The Silicon Vertex Detector of Belle II

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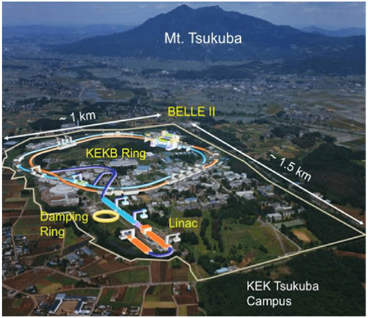
PSD12, 13 September 2021

Outline

1. Introduction to the Silicon Vertex Detector of the Belle II experiment
2. Operation and performance
3. Beam background and radiation effects
4. Conclusions

Belle II @ SuperKEKB

- Luminosity-frontier experiment exploring new physics beyond the Standard Model
- Asymmetric e^+e^- collisions at $\Upsilon(4S)$ mass (10.58 GeV)
- Target integrated luminosity: 50 ab^{-1}
- Target instantaneous luminosity: $6 \times 10^{35}\mathrm{cm}^{-2}\mathrm{s}^{-1}$
- Current record instantaneous luminosity: $3.1 \times 10^{34}\mathrm{cm}^{-2}\mathrm{s}^{-1}$



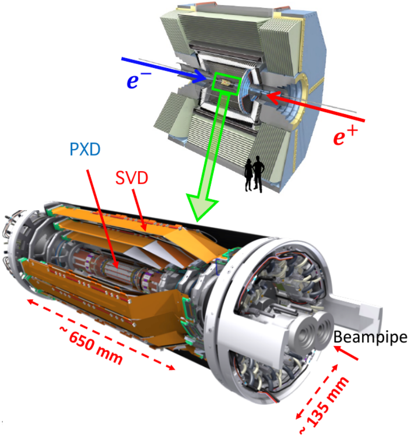
Essential for physics program

- Precise determination of decay vertices
- Low momentum tracking
- Good particle identification

The vertex detector

Requirements

- Better vertex resolution w.r.t. Belle to compensate reduced Lorentz boost
  - improved point resolution
  - reduced inner radius
  - lower material
- Operate in high background environment
  - Hit rates: 20-3 MHz/cm^2 @ R = 14-40 mm
- Radiation hard
  - 2-0.2 Mrad/yr @ R = 14-40 mm



Pixel Detector (PXD)

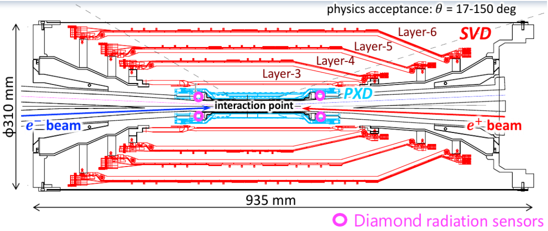
- DEPFET pixel sensors: layer-1-2
- Innermost layer 1.4 cm from interaction point

Silicon Vertex Detector (SVD)

- Double-sided Si strip sensors: layer-3-4-5-6

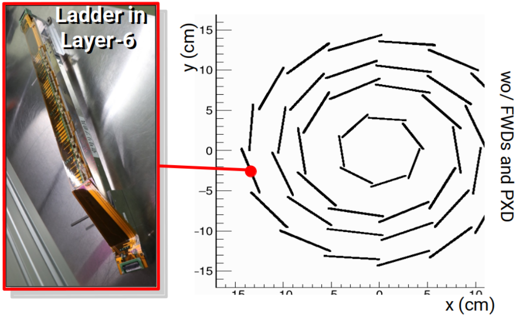
The Silicon Vertex Detector (SVD)

- Low material budget: $0.7\% X_0$ per layer
- Diamond sensors for radiation monitor and beam abort



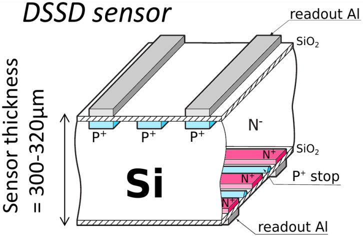
SVD Roles

- Extrapolate tracks to PXD
  - essential for reconstruction of decay vertices
  - PXD region of interest for data reduction
- Stand-alone tracking for low p_T tracks
- PID with dE/dx

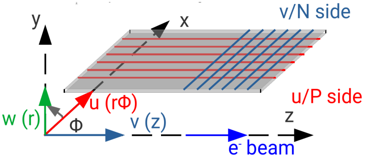


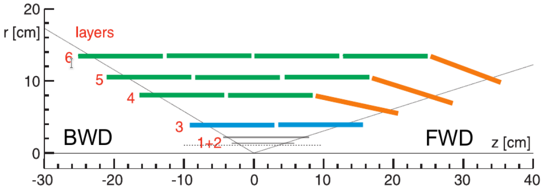
SVD: Double-side Silicon Strip Detector

Provide 2-D spatial information

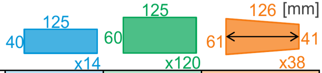


AC-coupled strips on N-type substrate
Full depletion voltage: 20-60V
Operation voltage: 100V





172 sensors



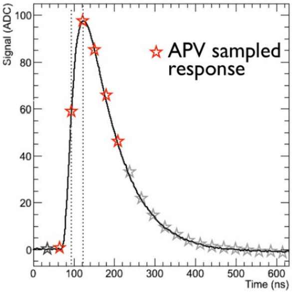
	Small	Large	Trapezoidal
# of p-strips*	768	768	768
p-strip pitch*	50 μm	75 μm	50-75 μm
# of n-strips*	768	512	512
n-strip pitch*	160 μm	240 μm	240 μm
thickness	320 μm	320 μm	300 μm
manufacturer	HPK	HPK	Micron

*readout strips – one floating strip on both sides

Total: 172 sensors, 1.2 m^2 sensor area and 224k readout strips

Front-end ASIC: APV25

- Originally developed for CMS silicon tracker
- Fast: 50 ns shaping times
- Radiation hard: >100 Mrad
- Power consumption: 0.4 W/chip (700 W in total)
- 128 channel inputs per chip

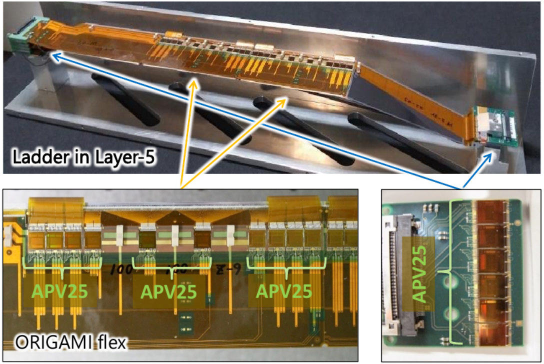


- Operated in a multi-peak mode @ $\sim$32 MHz
  - Bunch-crossing frequency $\sim$8*32 MHz, clock not synchronous with them as in CMS
  - 6 subsequent samples recorded
  - 3/6-mixed acquisition mode also prepared to reduce the dead time, data size and occupancy at higher luminosity

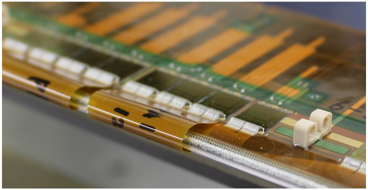
Origami chip on sensor concept

Readout chips directly on each middle sensor

- shorter signal propagation length (smaller capacitance and noise)
- Thinned to 100 μm to reduce material budget



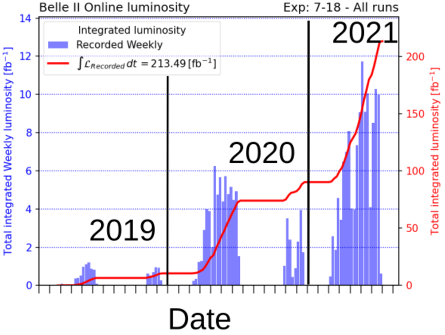
- Wrapped flex to read both sides from the same side
- Cool only one side with bi-phase -20° CO_2



Operation and performance

Operational experience

- SVD installed in 2018, operated since 2019
- Reliable and smooth operation without major problems
  - Total fraction of masked strips $\sim 1\%$
  - One APV25 chip disabled in spring 2019 (out of 1748), fixed by cable reconnection in summer 2019
- Excellent detector performance
  - Average sensor hit efficiency $> 99\%$ and stable with time



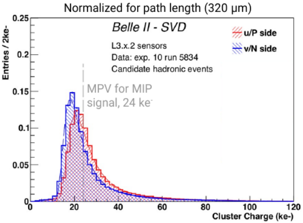
Signal charge and signal to noise ratio

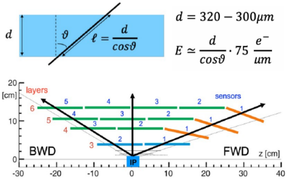
Signal charge normalised for the track path length in silicon similar in all sensors and matches expectations

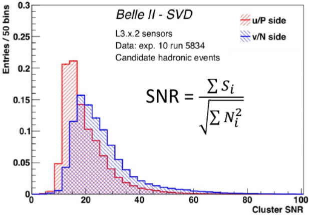
- **u/P side:** charge in agreement with expectation from MIP taking into account $\sim$ 15% uncertainty in APV25 gain calibration
- **v/N side:** 10%-30% signal loss due to large pitch and presence of floating strip

Very good SNR in all 172 sensors (most probable value: 13-30)

- **u/P side:** larger noise due to longer strip length (larger inter-strip capacitance)

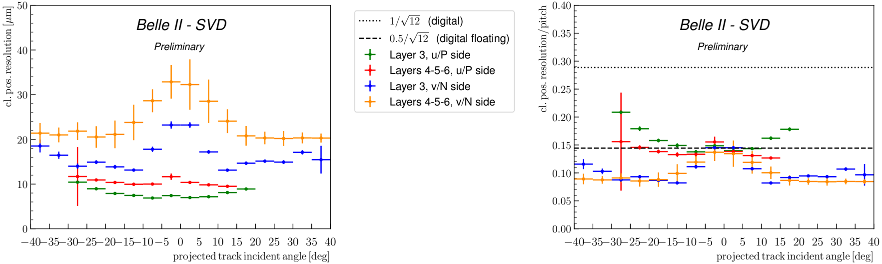






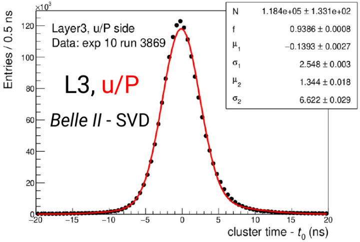
Cluster position resolution

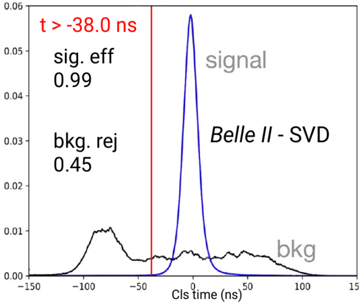
- Preliminary cluster position resolution measured on data
- Estimated from the residuals of the cluster position with respect to the track (unbiased) using $e^+e^- \rightarrow \mu^+\mu^-$ events
- Effect of the track extrapolation error subtracted
- Excellent position resolution in agreement with the expectations from the pitch
- Still room for improvement for the u/P side (work ongoing)



Hit time resolution

- Excellent hit time resolution wrt event time provided by CDC ($\sim$ 2.9 ns u/P, $\sim$ 2.4 ns v/N)
- Possible to efficiently reject off-time background hits
  - Will be used for higher luminosity and background levels



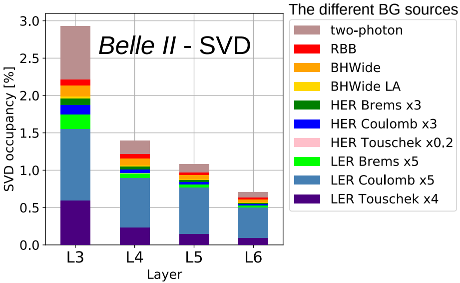


Beam background and radiation effects

Beam background

Beam background increases SVD hit occupancy which degrades tracking performance

- Present occupancy limit in layer-3: $\sim 3\%$
- Using hit time information to reject background can approximately be doubled
- With current luminosity average hit occupancy in layer-3 is well under control ($< 0.5\%$)
- Projection of hit occupancy at $\mathcal{L} = 8 \times 10^{35}$ cm^{-2} s^{-1} is about 3% in layer-3
  - estimated scaling MC with data/MC ratio
  - correspond to dose of ~ 0.2 Mrad/smy and 1-MeV neutron fluence of $\sim 5 \times 10^{11}$ n_{eq}/cm^2/smy (smy = 10^7 s)

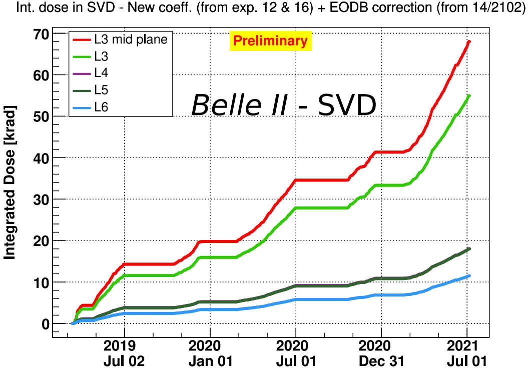


- Long term BG extrapolation affected by large uncertainties related to collimation and injection BG still not included

Integrated dose

SVD dose estimated by dose on diamond sensors: 70 krad in layer-3 mid plane (the most exposed to radiation)

- Dose estimate based on correlation between SVD occupancy and diamonds dose
- Several assumptions and large uncertainty ($\sim$ 50%)



1-MeV equivalent neutron fluence: $\sim 1.6 \times 10^{11}$ n_{eq}/cm^2 in first 2.5 years (assuming dose/n_{eq} fluence ratio = 2.3×10^9 n_{eq}/cm^2/krad from MC)

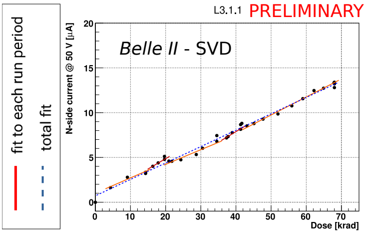
Radiation effect on leakage current

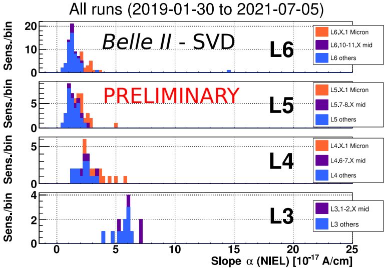
Good linear correlation between leakage current and estimated dose

- Slope: 2-5 μA/cm^2/Mrad with large variations due to temperature effects and dose spread among sensors in layer (average dose in layer used in estimate)
- Same order of magnitude as BaBar measurement (1 μA/cm^2/Mrad @ 20°C) [NIMA 729, 615-701, 2013]

Even after 10 Mrad irradiation, leakage current will not significantly affect strip noise

- Noise dominated by sensor capacitance because of short shaping time (50ns) in APV25

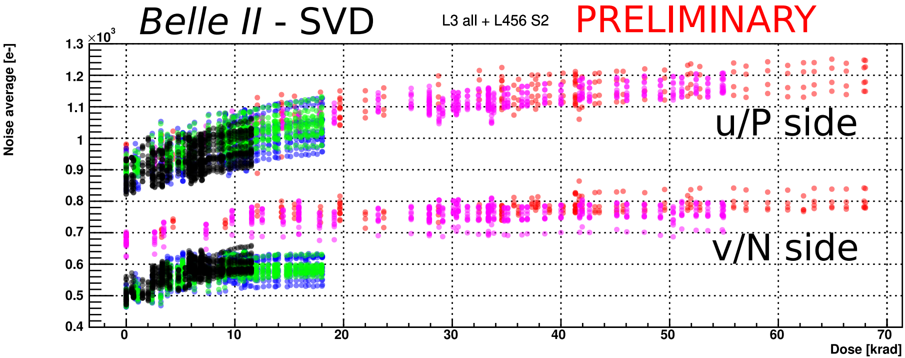




Radiation effect on strip noise

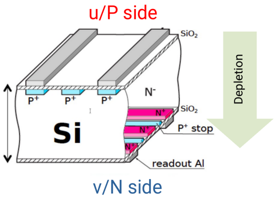
Noise increase of 20-25% in layer-3

- Not affecting performance
- Likely due to radiation effects on sensor surface
  - Non-linear increase due to fixed oxide charges that increase inter-strip capacitance,
  - expected to saturate
- Saturation seen on v/N side and starting to be seen on u/P

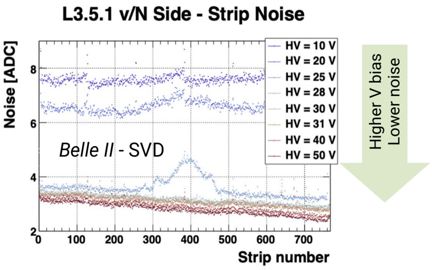


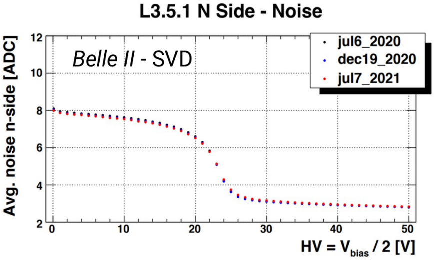
Radiation effect on depletion voltage

- Minimum of v/N side strip noise at full depletion
  - v/N side insulated only when the n-type bulk is fully depleted
  - Over-depletion bias still slightly decrease noise (reduce electron accumulation layer on n-side surface)



- No change in full depletion voltage observed with time: consistent with low integrated neutron fluence ($\sim 1.6 \times 10^{11}\ n_{eq}/cm^2$)





Conclusions

- SVD has been taking data in Belle II since March 2019 smoothly and reliably
- Excellent performance in agreement with expectations
  - Still some room for improvement in cluster position resolution
- Seen first effects of radiation damage at the expected level but not affecting performance
- Ready to cope with increased beam background
  - Reject off-time background
  - 3/6 mixed acquisition mode to reduce dead time, data size and occupancy