*Belle II*

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# **Performance estimation of the Belle II Aerogel RICH counter in the first beam collision**

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- Introduction
- ARICH counter
- Operation with beam
- Summary

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# **Introduction**

# Belle II ARICH detector

- **Belle II experiment starts full operation in 2019**
  - Search for New Physics in Flavor sector using 50 ab$^{-1}$ of data
- **Particle identification (PID)** is a major upgrade in the Belle II
  - $K/\pi$ ID is essential for many $B$ decays sensitive to NP models

- **Belle :** Aerogel Cherenkov Counter
  - Threshold type PID detector
- **Belle II :** Two new PID devices
  - **Ring Imaging Cherenkov detectors**



TOP: Barrel PID

e$^-$ (7GeV)

e$^+$ (4GeV)

**Belle II detector**
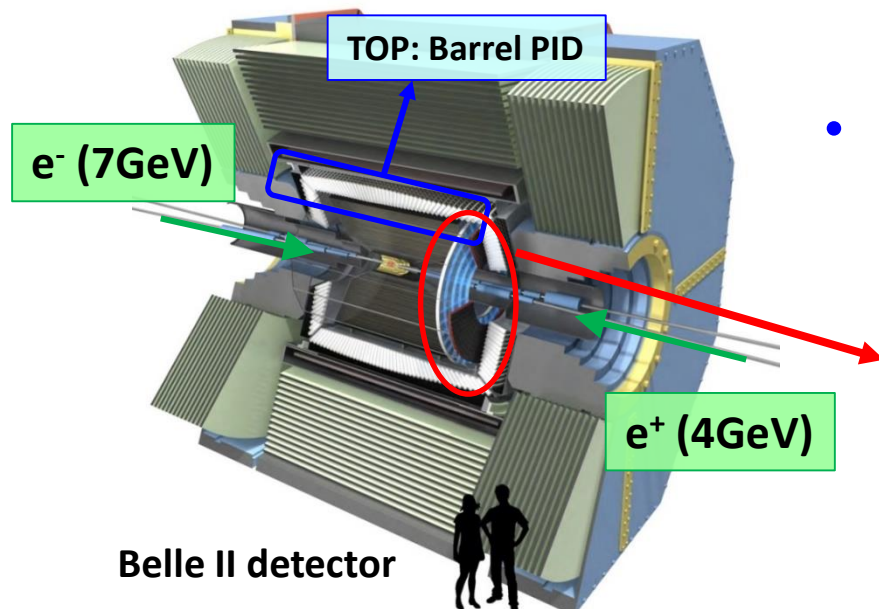
**End-cap PID:**
**Aerogel RICH counter (ARICH)**
- Target range: $0.5 < p < 4$ GeV

# Principle of Aerogel RICH

- Proximity-Focusing Ring Imaging Cherenkov counter using Aerogel
- Particle mass is identified according to emission angle in aerogel radiator
  - $m = \frac{p}{c}\sqrt{n^2\cos^2\theta_c - 1}$ ($n$: refractive index, $p$: particle momentum)
- Cherenkov photons are measured as 2-D ring image
  - **6 mm** difference in $K/\pi$ Cherenkov rings on photo detectors

**Target performance : $K/\pi$ separation at > 4σ C.L. @ $p$ =4 GeV/c**
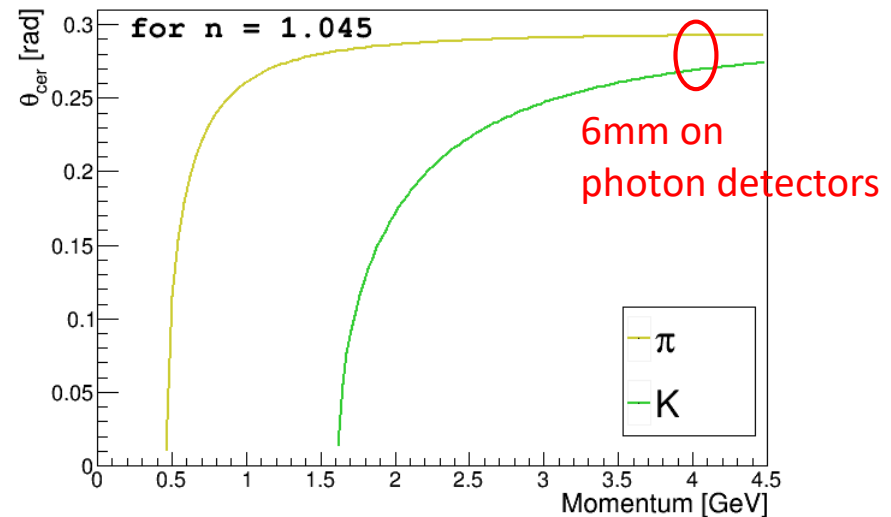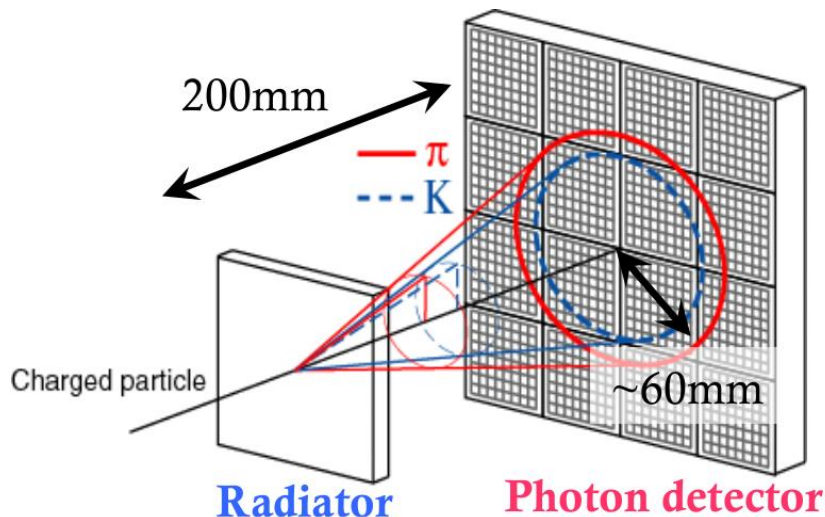
# Practical requirements for ARICH

- Several technical challenges for the Belle II operation
  - **Compact detector** in the Belle II end-cap
  - Operation in **high magnetic field of 1.5T**
  - Radiation hardness with **20 times higher γ/n** than Belle I
  - Readout capability for **30 kHz** of maximum trigger rate

- 2 layers of aerogel radiators for focusing ring image
- Position sensitive photo detector in magnetic field
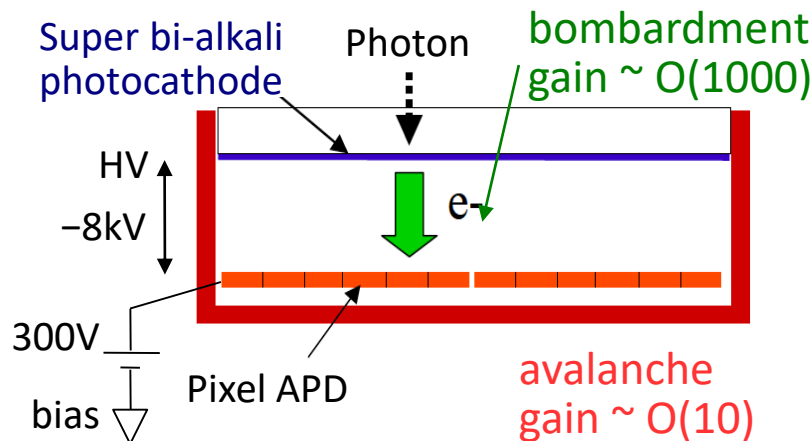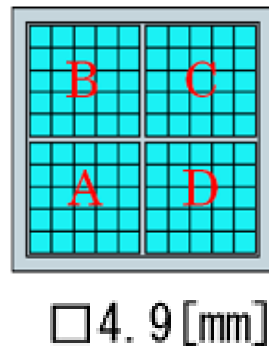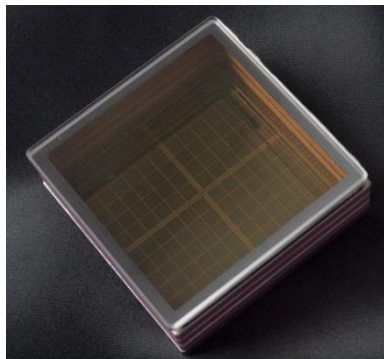- Two level readout electronics to the Belle II DAQ

# ARICH counter

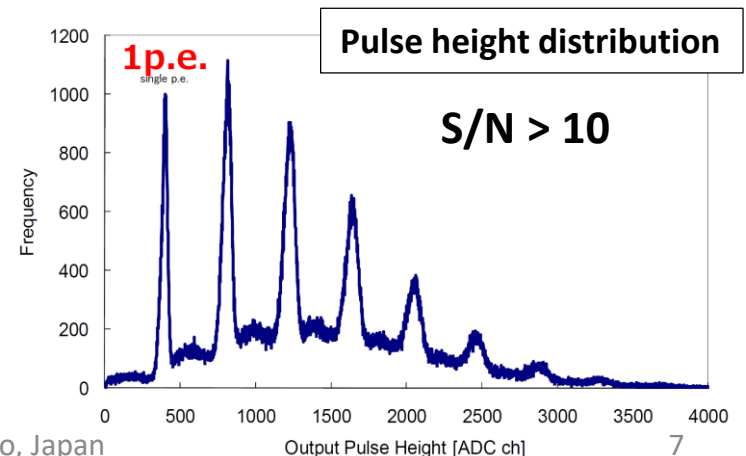# Photo detector for ARICH

**Hybrid Avalanche Photon Detector (HAPD)**

- Developed with Hamamatsu Photonics K.K.
- Good single photoelectron separation

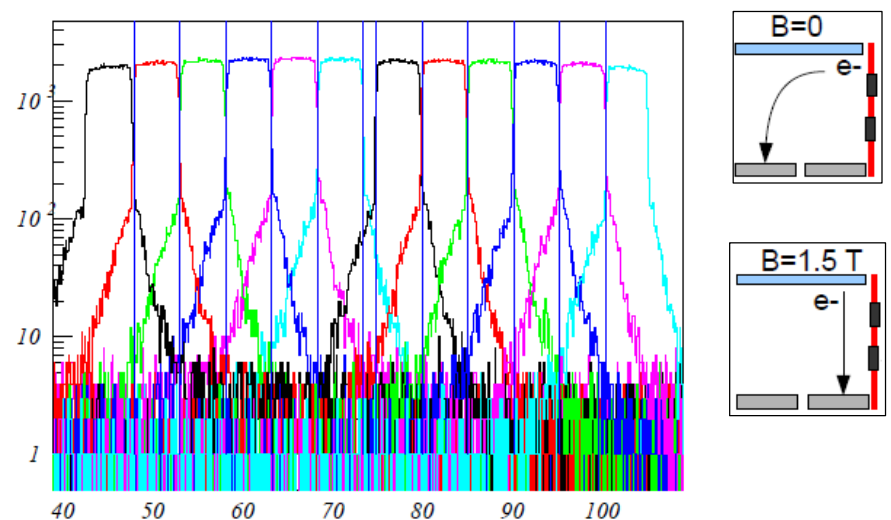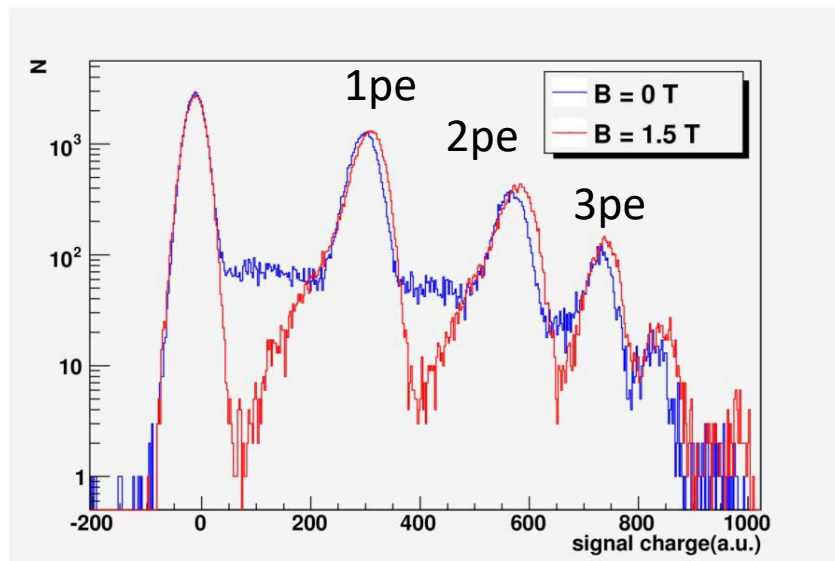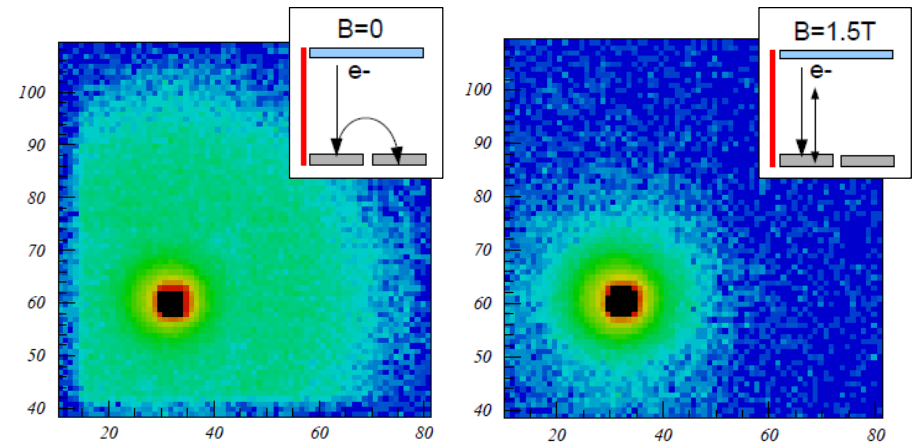=> 420 HAPDs are installed in ARICH



□ 4. 9 [mm]

### HAPD specification

| Parameter | Requirements |
|---|---|
| Size | 72 x 72 mm$^2$ |
| # of pixels | 144 ch (36 x 4 ch) |
| Pixel size | 4.9 x 4.9 mm$^2$ |
| Effective area | 64 % |
| Peak Q.E. | 28 % |
| Dark current | < 1 $\mu$A |
| HV | -8500V |
| Total gain | > 45000 |



Super bi-alkali photocathode

Photon

bombardment gain ~ O(1000)

HV

−8kV

e-

300V

bias

Pixel APD

avalanche gain ~ O(10)

**Pulse height distribution**

1p.e.
single p.e.

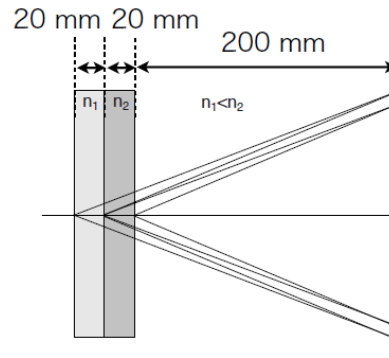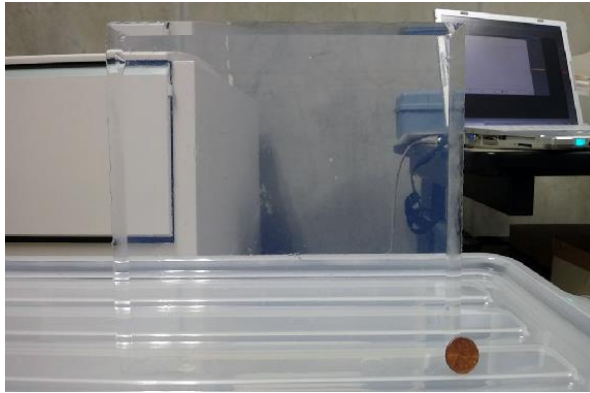**S/N > 10**

# Performance in 1.5 T magnetic field

**HAPD performance is measured to be totally improved in the magnetic field**

- Reduces p.e. back-scattering cross-talk
- Increases detection efficiency
  - p.e. energy deposited at one place
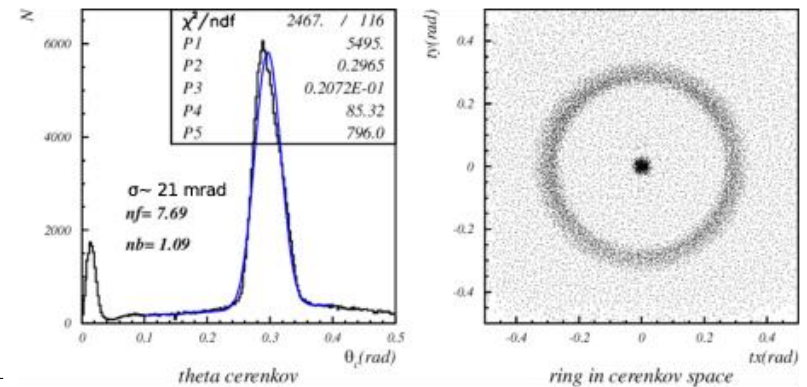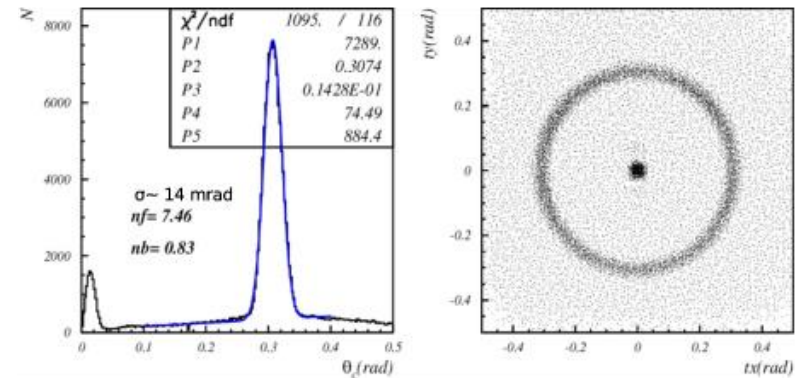- Rate non-uniformity due to electric field clearly disappears

# Silica Aerogel radiator



Single 4cm aerogel layer



| $\chi^2$/ndf | 2467. / 116 |
|---|---|
| P1 | 5495. |
| P2 | 0.2965 |
| P3 | 0.2072E-01 |
| P4 | 85.32 |
| P5 | 796.0 |

$\sigma \sim 21$ mrad
nf= 7.69
nb= 1.09

theta cerenkov

ring in cerenkov space

Two 2cm aerogel layers in focusing configuration



| $\chi^2$/ndf | 1095. / 116 |
|---|---|
| P1 | 7289. |
| P2 | 0.3074 |
| P3 | 0.1428E-01 |
| P4 | 74.49 |
| P5 | 884.4 |

$\sigma \sim 14$ mrad
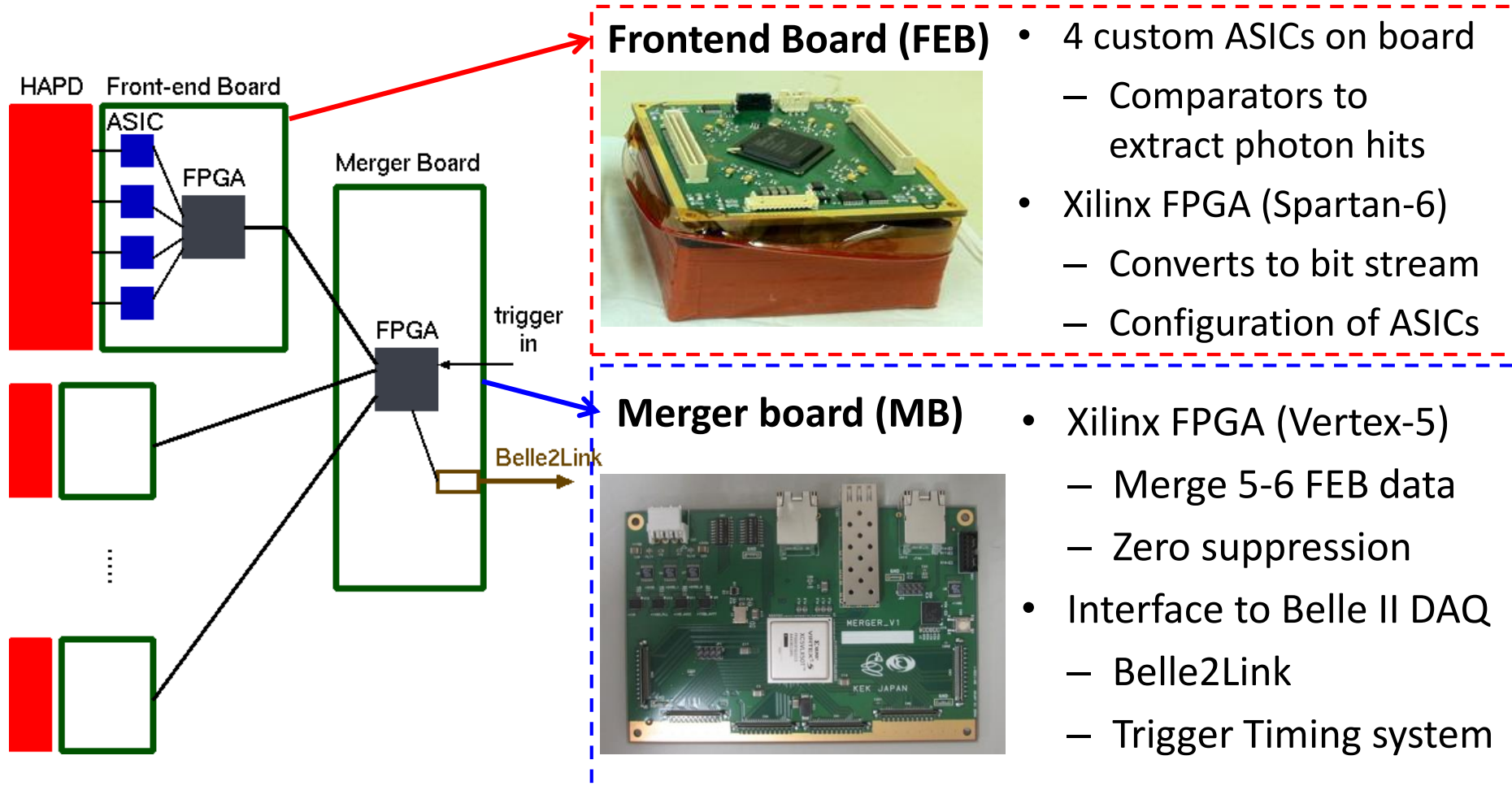nf= 7.46
nb= 0.83

**New Aerogel with high transparency**

– Transmission length : > 40 mm

– Flexible refractive indexes

• Dual layers to focus ring images

– Up/down: 1.045/ 1.055 $\pm$ 0.002

• 248 tiles for 3m$^2$ acceptance

– Cut using water jut cutter

# HAPD readout electronics

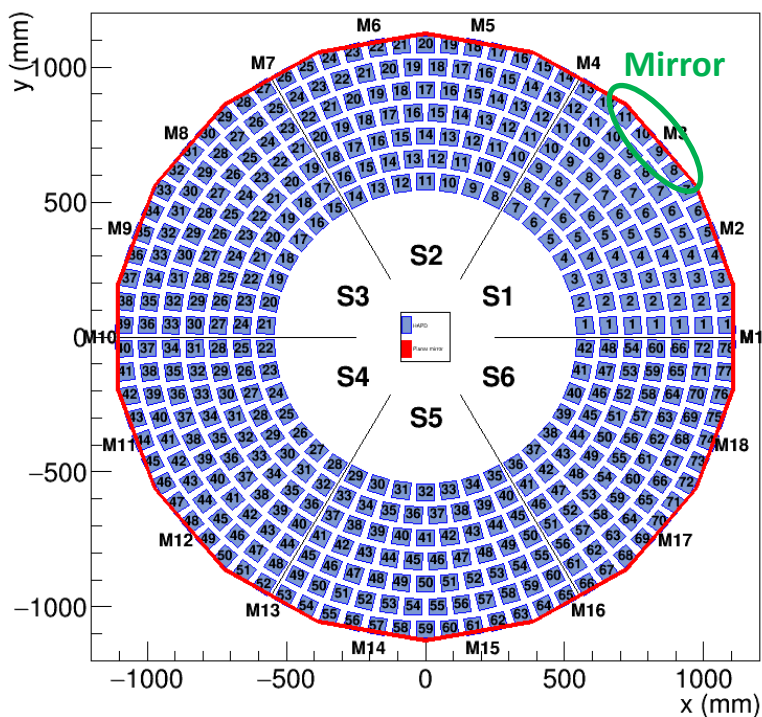**Two level of readout electronics located on behind the HAPDs**

- 420 Frontend and 72 merger boards are installed connected to Belle II DAQ



**Frontend Board (FEB)**

- 4 custom ASICs on board
  - Comparators to extract photon hits
- Xilinx FPGA (Spartan-6)
  - Converts to bit stream
  - Configuration of ASICs

**Merger board (MB)**

- Xilinx FPGA (Vertex-5)
  - Merge 5-6 FEB data
  - Zero suppression
- Interface to Belle II DAQ
  - Belle2Link
  - Trigger Timing system

# ARICH support structure
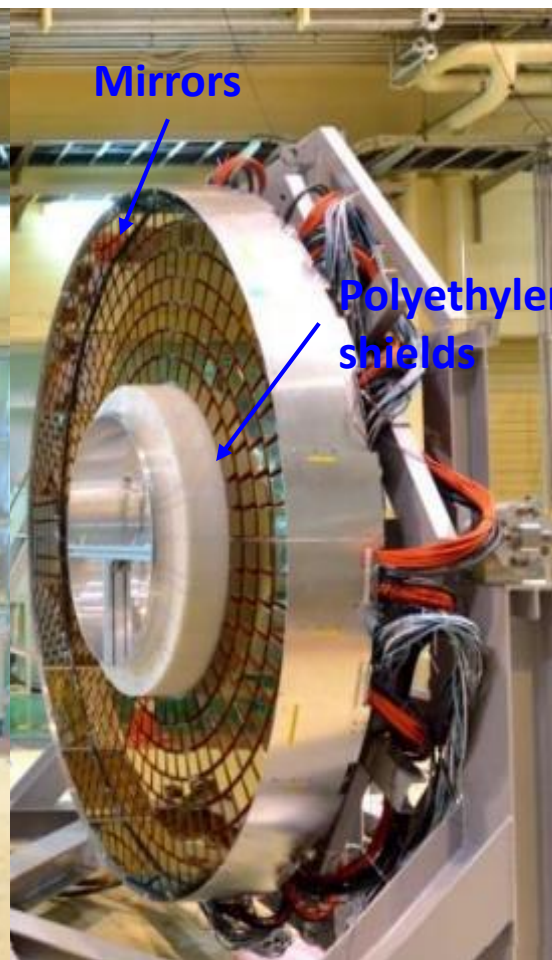
## Aluminum frame for HAPDs and Aerogels

- Mirrors to reflect photons
- Polyethylene shields for neutrons
- 6 sectors for cable outputs
- HAPD and Aerogel planes are combined in 2018



**Aerogel plane**

**HAPD plane**

**Mirrors**

**Polyethylene shields**

# Operation in Beam runs

# Beam data in commissioning runs



Hit APD pixels

Particle track
extended from CDC



*Belle II
preliminary*

**Commissioning runs with beam collision**

- 3 months operation from Apr to July 2018
- ARICH running with beam collision
  - Consistent to reconstructed tracks extended from CDC

**Ring image performance estimation**

- Cherenkov angle from BhaBha events
  - $\mu_\theta$ = 293 $\pm$ 17 mrad
  - $\sigma_\theta$ = 16.68 $\pm$ 0.26 mrad
  - $N_{\text{p.e.}}$ = 8.77 in 3 σ region of a track

  => $\sigma_{\text{track}} = \dfrac{\sigma_\theta}{\sqrt{N_{\text{p.e.}}}} = $ 5.63 mrad

- K/π separation power :

$$\frac{\Delta\theta}{\sigma_{\text{track}}} = 4.2\sigma \text{ at } (4\text{GeV}/c)$$
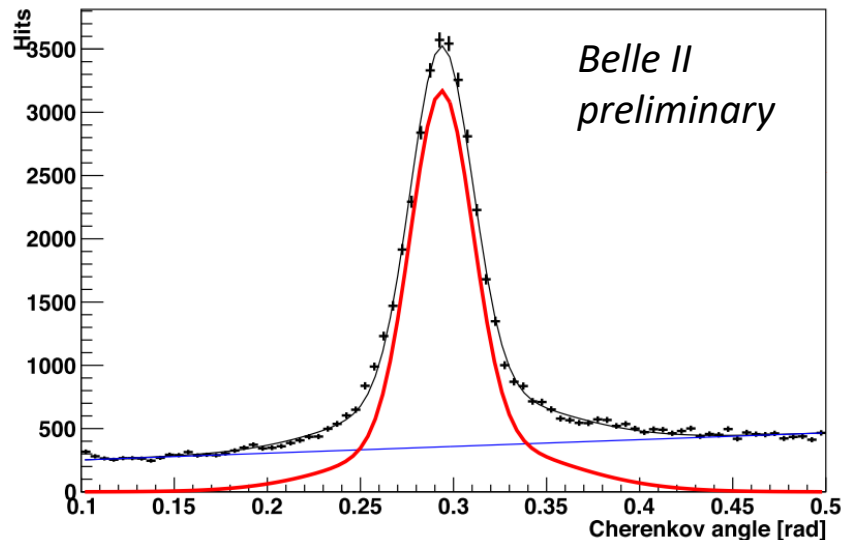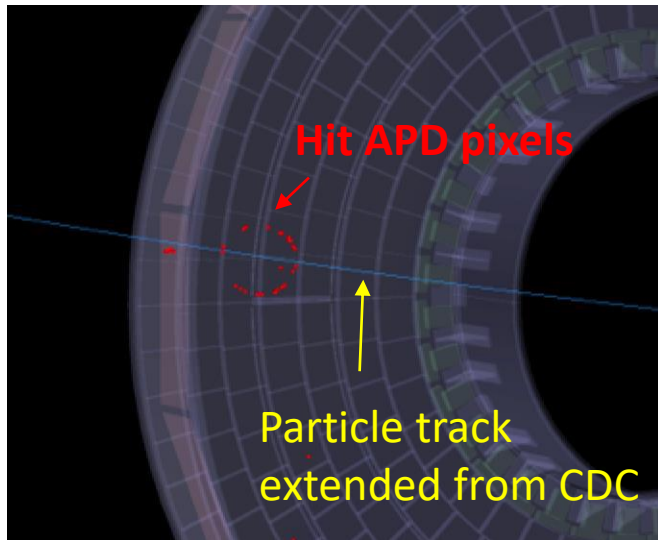
# PID performance test

- PID likelihood is studied by fitting invariant mass of reconstructed $K_s^0$ and $D^0$ as control samples
  - Likelihood ratio is obtained to check the consistency of PID
- Not well calibrated yet
  - **Missing hits in excluded channels**
    - Masked Mergers / HAPDs
    - Hot / Dead APD channels
    => Low energy π is mimicked as K
  - Collection efficiency of hit photons
  - Reflected photons
  - Beam related background
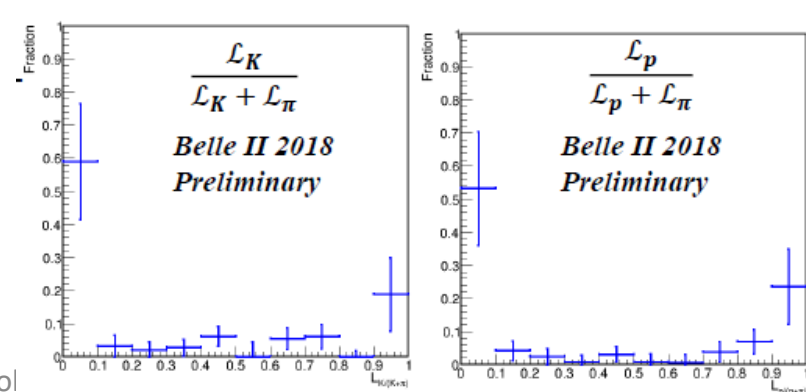
**Pion from $K_s^0 \rightarrow \pi^+\pi^-$**
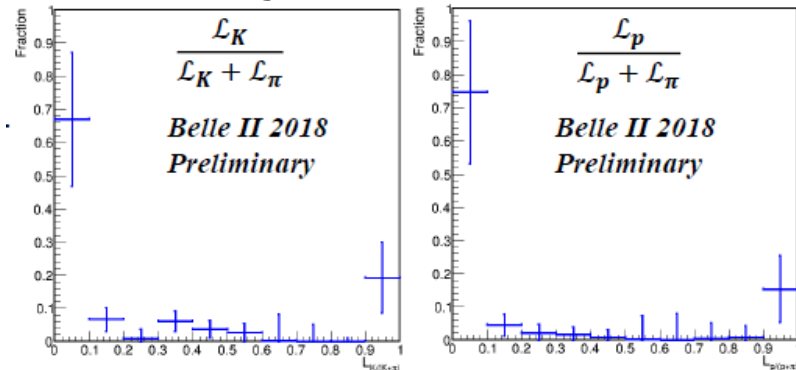


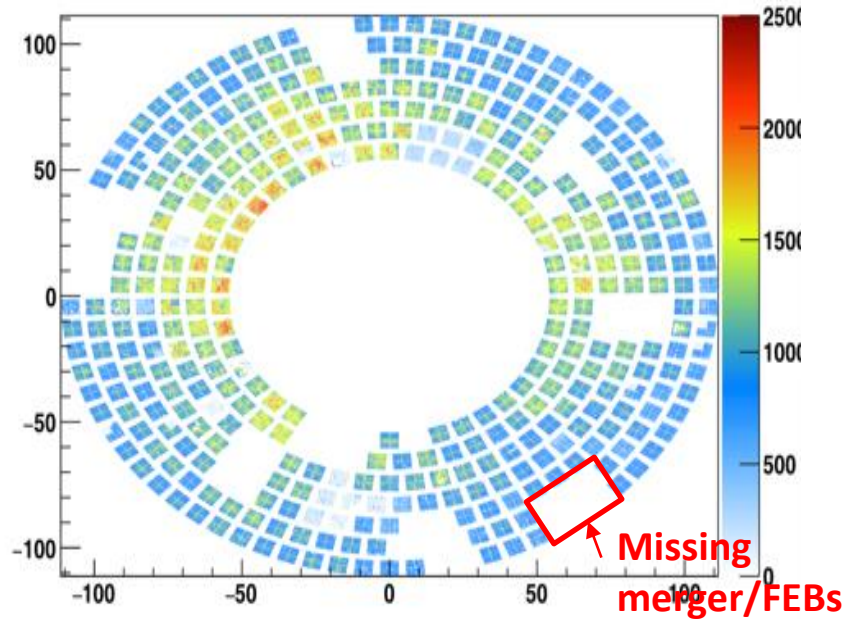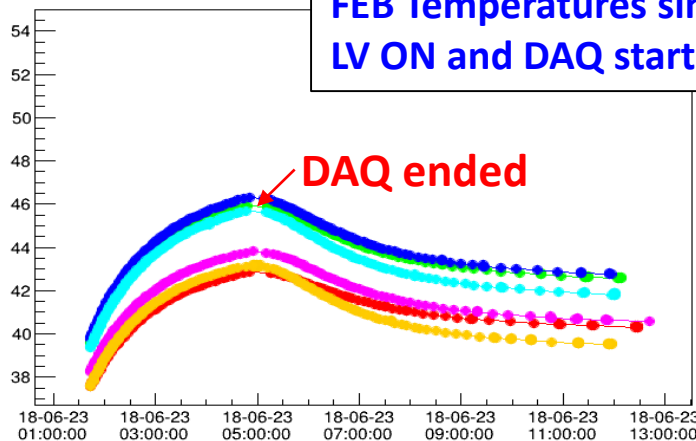**Kaon from $D^0 \rightarrow K^-\pi^+$**
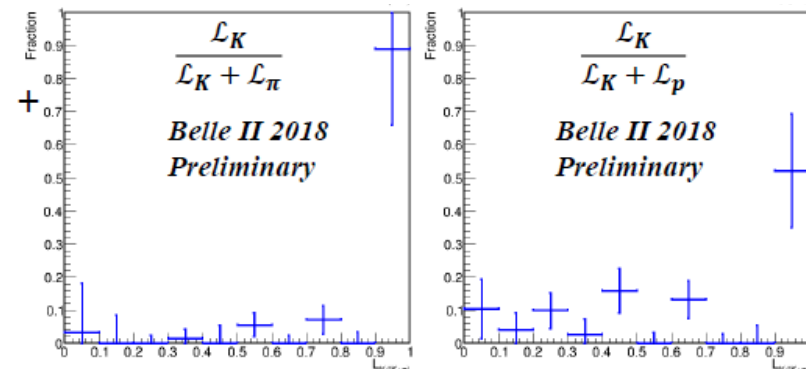


**Pion from $D^0 \rightarrow K^-\pi^+$**

# Issues in beam runs

**Hit APD pixel in full ARICH operation**



Missing merger/FEBs

**FEB Temperatures since LV ON and DAQ start**



DAQ ended

## Cooling Electronics was not enough

- HAPDs get hot close to limitation
  - Heats from merger boards
  - Monitoring FEBs behind HAPDs
- Upper or lower parts of ARICH are switched periodically
  - Avoided overheat of HAPDs
  - All sectors are ON for short terms (3 hours at maximum)
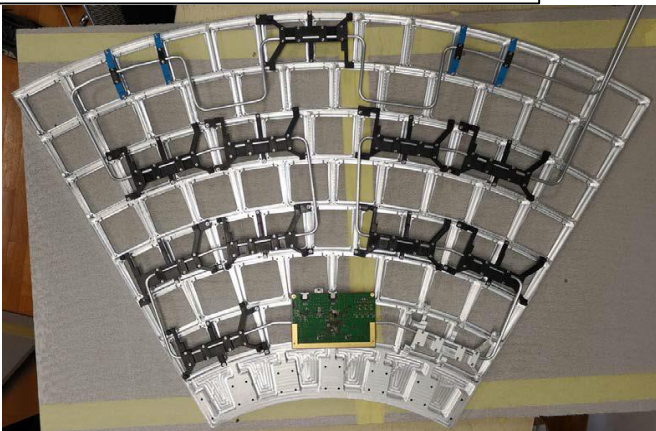
## DAQ related troubles

- 9 merger boards are excluded due to DAQ troubles
  - Bad connection of DAQ cables

# Modification after commissioning
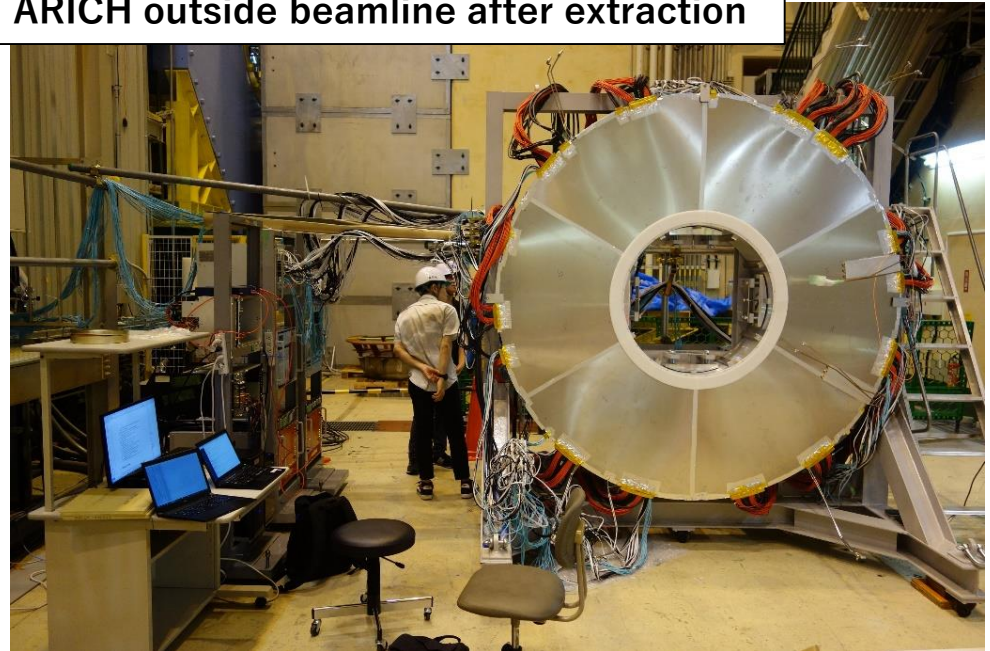
**FEB temperatures after replacement**
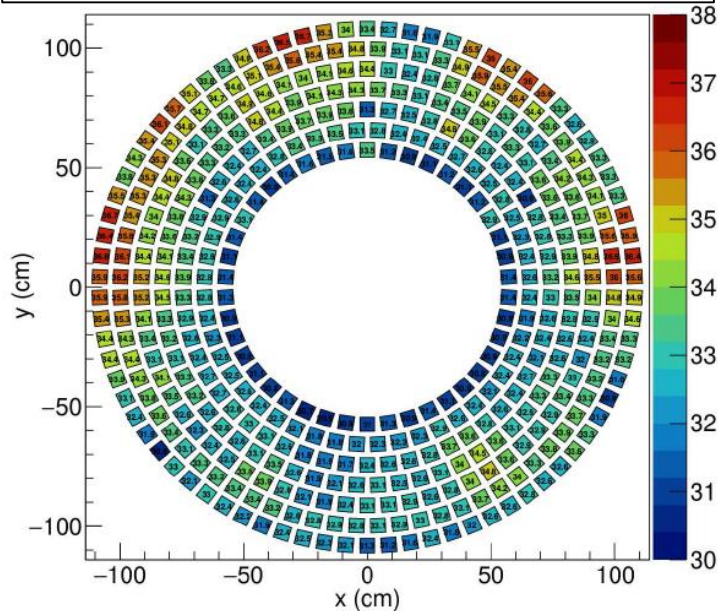


**Mockup of new cooling system**



## Extracted from Belle II in Aug. 2018

- Replacement of cooling system
  - New cooling pipes touched to mergers
  - Test is on going with good progress
- All DAQ issues are cleared by fixing cables

**ARICH outside beamline after extraction**

# Summary

- Belle II experiment started beam collision in 2018
  - Phase 2 run: Beam commissioning with Belle II detector
- The ARICH counter joined the beam measurement
  - As a major upgrade for the Belle II PID
- Performance of ARICH was studied using the collision data
  - K/π separation based on Cherenkov angle : 4.2σ at 4 GeV/c
  - PID performance studies are on going using control samples
    - More calibration studies are necessary and on going
- Fixed issues during the commissioning runs
- Full Belle II operation (Phase 3) starts in early 2019

# Power supply

**A power supply system for HAPDs**

- 3 kinds of power inputs for each HAPD
    - HV for bombardment : 8000 V
    - Bias for a APD chip: 350 V
    - Guard for protection: 175 V
    => 6 input channels for a HAPD
- CAEN HV crate and modules
    - HV : A1590N x 27 modules
    - Guard / Bias : A7042P x 45 modules
- Control software based on Belle II DAQ
    - Network based control
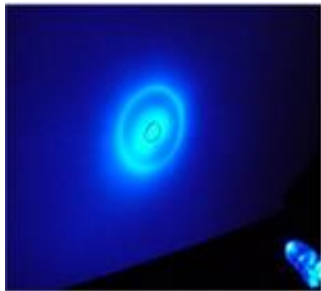    - Software protection of HAPDs
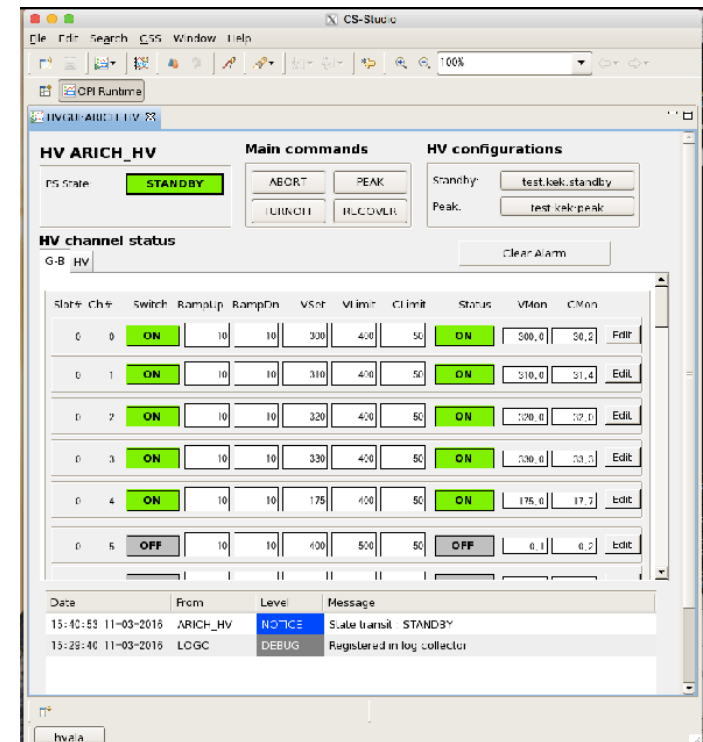
# Light injection monitor system
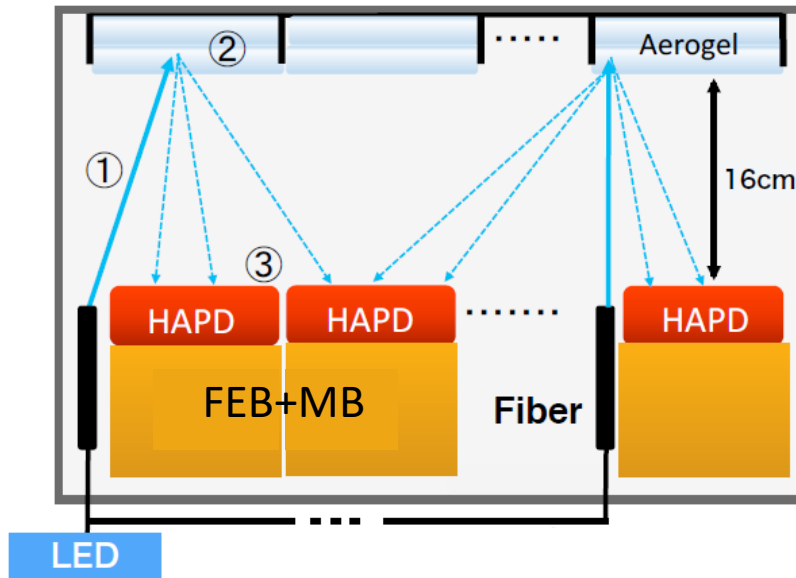


**LED light injection system into ARICH**

- Monitor APD channels
  - 1 p.e. level measurement
- Light diffused from aerogel surfaces
  - Flat intensity on HAPD surfaces
  - 90 injection points with 6 LEDs
- Ready to be installed in coming month

Blue LED



Optical fiber cables
(22 fibers to a LED)



Hit rate distribution on installed HAPDs