Status and Perspectives of Vacuum-based Photon Detectors

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New !

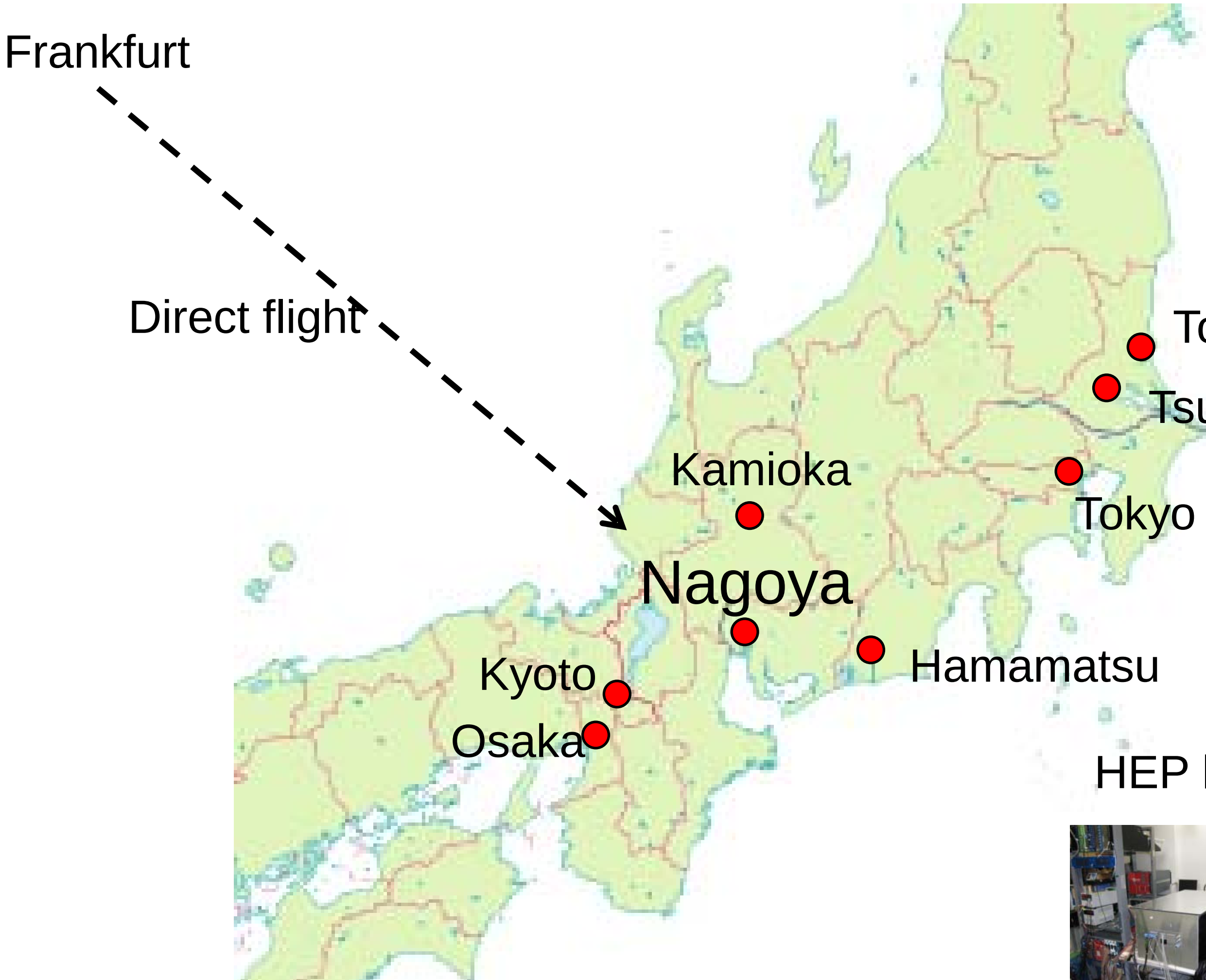
No Logo Yet !

Nagoya University
タウ・レプトン物理研究センター
Tau Lepton Physics Research Center

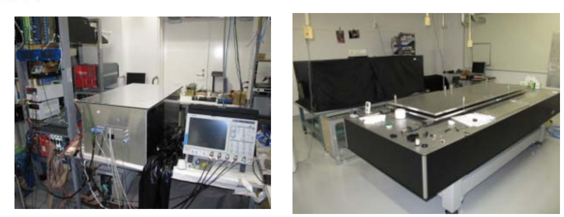
LAB

BELLE

Where is Nagoya ?



HEP lab. Nagoya Univ.



Please visit us !

Talk Outline

- Introduction
- Multi-anode PMTs (MaPMTs)
- Hybrid Photodetectors (HPD/HAPD)
- Micro-channel PMT (MCP-PMT)
- PD with luminescent anode (X-HPD etc.)
- Summary

Apologies:
There are much more than what I can discuss within 40 minutes !
I am sorry if I miss your favorite photodetectors & applications.

Vacuum-based Photodetectors

- The most traditional technology and offers reliable way to detect single photon with low noise.
- Still improving to meet requirements in modern particle, nuclear and astroparticle physics experiments.

Recent emphasis

Single photon counting with good

Position sensitivity	O(mm)		
Efficiency (QE, gain, S/N)	>20%		
Timing	<100ps	⇐	TOP/FDIRC
Magnetic field immunity	1.5 T		New trend
Total area to cover	O(1m^2)-O(10^{5}m^2)		

++ ASIC development to readout many channels. O(10^5)

Example1: B decay experiments

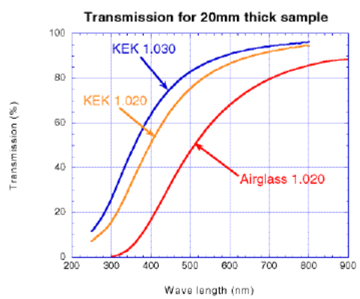
- K/π identification in the GeV/c region is important.
- Development of RICH with aerogel and quartz radiators.

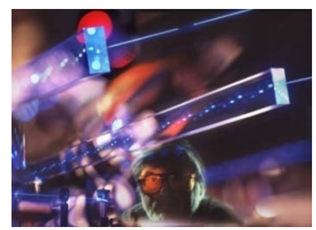
Aerogel

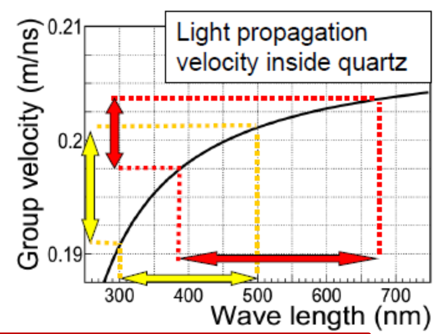
- Great improvement in optical transmission of aerogel.
- Development of RICH with aerogel for LHCb and Belle II.
- **Visible light domain** (Rayleigh scattering suppress the UV region).

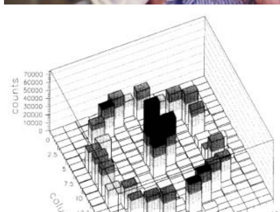
Quartz

- Successful operation of DIRC at BaBar .
- Use of TOP in reconstruction
- **Precision timing**
- **Visible light is more useful** than UV in the limit where chromatic dispersion dominate the error.







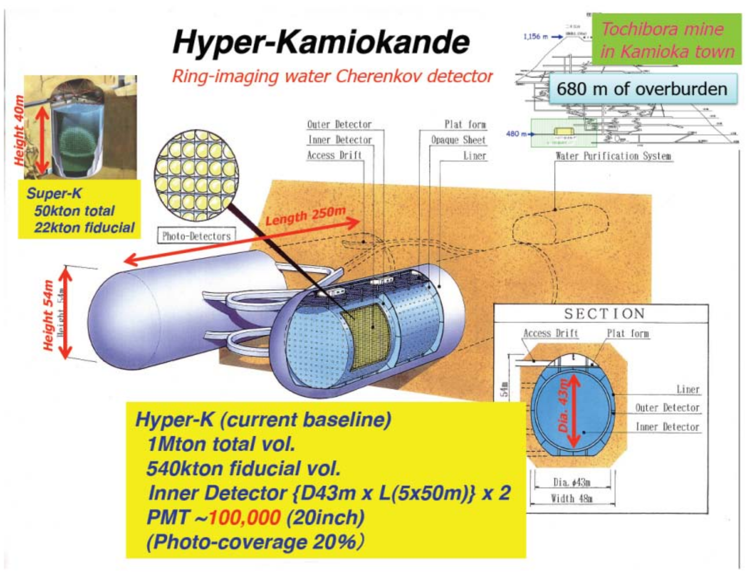


R. De Leo et al., NIM A401 (1997) 187

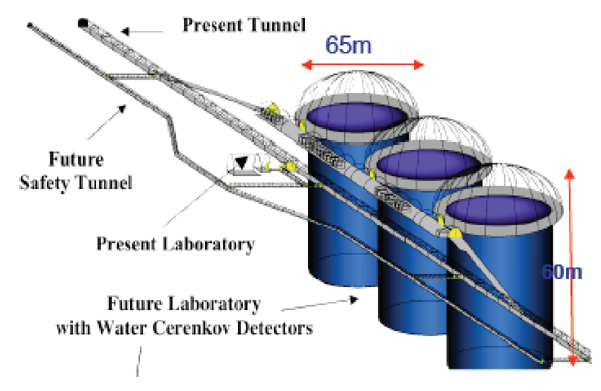
Require also:
- Immunity to B field.
- Tolerance for increase background/ radiation

Example 2: Next generation water Cherenkov

- Physics goal:
  - Search for proton decays (t > 10^{35} yrs).
  - Precision neutrino oscillation & CPV measurements.
  - Neutrino astronomy.
- Require cost-effective method to cover the large surface.



MEMPHYS

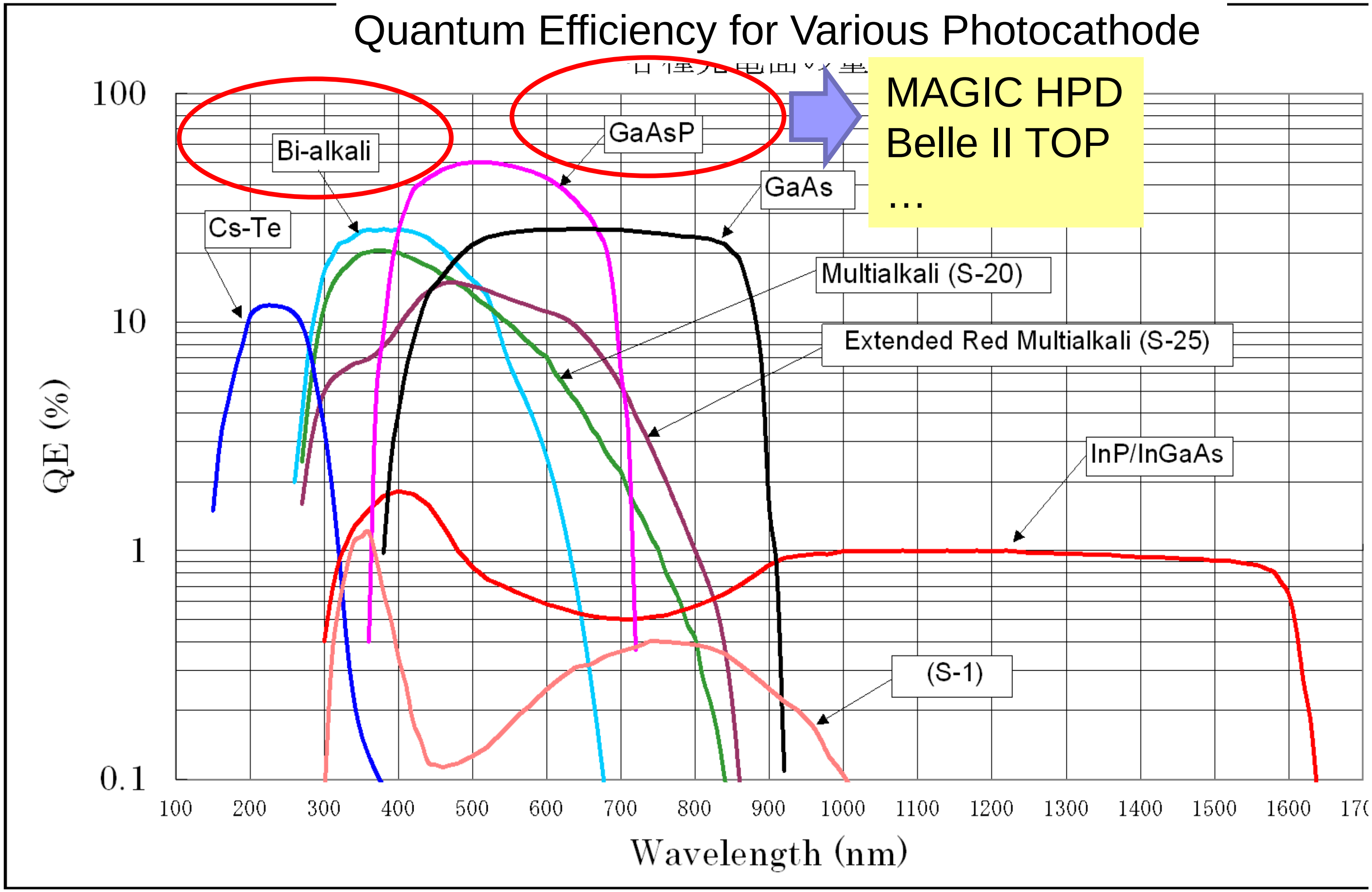


4800m water equivalent

+ KM3Net

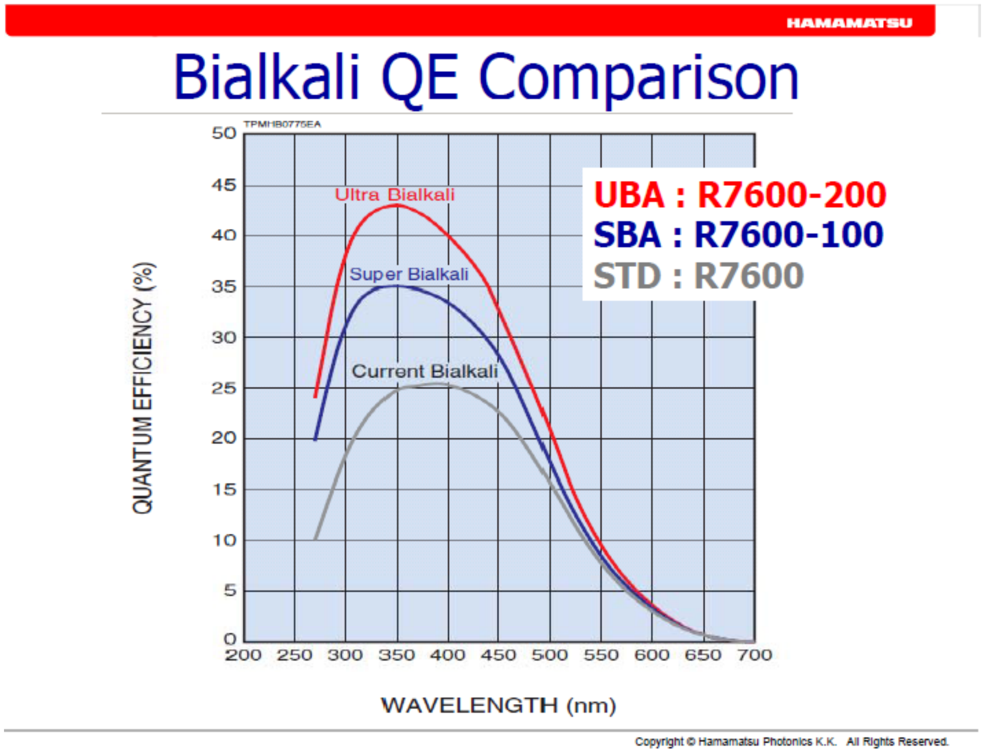
Remark1: Quantum Efficiency

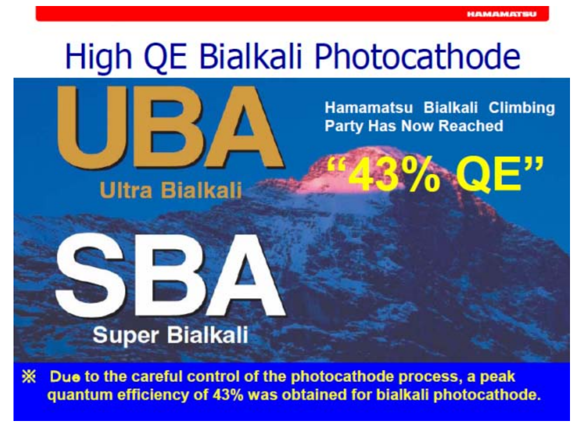
Figure from HPK

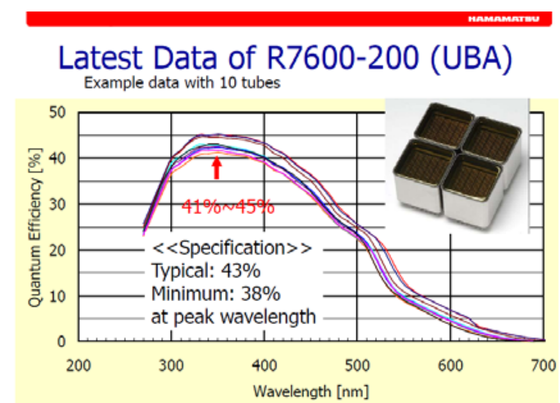


Remark: High QE Bialkali Photocathode

K. Nakamura @ TIPP09





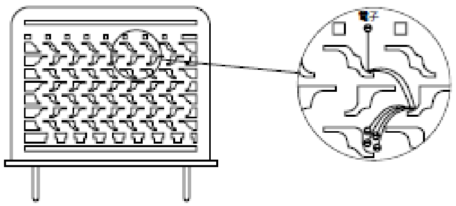


- Available for MaPMT
- Being applied also for others…

Similar improvement also at Photonis.

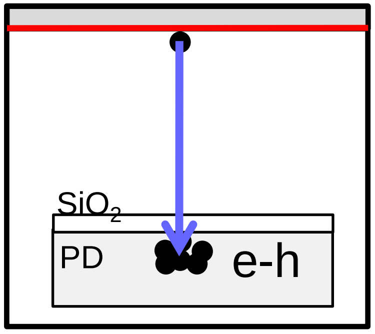
Pulse Height Resolution

- Statistical fluctuation in the 1 stage of the amplification
  - Gain at the 1st dynode in multiplicative amplification



$$G = \delta_1 \times \delta_2 \times \delta_3 \cdots \times \delta_n$$

  - Number of e-h pairs in electron bombarding



$$N_{e-h} \simeq \frac{V - V_{th}}{3.6eV}$$

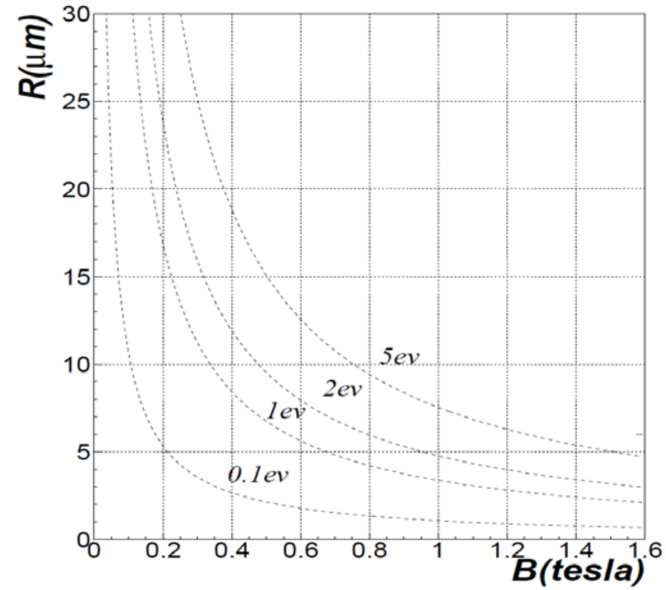
+ Fluctuation in later processes

Excess noise factor (ENF) in multi-photon case

$$\frac{\sigma_E}{E} = \sqrt{\left(\frac{f_{ENF}}{N_{p.e.}}\right)^2 + \left(\frac{N_e}{S}\right)^2}$$

- Electronics noise

Magnetic Field Effects

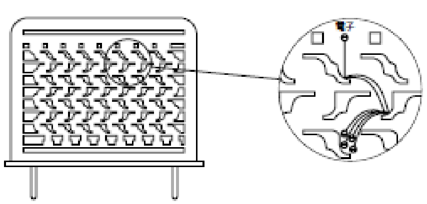


Electron motion in B field = Helix motion

- Lamor Radius $R = \dfrac{v_{\perp}}{\omega_c}$
- Photoelectron ~ 0.5eV
- Secondary electron ~ 6eV

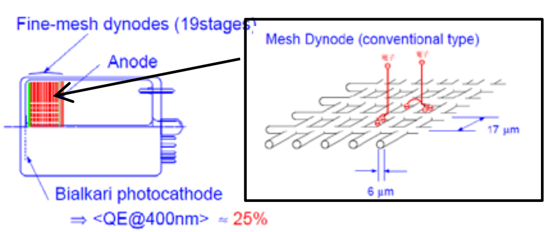
- Conventional PMT does not work.
- Effect is reduced for dynodes with micro structure (but not perfect)
- Proximity configuration is necessary.

Metal channel



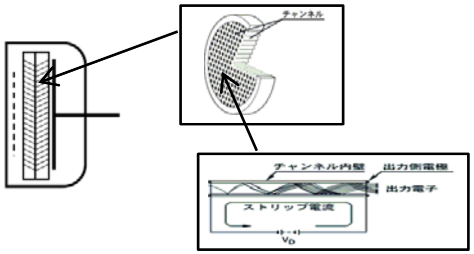
Up to ~100 Gauss

Fine-mesh



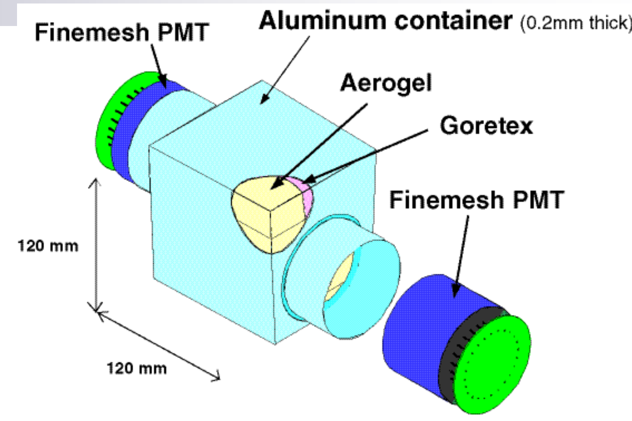
Up to 1.5 Tesla

Micro-channel-plate



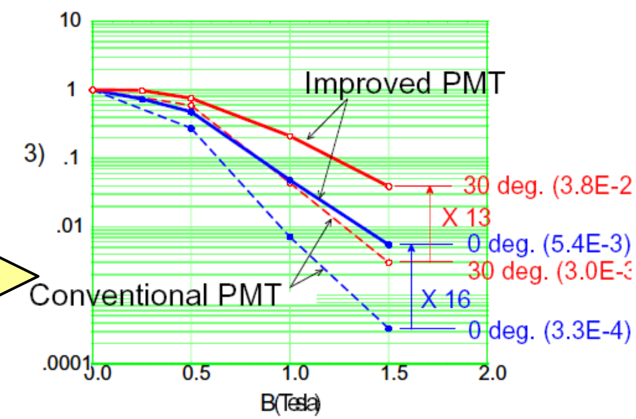
Up to 1.5 Tesla

Fine-mesh PMT (Belle-ACC)



- Have been working fine for 10 years.
- System is robust and reliable.
- Usable in magnetic field.
- Good enough for multi-photon countings;
  - <Npe> = 15-20 for Barrel (n=1.01-1.028),
    30 for endcap (n=1.03)

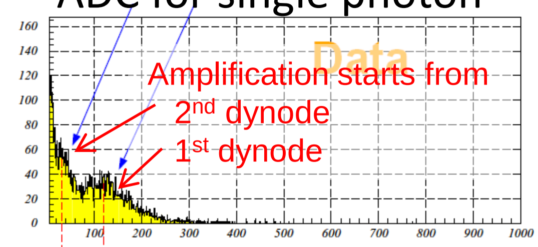
Relaive gain vs B-field;
Improvement by using finer mesh
(1500# →2000#)



However,

- B-field immunity is not perfect.
- Large gain fluctuation in multiplicative amplification (ENF=2)
- Some annoying features (dynode touch…)
- Hard to use for single photon (RICH application)

ADC for single photon



Pulse height ratio ≈ δ (eff) for the 1st dynode
(see NIM A332(1993)129)

Multi-anode PMT

- Metal channel dynodes (10-12 stages)
- Gain: 1-2x10^6 @ 800V (TYP.)
- Bialkali photocathode:

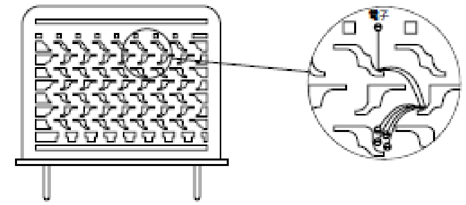
  QE_{peak}=24% → 35%(SBA) →43%(UBA
- T.T.S. = 0.3-0.8ns
- Effective area
  - R8900-100-M16

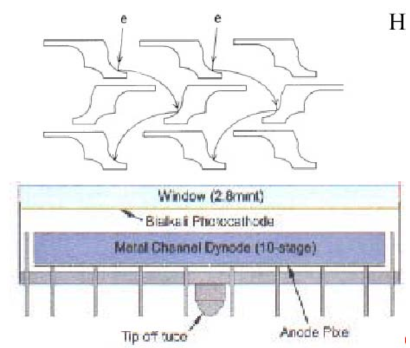
    23.5x23.5mm²/26.2x26.2mm² (80%)
  - Flat pannel

    H8500C: 8x8 anodes

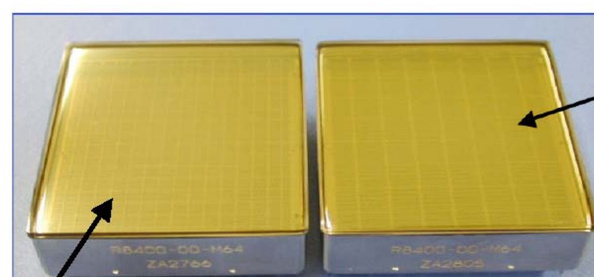
    H9500: 16x16 anodes

    49x49mm²/52x52mm²(89%)





lamamatsu Co. data sheet



New

(We have not tested the new one yet)

256 ch Focusing Type

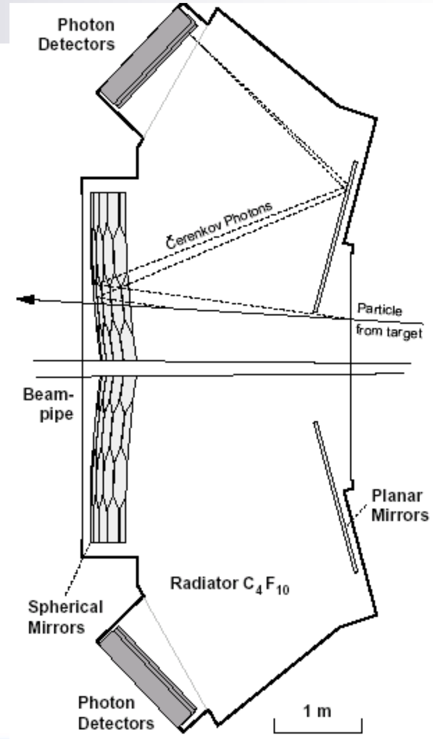
64 ch Focusing Type

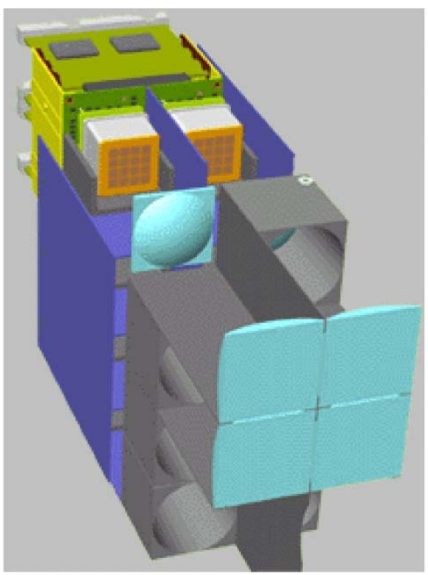
Collection Efficiency is improved.

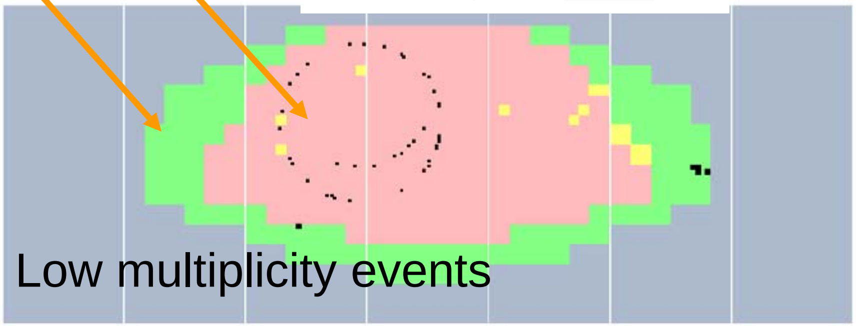
Tested this one so far

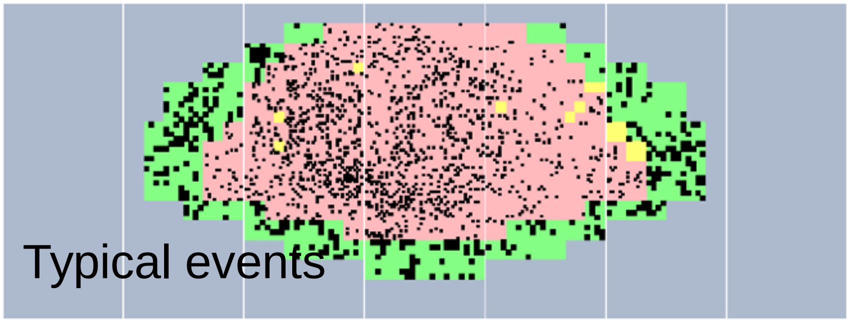
HERA-B RICH

- C_4F_{10} gas (n =1.00137), L=2.8m
- Spherical mirror: Al(200nm)+MgF_2(30nm)
- Multi-anode PMT readout
  - R5900-00-M16 (4.5×4.5mm^2/pixel)
  - R5900-03-M4 (9×9mm^2/pixel)
- 2-lens system to increase effective area (×2)
- σ_0 = 0.7mr / Npe =32 for β=1



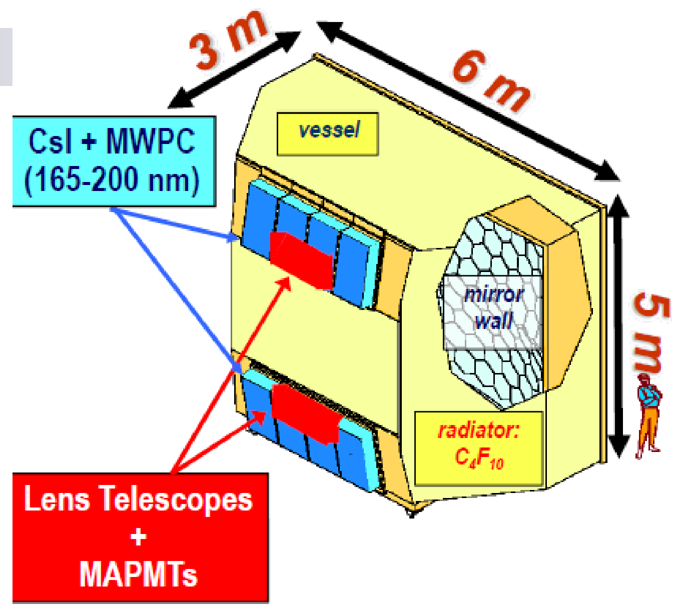



Low multiplicity events

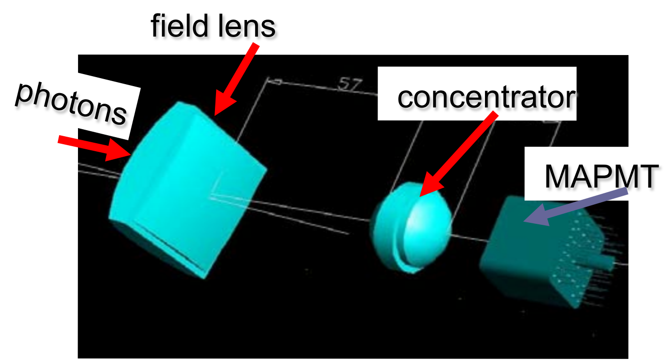

Typical events

COMPASS RICH1

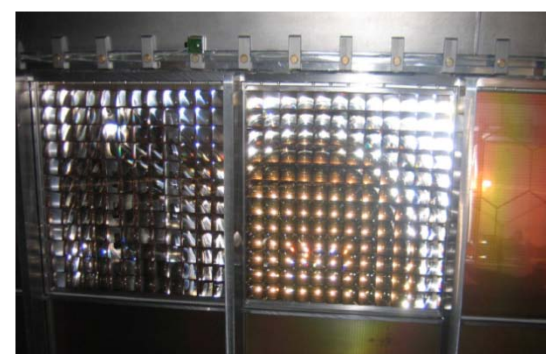
Talk by
Fulvio Tessarotto



- Major upgrade to implement new fast photon detection system in the central area(25%) + APV readout for CsI+MWPC in the outer area.
- MAPMTs (R7600-03-M16,)
  - 576 pcs. In total.
  - 18x18 mm^2 active area
  - 16 pixel (4.5x4.5mm^2)
  - Bialkali PC, UV extended glass window.
    - QE at 420nm >20%
    - QE at 250nm >5%
  - TTS = 300ps
  - Placed in soft iron box.



- Fused silica lens telescope
  - Focusing factor of 7.3
  - Dead zone fraction only 2%.



COMPASS RICH1

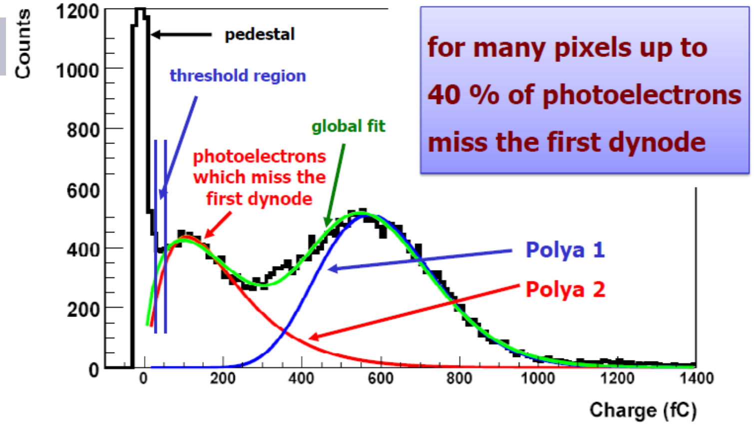
- Typical QDC dist. exhibits two-peak structure; amplification w/ full 12-stage + 1st dynode missed.

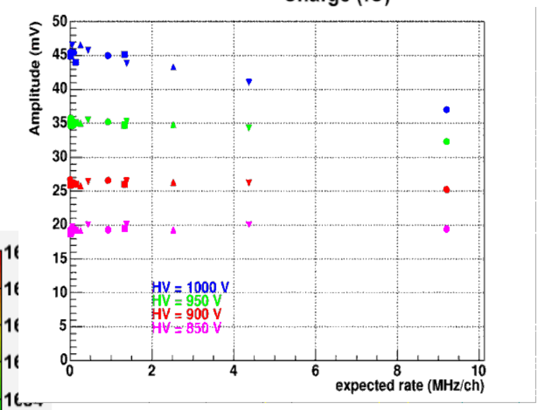
  HV setting at the minimum voltage to give 95% efficiency.
- Readout system;
  - MAD4 pre-amplifier-discriminator (<1MHz/channel).

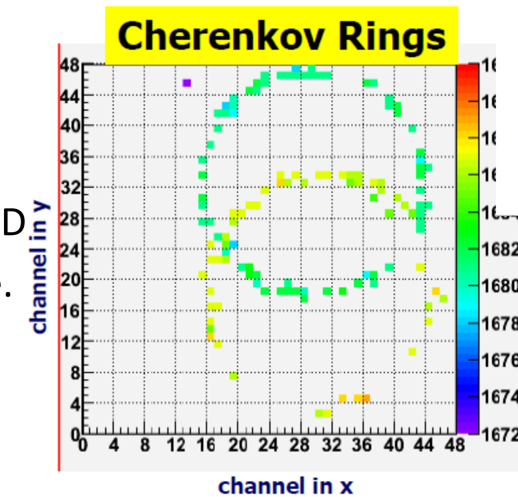
    CMAD in 2009 (<5MHz/channel)
  - DREISAM readoout board w/ 8 F1 TD
  - Up to 10MHz at 100kHz trigger rate.
- Achieved performance
  - $\langle N_{pe} \rangle$~60p.e.
  - σ_{ph} = 2mrad.
  - σ_{ring}=0.3mrad.
  - 2σ K/π up to 55GeV/c

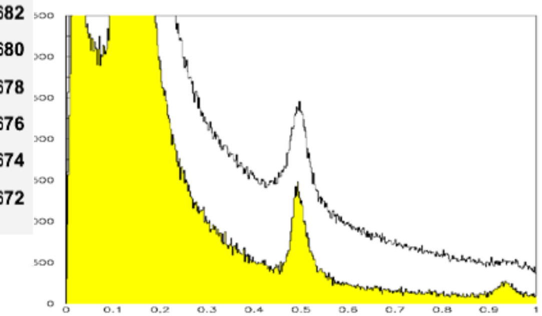
	In 2004
σ_{ring}	0.6mrad
2σ K/π	43GeV/c

- σ_t<1ns





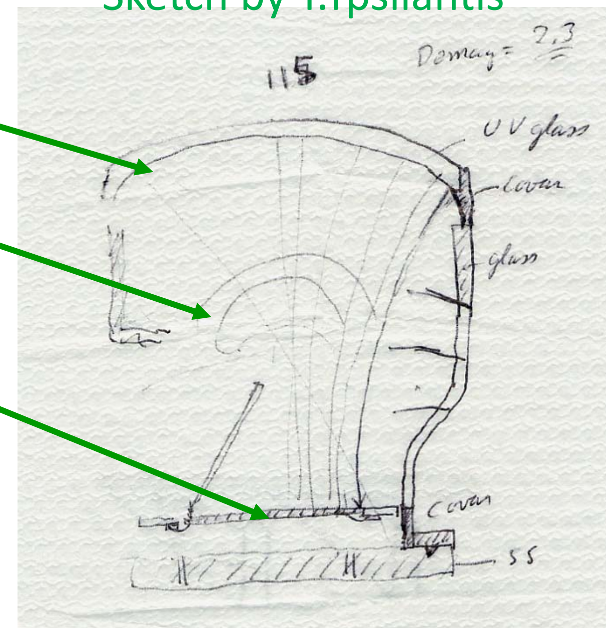




Application also in astoparticle exp.
AMS → talk by Rui Pereira
EUSO etc.

Hybrid Photodetector (HPD)

pad-HPD (CERN/LHCb)
Sketch by T.Ypsilantis



- Marriage of vacuum photocathod and silicon device technologies.
- Photoelectrons are accelerated w/ 10-20KV, bombarded on Si and lose its whole energy.
- Create electron-hole pair per 3.6eV loss.

  ⇨ Gain = 3000-5000 / pe
- No multiplicative process

  Much less gain fluctuation for each photoelectron. ⇔ Conventional PMT
- Geometry: Electrostatic / proximity focusing
- Sensor: PD / APD

  ↳ Operate in B field

  ↳ Additional 10-100 gains

Franz Muheim, Ross Young

Pixel HPD by LHCb & Photonis+DEP

- 80mm ϕ S20 photocathod window
  Cover 70% of 2.6m^2 total area
- Electron optics
  - 20KV→ 5000 e$^-$ / photon
  - Cross focusing (x5 demagnification)
- 8192 pixels (62.5μmx500μm)
  →1024 super-pixel (0.5mmx0.5mm)
- LHCBPIX1 chip bump-bonded in vacuum

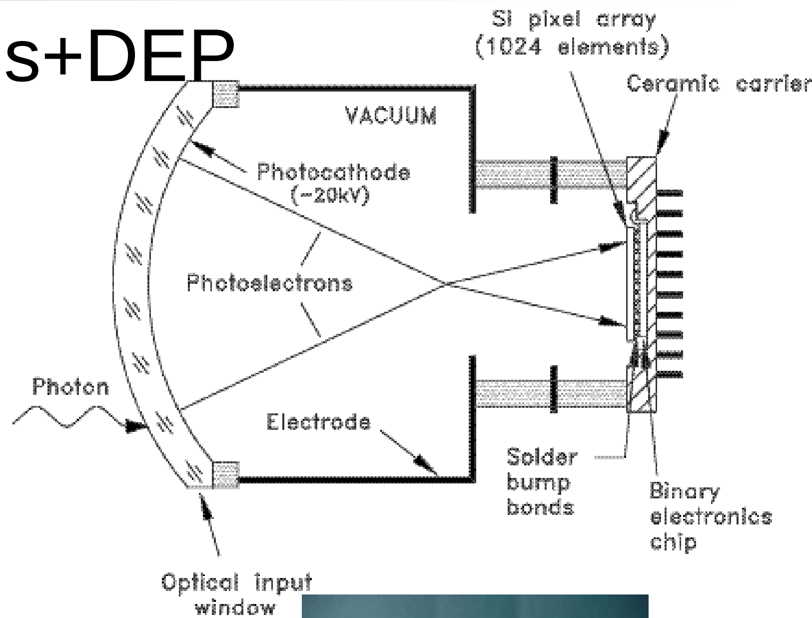
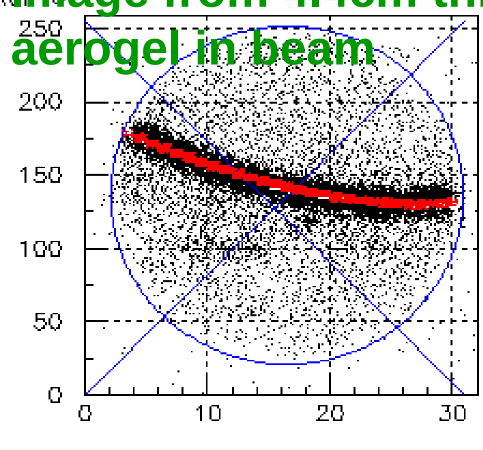
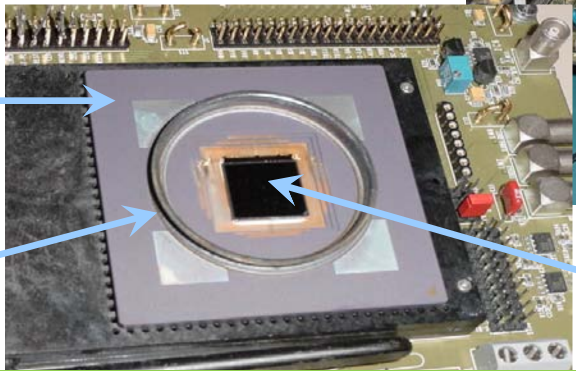


Image from 4.4cm thick aerogel in beam



PGA ceramic carrier

Kovar ring

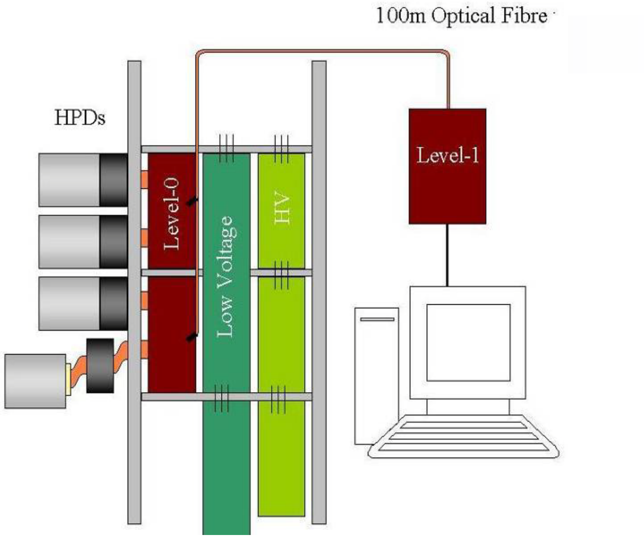


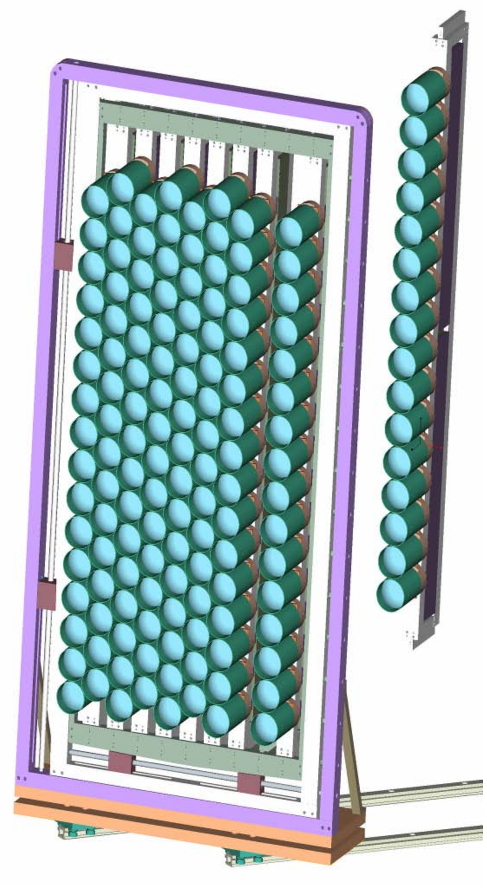
Bump-bonded sensor/chip assembly

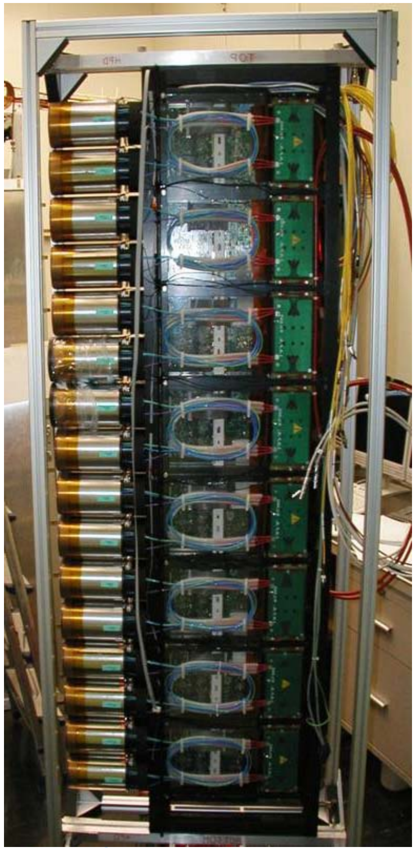
The 1st large scale application of HPD to a real experiment.

HPD Installation

- HPDs mounted in columns, to cover detector plane
- Mumetal magnetic shield tube around each HPD
- Services for HV, LV, and readout electronics mounted in frame





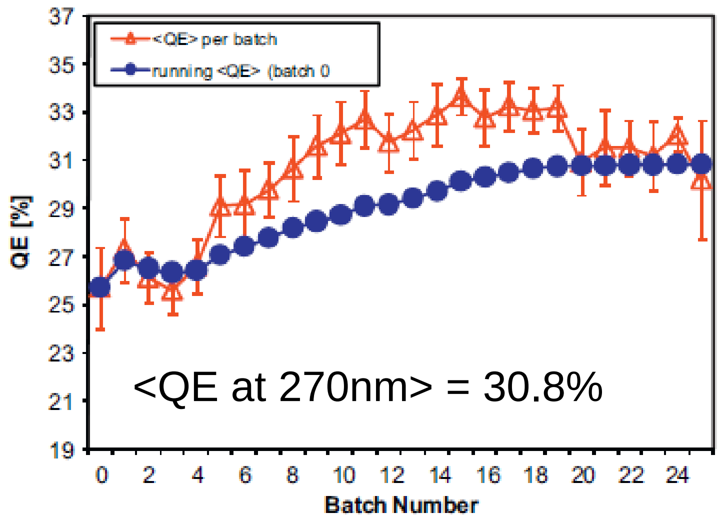


S. Eisenhardt, NIM A595 (2008) 142

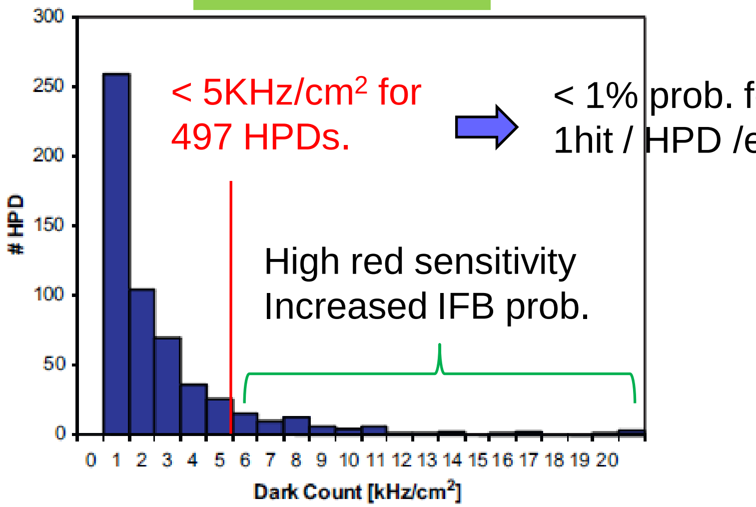
HPD Quality

559 HPDs have been produced (~30/mo.) , and tested at Photon Detector Testing Facility (PDTF).

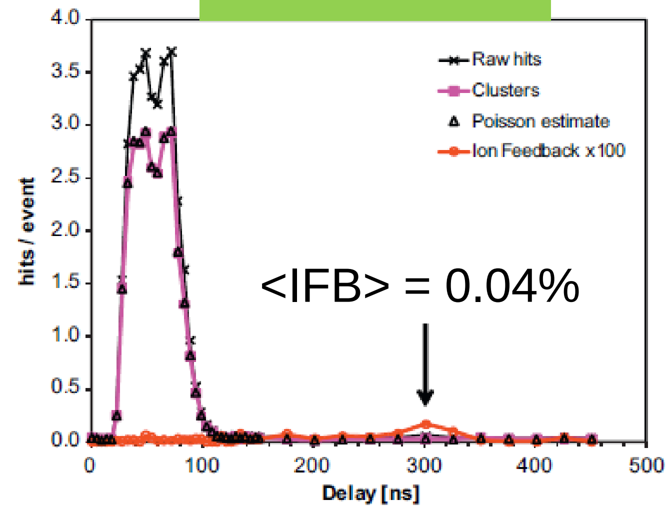
S20 Quantum Efficiency



Dark counts

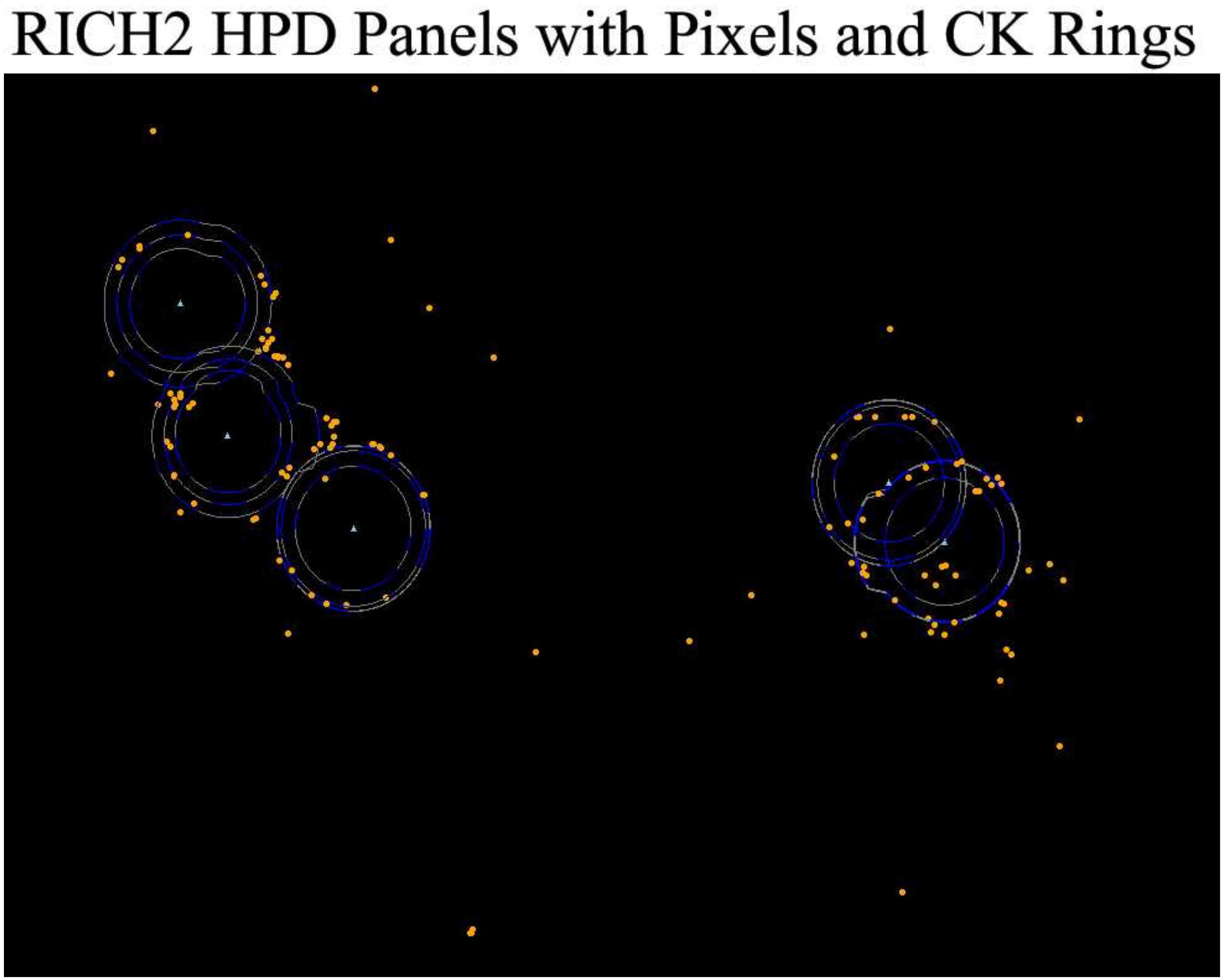


Ion Feed Back



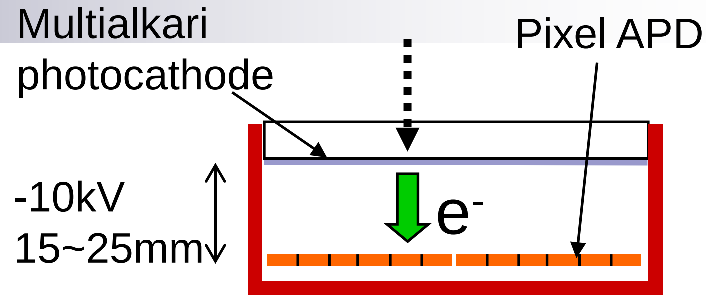
- Noise of readout electronics <N>=145 e-
- Readout Threshold <T> = 1065e-
- <S/N >= (<S>-<T>)/<N>=27

LHC turned on !

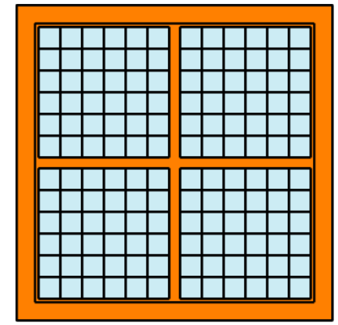


144ch HAPD

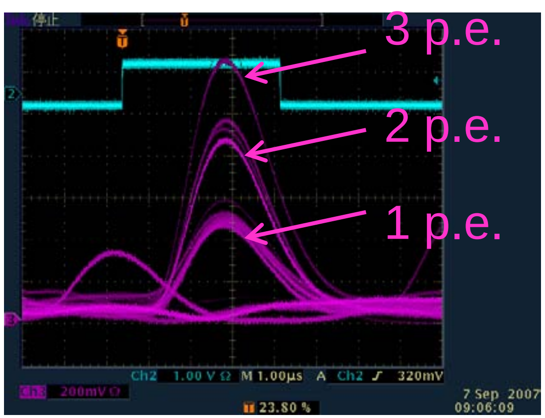
I. Adachi

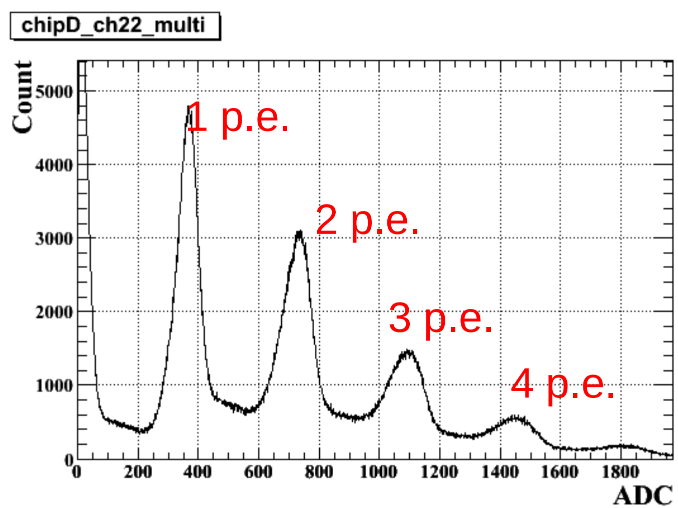


- Newly developed under collaboration with Hamamatsu Photonics.
- 4 APD chips (6x6pixel/chip)
- 5x5mm2 pixel
- 64% effective area
- High gain: $O(10^4)$



Test at bench



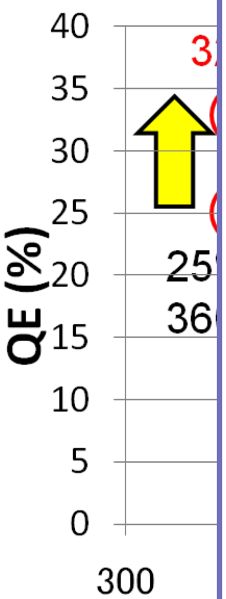


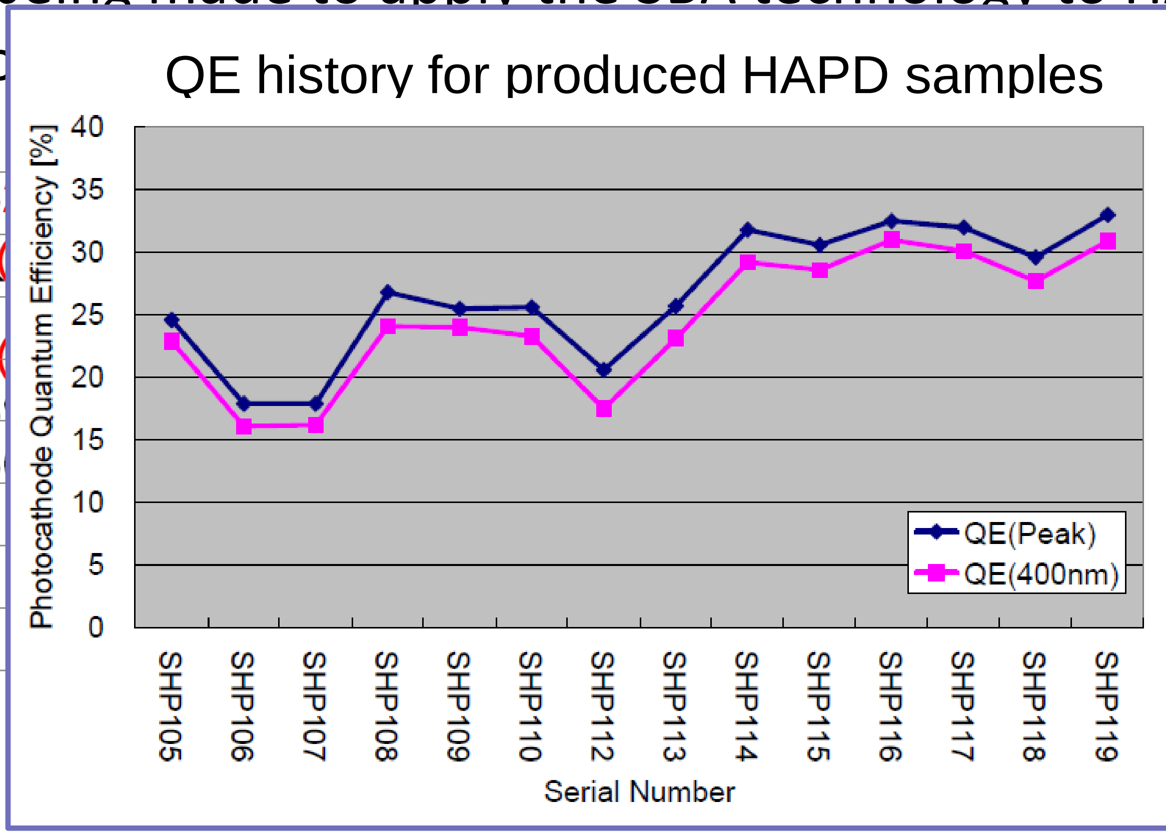
Total gain
~ 5×10^4

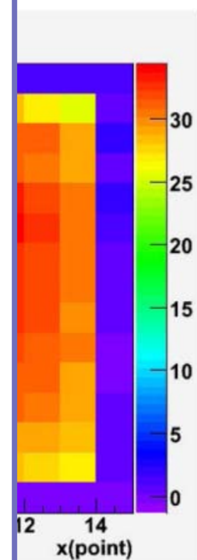
S/N = 8-15
for single p.e.

Improvement of QE

- Trial being made to apply the SBA technology to HAPD photo



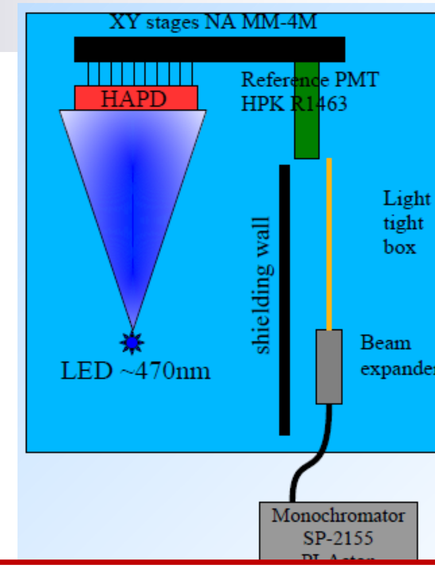


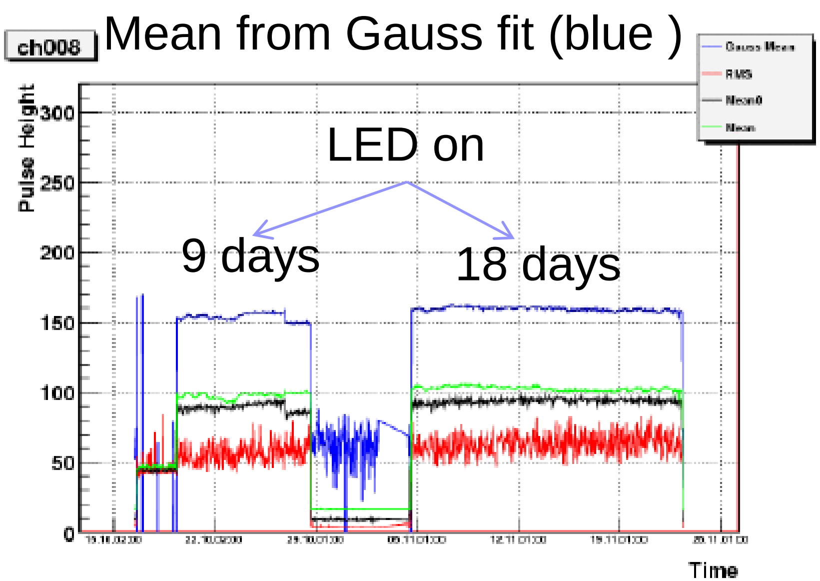


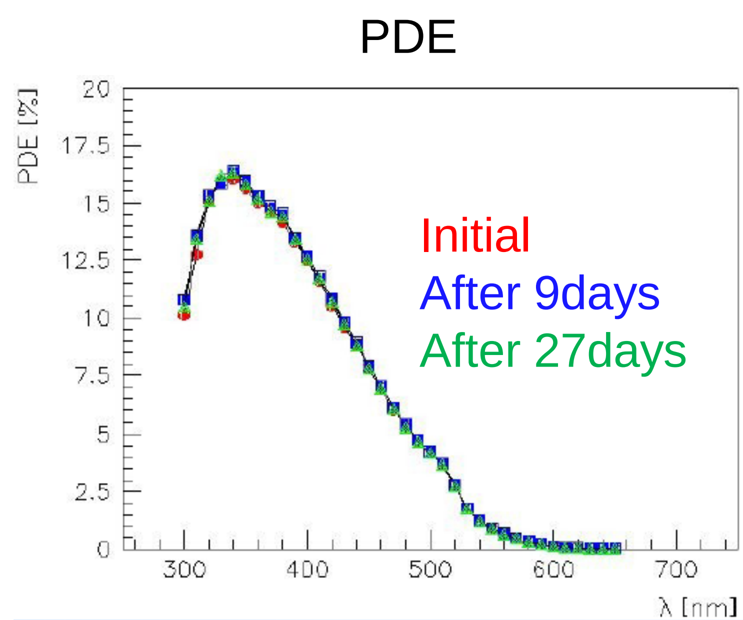
HAPD w/ QE(400nm) >30% possible !

HAPD aging

- Tested at Ljubljana.
- Monitoring currents from 3 chips.
- Monitoring ADC from 3 channels (chip B)
- Gain at 6x104 (APD~50, bombarding~1200)
- 1MHz / ch → 4days / TOP year



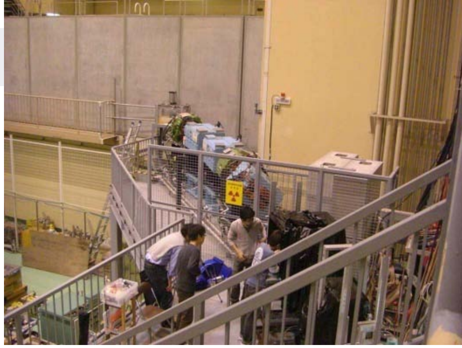




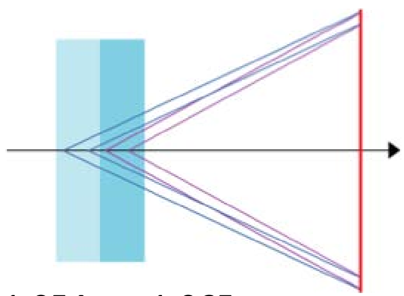
No degradation is seen after 27 days (~25 Belle II RICH years)

Beam Test with HAPD

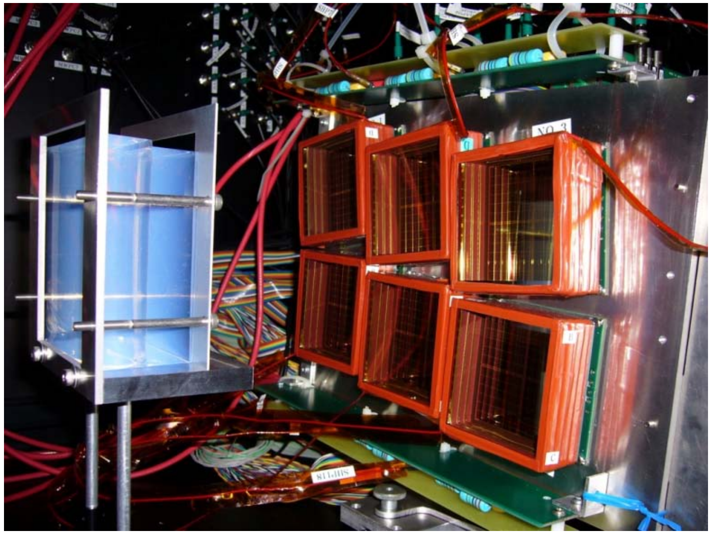
2GeV electrons at
KEKB FUJI test beam

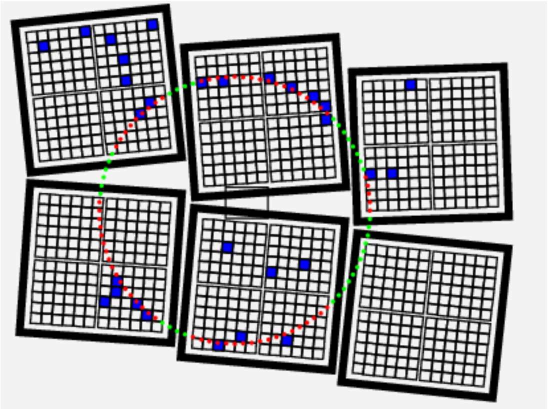


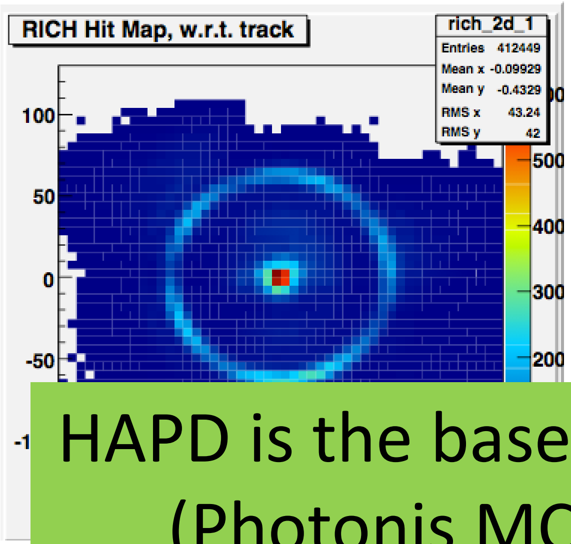
"focusing" configuration
of 2 aerogel layers.

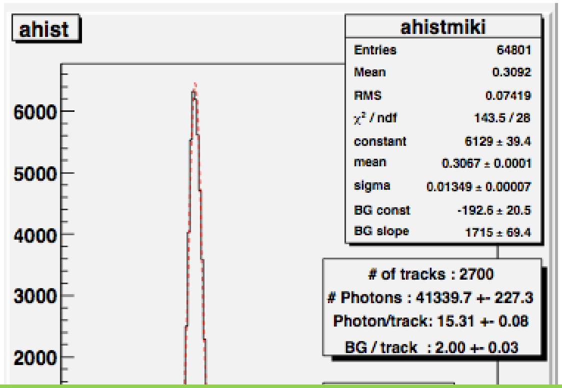


n=1.054   n=1.065
20mm / each









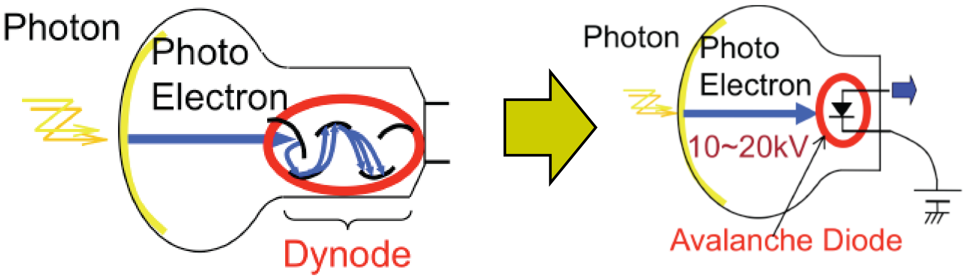
- σ_{ph} = 13.5mrad.
- $\langle N_{pe} \rangle$=15.3
- ➡ ~6σ K/π @ 4GeV/c

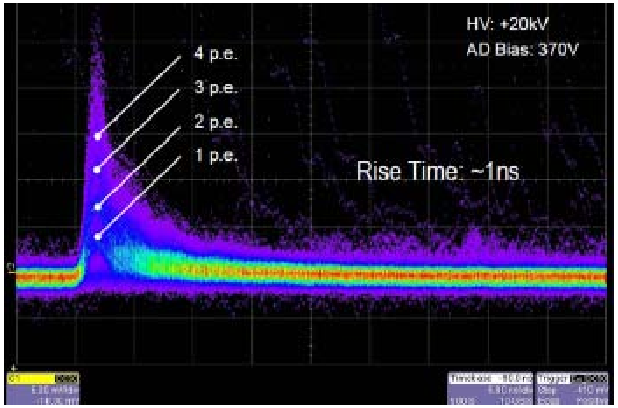
※Slight dependence on
...ondition.

HAPD is the baseline for Belle II RICH with aerogel (Photonis MCP-PMT is the backup option.)

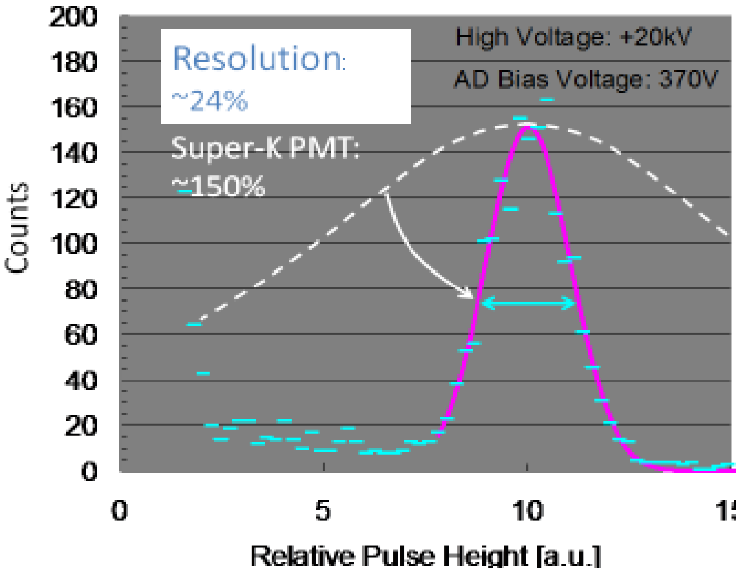
Large Aperture HAPD

- Under development by Tokyo-KEK-HPK for the next generation water Cherenkov.
- Better performance and fewer components leading to reduced costs.



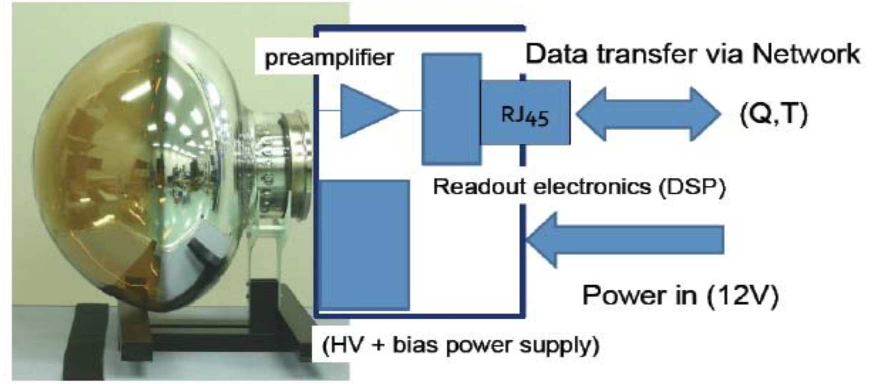


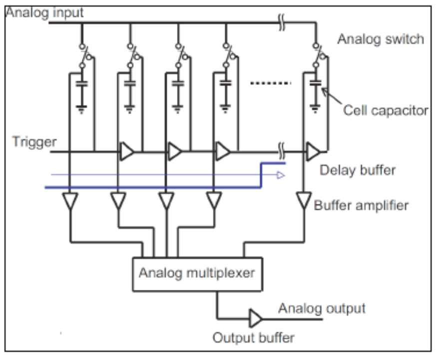
	13inch HPD	13inch PMT (R8055)	20inch PMT (for SK)
Single Photon Time Resolution	190ps	1400ps	2300ps
Single Photon Energy Resolution	24%	70%	150%
Quantum efficiency	20%	20%	20%
Collection efficiency	97%	70%	70%
Power consumption	<<700mW	~700mW	~700mW
Gain	10^5	10^7	10^7

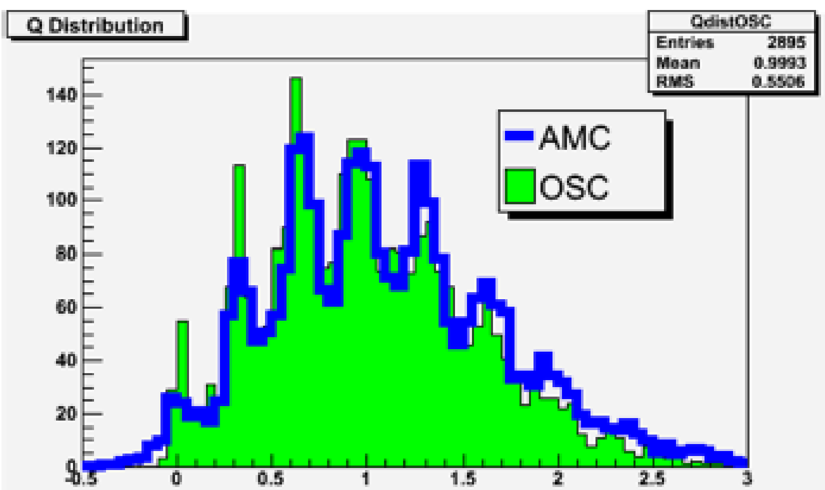


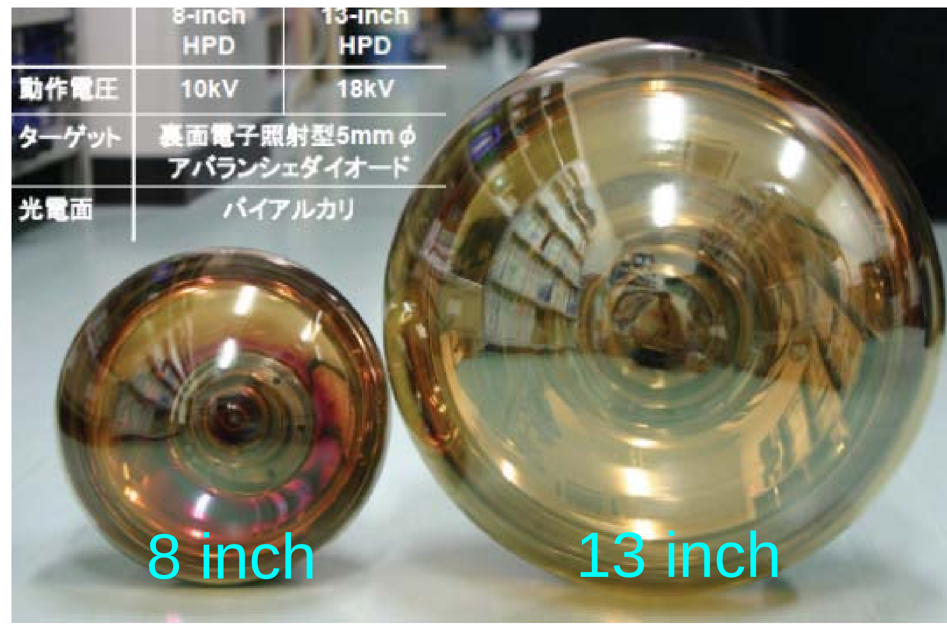
Digital HAPD

- Wave form sampling with a switched capacitor array being developed.



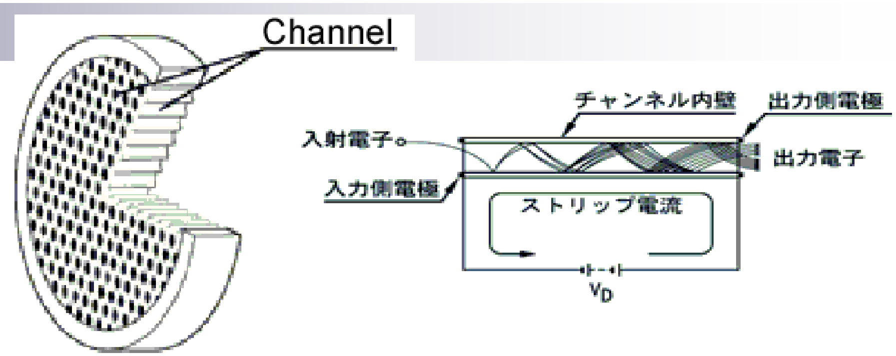




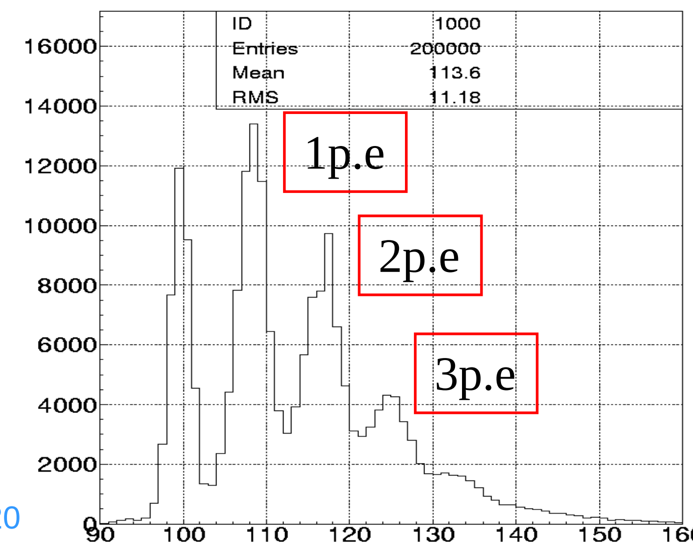


Will be available from HPK in 2012.

MCP-PMT



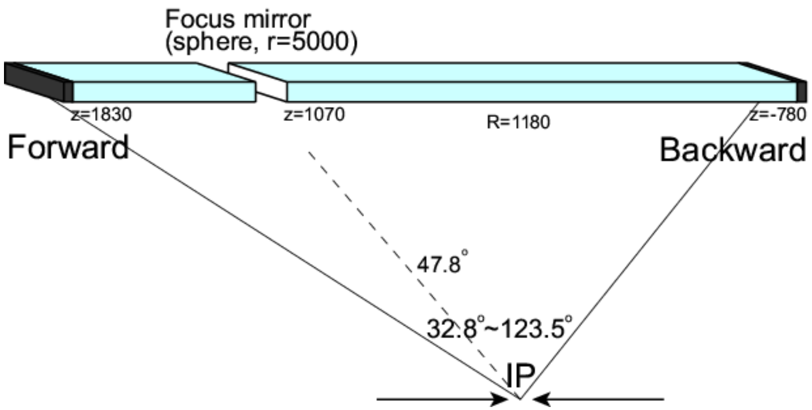
- Electron amplification in micro channel (ϕ ~10μm)
  - Fast/small transit time spread
  - Gain saturation
  - B field immunity
- Geometrical apperture ~ 60%
  ※ without Al film at MCP-in
- Gain ~O(10^6) w/ 2-3 stages
- R&D in progress for
  - Focusing DIRC (SLAC)
  - TOP (Belle/ Nagoya)

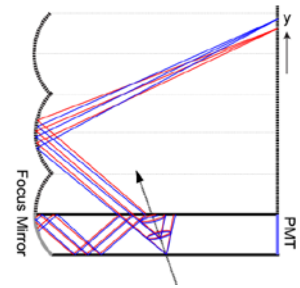


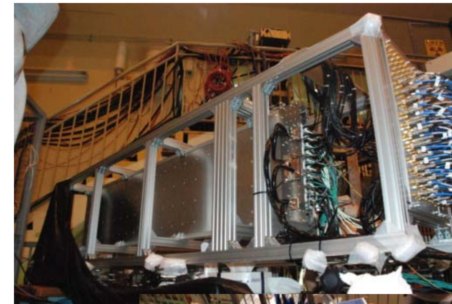
Photon counting In B=1.5T
w/ 6μm MCP-PMT
(HPK R3809-U50-11X, Nagoya R&D)

f-TOP/ f-DIRC

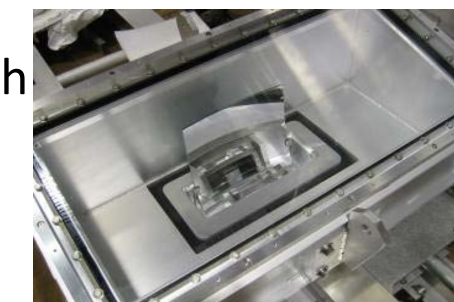
- TOP with focusing optics to measure (TOP, X, Y), considered for Belle II.

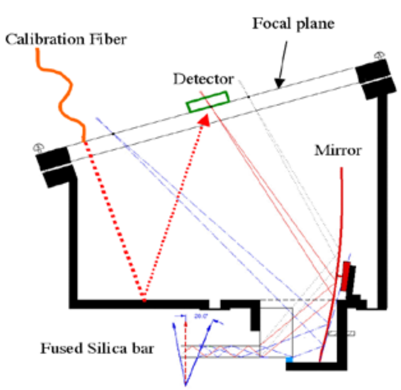


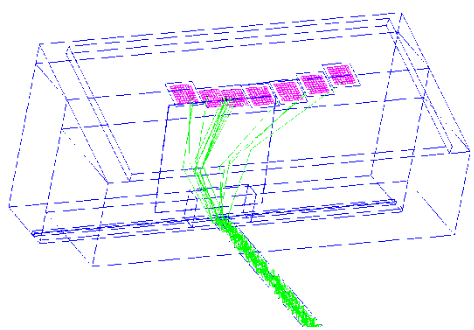


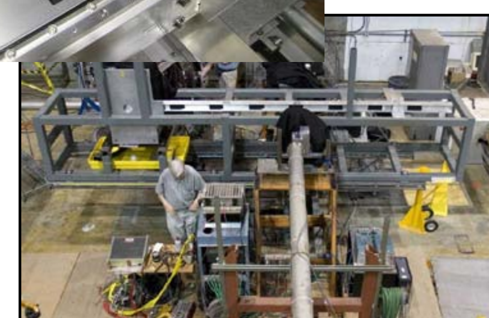


- DIRC with focusing optics to measure (X,Y,TOP) with a small standoff, considered for INFN Super-B.





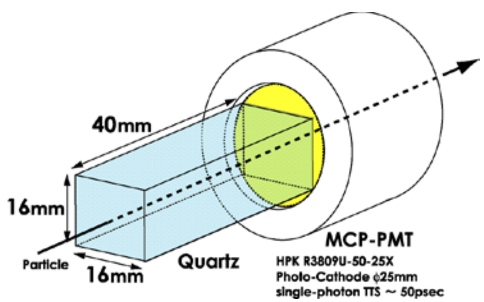


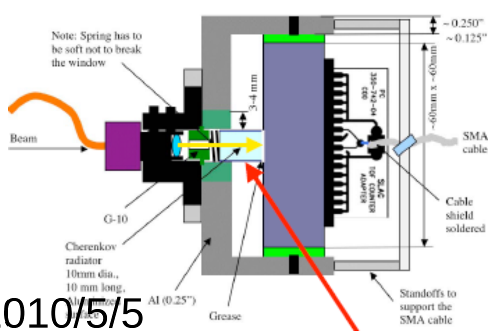


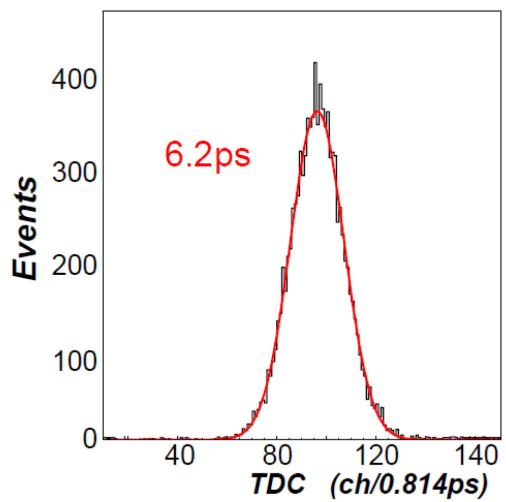
Other Application

- Similar quartz-based PID are considered in other experiments; PANDA, J-Lab, LEPS2@SPring-8, LHCb upgrade
- Aerogel RICH w/ TOF
- Possibility for **Pico-second TOF**
- Medical application (TOF-PET)

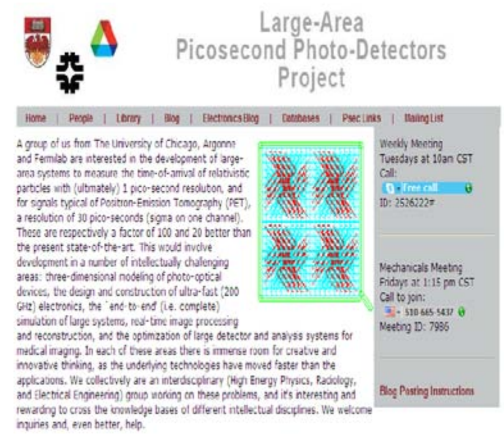
Photodetection with precision timing
New trend !





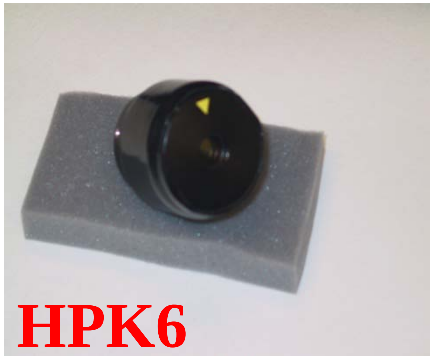


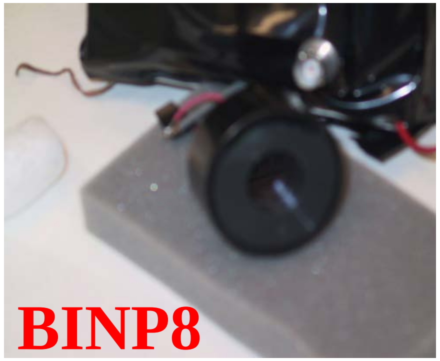
Picosecond Photo-Detectors Project
(U.Chicago, ANL, FNAL)

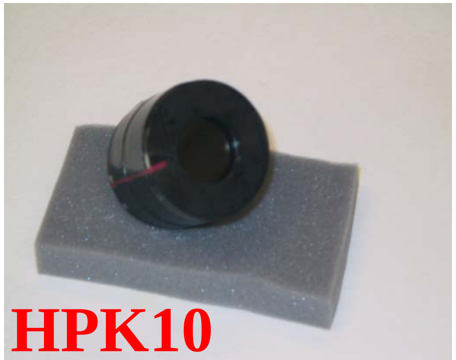


MCP-PMT for single photon

M. Akatsu et al.
NIM A528 (2004) 763





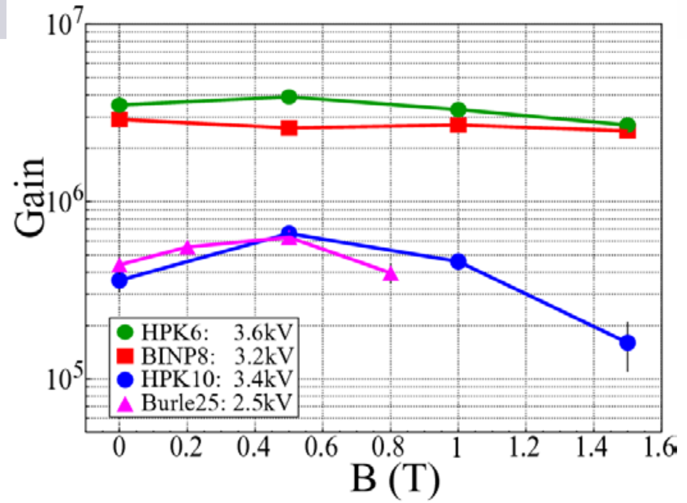


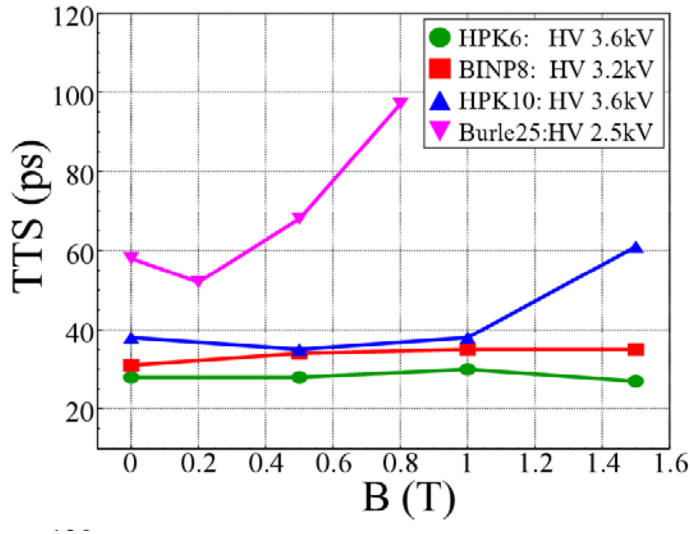
MCP-PMT	HPK6 R3809U-50-11X	BINP8 N4428	HPK10 R3809U-50-25X	Burle25 85011-501
PMT size(mm)	45	30.5	52	71x71
Effective size(mm)	11	18	25	50x50
Channel diameter(μm)	**6**	**8**	**10**	**25**
Length-diameter ratio	40	40	43	40
Max. H.V. (V)	3600	3200	3600	2500
photo-cathode	multi-alkali	multi-alkali	multi-alkali	bi-alkali
Q.E.(%) (λ=408nm)	26	18	26	24

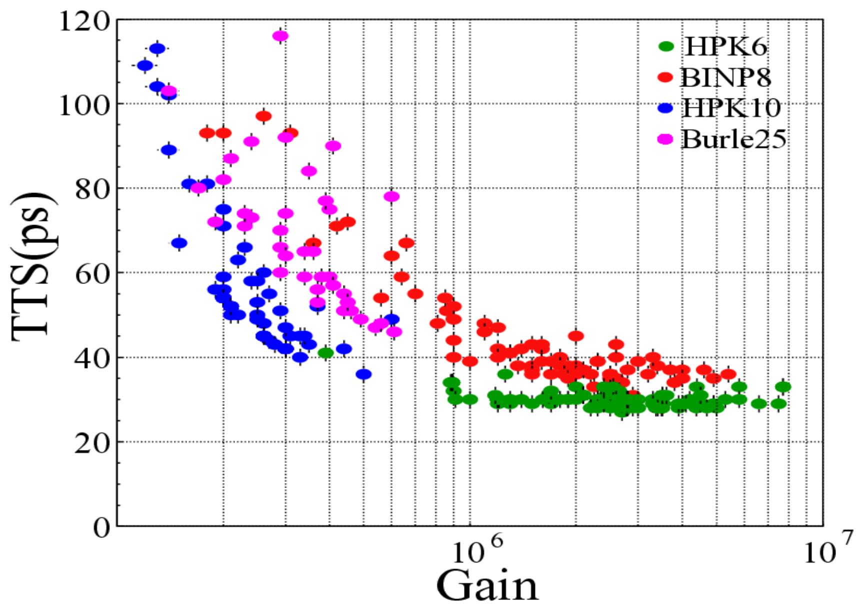
Gain, TTS in B field

- Small pore diameter shows high stability against B-field for both gain and TTS.

  Can be understood qualitatively by relation btw hole size and Larmor radius of electron motion under B-field
- TTS = 30~40ps can be obtained for gain>10^6

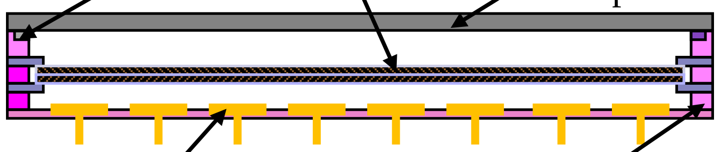


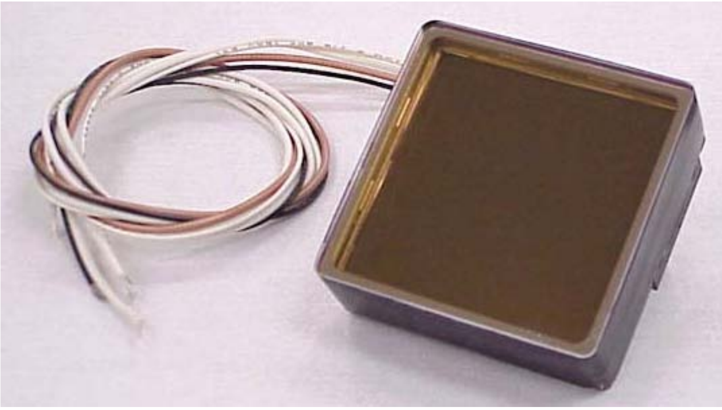




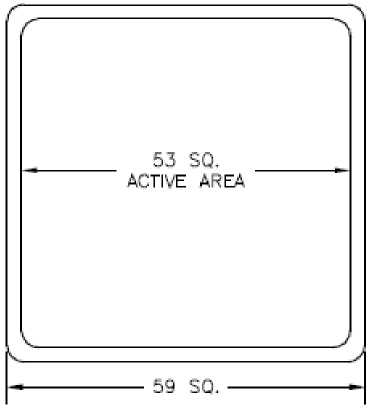
2 Need MCP-PMT w/ pore diam.<10μm to operate in B=1.5T

8x8 MCP-PMT (Burle/Photonis)





Model	85011-501	85015-A1
# MCP	2	
PC	Bialkali	
QE (400nm)	24%(TYP)	
Gain	6×10^5(TYP)	
Pore size	25μm	10μm
Open area	60%	70%
TTS	50ps	<40ps
K - MCP	6.1mm	4.4mm
MCP- A	5.2mm	3.7mm
Window thickness	2mm	1.5mm

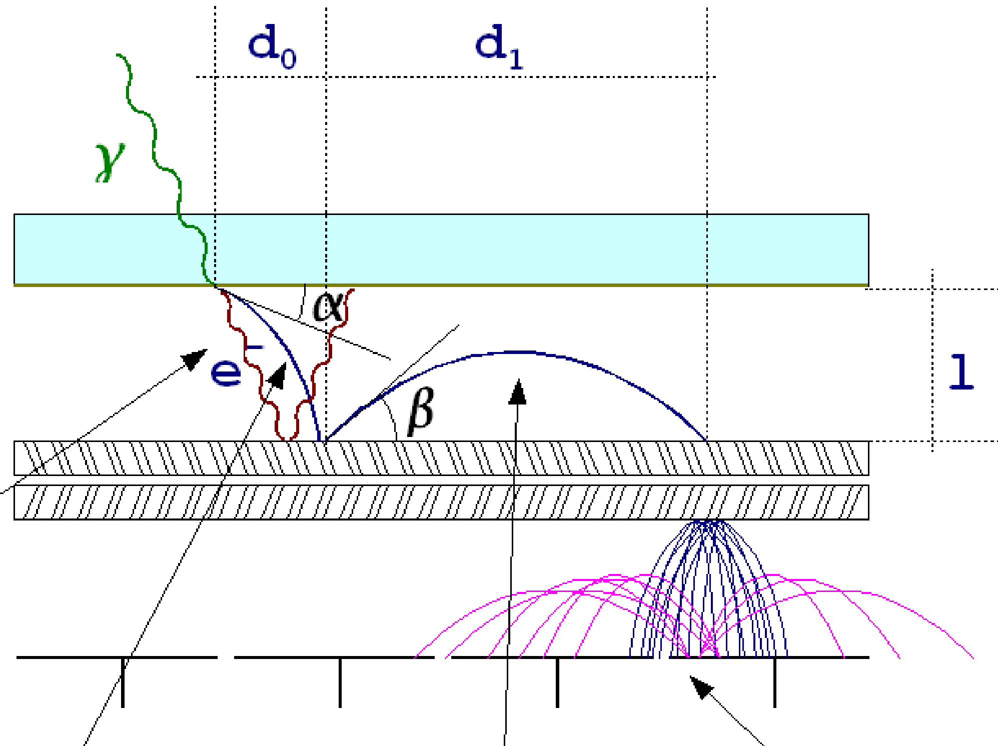


These values are for the sample acquired at IJS (85015-A1).

Processes involved in MCP-PMT

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



Internal-reflection

Photo-electron:

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

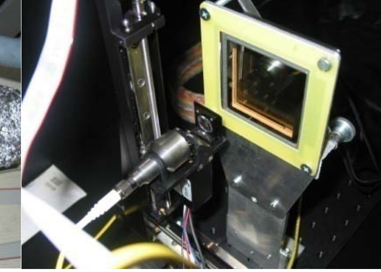
Backscattering:

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

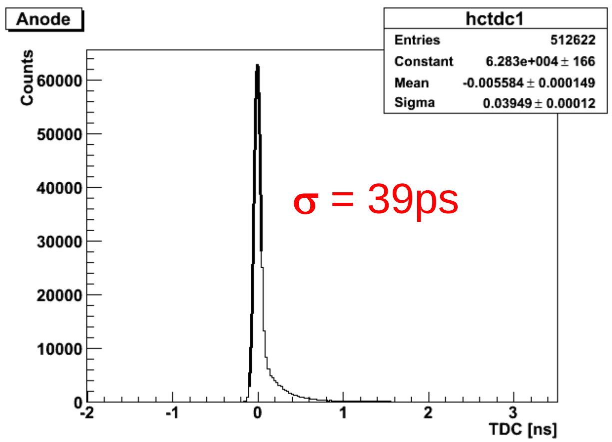
Charge sharing

Time response

for single photon irradiation

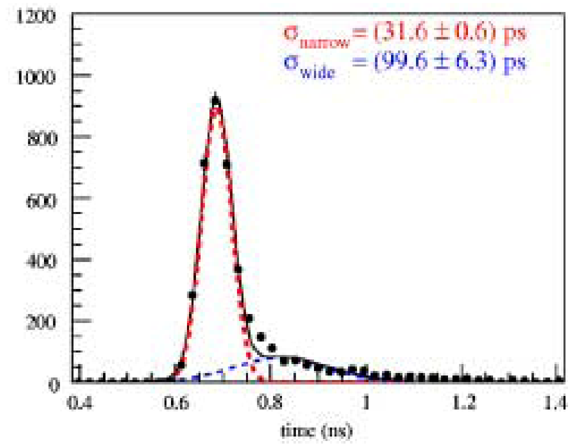



- Measurement at IJS (S. Korpar et al.)



85015-A (10μm pore, 8x8pad)
PiLas laser diode, 404nm head.
ORTEC FTA820A amplifier
Philip Model 806 discri. (300MHz)
(off-line time-walk correction)
Kaizue TDC (25ps LSB)

- Measurement at SLAC (J. Va’vra et al.)



85012-501 (10μm pore, 8x8pad)
PiLas laser diode, 635nm head.
ORTEC VT120A amplifier +6dB attn.
Philip Model 715 CFD.
LeCroy TDC (24ps LSB)

J. Va’vra et al.
NIM A572(2007) 459

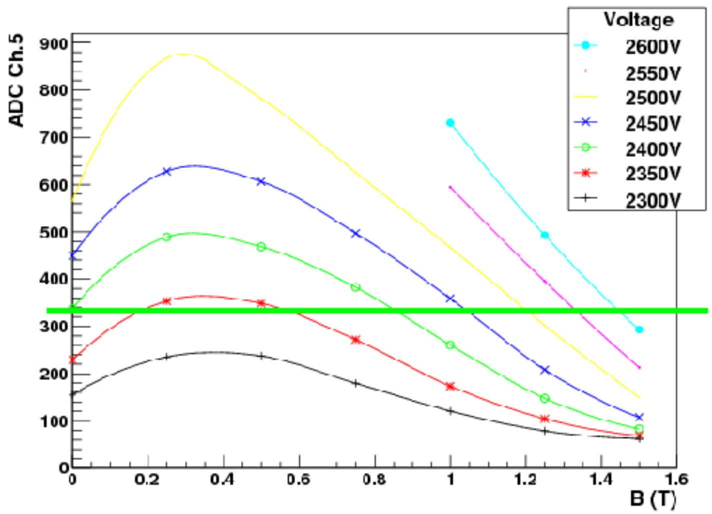
Note
σ= 54±4ps
for 25μm
pore sample

Tail due to electron backscattering at MCP surface,
Can be reduced significantly by
1) decreasing cathode-MCP distance,
2) increasing voltage difference.

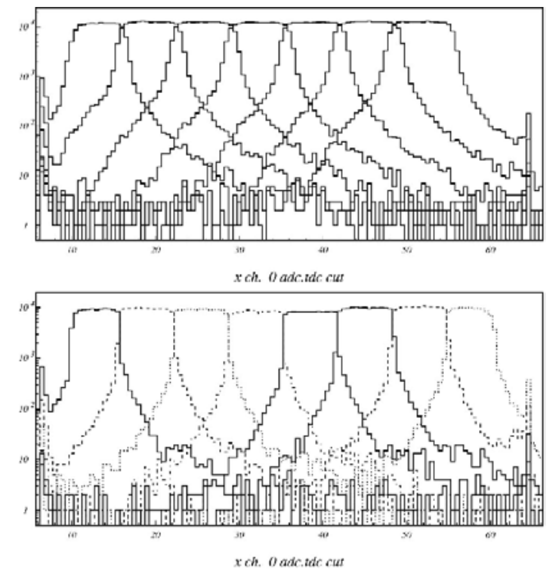
Performance in B field

- 85015-A1(8x8, 10μm pore)
  see poster by P. Krizan

Gain as a function of magnetic field for different operation voltages



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



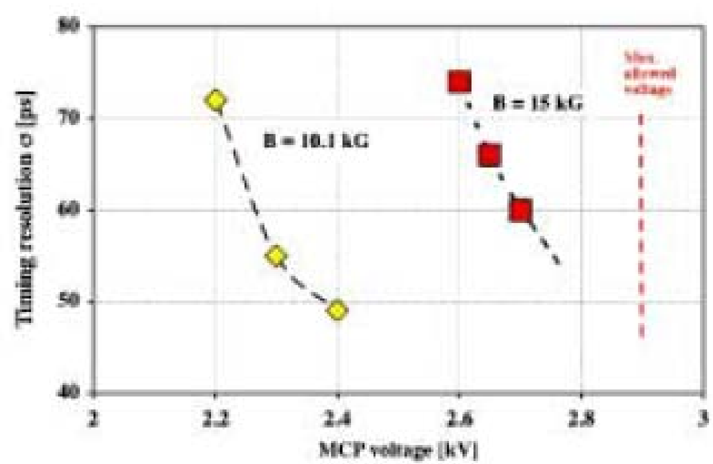
B = 0 T,
HV = 2400 V

B = 1.5 T,
HV = 2500 V

In B field, long range photoelectron back-scattering are considerably reduced.

- 85001-501(2x2, 10μm pore)
  by J. Va'vra et al.

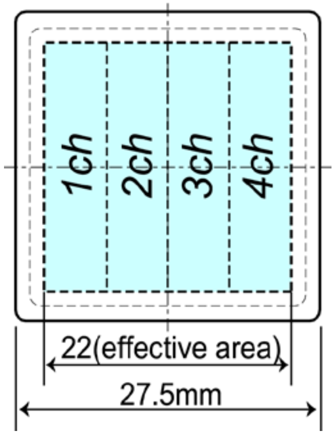
J. Va'vra et al.
NIM A572(2007) 459

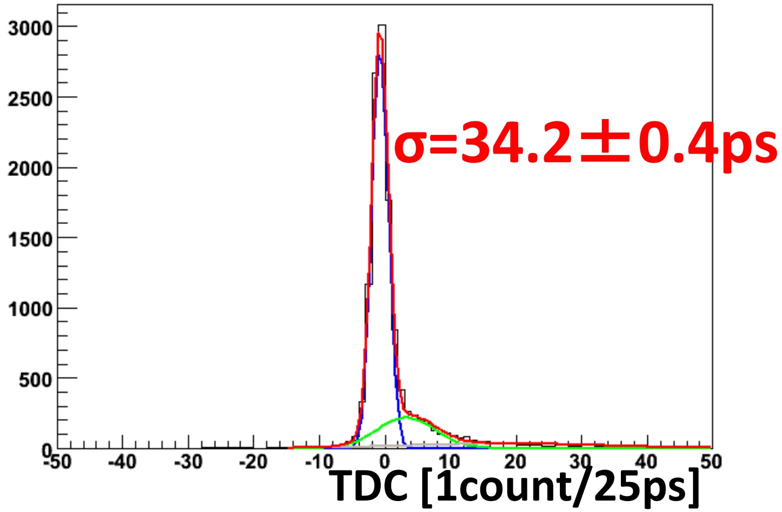


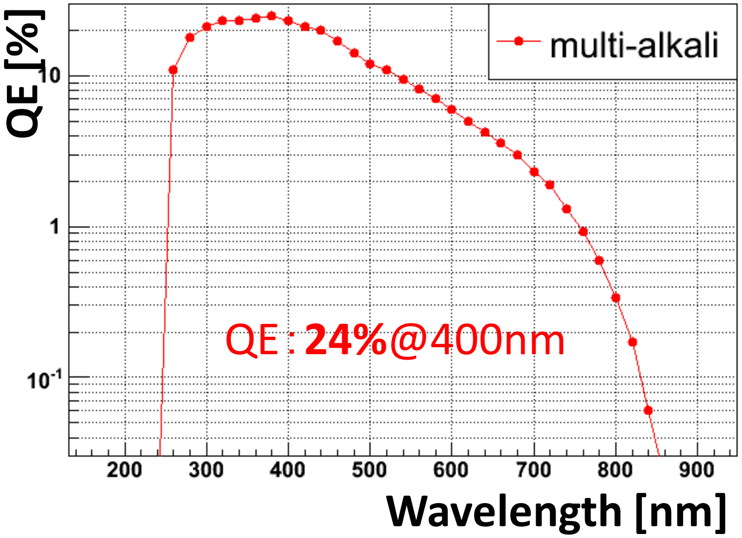
Hamamatsu MCP-PMT (SL-10)

by Nagoya & Hamamatsu

- Square-shape multi-anode MCP-PMT
  - Multi-alkali photo-cathode
  - Single photon detection
  - Fast raise time: ~400ps
  - Gain=1.5x10^6 @B=1.5T
  - T.T.S.(single photon): ~35ps @B=1.5T
  - Position resolution: <5mm
- Semi-mass-production (14 PMTs)



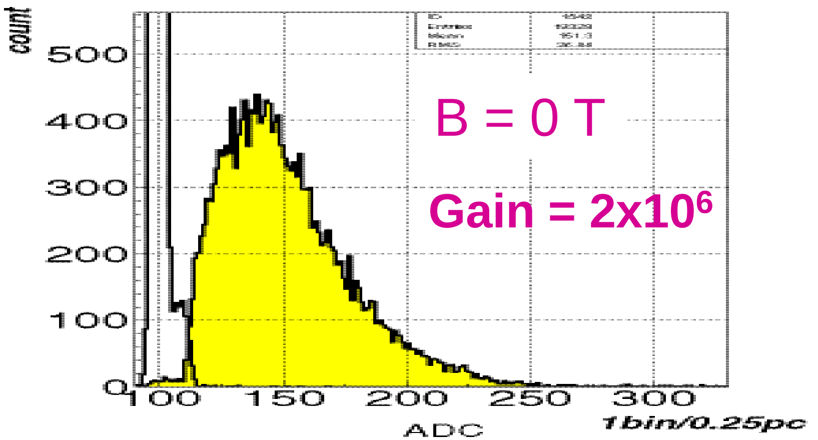


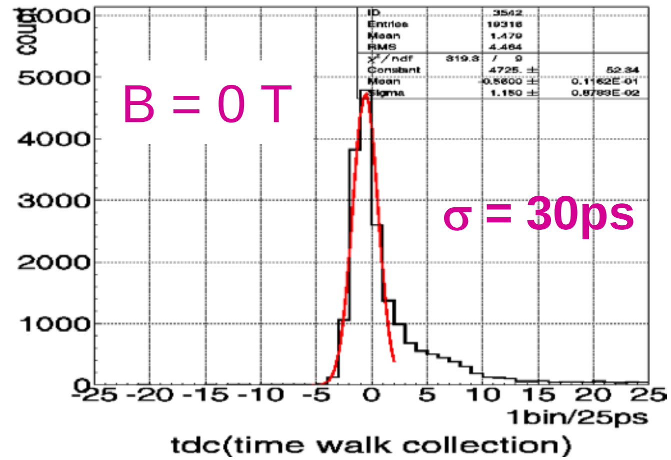


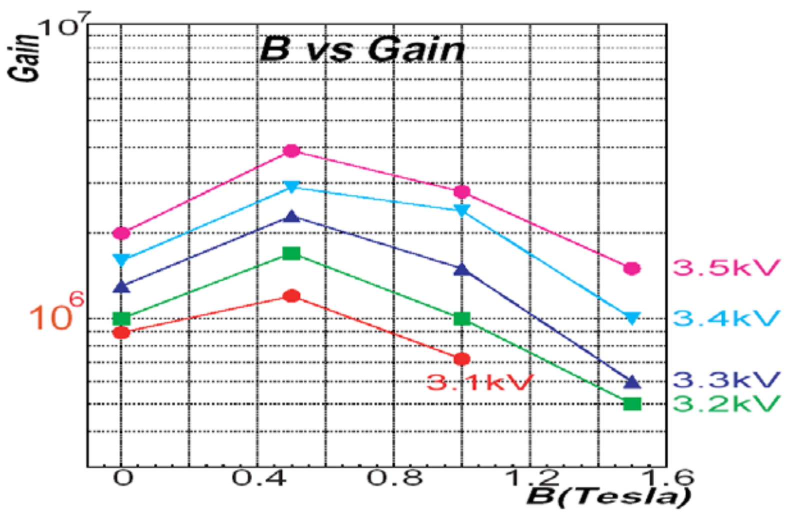
→ TTS＜40ps for all channels

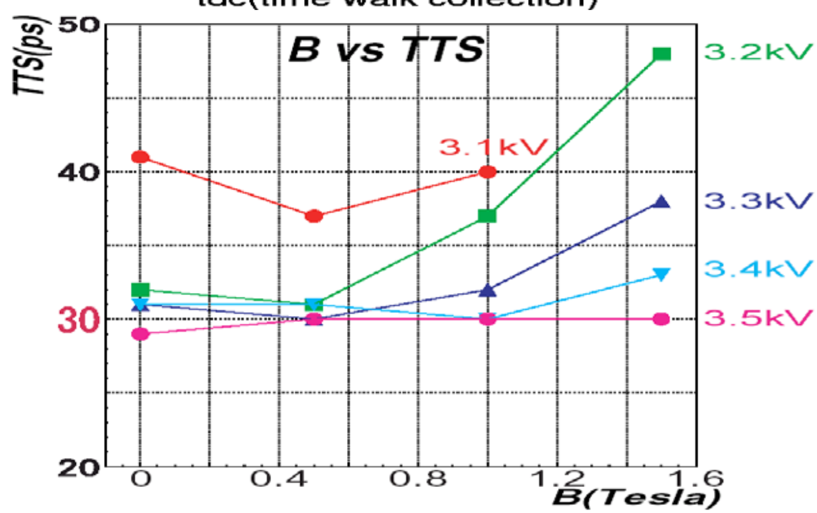
→ Ave. QE : 17%@400nm

SL10 basic performance (for single photon)









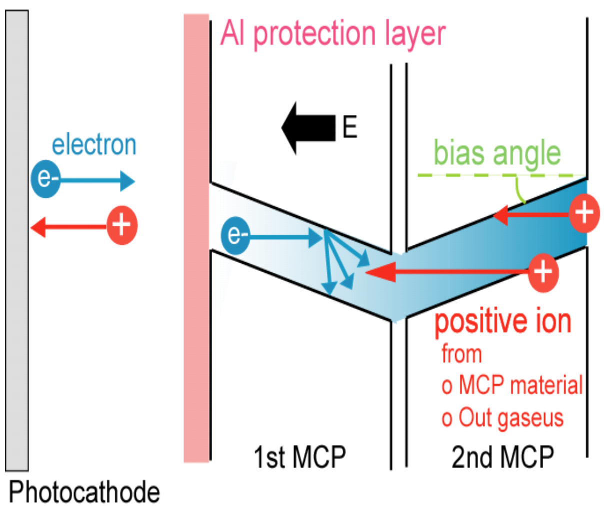
Confirmed gain > 10^6 and TTS = 30ps(σ)
In B=1.5T magnetic field.

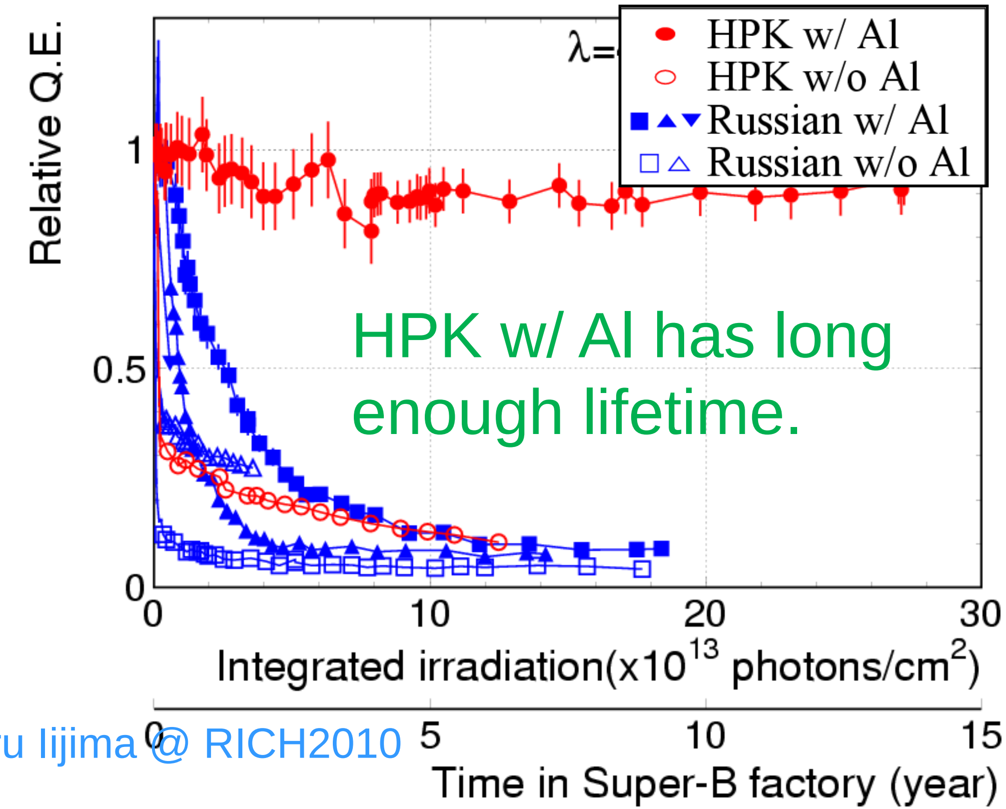
MCP-PMT Lifetime

- Feedback of ions from MCP surface or out gases causes PC deterioration.
- Aluminum protection layer (either at 1st MCP or 2nd MCP) can be applied to block IFB at some loss of signal efficiency or gain.

	HPK (x2)		Russian (x5)	
Al protection	**O**	**X**	**O**	**X**
Correction eff.	**37%**	**65%**	**40-60**	**55-60**
Effective area	11mm$^{\phi}$		18mm$^{\phi}$	
Gain	1.9×10^6	1.5×10^6	$3\sim4\times10^6$	
TTS	34ps	29ps	30~40ps	
Photo-cathode	Multi-alkali (NaKSbCs)			
QE at 400nm	21%	19%	16-20%	
Bias angle	13deg		5deg	

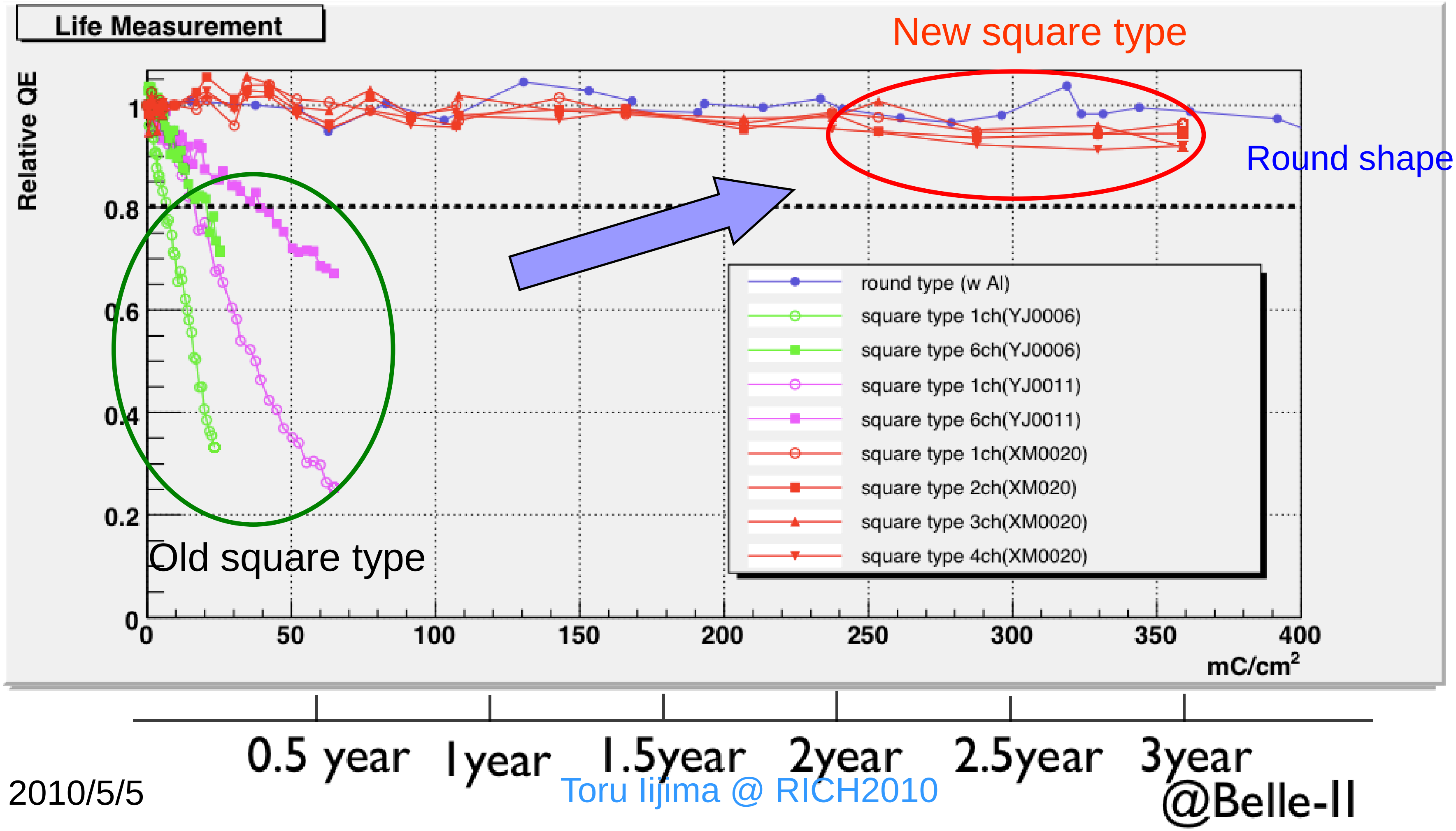
20-100 p.e. light load by LED pulse (1~5kHz)





MCP-PMT lifetime result

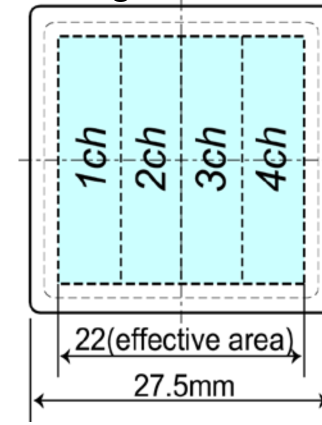
- QE variation
  - <10% drop at 350mC/cm² ; sufficient lifetime



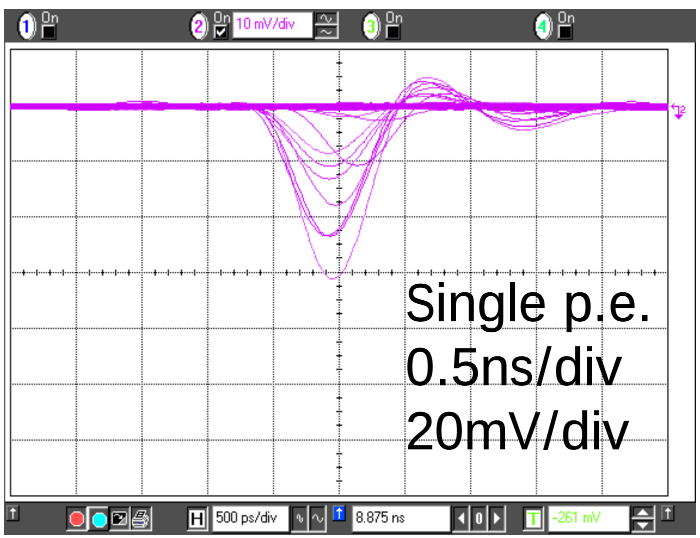
GaAsP MCP-PMT

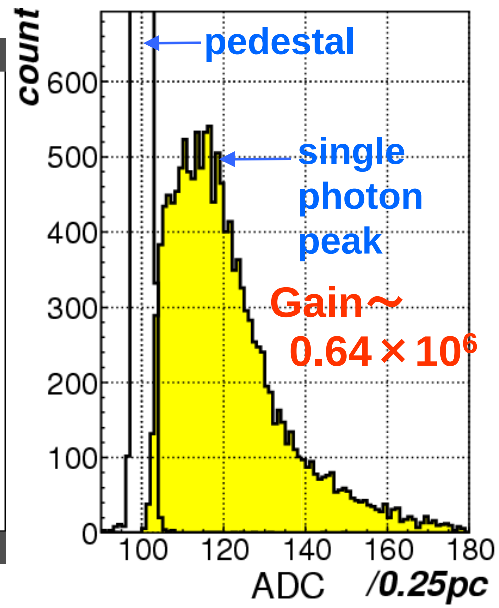
- GaAsP photocathode w/ Al protection layer
- 2 MCP layers with ϕ=10μm hole

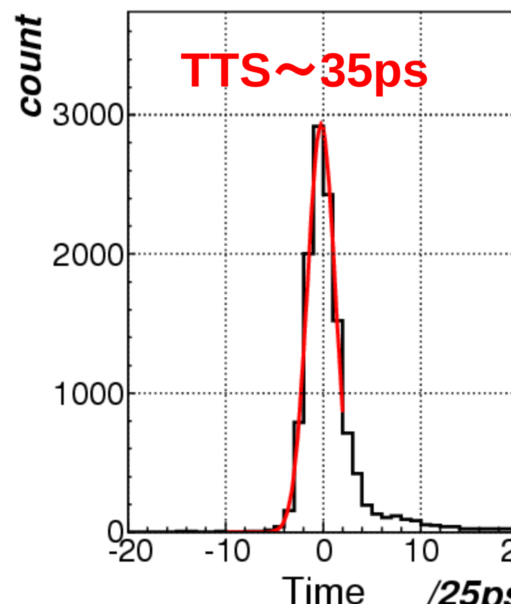
Target structure



- Wave form, ADC and TDC distributions for single photon





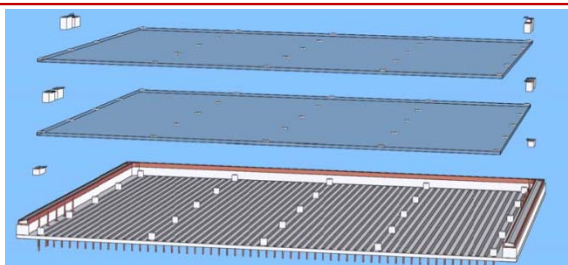


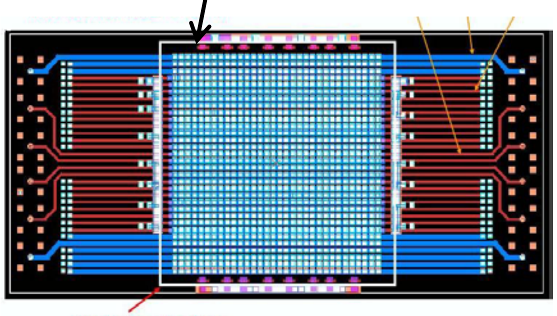
- Enough gain to detect single photo-electron
- Good time resolution (TTS=35ps) for single p.e.

LAPPD: Large Area Picosecond Photodetectors

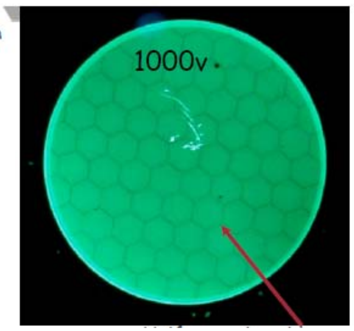
- A part of a new program in U.S. to develop cheap, large area photon detectors, using MCP technology:
- Collaboration of Chicago-Argonne-Fermilab and other institutes.

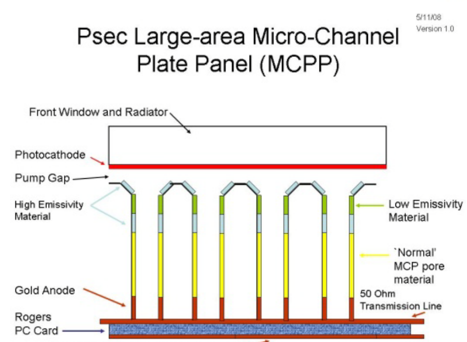
Photocathode: conventional bialkali (SSL at Berkley)
→ innovative solutions



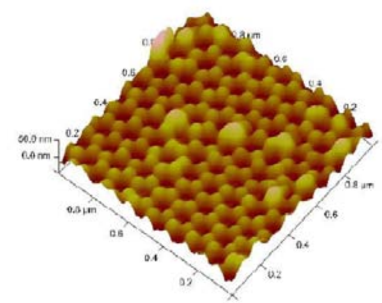


Transmission line readout to cover large area with reduced channel account.





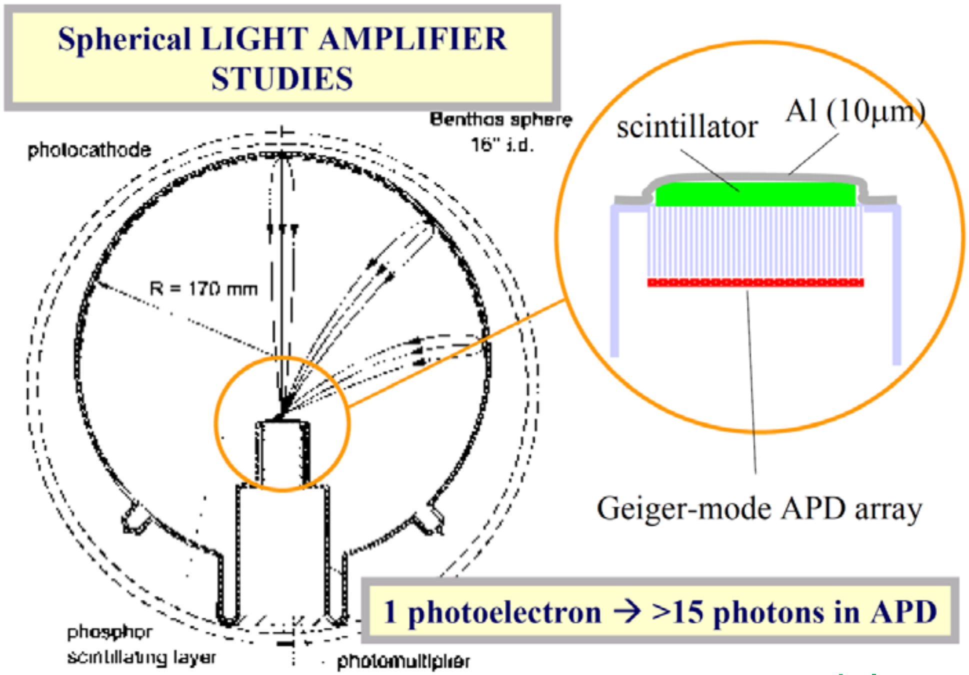
Atomic layer deposition (ALD) to form pore with active and passivated layers..



Anodic Aluminum Oxide (AA0) MCP's being developed at Argonne's Materials Science Division.

Hybrid Photodetector w/ luminescent anode

- Bombarding photoelectron to scintillator (decay constant τ).
- O(10) gain (G) with ~20kV
- Detect photons with a small PMT or G-APD.
- No active material inside vacuum. Simple structure.
- A possible cost-effective way for large scale experiments (ex. next generation water Cherenkov)



SMART PMT, QUASAR

Excellent single photon
energy resolution.
$\propto 1/\sqrt{G}$
time resolution
Transit time dist;
$W(t) \sim \exp[(-G/\tau)t]$

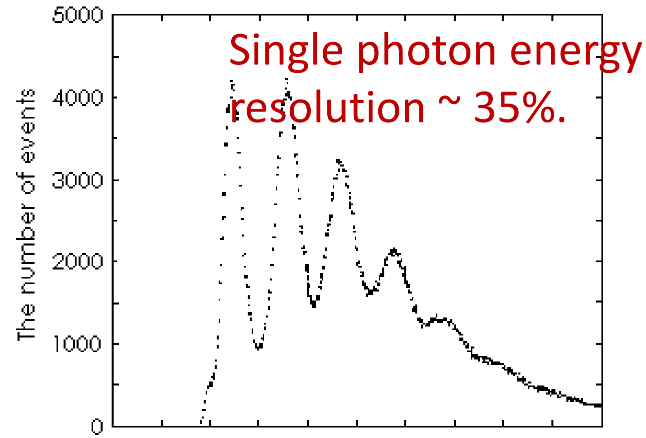
B. Lubsandorzhiev, NIM A610, 68 (2009)

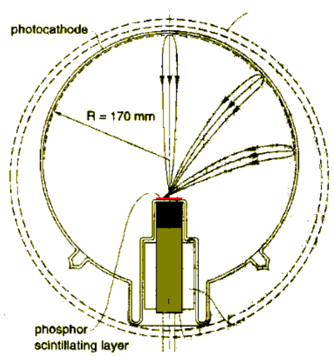
Daniel Ferenc @ RICH2004

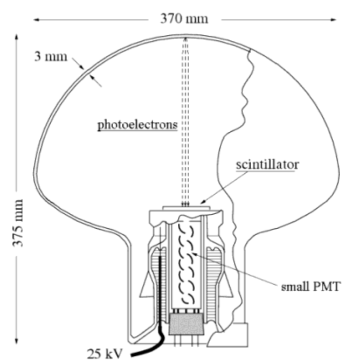
SMART / QUASAR PMT

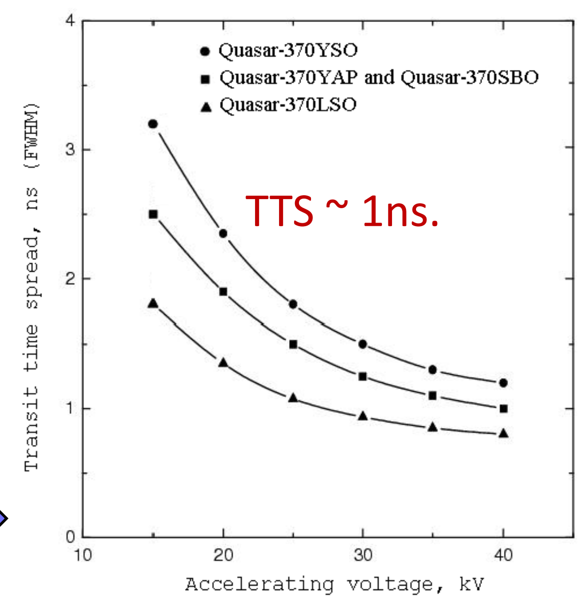
See B. Lubsandorzhiev, NIM A610, 68 (2009) and reference therein

- The idea using is not new, and already used for DUMAND SMART and Lake Baikal QUASAR PMT.









YSO(Y_2SiO_5:Ce) = P47 phospher
YAP($YALO_3$:Ce)
SBO(ScB_3:Ce)
LSO(Lu_2SIO_5:Ce)

Quasar-370LSO w/ LSO crystal

Talk by C. Joram @ NDIP08

A. Braem, C. Joram, J.Suginot, P. Lavoute, C. Moussant, NIM A570 (2007) 467.

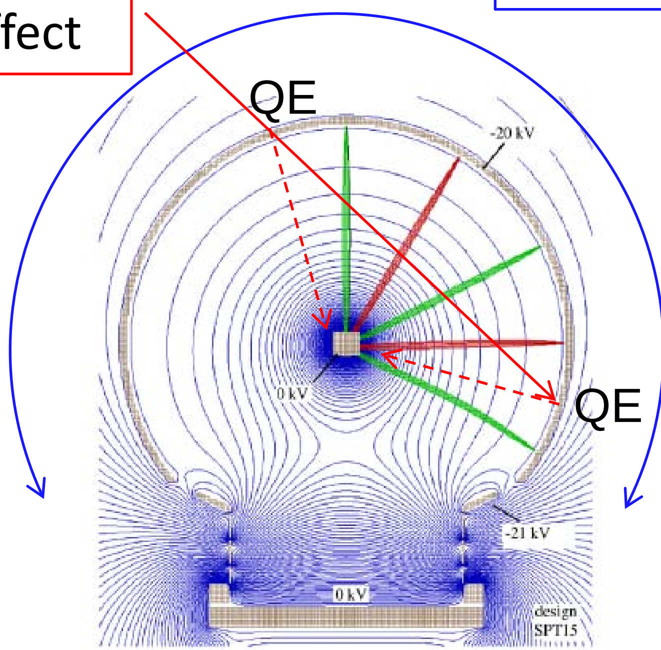
A. Braem, C. Joram, J.Suginot, P. Solevi, A-G. Dehaine, NIM A610 (2009) 61.

X-HPD

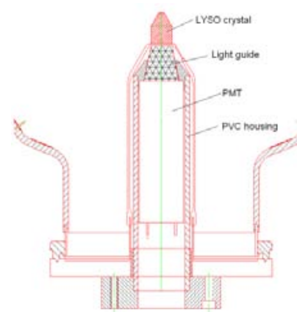
A modern implementation of a SMART concept

Double cathode effect

Large acceptance (3π)



Low transit time spread

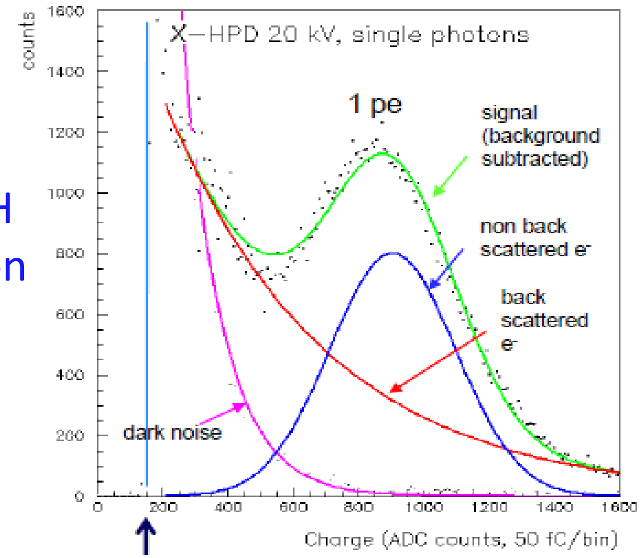


Production at CERN facility

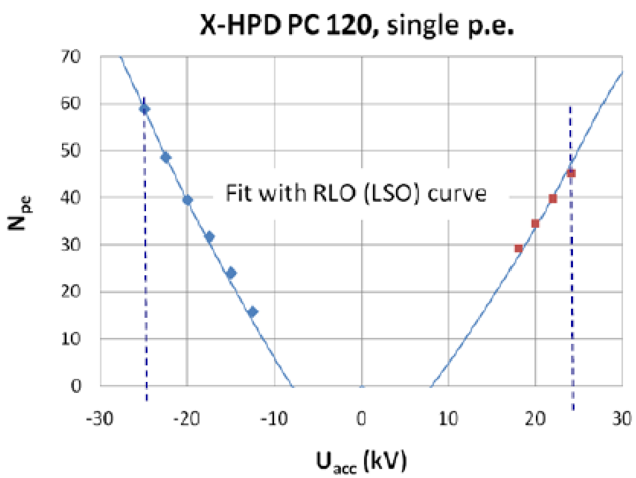
X-HPD: Response to primary single photons

- 208mm diameter X-HPD
- LYSO:Ce
  - LY=25γ/KeV,
  - τ~40ns,
  - Z_{eff}=64,
  - ε_{BC}=0.45,
  - $\lambda_{emission}$=420nm)
- Readout by XP3102 PMT

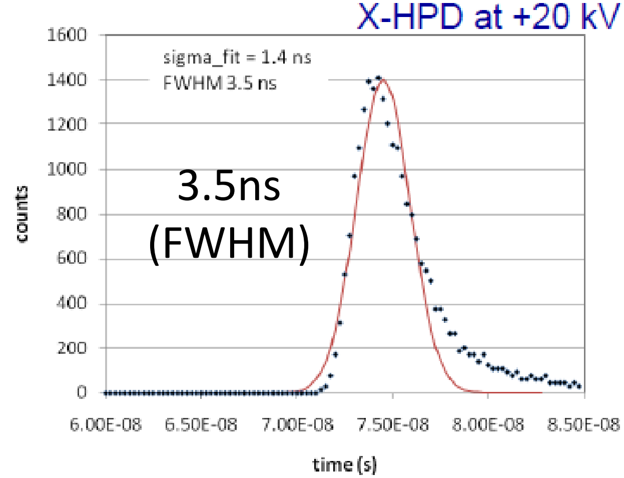
XP3102 PH distribution



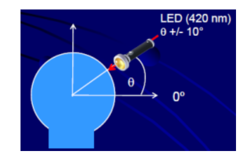
Npe vs HV

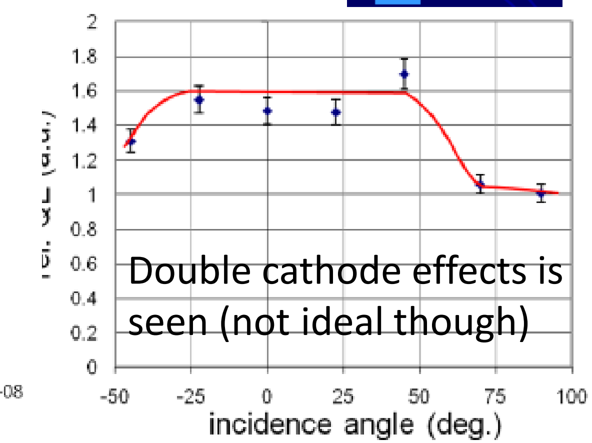


Time distribution



Relative QE





Double cathode effects is seen (not ideal though)

Faster Phosphor ?

Q: What is this ?

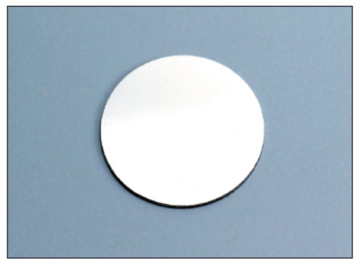
A: A kind of …

HAMAMATSU FAST DECAY PHOSPHOR
J9758

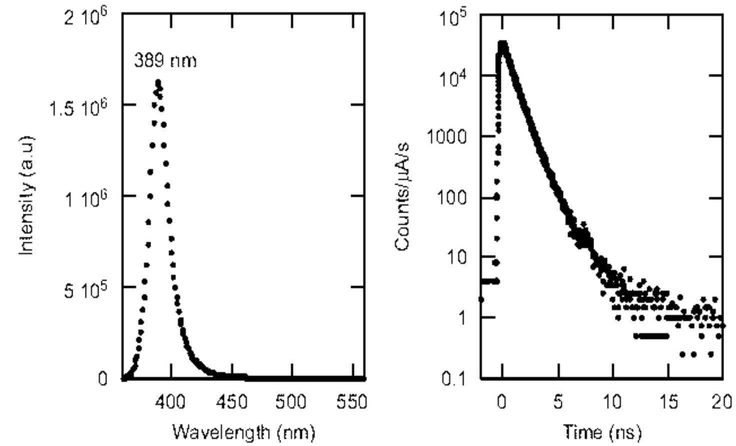
For Electron Beam Detection,
High Speed and Long Life Phosphor

FEATURES
- High Speed Decay (Decay Time: 500 ps)
- Long Life
- High Brightness Efficiency

APPLICATIONS
- Semiconductor Inspection Instrument
- SEM (Scanning Electron Microscopy)
- Mass Spectrometry
- General Electron Detection

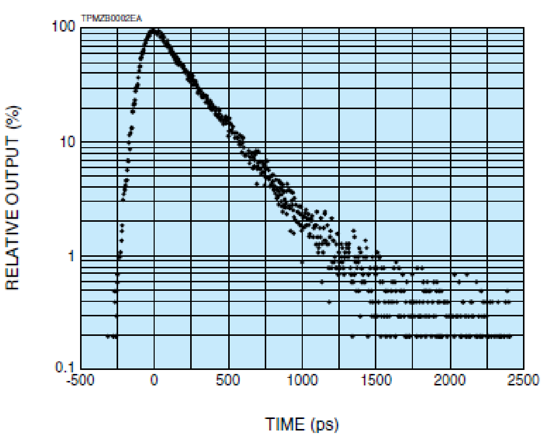


ZnO (Ga)

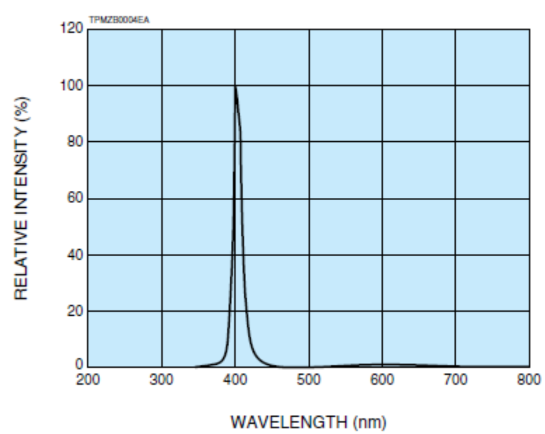


E.D. Bourett-Courchesne et al. NIMA
Poster by B. Lubsandorzhiev

Decay time (90→10%)
= 500ps (typ.)

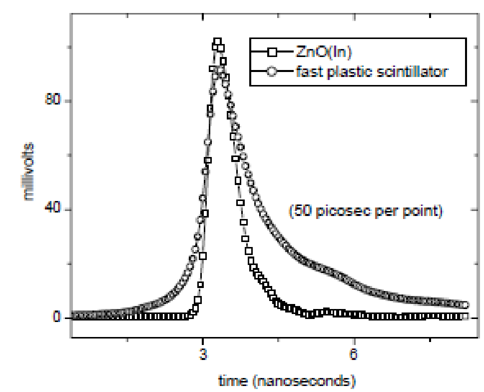


Emission peak = 400nm



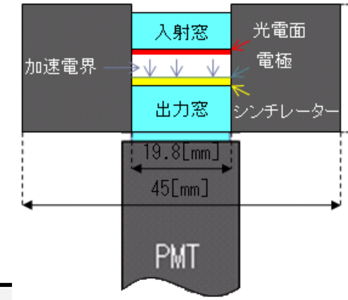
ZnO (In)

P.J. Simpson et al.
NIM A505, 82 (2003)



Test of J9758 w/ PIC

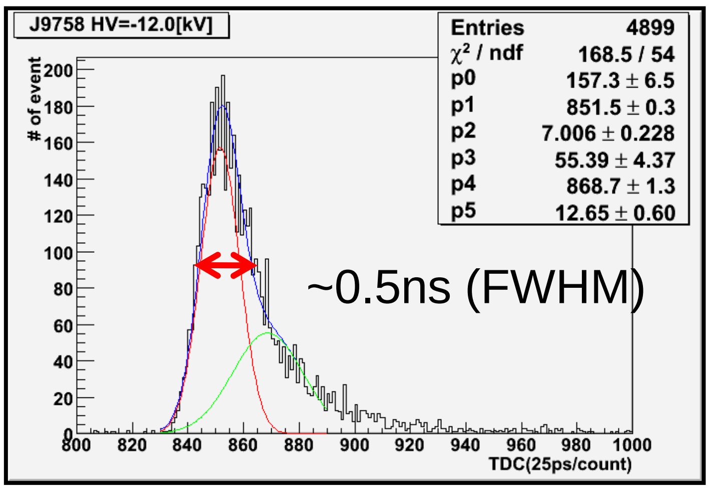
PIC = Proximity Image Converter



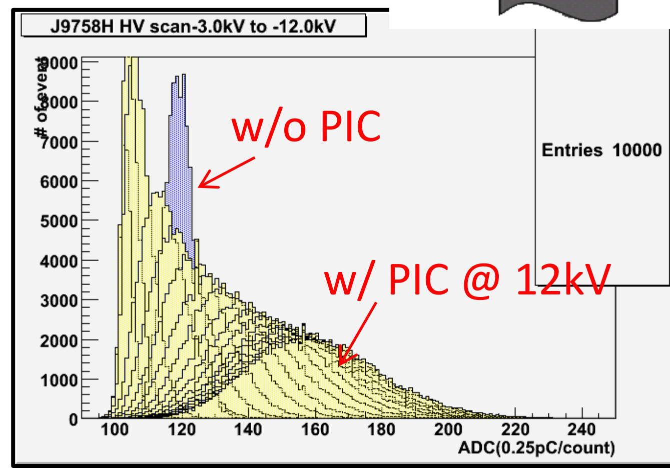
- 1”PMT (H6533) directly attched to PIC output window.

  Bialkali PC, TTS = 270ps (FWHM)
- The maximum PIC HV = 12kV.
- Pulse laser w/ 408nm head.

TDC distribution

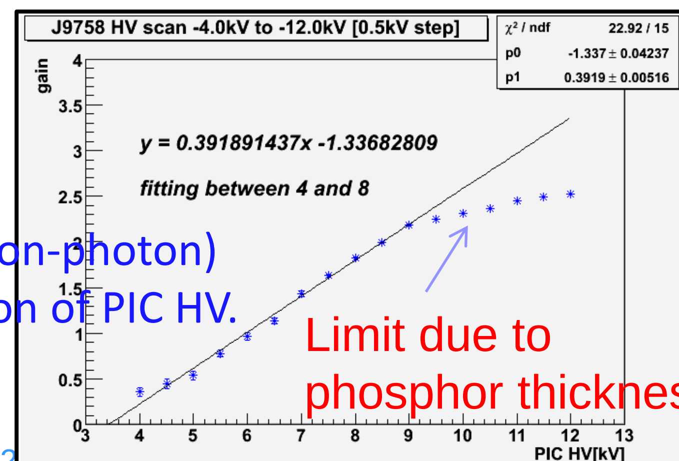


ADC distribution



Sub-nsec resolution possible

Gain (photon-photon) as a function of PIC HV.



Tsunada (Nagoya) @
JPS meeting, March 2010.

Summary

- There have been good progress in vacuum-based photodetectors for single photon counting.
  - Improvement in quantum efficiency
  - Precision timing   new trend !
  - Use in magnetic field.
- MA-PMTs: established and widely used. Optical systems to minimize dead area have been successfully developed too.
- HPD/HAPD: in good shape. Large scale application to real experiments: LHCb, Belle II in near future (in 1.5T).
- MCP-PMT: in good shape. Application to measure TOP as well as positions → 3D imaging.
- Efforts are being made to realize cheap large size detector;

  Large aperture HAPD, LAPPD, X-HPD etc.

Possibility for in-house fabrication

Backup Slides

Requirements on Photodetectors

- Photodetection is the heart of RICH, the most powerful tool of PID.
- RICH requires positioning of single photon with good S/N ratio.
- There are broad range of requirements, depending on application in a variety of scientific fields.

Requirements;

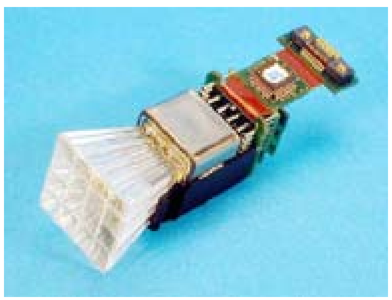
- Total area
- Granularity
- Quantum efficiency (band width)
- Time resolution
- Rate capability
- Magnetic field
- Radiation damage

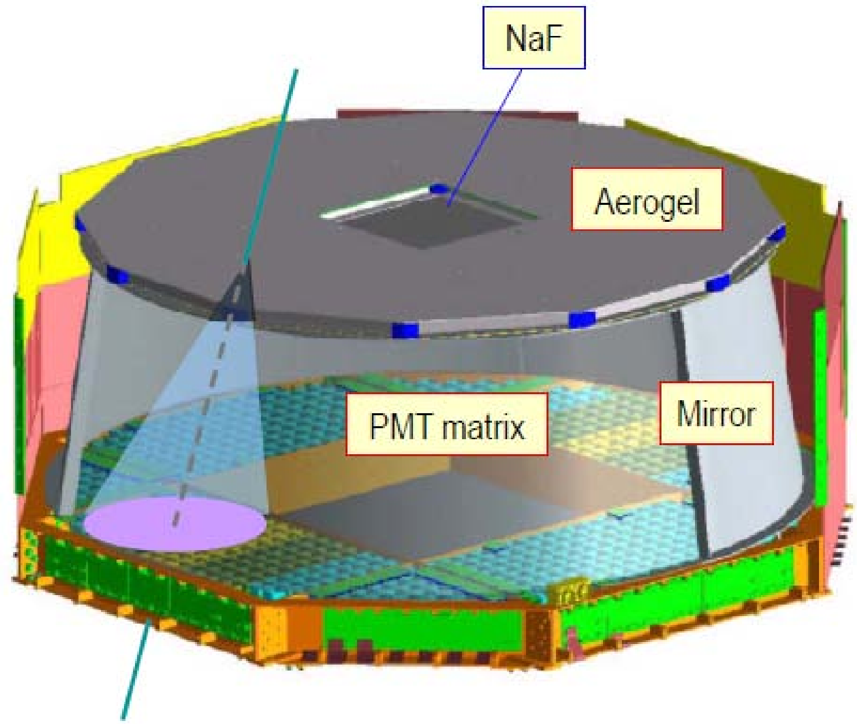
Scientific fields (examples)

- Heavy flavor physics
  LHCb, Super B factories, …
- Hadron/Nuclear physics
  COMPASS, …
- Neutrino & Astroparticle
  Water Cherenkov , Satellite, …

Application in Astroparticle Physics

- AMS
  - R7900-M16 x 680
  - Plexiglass light guide





Key Technology: Photodetectors

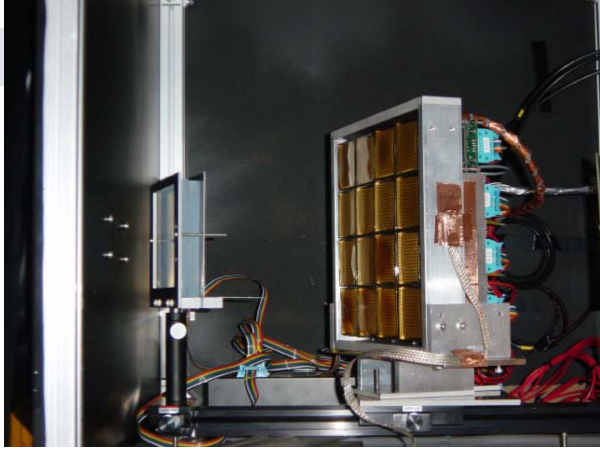
- High gain, Q.E., C.E.
- Good time resolution
- Good effective area

in magnetic field (1.5T)

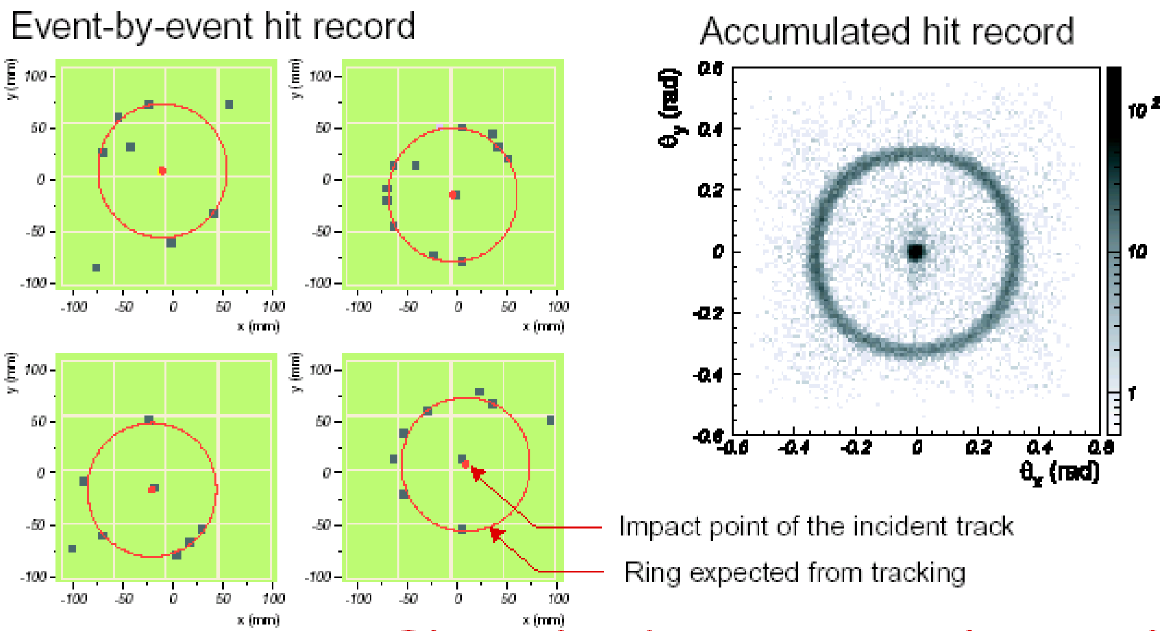
- MCP-PMT
- HPD/HAPD
- Geigermode-APD

	PMT	**MCP-PMT**	**HPD / HAPD**	**Geigermode-APD**
Gain	$>10^6$	～10^6	～10^3 X10～100 w/ APD	～10^6
Quantum Eff.	～20%, ～400nm (bialkali)			**> 50%,** ～600nm
Collection Eff.	70%	60%	**100%**	50%
Time resolution	～300ps	**～30ps**	～150ps Depends on readout	<100ps To be checked
B-field immunity	×	△ Depends on angle		○
Problems		lifetime		Noise, size

Beam Test w/ Flat Panel PMT



- Demonstration of principle
  - 4 × 4 array of H8500 (85% effective area)
  - Various aerogel samples
- σ_0 ~14mr → trying to understand the difference from expectation
  (chromatic dispersion, aerogel uniformity, surface effects etc.).
- Npe ~ 6 → ~9 if normalized to the best PMT sensitivity
  (some PMTs are from early batch and less sensitive).



Data taken w/ 3GeV/c pions

Clear ring images are observed !

LHCb RICH

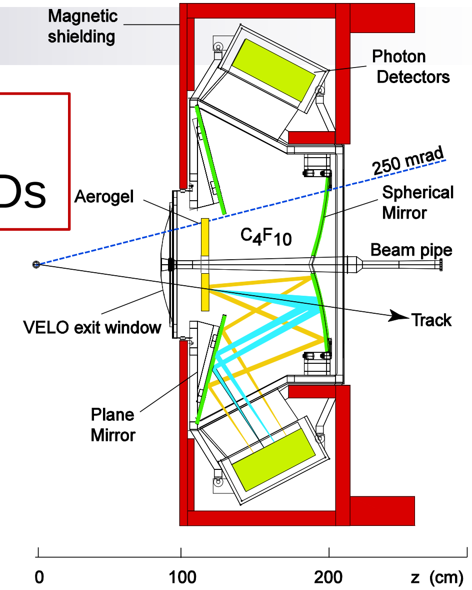
Franz Muheim
Ross Young

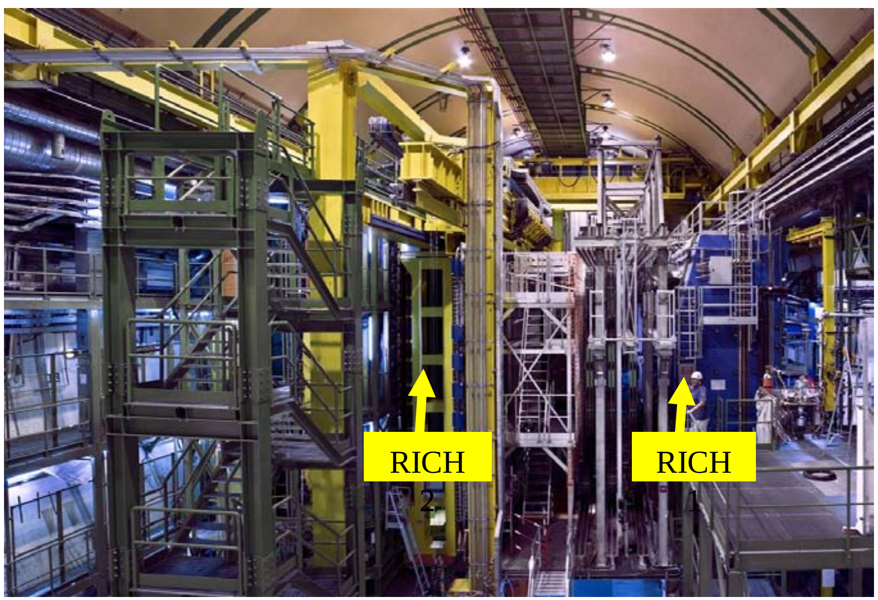
- 2 RICHs w/ 3 radiators to cover 1~100 GeV/c
- Photodetection by HPD array

  2.5 × 2.5mm granularity, total area = 2.6m^2

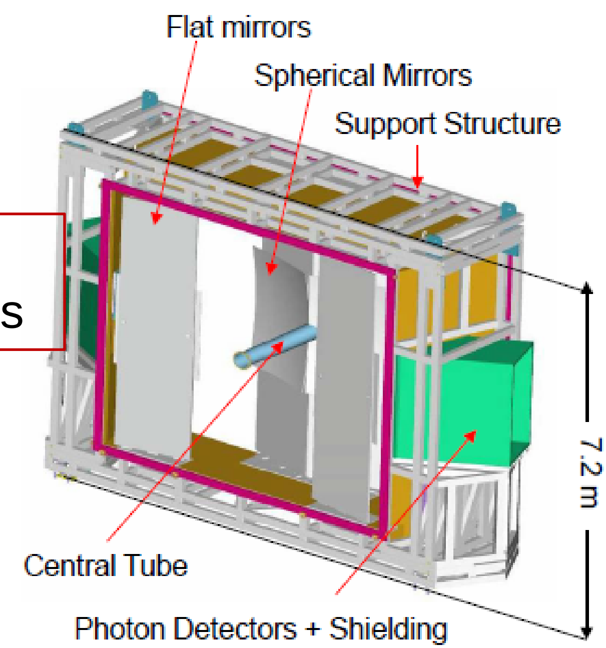
  - Aerogel(n=1.03) 5cm 1-10 GeV/c
  - C_4F_{10} (n=1.0014) 80cm 10-60 GeV/c
  - CF_4 (n=1.0005) 2m -100 GeV/c

RICH1
196 HPDs





RICH2
288 HPDs

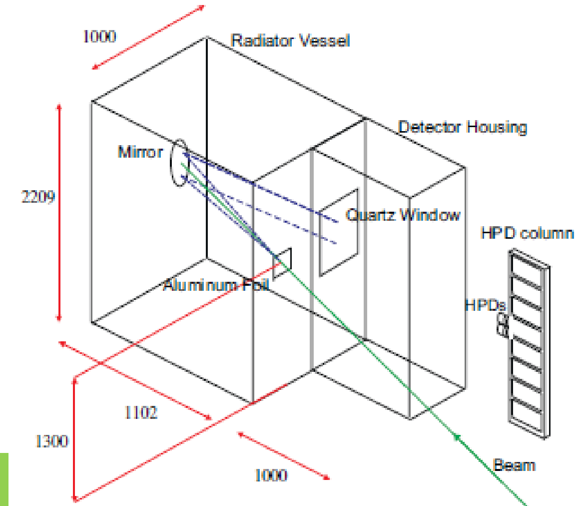


The 1st large scale application of HPD to a real experiment.

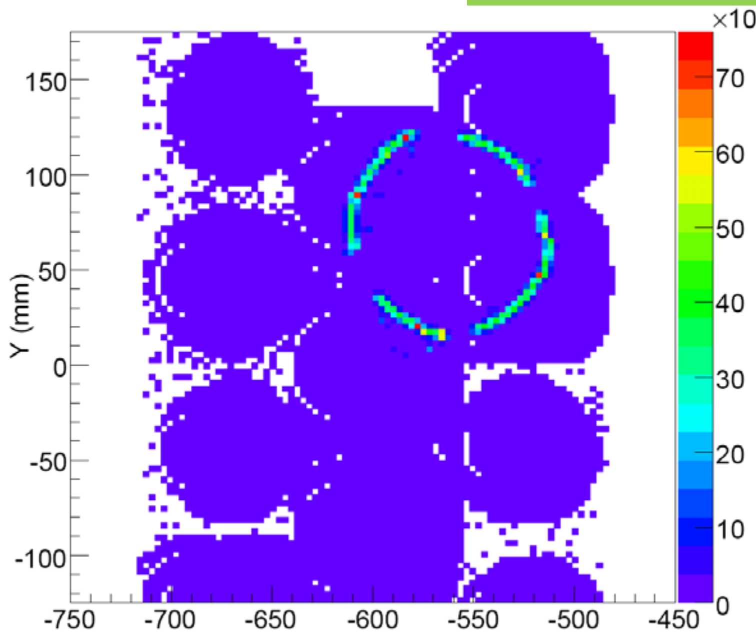
S. Brisbane, NIM A595 (2008) 146

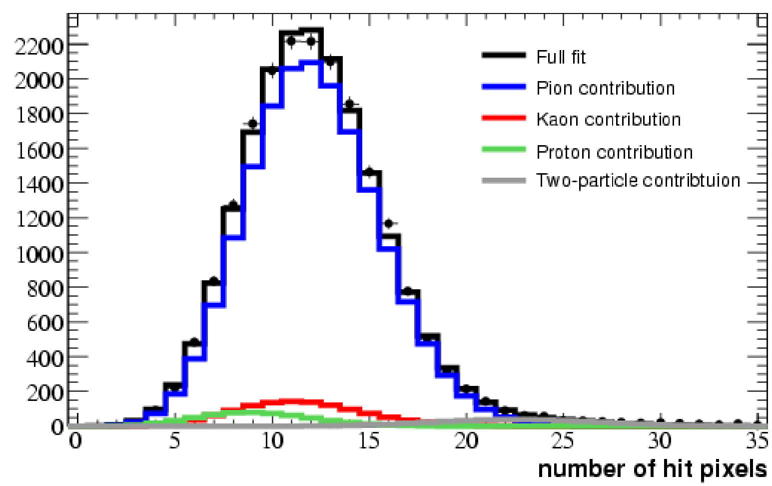
Beam Test of LHCb RICH Photodetection System

- Before the final installation, HPD columns were tested with SPS beams with N_2 and C_4F_{10} radiators.
- Number of detected photoelectrons matches expectation from the GEANT-based full simulation



Results with C4F10 radiator





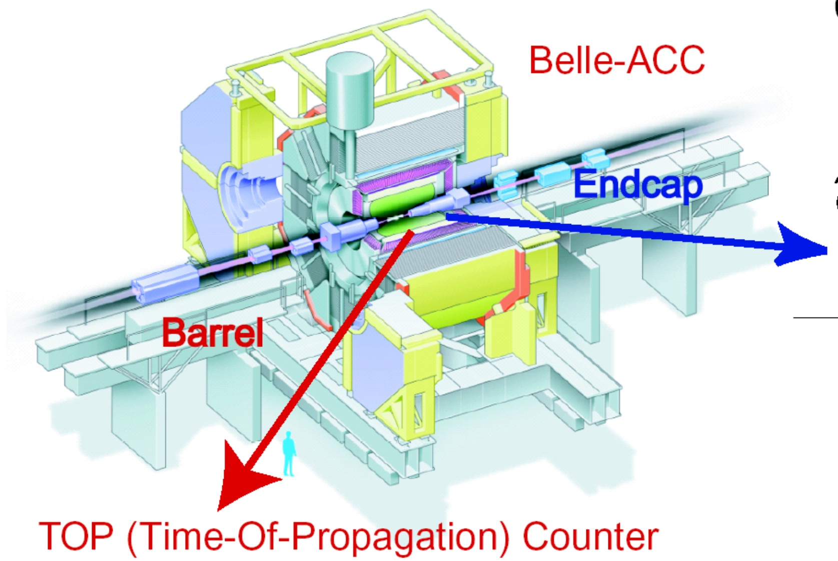
Belle II Proximity Focusing Aerogel RICH

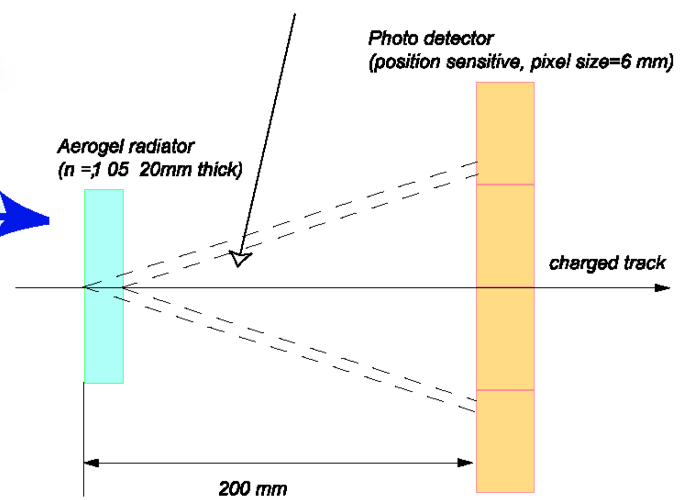
- For Belle upgrade in the forward endcap
- $>4\sigma$ K/π for $0.7 < p < 4.5$ GeV/c
- Proximity focusing w/ n =1.05, 2cm.
- Photodetection in B=1.5T w/ 5×5mm^2 granularity. → HAPD (baseline)

Design values

Npe	~10
σ_0	11 mr
σ(pix)	6.4 mr
σ(em)	8.6 mr
σ(chr)	2.0 mr

$\theta c(K)-\theta c(\pi)$=23mrad at 4GeV/c

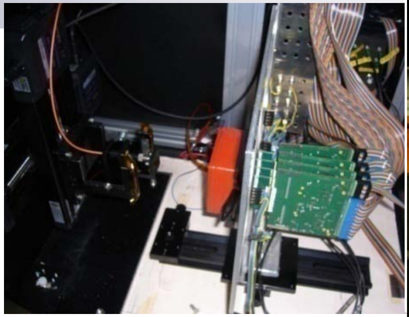




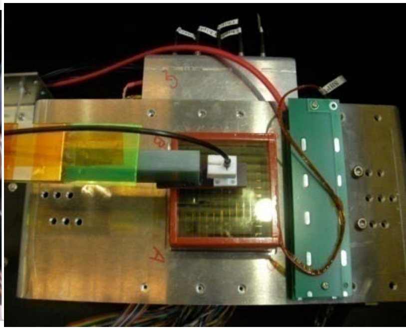
Challenge:
Photodetection in B field (1.5T)

HAPD Test

- > 28 HAPD samples have been tested.
  - Avg. total gain = 7×10^4
  - ENC <~ 5×10^3



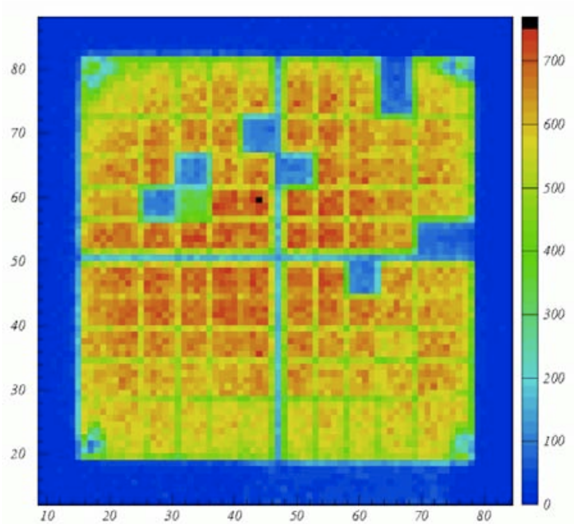
HPAD w/ ASIC



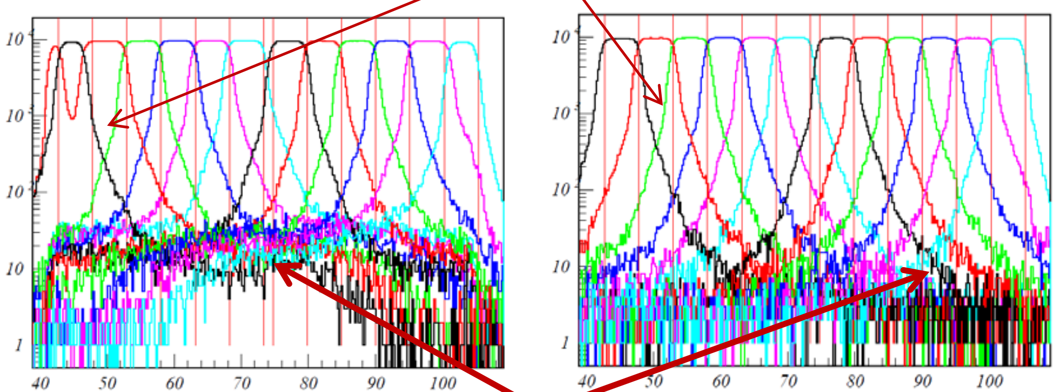
Test in B field

- HAPD samples (+ASIC) are being tested w/o and w/ magnetic field. .

Response to single photon irradiation



Effects due to electric field distortion at edge disappear in B filed.



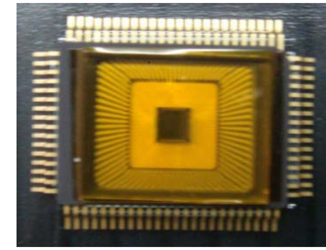
Tails due to electron backscattering is reduced

- Remaining issues: improvement of QE, rad. hardness.

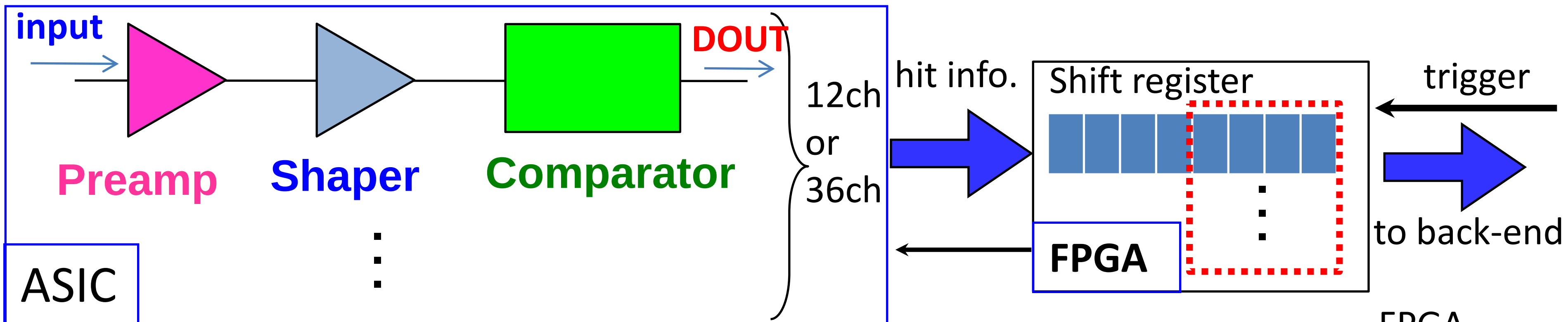
ASIC for readout of 144ch HAPD

We need high density front-end electronics including high-gain and low-noise amplifier for A-RICH.

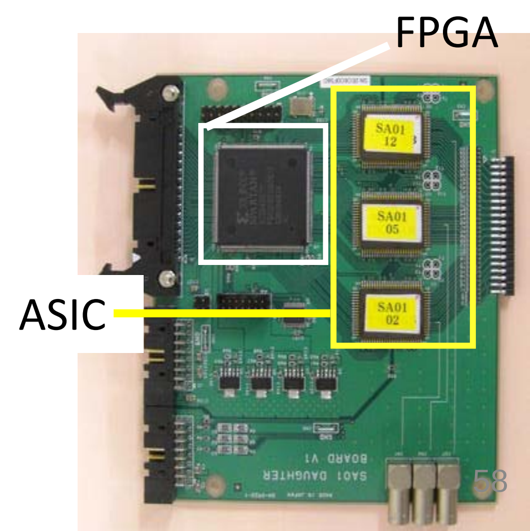
→ We have been developing ASICs for front-end electronics.
We planed to readout output of ASIC with FPGA.



Circuit configuration



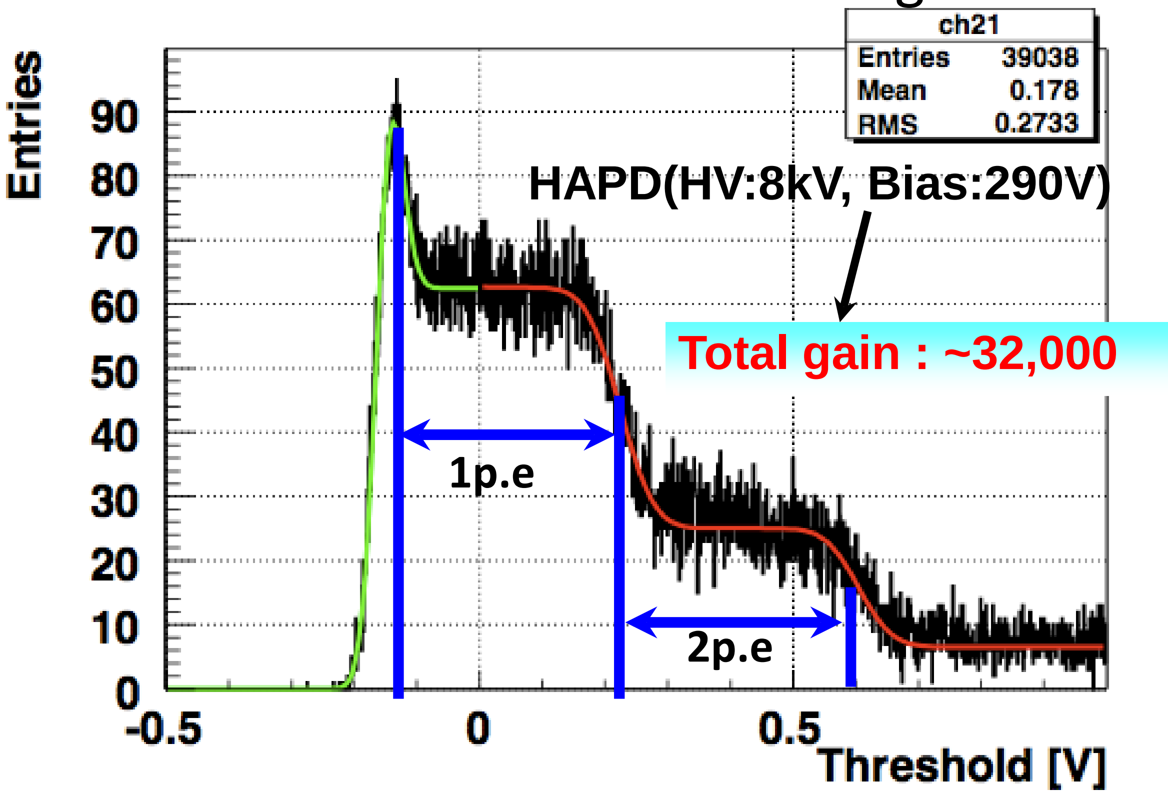
- 4 step variable gain preamplifier.
- 4 step variable shaping time shaper.
- Comparator for the digitization of analog-signals.
  (We need **only on/off hit information**)
- We have developed new ASIC SA01 and SA02.

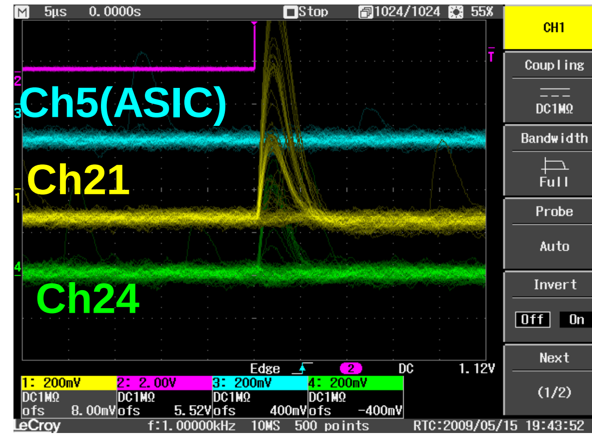


Readout test of HAPD with ASIC

Threshold scan

- Distribution of output ASIC for 100 LED light irradiations at each threshold voltage.





Result

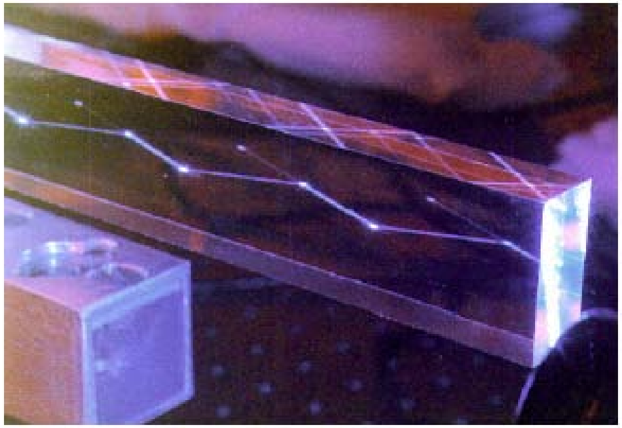
- Noise : ~2,000e⁻
- Pulse height
  - 1p.e signal : 32,700e⁻
  - 2p.e signal : 66,200e⁻

S/N : ~17

- **Clear separation between 1p.e and 2p.e!**
- **Very high S/N ratio (target > 7)!**

Good performance of readout system with ASIC + FPGA is confirmed!

Quartz based RICH



- Use of total internal reflection in accurately polished quartz bar.

  A concept was invented by B.Ratcliff et al.

Measurement coordinates

- DIRC (Detector of Internally Reflected Cherenkov light)

  NIM A479(2002)1

  (X, Y)

- TOP (Time Of Propagation) Counter

  NIM A453(2000)331

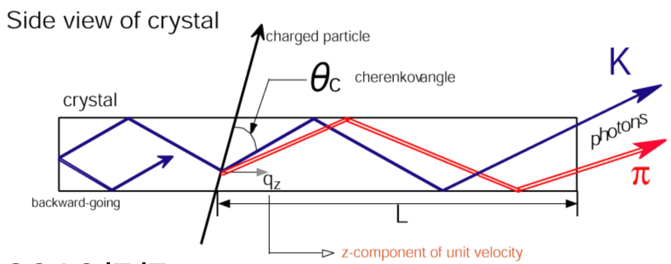
  (X, TOP)

  Nagoya, Ohshima et al.

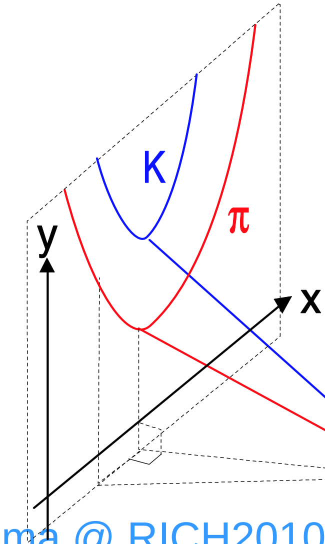
- Focusing DIRC/TOP

  NIM A595(2008)104

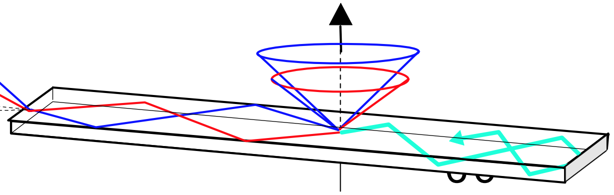
  (X, Y, TOP)



TOP or



New Trend; 3D imaging !

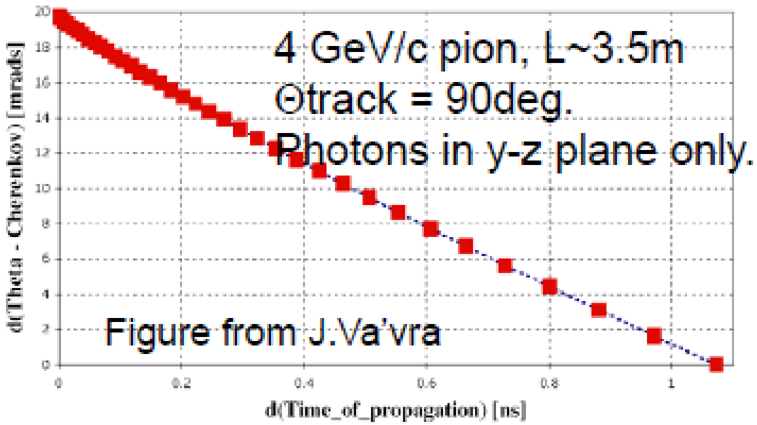


Chromatic Dispersion in Quartz

- Cherenkov production: $\cos\theta_c = 1/\beta n_p(\lambda)$
- Cherenkov propagation: $TOP = \dfrac{L \cdot n_g(\lambda)}{c \cdot q_z}$

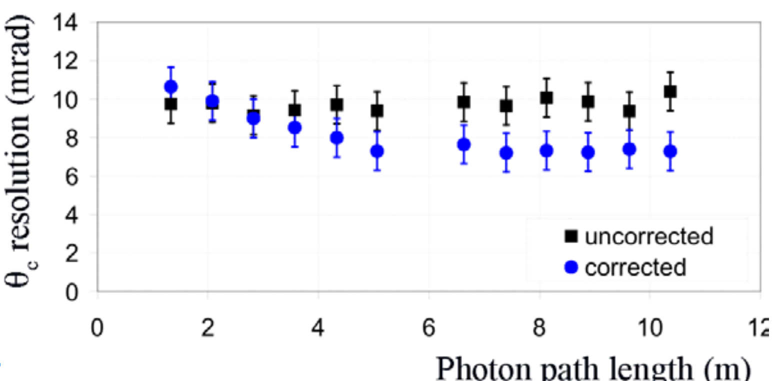
  ※ group index must be used here !
- Relationship between two indices;

$$n_g(\lambda) = n_p(\lambda) - \lambda \cdot dn_p(\lambda)/d\lambda$$



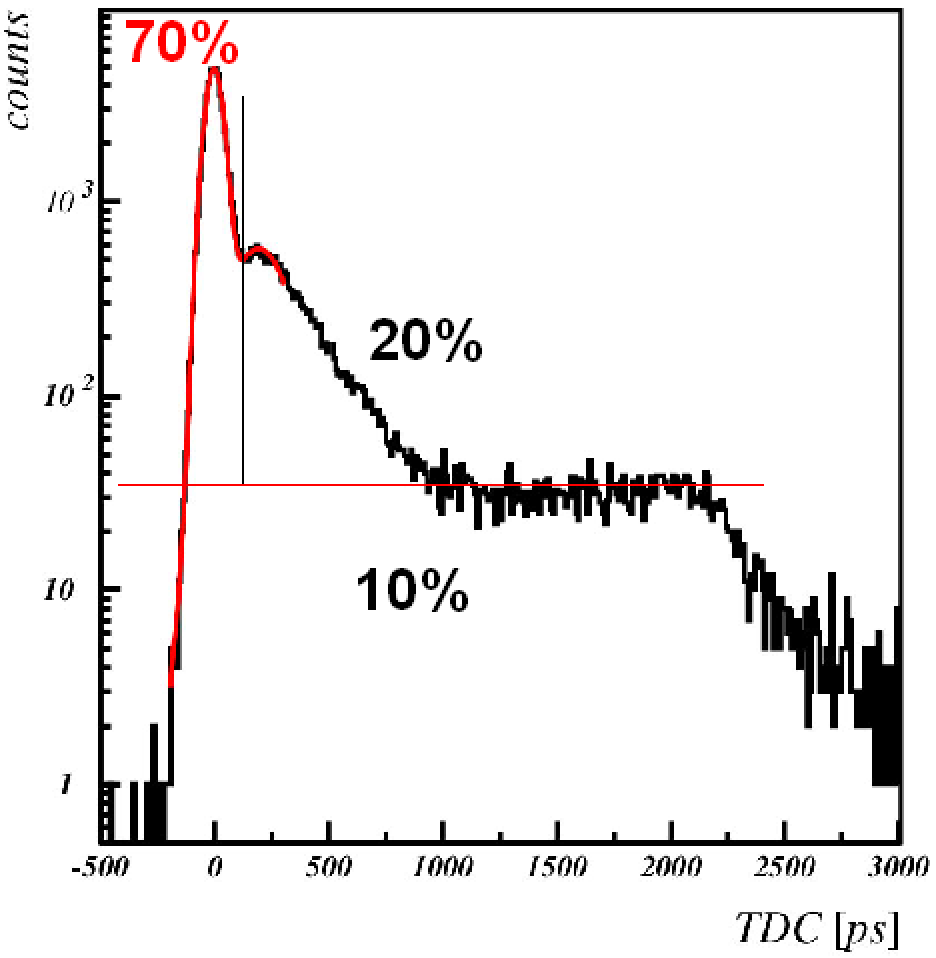
Changes in TOP correlates almost linearly with a change in θc

SLAC beam test result: f-DIRC resolution w/ and w/o timing correction.



Correlation between $n_p(\lambda)$ and $n_g(\lambda)$ allows to correct chromatic dispersion !!!

MCP PMT timing



Tails can be significantly reduced by:

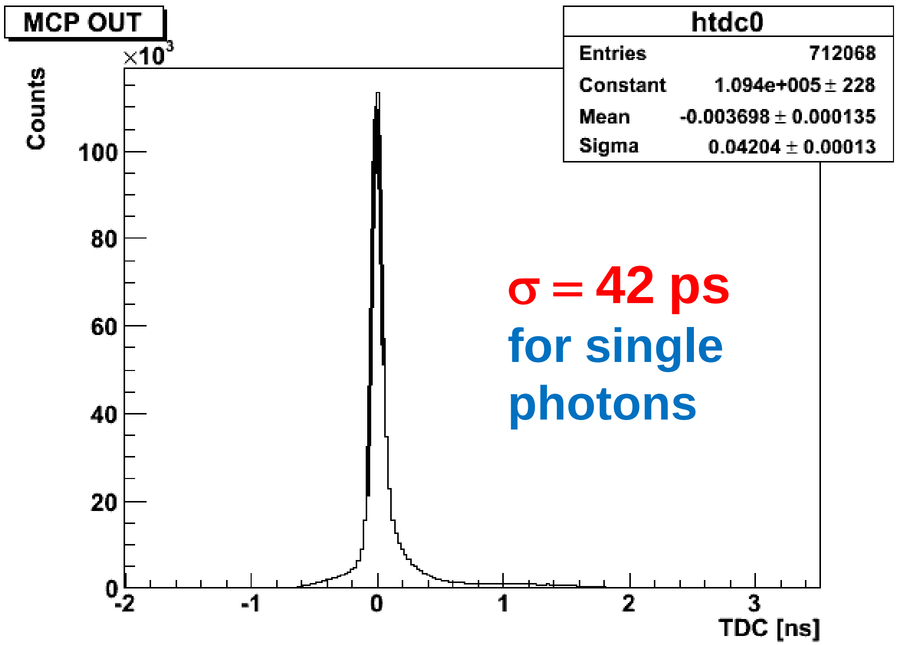
- decreased photocathode-MCP distance and
- increased voltage difference

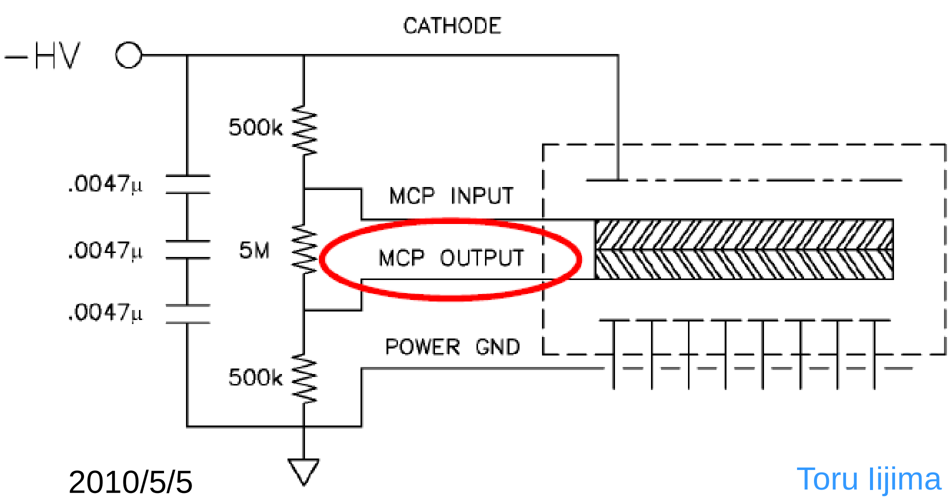
- prompt signal ~ 70%
- short delay ~ 20%
- ~ 10% uniform distribution

Timing with a signal from the second MCP stage

If a charged particle passes the PMT window, ~10 Cherenkov photons are detected in the MCP PMT; they are distributed over several anode channels.

Idea: read timing for the whole device from a single channel (second MCP stage), while 64 anode channels are used for position measurement

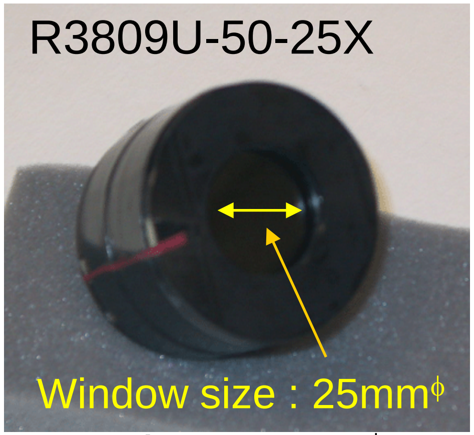




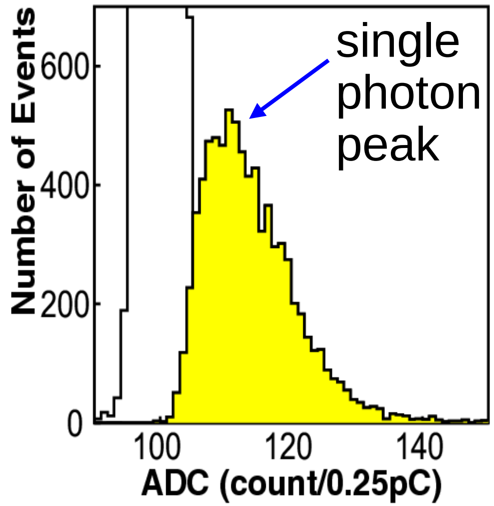
MCP second stage output, CF discriminator

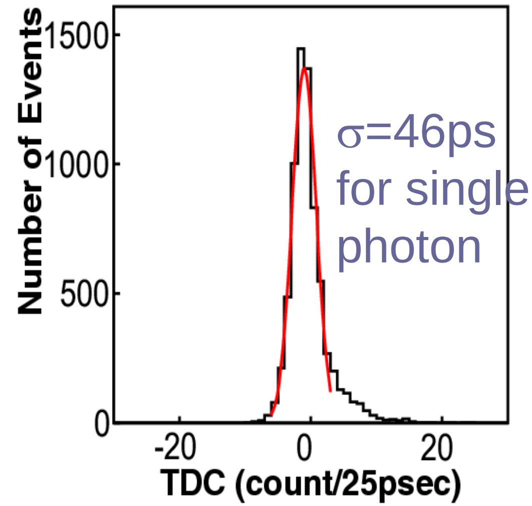
MCP-PMT output

- Hamamatsu R3809U-50 (multi-alkali photo-cathode)

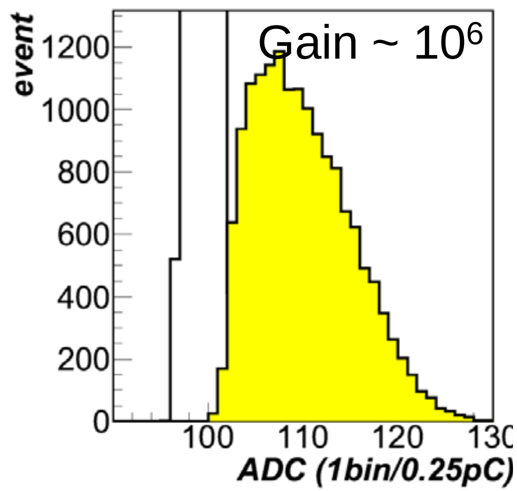


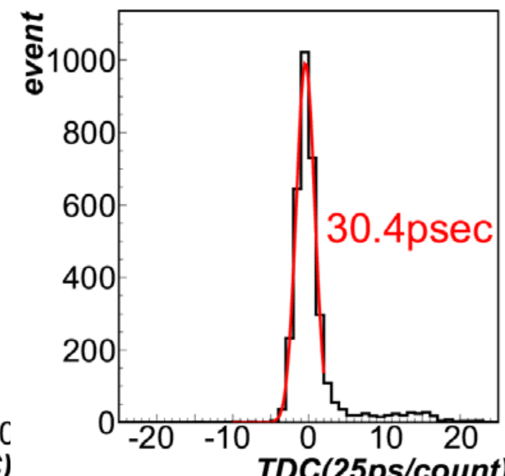
MCP hole 10μm$^{\phi}$





MCP hole 6μm$^{\phi}$

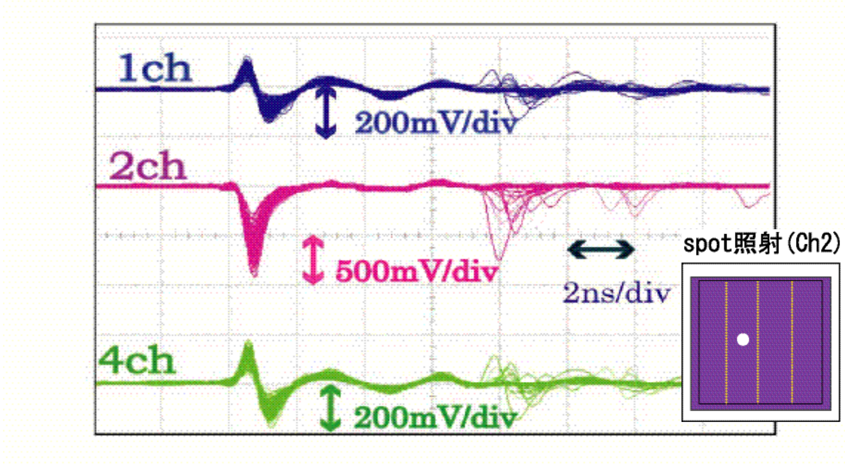


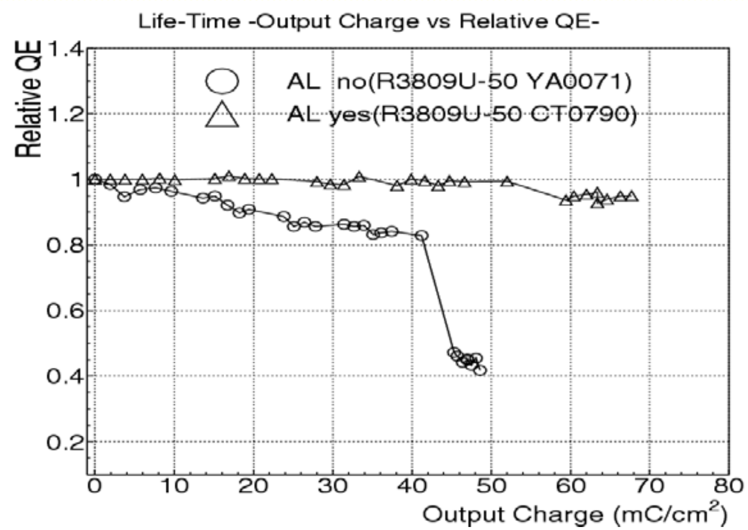


Cross Talk/Lifetime of MCP-PMT

- Cross talk
  - Induced by a neighboring hit (ch-ch coupling).
  - Resolution become worse when > 2hits on a PMT (σ~30ps → 70-90ps)
- Lifetime
  - Al protection layer helps but collection eff. drops (x60%)
  - How about in B-field?
  - Depend on photocathode?

cf) ~700mC/cm^2 if TOP used in Super-Belle.





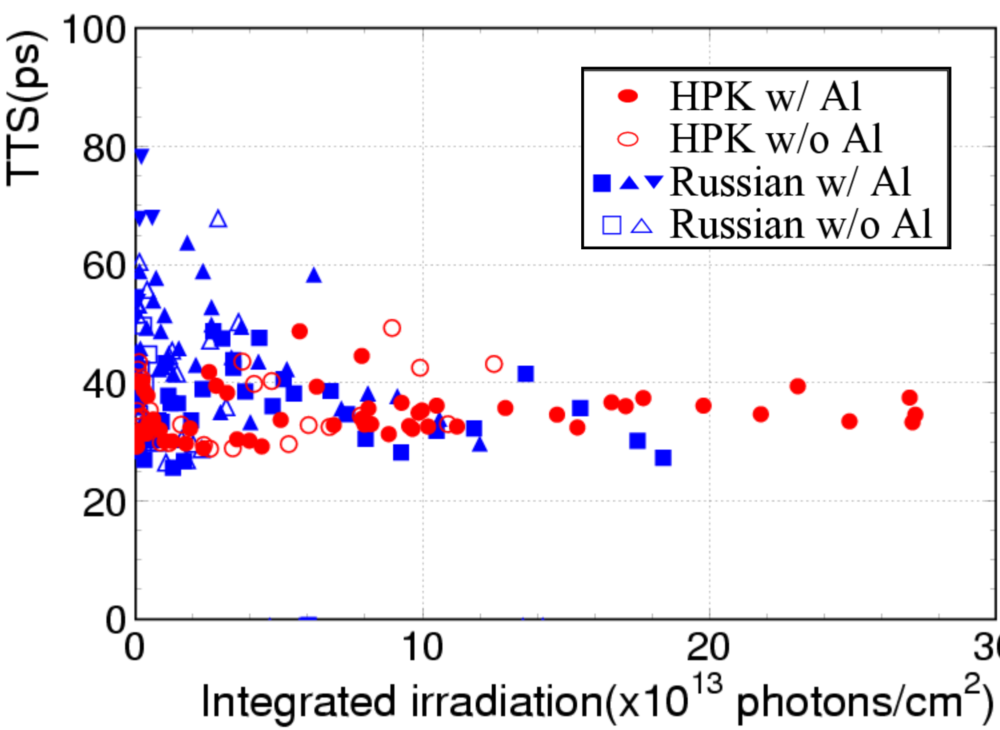
Need more studies…

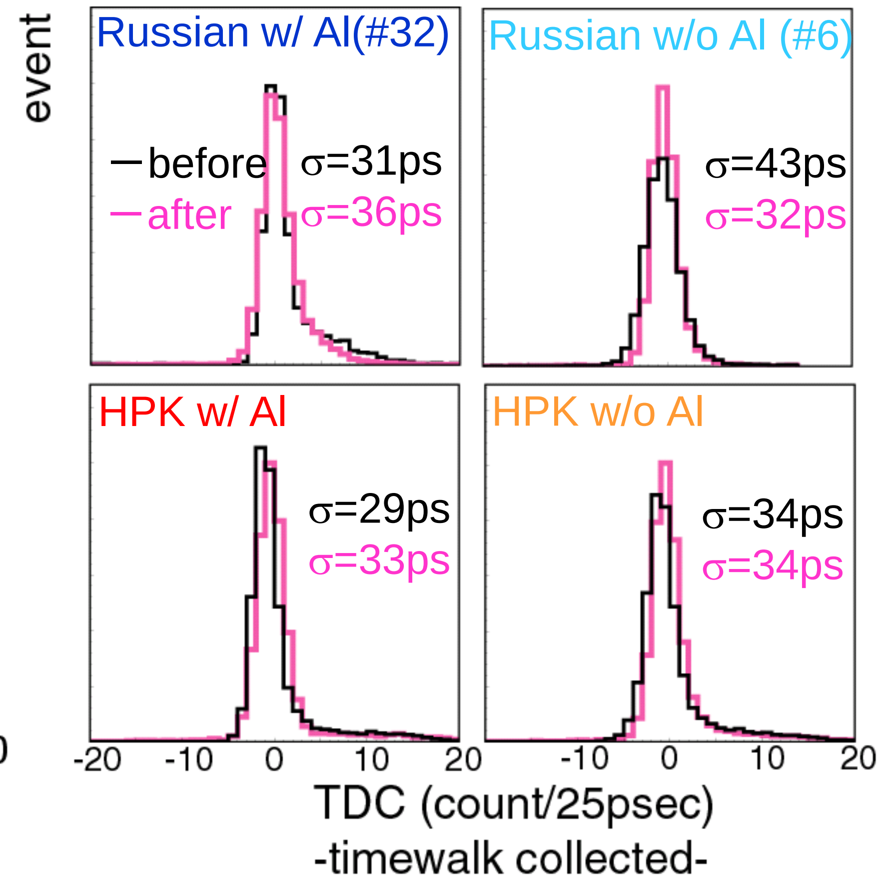
MCP-PMT Lifetime (T.T.S.)

- Time resolution for single photon

  → No degradation!

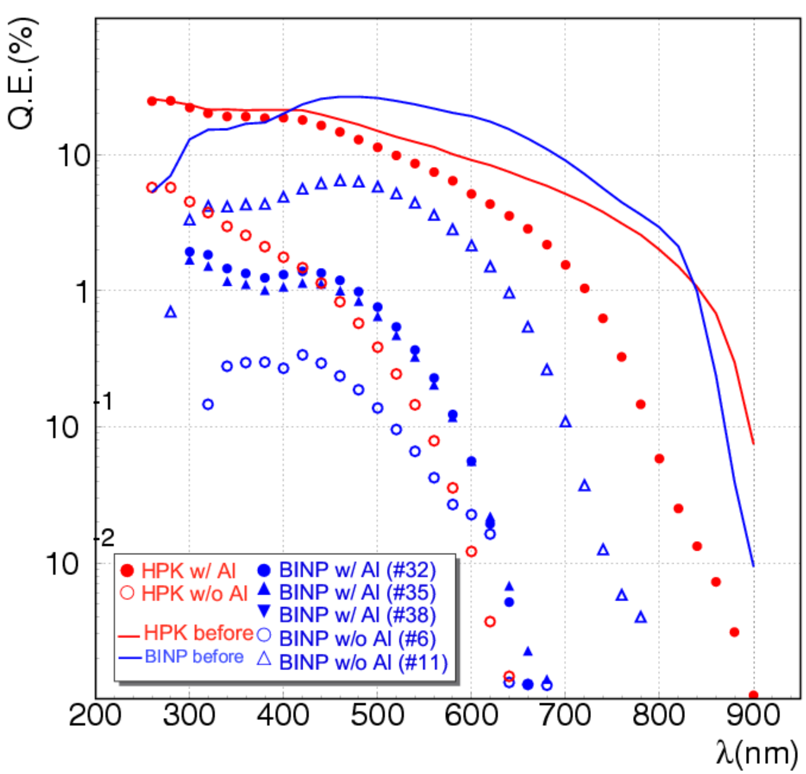
  Keep ~35ps !

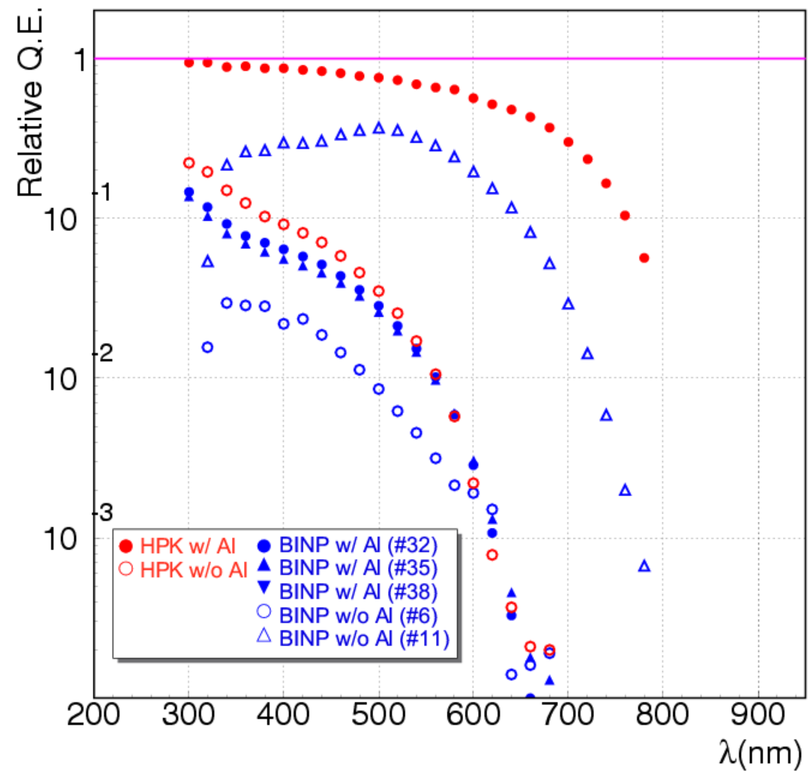




Lifetime - Q.E. vs wavelangth -

- Q.E. after lifetime test (Ratio of Q.E. btw. before,after)



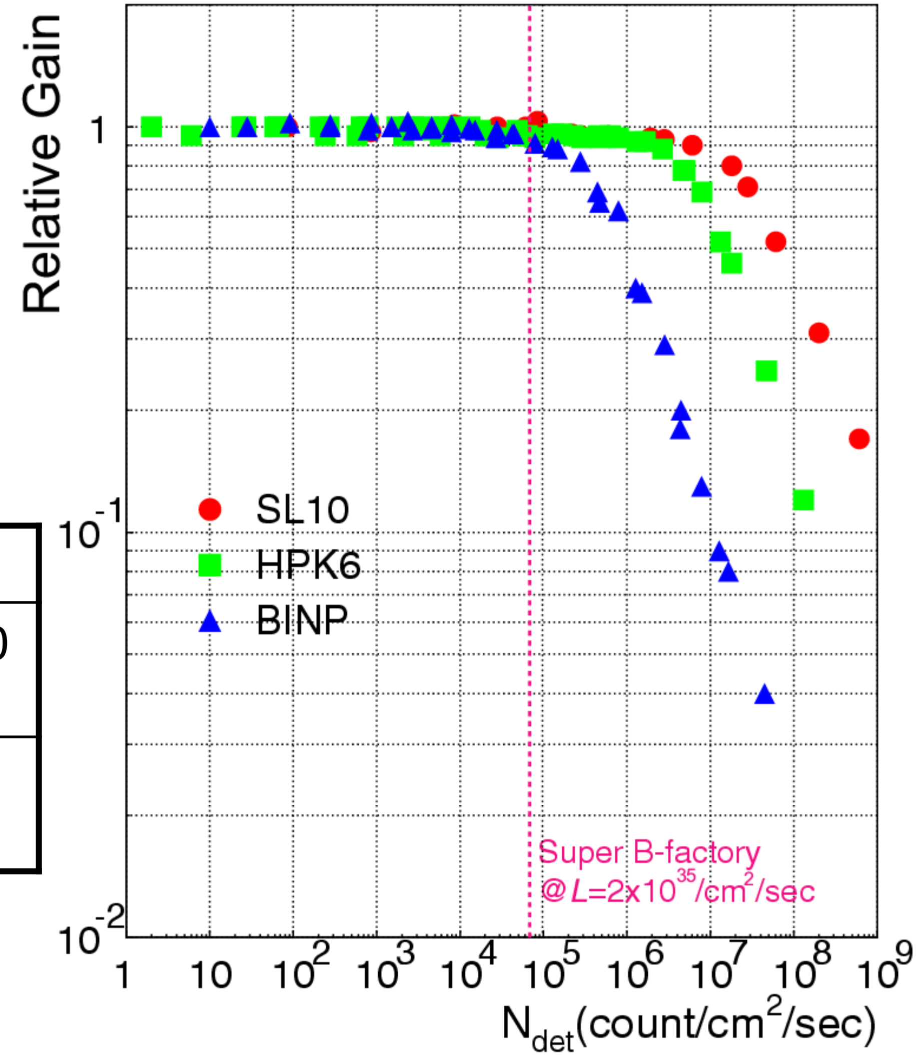


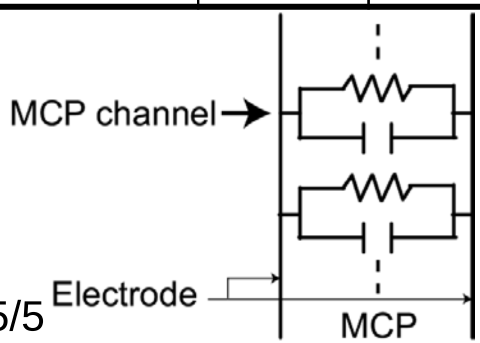
- Large Q.E. drop at longer wavelength
- Number of Cherenkov photons ; only 13% less (HPK w/Al)
  - Number of generated Cherenkov photon:~$1/\lambda^2$

Rate dependence

- Gain vs. photon rate
  - For high intensity beam
- Gain drop for high rate
  - $>10^5$ count/cm^2/s
  - Due to lack of elections inside MCP holes
  - Dep. on RC variables

	SL10	HPK6	BINP
MCP resistance ($M\Omega$ cm^2)	96	143	380~1000
MCP capacitance (pF/cm^2)	16	31	24~39



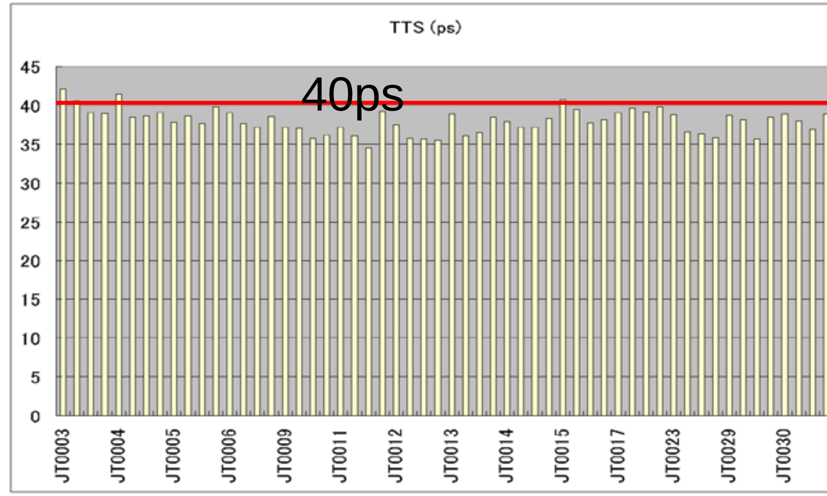


Enough for TOP counter

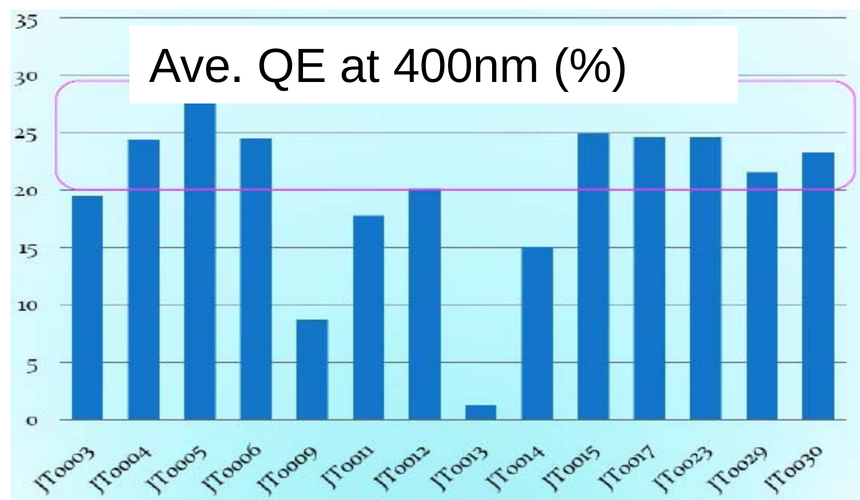
Toru Iijima @ RICH2010

Semi Mass Production Results

- TTS
  - 35~40ps
  - Stable

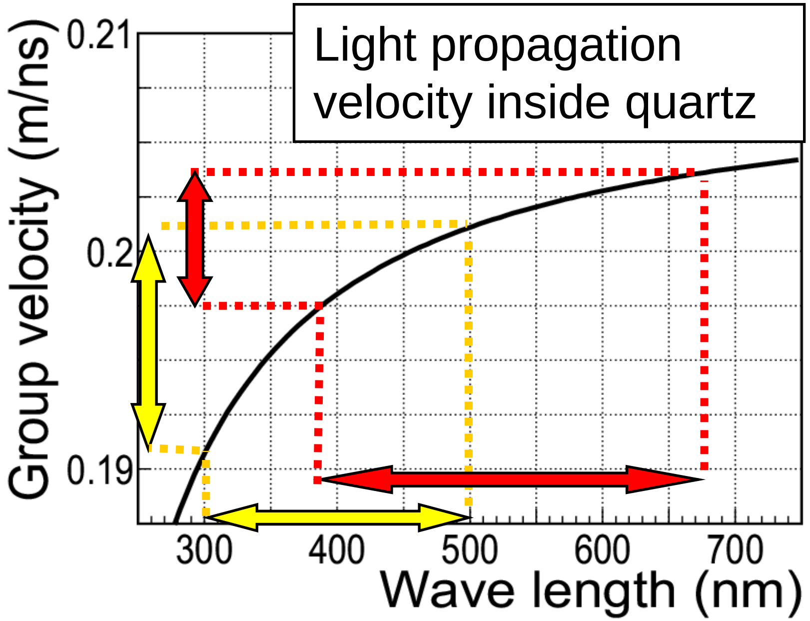


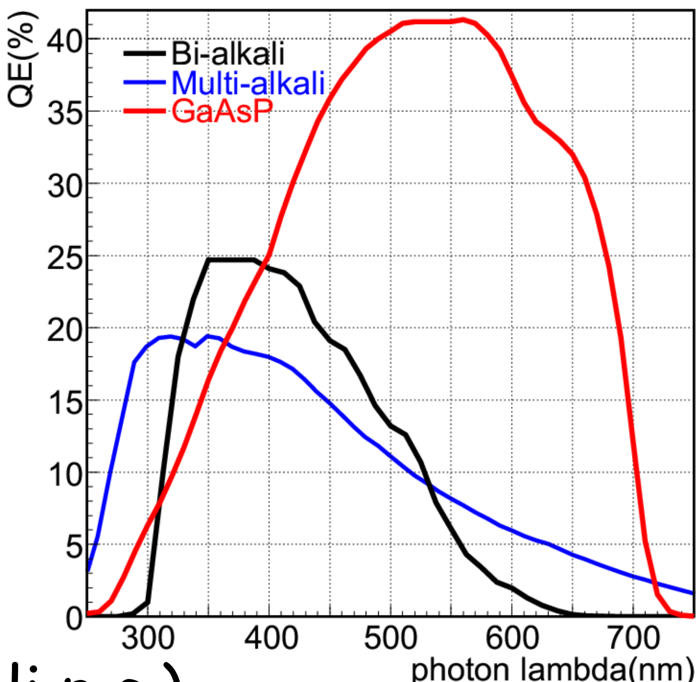
- QE



Chromatic Dispersion

Variation of propagation velocity depending on the wavelength of Cherenkov photons





- GaAsP photo-cathode (←→ alkali p.c.)
  - Higher quantum-efficiency
  - at longer wavelength → less chromatic error

Photon sensitivity at longer wavelength shows the smaller velocity fluctuation.

Other related R&D's for high precision timing

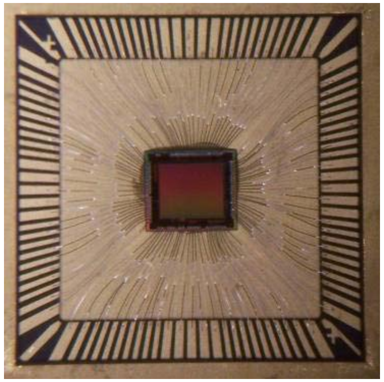
High Resolution TOF

Sub 10ps Readout

Buffered LABRADOR (BLAB1) ASIC

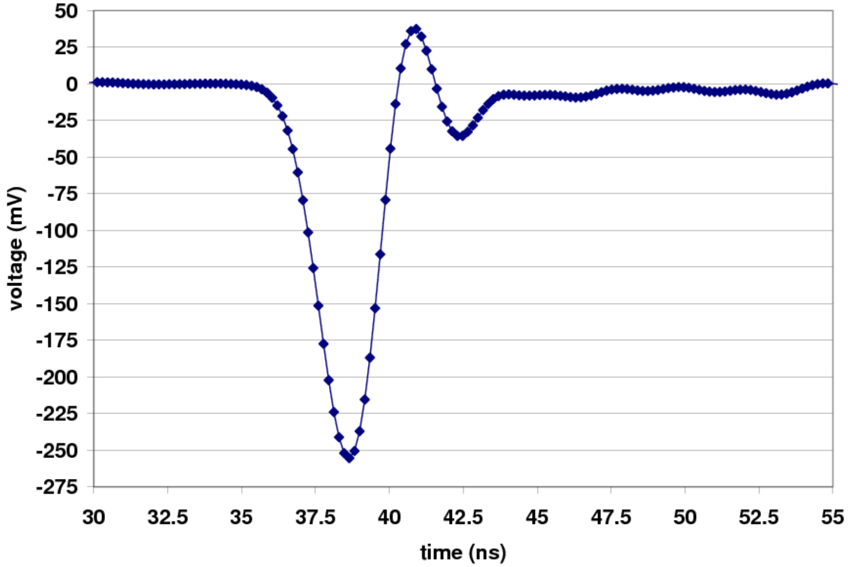
Gary Varner, Larry Ruckman (Hawaii)

- 64K cell deep waveform sampling ASIC.
- Sampling seed: 0.1-6.0GSa/s.
- Low power, cost-effective.

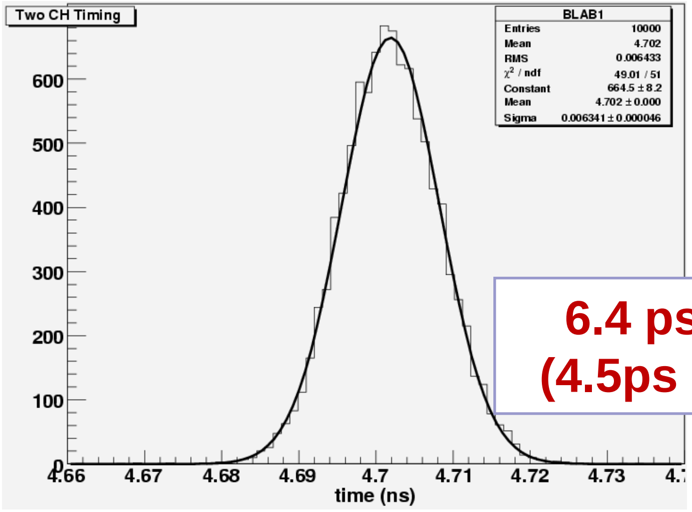


BLAB1 NIM **A591** (2008) 534

Observed MCP-PMT signal (Burle 85011)



Measured jitter between 2 channels

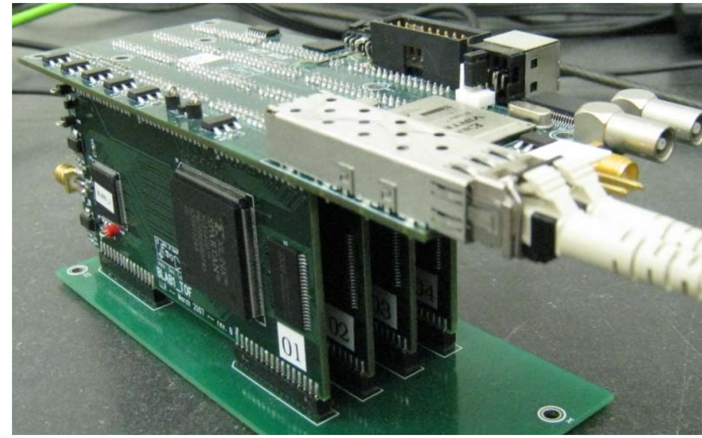


6.4 ps RMS
(4.5ps single)

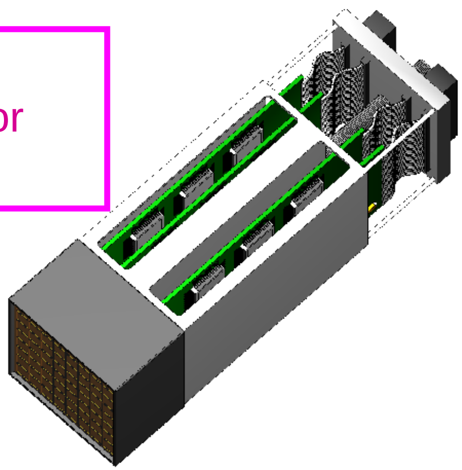
Highly Integrated Readout w/ BLAB2

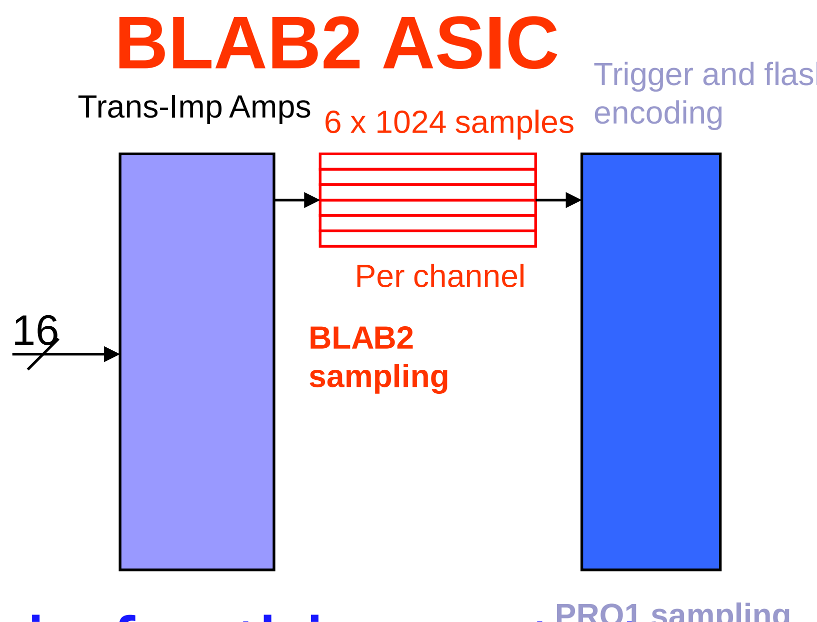
TABLE II: *BLAB2 ASIC Specifications.*

Item	*Value*
Photodetector Input Channels	16
Linear sampling arrays/channel	~~2~~ 6
Storage cells/linear array	~~512~~ 1024
Sampling speed (Giga-samples/s)	2.0 - 10.0
Outputs (Wilkinson)	32



Integrated Photodetector packaging





HPK H-8500 Readout basis for this next step