Development of a 144-channel HAPD for Belle II Aerogel RICH

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KEK

NDIP 14 @ Tours

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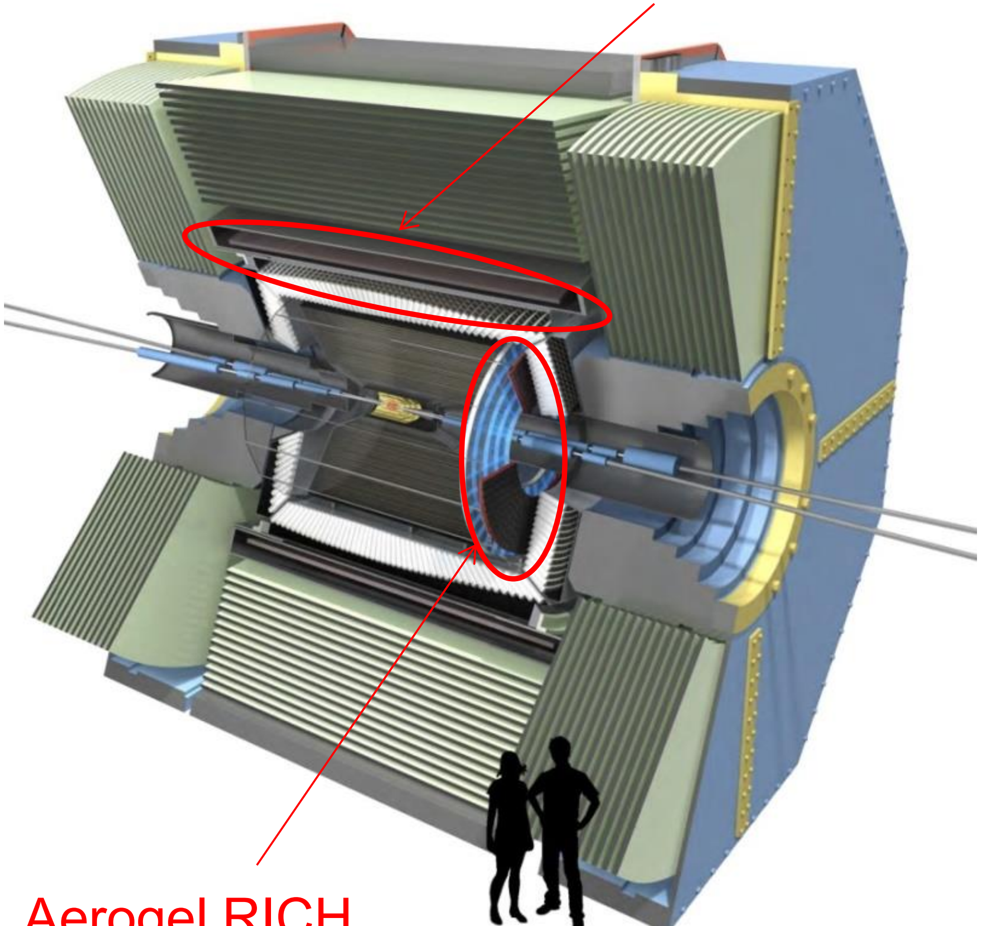
(Belle II Aerogel RICH Group)

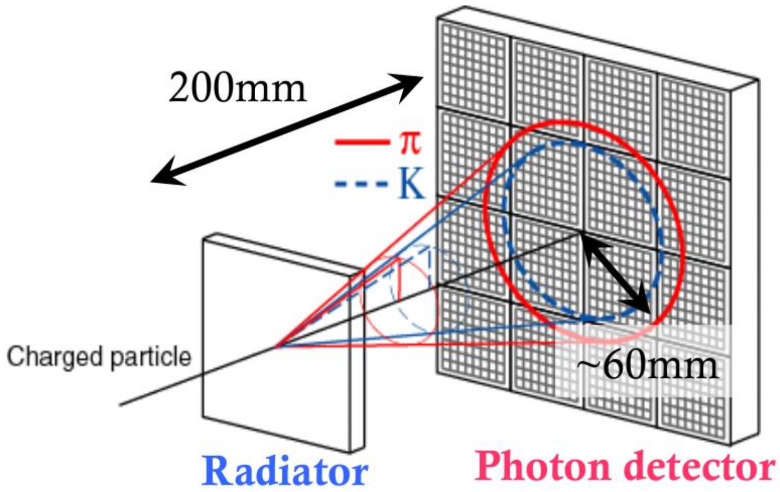
Belle II Experiment

Belle II Experiment



- KEKB / Belle : B factory experiment @ KEK (1999-2010)
  - ✓ Asymmetric e^+-e^- collider
  - ✓ World highest luminosity (2.11×10^{34} cm^{-2} s^{-1}).
  - ✓ Discovery of CP Violation in B system.
- Upgrade to SuperKEKB and Belle II.
  - ✓ 40 times higher luminosity, aiming at 50 ab^{-1}.
  - ✓ Search and study of New Physics.
  - ✓ Commissioning starts in 2015.
- Particle identification (K/π separation) is a key issue.
  - ✓ e.g. $B \to \rho\gamma$ v.s. $K^*\gamma$
  - ✓ TOP and Aerogel RICH.

Aerogel RICH



$$m = p\sqrt{n^2\cos^2\theta_c - 1}$$

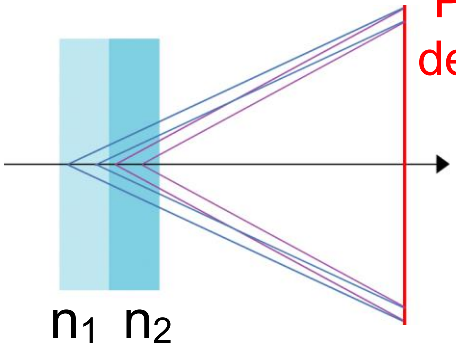
$$\theta_C(\pi) - \theta_C(K) \simeq 23 \text{ mrad}$$

(@ 4 GeV; n = 1.05)

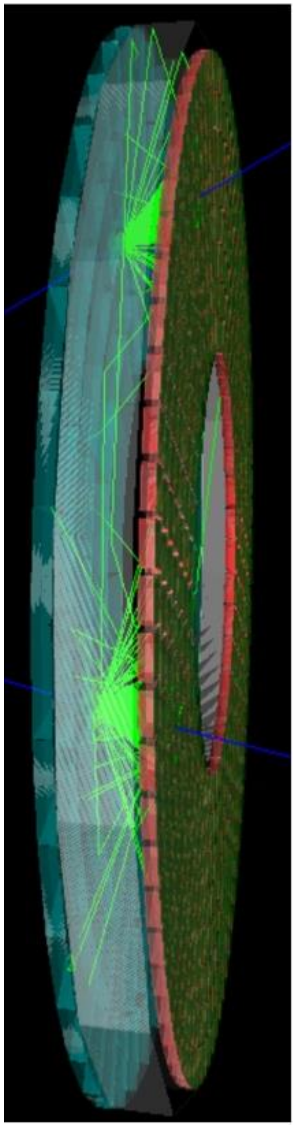
- target: π/K separation up to ~4GeV.
- Replace threshold-type PID device at Belle.

Aerogel

Focusing Scheme



- 2-layer (2cm+2cm) aerogel tiles.
- $n_1<n_2$: focusing (n_1=1.045, n_2=1.055).
- High transmission length (40-60mm) required.

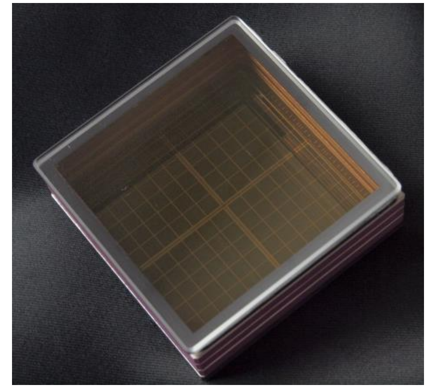


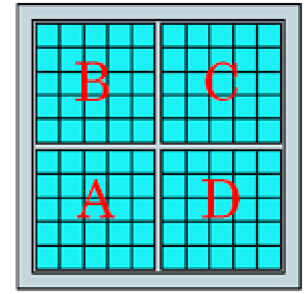
HAPD

Photo-detector

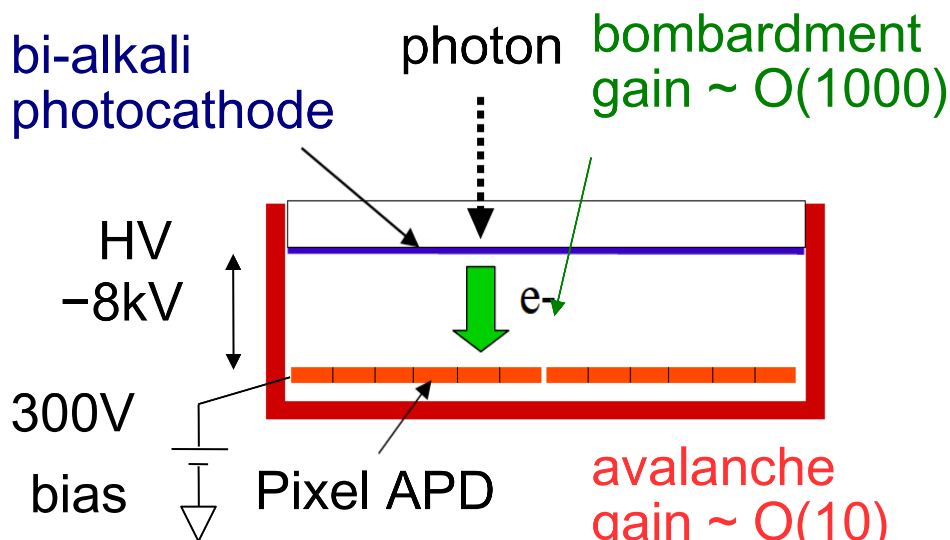
- ~5mm pixel size. Large coverage.
- Immune to 1.5T magnetic field.
- Radiation tolerance (neutron, gamma).

⇨ HAPD (Hybrid Avalanche Photo-Detector)





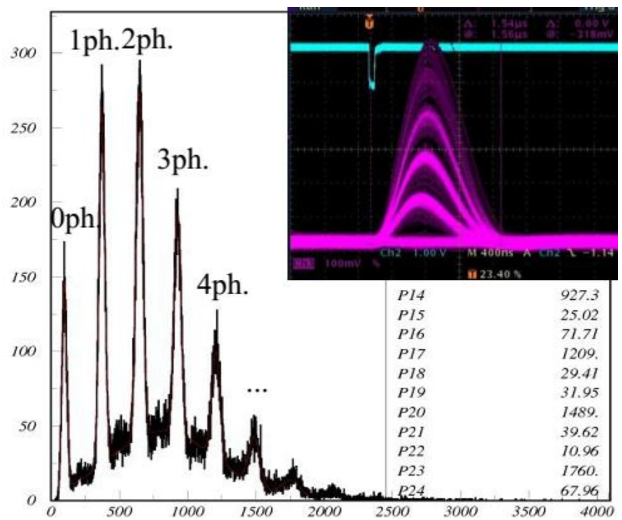
□4.9 [mm]

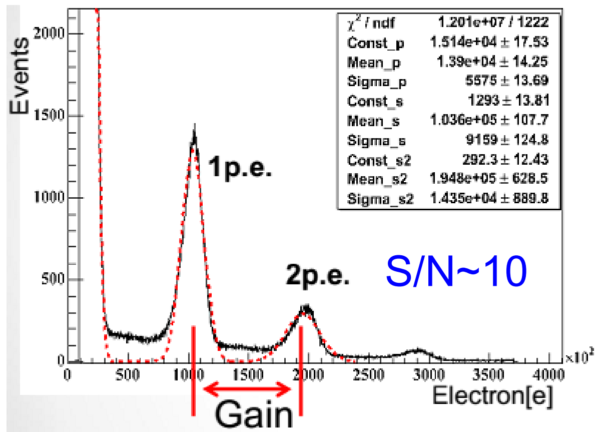


- Developed with Hamamatsu Photonics.
- 144 channels (36-ch APD chip × 4).
- Gain ≥45000.
- Peak QE ~28%
- Size 73mm × 73mm.
- Effective area 63mm × 63mm (65%).

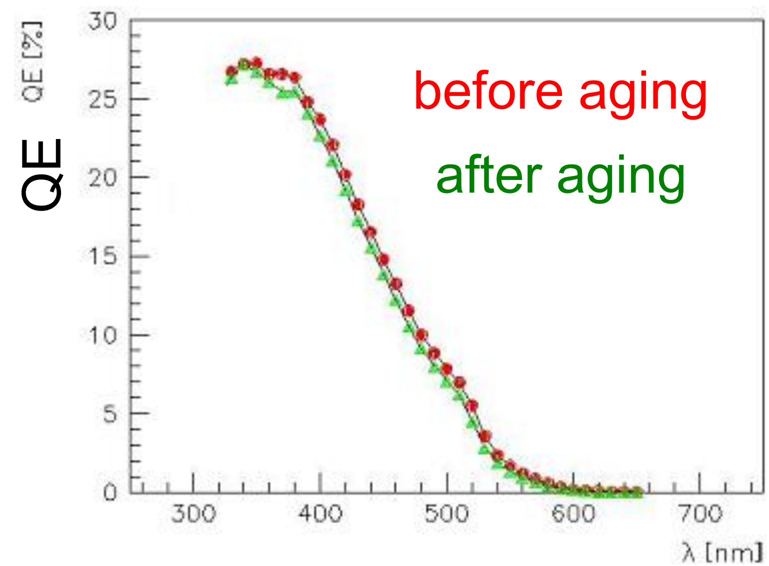
Total 420 HAPDs

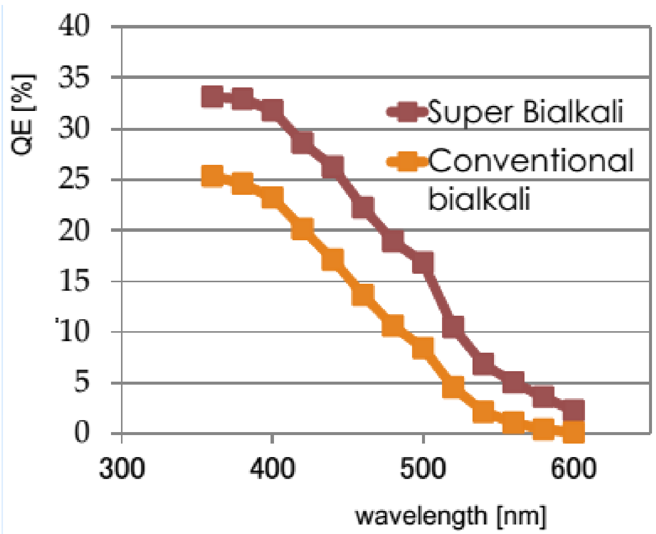
HAPD





Aging test at IJS
20 years of Belle II operation

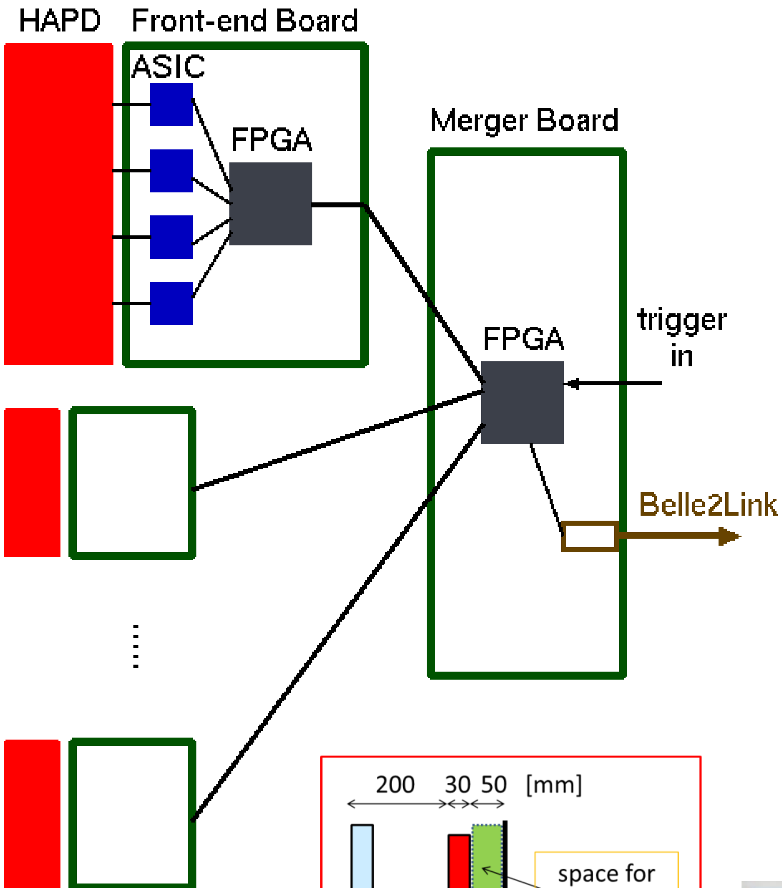




QE increased by super bialkali photocathode (25%→ 35%)

- Lifetime test is also performed at HPK (70mC [~10y Belle II] in 1000h)
  - ✓ No change in QE, bombardment/avalanche gain.
  - ✓ Minor increase in leakage current

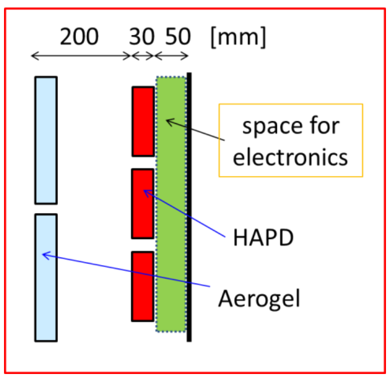
Electronics



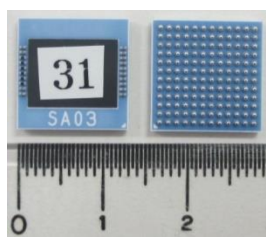
- Total 60000 channels.
  - ✓ 1-bit ON/OFF information
- High-gain, low-noise.
- Only 5 cm available behind HAPD

➡ ASIC (SA03)

- CMOS 0.35 μm process @ X-FAB.
- 36 ch / chip (i.e. 4 ASIC for one HAPD).
- Pre-amplifier + shaper + comparator.
- Typical peaking time ~100ns

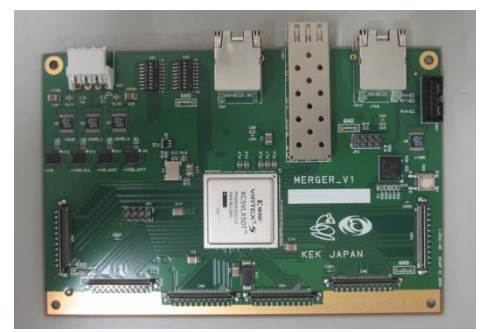


ASIC (SA03)



Front-end Board

Merger Board

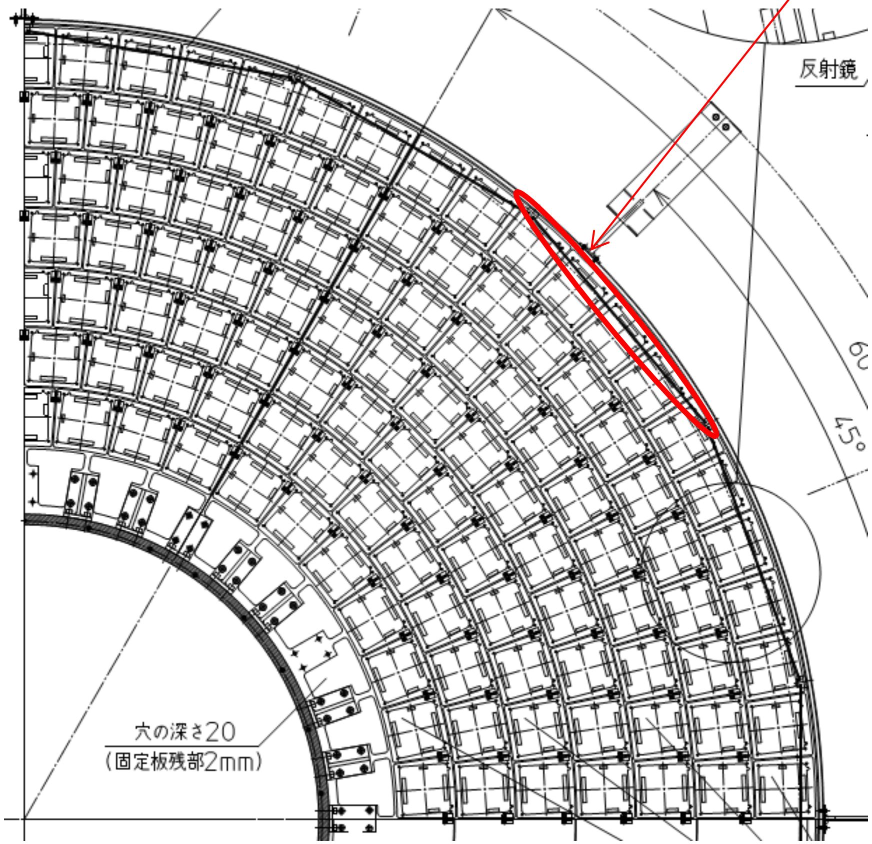


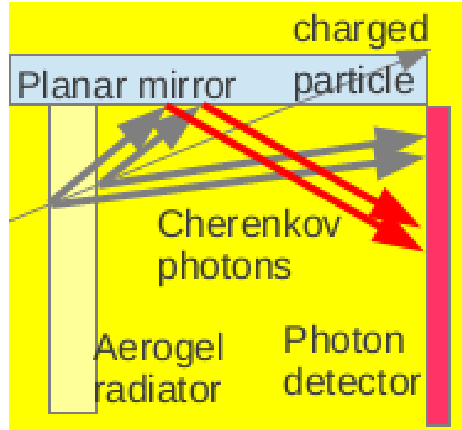
Aerogel RICH

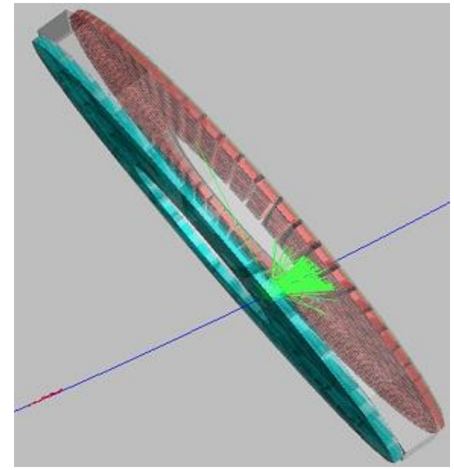
Aerogel RICH detector consists of

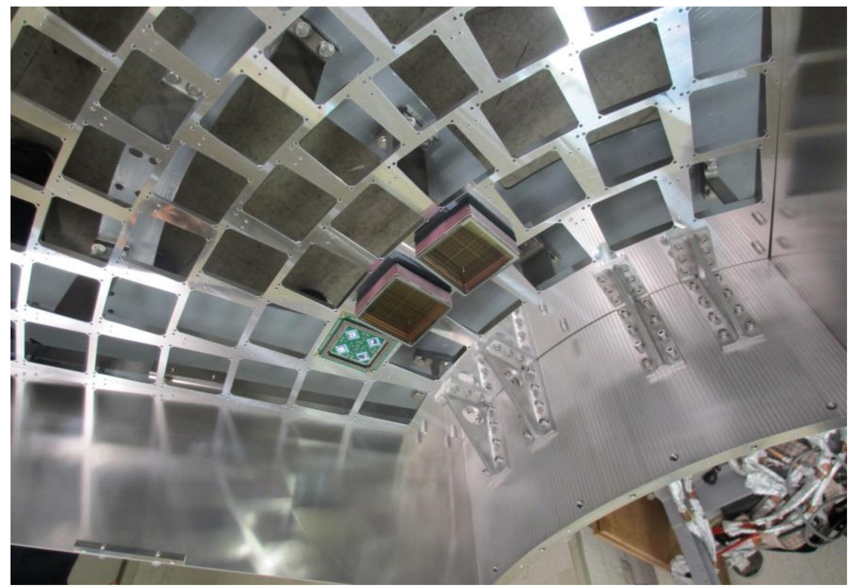
- 420 HAPD
- 248 Aerogel Tiles

Mirror









HAPD: 8 rings → 7 rings

Radiation

Radiation Tolerance was a concern for HAPD

[ ] : original estimation for 10 years operation of Belle II

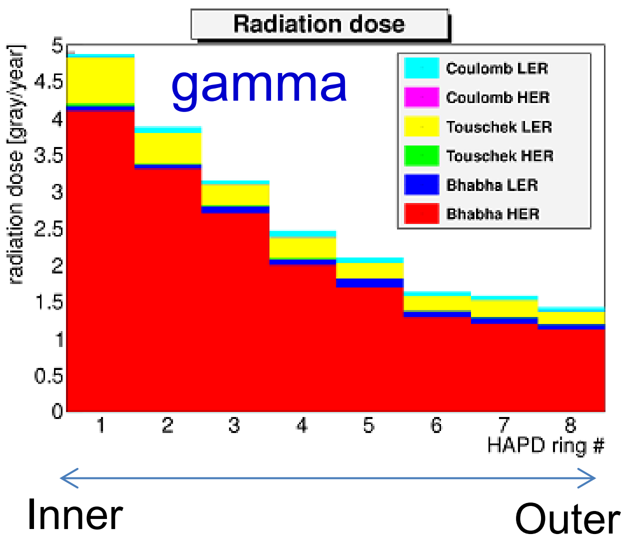
- **Neutron** : [10^{12} n/cm^2 (1MeV equiv.)]
  - ✓ lattice defects → leakage current, worse S/N.
- **Gamma** : [1000 Gy]
  - ✓ surface effect (charge-up) → breakdown

Details were discussed at

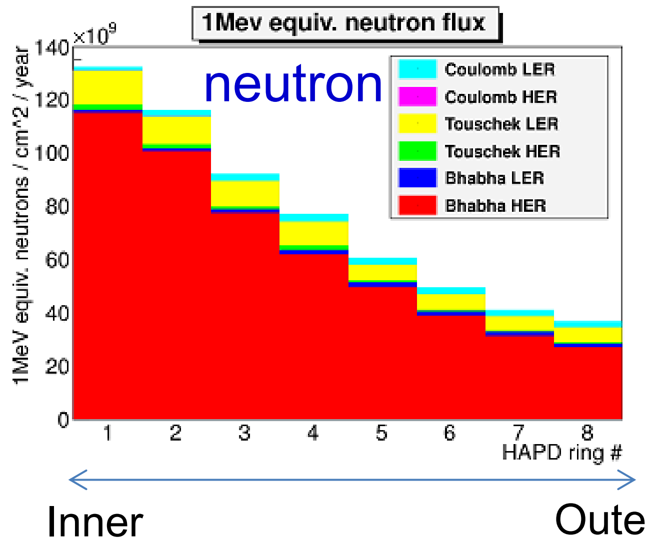
NDIP11 K.Hara (ID-161) "Study of 144-channel Hybrid Avalanche Photo Avalanche Photo-Detector for Belle II RICH Counter"

Irradiation test of the HAPD was done up to 1000 Gy and 2×10^{12} n/cm^2.

Simulation (with 8 HAPD rings)



< 50 Gy (10years)



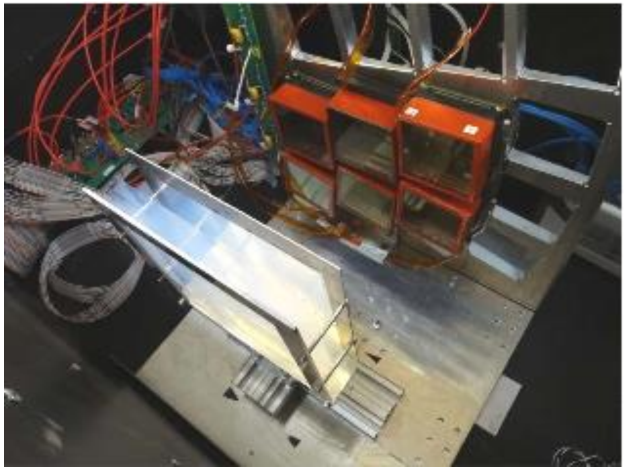
< 1.3×10^{12} n/cm^2 (10years)

Remove innermost HAPD layer and replace it with neutron shield. Neutron can be reduced to

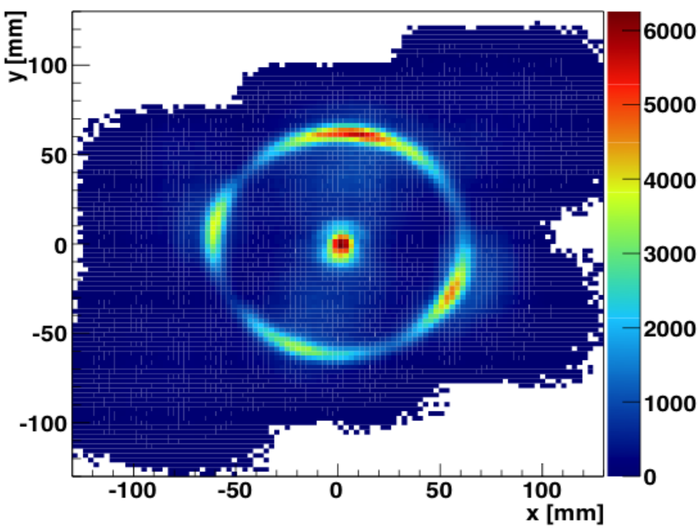
< 0.4×10^{12} n/cm^2.

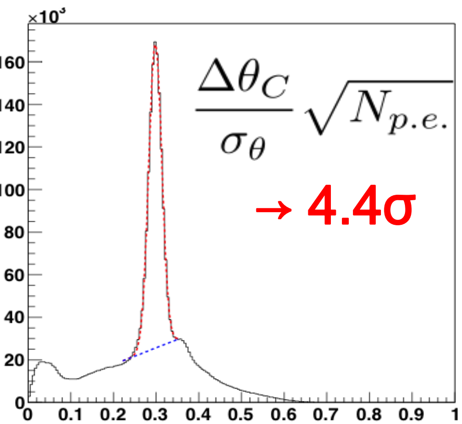
Prototype Beam Test

Beam test at DESY (2013) using prototype Aerogel RICH.

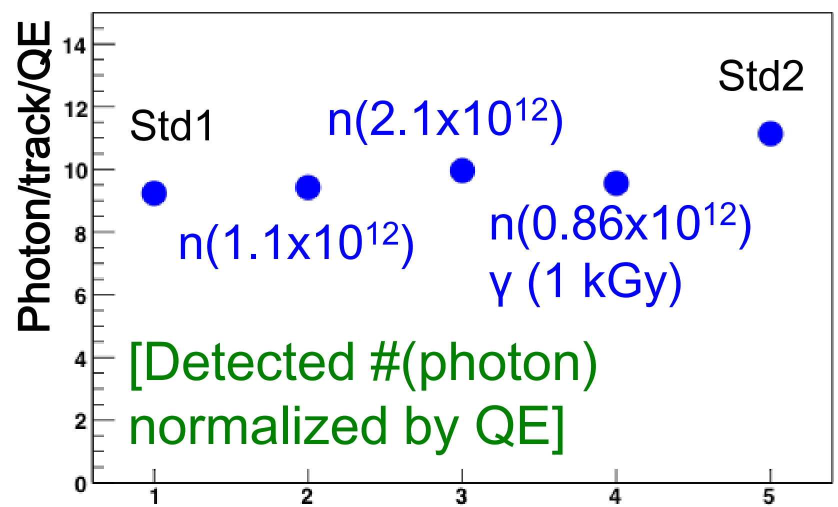


- 2 ×3 HAPD configurations (part of the actual layout).
- Front-end board with ASIC (close to final).
- During the test, HAPD is replaced with the one irradiated to neutrons and/or gamma.
  - ✓ No degradation of the number of photons
  - ✓ No significant performance degradation is expected for the predicted radiation.



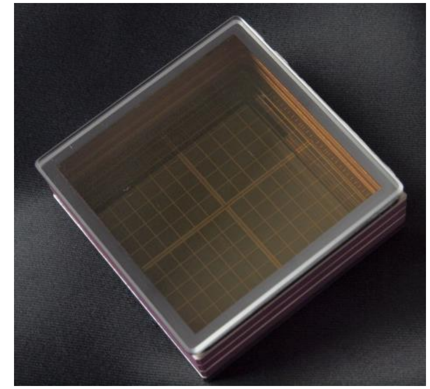


σ = 15.4 mrad
photon/track: 8.6



HAPD Mass Production

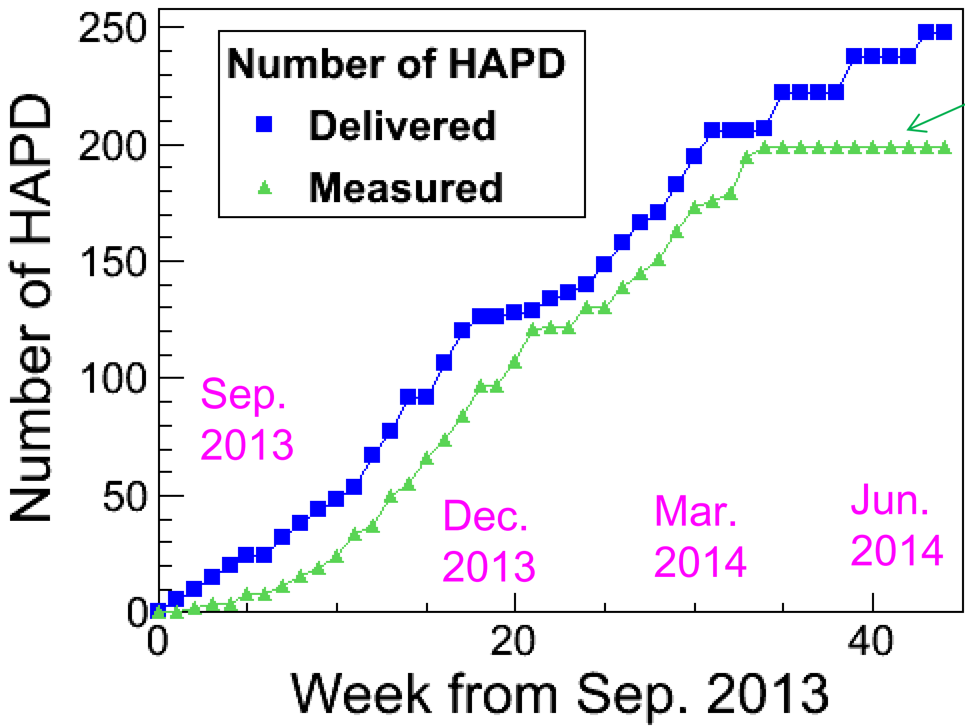
- 420 HAPDs are used in Aerogel RICH.
- The mass production started in Sep. 2013.
- Measurement (quality assessment) is performed at KEK
  - ✓ Leakage current.
  - ✓ Noise, S/N.
  - ✓ 2D hit map.
  - ✓ QE.



<Specification>

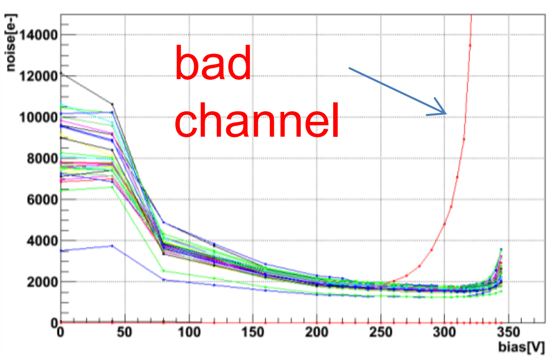
Item	Standard	Allowed	
QE	28%	>24%	
Leakage Current¶		<1uA	per channel
Avalanche Gain¶	40	>30	
Electron Bombardment Gain	1800	>1500	
Total Gain	~70000	>45000	
Number of Bad Channels		≦10	bad: ¶ not satisfied

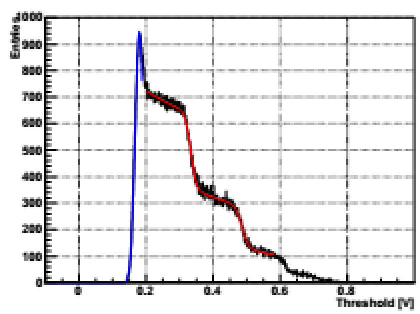
HAPD Mass Production



A part of measurement system is in trouble. Under recovery.

- Mass production started in Sep. 2013.
- Original plan
  - ✓ Finish in Sep. 2014.
  - ✓ 35 HAPDs per month.
- However, the production is delayed.
  - ✓ Low yield at HPK, especially around Dec. 2013.
  - ✓ Tentative plan: 27 HAPDs per month to complete production in Mar. 2015.

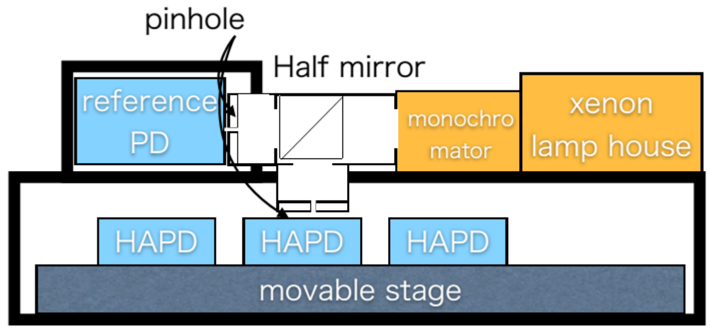


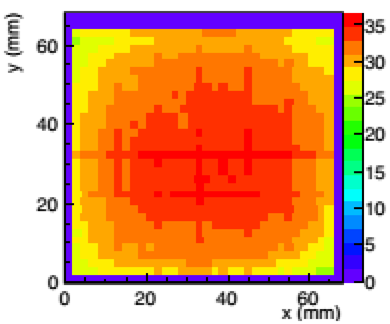


V(threshold)

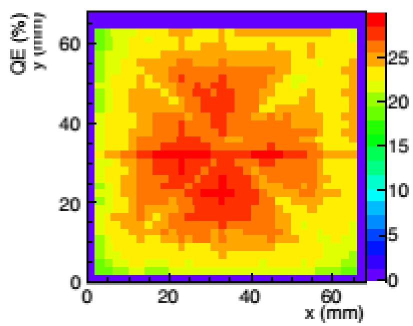
Quantum Efficiency

- High QE is essential to get high performance.
- Measure photo-current with light from Xe lamp.
- Scan over the photo-cathode (spot size < 1mm).
- In general, good agreement btw KEK and HPK. Some deviation when compared individually.
  - ✓ HPK irradiates light to the whole region.
- Some structures are sometimes observed in QE.
- QE is increasing as production proceeds.
  - ✓ Last year 20-30%; Now 25-35% at HPK.

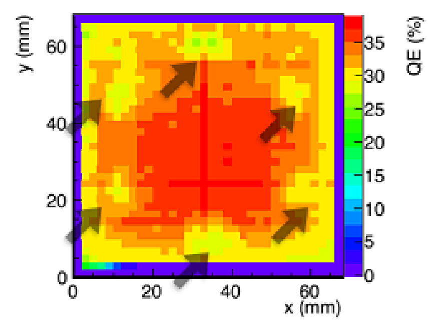




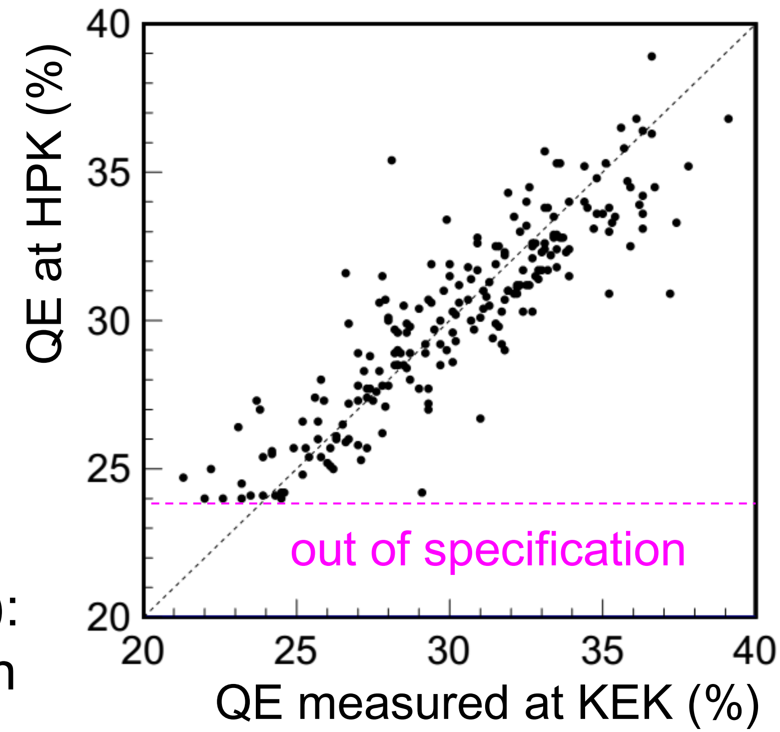
Normal



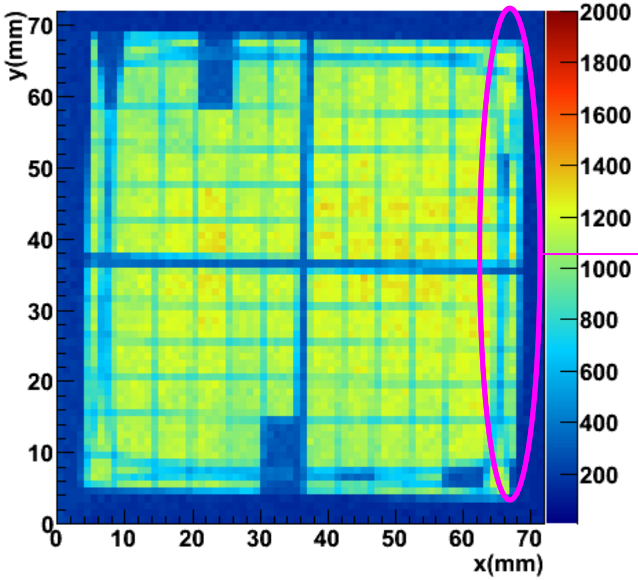
Cross (reason unknown)



Low spot (arrow): metal is found on quartz window

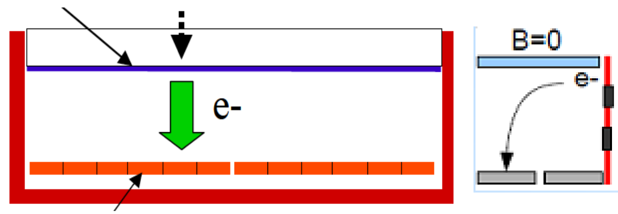


2D Hit Distribution

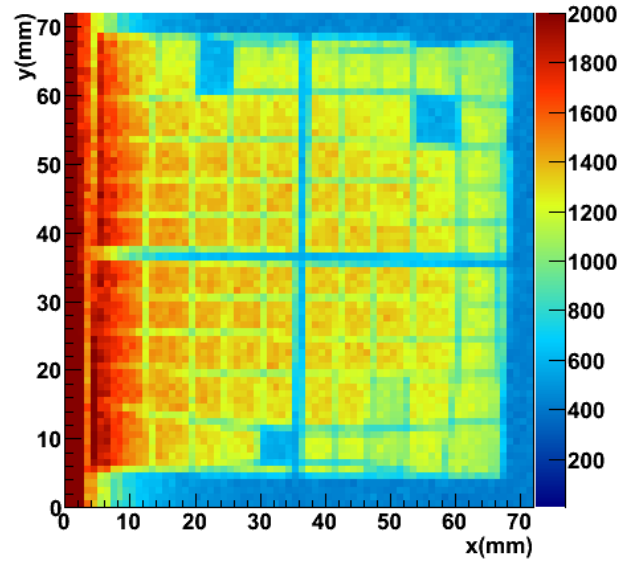


- Single photon response.
- Scan by moving the laser position and measure the hit distribution.

Effect of the distortion of the electric field.
Will disappear under magnetic field.



- In around 10% of HAPDs, a region with high noise is observed (HAPD-dependent, reproduceable)
- It is turned out that the noise is due to instability of HAPD after the exposure to light.
- Time to stabilize is O(10) min (sometimes > 2h).
- Under investigation, but no problem to use in Aerogel RICH.

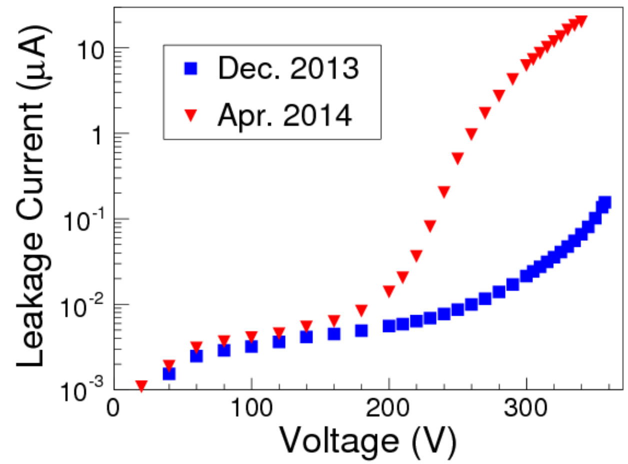


scan direction

Leakage Current Problem

- Several HAPDs show rather large leakage current (>1μA), even though they passed the pre-measurement at HPK.
- There is one sample, for which the leakage current increased more than three months after production.
- According to the investigation at HPK, light emission is observed for such a sample, and small object is sometimes observed in the corresponding location.
- However, the reason is not understood (especially why the problem happens after production).
- Plan to measure the leakage current for all the samples again.

(Chip Current)



HAPD Mass Production

Status of Quality Assessment.

	Number
Qualified	150
Low Quality	26
Need Investigation	14
Investigation at HPK	4
NG (Broken etc.)	6
Total	200

Low Quality: Mainly large leakage current (~μA) (usable at this stage, but worry in long term operation)

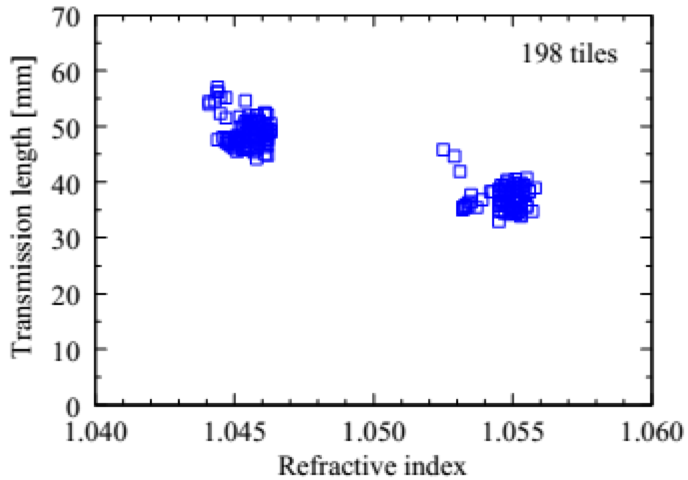
Need Investigation: Noisy samples etc. (4 of them are already repaired)

Investigation at HPK, NG (Broken etc.): Mostly problem in leakage current.

- Leakage current is an issue.
  - ✓ Improvement in the production at HPK is desired.

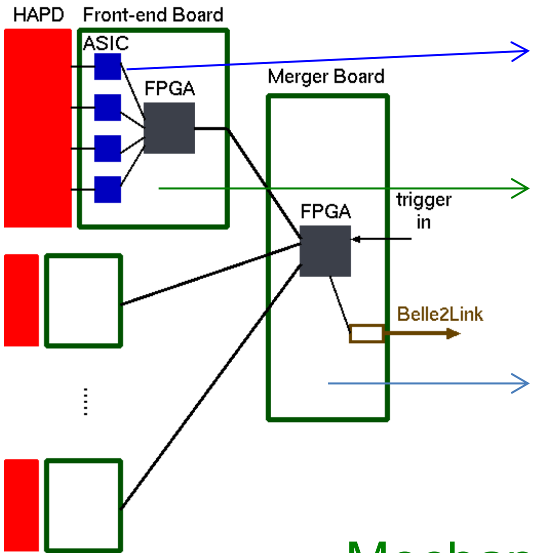
Status of Other Components

Aerogel



- The production of aerogel tiles (248 + spare) is completed.
  - ✓ Measurement of optical property is in progress.
  - ✓ Manufacturing (cut by water jet) will be done.

Electronics



- Mass production of ASIC is done.
  - ✓ Now under test.
- Final version of the Front-end board is designed and is being tested.
  - ✓ Mass production in autumn.
- Final version of the merger is under test.

Mechanical structure will be ready within this year.

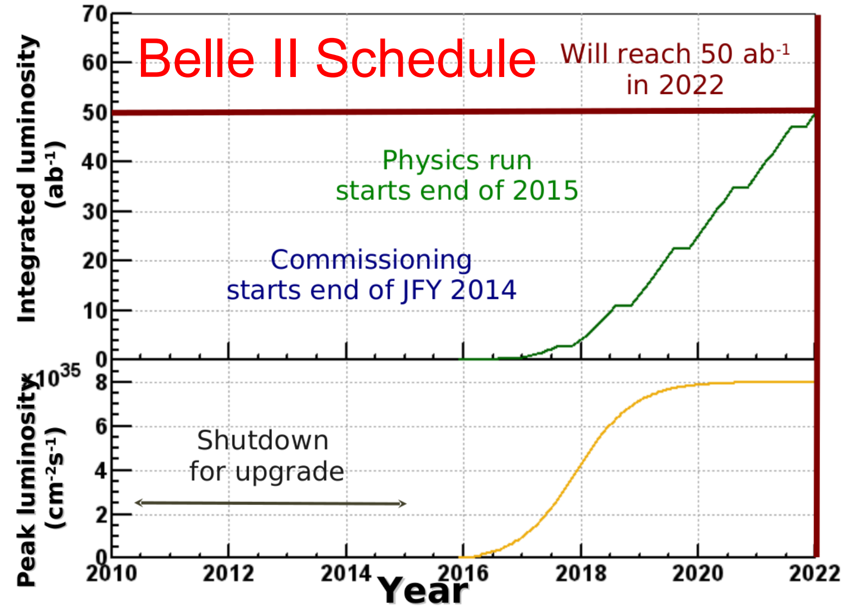
Summary and Schedule

- We are constructing Aerogel RICH Counter for the Belle II forward PID.
    - ✓ 2-layer aerogel (n=1.045 & 1.055).
    - ✓ 144 channel Hybrid Avalanche Photo-Detector (HAPD).
    - ✓ Readout electronics based on the ASIC.
- There had been an issue of the radiation hardness, but it is solved.
    - ✓ Specification determined. More understanding with simulation.

- Mass Production of HAPD started.
    - ✓ Leakage current is an issue.

Schedule

- HAPD mass production will finish around Mar. 2015.
- Other components mostly within 2014
    - ✓ Start constructing the detector from 2015.
- Complete the construction around July 2015. Installation in summer.



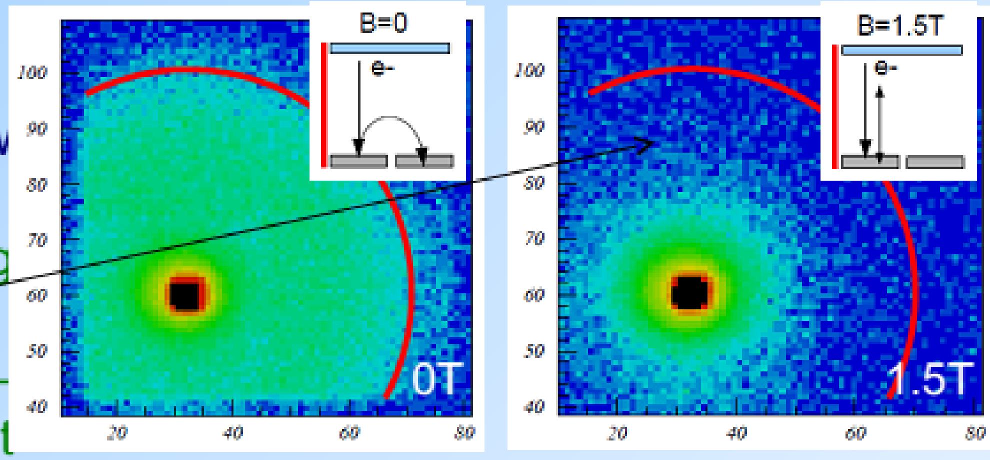
more than 6 months delay

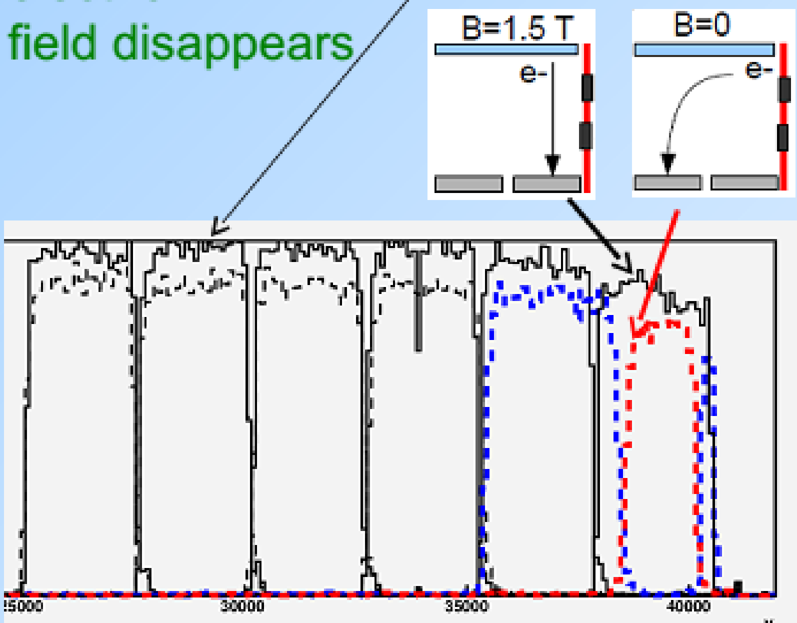
Backup

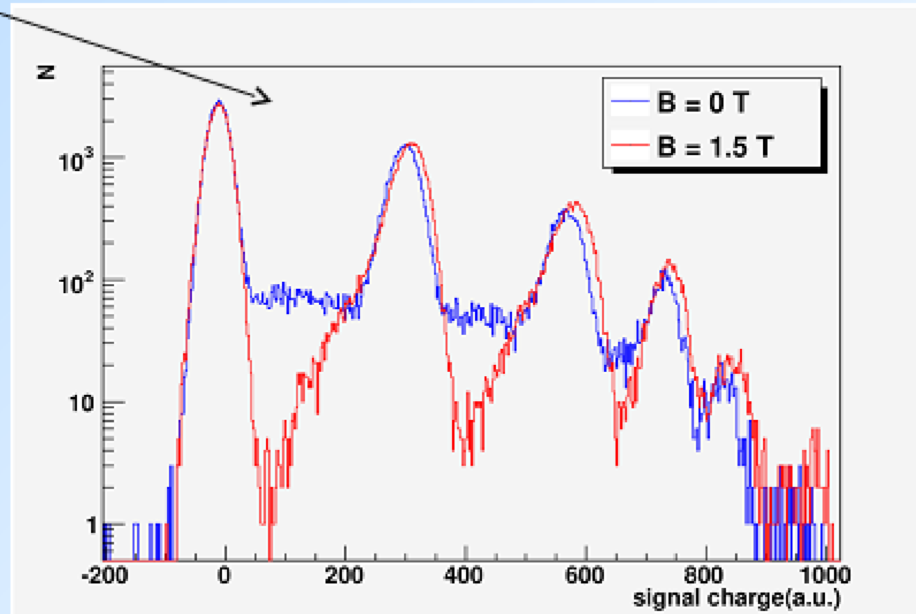
HAPD: operation in 1.5 T

Tests in 1.5 T magnetic field show improved HAPD performance:

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



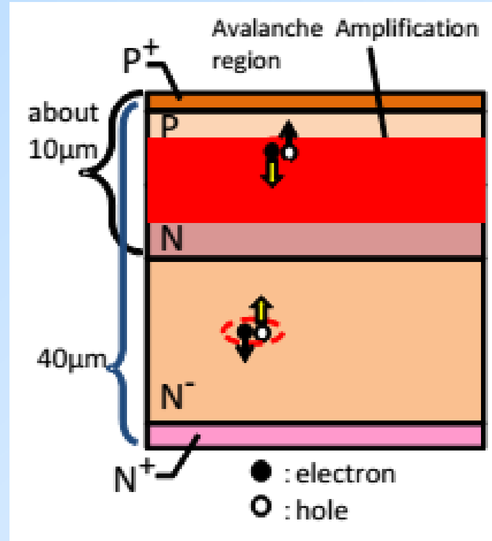


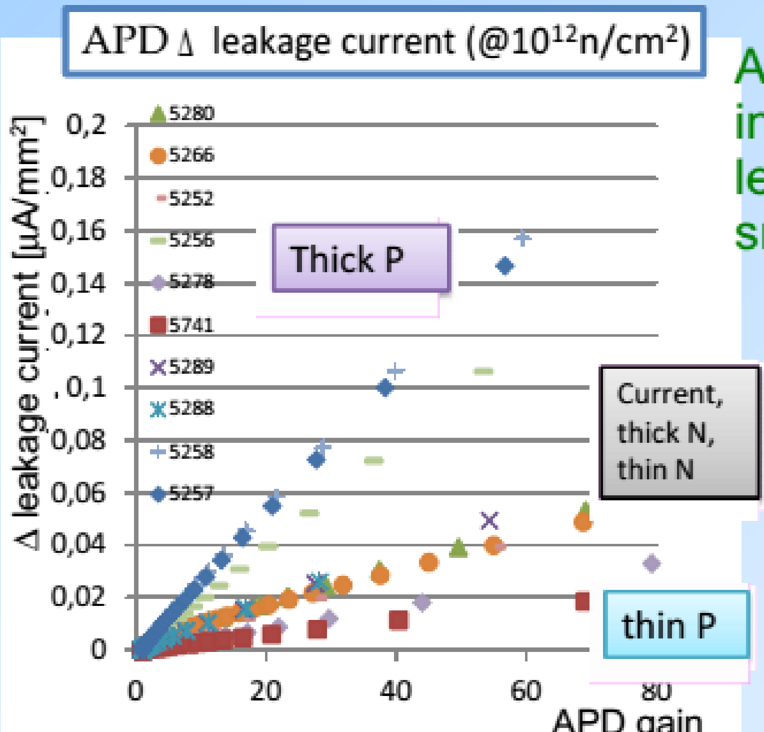


Neutron damage

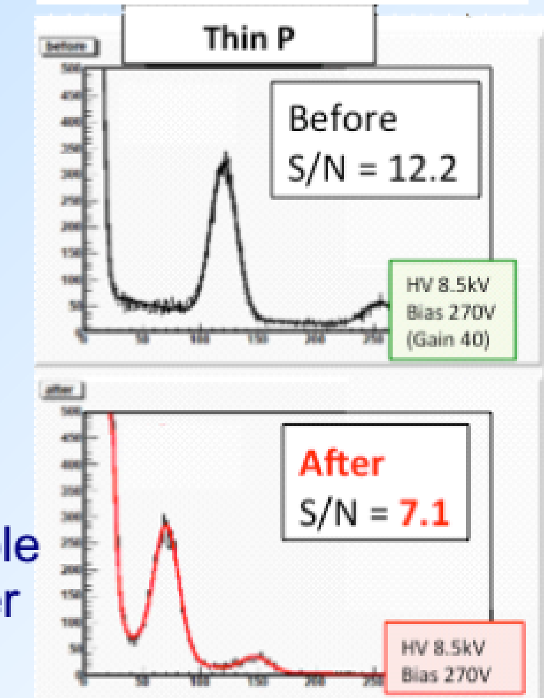
Modification of APD structure:

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





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



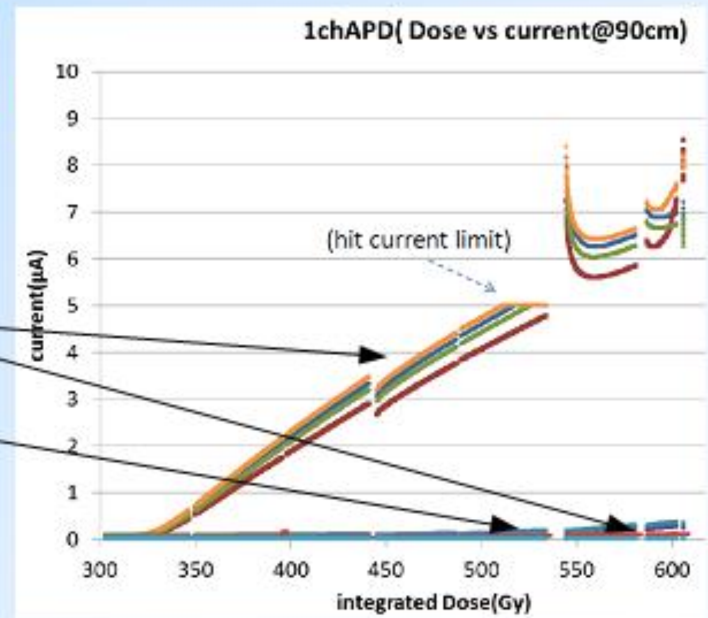
S/N for thin p sample is better than 7 after fluence 10^{12}n/cm²

Gamma irradiation

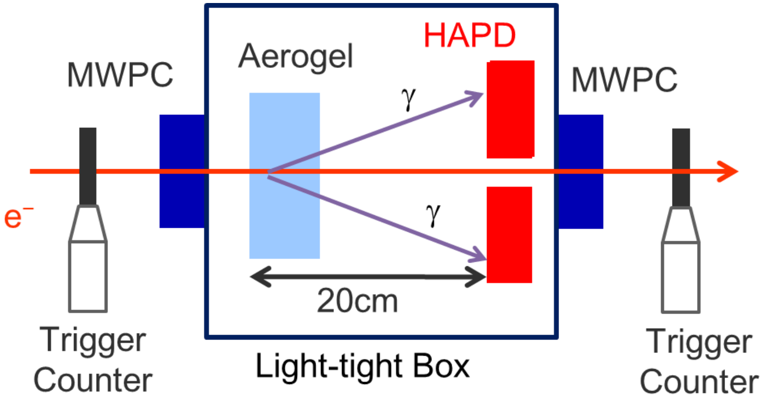
- Expected total dose 100-1000 Gy
- Initial tests indicated fast raise of leakage current and reduction of breakdown voltage – not previously observed with similar APDs
- Possible source: APD for HAPD had additional alkali protection layer to protect APD during photocathode activation process
- To identify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

→ APD structure was optimized

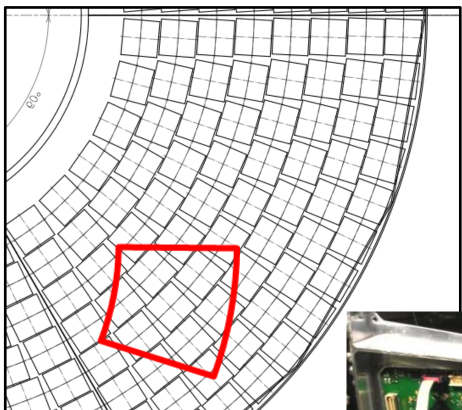
^{60}Co irradiation facility @ Nagoya U.



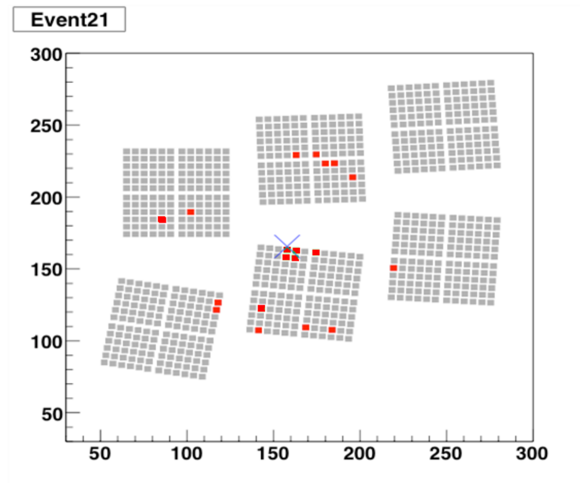
Beam Test with Prototype ARICH

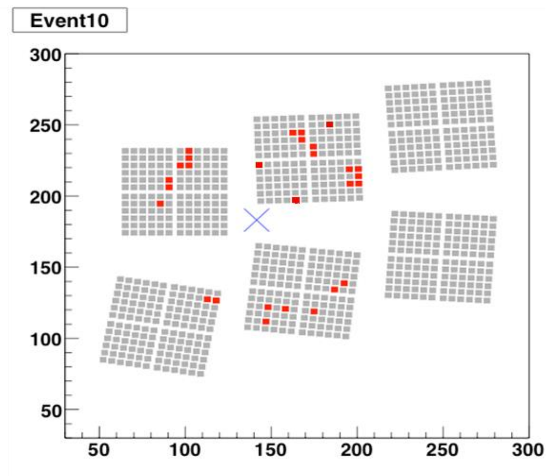


- 2-layer aerogel & 2 × 3 HAPD configurations
- Front-end board with ASIC (close to final).
- Study items:
  - ✓ System test with the latest electronics.
  - ✓ Aerogel Study.
  - ✓ Effect of radiation.

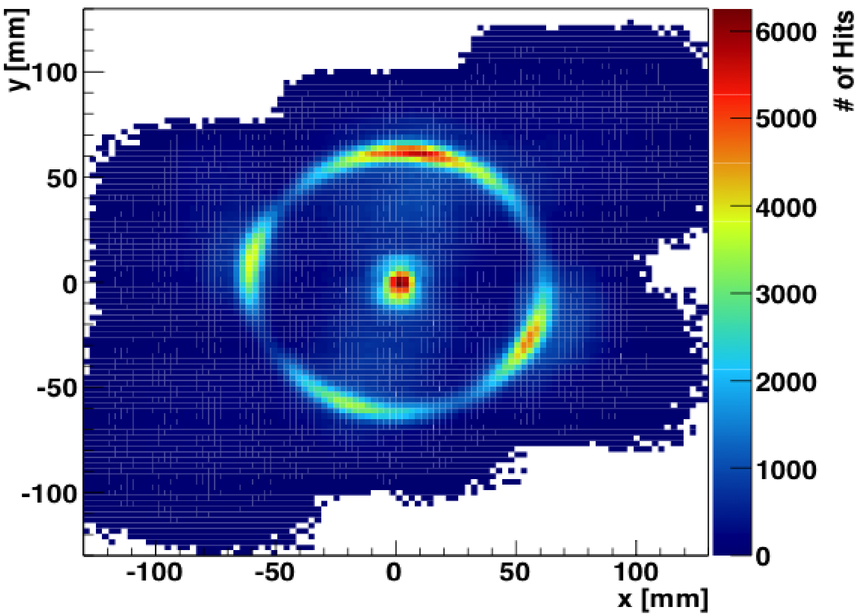


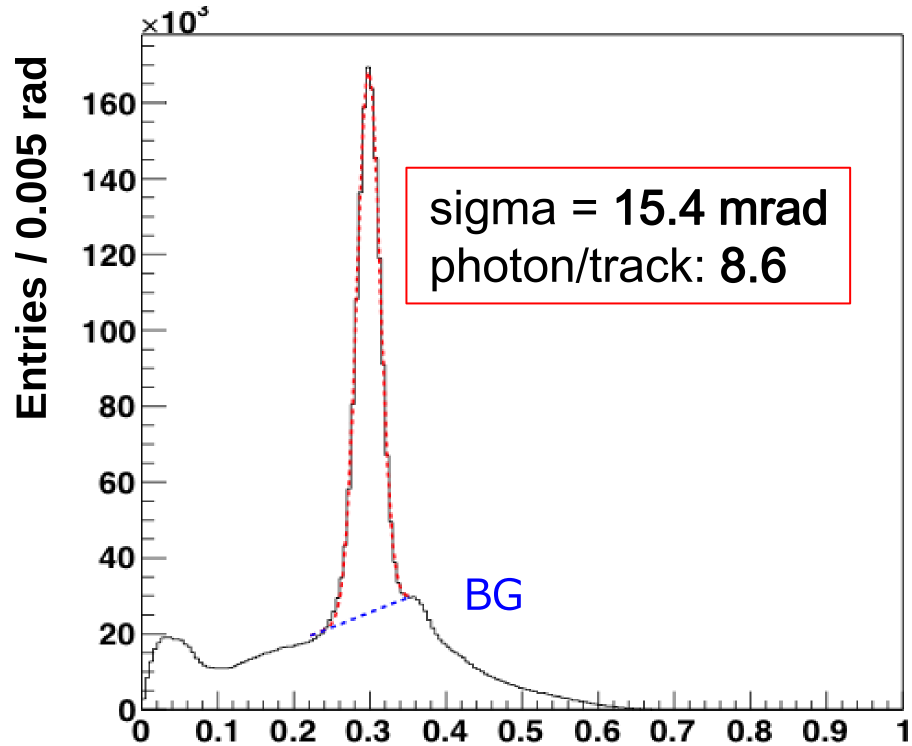
Event Display





Accumulated hits





Naïve estimate from accumulate hits.

$$\frac{\Delta\theta_C}{\sigma_\theta}\sqrt{N_{p.e.}} \Rightarrow \mathbf{4.4\sigma}$$

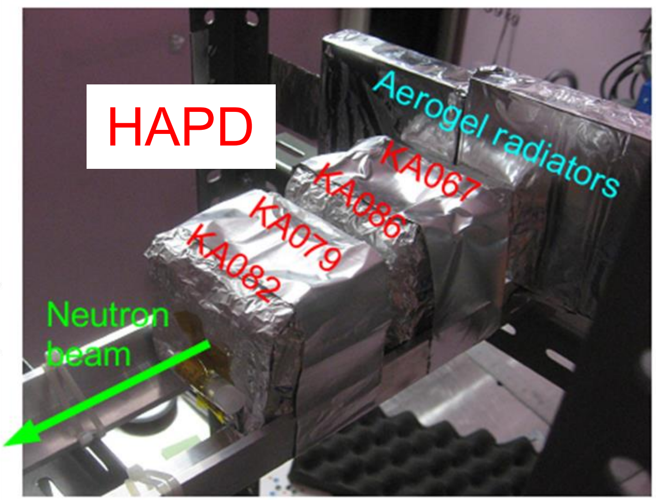
Performance with Irradiated HAPDs

One issue of the HAPDs has been the radiation tolerance.

→ Check the performance using HAPDs after irradiations at the beam test.

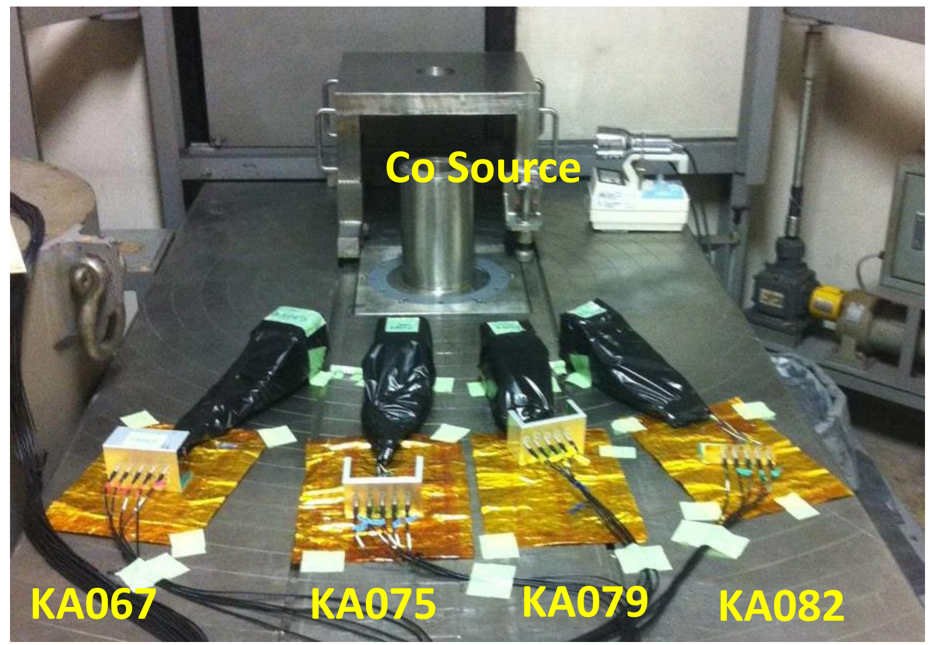
Neutron irradiation @ J-PARC MLF

- 1-2 $\times 10^{12}$ n/cm^2

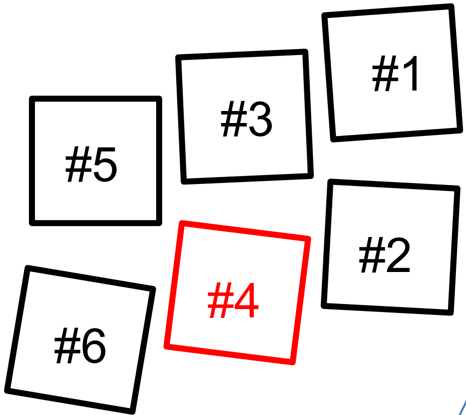


Gamma irradiation @ Nagoya Univ.

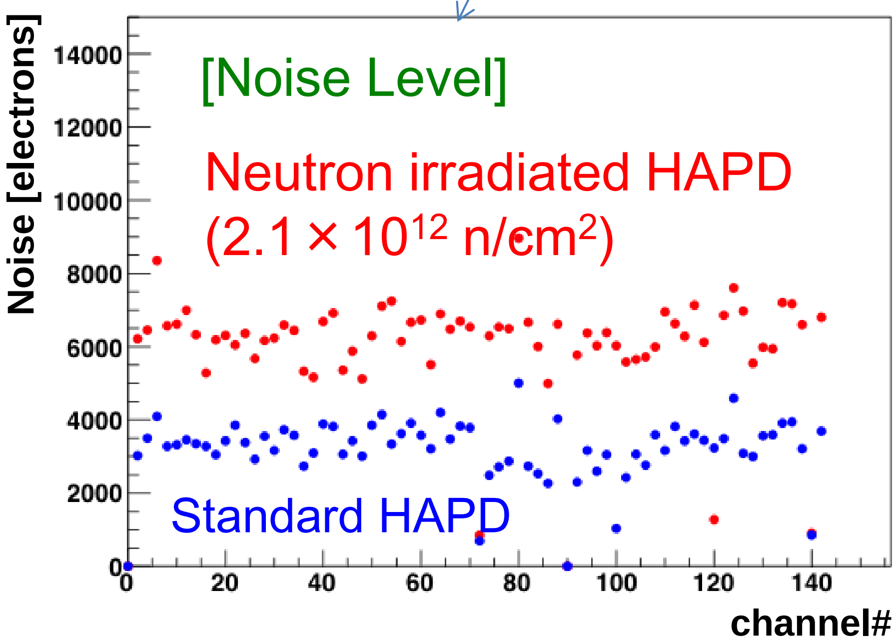
- ^{60}Co
- ~1000Gy (50Gy/hour)

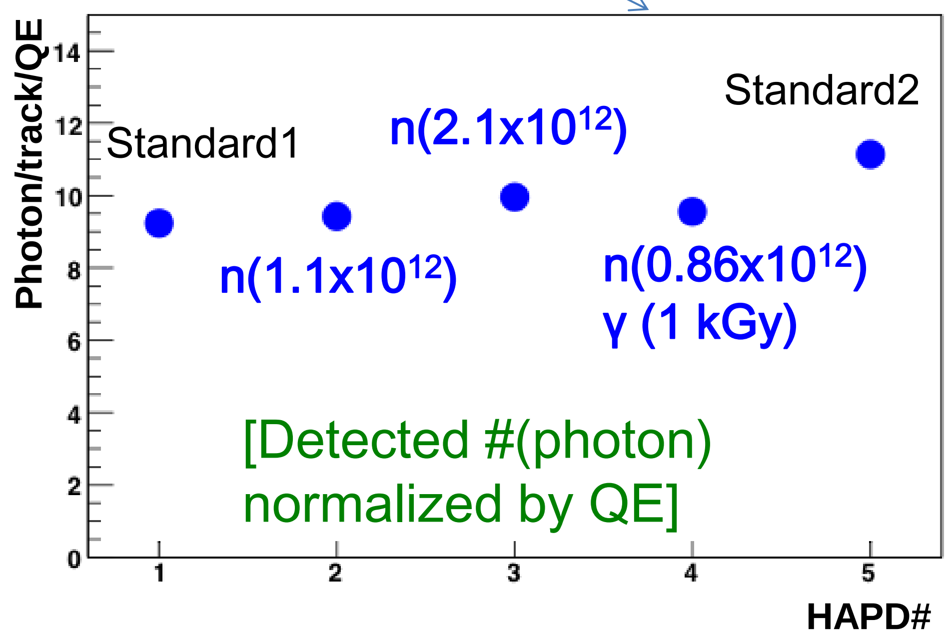


Performance with Irradiated HAPDs



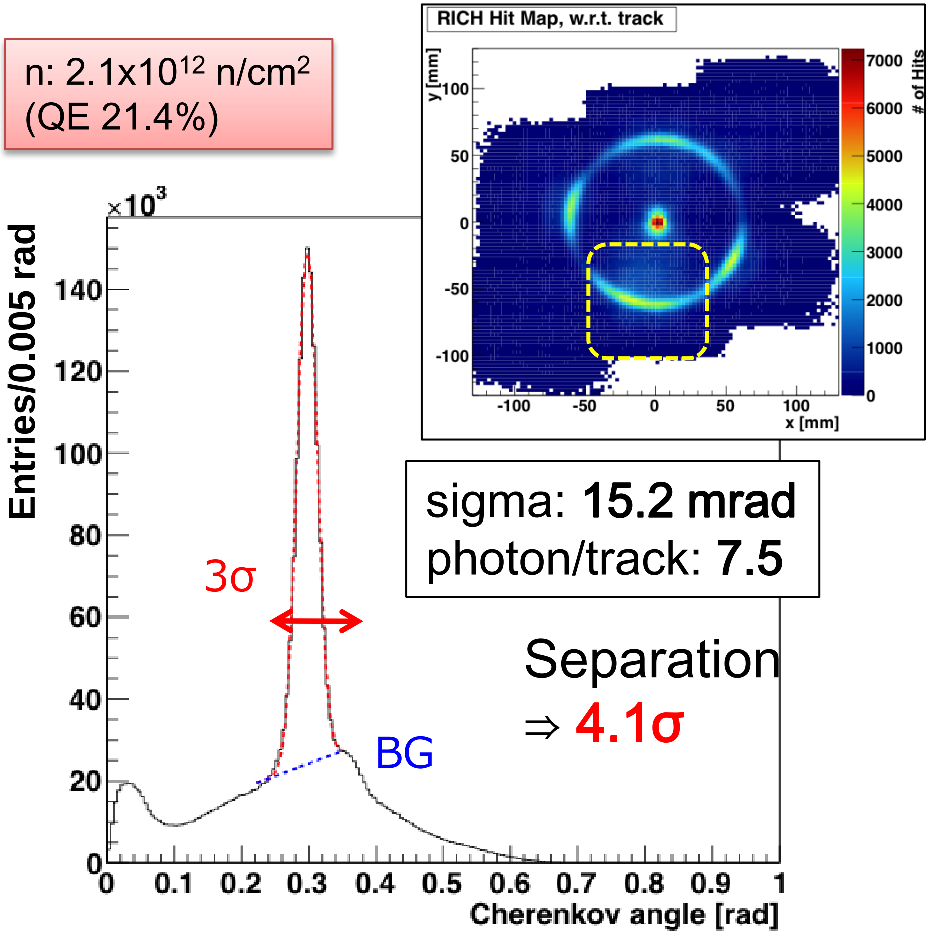
- Beam test performed using irradiated HAPDs.
- Replace one of the HAPDs (#4) to irradiated samples.
  - ✓ Neutron 2.1×10^{12} n/cm^2.
  - ✓ Neutron 0.9×10^{12} n/cm^2 and gamma 1000 Gy.
- Threshold level increased to the irradiated samples.
- No difference found in the detected number of photons/



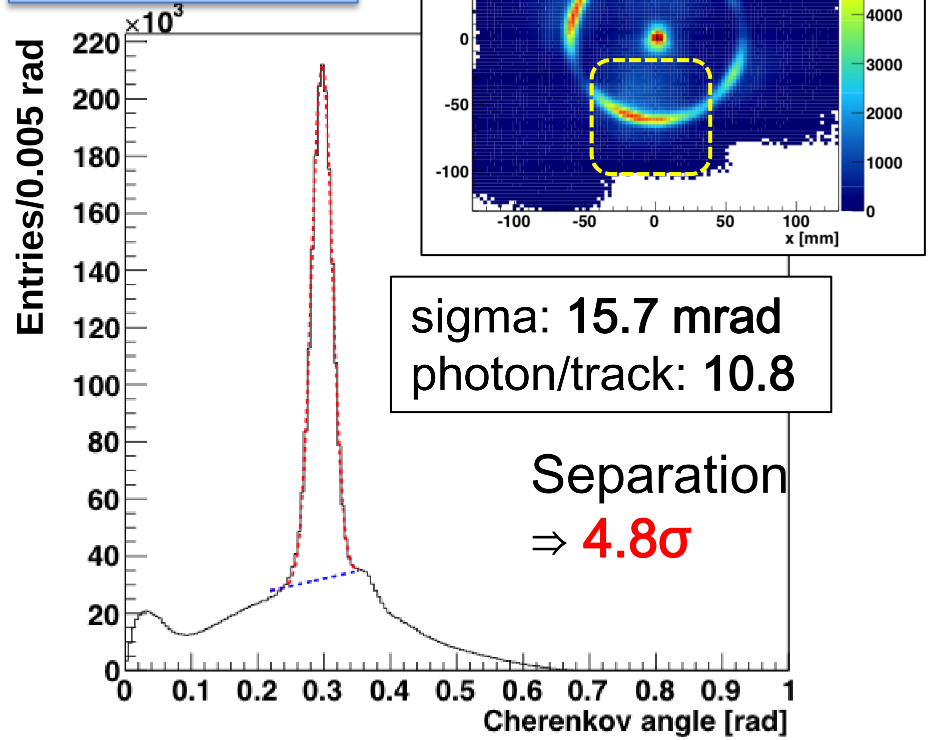


Performance with Irradiated HAPDs

n: 2.1×10^{12} n/cm^2
(QE 21.4%)

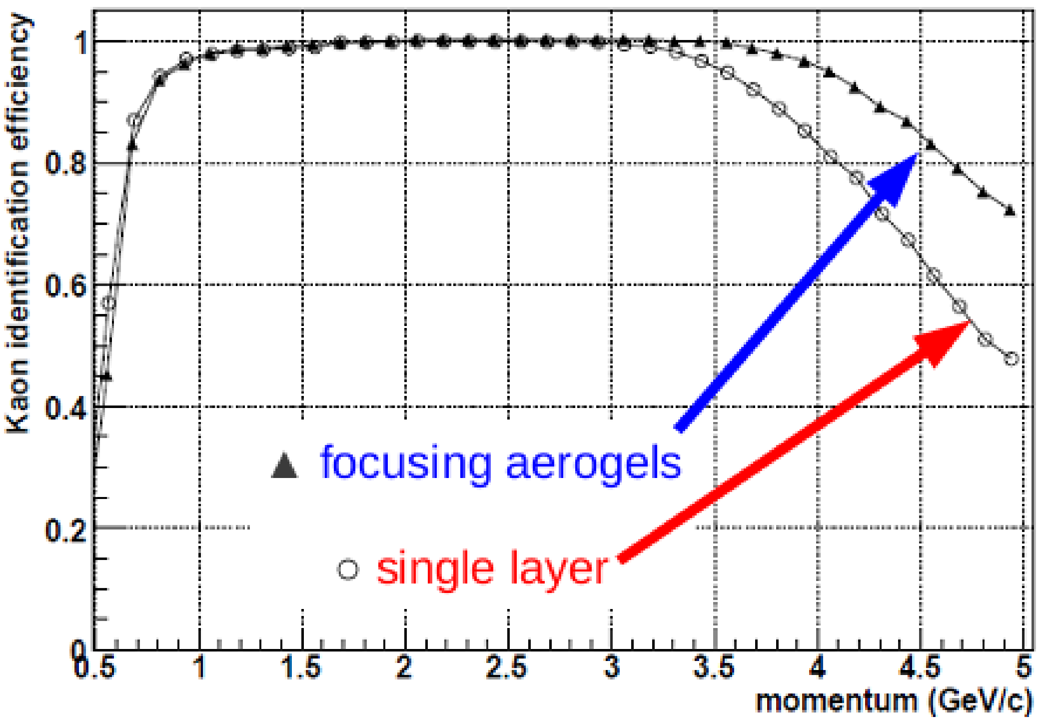


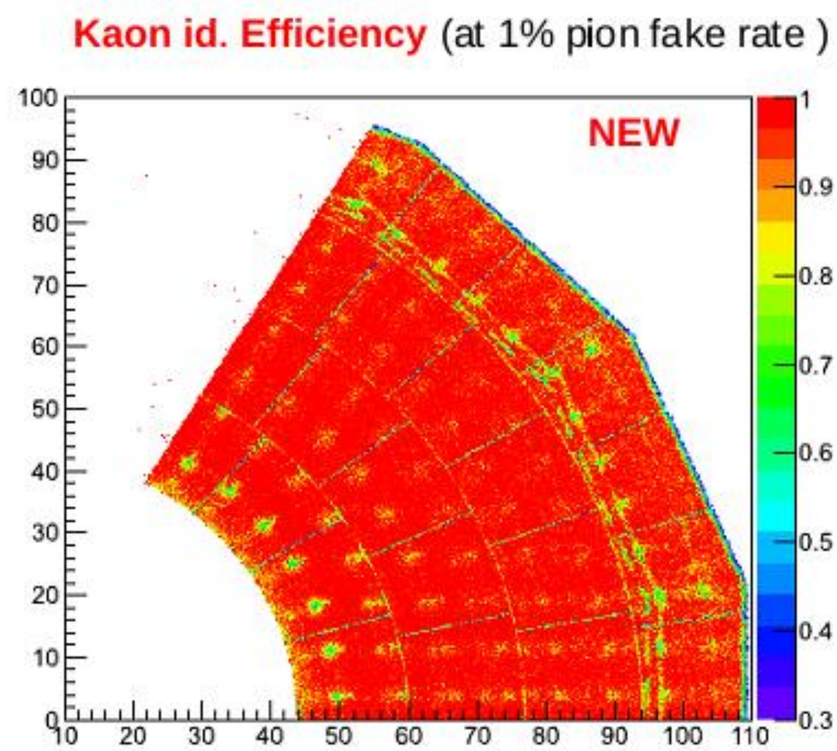
n: 0.86×10^{12} n/cm^2
γ: 1 kGy
(QE 31.1%)



No significant performance degradation is expected for the predicted radiation.

Performance





- Monte Carlo simulation is performed under Belle2 software framework.
- Excellent PID performance over wide range of momentum.