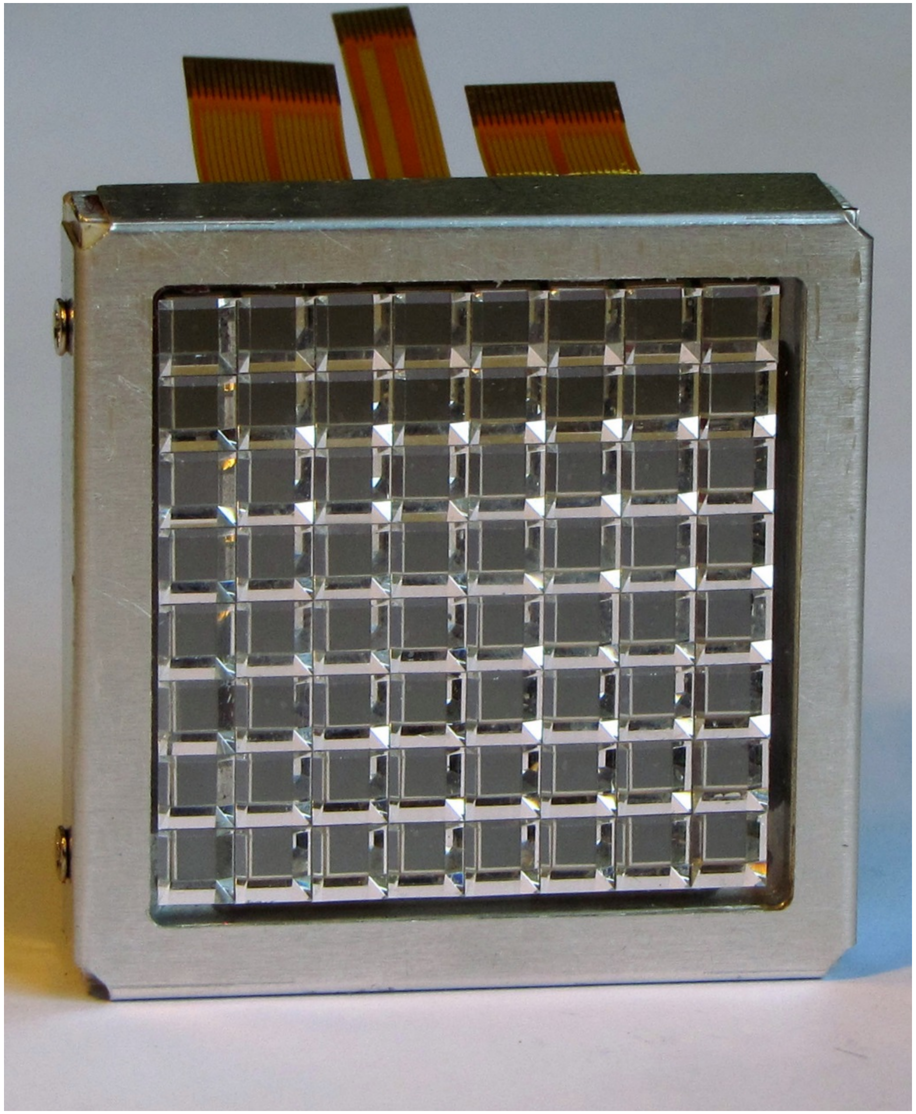


Detector module

Consists of the MPPC, light concentrator and support

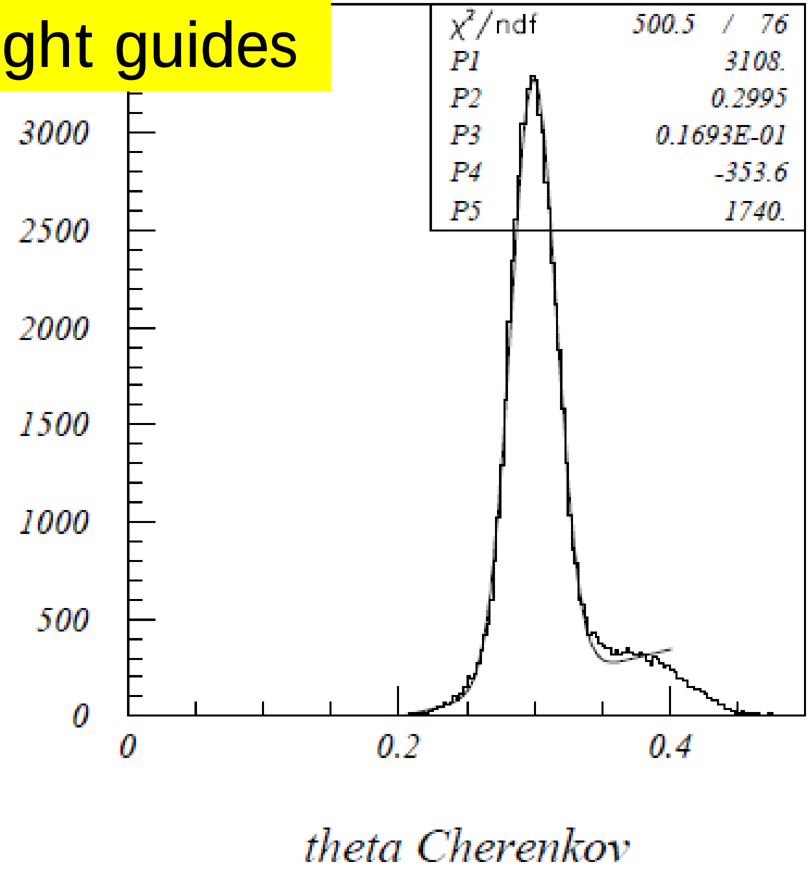
Measured gain: ~3.5×10^5 @ 72.8 V



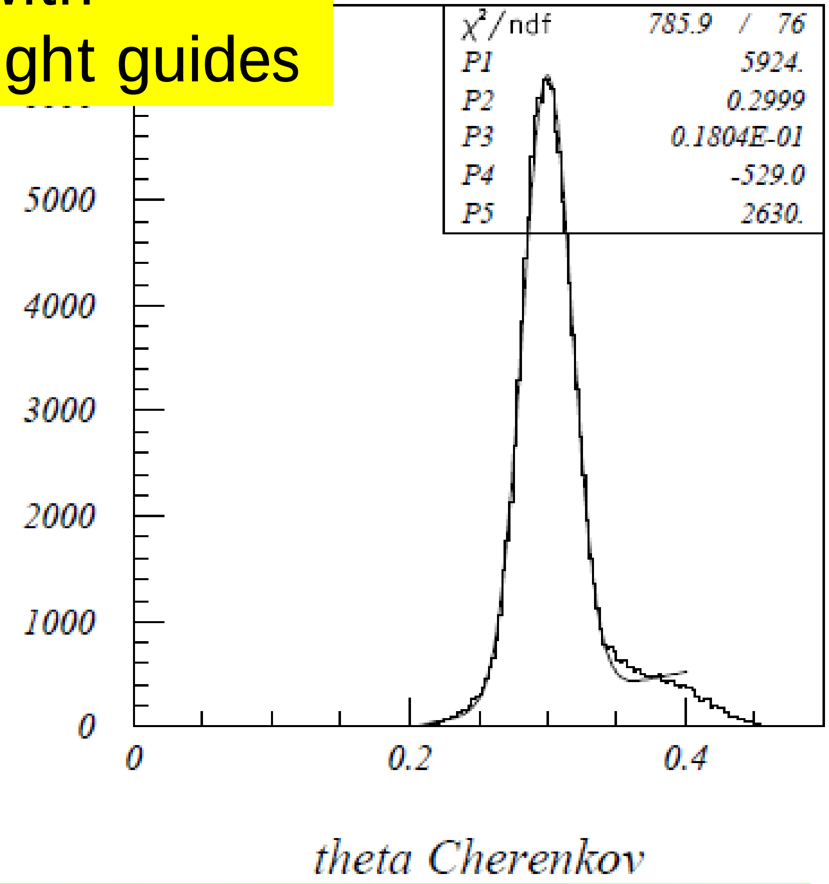


Beam test – light guide performance

no
light guides

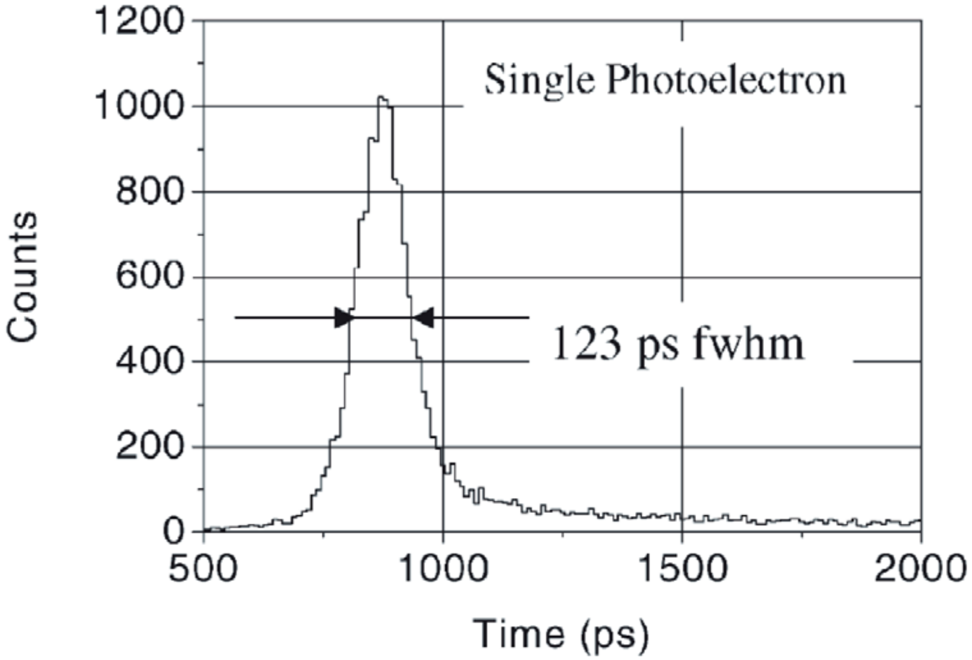


with
light guides

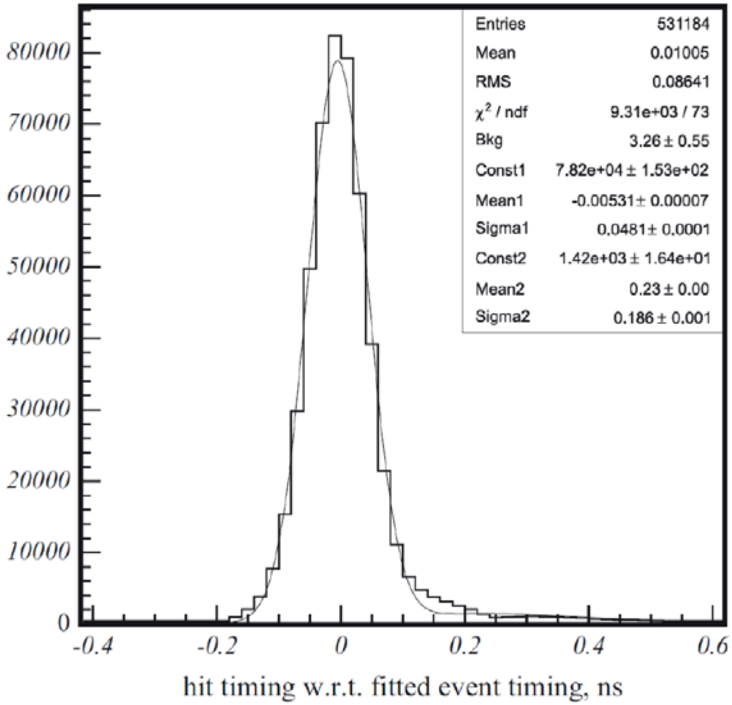


SiPM: time resolution for single photons

Very fast analog SiPM



Digital SiPM



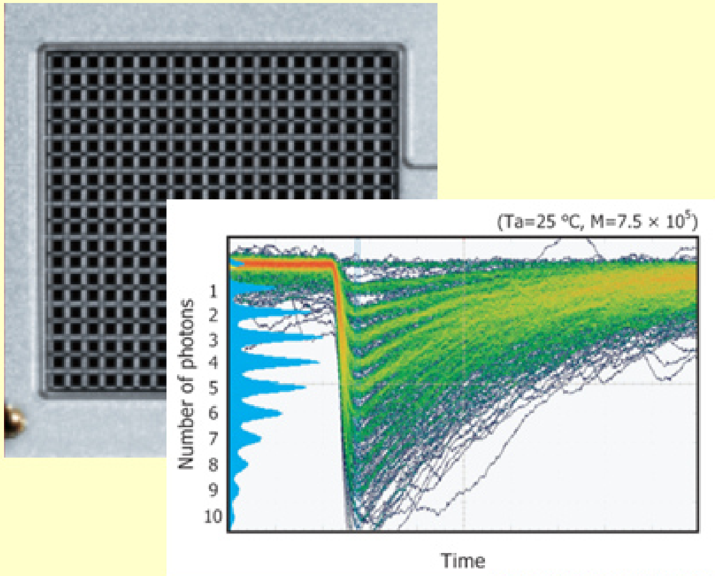
Analog SiPMs: typically 80 ps (sigma), 200 ps FWHM

Digital SiPMs: main peak 48 ps (sigma)!

New player: digital dSiPM

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

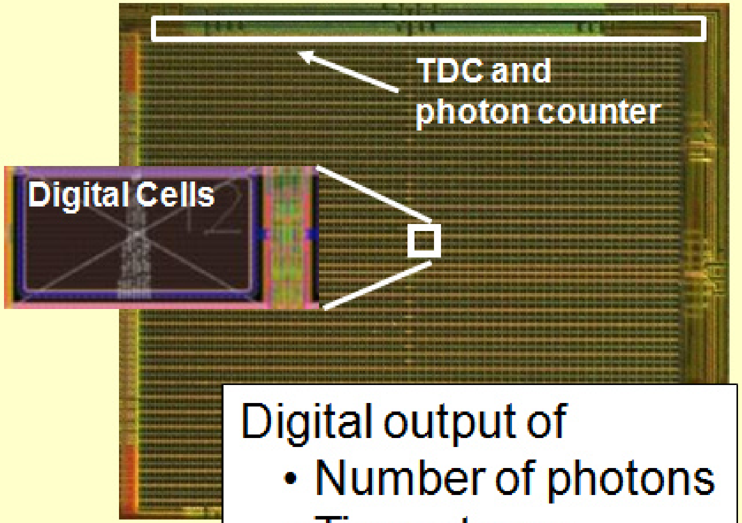
analog SiPM



www.hamamatsu.com

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

digital SiPM (dSiPM)

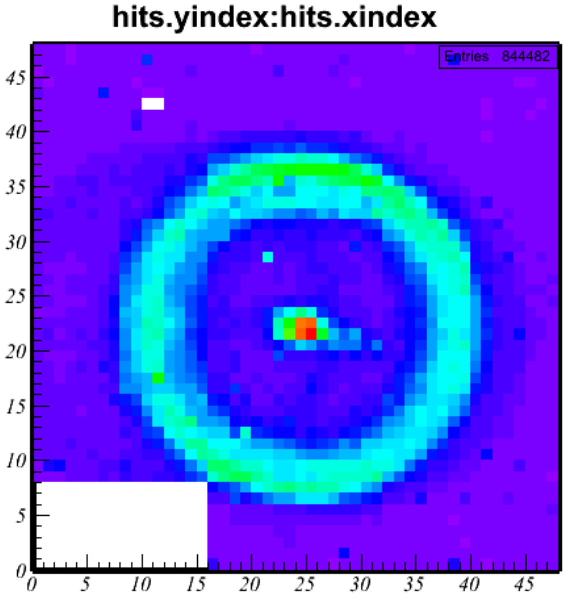


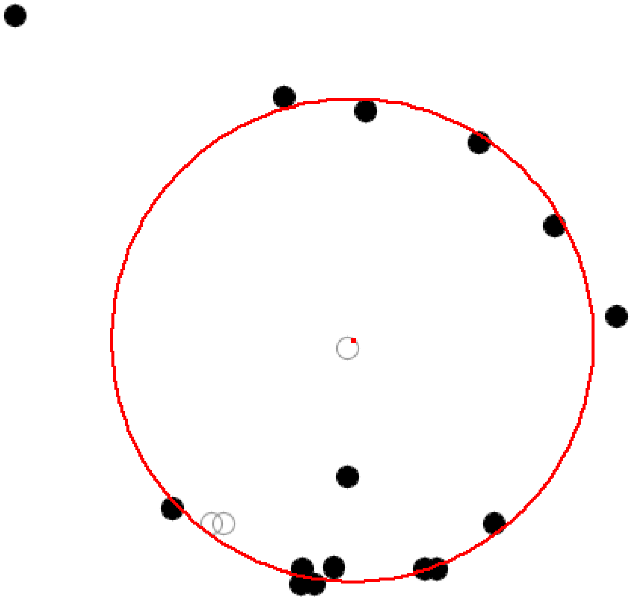
Digital output of
- Number of photons
- Time-stamp

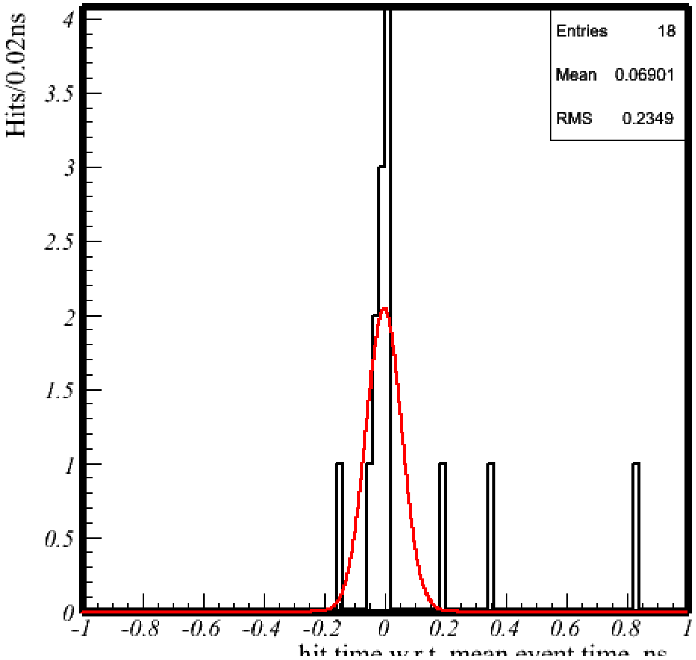
Integrated readout electronics is the key element to superior detector performance

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

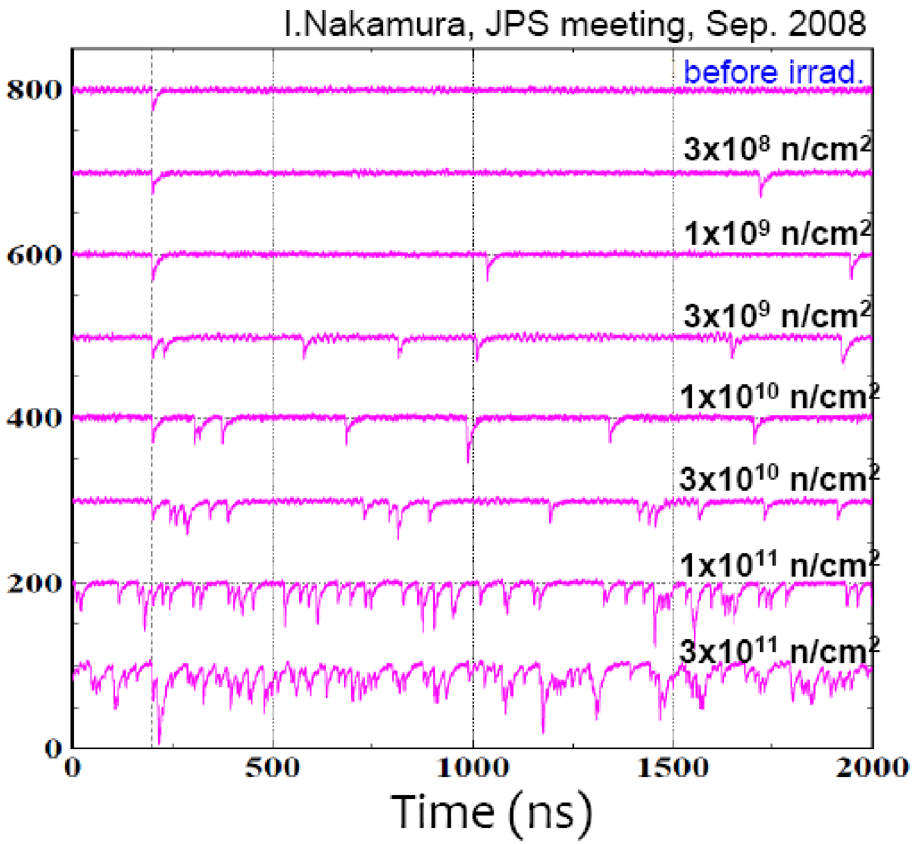
dSiPM in beam tests







Radiation damage



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

New possibilities in medical imaging: TOFPET with Cherenkov light

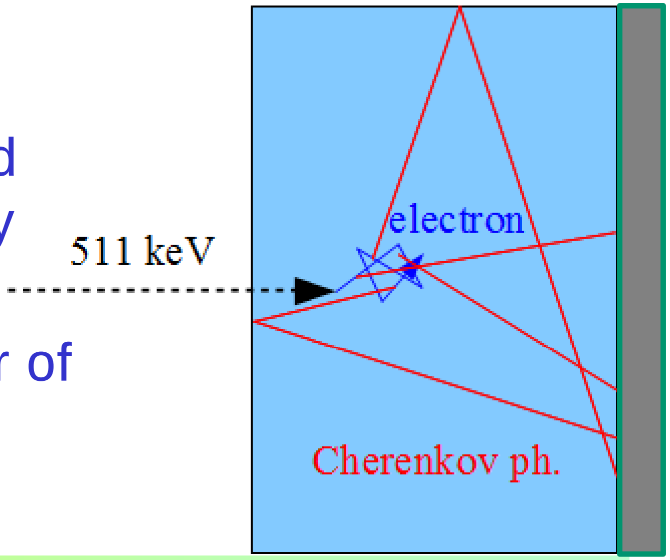
Time-of-Flight difference of annihilation gammas is used to improve the contrast of images obtained with PET:

- localization of source position on the line of response
- reduction of coincidence background
- improvement of S/N

Novel photon detectors – MCP-PMT and SiPM – have excellent timing resolution → TOF resolution limited by the scintillation process

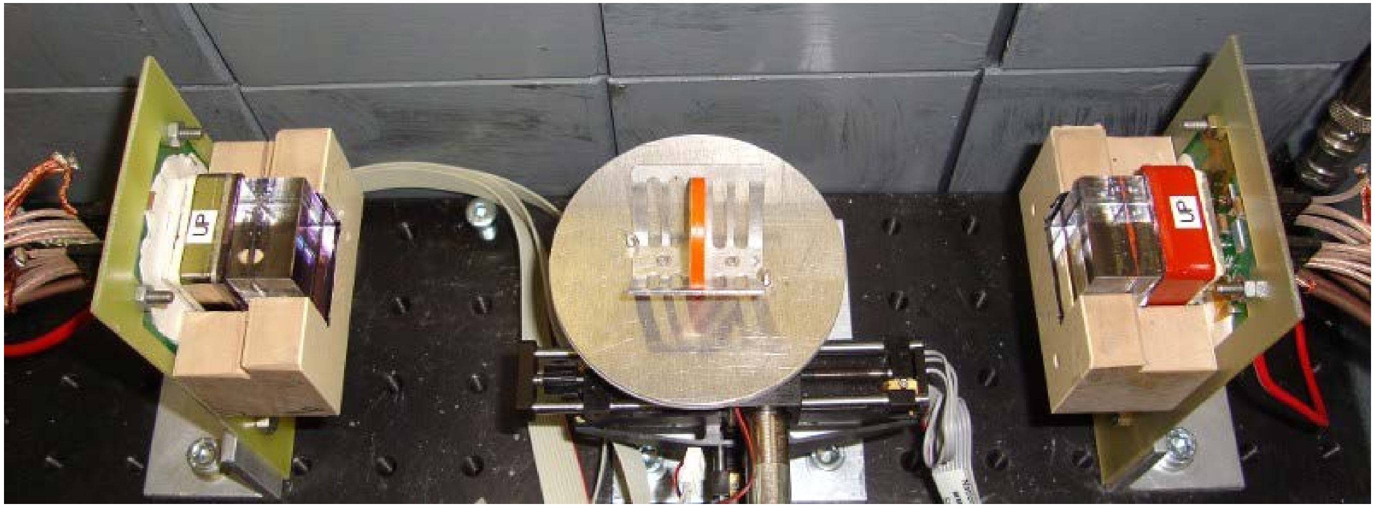
Cherenkov light is promptly produced by a charged particle traveling through the medium with velocity higher than the speed of light c_0/n.

Disadvantage of Cherenkov light is a small number of Cherenkov photons produced per interaction → detection of single photons!



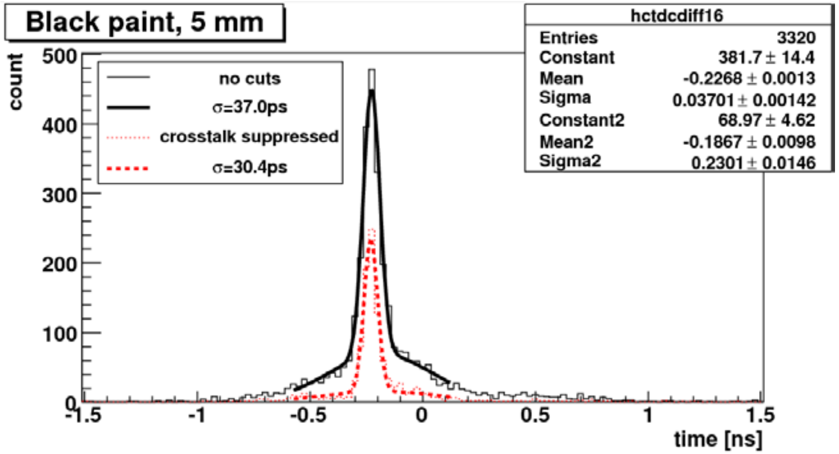
TOF-PET with Cherenkov light

Two detectors in a back-to-back configuration with 25x25x15 mm^3 crystals coupled to MCP-PMT with optical grease.



5 mm long crystal:

→ FWHM ~ 70 ps



→ NIM A654(2011)532–538

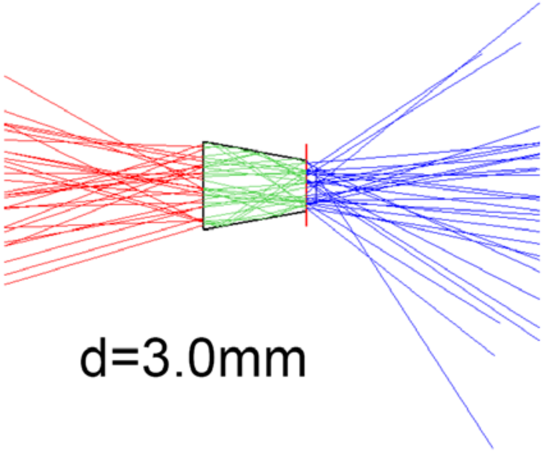
→ Talk by P. Križan - tomorrow

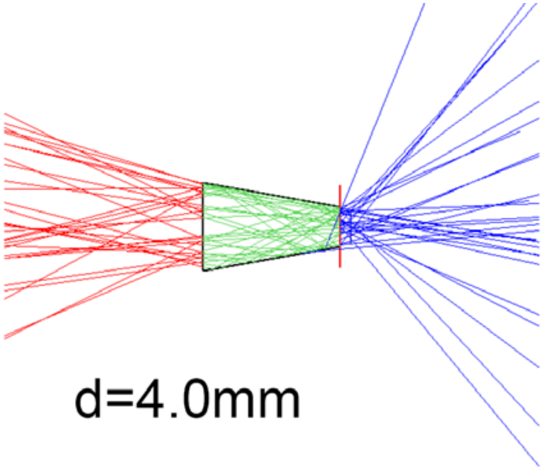
Summary

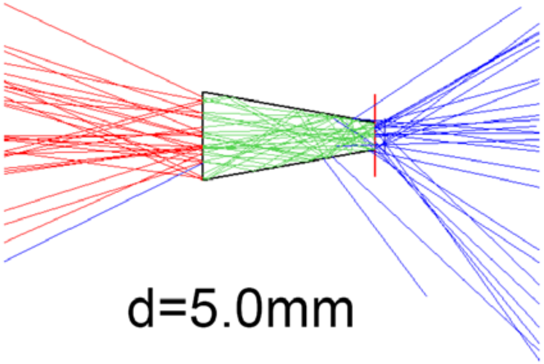
- Single photon detection is at the hearth of the RICH detectors
- New methods require very fast timing in radiation harsh environments
- A number of new detectors has been developed recently to cope with these requirements
- A very active field!
- My talk can only be seen as a warming up – there will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

Back-up slides

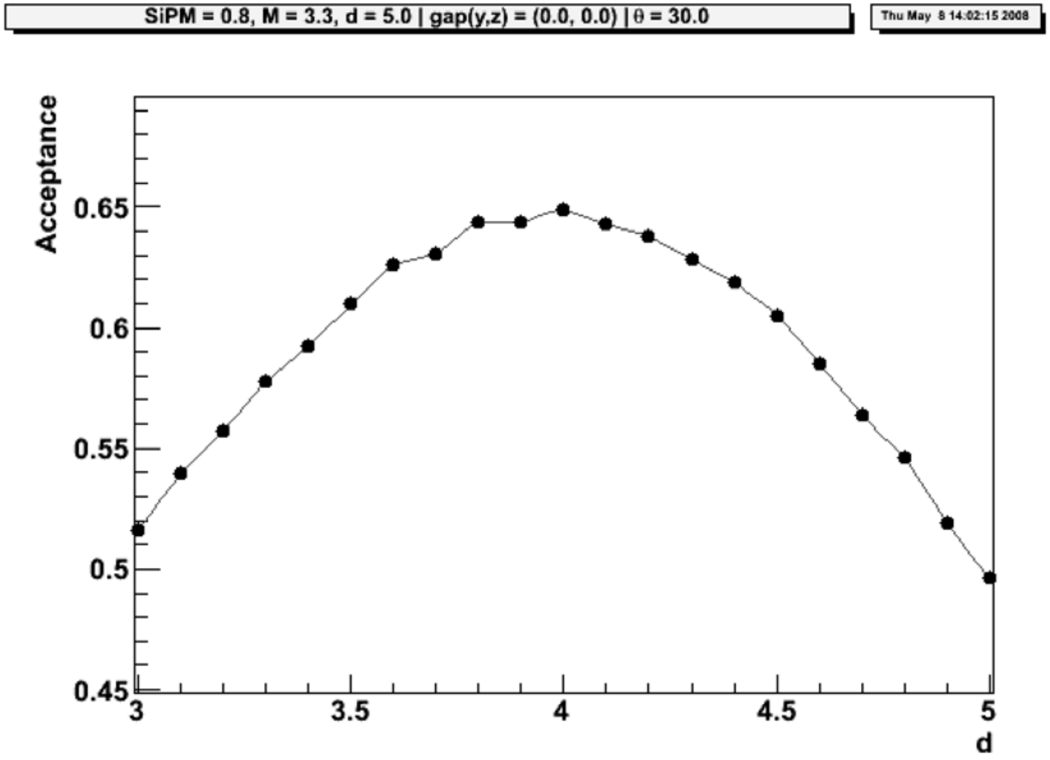
Light guide geometry optimisation


d=3.0mm


d=4.0mm


d=5.0mm

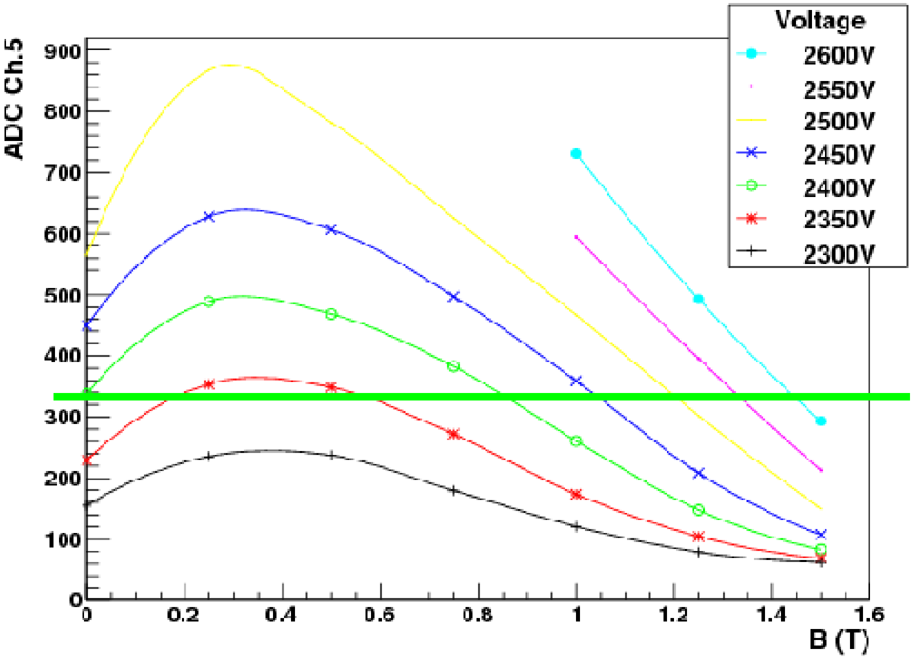
d (mm)	out (mm)	accept. (%)
3.0	1.48	51.6
3.1	1.45	54.0
3.2	1.41	55.7
3.3	1.38	57.8
3.4	1.34	59.2
3.5	1.31	61.0
3.6	1.27	62.6
3.7	1.24	63.1
3.8	1.20	64.4
3.9	1.16	64.4
4.0	**1.13**	**64.9**
4.1	1.09	64.3
4.2	1.06	63.8
4.3	1.02	62.8
4.4	0.99	61.8
4.5	0.95	60.5
4.6	0.92	58.5
4.7	0.88	56.4
4.8	0.85	54.6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

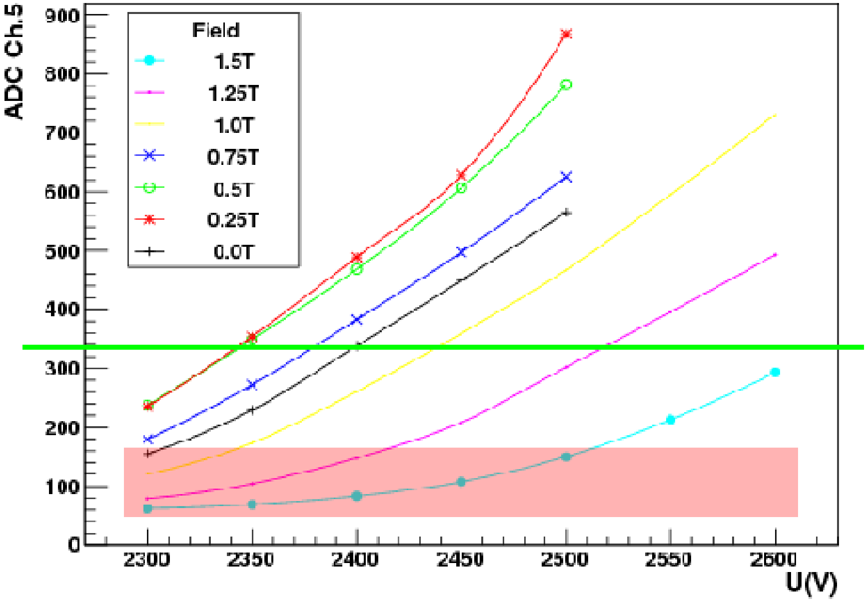


MCP PMT: Gain in magnetic field

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

.

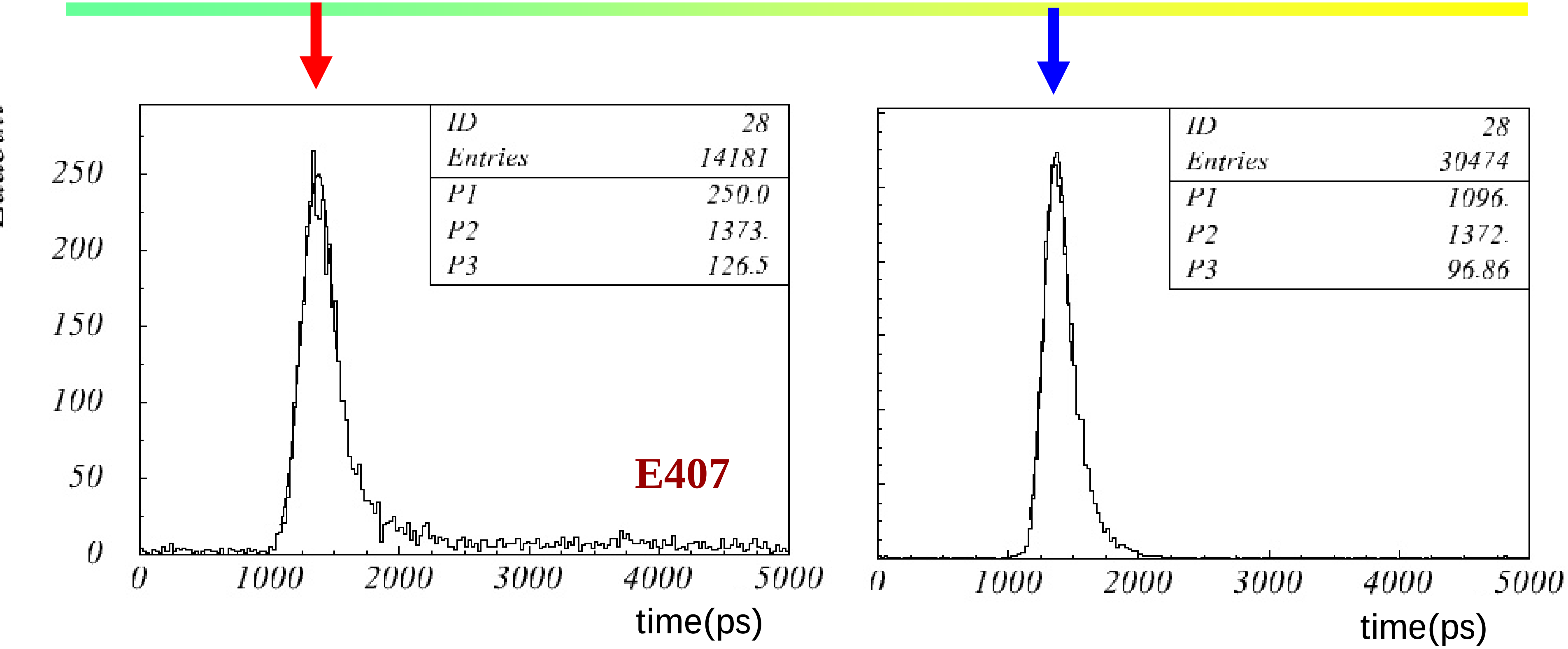




High B field: no problem, to run at the same gain HV → +200V

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

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**

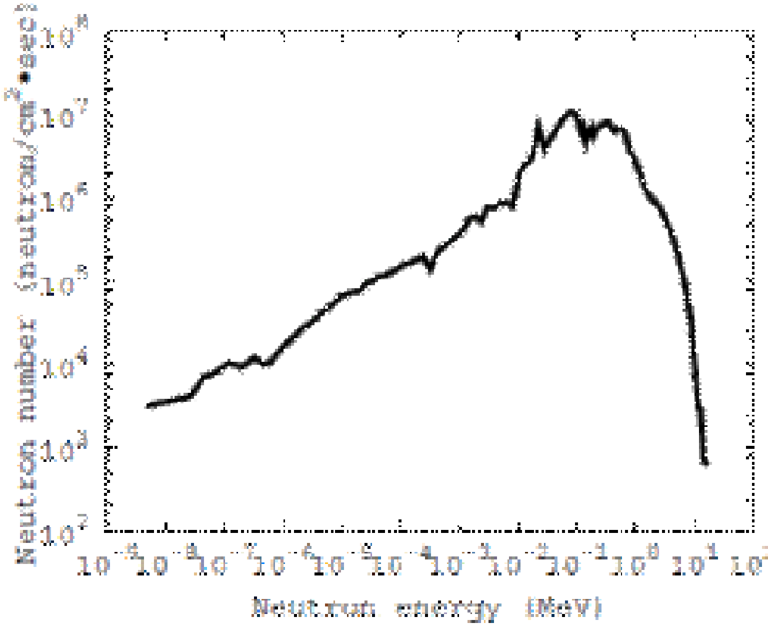
- $\sigma \approx 100$ ps

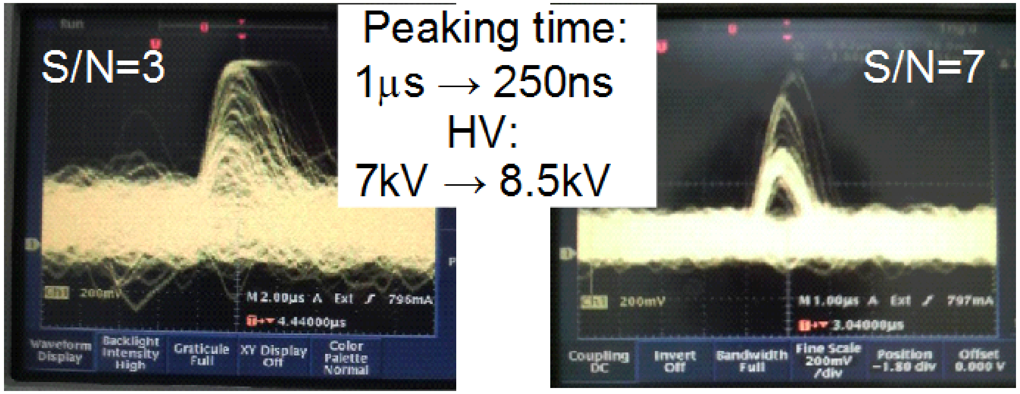
- $\sigma_{red} > \sigma_{blue}$

Neutron irradiation

- Expected total fluence 10^{12} n/cm^2
- Tests of original design: S/N drops to 7 @ 5×10^{11}n/cm^2

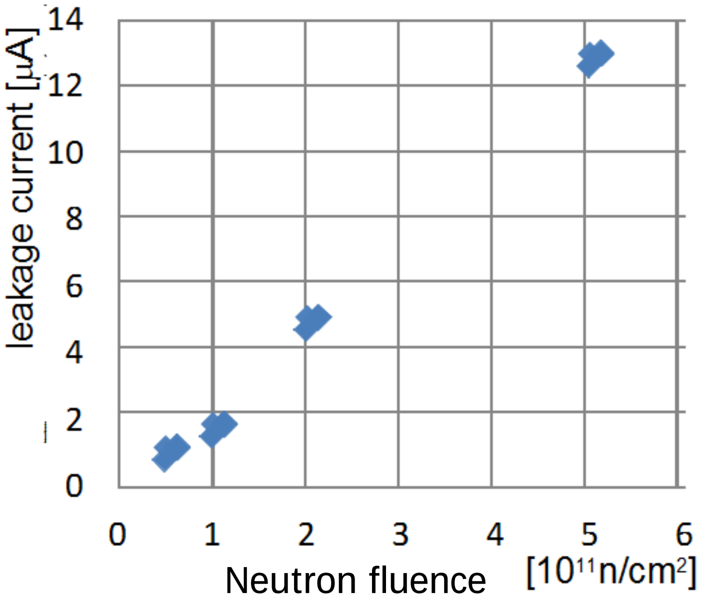
Reactor "Yayoi" @ Tokyo U.





Peaking time:
1µs → 250ns
HV:
7kV → 8.5kV

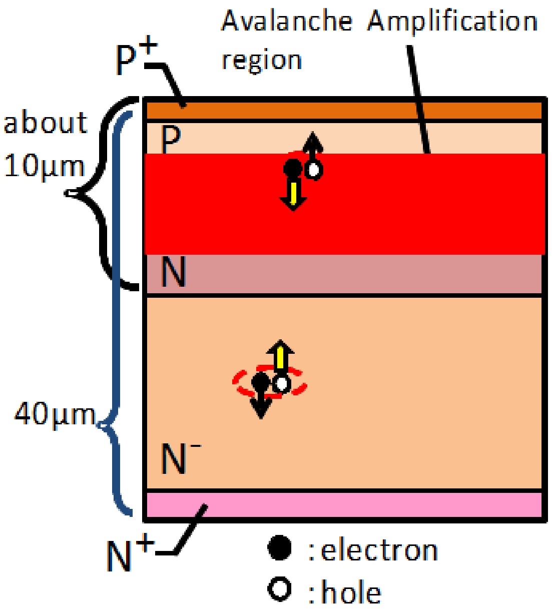
→ Expected S/N~5 @ fluence 10^{12} n/cm^2, marginal operation

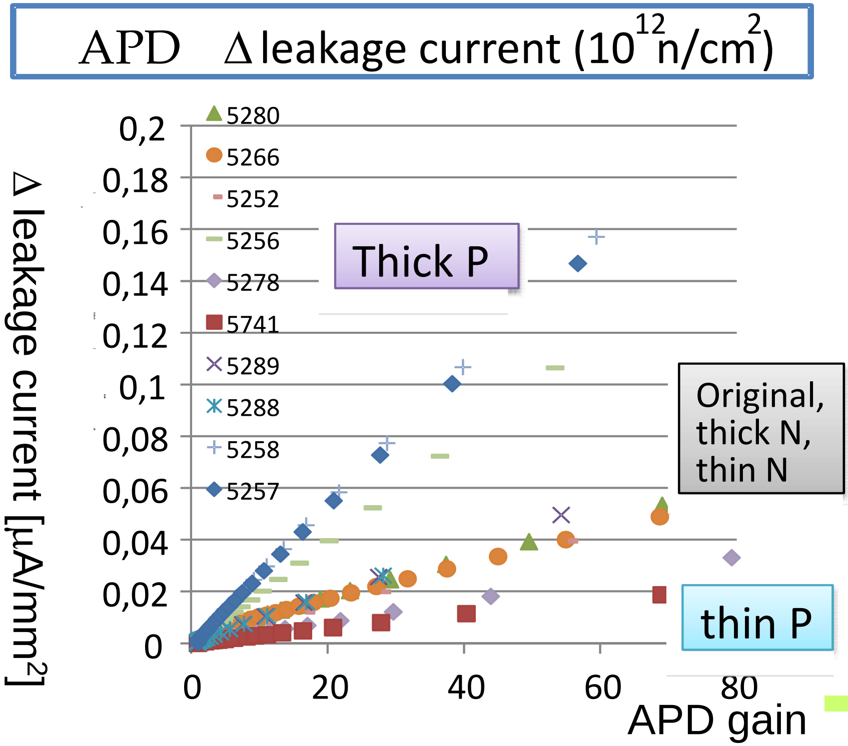


- Re-optimization of peaking time for larger leakage currents → shorter peaking time in final ASIC version
- Optimization of APD structure

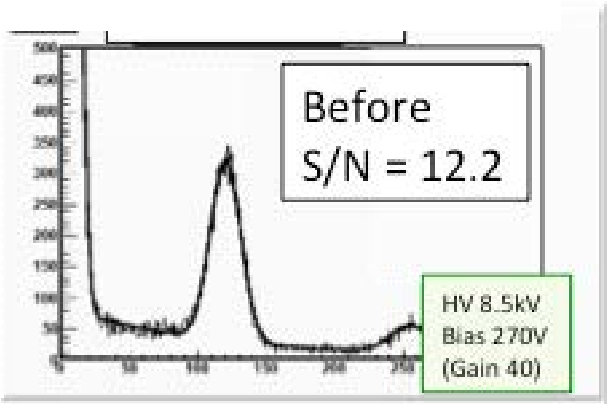
Neutron damage

Modification of APD structure:
- Thinner p layer to reduce increase of the leakage current after irradiation – main source of leakage current are thermally generated electrons in p layer due to the lattice defects produced by neutrons
- Thinner p^+ layer to increase bombardment gain

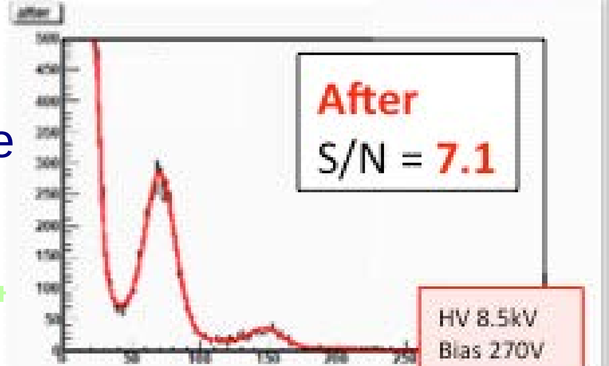




As expected, the increase of the leakage current is smaller with thin p



S/N for thin p sample is better than 7 after fluence 10^{12}n/cm^2

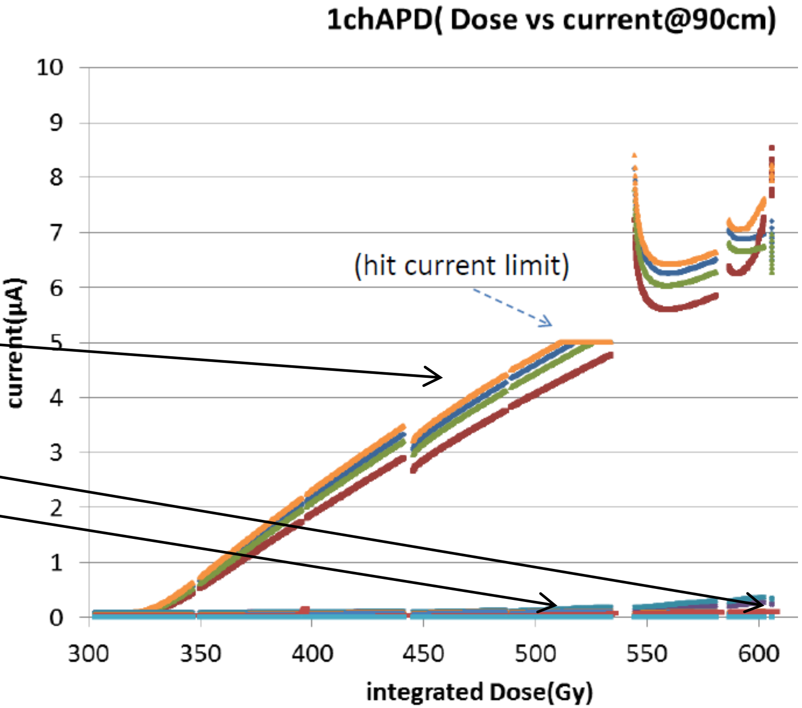


Gamma irradiation

- Expected total dose 100-1000 Gy
- Initial tests indicated fast raise of leakage current and reduction of breakdown voltage – not previously observed with similar APDs
- Possible source: APD for HAPD had additional alkali protection layer to protect APD during photocathode activation process
- To identify the reason extensive tests were done with single channel APDs with different structure prepared by Hamamatsu:
- “Standard” alkali protection
- No alkali protection
- “New” alkali protection

→ APD structure had to be optimized

^{60}Co irradiation facility @ Nagoya U.



Optimized APD structure

Neutron irradiation (nonionizing energy loss):

modification of APD internal structure to increase S/N after irradiation:

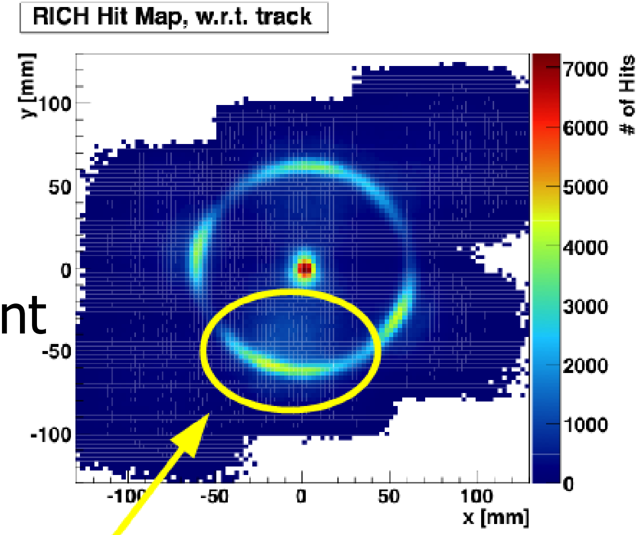
- reduced p layer thickness → reduced leakage current
- reduced p+ layer → increased bombardment gain

Gamma irradiation (ionizing radiation):

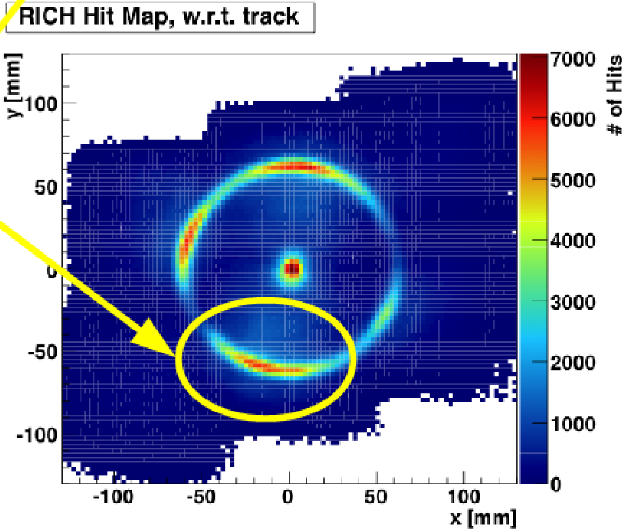
modifications to avoid charge-up efects:

- optimization of protective films
- additional intermediate electrode
- no alkali protection layer

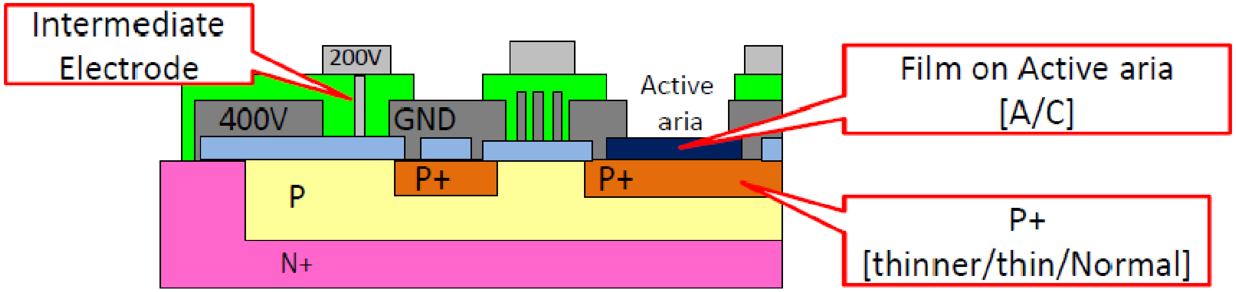
irradiated HAPDs showed comparable results to non-irradiated samples in a beam test



n: 2.1x1012 n/cm2
(QE 21.4%)



n: 0.86x1012 n/cm2
γ: 1 kGy
(QE 31.1%)



Intermediate Electrode

Film on Active aria [A/C]

P+ [thinner/thin/Normal]

Ageing test - setup

Estimated number of photoelectrons @ Belle II:

- ~ 4×10^{11} ph.e./cm^2/y
  → ~ 10^{11} ph.e./ch./y

Operation parameters:

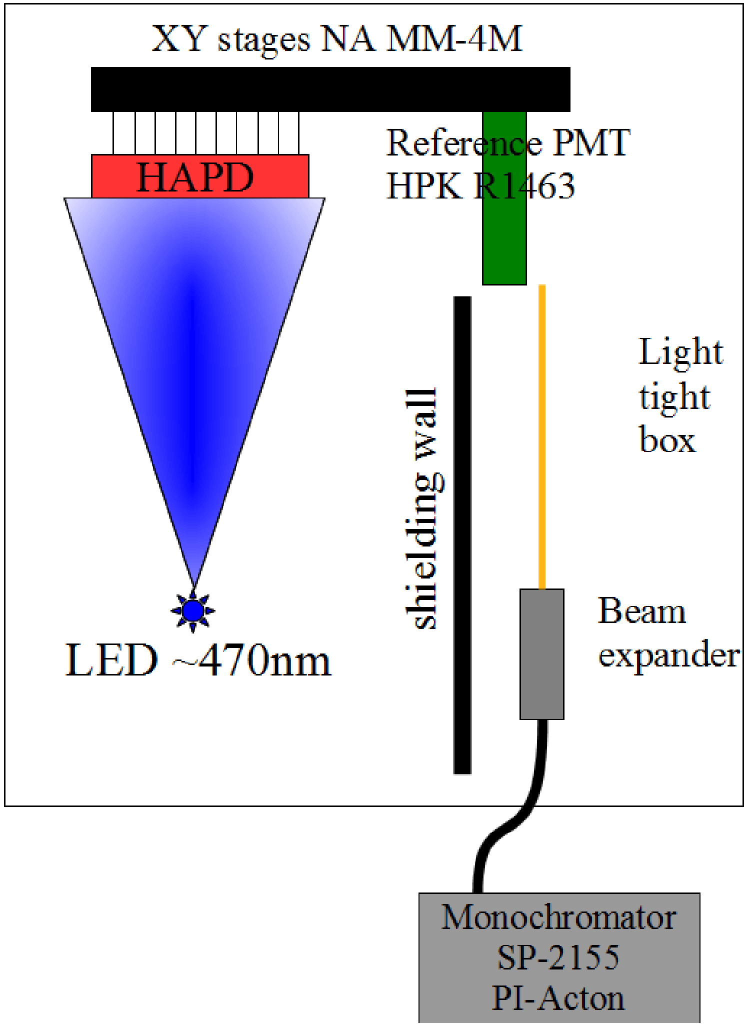
- gain ~ 6×10^4
  (APD ~50, bombardment gain ~1200)
- HV 7 kV

Monitoring:

- anode currents
- signal from 3 channels – ADC and rate
- QE at the beginning and the end

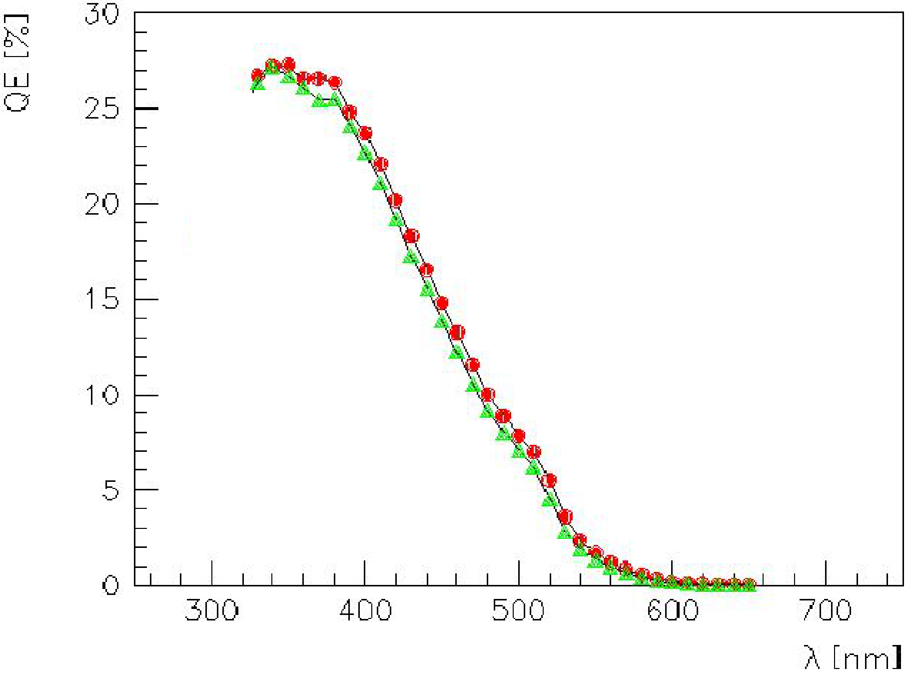
Aging with blue LED:

- ~1 MHz/ch. for 27 days
  → ~20 years of Belle II operation

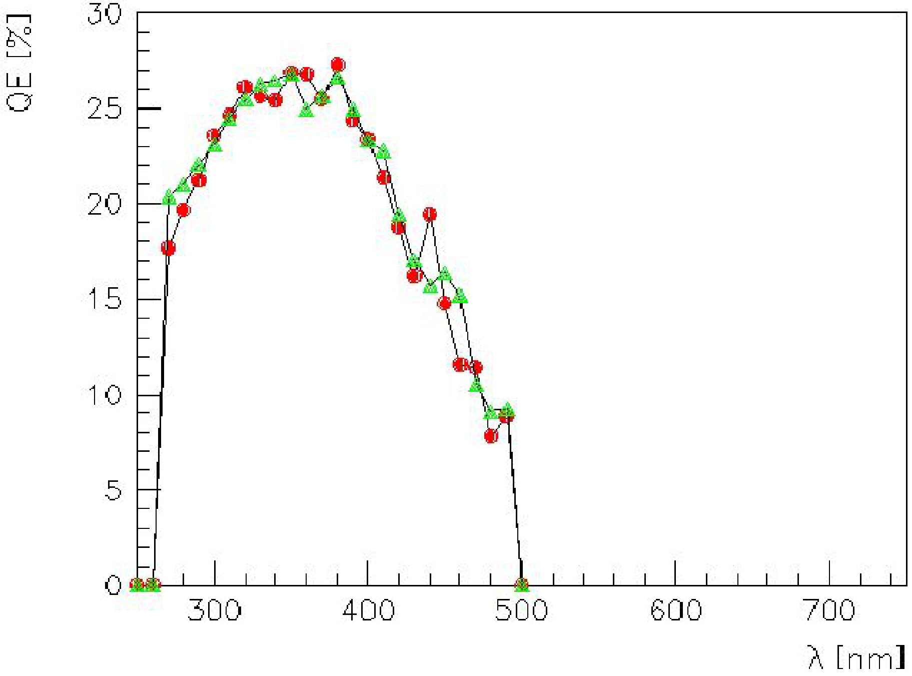


Ageing test - QE measurement

- comparison of initial QE and QE after ~20 years of Belle II show practically no change in performance



- Tungsten lamp



- Deuterium lamp

→ no significant change of QE expected during the lifetime of the Belle II