Development of Hybrid Avalanche Photo Detector and its Readout Electronics for the Belle II Aerogel RICH counter

Shuichi Iwata

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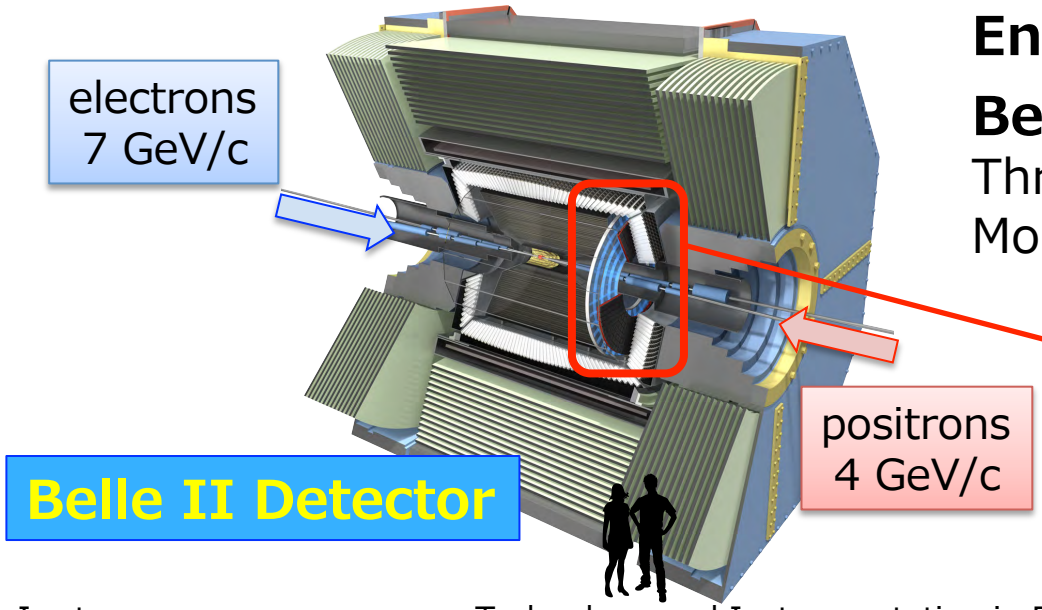
(Belle II Aerogel RICH group)

Contents

- Introduction
- Status of Development
  - Hybrid Avalanche Photo-Detector
  - Readout ASIC
  - Related Electronics
- Summary

Belle II experiment

- **Belle experiment**
  - KEKB accelerator/Belle detector: B-Factory experiment
  - Discovery of CP Violation in B system
  - Verification of Kobayashi-Maskawa mechanism
  - Finished in 2010.6
- **Upgrade to SuperKEKB accelerator / Belle II detector**
  - Integrated Luminosity: 50 ab^{-1}
  - Physics Goal: Search for New Physics



End-cap K/π ID (PID):

Belle

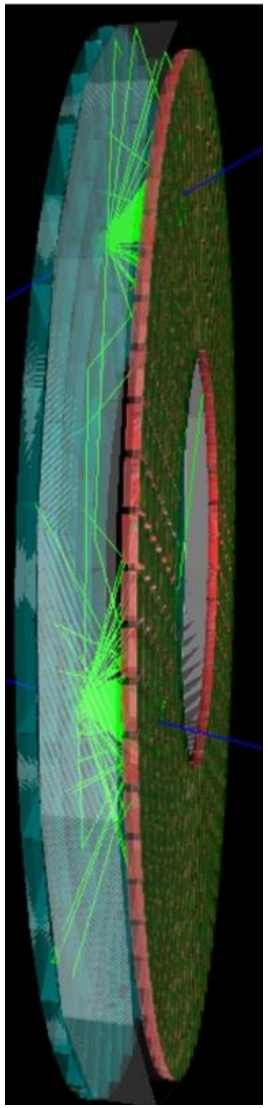
Threshold-type Cherenkov Counter
Momentum range: up to 2 GeV/c

Upgrade!

Aerogel RICH counter

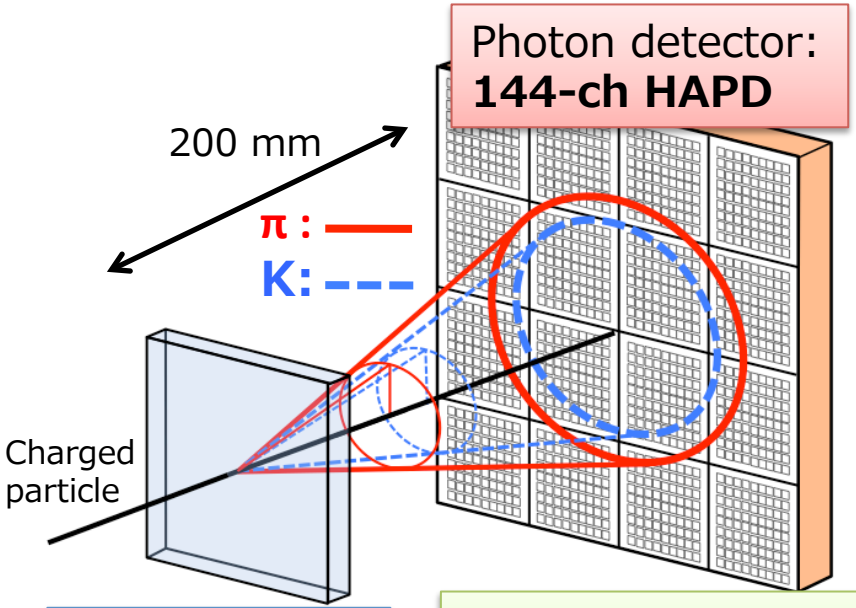
Target: 4σ π/K separation
up to 4 GeV/c

Aerogel RICH (A-RICH)



Proximity-Focusing **R**ing **I**maging **Ch**erenkov counter using **aerogel** as radiator

Principle of A-RICH



1. Produce Cherenkov light in the aerogel.
2. Detect photons as a ring image using a position sensitive detector array.
3. The radiation angle θ_C is calculated.
4. K/π ID is performed by the equation:

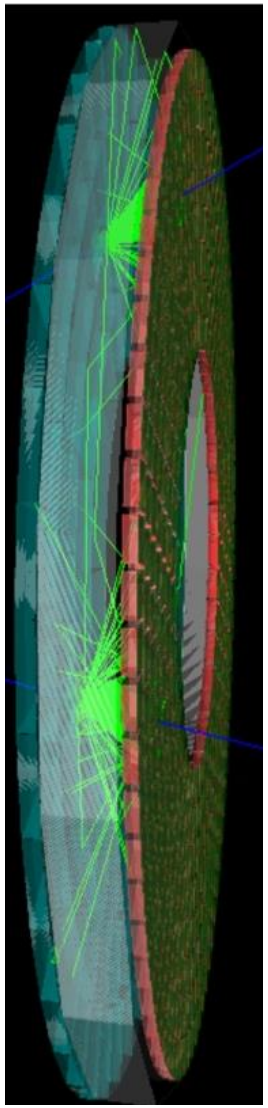
$$m = \frac{p}{c}\sqrt{n^2 \cos^2\theta_C - 1}$$

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

@ 4 GeV/c, n = 1.05

➔ Poster by M. Tabata

Aerogel RICH (A-RICH)



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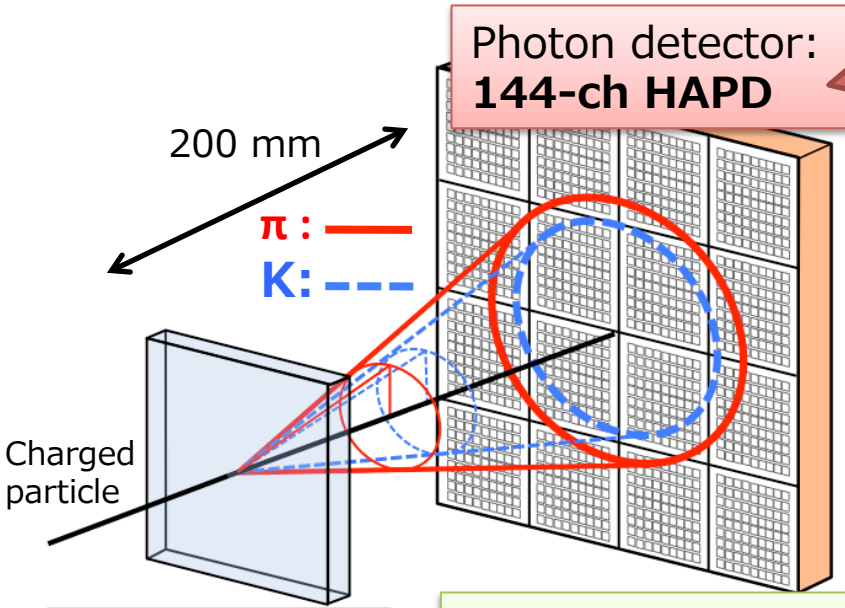


Requirement

- Position resolution ~5 mm
- Single photon sensitivity
- Tolerance to magnetic field
- Radiation hardness

- High-gain, low-noise Amp.
- Hit/No-Hit for each ch.
- Space is limited (5 cm)

Hit information
→ **Front-end electronics**

➔ Poster by M. Tabata

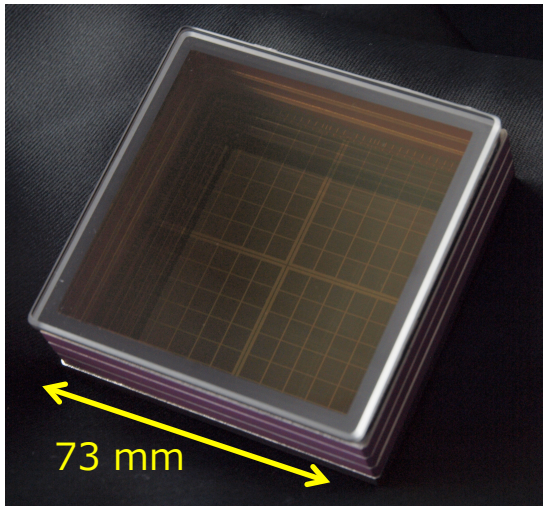
We are developing 144-ch HAPD and Electronics for it.

144-ch HAPD

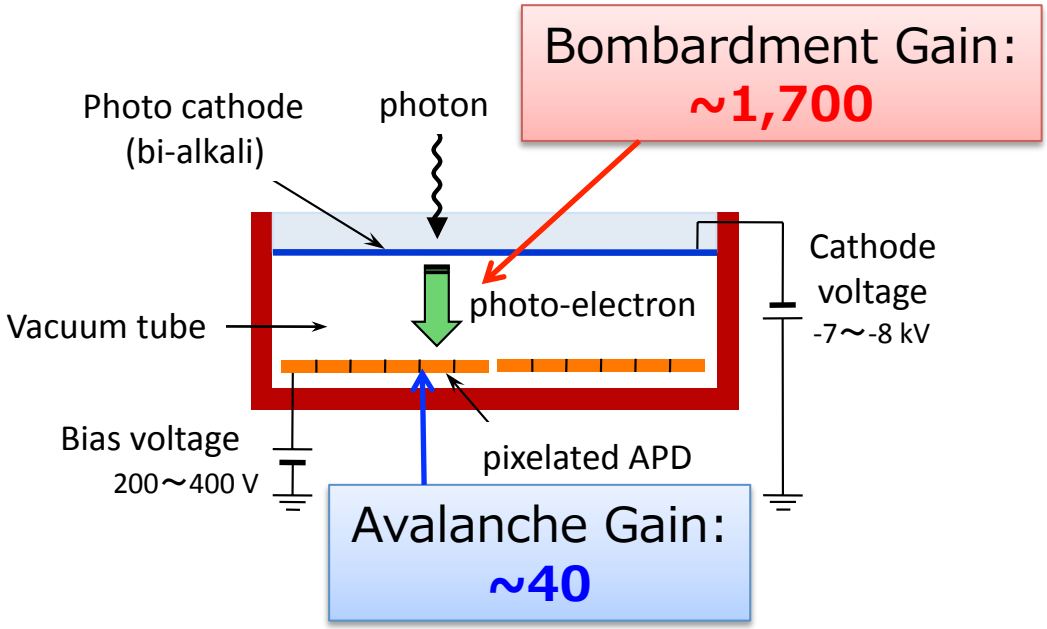
Hybrid **A**valanche **P**hoto-**D**etector

We have been developing the HAPD with Hamamatsu Photonics K.K. since 2002.

420 modules will be installed in Belle II.



Structure of the HAPD



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
typical QE	28% @400 nm
Total gain	**~7 × 10^4**

144-ch HAPD

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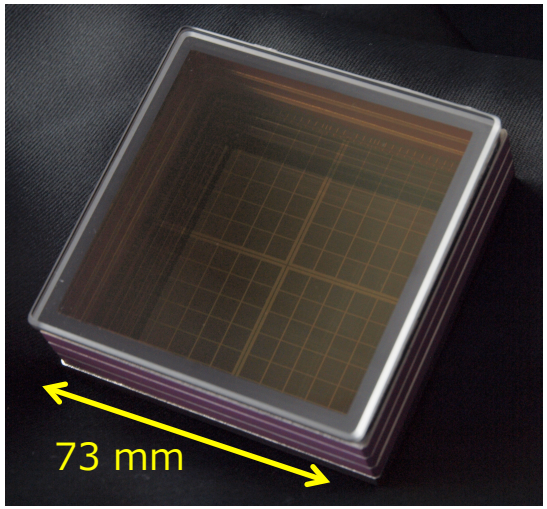
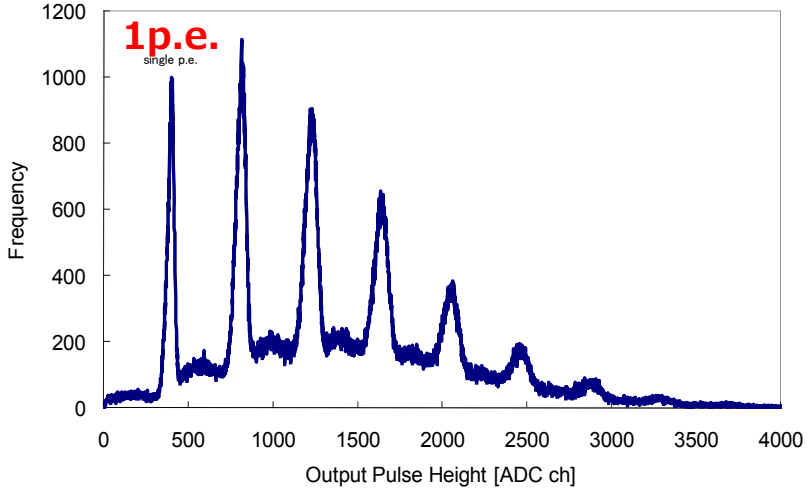


Pulse height distribution



Good single photon separation in every pixel.

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
typical QE	28% @400 nm
Total gain	**~7 × 10^4**

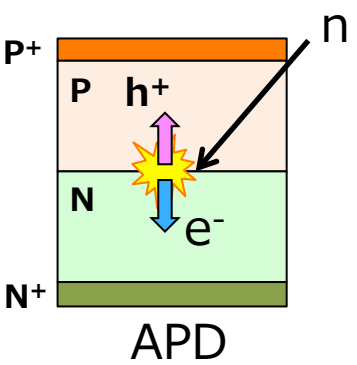
Radiation Hardness of HAPD

HAPDs will be used in radiation environment for **10 years** operation.

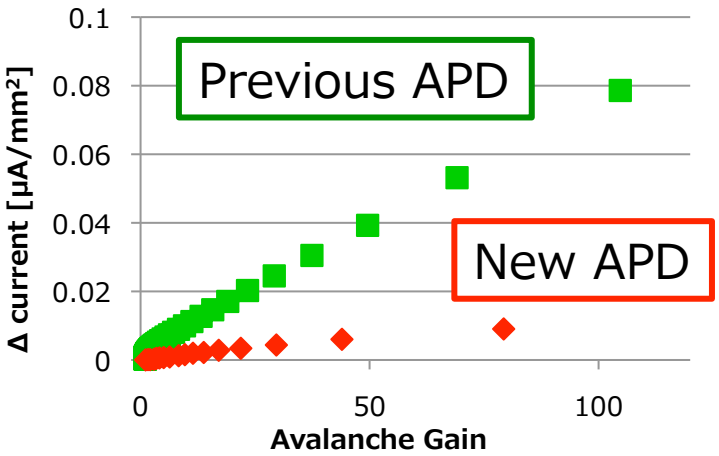
Neutrons: **$1x10^{12}$ neutrons/cm^2** (1 MeV equiv.)

Neutrons induce **lattice defects** in APD bulk region.
They cause **increasing leakage current**.
➔ **S/N** become worse

We changed **P and P+ layer** structure in APD.
Thinner **P** : To **suppress** increase of current.
Thinner **P+** : To **improve** bombardment gain.



We confirmed thinner P layer can suppress increase of leakage current.



History of radiation test

2011: Thinner P/P+ layer

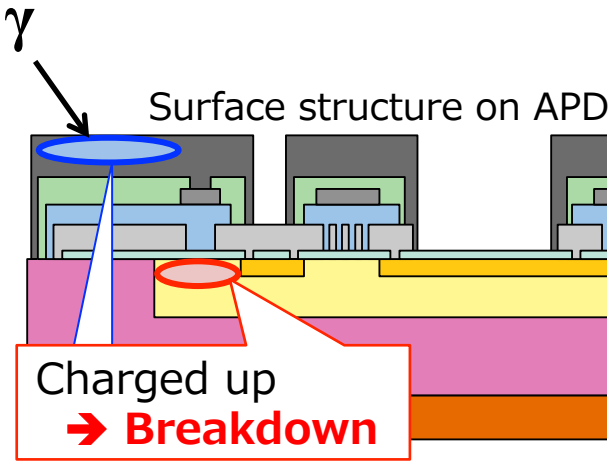
2012~2013:
Production type is irradiated with expected neutron flux

Radiation Hardness of HAPD

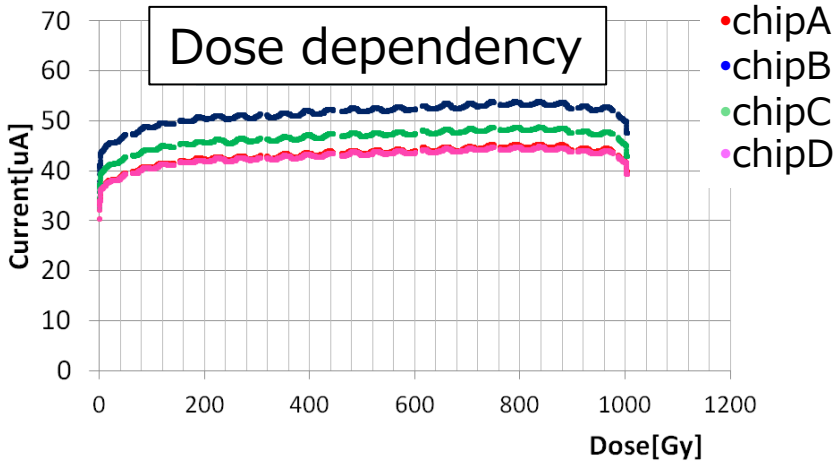
HAPDs will be used in radiation environment for **10 years** operation.

Gamma-ray: 1 kGy

Charge-up around the structure on APD surface occurred by gamma-ray.
Breakdown voltage is degraded.
➔ lowers **Avalanche gain**.



We changed surface structure on APD to prevent it, and carried out radiation tests after neutron test.



Breakdown is not observed up to **1 kGy** radiation.

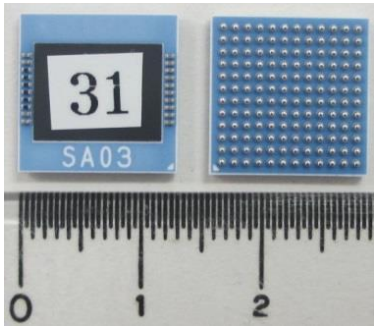
Trial samples have sufficient **neutron and gamma radiation hardness** for Belle II.

Readout Electronics

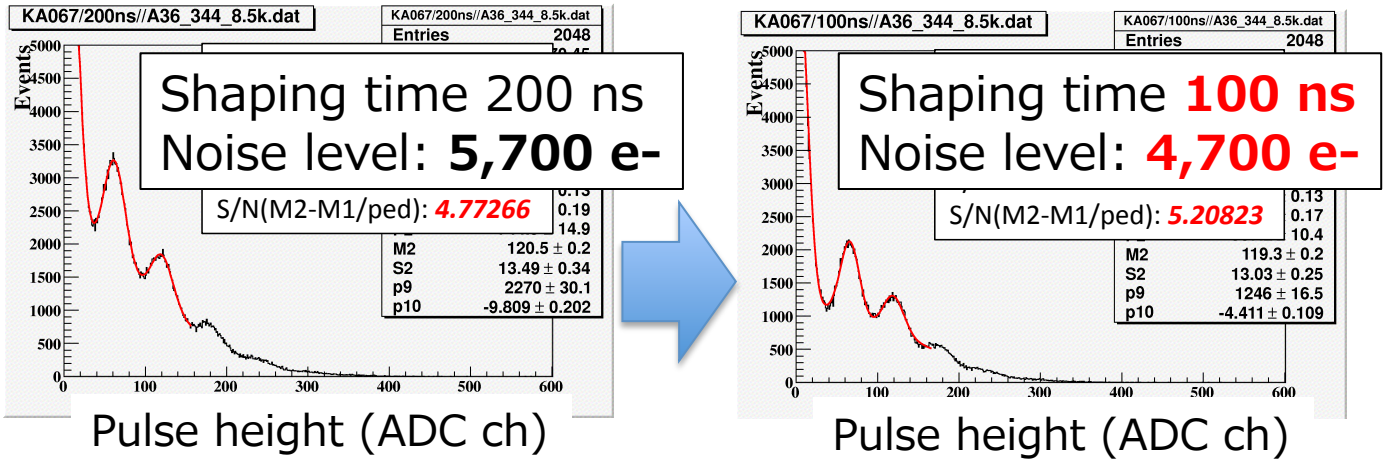
- High-gain, low-noise Amp.
- Hit/No-Hit information
- Space is limited

We developed **original ASIC** and **related circuit** for A-RICH.

- **Readout ASIC**
  - 36 channels/chip (=4 chips for 1 HAPD)
  - variable shaping time
    - 100~200 ns for noise reduction due to neutron irradiation



Neutron test in 2013



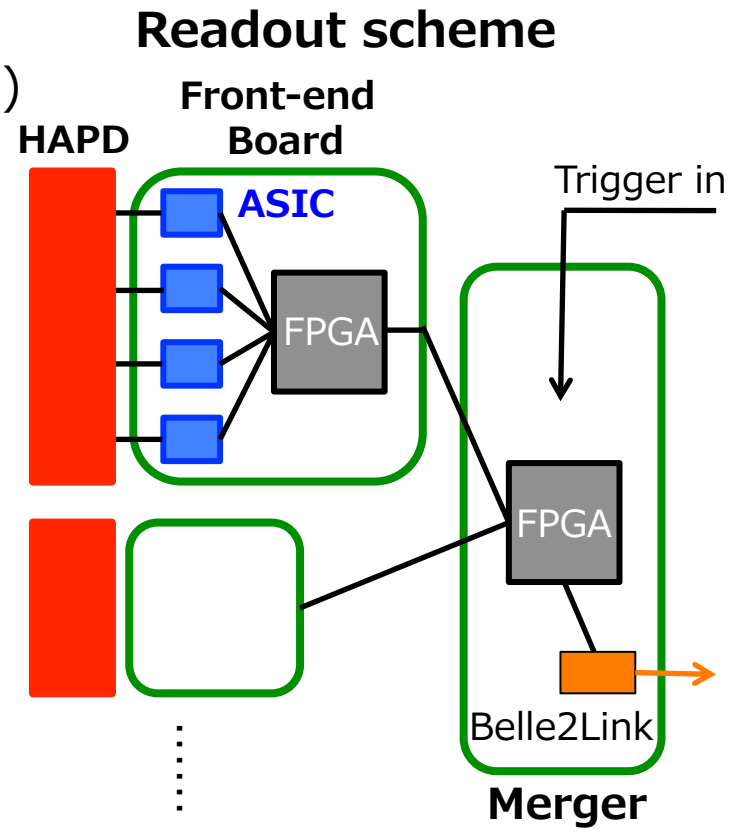
We confirmed noise reduction with **shorter shaping time**.

Readout Electronics

- High-gain, low-noise Amp.
- Hit/No-Hit information
- Space is limited

We developed **original ASIC** and **related circuit** for A-RICH.

- **Readout ASIC**
  - 36 channels/chip (=4 chips for 1 HAPD)
  - variable shaping time
    - 100~200 ns for noise reduction due to neutron irradiation
- **Front-end board**
  - FPGA
    - Process Digital hit signals treatment
    - Setting ASIC parameters
- **Merger system**
  - Merge data from 5~6 FE board
  - Suppress size of signals



Status of Development

HAPD

- Mass production already started in 2013.
  - **420**(main)+Spare = 450 in total
  - Delivery Schedule
    - Aug. 2013 ~ Sep. 2014
    - 30 ~ 40 samples every month
- Quality check is on-going at KEK.
  - **Quantum Efficiency** (QE)
  - **Dead channel check**
    - Leakage current
    - Noise level
    - Gain
    - 2D Hit-map

QE Measurement Result

Requirement	Measured (Average)
28% (Typically) >24%	**30.0%** (RMS 3.7%)

(#samples = 193)

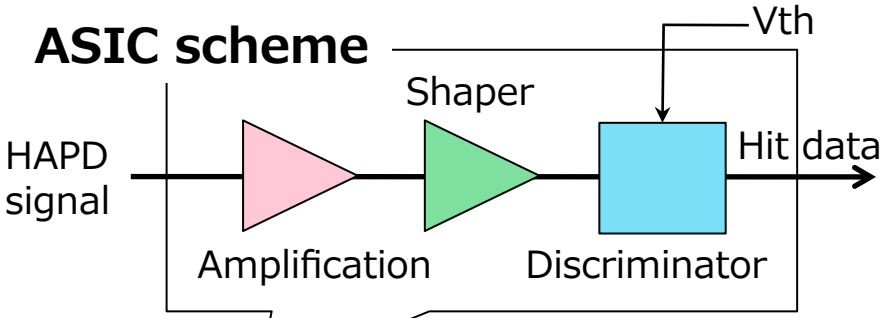
Good Sample Selection

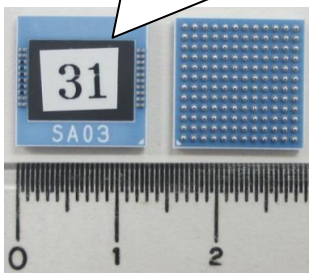
	#HAPDs
Good	**134 (86%)**
Low Quality	5 (3%)
Under Investigation	15 (10%)
Rejected	2 (1%)
Checked (Total)	156

(Mar. 2014)

Readout ASIC

- The ASIC is designed in order to satisfy our requirement.
- ASIC production had been finished.
  - **2,500** samples had been produced.
- We will choose good chips from them.
  - **1,680** chips are needed.
  - **Test system** is developed for this purpose.

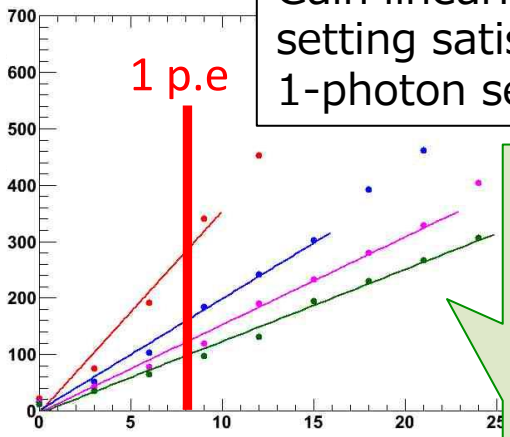




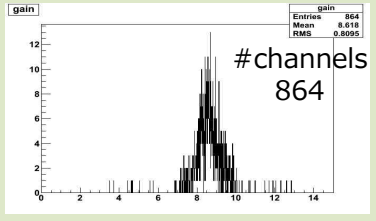
CMOS 0.35 μm
@ TSMC/X-FAB

LTCC packaged

Gain linearity of each setting satisfies 1-photon separation



Mean 8.6 mV/fC
(RMS 0.8 mV/fC)



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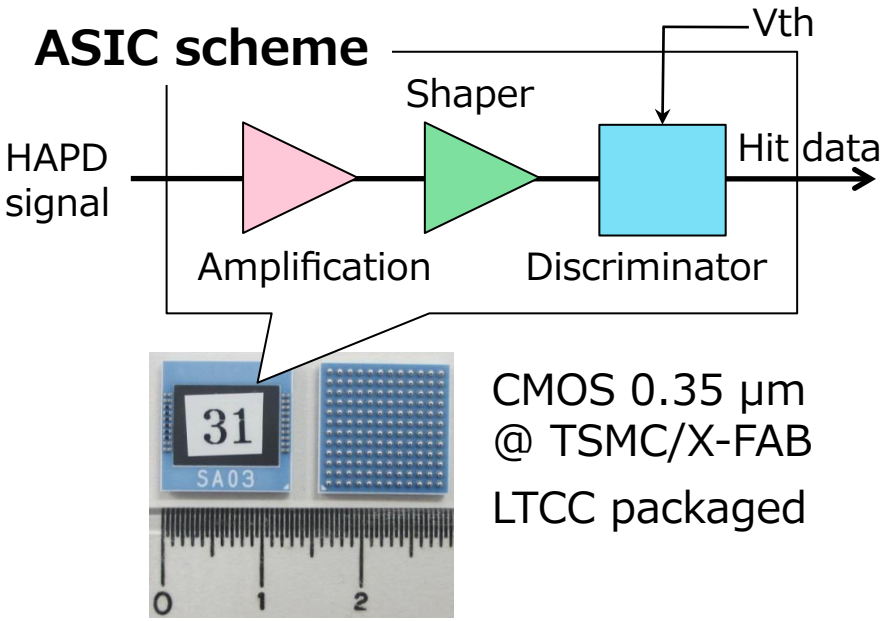


CMOS 0.35 μm
@ TSMC/X-FAB

LTCC packaged

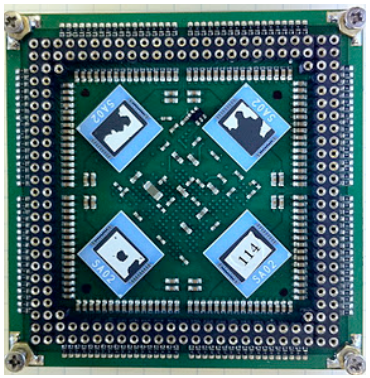
Dead channel Appearance

Tested	Dead
6,480 ch. (= 180 chips)	**47 ch.** (in 30 chips)

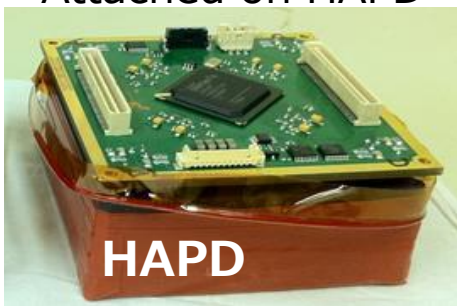
Related Electronics

- **Front-end board**
  - 4 ASIC and FPGA
  - The final version is under designing

Connector side

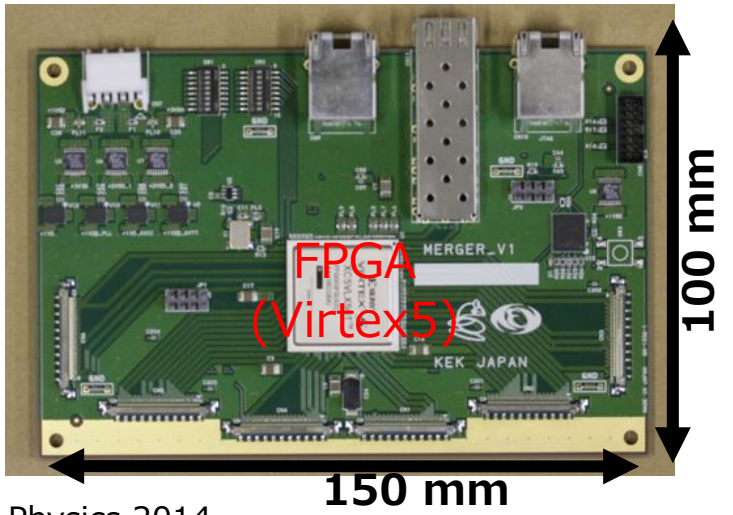


Attached on HAPD



- **Merger system**
  - Designing the final version.
    - Merge data from 5-6 HAPDs
    - Send data to central DAQ
    - Trigger/clock distribution
    - Configuration for the front-end
  - Communication test is on-going with prototype.

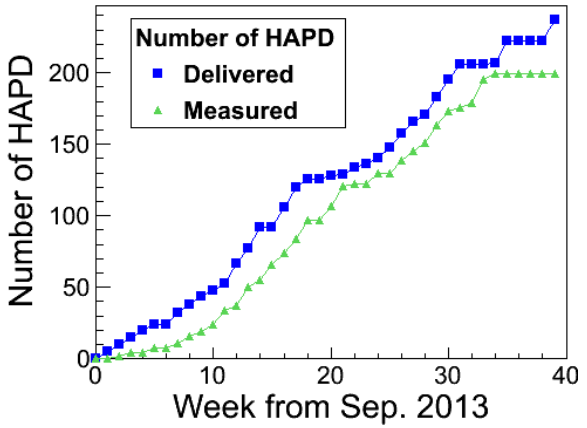
Merger Prototype



Mass Production Status

- **HAPD**:
  - Delivery is delayed about a few months.
  - Quality check of delivered HAPDs are mostly done.

Trends of HAPD Production



❖ Investigation of Noisy Sample

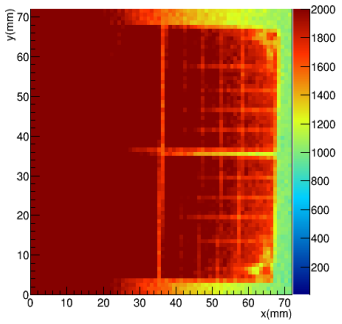
We found some samples are noisy in 2D hit-map.

This noise occurred **after light exposure**.

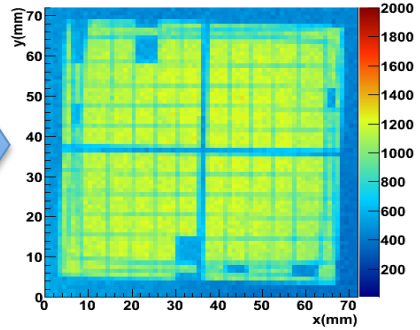
Noise in most samples of this reason **disappear in ~30 min** **after light exposure** and **HV ON**.

➔ ~30 min: **10** samples, >1hour: **7** samples

Noisy sample



30min after HV ON

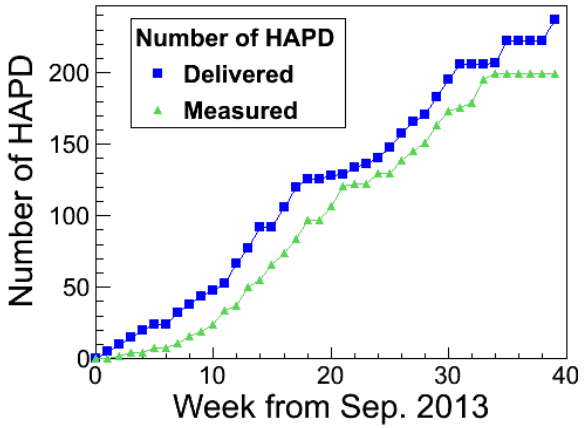


Noise disappeared

Mass Production Status

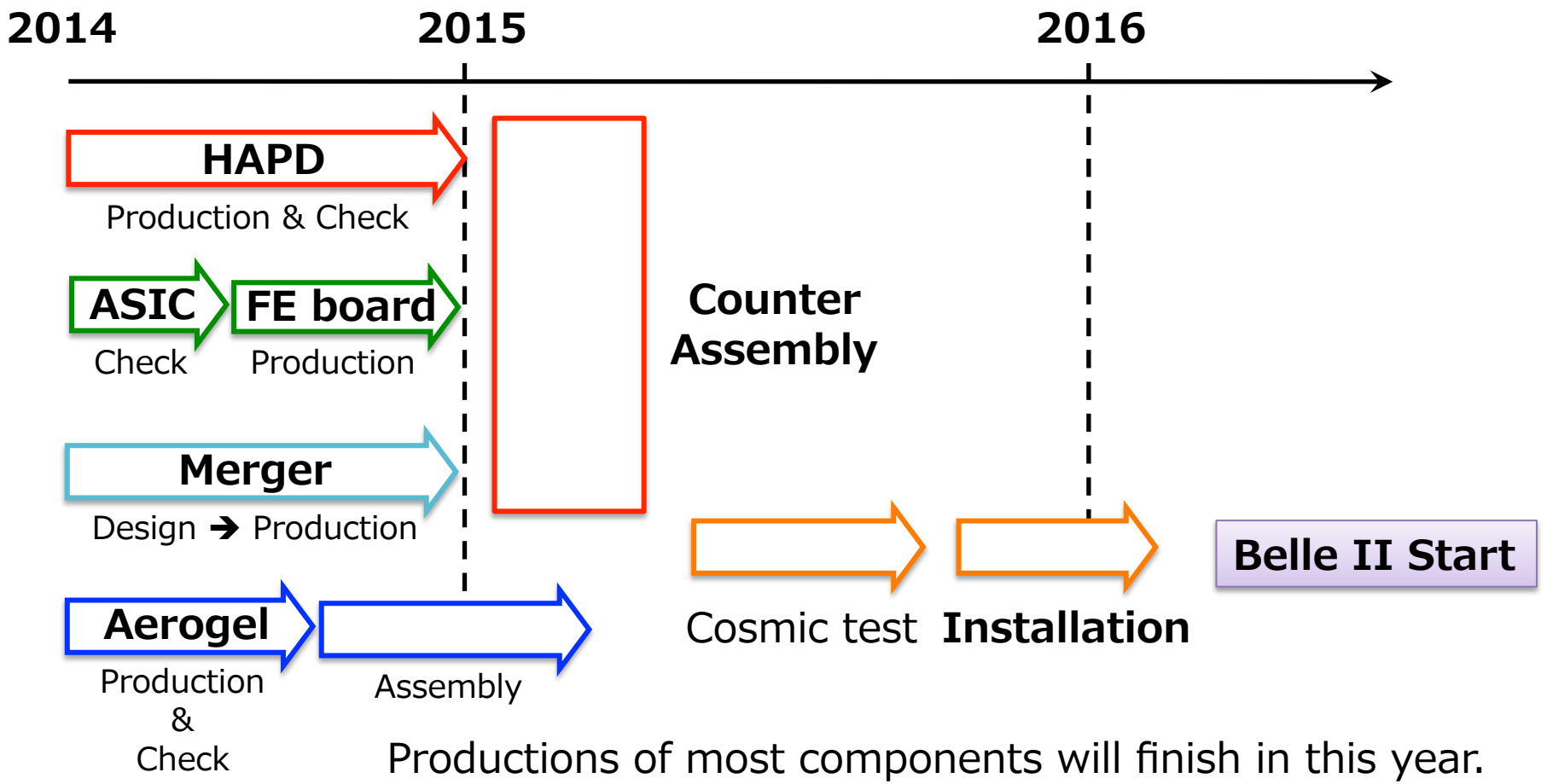
- **HAPD**:
  - Delivery is delayed about a few months.
  - Quality check of delivered HAPDs are mostly done.
- **Electronics**:
  - The ASIC production was finished.
  - Quality check is on-going.
    - We developed the **test system** for produced ASICs.
  - Front-end board and Merger are under final design.
    - Mass production will start in this year.

Trends of HAPD Production



ASIC test system

Schedule



Productions of most components will finish in this year.
Counter assembly will start in 2015.
After counter assembly, we are planning the cosmic test.

Summary

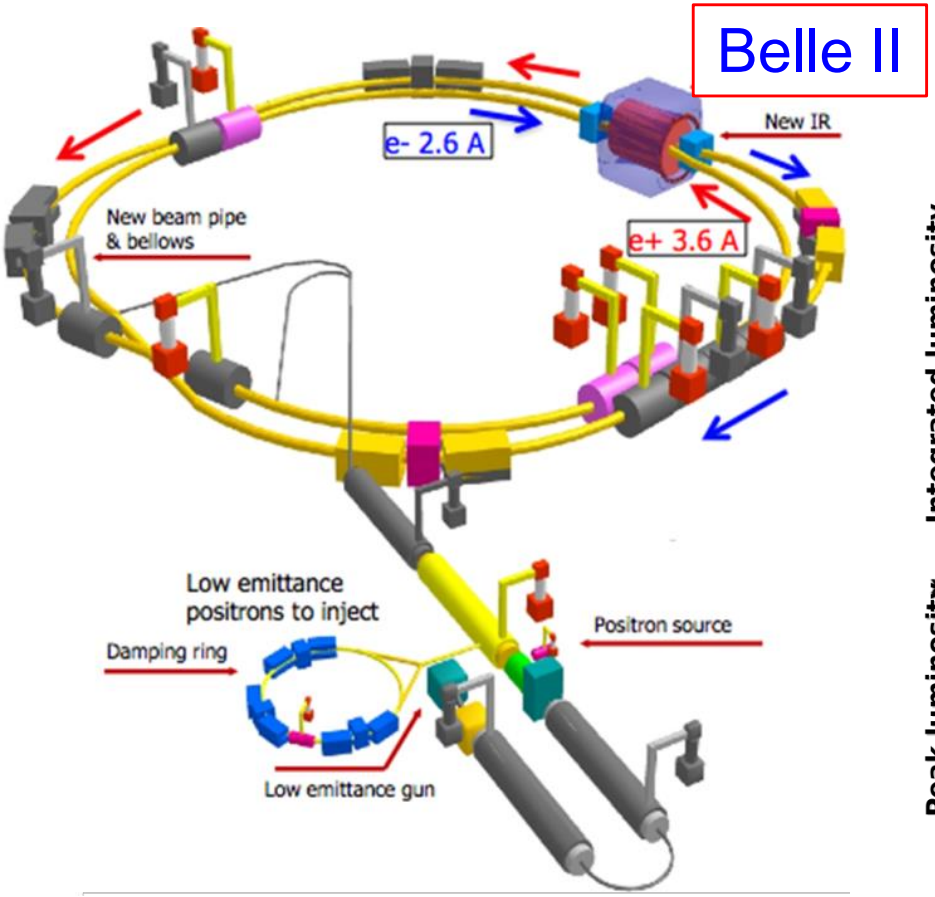
- The **Belle II** experiment will start from 2016.
- We have been developing **Aerogel RICH (A-RICH)** using 144-ch HAPD for the end-cap PID device.
- We have been producing components of A-RICH.
- **HAPD**:
  - Mass production had been started in 2013.
  - Noise issue are found, further investigation is on-going.
  - Delivery schedule is delayed, it will finish in this year.
- **Readout ASIC**:
  - Mass production had finished ➔ ASICs are under quality check.
- **Other Electronics**:
  - Production of Front-end boards and Merger system will start in this year.
- **All components will be ready** in this year. We will start assembling the A-RICH counter in 2015.

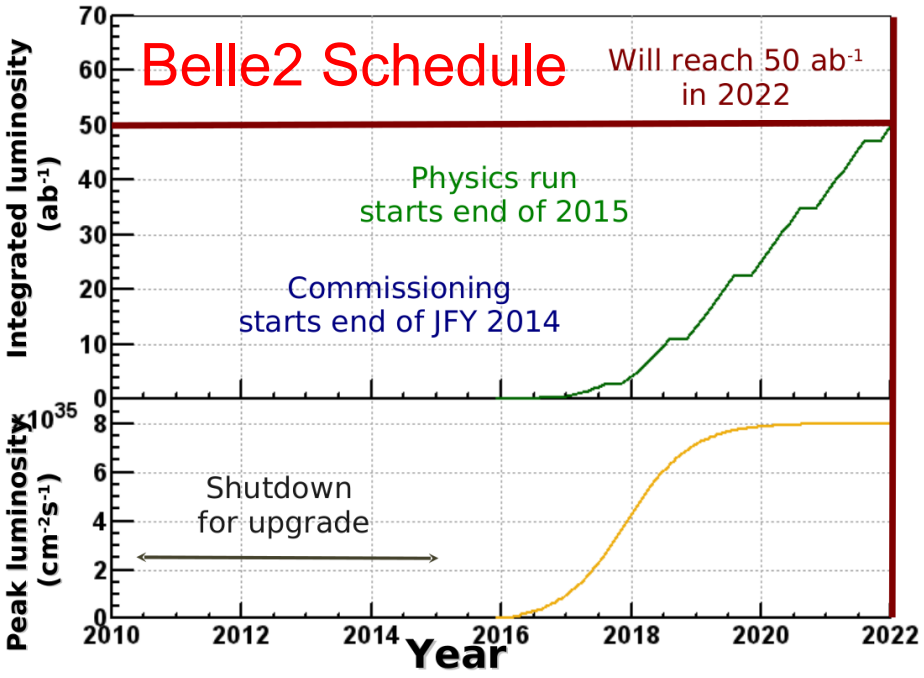
Plan

- After assembly of the counter, we are planning the cosmic test.
- Installation of A-RICH in the Belle II is in 2015.

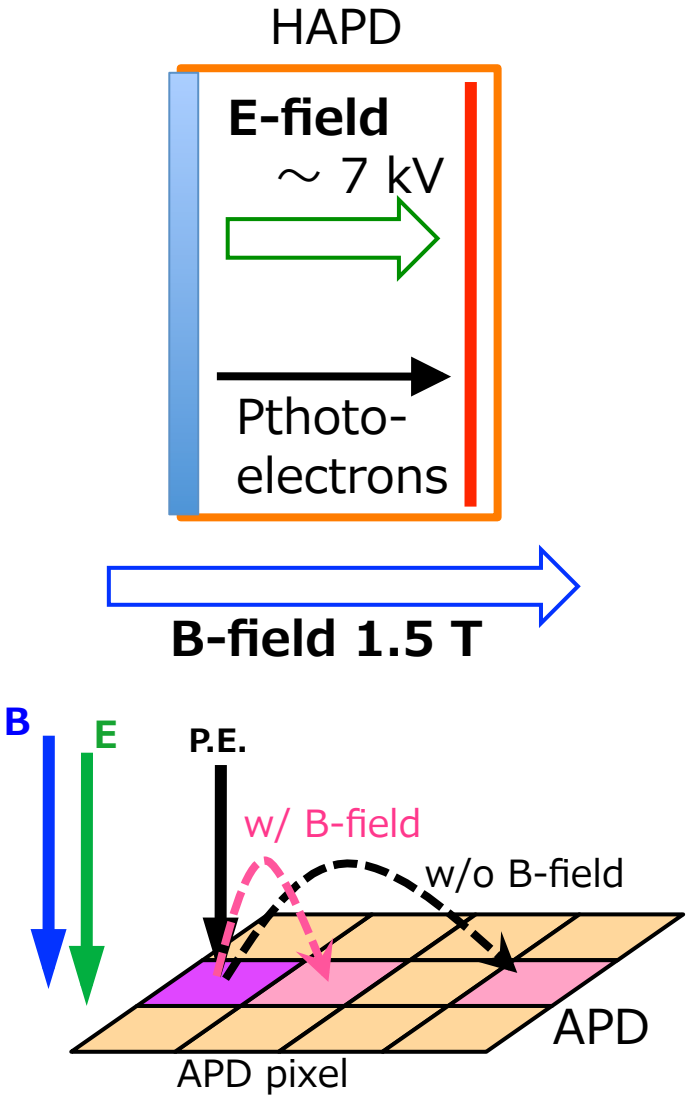
Back up

SuperKEKB accelerator

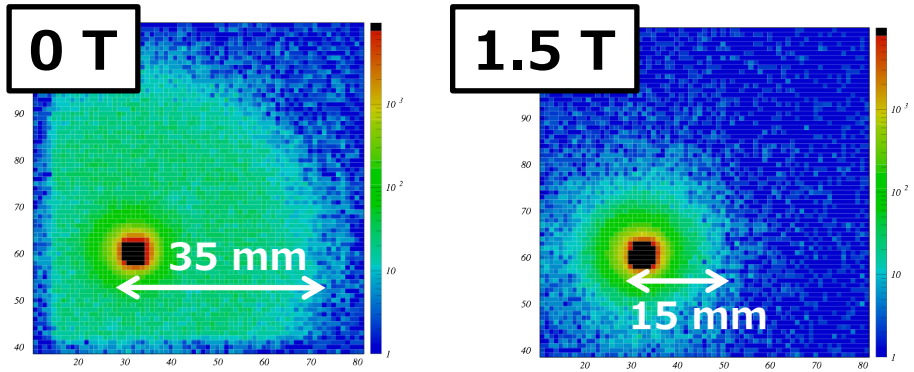


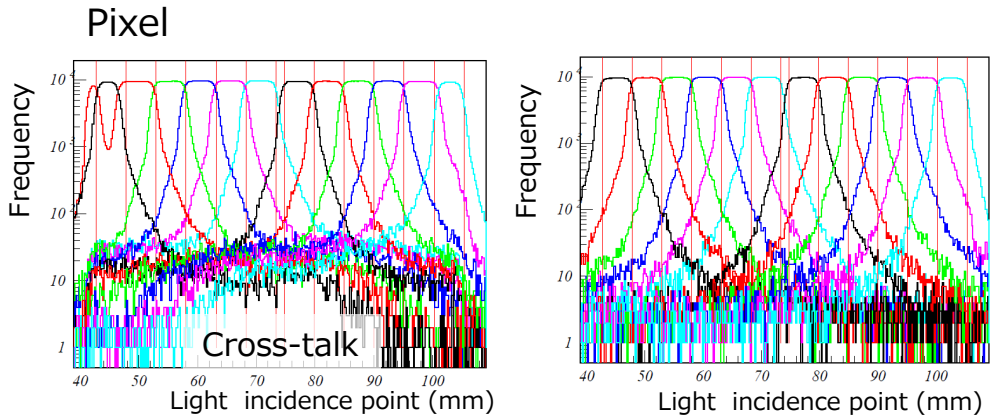


Tolerance to Magnetic field



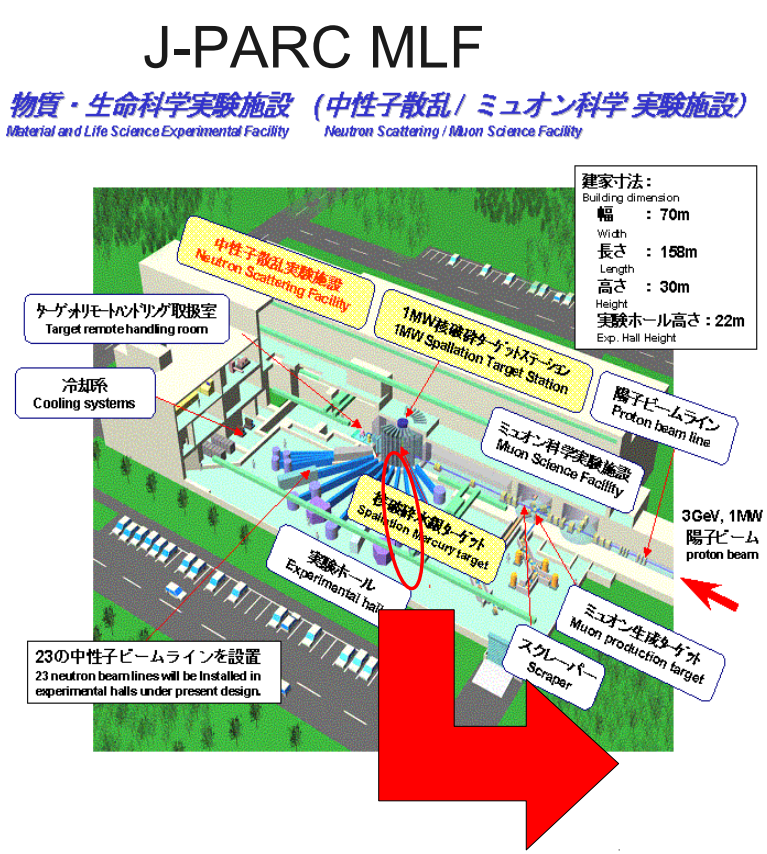
Scattering radius of photoelectrons

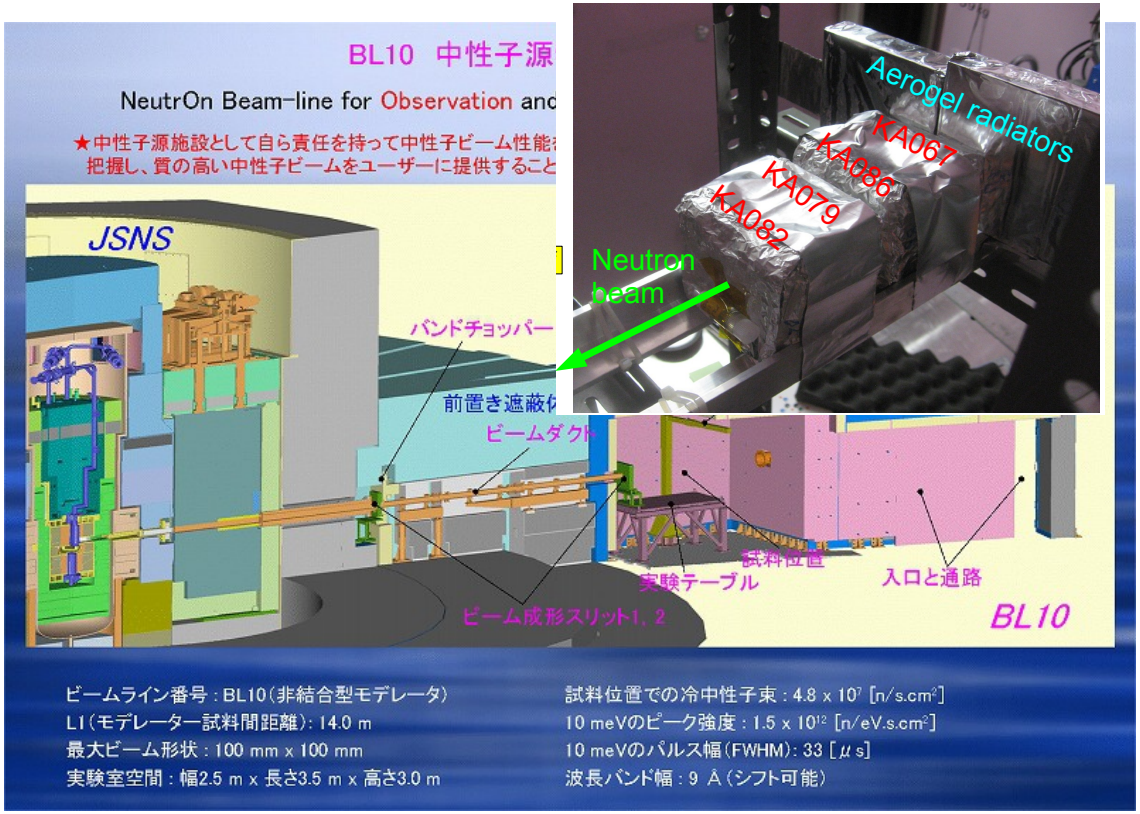




Colored lines show detection efficiency of each channel.

Neutron Test 2013



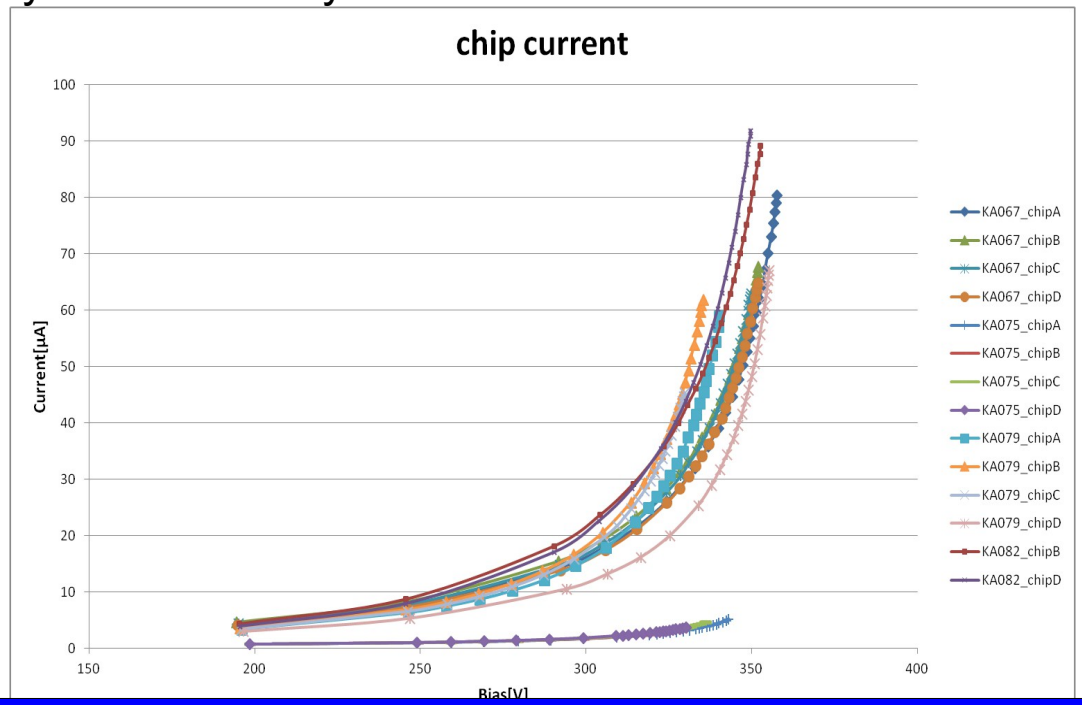


Gamma-ray Hardness

Chip Current VS Bias

Bias voltage scan during the irradiation

γ-ray dose: ~950Gy



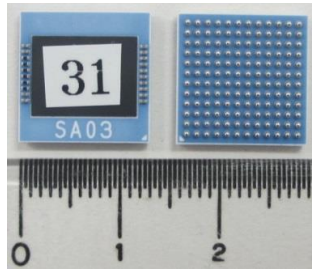
Breakdown is not observed up to maximum bias voltage for all the HAPDs

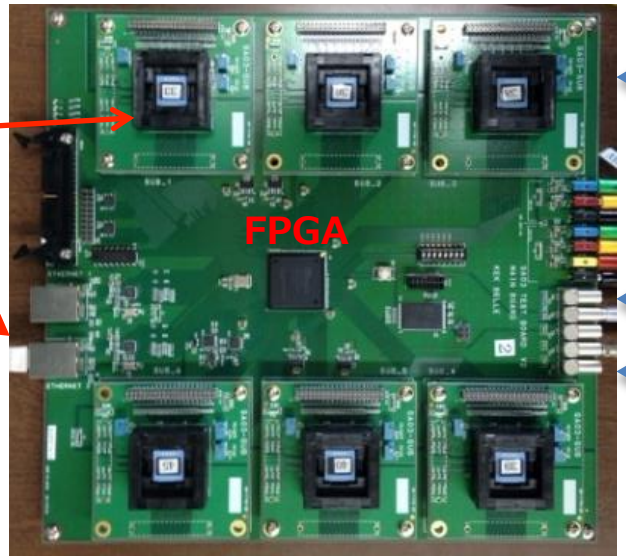
6

Readout ASIC

- ASICs: 2500 chips
  - Already finished mass production.
  - Quality check is on-going.
  - We developed the **test system** for mass productions.
    - Max. 6 ASICs are available.
    - Adopt removable sockets
    - TCP/IP communication
  - We are preparing automatic test software.

LTCC package

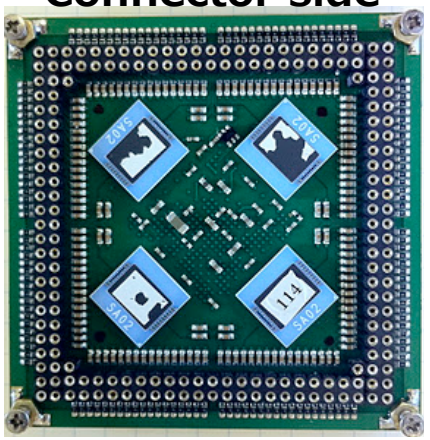




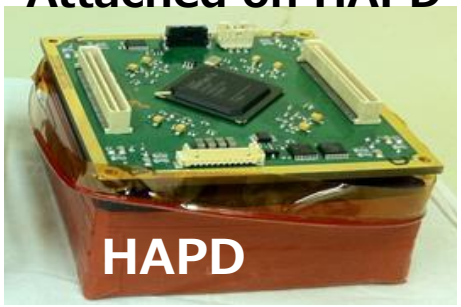
Front-end Board

- Front-end boards are under final design.
  - 4 ASIC + Xilinx FPGA (Spartan6)
  - Correct hit information from HAPD
  - Set ASIC parameters
  - HAPD bias voltage distribution
- Basic performance are confirmed by beam test.
  - @DESY, 2013
- Mass production will be start in this year.

Connector side



Attached on HAPD



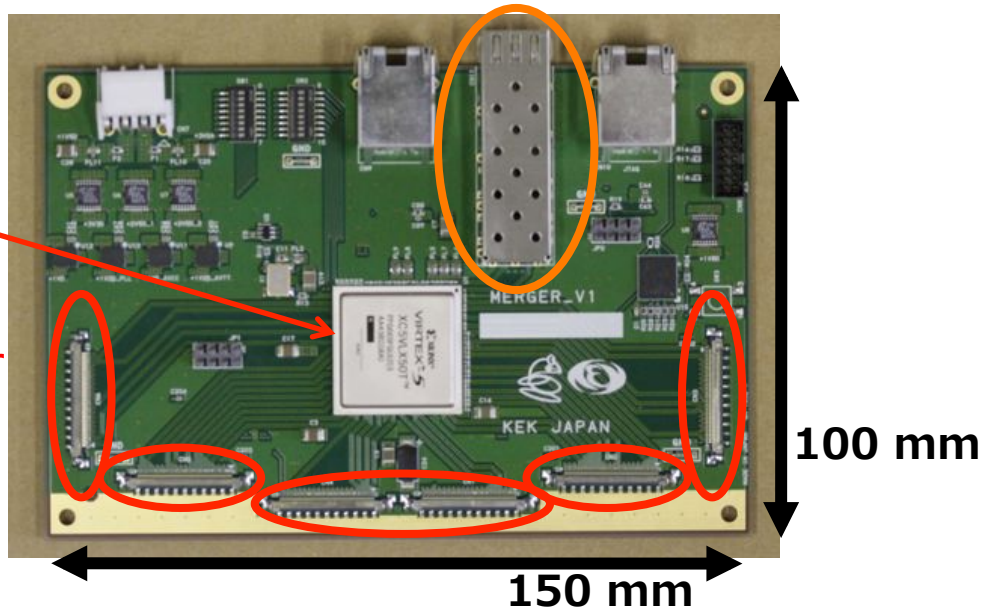
Merger system

- Merger Board: > 72 units
- Specifications are almost fixed
  - Collect hit data from 5~6 FE boards
  - Distribute the trigger
  - Set parameters

✔Data transfer
✔Slow control
✔Trigger, Clock
✔JTAG for FPGA

Optical connector
➔ Belle2Link

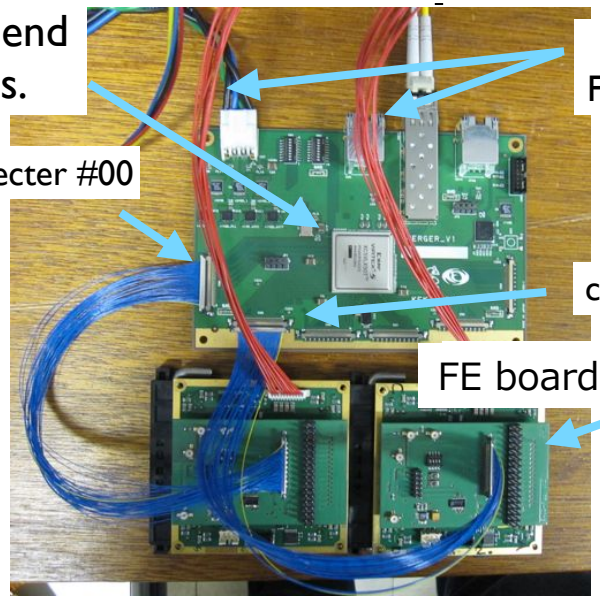
Prototype of Merger Board



KEK Electronics System group
has been developing.

Merger system

- Communication test with Prototype is on-going.
  - Slow control for FE boards by Belle2Link
  - Readout from 1~multi FE board(s)
  - Configuration of FPGA on a FE board



Basic functions were confirmed,

Mass production had started from April.

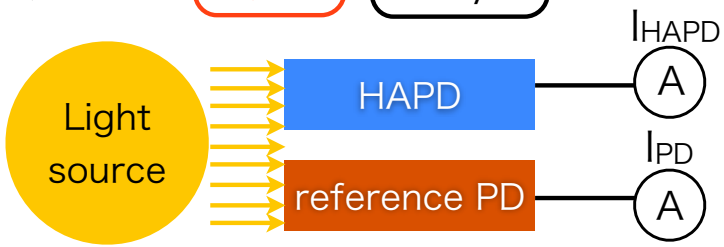
QE measurement

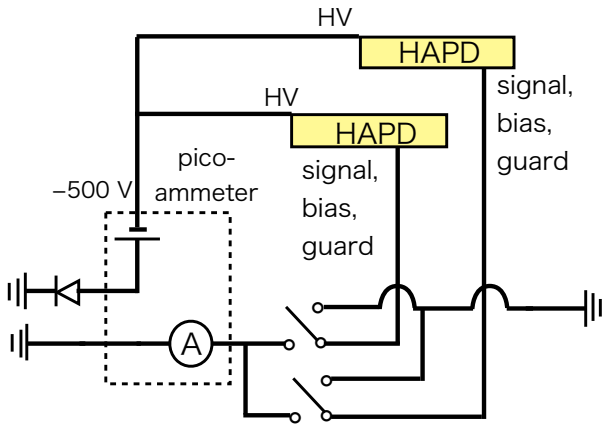
Overview of QE measurement system

Measure currents of HAPD using pico-ammeter and compare it to that from reference PD.

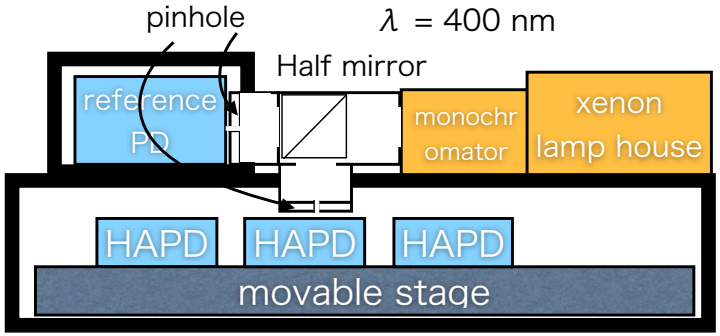
Move HAPD on the stage and measure current when illuminating ~1mm size spot light (50 times/point).
→ 2D QE map on photocathode.

$QE_{HAPD} = \text{calibrated } QE_{PD} \times \text{Measured } I_{HAPD}/I_{PD}$





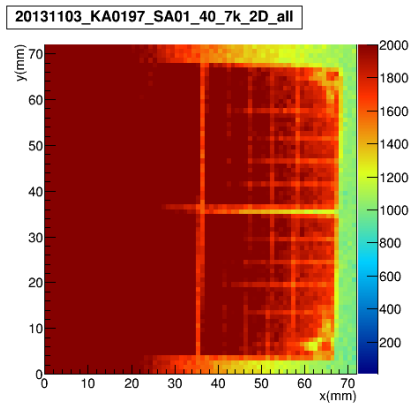
No APD/bombardment gain



By Y. Yusa
(Niigata Univ.)

2

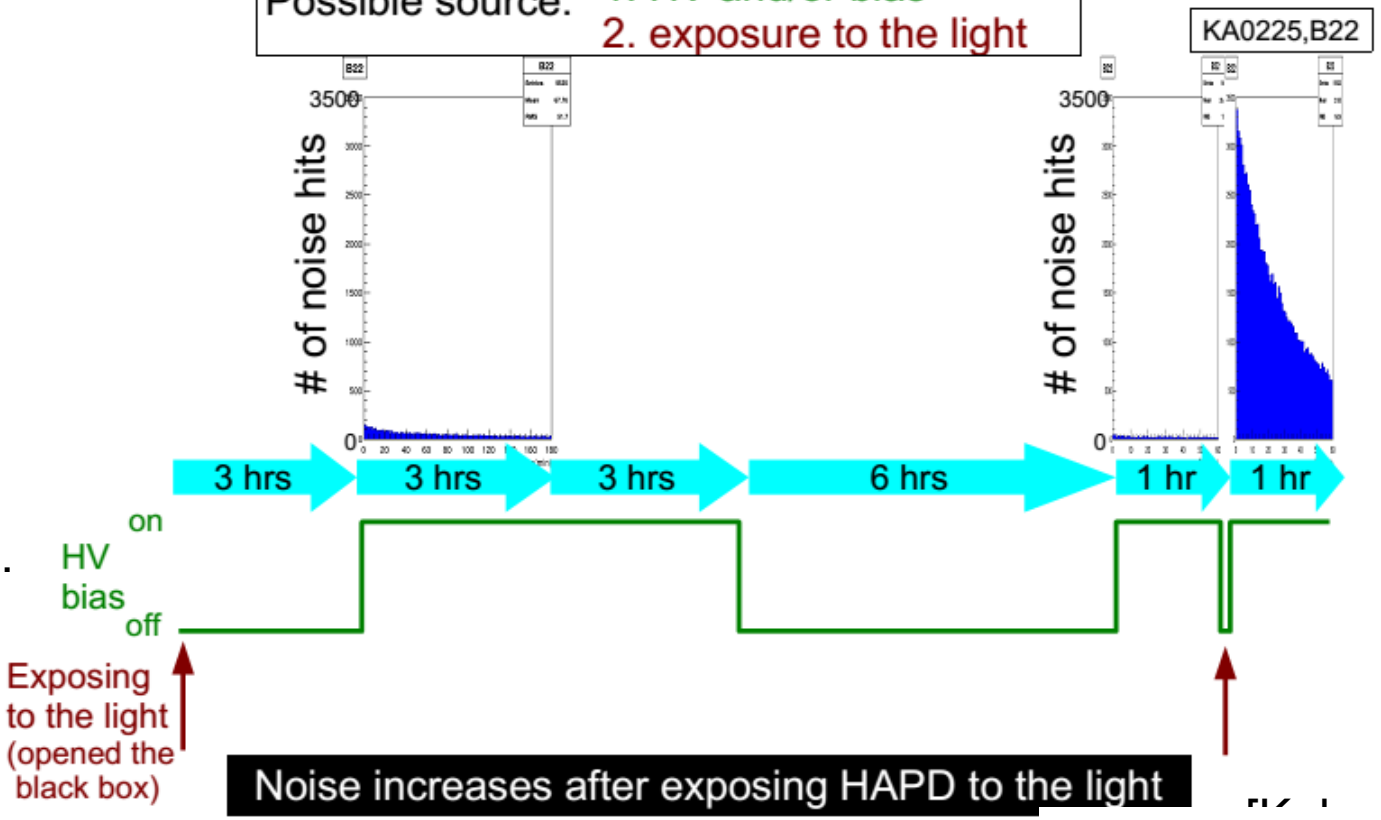
Noisy HAPD Issue



Seems the problem is related to exposure to light.

Source of the time dependent noise

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



By H. Kakuno
(Tokyo Metro. Univ.)

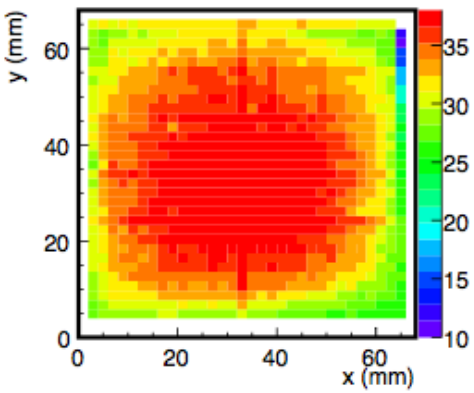
Investigation for productions

Some troubles are found from some HAPDs.
They are also investigated by our system.

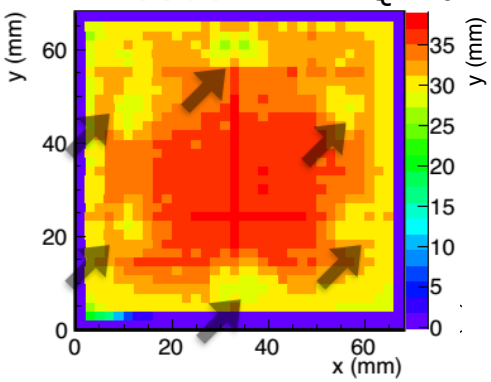
❖ QE 2D Distribution

- We found some samples with **funny structure** of QE by our measurement system.
- This problem is not resolve, we and Hamamatsu Photonics are researching about the detail cause.

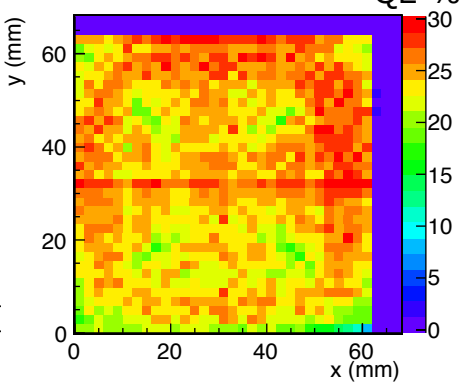
Typical sample



Pointed



Diagonal



Hamamatsu people also observe same structure. They try to understand why this structure appears.