Belle II aerogel RICH detector

Leonid Burmistrov

LAL, CNRS/IN2P3, Orsay, France

I. Adachi¹,², L. Burmistrov³, F. Le Diberder³, R. Dolenec⁴, K. Hataya⁵, T. Iijima⁶, S. Kakimoto⁵, H. Kakuno⁵, H. Kawai⁷, T. Kawasaki⁸, H. Kindo², T. Kohriki¹, T. Konno⁶,⁵, S. Korpa⁹,¹⁰, P. Krizan⁴,¹⁰, T. Kumita⁵, Y. Lai¹, M. Machida¹¹, M. Mrvar¹⁰, S. Nishida¹,², K. Noguchi¹, K. Ogawa¹², S. Ogawa¹³, R. Pestotnik¹⁰, L. Santelj⁴,¹⁰, M. Shoji¹, T. Sumiyoshi⁵, M. Tabata⁷, S. Tamechika⁵, M. Yonenaga⁵, M. Yoshizawa¹², Y. Yusa¹²

¹ High Energy Accelerator Research Organization (KEK), Tsukuba, Japan
² SOKENDAI (The Graduate University of Advanced Science), Tsukuba, Japan
³ Laboratoire de Laccelerateur Lineaire (LAL), Orsay, France
⁴ University of Ljubljana, Slovenia
⁵ Tokyo Metropolitan University, Hachioji, Japan
⁶ Nagoya University, Nagoya, Japan
⁷ Chiba University, Chiba, Japan
⁸ Kitasato University, Sagamihara, Japan
⁹ University of Maribor, Slovenia
¹⁰ Jožef Stefan Institute, Ljubljana, Slovenia
¹¹ Tokyo University of Science, Noda, Japan
¹² Niigata University, Niigata, Japan
¹³ Toho University, Funabashi, Japan

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Outline

1. Flavour physics, SuperKEKB accelerator and BELLE II experiment
   1.1 One word about the physics
   1.2 The accelerator
   1.3 The detector

2. Aerogel RICH : Particle identification detector in forward region of BELLE II
   2.1 Aerogel Ring Imaging CHerenkov counter (ARICH) : concept
   2.2 The aerogel radiator
   2.2 The photon detector : HAPD


4. Backup slides, appendix, ...
One word about the physics

An ultimate goal of modern particle physics experiments is a search of a new physics.

Quark flavor mixing and CP-violation are described by the Cabibbo-Kobayashi-Maskawa matrix (3 x 3).

The matrix is unitary and therefore can be graphically represented as triangle (unitary) in a complex plane.

B physics plays an important role in constraining the angles and the sides of the Unitary Triangle (UT).

At present knowledge the UT apex determined within statistical errors.

Central values of the constraints are from the present data (ICHEP 2016). While errors are those expected to be with Belle II data.

In case the measurements will not sum – up to a close triangle → New Physics !!!
Time line of the Belle II experiment

Phase 1
- 2017
- Accelerator study
- Test of the the nano-beam scheme
- Beam background study

Phase 2
- April 2018
- First collision and Belle II detector data taking
- Background study
- Calibration of the Belle II detector subsystems

Phase 3
- Upgrade and bug removals
- ARICH cooling system upgrade
- ARICH daq bug fixing, H.V. bug fixing ...

- Machine dedicated runs: March 2019
- Data taking campaign: Beginning of April 2019 – End of June
SuperKEKB machine

- Located at Japan (Tsukuba)
- Upgrade of existing KEKB machine
- Luminosity frontier
- Electron positron asymmetric collider.
- Energy in the center of mass is 10.58 GeV, corresponding to the mass of the \( \Upsilon(4S) \) resonance.

The design of SuperKEKB is based on the new concept of the nano-beam scheme.

\[ e^- 7.0 \text{ GeV/c} \quad \Upsilon(4S) \quad e^+ 4.0 \text{ GeV/c} \]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>LER</th>
<th>HER</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>E</td>
<td>4.000</td>
<td>7.007</td>
<td>GeV</td>
</tr>
<tr>
<td>I</td>
<td>3.6</td>
<td>2.6</td>
<td>A</td>
</tr>
<tr>
<td>( \beta_x^* )</td>
<td>32</td>
<td>25</td>
<td>mm</td>
</tr>
<tr>
<td>( \beta_y^* )</td>
<td>270</td>
<td>300</td>
<td>( \mu )m</td>
</tr>
<tr>
<td>( \sigma_z )</td>
<td>6</td>
<td>5</td>
<td>mm</td>
</tr>
</tbody>
</table>

* indicates values at the IP

Table 9: Machine parameters.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>( N_b )</td>
<td>2500</td>
<td></td>
</tr>
<tr>
<td>C</td>
<td>3016.315</td>
<td>m</td>
</tr>
<tr>
<td>( 2\phi_x )</td>
<td>83</td>
<td>mrad</td>
</tr>
<tr>
<td>L</td>
<td>( 8 \times 10^{35} )</td>
<td>( \text{cm}^{-2}\text{s}^{-1} )</td>
</tr>
</tbody>
</table>
ARICH detector located in forward endcap (PID) two meters from interaction point.

Target performance: K/π separation at > 4σ C.L. @ 0.5 < p < 4 GeV/c.

Aerogel Ring Imaging CHerenkov counter (ARICH) : concept

\[ \cos \theta_c = \frac{1}{n \beta} \]
\[ \beta = \frac{v}{c} \]
\[ \frac{\partial^2 N}{\partial x \partial \lambda} = \frac{2\pi \alpha z^2}{\lambda^2} \left( 1 - \frac{1}{(n(\lambda))^2 \beta^2} \right) \sim \frac{1}{\lambda^2} \]

Particle mass

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

Particle momentum

Particle Cherenkov angle

Aerogel refractive index

\( \pi \) \hspace{1cm} \( K \)

charged particle

radiator \hspace{1cm} photon detector

\( 20 \text{ cm} \)

\( \sim 6 \text{ cm} \)

\text{for } n = 1.045

\( \theta_{\text{Cer}} \) [rad]

Momentum [GeV]
Why we choose aerogel radiator? Why double layer?

\[ \beta = \frac{1}{n \cos(\theta)} \rightarrow \frac{\sigma_\beta}{\beta} = \sigma_\theta \tan(\theta) \rightarrow \frac{\sigma_\beta}{\beta} \rightarrow 0 \quad \theta \rightarrow 0 \quad n \rightarrow 1 \]

\[ N_{\text{Cherenkov light}} \sim \left(1 - \frac{1}{n^2 \beta^2}\right) L \]

As a consequence we need to use thicker radiator

Fine adjustment of \( n \) for aerogel:

\[ n(\lambda) = p_{\text{Intercept}} + k(\lambda) \rho \]

**Nuclear Instruments and Methods in Physics Research**

Single thick radiator

Double layer radiator

Focusing configuration

Fig. 7. Distribution of the Cherenkov angle for accumulated single photons from 4GeV/c pions in the case of a focusing dual radiator combination with 20mm thick radiators (\( n = 1.047 \) and \( n = 1.057 \)).
The photon detector: HAPD

Hybrid Avalanche Photo Detector (HAPD).

- 144 pixelated APDs: 4.9 x 4.9 mm$^2$ channel size. Effective area: 63 mm x 63 mm.
- Signal gain > $4 \times 10^4$ by Hybrid amplification process.
- Operation in 1.5 T magnetic field.

Signal gain > $4 \times 10^4$ by Hybrid amplification process.

Separate 1 – 2 – 3 p.e.
Enhancement in the magnetic field

Front end board
**ARICH aerogel plane**

- Two aerogel layers
- 124 aerogel tiles per layer
- 248 aerogel tiles in total

Two layers of wedge-shaped aerogel single tiles of size: $17 \times 17 \times 4 \, \text{cm}^3$
ARICH photon detector

- 420 HAPD modules with
- 60480 redout channels
- 18 planar mirror plates

Mirrors from the edge
ARICH performance estimation with BhaBha and radiative BhaBha events.

The first collisions at SuperKEKB took place on 26 of April in 2018.

Track selection criterion:

- Charged track
- BhaBha triggered events: back to back isolated tracks with ECL energy deposition.
- Kinematics cuts:
  - Momentum > 6 GeV/c
  - $z_0$ from IP within 1 cm
  - Impact parameter from IP less than 1 cm

Other considerations:

- Excluding dead or masked channels/regions
- Including central drift chamber and ARICH alignment.
Single Cherenkov photon angle resolution.

Reconstructed Cherenkov ring visualized with event display.

- Black line - non correlated background (electronics, beam background ...)
- Magenta line - correlated background (Rayleigh scattered photons, reflection from APD ...)
Data vs Monte Carlo (without any tuning)

The number of signal photons is ~20% less with respect to the simulation.

- The signal threshold is the same for all the HAPD's. However, the gain and single photon amplitude is different for a given HAPD.
- The masking of the dead and not working channels is not fully implemented.

Photons from HAPD window

Number of reflected photons from APD is too high in MC
Baseline cooling system* - was not sufficient to cool down the full detector.

New cooling system has been designed, simulated, fabricated, installed and tested after phase 2.

* Designed and installed by the external company.
Conclusions

BELLE II detector had take first collision data (started 26 of April 2018)

Estimation of the ARICH detector performance have been done with BhaBha electrons.

Single photon resolution measured to be ~14 mrad (in agreement with simulation within 10 %).

Number of signal photons is ~20% less with respect to the simulation.

It corresponds to ~4 $\sigma$ K/pi separation for tracks with 4 GeV/c momentum.

Monte Carlo tuning in ongoing.

Upgrade of the ARICH cooling system have been done.
Backup slides, appendix, ...

Reconstructed Cherenkov ring from direct photons

Reconstructed Cherenkov ring from reflected photons

Track coordinate system
RICH reconstruction. PID.

“Simple” ring fit and Cherenkov angle reconstruction provide PID information but less precise than logarithm likelihood analysis.

PID with ARICH detector based on logarithm likelihood analysis.

\[ \ln L = -N + \sum_{\text{hit } i} n_i + \ln \left( 1 - e^{-n_i} \right) \]

- \( n_i \) = \( n_s^i + n_b^i \)
  - Signal
  - Background

- Expected number of detected photons
- Number of detected photons
- Probabilities for a HAPD pad to be hit.

Detection efficiency

\[ n_{s,r}^i = \varepsilon_i n_{t,r} \int_{\Omega_i} S_r(\theta_r, \phi_r) d\theta_r d\phi_r \]

- Hit probability
- Radiator
- Total number of photons emitted in the radiator of type \( r \)
- Is the probability for a Cherenkov photon being emitted by particle.

PID with Cherenkov angle reconstruction

@ 3.5 GeV
\sim 12 \text{ phot./track}

PID with likelihood analysis

K.id. Efficiency

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CKM unitary matrix and Wolfenstein parametrization

Weak eigenstates \((d', s', b')\) are linear combinations of the mass eigenstates \((d, s, b)\)

\[
\begin{pmatrix}
  d' \\
  s' \\
  b'
\end{pmatrix} = \begin{pmatrix}
  V_{ud} & V_{us} & V_{ub} \\
  V_{cd} & V_{cs} & V_{cb} \\
  V_{td} & V_{ts} & V_{tb}
\end{pmatrix} \begin{pmatrix}
  d \\
  s \\
  b
\end{pmatrix} = V_{\text{CKM}} \begin{pmatrix}
  d \\
  s \\
  b
\end{pmatrix}
\]

The non–diagonal elements of the CKM matrix allow for the transitions between quarks of different families.

Wolfenstein parametrization of the CKM matrix is shown below:

\[
V_{\text{CKM}} = \begin{pmatrix}
  1 - \frac{\lambda^2}{2} & \lambda & A\lambda^3(\rho - i\eta) \\
  -\lambda & 1 - \frac{\lambda^2}{2} & A\lambda^2 \\
  A\lambda^3(1 - \rho - i\eta) & -A\lambda^2 & 1
\end{pmatrix} + \mathcal{O}(\lambda^4)
\]

3 real parameters \((\lambda, \rho, A)\) and 1 CP–violating complex phase \((\eta)\)
Weak eigenstates \((d', s', b')\) are linear combinations of the mass eigenstates \((d, s, b)\).

Quark flavour mixing and CP-violation are described by the Cabibbo-Kobayashi-Maskawa (CKM) unitary \((3 \times 3)\) matrix.

\[
\begin{pmatrix}
    d' \\
    s' \\
    b'
\end{pmatrix} = V_{\text{CKM}} \begin{pmatrix}
    d \\
    s \\
    b
\end{pmatrix}
\]

\[
V_{\text{CKM}} V_{\text{CKM}}^\dagger = 1
\]
$e^- 7.0 \text{ GeV/c} \rightarrow \Upsilon(4S) \rightarrow e^+ 4.0 \text{ GeV/c}$

- $e^-$: Electron with momentum 7.0 GeV/c
- $e^+$: Positron with momentum 4.0 GeV/c
- $\Upsilon(4S)$: Psi(4S) meson
- B meson
- Anti B meson
Focusing configuration \( n_1 < n_2 \)

charged particle

aerogel

\( n_1 < n_2 \){\text{A}}

photon detector

Cherenkov photons
Central values of the constraints are from the present data (2010). While errors are those expected to be 10 time less with Belle II data.

In case the measurements will not sum – up to a close triangle → New Physics !!!
Why we choose aerogel radiator? Aerogel parameters.

\[ \beta = \frac{1}{n \cos(\theta)} \quad \Rightarrow \quad \frac{\sigma_\beta}{\beta} = \sigma_\theta \tan(\theta) \quad \Rightarrow \quad \frac{\sigma_\beta}{\beta} \rightarrow 0 \quad \theta \rightarrow 0 \quad \Rightarrow \quad n \rightarrow 1 \]

As a consequence we need to use thicker radiator

Fine adjustment of n

\[ n(\lambda) = p_{\text{Intercept}} + k(\lambda)\rho \]

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Aerogel Ring Imaging CHerenkov counter (ARICH) : concept

Cherenkov radiation is electromagnetic radiation emitted when a charged particle passes through a dielectric medium of refractive index $n$ with a velocity $v$ greater than the speed of light $(c/n)$ in that medium.

First observation in 1934 by Pavel Cherenkov. (During the experiments on luminescence of liquids under gamma rays)

Theoretical explanation has been given by Ilya Frank and Igor Tamm in 1937. (Based on classical electrodynamics)

Nobel Price (by P. Cherenkov, I. Frank, I.Tamm) in 1958

$$\cos \theta_c = \frac{1}{n \beta}$$

$$\beta = \frac{v}{c}$$

$$\frac{\partial^2 N}{\partial x \partial \lambda} = \frac{2\pi \alpha z^2}{\lambda^2} \left(1 - \frac{1}{(n(\lambda))^2 \beta^2}\right) \sim \frac{1}{\lambda^2}$$

Particle mass $m = \frac{p}{c} \sqrt{n^2 \cos^2 \theta_c - 1}$

Particle momentum

Particle Cherenkov angle

Aerogel refractive index

For $n = 1.045$

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DAQ

- in total 60,000 channels.
- limited space of 5 cm behind array of HAPDs.
- ASIC SA03 (36 ch/chip → 4 ASICS / HAPD).
- Variable gain (3.1-12.5 V/pC) and
  shaping time (100-200 ns)
  → optimization for increasing noise levels (neutron radiation)
- mass production completed.

Front-end Board

4x ASIC (SA03)

Preamp        Shaper        Comparator

FPGA

for hit detect.
DAQ, monitoring (Spartan6)

Merger Board

- Collects hit data from
  5-6 F.E.B.s
- Send to DAQ system.

FPGA

(Virtex5)

Belle2Link

trigger