Development of a 144-channel HAPD for Belle II Aerogel RICH

Shohei Nishida
KEK
NDIP 14 @ Tours
Jul. 2, 2014
Contents

- Introduction
- Belle II Aerogel RICH and HAPD
- Status of the Mass Production
- Summary

Ichiro Adachi¹, Nao Hamada², Koji Hara¹, Toru Iijima³, Shuichi Iwata⁴, Hidekazu Kakuno⁴, Hideyuki Kawai⁵, Takeo Kawasaki⁶, Samo Korpar⁷, Peter Krizan⁷, Shohei Nishida¹, Satoru Ogawa², Rok Pestotnik⁷, Luka Santelj¹, Andrej Seljak⁷, Takayuki Sumiyoshi⁴, Makoto Tabata⁵, Elvedin Tahirovic⁷, Keisuke Yoshida⁴, Yosuke Yusa⁶

¹KEK, ²Toho Univ., ³Nagoya Univ., ⁴Tokyo Metropolitan Univ., ⁵Chiba Univ., ⁶Niigata Univ., ⁷Joseph Stephan Institute
(Belle II Aerogel RICH Group)
Belle II Experiment

• KEKB / Belle : B factory experiment @ KEK (1999-2010)
  ✓ Asymmetric e⁺-e⁻ collider
  ✓ World highest luminosity (2.11 × 10³⁴ cm⁻² s⁻¹).
  ✓ Discovery of CP Violation in B system.

• Upgrade to SuperKEKB and Belle II.
  ✓ 40 times higher luminosity, aiming at 50 ab⁻¹.
  ✓ Search and study of New Physics.
  ✓ Commissioning starts in 2015.

• Particle identification (K/π separation) is a key issue.
  ✓ e.g. B → ργ v.s. K*γ
  ✓ TOP and Aerogel RICH.

S. Nishida (KEK) Jul. 2, 2014
Development of a 144-channel HAPD for Belle II Aerogel RICH
Aerogel RICH

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

\[ \theta_C(\pi) - \theta_C(K) \simeq 23 \text{ mrad} \]

(@ 4 GeV; n = 1.05)

- target: \( \pi/K \) separation up to \( \sim 4 \text{GeV} \).
- Replace threshold-type PID device at Belle.

- 2-layer (2cm+2cm) aerogel tiles.
- \( n_1 < n_2 \): focusing (\( n_1 = 1.045 \), \( n_2 = 1.055 \)).
- High transmission length (40-60mm) required.
HAPD

Photo-detector

- ~5mm pixel size. Large coverage.
- Immune to 1.5T magnetic field.
- Radiation tolerance (neutron, gamma).

HAPD (Hybrid Avalanche Photo-Detector)

- Developed with Hamamatsu Photonics.
- 144 channels (36-ch APD chip x 4).
- Gain ≥45000.
- Peak QE ~28%
- Size 73mm x 73mm.
- Effective area 63mm x 63mm (65%).

Total 420 HAPDs
Development of a 144-channel HAPD for Belle II Aerogel RICH

Aging test at IJS
20 years of Belle II operation

• Lifetime test is also performed at HPK (~10y Belle II) in 1000h
  ✓ No change in QE, bombardment/avalanche gain.
  ✓ Minor increase in leakage current

QE increased by super bialkali photocathode (25%→ 35%)

S. Nishida (KEK)
Jul. 2, 2014
Electronics

- Total 60000 channels.
  - 1-bit ON/OFF information
- High-gain, low-noise.
- Only 5 cm available behind HAPD

ASIC (SA03)
- CMOS 0.35 μm process @ X-FAB.
- 36 ch / chip (i.e. 4 ASIC for one HAPD).
- Pre-amplifier + shaper + comparator.
- Typical peaking time ~100ns
Aerogel RICH detector consists of

- 420 HAPD
- 248 Aerogel Tiles

HAPD: 8 rings → 7 rings
Radiation Tolerance was a concern for HAPD

[ ] : original estimation for 10 years operation of Belle II

- **Neutron** : $[10^{12} \text{ n/cm}^2 (1\text{MeV equiv.})]$  
  - lattice defects $\rightarrow$ leakage current, worse S/N.
- **Gamma** : $[1000 \text{ Gy}]$  
  - surface effect (charge-up) $\rightarrow$ breakdown

Simulation (with 8 HAPD rings)

**Gamma**
- Inner $<$ 50 Gy (10 years)
- Outer $<$ 50 Gy (10 years)

**Neutron**
- Inner $<$ $1.3 \times 10^{12} \text{ n/cm}^2$ (10 years)
- Outer $<$ $1.3 \times 10^{12} \text{ n/cm}^2$ (10 years)

Irradiation test of the HAPD was done up to 1000 Gy and $2 \times 10^{12} \text{ n/cm}^2$.

Remove innermost HAPD layer and replace it with neutron shield. Neutron can be reduced to $< 0.4 \times 10^{12} \text{ n/cm}^2$.

Details were discussed at
NDIP11 K.Hara (ID-161) “Study of 144-channel Hybrid Avalanche Photo Avalanche Photo-Detector for Belle II RICH Counter”
Prototype Beam Test

Beam test at DESY (2013) using prototype Aerogel RICH.

- 2 × 3 HAPD configurations (part of the actual layout).
- Front-end board with ASIC (close to final).
- During the test, HAPD is replaced with the one irradiated to neutrons and/or gamma.
  - No degradation of the number of photons
  - No significant performance degradation is expected for the predicted radiation.

\[ \sigma = 15.4 \text{ mrad} \]

\[ \text{photon/track: } 8.6 \]

\[ \Delta \theta_C / \sigma_\theta \sqrt{N_{p.e.}} \rightarrow 4.4\sigma \]

\[ \text{Std1 n}(2.1 \times 10^{12}) \]
\[ \text{Std2 n}(1.1 \times 10^{12}) \]
\[ \text{n}(0.86 \times 10^{12}) \gamma \text{ (1 kGy)} \]

[Detected # (photon) normalized by QE]
HAPD Mass Production

- 420 HAPDs are used in Aerogel RICH.
- The mass production started in Sep. 2013.
- Measurement (quality assessment) is performed at KEK
  - Leakage current.
  - Noise, S/N.
  - 2D hit map.
  - QE.

<Specification>

<table>
<thead>
<tr>
<th>Item</th>
<th>Standard</th>
<th>Allowed</th>
</tr>
</thead>
<tbody>
<tr>
<td>QE</td>
<td>28%</td>
<td>&gt;24%</td>
</tr>
<tr>
<td>Leakage Current</td>
<td>&lt;1uA per channel</td>
<td></td>
</tr>
<tr>
<td>Avalanche Gain</td>
<td>40</td>
<td>&gt;30</td>
</tr>
<tr>
<td>Electron Bombardment Gain</td>
<td>1800</td>
<td>&gt;1500</td>
</tr>
<tr>
<td>Total Gain</td>
<td>~70000</td>
<td>&gt;45000</td>
</tr>
<tr>
<td>Number of Bad Channels</td>
<td>≤10</td>
<td>bad: ‡ not satisfied</td>
</tr>
</tbody>
</table>

‡ not satisfied
A part of measurement system is in trouble. Under recovery.

- Original plan
  - Finish in Sep. 2014.
  - 35 HAPDs per month.
- However, the production is delayed.
  - Low yield at HPK, especially around Dec. 2013.
  - Tentative plan: 27 HAPDs per month to complete production in Mar. 2015.
Quantum Efficiency

- High QE is essential to get high performance.
- Measure photo-current with light from Xe lamp.
- Scan over the photo-cathode (spot size < 1mm).
- In general, good agreement btw KEK and HPK. Some deviation when compared individually.
  - HPK irradiates light to the whole region.
- Some structures are sometimes observed in QE.
- QE is increasing as production proceeds.
  - Last year 20-30%; Now 25-35% at HPK.

- Normal
- Cross (reason unknown)
- Low spot (arrow): metal is found on quartz window

out of specification

QE measured at KEK (%)

QE at HPK (%)
2D Hit Distribution

- Single photon response.
- Scan by moving the laser position and measure the hit distribution.

Effect of the distortion of the electric field. Will disappear under magnetic field.

- In around 10% of HAPDs, a region with high noise is observed (HAPD-dependent, reproduceable)
- It is turned out that the noise is due to instability of HAPD after the exposure to light.
- Time to stabilize is O(10) min (sometimes > 2h).
- Under investigation, but no problem to use in Aerogel RICH.
Leakage Current Problem

- Several HAPDs show rather large leakage current (>1µA), even though they passed the pre-measurement at HPK.
- There is one sample, for which the leakage current increased more than three months after production.
- According to the investigation at HPK, light emission is observed for such a sample, and small object is sometimes observed in the corresponding location.
- However, the reason is not understood (especially why the problem happens after production).
- Plan to measure the leakage current for all the samples again.
HAPD Mass Production

Status of Quality Assessment.

<table>
<thead>
<tr>
<th></th>
<th>Number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Qualified</td>
<td>150</td>
</tr>
<tr>
<td>Low Quality</td>
<td>26</td>
</tr>
<tr>
<td>Need Investigation</td>
<td>14</td>
</tr>
<tr>
<td>Investigation at HPK</td>
<td>4</td>
</tr>
<tr>
<td>NG (Broken etc.)</td>
<td>6</td>
</tr>
<tr>
<td>Total</td>
<td>200</td>
</tr>
</tbody>
</table>

Mainly large leakage current (~μA) (usable at this stage, but worry in long term operation)

Noisy samples etc. (4 of them are already repaired)

Mostly problem in leakage current.

• Leakage current is an issue.
  ✓ Improvement in the production at HPK is desired.
Status of Other Components

Aerogel

- The production of aerogel tiles (248 + spare) is completed.
  - Measurement of optical property is in progress.
  - Manufacturing (cut by water jet) will be done.

Electronics

- Mass production of ASIC is done.
  - Now under test.
- Final version of the Front-end board is designed and is being tested.
  - Mass production in autumn.
- Final version of the merger is under test.

Mechanical structure will be ready within this year.
Summary and Schedule

• We are constructing Aerogel RICH Counter for the Belle II forward PID.
  ✓ 2-layer aerogel (n=1.045 & 1.055).
  ✓ 144 channel Hybrid Avalanche Photo-Detector (HAPD).
  ✓ Readout electronics based on the ASIC.
• There had been an issue of the radiation hardness, but it is solved.
  ✓ Specification determined. More understanding with simulation.
• Mass Production of HAPD started.
  ✓ Leakage current is an issue.

Schedule

• HAPD mass production will finish around Mar. 2015.
• Other components mostly within 2014
  ✓ Start constructing the detector from 2015.
• Complete the construction around July 2015. Installation in summer.
Backup
HAPD: operation in 1.5 T

Tests in 1.5 T magnetic field show improved HAPD performance:
- no photoelectron back-scattering cross-talk
- increase of detection efficiency – photoelectron energy deposited at one place
- effect of non-uniformity of electric field disappears
**Neutron damage**

Modification of APD structure:
- Thinner p\(^+\) layer to increase bombardment gain
- Thinner p layer to reduce increase of the leakage current after irradiation – main source of leakage current are thermally generated electrons in p layer due to the lattice defects produced by neutrons

As expected the increase of the leakage current is smaller with thin p

S/N for thin p sample is better than 7 after fluence 10\(^{12}\)n/cm\(^2\)
Gamma irradiation

- Expected total dose 100-1000 Gy
- Initial tests indicated fast raise of leakage current and reduction of breakdown voltage – not previously observed with similar APDs
- Possible source: APD for HAPD had additional alkali protection layer to protect APD during photocathode activation process
- To identify the reason extensive tests were done with single channel APDs with different structure prepared by Hamamatsu:
  - No alkali protection
  - “Standard” alkali protection
  - “New” alkali protection

→ APD structure was optimized
Beam Test with Prototype ARICH

- 2-layer aerogel & $2 \times 3$ HAPD configurations
- Front-end board with ASIC (close to final).
- Study items:
  - System test with the latest electronics.
  - Aerogel Study.
  - Effect of radiation.

Event Display
Beam Test with Prototype ARICH

Accumulated hits

Naïve estimate from accumulate hits.

\[ \frac{\Delta \theta_C}{\sigma_\theta} \sqrt{N_{p.e.}} \Rightarrow 4.4\sigma \]

\( \sigma = 15.4 \text{ mrad} \)

photon/track: 8.6
Performance with Irradiated HAPDs

One issue of the HAPDs has been the radiation tolerance.

Check the performance using HAPDs after irradiations at the beam test.

Neutron irradiation @ J-PARC MLF
- 1-2 × 10^{12} n/cm^2

Gamma irradiation @ Nagoya Univ.
- ^{60}Co
- ~1000Gy (50Gy/hour)
Performance with Irradiated HAPDs

- Beam test performed using irradiated HAPDs.
  - Replace one of the HAPDs (#4) to irradiated samples.
    - Neutron $2.1 \times 10^{12}$ n/cm$^2$.
    - Neutron $0.9 \times 10^{12}$ n/cm$^2$ and gamma 1000 Gy.
- Threshold level increased to the irradiated samples.
- No difference found in the detected number of photons/

---

**[Noise Level]**

Neutron irradiated HAPD
$(2.1 \times 10^{12}$ n/cm$^2)$

Standard HAPD

---

[Graph showing noise level comparison between neutron-irradiated and standard HAPDs.]

---

**Detected #(photon) normalized by QE**

- Standard 1: n$(2.1 \times 10^{12})$
- Standard 2: n$(0.86 \times 10^{12})$
- γ (1 kGy): n$(1.1 \times 10^{12})$

---

S. Nishida (KEK)
Jul. 2, 2014

Development of a 144-channel HAPD
for Belle II Aerogel RICH

NDIP 14
Performance with Irradiated HAPDs

Performance with Irradiated HAPDs

No significant performance degradation is expected for the predicted radiation.
Performance

- Monte Carlo simulation is performed under Belle2 software framework.
- Excellent PID performance over wide range of momentum.