Performance and commissioning of HAPDs in the Belle II Aerogel RICH counter

2018/07/31
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10th International Workshop on Ring Imaging Cherenkov Detectors
2018/07/31
Outline

- Introduction
  - Belle II / ARICH counter
  - Photon detector : HAPD
  - Peripheral of HAPD
- Performance evaluation of HAPDs
  - Quality of installed HAPDs
  - Performance evaluation
  - Temperature dependency
- HAPDs in the commissioning of Belle II
  - Performance during Phase II operation
- Summary and plan
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- **Introduction**
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  - Photon detector : HAPD
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  - Temperature dependency

- HAPDs in the commissioning of Belle II
  - Performance during Phase II operation

- Summary and plan
The Belle II experiment at KEK aims to search for new physics beyond the Standard Model using 50 ab$^{-1}$ integrated luminosity.

**the Belle II experiment**

**the SuperKEKB accelerator**

target luminosity : $8 \times 10^{35}$[cm$^{-2}$s$^{-1}$]

(luminosity at KEKB $\times 40$)

**the Belle II detector**

- $4 \pi$ acceptance
- 30 kHz readout
- high background resistance

**ARICH counter**

Identify charged $\pi/K$ between 0.5 GeV/c and 4.0 GeV/c at the endcap region
Particle identification in ARICH

- Cherenkov photons emitted in aerogel are detected on the HAPD as 2D image.
- Measuring emission angle from 2D image ⇒ perform particle identification.

\[ m = p \sqrt{n^2 \cos^2 \theta - 1} \]

- \( m \): mass
- \( n \): refractive index
- \( p \): momentum

radius of ring at \( p = 3.5 \text{ GeV/c}, \ n = 1.05 \)

- \( \pi : r = 54 \text{ mm} \ (307 \text{ mrad}) \)
- \( K : r = 48 \text{ mm} \ (277 \text{ mrad}) \)

difference is 6 mm at 3.5 GeV/c

We have developed photon detector which has high position resolution

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RICH2018
ARICH (Aerogel tiles and HAPDs)

aerogel side

HAPD side

aerogel: 248 tiles

HAPD: 420 sensors

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History and schedule

2017/9/20 : ARICH was installed to Belle II
2018/3/19~7/17 : Phase II run (Belle II detector w/o VXD)  now
2018/9 : ARICH is extracted from Belle II
preparation for Phase III
2019/2 : Phase III run start (full Belle II detector)

Phase II main purpose for ARICH
- Belle II integrated operation of ARICH
- Optimize ARICH parameters by integrated operation

Preparation for Phase III
- Extract ARICH and improve hardware
**HAPD**

- Single photon detection
- Usable in high magnetic field (1.5 T)
- 4 APD chips
- 144ch multi-pixel
- 1 pixel : 4.9mm×4.9mm

ARICH use 420 HAPDs

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Cherenkov photon

- HV:-6 - -8kV
- Quartz window
- Photo-electron acceleration

- Reverse bias: ~350 V
- Guard electrode: 175 V

Hamamatsu Photonics K.K.

- High QE : ~30%
- Two amplitude mechanism
  - Bombardment gain : 1800
  - Avalanche gain : 40
  - Total gain : 72000

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HAPD

- Single photon detection
- Usable in high magnetic field (1.5 T)
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- 144ch multi-pixel
- 1 pixel : 4.9mm×4.9mm

ARICH use 420 HAPDs

Pixelated APD (Avalanche Photo Diode)

Hamamatsu Photonics K.K.

- Accelerated p.e. enters to APD and 1800 electron-hole pairs are generated.
- Generated electron is amplified (~40) at avalanche amplification region.
- HAPD has 72000 gain in total.
ARICH readout electronics consists of two components.

1. Front End Board (FEB)
   - Digitize analog signal from HAPD.
2. Merger Board (Merger)
   - Merge data from 5 or 6 FEBs.

ARICH sends only hit/no hit data.

※hit is generated only raising edge
Power supplies for HAPDs

- Supply voltages to HAPDs using two types: HV and bias-guard

<table>
<thead>
<tr>
<th></th>
<th>HV</th>
<th>Bias-guard</th>
</tr>
</thead>
<tbody>
<tr>
<td>model number</td>
<td>A1590</td>
<td>A7042A</td>
</tr>
<tr>
<td>Max voltage</td>
<td>-9000V</td>
<td>500 V</td>
</tr>
<tr>
<td>Max current</td>
<td>50 uA</td>
<td>500 uA</td>
</tr>
<tr>
<td># of channels</td>
<td>16</td>
<td>48</td>
</tr>
</tbody>
</table>

HAPD power supply control GUI

ARICH usage
(to operate 420 HAPDs)

<table>
<thead>
<tr>
<th></th>
<th>HV</th>
<th>Bias-guard</th>
</tr>
</thead>
<tbody>
<tr>
<td># of crates</td>
<td>7</td>
<td></td>
</tr>
<tr>
<td># of modules</td>
<td>28</td>
<td>45</td>
</tr>
<tr>
<td># of channels</td>
<td>448</td>
<td>2160</td>
</tr>
<tr>
<td># of cables</td>
<td>24</td>
<td>48</td>
</tr>
</tbody>
</table>
LED monitor system

- To measure HAPD healthiness, we implement LED monitor system.
  - Transmit LED light via optical fiber.
  - Illuminate aerogel tiles direction from HAPD side.
  - Photons are scattered in aerogel tiles and go back to HAPD.
  - By detecting scattered photons, measure the HAPD healthiness.
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  – Performance evaluation
  – Temperature dependency

• HAPDs in the commissioning of Belle II
  – Performance during Phase II operation

• Summary and plan
Issue: HAPD in magnetic field

- Large pulse were observed when we operate in the magnetic field.
  - The frequency of large pulses varies HAPD by HAPD.
  - The frequency of large pulses ranges from 0 to 10Hz.
  - The frequency is stable in few hours.
- The large pulse makes dead time.
  - After large pulse, almost channels of readout don’t respond ~0.1s.
- Getter re-activation improves the dead time.
  - A small piece of gas absorbing metal to improve the vacuum within tube.
Quality of Installed HAPDs

- 92 out of 524 HAPDs have large dead time (≥2%).
- After the getter re-activation for HAPDs which has large dead time, dead time of 90 HAPDs are reduced to be less that 2%.
- As the result, we prepare more than 420 HAPDs.

- HAPDs are installed based on QE.
  - mean value of QE is 32.2%
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  - Temperature dependency
- **HAPDs in the commissioning of Belle II**
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- **Summary and plan**
Measurement items

We have three main measurement items for HAPD.
Considering these three items, we evaluate HAPD performance.

- **offset**
  - Aligned since we use same threshold voltage for all channels.

- **noise**
  - Enough small value comparing with pulse height.

- **pulse height**
  - Enough large value comparing with noise.

We use two measuring conditions.
- **Noise measurement**: random trigger
- **Signal measurement**: monitor system

Results include all HAPDs data.
- except unusable HAPD (detail will be explained)
Signal using LED monitor system

Trigger : 1000 triggers
All voltages : on
Threshold voltage : operation value
LED : ~0.1 p.e./channel/pulse

Number of hits
LED off : $2.7 \times 10^{-5}$ hits/ch/triggers
LED on : 0.18 hits/ch/triggers

Using LED monitor system, we can check HAPD response.

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Noise level with/without bias

APD put on HAPD is applied bias voltages and depletion region is generated. As the result, noise level is decrease while applying bias voltage.

Noise reduction is clearly seen by applying bias. Noise level is reduced by half.
Offset and pulse height

**Offset distribution**

- **mean:** 61.7 mV
- **sigma:** 2.3 mV

**Pulse height distribution**

- **mean:** 63.2 mV
- **sigma:** 11.4 mV

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<table>
<thead>
<tr>
<th></th>
<th>mean [mV]</th>
<th>sigma [mV]</th>
</tr>
</thead>
<tbody>
<tr>
<td>offset</td>
<td>61.7</td>
<td>2.3</td>
</tr>
<tr>
<td>noise</td>
<td>6.5</td>
<td>0.67</td>
</tr>
<tr>
<td>pulse height</td>
<td>63.2</td>
<td>11.4</td>
</tr>
</tbody>
</table>

We set
- 60 mV as offset
- 120 mV as threshold voltage

**Offset sigma (2.3 mV) is less than noise mean (6.5 mV).**
**Pulse height is sufficiently larger than noise.**
Unusable HAPDs

- We can use not all HAPDs ascribed to three reasons:
  - Power supply: 3 HAPDs and 4 APDs
    + cables, patch panel etc.
  - Trouble in HAPD: 4 HAPDs and 10 APDs
    + broken APD, circuit etc.
  - Trouble in readout electronics: 59 HAPDs
    + 10 out of 72 merger boards are unusable
- Dead channels in used HAPDs are also measured.
  - Comparing number of hits LED on / off data
  - dead channels: 381 channels

<table>
<thead>
<tr>
<th>Total unusable fraction (reason in HAPD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.5% of HAPDs due to applying voltage</td>
</tr>
<tr>
<td>0.8% of channels are dead</td>
</tr>
</tbody>
</table>
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  - Quality of installed HAPDs
  - Performance evaluation
  - *Temperature dependency*

- **HAPDs in the commissioning of Belle II**
  - Performance during Phase II operation

- **Summary and plan**
Noise and pulse height study

- Readout electronics has too high temperature than our expectation.
- Temperature of ARICH is closes to limitation, if all electronics are on.
  - We switch on only up to 4 out of 6 ARICH sectors at usual operation.
- We concern temperature effect especially noise level and pulse height.

Measurement of temperature effect

- Measuring at three different temperatures.
  - 1 (~30°C) : just after turned on electronics
  - 2 (~36°C) : stable temperature operating 4 out of 6 ARICH sectors
  - 3 (~41°C) : near the temperature limit
- The following parameters are checked.
  - offset
  - noise
  - pulse height

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Temperature dependency

- Measuring with three different temperatures.
- Bias are NOT applied for offset and noise measurement
  - note: noise level is decreased by half while applying bias voltage.
- Voltages are applied for pulse height measurement

<table>
<thead>
<tr>
<th></th>
<th>offset</th>
<th>noise</th>
<th>pulse height</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>61.7</td>
<td>13.4</td>
<td>66.4</td>
</tr>
<tr>
<td>2</td>
<td>60.8</td>
<td>15.8</td>
<td>62.0</td>
</tr>
<tr>
<td>3</td>
<td>60.5</td>
<td>15.7</td>
<td>55.7</td>
</tr>
</tbody>
</table>

**Offset**: little change by changing temperature.

**Noise**: increased with higher temperature.

**Pulse height**: decreased with higher temperature.

Considering reduction of noise level by applying bias, pulse height is still sufficiently larger than noise level.
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Long term stability in Phase II

Use only a sector that is used throughout the Phase II period.
Data taken at 6/14, 6/18, 7/17
Signal-noise ratio and fraction of dead channels are evaluated.

Signal-noise ratio is more than 6.
Fraction of dead channels is less than 1%.
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Summary and plan

- 420 HAPDs are used as photon detector for ARICH.
- Behavior of each HAPDs are as expected
- Temperature dependency is seen, but is acceptable.
- Photon detection is correctly working.

HAPDs in the ARICH counter are working in the Belle II Phase II operation.

Plan

- Investigate problematic HAPDs
- Preparation for Phase III
  - Improve cooling system
Thank you for your attention!
Back up
Quantum Efficiency [%] vs Wavelength [nm]

The graph shows the quantum efficiency (%) of a device as a function of wavelength (nm). The quantum efficiency peaks around a wavelength of 390 nm, with values exceeding 30%. The efficiency then decreases sharply as the wavelength increases, reaching near zero at approximately 700 nm.
HAPD gain

**Electron Bombarded Gain**

- **Bombardment gain**
  - Graph shows the relationship between Photocathode Applied Voltage [-kV] and Electron Bombarded Gain.
  - Voltage ranges from 0 to 9 kV.
  - Gain ranges from 0 to 2200.
  - Various curves represent different samples (e.g., a-22, b-22, c-22, d-22).

- **Avalanche gain**
  - Graph shows the relationship between AD Reverse Bias Voltage [V] and Avalanche Gain.
  - Voltage ranges from 0 to 400 V.
  - Gain ranges from 0 to 1000.
  - Various curves represent different samples (e.g., a-22, b-22, c-22, d-22).
Single photon separation
Pulse height distribution

Many lower pulse height.
It is due to fitting accuracy.
Improvement of fitting algorithm is needed.
QE distribution

Using average QE of HAPD. HAPD placement is sequenced for uniform about QE.
Flash over

- Electron emitted from photocathode hit the ceramic surface and cause secondary emission.
- By repeating the crashes and emissions, a gas is desorbed from ceramic surface.
- The gas is energized between the parts applied HV and APD \(\rightarrow\)”large pulse”}

![Diagram of Flash over process:](image)
Masked HAPD

- Applying voltages is most basic way to check healthiness of HAPD.
- Some HAPDs are masked by two reasons
  - Power supply system $\rightarrow$ cable, patch panel, connector, power supply
  - HAPD problem $\rightarrow$ APD, circuit in HAPD, heavy noise

<table>
<thead>
<tr>
<th># of masked PS channels</th>
<th>before installation</th>
<th>beginning of Phase II</th>
<th>end of Phase II</th>
</tr>
</thead>
<tbody>
<tr>
<td>PS side</td>
<td>HV channel</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>Bias channel</td>
<td>2</td>
<td>4</td>
</tr>
<tr>
<td>HAPD side</td>
<td>Bias</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>Guard</td>
<td>0</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>HV</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>Heavy noise</td>
<td>0</td>
<td>2</td>
</tr>
</tbody>
</table>

| ratio of masked region   | in total            | 0.9%                  | 1.9%            | 2.7%            |
|                         | HAPD issue          | 0.06%                 | 1.0%            | 1.8%            |

- Problem in PS side will be repaired in this summer.
- Problem in HAPD side will be confirmed in this summer.
  - Replace the HAPD if needed.

# of channels
- HV: 420
- Bias: 1680
- Guard: 420
Summary of unused HAPDs

10 out of 72 merger boards are masked by readout problem.
- not send data
- not receive trigger
- cannot download firmware
- connection fail

⇒ 59 HAPDs are masked by merger boards.

$$\frac{59}{420} = 14.0\% \quad \Rightarrow \quad N(\text{LED hits}) < 10$$
$$N(\text{LED trigger})$$

<table>
<thead>
<tr>
<th>unused HAPDs</th>
<th>PS issue</th>
<th>3 HAPDs and 4 APDs</th>
<th>0.9%</th>
</tr>
</thead>
<tbody>
<tr>
<td>HAPD issue</td>
<td></td>
<td>4 HAPDs and 10 APDs</td>
<td>1.5%</td>
</tr>
<tr>
<td>readout issue</td>
<td></td>
<td>59 HAPDs</td>
<td>14.0%</td>
</tr>
<tr>
<td>dead channel in used HAPDs</td>
<td>470 channels</td>
<td>0.9%</td>
<td></td>
</tr>
<tr>
<td>total</td>
<td>caused by HAPD</td>
<td>-</td>
<td>2.4%</td>
</tr>
</tbody>
</table>
Threshold scan

Getting analog information from data (hit/no hit).
⇒ Measure the hit rate while changing threshold voltage.

(a) noise
- shape: gaussian
  - mean: offset
  - sigma: noise level

(b) ideal signal
- shape: rectangle
  - width: pulse height

(c) practical signal
- shape: error function for shoulder
  - gaussian for peak
  - difference between step and mean is 1 p.e. pulse height.

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Results of threshold scan for one channel is shown.

- left: no voltages and random trigger
- right: all voltages are applied and LED monitor system

Threshold scan method is used to evaluate HAPD performance.
Threshold scan result with LED monitor system.

Fitting

- peak : gaussian
- shoulder : error function

Fit result for threshold scan

![Graph showing fit result for threshold scan with y-axis labeled 0 to 800 and x-axis labeled -100 to 300 with pulse height indicated.](image)
Temp. dependency offset

- Threshold scan with three different temperatures.
  - cooler, usual, warmer
- All voltages are not applied to see noise level.

Offset distribution

- mean value
  - cooler: 61.7
  - usual: 60.8
  - warmer: 60.5

Noise level distribution

- mean value
  - cooler: 13.4
  - usual: 15.8
  - warmer: 15.7

Offset has little change by changing temperature. Noise level is increased with higher temperature.

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Compering pulse height with noise

Pulse height is decreased with higher temperature.

<table>
<thead>
<tr>
<th></th>
<th>noise</th>
<th>pulse height</th>
</tr>
</thead>
<tbody>
<tr>
<td>cooler</td>
<td>13.4</td>
<td>66.4</td>
</tr>
<tr>
<td>usual</td>
<td>15.8</td>
<td>62.0</td>
</tr>
<tr>
<td>warmer</td>
<td>15.7</td>
<td>55.7</td>
</tr>
</tbody>
</table>

note:
Applying Bias noise level is decreased by half.

Pulse height is enough larger than noise level.
⇒ We can use same threshold voltage at every temperature.