Performance of the Belle II Silicon Vertex Detector

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Joint Annual Meeting of the Swiss and Austrian Physical Societies
August 26-30, 2019, Zurich University, Switzerland
HARDWARE OVERVIEW
SuperKEKB and Belle II Experiment

• SuperKEKB collider at KEK
  – $e^+ e^-$ collider with $\sqrt{s}$ of 10.58 GeV ($= M_{Y(4S)}$)
    • Asymmetric beam: $e^+ 4$ GeV, $e^- 7$ GeV
  – World-highest designed luminosity: $L = 8.0 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$

• Belle II experiment
  – Intensity frontier experiment at SuperKEKB to discover and understand physics beyond the SM (BSM).
  – Precise determination of the decay vertices and low-momentum tracking are essential to perform the BSM search.
Belle II Vertex Detectors

- PiXel Detector (PXD)
  - Based on DEPFET pixels – see previous talk
- Silicon Vertex Detector (SVD)
  - Double-sided silicon strip detectors (DSSDs)

**VXD requirements**
- Fast – to operate in high background environment
- Better resolution at IP – to compensate reduction of boost wrt. Belle I
- Radiation hard (up to 100 kGy)
- Self-tracking capable – to track particles down to 50 MeV in $p_T$
Components of the Belle II SVD

- Carbon fiber (CF) cone
- Outer CF shell
- End flange
- End rings
- Ladders
- Beam pipe
- PXD (independent sub-detector inside SVD)
SVD ladders

<table>
<thead>
<tr>
<th>Layer</th>
<th>Ladders (spares)</th>
<th>DSSDs / ladder</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>16 (4)</td>
<td>5</td>
</tr>
<tr>
<td>5</td>
<td>12 (3)</td>
<td>4</td>
</tr>
<tr>
<td>4</td>
<td>10 (2)</td>
<td>3</td>
</tr>
<tr>
<td>3</td>
<td>7 (2)</td>
<td>2</td>
</tr>
</tbody>
</table>

47 FW/BW + additional modules
SVD Silicon Sensor

DSSD (Double-sided Si strip detector)

Strip numbers and pitches

- 3 types of DSSD sensors

<table>
<thead>
<tr>
<th>Sensors</th>
<th>Rectangular (Large)</th>
<th>Rectangular (Small)</th>
<th>Trapezoidal</th>
</tr>
</thead>
<tbody>
<tr>
<td># of p-strips</td>
<td>768</td>
<td>768</td>
<td>768</td>
</tr>
<tr>
<td>p-strip pitch</td>
<td>75μm</td>
<td>50μm</td>
<td>50...75μm</td>
</tr>
<tr>
<td># of n-strips</td>
<td>512</td>
<td>768</td>
<td>512</td>
</tr>
<tr>
<td>n-strip pitch</td>
<td>240μm</td>
<td>160μm</td>
<td>240μm</td>
</tr>
</tbody>
</table>
Front-End Readout ASIC

• **APV25 chip**
  - A high background in Belle II requires, short signal shaping time and a good radiation hardness.
  - APV25 chip is a suitable solution for SVD.
    - Originally developed for CMS.

• **APV25 Specification**
  - # of input channels: 128 ch.
  - Shaping time: 50nsec
  - Radiation hardness: > 1MGy

• **Chip-on-Sensor (see next slide)**
  - Thinned to 100μm thickness for the material budget reduction.
  - Max. heat dissipation: 0.4W
    - → Necessity of cooling
**Chip-On-Sensor Concept**

**ORIGAMI flex**
*(Si sensor is under the flex)*

- Flex circuit (ORIGAMI flex) is glued on sensor *n*-strip surface with an electrical/thermal-isolation foam.
- APV25 are placed on the ORIGAMI flex to minimize the analog path length (capacitive noise).
  - Sensor strips and ORIGAMI flex are connected with Al wire-bonding (φ25μm).

Wire bonding with Al wires.

Sensor under ORIGAMI (**n**-strips)

Sensor from other side (**p**-strips)
FADC Readout System

- SVD
- x1748 APV25s
- TRG/CLK signals
- x48 FADC
- x4 buffer
- FADC Ctrl
- Decoder
- Central DAQ
- "COPPER" board
- RX
- CPU
- Data stream
- Data size reduction
- Trigger/timing distributor
- PXD region of interest gen
- to HLT
- to PXD
- Central TRG
- SVD readout system
SVD COMMISSIONING
SVD assembly and commissioning

- +X half mount was completed in Feb 2018
- -X half mount finished in Jul 2018
- From Jul to Sep 2018 the two half shells were operated in a dry box in Tsukuba experimental hall (SVD commissioning)
- End of Sep/beginning of Oct 2018 the SVD was moved into the VXD clean room, mounted on the PXD

SVD +X completion (Feb 2018)  SVD -X completion (Jul 2018)
Completed VXD detector (Oct 2018)
SVD commissioning (Jul-Sep 2018)

• The two SVD halves were operated from Jul to Sep in Tsukuba B4
• Cosmic data and special background runs have been taken to understand the system prior to the start of data taking

First cosmic event in SVD +X (Jul 10, 2018)  
First cosmic event in full SVD (Aug 17, 2018)
SVD commissioning – SNR, cluster energy

- We have collected about $30 \times 10^6$ cosmic events with both SVD halves
- The SNR is larger than 25 for N side, slightly lower on P side due to the longer strips and larger capacitance load to the preamplifier

- Cluster energy in horizontal silicon sensor (300 µm thick) by a cosmic ray (MIP) is peaking at 80 keV
- Larger energy deposited in slanted and vertical sensors, as expected
- Low energy peak due to noise cluster
SPRING 2019 RUN ("PHASE 3", EXP. 7/8)
Integrated luminosity by the end of the first run (March to June 2019)

• Slightly below 7/fb, about half of the original projection
Instantaneous luminosity history

- $>10^{34}/\text{cm}^2/\text{s}$ was achieved in the very last days
SVD operation in spring 2019

- SVD operation has been smooth and stable throughout the spring run, no major issue has been encountered.
- Excellent performance:
  - Cluster efficiency above 99% in L3-L6 and on both n- and p-sides (see following slides).
- SVD background situation:
  - Currently the occupancy is ~<0.3% in physics runs
  - Limit for good tracking performance is 2-3%
Signal-to-noise ratio for SVD clusters included in tracks (exp. 7)

- SNR > 15 in every SVD sensor
- Higher SNR for forward and backward sensors

\[ SNR_{cls} = \frac{\sum_{i} S_i}{\sqrt{\sum_{i} N_i^2}} \]
Energies of SVD clusters included in tracks (exp. 7)

\[ l = \frac{d}{\sin \alpha} \]

\[ d = 300 \mu m \]

\[ E \approx \frac{d}{\sin \alpha} \cdot 80 \frac{e^{-}}{\mu m} \]
• Sensor efficiency is calculated as the fraction of times a cluster is found within ±0.5 mm from the extrapolated position of tracks on the sensor.
• Forward and Backward sensors have efficiency slightly higher than barrel sensors.
• On average, efficiency is above 99% for most of the sensors, with the exception of a L3 sensor that had a read-out chip masked.
Summary

• SVD construction and commissioning
  – After years of construction and preparation, SVD assembly was completed in Feb 2018 (+X half shell) and Jul 2018 (-X half shell)
  – From Jul to Sep 2018, the entire SVD was operated for the first time outside of Belle II (SVD commissioning)
  – Finally, the detector was successfully combined and installed in Belle II in Oct to Dec 2018

• Spring 2019 run (“phase 3”)
  – SVD operated successfully throughout Belle II’s first physics run from Mar to Jul 2019
  – All sensors worked as expected, with efficiencies above 99% and Signal-to-Noise Ratios above 15
  – No major issues were observed in SVD during the first period of data taking
BACKUP
## SKB parameters

<table>
<thead>
<tr>
<th>Parameter</th>
<th>July 1 08:58</th>
<th>June 26 14:09</th>
<th>June 20 19:10</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\beta_x$ (mm)</td>
<td>80</td>
<td>80</td>
<td>100</td>
</tr>
<tr>
<td>$\beta_y$ (mm)</td>
<td>2</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>$I_{LER}/I_{HER}$ (mA)</td>
<td>799.7 / 821.5</td>
<td>396 / 398</td>
<td>494.7 / 496.1</td>
</tr>
<tr>
<td>$n_b$</td>
<td>1576</td>
<td>789</td>
<td>1576</td>
</tr>
<tr>
<td>$I_{b LER}/I_{b HER}$ (mA)</td>
<td>0.507 / 0.521</td>
<td>0.502 / 0.504</td>
<td>0.314 / 0.317</td>
</tr>
<tr>
<td>$\xi_{y LER}/\xi_{y HER}$</td>
<td>0.0355 / 0.0197</td>
<td>0.0389 / 0.0220</td>
<td>0.0335 / 0.0189</td>
</tr>
<tr>
<td>$L_{sp} \times 10^{30}$</td>
<td>29.5</td>
<td>30.7</td>
<td>21.5</td>
</tr>
<tr>
<td>$L \times 10^{32}$</td>
<td>122.94</td>
<td>61.25</td>
<td>47.85</td>
</tr>
</tbody>
</table>
From Belle to Belle II

CsI(Tl) EM calorimeter:
- waveform sampling electronics, pure CsI for endcaps

RPC $\mu$ & $K_L$ counter:
- scintillator + Si-PM for end-caps

4 layers DS Si vertex detector $\rightarrow$ 2 layers PXD (DEPFET) + 4 layers DSSD

Central Drift Chamber:
- smaller cell size, long lever arm

Time-of-Flight, Aerogel Cherenkov Counter $\rightarrow$
- Time-of-Propagation (barrel), prox. focusing
- Aerogel RICH (forward)
Ladder Anatomy (L6 ladder)

**DSSDs**
- 2 small rectangular (L3)
- 2-4 large rectangular (L4-6)
- 1 trapezoidal (L4-6)

**Origami hybrid**
Flexible circuit to transmit detector signals to the ladder ends

**APV25**
Readout ASIC of the strips

**FlexPA (PA/PF/PB)**
Flexible circuit to transmit detector signals to the APV25

**PA0**
Flexible circuit glued on the Origami hybrid to transmit $n$-side detector signals to the APV25

**AIREX**
Thermal insulator between the DSSD and APV25
The backside signals are transmitted to the APV25 via bent (and glued) flex circuits.
• Necessity of cooling
  – SVD total heat dissipation from all APV25 chips can be 700W in max.
• 2-phase (liquid and gas mixture) CO2 cooling system
  – Efficient and low mass cooling
  – Simple control of coolant temperature (only with pressure)
  – Small pressure loss in tubes
• Thin stainless tube (OD:1.6mm, thickness:0.1mm) is employed.
  – Less material budget