A RICH Photon Detector Module with G-APDs

S. Korpar [a,b], H. Chagani [b], R. Dolenec [b], P. Križan [b,c], R. Pestotnik [b], A. Stanovnik [b,c]

[a] University of Maribor, [b] J. Stefan Institute, [c] University of Ljubljana

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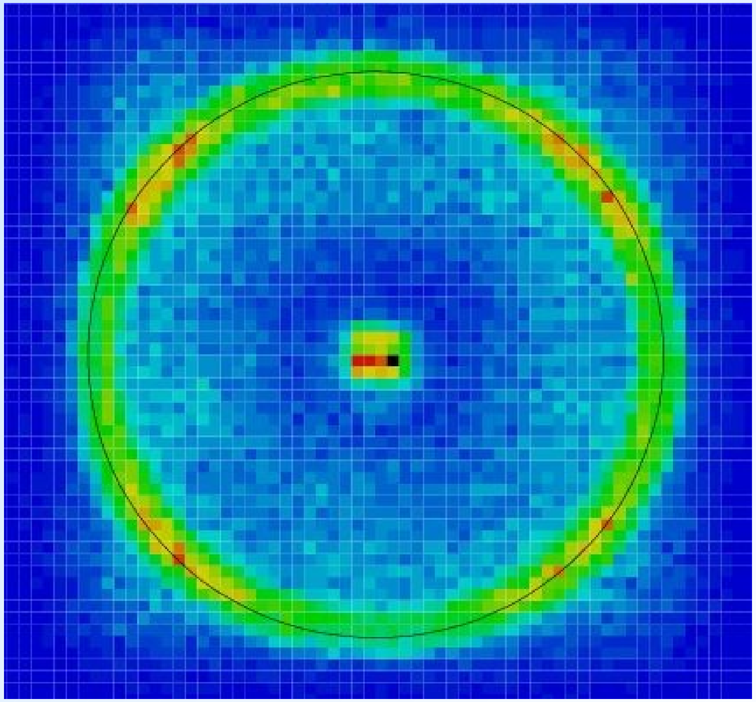
Outline:

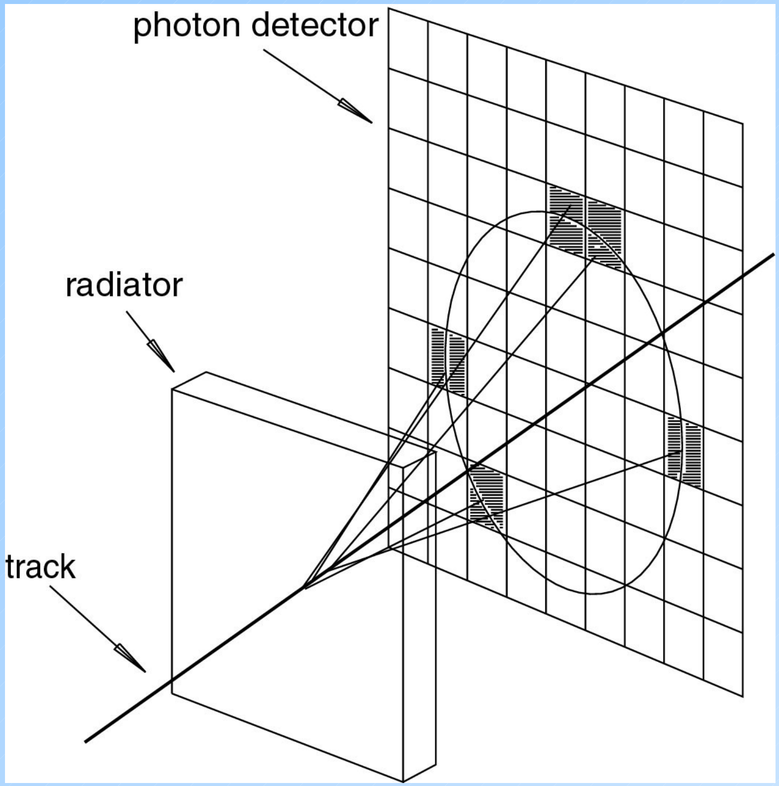
- Aerogel RICH for Belle II
- RICH with G-APDs
- Beam test set-up and results
- Summary
- HAPD poster summary:

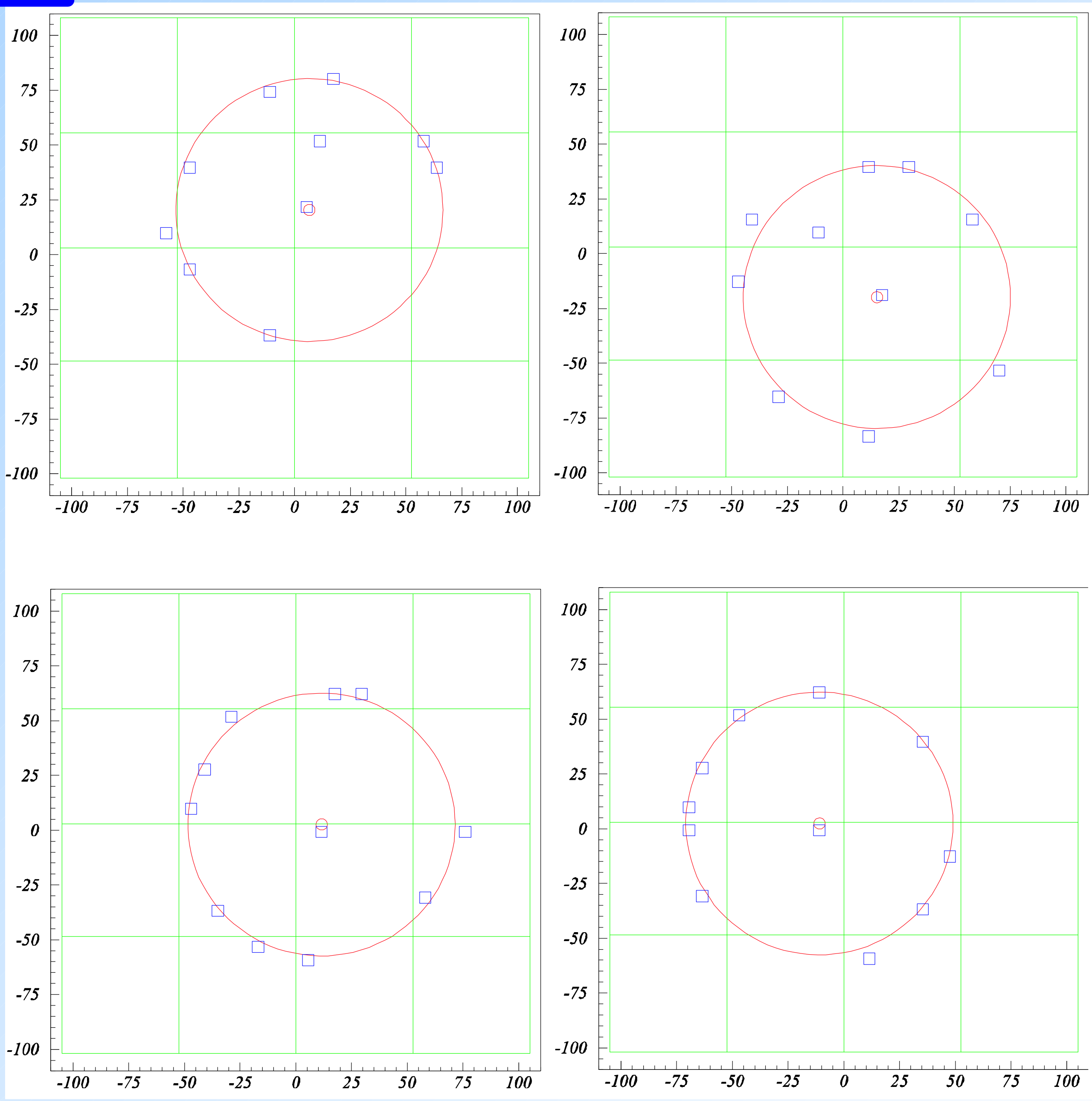
Study of 144 Channel Multi-Anode Hybrid Avalanche Photo-Detector for the Belle RICH Counter

Ichiro Adachi
for the Belle aerogel RICH group



Measuring Cherenkov angle





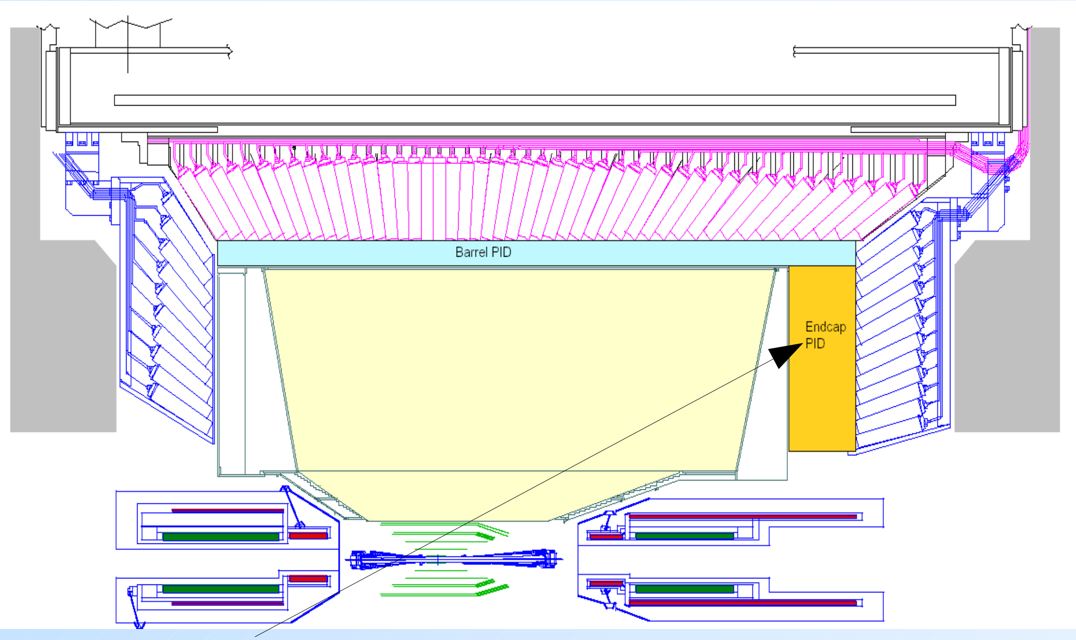
From hits of individual photons → measure the angle

Few photons detected → Important to have a low noise detector

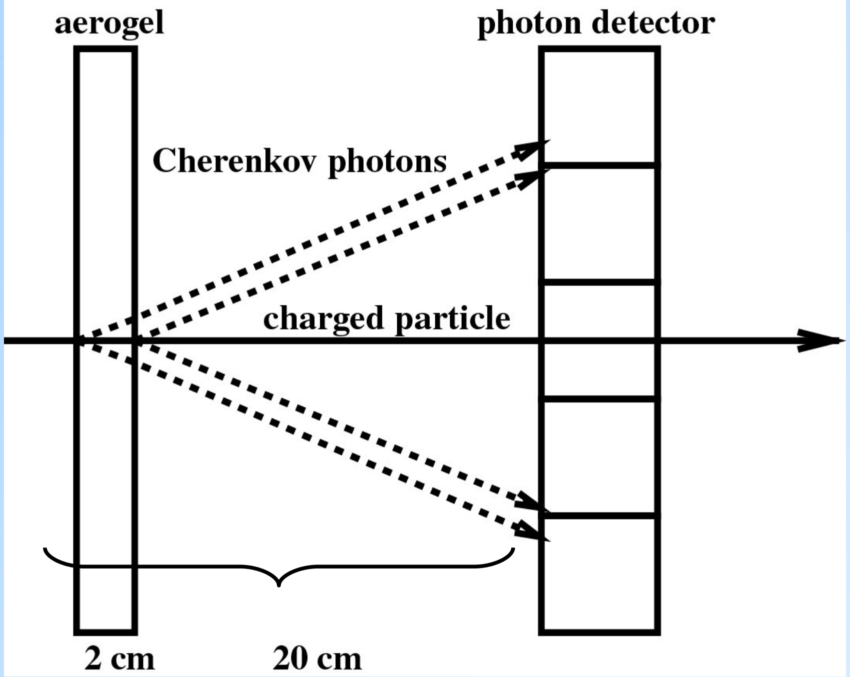
Forward PID for Belle II

Requirements and constraints:

- ~ 5 σ K/π separation @ 1-4 GeV/c
- limited available space ~ 250 mm
- operation in magnetic field 1.5T
- photon detector candidates: HAPD, MCP-PMT, **G-APD**



Selected type: proximity focusing aerogel RICH



- <n> ~ 1.05 (focusing configuration)
- $\vartheta_c(\pi)$ = 308 mrad @ 4 GeV/c
- $\vartheta_c(\pi) - \vartheta_c(K)$ = 23 mrad @ 4 GeV/c
- pion threshold 0.44 GeV/c, kaon threshold 1.54 GeV/c
- time-of-flight difference (2m from IP): $t(\pi) - t(K)$ = 180(45) ps @ 2(4) GeV/c

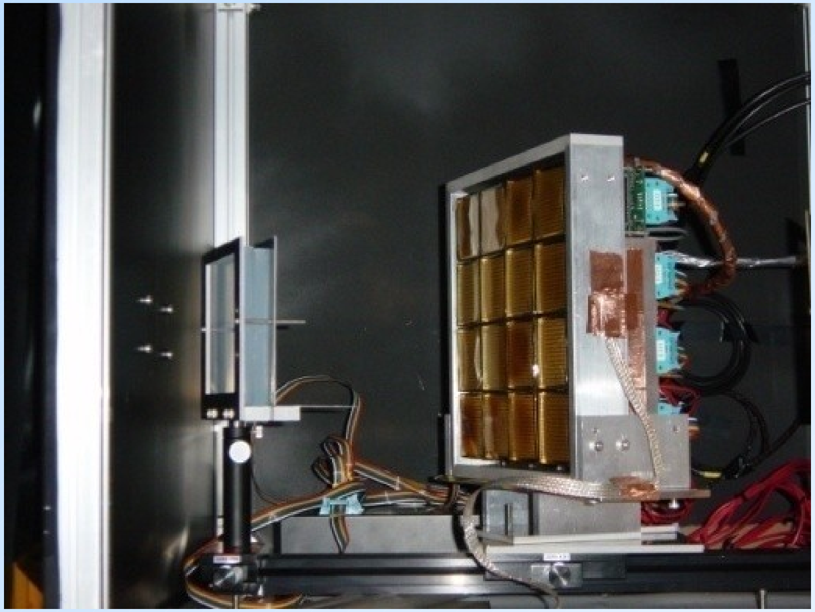
Beam test with flat-panel PMT array

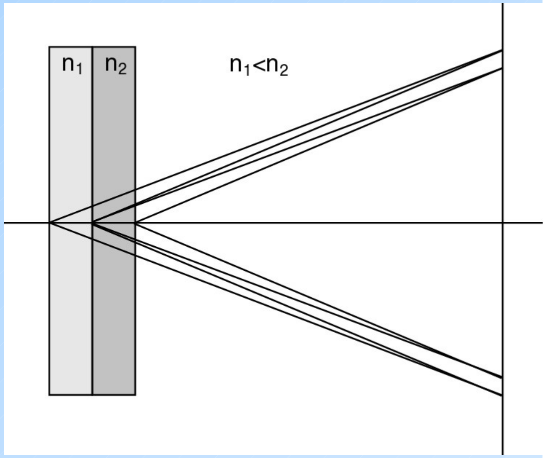
NIM A548 (2005) 383

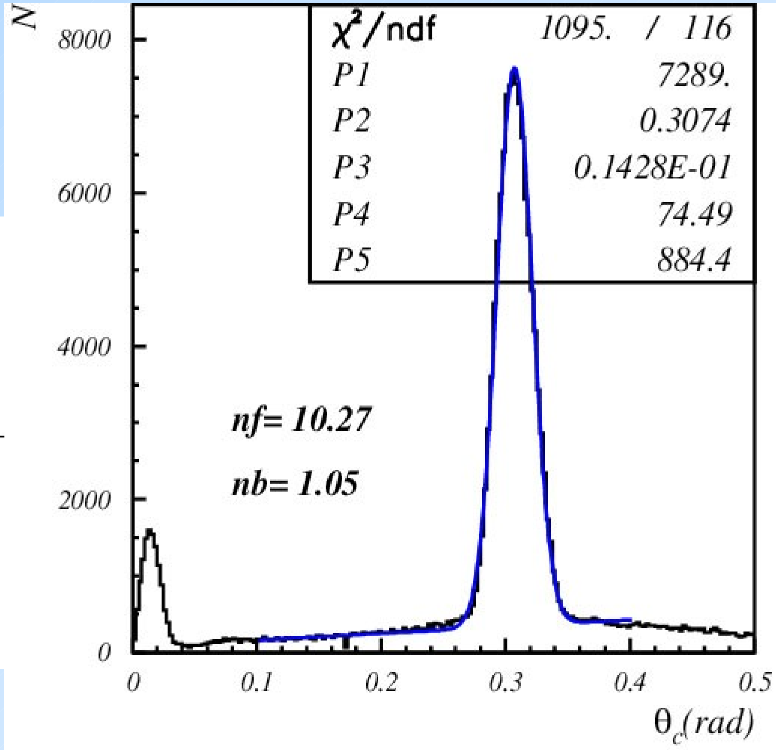
Study of aerogel radiator with flat-panel PMT array - standard configuration:
2cm(1.045)+2cm(1.055) focusing aerogel:

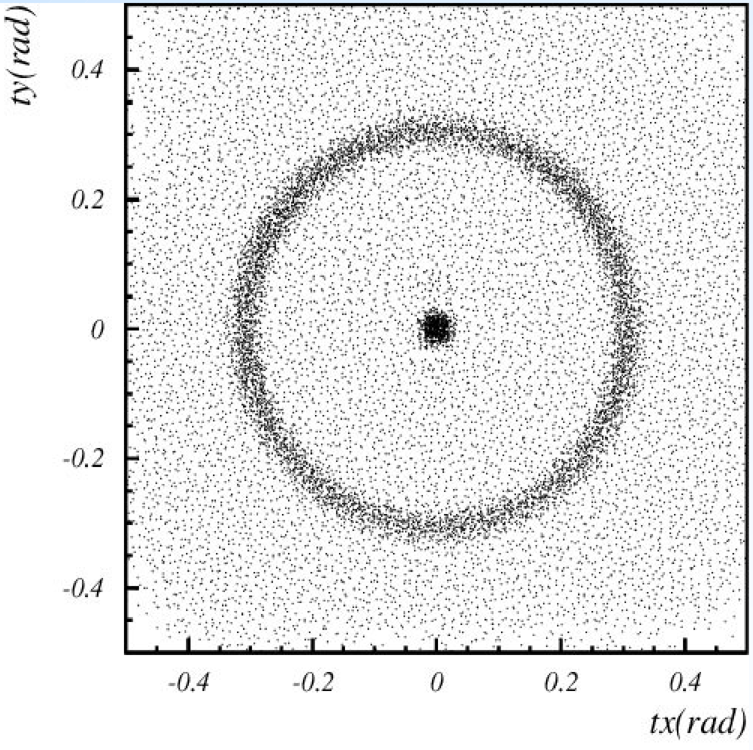
- $N_{ph.} \sim 10$
- $\sigma_{single} = 14$ mrad
- $\sigma_{track} = 4.6$ mrad

5σ @ 4GeV/c







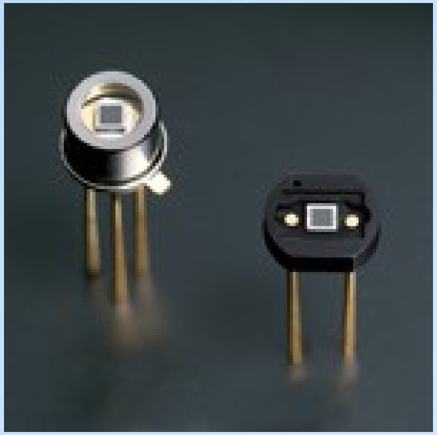


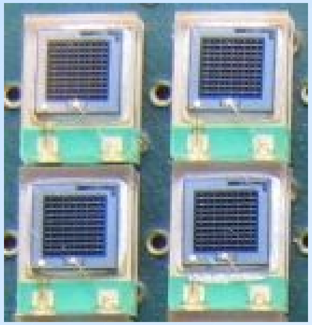
G-APD characteristics

- **works in magnetic field**
- low operation voltage ~ (10-100)V
- peak PDE (= QE x ε_{geiger} x ε_{geo}) up to 65% (@400nm - Hamamatsu data sheet),
- gain ~ 10^6
- time resolution ~ 100-200 ps
- dark counts ~ few 100kHz/mm^2
- radiation damage (p,n)

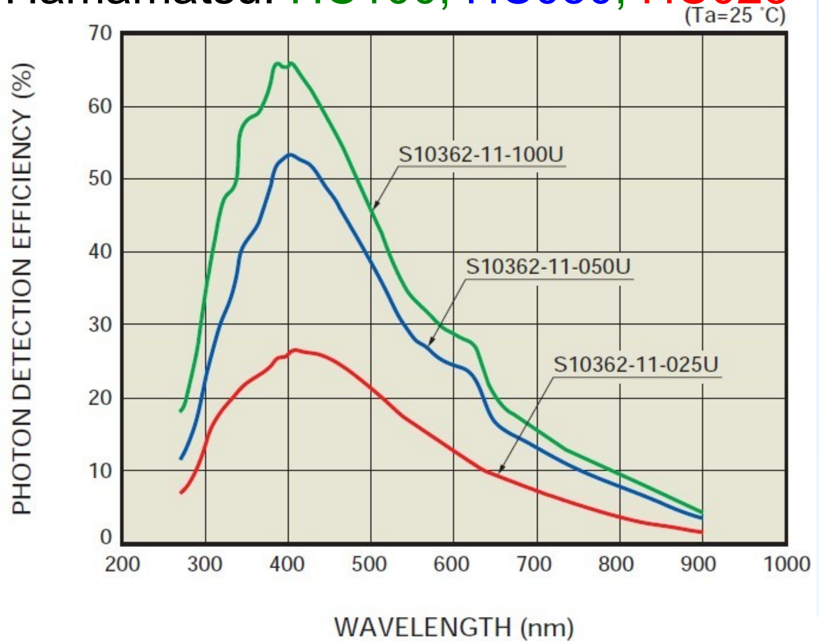
Can such a device be used for detection of single photons in a RICH counter?

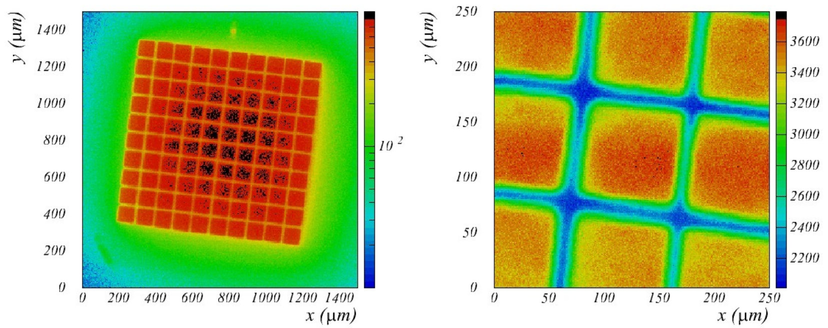
- linearity is not needed → HC100 is preferred due to higher efficiency





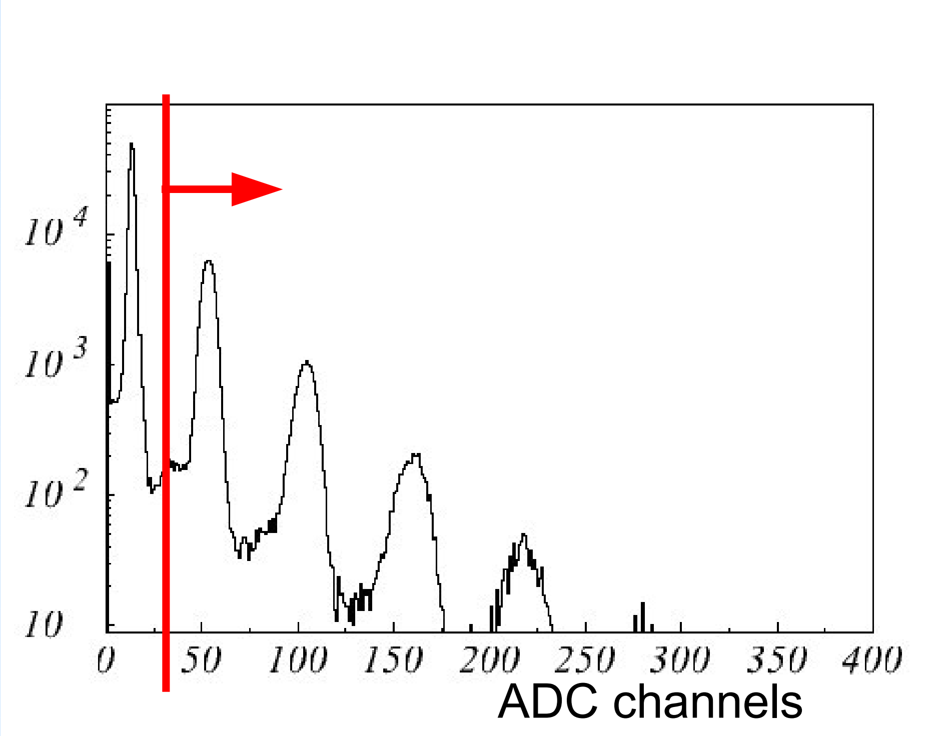
Hamamatsu: HC100, HC050, HC025



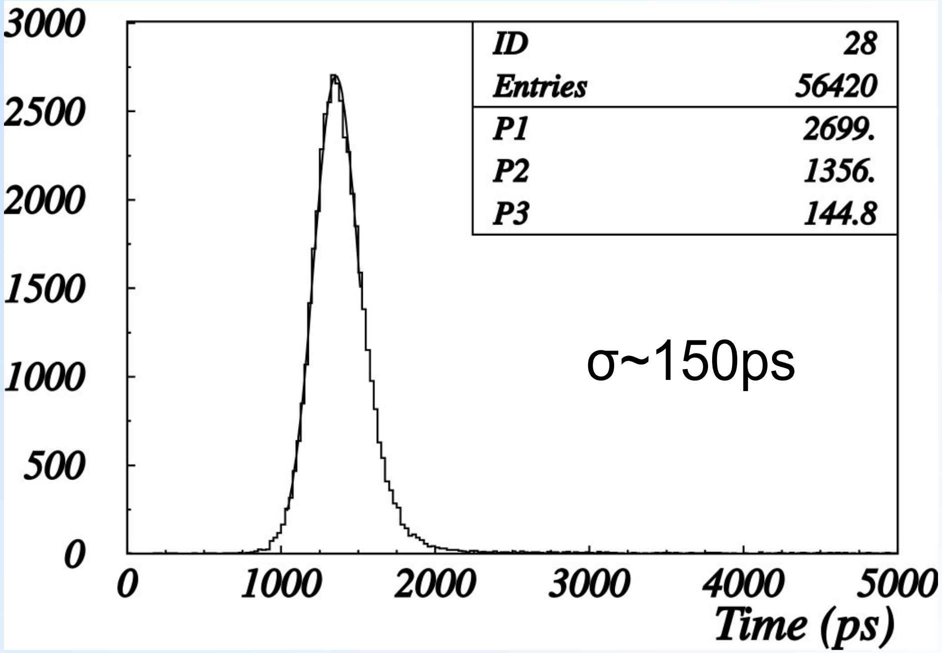


G-APD characteristics - 2

Typical pulse height distribution:
- signal is well separated from pedestal level
- single photon pulses are the same as dark current pulses



Typical timing distribution:
- narrow time window can be used to separate Cherenkov photons from dark current pulses

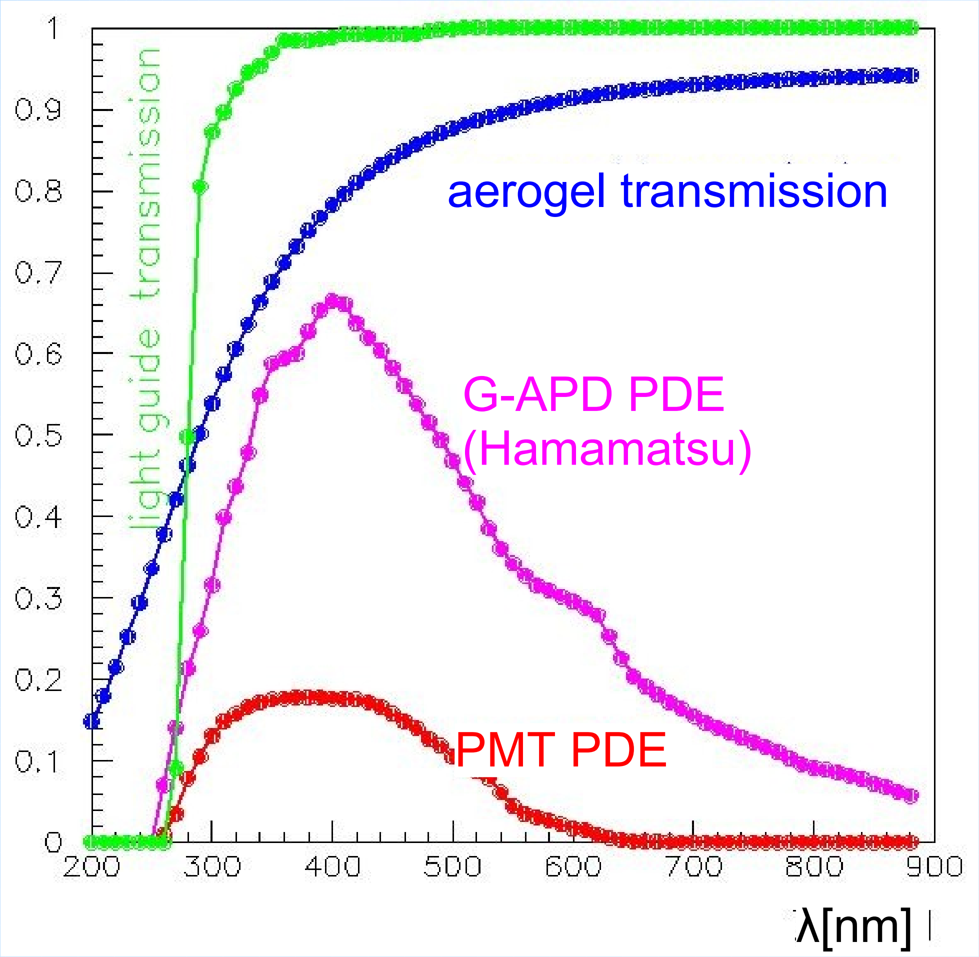


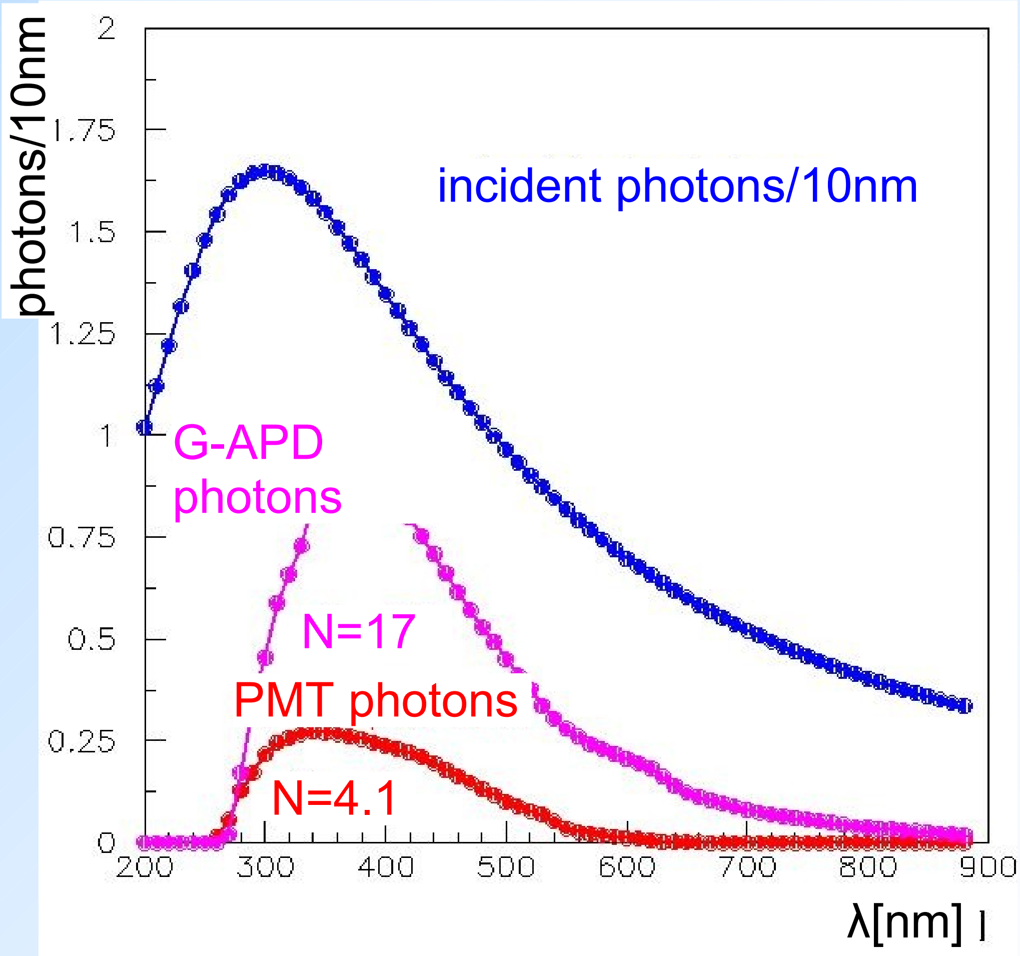
Expected number of photons

Expected number of photons for aerogel RICH (beam test prototype):

- multianode PMTs (peak QE ~ 25%, collection eff. ~ 70%) or MPPCs (HC100)
- aerogel radiator: thickness 1 cm, n = 1.03 and transmission length 1.4 cm (@400nm)

N_{SiPM}/N_{PMT}~4

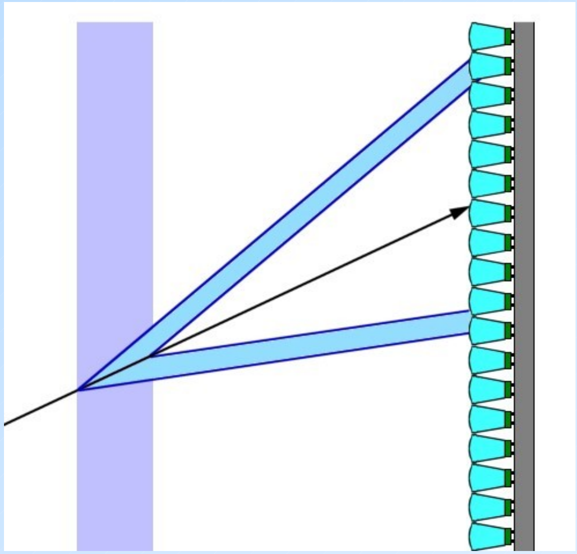




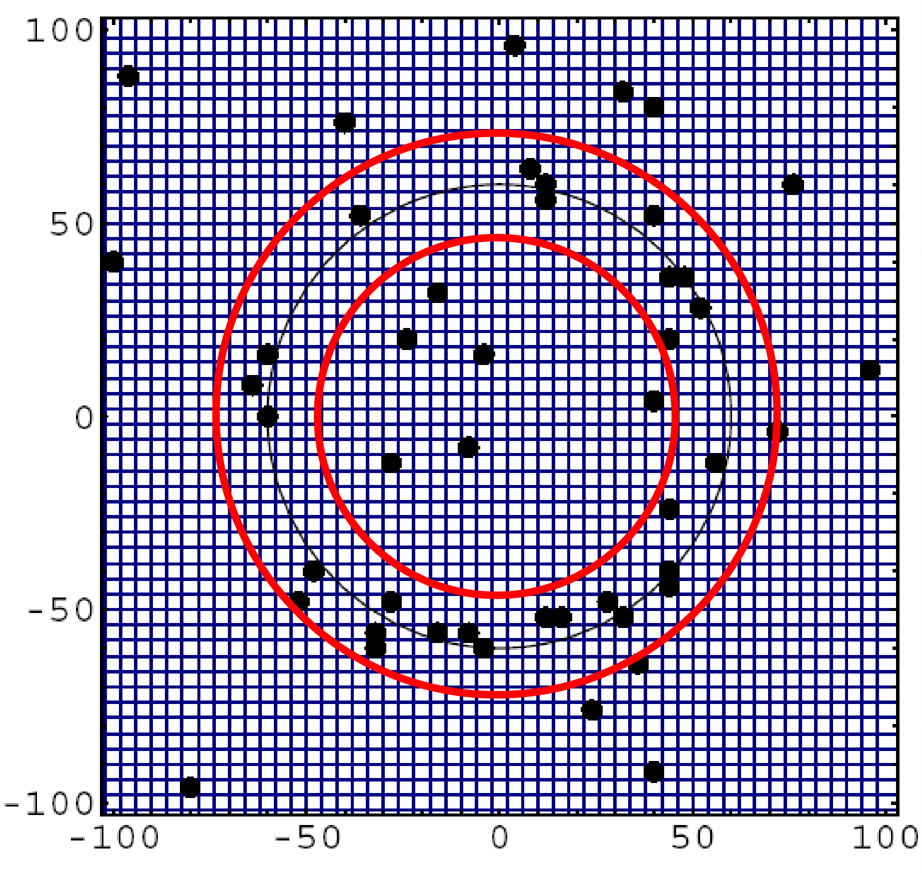
Signal to noise

Expected number of background hits depends on:

- ring area ~ 2000 mm² (±3σ)
- dark count rate ~ 600kHz/mm²
- coincidence window ~ 5ns



$N_{dark} \sim 6 \quad \rightarrow \quad N_{ph}/N_{dark} \sim 3$

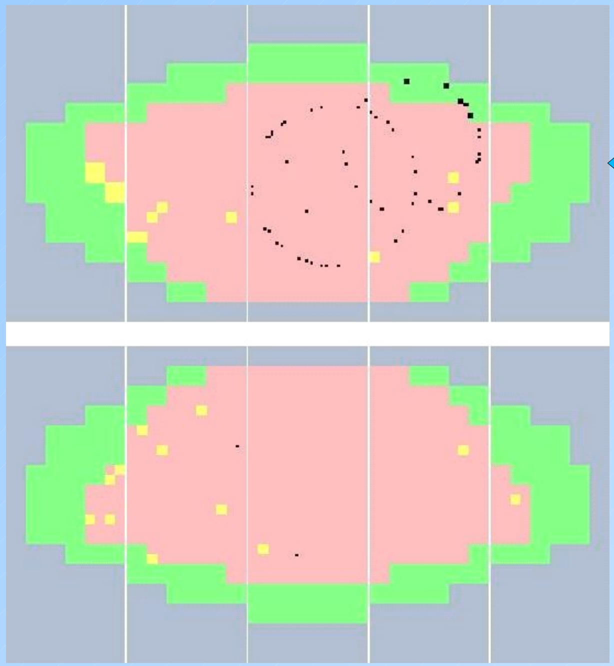


Ratio can be increased by:

- **smaller ring image area → high Cherenkov photon density**
- **narrower time window**
- **use of light collection system (light guides) to increase effective area of the sensor**

Can such a detector work?

Can such a detector work?

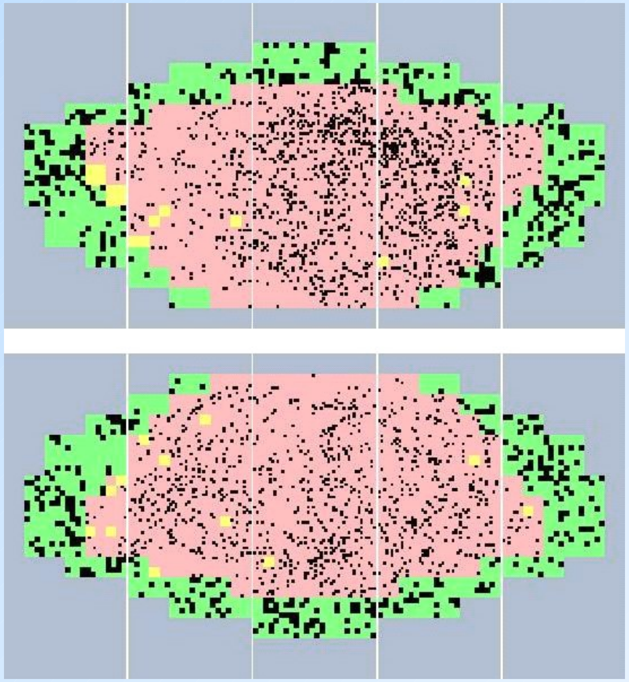


HERA-B RICH experience:

Little noise,

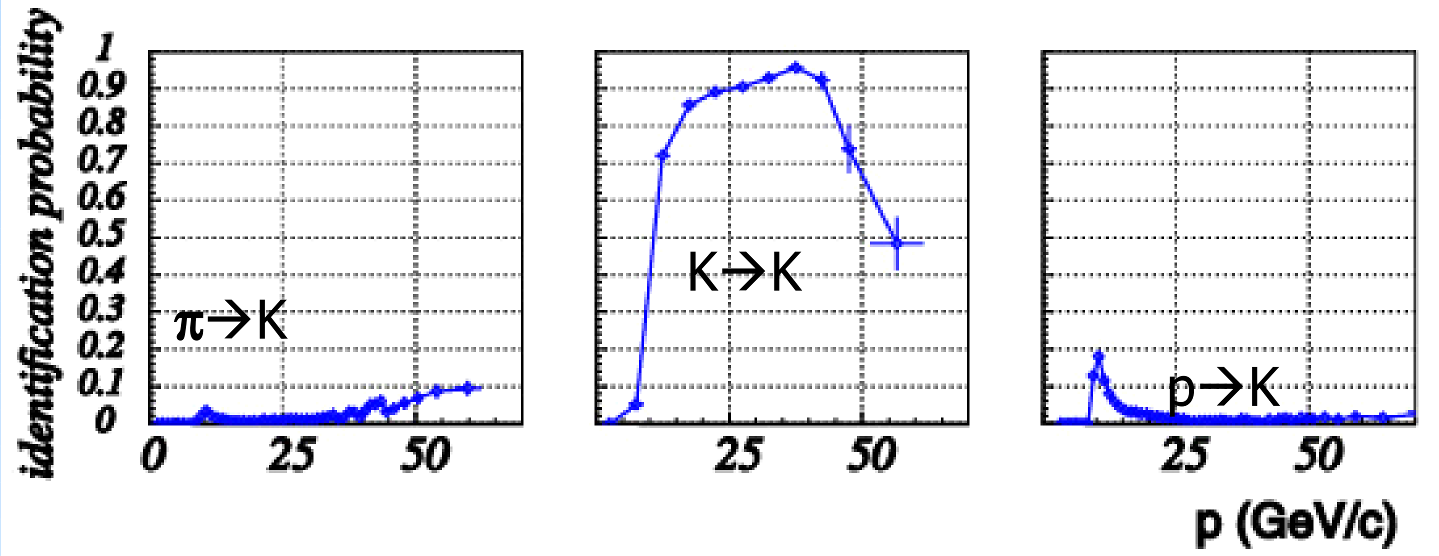
~30 photons per ring

Typical event



Worked very well!

Kaon efficiency and pion, proton fake probability

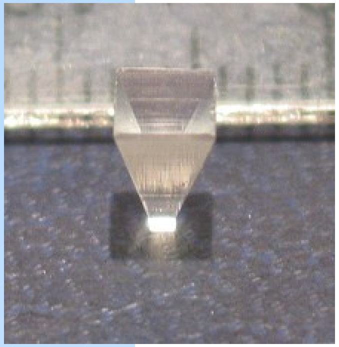


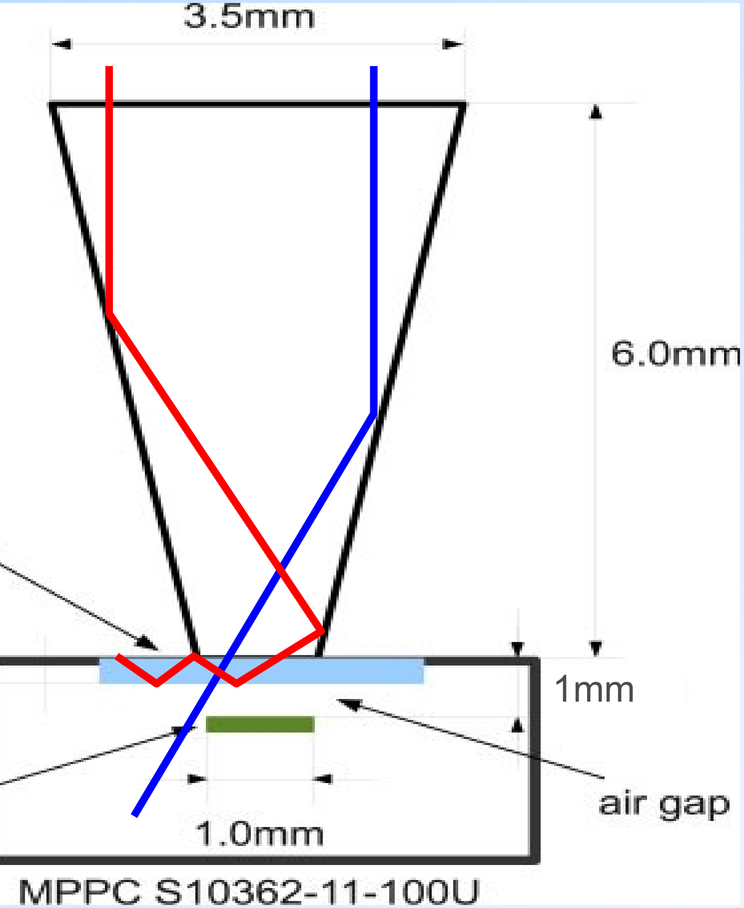
Need > 20 photons per ring for reliable PID

Light guide 3.5x3.5mm² to 1x1mm²

First attempt to attach light guides to MPPCs.

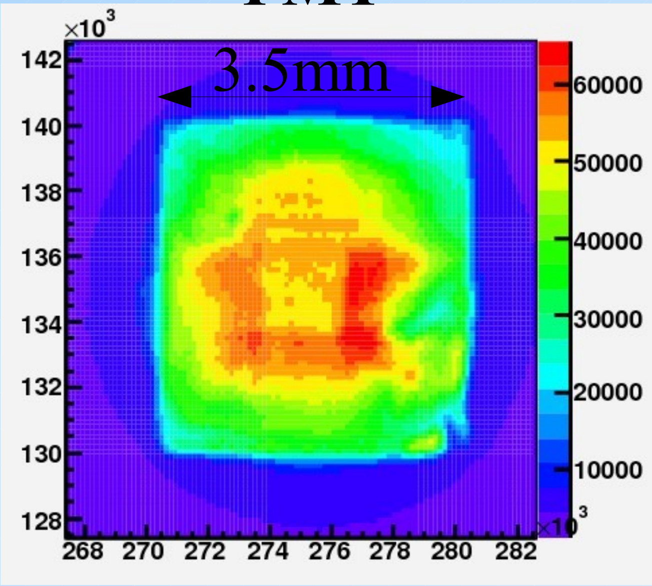
- area ratio ~ 12
- average efficiency ~ 0.5 (entrance to exit surface)



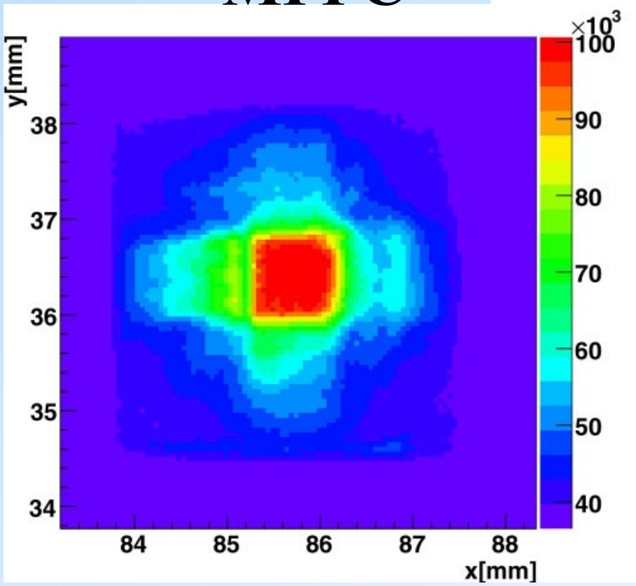


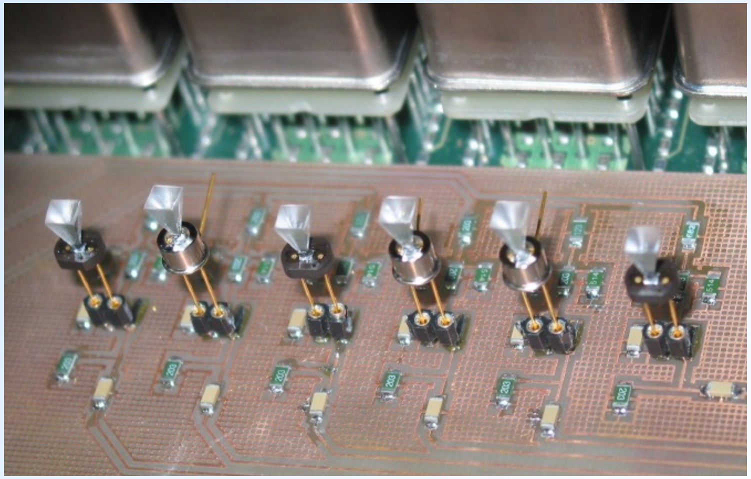
- light guide test with pencil beam (400nm, 90⁰)

PMT



MPPC





Test with cosmic rays

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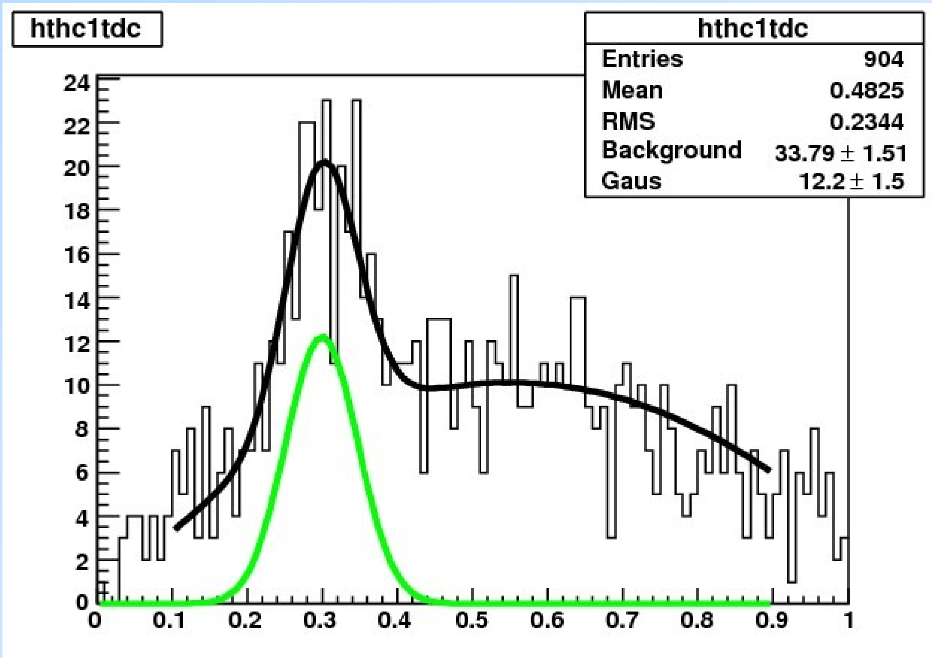
First successful tests with cosmic rays:

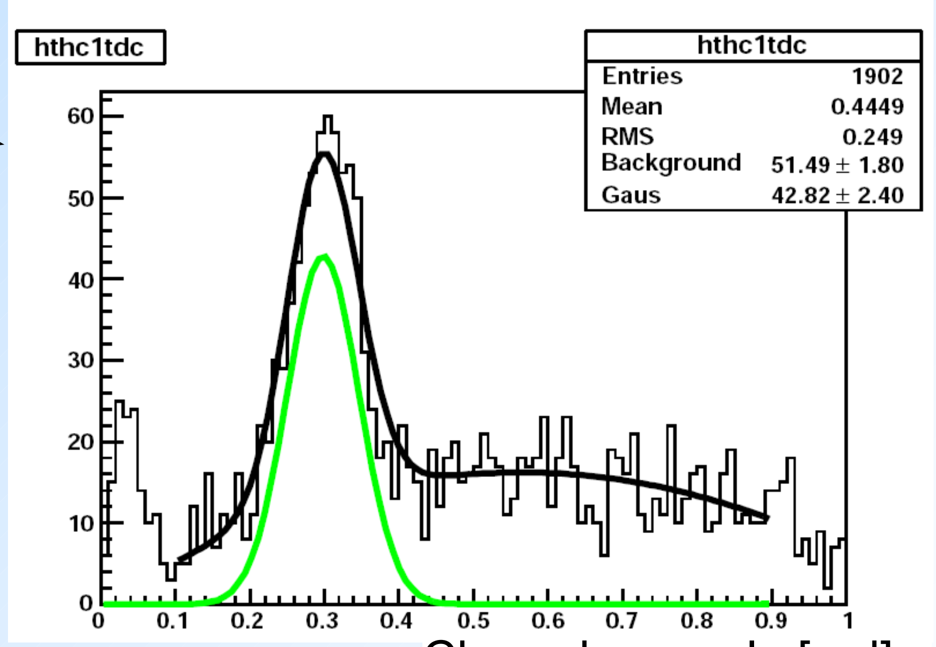
No light guides:

- 43600 tracks
- Cherenkov photons ~ 146
- 0.0033 photons per track



With light guides:

- 38100 tracks
- Cherenkov photons ~ 285
- 0.0072 photons per track



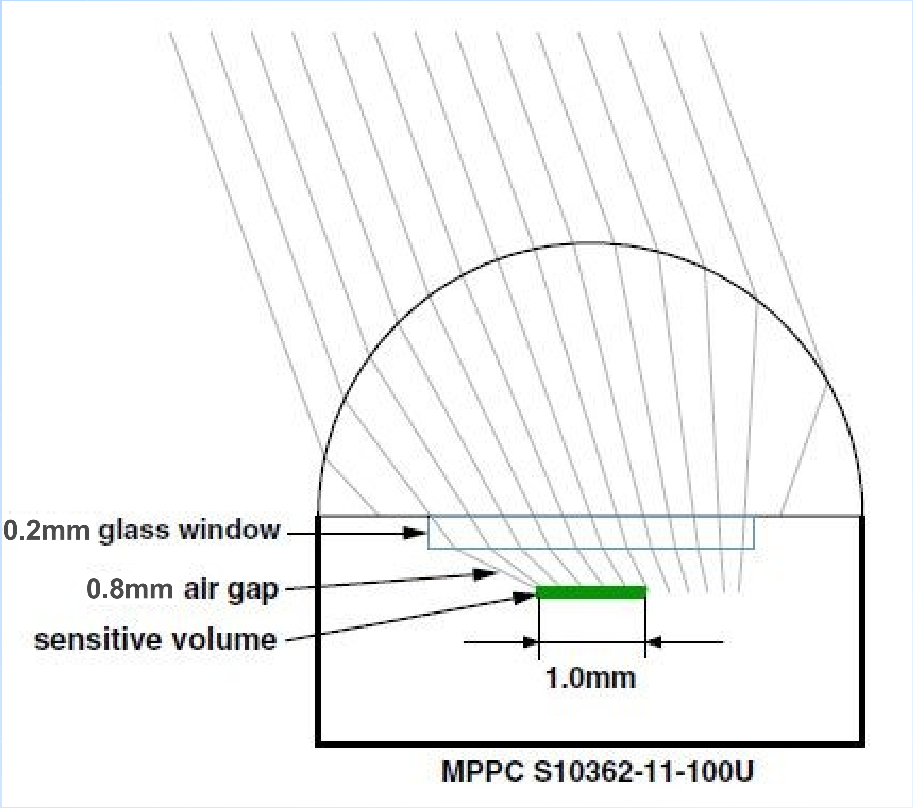
$N_{w/} / N_{w/o} \sim 2.2$

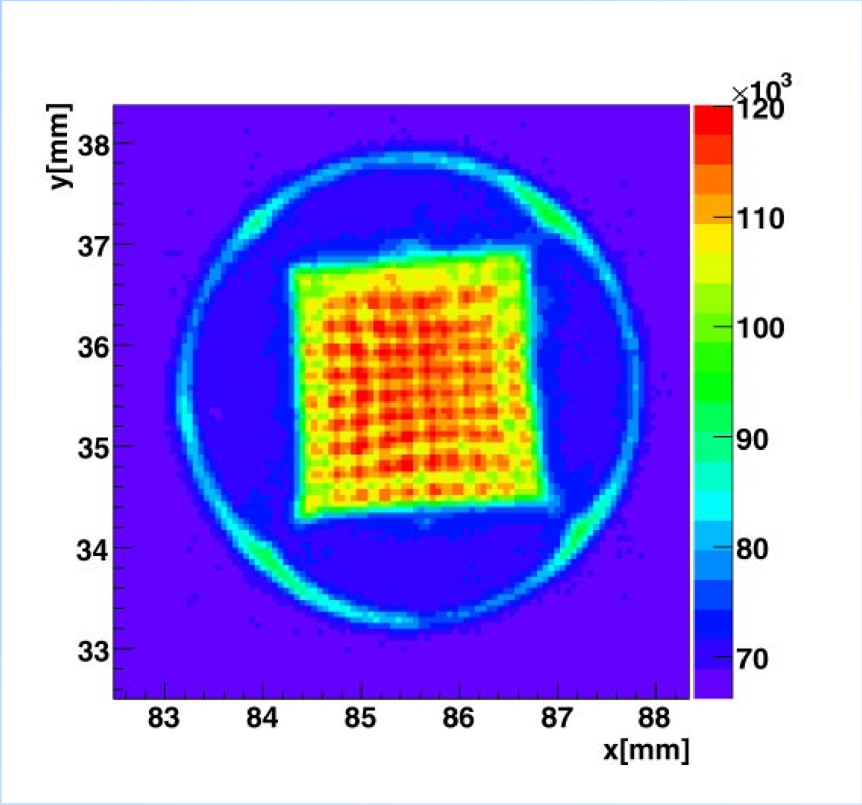
Light guide should be as close as possible to the MPPC surface.

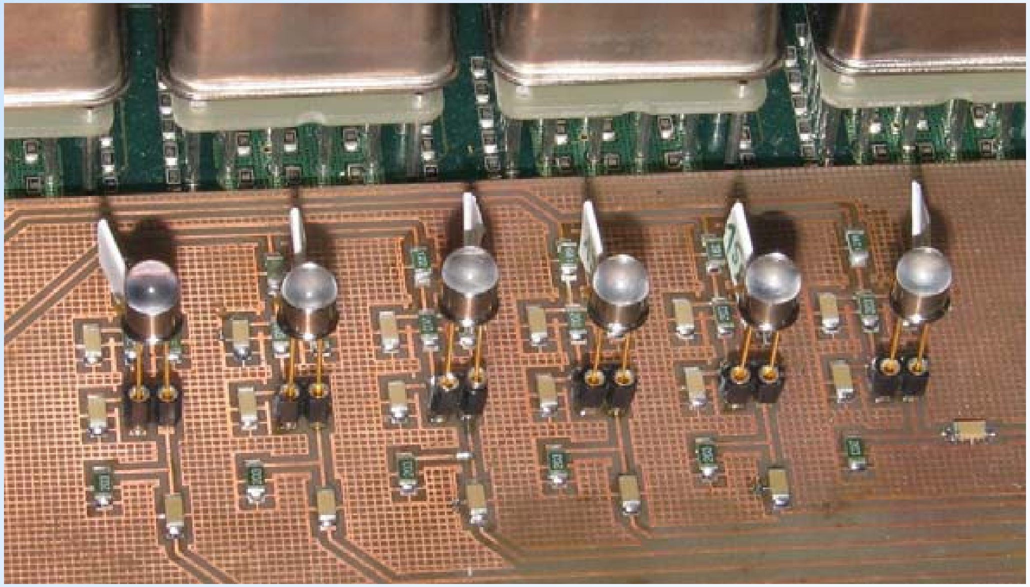
Hemispharical light guides

• Spherical light guides give better results with metal package:

$$N_{w/} / N_{w/o} \sim 3.6$$







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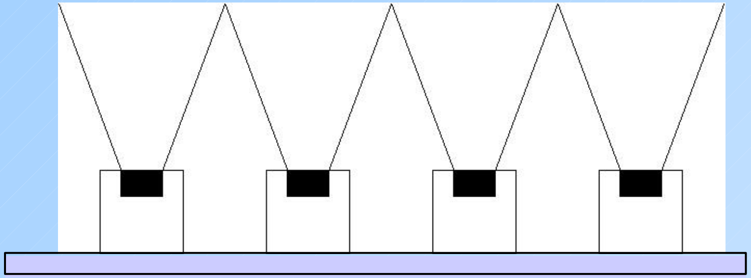
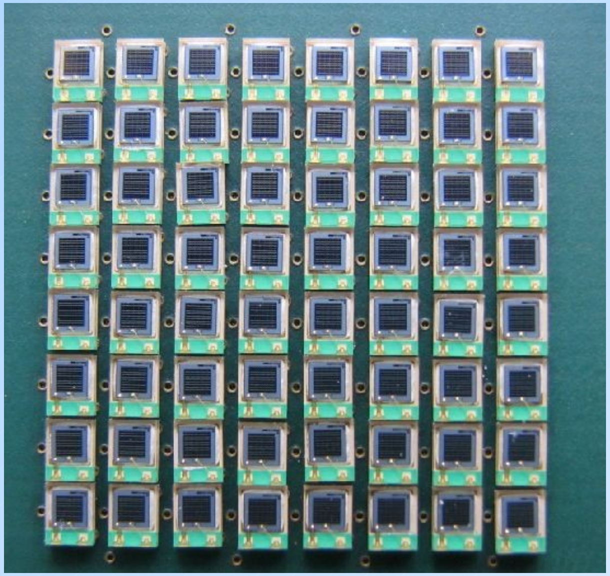
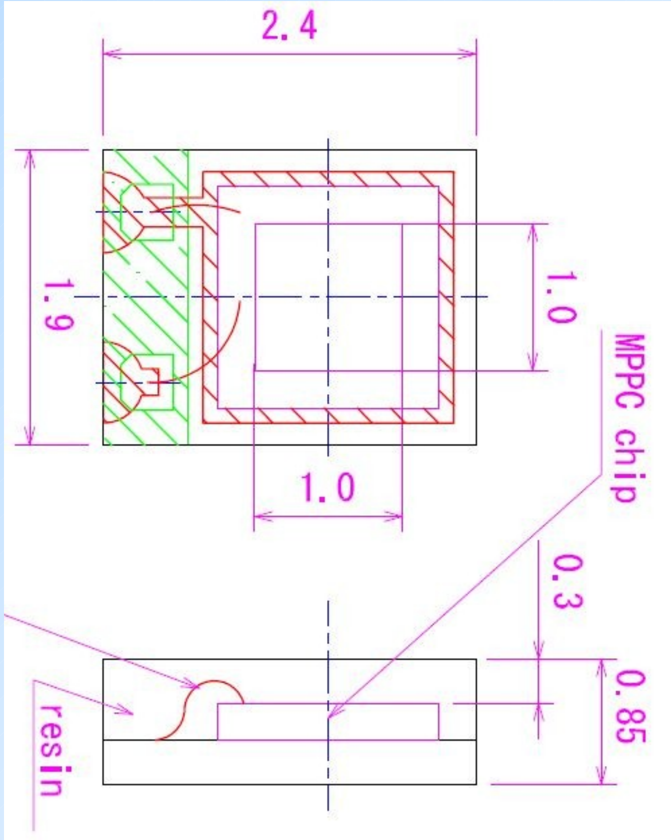
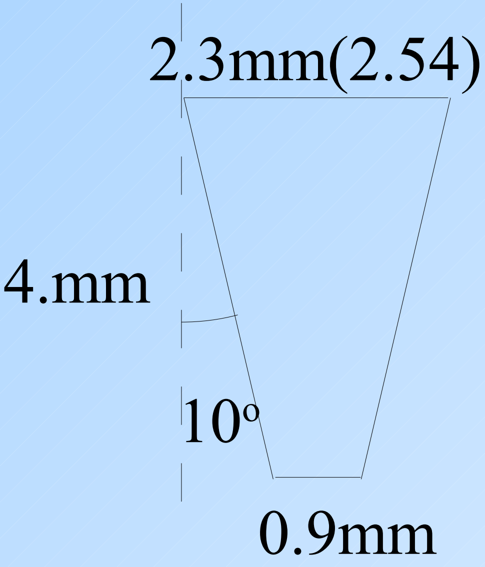
8x8 array of SMD-MPPCs

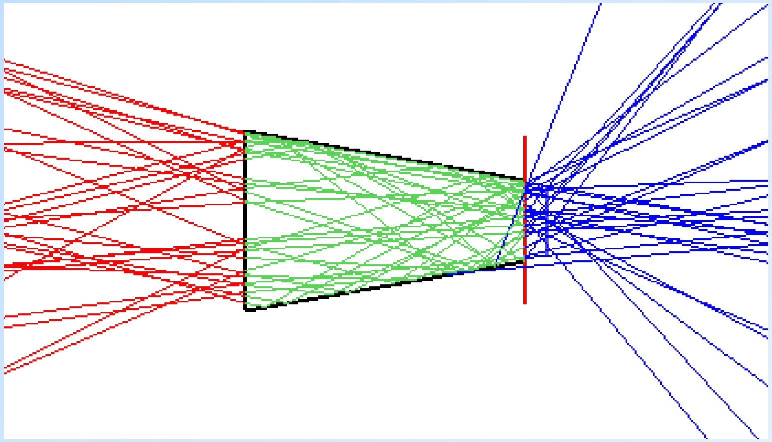
- Detector module with 8x8 array of SMD MPPCs at 2.54 mm pitch

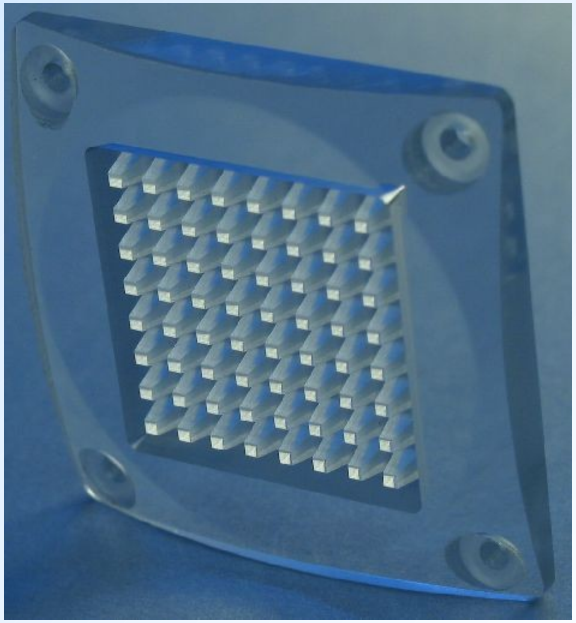












Light guides were machined from plastic (HERA-B lens material).

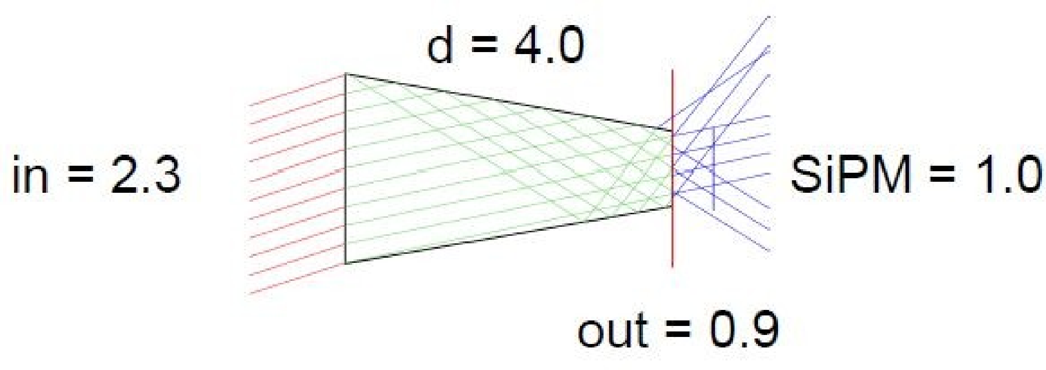
Light guide simulation

Simulation includes:

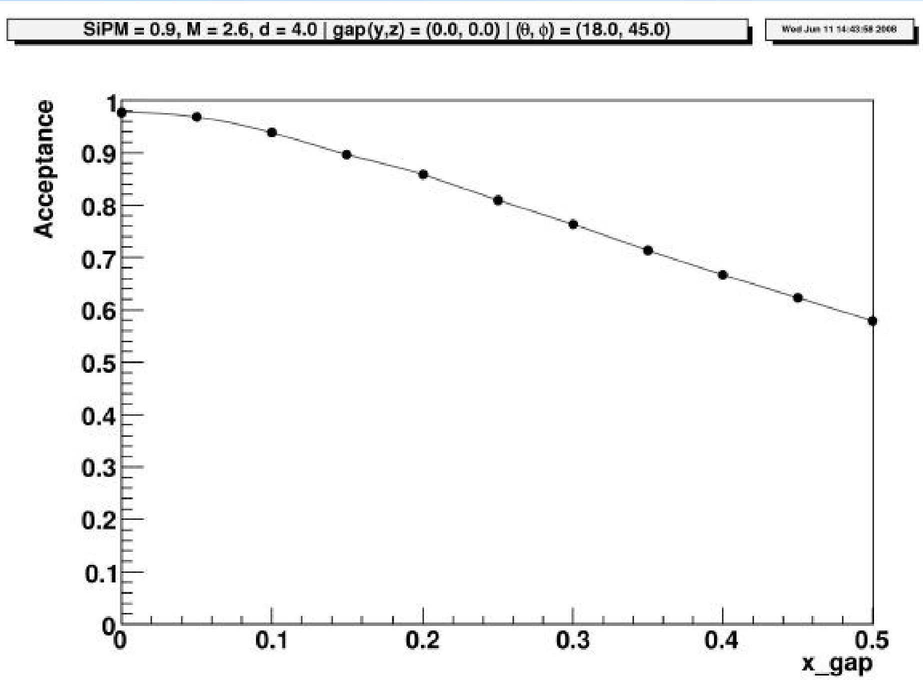
- refraction at LG entrance
- total reflection
- gap between LG exit and MPPC surface

Not included:

- absorption
- imperfect light guide surface



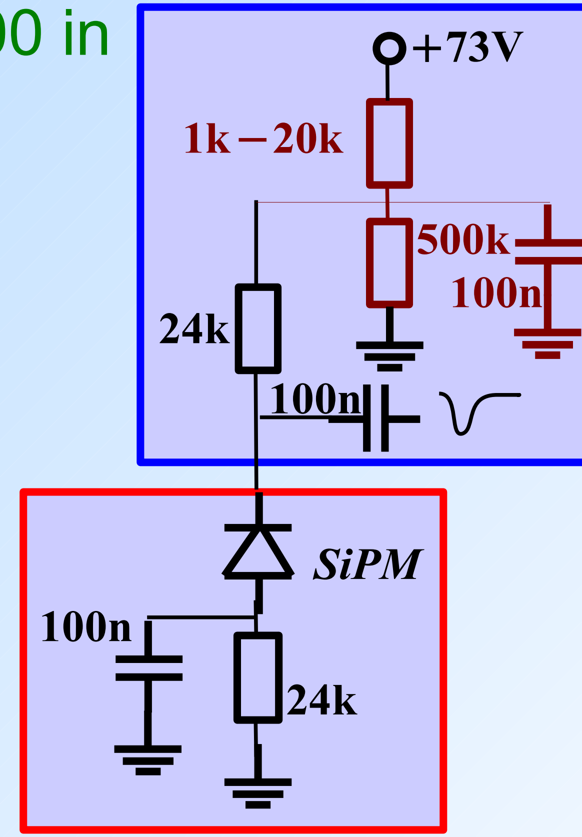
θ = 18°
φ = 45°

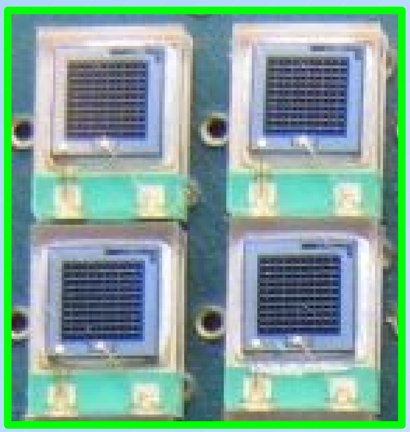


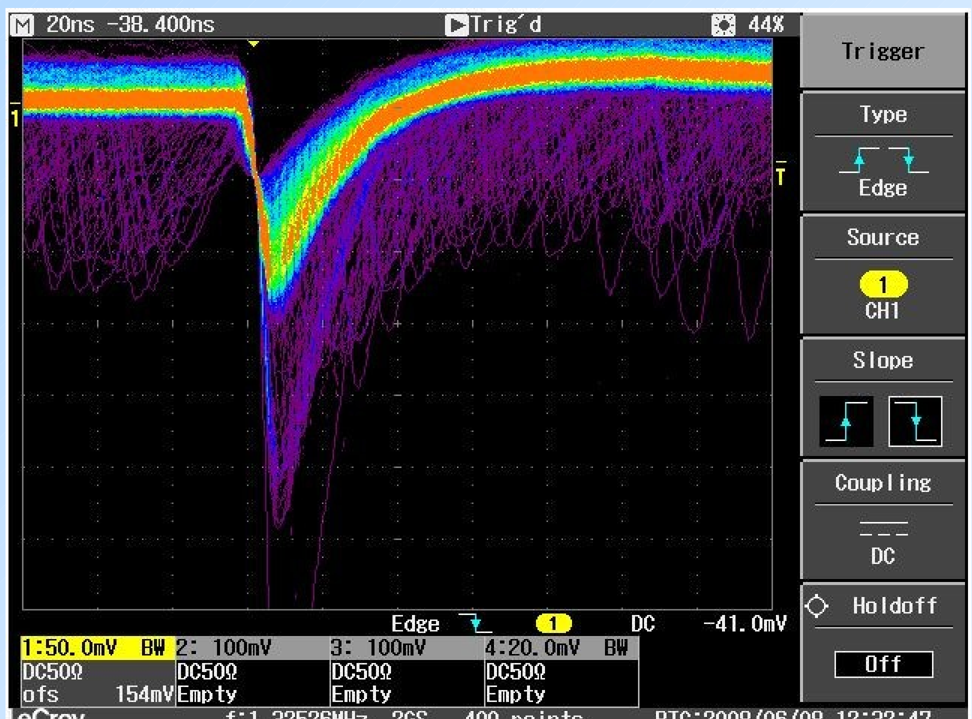
t=18,p=45		
gap	w	w/o
	0.00	97.67
	0.05	96.62
	0.10	94.11
	0.15	89.68
	0.20	85.99
	0.25	81.06
	0.30	**76.12**
	0.35	71.49
	0.40	**66.85**
	0.45	62.44
	0.50	**58.39**

MPPC module

- main board with dividers, bias and signal connectors
- piggy back board with MPPCs (8x8 array of HC100 in SMD package; background ~ 600kHz/MPPC)
- light guides
- 16 electronics channels (4x4) - 4 MPPCs connected to single channel







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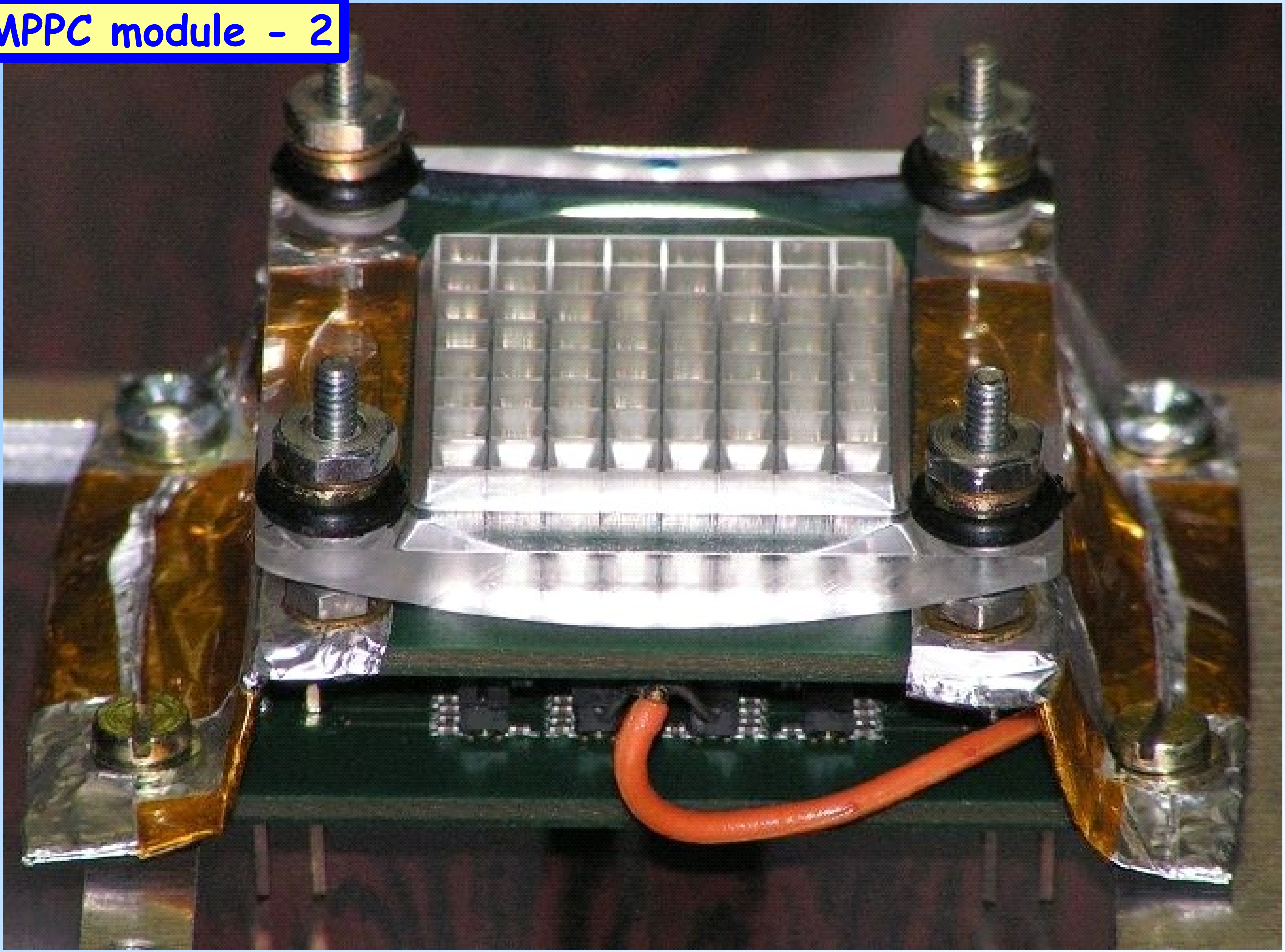
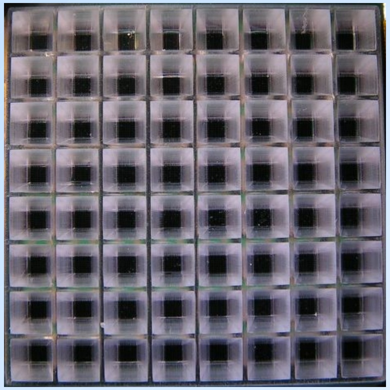
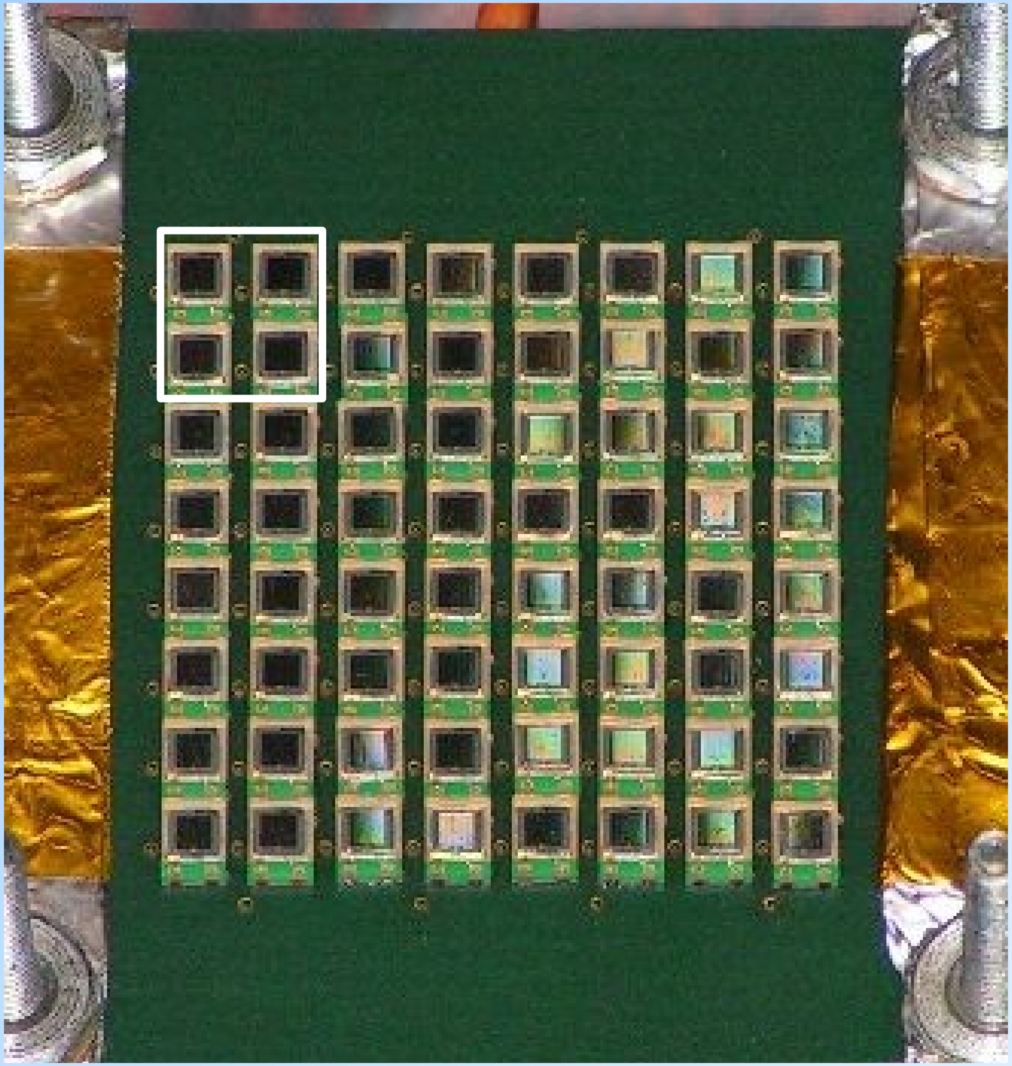
MPPC module - 2

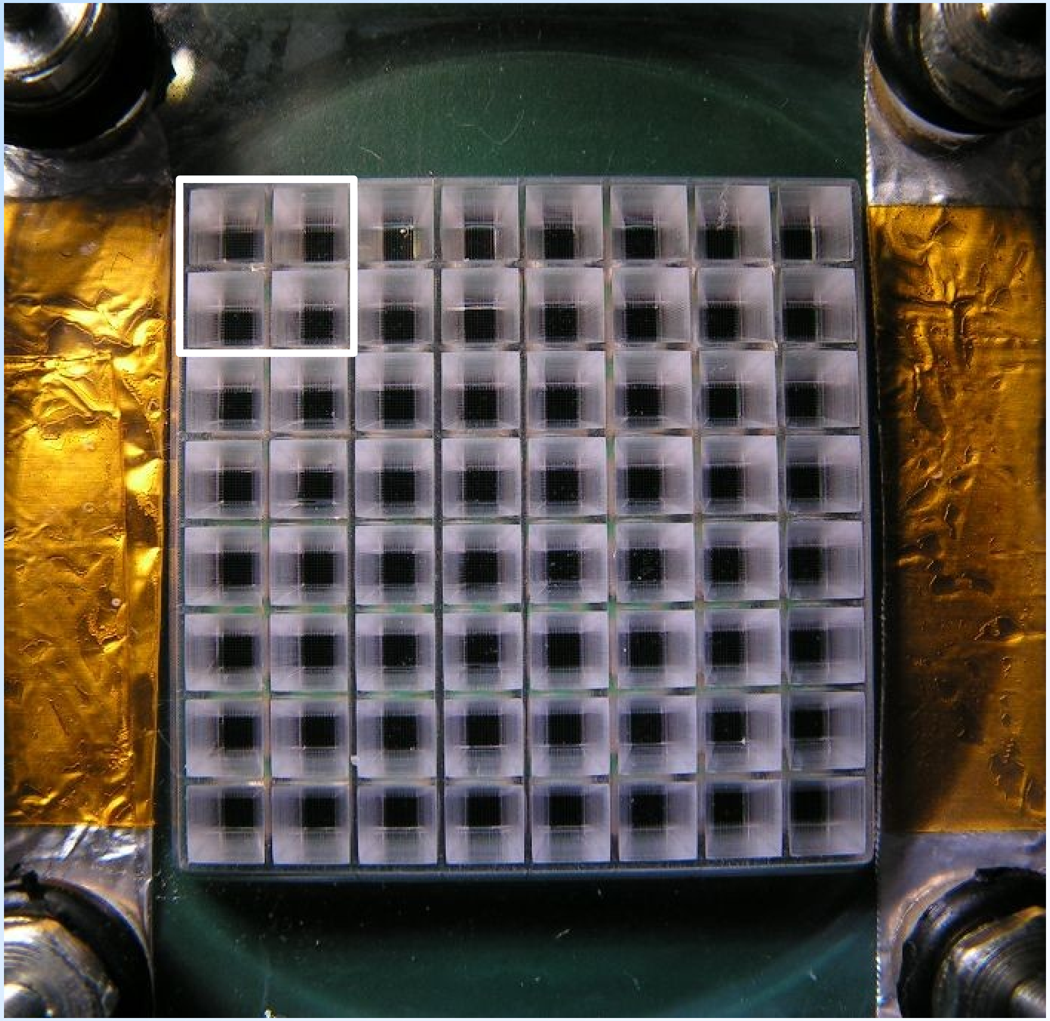


MPPC module - 3

- pad size 5.08 mm, 4 mm2 active (15.5% w/o LG)







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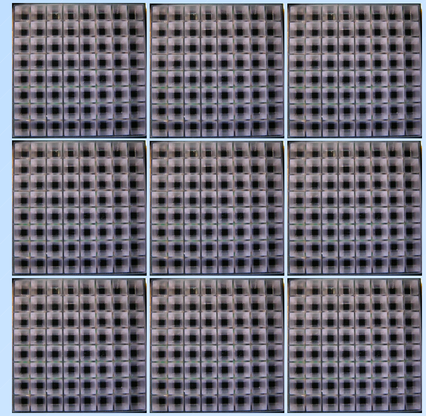
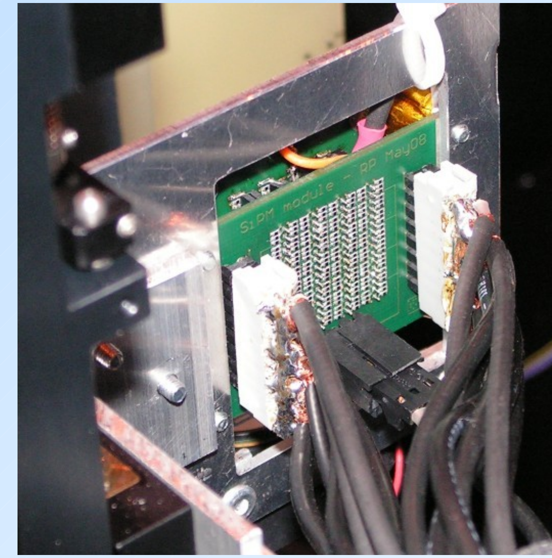
Beam test setup

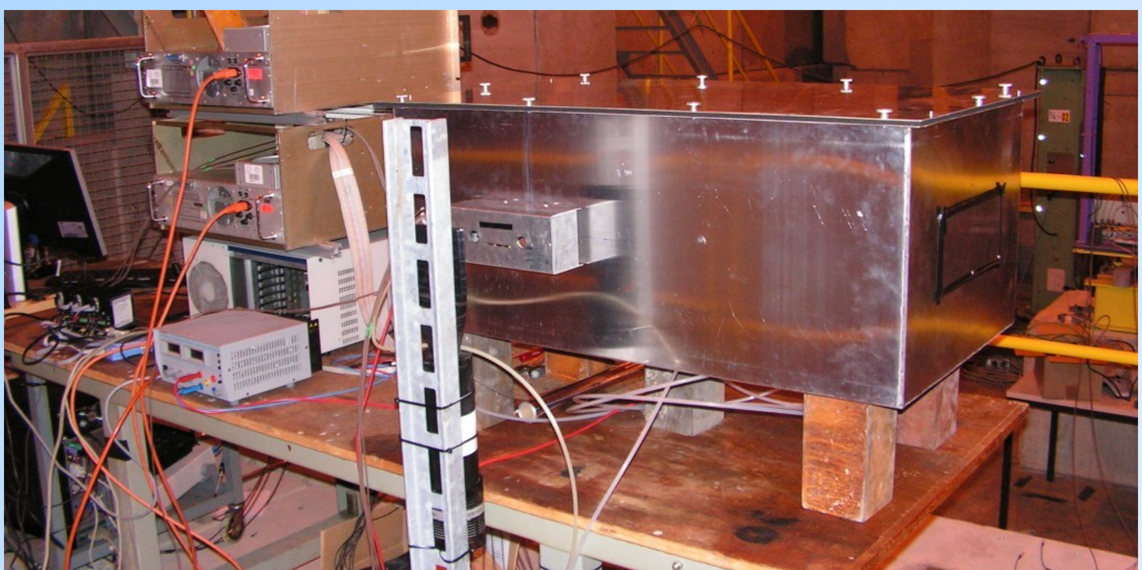
- MPPC array w/o or w/ light guide mounted on 3D stage

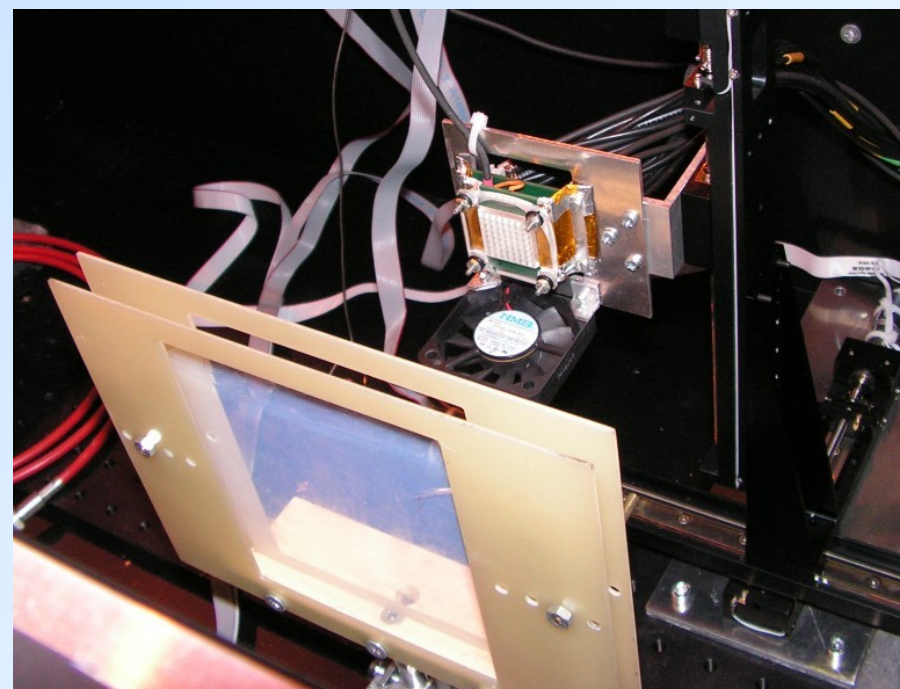
→ effective detector size 3x3

- aerogel n=1.03, d=10mm (distance 130mm)
- hits detected by multi-hit TDC
- +120 GeV/c pions, beam size ~1cm^2
- 2 MWPCs for tracking
- plastic scintillator for timing





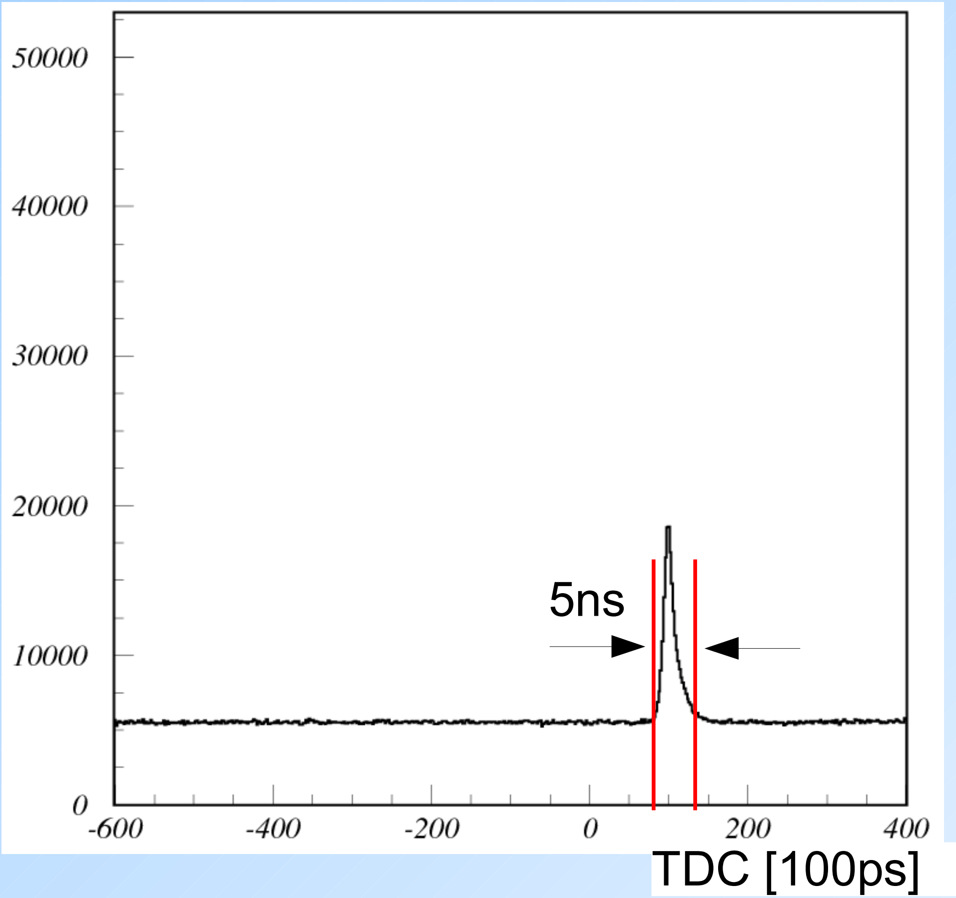




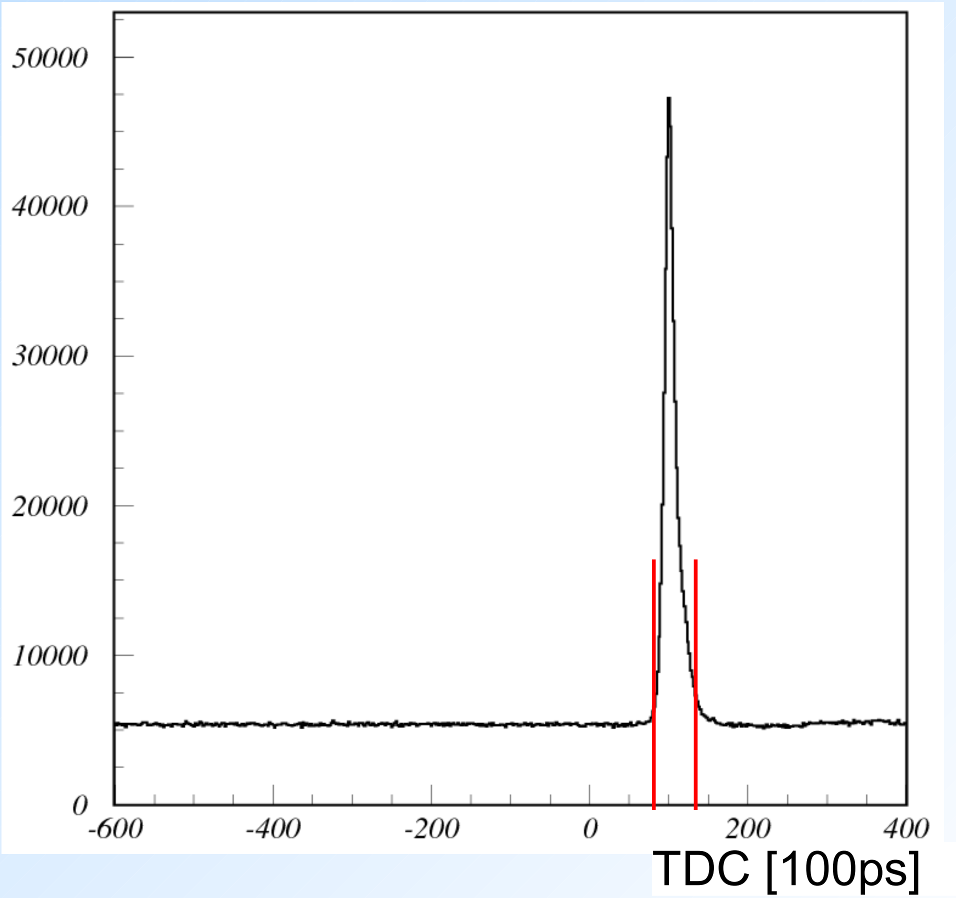
TDC distributions of MPPC hits for all events

- total noise rate ~ 35MHz (~600kHz/MPPC, ~2.4MHz/ch.)
- hits in the time window of 5ns around the peak are selected for Cherenkov angle analysis

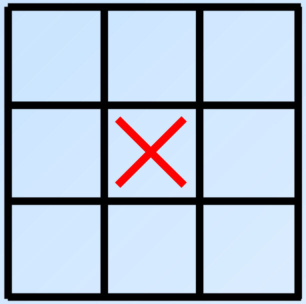
w/o light guides



w/ light guides

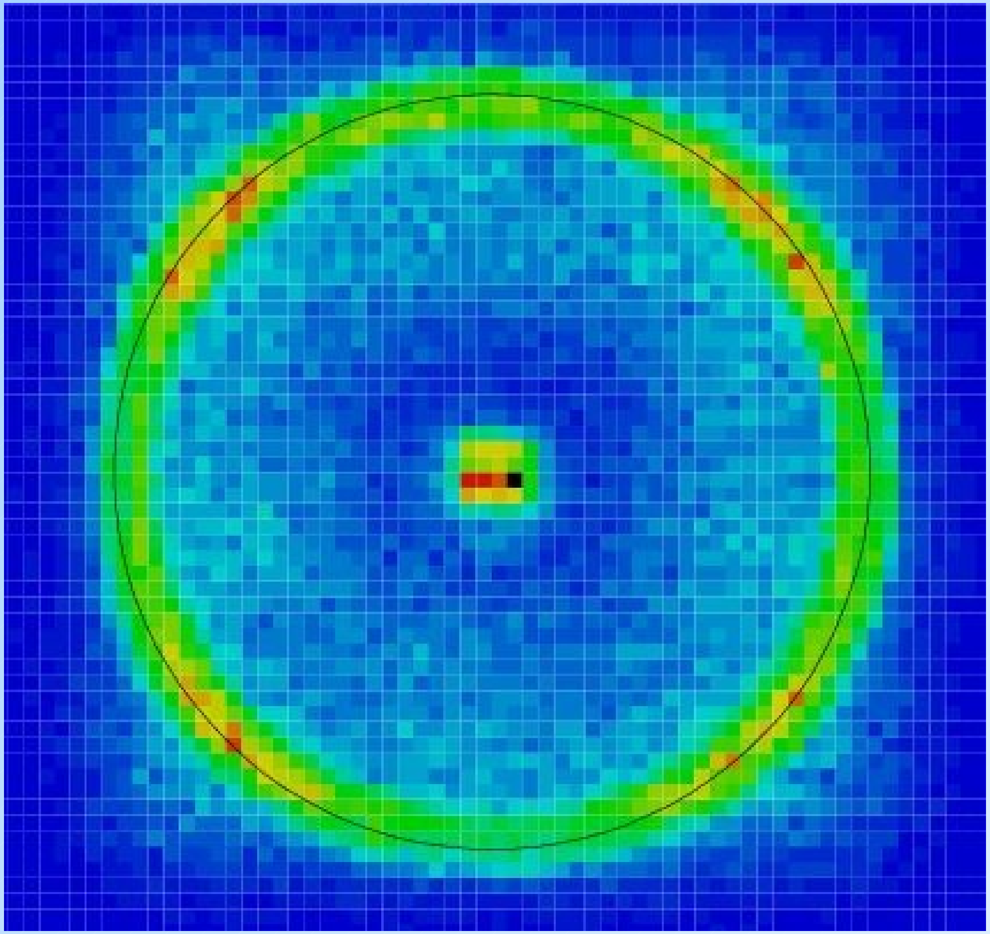


Ring images

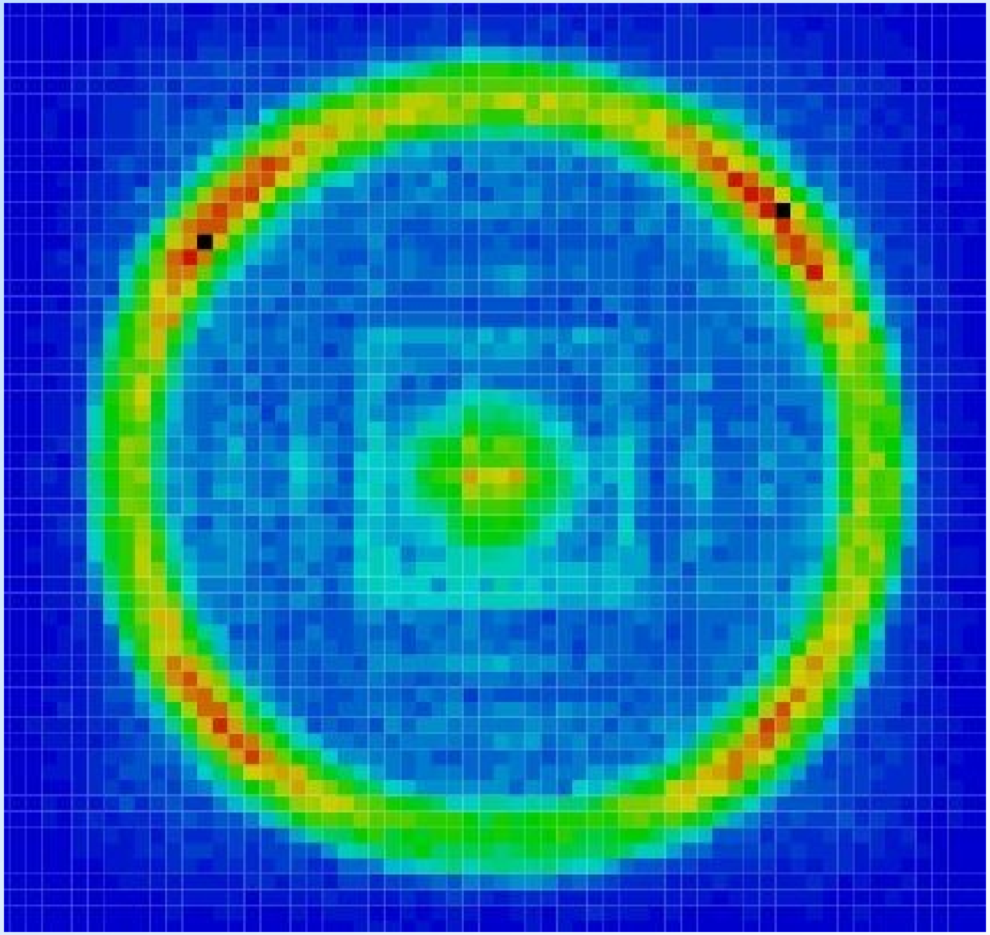


- module was moved to 9 positions to cover the ring area
- these plots show only superposition of 8 positions (central position is not included)

w/o light guides

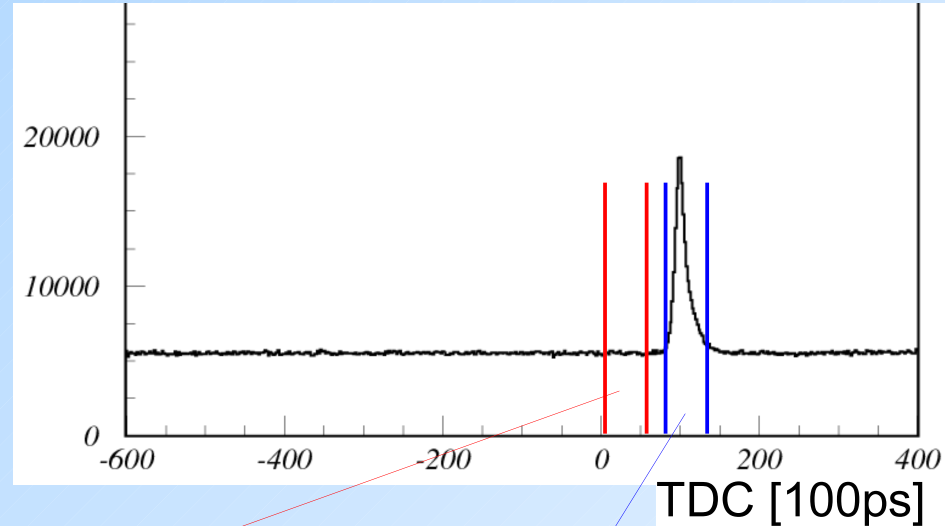


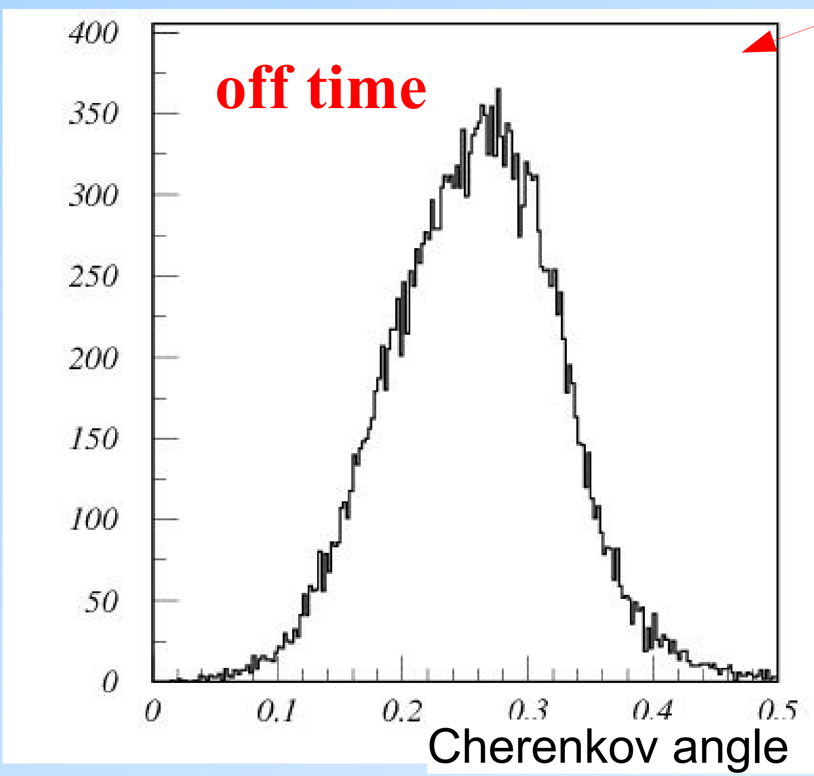
w/ light guides

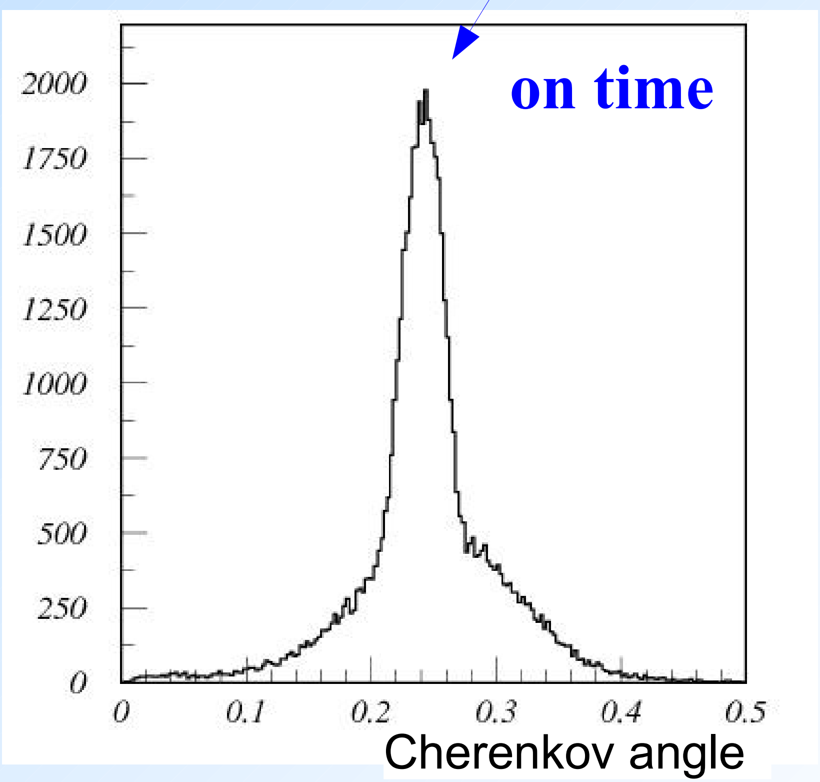


Cherenkov angle distributions

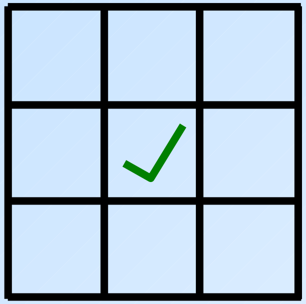
- background from MPPC noise hits is obtained from sideband in TDC distribution



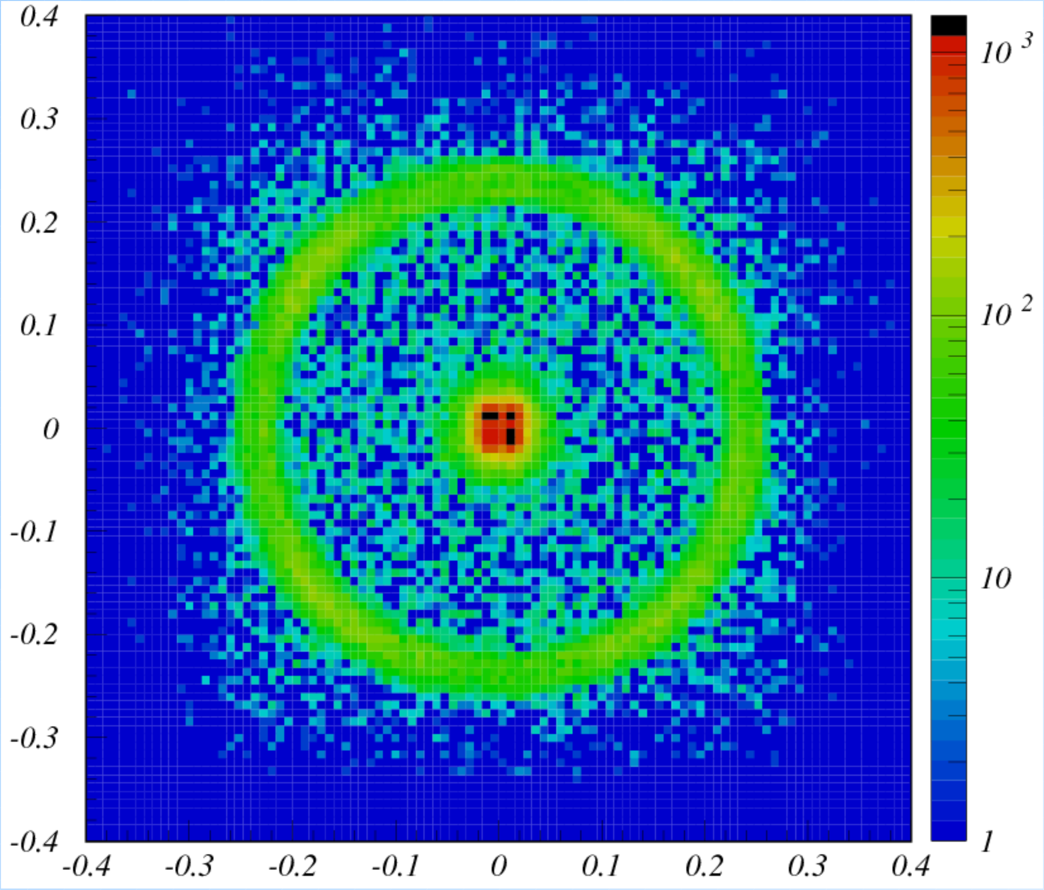




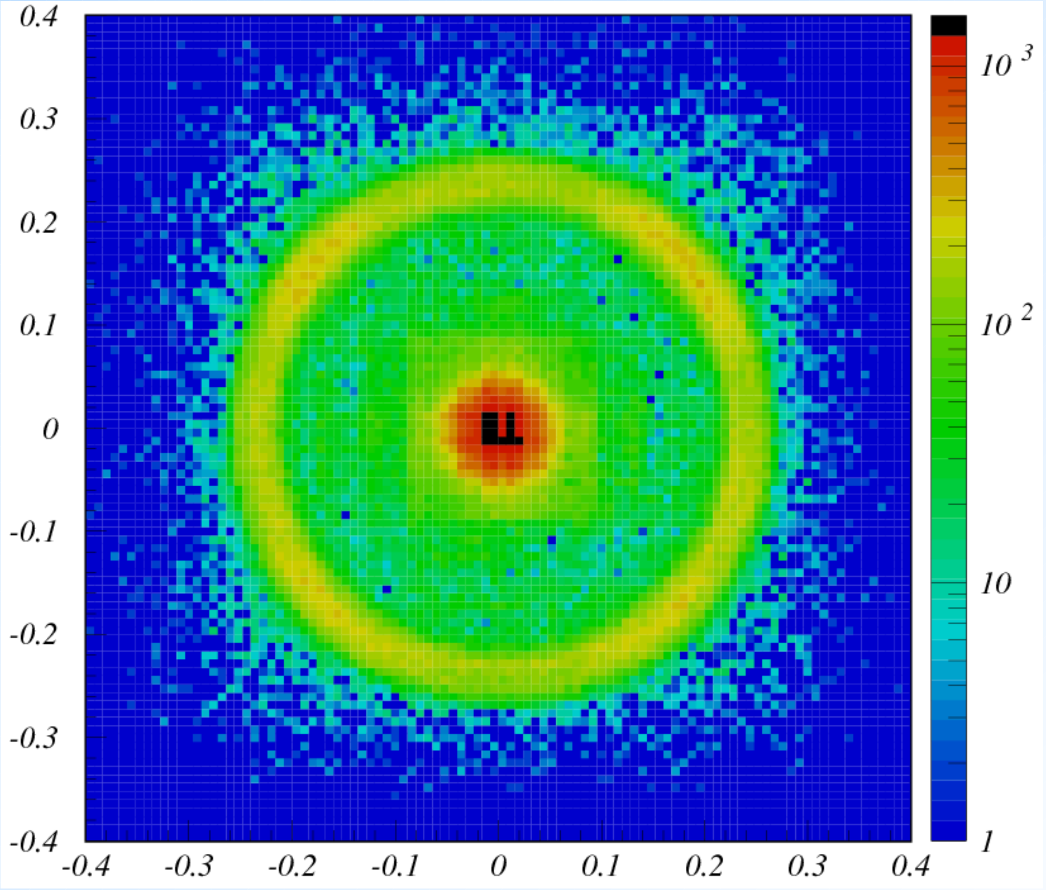
Ring images – background subtracted



w/o light guides



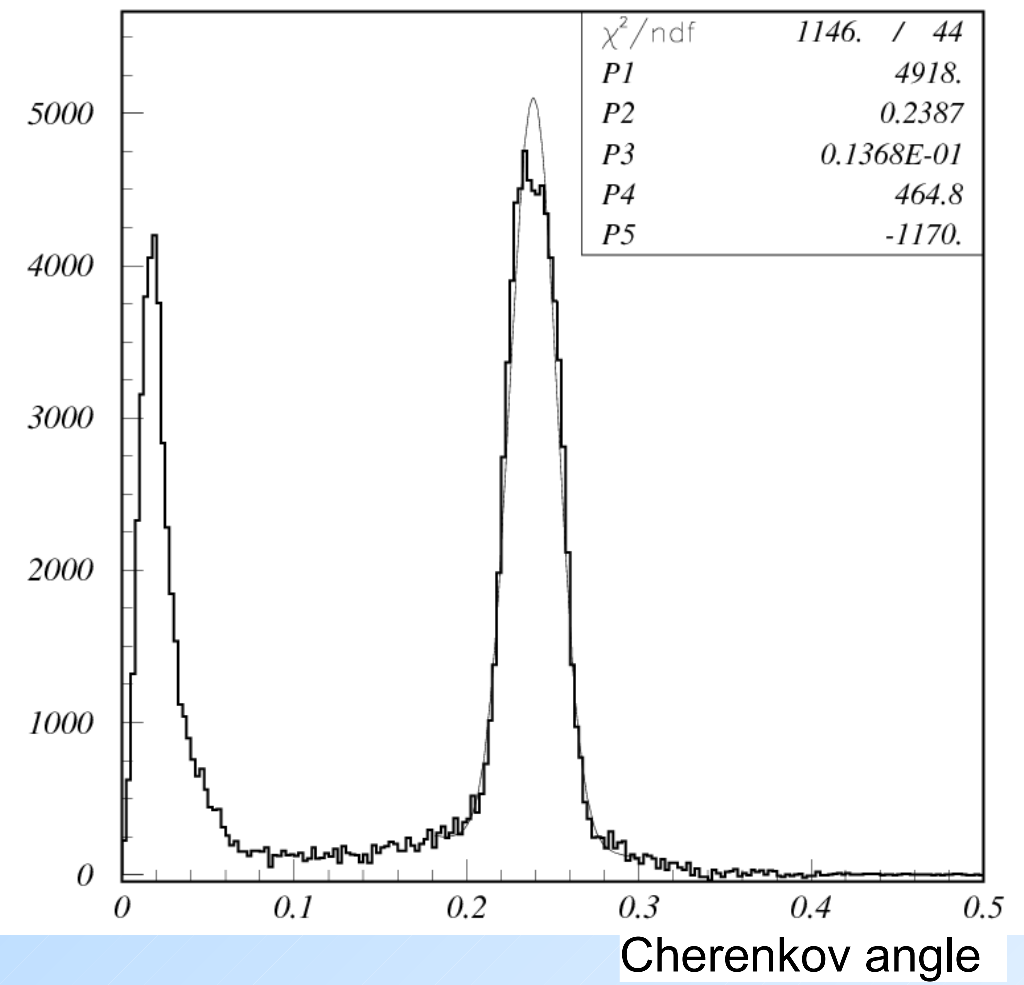
w/ light guides



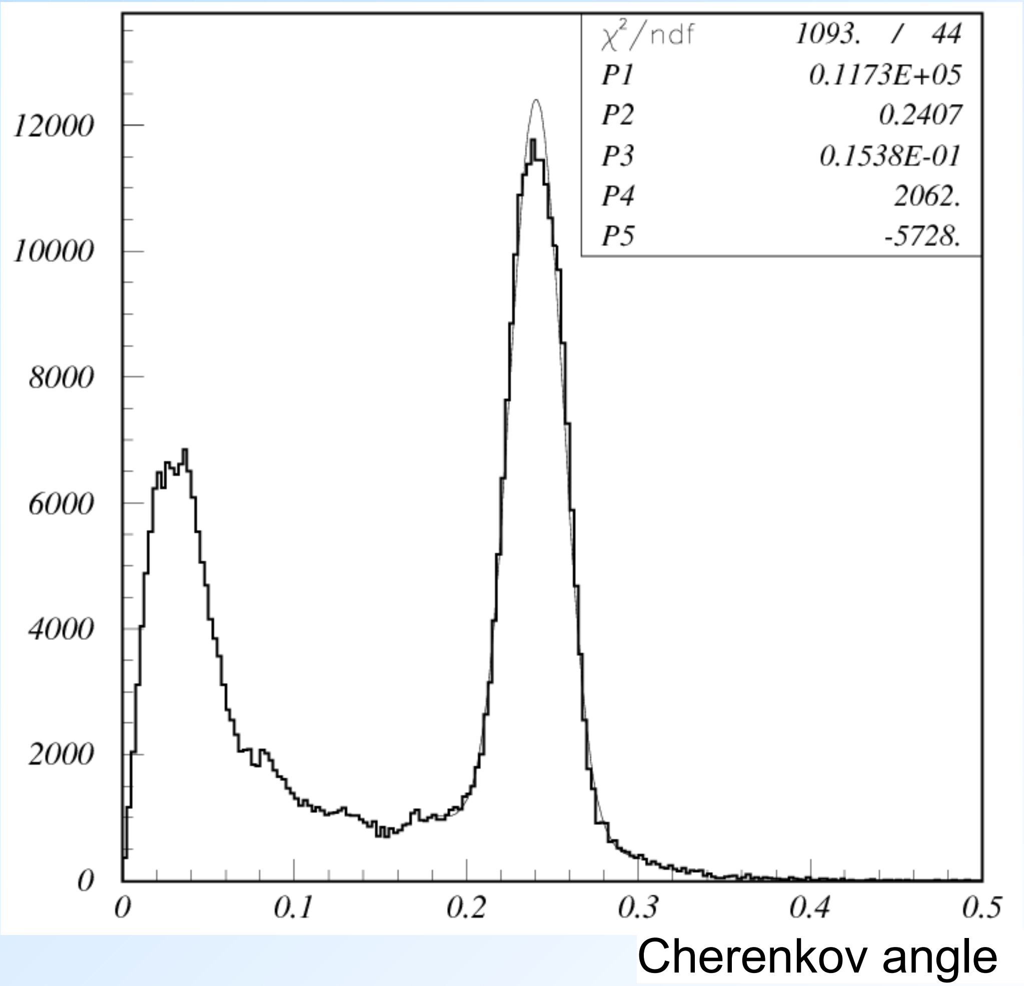
Cherenkov angle distributions

- background subtracted distributions
- ratio of detected photons w/ and w/o light guides: ~ 2.3
- resolution within expectations (~14mrad)

w/o light guides



w/ light guides



Number of photons

Expected number of photons is 2.5/full ring, this includes:

- Hamamatsu PDE
- aerogel: 1cm thickness, n=1.03, 14mm attenuation length
- dead time and double hit loss ~10%

Measured (extrapolated to full ring - acceptance corrected):

- w/o LG ~ 1.6
- w/ LG ~ 3.7

Estimated numbers for aerogel with n=1.05 and thickness of 4cm (~5x) and better quality of the surface of light guides (~2x) are

- w/o LG ~ 8
- **w/ LG ~ 37**

Summary

• A photon detector module was constructed using 8x8 array of MPPCs (SMD package, 4x4 electronic channels) and a light guide array

• A proximity focusing RICH with 1cm aerogel radiator (n=1.03) and the detector module was successfully tested in a test beam at CERN

• The number of detected photons per ring is about 60% of the expected number

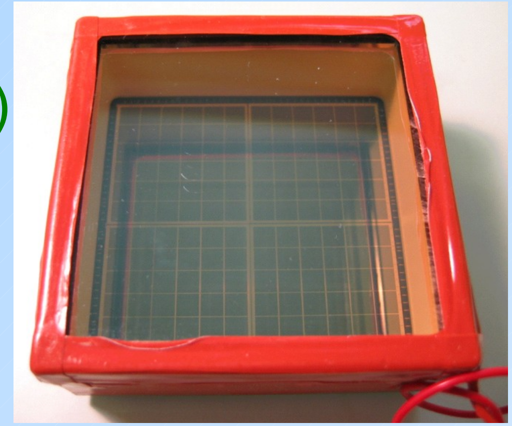
• Efficiency increase with light guides ~ 2.3 (area ratio ~ 5.5)

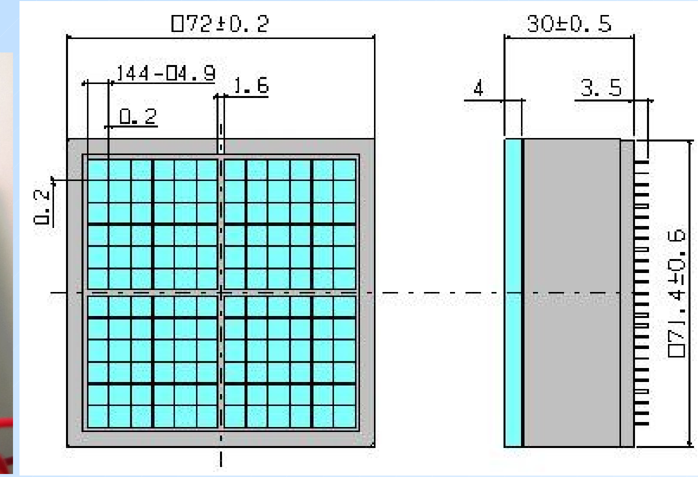
• **Geiger-mode APD can be used as a detector of single photons in RICH counters.**

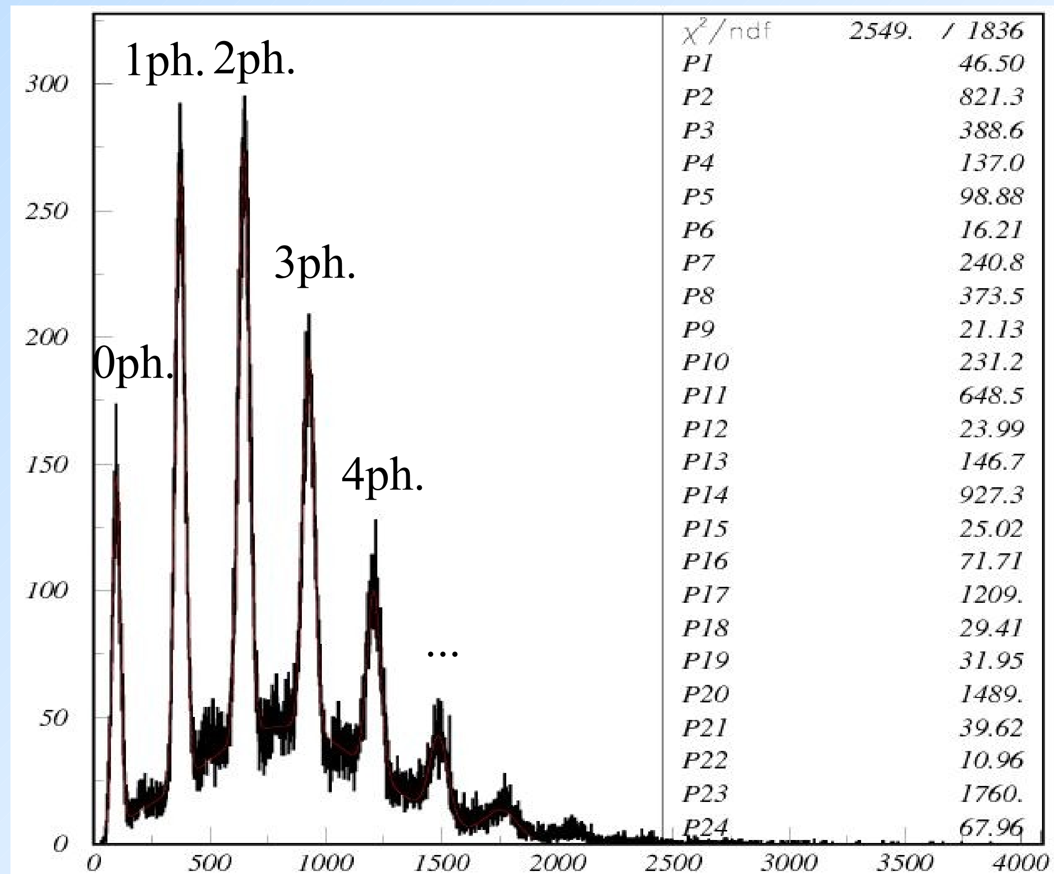
Photon detector candidate: HAPD

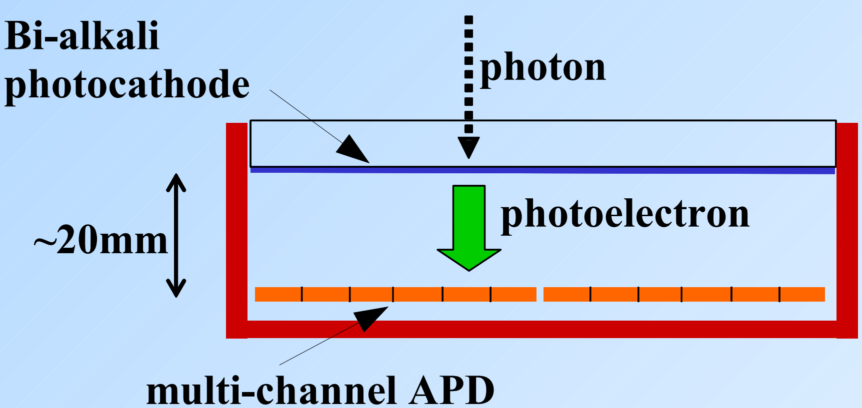
Hybrid avalanche photo-detector (proximity focusing configuration)

- 12x12 channels (~5x5 mm^2)
- size ~ 72mm x 72mm
- ~ 65% effective area
- total gain ~ $10^4 – 10^5$ (bombardment~1000, avalanche~40)
- detector capacitance ~ 80pF/ch.
- typical peak QE ~ 25%
- works in mag. field (~perpendicular to the entrance window)



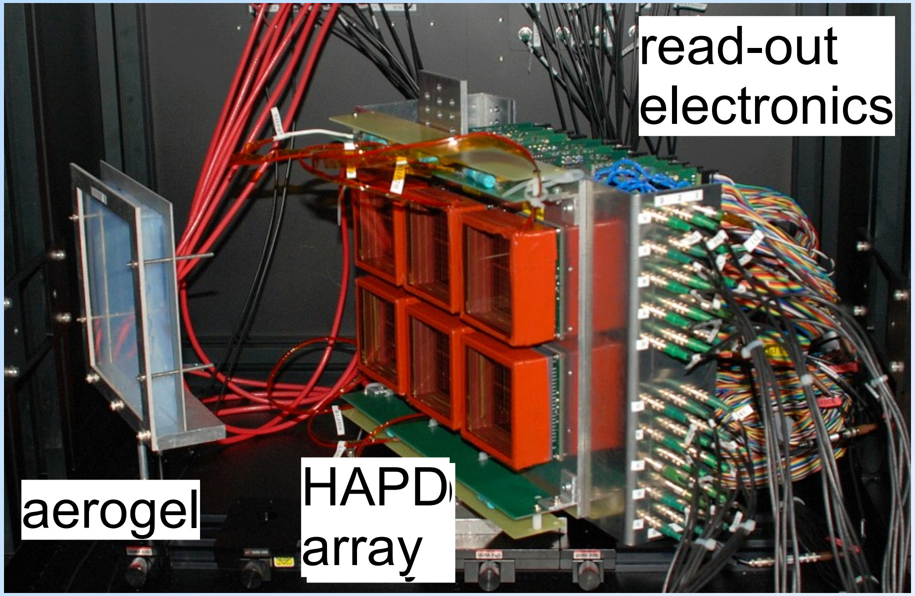


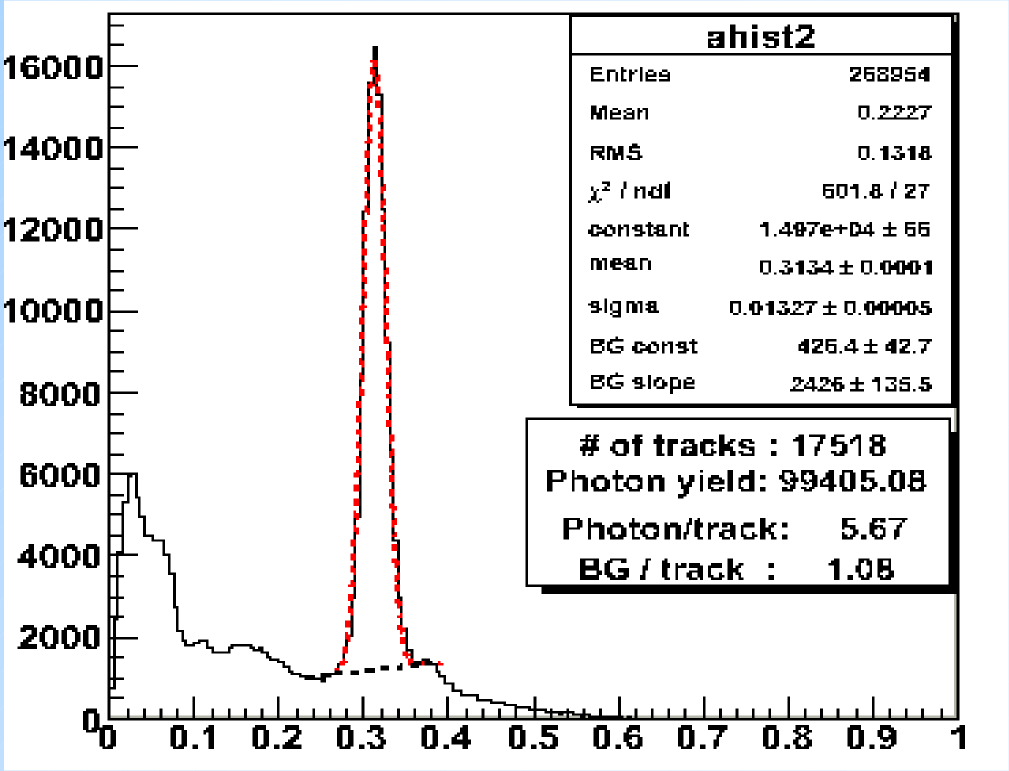


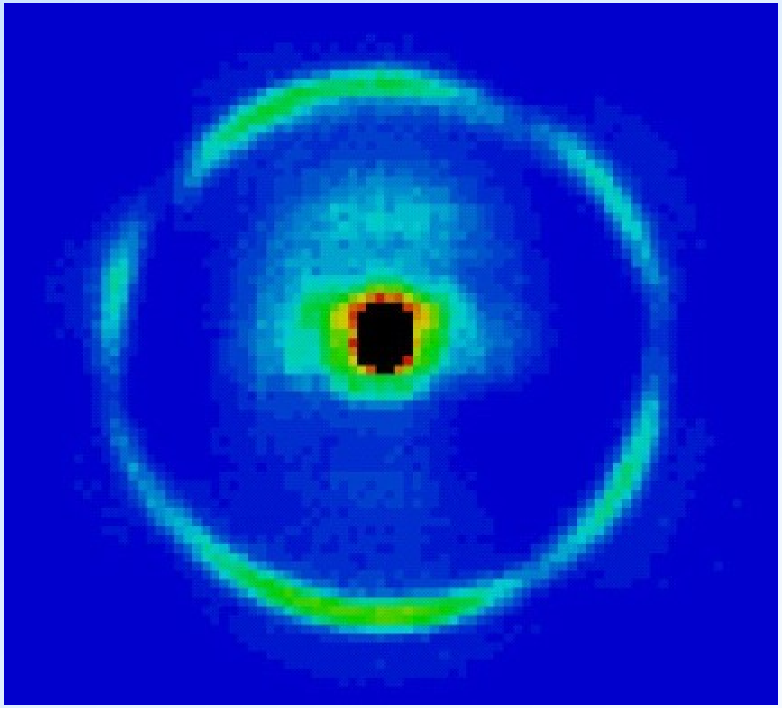


Beam test results

- test with 2 GeV/c electrons @ KEK
- detected number of photons: ~ 6
- Cherenkov angle resolution: ~ 13mrad
- large background due to the Cherenkov photons produced in the HAPD window
- second ring due to reflection on APD



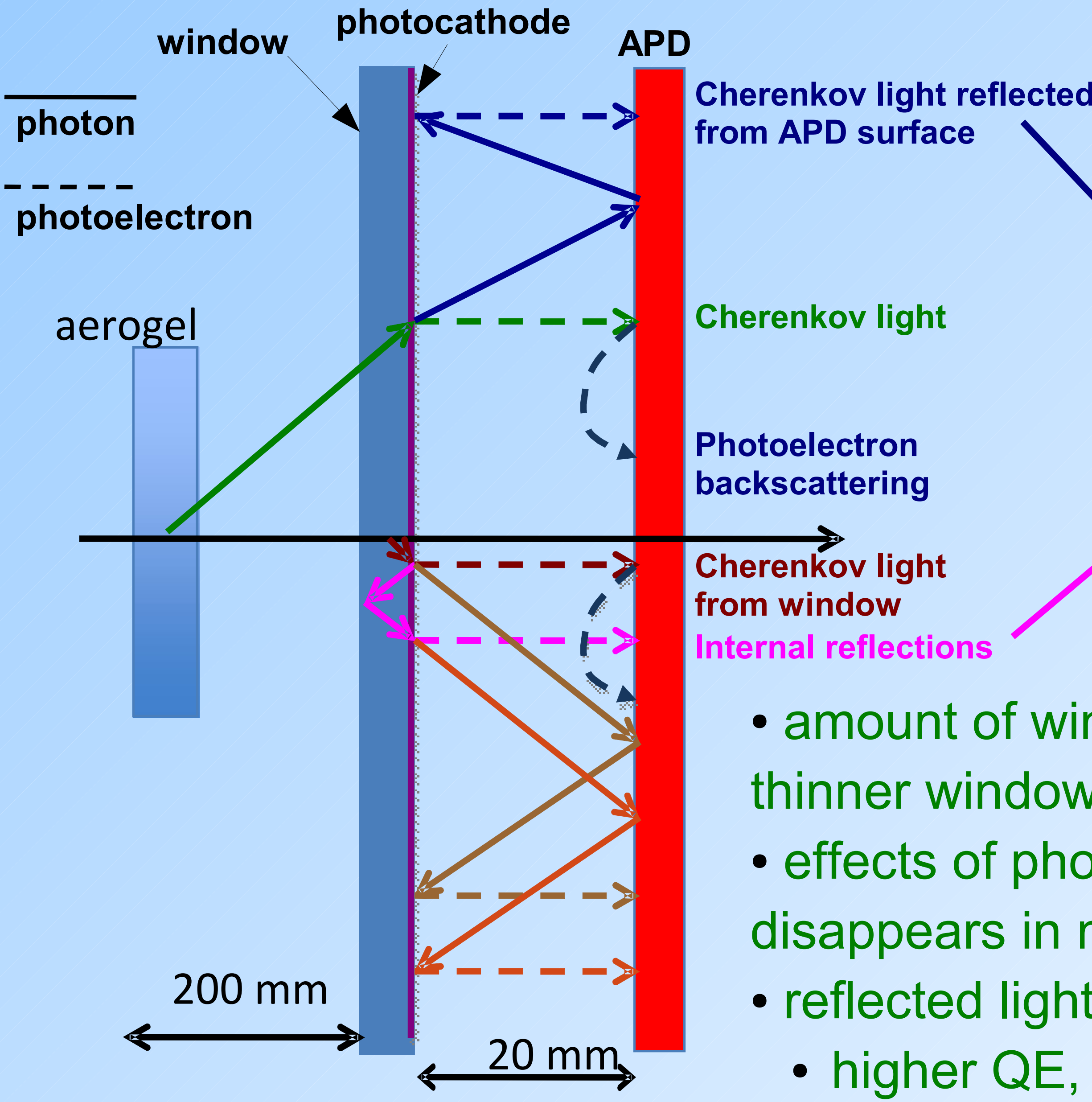


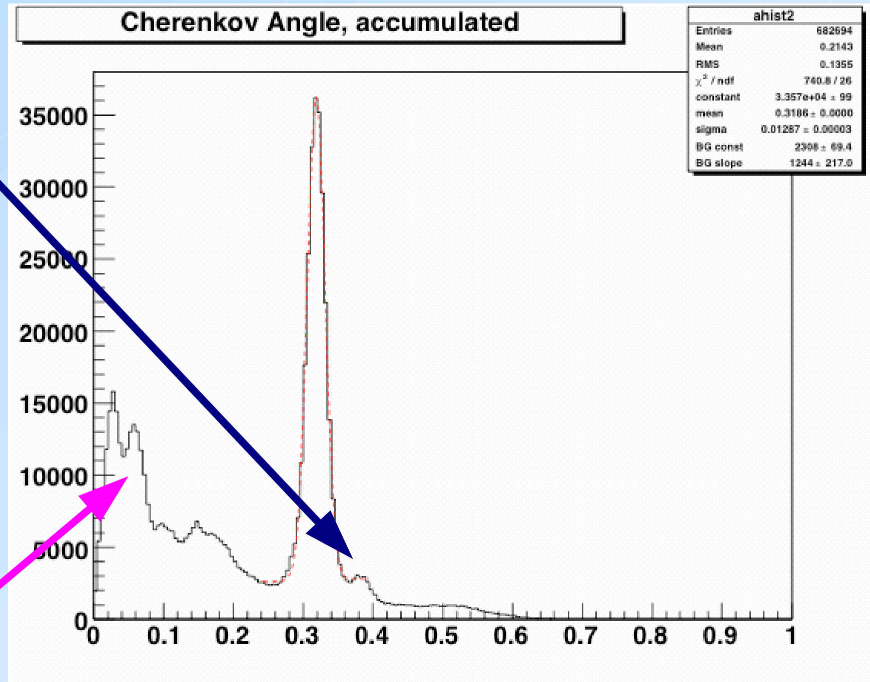


ring image

Better than 4 s p/K separation @ 4 GeV/c

Background contributions





- amount of window light can be reduced by thinner window
- effects of photoelectron backscattering disappears in magnetic field
- reflected light:
  - higher QE, more absorption at first pass
  - anti-reflective coating?

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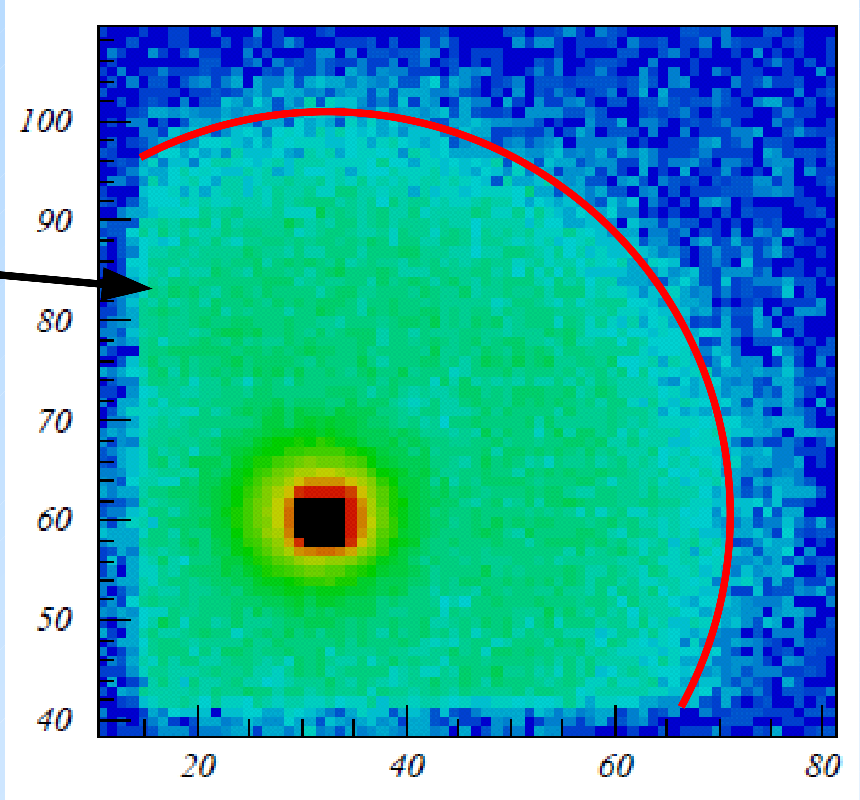
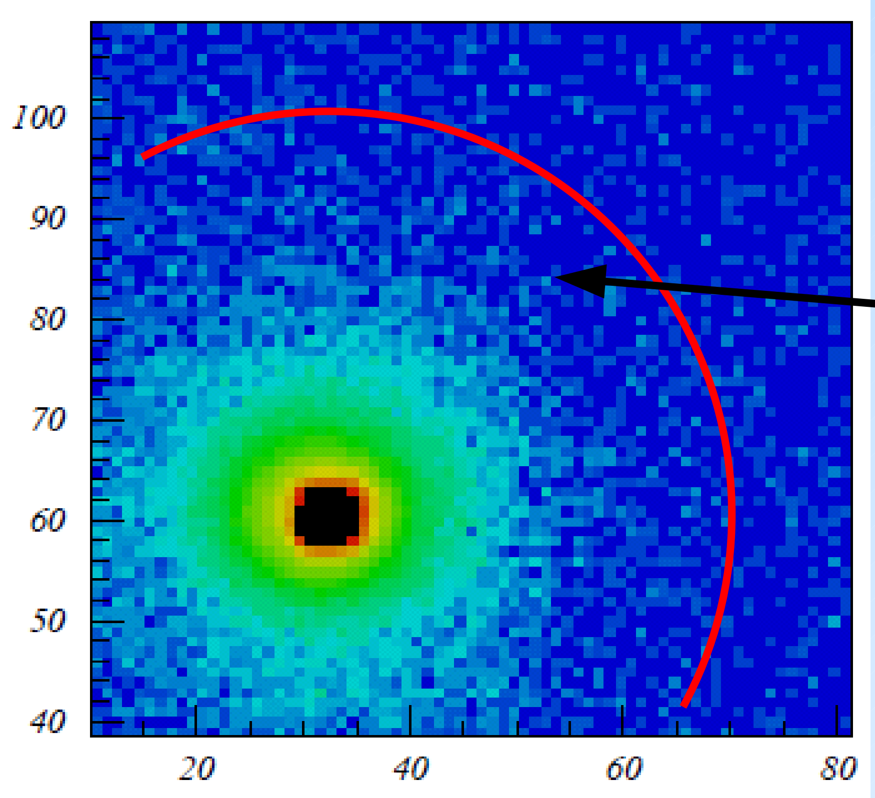
Test in magnetic field 1.5 T

- around 20% of photoelectrons back-scatter and the maximum range is twice the distance from photocathode to APD ~40mm





- again in magnetic field these photoelectrons follow magnetic field lines ad fall back on the same place

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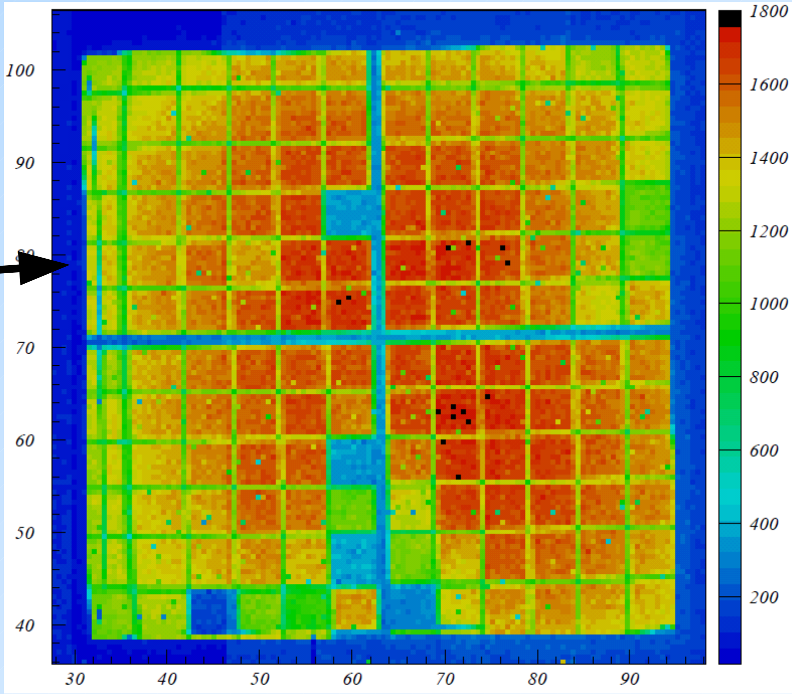
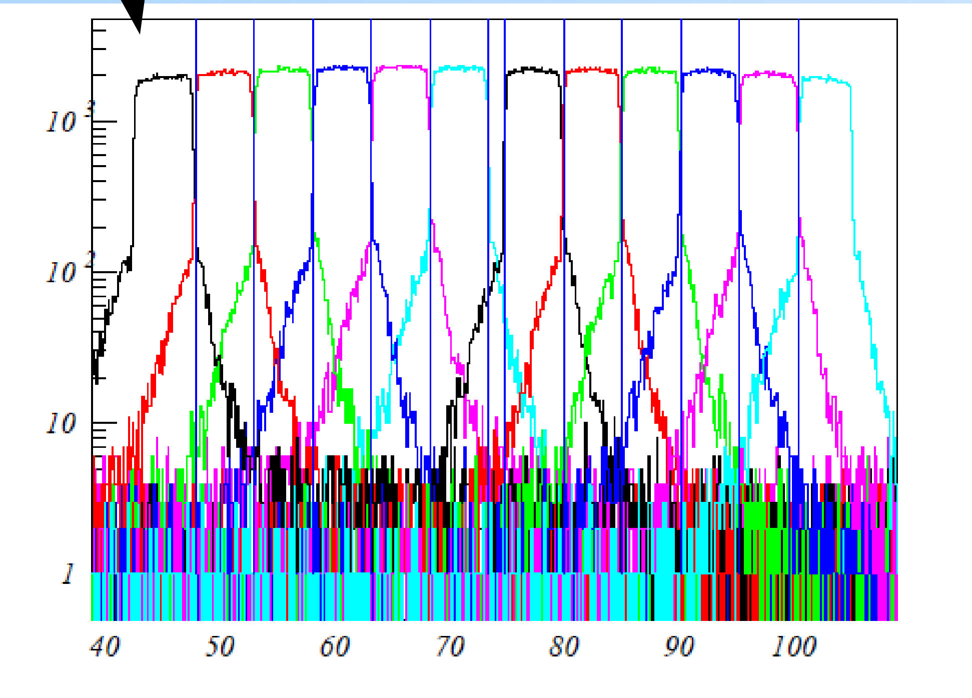
Test in magnetic field 1.5 T

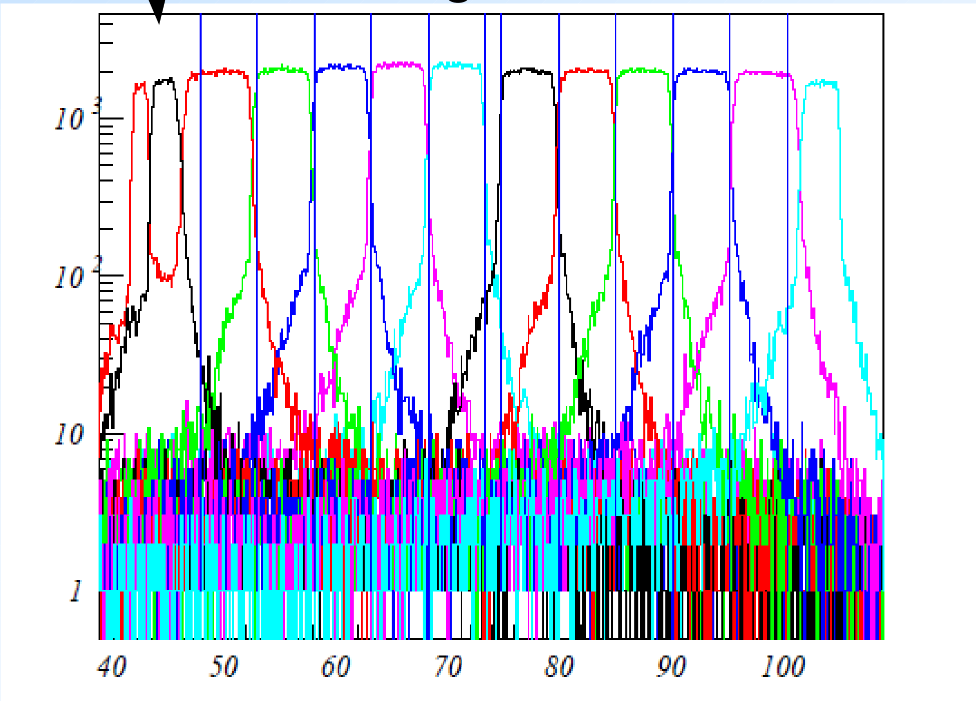
- distortion of electric field lines at HAPD edge produces irregular shapes of areas covered by each channel
- in magnetic field photoelectrons circulate along the magnetic field lines and distortion disappears



magnetic field 1.5 T



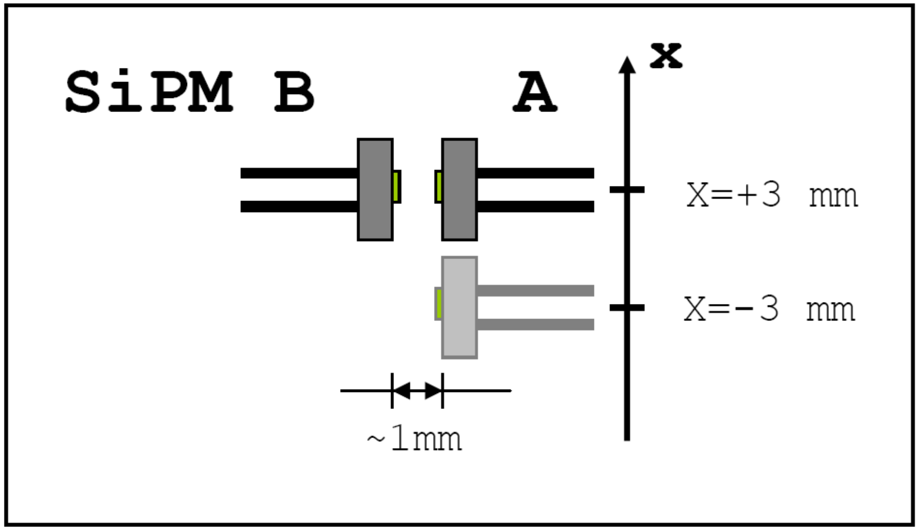
no magnetic field

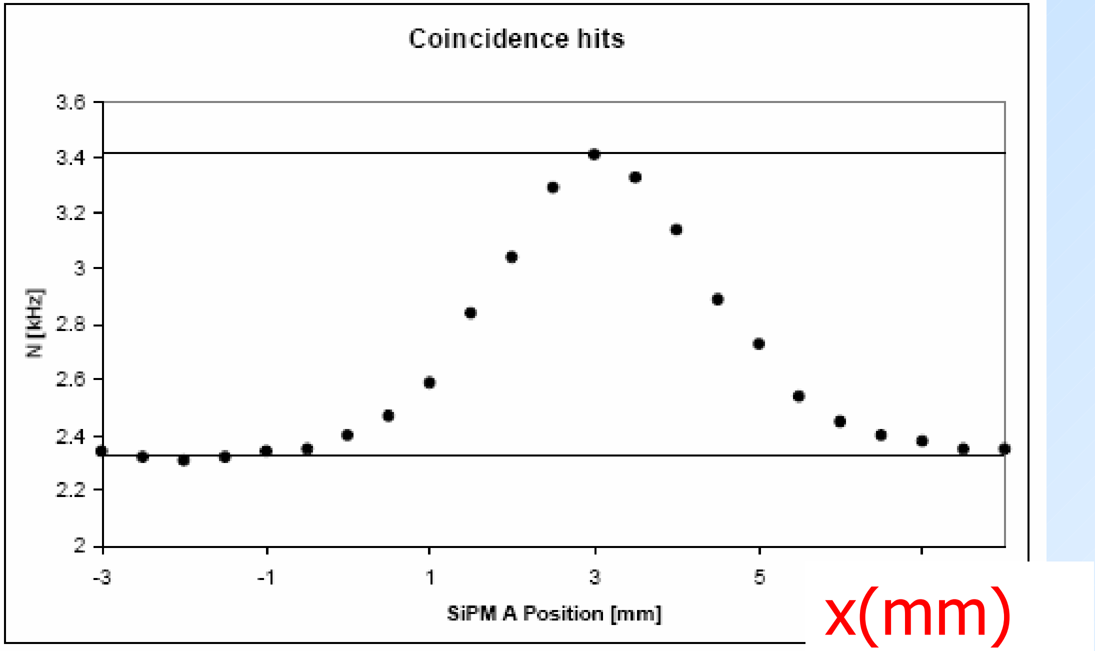


BACKUP SLIDES

External secondary photon cross talk

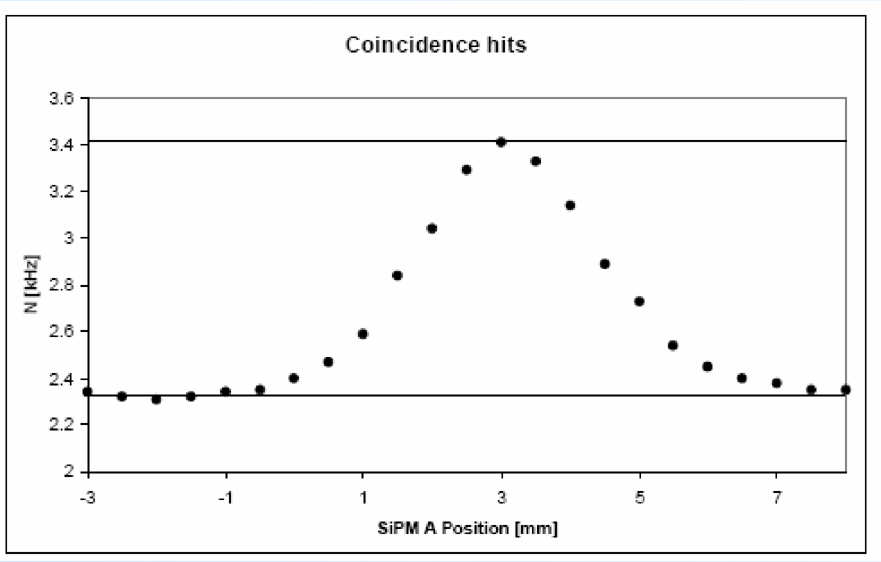
Scan a SiPM in front of a second one, observe coincidence rate





SiPM A and B: Hamamatsu MPPCs

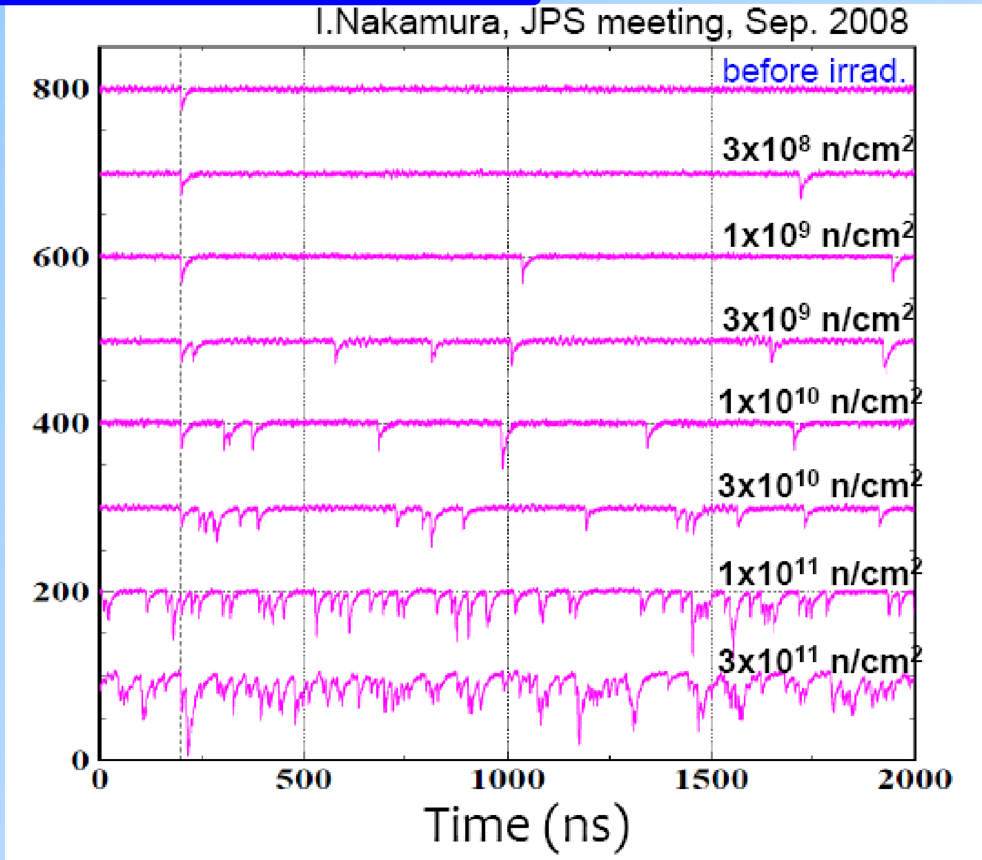
External secondary photon cross talk



- single detector dark rate ~ 200 kHz
- coincidence background ~ 2.4 kHz
- when SiPMs overlap, coincidence rate increases by ~1 kHz
- 1mm active area 1mm away ~ 15% of 2 π solid angle
- full (2π) solid angle: 1kHz/(2 x 200kHz) /15% **~ 2%**

→OK (even with an assumption of a 100% reflectivity of the radiator surface → gets reduced by two further orders of magnitude)

Neutron damage



Measured fluence:

90/fb → 1-10 10^9 n cm^{-2}

Expected fluence at 50/ab

→ if bckg x20: 2-20 10^{11} n cm^{-2}

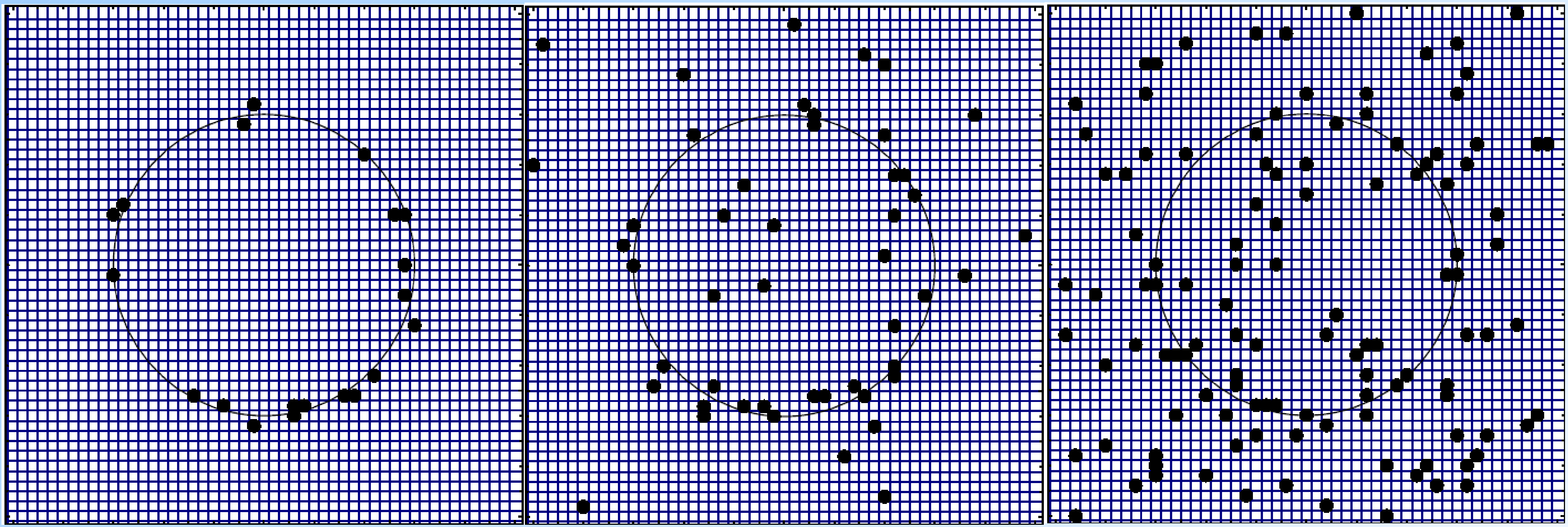
→ Worst than the lowest line

The monitoring diodes were not at the right place (mounted behind ECL instead of in front of it). However, n flux is probably quite similar – check with new data.

→Very hard to use present SiPMs as single photon detectors in Belle because of radiation damage by neutrons

RICH with SiPM - expected hit distribution

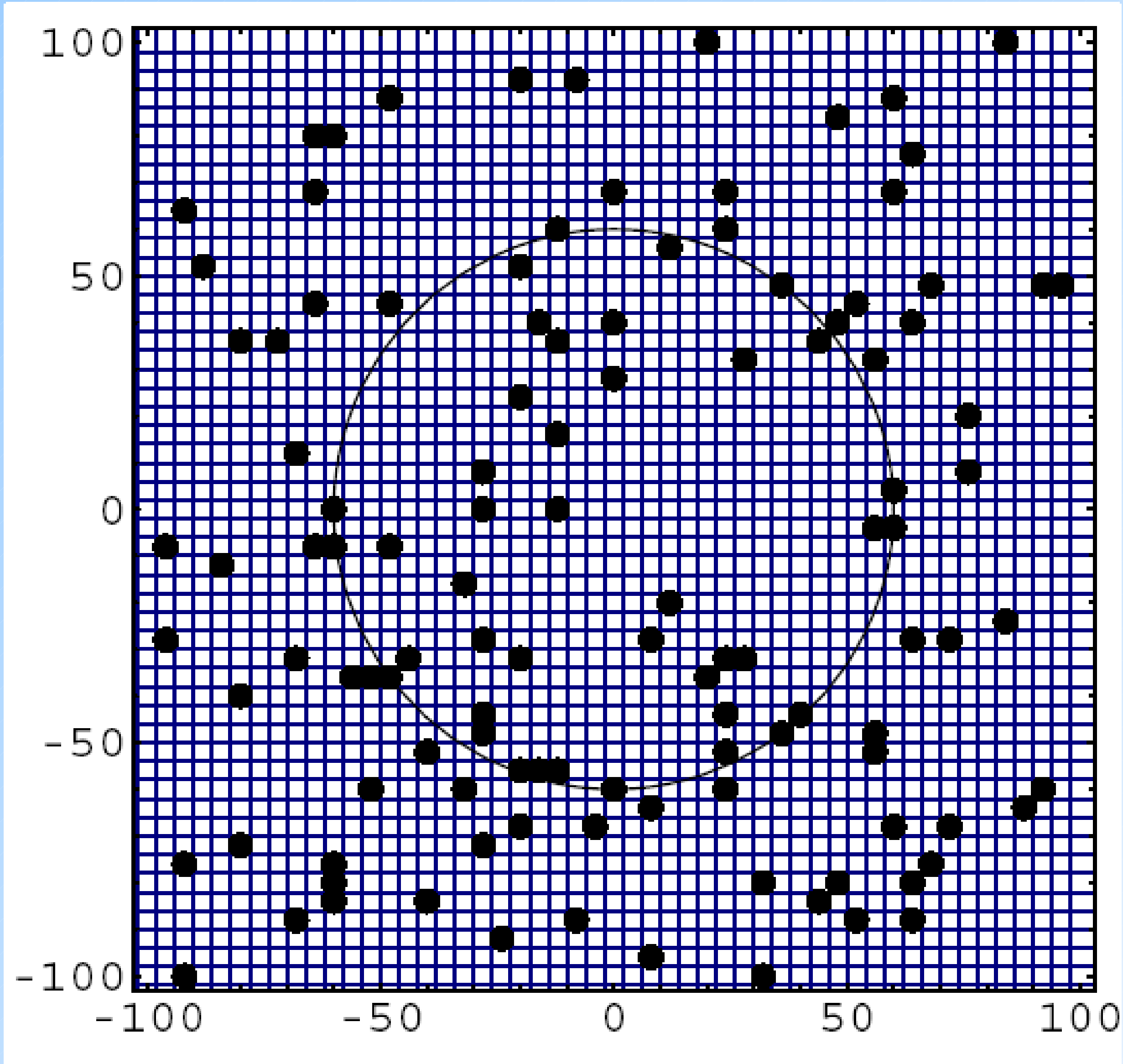
- Ring on a uniform background



Can such a detector work?

RICH with SiPM - expected hit distribution

- Ring on a uniform background

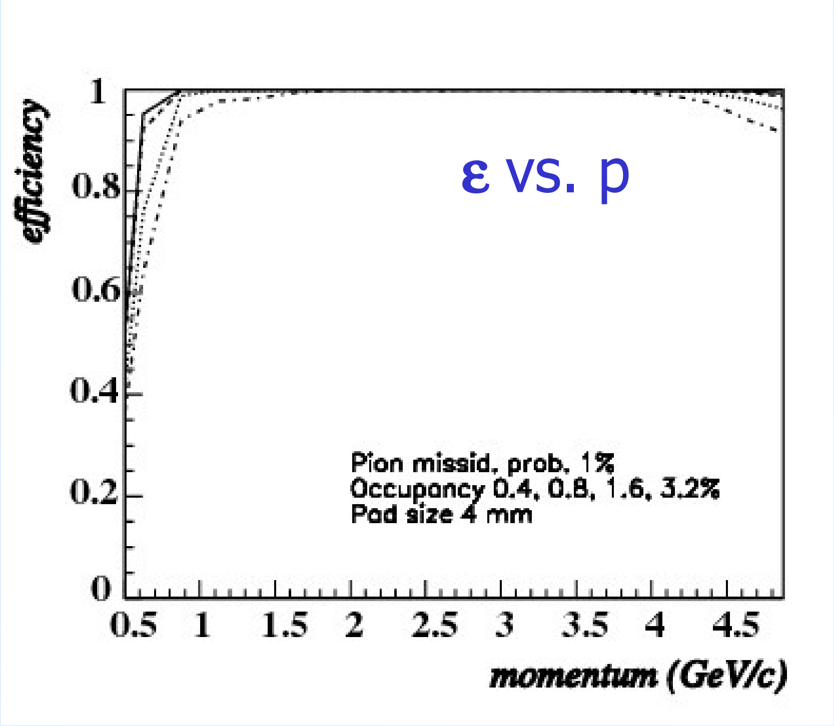


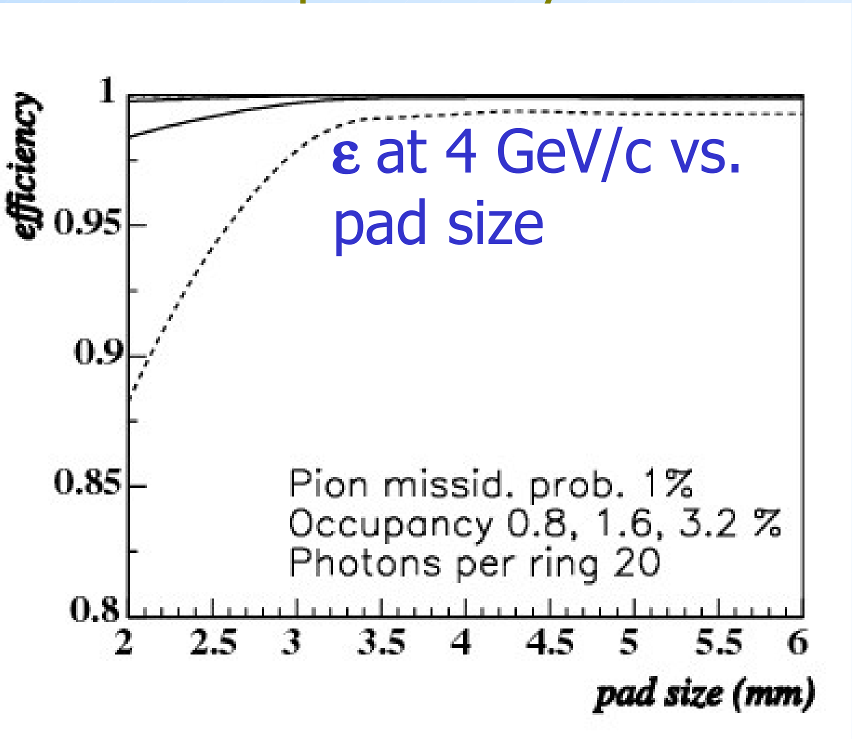
Can such a detector work?

Can such a detector work?

MC simulation of the counter response: assume 1mm ^{2} active area SiPMs with 0.8 MHz (1.6 MHz, 3.2 MHz) dark count rate, 10ns time window. Vary light collector demagnification (=pad size).

K identification efficiency at 1% π missid. probability





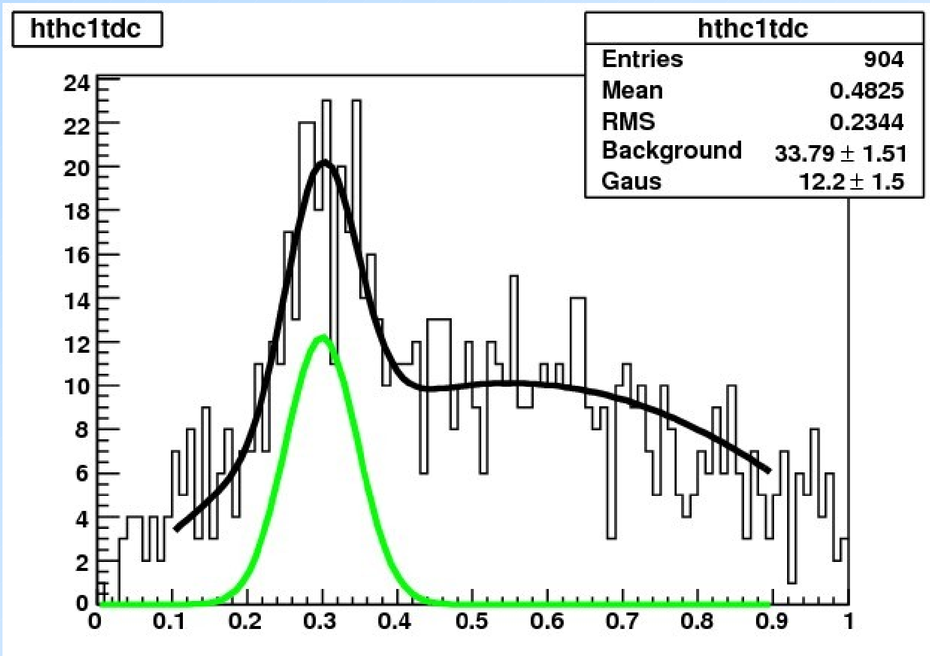
→ Looks OK!

Test with cosmic rays

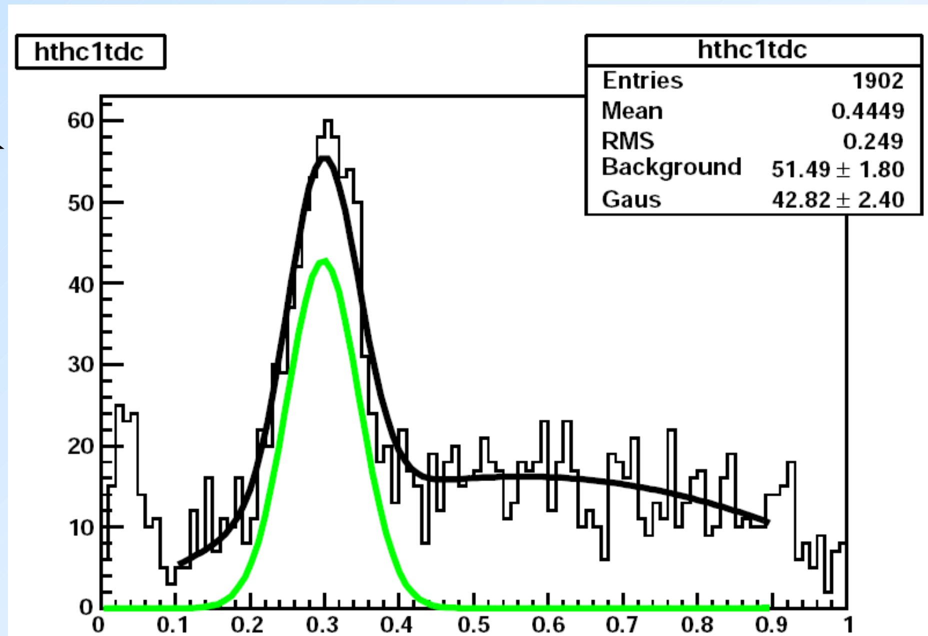
NIM A594 (2008) 13

First successful tests with cosmic rays:

No light guides:
- 43600 tracks
- Cherenkov photons ~ 146
- 0.0033 photons per track



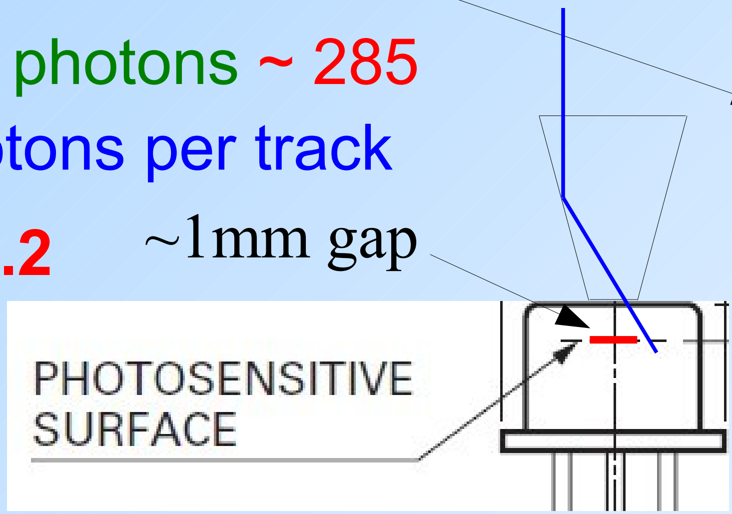
With light guides:
- 38100 tracks
- Cherenkov photons ~ 285
- 0.0072 photons per track



Cherenkov angle [rad]

$N_{w/} / N_{w/o} \sim 2.2$

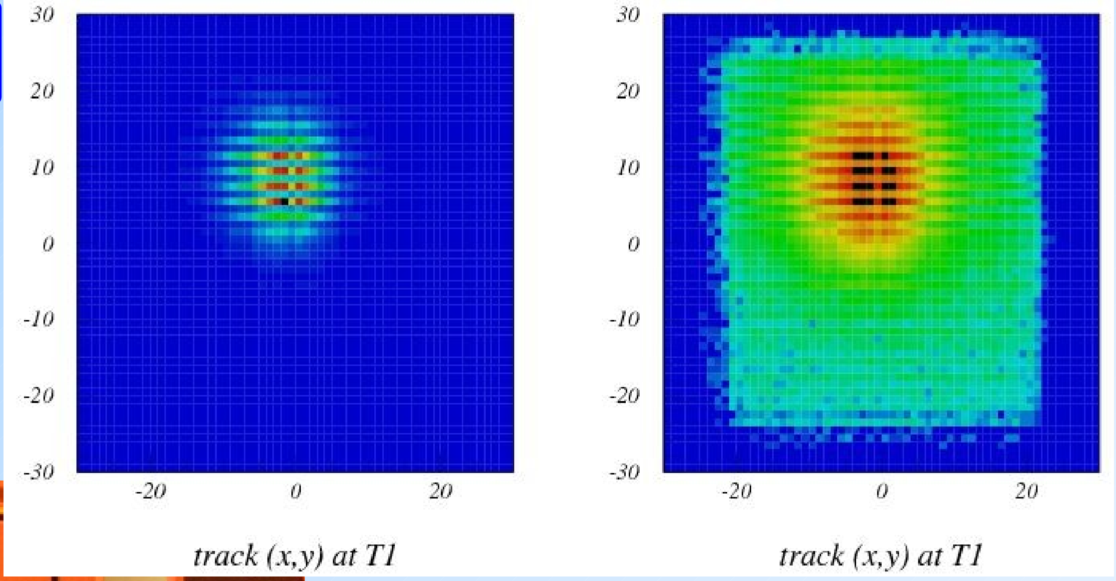
~1mm gap



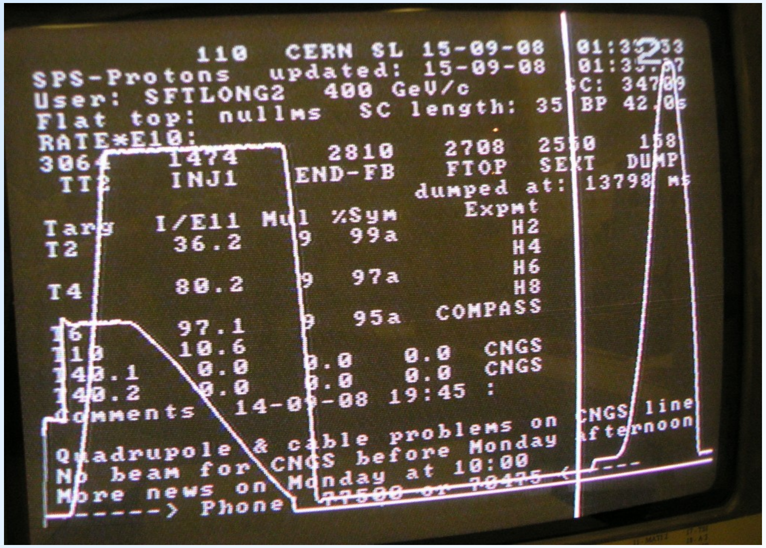
Light guide should be as close as possible to the SiPM surface.

Beam area T4-H6-B @ CERN

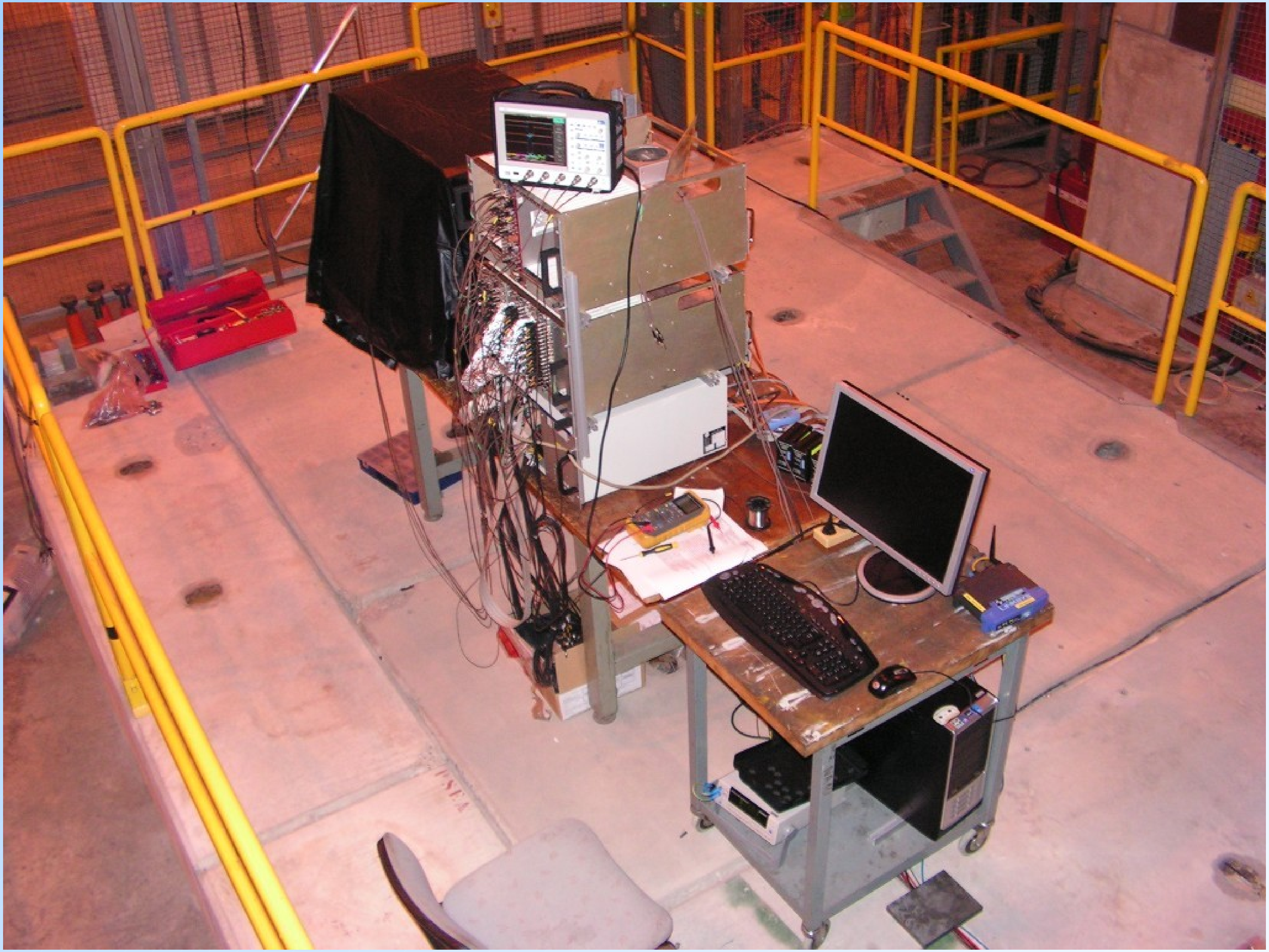
- +120 GeV/c pions
- spills every 42s for ~5s
- beam size ~1cm^2



- beam profile (scale in mm)



Beam area T4-H6-B

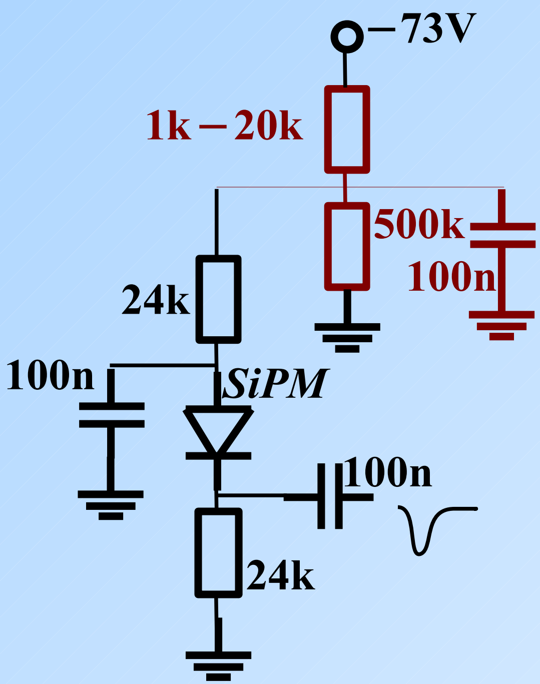


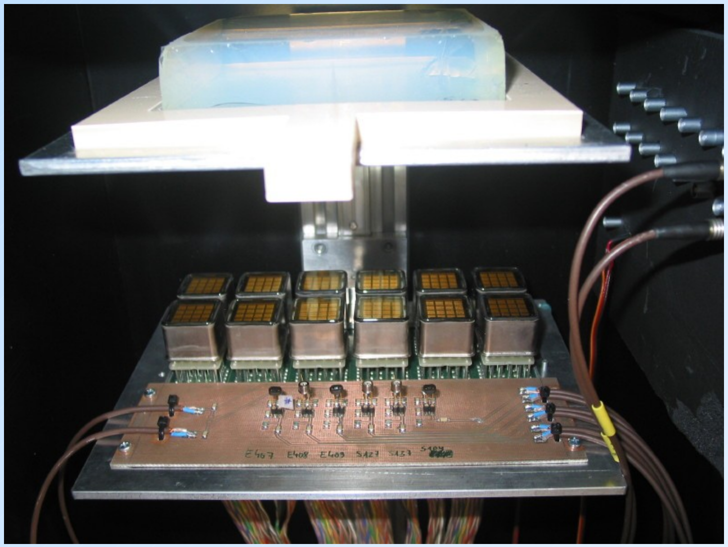
Cosmic test setup

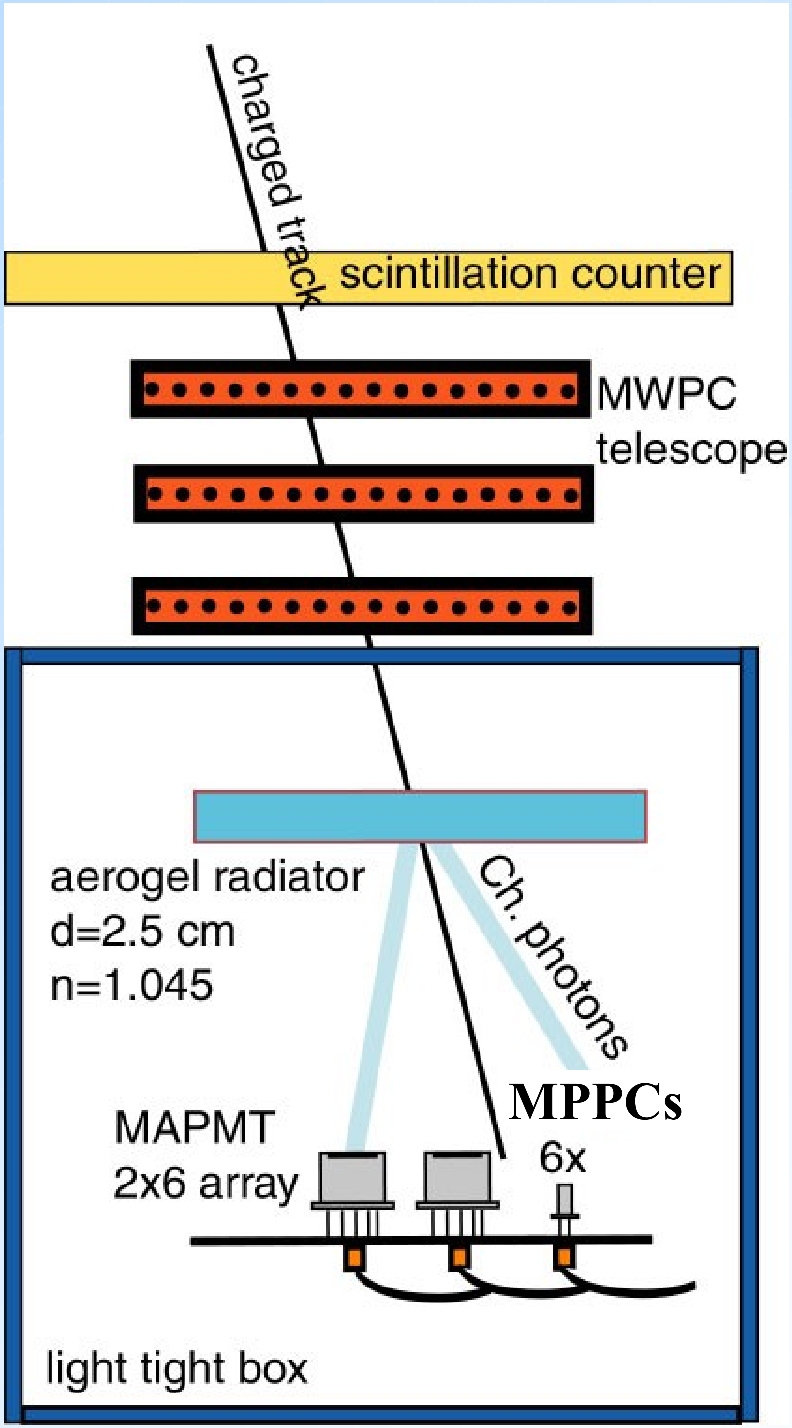
Two configurations of 6 Hamamatsu MPPCs were used:

- (HC100, HC050, HC025)x(metal, ceramic)
- 6 x HC100, metal

All six MPPCs were connected to same supply line using additional dividers:







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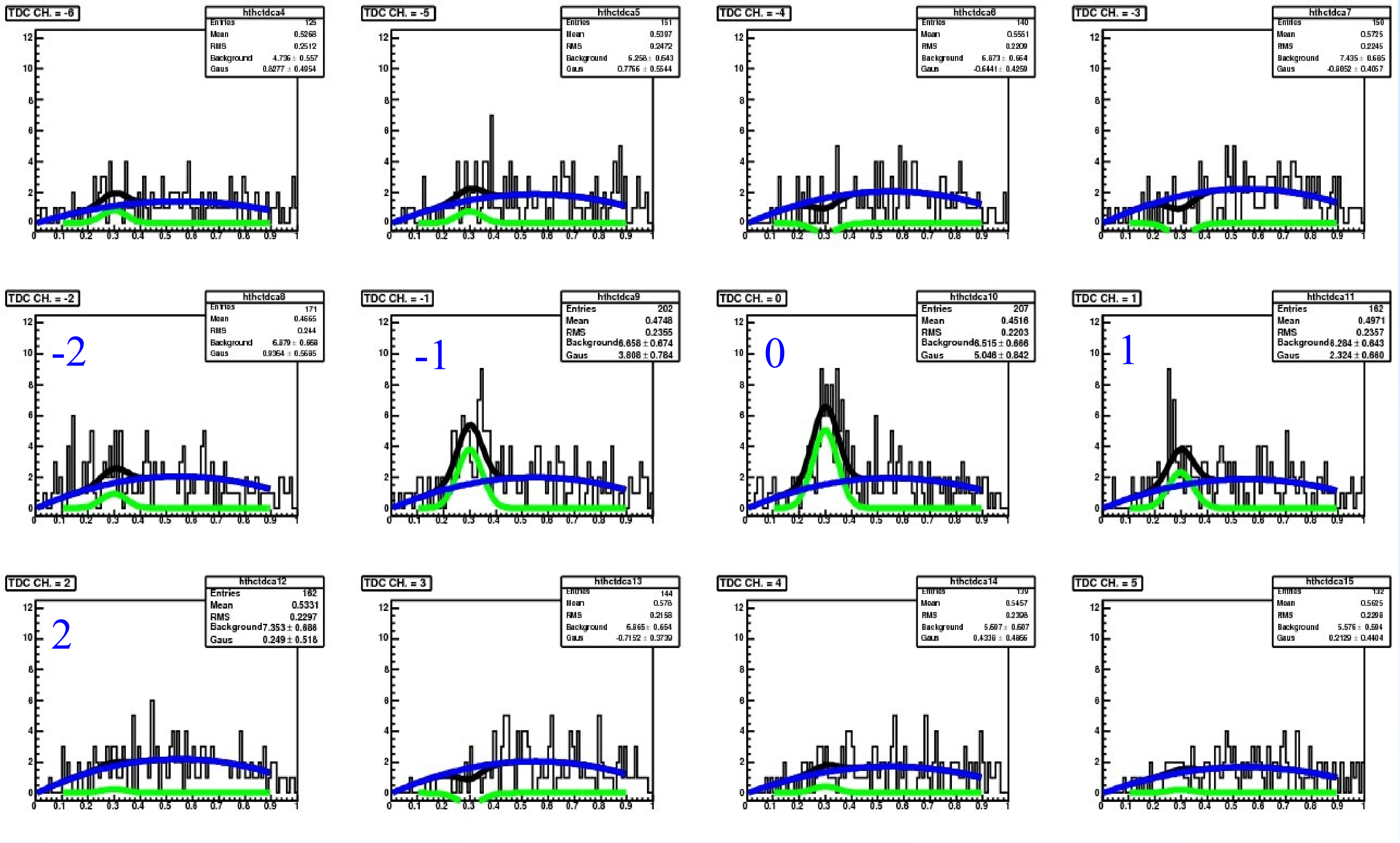
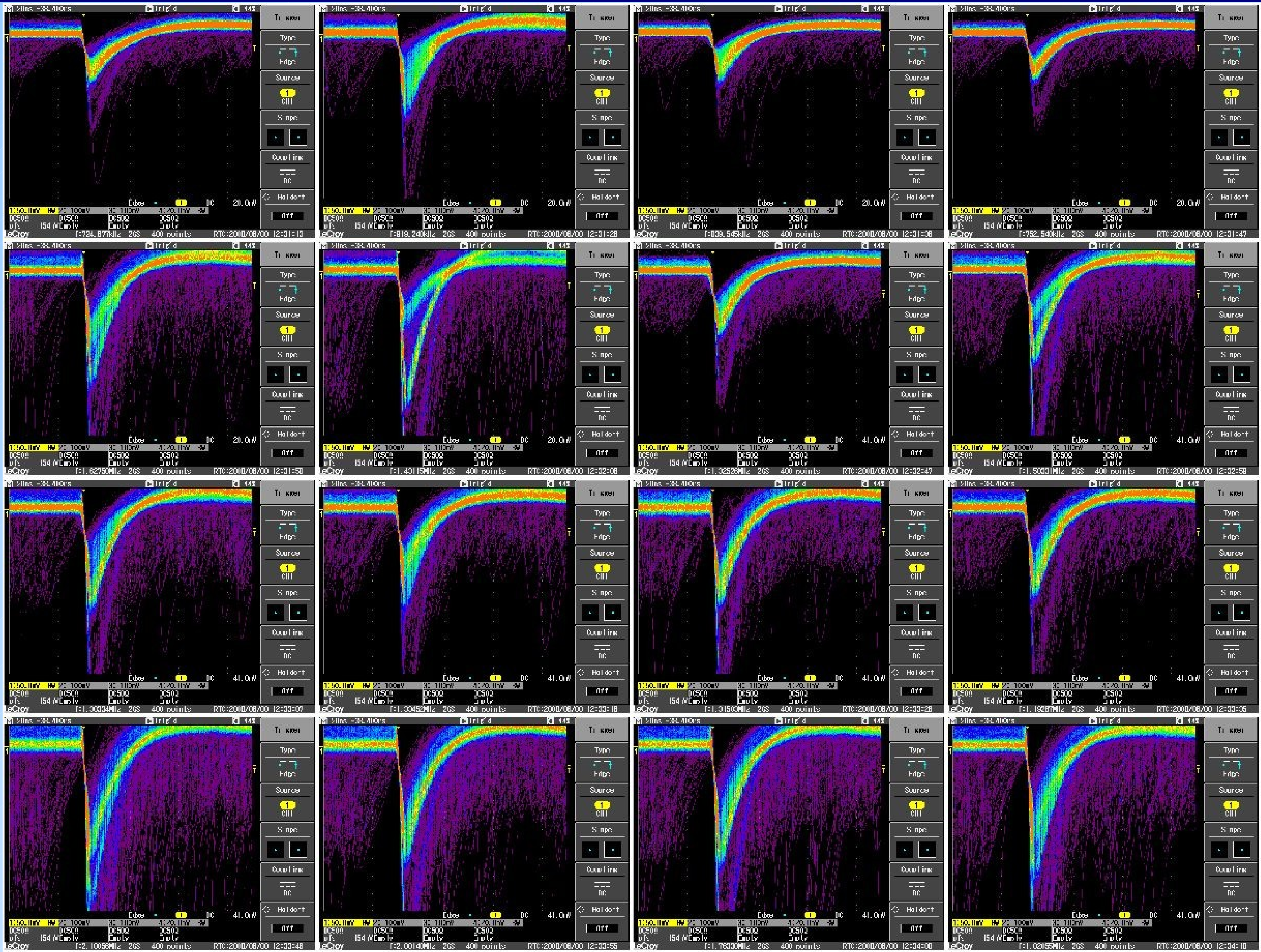
University of Maribor and Jožef Stefan Institute

Cherenkov angle distributions for 1ns time windows





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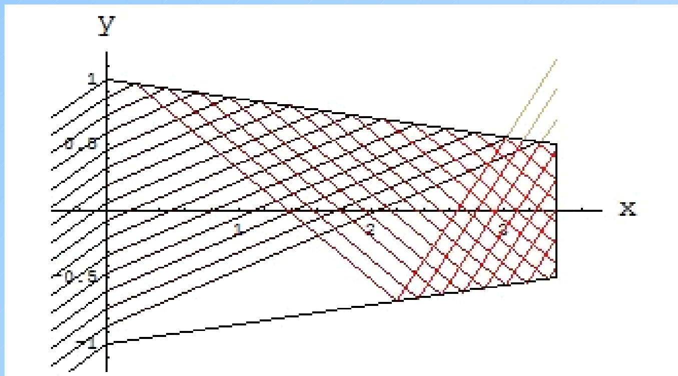
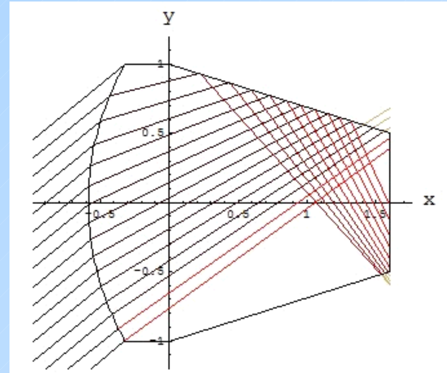
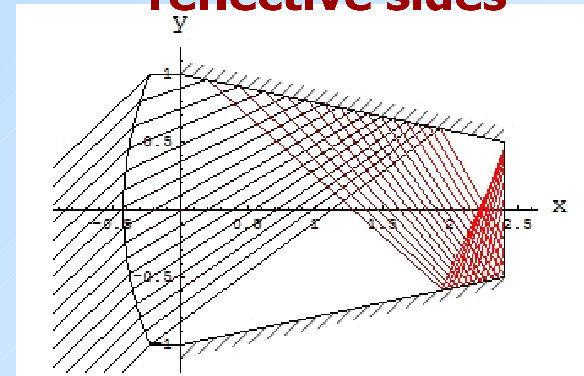
Planar entry window



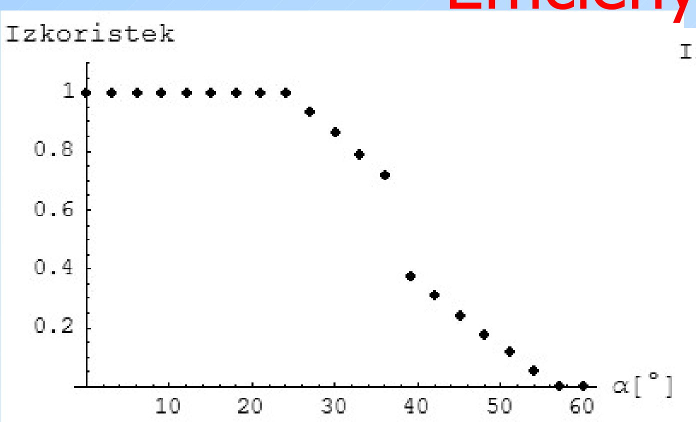
Spherical entry window

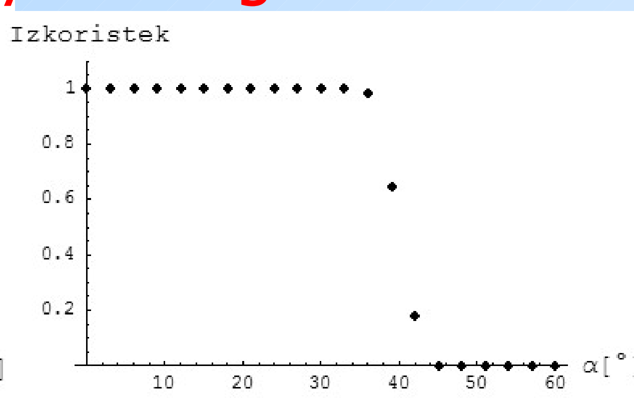


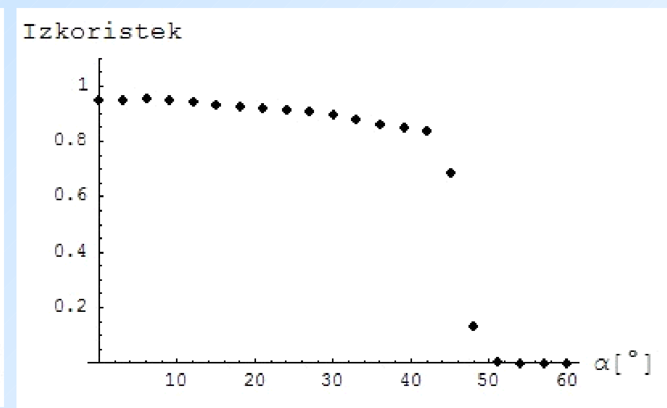
Spherical entry window, reflective sides



Efficieny vs. angle of incidence α



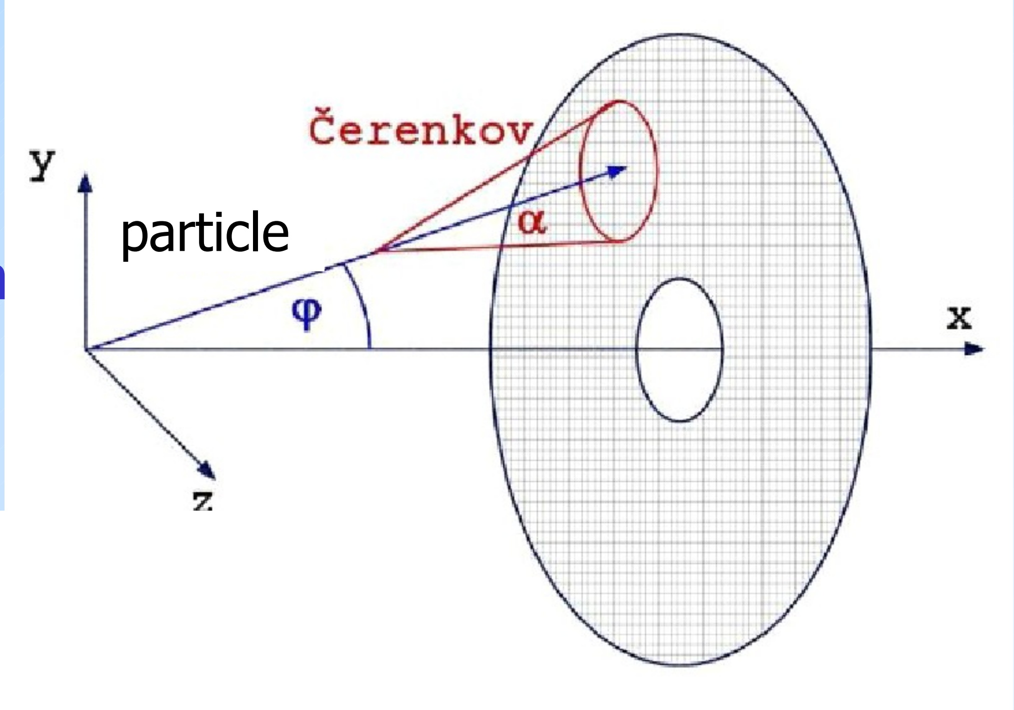


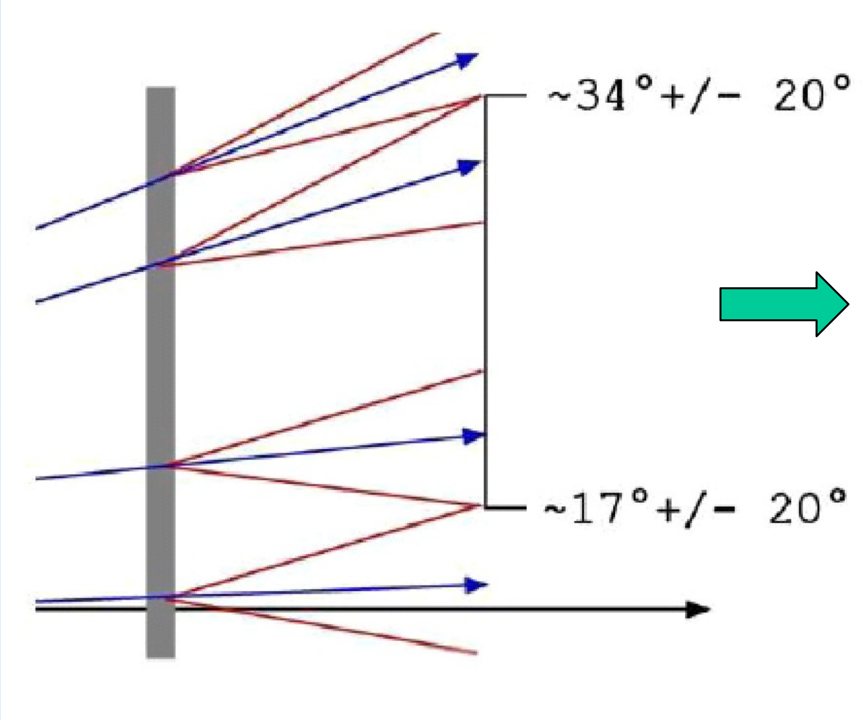


Light guide	d/a	R/a	α_{min}, α_{max}	I(-60°, 60°)
Planar entry	**3.4**	-	**-24°, 24°**	**64%**
Sph. entry	**1.6**	**2.0**	**-35°, 35°**	**66%**
Reflective sides	**2.4**	**2.6**	**-44°, 44°**	**69%**

Light collection: required angular range

For our application only a limited angular range of incident has to be covered at a given position on the detector

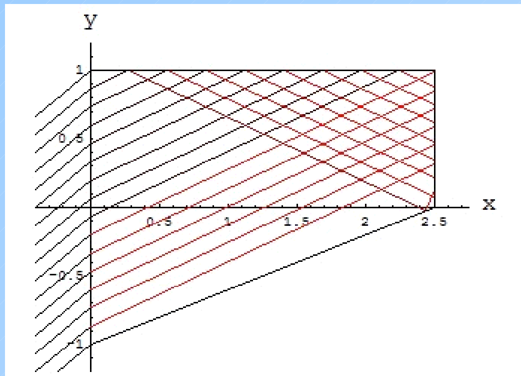




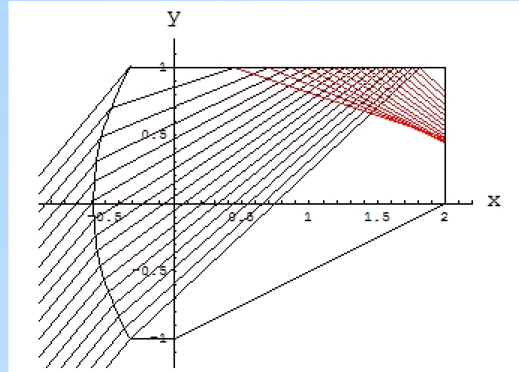
~ -3°... 54°

→ Take this asymmetry into account when designing the light collection system.

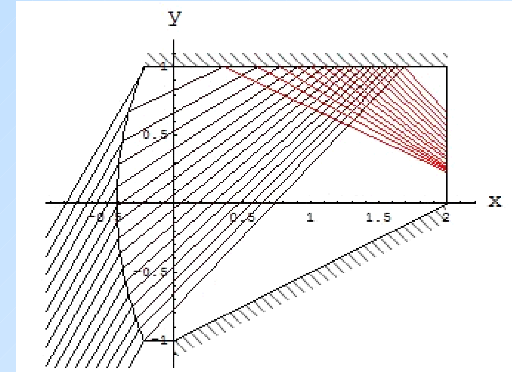
Planar entry window



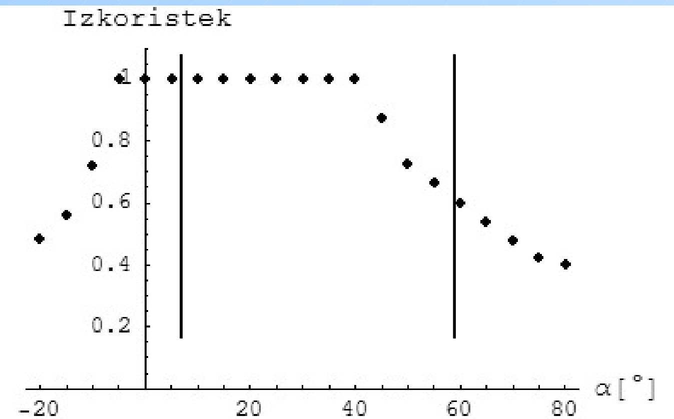
Spherical entry window

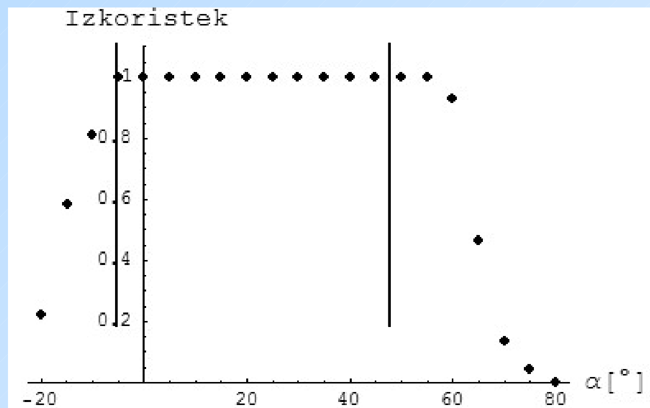


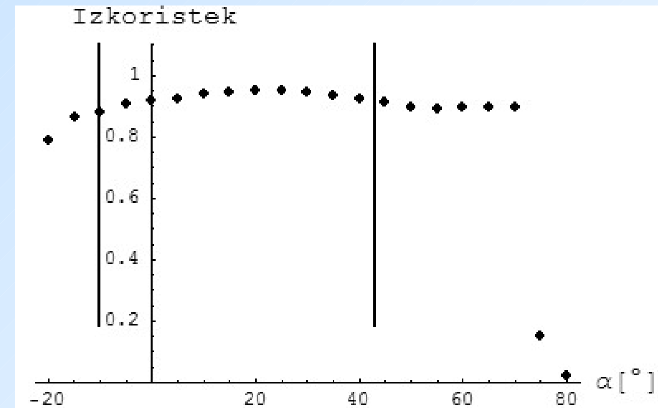
Spherical entry window, reflective sides



Efficieny vs. angle of incidence α

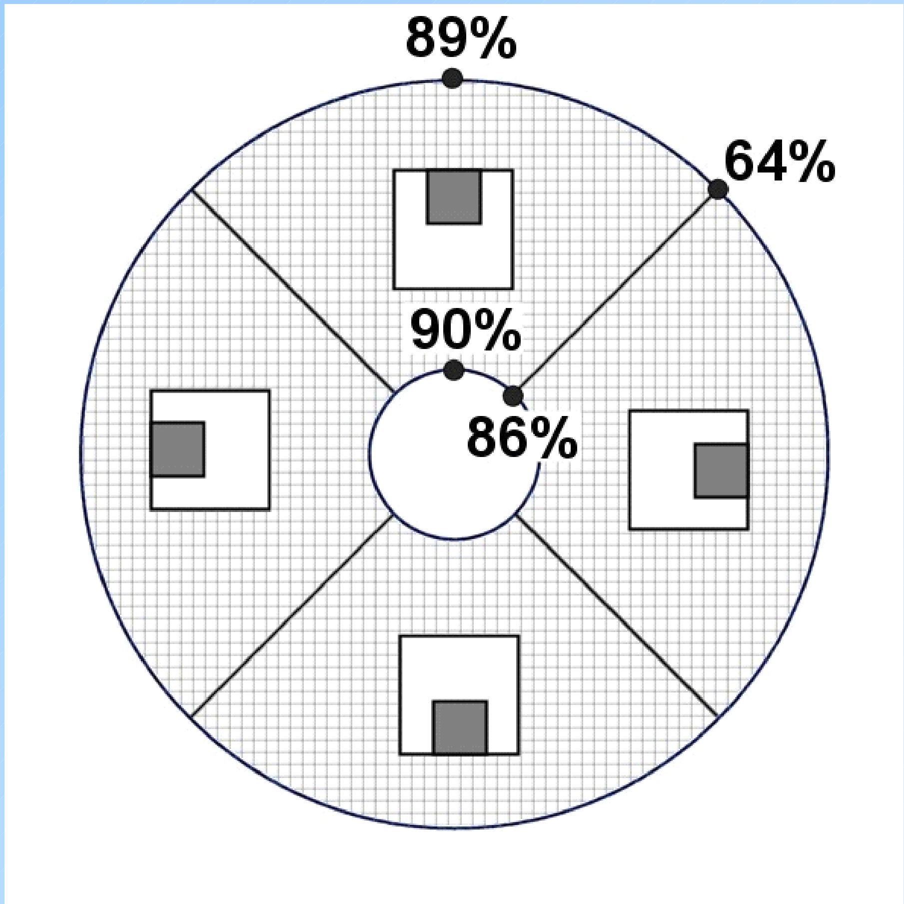




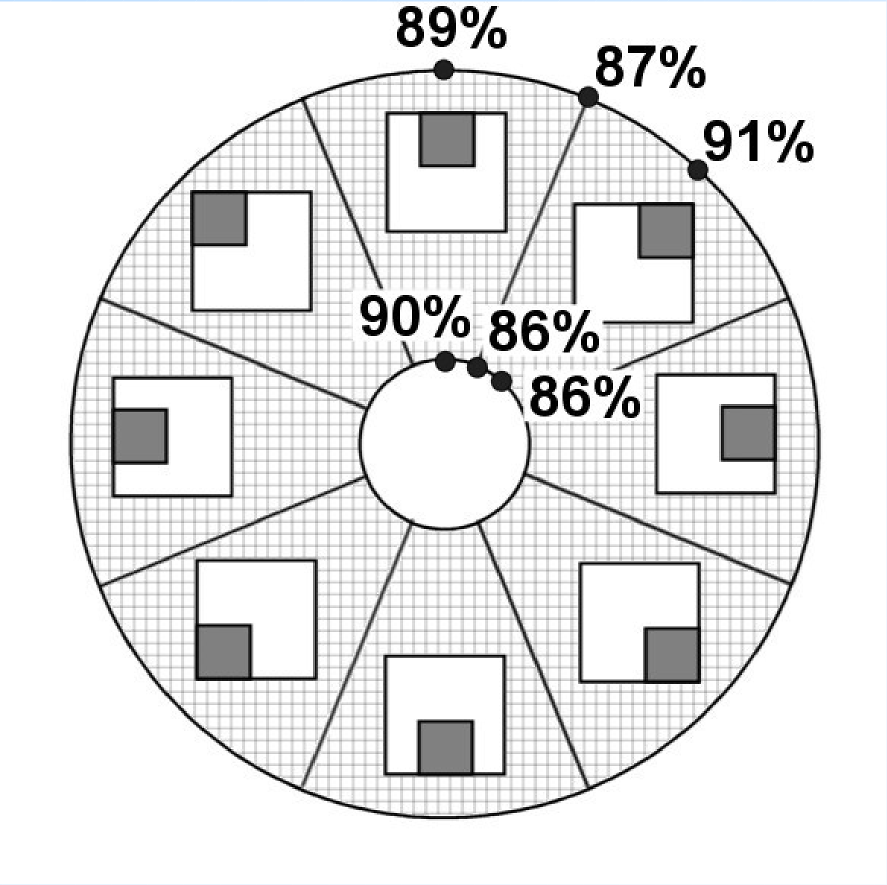


Light guide	D	R	α_{min}, α_{max}	I(-3°, 54°)
Planar entry	**3.4**	–	**–6°, 41°**	**95%**
Sph. entry	**1.6**	**2.0**	**–6°, 58°**	**100%**
Reflective sides	**2.4**	**2.6**	**–19°, 71°**	**93%**

Light collection: efficiency



Design with a single light guide type



Design with a two light guide types