The ARICH detector at Belle II experiment

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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 Belle II is ongoing (for 40 times larger 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 \( \cos \theta_C = 1/n\beta \)
  \((n: \text{aerogel refractive index, } \beta: \text{particle velocity})\)

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

**Target:** \( K/\pi \) separation at \( >5\sigma \) 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 \( \pi \) (~23 mrad)

\( \sigma_c \): Observed Cherenkov angle resolution.

\( N_{p.e.} \): Detected number of photo electron. \( \Rightarrow \) Highly depends on detector performance.

- Survives in Belle II environment for 10 years.
  - Radiation hardness both for \( \gamma/\)neutron.
- Works in high background environment.
- Covers acceptance of other sub-detectors in endcap region.
  → Round shape detector.
Photon detector

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

⇒ Hybrid Avalanche Photo Detector (HAPD) is developed with Hamamatsu Photonics K. K.
5 mm pitch pixelated 144 channels cathode APD. High gain with hybrid amplification process. 420 sensors are used in total for ARICH.

- Bi-alkali photocathode
- Bombardment gain = 1500
- ~20mm
- ~8kV
- Multi-channel APD
- APD gain = 50

⇒ Total gain ~7×10^5.
HAPD front-end readout

Signal from HAPD is converted to hit information by pre-amplifier, shaper and discriminator in front-end ASIC. → send to Belle II global DAQ readout through merger circuit.

Settings of ASIC components (gain, peaking time, offset level) are controlled by FPGA.

Front-end electronics design is close to final version and production will start soon.
Aerogel radiator

- Distance between aerogel and HAPD window is 200 mm. ⇒ refractive index ~1.04-1.06
- Need to be transparent to suppress photon scattering.
Target transmission length: >40 mm (@\(\lambda\) = 400 nm).
→ Introduce new technique to produce high transparency and refractive index aerogels. (pin-hole drying)

![Graphs showing transmission length vs. refractive index with and without pin-hole drying.](image)

Without pin-hole drying

With pin-hole drying
HAPD radiation hardness

Requirement for 10 years Belle II operation:
HAPD should keep performance for irradiation of
- 1000 Gy $\gamma$
- $1.0 \times 10^{12}$ neutron / cm$^2$

**APD degradation scenarios**

- For $\gamma$:
  Charge around structure on APD surface.
  $\rightarrow$ Degrade breakdown HV and can not reach enough APD gain.

- For neutron:
  Neutron induce lattice defects in bulk and leakage current increases.
  $\rightarrow$ S/N becomes worse.

$\Rightarrow$ Perform irradiation tests and determine APD design and materials to minimize the effect.
HAPD radiation hardness test

Changing APD structure (active area window film material, w/ or w/o alkali protection layer/intermediate electrode...) and \( \gamma \) irradiation tests have been done.

\( \Rightarrow \) Changing the structure on APD surface prevents breakdowns.

Neutron irradiation setup @ MLF in JPARC

\( \Rightarrow \) Thinner P/P+ layer structure improves S/N.
S/N can be further improved by increasing of HV and optimization of shaping time in front-end electronics.
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/$\gamma$ irradiated HAPD.

Picture in light shielding box
Beam test result

- Simple performance estimation from cumulative Cherenkov angle distribution:

\[ \Delta \theta_c = 14.1 \text{ mrad}, N_{p,e} = 11.4. \]

\[ \Rightarrow K/\pi \text{ separation} = 5.5\sigma \]

(SP5 120 GeV/c hadron beam, incident angle = 0° case, similar for non-zero incidence)

- Neutron/\gamma irradiated HAPD works well after HV/readout parameter tuning.
(preliminary)
Validation system for HAPD

Photocathode Quantum efficiency (QE) measurement system
Illuminate monochromatic spot light and measure photoelectric current together with reference photo diode.
- 2D scan on whole effective area.
- Wavelength dependence.

<table>
<thead>
<tr>
<th>Year</th>
<th>HAPD R&amp;D</th>
<th>Electronics R&amp;D</th>
<th>Mechanical structure test &amp; design</th>
<th>Aerogel radiator R&amp;D</th>
</tr>
</thead>
<tbody>
<tr>
<td>2011</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2012</td>
<td></td>
<td></td>
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<td>2013</td>
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<tr>
<td>2014</td>
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<tr>
<td>2015</td>
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- APD spec frozen
- Installation

All produced 450 HAPDs are checked before installation.
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 $\sim 7 \times 10^5$).

- HAPD design is determined by results of radiation hardness tests.
  HAPD samples after neutron/$\gamma$ irradiation corresponding to 10 years Belle II
  operation perform well in beam test.

- New technique was introduced for aerogel production process for
  high transparency/refractive index sample.

- Beam test result with prototype ARICH satisfies requirement from physics
  motivation.
  Achieve $>5\sigma$ separation power for $K$ and $\pi$. (Simple estimation from single photon
  Cherenkov angle resolution and number of detected photon hits)

- Production of final version electronics and HAPD will start soon and
  ARICH will be installed at beginning of 2015.
Belle experimental data (657 million B̅B sample)

ΔE: energy difference between reconstructed B° and beam

Belle II 7.5 ab⁻¹ expectation from MC
with Belle PID

with Belle II PID (TOP+ARICH)
ARICH readout electronics

- Front-end board with 4 ASICs and Spartan6 FPGA
- Merger board prototype with Virtex5 FPGA
Wavelength dependence of Cherenkov photon

Number of Cherenkov photon

200 250 300 350 400 450 500 550 600
Wavelength (nm)

n = 1.05, c = 2\times 10^8 \text{ m/s}
Typical HAPD performance

(data sheet)

<table>
<thead>
<tr>
<th>Quantum efficiency</th>
<th>KA0041</th>
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<tbody>
<tr>
<td>400nm</td>
<td>26.2%</td>
</tr>
<tr>
<td>peak</td>
<td>28.9%</td>
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<table>
<thead>
<tr>
<th>Maximum high voltage</th>
<th>~8500 V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bad channel</td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>None</td>
</tr>
<tr>
<td>B</td>
<td>None</td>
</tr>
<tr>
<td>C</td>
<td>None</td>
</tr>
<tr>
<td>D</td>
<td>ch1</td>
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</table>

<table>
<thead>
<tr>
<th>Maximum high voltage for each APD chip</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>A–ch22</td>
<td>161900 (8.5kV, 377V)</td>
</tr>
<tr>
<td>B–ch22</td>
<td>164600 (8.5kV, 368V)</td>
</tr>
<tr>
<td>C–ch22</td>
<td>104000 (8.5kV, 364V)</td>
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<tr>
<td>D–ch22</td>
<td>162500 (8.5kV, 377V)</td>
</tr>
</tbody>
</table>

- Avalanche gain (chipA–ch22)
- Leakage current (chipA–all)

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

### HAPD performance

<table>
<thead>
<tr>
<th>item</th>
<th>typical</th>
<th>requirement</th>
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</thead>
<tbody>
<tr>
<td>QE</td>
<td>λ=400nm 28%</td>
<td>&gt;=24%</td>
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<tr>
<td>bias voltage</td>
<td>250-500V</td>
<td></td>
</tr>
<tr>
<td>leakage current</td>
<td>each ch at Vb-10V</td>
<td>&lt;= 1μA</td>
</tr>
<tr>
<td>avalanche gain</td>
<td>each ch at Vb-10V</td>
<td>&gt;=30</td>
</tr>
<tr>
<td>HV</td>
<td>-8.5kV</td>
<td>&lt;= 300pA</td>
</tr>
<tr>
<td>bombardment gain</td>
<td>-8kV 1800</td>
<td>&gt;=1500</td>
</tr>
<tr>
<td>Total gain</td>
<td>-8kV at gain=30</td>
<td>&gt;=45000</td>
</tr>
</tbody>
</table>

# of dead channels ≤ 10
**KA058**

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

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

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**E-PID summary**

**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.
Registration is now opening.
http://rich2013.kek.jp

Abstract deadline is 31 July.