The Belle II
Silicon Vertex Detector

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on behalf of the Belle II SVD collaboration

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Belle II

- **The Belle II experiment**
  - Belle II is a particle physics experiment in KEK, Japan motivated by a quest for new physics search.
  - Vertex-detector commissioning is now ongoing and the physics data taking with the complete detector starts early next year.

- **The SuperKEKB accelerator**
  - SuperKEKB is an $e^+e^-$ collider for Belle II.
  - The collision energy is $\sqrt{s} = 10.58$ GeV.
  - The design luminosity is $8 \times 10^{35} / \text{cm}^2 \text{s}$, and the expected total integrated luminosity after 10-year operation is $50 \text{ ab}^{-1}$. 

800+ researchers from 25 countries and regions

KEK, Japan
Belle II Detector

- Seven subdetectors
  - Tracking detector
  - PID detectors
  - Electromagnetic calorimeter

At the heart of Belle II, a vertex detector (VXD) made of pixel (PXD) + strip (SVD) silicon detectors is installed.

PID detector

$K_L^0 \mu$ detector

Calorimeter

Tracking detector

7.5m(H) × 7.5m(W) × 7m(D)

Much better impact parameter resolution than its predecessor Belle

15µm @ $p_T=2$GeV/c

Fit function: $\sigma = \sqrt{a^2 + \frac{b^2}{p\beta\sin(\theta)^{3/2}}}$
SuperKEKB/Belle II Commissioning

<table>
<thead>
<tr>
<th>2016</th>
<th>2017</th>
<th>2018 now</th>
<th>2019</th>
</tr>
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</table>

**Phase 1**
S-KEKB commissioning w/o Belle II, final focus magnets.

**Cosmic run w/o VXD**

**Phase 2**
S-KEKB and Belle II commissioning including BG study
\[ \int L dt = 454 \text{pb}^{-1} \]

**Phase 3**
Data taking with full detectors.

**First \(e^+e^-\) collision**
@ 0:38AM 2018/04/26

**Installation of a reduced-scale version of VXD for Phase 2**

Belle II roll in on the beam line

Full VXD installation
The First $e^+ - e^-$ Collision

The first of $e^+ - e^-$ collisions provided by SuperKEKB were confirmed by Belle II at 0:38AM April 26, 2018.

Excitement in the control room for the first collisions

Observed $e^+ e^- \rightarrow q\bar{q}$ in early collisions
Silicon Vertex Detector (SVD)

- The characteristic lantern shape contributes to maximize the forward acceptance reducing the material in the tracking region.
- The SVD outer radius is extended with respect to Belle allowing for an improved $K_S^0$ reconstruction efficiency and low-$p_T$ standalone tracking efficiency.

### Layer | $R$ [mm] | $N_{\text{Ladder}}$ | Assembly site
--- | --- | --- | ---
L6 | 135 | 16 | Kavli IPMU (JPN) +
L5 | 104 | 12 | HEPHY (AUT)
L4 | 80 | 10 | TIFR (IND)
L3 | 39 | 7 | Melbourne U (AUS)
FW/BW | – | 38+38 | INFN Pisa (ITA)

- The ladders were assembled in 5 collaborating institutes.
Silicon Vertex Detector (SVD)

**SVD ladders**

- L6
- L5
- L4
- L3

**Double-sided Si Strip Detector**

*P-in-N 6" wafer*

- **Sensor thickness** = 300-320μm

<table>
<thead>
<tr>
<th></th>
<th>Trapezoidal</th>
<th>Rectangular (L3/L4,L5,L6)</th>
</tr>
</thead>
<tbody>
<tr>
<td># of P-strips</td>
<td>768</td>
<td>768/768</td>
</tr>
<tr>
<td>P-strip pitch</td>
<td>50...75μm</td>
<td>50μm/75μm</td>
</tr>
<tr>
<td># of N-strips</td>
<td>512</td>
<td>768/512</td>
</tr>
<tr>
<td>N-strip pitch</td>
<td>240μm</td>
<td>160μm/240μm</td>
</tr>
<tr>
<td>Total area</td>
<td>5048.90mm²</td>
<td>7442.85mm²</td>
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</table>
Ladder Anatomy

Two novel concepts in the ladder
- Chip-on-sensor concept for the noise reduction
- Origami concept to bring the P-side signals on the N side
Novel Concepts in the Ladders

Readout chip APV25
- Short shaping time (50ns).
- Radiation hardness ~0.3MGy.
- 192 cells deep-analog pipeline for dead-time reduction.
- Developed originally for CMS.
- Chips on the sensors thinned down to 100µm for the material budget reduction.
Ladder Mass-Production

Mass production of SVD ladders plus spares was completed by May 2018.

Ladder assembly procedures R&D:
• High Precision sensor-handling jigs
• Glue spread control
• Wire bonding parameter optimization

Internal review process:
• Design a stable and reliable procedures
• Document the procedures for the quality control and assurance
• Communicate with other production sites
• Organize the manpower and schedule

Very good ladder quality achieved
• Electrical: ~ 1% defects and very few additional defects introduced during the assembly
• Mechanical: sensor displacement below 300µm achieved in all ladders

• The poster “Construction and QA of the Belle II SVD” by Resmi.
Ladder Mounting

Ladders are mounted on support rings to assemble SVD half shells.

Mechanical and electrical quality of each ladder was tested before and after its mounting.
We confirmed in the tests that:
• No new electrical sensor defects introduced and
• Sensor displacement under control.
Thermal contact between the cooling pipe and APV25 chips was confirmed with an IR camera.
Ladder Mounting

Half-shell outside

Half-shell inside
Full-Scale SVD Commissioning

The completed SVD half shells were moved to a testbench for the full-scale cosmic-ray commissioning.
Full-Scale SVD Commissioning

Trigger scintillators
SVD readout system is driven by 32MHz clock.
Control and Monitoring during Commissioning

Nice slow control panel (PC screenshot):

- SVD temperature monitor by NTCs
- Environmental monitor/interlock
- SVD cross-sectional view
- Cooling plant monitor:
  - Cooling plant (liquid/gas CO₂)
- Run#, Evt#

Cooling plant monitor:
Sensor bias current and occupancy were monitored by remote shifters covering 24/7.

Time propagation of the occupancy

Occupancy in cosmic-ray runs: The occupancy is properly dominated by hits.
Detector Online Monitor

Sensor bias current and occupancy were monitored by remote shifters covering 24/7.

Time propagation of the sensor bias currents

L4 FW bias currents
Calibration Stability during Commissioning

The calibration constants (noise, gain) were very stable over more than 2 months of running.

Average gain as a function of the run#
Calibration Stability during Commissioning

The calibration constants (noise, gain) were very stable over more than 2 months of running.

Average noise as a function of the run#

SVD commissioning preliminary
Cosmic-Ray Commissioning

SVD has run stably since July to mid Sept, collecting $30 \times 10^6$ cosmic events.

Cluster energy in horizontal silicon sensor (300µm thick) by a cosmic-ray muon (MIP) is peaking at 80keV. Larger energy deposited in slanted and vertical sensors, as expected. Low energy peak due to noise cluster.

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.

- The poster “Performance Study of the Belle II SVD” by Kavita.
Cosmic-Ray Commissioning

Sensor efficiencies:

First cosmic event in SVD +X (Jul 10, 2018)

All sensors are expected to have the similar efficiencies with the ones estimated on the horizontal sensors.
Cosmic-Ray Commissioning

Cluster residuals:

Unbiased residuals are computed with cosmic-ray tracks reconstructed without the clusters on the sensor.

SVD commissioning preliminary

\[ \epsilon = (99.87 \pm 0.07)\% \]

Excellent performance of the SVD was confirmed with tracking.

- Efficiency >99% for most of the sensors and nice Gaussian residuals were confirmed. Efficiency and residuals estimated on horizontal sensors are quoted here (otherwise too large incident angles) after the alignment.
PXD + SVD “Marriage”

The combined VXD will be commissioned for one month before the installation to the Belle II detector by the end of 2018.
SVD Sub-systems Commissioned in Phase 2

- A reduced-scale VXD (one ladder per layer) was installed on the SuperKEKB beam line (Phase 2) to verify radiation safe environment for installing final VXD.
- Radiation monitor and beam abort system, and hard-wired interlock were commissioned during Phase 2.

The poster “Spatial resolution of the Belle II SVD” by Soumen for the Phase 2 performance.

\[ \int L dt = 454 \text{pb}^{-1} \]

\[ L_{\text{peak}} = 2.29 \times 10^{33} \text{cm}^{-1} \text{s}^{-1} \]
Radiation Monitoring in Phase 2

Radiation monitoring:
Radiation monitoring is very essential to protect the VXD from a large instantaneous and/or time-integrated dose by aborting the beams.

Diamond “chamber”:
Diamond is a good detector for its high radiation tolerance, proper response to both rapid and slow increases of the radiation level, and less dependence of the leakage current on the total dose.

Diamond on the reduced-scale VXD:

The diamonds are calibrated with $^{90}\text{Sr}$.

The highest dose was 11.6krad in Phase 2.
Beam Abort System in Phase 2

Beam-abort request to protect the SVD and/or final focus magnets:
- Fast abort: 1rad/ms → reaction time 10µs
- Slow abort: 100mrad/s
- Both are adjustable.

Dump the last 1s data before the abort:
- Dump the last 100k samples in a R/O buffer (100kHz for 1s) to a memory.

Issued aborts in Phase 2:
- Fast ... 86 aborts
- Slow ... 12 aborts
- After each abort, the contents in the R/O buffer were correctly frozen and dumped.
- Analysis of the dumped data showed the abort was correctly issued when the threshold had been exceeded.
Interlock System in Phase 2

Other environmental monitors (ex: SVD temperature):
26 NTC thermistors (HW)  26 FOSs on 5 fibers (SW)

In the real VXD (Phase 3),
64 NTCs and 248 FOSs on 40 fibers.

User I/F for the SVD HW/SW interlock system:

Minor but real instances had occurred in the commissioning.
For each instance, the interlock system properly halted the SVD power supplies.
Global Schedule

<table>
<thead>
<tr>
<th>High level milestones</th>
<th>Completion</th>
</tr>
</thead>
<tbody>
<tr>
<td>VXD (= PXD+SVD) installation to Belle II</td>
<td>– early Dec. 2018</td>
</tr>
<tr>
<td>VXD cabling and system test</td>
<td>– end of Dec. 2018</td>
</tr>
<tr>
<td>Restart of SuperKEKB</td>
<td>– March 2019</td>
</tr>
<tr>
<td><strong>Start of the physics data taking with the complete detector</strong></td>
<td><strong>Soon after</strong></td>
</tr>
</tbody>
</table>

Please stay tuned.
Summary and Outlook

• The Belle II experiment will be completed with a vertex detector made of silicon strip sensors and pixels for the physics run starting in early 2019.
• Mass production of SVD ladders has been completed and ladders have been mounted in two half shells.
• SVD shells have been successfully commissioned with cosmic rays for 2 months, showing excellent performance, very high efficiency and stable conditions.
• After combination with pixel detector the final vertex detector will be commissioned for next few weeks before installation in Belle II.
• Radiation safe environment has already been verified during Phase 2 run, while VXD interlock and radiation abort systems have been also commissioned.
Backup Slides
PiXel Detector (PXD)

• **Depleted p-channel FET**
  – Low capacitance and internal amplification → low noise.
  – The collected charge is digitized only when the FET is on → low power consumption.

• **Monolithic silicon sensor**
  
<table>
<thead>
<tr>
<th>Thickness</th>
<th>75μm</th>
</tr>
</thead>
<tbody>
<tr>
<td># of pixels</td>
<td>768 x 256</td>
</tr>
<tr>
<td>Pixel size</td>
<td>50 × (55…80)μm²</td>
</tr>
</tbody>
</table>

• **Readout ASIC functions**
  – FET array switching.
  – Drain current digitization.
  – Zero suppression.

• **Status of the PXD**
  – 10 PXD ladders have been mounted on the PXD structure.
  – The PXD is under commissioning at KEK.
Origami Concept

- DSSD p-side (768 strips)
- Flip the sensor
- Glue flex module on the sensor
- Bend and glue the flex tails to the chip
SuperKEKB + Belle II

Event display (2D and 3D):

Re-discovery of particles:

$\pi^0$, $D^0$, $D^{\ast\pm}$, $B^0$, $B^\pm$

88 events
**SVD and Beam Background**

**Detector Limits:**
- SVD sensors and APV readout chips are radiation hard up to high doses → TID limit set conservatively to 10 Mrad over 10 yr operation.
- Optimal tracking performance with SVD Occupancy < 2-3%

**Background MC simulation @ full luminosity (Phase 3) for innermost layer:**
- 100 krad/yr → 10 times below detector limit
- ~1 % strip occupancy

**Breakdown of various SVD background sources in MC:**
- In **Phase 3 @ full luminosity**:
  - Single beam contribution (Touschek/Beam Gas):
    - LER ~ 15%, HER ~ 2%
  - Luminosity term ~ 83%
- In **Phase 2 commissioning** dominated instead by single beam contributions
  - Single beam contribution (Touschek/Beam Gas):
    - LER ~ 80%, HER ~ 2%
  - Luminosity term ~ 18%

**Background levels measured during Phase 2 with SVD occupancy used to validate MC predictions and extrapolate bkg @ full luminosity:**
- LER bkg in “reasonable” agreement with MC (within a factor 3-10), but large disagreement observed for HER contribution and is currently under study.
- Ratio among June 2018 Phase 2 LER + HER data over corresponding MC prediction ~12-21
- Extrapolation to final Phase 3 conditions gives x10 discrepancy with MC prediction
- During early Phase 3 (@ half final beam currents) SVD predicted occupancy (1.4-3.6%) will be close to the limit for good tracking performance

**At the beginning of Phase 3 background improvement will be further pursued tuning SuperKEKB parameters and the new collimators installed**
VXD Backgrounds in Phase 2

- Example of background levels measured for PXD/SVD & diamonds during Phase 2 background studies campaign
Efficiency and Residuals (Phase 2)

- Efficiencies and residuals estimated on Bhabha events with $p_T > 3$ GeV/c.
- Unbiased residuals are computed with tracks reconstructed without the clusters on the DUT, after alignment.

- Good efficiencies $\geq 95\%$, considering lower quality sensors installed.
- Nice gaussian residuals, cluster position resolution not quoted yet, work in progress to estimate contribution from track extrapolation.

U Cluster Residuals (layer 3, ladder 1, sensor 1, sideU/P)

<table>
<thead>
<tr>
<th>Statistic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Entries</td>
<td>7100</td>
</tr>
<tr>
<td>Mean</td>
<td>-0.0006873</td>
</tr>
<tr>
<td>Std Dev</td>
<td>0.005718</td>
</tr>
<tr>
<td>$\chi^2$/ndf</td>
<td>200.2 / 36</td>
</tr>
<tr>
<td>Prob</td>
<td>1.146e-24</td>
</tr>
<tr>
<td>N1</td>
<td>1790 $\pm$ 40.4</td>
</tr>
<tr>
<td>mean1</td>
<td>-0.0002248 $\pm$ 0.0000396</td>
</tr>
<tr>
<td>sigma1</td>
<td>0.001932 $\pm$ 0.000043</td>
</tr>
<tr>
<td>N2</td>
<td>307.9 $\pm$ 19.3</td>
</tr>
<tr>
<td>mean2</td>
<td>-0.001152 $\pm$ 0.000144</td>
</tr>
<tr>
<td>sigma2</td>
<td>0.006579 $\pm$ 0.000164</td>
</tr>
</tbody>
</table>

SVD Efficiency - Phase 2

- Taking into account that some chips were masked, the efficiencies are quite high ~ 95%, but lower than those found in commissioning (see slides 25, 26).

- Nice gaussian residuals, wider tails with respect to cosmics due to different track spectrum. Need more data to capture the higher tails of the residual distributions in the fit.

- The cluster position resolution measurement is possible with Phase2 data, but it's not ready yet.
SVD Occupancy in background simulation

**Phase 2.3**
- Occupancy in L3 (mid plane) = 0.29%
- Luminosity term still small in phase 2
- Single beam contribution from LER (Touschek+Coulomb) dominates, HER terms negligible
- Breakdown fractions: LUMI ~ 18%, LER ~ 80%, HER ~ 2%

**Phase 3**
- Occupancy in L3 (average) = 1.3% (2.1% mid plane)
- Luminosity term dominates in phase 3
- Breakdown fractions: LUMI ~ 83%, LER ~ 15%, HER ~ 2%

Detector limit (from tracking): 2-3% occupancy