ARICH for Belle II

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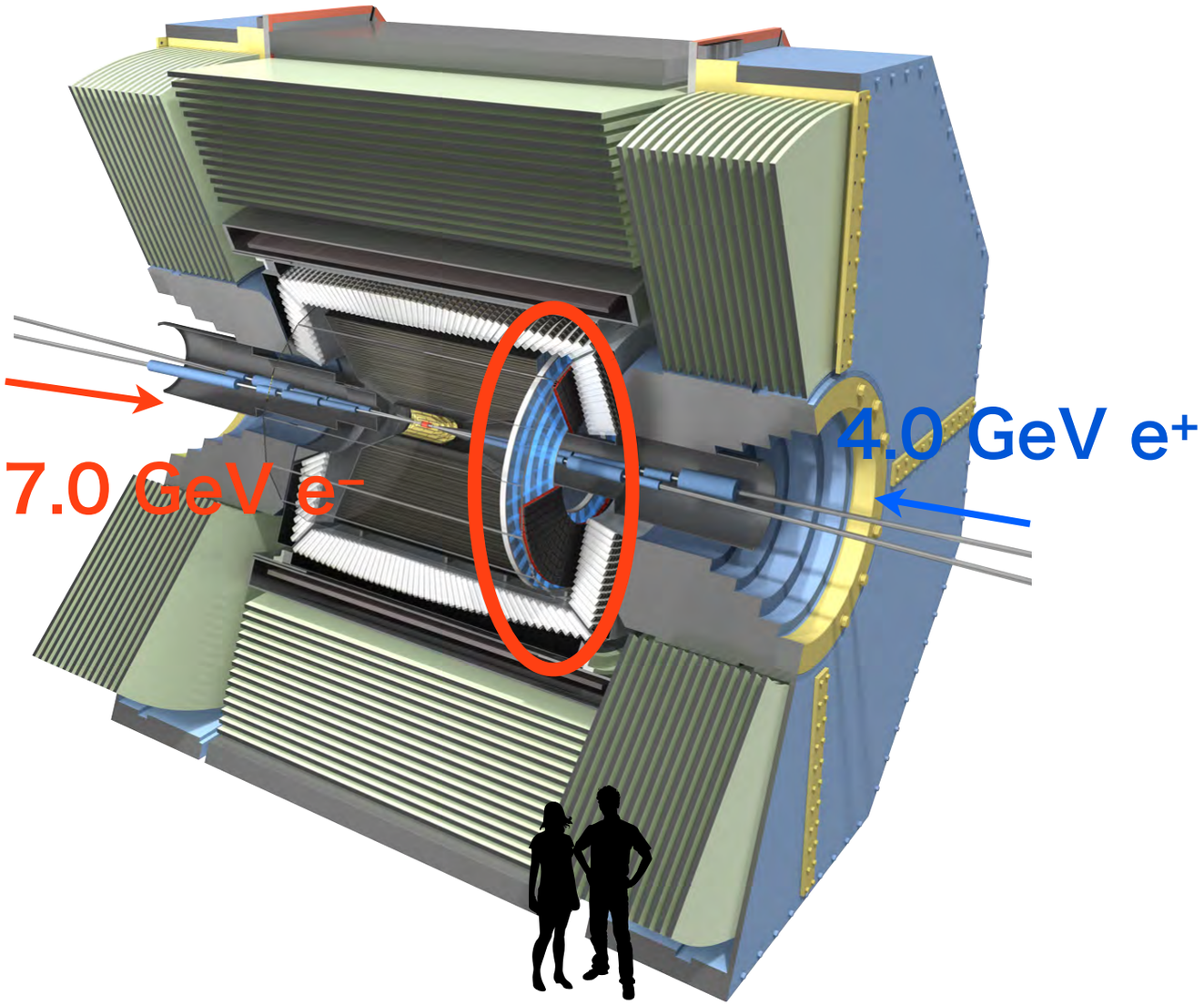
on behalf of Belle II ARICH group

Introduction

Belle is a luminosity frontier B-factory experiment run until 2010.
→ Upgrade for superKEKB and Belle II (to achieve 40 times peak luminosity).
Particle identification (PID) system will be replaced with new detectors.



Belle PID

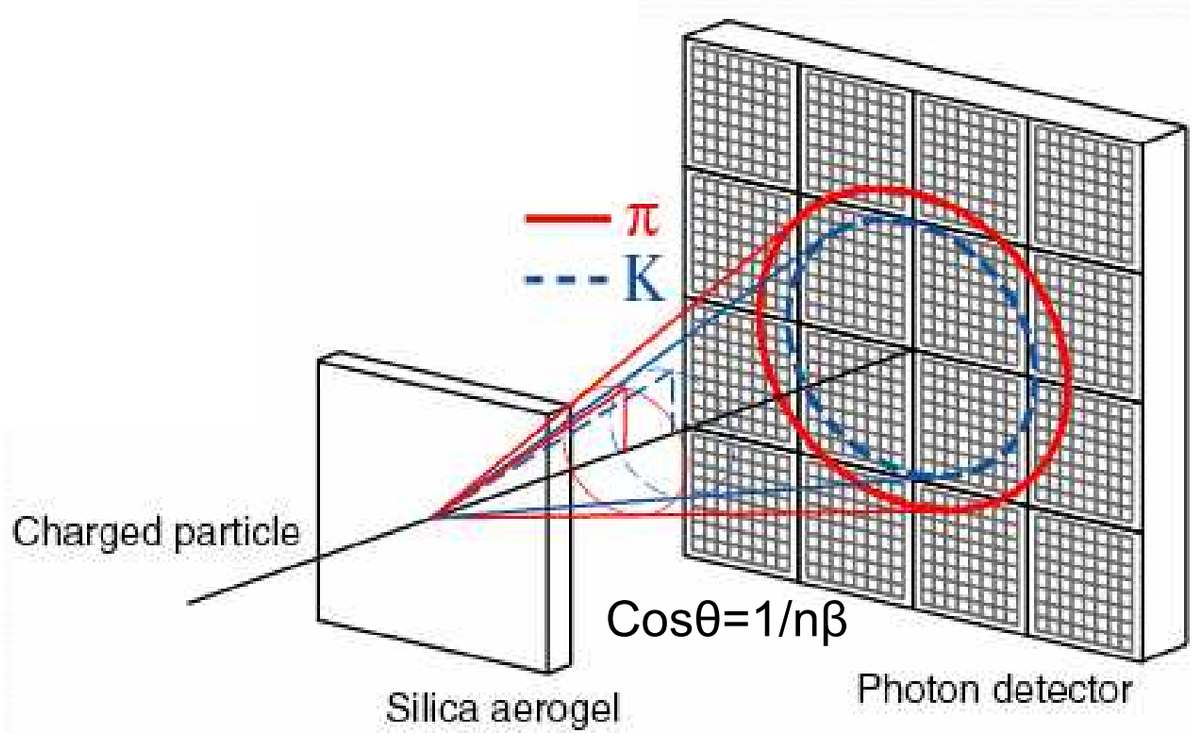
Aerogel Cherenkov Counter (ACC).
Threshold type PID detector.
→ Effective momentum range is not wide enough for all particles from various B meson decays.

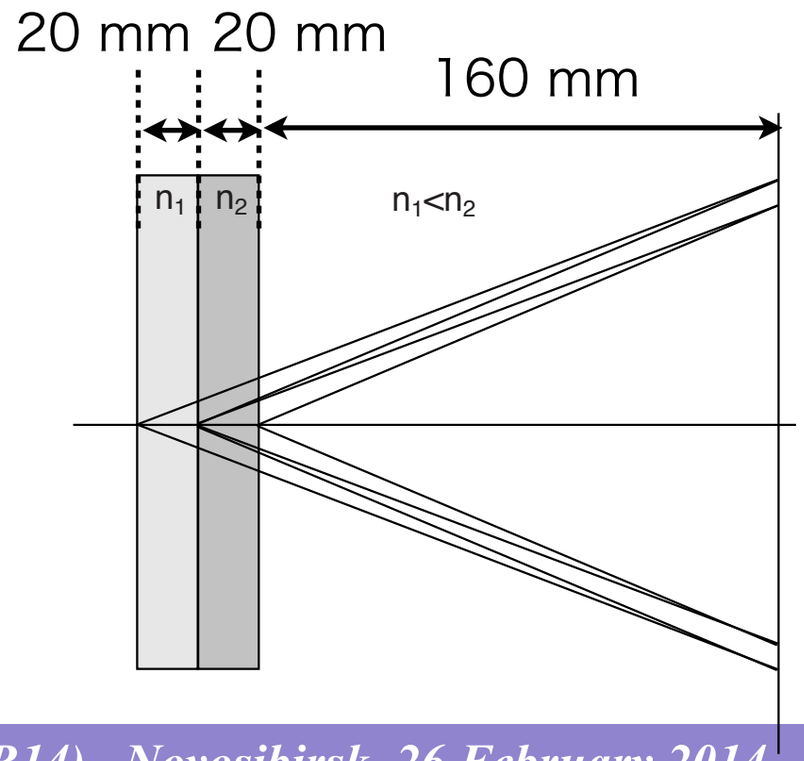
Belle II PID

Two detector systems cover the whole momentum range.
- Barrel part:
  Time Of Propagation counter (TOP).
- **Forward endcap part:**
  Aerogel Ring Imaging CHerenkov detector (ARICH).

Overview of ARICH detector

- Identify particle by difference of Cherenkov angle emitted in aerogel radiator.
  Cherenkov angle $\cos\theta_C = 1/n\beta$
  (n: aerogel refractive index, β: particle velocity)
- Proximity focusing due to limited space between drift chamber and electromagnetic calorimeter.
- Aerogel radiator in the focusing configuration
  (2 layers of aerogel with different refractive indices).
  → Increase photon yield without degrading the single photon resolution.





Requirement for system

- Requirement from physics analysis:

  K/π separation is essential for many B decay modes sensitive to new physics: $B^0 \to K^{*0}(\to K^+\pi^-)\gamma$/ $B^0 \to \rho^0(\to \pi^+\pi^-)\gamma$, $B^0 \to K^+\pi^-/\pi^+\pi^-$ ...

  Target: K/π separation at >5σ confidence level @ p =4 GeV/c.

  Separation = $\Delta\theta_C\sqrt{N_{p.e.}}/\sigma_C$

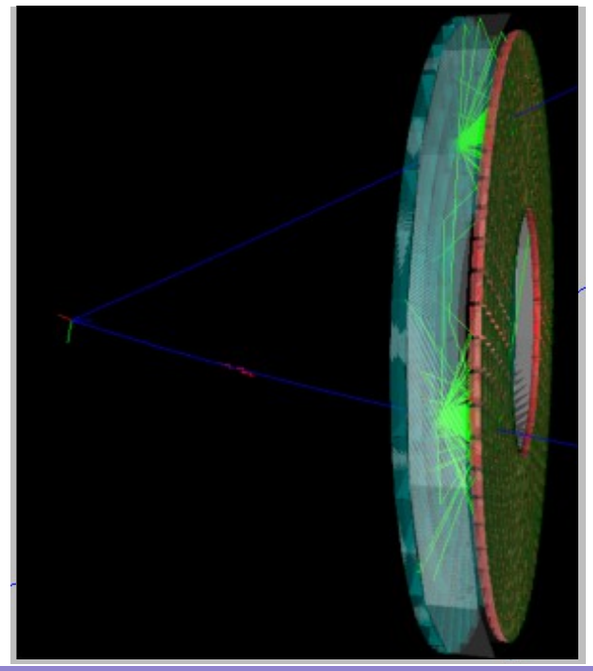
  $\Delta\theta_C$: Difference of Cherenkov angle between K and π (~23 mrad)

  σ_C: Observed Cherenkov angle resolution.

  $N_{p.e}$: Detected number of photo electron.

  } ⇒ Highly depends on detector performance.

- Survives in Belle II environment for 10 years.
  Radiation hardness both for γ/neutron.
- Works in high background environment.
- Covers acceptance of other sub-detectors along beam direction.
  → Round shape detector in endcap region.



Photon detector

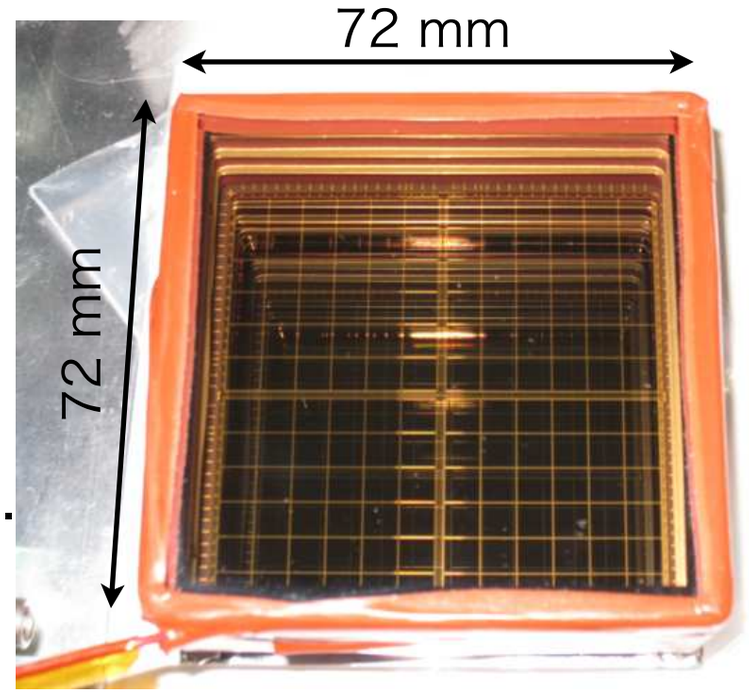
- Detect photon position with good resolution.
- Number of detected Cherenkov photon is not large.
  (~10 photons/charged track)

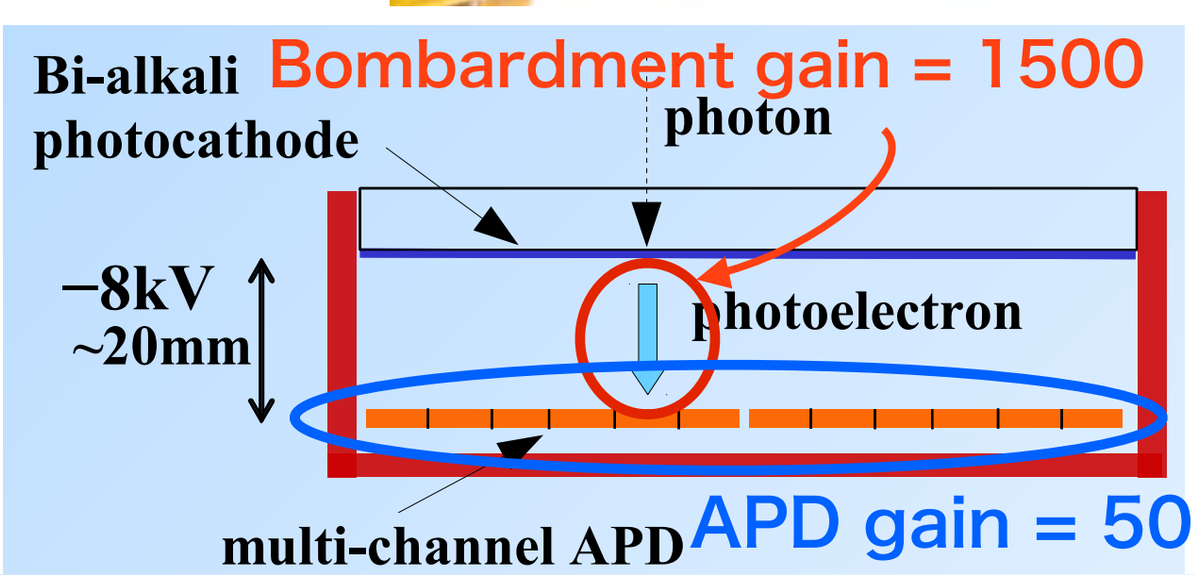
⇒ **Hybrid Avalanche Photo Detector (HAPD)**
is developed with Hamamatsu Photonics K. K.

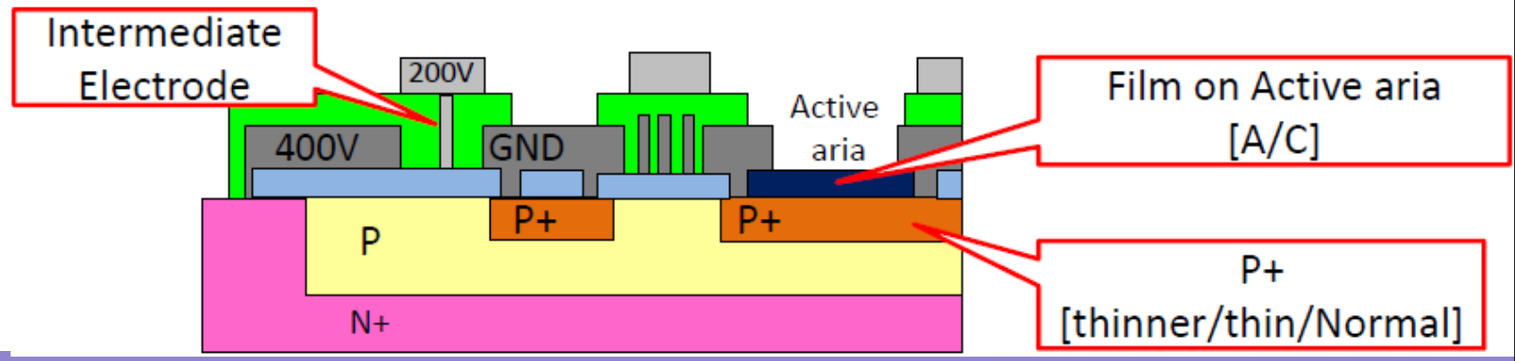
5 mm pitch pixelated 12×12 channels cathode APD.
High gain with hybrid amplification process.
Total gain ~7×10^5.
⇒ capability for single photon.

420 HAPDs are used in total for ARICH.

APD design is optimized considering results of γ /neutron radiation hardness test.
Tolerance for >10 years
Belle II operation. (1000 Gy γ,
1.0×10^{12} neutron / cm^2)







Validation for HAPD

Before installation to ARICH, all HAPD samples are checked.

- Leakage current and noise level without illuminating light.
- S/N and 2D scan with laser light source and readout ASIC.
- Quantum efficiency (QE) of photocathode.

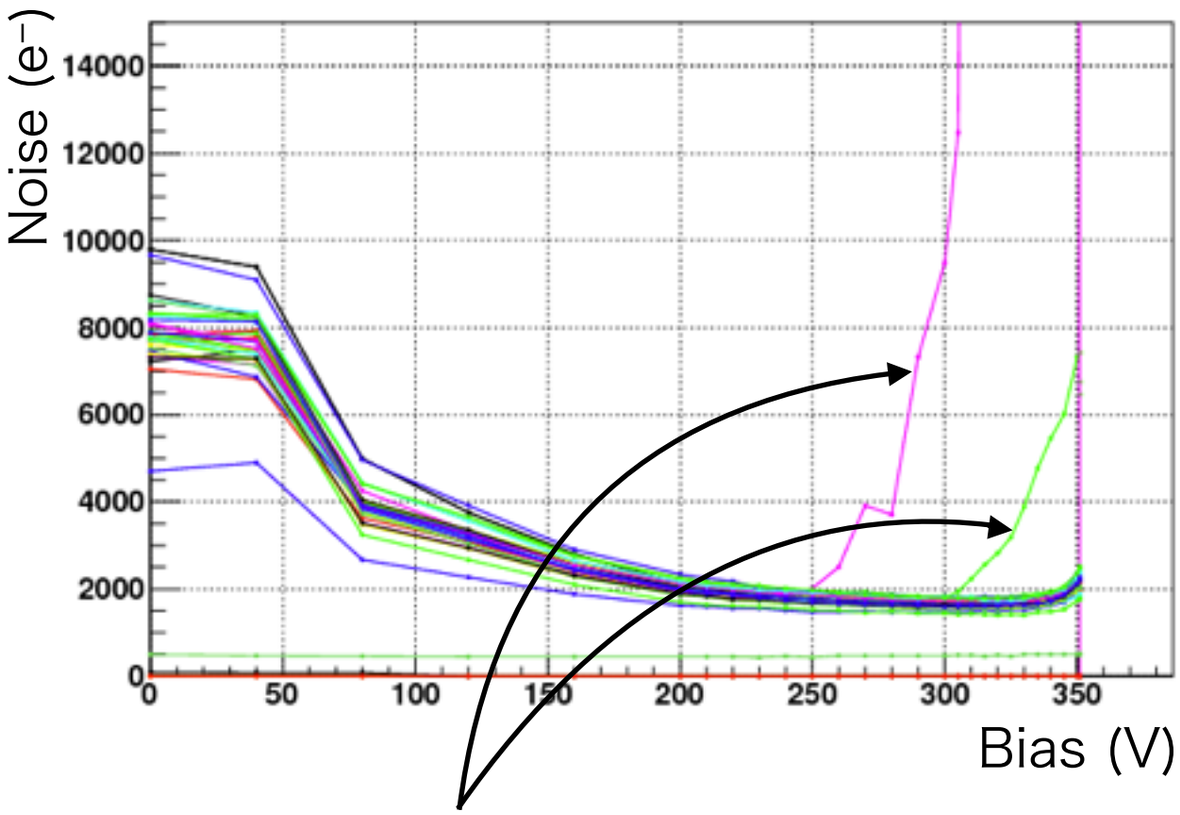
→ Confirm data sheet performance/Check unexpected problem and feedback to Hamamatsu.

HAPD various factors

item		typical	requirement
QE	λ=400nm	28%	>=24%
bias voltage		250-500V	
leakage current	each ch at Vb-10V		<= 1μA
avalanche gain	each ch at Vb-10V		>=30
HV	-8.5kV		<= 300pA
bombardment gain	-8kV	1800	>=1500
Total gain	-8kV at gain=30		>=45000
# of dead channels			≦ 10

Validation for HAPD

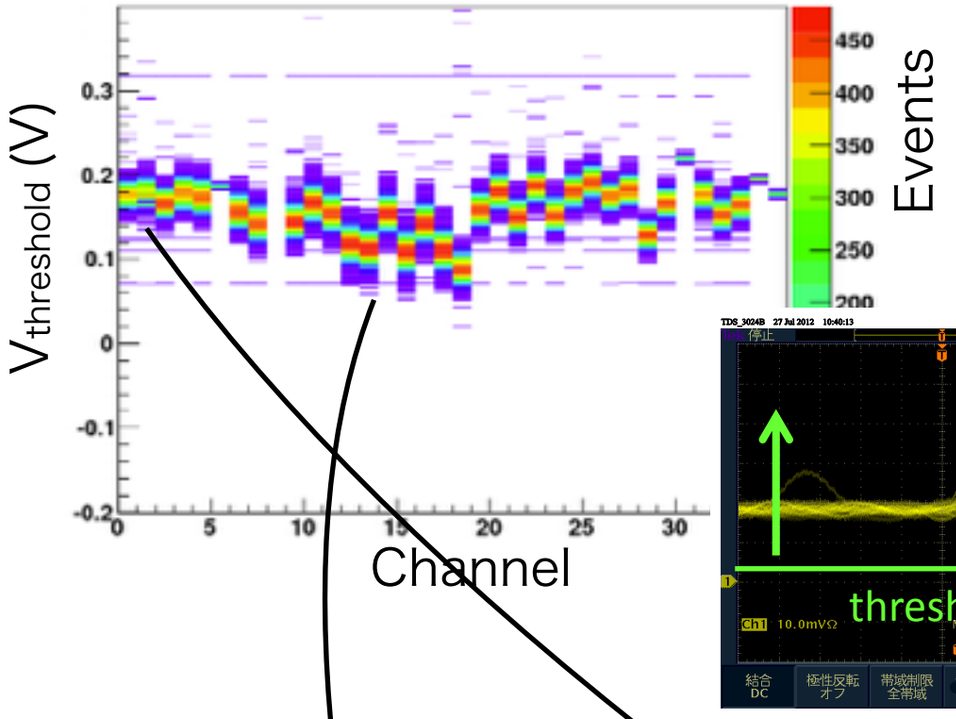
Noise-bias dependence without light



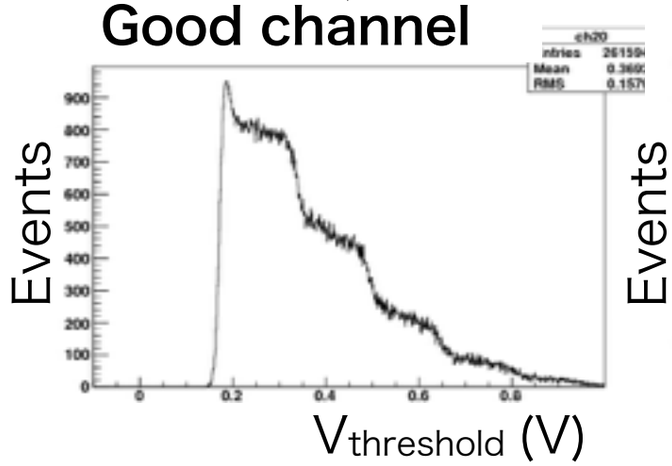
Noisy channels

Some of them are found after delivered to KEK.

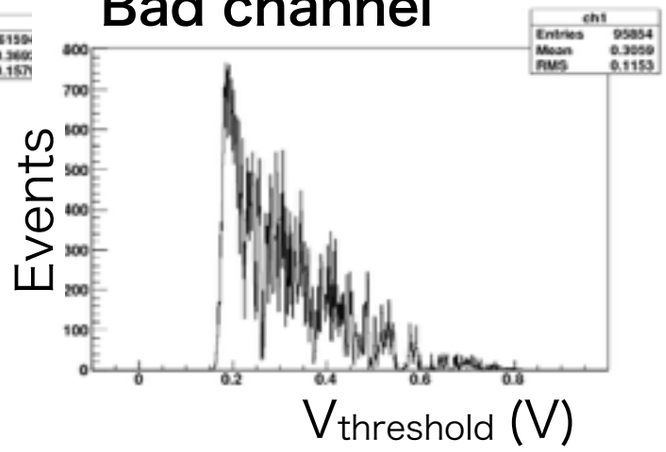
Signal-to-noise check (Pulse hight by changing threshold)



Good channel



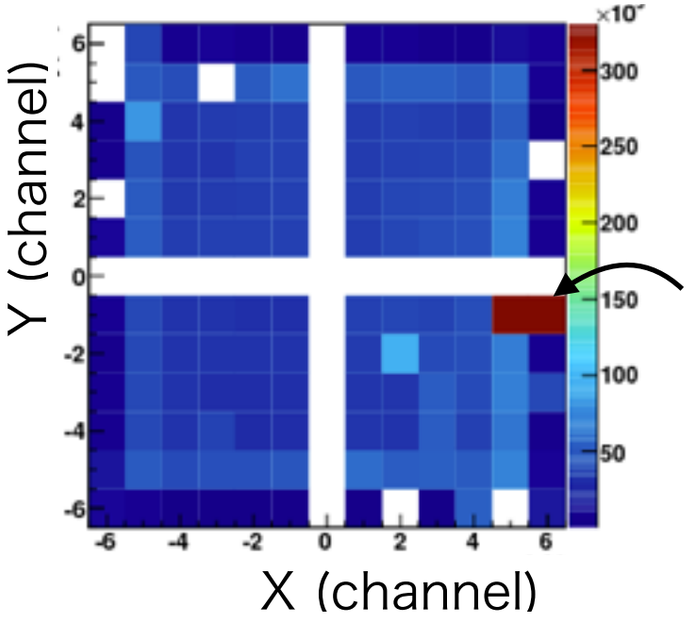
Bad channel



Check HAPD correctly identify pulse of n p.e. signal.

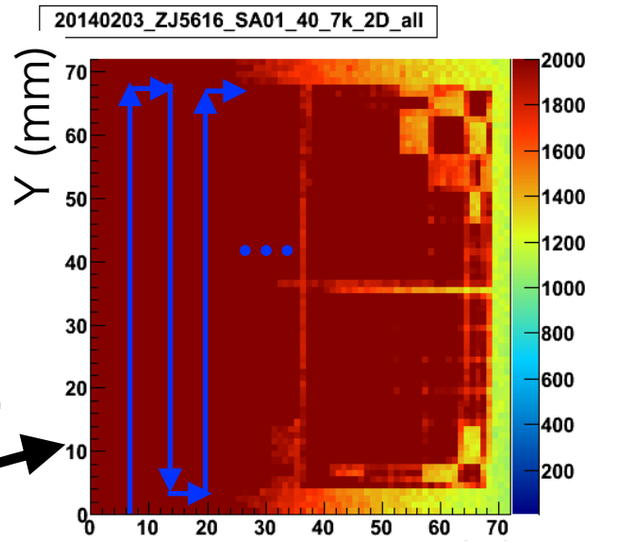
Validation for HAPD

Channel hit map with laser emission

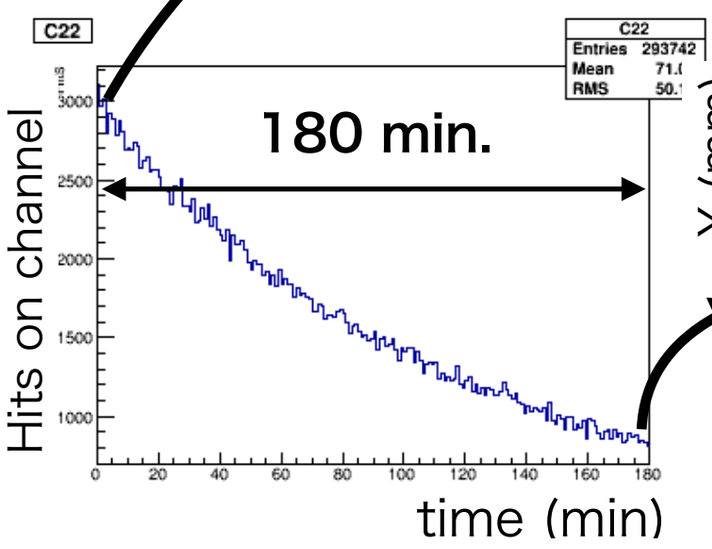


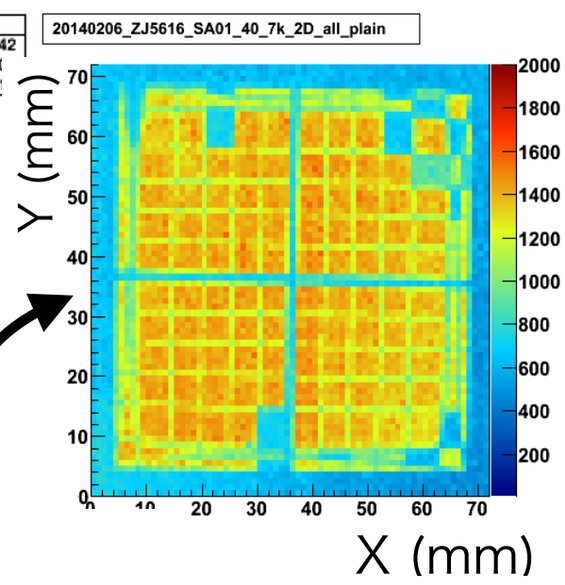
Noisy channels

In some samples, large noise is overlapped at beginning of scan.

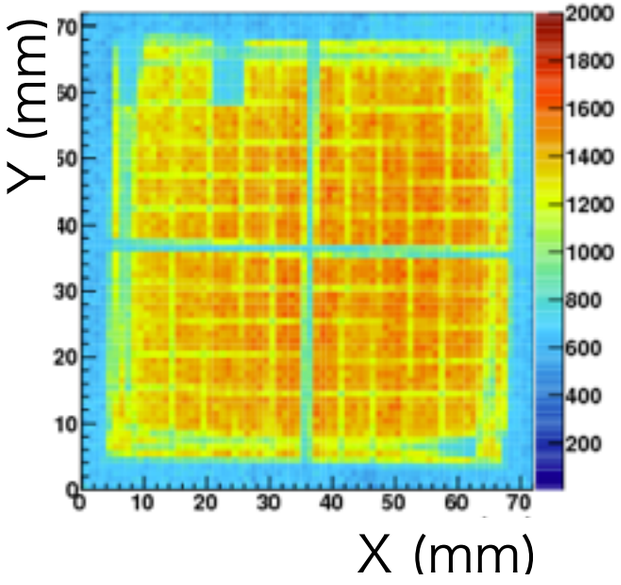


Scan laser light motion

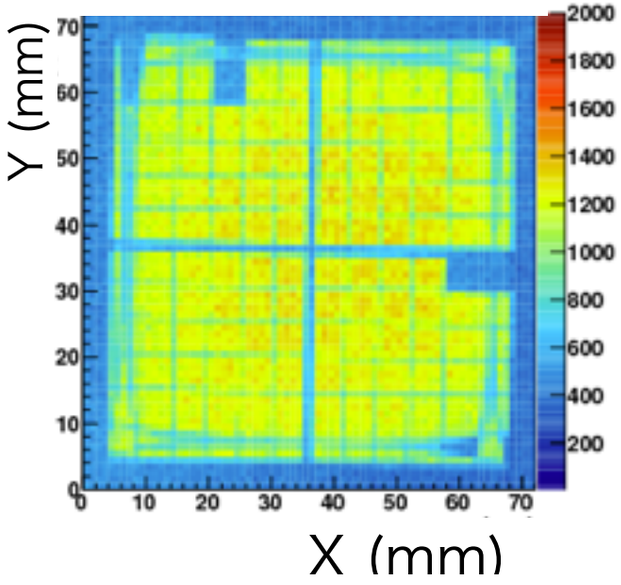




2D scan result without mask



After masked

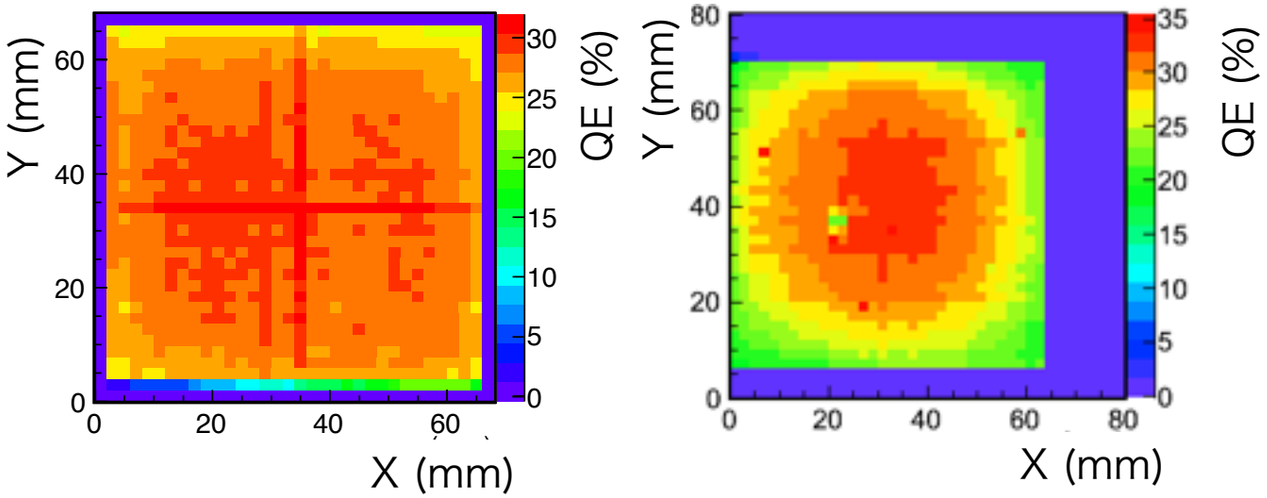


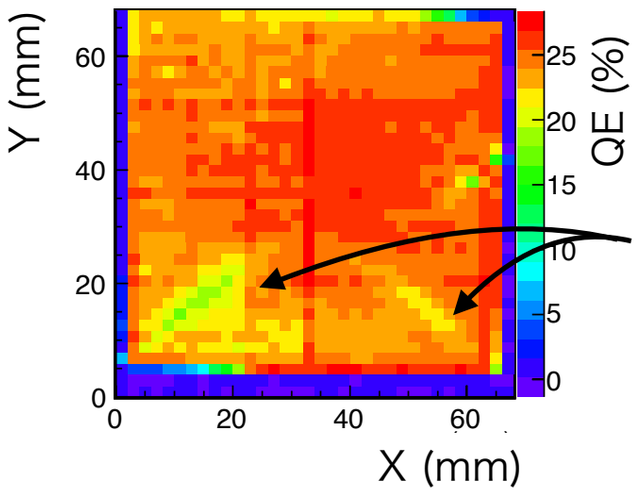
A part of HAPD dark noise depends on the time after exposing to environmental light. (sample dependent)

Validation for HAPD

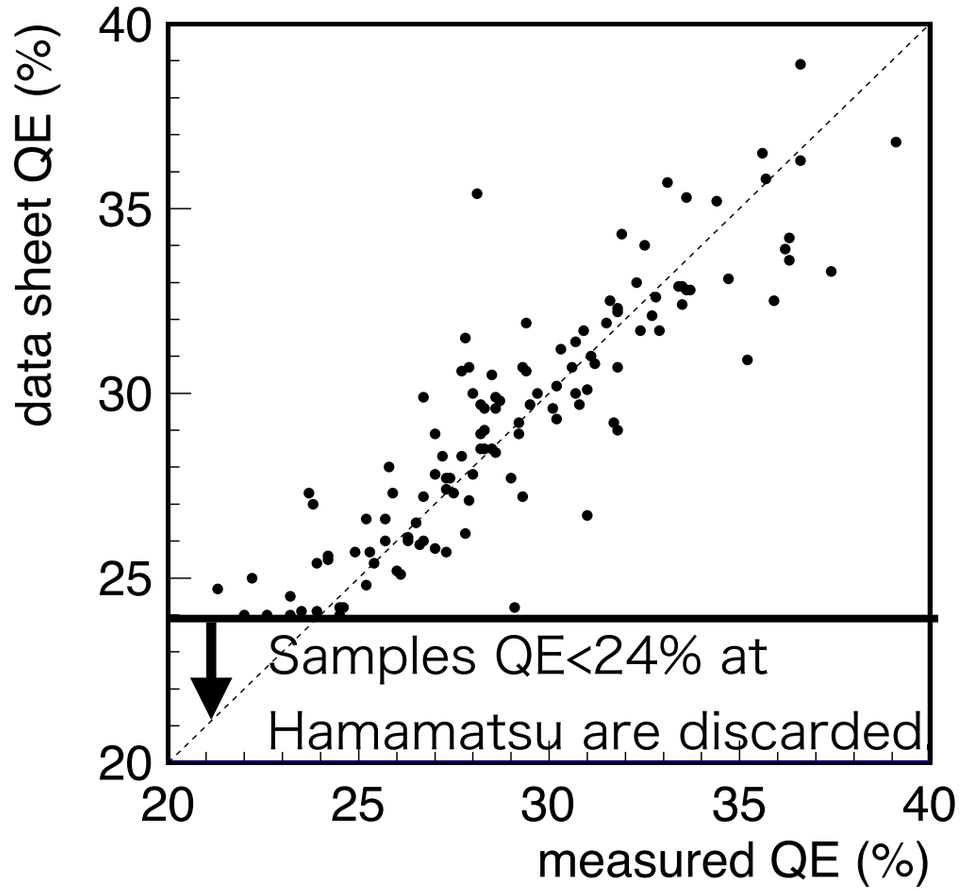
Quantum efficiency (QE) scan on photocathode with light (λ=400nm)

- Average QE in effective area satisfies requirement (>24%)
- No damage on photocathode.
- Flatness of distribution.





In some sample, unexpected low QE region along diagonal line of photocathode.
→ Under investigation.

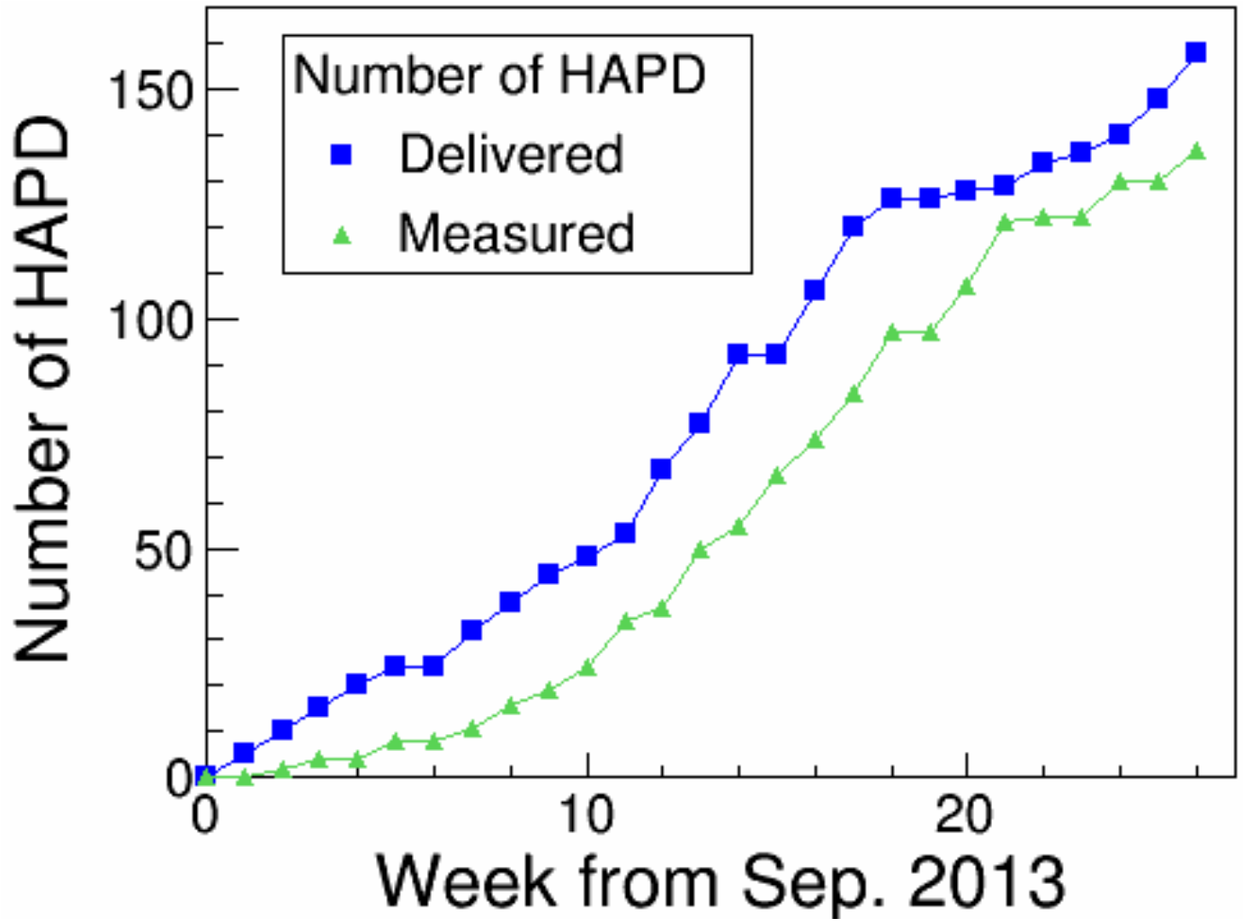


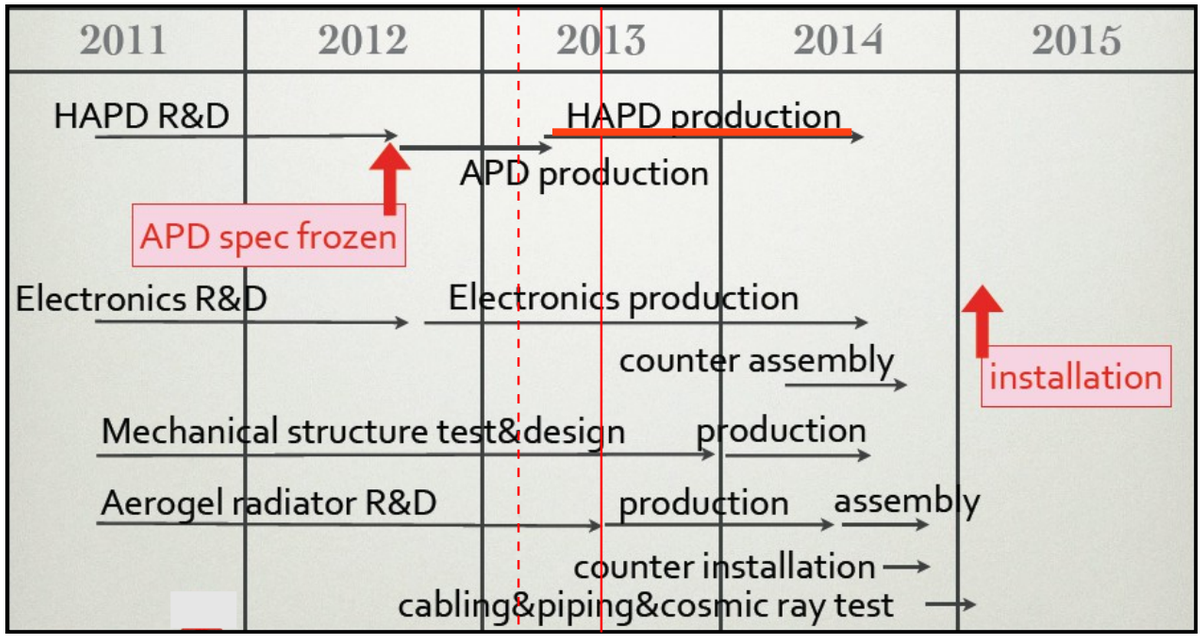
Measured QE is consistent with data sheet from Hamamatsu within a few %.
Some of measured QE are below requirement.
→ Checking the discrepancy between data sheet is real.

Validation for HAPD

Mass production of HAPD has been started in last September.
Validation measurement keeps up with sample delivery from Hamamatsu.
All produced 450 HAPDs will be measured before ARICH construction starts.

History of HAPD measurement

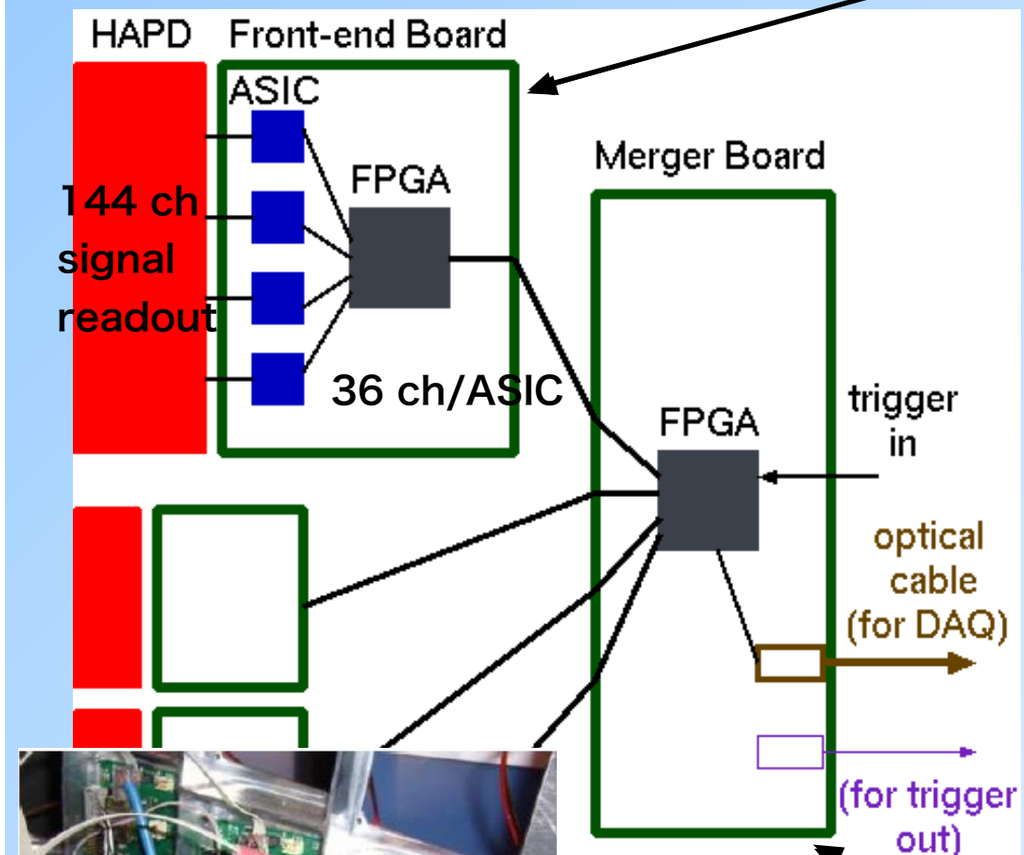




HAPD front-end readout

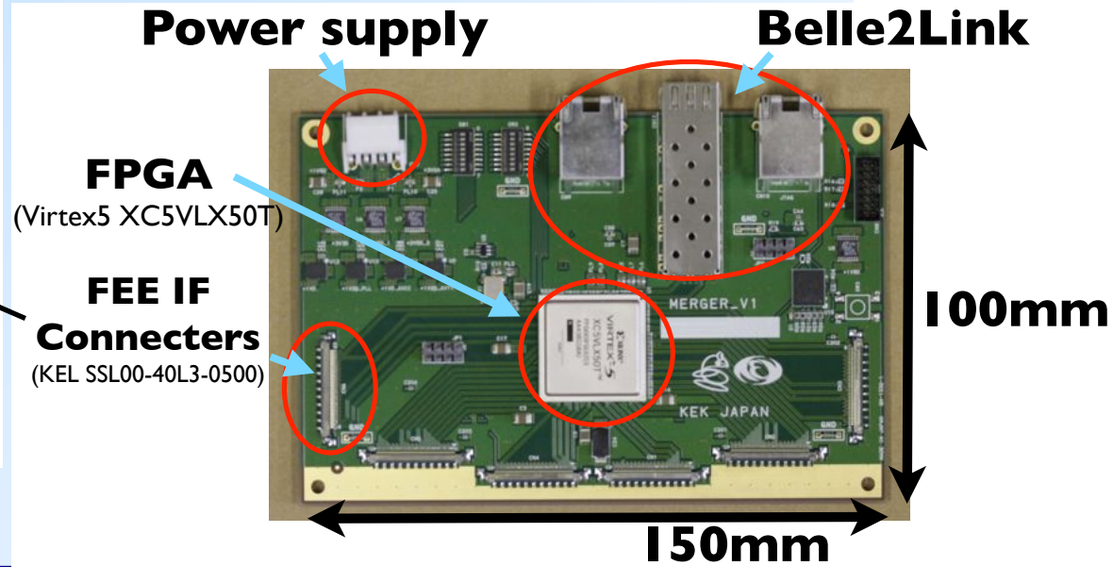
144 channels of signal from HAPD is digitized by ASIC in front-end board.
Data from 5 or 6 front-end boards is integrated by merger board.
→ send to Belle II global DAQ readout through optics cable (Belle2Link).

ARICH readout electronics



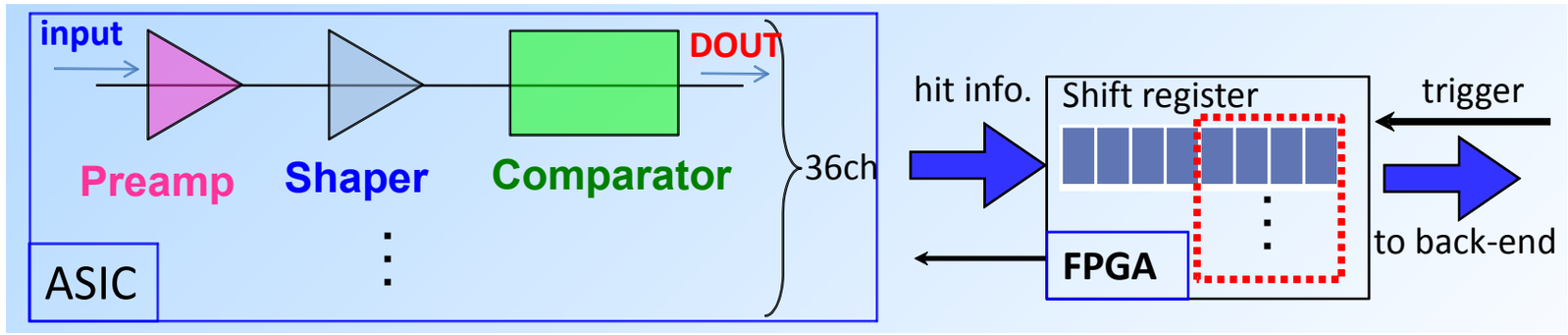
• Front-end board with 4 ASICs and Spartan6 FPGA

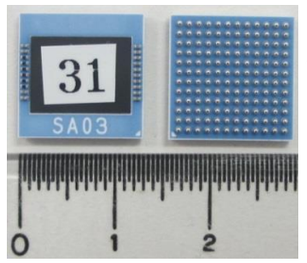
• Merger board prototype with Virtex5 FPGA



HAPD front-end readout

Settings of ASIC (gain, peaking time, offset level) are controlled by FPGA.
Hit information is stored on shift register in FPGA and send to back-end in response to trigger input from Belle II global DAQ.
Mass-production of ASIC for front-end electronics starts.



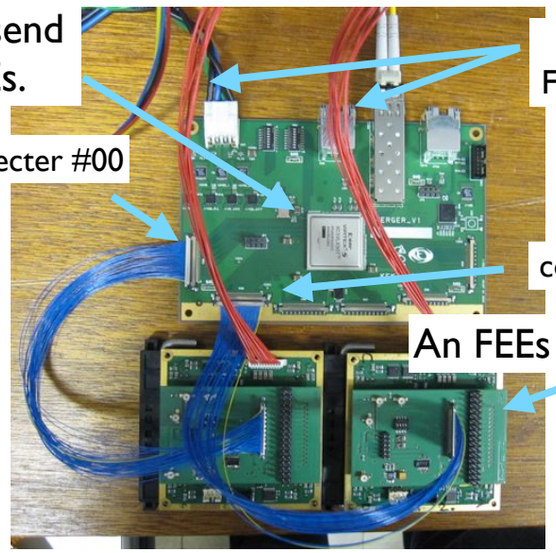


ASIC
LTCC
package

Prototype of merger is ready and tests (slow control, readout, FPGA configuration…) are ongoing.

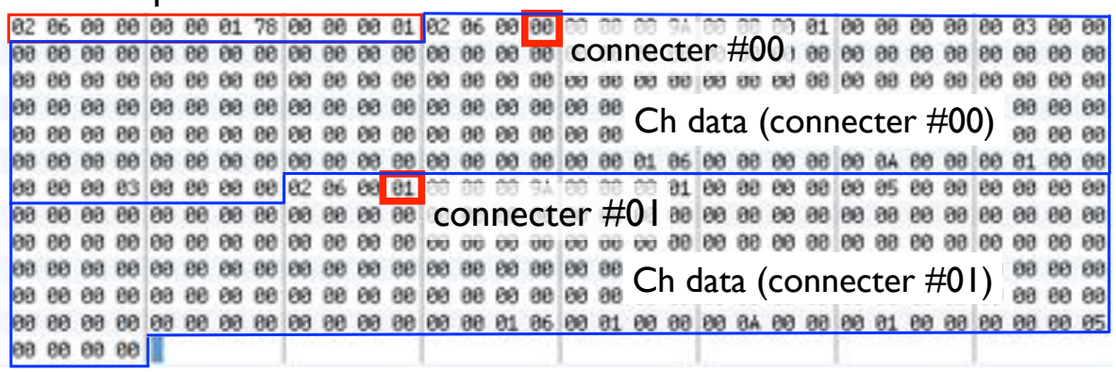
Merger and FEE test

The merger board send a test trigger to FEEs.



Start of data

Event packed header



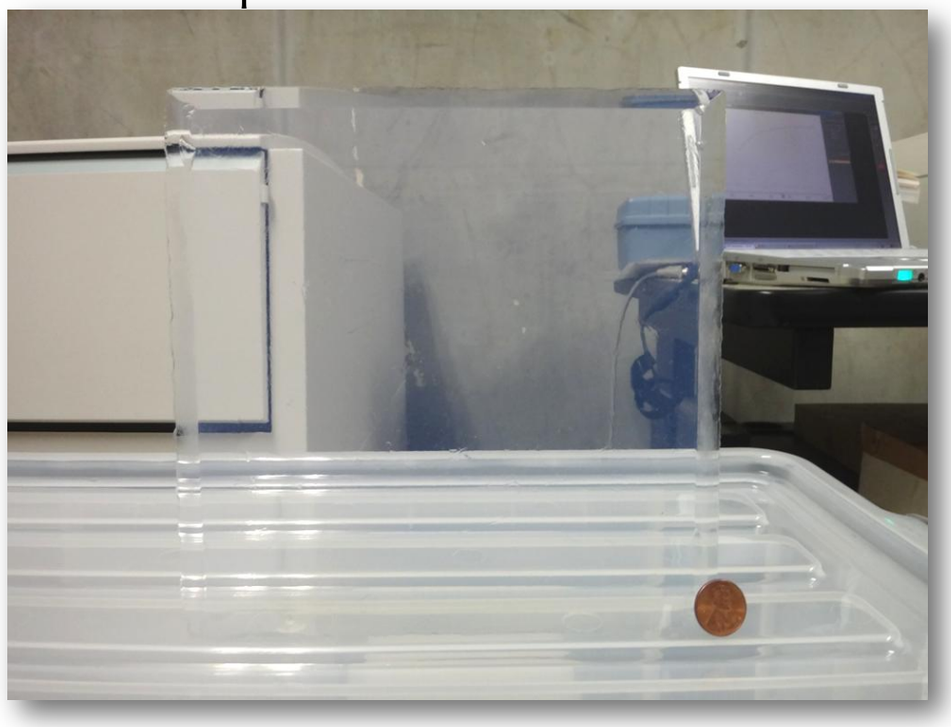
Data from 2 front-end boards is correctly transferred through merger. Further test is ongoing.

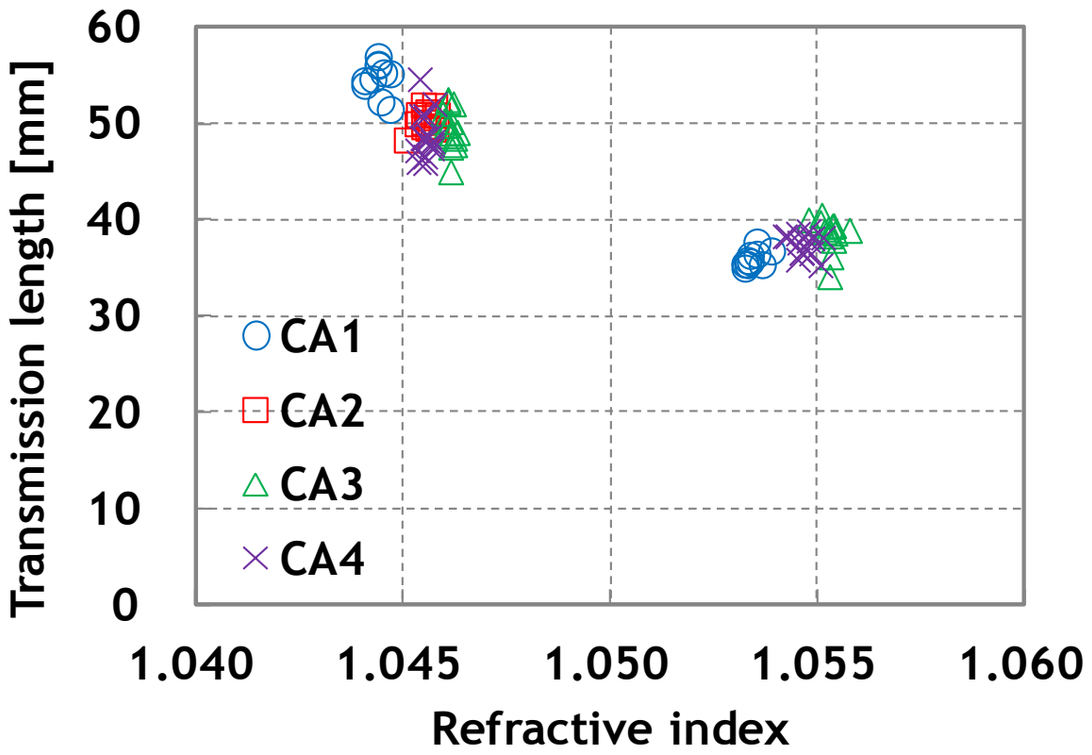
Aerogel radiator

- Distance between aerogel and HAPD window is 200 mm. ⇒ refractive index ~1.04-1.06
  From beam test results, we decide to use combination of two aerogels whose refractive indices are1.045 and 1.055.
- Need to be transparent to suppress photon scattering.
  Target transmission length @λ = 400 nm:
  >40 mm for refractive index = 1.045,
  >30 mm for refractive index = 1.055.

In total, 280 tiles are used for ARICH.
Mass-production has been started.
At the end of January, 150 tiles are available.
100 tiles are checked.
92% samples are crack-free and most of them satisfies requirements for optical performance.

First sample for ARICH construction

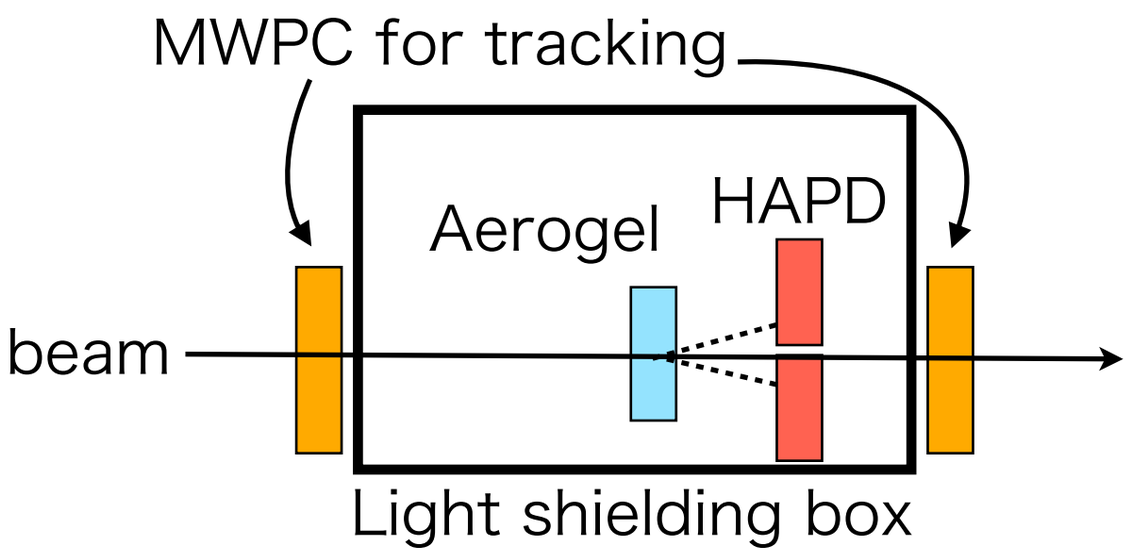




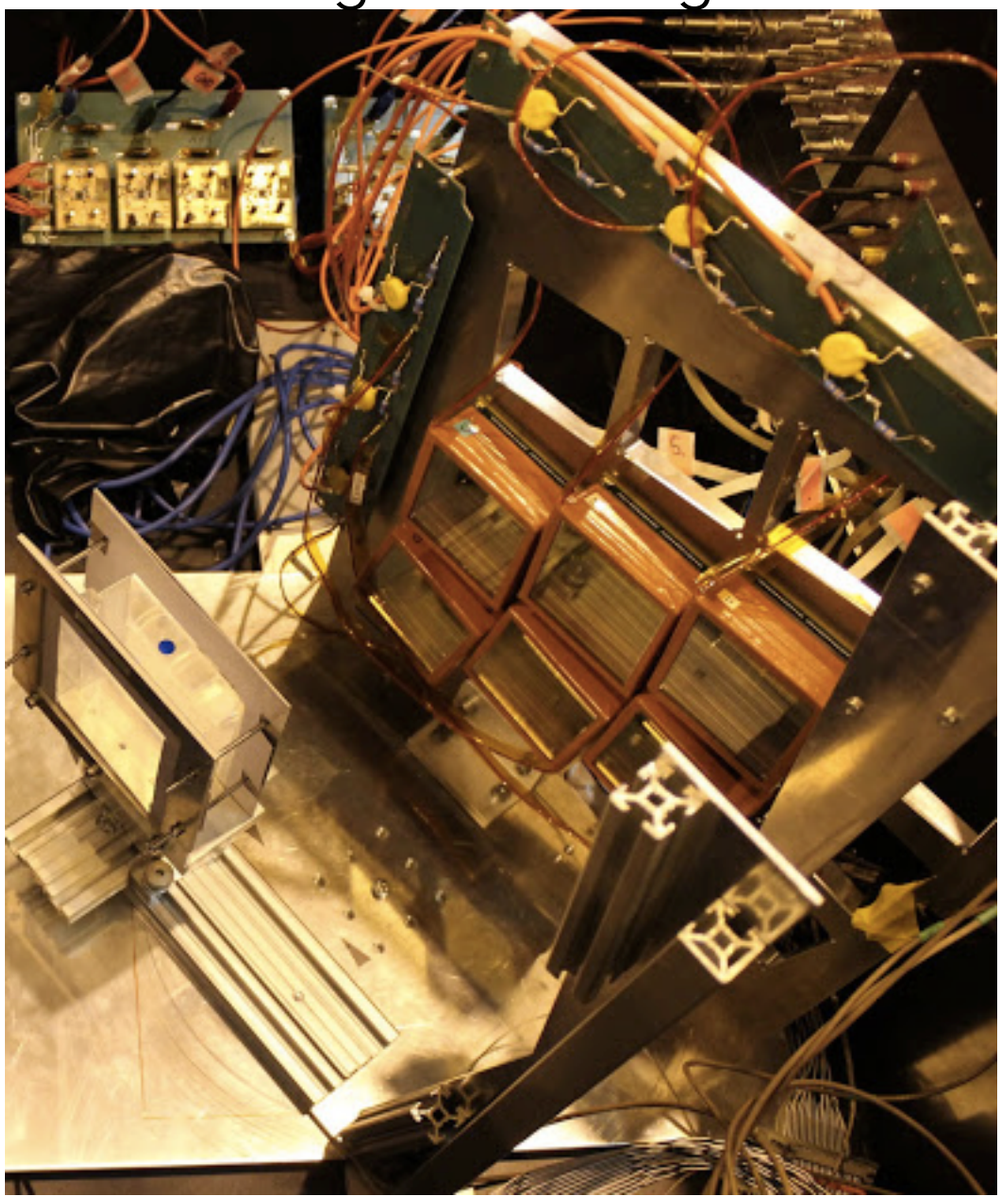
Beam test

Setup prototype ARICH with 6 HAPDs in real geometry and check performance for hadron beam @SPS in CERN and electron beam @DESY and Fuji exp. hall in KEK.

Several setups and checks of performance.
- Different refractive index of aerogel.
- At different track incident angles.
- Readout front-end ASIC settings.
- Neutron/γ irradiated HAPD.



Picture in light shielding box



Beam test result

- Simple performance estimation from cumulative Cherenkov angle distribution:

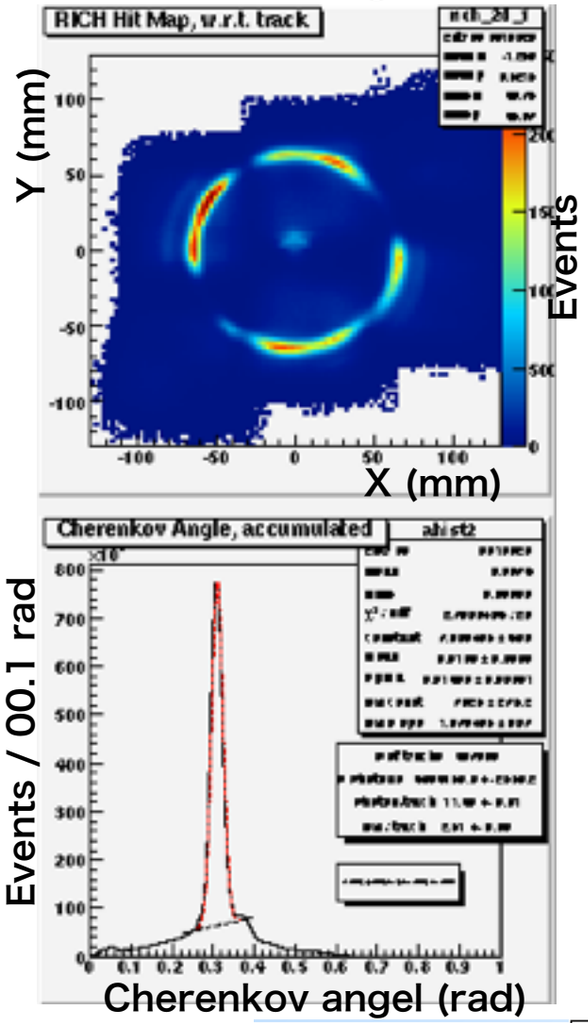
  $\Delta\theta_C$ = 14.1 mrad, $N_{p.e}$ = 11.4.

  ⇒ K/π separation = 5.5σ

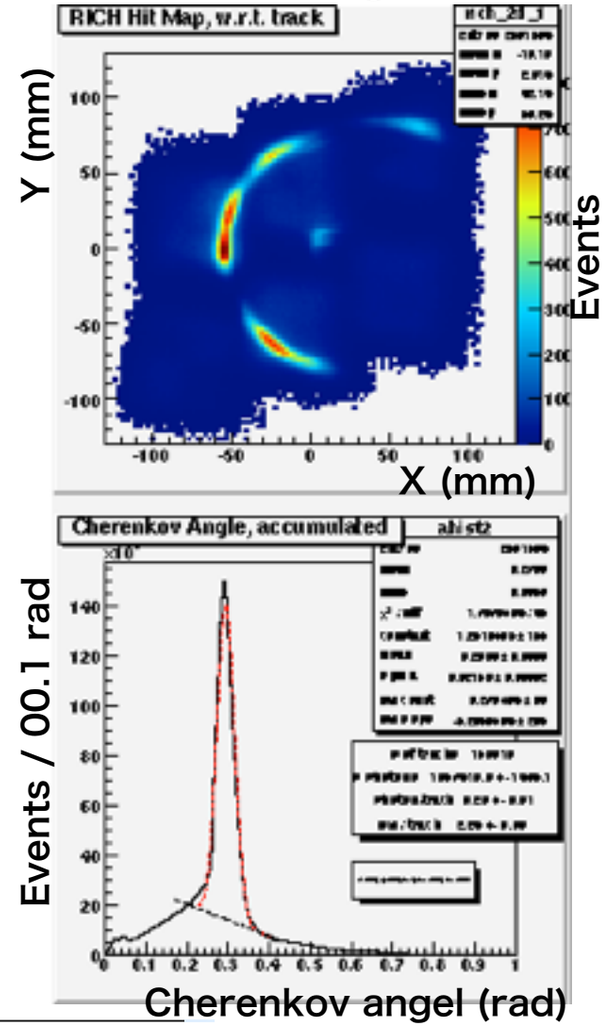
  (SPS 120 GeV/c hadron beam, incident angle = 0° case, similar for non-zero incidence)

- Neutron/γ irradiated HAPD works well after HV/readout parameter tuning.

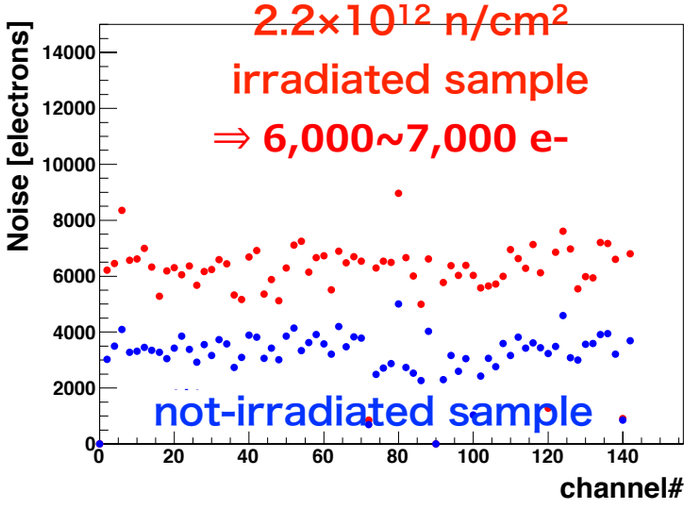
Incident angle = 0°



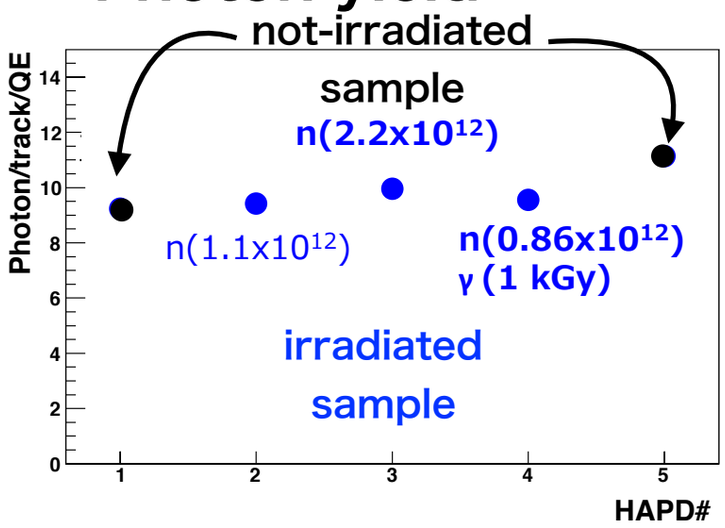
Incident angle = 30°

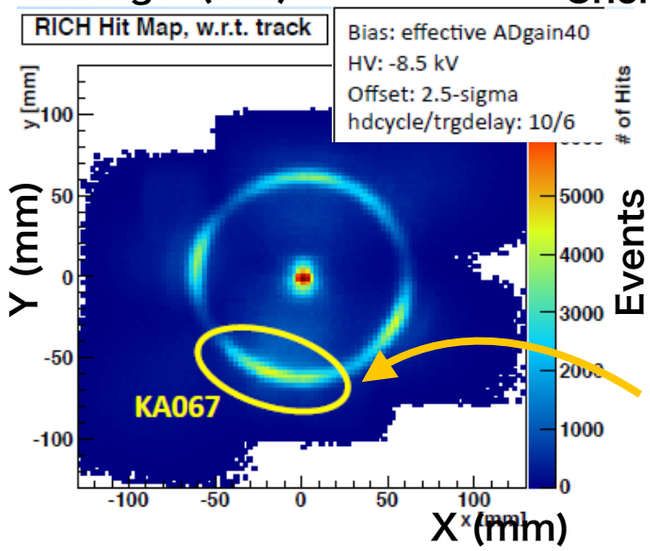


Noise level



Photon yield





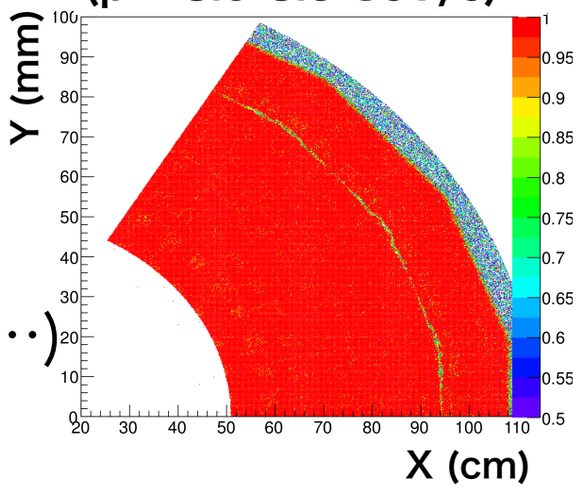
Ring image from irradiated HAPD

Simulation study

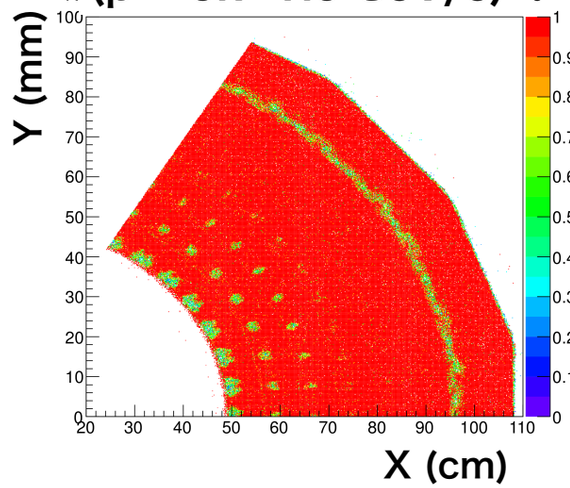
GEANT4 based study with full Belle II configuration is done and analysis software (reconstruction, probability calculation…) is developing.

→ Confirm good PID performance for several conditions. (background level, HAPD spec.…)

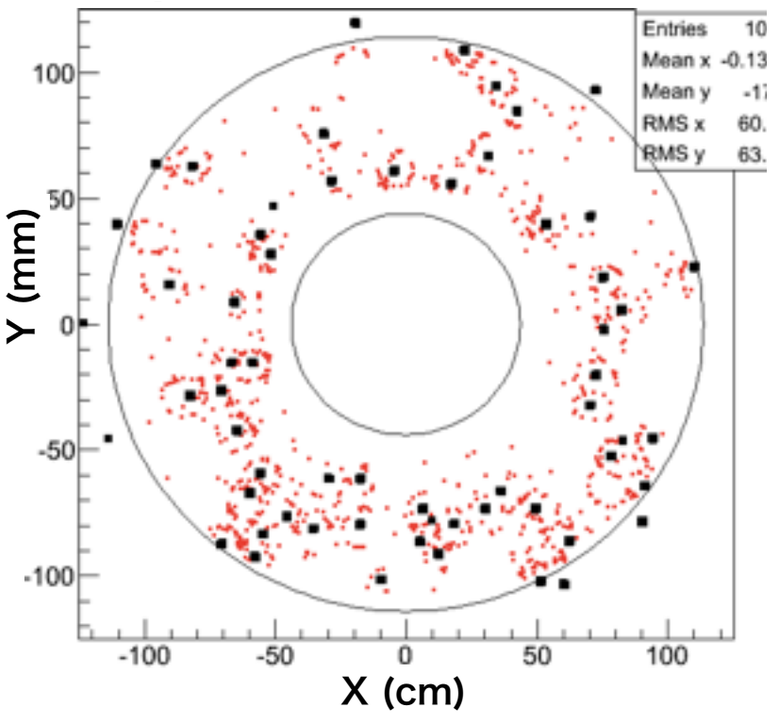
Kaon efficiency for high momenta track (p = 3.0-3.5 GeV/c)



Kaon efficiency for low momenta track (p = 0.7-1.0 GeV/c)



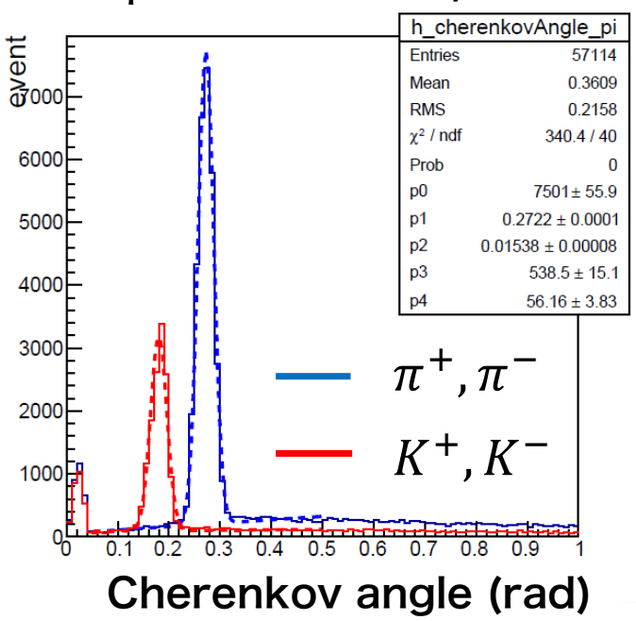
Accumulative photon hit map in ARICH (100 tracks)



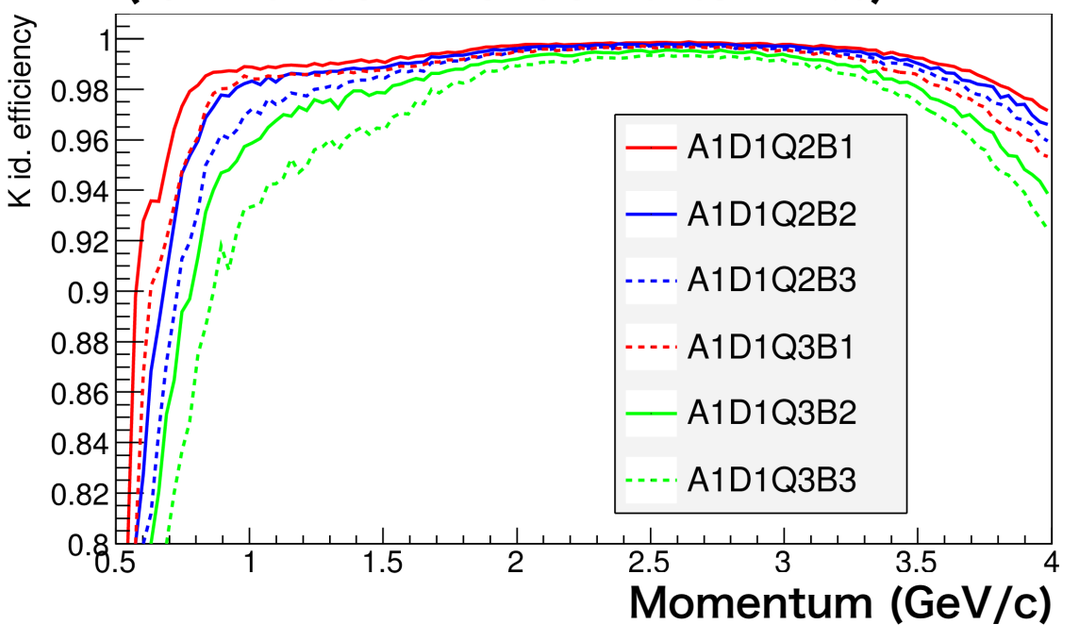
■ track cross point on ARICH

• photon hit position in ARICH

p = 2.0 GeV/c



Kaon efficiency for several conditions (π mis-identification tate = 2%)



B1 – +0 background hits (0.56 bkg photons per ring)
D2 – +70 background hits / m^2 (0.95 bkg photons per ring)
D3 – +140 background hits / m^2 (1.35 bkg photons per ring)

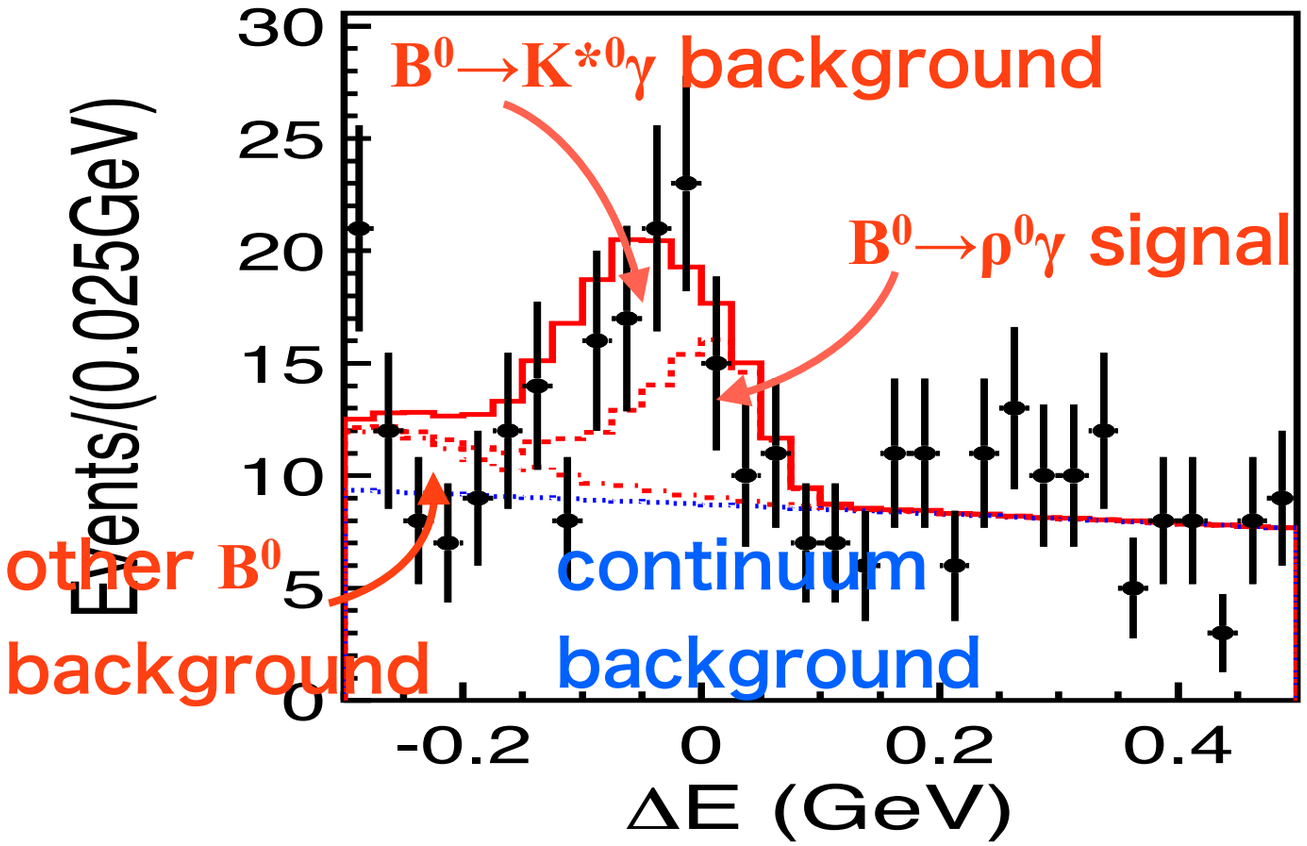
Q2 – Q.E. peak = 30% Q3 – Q.E. Peak = 24%

Summary

- **For endcap PID in Belle II, ARICH detector will be installed.**
  Identify charged particles using information of Cherenkov ring image.
- **To detect Cherenkov photon position with high efficiency, a new device (HAPD) has been developed.**
  Hybrid amplification with electric field between photocathode and sensor part and 5 mm pixelated 144 channels APD (total gain ~7×10^5).
  HAPD samples after neutron/γ irradiation corresponding to 10 years Belle II operation perform well in beam test.
- **Production of HAPD, aerogels and electronics components for ARICH have been started.**
  Validations for each component are ongoing without any serious problem.
- **Both results of beam test with prototype ARICH and GEANT based simulation shows excellent performance on K/π separation.**
- **ARICH will be installed at beginning of 2015.**

backup

PID impact on physics analysis

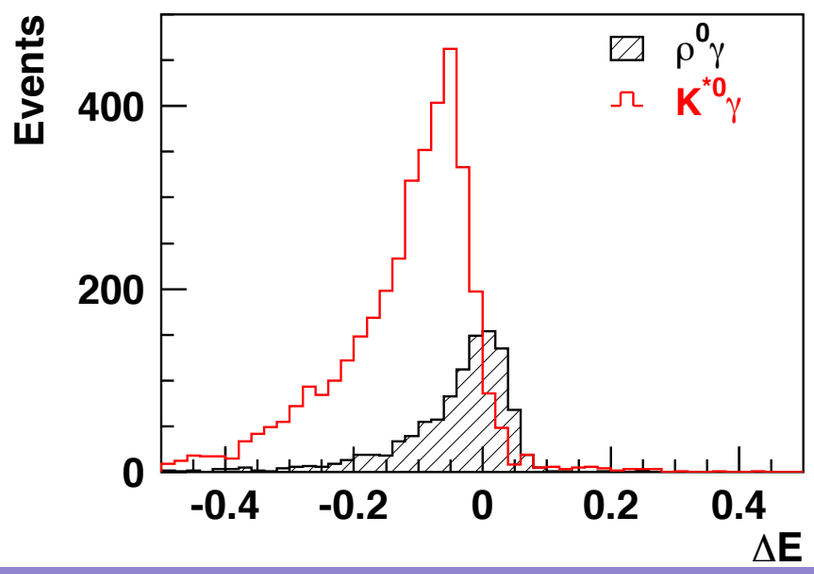


Belle experimental data (657 million $B\bar{B}$ sample)

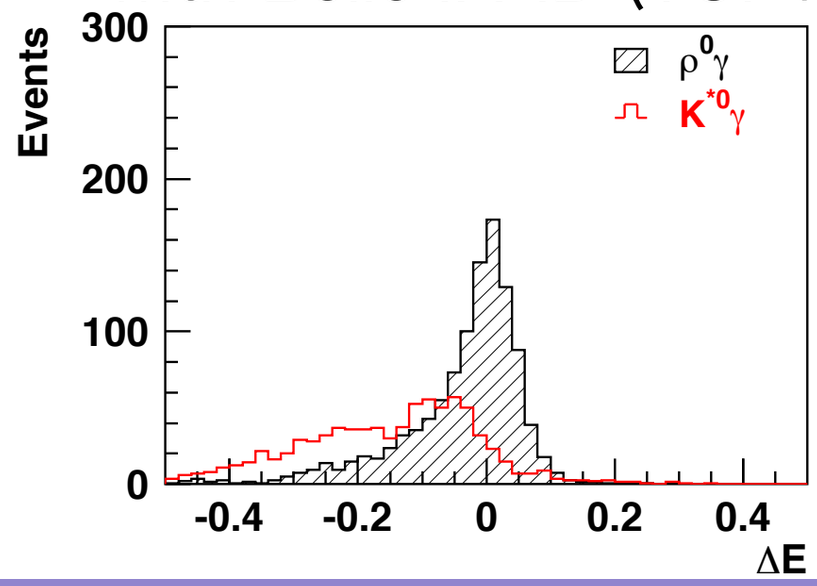
ΔE: energy difference between reconstructed B^0 and beam

Belle II 7.5 ab^{-1} expectation from MC

with Belle PID



with Belle II PID (TOP+ARICH)

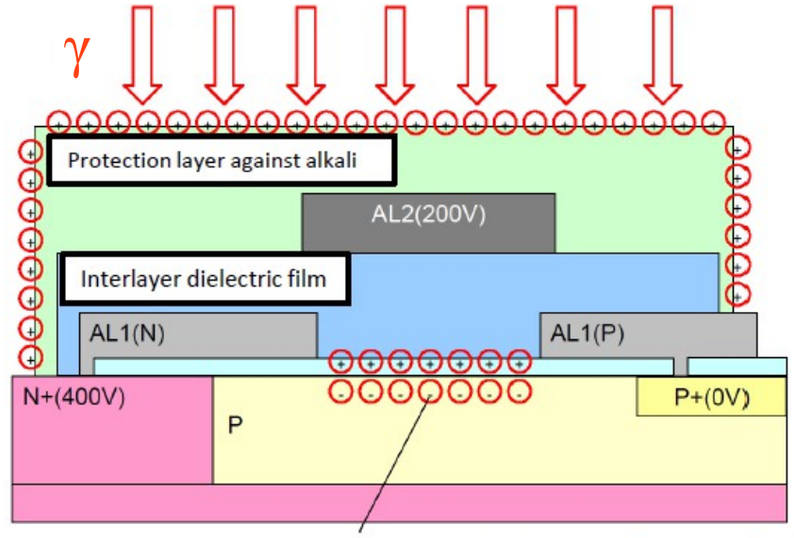


HAPD radiation hardness

Requirement for 10 years Belle II operation:

HAPD should keep performance for irradiation of

- 1000 Gy γ
- 1.0×10^{12} neutron / cm^2



1. Positive charges accumulate in the interlayer dielectric film **and/or** the protection layer against alkali
2. P layer under it changed to "N" layer
3. P-"N" junction around the APD sensitive region breaks down

APD degradation scenarios

- For γ:

  Charge around structure on APD surface.

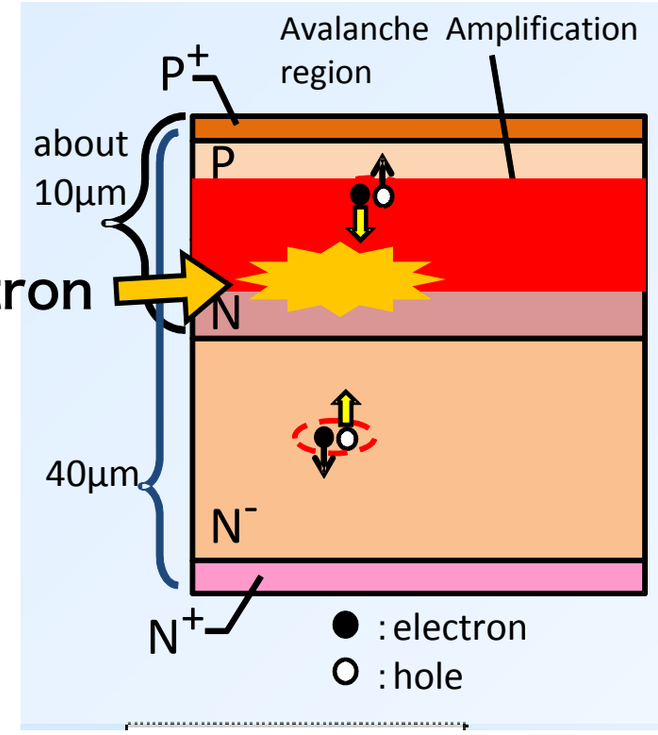
  → Degrade breakdown HV and can not reach enough APD gain.

- For neutron:

  Neutron induce lattice defects in bulk and leakage current increases.

  → S/N becomes worse.

⇒ Perform irradiation tests and determine APD design and materials to minimize the effect.

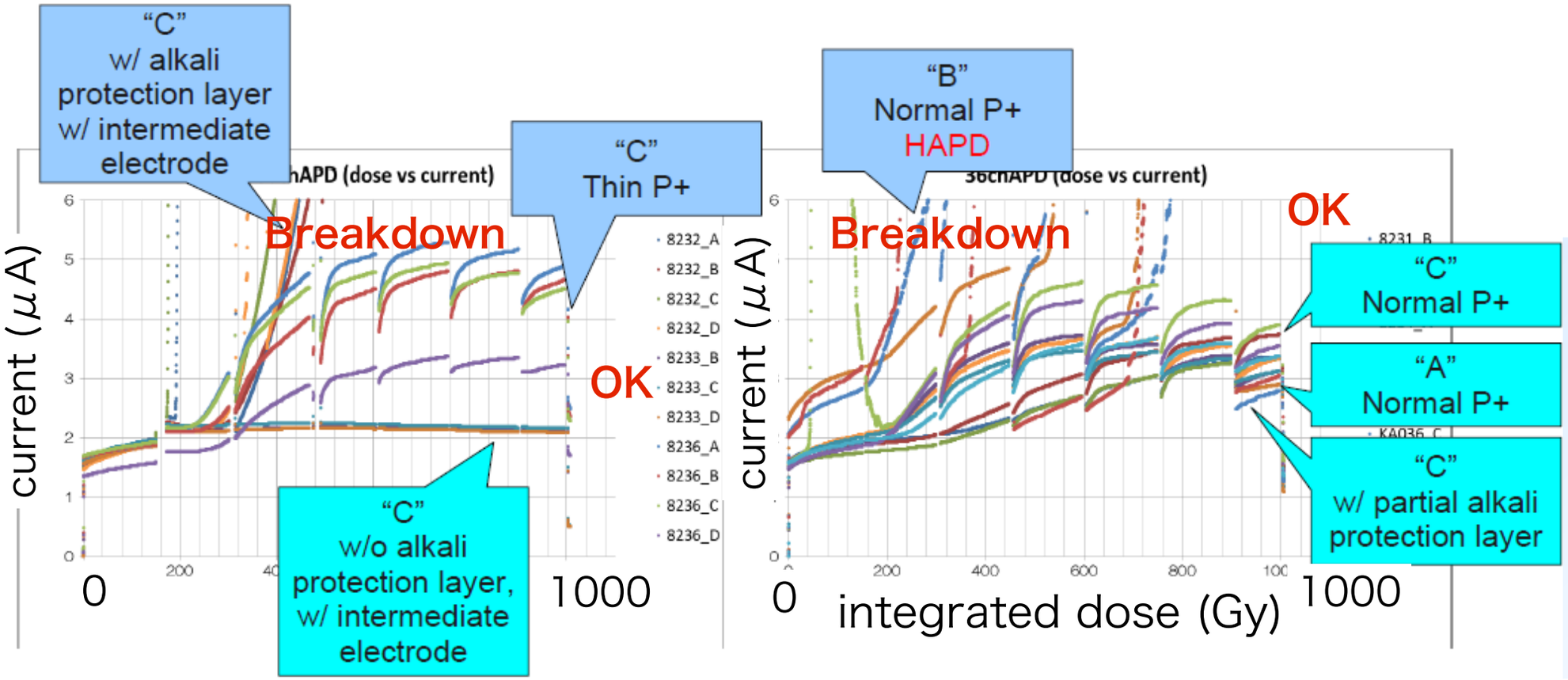


HAPD radiation hardness test

γ irradiation tests

Prototype APD with different configuration (active area window film material, w/ or w/o alkali protection layer/intermediate electrode…) are tested.

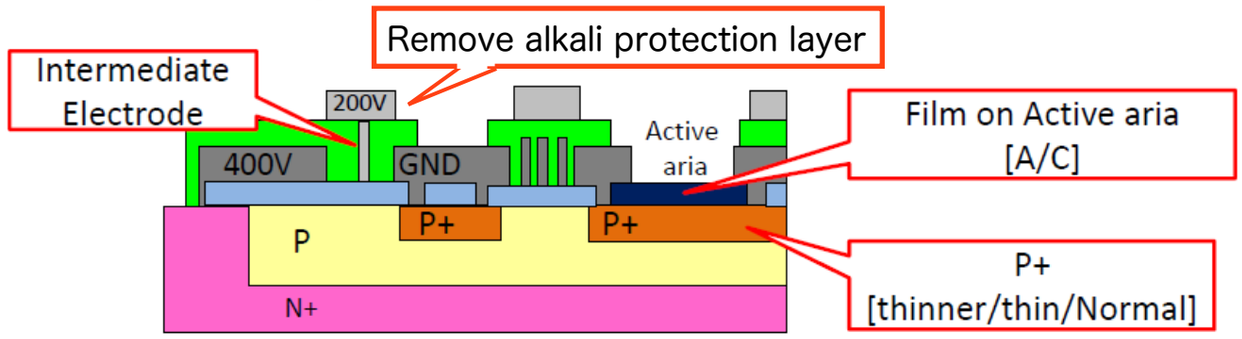
Apply bias during irradiation and measure leakage current.



integrated dose (Gy)

⇒ Changing the structure configuration on APD surface prevents breakdowns.

APD design to prevent breakdown



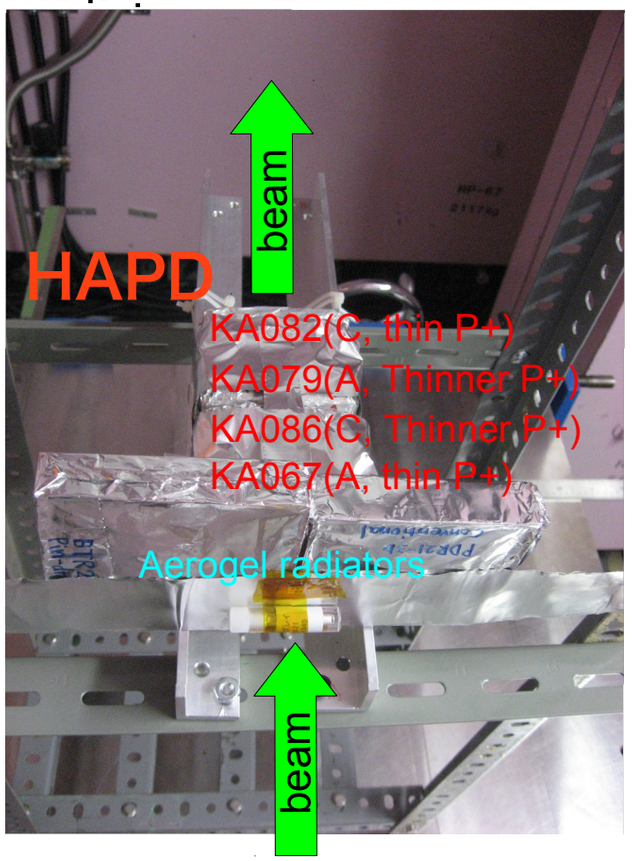
HAPD radiation hardness test

Neutron irradiation test

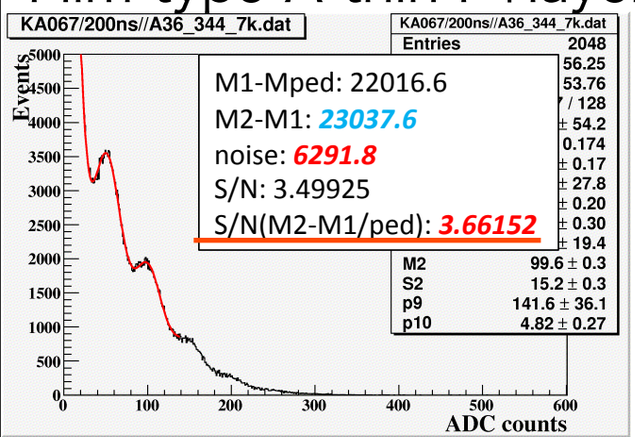
HAPD is irradiated by neutron beam from accelerator.

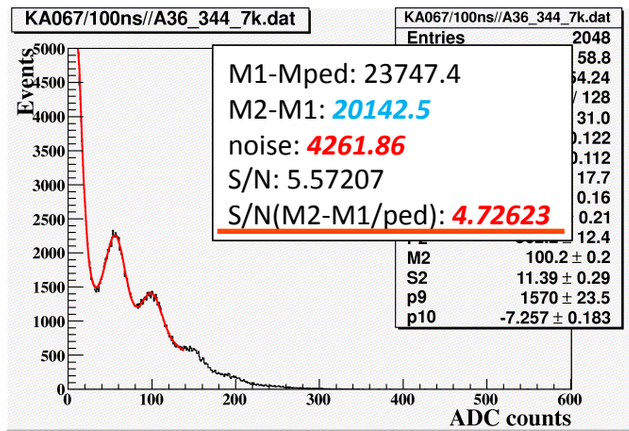
Neutron flux > 1.0×10^{12} n/cm^2

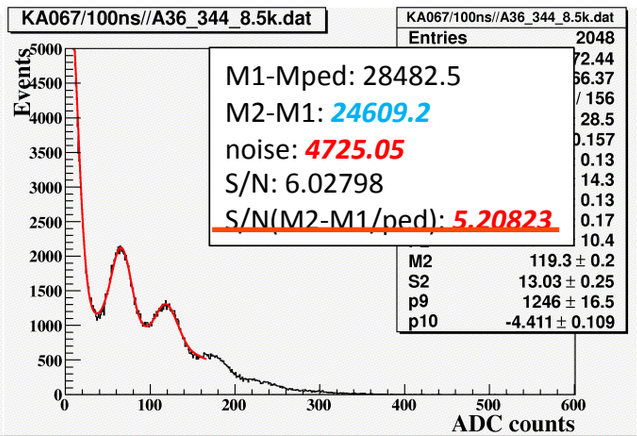
Setup @ MLF in JPARC



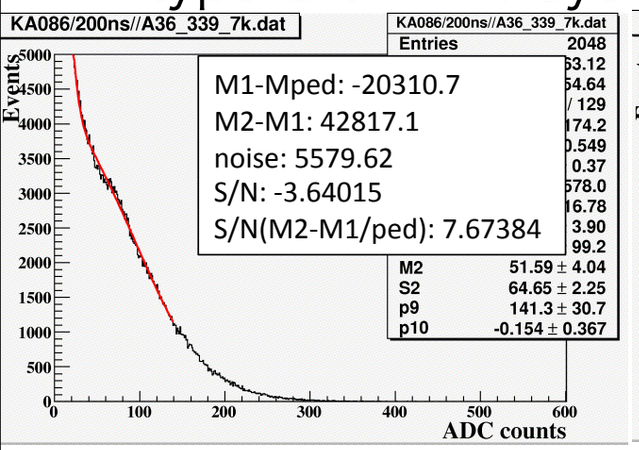
Film type A thin P+layer

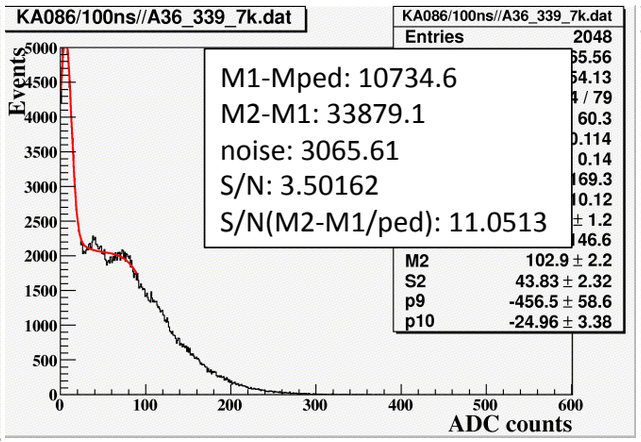


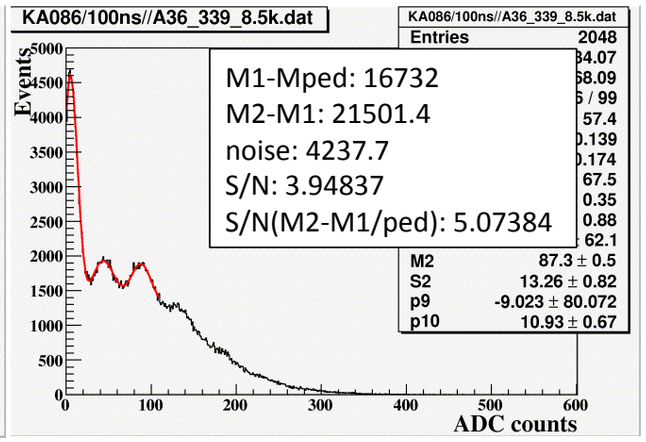




Film type C thin P+layer







Shaping time = 200 ns,
HV = −7kV

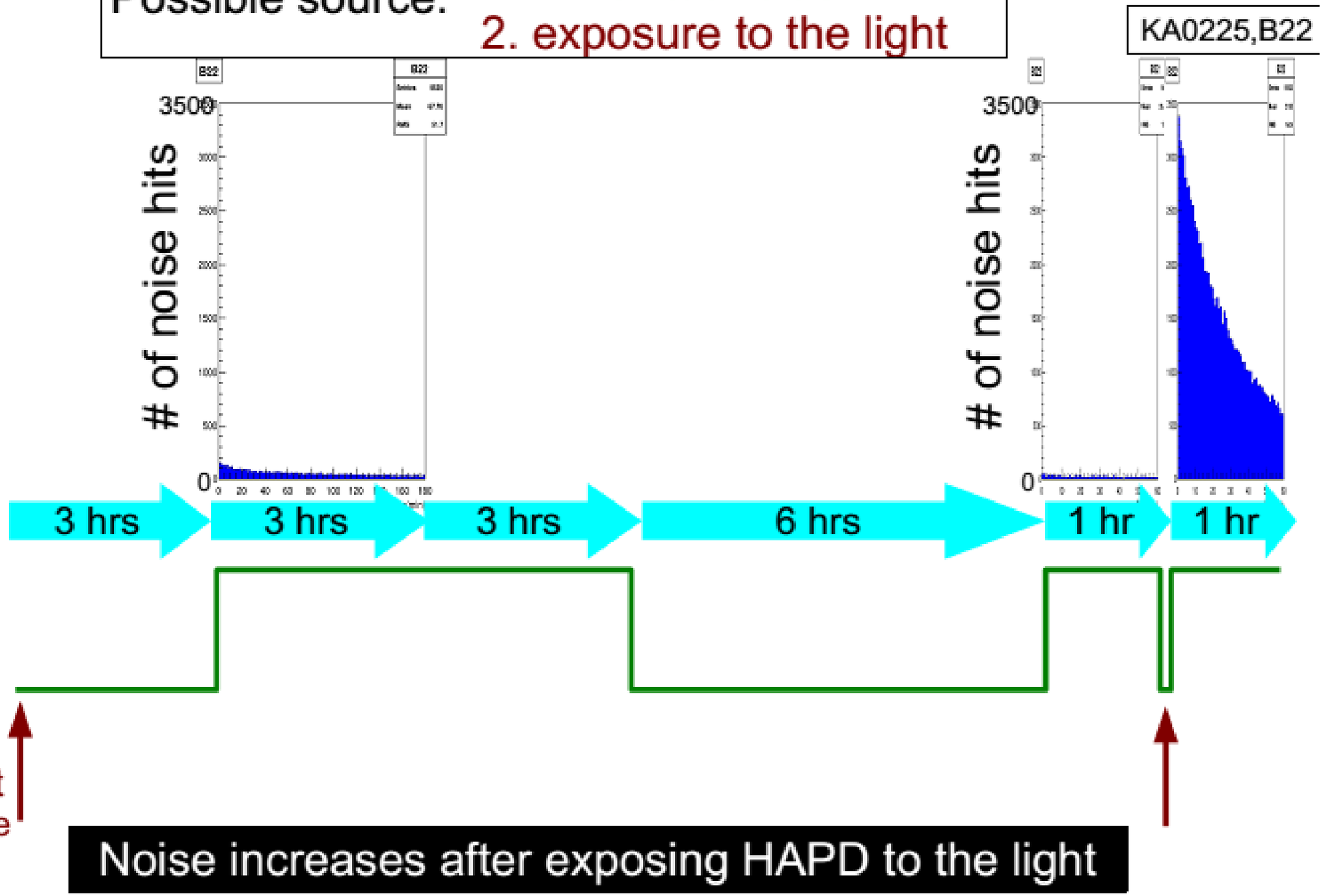
Shaping time = 100 ns,
HV = −7kV

Shaping time = 100 ns,
HV = −8.5kV

⇒ Film material and P/P+ layer structure improves S/N. It can be further improved by increasing of HV and optimization of shaping time in front-end electronics.

Source of the time dependent noise

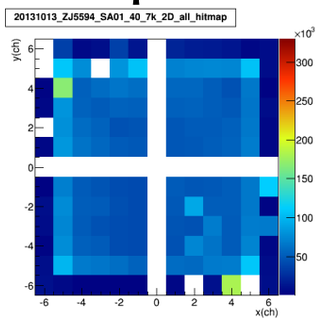
Possible source: 1. HV and/or bias
2. exposure to the light



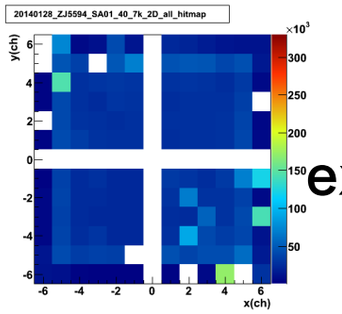
Noise increases after exposing HAPD to the light

Quench of noise induced by light

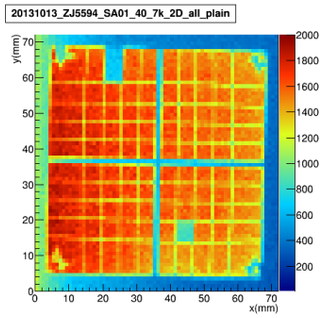
sample A

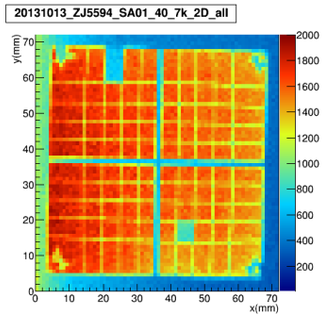


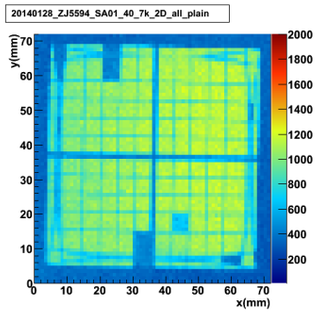
Just after exposing to light

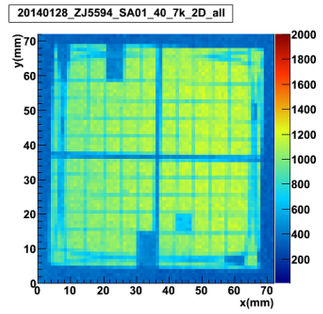


30 min after exposing to light

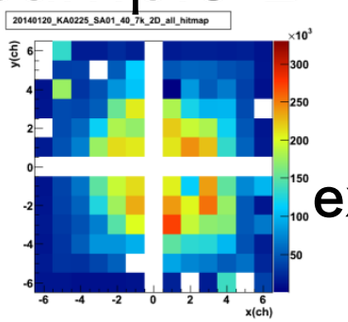




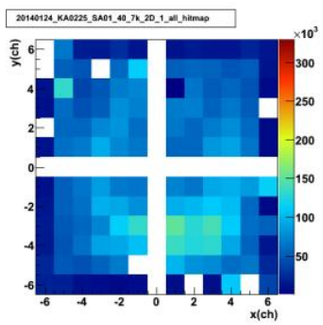




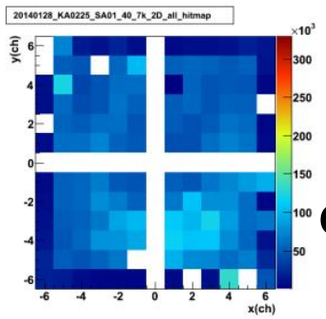
sample B



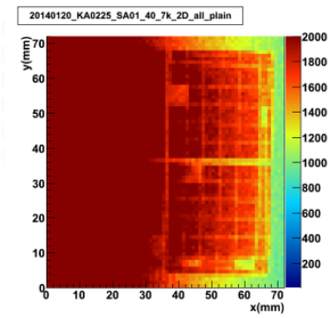
Just after exposing to light

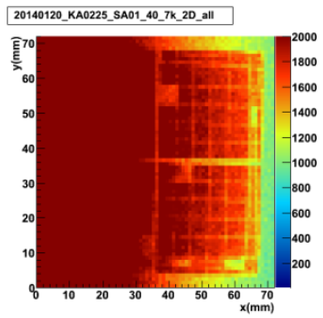


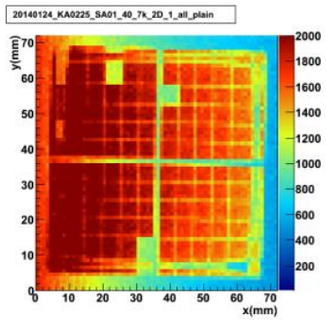
30 min after exposing to light

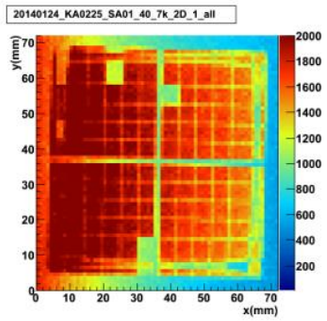


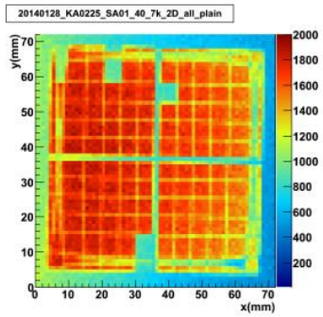
120 min after exposing to light

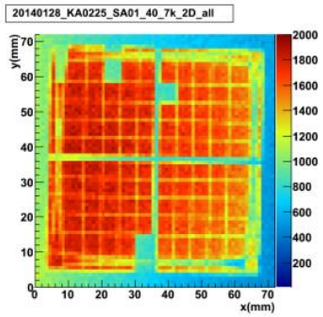












HAPD lifetime for normal use

Life test

Test @ HPK

Life test :1000hours operation w/ 70mC/10d anode current

Finished above test for two HAPD chips
(KA0136 ChipC, ZJ5591 ChipC)

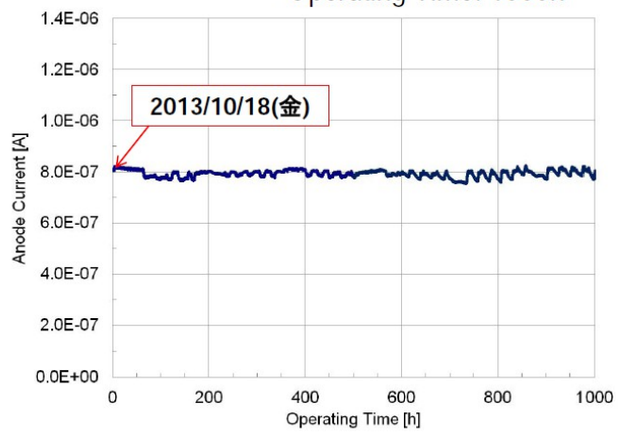
HAMAMATSU
PHOTON IS OUR BUSINESS

KA0136 chipC

●電子照射試験

Anode: 70mC/10y

- Photocathode Voltage: -8kV
- AD Reverse Bias Voltage: +341V
- Guard Voltage: +175V
- Initial Anode Current: 800nA
- Operating Time: 1000h



1000hで70mC

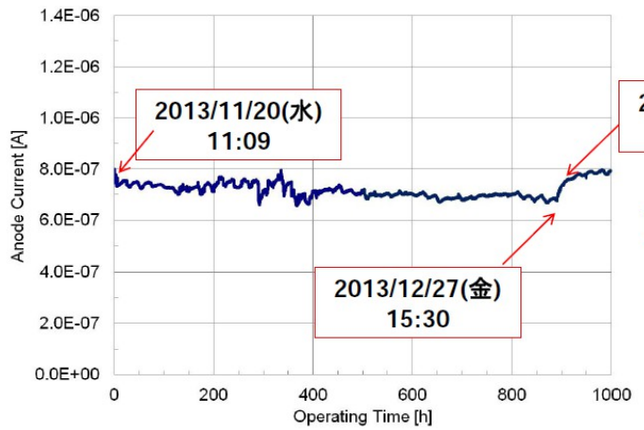
HAMAMATSU
PHOTON IS OUR BUSINESS

ZJ5591 chipC

●電子照射試験

Anode: 70mC/10y

- Photocathode Voltage: -8kV
- AD Reverse Bias Voltage: +341V
- Guard Voltage: +175V
- Initial Anode Current: 800nA
- Operating Time: 1000h



1000hで70mC

- HAPDs are not broken after 1000 hours operation
- Leakage current of APDs are below 0.1μA for all the channels
- degradation of QE is not seen

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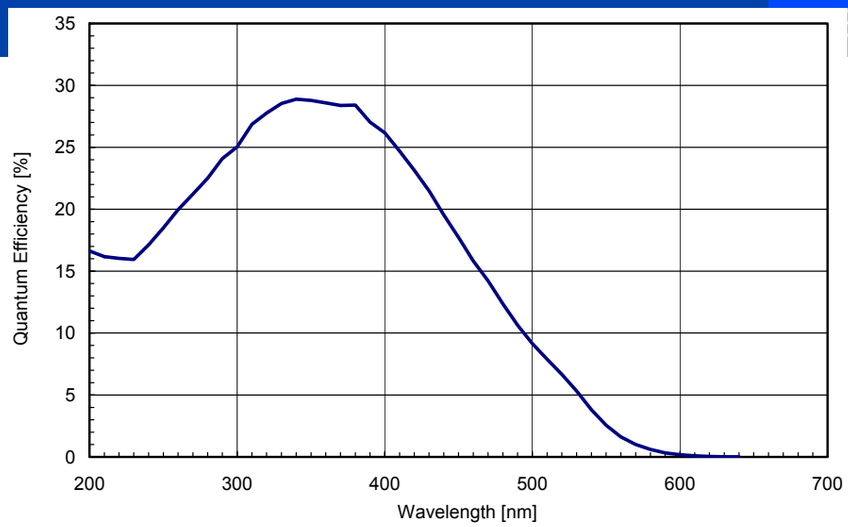
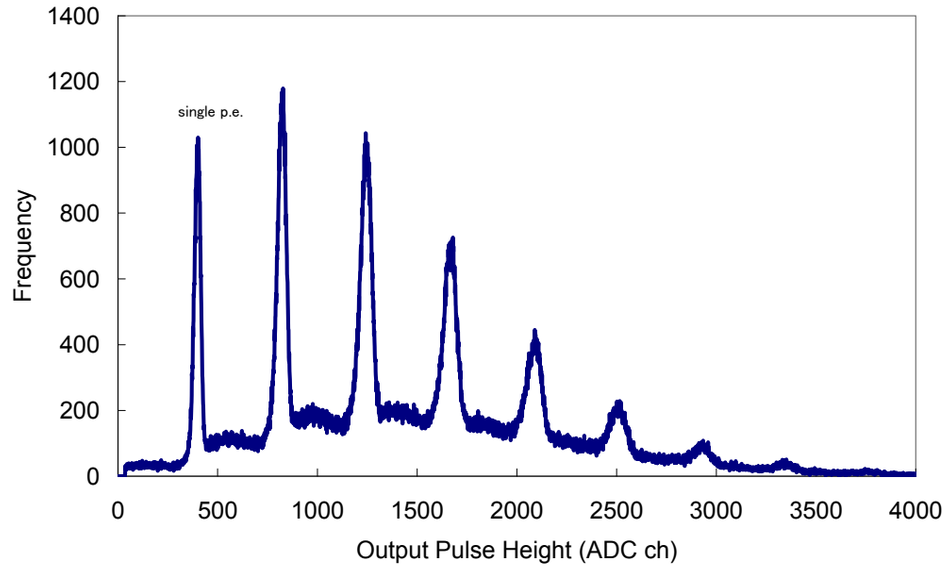
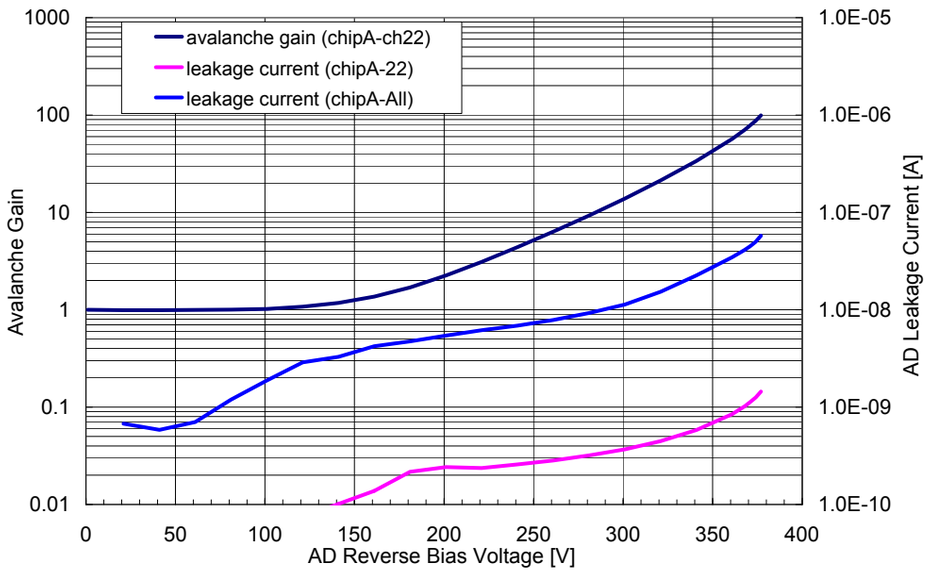
Typical HAPD performance

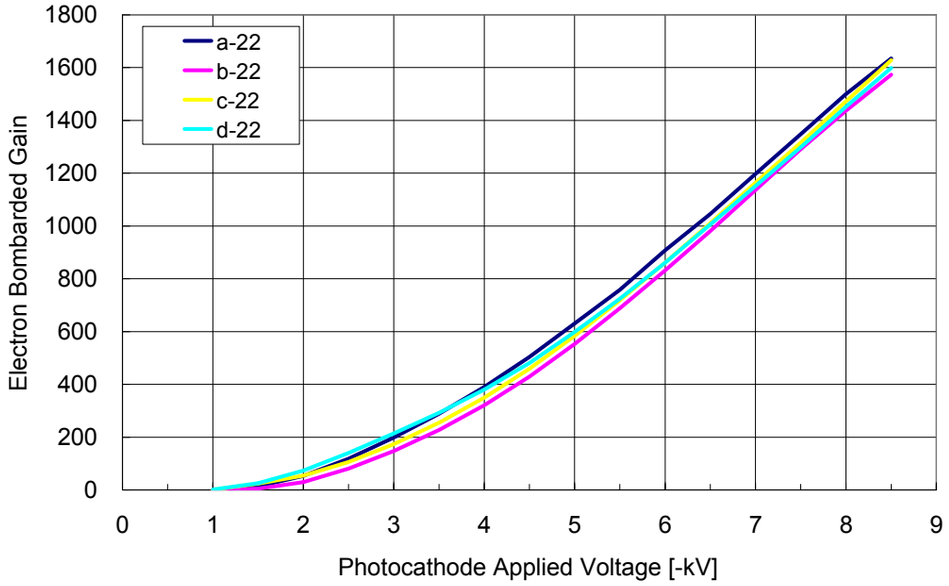
(data sheet)

		KA0041	
Quantum efficiency	400nm	26.2	%
	peak	28.9	%
Maximum high voltage		-8500	V
Bad channel	A	None	
	B	None	
	C	None	
	D	ch1	
Maximum high voltage for each APD chip	A	377	V
	B	368	
	C	364	
	D	377	
Maximum gain	A-ch22	161900 (8.5kV, 377V)	
	B-ch22	164600 (8.5kV, 368V)	
	C-ch22	104000 (8.5kV, 364V)	
	D-ch22	162500 (8.5kV, 377V)	

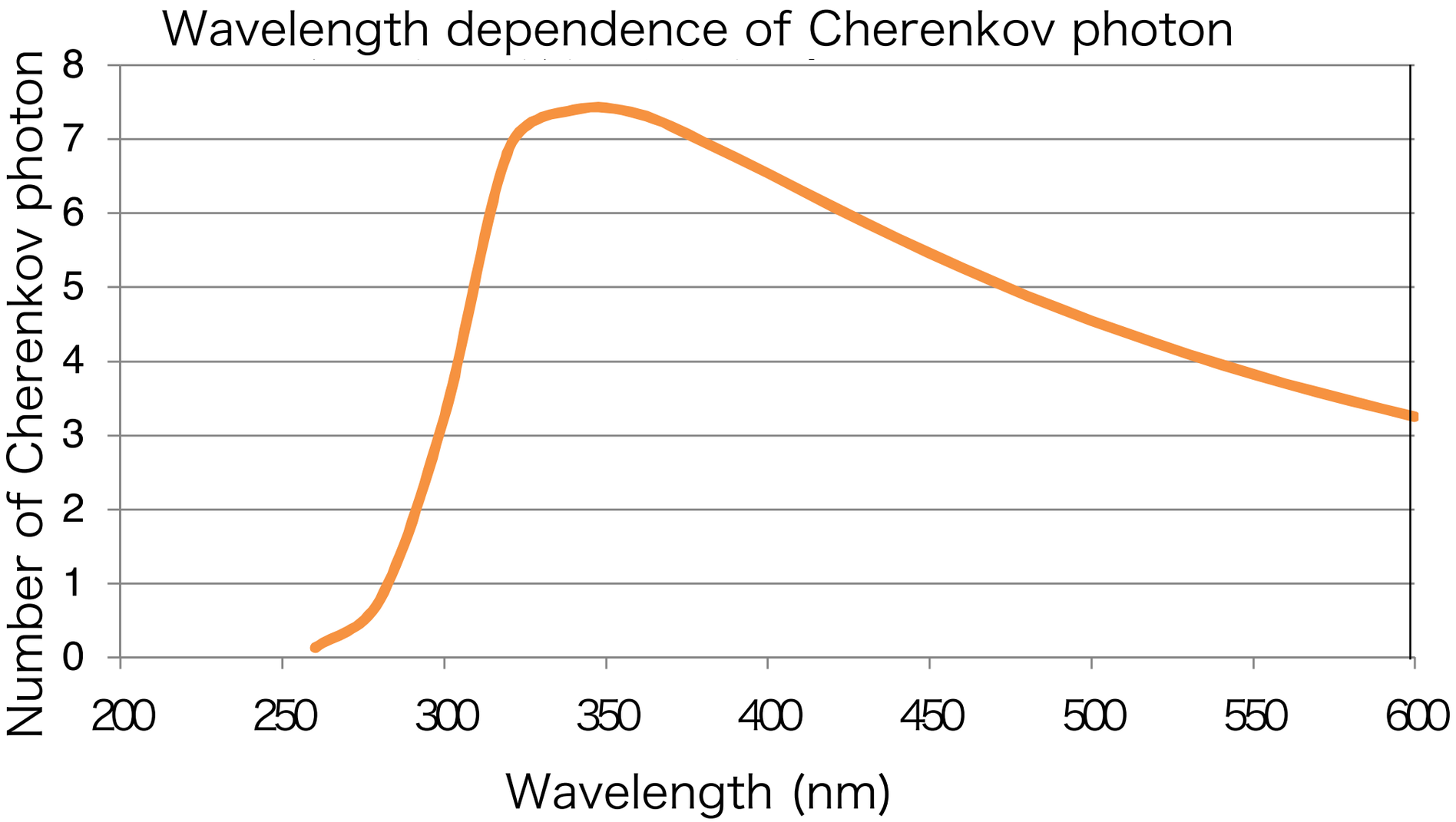








Photocathode Voltage: -8kV
AD Reverse Bias Voltage: 341V
Guard Voltage: +200V
Amplifier: Clear-Pulse 580K
Light Source: LED 470nm, 2kHz

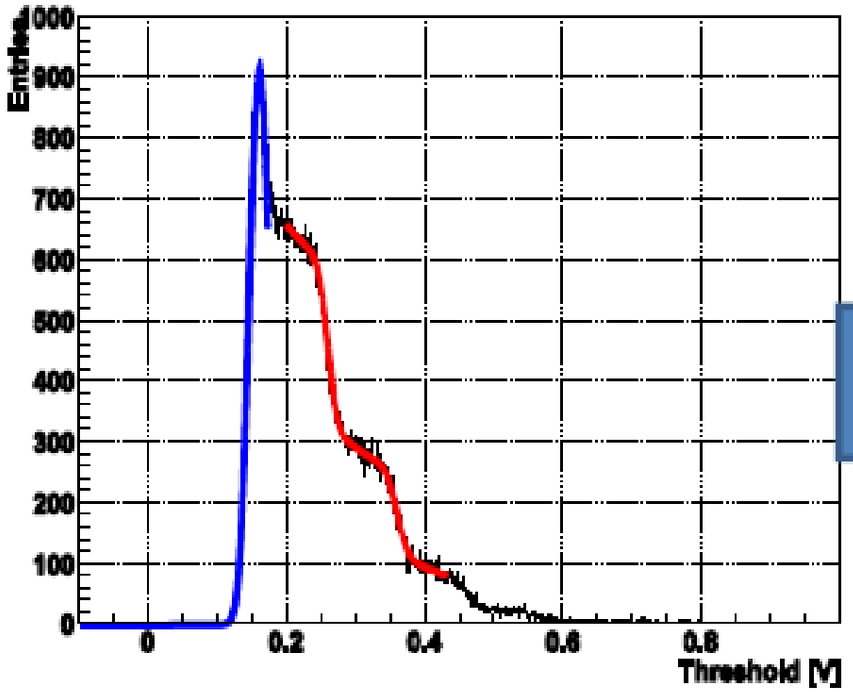

Wavelength dependence of Cherenkov photon
Number of Cherenkov photon
0
1
2
3
4
5
6
7
8
200
250
300
350
400
450
500
550
600
Wavelength (nm)

(threshold scan@SA03)

KA058
Film A
Electrode ○
P+ thin
Neutron
8.5*10^11

*measured
by SA03(X-FAB,QFP)
(shaping time 100ns)

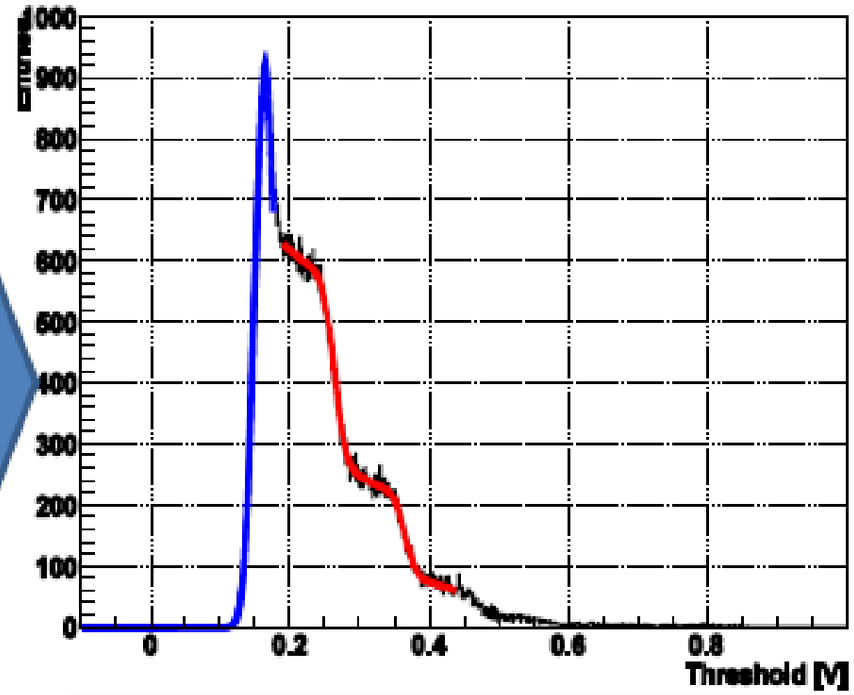
Before Gamma Irradiation



chip A-34ch:326.5V(17.26μA)
HV:-8.5kV

noise(gaus0) = 5464.03[e-]
2pe - 1pe = 39137.45[e-]
S/N(2pe-1pe/sigma0) = 7.16

After Gamma Irradiation



chip A-34ch: 326.5V(17.02μA)
HV:-8.5kV

noise(gaus0) = 5665.96[e-]
2pe - 1pe = 39763.47[e-]
S/N(2pe-1pe/sigma0) = 7.02

- **Noise Level & Total Gain dose not change before and after irradiation.**