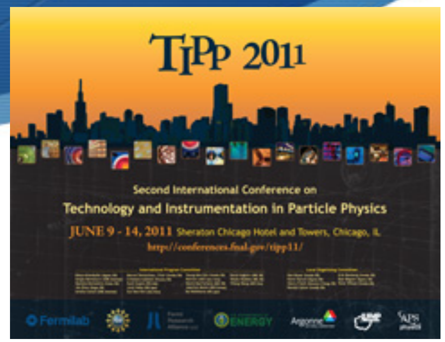
Development of Ring Imaging Cherenkov counter for Belle II experiment at SuperKEKB

Shuichi Iwata
Tokyo Metropolitan University

I. Adachi[2], R. Dolenec[3], K. Hara[2], T. Iijima[4], M. Imamura[4], M.Kubo[5], H. Kawai[5], S. Korpar[6,3], P. Krizan[7,3], T. Kumita[1], E. Kuroda[1], W. Mori[8], S. Nishida[2], S.Ogawa[8], R. Pestotnik[3], S. Shiizuka[4], T. Sumiyoshi[1], M. Tabata[9,5], H. Takagaki[1], S. Tagai[8] and R. Verheyden[3]
(Belle II Aerogel RICH group)

[1]Tokyo Metropolitan University,
[2]High Energy Accelerator Research Organization (KEK),
[3]J. Stefan Institute,
[4]Nagoya University,
[5]Chiba University,
[6]University of Maribor,
[7]University of Ljubljana,
[8]Toho University,
[9]Japan Aerospace Exploration Agency (JAXA)

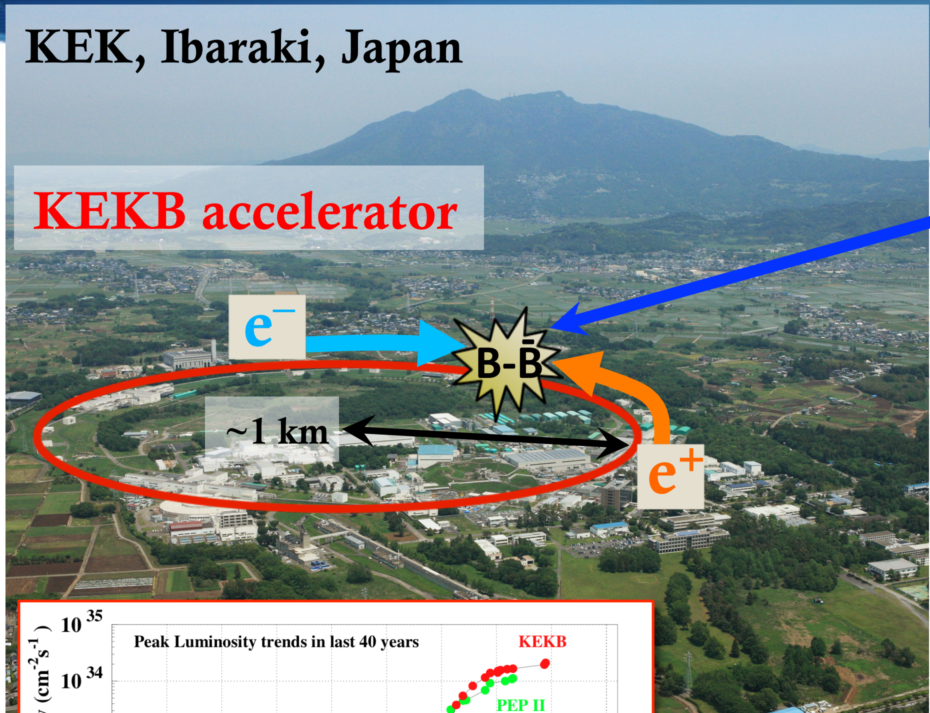


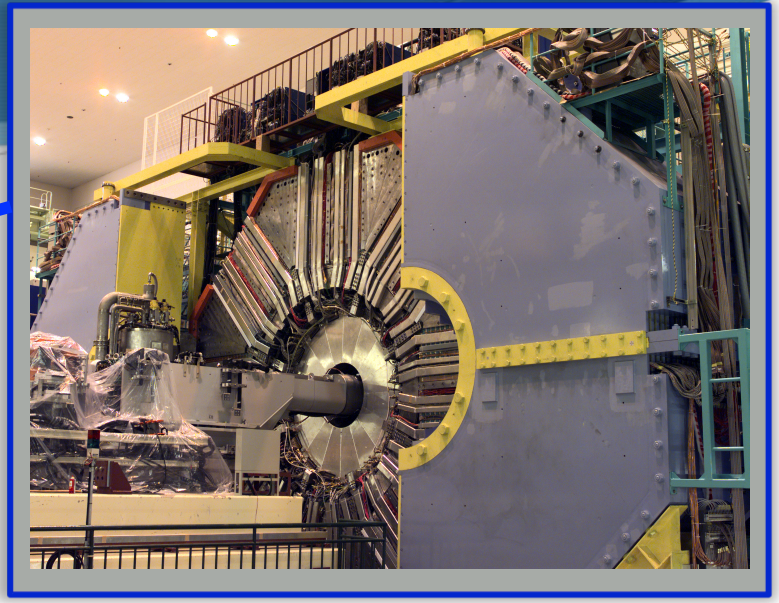
Outline

- Introductions
- 144-ch HAPD performance
  - Prototype Beam test @KEK
- Radiation hardness of HAPD
- Conclusions

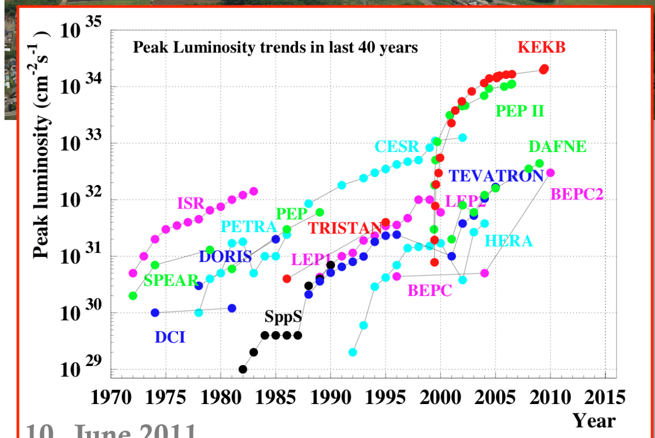
INTRODUCTIONS

Belle Experiment





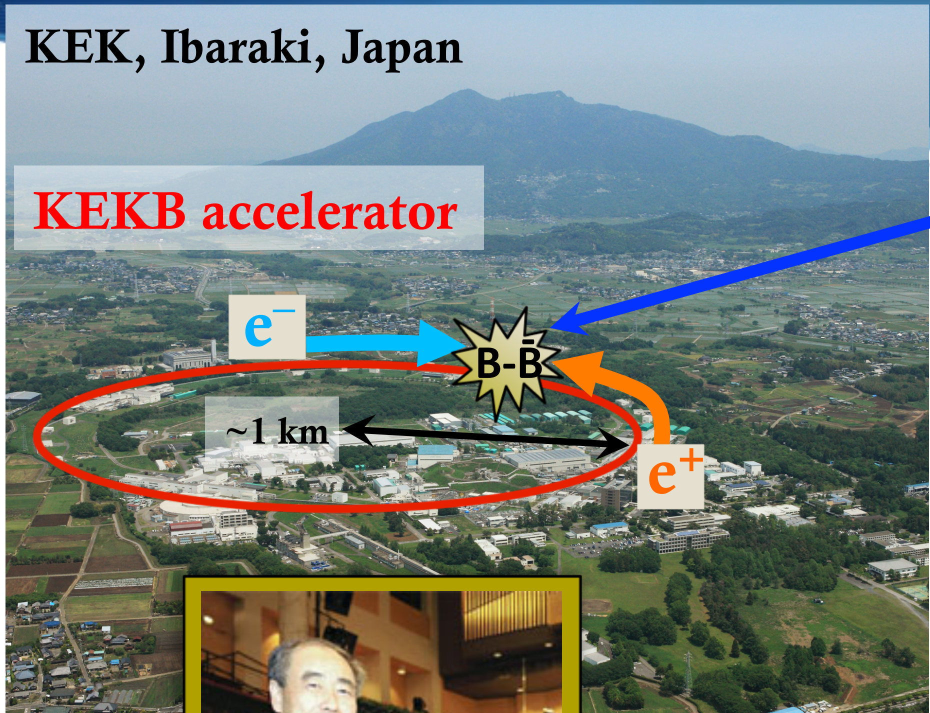
Belle Detector

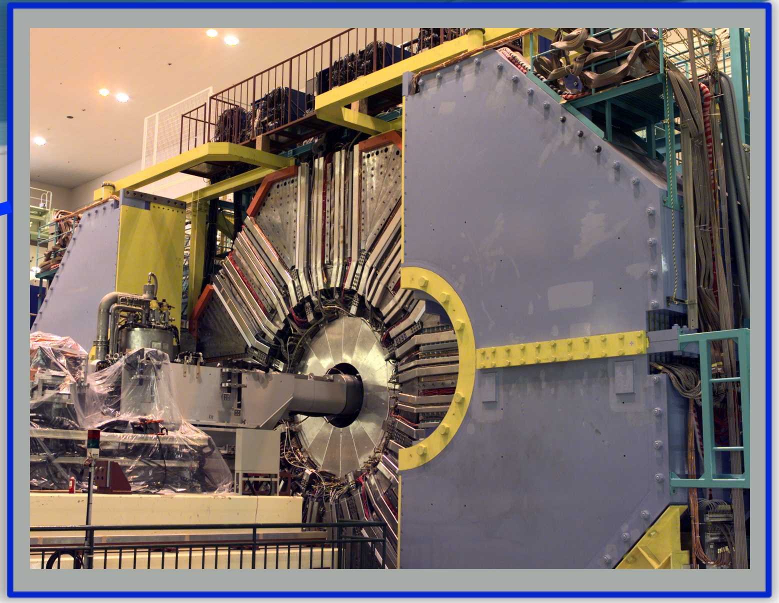


The Belle is the B-factory experiment.
The KEKB is $e^+ e^-$ collider
and **the highest luminosity machine** in the world.

Integrated Luminosity : 1,020 fb^{-1}
Peak Luminosity : 2.11 x 10^{34} $cm^{-2}s^{-1}$ (World record!)

Belle Experiment

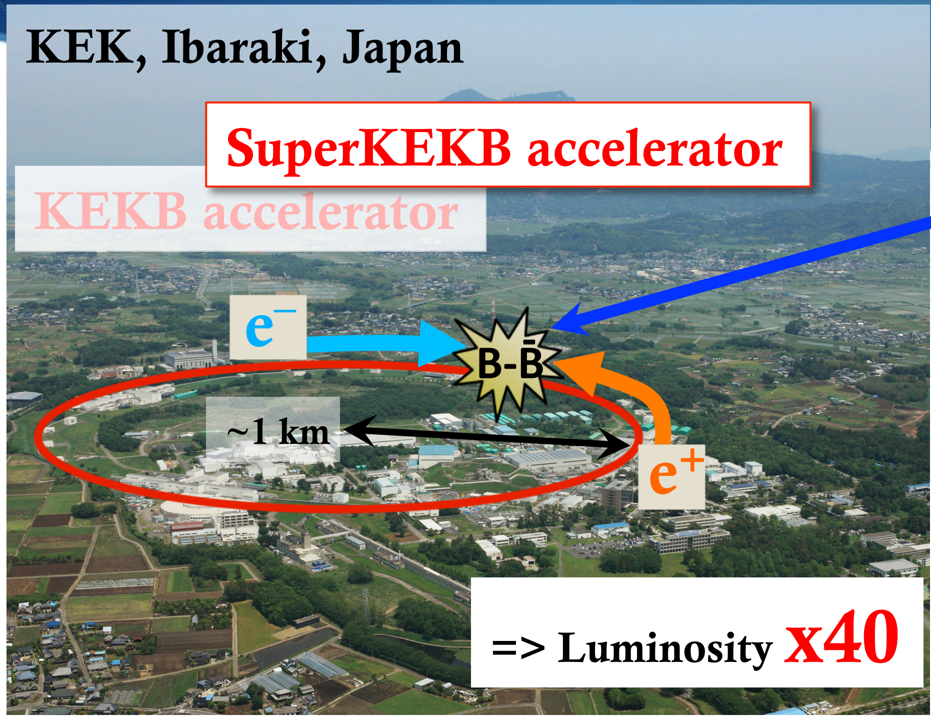


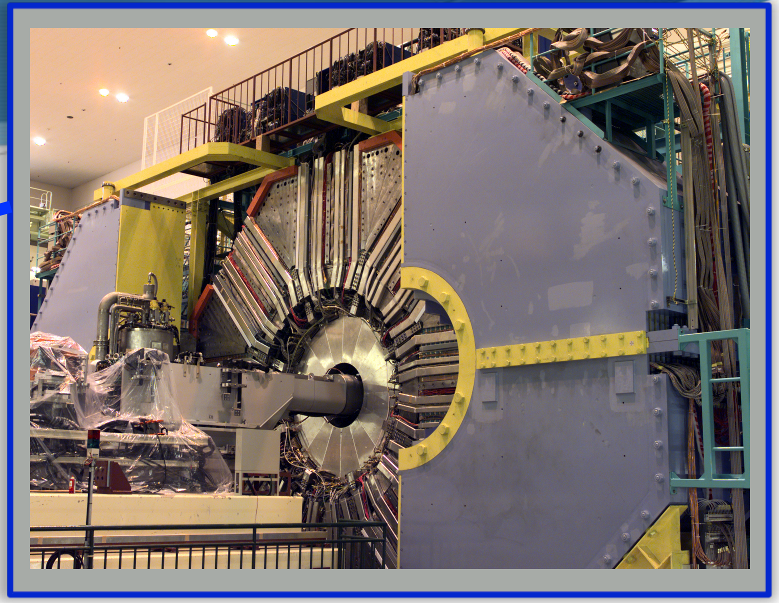


Belle Detector

In 2001, KEKB/Belle observed the first evidence for CP-violation in the B meson system.
As a result, **the 2008 Nobel Prize in Physics** was awarded to **M. Kobayashi and T. Maskawa.**

Belle II Experiment





Belle Detector

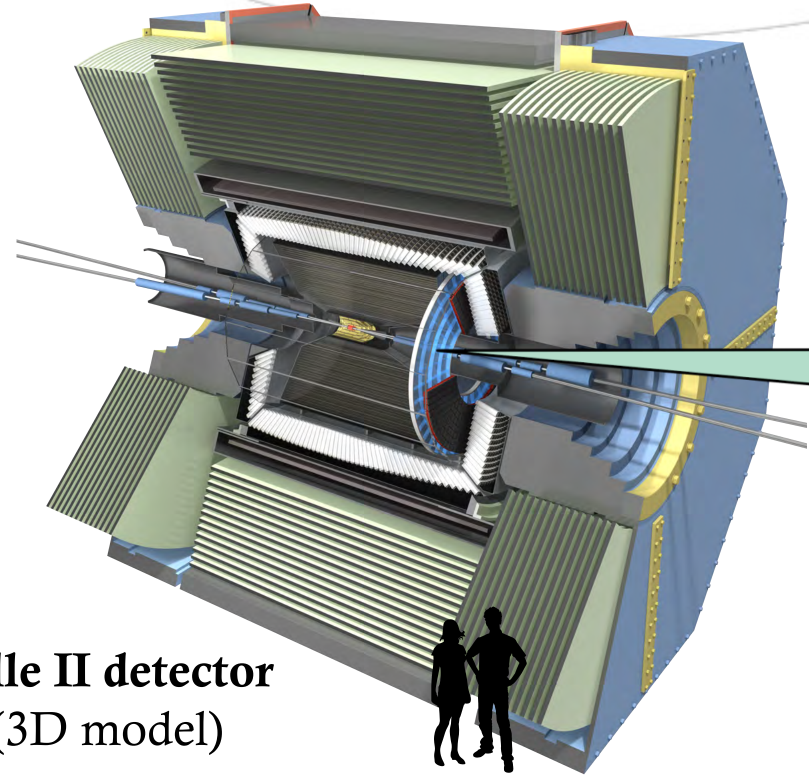
Belle II detector

The Belle stopped operation in 2010,
and is being **upgraded to the Belle II experiment**.

⇨ **2014 start!**

Belle II Particle ID upgrade

The **K/π identification** (**PID**) device plays an important role in Belle II experiment.



Belle II detector
(3D model)

Ex) $B \rightarrow \pi\pi$ or $B \rightarrow K\pi$
$B \rightarrow \rho\gamma$ or $B \rightarrow K^*\gamma$

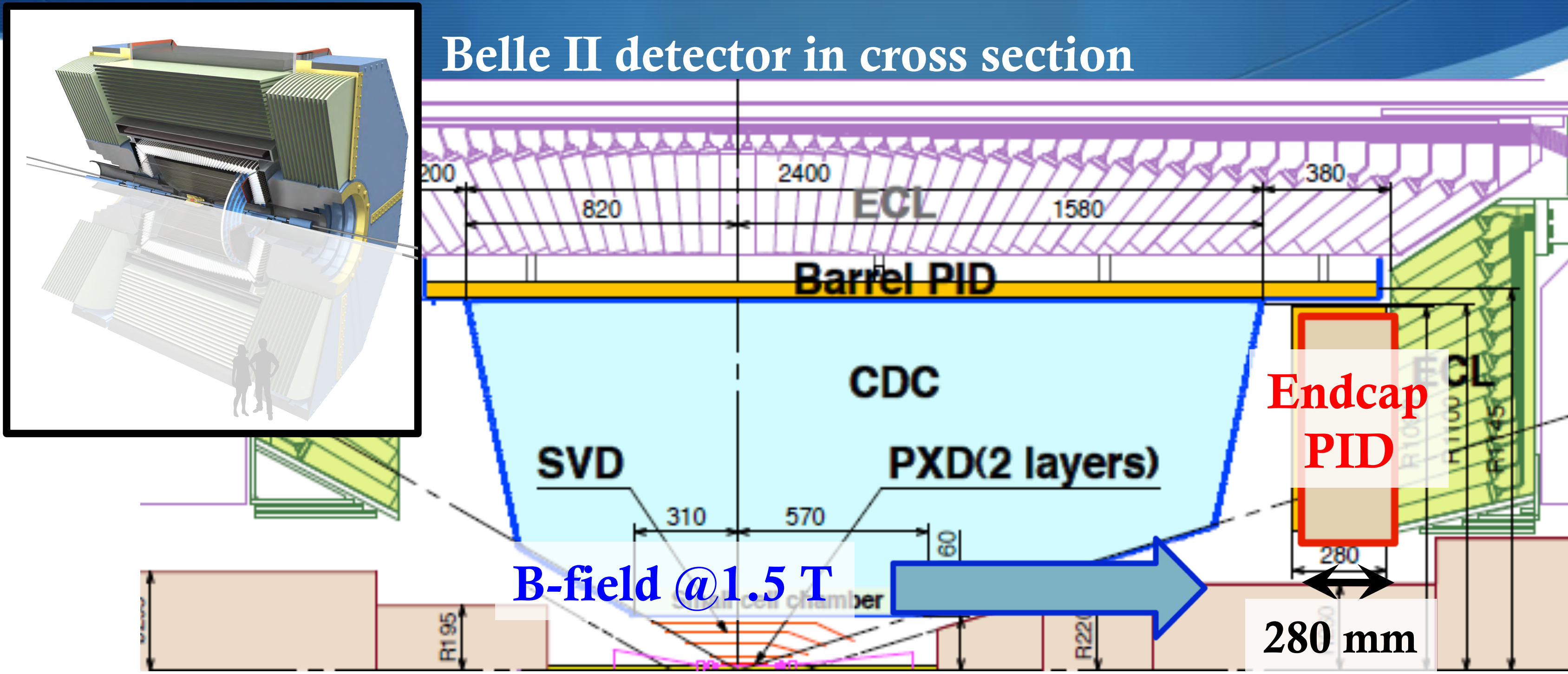
Efficient identification of these mode
is essential for precision measurement.

Need up to 4 GeV/c for endcap K/π separation

Belle endcap PID : < 2 GeV/c
by threshold-type Cherenkov counter (ACC)

Conditions for endcap PID

Belle II detector in cross section

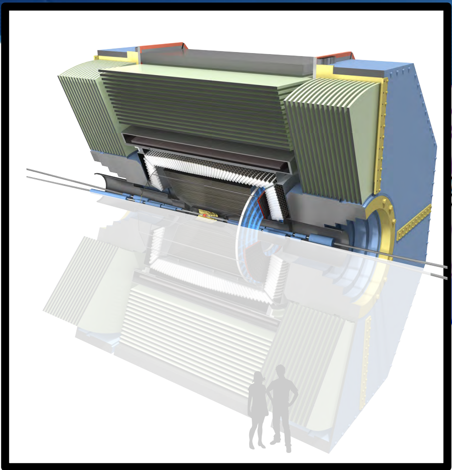


- ❖ Immunity B-field
- ❖ Limited space

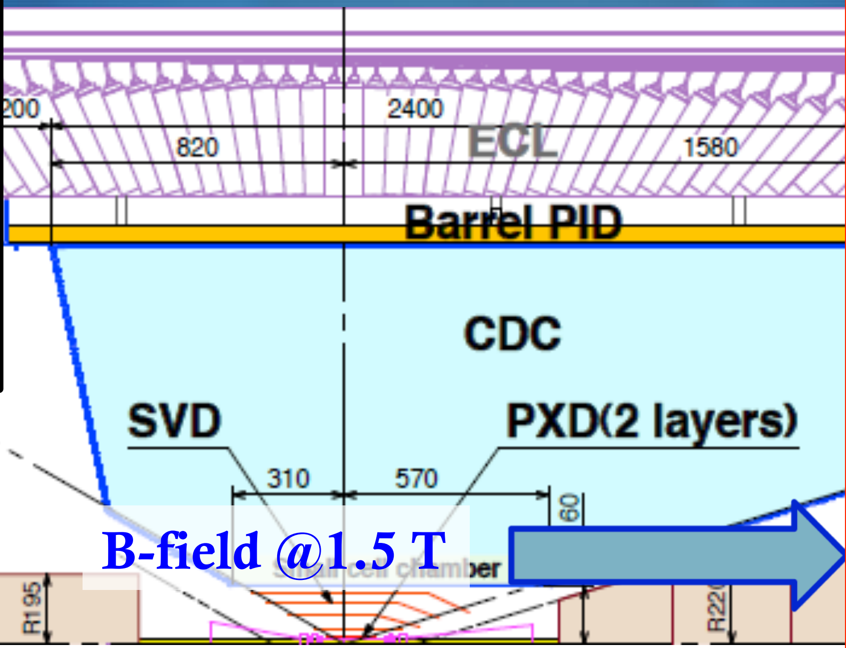
⇨

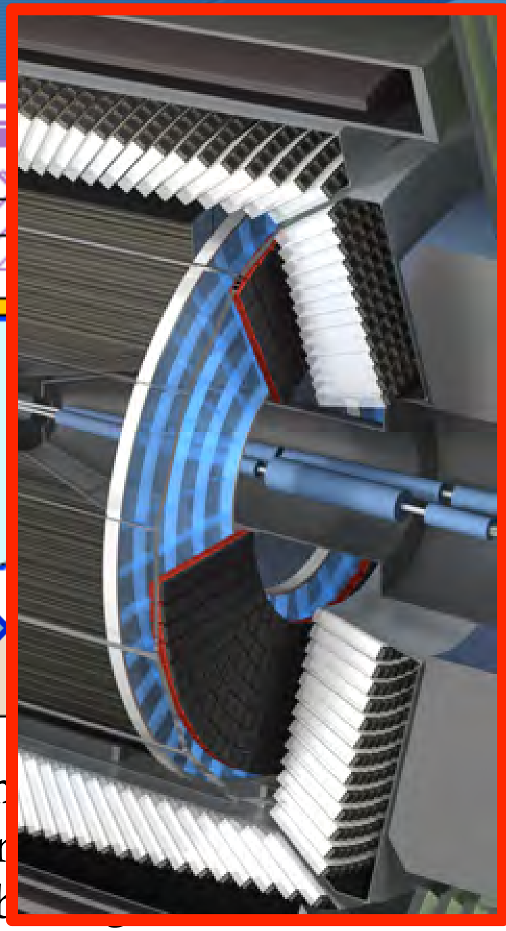
- ✔ Structure of the detector must be carefully designed
- ✔ Suitable photon detectors must be chosen.
- ✔ A whole structure cannot be larger.

Conditions for endcap PID



Belle II detector in cross section





- ❖ Immunity B-field
- ❖ Limited space

⇨

- ✔ Structure of the detector m
- ✔ Suitable photon detectors r
- ✔ A whole structure cannot b

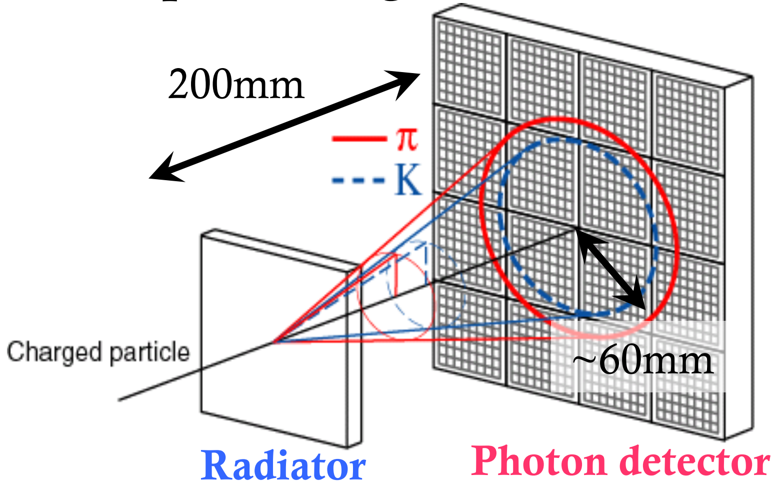
We decided to use Proximity-Focusing Aerogel RICH for endcap.

Aerogel RICH counter

Proximity-Focusing Ring Imaging Cherenkov counter using aerogel as radiator

Target : more than 4 σ K/π separation @ 4 GeV/c

Concept of Aerogel RICH counter



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

angular resolution : $\sigma_\theta/\sqrt{N_{p.e.}} \leq 6$ mrad

(σ_θ : angular resolution/track)

Silica aerogel

- Refractive index : ~1.05
- High transparency

Oral talk by M. Tabata (ID 221)

144-ch Hybrid Avalanche Photo Detector

- High sensitivity to single photon
- Pixel size : 5x5mm^2
- Immunity to high magnetic field (~1.5 Tesla)
- Large sensitive area

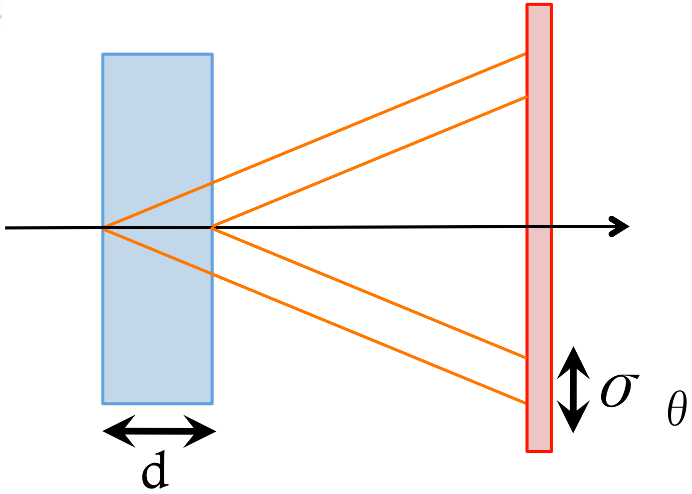
Readout electronics

- Necessary to read out ~10^5 channels at once
- Develop new ASICs

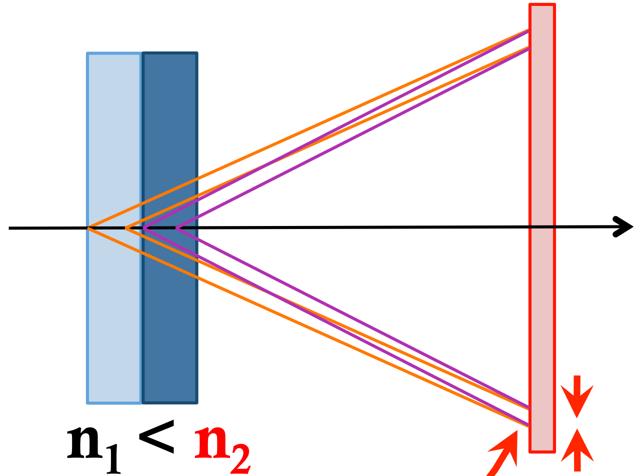
Poster by S. Nishida (ID 65)

Dual-layer Focusing scheme

Single layer



Dual layers



angular resolution $\sigma_\theta \propto \frac{d}{\sqrt{N_{\mathrm{p.e.}}}}$

Radiator thickness ***d*** is larger
=> angular resolution $\boldsymbol{\sigma_\theta}$ degrades.

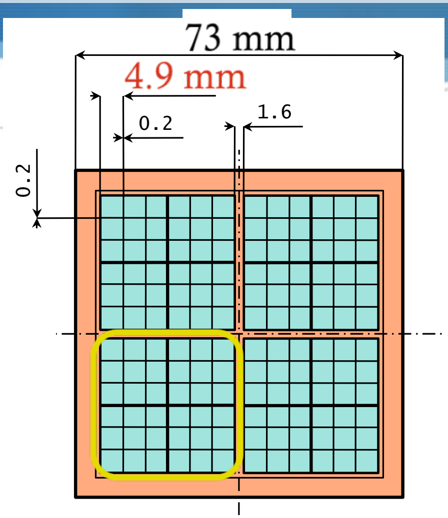
Increase detected photons without degrading the angular resolution.

T. Iijima, *et al.* NIMA 548,383 (2005)

144-ch HAPD PERFORMANCE

Photon detector : HAPD

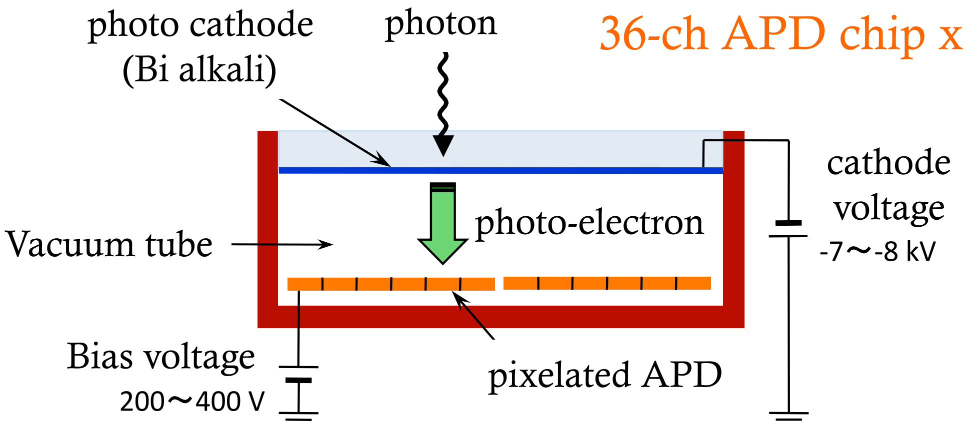
We have been developing **144-ch multi anode Hybrid Avalanche Photo-detectors** with Hamamatsu Photonics K.K.



36-ch APD chip x 4

Specification

# of channel	12 × 12 = 144
tube size	73 × 73 mm^2
effective area	~65%
pixel size	4.9 × 4.9 mm^2
APD capacitance	80 pF
peak QE	32%
S/N	~15
# of required	~450 HAPDs



Hybrid amplification

Electron bombardment gain : ~ 10^4

×

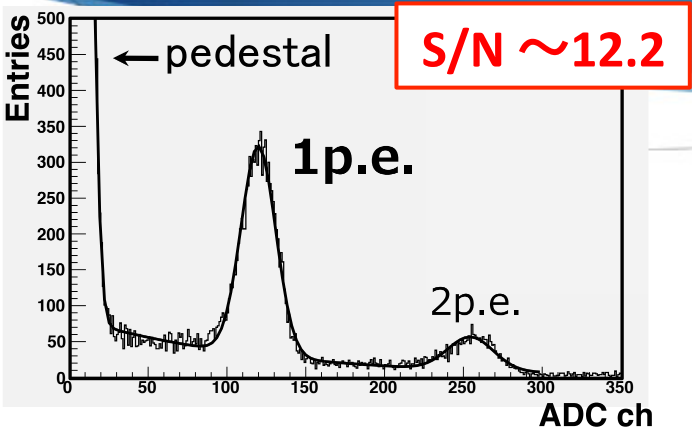
Avalanche gain : ~ 40

⇩

Total gain : ~ 10^5

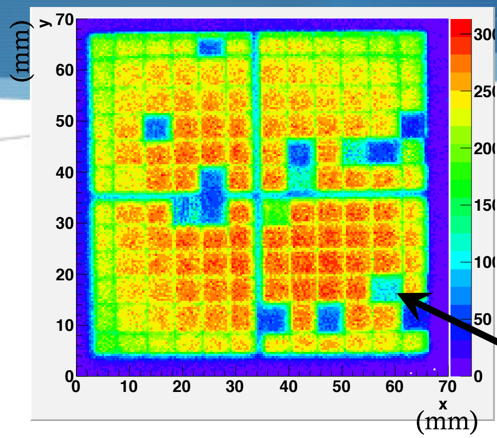
HAPD performance

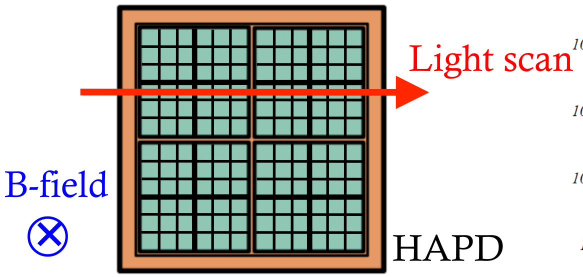
Single photon detection



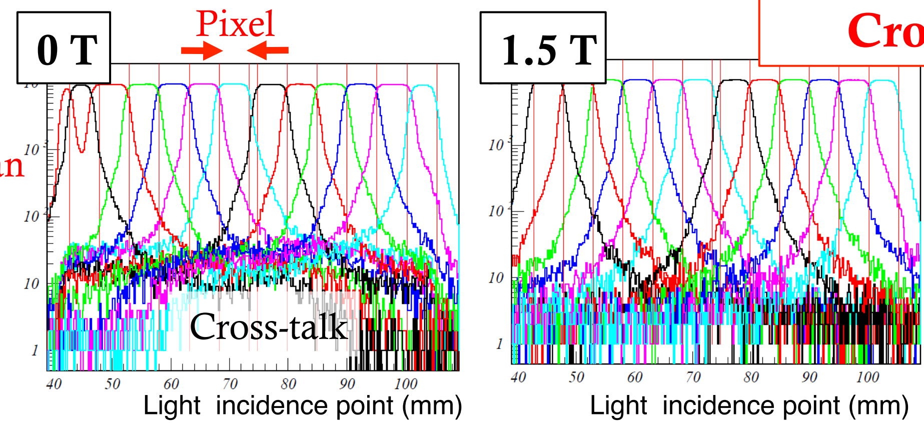
HV:8.5 kV (bombarded gain ～ 1,700)
Bias:270 V (avalanche gain～ 40)
Total gain = 68,000
QE～22%(400 nm)

2D scan response





Operation under B-field



Efficiency unchanged
Cross-talk lower

Colored lines show detection efficiency of each channel.

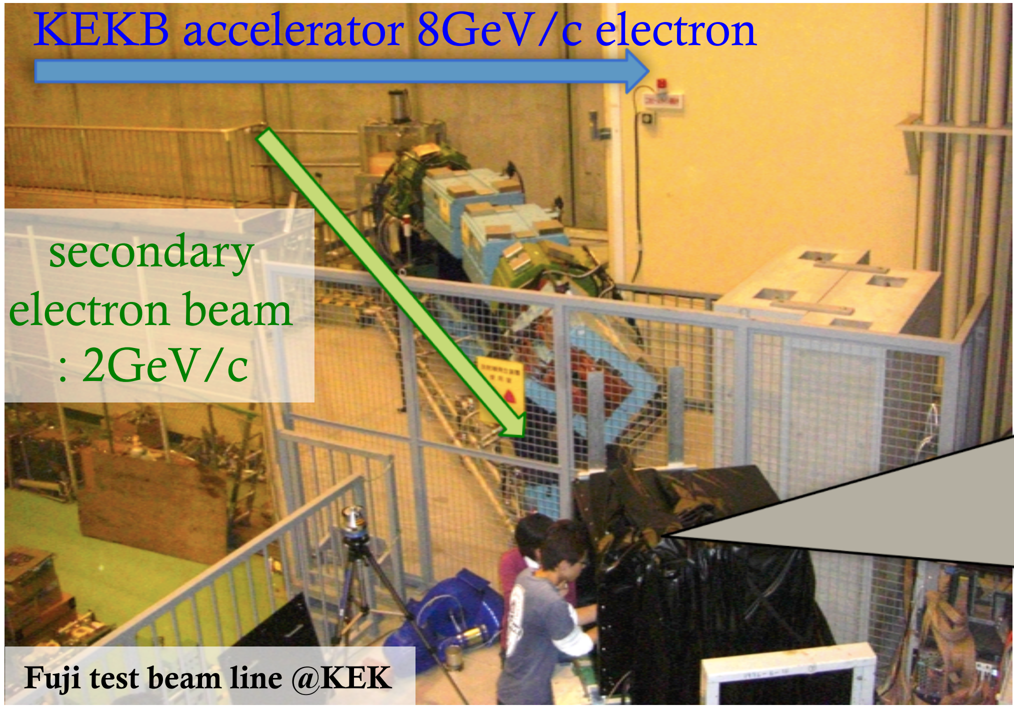
Results from HAPD bench test indicated remarkable performance

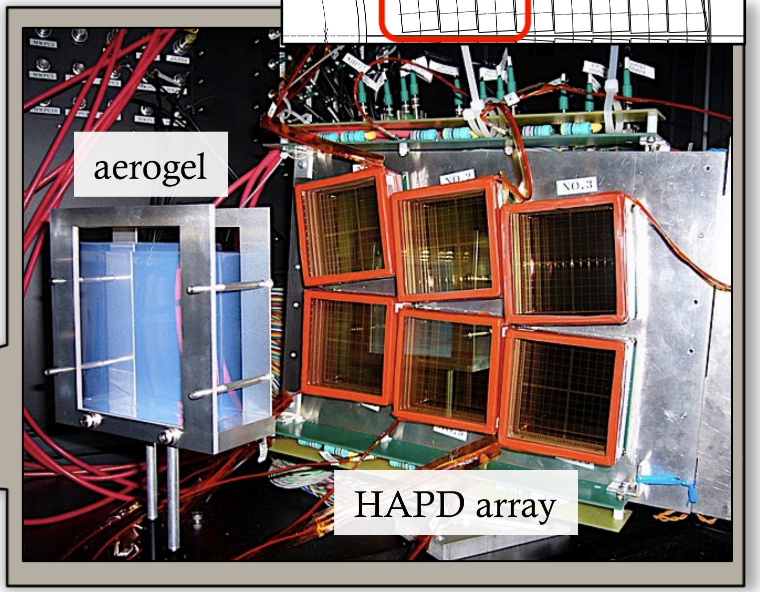
Performance of Prototype Aerogel RICH

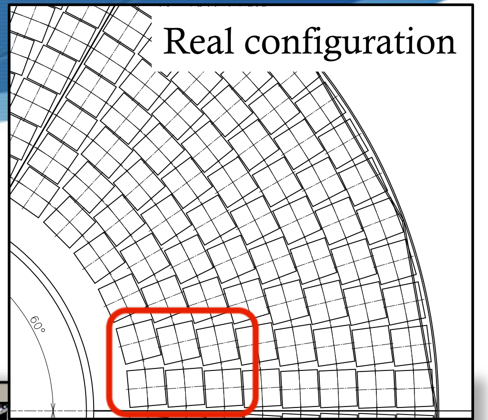
Prototype configuration

We constructed **a prototype Aerogel RICH**

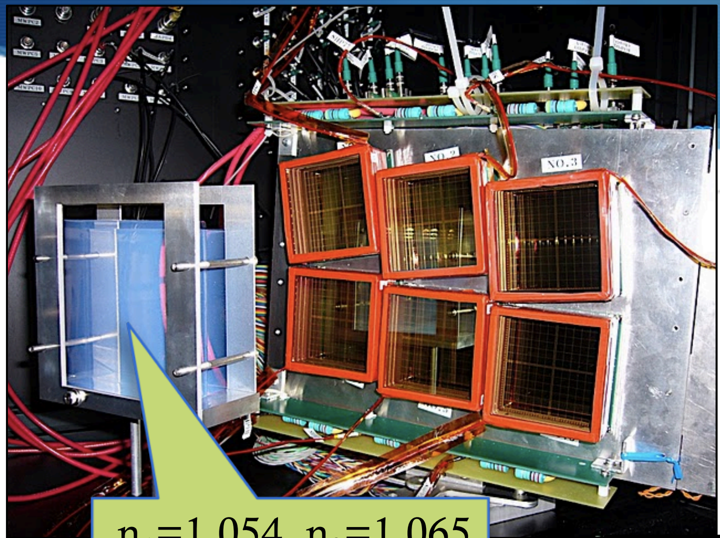
- Using 6 HAPDs (2x3 array)
- Focusing radiator scheme : 2 layers
- Prototype readout electronics







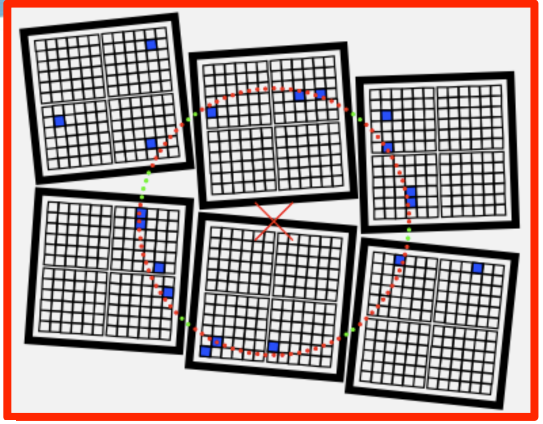
Beam test results 1



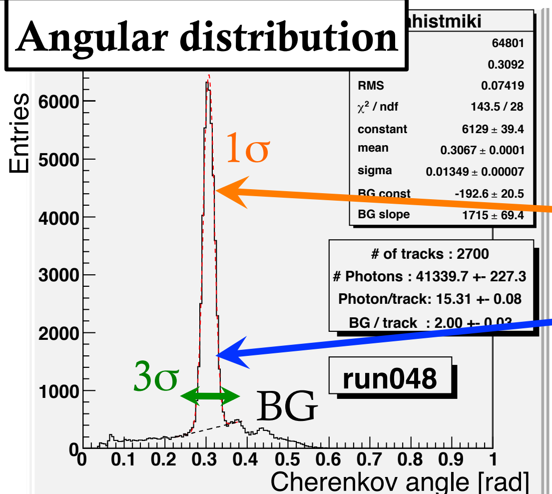
n_1=1.054, n_2=1.065
(20 mm thick each)

HAPD Condition
HV: -7kV
Bias: ~350V(gain40)

Event Display



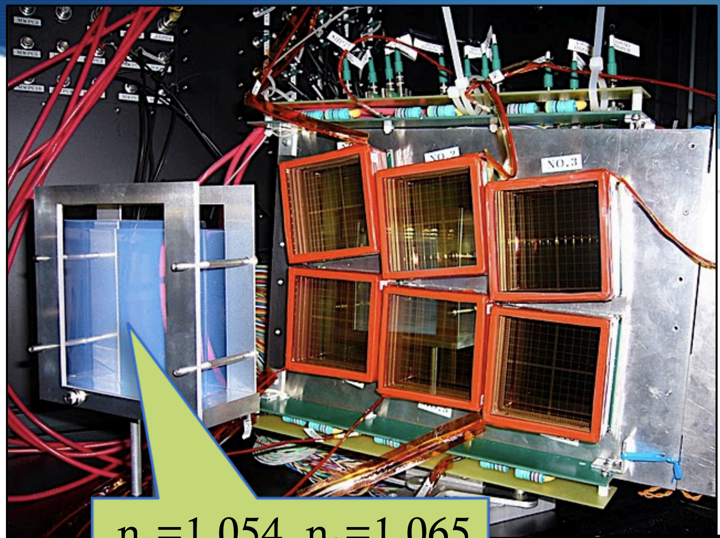
Angular distribution



Cherenkov angle resolution :
σ_θ = 13.5 mrad/photon
# of photo-electrons :
15.3/track

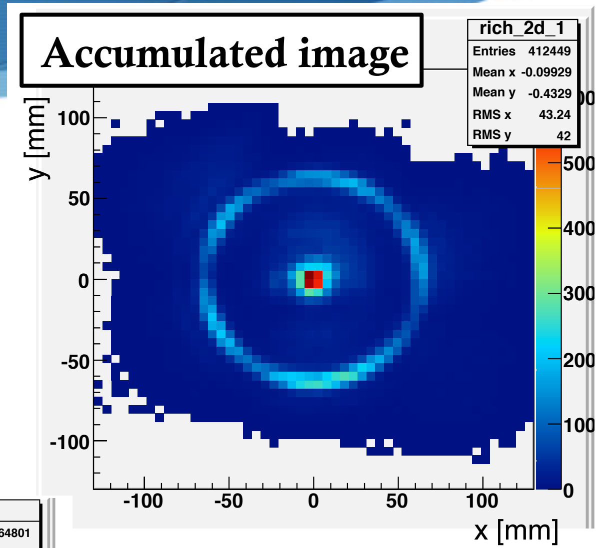
Beam test results 1

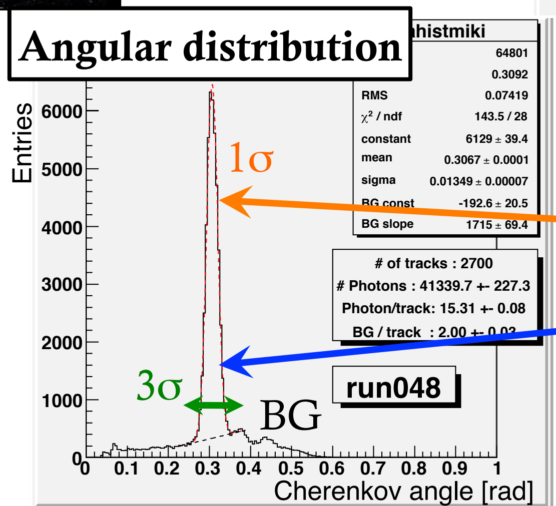
Clear ring image was observed!



n_1=1.054, n_2=1.065
(20 mm thick each)

HAPD Condition
HV: -7kV
Bias: ~350V(gain40)





Cherenkov angle resolution :
σ_θ **= 13.5 mrad/photon**
# of photo-electrons :
15.3/track

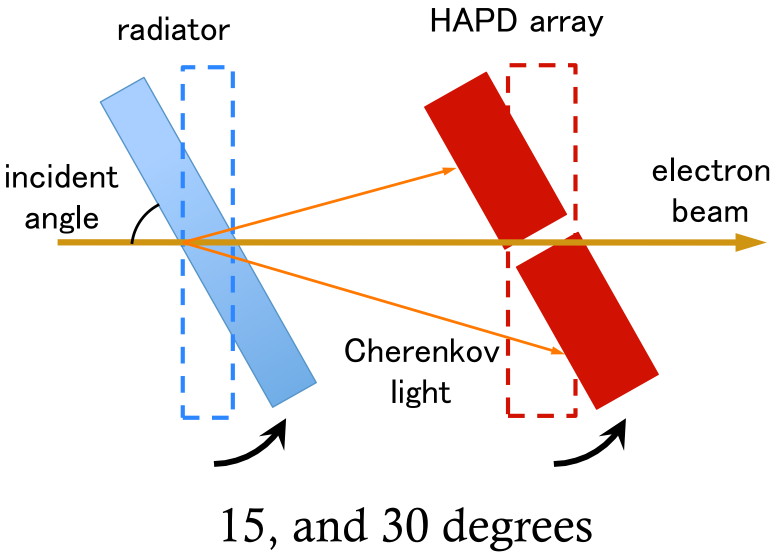
Ability of K/π separation

$$\frac{\Delta\theta_C}{\sigma_\theta}\sqrt{N_{p.e.}} \qquad \Delta\theta_C \simeq 23 \text{ mrad} \quad @4 \text{ GeV}/c$$

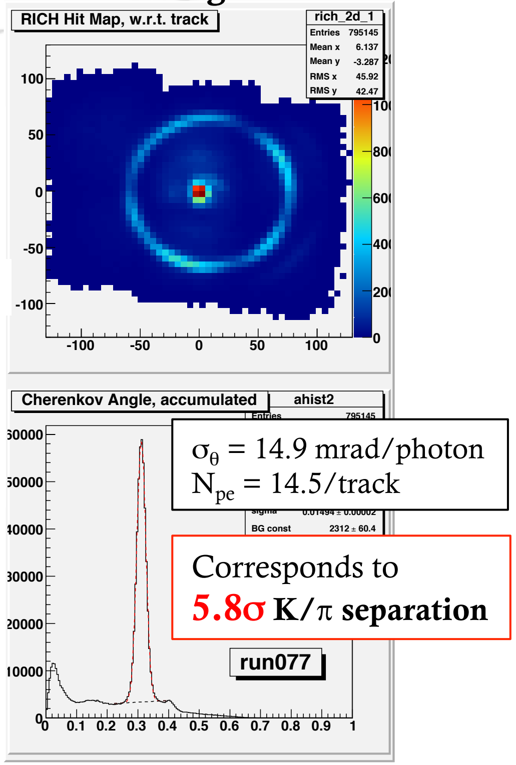
Corresponding to **6.6 σ**
K/π separation at 4 GeV/c

Performance for inclined tracks

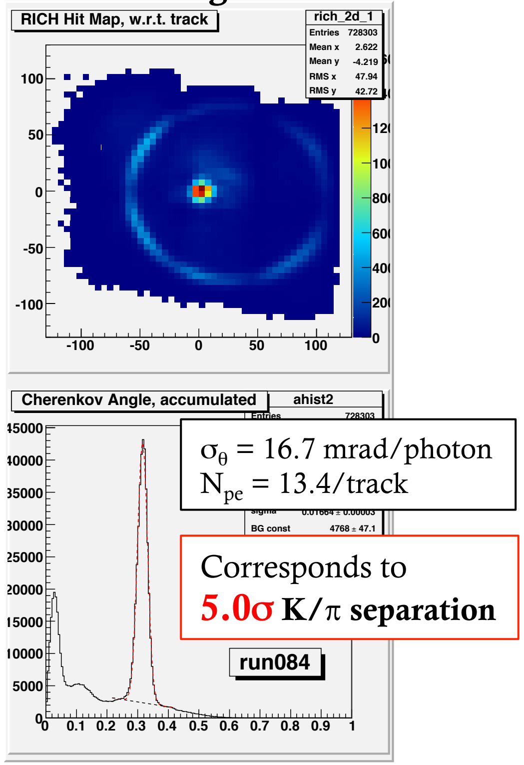
For Belle II forward endcap device, incident angles of tracks are 17~30 degrees.
We tested performance of prototype Aerogel RICH for inclined tracks.



15 degrees



30 degrees



Aerogel RICH can still keep good PID capability for the realistic environment

Summary of HAPD performance

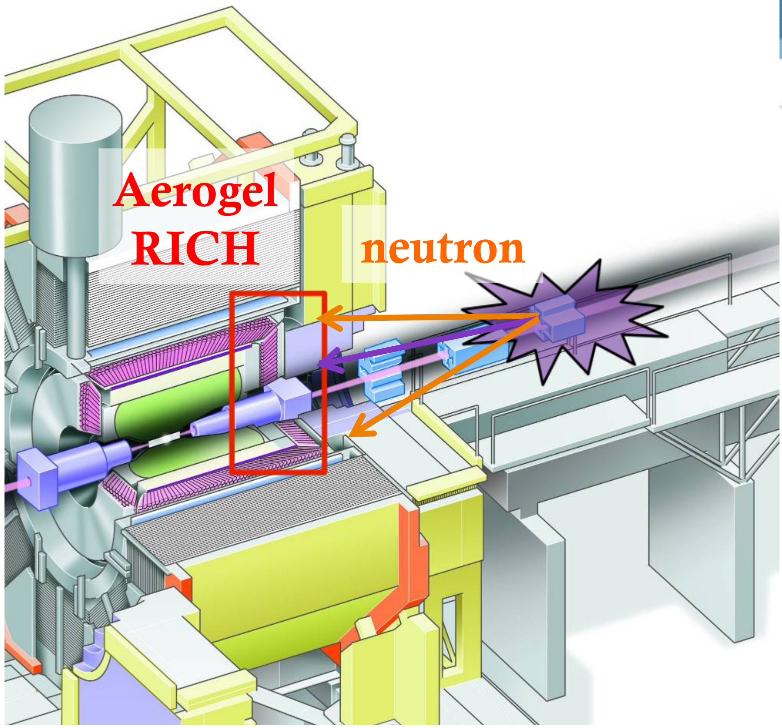
Aerogel RICH with the HAPDs demonstrated notable performance,

- single photon detection => **S/N~12**
- position resolution is 5x5 mm^2 => **OK**
- operation in high B-field => **OK under 1.5 T**
- prototyping test of 6 HAPDs
  - real arrangement
  - inclined injection angle

=> **Excellent performance!**

RADIATION HARDNESS OF HAPD

Neutron radiation hardness



We estimate irradiation dose for 10-year Belle II operation.

Neutron : 10^{12} /cm^2

Neutron radiation damage in APD
=> Increase leakage current => shot noise

$$\sigma_{\text{shot}} \propto \sqrt{I_{\text{leak}}}$$

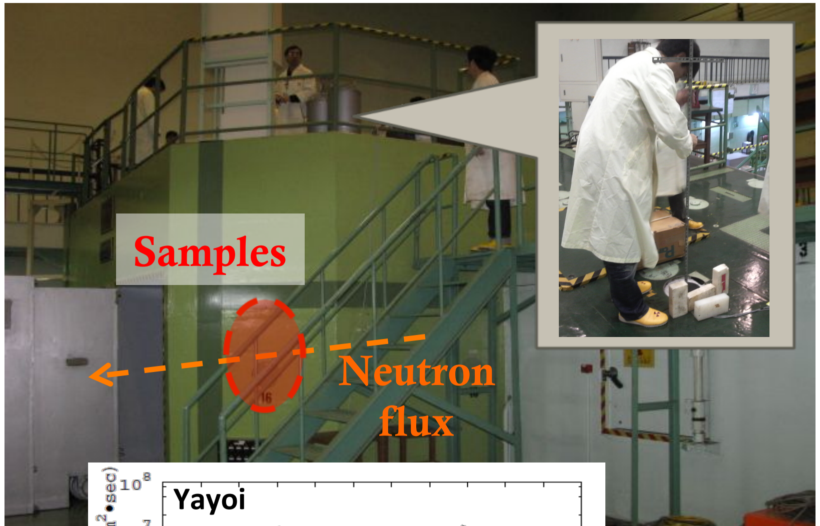
As the result, single photon separation will be worse.

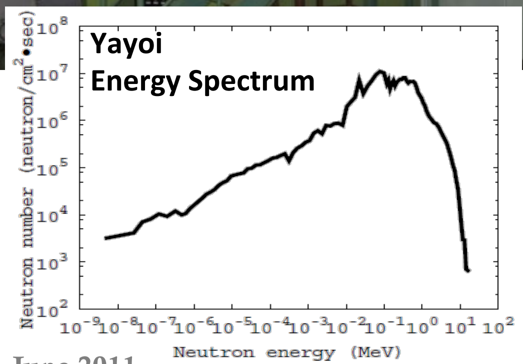
We studied the neutron radiation hardness of HAPDs.

Irradiation test result 1

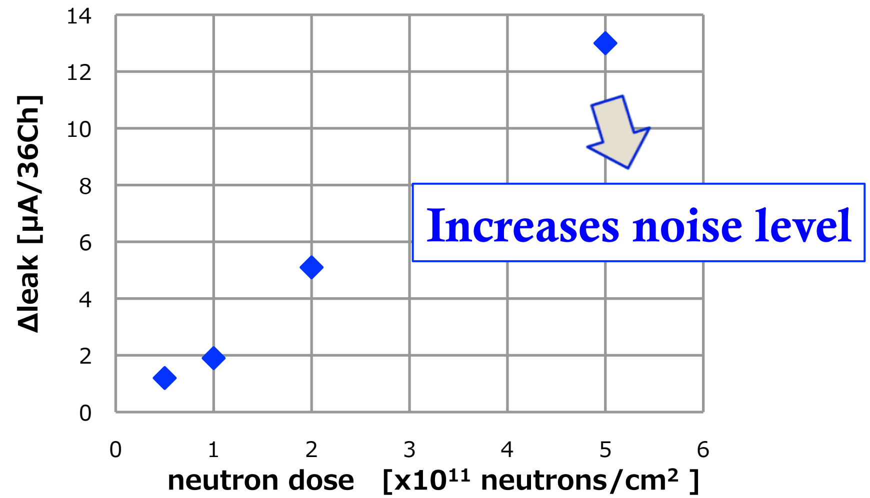
We carried out the neutron irradiation test at Yayoi Reactor (Tokyo Univ.).

Yayoi reactor (Tokai, Ibaraki)



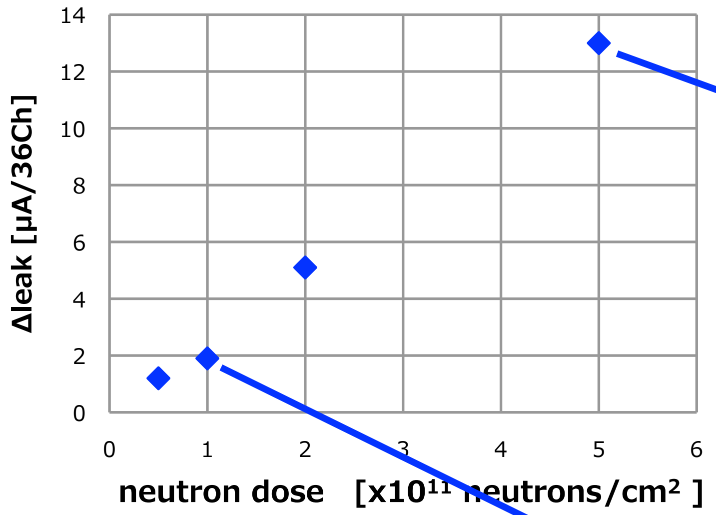


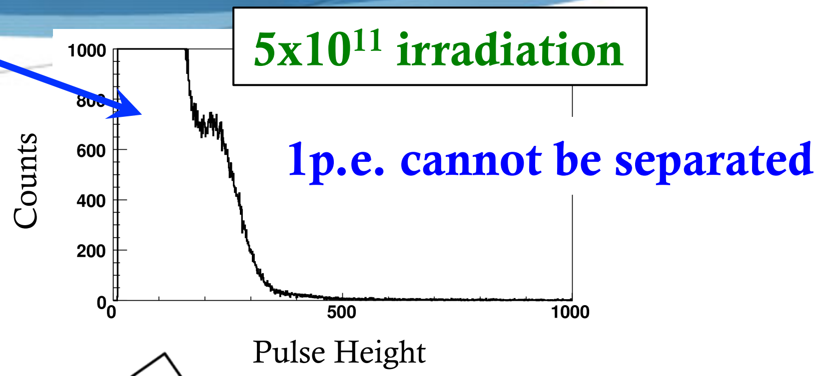
Neutron dose vs. increase of leakage current with HAPD

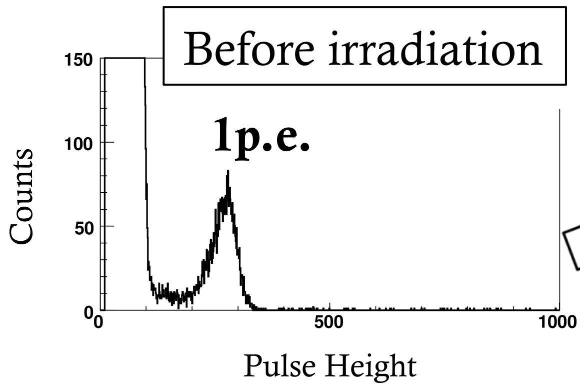


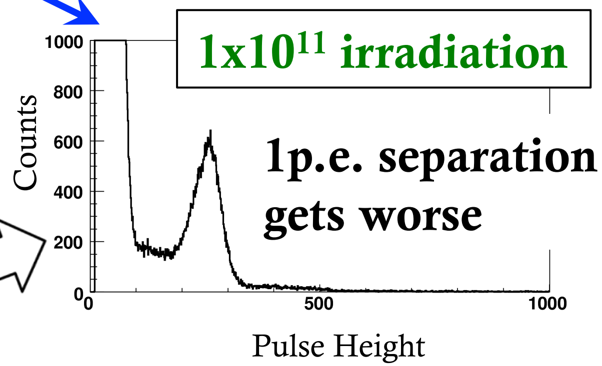
Increase of leakage current is proportional to neutron dose.

Noises depend on leakage current









In order to suppress noises, we need to reduce a increase of leakage current.

How to reduce the noise 1

- Shortening the shaping time
  - Shot noise is dependent on shaping time.
  - Shorter shaping time of the amplifier can reduce the shot noise.

Description of noise in APD

$$\sigma^2_{\mathrm{noise}} = \left(A C_{\mathrm{det}} \frac{1}{\sqrt{\tau}} \right)^2 + \left(\sqrt{\frac{I_{\mathrm{leak}}}{e} \tau F G} \right)^2$$

Amplifier noise — shot noise from I_{leak} in APD

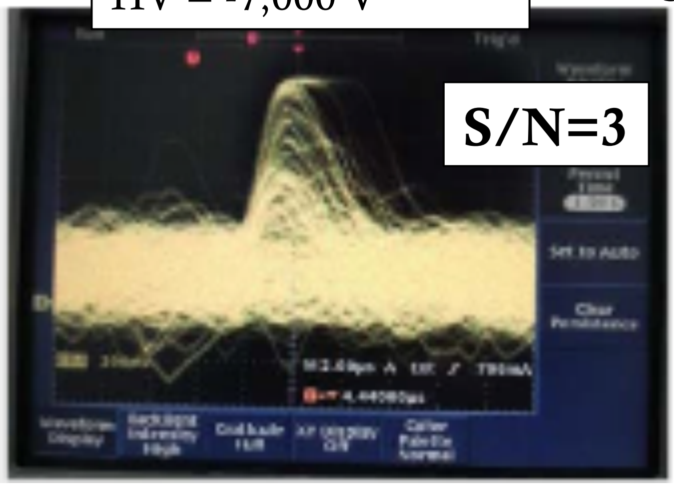
A : APD capacitance/ch
C_{det} : Capacitance depends on amplifier design
τ : Peaking time of shaping amplifier
I_{leak} : Leakage current in APD
e : Elementary charge
F : Excess noise factor (∼2)
G : Avalanche gain

ASIC & HV Optimization

We verified whether the noise can be reduced
by shortening the shaping time of amplifiers in the ASIC chips and higher HV.

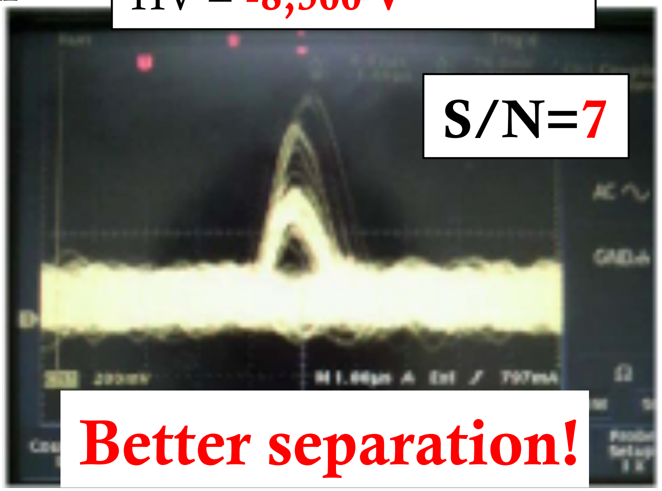
Neutron dose
5x10^{11} n/cm^{2}

Shaping time : 1 μsec,
HV = -7,000 V



S/N=3

Shaping time : **250 nsec**,
HV = **-8,500 V**



S/N=7

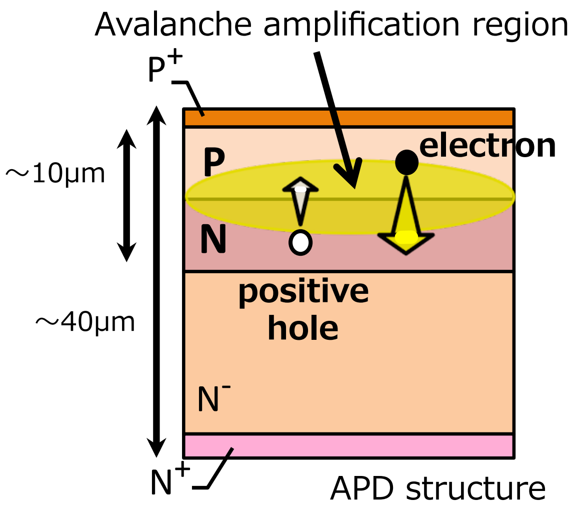
Better separation!

Further noise reduction may be possible with shorter shaping time.

⇨ Next version of ASIC is designed to enable shaping time of ~100 ns.

How to reduce the noise 2

- Improvement of APD structure
  - Avalanche amplification region
    - Source of noise : lattice defects in APD
    - Contribution of electrons in P-layer is about 100 times of that of holes in N-layer.
    - We expect that APD with a thin-P layer yields lower noise.
  - APDs with Thin-P layer were developed and tested at Yayoi reactor in 2010.

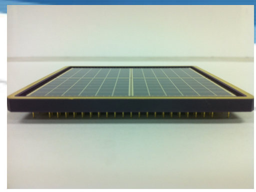


Irradiation test result 2

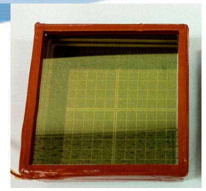
Increase of leakage current

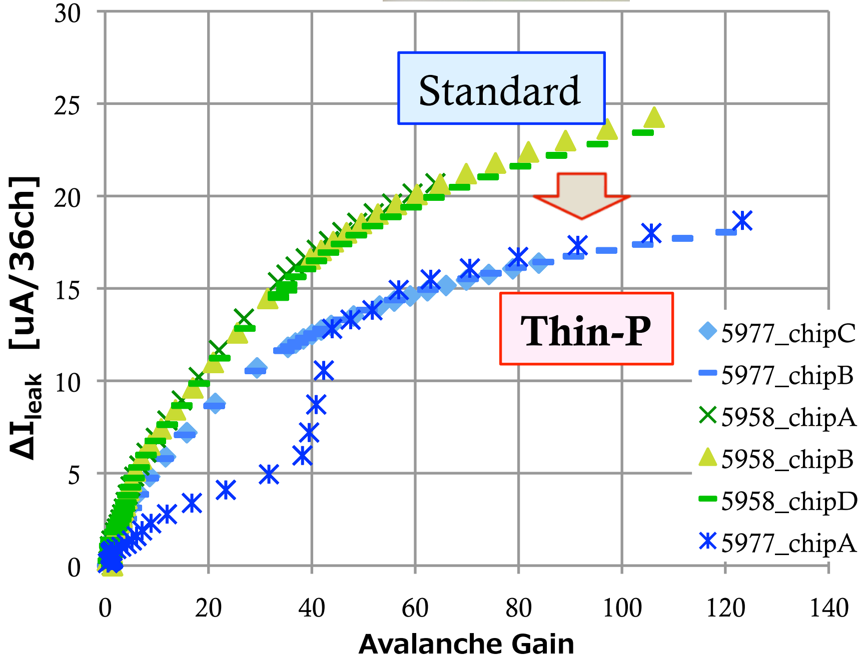
Irradiated Dose : 10^{12} n/cm^2
(Correspond to 10-year Belle II operation)

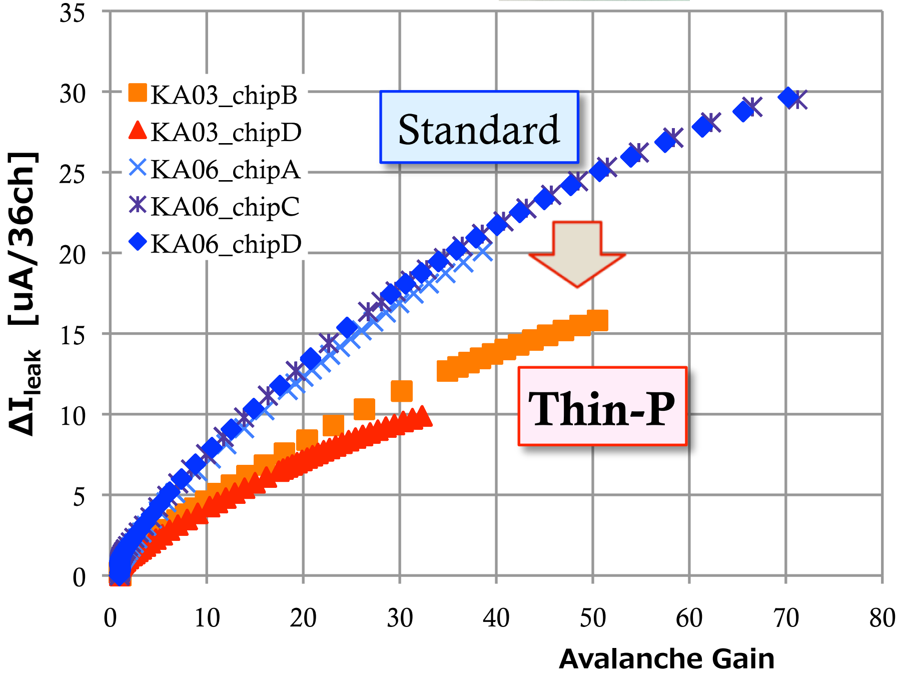
144-ch APD



144-ch HAPD



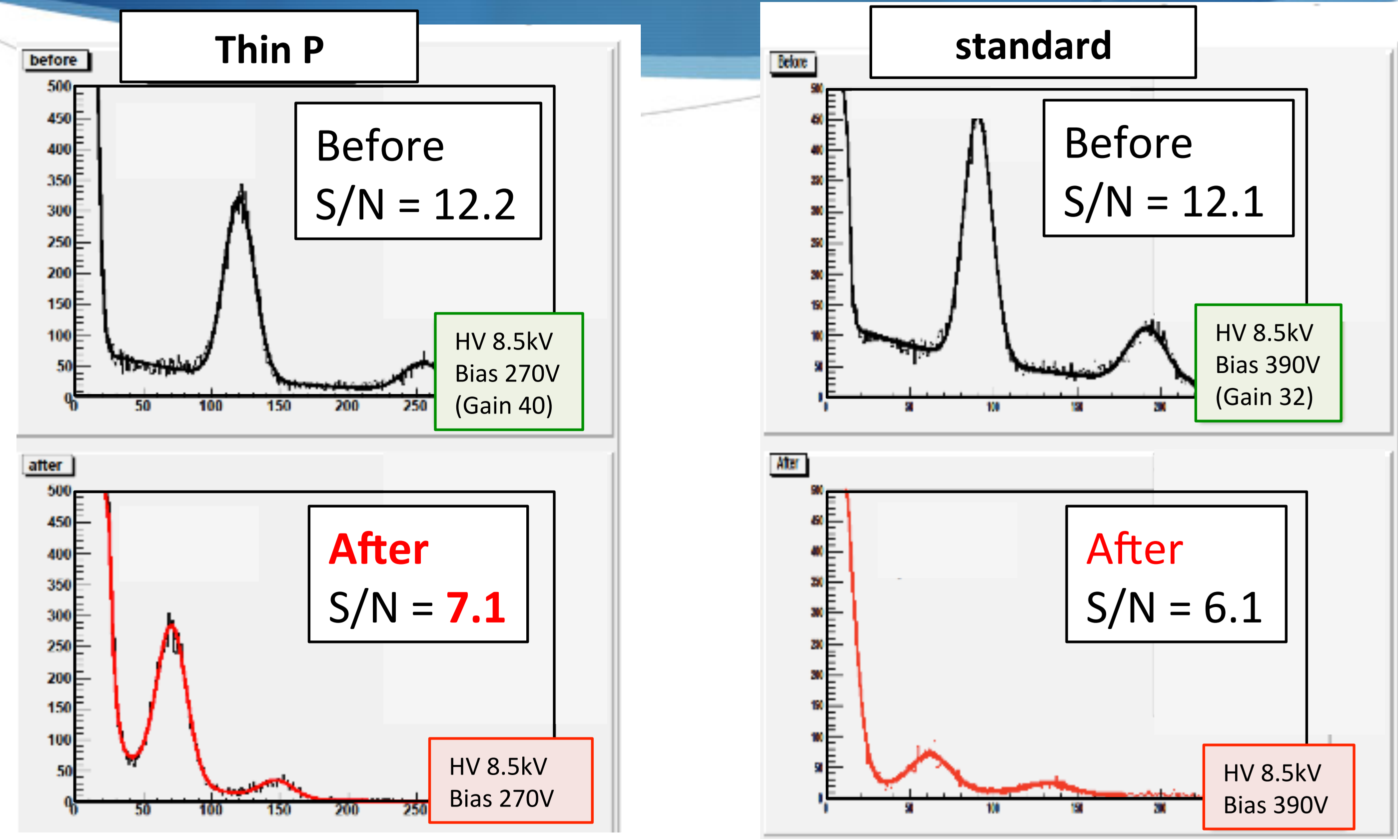




We confirmed reduction of leakage current by APDs with thin-P.

Irradiation test result 3

Pulse height distribution



APD with thin-P shows better S/N than standard.

Conclusions

- We have been developing **Aerogel RICH** counter for the Belle II endcap PID.
- We use **144-ch HAPDs** as the photon detector.
  - High single photon sensitivity
  - 5x5 mm^2 position resolution
  - Large effective area
  - Operation under high B-field
- Prototype Aerogel RICH with 6 HAPDs achieved **6.6 σ K/π separation** at 4 GeV/c.

We succeeded in producing HAPDs with excellent performance for Belle II.

- Present concern is neutron radiation hardness of HAPDs.
- **Improved HAPDs + electronics** show better performance with 10^{12} neutrons/cm^2 .

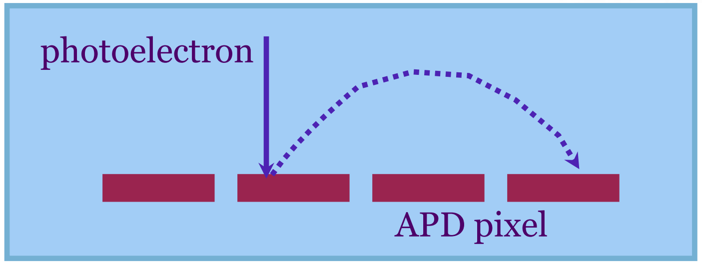
Further Works

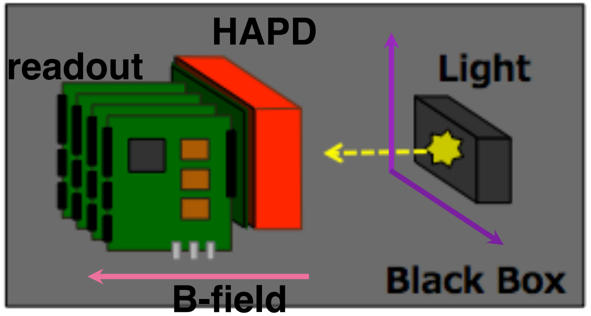
- More studies of HAPDs for radiation hardness
- Prototype Aerogel RICH test with proton beam is scheduled in September, 2011 @CERN (SPS)
- Prepare for HAPD mass production

Back up

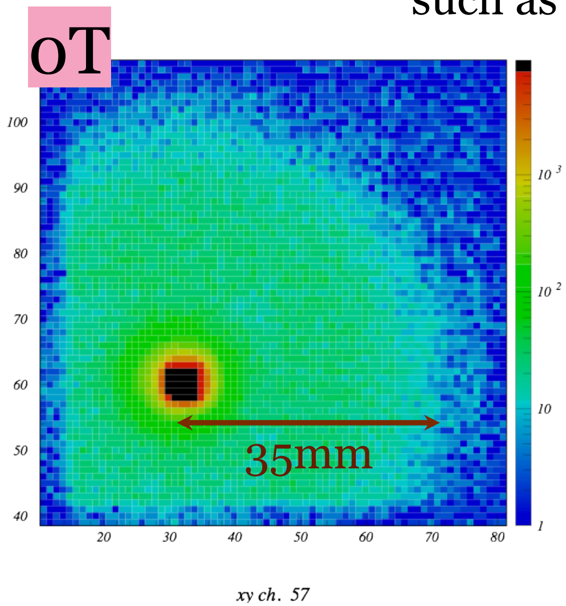
Back-scattering Effect

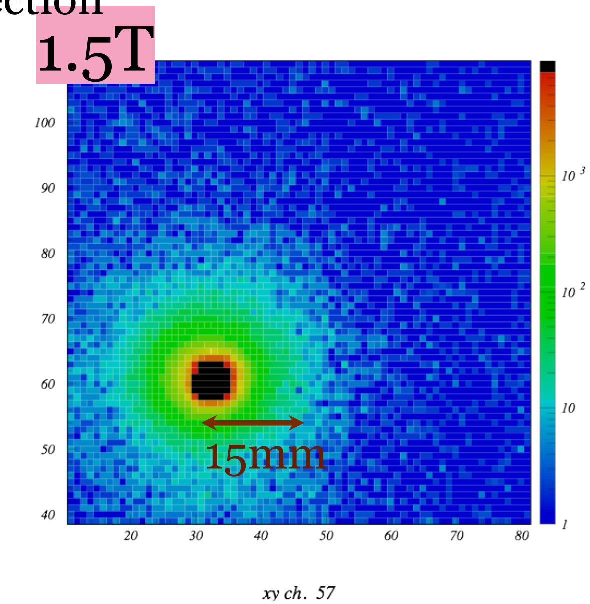
- photoelectrons back-scattered onto the APD surface : significantly reduced when B-field turned on



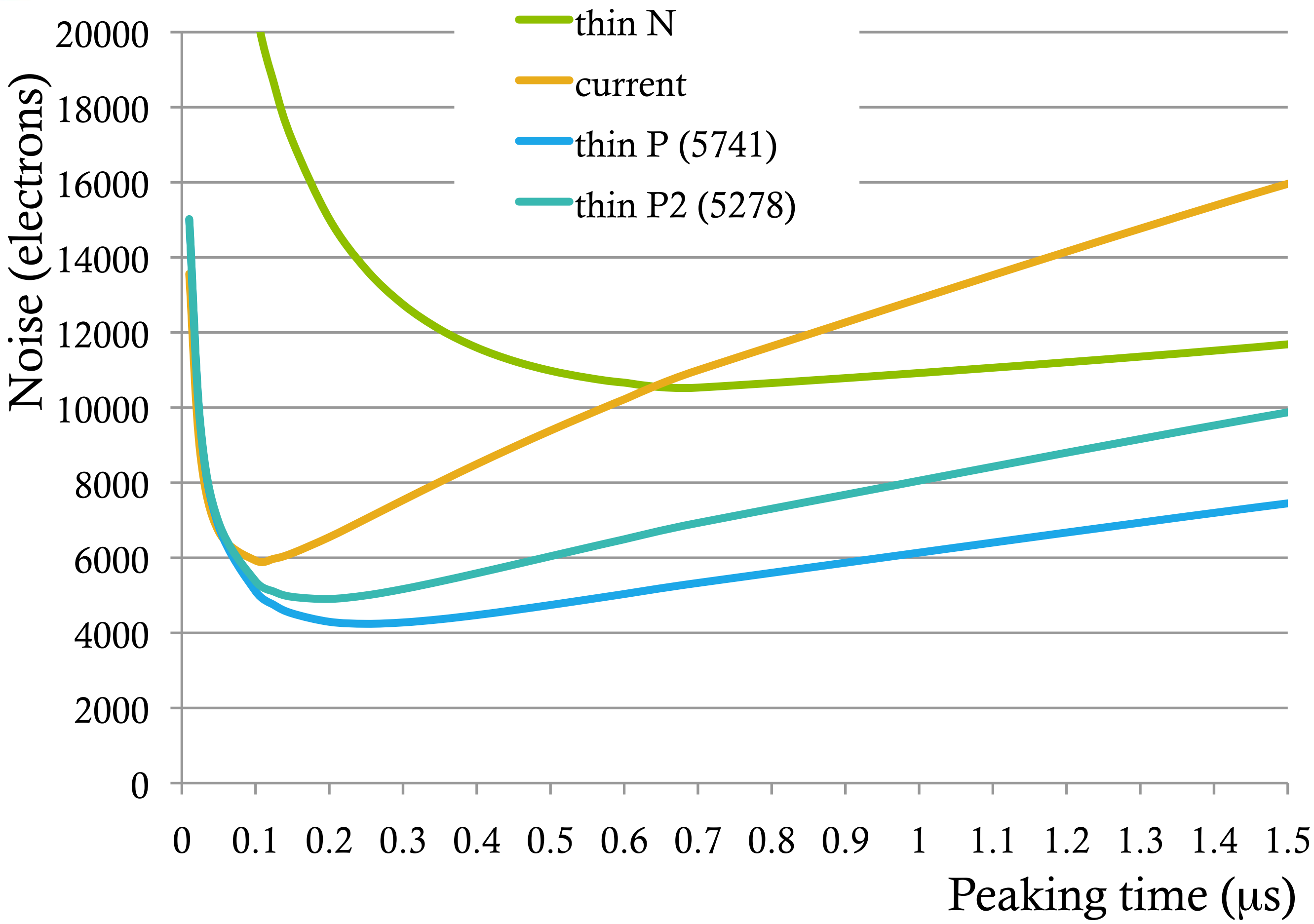


Residual spread can be considered as other effect such as light reflection





Expected noise for HAPD at 10^{12} n/cm^2



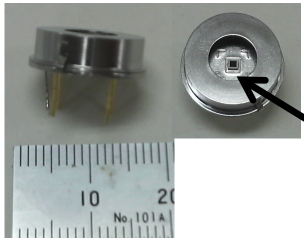
"Current" is calculated by $n^2=1350^2/\tau+(13000)^2\tau$

Neutron irradiation test

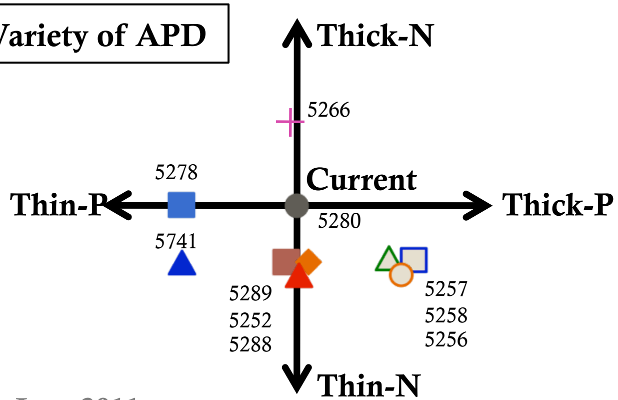
Jan. & June 2010 @Yayoi reactor

We verified neutron tolerance of APD type from increase of leakage current.

Test sample :
Single pixel APD

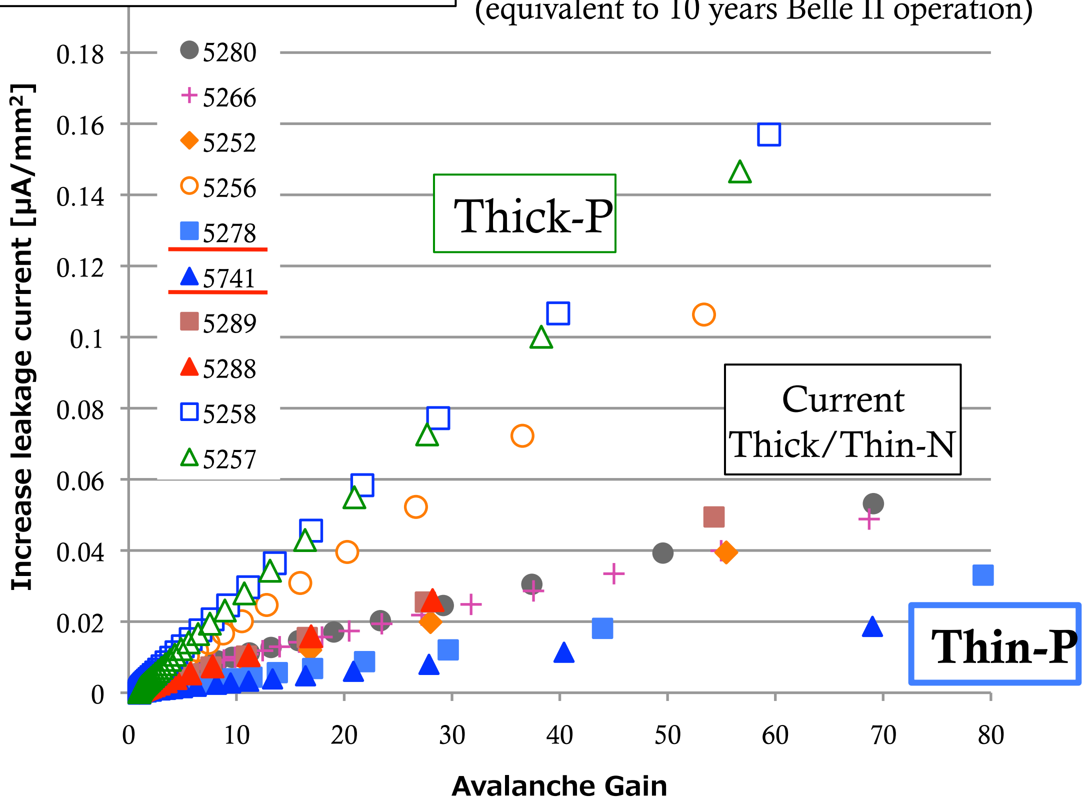


Variety of APD



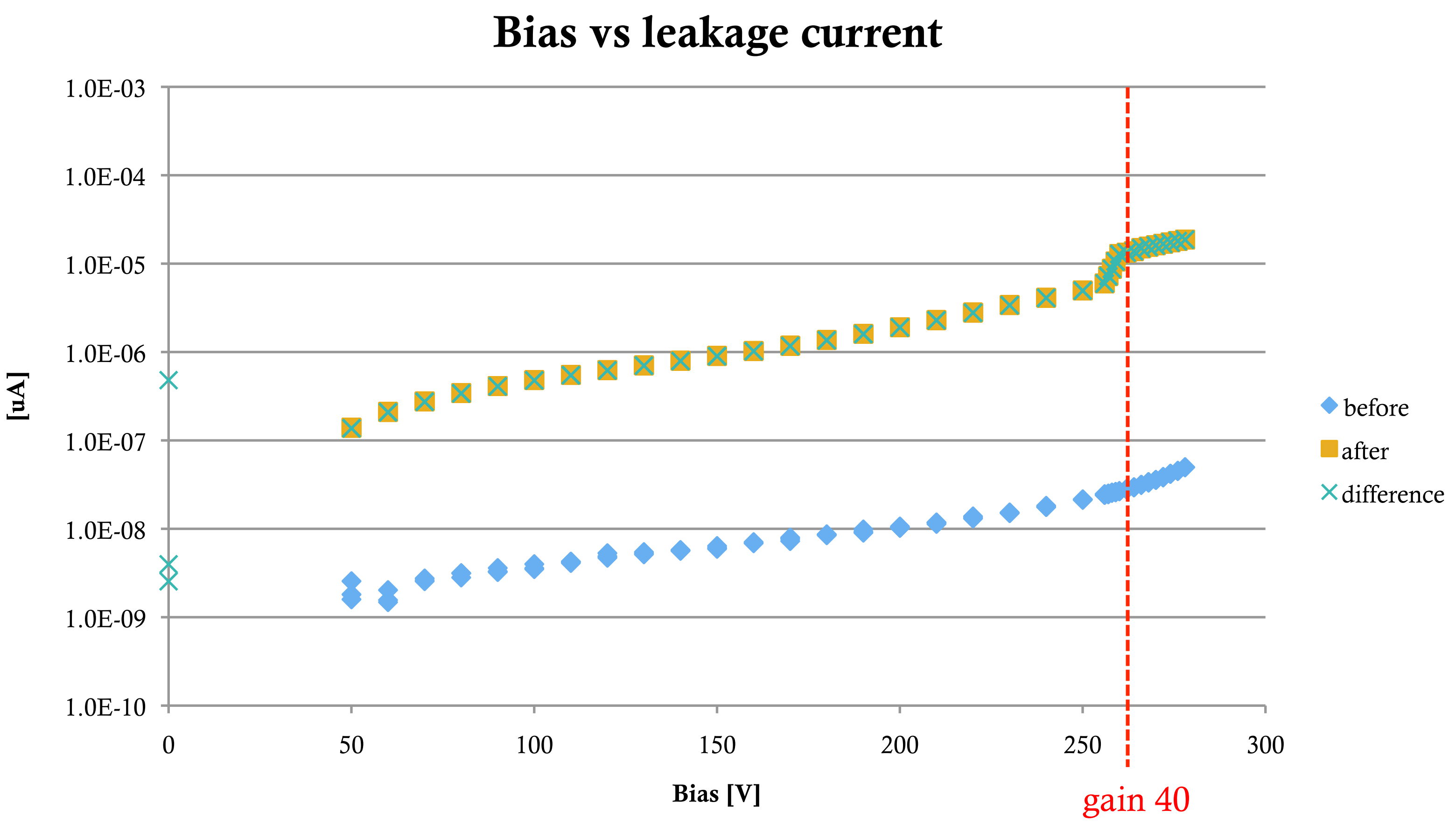
Increase of leakage current

Dose : 10×10^{11} n/cm²
(equivalent to 10 years Belle II operation)



Thin-P gave the smallest leakage current after irradiation.

Thin-P 144-ch APD (5977 chipA)



Neutron irradiation test

Nov. 2010 @Yayoi reactor

Pulse height distribution

Measuring setup