Study of 144-Channel Multi-Anode Hybrid Avalanche Photo-Detector for the Belle II RICH Counter

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Orsay

Outline of this talk

Belle II experiment and proximity focusing RICH
Hybrid avalanche photo-detector (HAPD)
QE and single photon sensitivity
Radiation damage
Beam test
Conclusions

Authors

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W. Mori[10], S. Nishida[1], S.Ogawa[10],R. Pestotnik[2], L. Santelj[2], Y. Sakashita[5],
A. Seljak[2], T. Sumiyoshi[3], M. Tabata[6,11], H. Takagaki[5], Y. Yusa[7] and R. Verheyden[2]

(Belle II ARICH group)

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[5]Tokyo Metropolitan University, [6]Chiba University, [7]Niigata University,
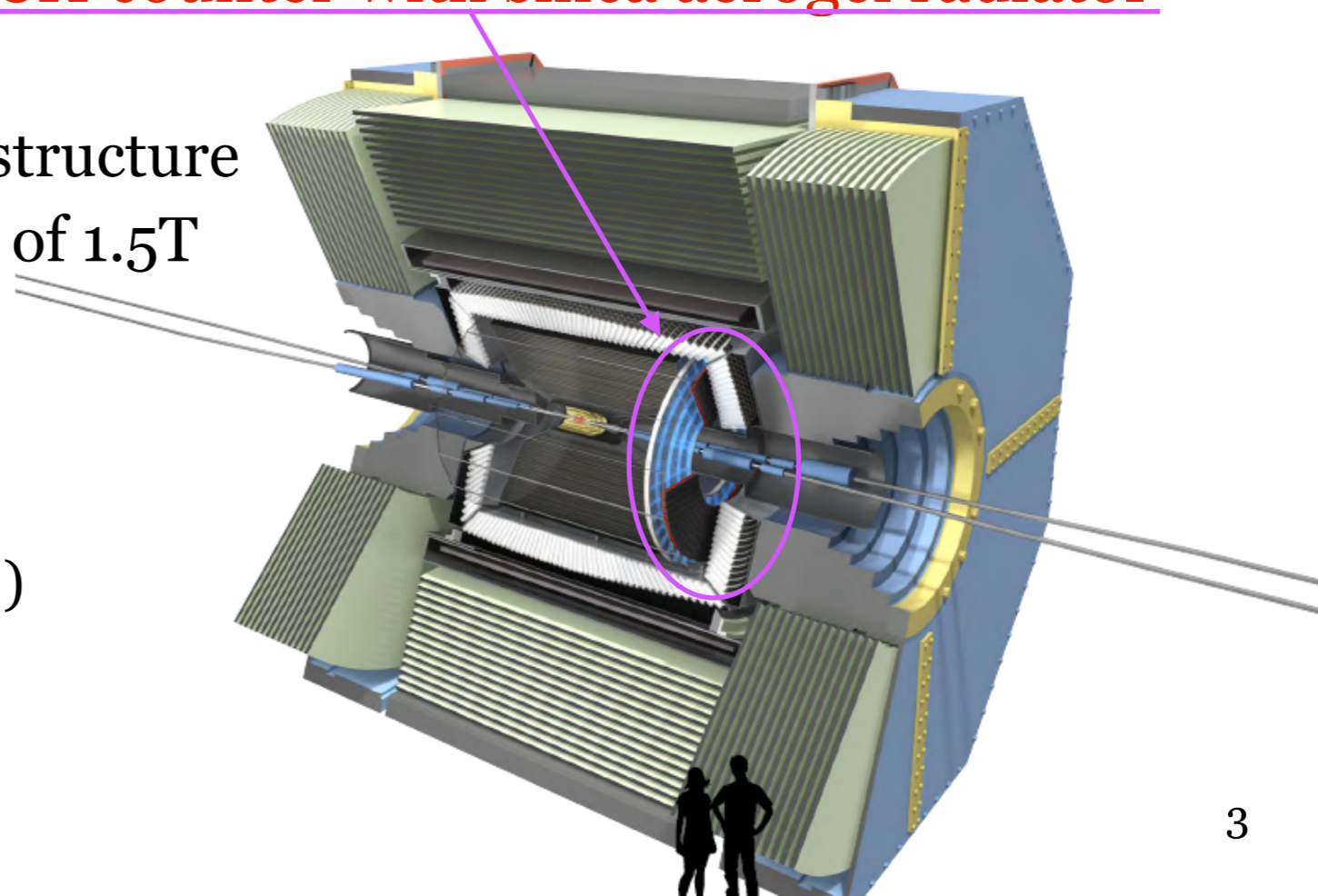[8]University of Maribor, [9]University of Ljubljana,
[10]Toho University, [11]Japan Aerospace Exploration Agency (JAXA)
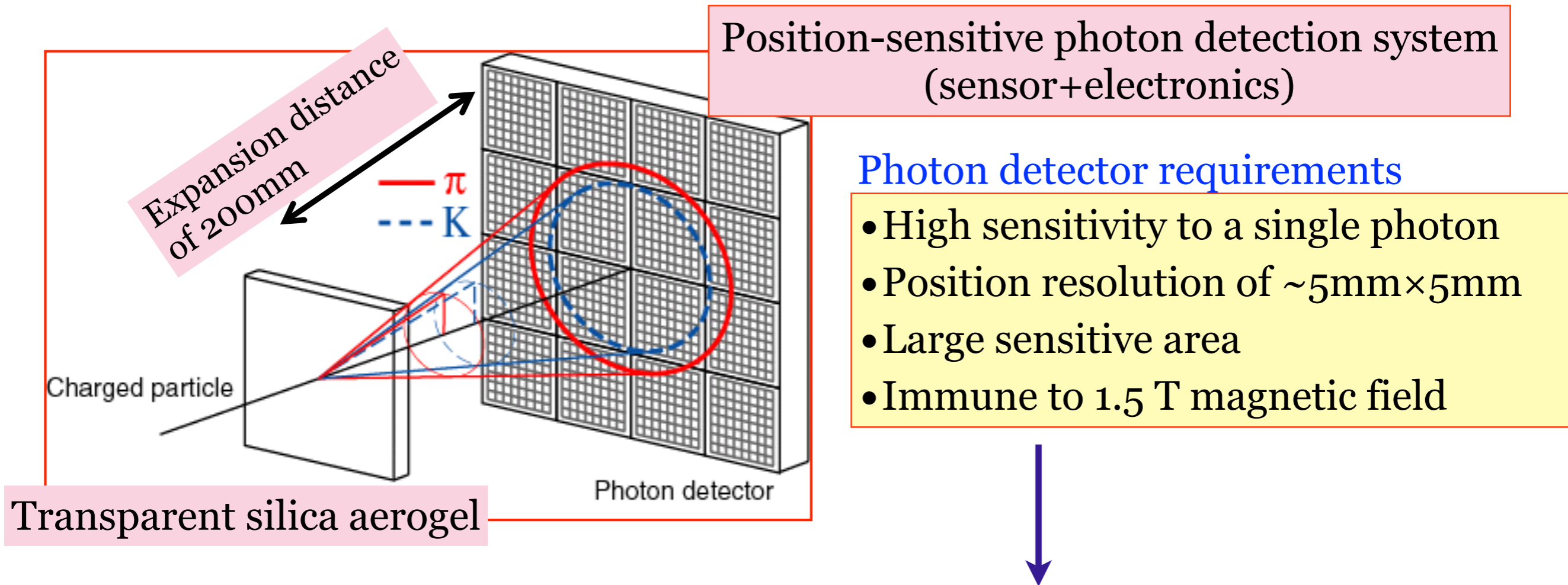
Belle II RICH Counter

- Particle identification devices at the Belle II experiment newly constructed and installed.

  - Further expand K/π separation capability
    - More sensitivity for New Physics search via B→ργ, for instance
  - Cope with higher background

- End-cap: Proximity focusing RICH counter with silica aerogel radiator

  - Limited space due to the Belle structure
  - Located inside a magnetic field of 1.5T

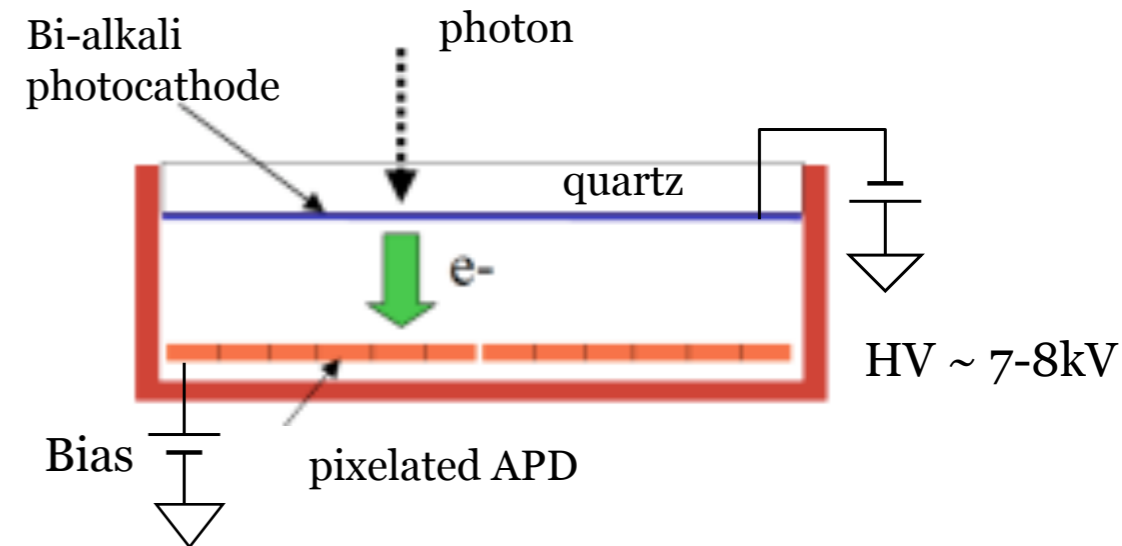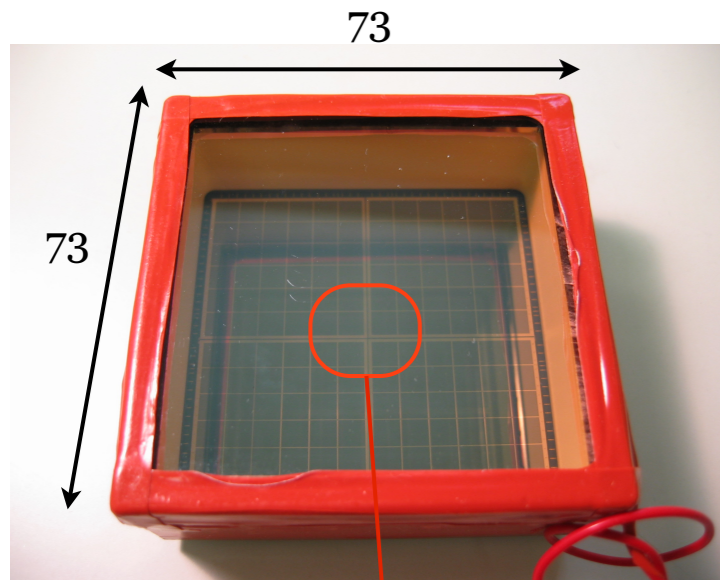 (Barrel: Time-of-Propagation counter)

Proximity Focusing RICH

Target: more than 4 σ K/π separation at p=4 GeV/c

Expansion distance of 200mm

— π
- - - K

Charged particle

Photon detector

Transparent silica aerogel

Position-sensitive photon detection system (sensor+electronics)

Photon detector requirements

- High sensitivity to a single photon
- Position resolution of ~5mm×5mm
- Large sensitive area
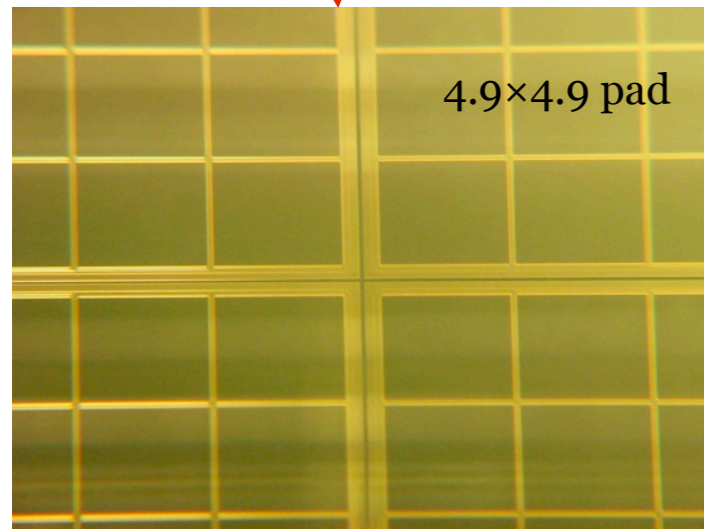- Immune to 1.5 T magnetic field

Multi-anode Hybrid Avalanche Photo-Detector (HAPD)

developed with Hamamatsu Photonics K.K. for Belle II RICH counter

Hybrid Avalanche Photo-Detector (HAPD)

73

73
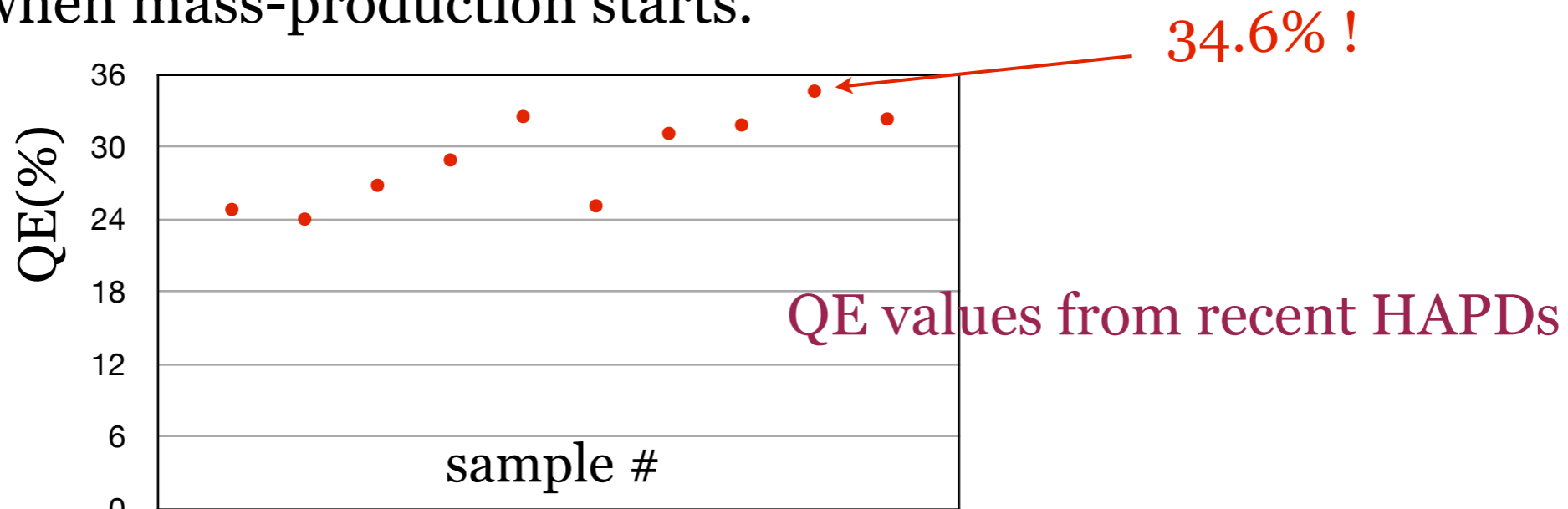
4.9×4.9 pad

4 pixelated APDs are housed

HAPD72X72/B-M144

Bi-alkali photocathode

photon

quartz

e-

HV ~ 7-8kV

Bias

pixelated APD

Specifications

package	73×73mm²
sensitive area	64%
# of pixels	144(36×4chips)
capacitance	80pF
weight	220g
peak QE	27~31%
bombardment gain	1300~1500
avalanche gain	~50
total gain	$\sim 10^5$

Quantum Efficiency

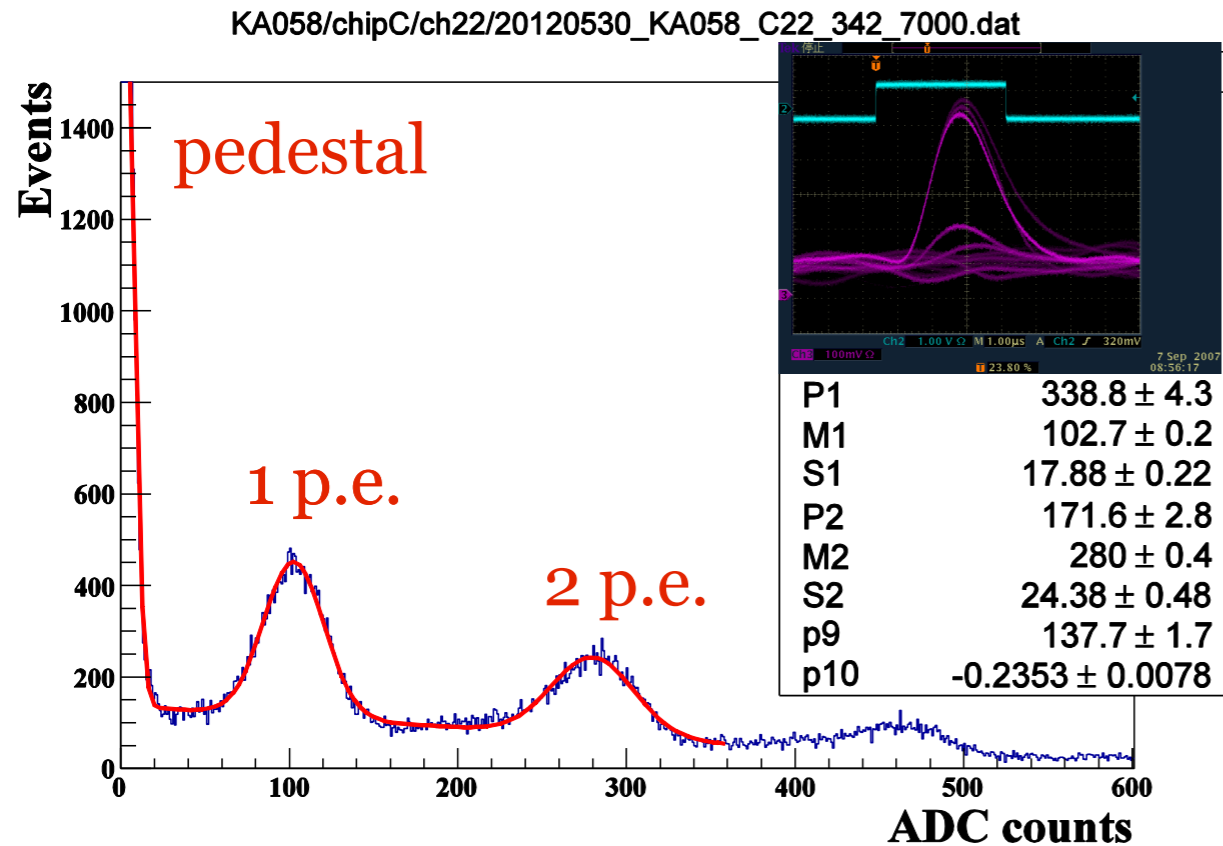- We achieved high QE of 33 % in 2009 based on HPK "super bi-alkali" technology.
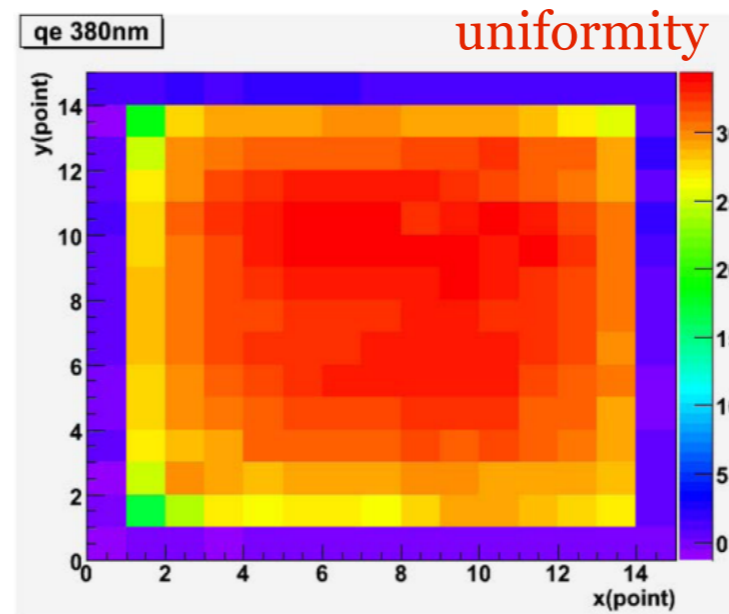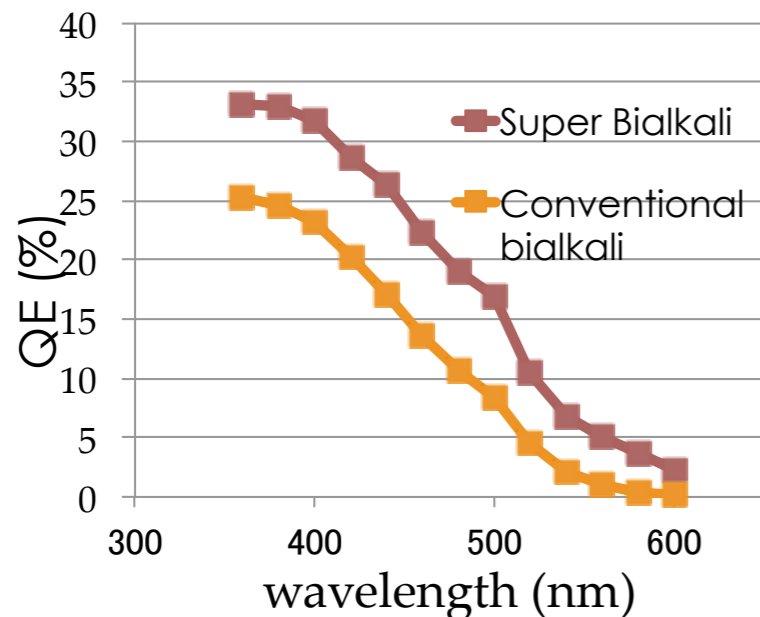
- Since then we have been trying for further improvements... Recent new HAPD samples show ~35 % at the best. Expect more stable and high values when mass-production starts.

34.6% !

QE values from recent HAPDs

Single Photon Response

pulse heigh distribution

blue LED illuminated
HV: -7kV bias: 342V

KA058/chipC/ch22/20120530_KA058_C22_342_7000.dat

pedestal

1 p.e.

2 p.e.

P1	338.8 ± 4.3
M1	102.7 ± 0.2
S1	17.88 ± 0.22
P2	171.6 ± 2.8
M2	280 ± 0.4
S2	24.38 ± 0.48
p9	137.7 ± 1.7
p10	-0.2353 ± 0.0078

1 APD uniformity scan

HDD_3TB/neutrontest201206/KA058/before/2dscan/20120603_KA058_SA01_40_7k_A.root

$\sigma_{pedestal} = 2.9 \times 10^3$ electrons

Gain $= 8.2 \times 10^4$
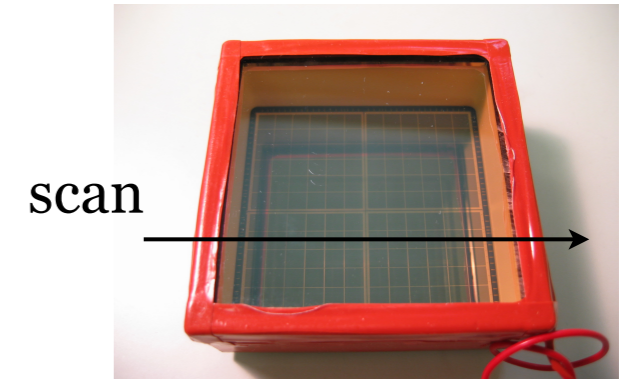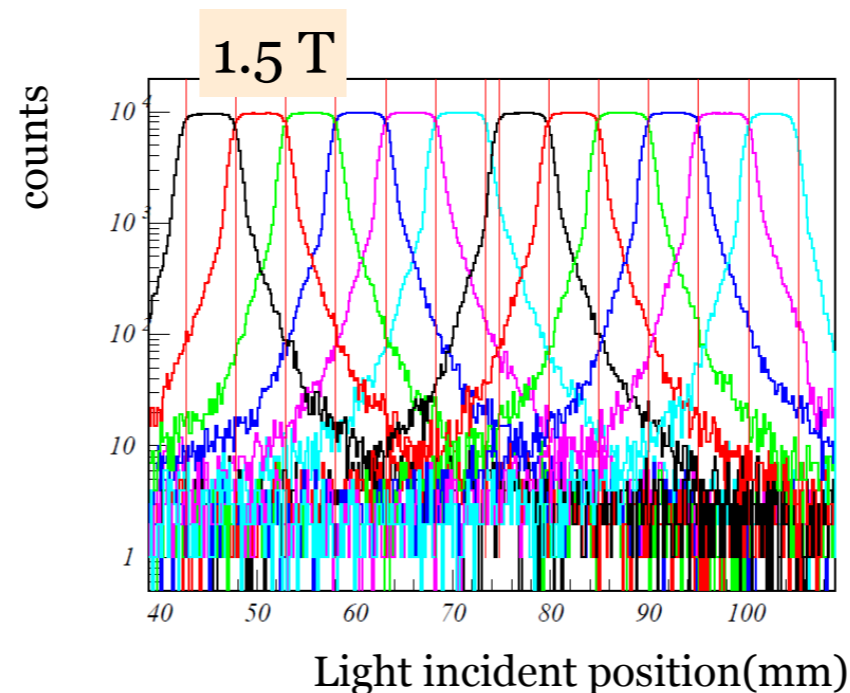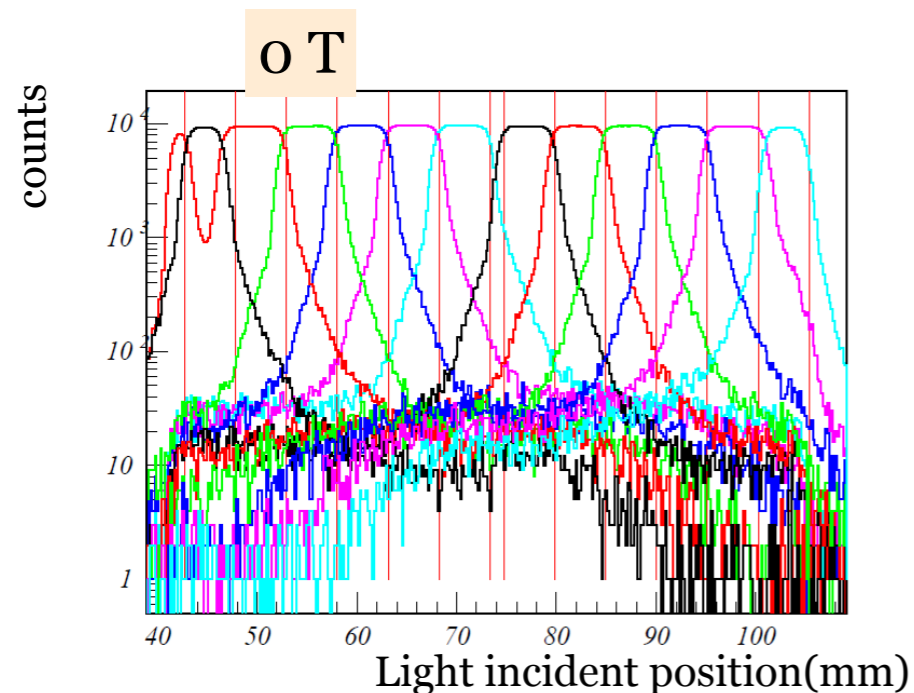from 1 and 2 p.e. peaks

$S/N = G/\sigma_{pedestal} \sim 28$
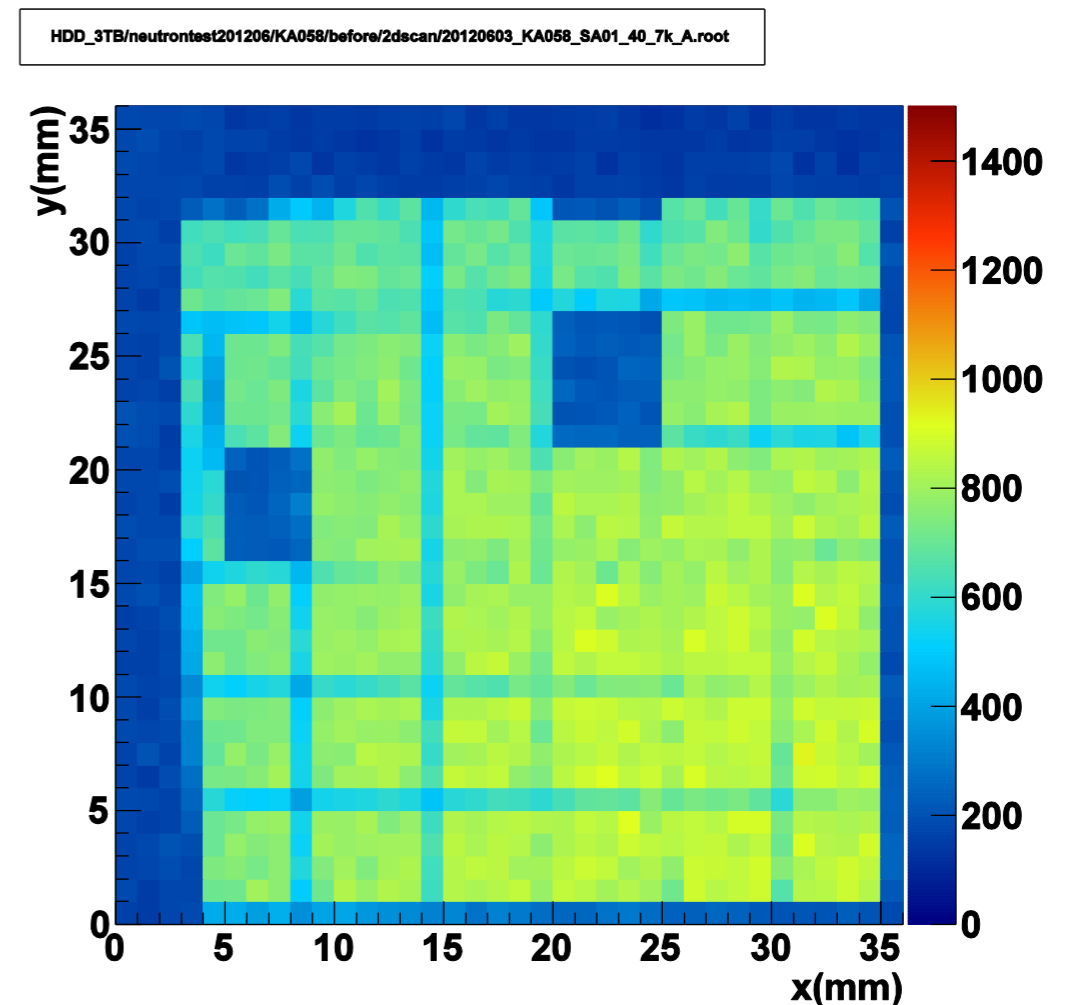
Clear single photon signal observed !

Test under a Magnetic Field

- Response scan for entire HAPD channels were done under an axial magnetic field of 1.5 Tesla.

The excellent response for single photon and background becomes better

Performance is improved in the presence of a magnetic field !

Radiation Damage

- Severe beam-related background is predicted in the Belle II experimental environment.
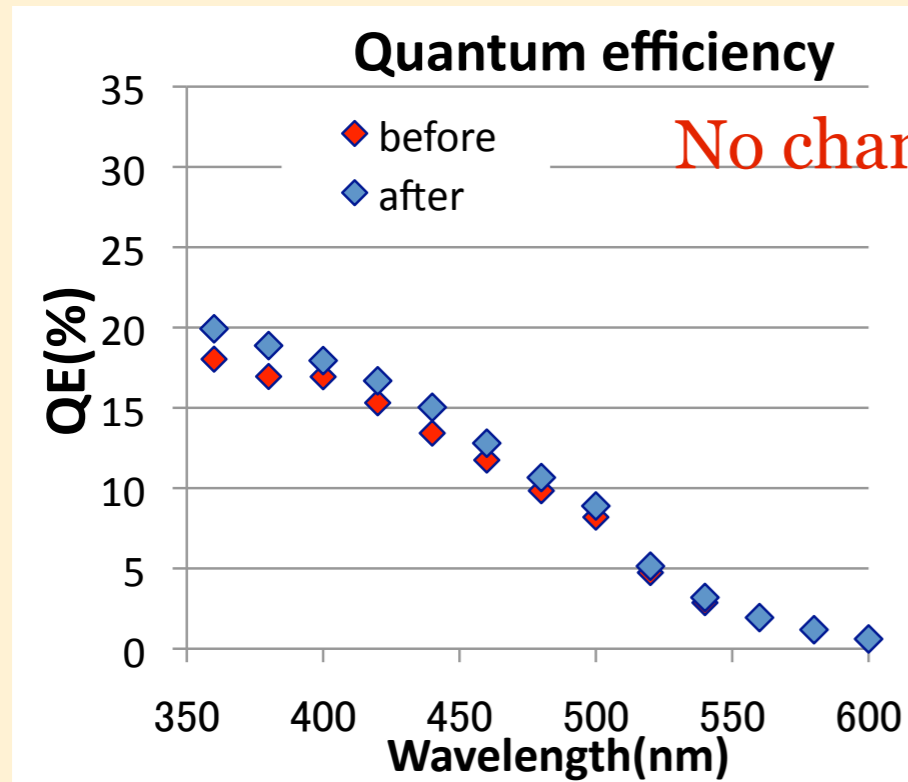
  for 10-year Belle II operation

  - Neutrons: 10^{12} neutrons/cm^2
  - Gamma-rays: 1000 Gy
    - Depending on an accelerator design, and keep improving these days...

- HAPD should be radiation-tolerant for those background sources.

- A series of studies on HAPD irradiation tests has been done in recent years.

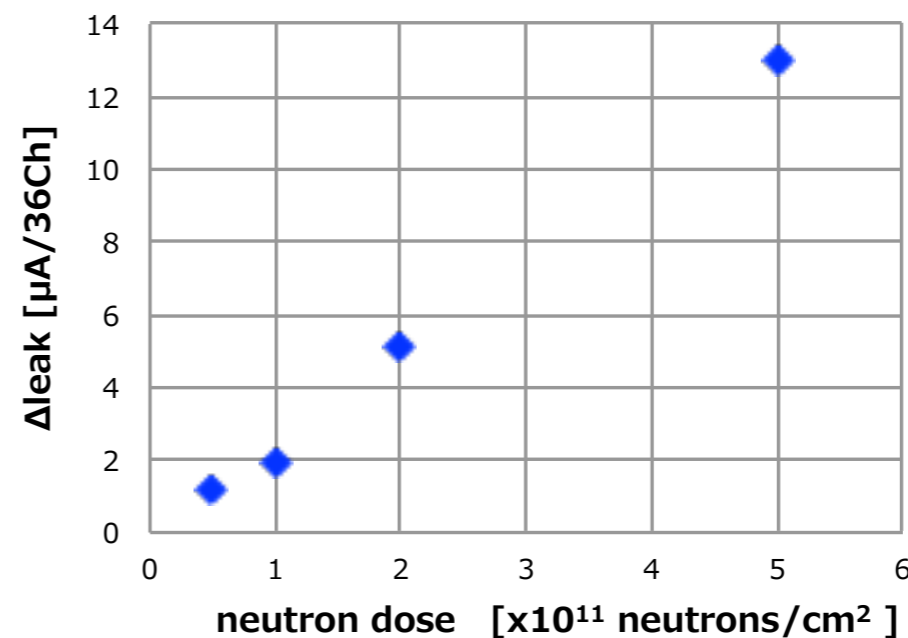 - Nuclear facility for neutrons
  - ^{60}Co facility for gamma-rays

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Neutron Radiation

HAPD irradiated at a nuclear reactor "Yayoi" at Univ. of Tokyo.
average energy ~ 370keV

After 5×10^{11} /cm² irradiation

Quantum efficiency
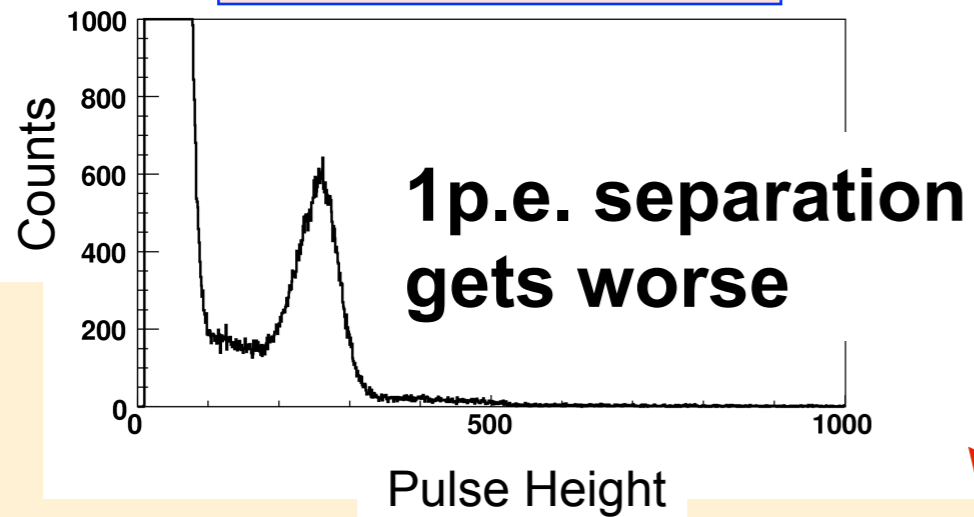
No change in QE

Increase in APD leakage current

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Neutron Radiation

S/N deterioration

1×10^{11} irradiation

1p.e. separation gets worse

5×10^{11} irradiation

1p.e. cannot be separated
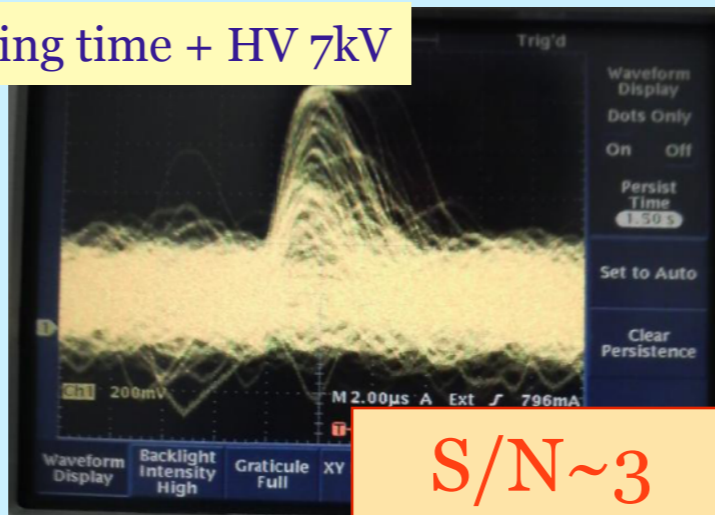
Before irradiation

1p.e.
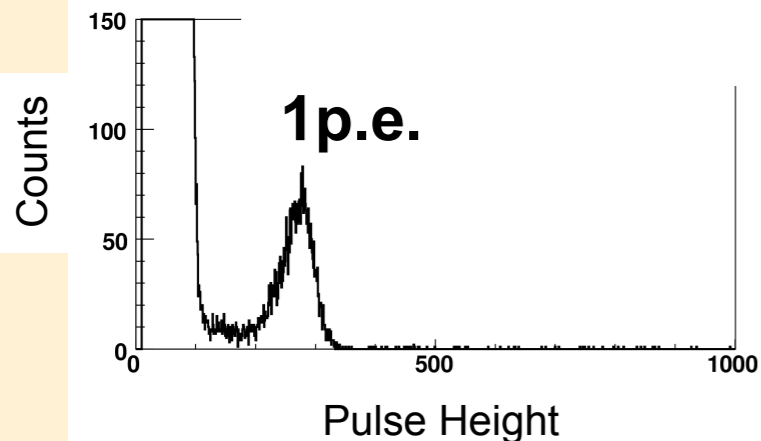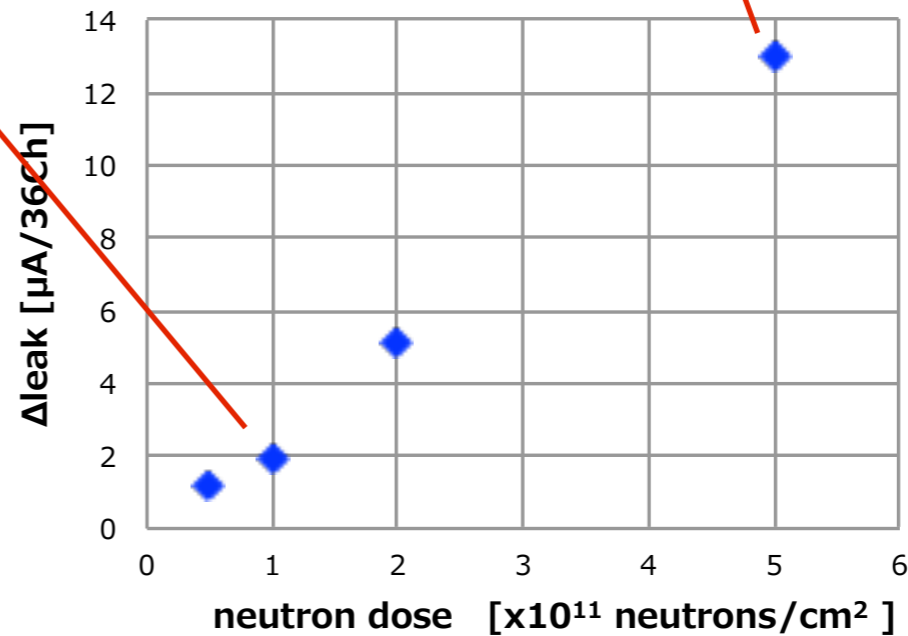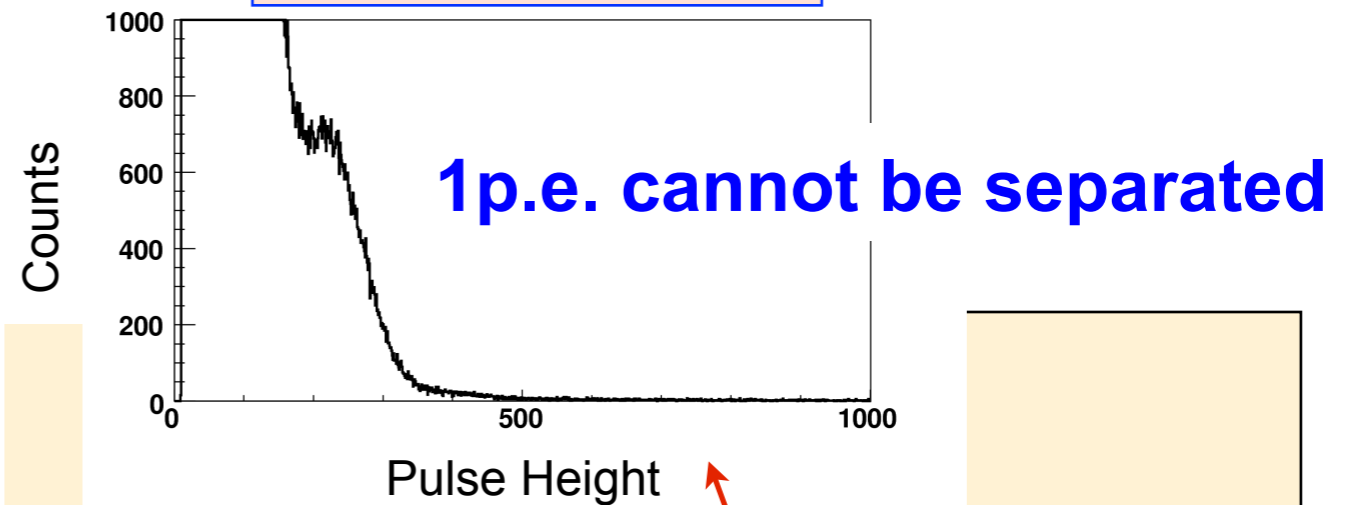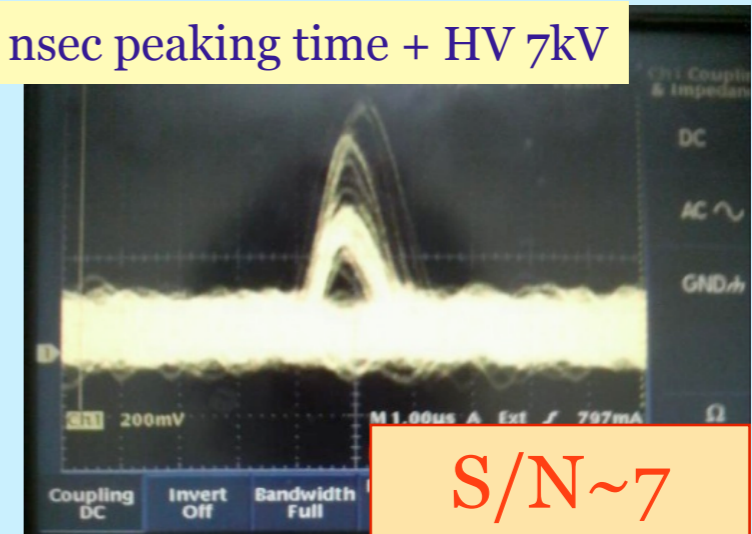
Need improve S/N

Neutron Radiation Prescriptions

(1) Shorter shaping time : Readout electronics with flexible functionality

1 μsec peaking time + HV 7kV

signal from 5×10^{11} sample
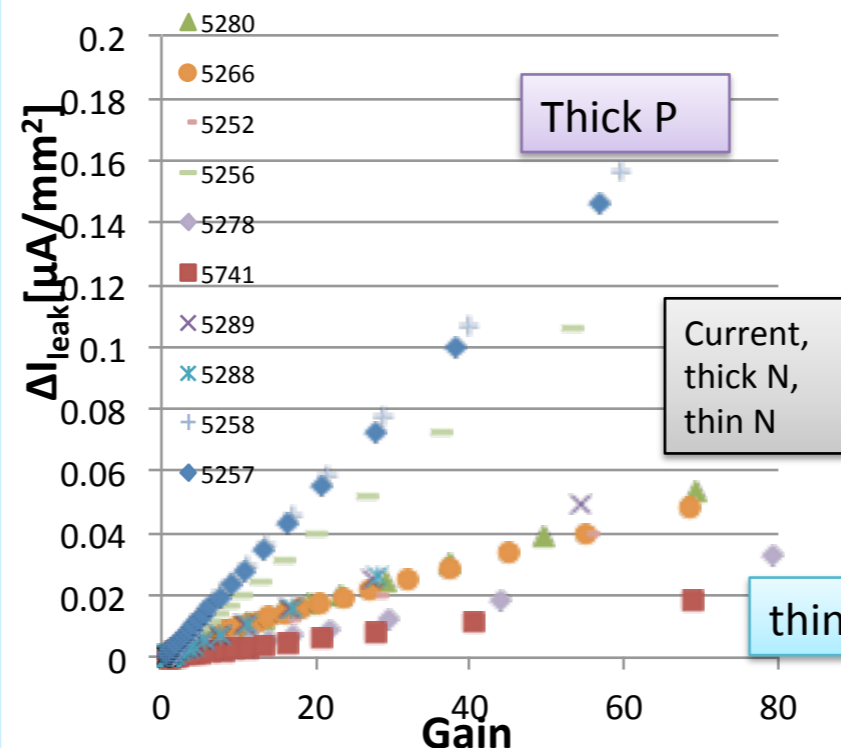
S/N~3

250 nsec peaking time + HV 7kV

S/N~7

(2) Thinner APD

Avalanche amplification region

P^+

P

~10μm

N

electron

positive
hole

~40μm

N^-

N^+

APD structure

ΔI(leak) for various APDs irradiated up to 10^{12}

- ▲ 5280
- ● 5266
- - 5252
- — 5256
- ◆ 5278
- ■ 5741
- ✕ 5289
- ✳ 5288
- + 5258
- ◆ 5257

Thick P

Current,
thick N,
thin N

thin P

ΔI_{leak} [μA/mm²]

Gain
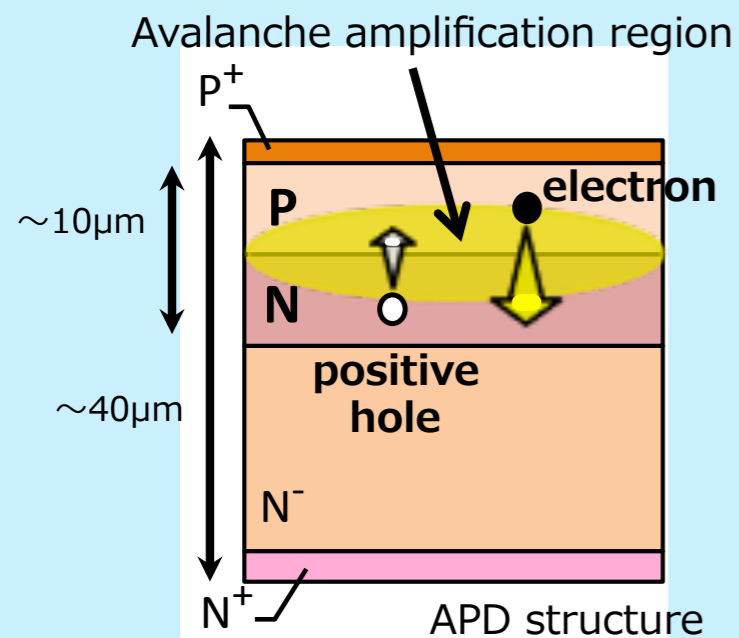
Both methods are expected
suppress degradation up to
10^{12}
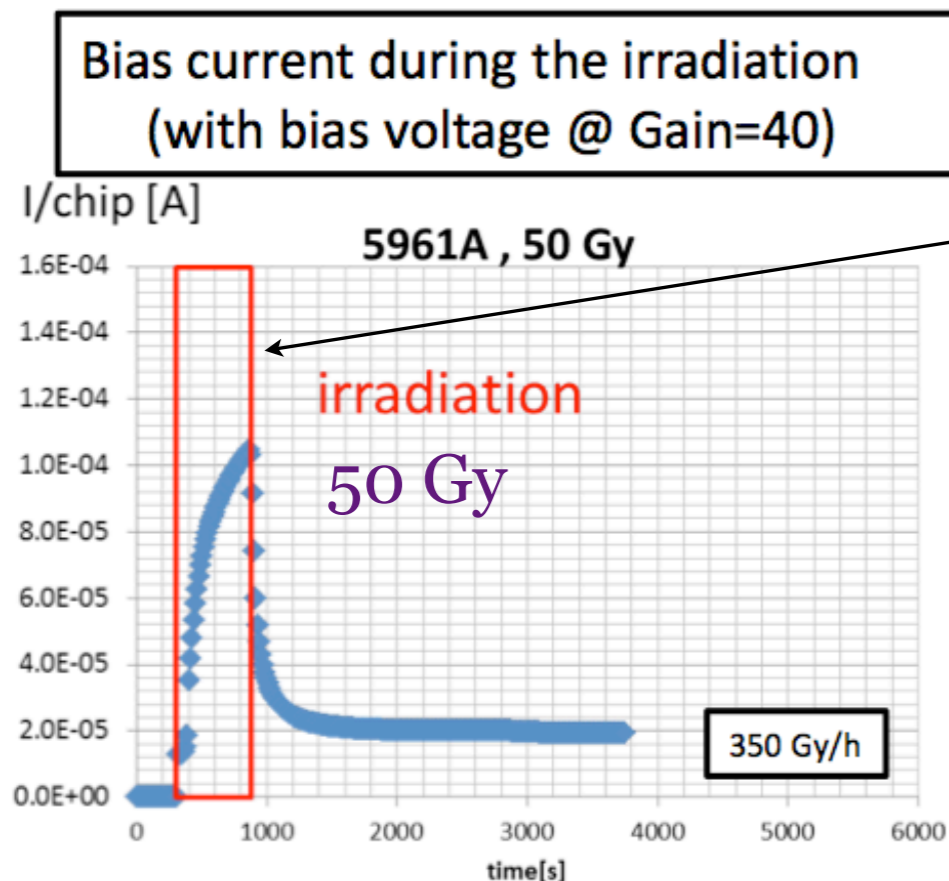
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Gamma-ray Radiation

First irradiation in 2010 using ^{60}Co facility

Bias current during the irradiation (with bias voltage @ Gain=40)

I/chip [A]

5961A , 50 Gy

irradiation

50 Gy

350 Gy/h

time[s]

Quick increase of leakage current observed even at 50 Gy, different from normal APDs

Some annealing effect found, however V-I measurements indicated Ohmic response once bias voltage exceeds "threshold" ("breakdown")

I_{bias}[A]

5961D (50 Gy)

- ■ 8 days
- ▲ 15 days
- × 2 months
- ◆ 1 day

8 day

15 day

after 1 day

60 days

Bias[V]

Gamma-ray Radiation

First irradiation in 2010 using ^{60}Co facility

Bias current during the irradiation (with bias voltage @ Gain=40)

I/chip [A]

5961A , 50 Gy

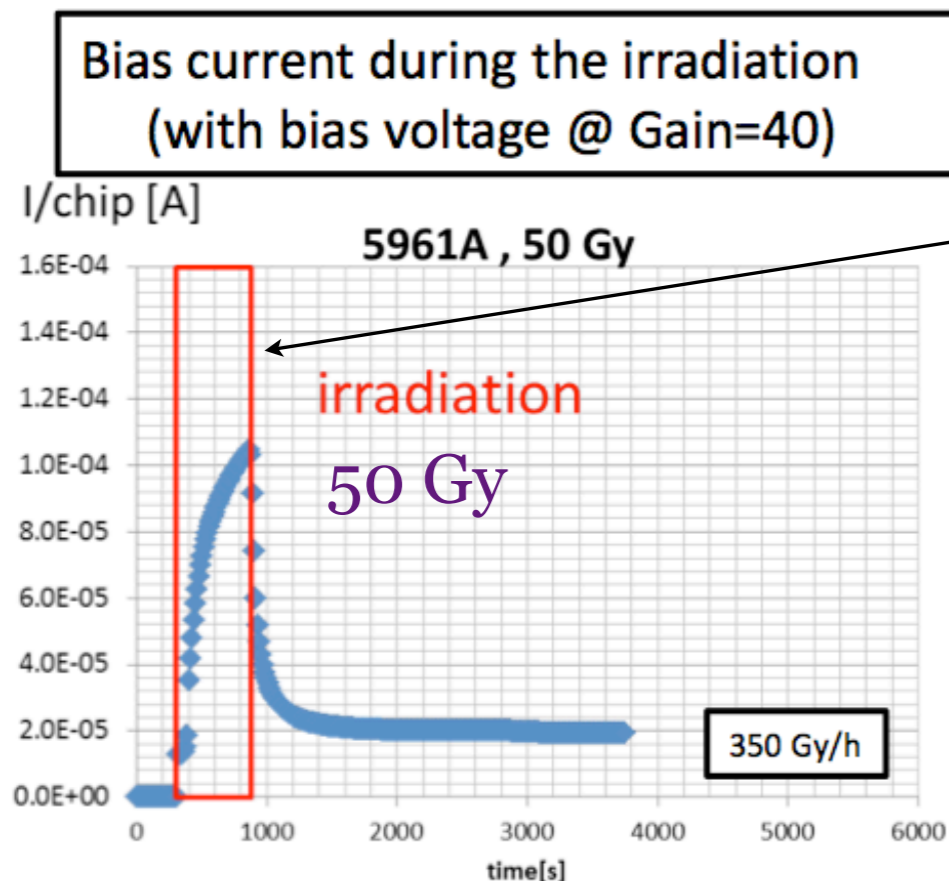irradiation

50 Gy

350 Gy/h

time[s]

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I_{bias}[A]

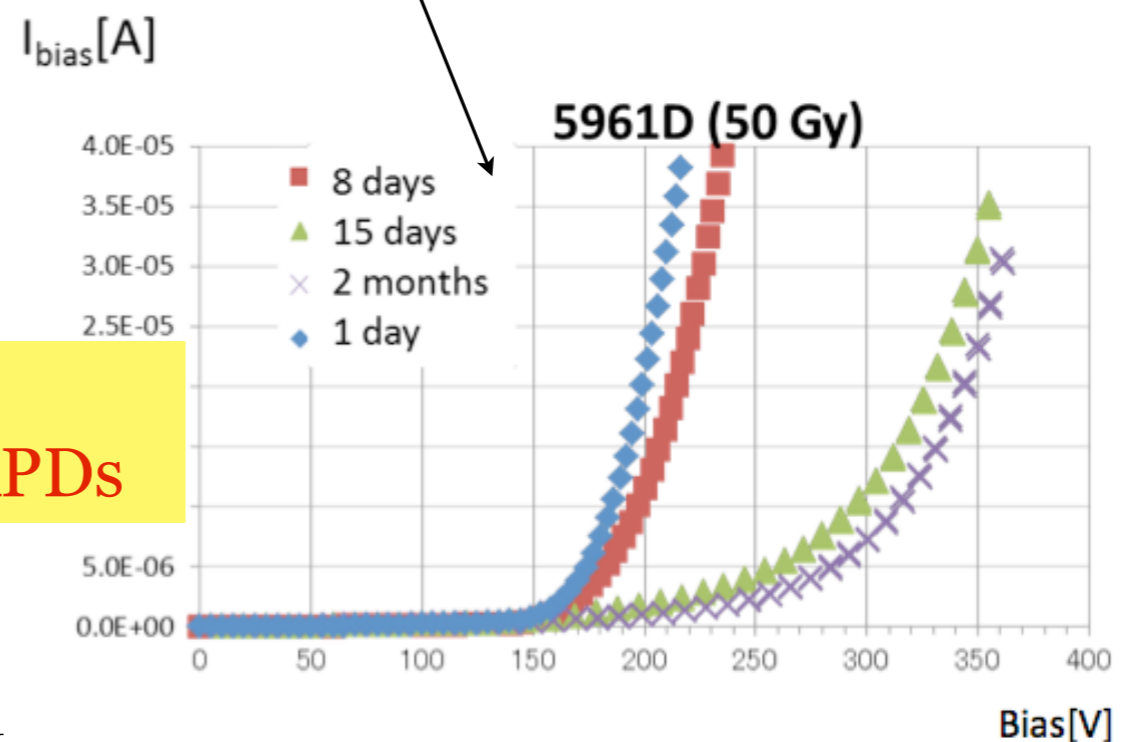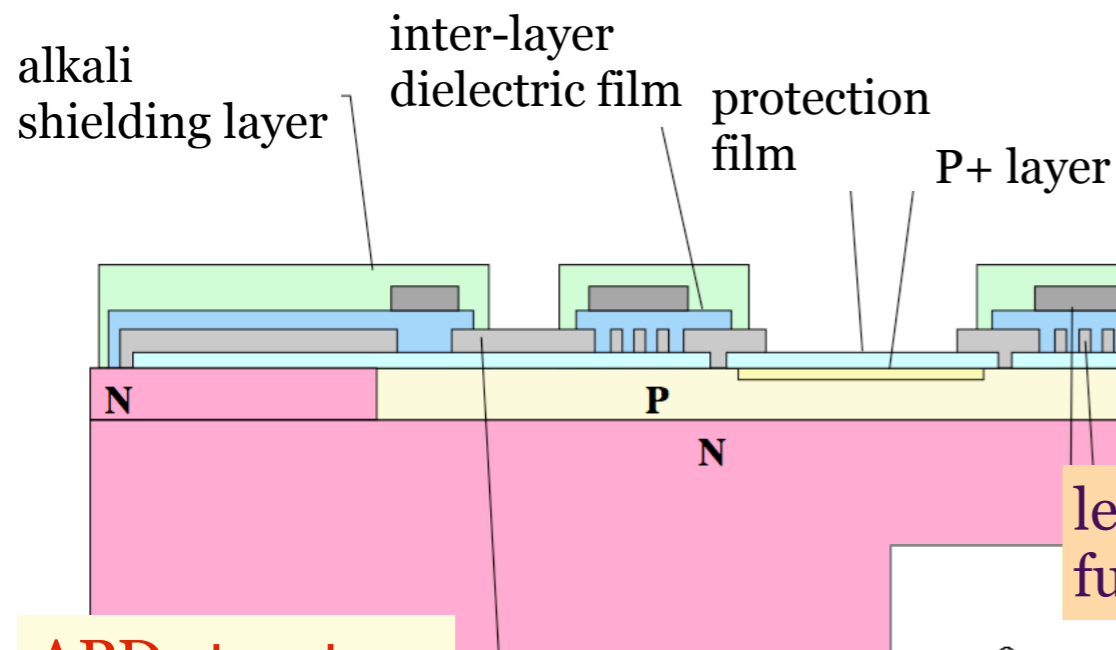5961D (50 Gy)

- 8 days
- 15 days
- 2 months
- 1 day

Bias[V]

Those problems initiated a series of irradiation tests using various types of APDs

Gamma-ray Radiation Prescriptions

alkali
shielding layer

inter-layer
dielectric film

protection
film

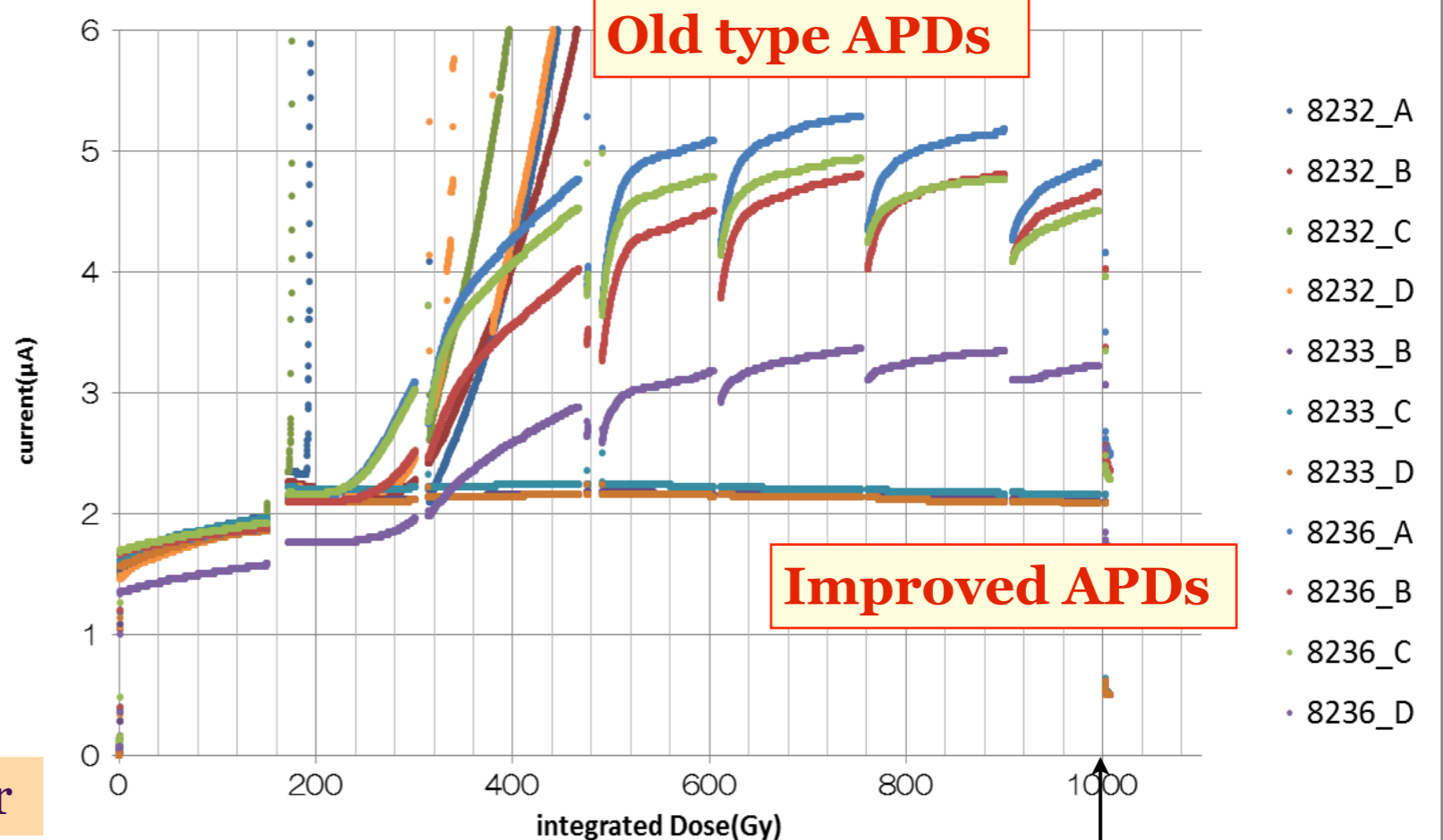P+ layer

N

P

N

N

ボンディングパッド

電

APD structure

Increase of leakage current suppressed by improving a protection film covering sensitive area

Material for alkali shielding changed to avoid a drop of "breakdown" voltages

leakage current measurements as a function of integrated dose

Old type APDs

Improved APDs

- 8232_A
- 8232_B
- 8232_C
- 8232_D
- 8233_B
- 8233_C
- 8233_D
- 8236_A
- 8236_B
- 8236_C
- 8236_D

current(μA)

integrated Dose(Gy)

tested on 2011 December

1000Gy

Rad-tolerant HAPD

- Based on those tests, radiation-improved HAPD candidates have been listed up.

- These samples are now being delivered.

- Further examinations for these candidates will be made in the coming months.
  - Including neutron & gamma-ray irradiation tests
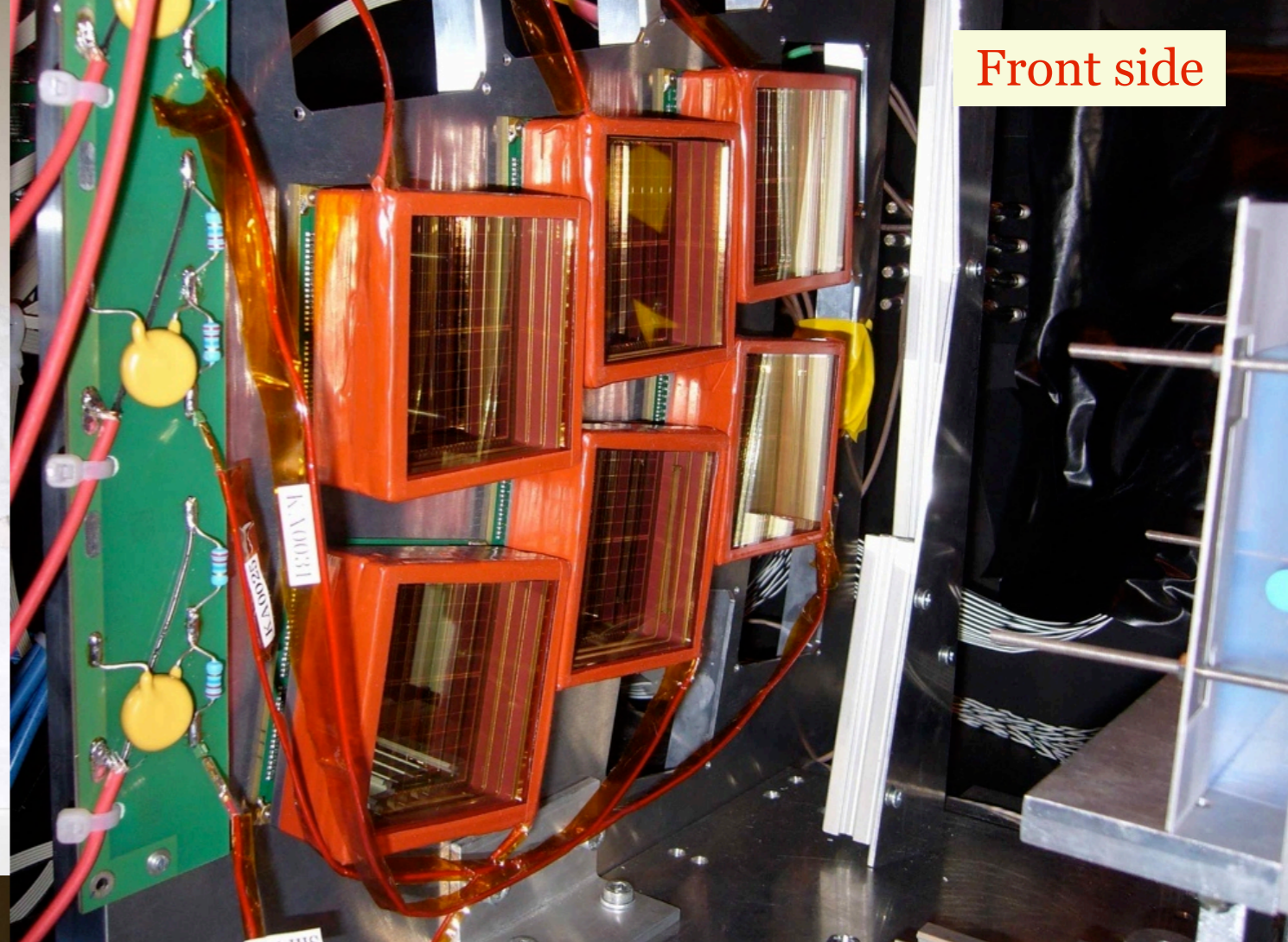
Test Beam Experiment

- We carried out a test beam experiment at T4-H6 CERN SPS 2011 autumn.

  - 6 HAPDs arranged in the almost final positions

  - new batch of HAPDs

  - new aerogel radiator

  - front-end electronics ~ close to final version
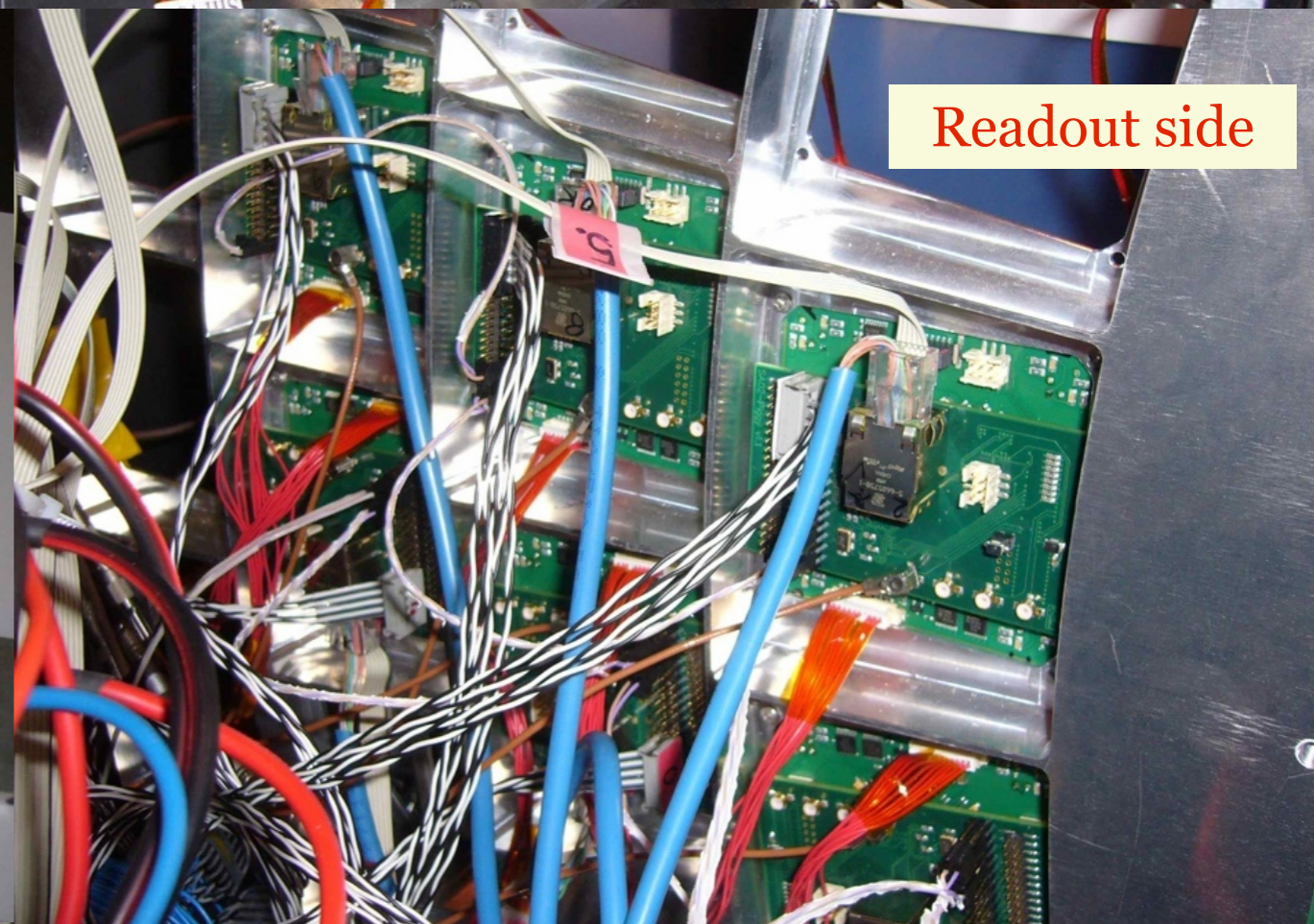
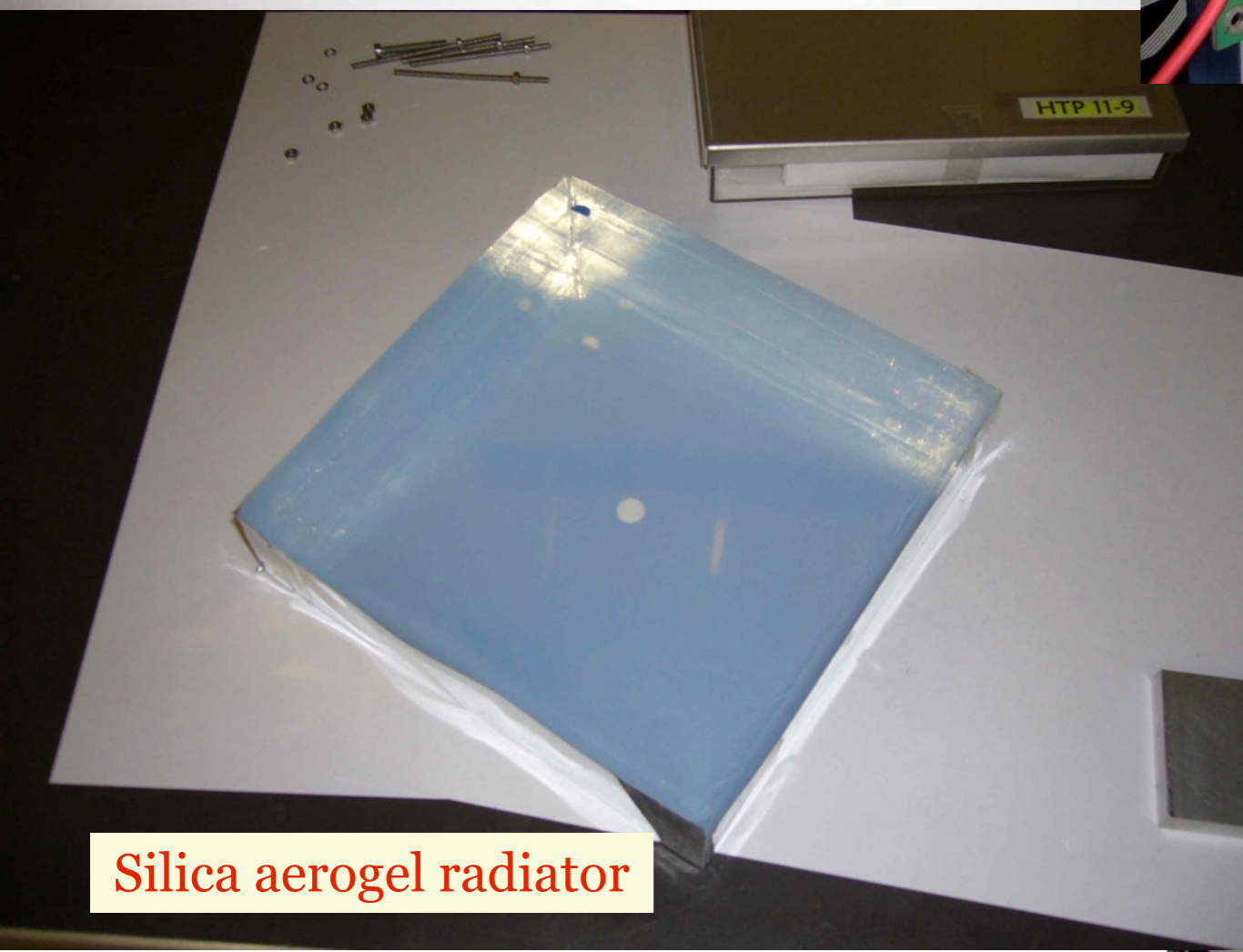 - mirror tested
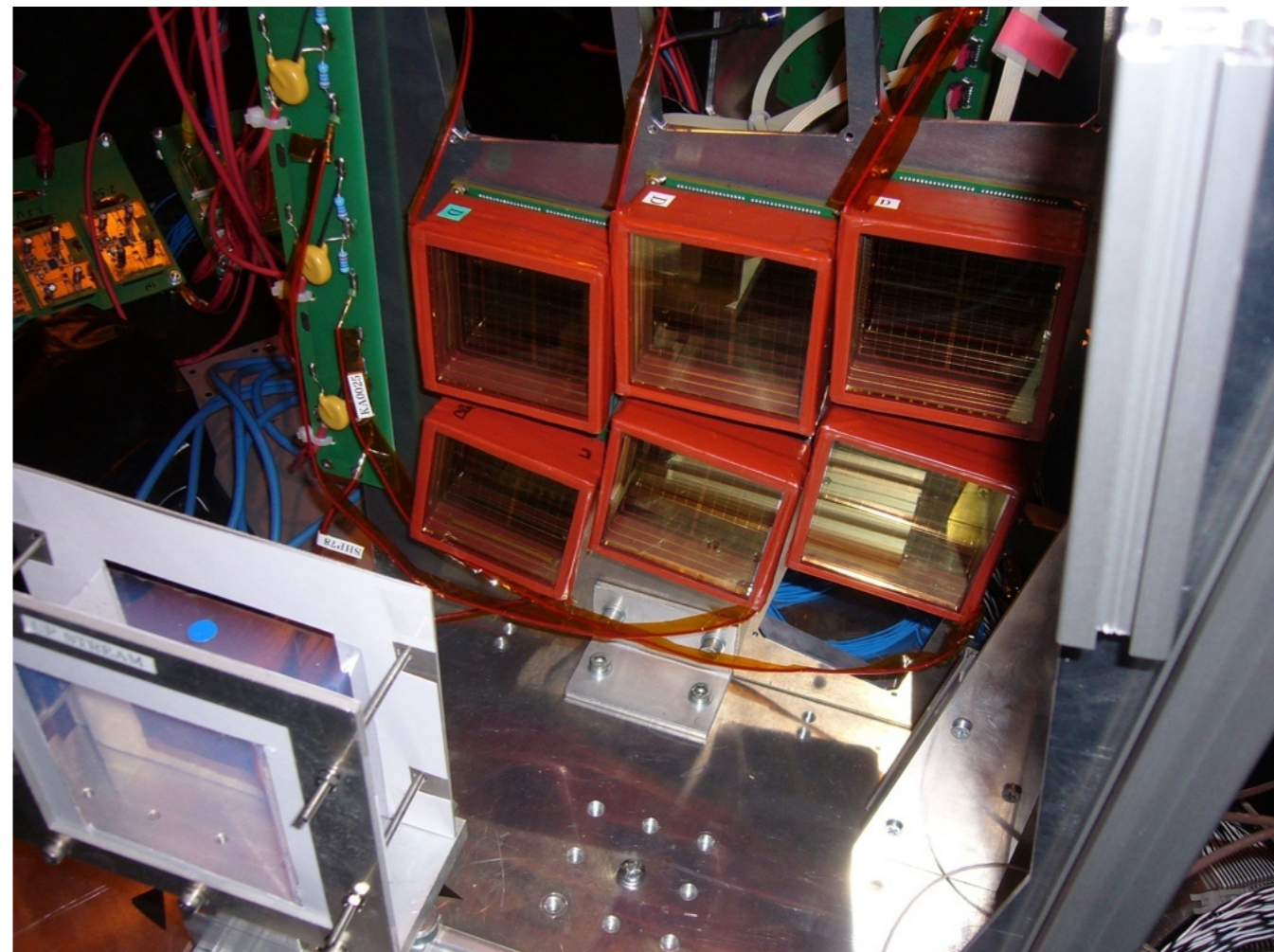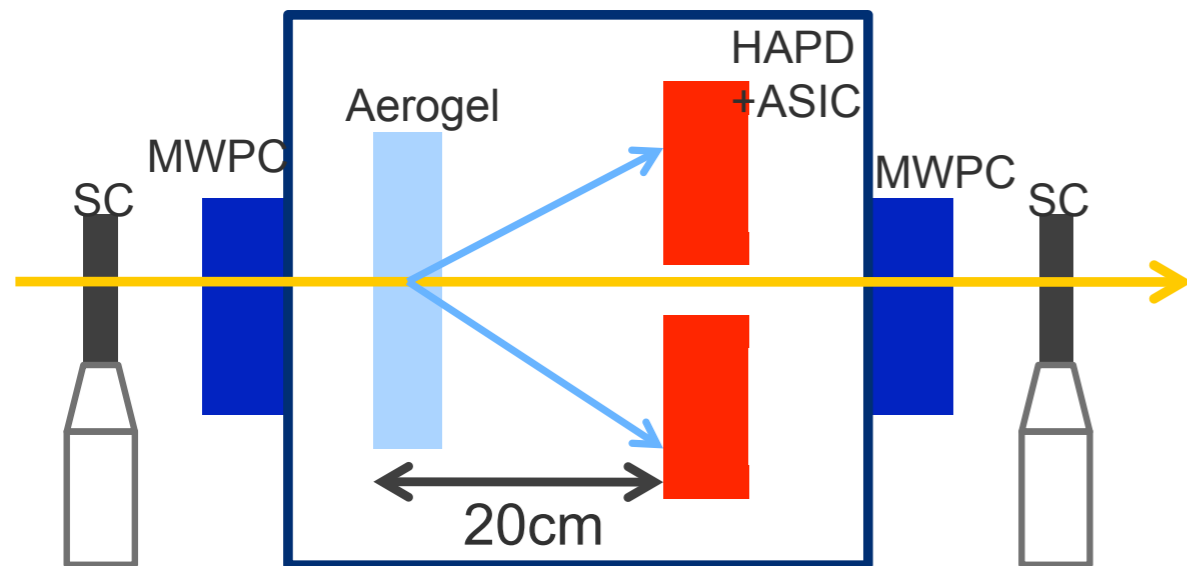
HAPD and readout front-end board

Front side

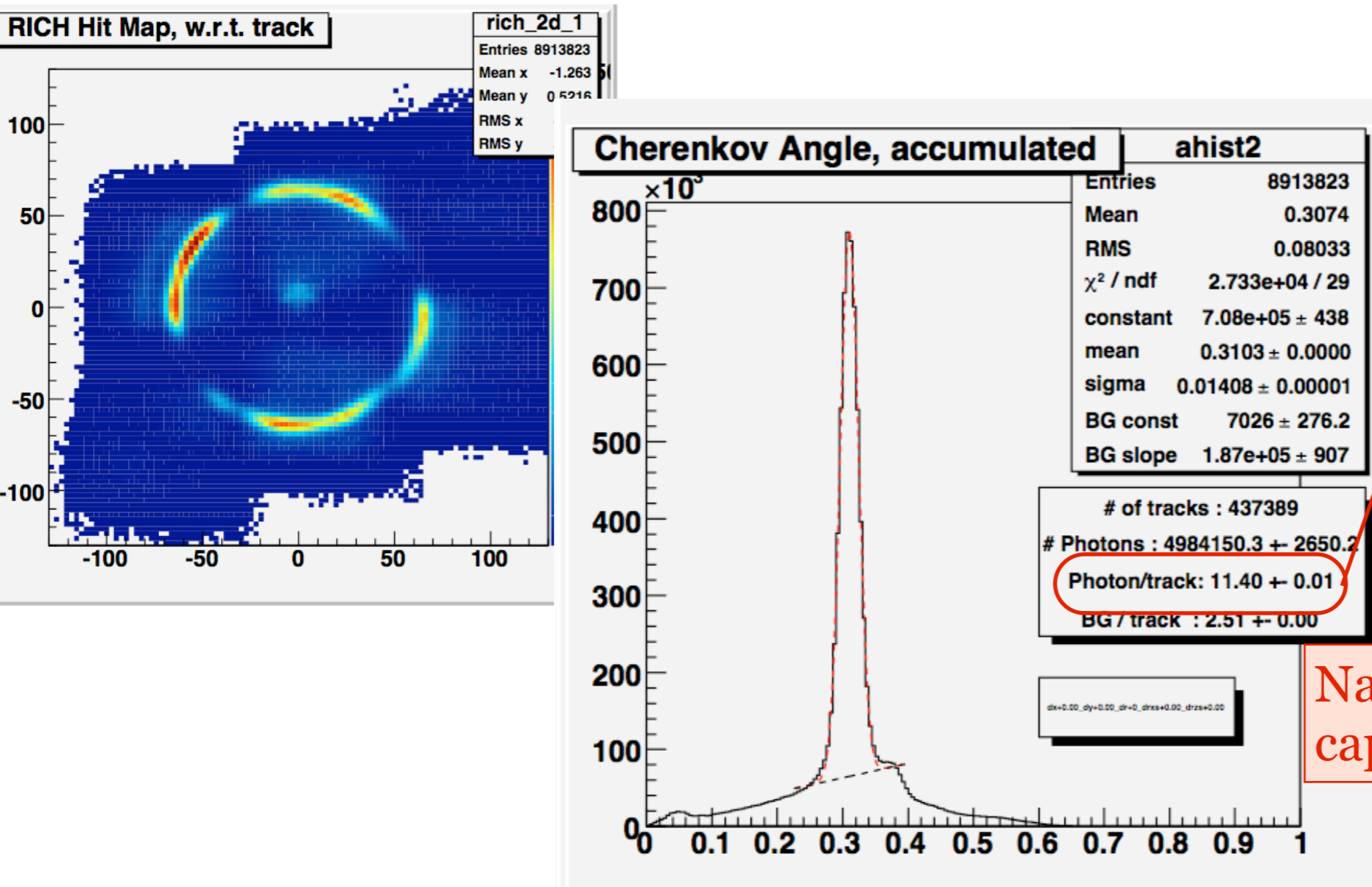Silica aerogel radiator

Readout side

Analysis Results (1)

The results shown here are preliminary

Clear Cherenkov image detected

RICH Hit Map, w.r.t. track

rich_2d_1
Entries 8913823
Mean x -1.263
Mean y 0.5216
RMS x
RMS y

Cherenkov Angle, accumulated | ahist2

Entries	8913823
Mean	0.3074
RMS	0.08033
χ^2 / ndf	2.733e+04 / 29
constant	7.08e+05 ± 438
mean	0.3103 ± 0.0000
sigma	0.01408 ± 0.00001
BG const	7026 ± 276.2
BG slope	1.87e+05 ± 907

# of tracks : 437389
Photons : 4984150.3 +- 2650.2
Photon/track: 11.40 +- 0.01
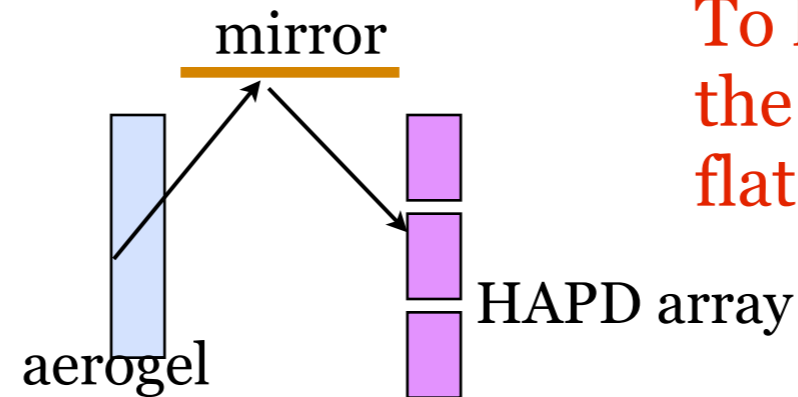BG / track : 2.51 +- 0.00

Npe observed = 11.4
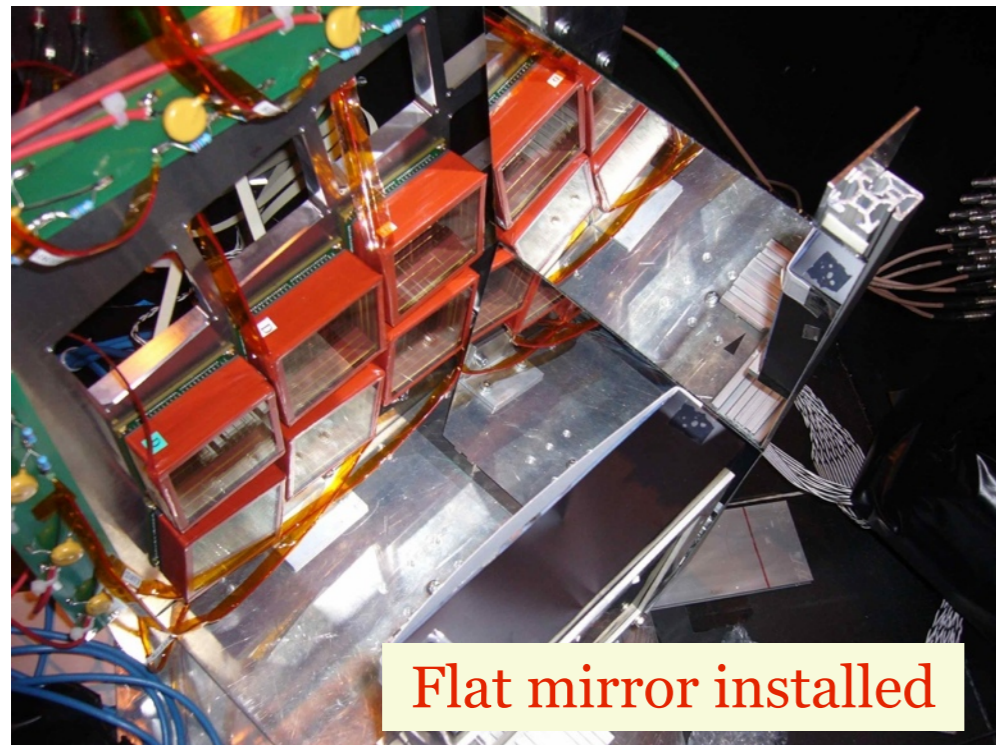
σ = 14.1 mrad

$|\theta_\pi - \theta_K| \sim$ 23 mrad at 4GeV/c

Naively 5.5 σ K & π separation capability at 4 GeV/c
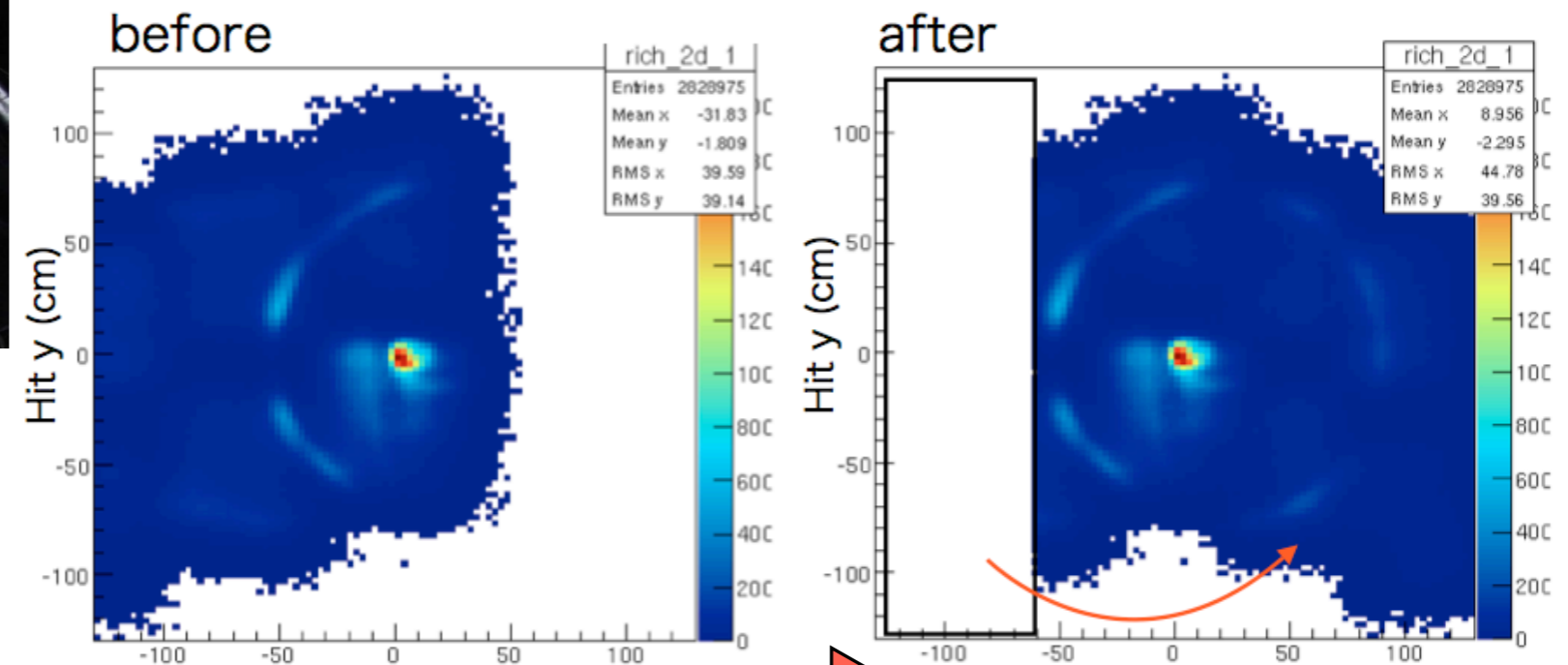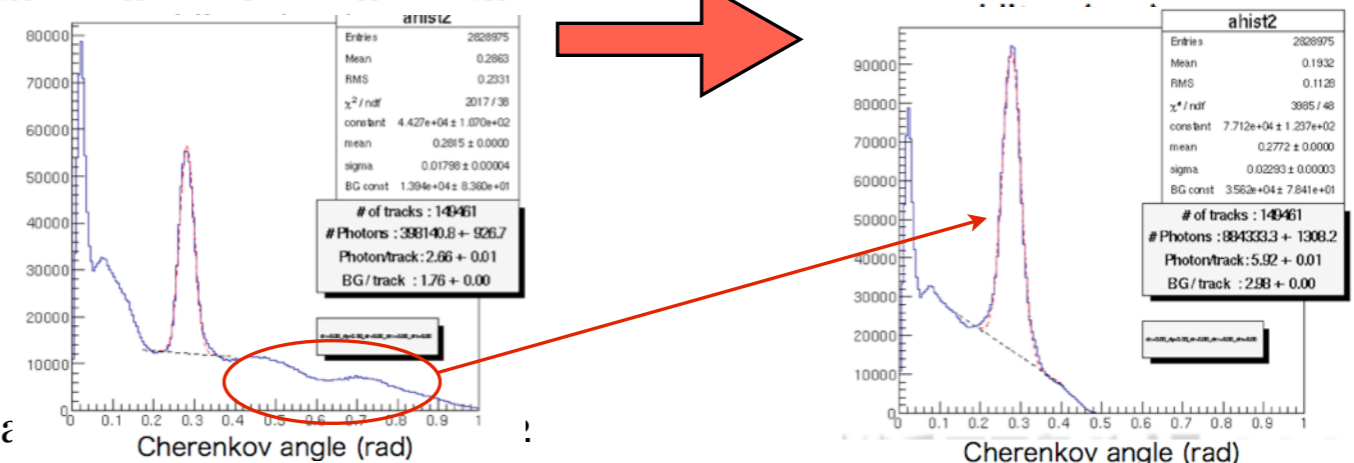
The result obtained was consistent with that from the previous beam tests

Mirror image reconstruction examined

To keep efficiency around the edge of the detector, flat mirror is considered

Flat mirror installed

mirror

aerogel

HAPD array

before

after

Reflected image can be reconstructed. Further analysis will be done

Conclusions
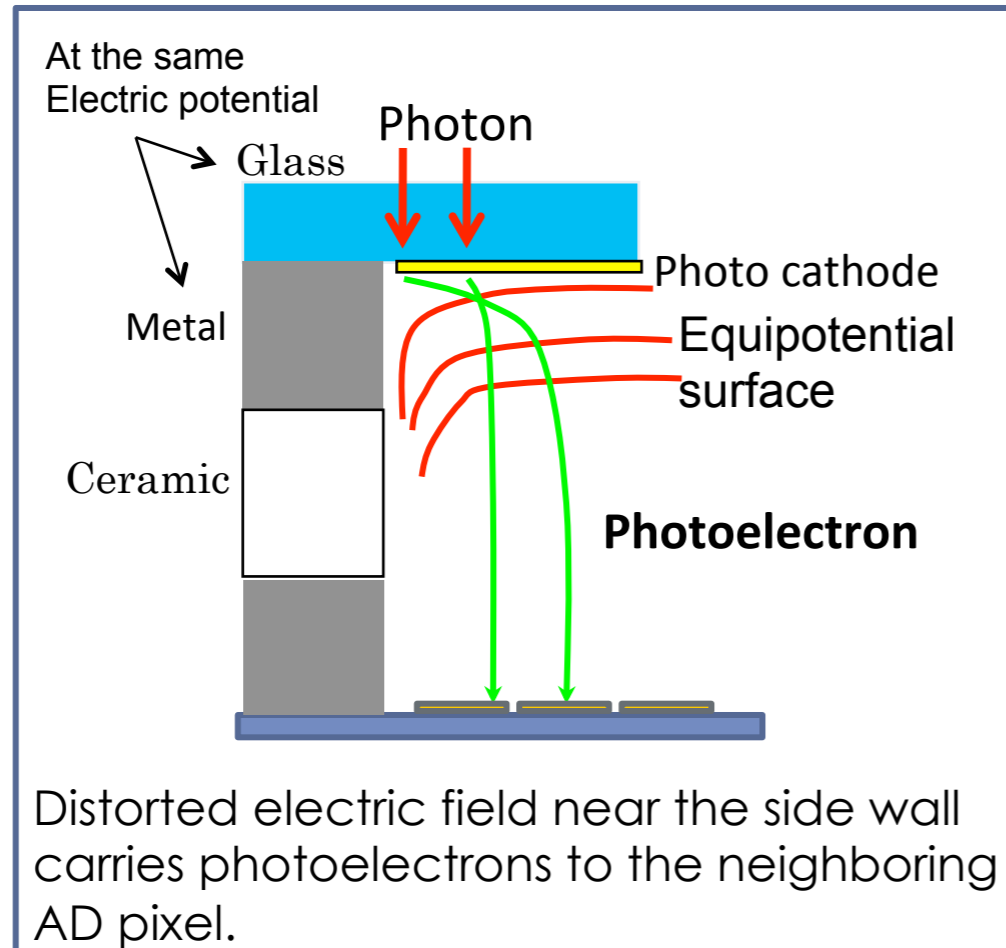
- We have been developing 144-ch HAPD for the Belle II RICH counter.

- Results from HAPD bench test showed excellent performance in single photon sensitivity.
  - High QE ~35% expected

- Studies of radiation damage (neutrons: $10^{12}/cm^2$ & gamma-rays: 1000Gy) have been made and radiation-improved candidates are being delivered.

- Test beam experiment was carried out and clear Cherenkov image was observed. Expected PID capability was confirmed.

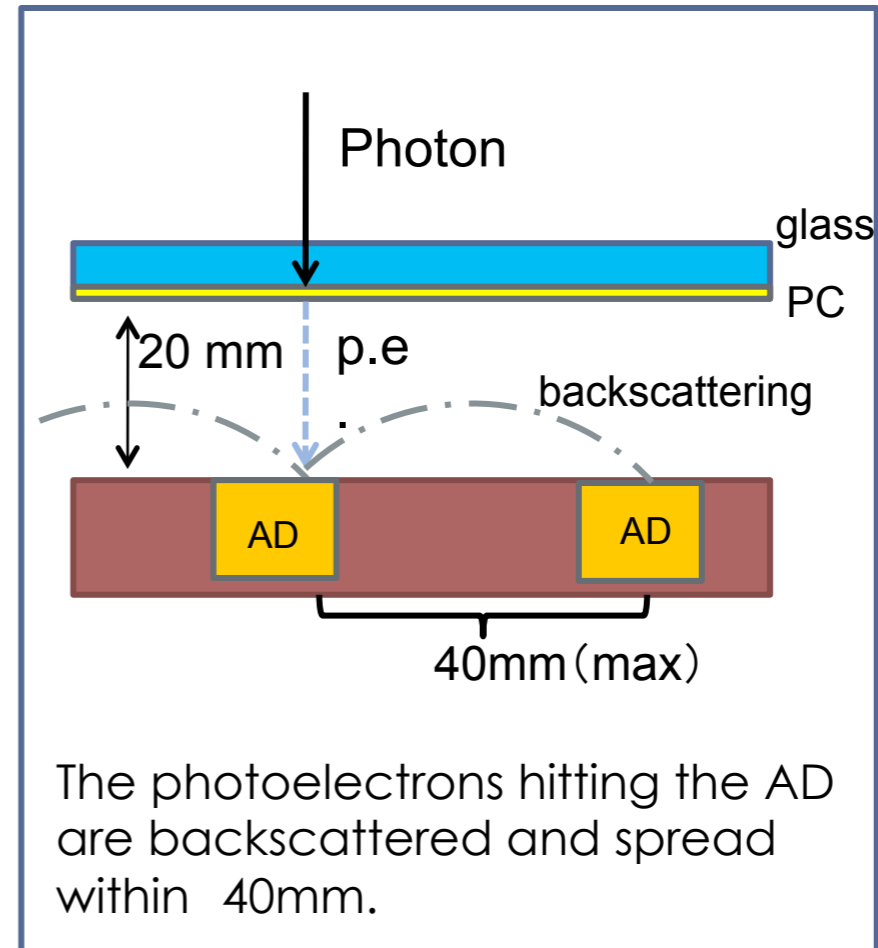- Detailed specifications will be settled down by this autumn for mass-production.

Merci bien !

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backup

Effect due to a Magnetic Field

Image distortion by a side wall

At the same Electric potential

Glass

Photon

Metal

Ceramic

Photo cathode

Equipotential surface

Photoelectron

Distorted electric field near the side wall carries photoelectrons to the neighboring AD pixel.

back-scattering

Photon

glass

PC

20 mm   p.e.

backscattering

AD   AD

40mm（max）

The photoelectrons hitting the AD are backscattered and spread within 40mm.

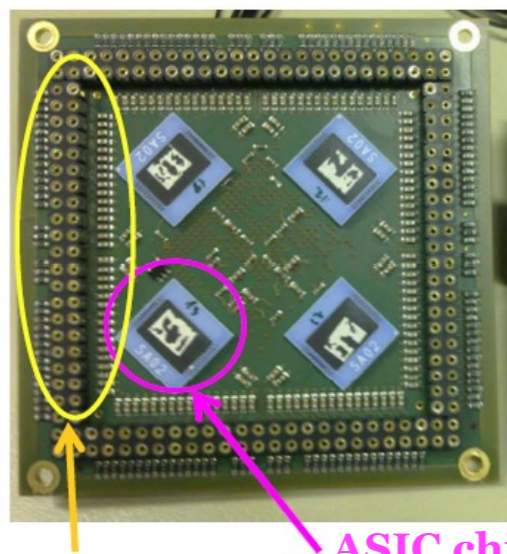**HAPD performance is expected to be improved in a magnetic field.**

Readout Electronics

- Custom-made front-end electronics dedicated for this detector has been developed several years in parallel to HAPD R&D
  - High density(~65K channels in limited space)

ASIC signal processing

36 channels/1ASIC chip
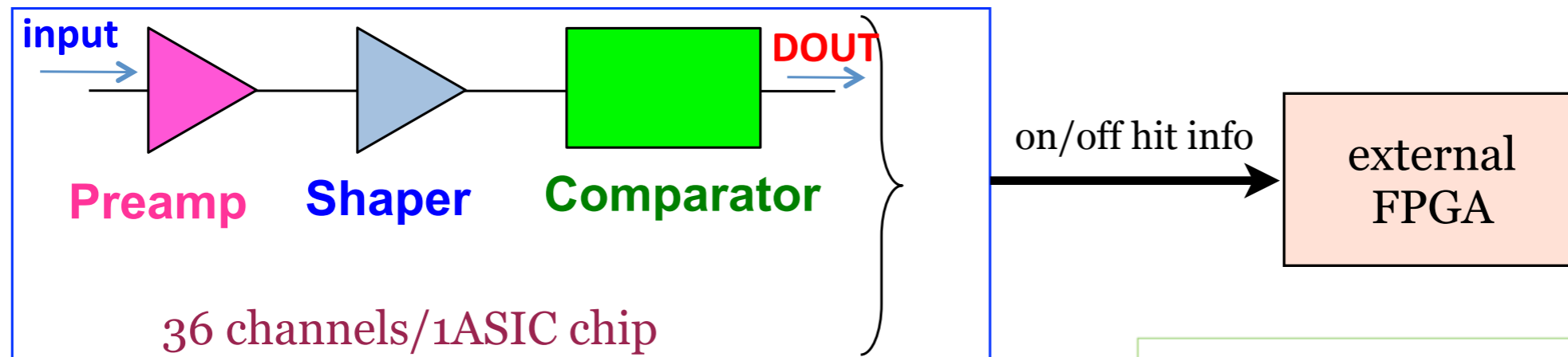
Readout implementation

connectors for HAPD pins

ASIC chip

FPGA

Specification (SA02)

- Process: TSMC CMOS 0.35 [µm]
- Production at MOSIS
- #(channel) = 36 [ch/chip]
- Std. Input Signal: 60000 [e]
- Target Noise Level: 1200 [e] @ 80pF (HAPD)
- Chip size = 6.5mm × 3mm
- Power consumption: 3.7 mW/ch
- Variable gain: 20-70 [mV/fC]
- Shaping time: 250-1000 [ns]
- Offset adjustment: ±300mV (8bit: 3mV step)

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