Probing Strangeness in Hard Processes
(PSHP2010)

Particle Identification at Belle II & Development of New Photodetectors

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Frascati, Italy

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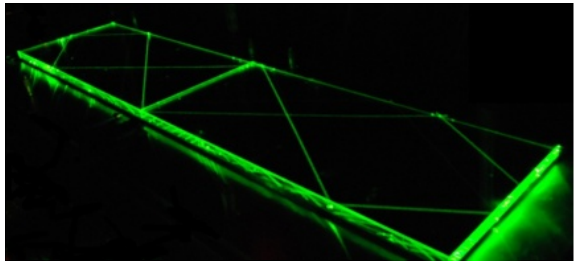
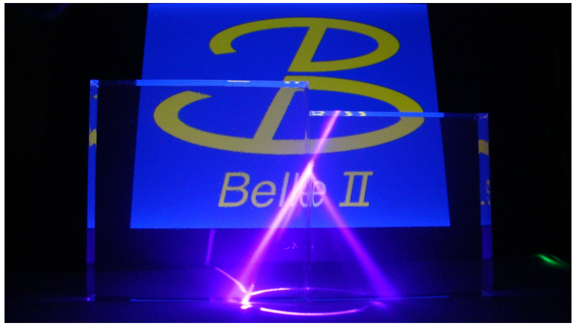
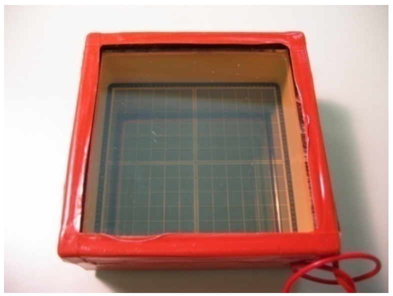


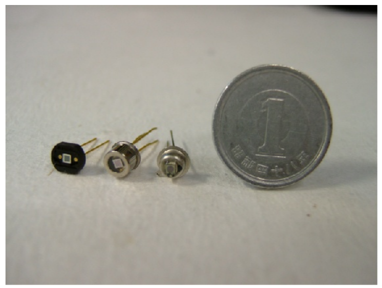


MCP-PMT

HAPD



G-APD (MPPC/SiPM)



Collaborators

- Japan:

  Nagoya, Tokyo Metropolitan, Toho, Chiba, KEK

- Slovenia:

  Josef Stefan Inst. Ljubljana, Maribor

- United States:

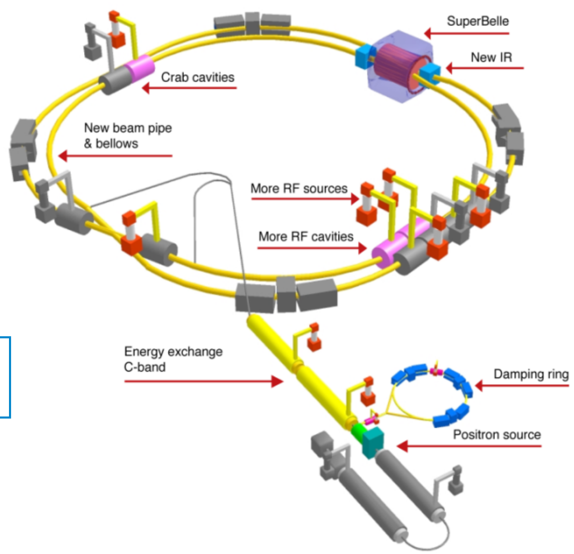
  Hawaii, Cincinnati

KEKB Upgrade

Target Lum. = $8\times10^{35}\mathrm{cm^{-2}s^{-1}}$

- Higher beam currents
- Smaller beam size

$$L = \frac{\gamma_\pm}{2er_e}\left(1+\frac{\sigma_y^*}{\sigma_x^*}\right)\frac{I_\pm \xi_{\pm y}}{\beta_y^*}\left(\frac{R_L}{R_y}\right)$$



Super-KEKB

$L=8\mathrm{x}10^{34}\mathrm{cm^{-2}s^{-1}}$

$I_{LER/HER}$=2.96/1.70A

β_y^* = 0.22mm

$\int Ldt = 50\mathrm{ab^{-1}}$

$\int Ldt = 10\mathrm{ab^{-1}}$

Three year shutdown to:

- install new beam pipe
- increase RF
- modify IR

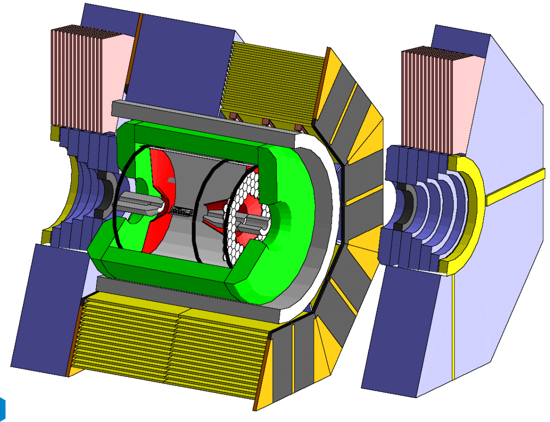
Present KEKB

$L=2\mathrm{x}10^{34}\mathrm{cm^{-2}s^{-1}}$

$I_{LER/HER}$=1.62/0.95A

β_y^* = 5.9mm

+ Belle upgrade



$\int Ldt = 1\mathrm{ab^{-1}}$

2010 2015 2020

Physics with O(10^{10}) B, τ, charm

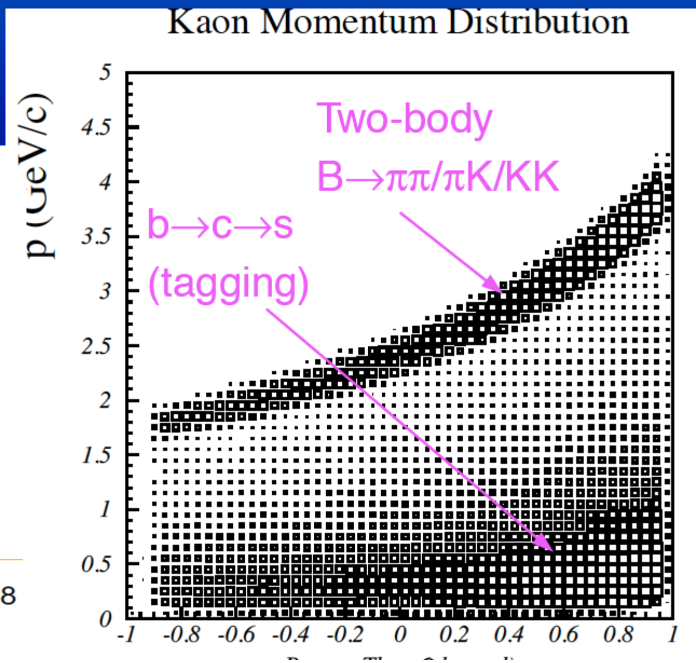
Particle ID in Belle

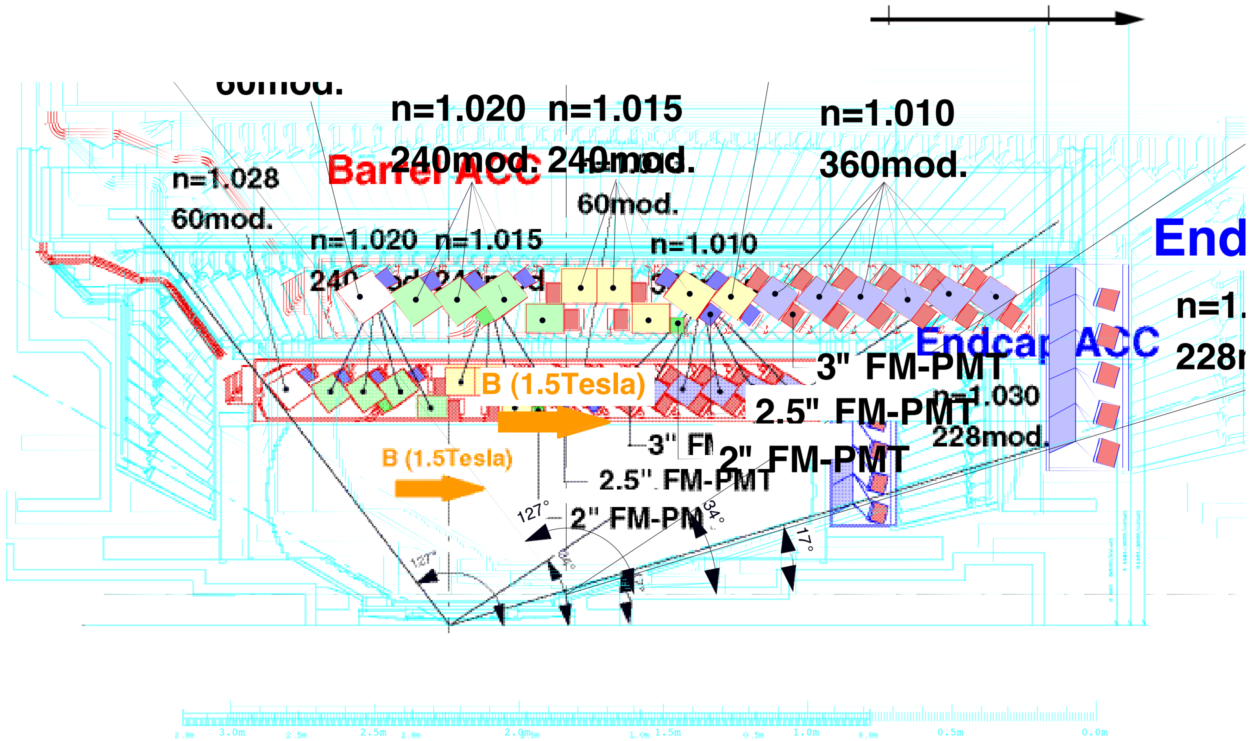
Physics Requirements

- Flavor Tagging
- B → π π
- B → DK

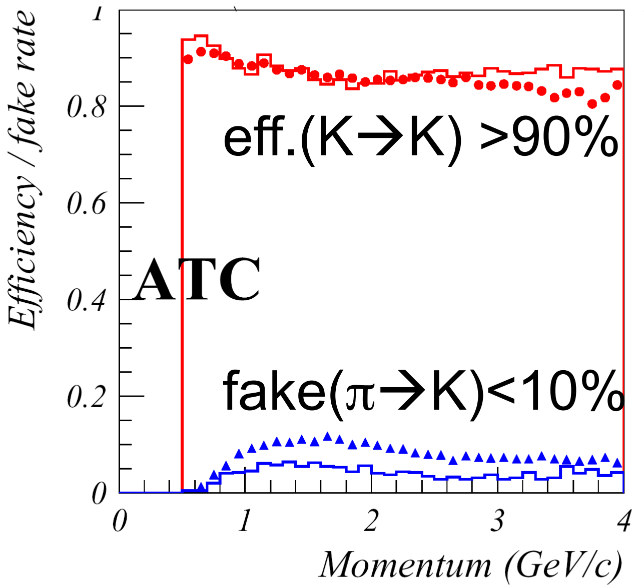
Detector Line-up

- dE/dx (CDC) — Δ dE/dX ~ 5 %
- TOF (only Barrel) — Δ T ~ 100 ps (r = 125cm)
- **Barrel ACC** — n = 1.010 ~ 1.028
- **Endcap ACC** — n = 1.030 (only flavor tagging)





Calibratiopn by
$D^{*+} \to D^0\pi^+$, $D^0 \to K^-\pi^+$



Motivation for PID upgrade

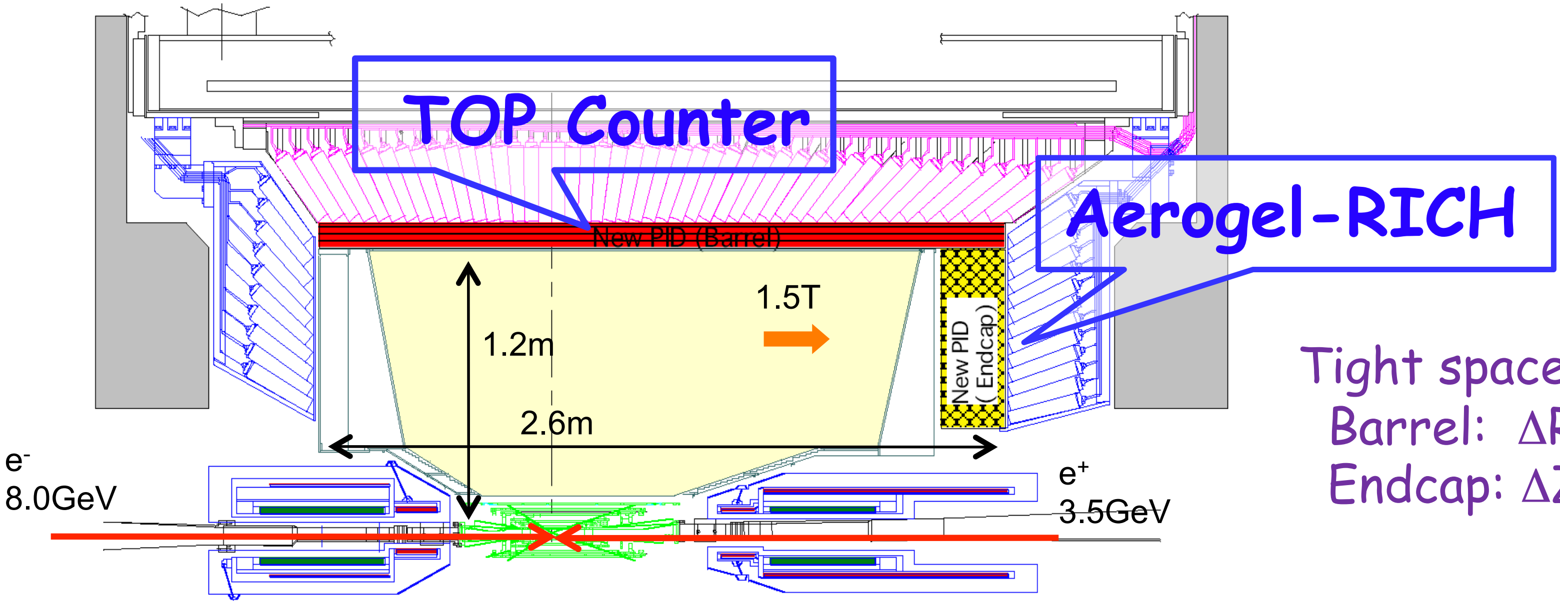
- To cope with increasing background.
  - TOF may not survive
  - ACC seems to be OK
- Improve separation for K/π, and also for μ/π hopefully.
- Extend momentum coverage in the forward endcap.
  - Endcap-ACC (n=1.03) functions only for flavor tagging in Belle
- Reduce material thickness, and more homogeneous distribution.
  - 30% in total = 18% (ACC) + 12% (TOF)
  - PMTs dominate for ACC

Physics Targets

- $B \to \pi\pi/K\pi$, $D\pi/DK$
- $B \to \rho\gamma/K^*\gamma$ ($b \to d\gamma/s\gamma$)
- $B \to K\,ll$, $K\,\nu\,\nu$
- Full reconstruction
- Less systematics for precise measurements

PID Strategy at Belle II

- To cope with increased background (present x ~20)
- To improve the performance.
  - Target: > 4σ at 4 GeV/c
  - Novel Ring Imaging Cherenkov Counters w/ advanced radiator & photo-detection technologies



Tight space limitation
Barrel: ΔR = 10-20cm
Endcap: ΔZ = 28cm

+ dE/dx for low momentum.

Impact of PID improvement

$B^0 \to \rho^0 \gamma$

No upgrade BAD ← → Upgrade GOOD

Luminosity loss / gain

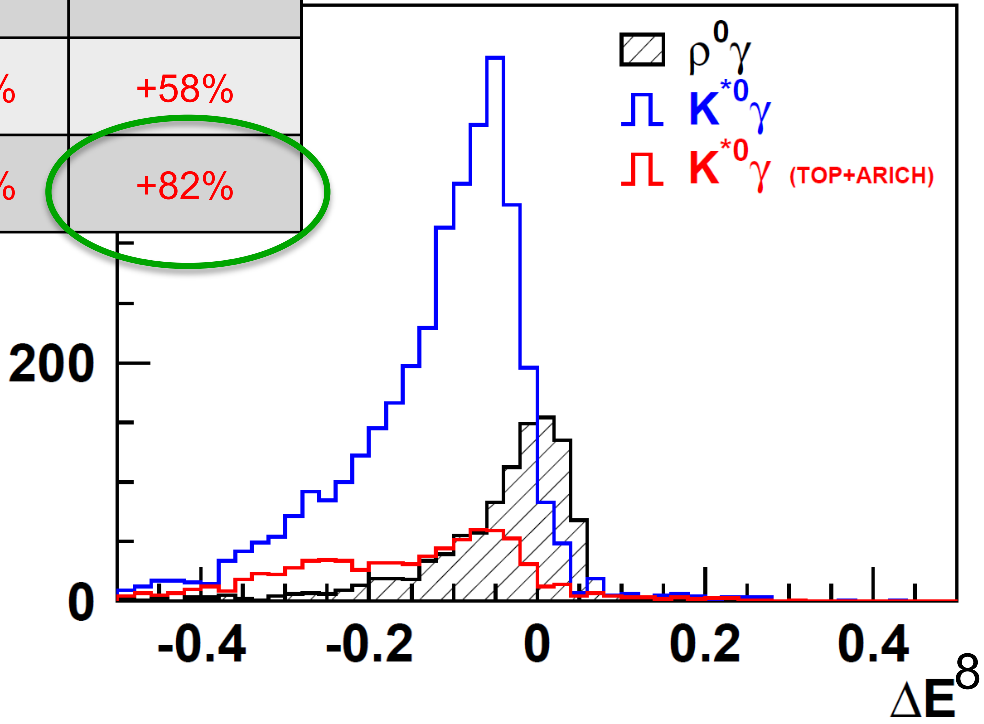
FWD / BRL	dE/dx NA	As good as Belle	A-RICH	A-RICH +TOF
TOF, dE/dx NA	–33%	–33%	–30%	–30%
TOF NA	–34%	–33%	–29%	-29%
As good as Belle	–1%	0% (definition)	+5%	+5%
TOP opt.0	+47%	+50%	+57%	+58%
TOP opt.2	+70%	+72%	+82%	+82%

No upgrade BAD ↑ ↓ Upgrade GOOD

Completely different world with excellent PID detectors!

$B^0 \to \pi^+ \pi^-$

FWD / BRL	As good as Belle	A-RICH
As good as Belle	0% (definition)	+6%
TOP opt.2	+16%	+23%



Key Technology: Photodetectors

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

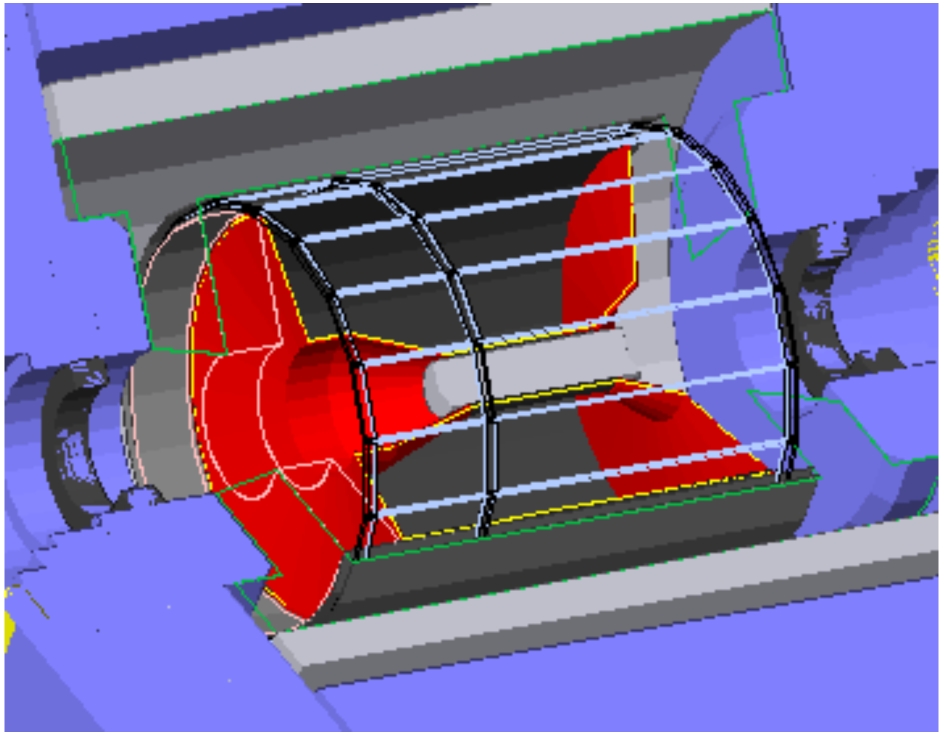
in magnetic field (1.5T)

- MCP-PMT
  Micro-channel-plate PMT
- HAPD
  Hybrid Avalanche Photodiode
- Geigermode-APD

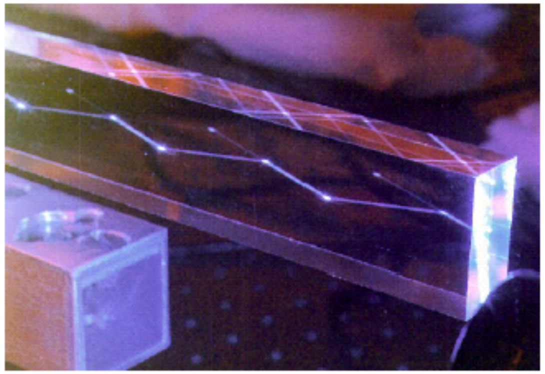
	PMT	**MCP-PMT**	**HPD / HAPD**	**Geigermode-APD**
Gain	$>10^6$	$\sim 10^6$	$\sim 10^3$ X10～100 w/ APD	$\sim 10^6$
Quantum Eff.	～20%, ～400nm (bialkali)			**> 50%,** ～600nm
Collection Eff.	70%	60%	**100%**	50%
Time resolution	～300ps	**～30ps**	～150ps Depends on readout	<100ps To be checked
B-field immunity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

Time-Of-Propagation Counter

Accurately polished quartz & precision timing



Quartz-based RICH



Measurement coordinates

- Use of total internal reflection in accurately polished quartz bar.
  A concept was invented by B.Ratcliff et al.
- DIRC (Detector of Internally Reflected Cherenkov light)
  NIM A479(2002)1

(X, Y)

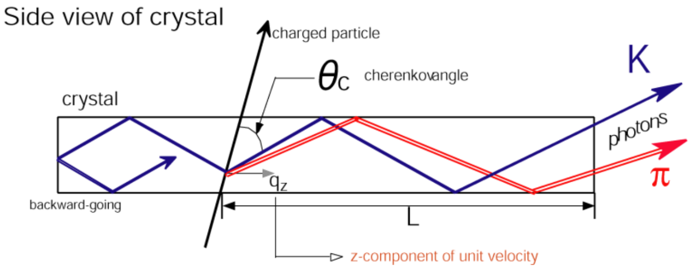
- TOP (Time Of Propagation) Counter
  NIM A453(2000)331

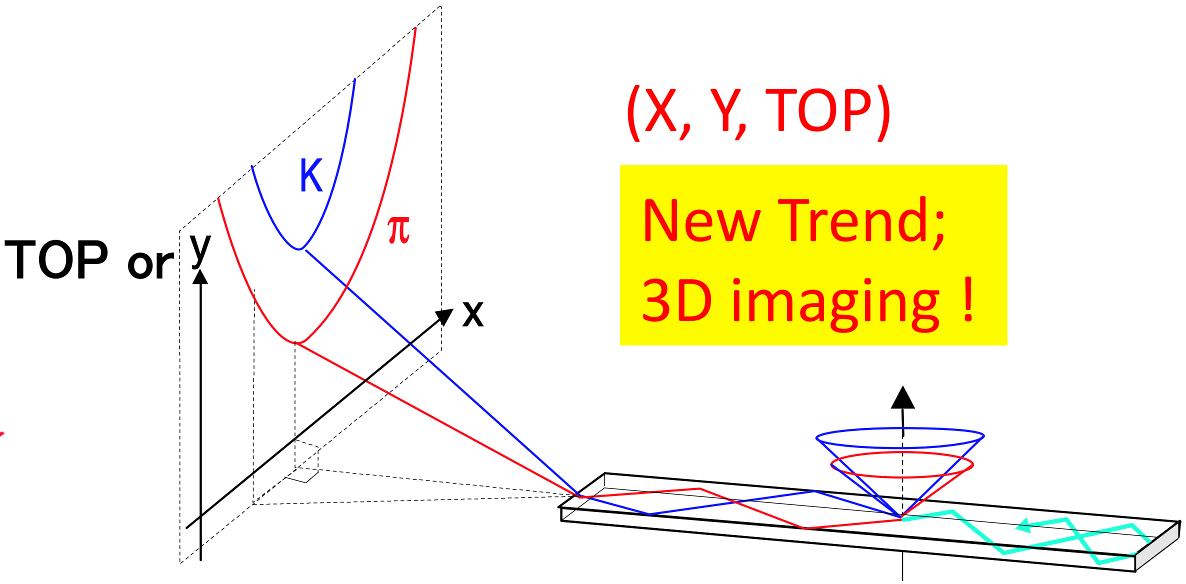
(X, TOP)
Nagoya, Ohshima et al.

- Focusing DIRC/TOP
  NIM A595(2008)104

(X, Y, TOP)

New Trend;
3D imaging !

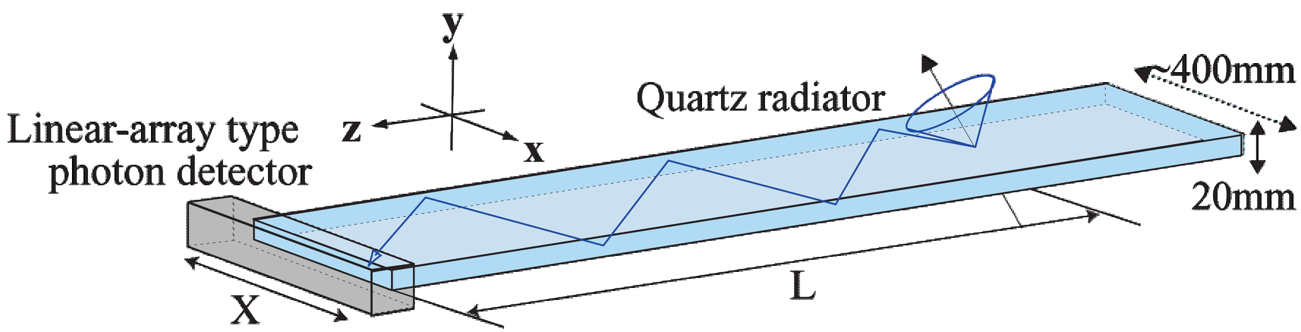




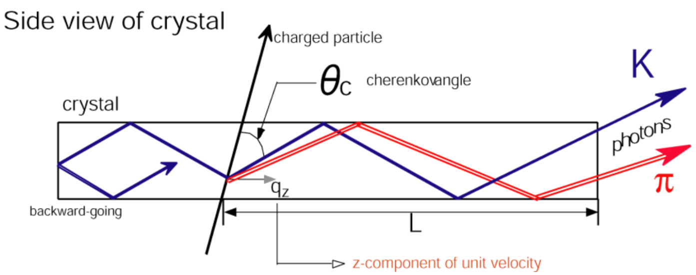
TOP counter

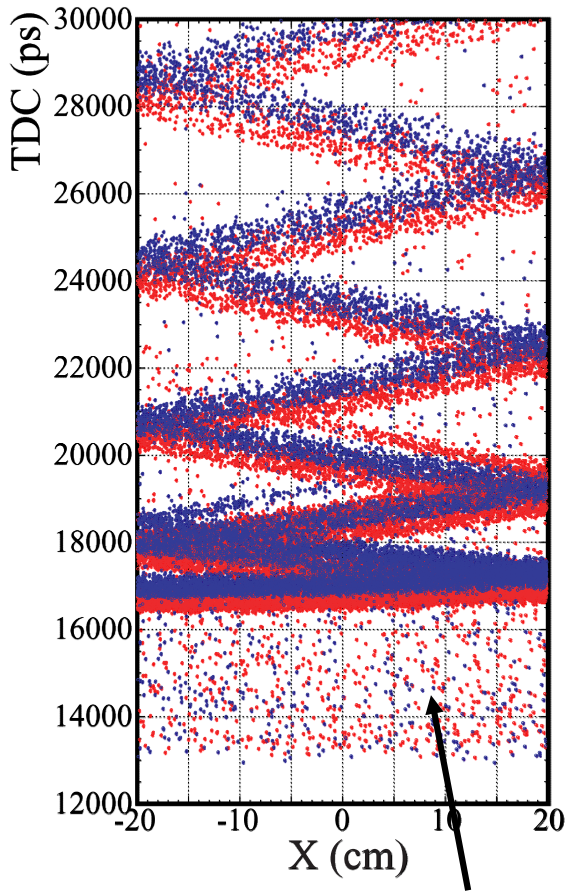
Simulation
2GeV/c, θ=90 deg.

- Cherenkov ring imaging using timing information
- Idea developed by Nagoya (Ohshima et al.)
- Very compact, suitable for collider geometry.



$$\cos\theta_c = \frac{1}{n(\lambda)\beta}$$





δ-ray,
had. int.

Difference of path length → Difference of time of propagation (TOP)
150~200ps from TOP + TOF from IP
with precise time resolution (s~40ps) for each photon

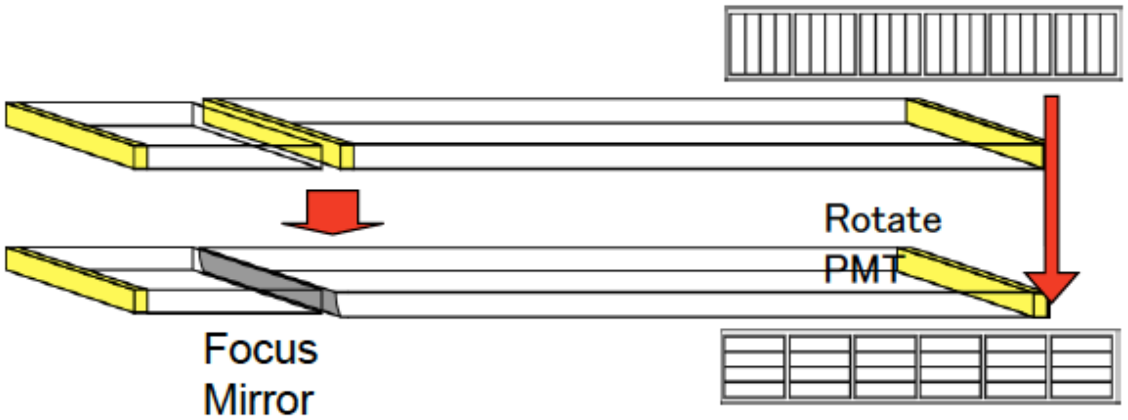
Focusing TOP

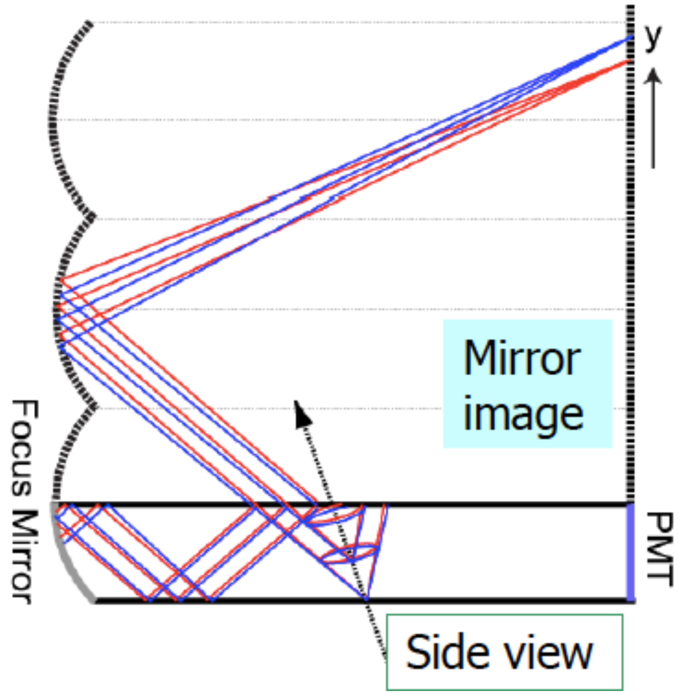
$$n_g(\lambda) = n_p(\lambda) - \lambda \cdot dn_p(\lambda)/d\lambda$$

- Remaining chromatic effect makes ~100ps fluctuation for TOP.
- Use λ dependence of Cherenkov angle to correct chromaticity

➔ Focusing system to measure θ_c
  - $\lambda \leftarrow \theta_c \leftarrow$ y position
  - Reconstruct ring image from 3D informations (time, x and y).

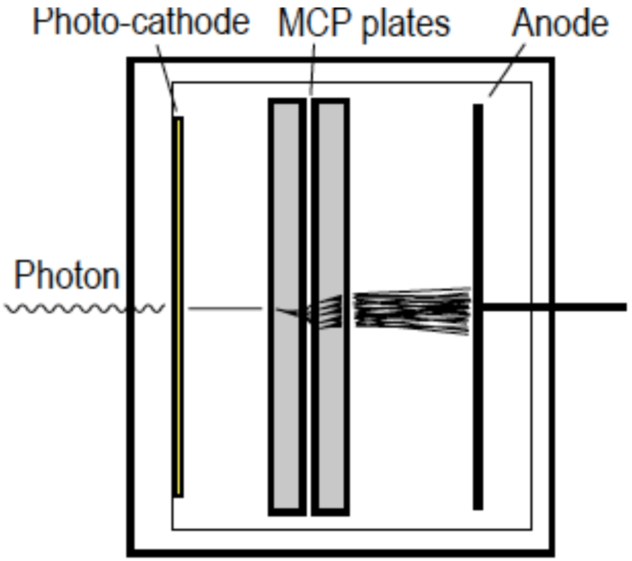
$$\theta_c(\lambda) = \cos^{-1}\left(\frac{1}{n(\lambda)\beta}\right)$$

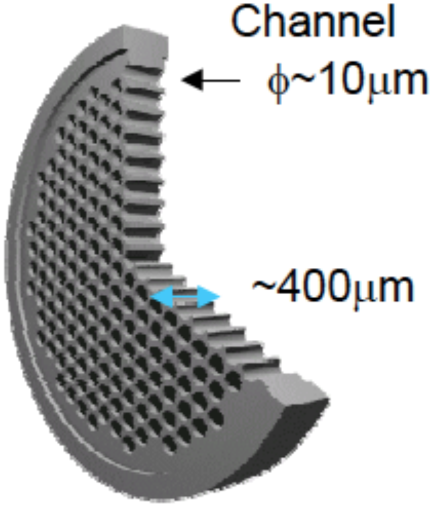


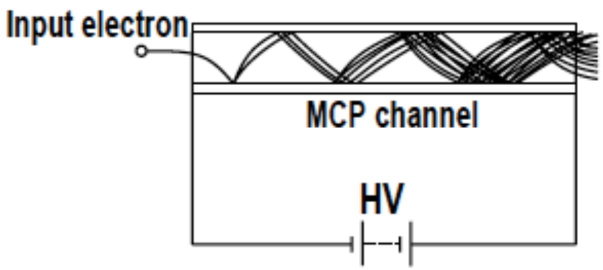


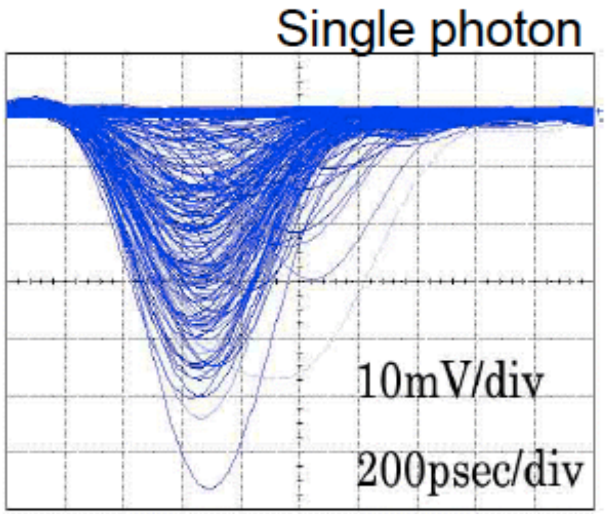
MCP-PMT

- Micro-Channel-Plate
  - Tiny electron multipliers
    - Diameter ~10μm, length ~400μm
  - High gain
    - ~10^6 for two-stage type
  - → Fast time response
    Pulse raise time ~500ps, TTS < 50ps
  - can operate under high magnetic field (~1T)





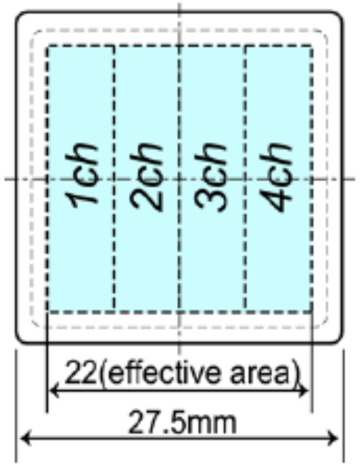


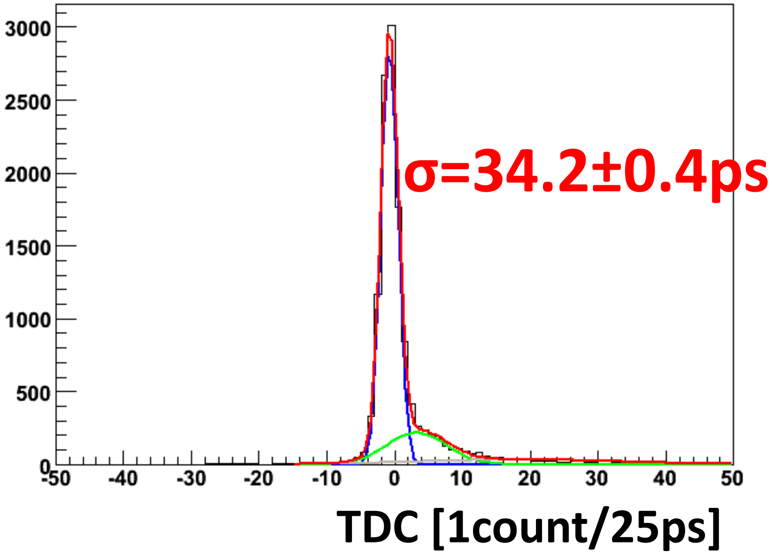


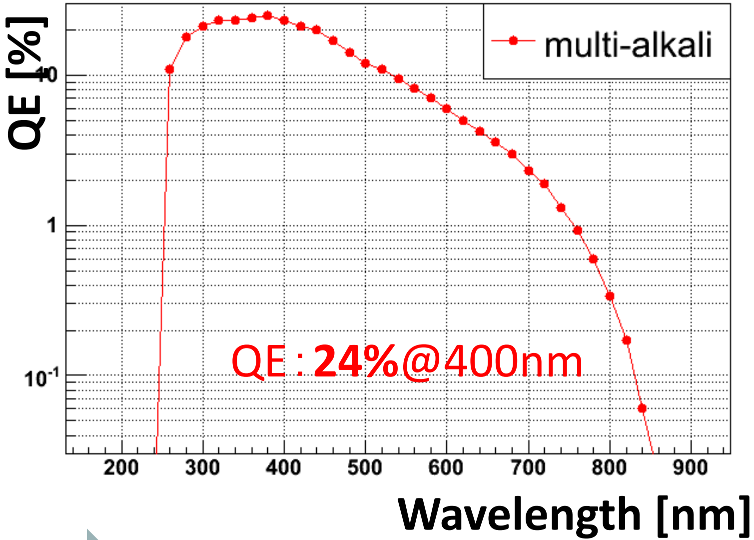
MCP-PMT

Developed by Nagoya and 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)





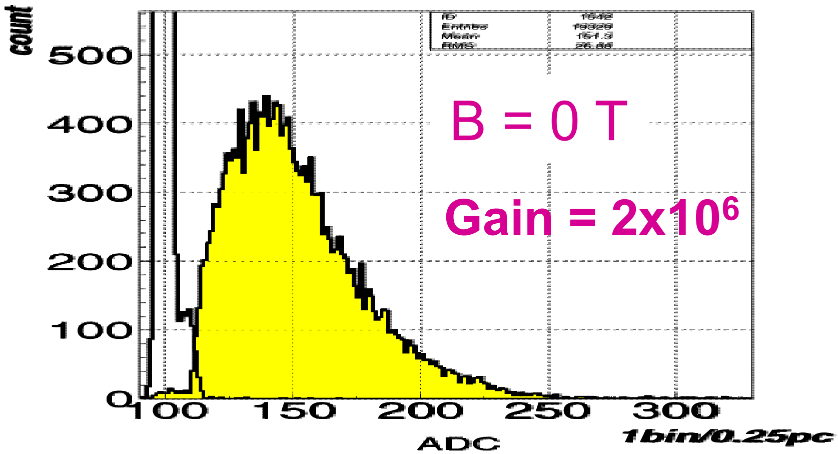


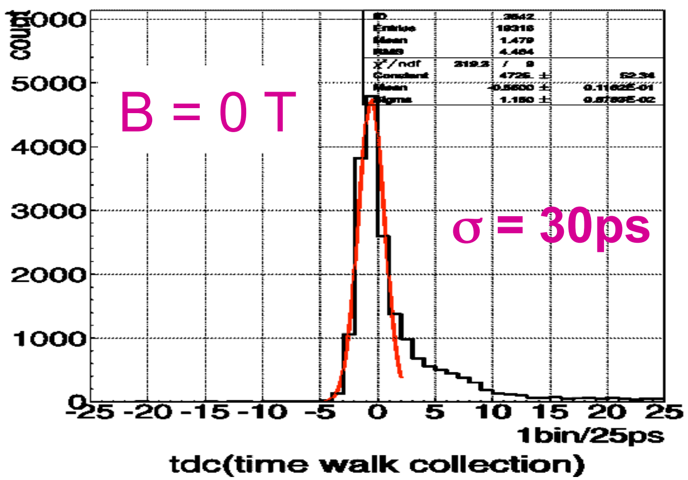
⇨ TTS＜40ps for all channels

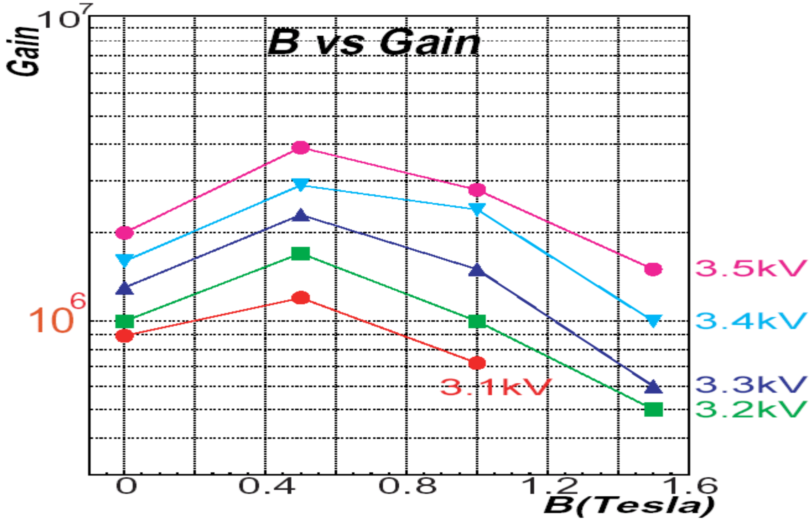
⇨ Ave. QE : **17%**@400nm

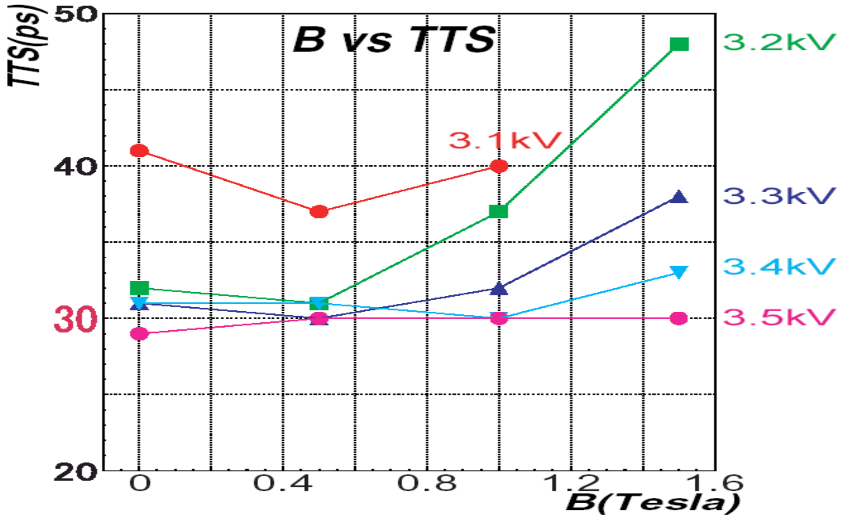
Improvement by Super Bialkali → >25%

SL10 basic performance (for single photon)







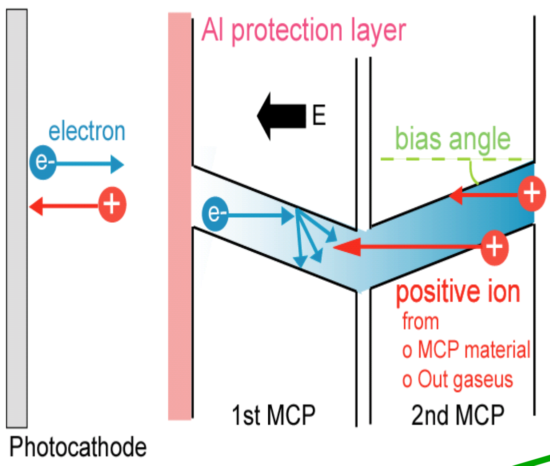


Confirmed gain > 10^6 and TTS = 30ps(σ)
In B=1.5T magnetic field.

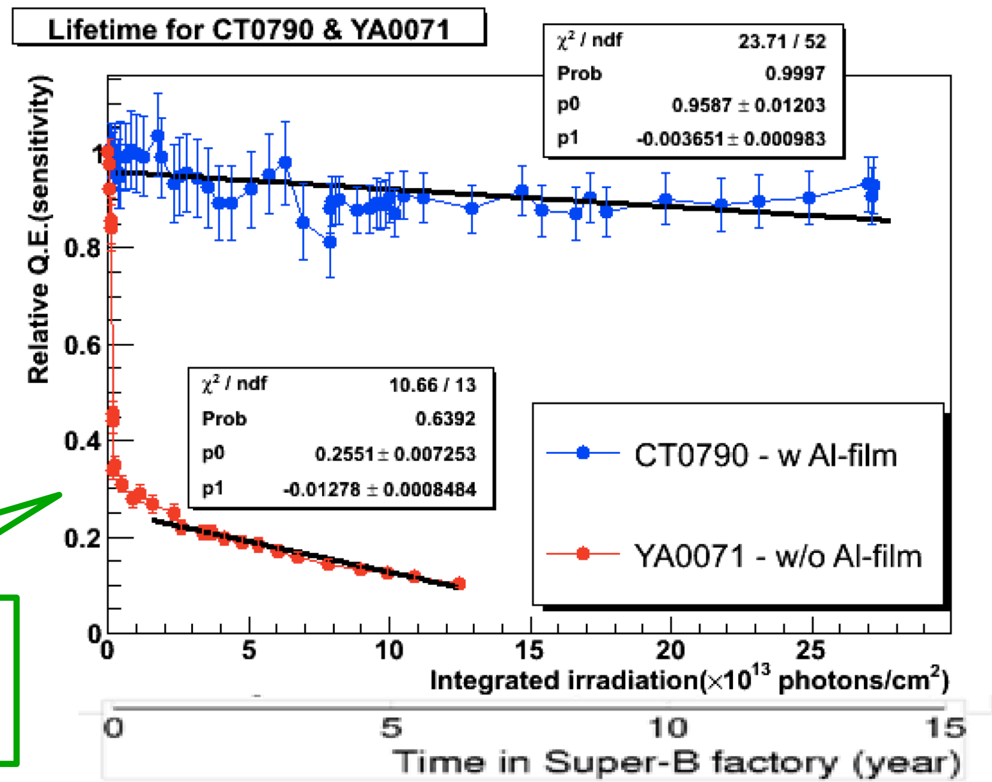
MCP-PMT Lifetime

- 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.

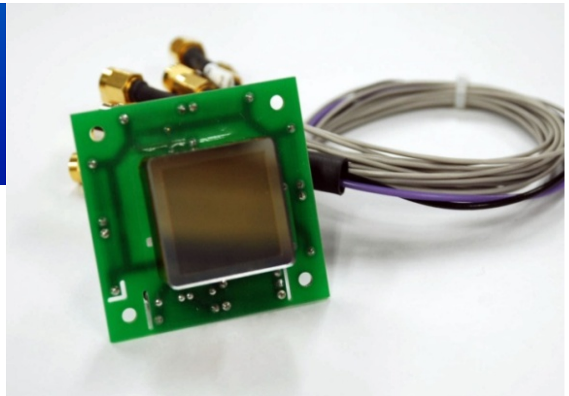
	Belle	Belle II
Luminosity (/cm2/s)	1x1034	8x1035
Num. of detected photons (/cm2/s)	3400	68000
Output Charge(mC/ cm2/year)	~6	~120



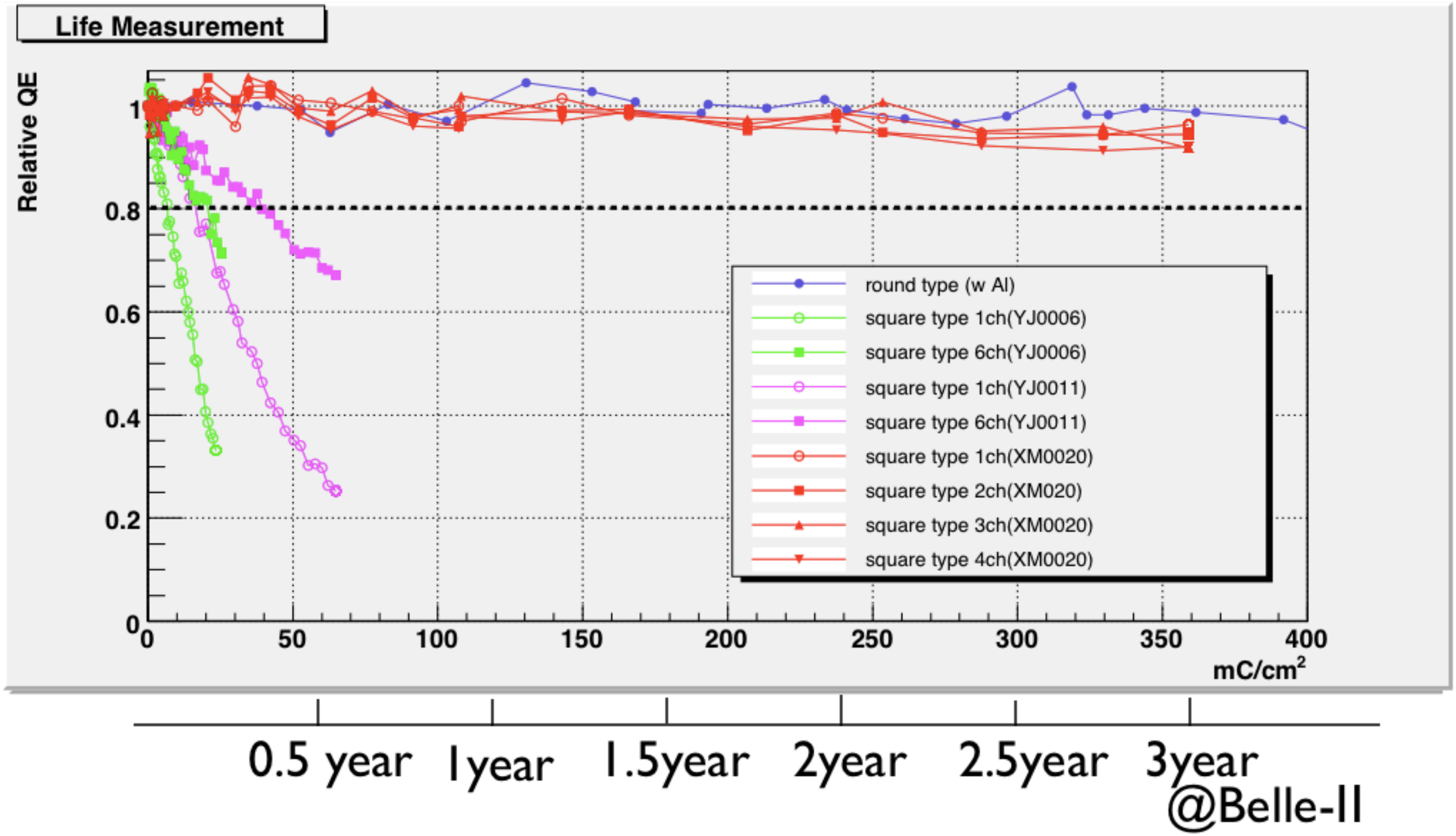
Test with earlier samples of round-shape MCP-PMT.



SL10 Lifetime



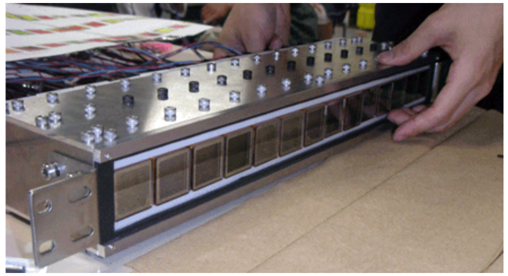
- QE variation
  - <10% drop at 350mC/cm^2 ; sufficient lifetime

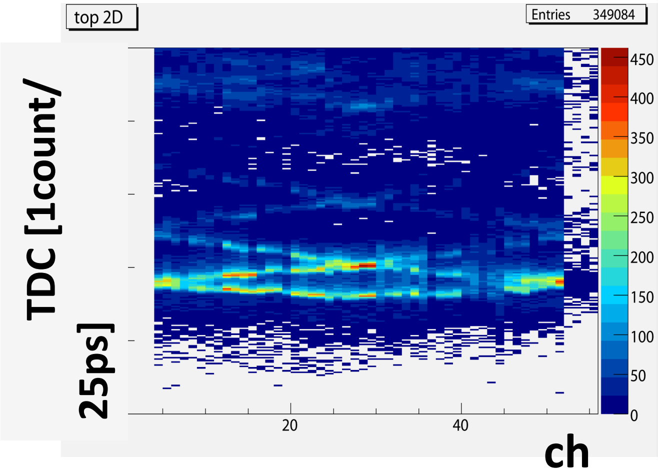


Beam Test Results

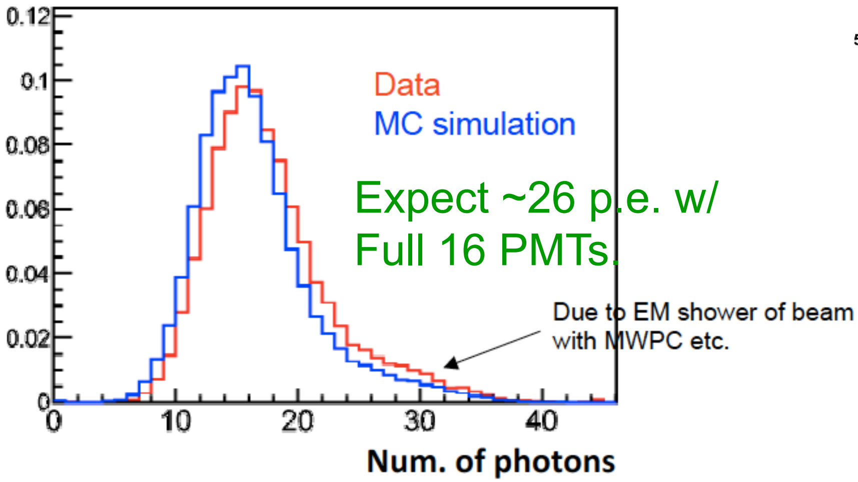
- 2GeV electron at Fuji beam line.
- Real size quartz and MCP-PMT

  MCP-PMT: Multi-alkali p.c., C.E.=60%

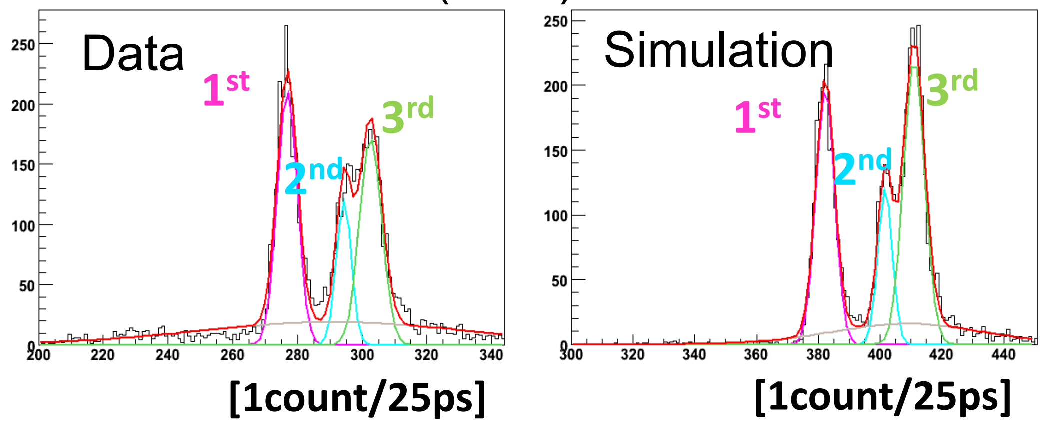




Number of detected photons



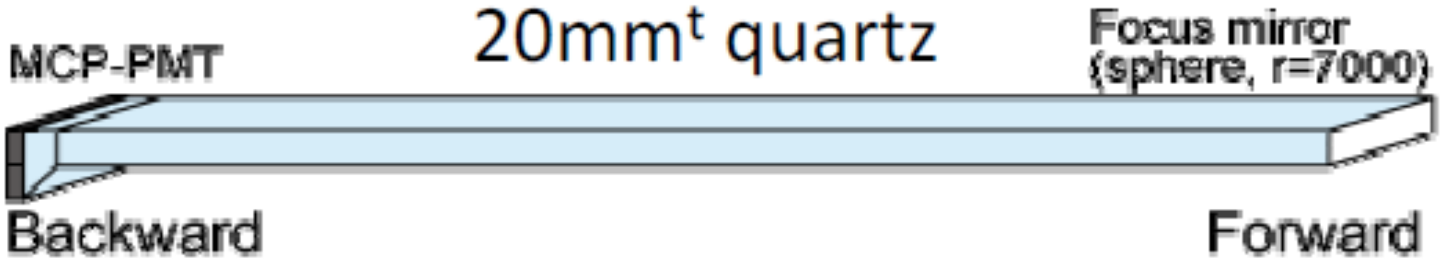
Time distribution (ch29)



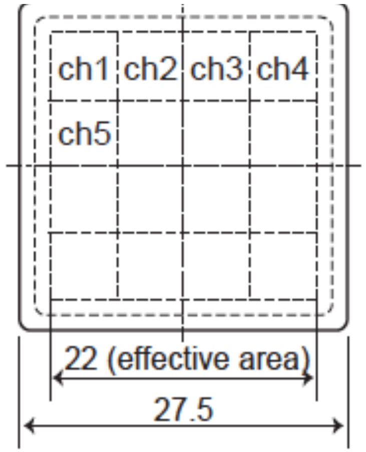
	Resolution(1st peak)
Data	76.0±2.0 [ps]
Simulation	77.7±2.3 [ps]

Good agreement between Data/MC

Final System

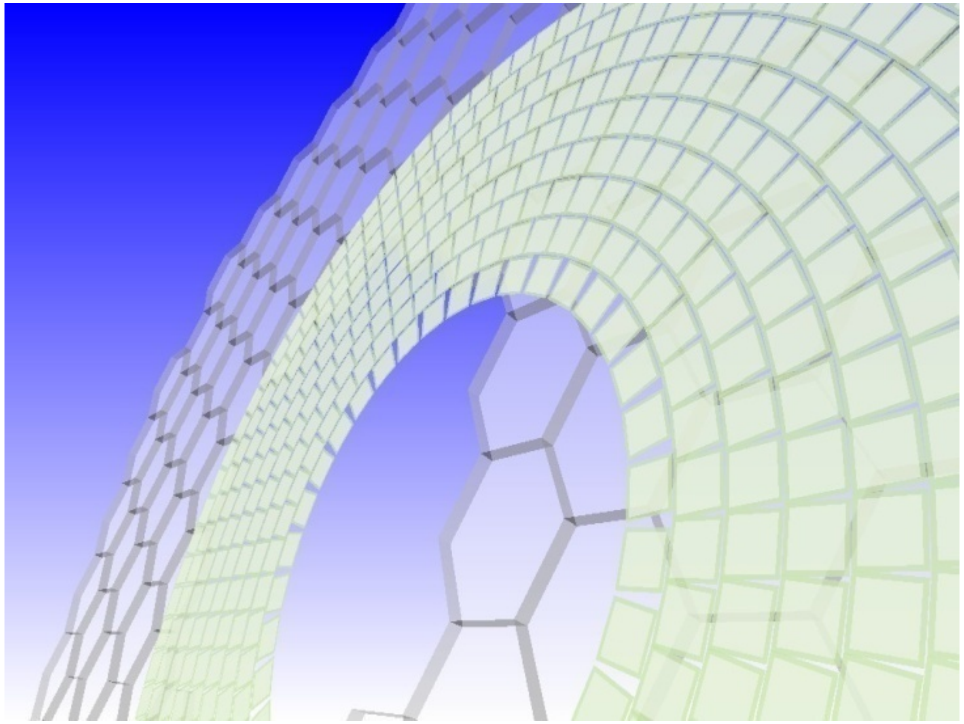


- MCP-PMT
  - 4x4 channel anode
    - Reduction of occupancy
    - Increase in Npe
  - Super bialkali photocathode
    - QE: 20% → 30% (or more)
  - Arranged in 2 layers
- Electronics
  - New ASIC chips (BLAB3) for very high-speed waveform sampling.



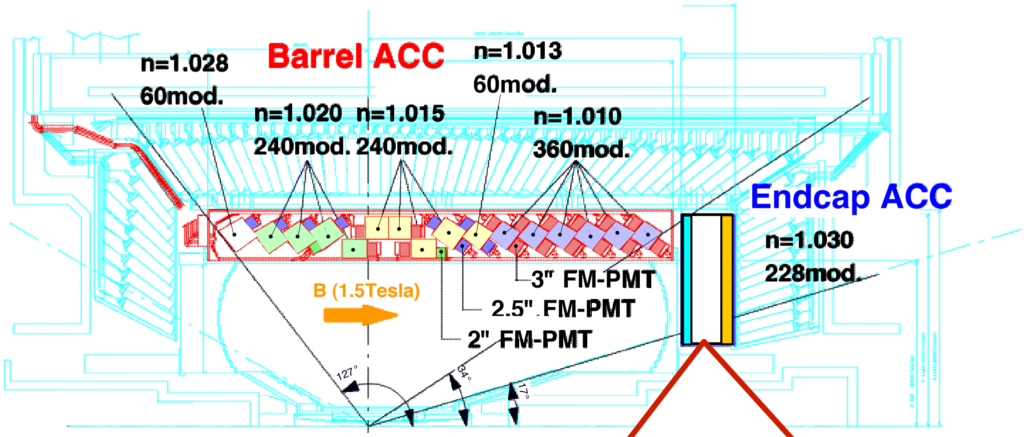
Proximity Focusing Aerogel RICH

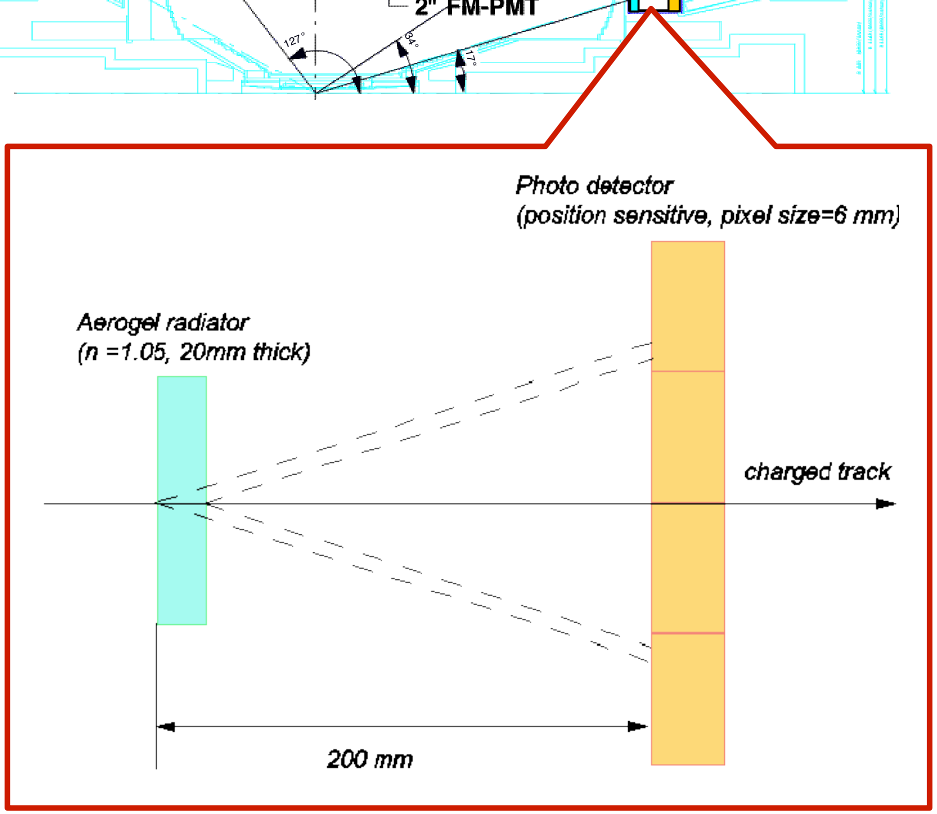
Highly transparent aerogel + Photon Imaging



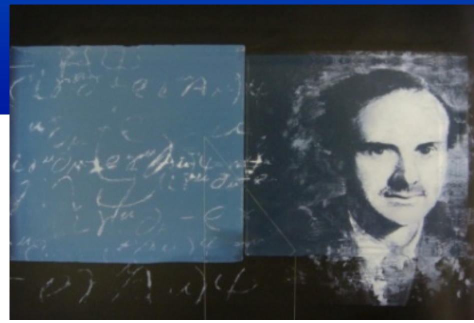
Belle II Proximity Focusing Aerogel RICH

- Aerogel radiator (n~1.05, ~2cm) + photodetector (Δx ~ 5mm)
- Proximity focusing geometry
  - No mirror complex.
  - Suitable for collider and space experiments.
- >4σ K/π for 0.7 < p < 4.5 GeV/c
  @ 4GeV/c, $\theta(\pi)$=310mrad.
  $\theta(\pi)-\theta(K)$=23mrad.
- Distance between aerogel to photodetector = 200mm.
- Track Incident angles = 17-34deg.

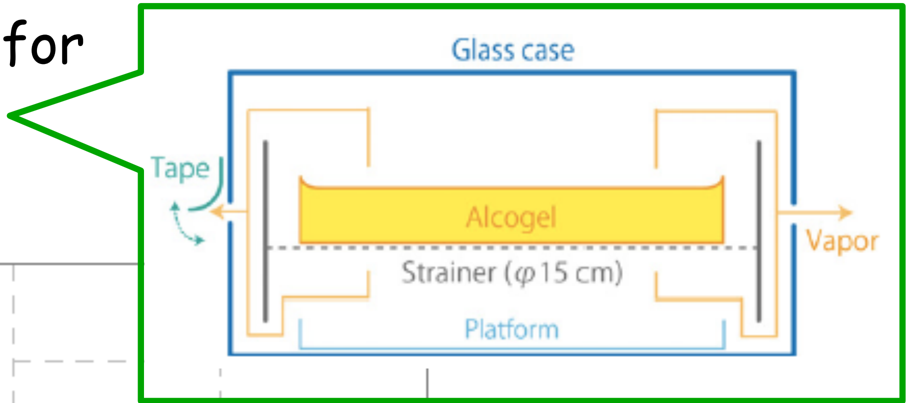


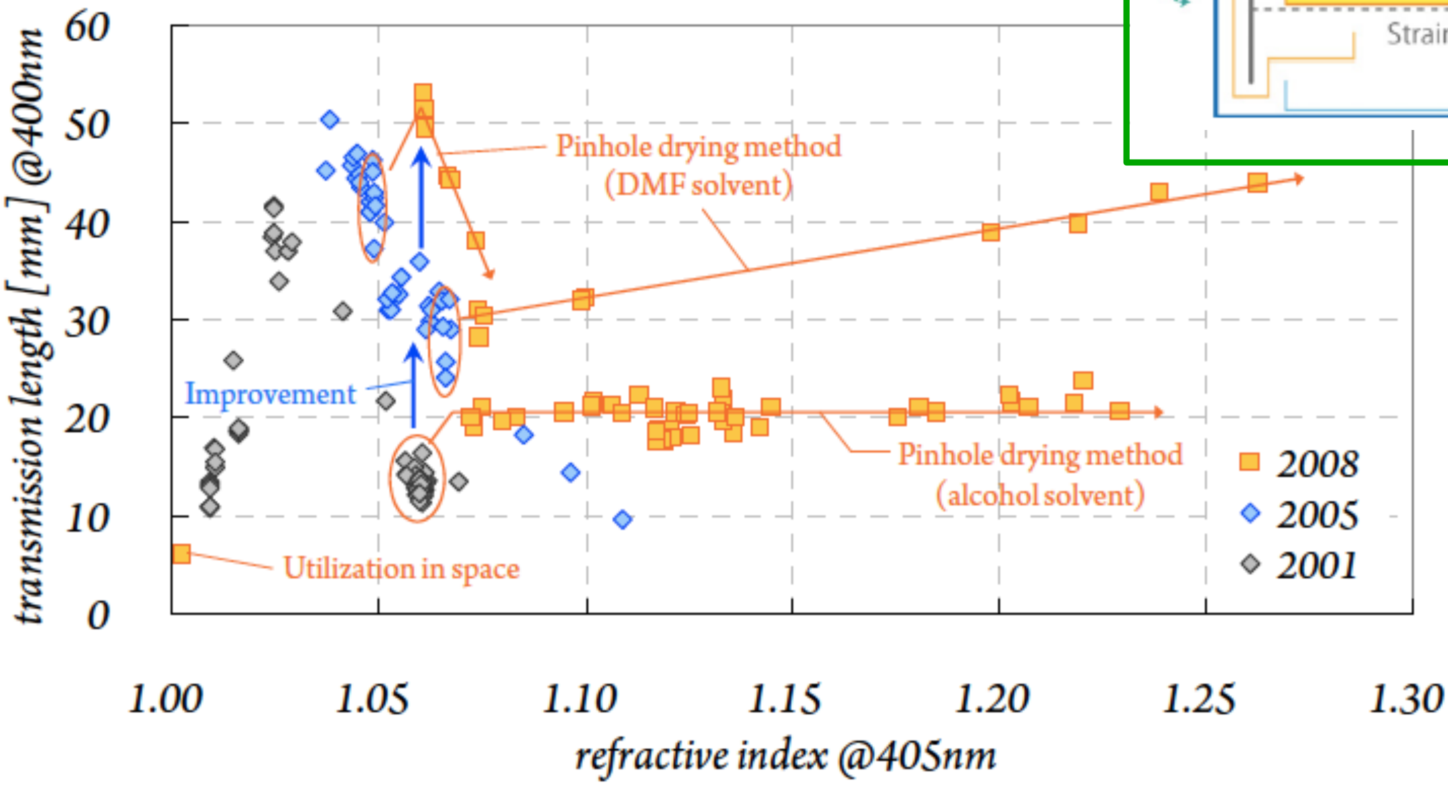


Aerogel Radiator

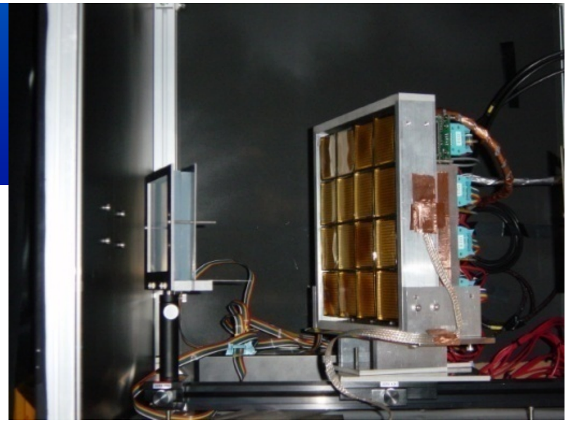


- Developed by collaboration w/ Matsushita.
- Hydrophobic for long term stability
- 2005: Improved transmission by new recipie.
- 2008: New method (pin-hole drying) for higher index.





RICH with Multiple Radiators

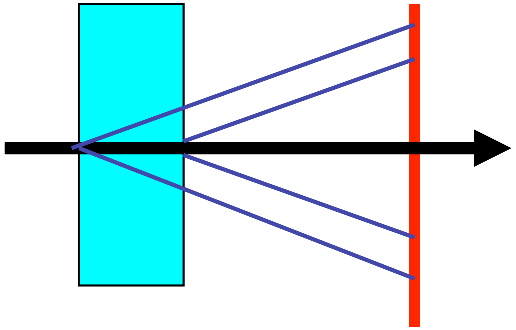


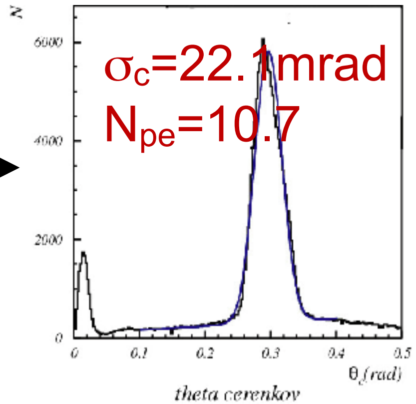
NIM A548(2005)383

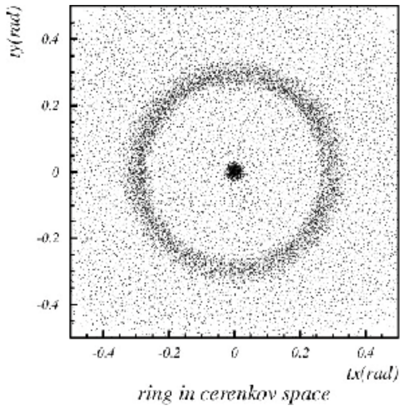
- Demonstration of principle
  - 4×4 array of H8500 (85% effective area)

Conventional

4cm thick aerogel
n=1.047

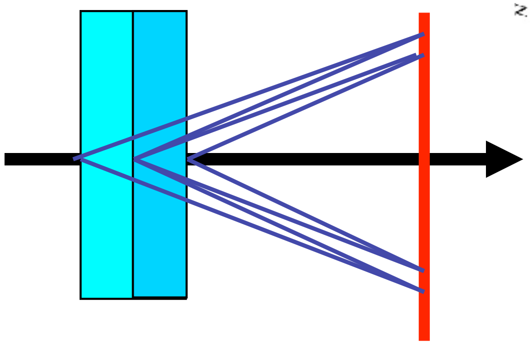


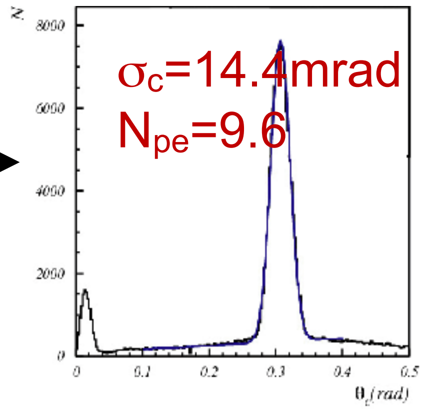


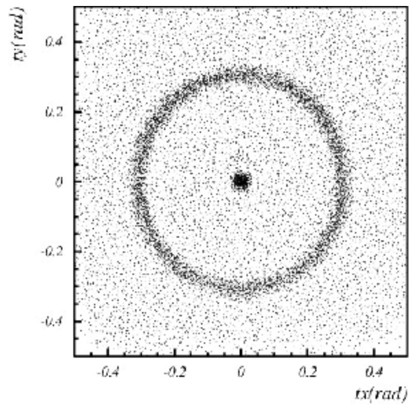


Multiple Radiator

2 layers of 2cm thick
n_1=1.047, n_2=1.057



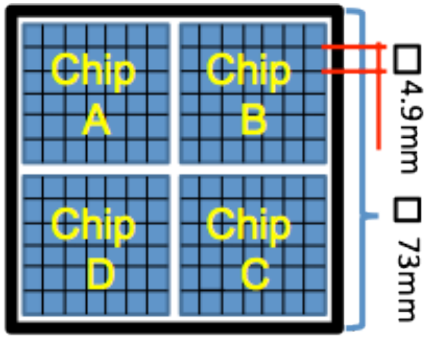




π/K separation with focusing configuration ~ 4.8σ @4GeV/c

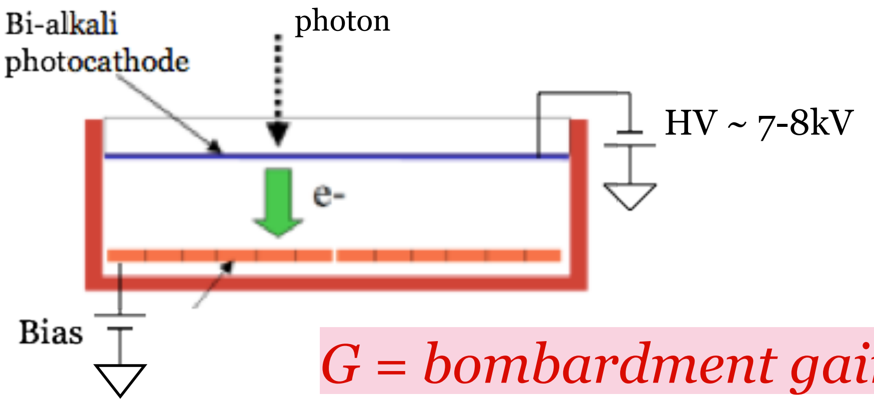
New 144ch HAPD

Hybrid avalanche photo-detector (HAPD) developed with Hamamatsu Photonics



4 avalanche diode (AD) chips (refer as A-D) are enclosed in one HAPD
Each AD is pixelated to 6×6 pads

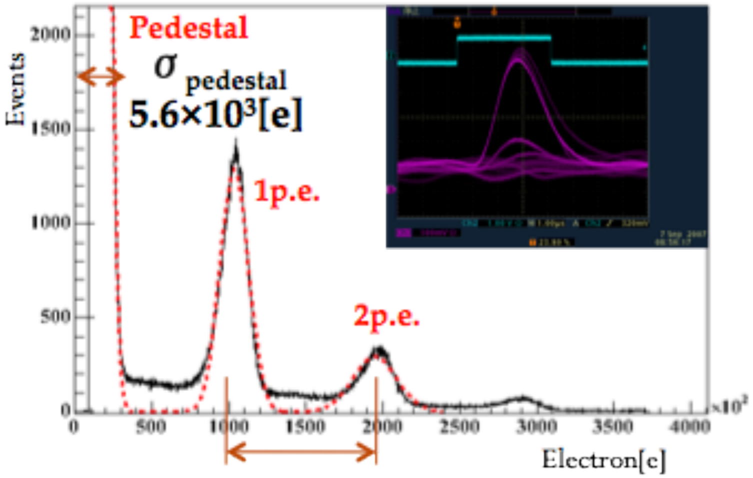
package	$73\times73mm^2$
sensitive area	64%
# of pixels	144(36×4chips)
capacitance	80pF
weight	220g



G = bombardment gain(~1000)×avalanche gain(~40)

Single Photon Response

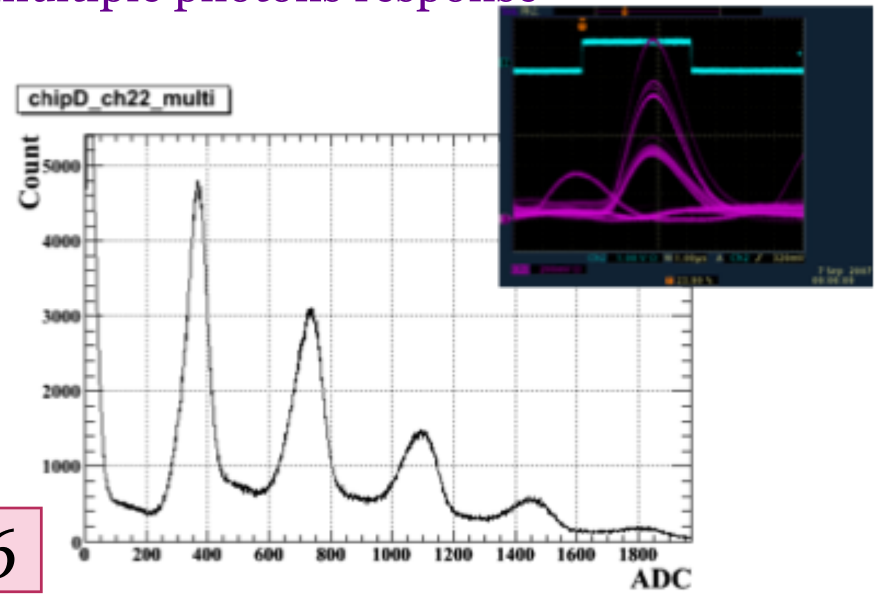
single photon response



pulse height spectrum
(HV:-8.5kV , bias:343V)

blue LED illuminated

multiple photons response



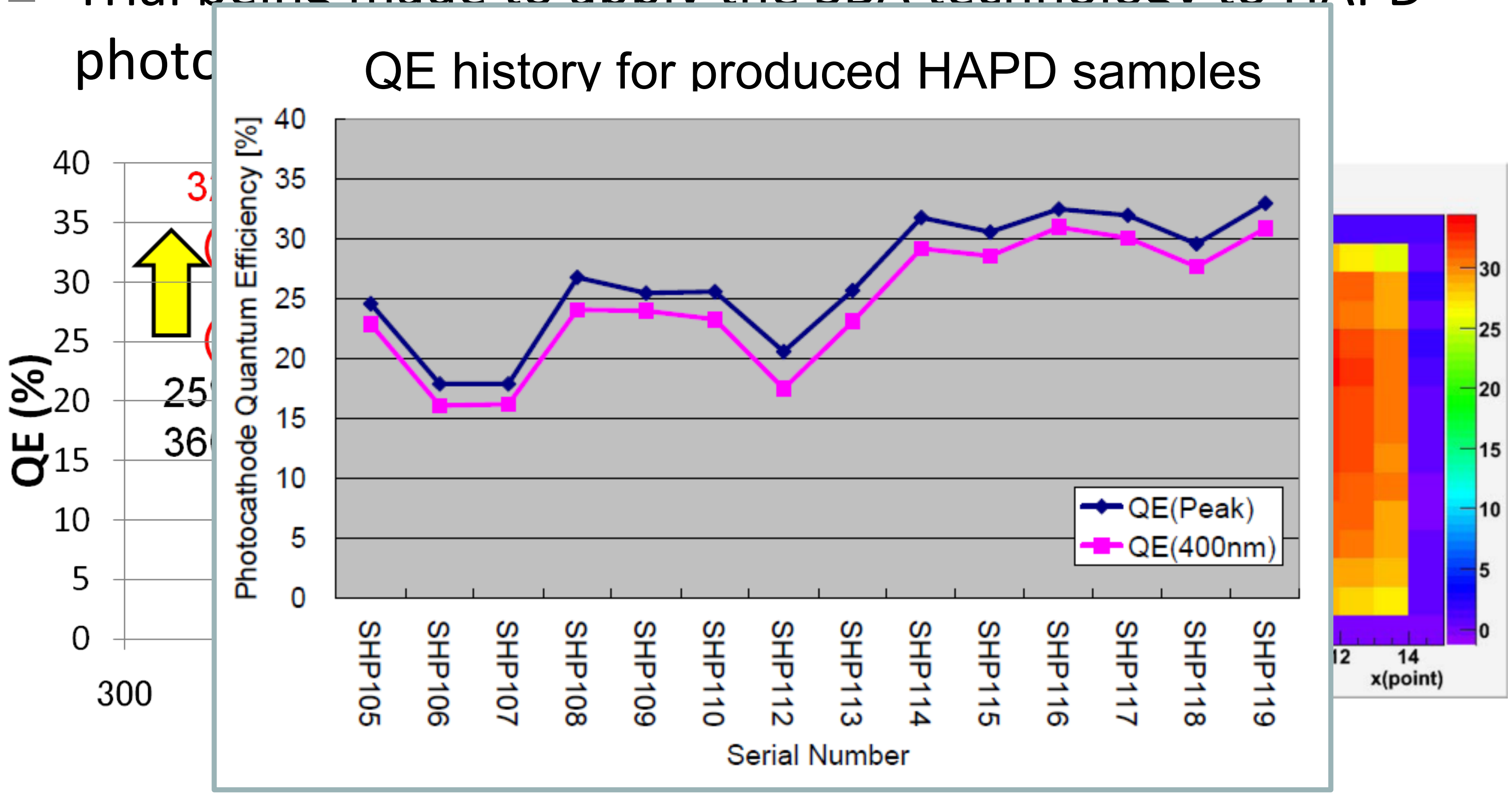
$$G = 9.1 \times 10^4$$

$$S/N = G/\sigma_{pedestal} \sim 16$$

Clear single photon signal observed

QE Improvement

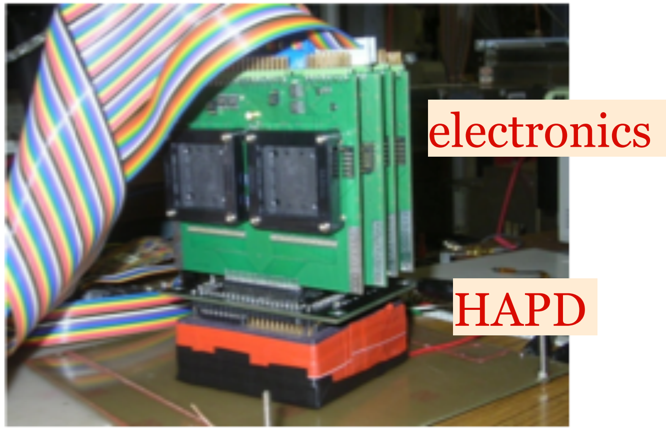
- Trial being made to apply the SBA technology to HAPD photo

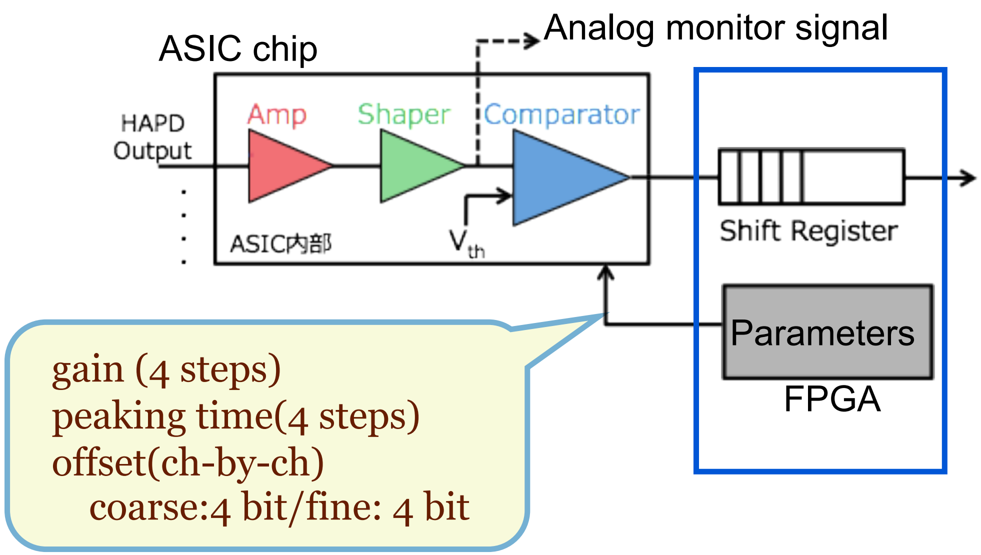


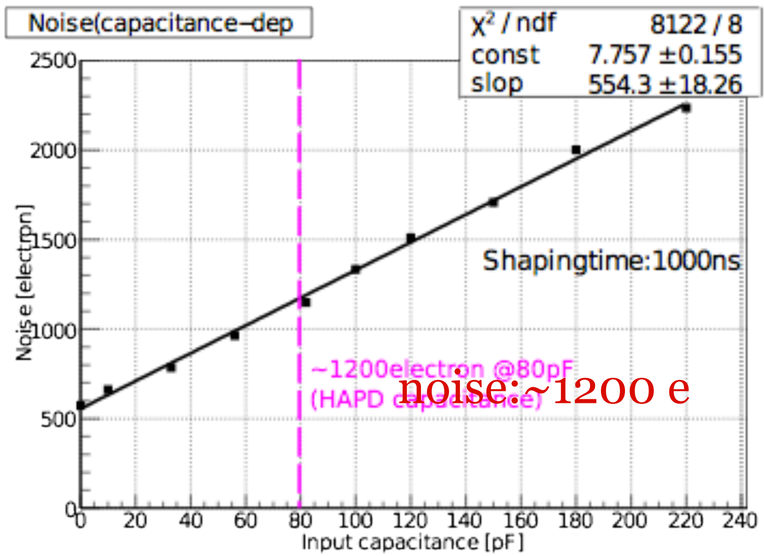
HAPD w/ QE(400nm) >30% possible !

HAPD Front-end Electronics

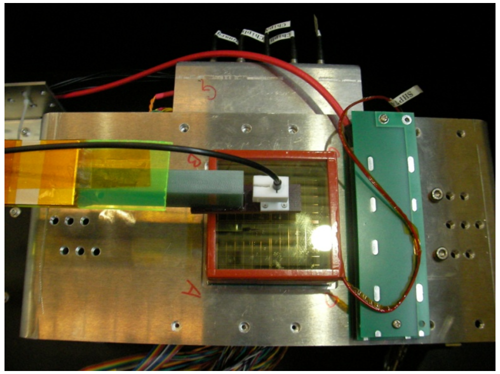
- Custom-made ASIC chips have been developed for 144ch HAPD.
  - manage ~80K channels
  - prototyping almost completed after several iterations

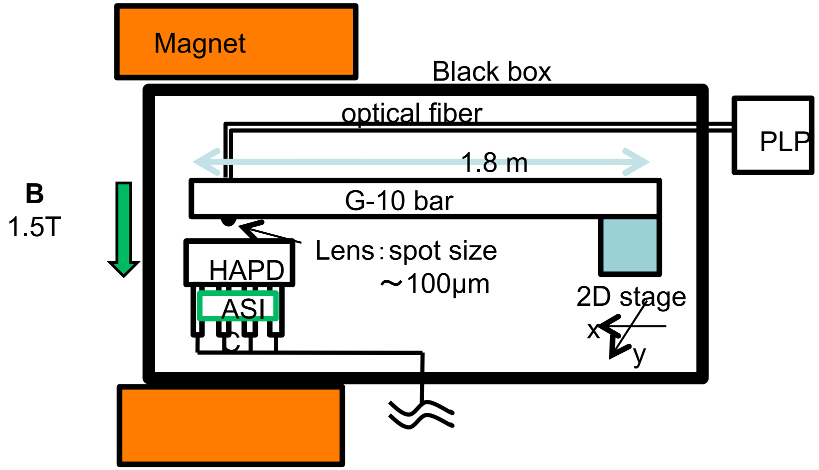


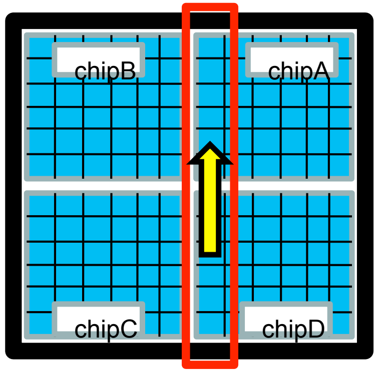


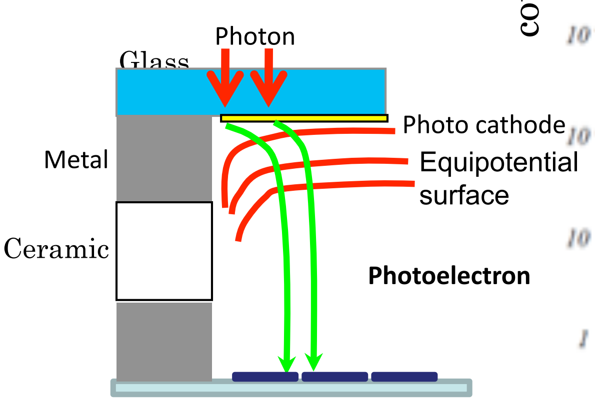


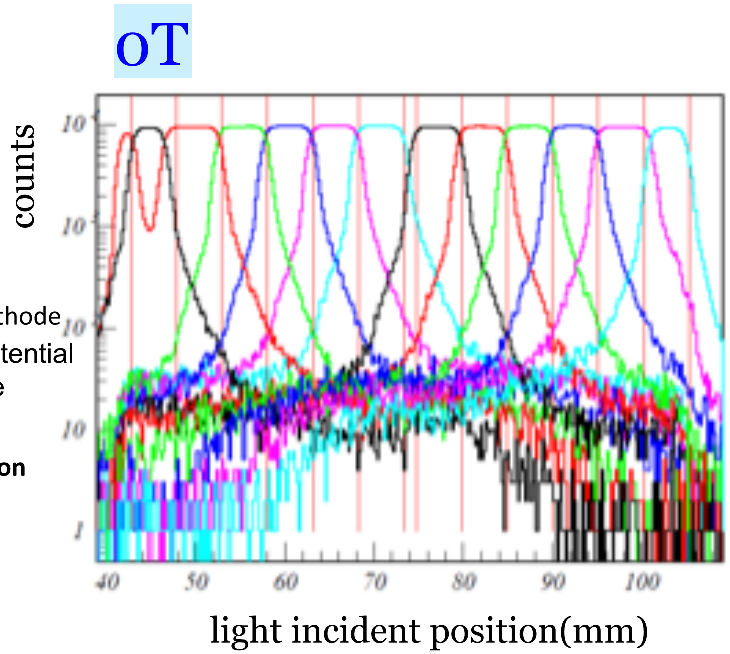
Response in Magnetic Field











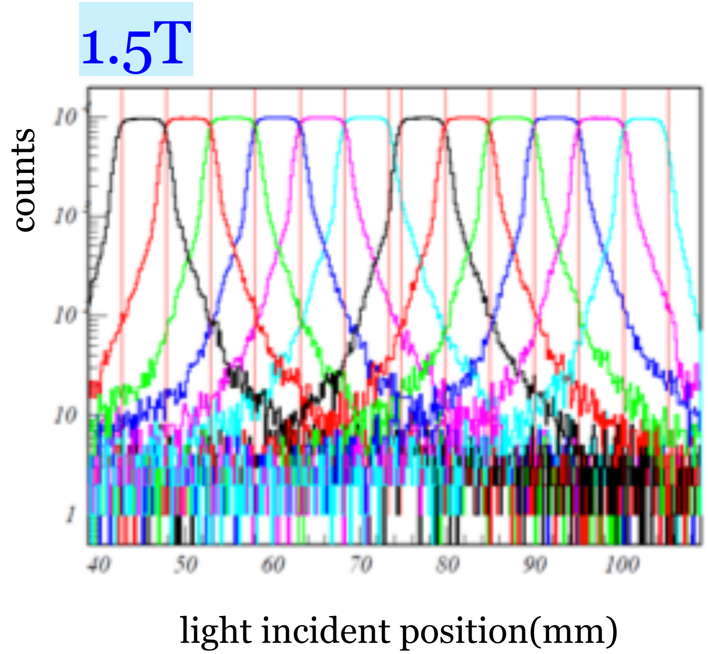
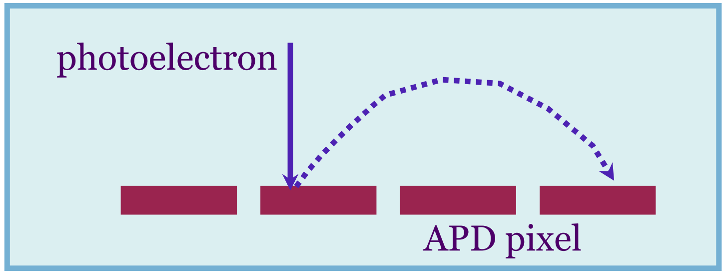


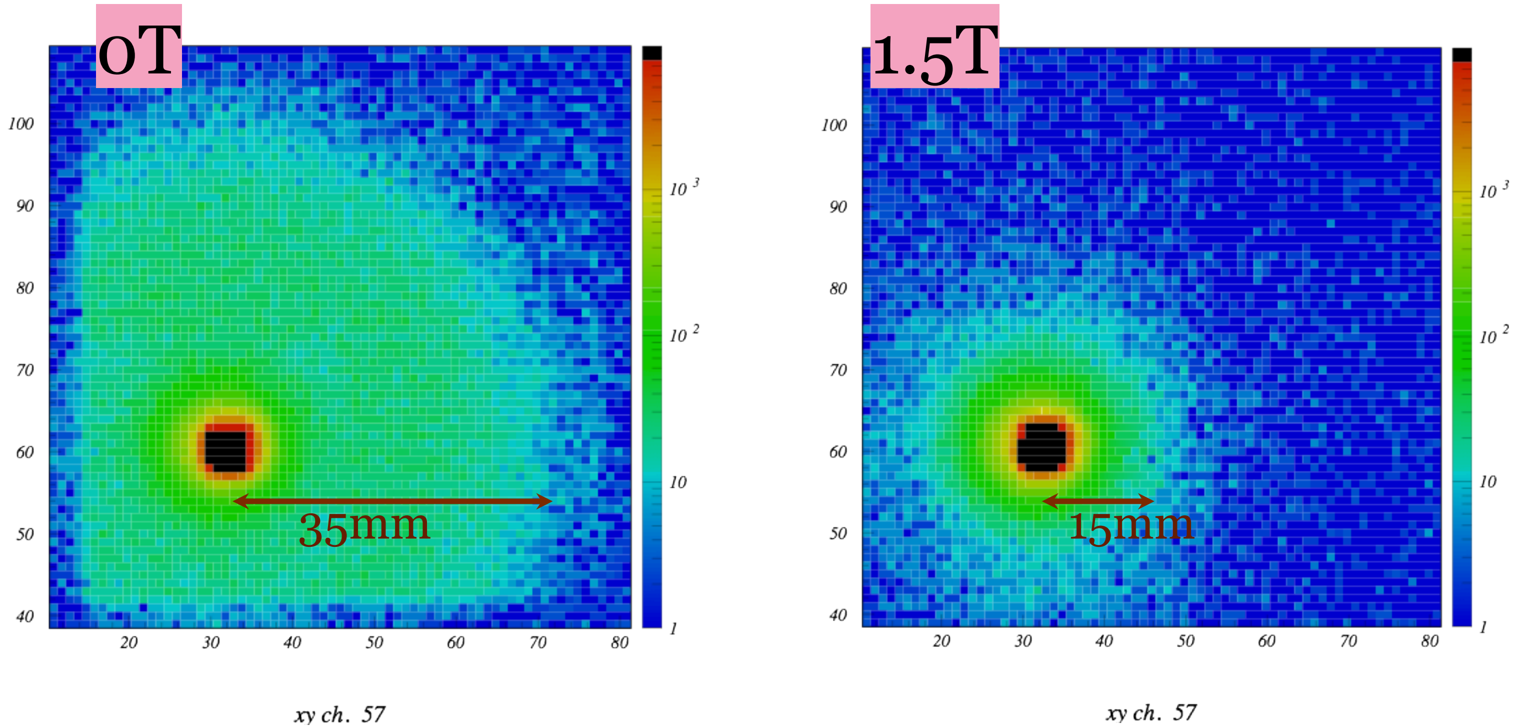
Image distortion near the wall can be removed in the magnetic field.

Electron Back-scattering

- Photoelectrons back-scattered onto the APD surface : significantly reduced when B-field turned on

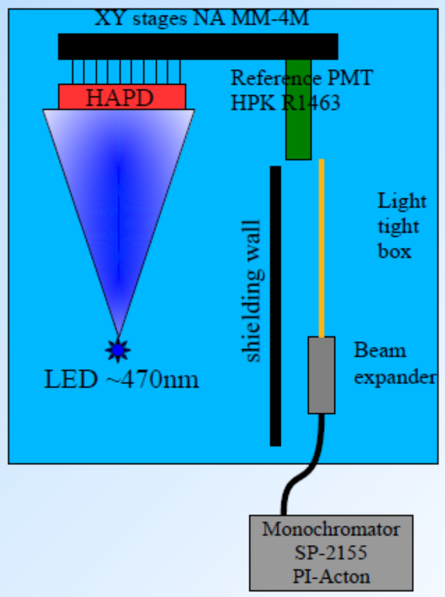


Residual spread can be considered as other effect such as light reflection

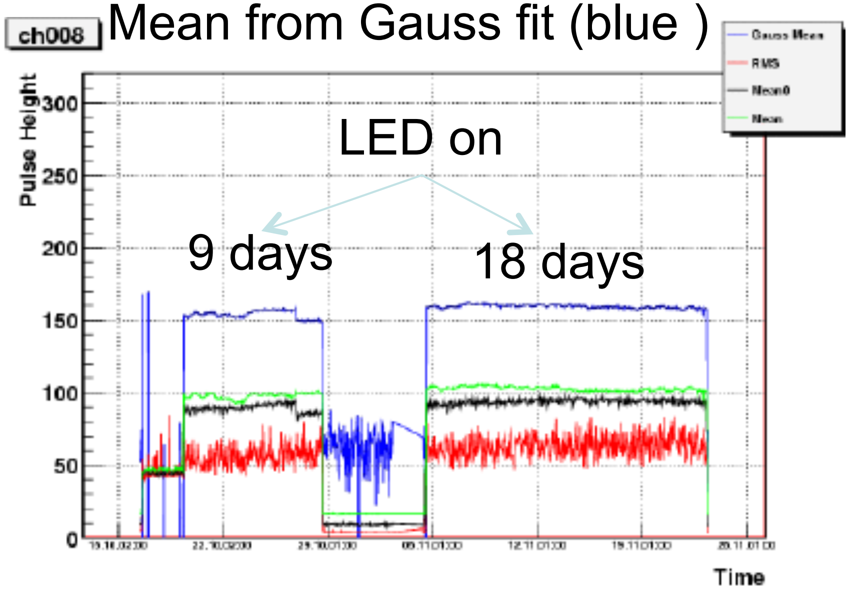


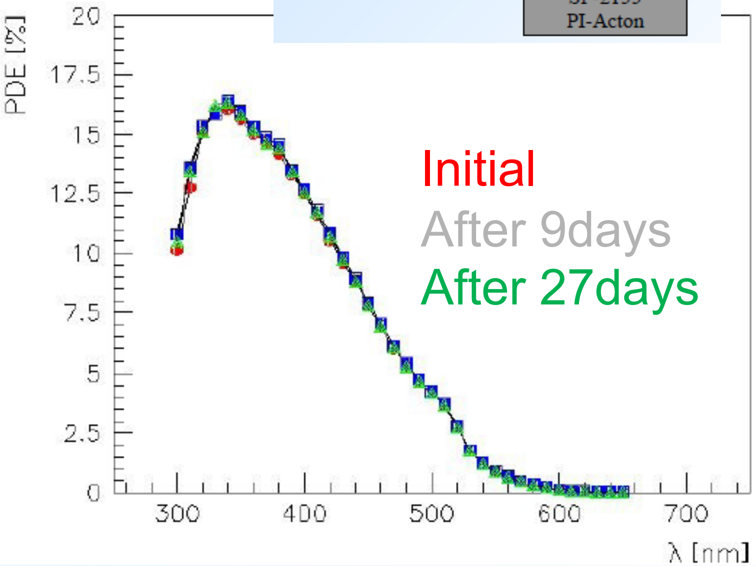
HAPD Aging

- Tested at Ljubljana.
- Monitoring currents from 3 chips.
- Monitoring ADC from 3 channels (chip B)
- Gain at 6×10^4 (APD~50, bombarding~1200)
- 1MHz / ch → 4days / TOP year



Mean from Gauss fit (blue)





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

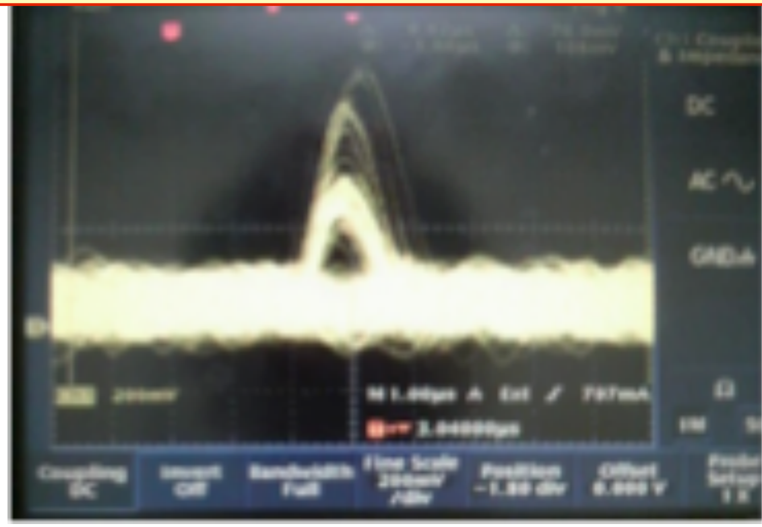
Neutron Irradiation Test

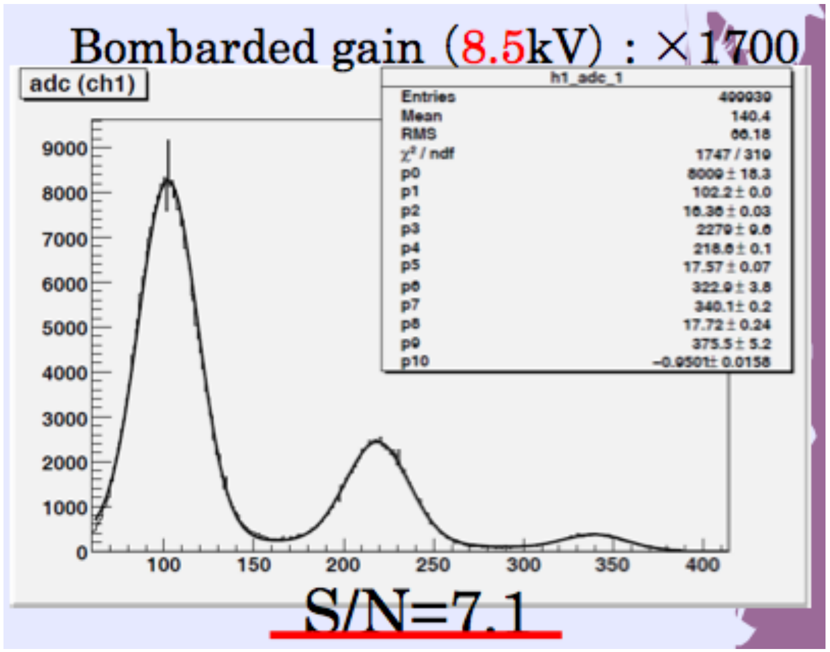
- Estimated neutron dose = 1×10^{12} neutron/cm^2 for 10 years in Belle II detector.

  → Bulk damage (lattice deficits)
- Neutron irradiation tests are carried out using a research reactor ("Yayoi" at U.Tokyo).
- Observed increase of leak currents

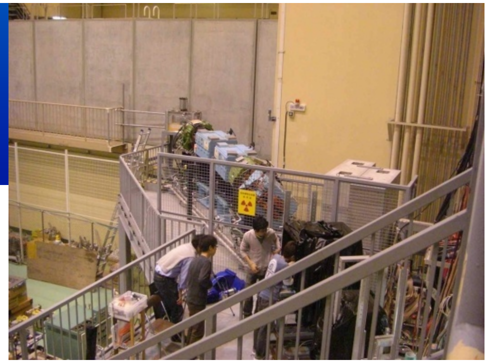
  → Noise
- Single-photons can be detected by optimizing the readout (shaping time, bombarding HV).
- APD w/ thinner p-layer are being tested to minimize the effect.

250 nsec peaking time + HV 8.5kV



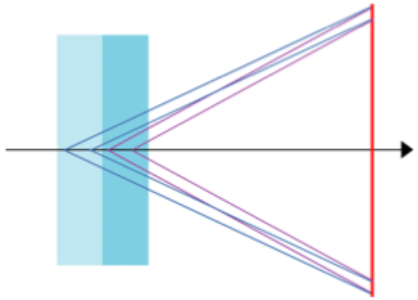


Beam Test Results w/ HAPD

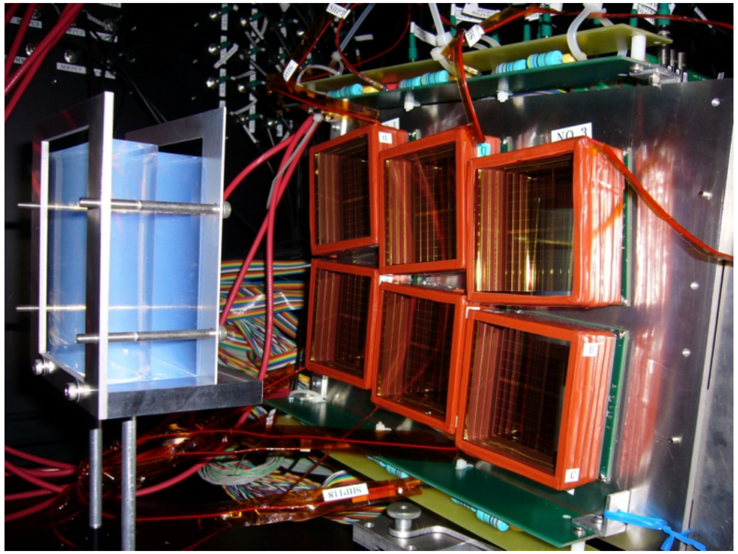


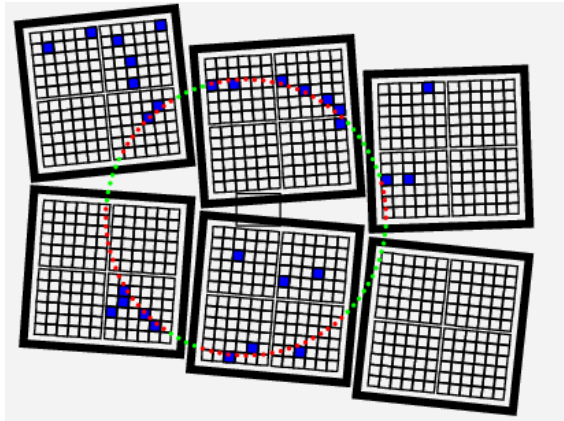
2GeV electrons at KEKB FUJI test beam

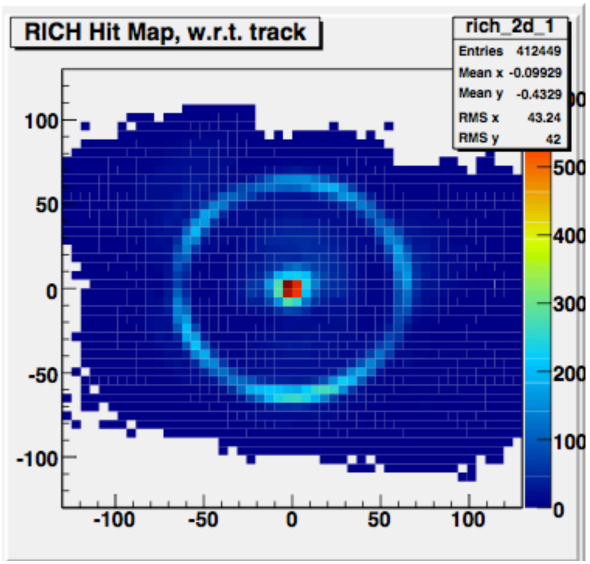
"focusing" configuration of 2 aerogel layers.

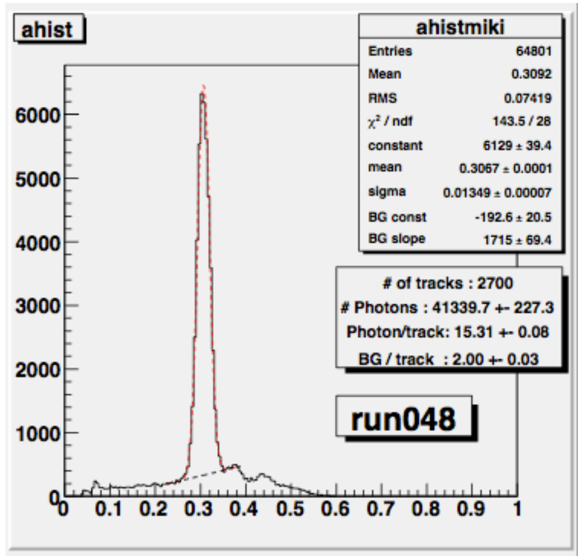


n=1.054 n=1.065
20mm / each









- σ_{ph} = 13.5mrad.
- $<N_{pe}>$=15.3

➡ ~6σ K/π @ 4GeV/c

※Slight dependence on the track incident condition.

Other Possibilities

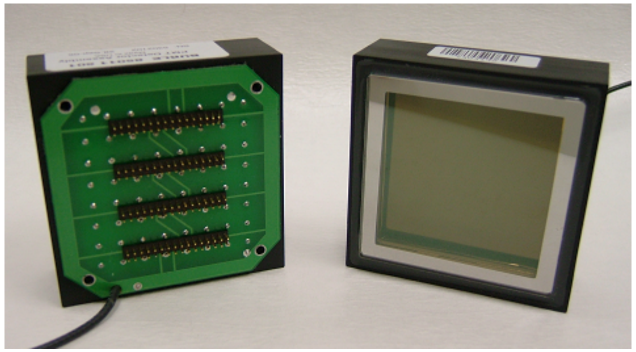
MCP-PMT

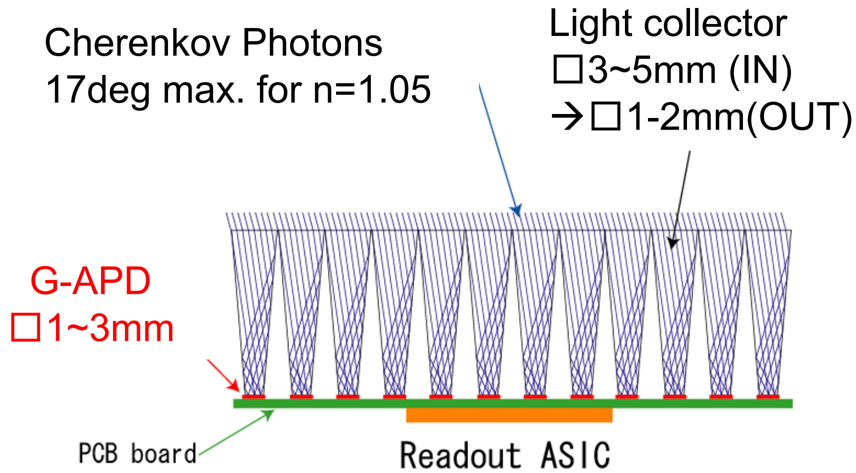
- High gain (~10^6)
- Good time resolution(~50ps/p.e.)
- Stable operation.
- Need
  - Smaller pore size (25μ → <10μ)
  - Better collection eff.
  - Lifetime ?

Geiger-mode APD

- High gain(~10^6)
- High Q.E.(>50%)
- B-field immunity independent of the direction.
- Concerns
  - High noise rate (~200KHz/mm)
  - Size (~1x1mm^2 →3x3mm^2)
  - Radiation damage ?

BURLE 85011-501



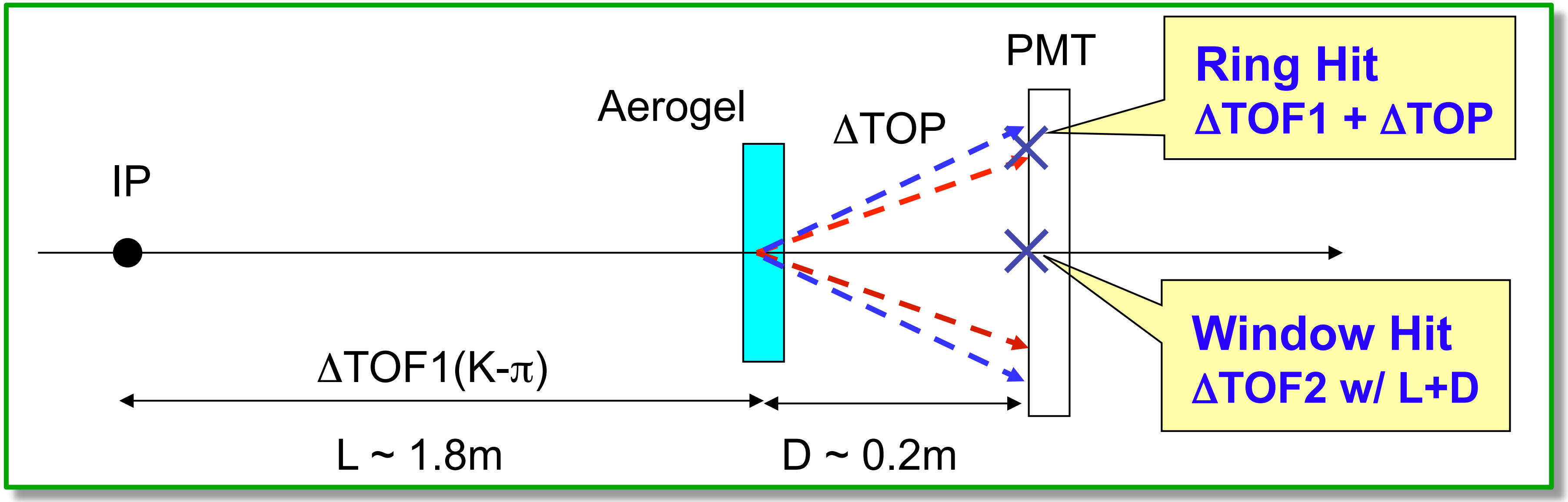


RICH w/ TOF Capability

- Possible PID improvement in low momentum region.
- Two timings can be used;
  - "Ring hit" : Cherenkov photons from aerogel.

    σ_{photon} ~ 60ps ➡ σ_{track} ~ 60ps/sqrt(9) =20ps
  - "Window hit": Cherenkov photons from glass window of PMT

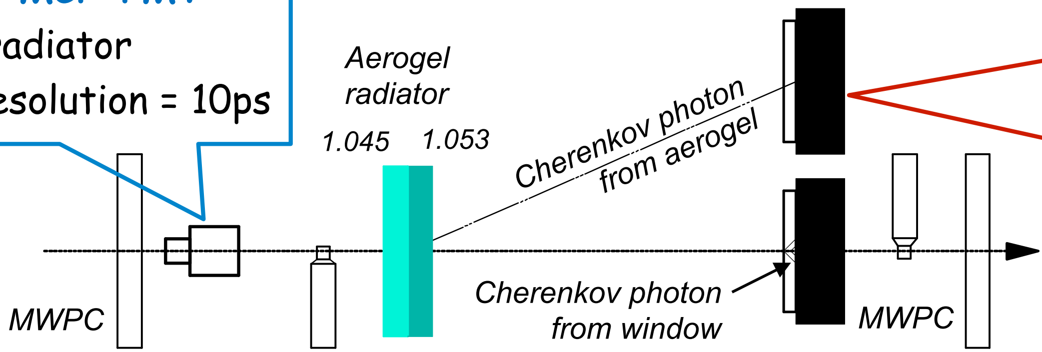
    σ_{track} ~10ps possible (from the TOF R&D @ Nagoya).



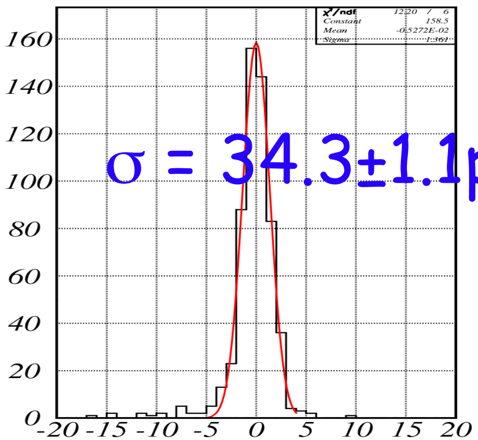
Beam Test w/ Burle MCP-PMT

Start counter:
HPK R3809U MCP-PMT
1cm quartz radiator
Start time resolution = 10ps

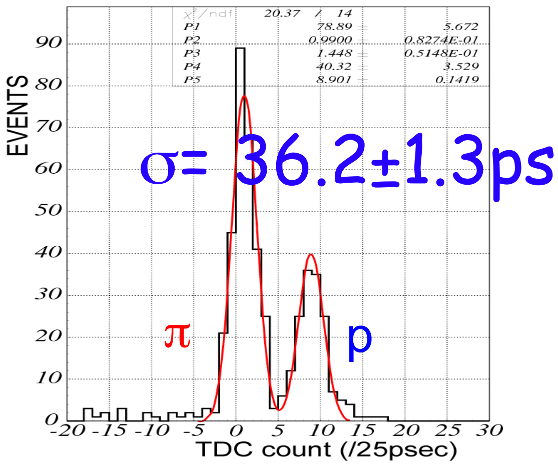
Multi-anode MCP-PMT
BURLE 85011-501
13 channels readout by
- FTA820 amplifier (ORTEC)
- L-edge discri (Phillips)
- KC3781A TDC (Kaizu works)



Time resolution for "window hits" (Time walk corrected)



TOF test w/ beam π and p (2GeV/c)



TDC count(/25psec)

Improvement in K/π separation

P (GeV/c)	RICH	+TOF
1.0	2.9σ	~4σ
2.0	4.7σ	~5σ

G-APD for RICH

Large advantage over other photodetectors

- Higher PDE (photo detection efficiency)

  Expected Npe (n=1.03,1cm)

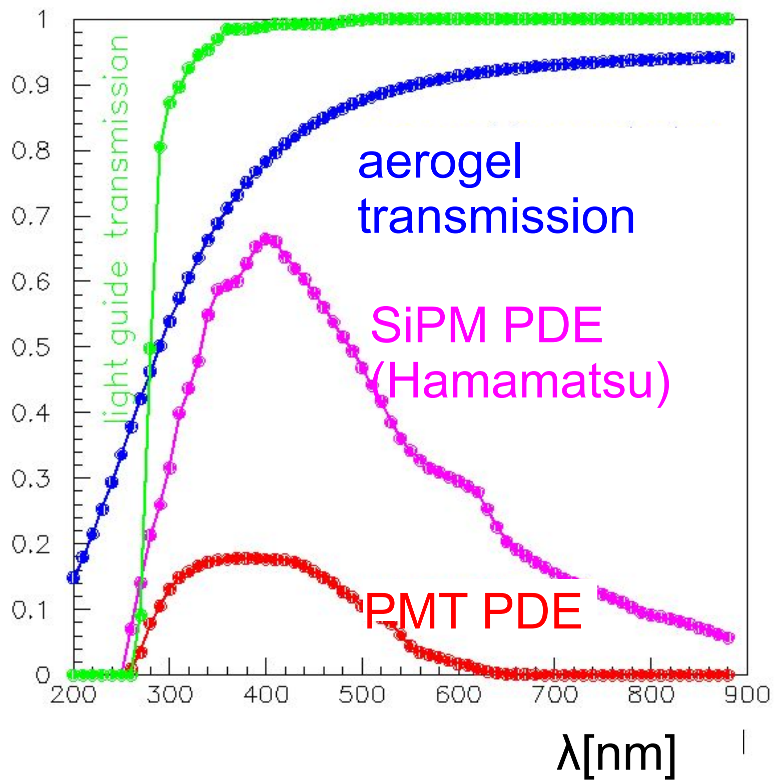
  17 for MPPC(HC100)

  4.1 for PMT (QE_{peak}=25%, CE=70%)
- Complete immunity to B-field

Concerns

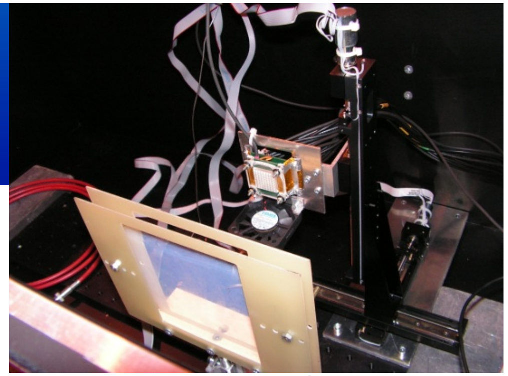
- High frequency noise.
- Small size.

  ⇨ **Light guide** to improve S/N and geometrical factor



- Rad. hardness

Beam Test Results



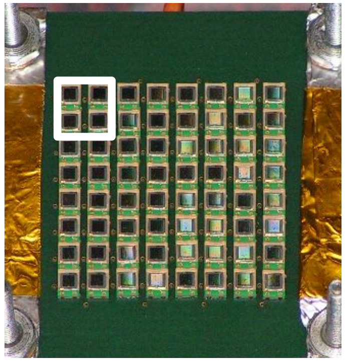
MPPC array on 3D stage
Aerogel n=1.03, d=10mm

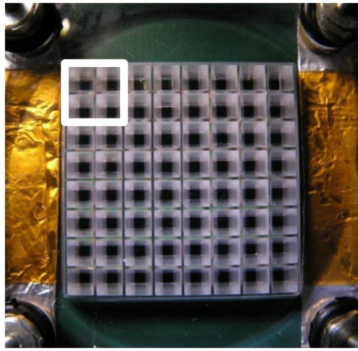
- Test w/ 120GeVπ beam at CERN
- Detector module with 8x8 array of SMD MPPCs at 2.54 mm pitch.
- Light guides were machined from plastic (HERA-B lens material).
- Hits detected by multi-hit TDC
  - total noise rate ~ 35MHz (~600kHz/ MPPC, ~2.4MHz/ch.)
  - Time window of 5ns around the peak.
- Measured number of photons (extrapolated to full ring)

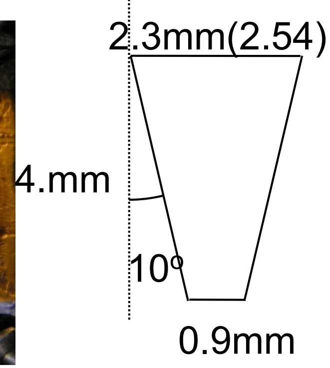
  1.6 w/o LG,   3.7 w/ LG

  X5 (if n=1.05,4cm)
  X2 (if polished LG)

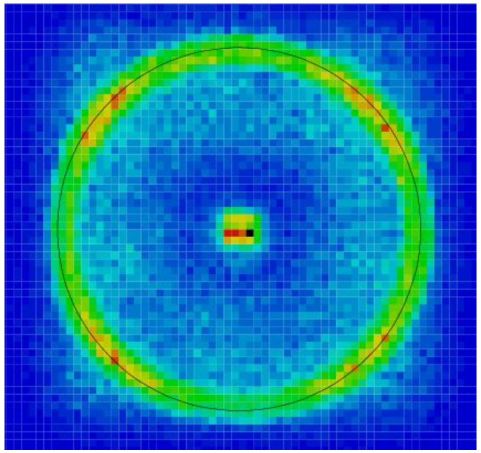
Npe~37 w/ LG ?!!!



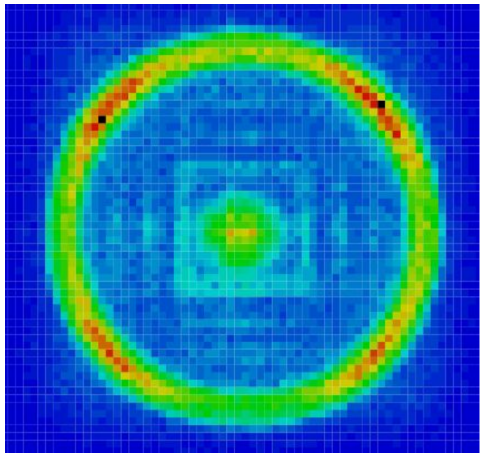




w/o LG



w/ LG



Summary

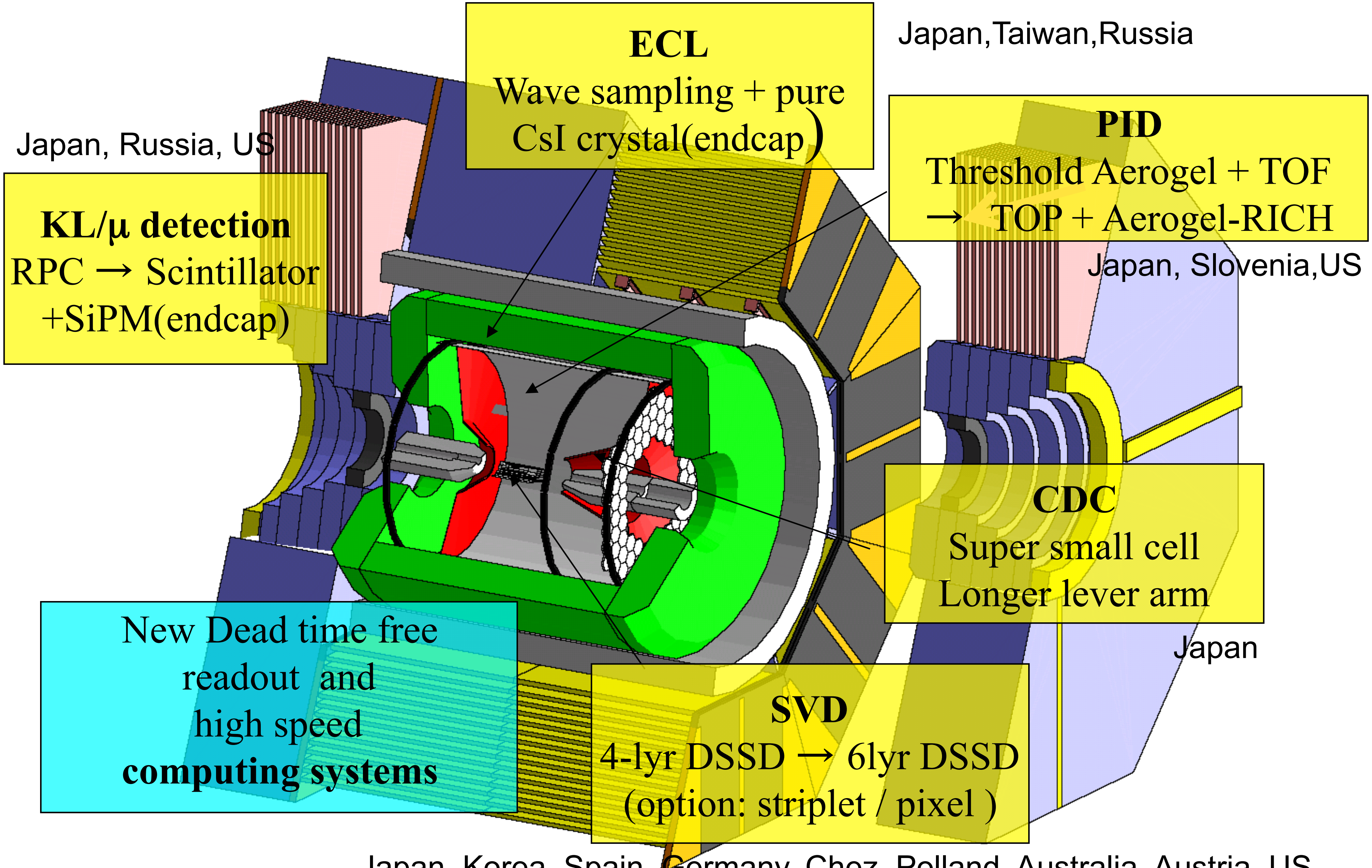
- Belle II employs RICH detectors to improve PID (K/π in GeV region);
  - TOP counter w/ focusing for barrel
  - Proximity focusing aerogel RICH for forward-endcap.
- Novel ideas are employed to overcome the performance limitation;
  - TOP w/ focusing → Chromatic dispersion
  - A-RICH w/ multiple radiators → Emission point uncertainty.
- New multi-pixel photodetectors have been developed;
  - MCP-PMT for TOP
  - HAPD for A-RICH
- R&Ds are nearly completion, and designs are being finalized.
- Production of components (photodetectors, radiators etc.) are starting.

Stay Tuned !

Backup Slides

Belle Upgrade

Better background tolerance
Better performance



Readout Electronics

Hawaii

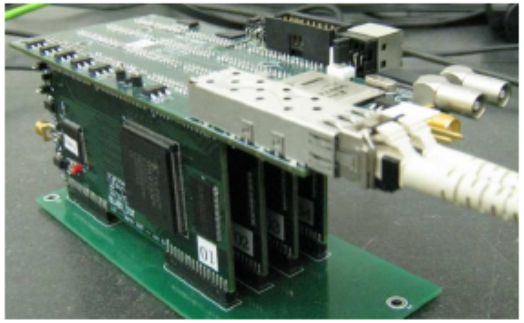
- Highly integrated readout
- <u>High-speed waveform sampling</u>

BLAB2 ASIC works fine.
12ps timing resolution
→BLAB3 ASIC
Higher sampling rate
Lower noise
→Better time resol.

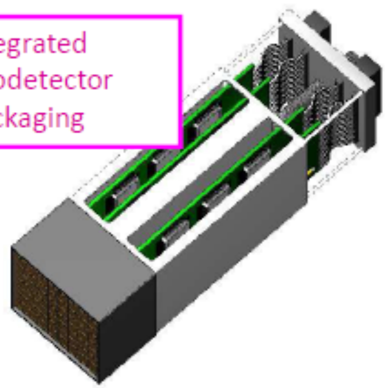
- **Buffered LABRADOR**

TABLE II: *BLAB2 ASIC Specifications.*

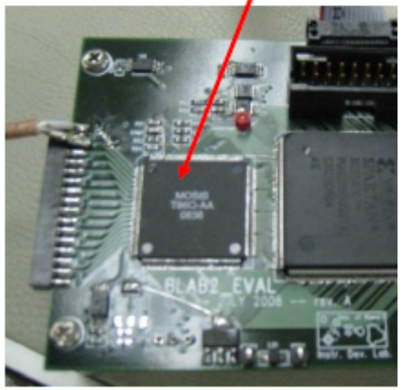
Item	*Value*
Photodetector Input Channels	16
Linear sampling arrays/channel	~~2~~ 6
Storage cells/linear array	~~512~~ 1024
Sampling speed (Giga-samples/s)	2.0 - 10.0
Outputs (Wilkinson)	32



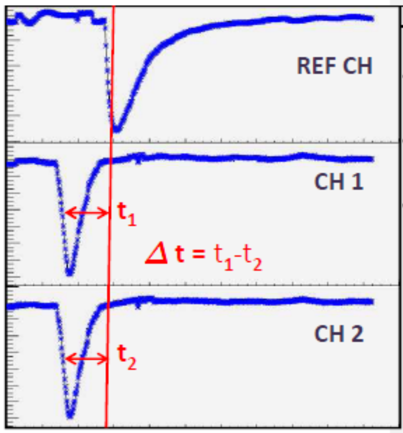
Integrated Photodetector packaging

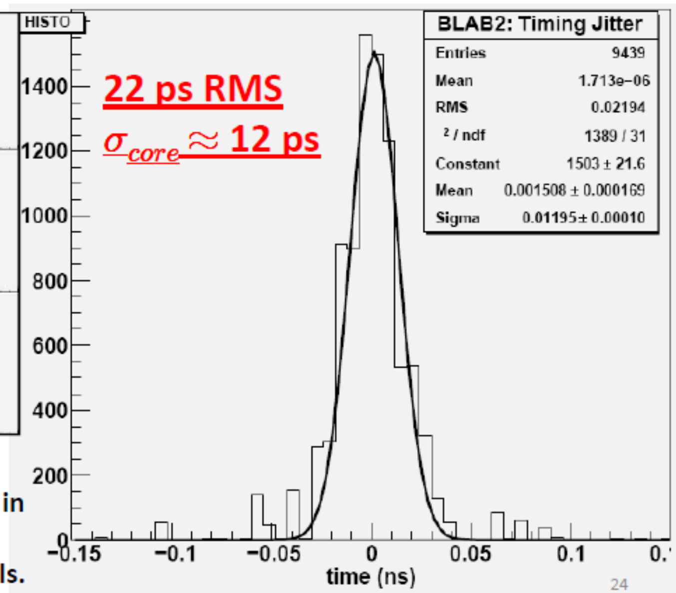


BLAB2 ASIC



Measured timing jitter between two channels (same BLAB2).



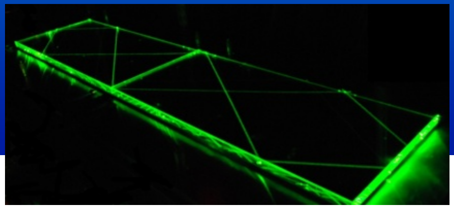


→Good timing calibration is vital! Ongoing improvements in calibration procedures may improve this result, reduce tails.

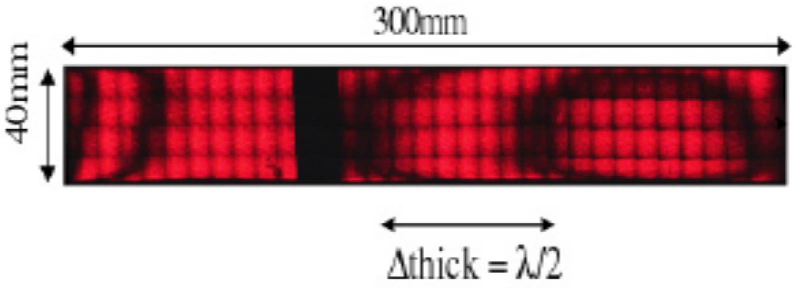
BLAB2 ASICs recently received: now being tes

Oscilloscope in ASIC !

Quartz bars / Mirrors

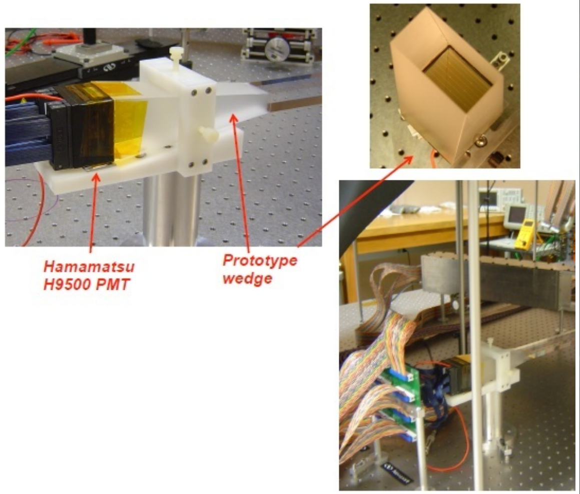


- Required specifications;
  - Synthetic fused silica (ex; Corning 7980, Shin-etsu Sprasil)
  - Index tolerance: ±0.001
  - Flatness: 10λ over full aperture
  - Roughness (r.m.s.): 5 Å
  - Angle bet. planes: 90±1/60deg.
  - Chamfer: < 0.20mm



- Candidate providers;
  - Okamoto Optics (Japan)
  - Zygo, OSI, … (US)

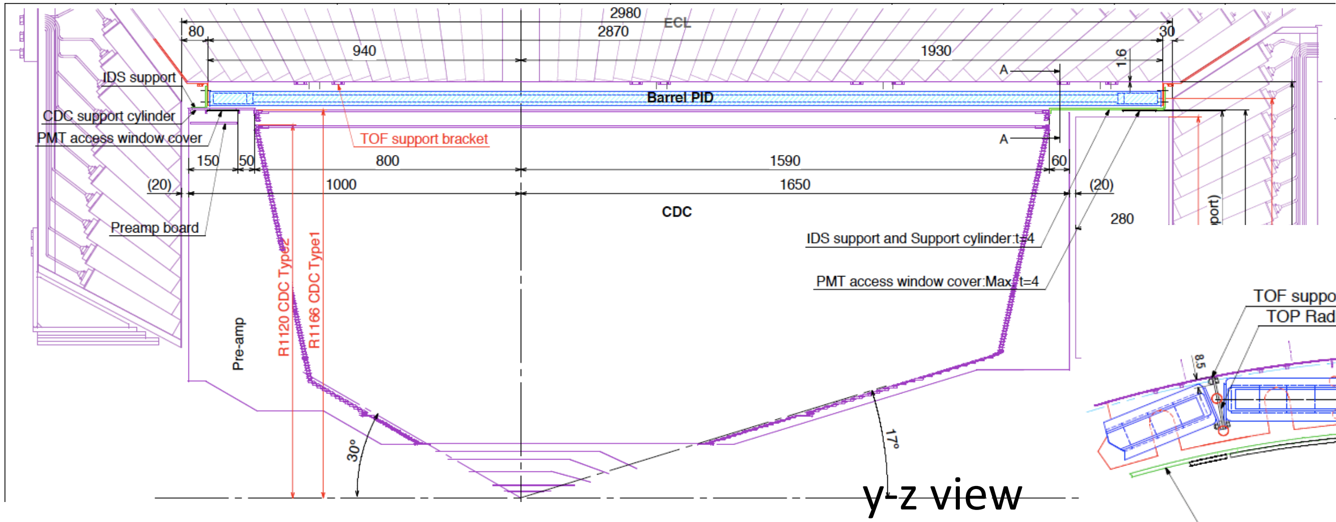
  (probably) need two providers
  for in-time construction.



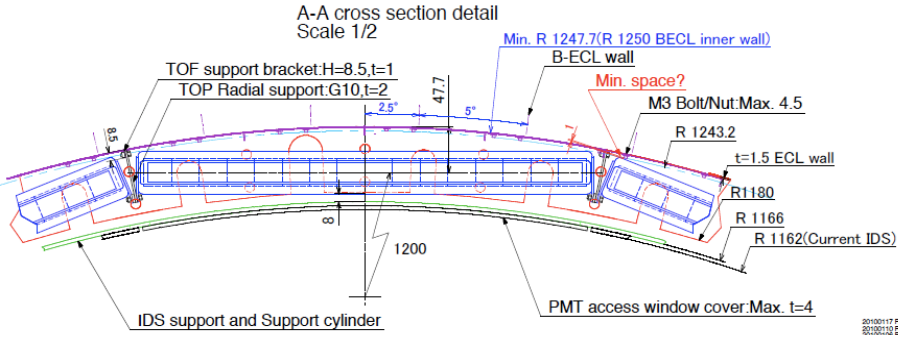
Nagoya, Cincinnati
Consultation to SLAC.

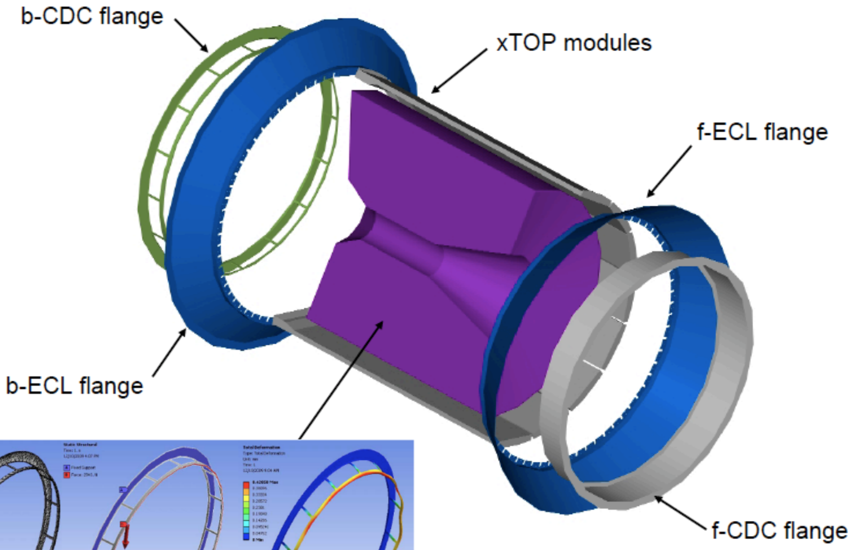
Structure designing

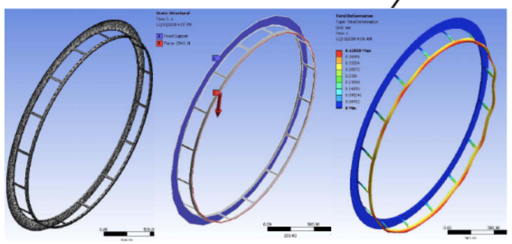
Nagoya, Hawaii, KEK



Mechanical Drawings
Boundary to CDC/ECL





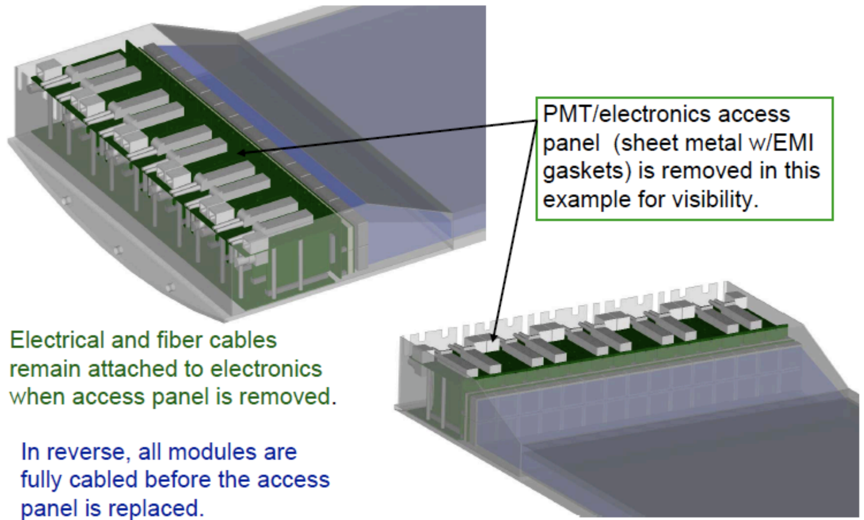


Φ2470 x 201mm wide
Mass = 21.53kg
6mm thick aluminum

Fixed support at the bECL contact surface.
Applied force = 2.94kN

Max deflection ~430μm
Max stress ~38.2MPa

Structural Analysis



PMT Housing