

Operational Experience and Performance of the Silicon Vertex Detector (SVD) during Run 2 of Belle II

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on behalf of the Belle II SVD Collaboration

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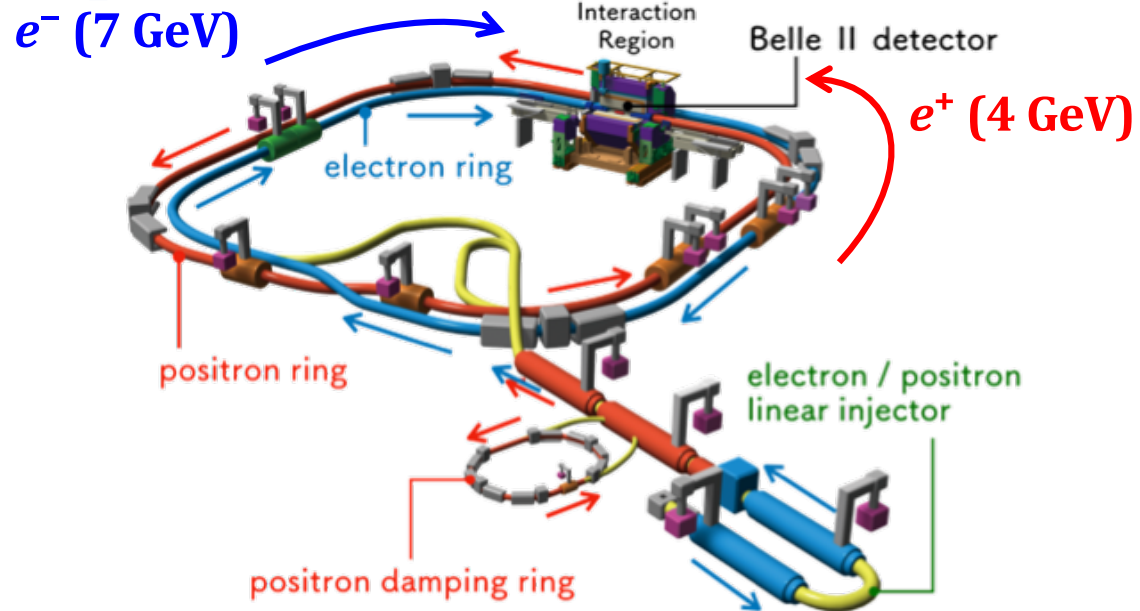
INSTR 2026 in Hefei, China



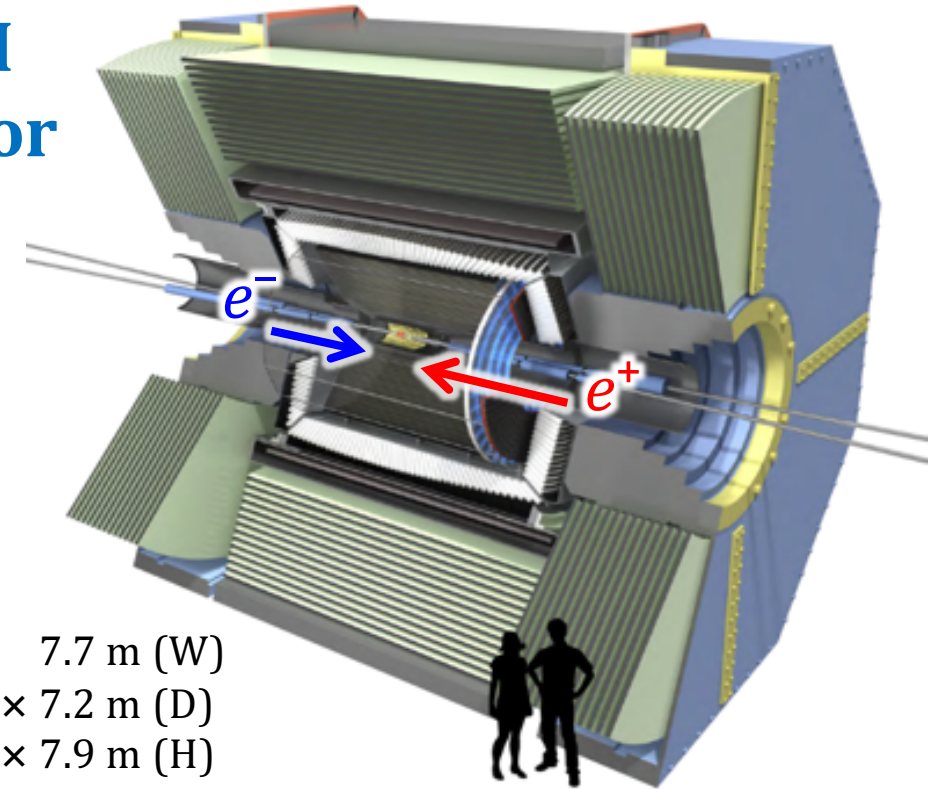
Belle II Experiment

- Belle II, a HEP experiment in Japan, aims to uncover new physics beyond the SM.

SuperKEKB accelerator



Belle II detector



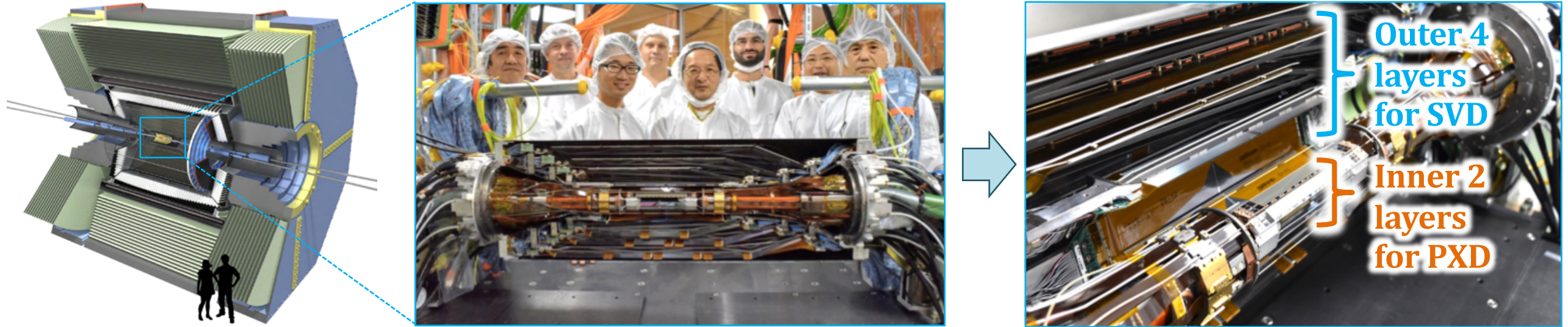
7.7 m (W)
 × 7.2 m (D)
 × 7.9 m (H)

**World
Records**

- $\sim 4\pi$ hermetic cylindrical detector.
- It consists of 7 subdetectors.

$\mathcal{L}_{\text{peak}}$	$5.32 \times 10^{34} \text{ cm}^{-2} \text{ s}^{-1}$
$\mathcal{L}_{\text{target}}$	$6 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$
$(\int \mathcal{L} dt)$	914 fb^{-1} (808 fb^{-1} for $\Upsilon(4S)$)
$(\int \mathcal{L} dt)_{\text{target}}$	50 ab^{-1}

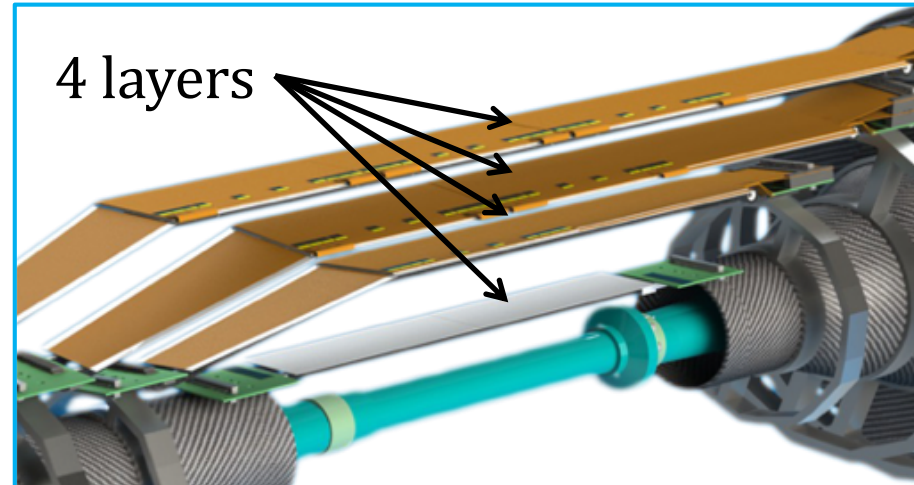
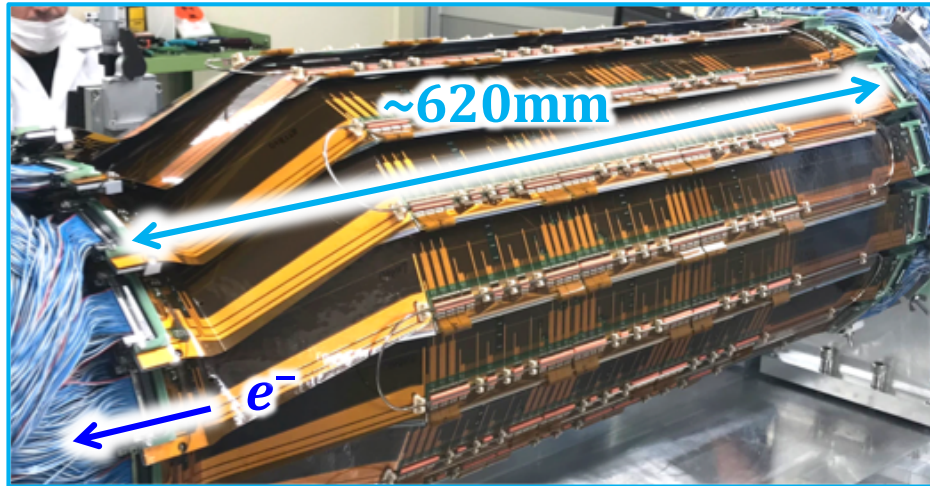
Belle II Vertex Detector (VXD = PXD + SVD)



- **PiXel Detector (PXD)**: inner 2 layers
 - 20 ladders of fully pixelated DEPFET sensors are arranged cylindrically.
- **Silicon Vertex Detector (SVD)**: outer 4 layers
 - 45 ladders of double-sided silicon strip detectors are arranged cylindrically.
 - The PXD and SVD provide precise charged-particle position measurements.
 - In addition, the SVD provides standalone low- p_T tracking and particle identification via dE/dx measurements.

Belle II Silicon Vertex Detector (SVD)

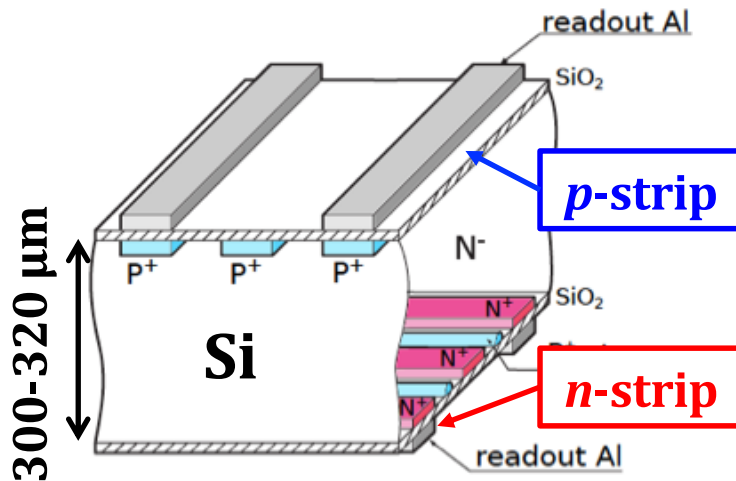
Structure of the SVD



Layer	R [mm]	$N_{\text{sen}} \times N_{\text{lad}}$
L3	39	2×7
L4	80	3×10
L5	104	4×12
L6	135	5×16
Total	–	172 sens

- Material budget $\sim 0.7\% X_0/\text{layer}$.

Double-sided silicon strip detector (DSSD)



- Perpendicular strip arrangement providing 2D spatial information.

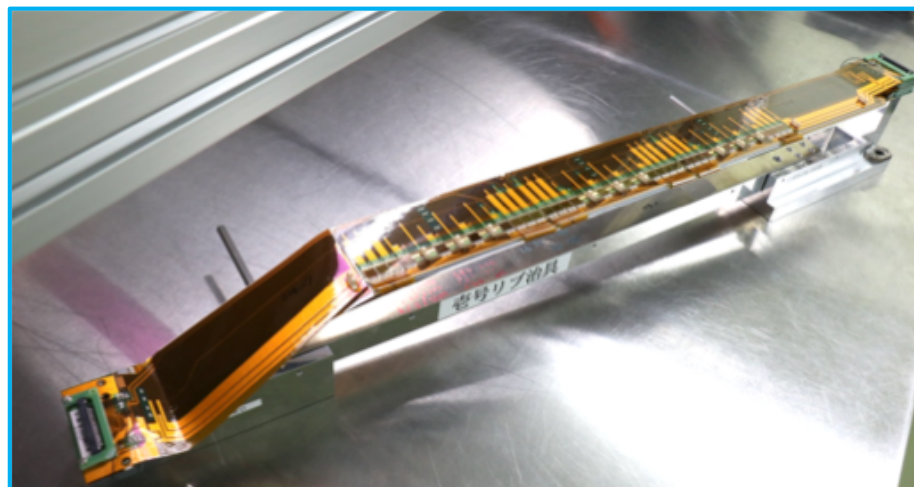
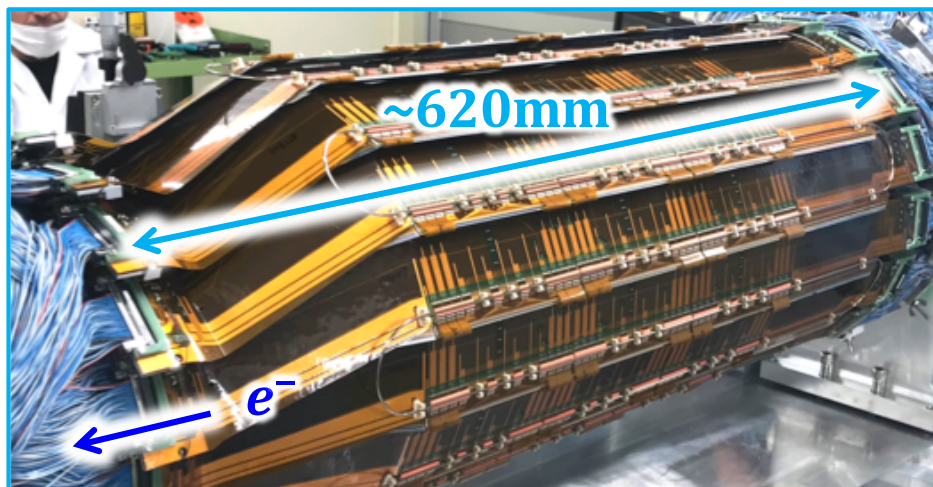


	Trapezoidal	Rectangular
# of p -strips	768	768
p -strip pitch	50–75 μm	75 μm
# of n -strips	512	512
n -strip pitch	240 μm	240 μm

- Full depletion voltage: 40-65 V.
- Bias voltage: 100 V.

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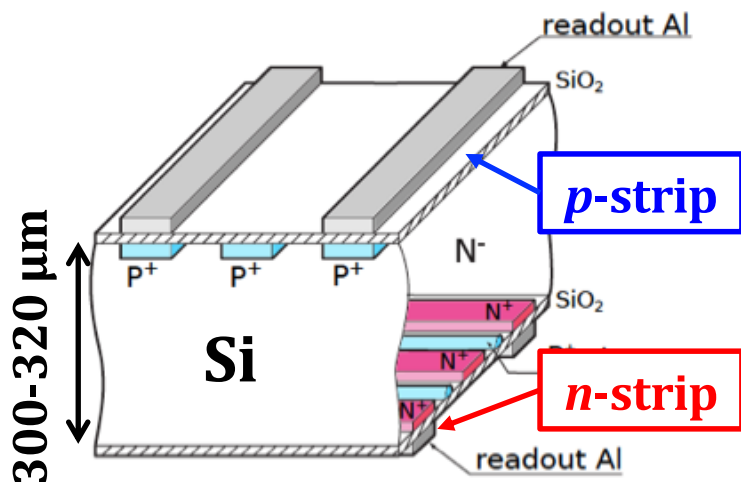
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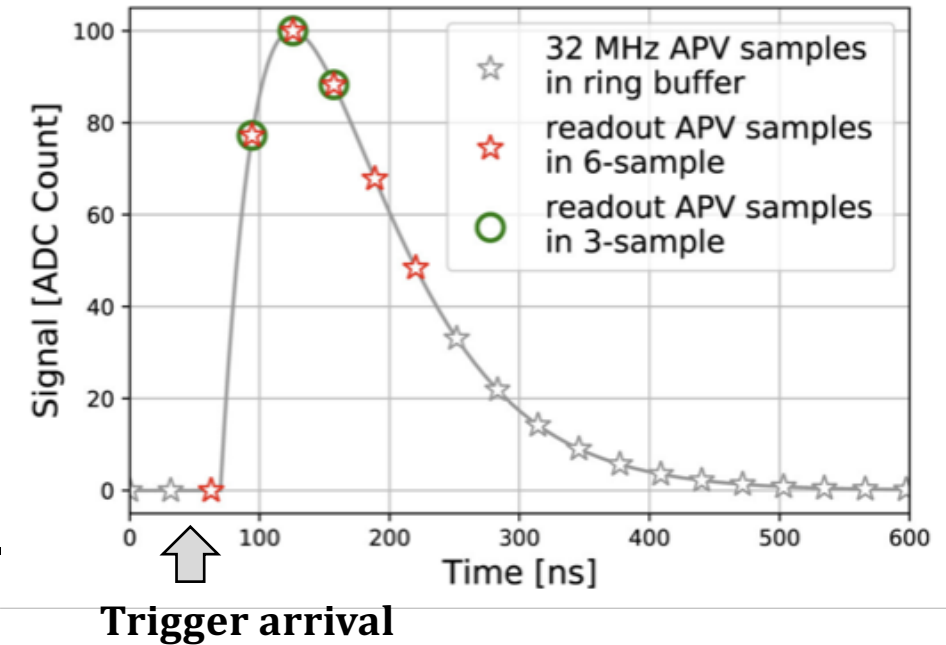
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APV25: Readout ASIC for SVD

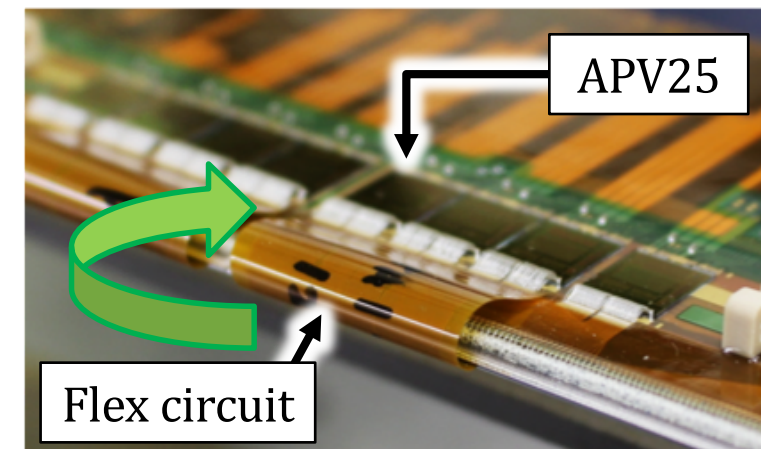
APV25: readout ASIC for SVD originally developed for CMS

- 128-strip inputs with 50-ns shaping time.
- Radiation hardness of >100 Mrad.
- Thinned to $100\text{ }\mu\text{m}$ for material budget reduction.
- Capability to sample multiple time points.
 - Typically, 6 consecutive time points are sampled; the 3/6 mixed sampling mode is available to reduce the data size at higher trigger rates (>25 kHz).



Chip-on-sensor and Origami concepts

- APV25s are placed directly on the sensor to minimize the signal path length and reduce capacitive noise.
- Signals from the DSSD backside are read out by APV25s on the sensor top side through a folded flex circuit.

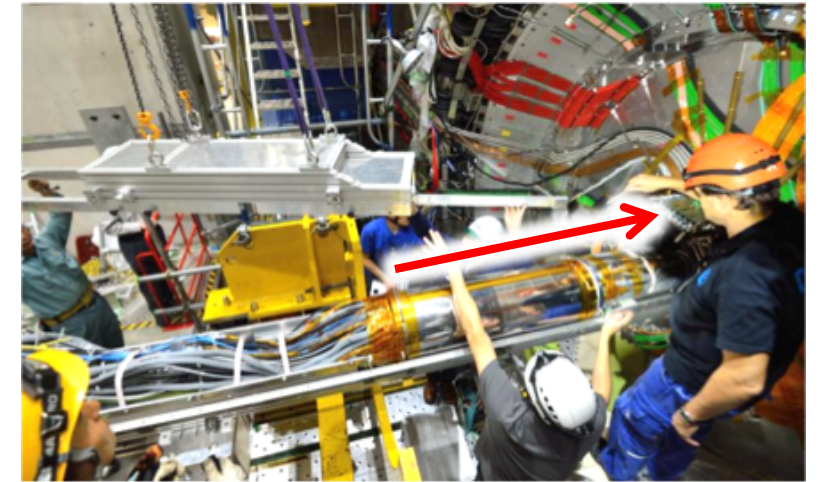
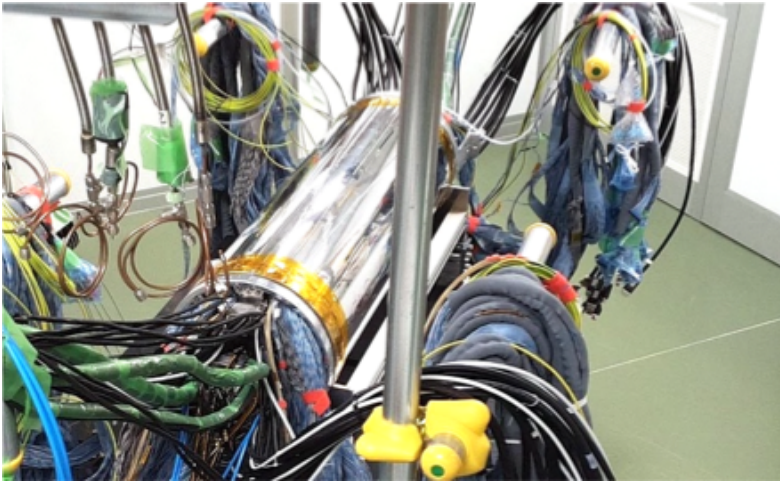


SVD Operational History ①

PXD1+SVD installation in Belle II: November 2018



- Only 2 of 12 L2 PXD ladders were installed for Run 1.



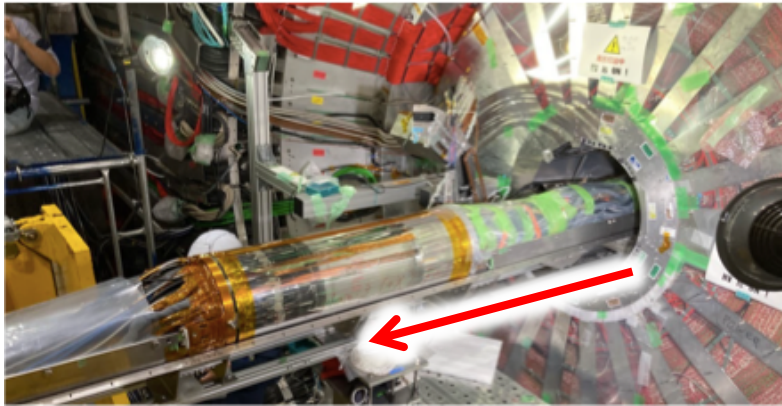
Run 1 operation: March 2019 – June 2022

- The SVD operated smoothly and stably without major issues.
 - The SVD demonstrated excellent performance: $<1\%$ masked strips, good signal-to-noise ratio, precise track-position and hit-time resolutions, and $>99\%$ hit efficiency.
 - Background effects were well under control.

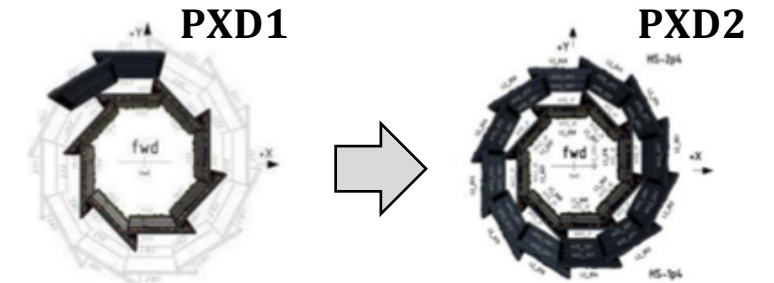
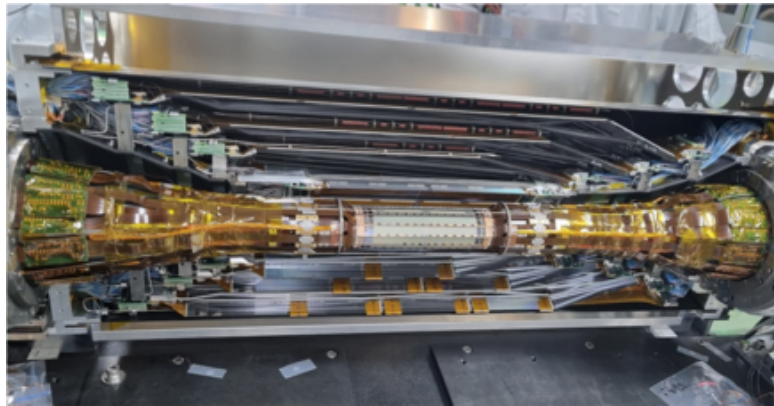
SVD Operational History ②

1st long shutdown (LS1): June 2022 – January 2024

PXD1+SVD extraction



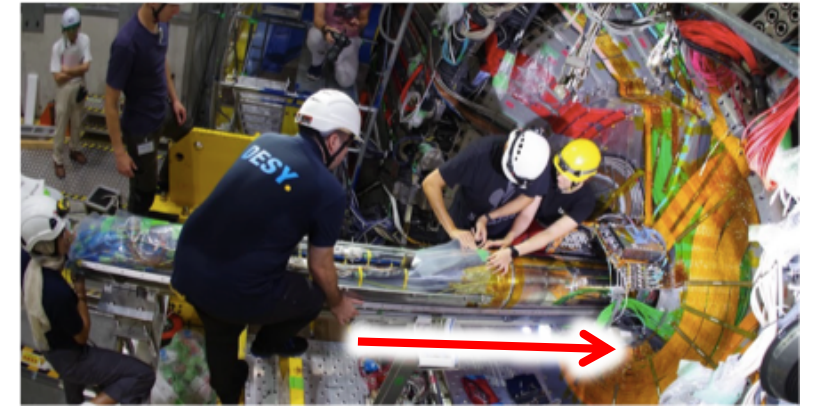
Attachment of PXD2 to SVD



Run 1

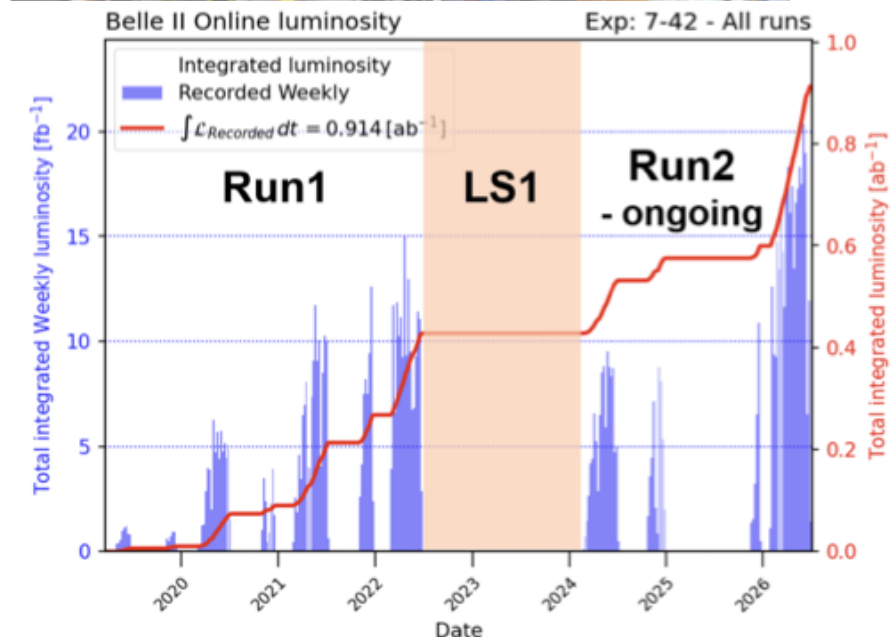
Run 2

PXD2+SVD installation



Run 2 operation: January 2024 – present

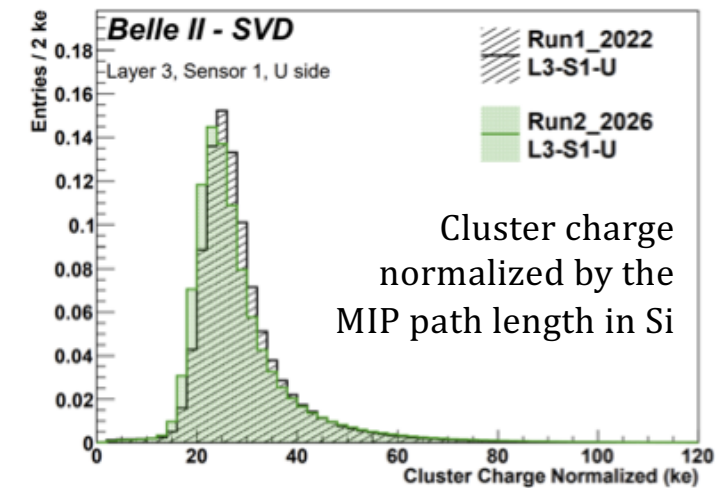
- 40 fb^{-1} of data were taken with the PXD2 turned on.
- However, we experienced multiple severe beam losses, which damaged the PXD2 readout
→ We turned off the PXD2 to avoid further damage.
- The SVD performance has been as good as in Run 1.



SVD Performance during Early Run 2 ①

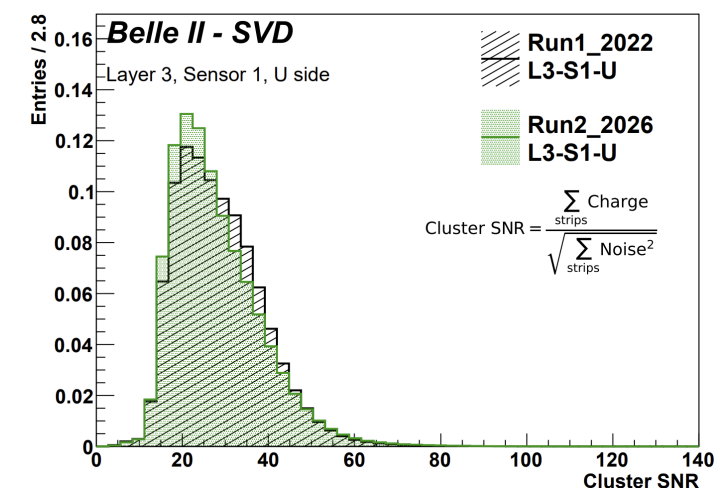
Cluster charge

- The observed cluster charges remain consistent with the expectation, within APV25 gain calibration uncertainty (15%), and with the Run 1 values.
 - A minimum-ionizing particle (MIP) is expected to generate $\sim 24 \text{ ke}^-$ in $320 \text{ }\mu\text{m}$ of silicon.



Signal-to-noise ratio (SNR)

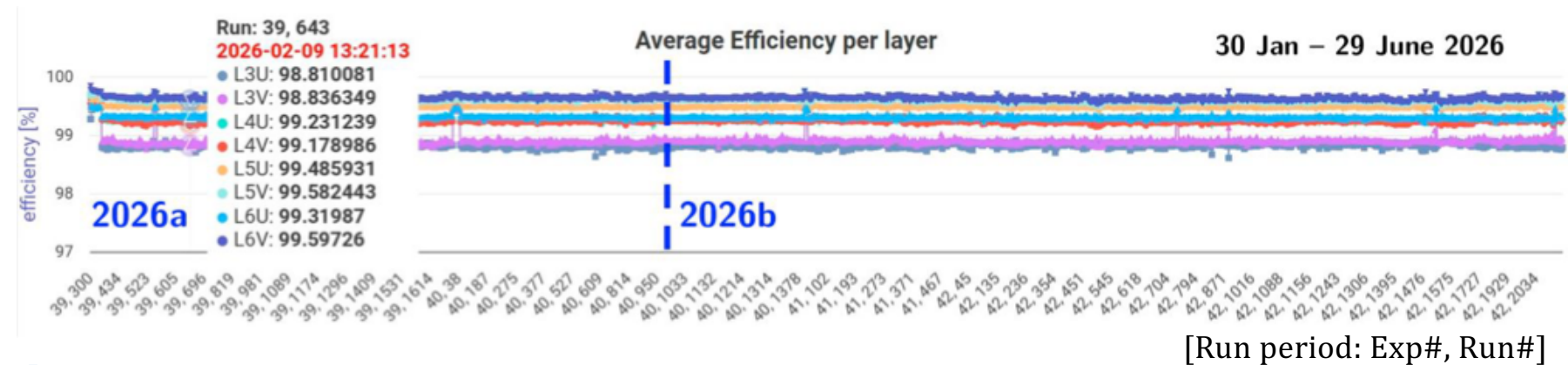
- Small changes in the SNR have been observed due to the expected increase in noise from radiation damage.
- The most probable SNR values, typically 13–30, still exceed the benchmark value of 10, indicating good hit-selection performance.
 - The SNR values depend on the sensor position.



SVD Performance during Early Run 2 ②

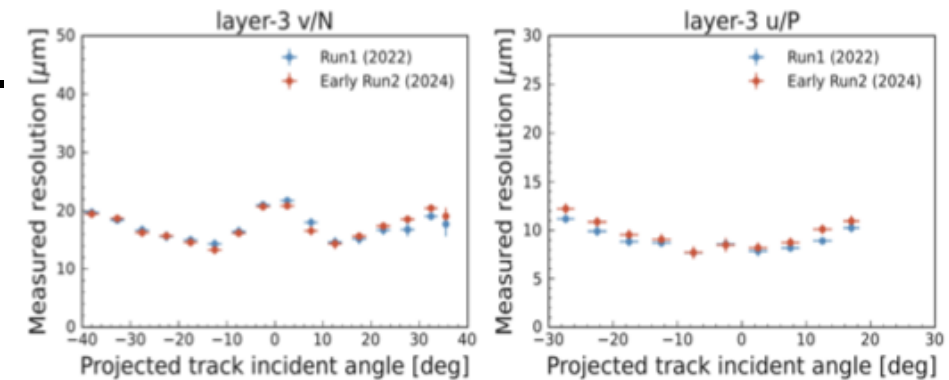
Hit efficiency

- The hit efficiency remains >99% for most sensors.



Track-position resolution

- The track-position resolution is stable at 7–25 μm .
 - The resolution is estimated using the cluster position relative to the track extrapolation position in $e^+e^- \rightarrow \mu^+\mu^-$ events.



Hit-time resolution

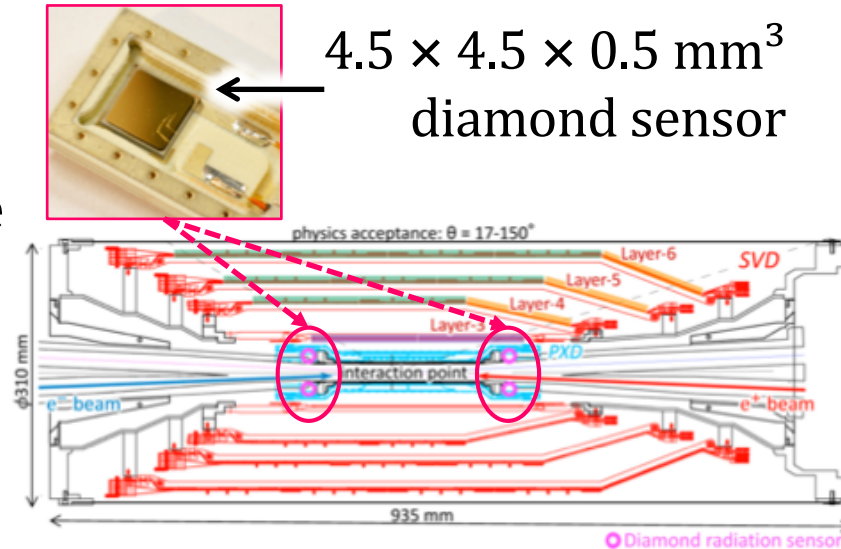
- The hit-time resolution is measured to be <3 ns.
 - The resolution is measured relative to the collision time provided by the Belle II Central Drift Chamber.

The SVD maintains good and stable performance.

Beam Background Effects ①

Radiation monitoring

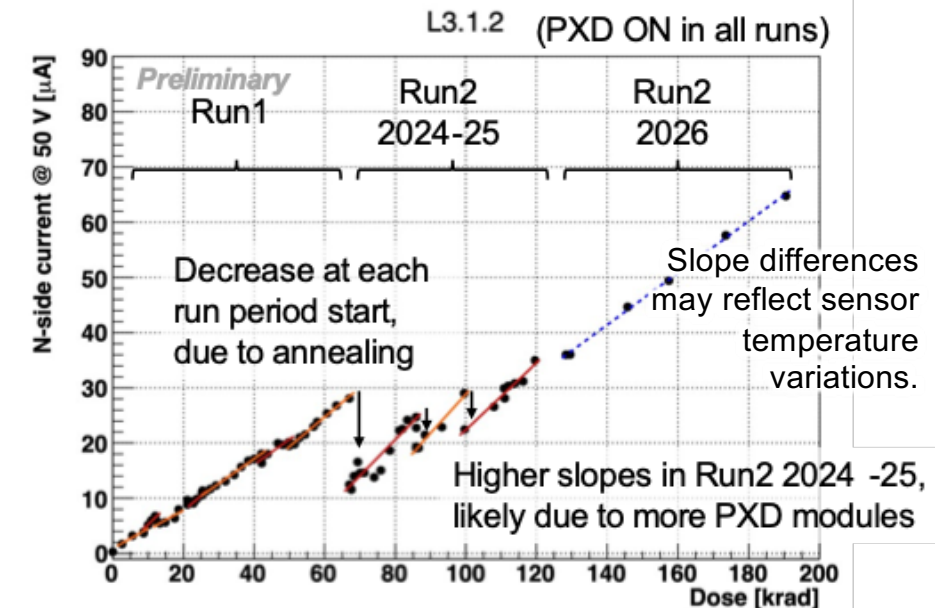
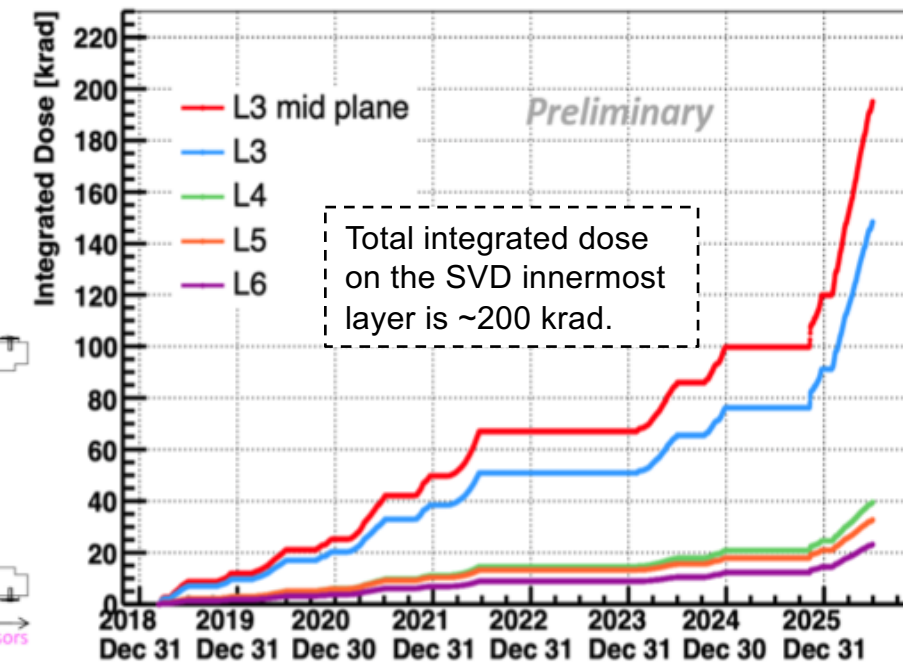
- Radiation dose on the VXD is continuously monitored with 28 diamond sensors.



Integrated radiation damage: leakage current

- Radiation effects from non-ionizing energy loss (NIEL) can deteriorate sensor performance, increase leakage current and strip noise, and change the depletion voltage.
- A linear dependence of **leakage current** on dose is observed, as expected from the NIEL model.

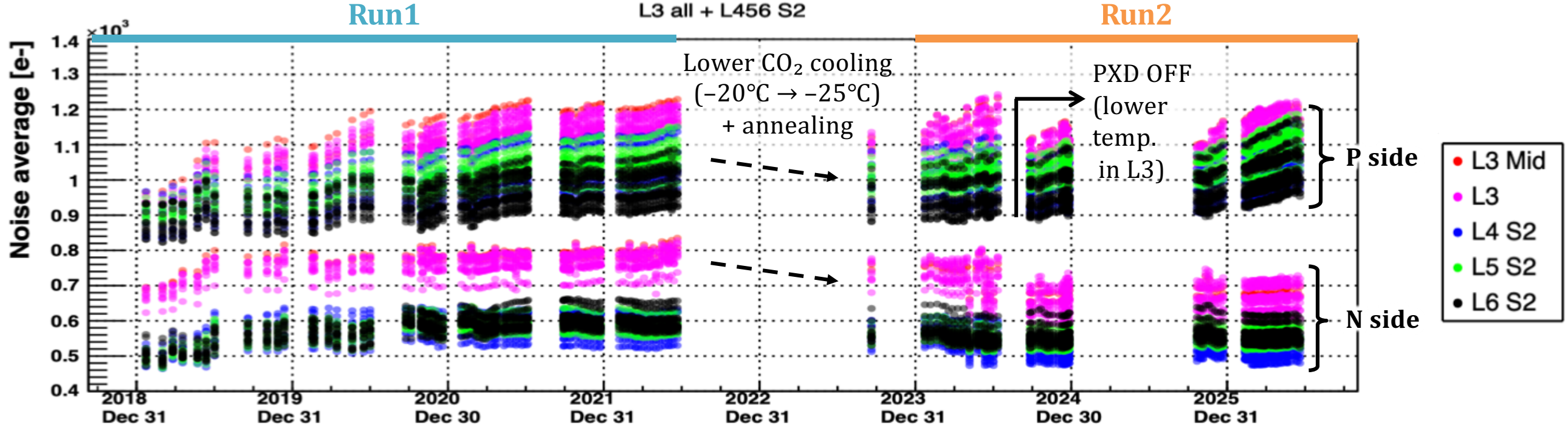
Integrated dose in SVD Layers



Beam Background Effects ②

Integrated radiation damage: noise and full depletion voltage

- No significant **noise** increase since Run 1, likely due to annealing and lower sensor temperatures from lower CO₂ cooling temp. and the turned-off PXD.



- No significant change in **full depletion voltage**.

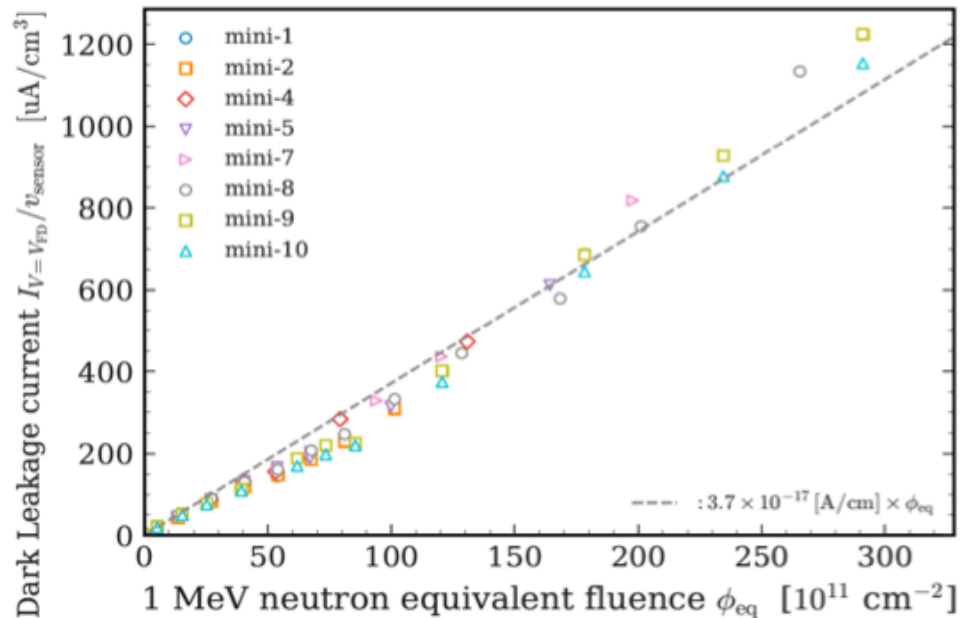
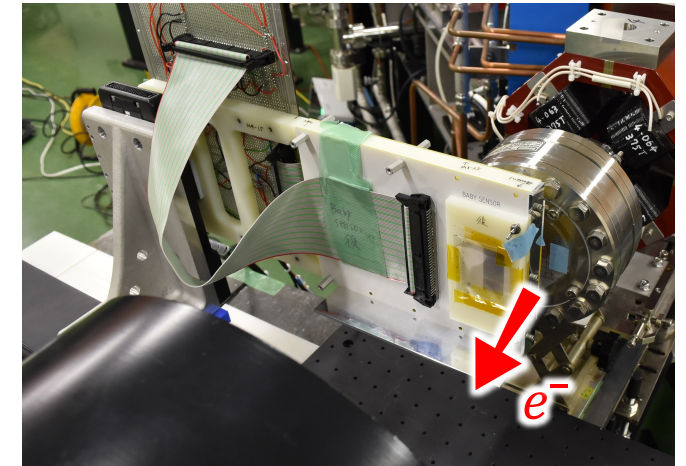
SVD sensors demonstrate good radiation hardness.

Beam Background Effects ③

Radiation hardness study with a 90 MeV e^- beam up to $3.1 \times 10^{13} n_{eq}/cm^2$

$\sim 3 \times$ the 10-year fluence
at $\mathcal{L}_{target} = 6 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$

- We irradiated 2 SVD sensors and 10 mini sensors, fabricated together with the SVD sensors.
- From the linear dependence of leakage current on fluence, we obtained the sensor damage constant of $4.9 \times 10^{-17} \text{ A/cm}$ at 20°C .



- The full depletion voltage increased to $\sim 160 \text{ V}$, but it was still below the HV limit of 200 V .
- The beam test and simulation studies indicate only a 3% or less decrease in cluster detection efficiency.

SVD sensors will maintain acceptable performance even after ~ 10 years at $\mathcal{L}_{target}$.

Beam Background Effects ④

Instantaneous effect: sensor defects and pinholes

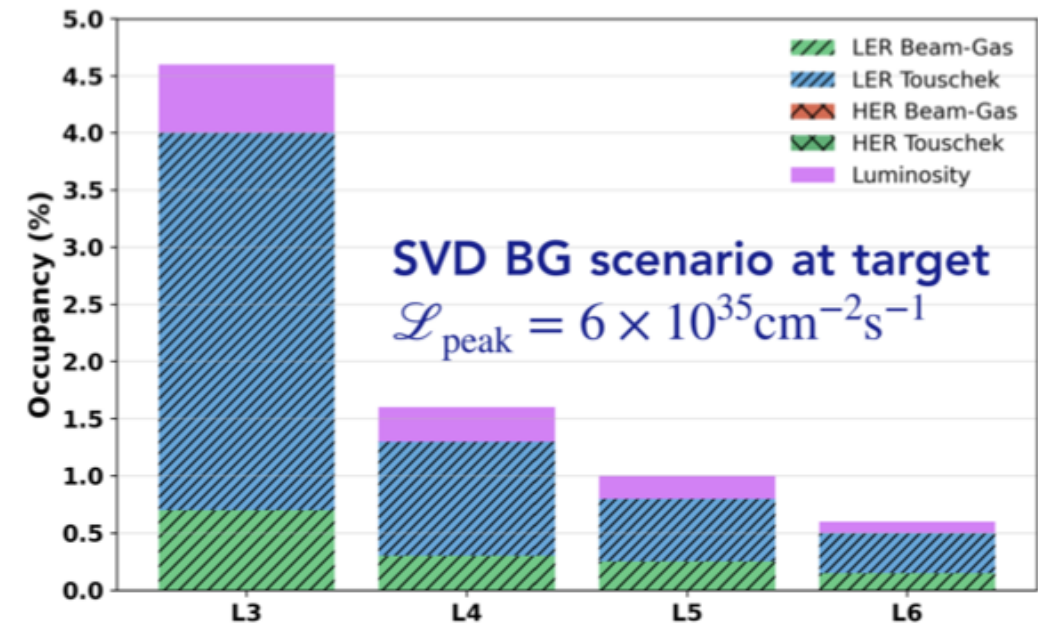
- No new sensor defects or pinholes have been observed despite multiple severe beam losses in early Run 2.

Instantaneous effect: single-event upset (SEU)

- A firmware-based SEU recovery mechanism was activated in 2025 to automatically recover from SEU-induced APV25 errors and prevent run stops.
 - The recovery completes within only 20 ms.
- ⇒ **This reduced the SVD-induced data-taking inefficiency from 7% to <3%, more than a factor 2 improvement depending on the beam background conditions.**

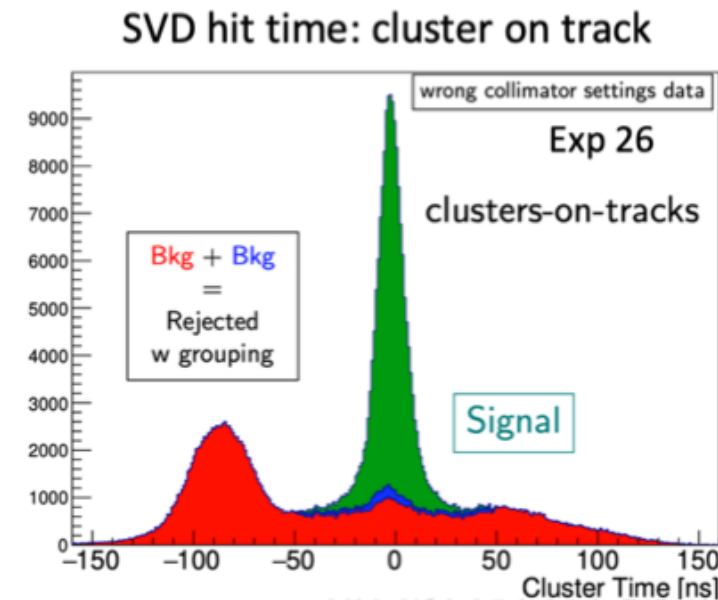
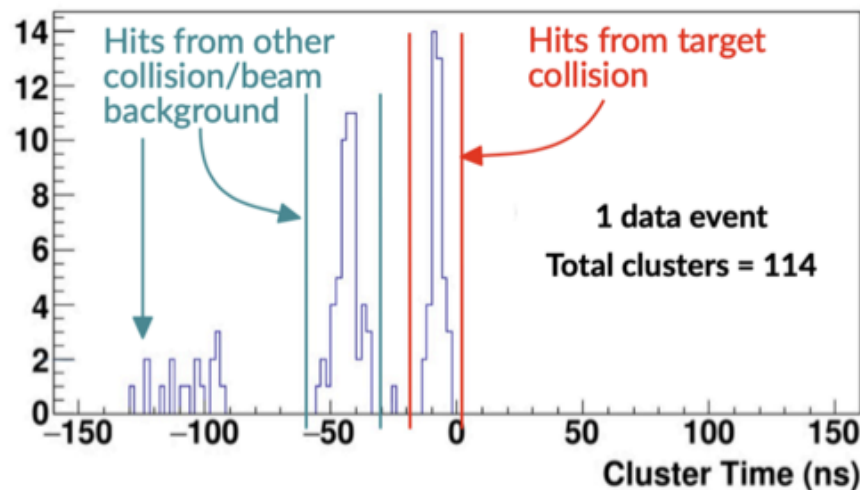
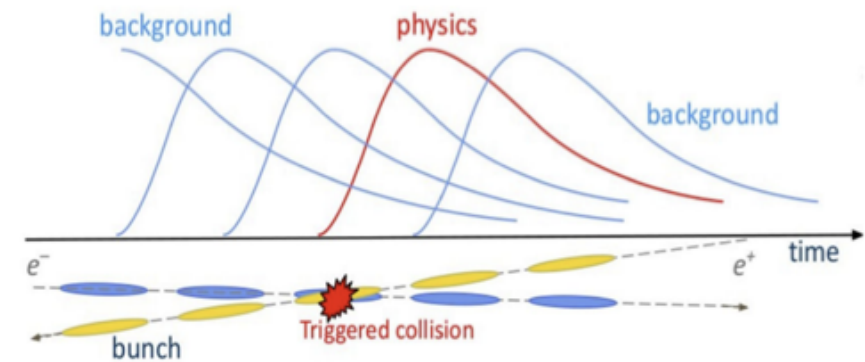
Hit-Occupancy Estimation

- The SVD hit occupancy, currently <1.2% for Layer 3, is estimated to increase to $\sim 4.7\%$ at $\mathcal{L}_{\text{target}}$.
 - However, the occupancy estimate has large uncertainties due to variations in SuperKEKB operating conditions.
 - Although tracking performance is expected to start degrading at around 6% occupancy, the large uncertainty in the occupancy projection calls for a sufficient safety margin.
- ⇒ **Mitigation measures are needed to cope with the expected occupancy increase.**



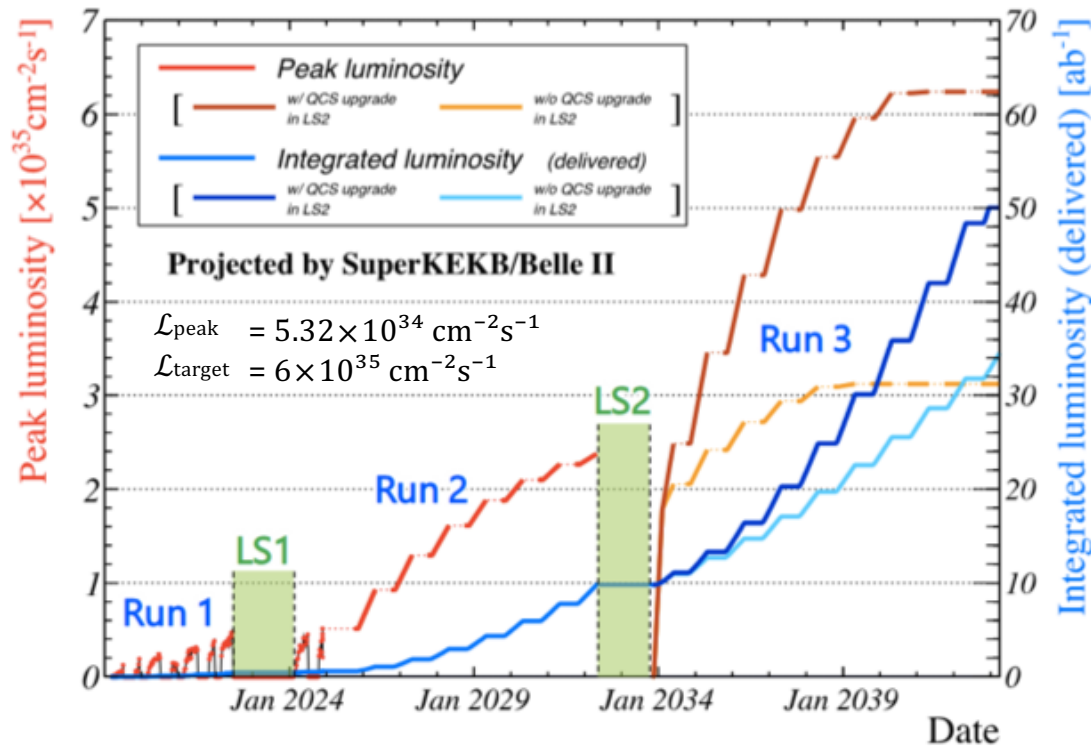
Hit-Occupancy Reduction

- To keep the SVD hit occupancy low even at a high $\mathcal{L}$, the off-time background hits should be reduced.
- The SVD's excellent hit-time resolution (<3 ns) was exploited in 2026 to reject off-time background hits by classifying clusters event-by-event based on timing information.
 - Off-time hits were reduced from 3.4% to 0.9%.
 - HLT execution time was reduced by 7%.



Belle II Future

Luminosity projection



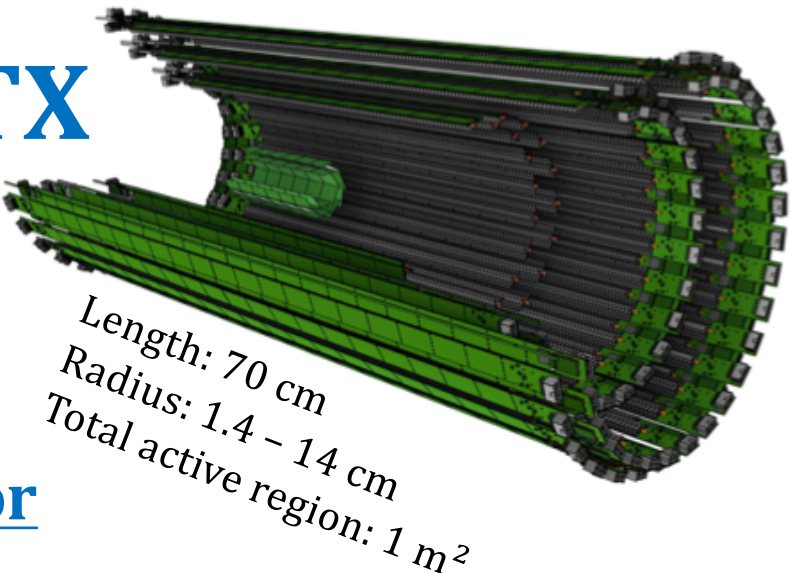
- We aim for a 11-fold increase in $\mathcal{L}$ through the 2nd long shutdown (LS2) in 2032-2033.

Proposed upgrade for the e^+e^- interaction region (IR)

- We are proposing modifications to the e^+e^- IR to increase $\mathcal{L}$.
 - Move a magnet 100 mm closer to the IR.
 - Switch from NbTi to Nb₃Sn to allow higher current.
 - Install a new compensation solenoid in the IR.
- These modifications will make the beam-background environment more challenging than today.

New Vertex Detector: VTX

- We want to maintain high vertexing performance even in the challenging beam-background environment
⇒ **proposal for a new vertex detector**



Layer	$N_{\text{sen}} \times N_{\text{lad}}$
L1	4×6
L2	4×10
L3	$(12-13) \times 36$
L4	$(16-17) \times 48$
L5	20×60
Total	$\sim 2,550$ sens

VTX structure

- Cylindrical detector with 2 inner and 3 outer layers, all using the same DMAPS sensor, called OBELIX.
- OBELIX v1 – taped out in May

Pixel size	$33 \times 33 \mu\text{m}^2$
Integration time	50 – 100 ns
Sensor thickness	50 – 100 μm
Power consumption	$\sim 200 \text{ mW/cm}^2$
Radiation hardness	$>1 \text{ MGy}, 5 \times 10^{14} n_{\text{eq}}/\text{cm}^2$

Expected performance improvement

MC simulation, preliminary

Item	VXD = PXD2+SVD	VTX
<i>B</i> -decay vertex resolution	35 μm	18 μm
Slow-pion detection efficiency	$\sim 40\%$ $(p_{\text{T}} = 100 \text{ MeV}/c)$	$\sim 60\%$ $(p_{\text{T}} = 100 \text{ MeV}/c)$

The VTX is planned to be installed during the LS2.

Summary

- The Belle II SVD has operated stably since March 2019. Cluster charge, SNR, and hit efficiency remain good. Radiation effects are not significant.
- Track-position and hit-time resolutions in early Run 2 were measured to be 7–25 μm and <3 ns, respectively.
- SVD sensors will maintain acceptable performance after ~ 10 years of radiation exposure at $\mathcal{L}_{\text{target}} = 6 \times 10^{35} \text{ cm}^{-2} \text{ s}^{-1}$.
- To keep the SVD hit occupancy low, a new software-based scheme to reject off-time beam background hits was introduced.
- Upgrade of the PXD2+SVD to a new vertex detector, VTX, is being proposed to maintain high vertexing performance even in a more challenging beam-background environment than today.