The Belle II Silicon Vertex Detector

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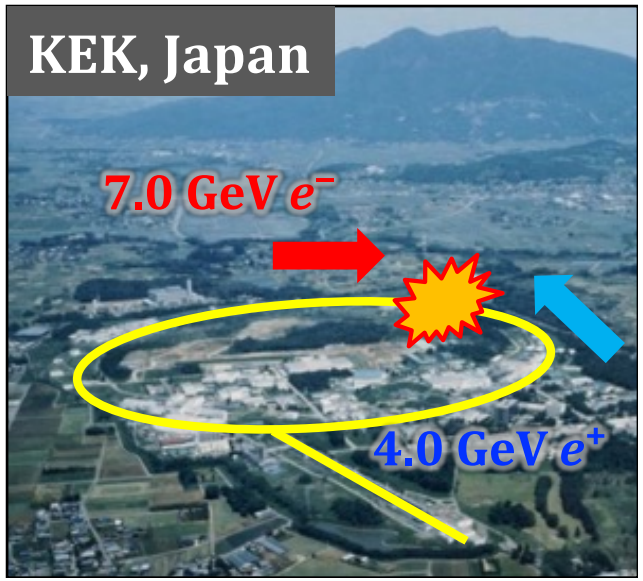
on behalf of the Belle II SVD collaboration

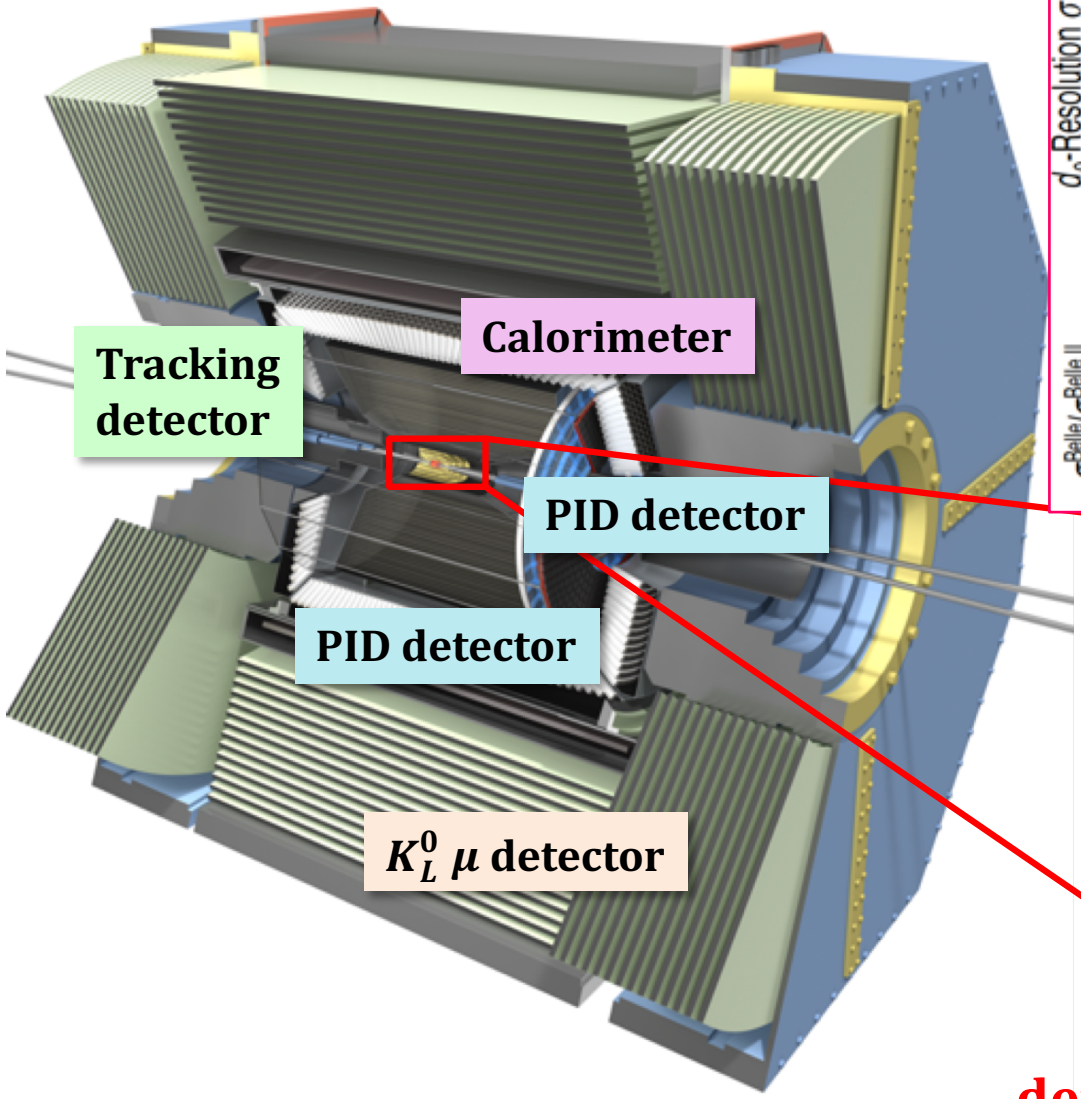
Belle II

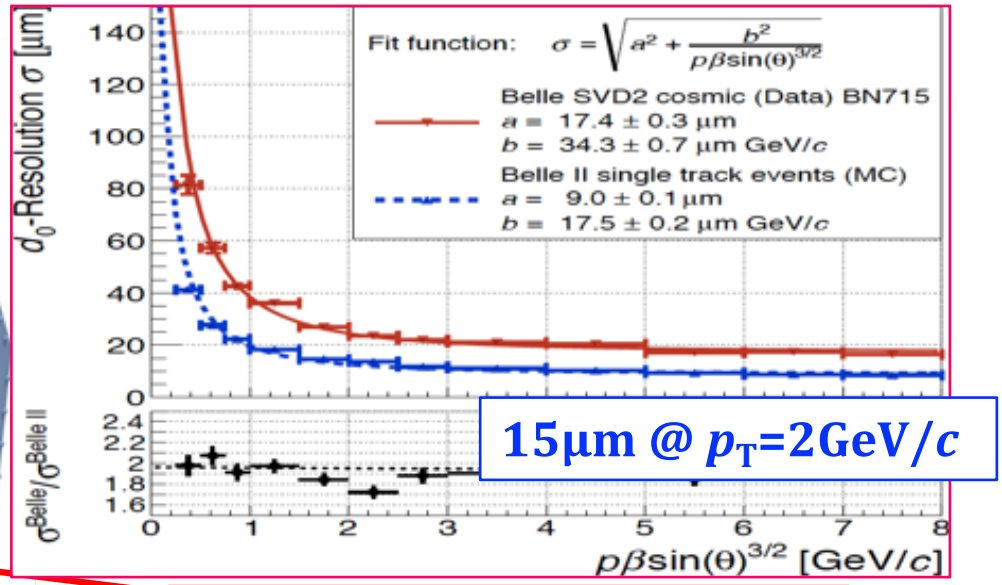
- **The Belle II experiment**
  - Belle II is a particle physics experiment in KEK, Japan motivated by a quest for new physics search.
  - Vertex-detector commissioning is now ongoing and the physics data taking with the complete detector starts early next year.

- **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 $8\times10^{35}/\mathrm{cm}^2\mathrm{s}$, and the expected total integrated luminosity after 10-year operation is 50 ab^{-1}.

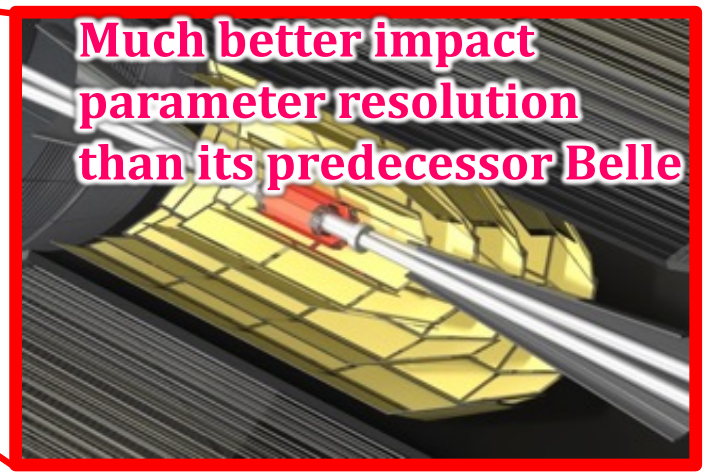


Belle II Detector





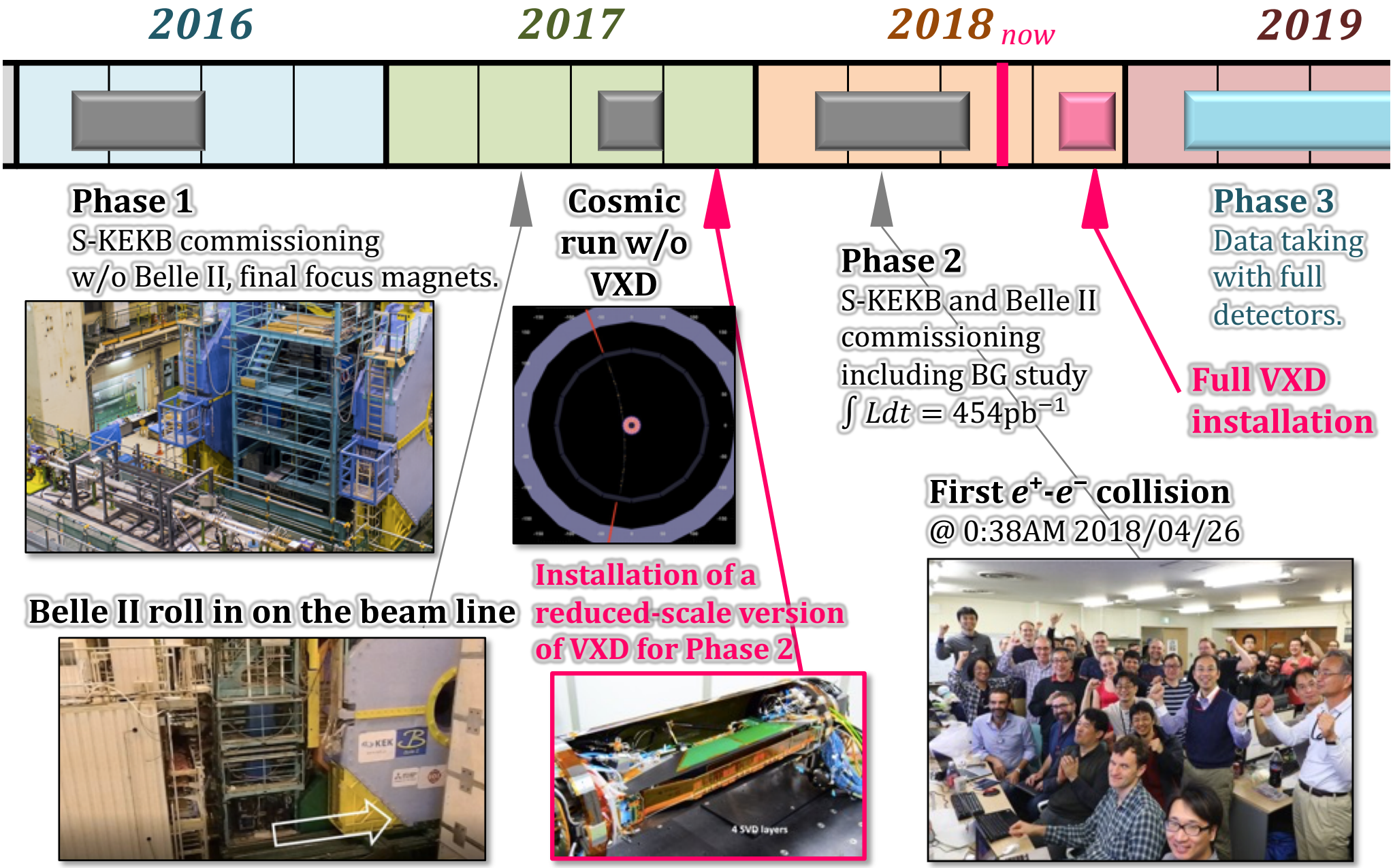
15μm @ p_T=2GeV/c



7.5m(H) × 7.5m(W) × 7m(D)

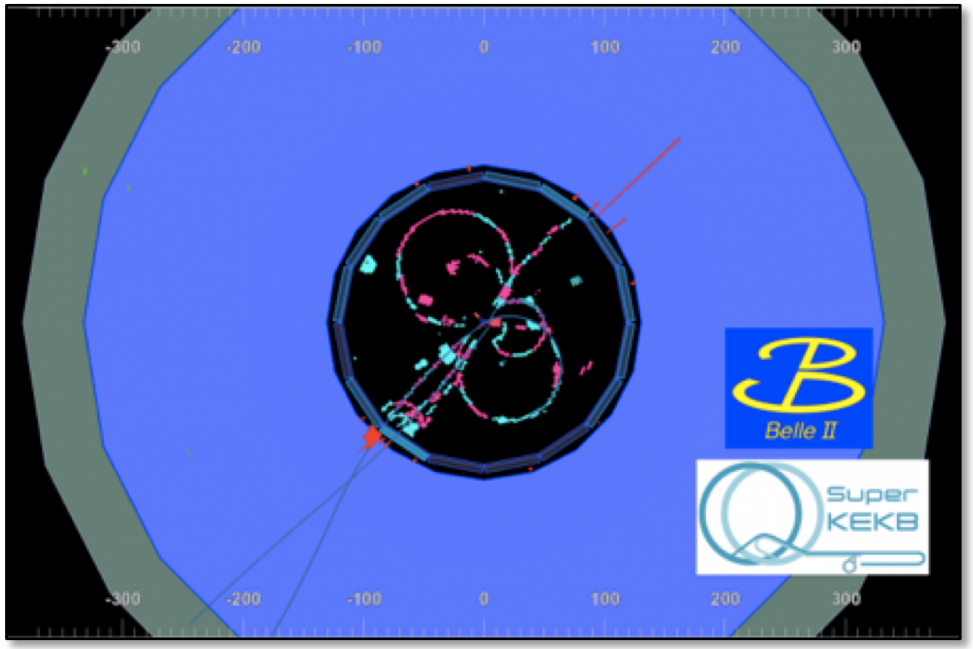
At the heart of Belle II, a vertex detector (VXD) made of pixel (PXD) + strip (SVD) silicon detectors is installed.

SuperKEKB/Belle II Commissioning



The First e^+-e^- Collision

Excitement in the control room for the first collisions

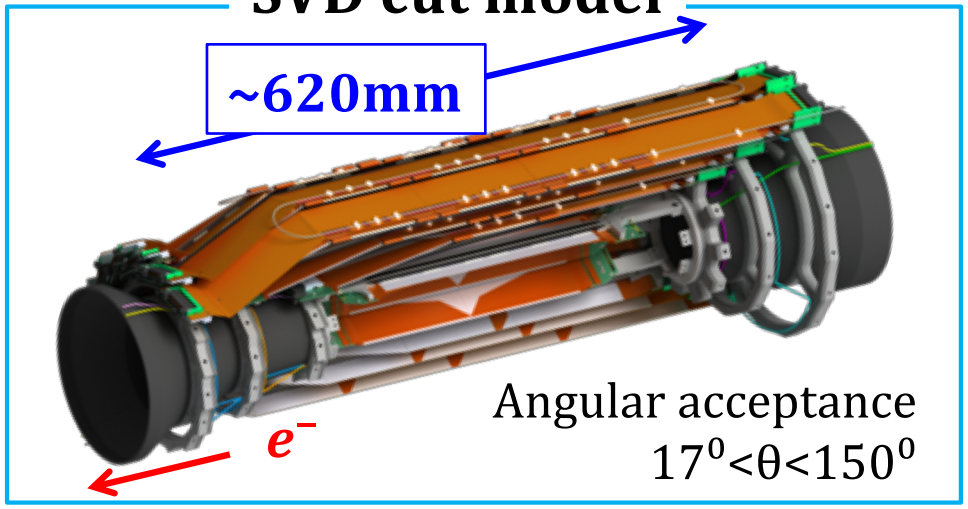


Observed $e^+e^- \to q\bar{q}$ in early collisions

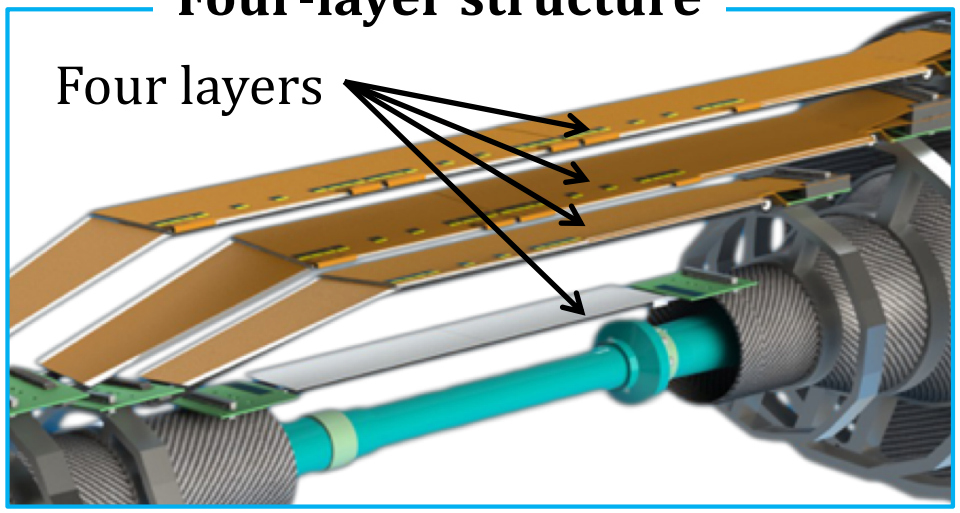
The first of e^+-e^- collisions provided by SuperKEKB were confirmed by Belle II at 0:38AM April 26, 2018.

Silicon Vertex Detector (SVD)

SVD cut model



Four-layer structure



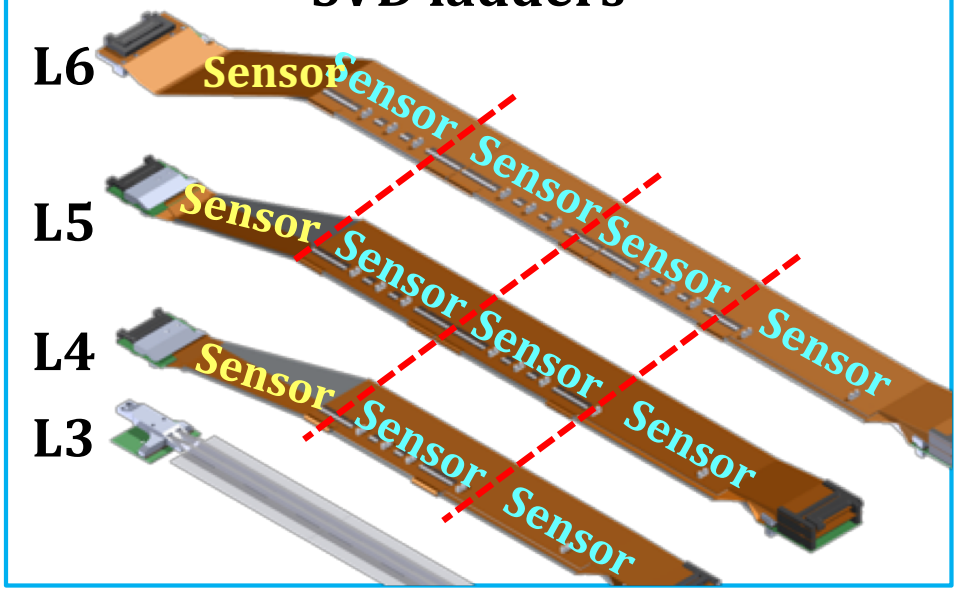
- The characteristic lantern shape contributes to maximize the forward acceptance reducing the material in the tracking region.
- The SVD outer radius is extended with respect to Belle allowing for an improved K_S^0 reconstruction efficiency and low-p_T standalone tracking efficiency.

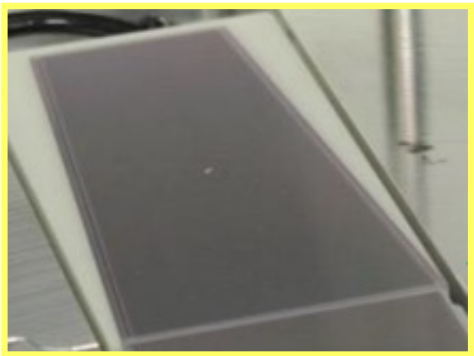
Layer	R [mm]	N_{Ladder}	Assembly site
L6	135	16	Kavli IPMU (JPN) +
L5	104	12	HEPHY (AUT)
L4	80	10	TIFR (IND)
L3	39	7	Melbourne U (AUS)
FW/BW	–	38+38	INFN Pisa (ITA)

- The ladders were assembled in 5 collaborating institutes.

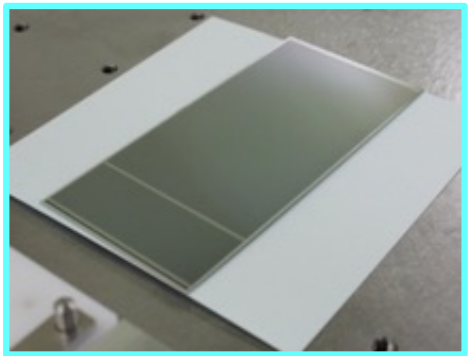
Silicon Vertex Detector (SVD)

SVD ladders





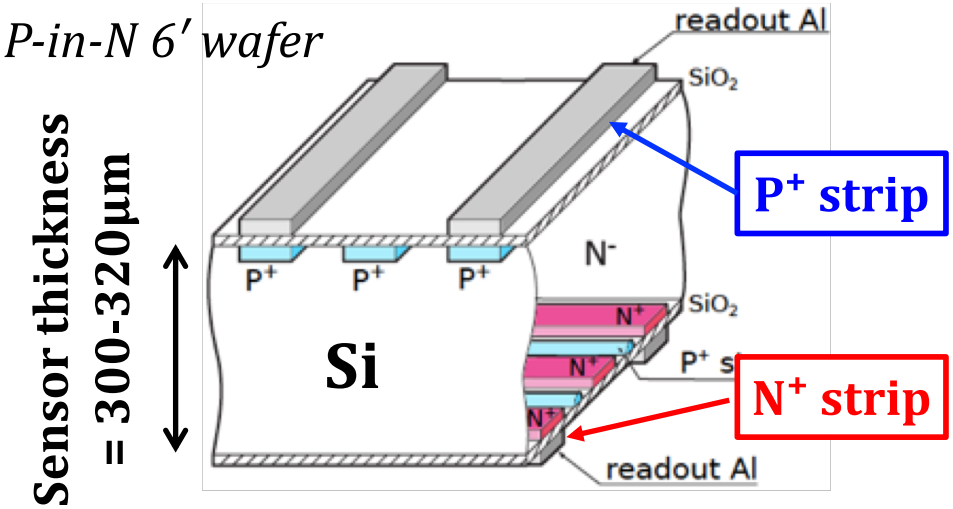
Trapezoidal sensor (Micron)



Rectangular sensor (HPK)

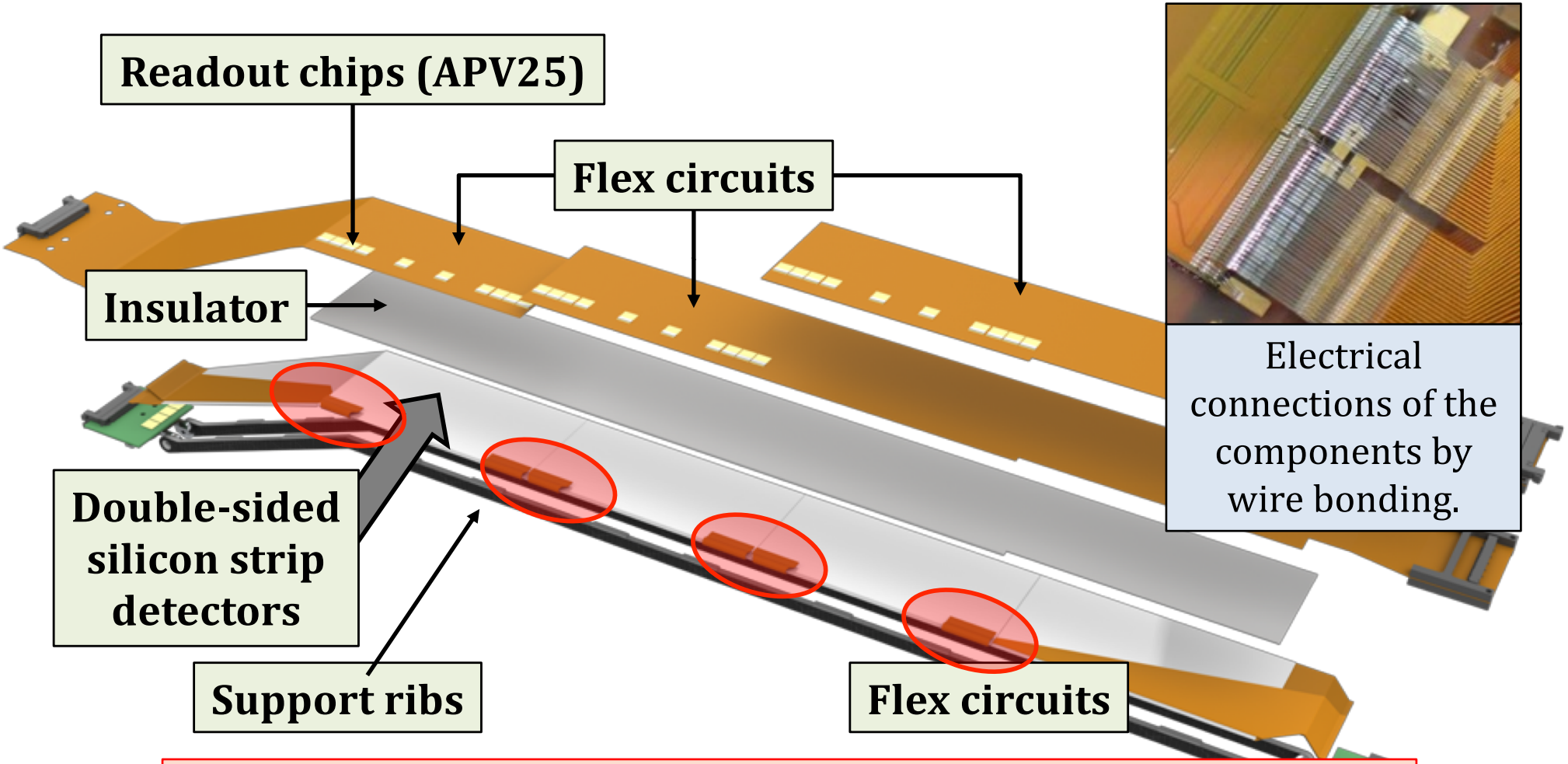
Double-sided Si Strip Detector

P-in-N 6′ wafer



	Trapezoidal	Rectangular (L3/L4,L5,L6)
# of P-strips	768	768/768
P-strip pitch	50…75μm	50μm/75μm
# of N-strips	512	768/512
N-strip pitch	240μm	160μm/240μm
Total area		5048.90mm²/ 7442.85mm²

Ladder Anatomy

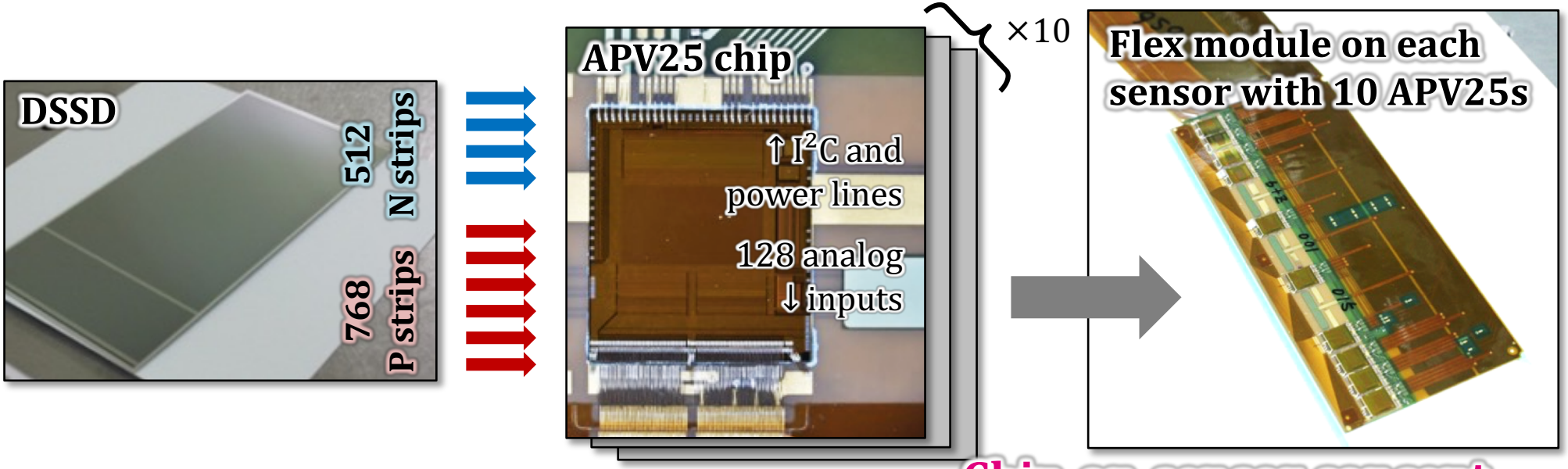


Electrical connections of the components by wire bonding.

Two novel concepts in the ladder

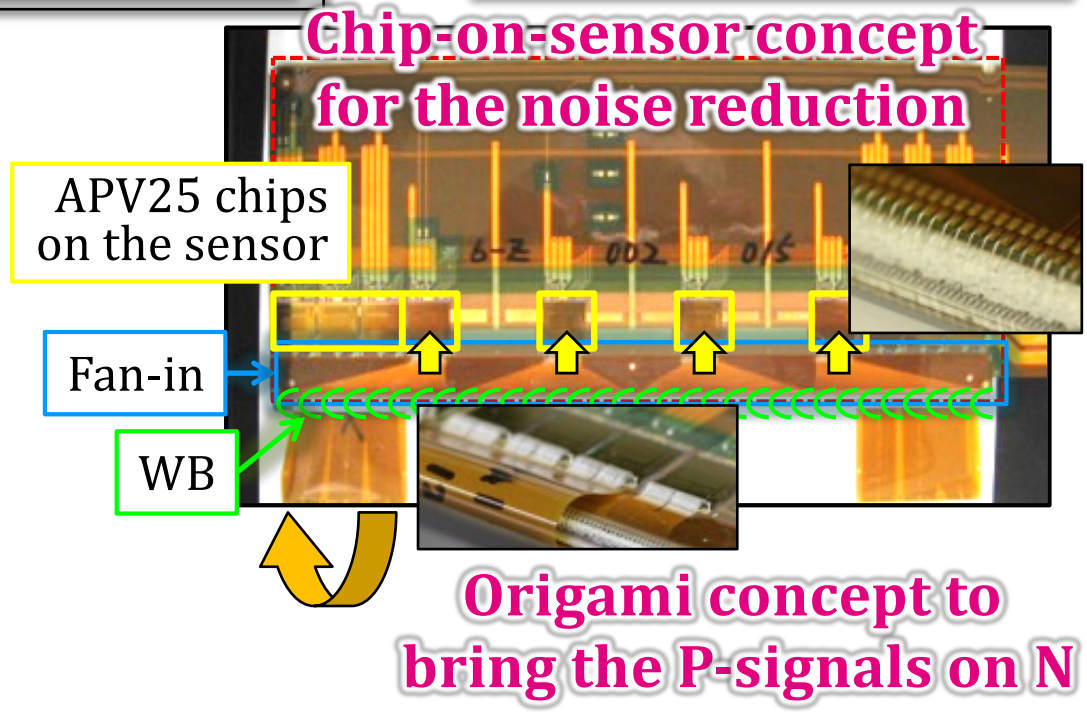
- Chip-on-sensor concept for the noise reduction
- Origami concept to bring the P-side signals on the N side

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

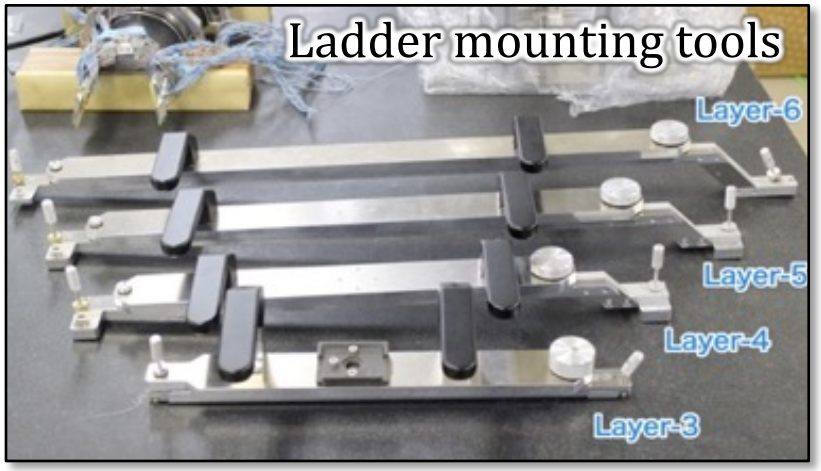
- **The poster "Construction and QA of the Belle II SVD" by Resmi.**

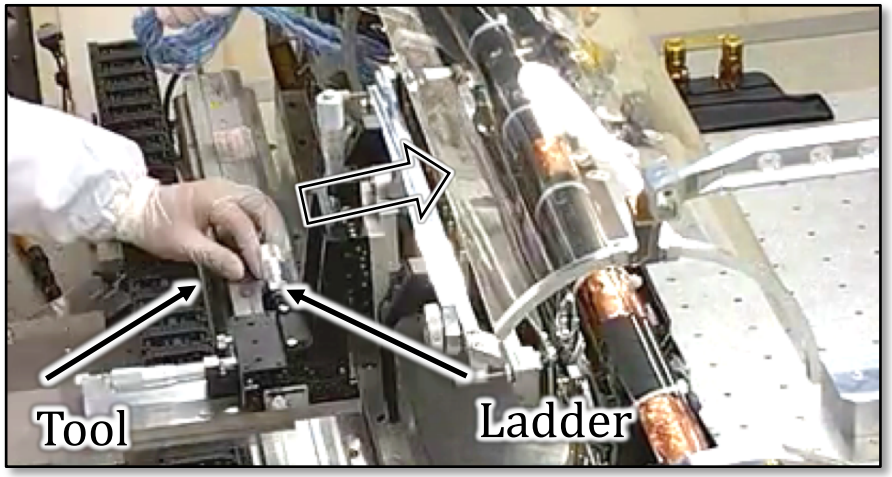
Very good ladder quality achieved

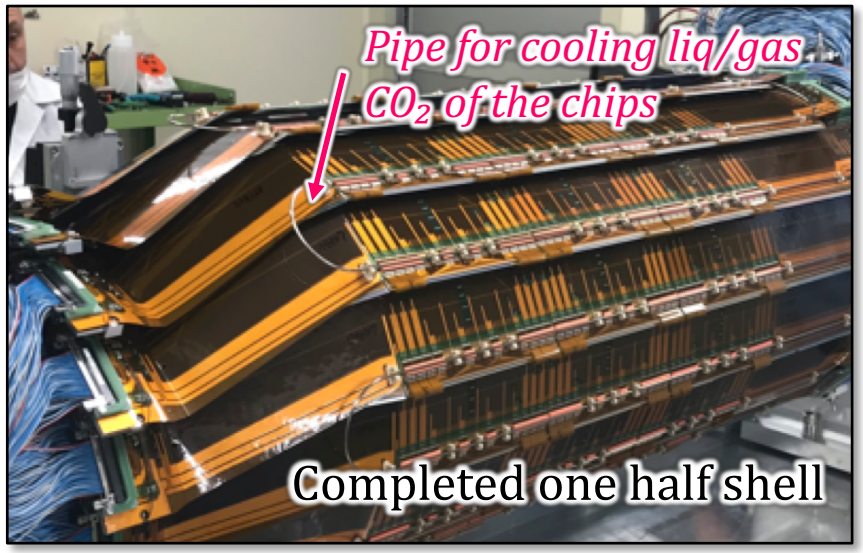
- Electrical: ~ 1% defects and very few additional defects introduced during the assembly
- Mechanical: sensor displacement below 300μm achieved in all ladders

Ladder Mounting

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







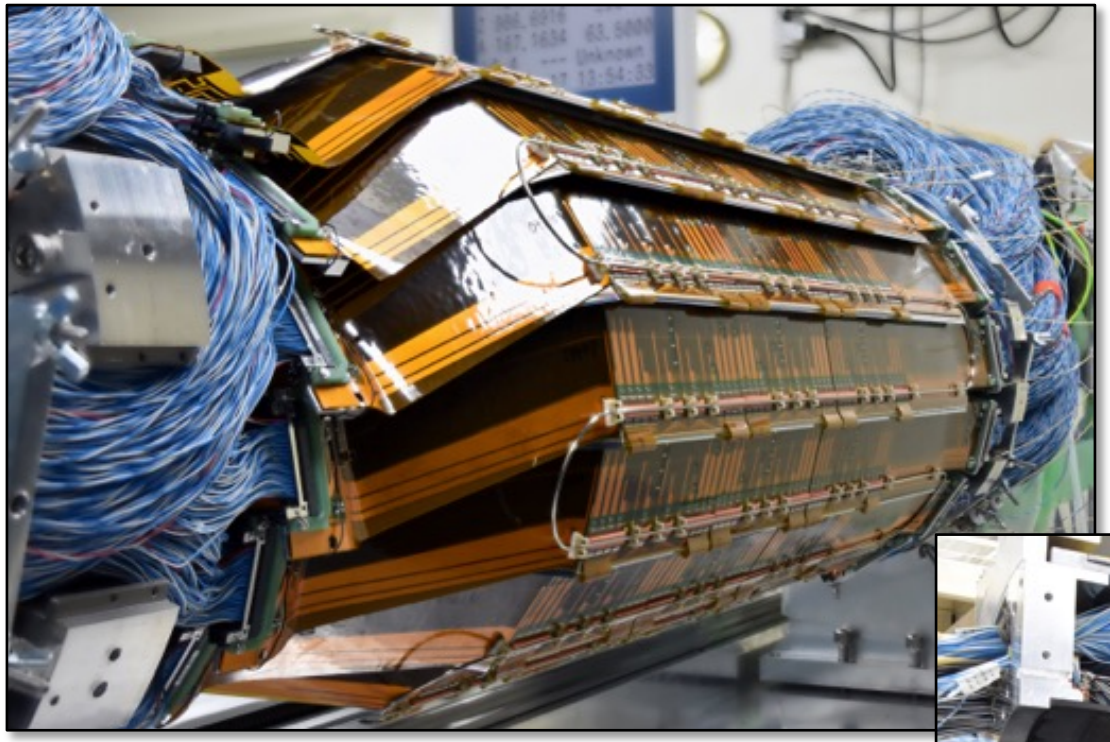
Mechanical and electrical quality of each ladder was tested before and after its mounting.

We confirmed in the tests that:

- No new electrical sensor defects introduced and
- Sensor displacement under control.

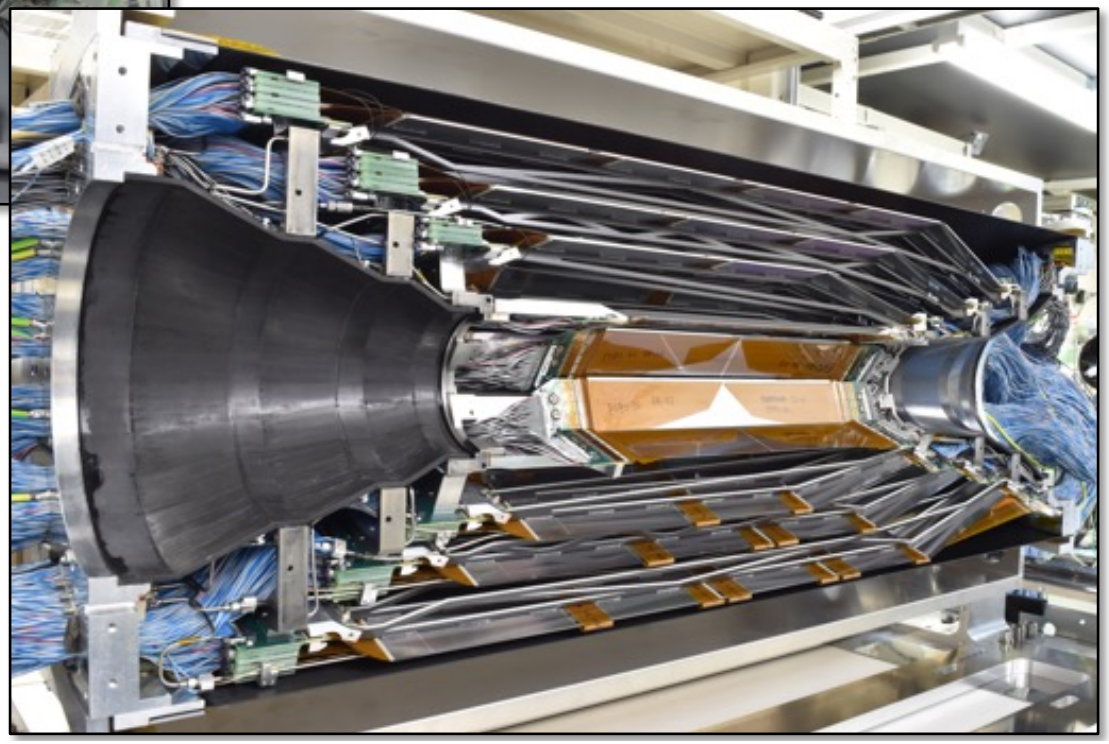
Thermal contact between the cooling pipe and APV25 chips was confirmed with an IR camera.

Ladder Mounting

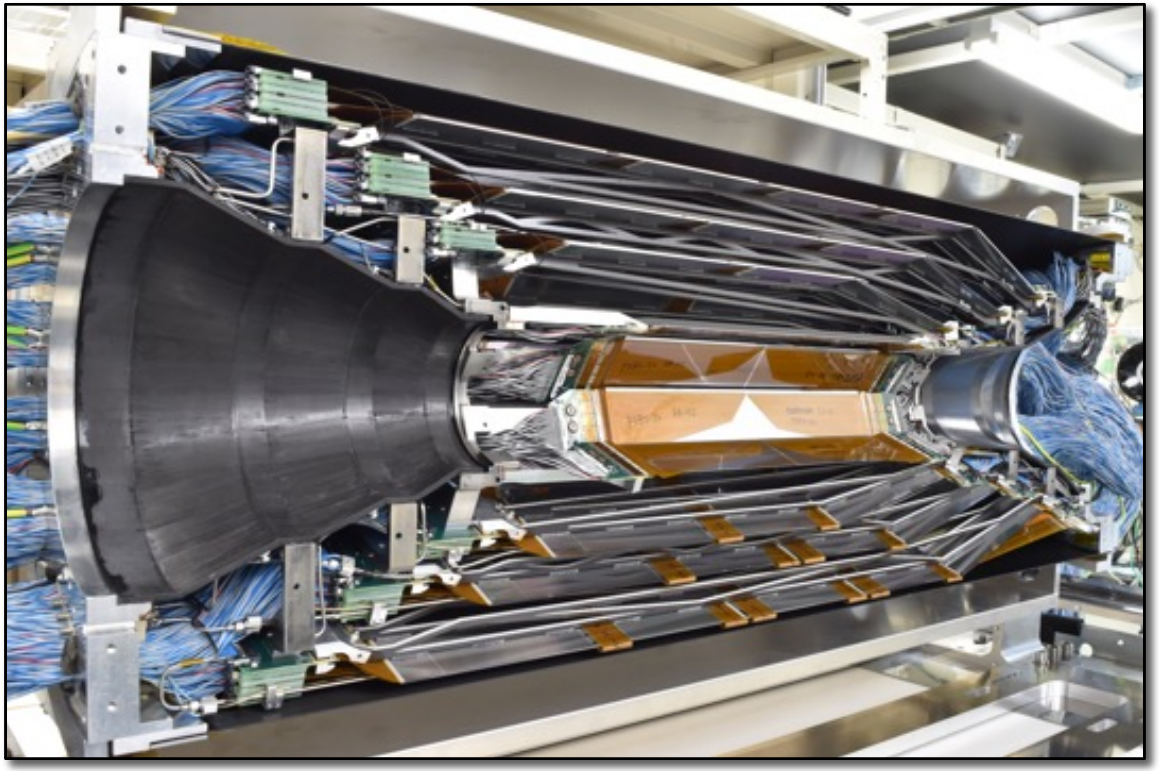


Half-shell outside

Half-shell inside

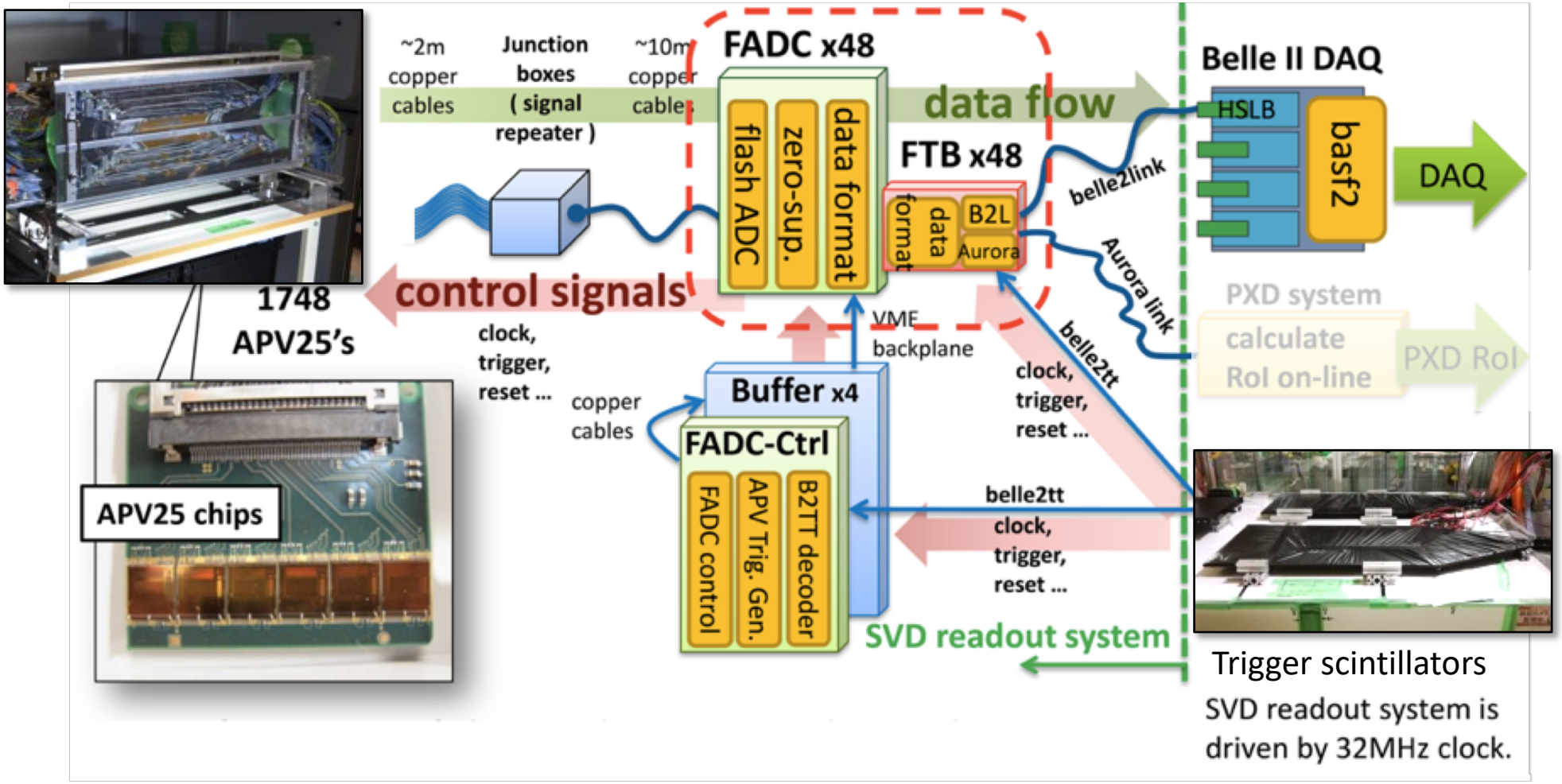


Full-Scale SVD Commissioning



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

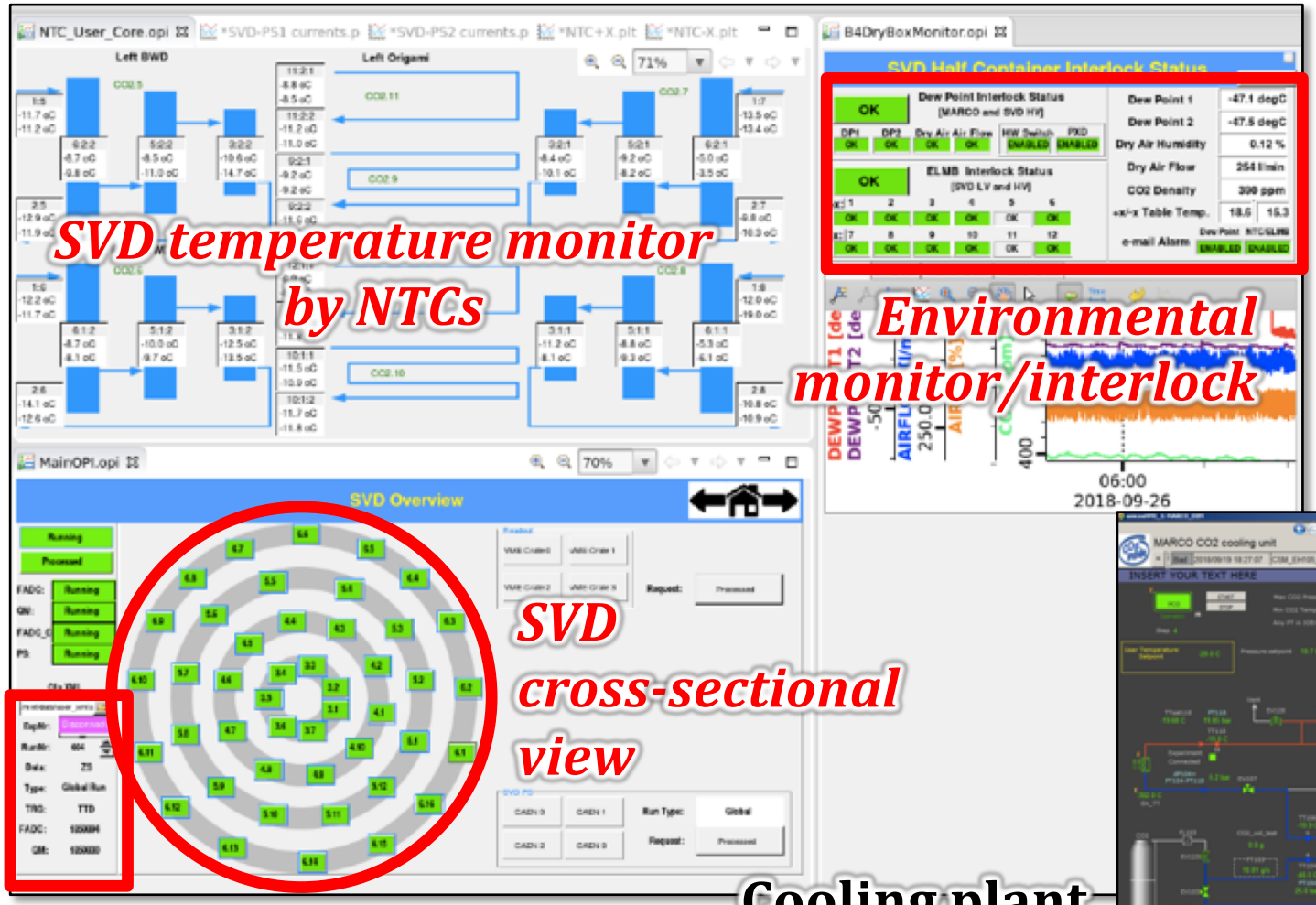
Full-Scale SVD Commissioning



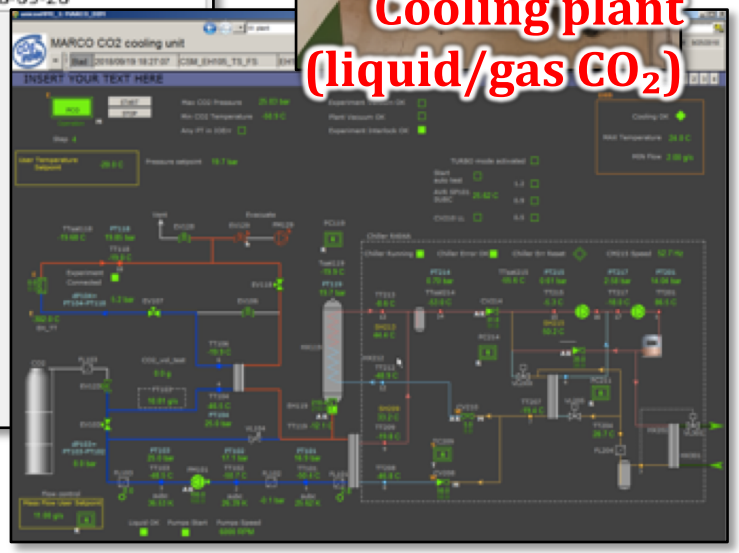
SVD readout system is driven by 32MHz clock.

Control and Monitoring during Commissioning

Nice slow control panel (PC screenshot):



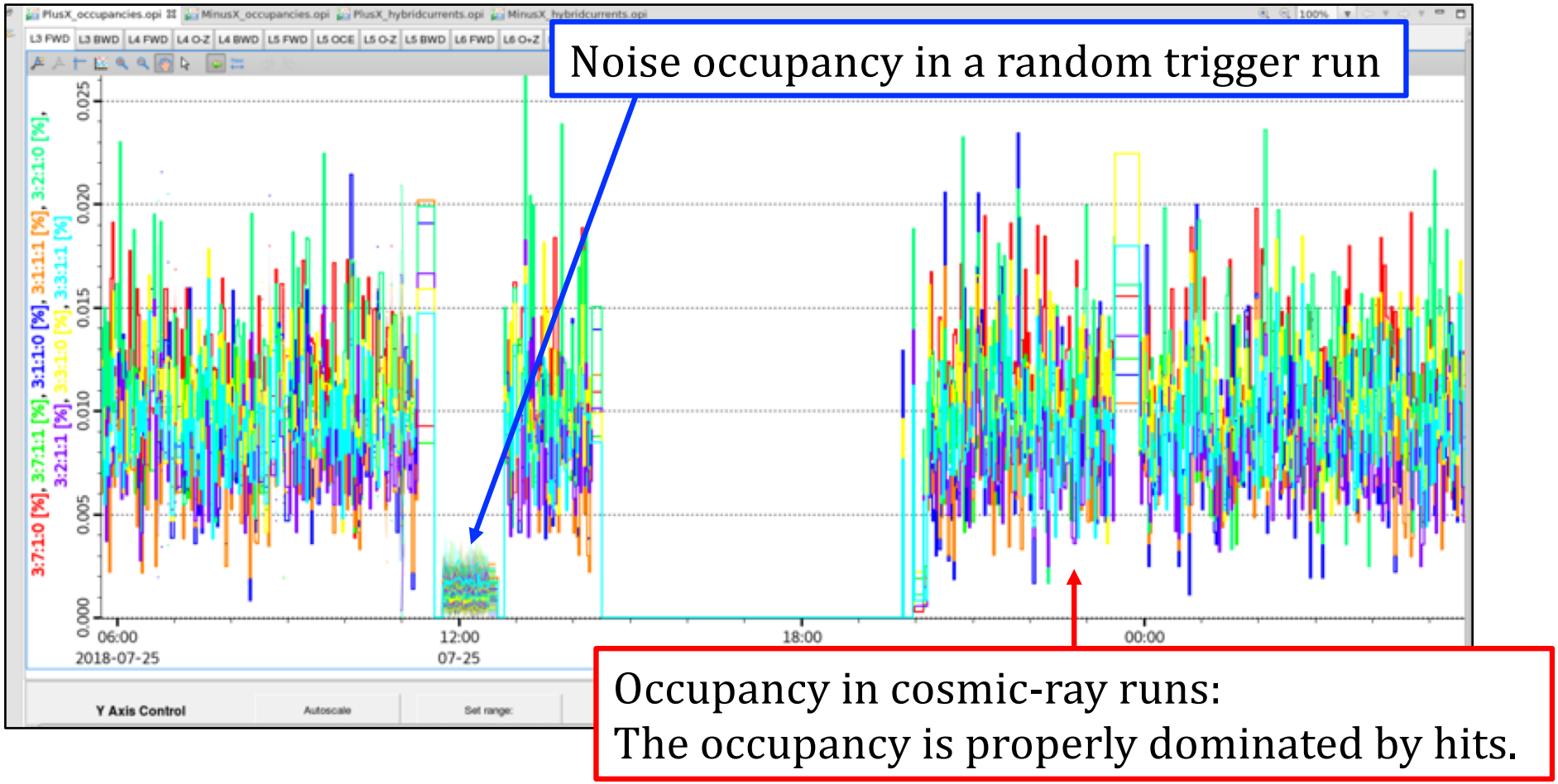
Cooling plant monitor:



Detector Online Monitor

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

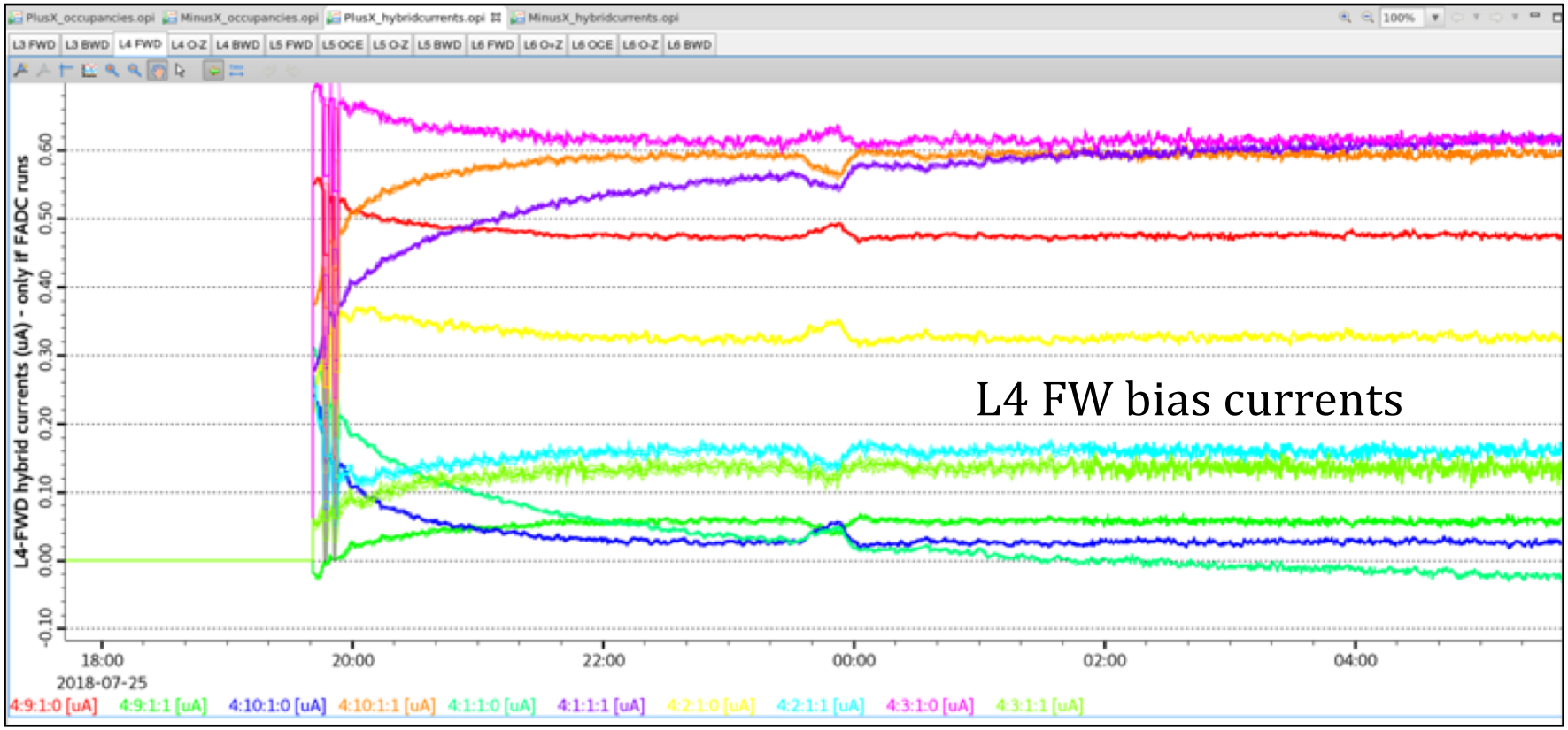
Time propagation of the occupancy



Detector Online Monitor

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

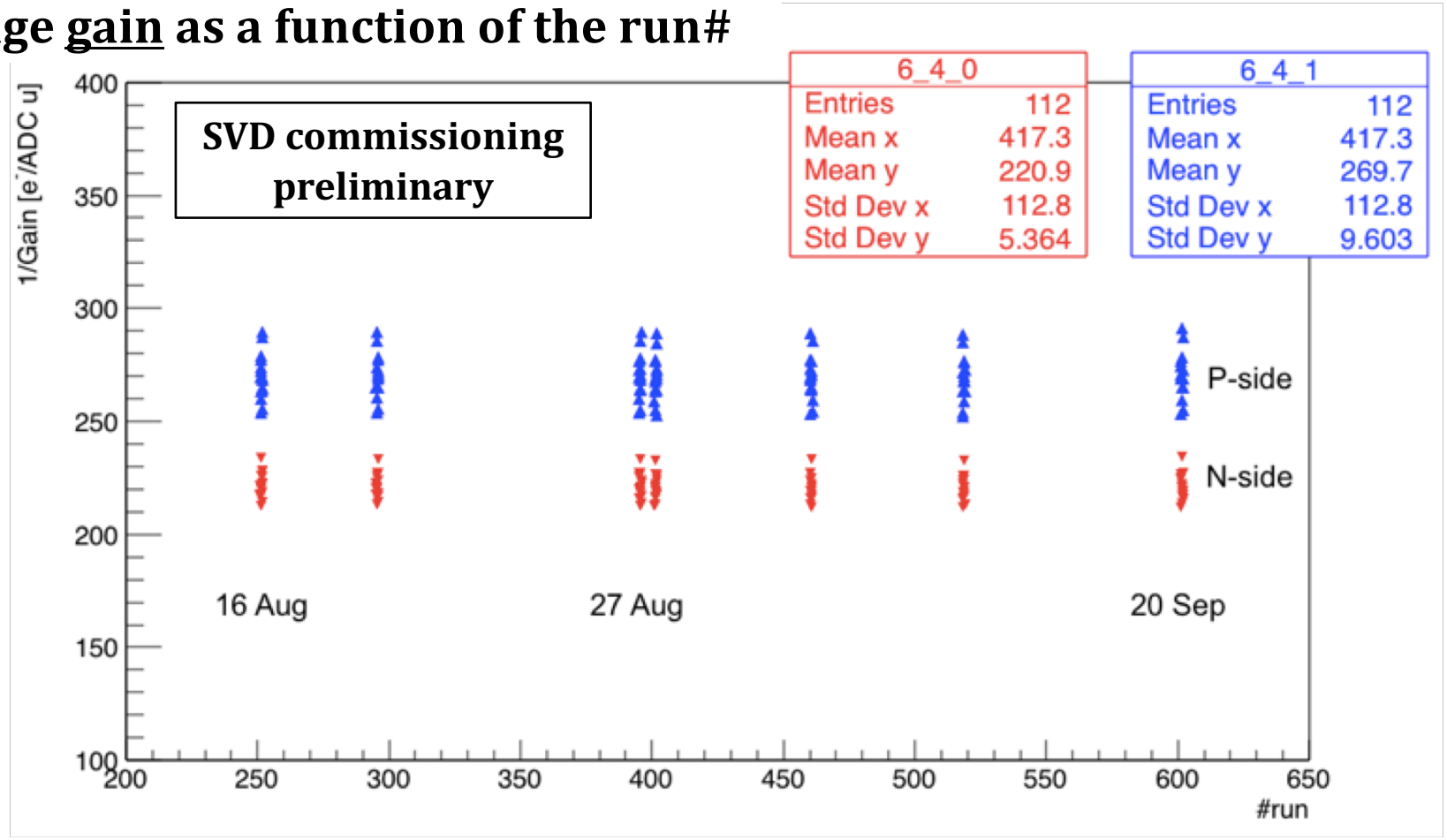
Time propagation of the sensor bias currents



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#



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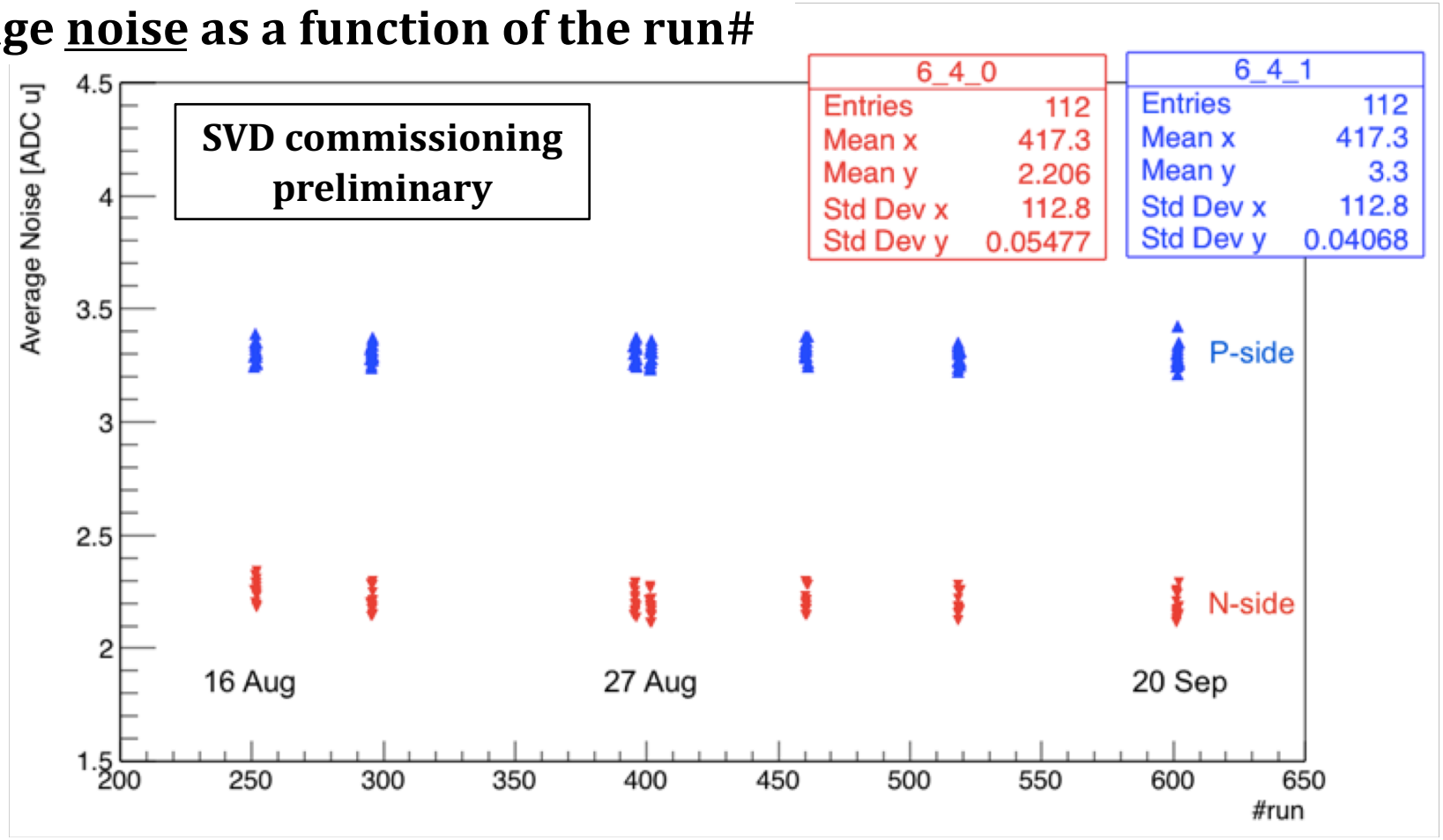
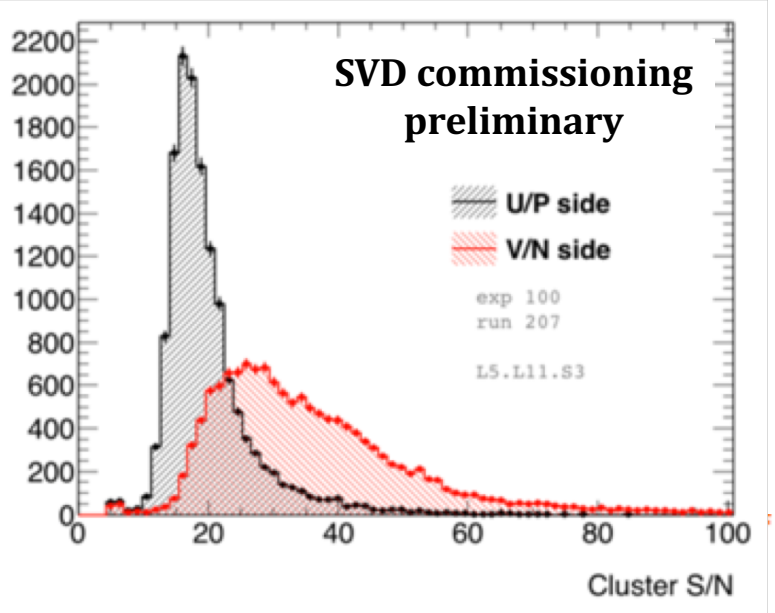


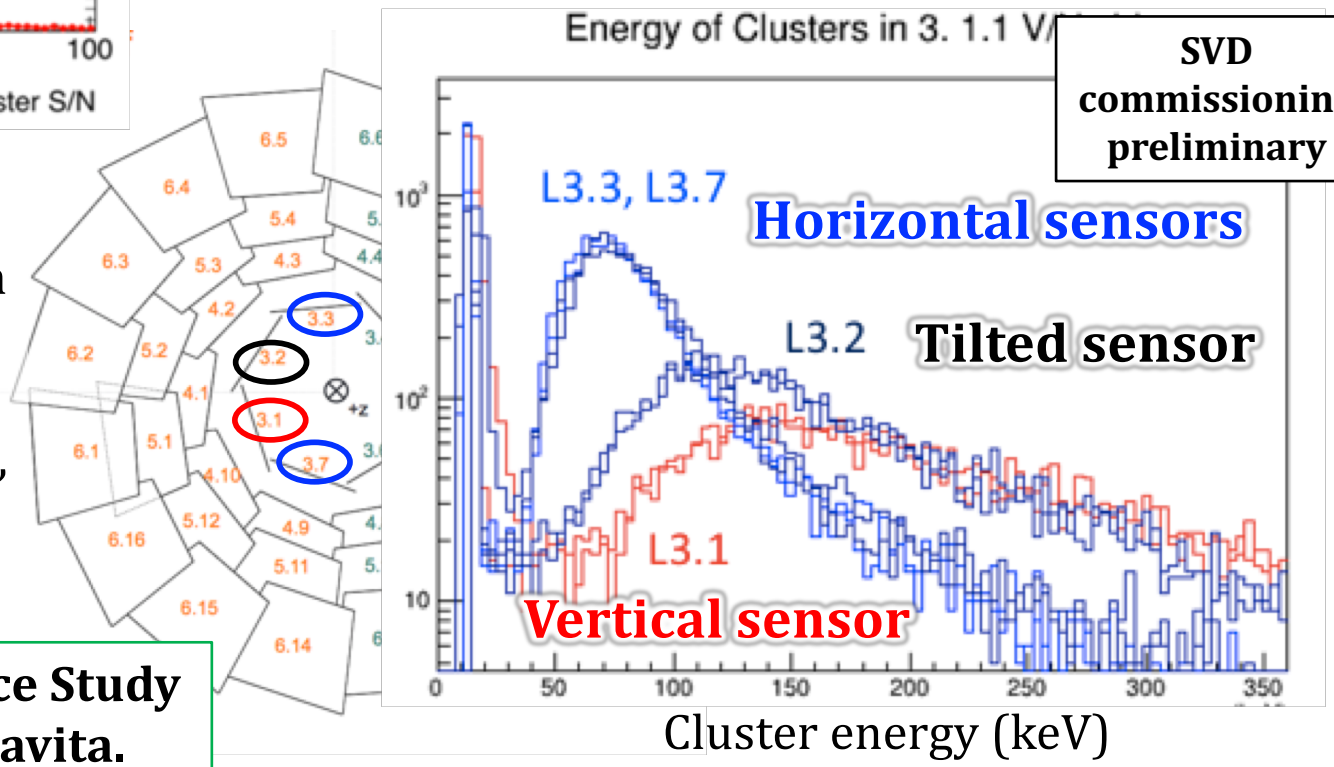
Cosmic-Ray Commissioning



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

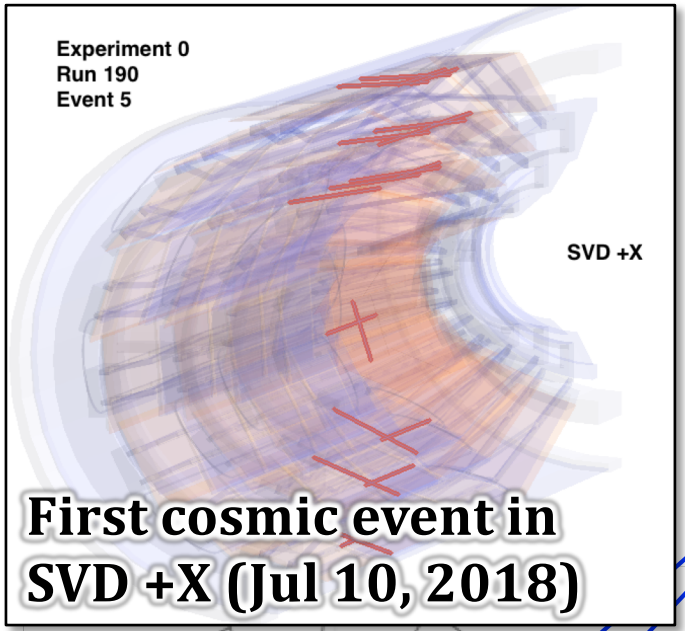
The SNR is larger than 25 for N side, slightly lower on P side due to the longer strips and larger capacitance load to the preamplifier.

Cluster energy in horizontal silicon sensor (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.

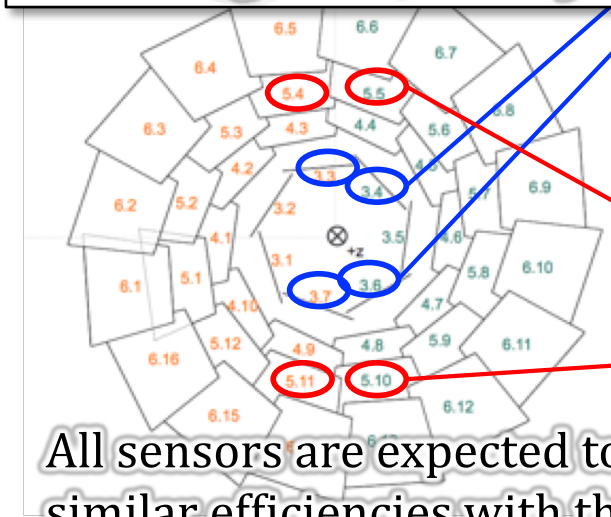


- **The poster "Performance Study of the Belle II SVD" by Kavita.**

Cosmic-Ray Commissioning

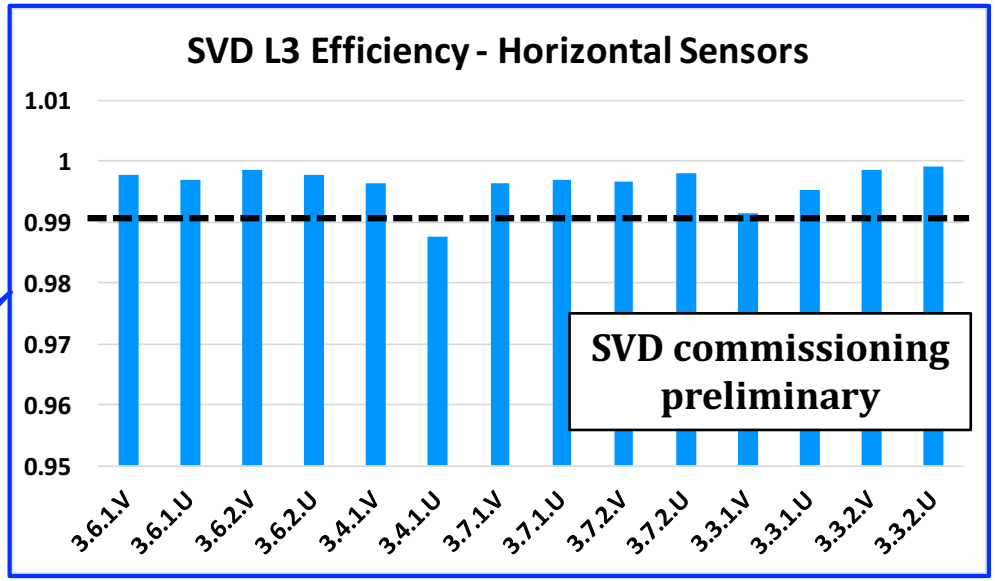


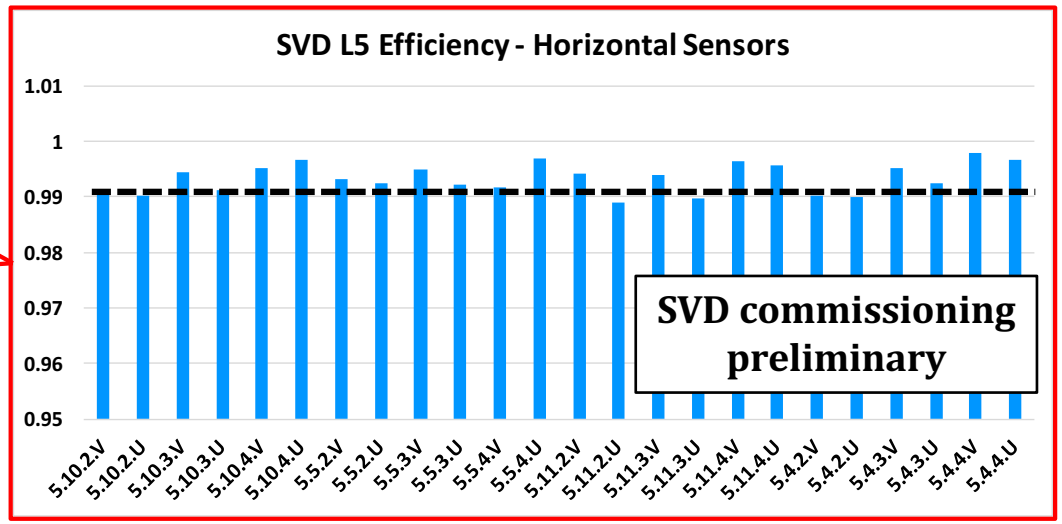
First cosmic event in SVD +X (Jul 10, 2018)



All sensors are expected to have the similar efficiencies with the ones estimated on the horizontal sensors.

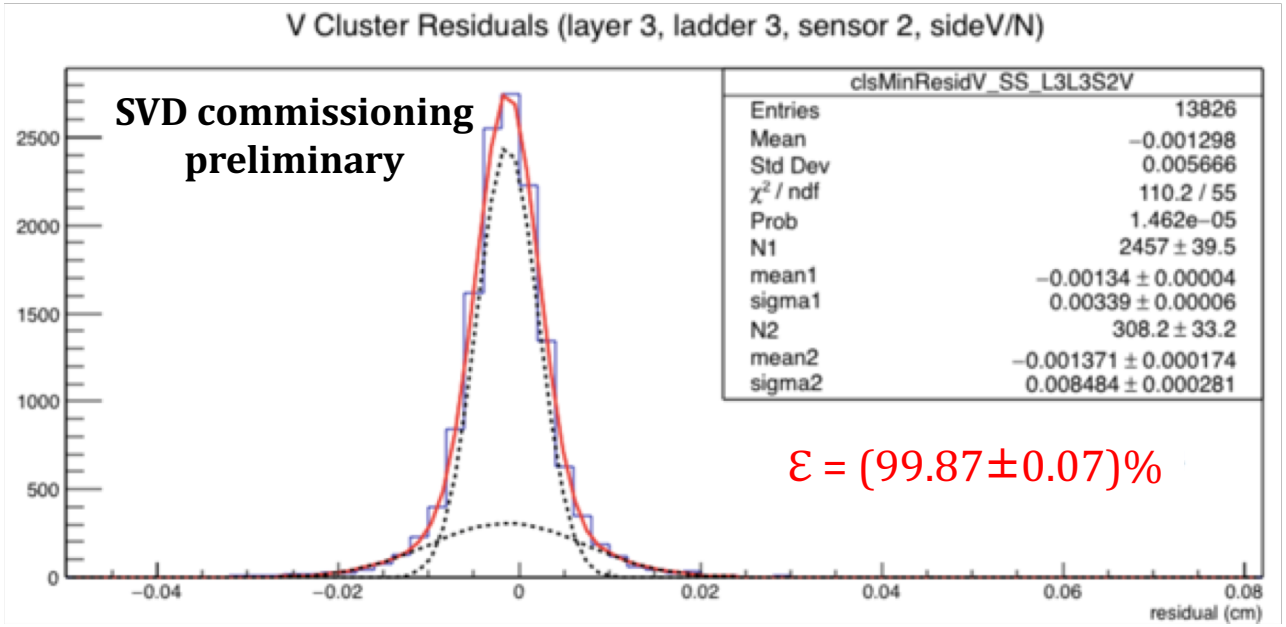
Sensor efficiencies:





Cosmic-Ray Commissioning

Cluster residuals:

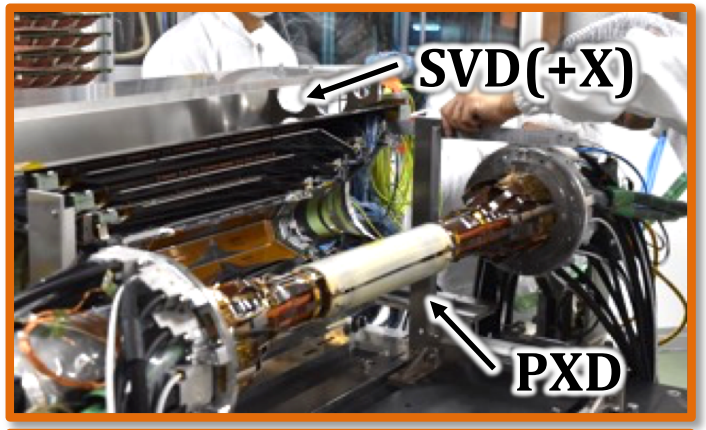


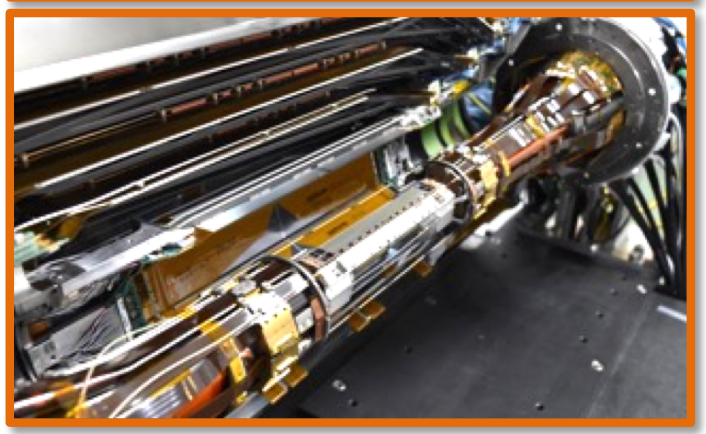
Unbiased residuals are computed with cosmic-ray tracks reconstructed without the clusters on the sensor.

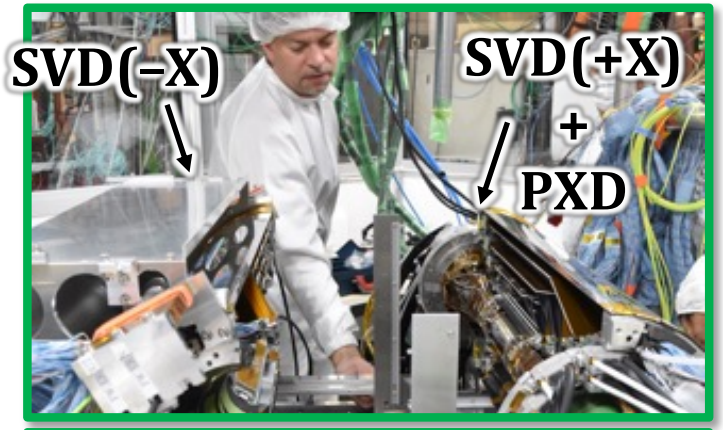
Excellent performance of the SVD was confirmed with tracking.

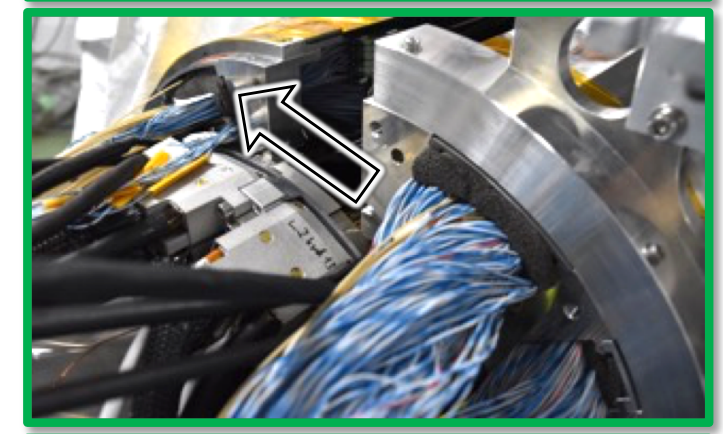
- Efficiency >99% for most of the sensors and nice Gaussian residuals were confirmed. Efficiency and residuals estimated on horizontal sensors are quoted here (otherwise too large incident angles) after the alignment.

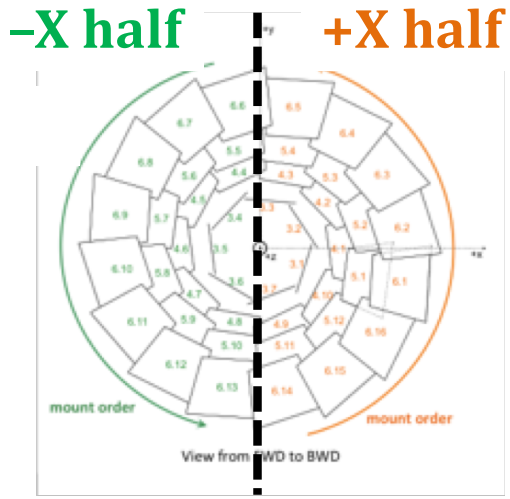
PXD + SVD "Marriage"









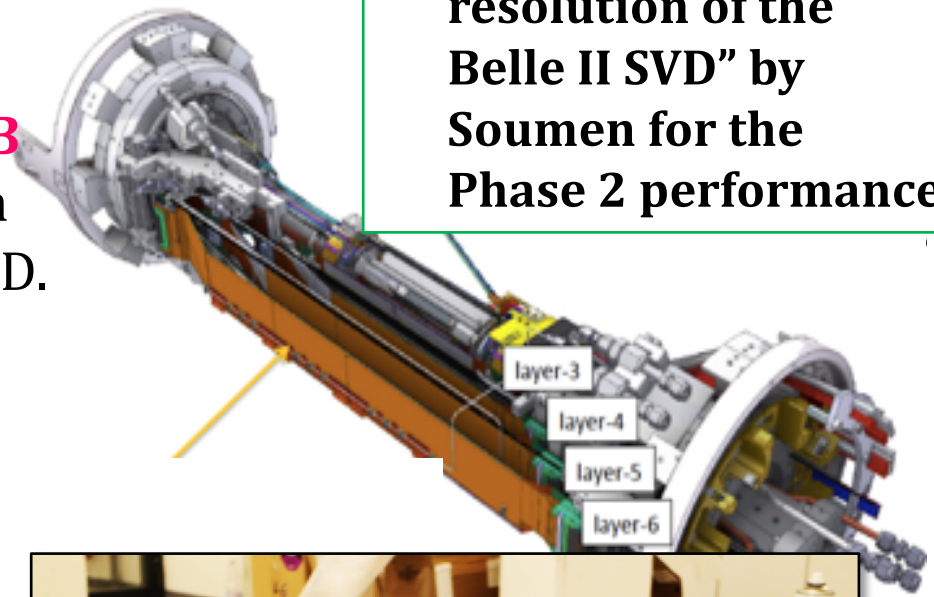


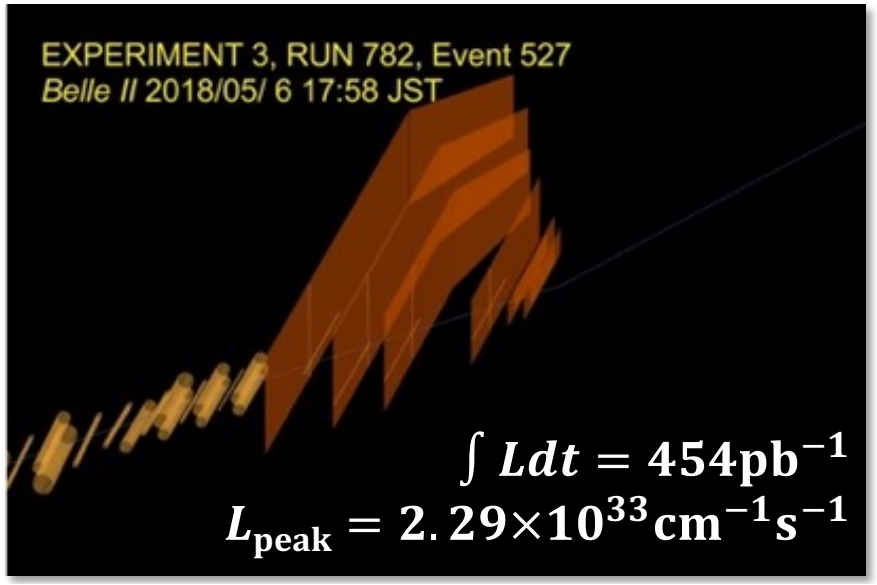
The combined VXD will be commissioned for one month before the installation to the Belle II detector by the end of 2018.

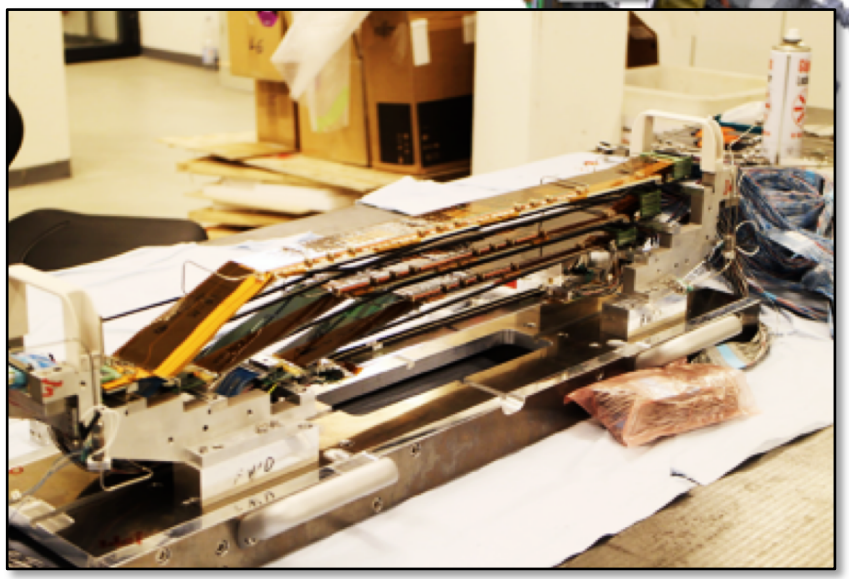
SVD Sub-systems Commissioned in Phase 2

- **The poster "Spatial resolution of the Belle II SVD" by Soumen for the Phase 2 performance.**

- 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.



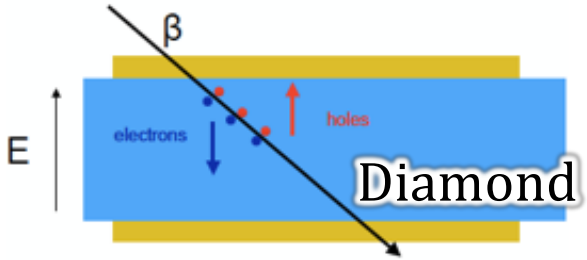




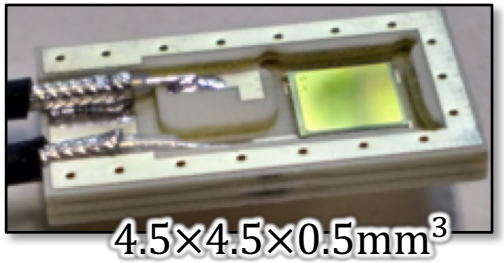
Radiation Monitoring in Phase 2

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":

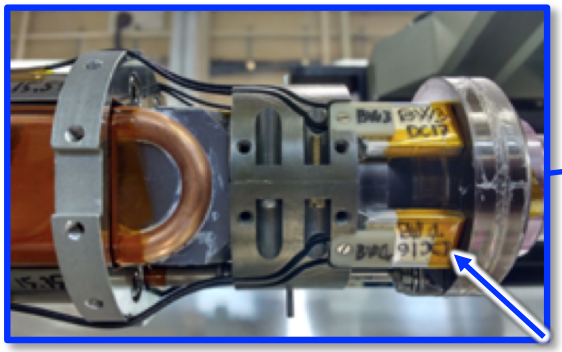


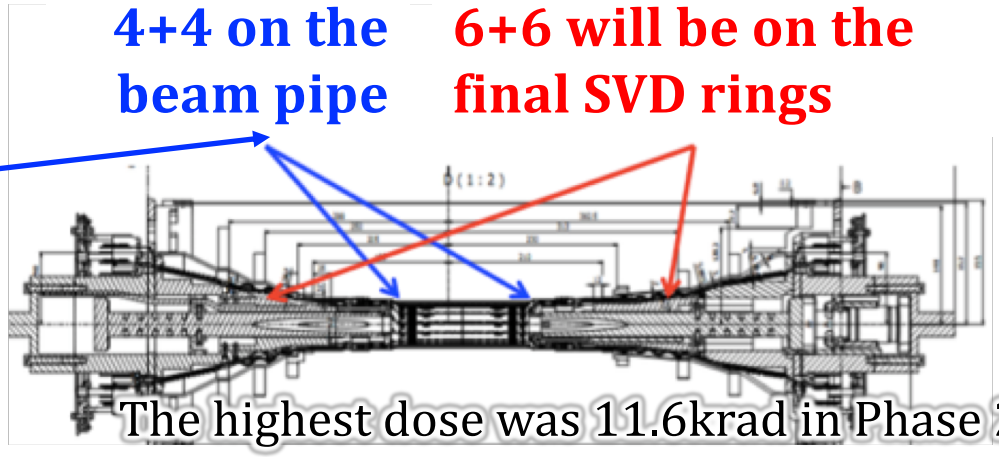
Metallized diamond



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:

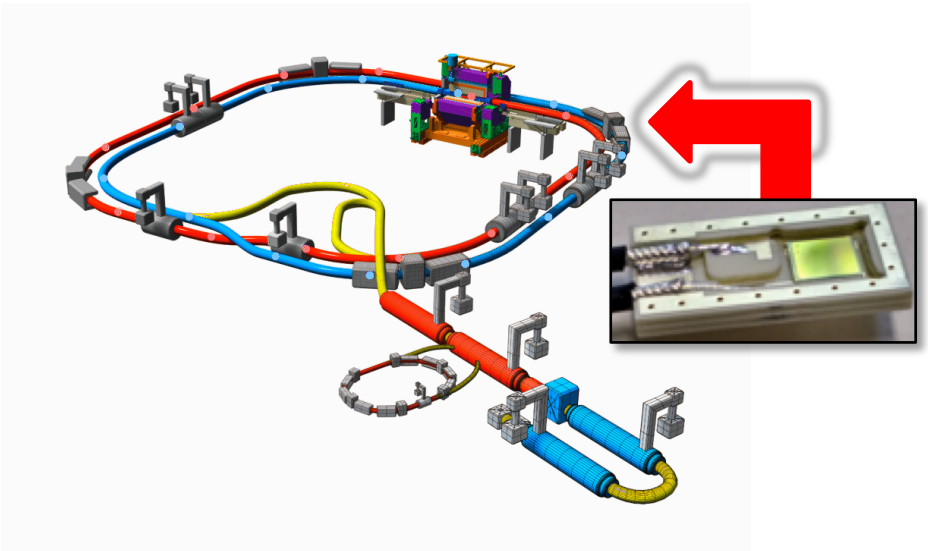




The diamonds are calibrated with ^{90}Sr.

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:

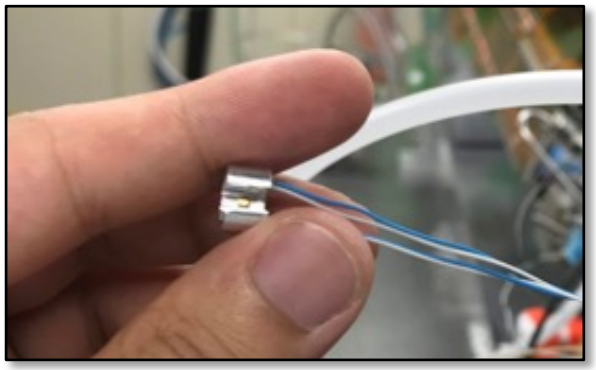
- Fast … 86 aborts
- Slow … 12 aborts

- 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)

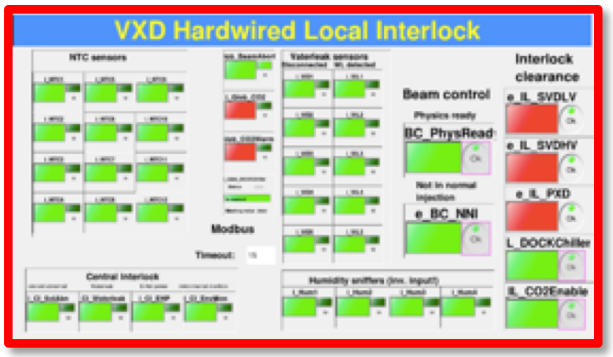


26 FOSs on 5 fibers (SW)

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

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

Interlock instance



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

Global Schedule

High level milestones	Completion
VXD (= PXD+SVD) installation to Belle II	– early Dec. 2018
VXD cabling and system test	– end of Dec. 2018
Restart of SuperKEKB	– March 2019
Start of the physics data taking with the complete detector	**Soon after**

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.

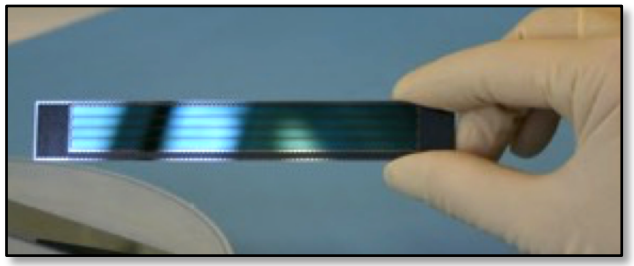
Backup Slides

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.

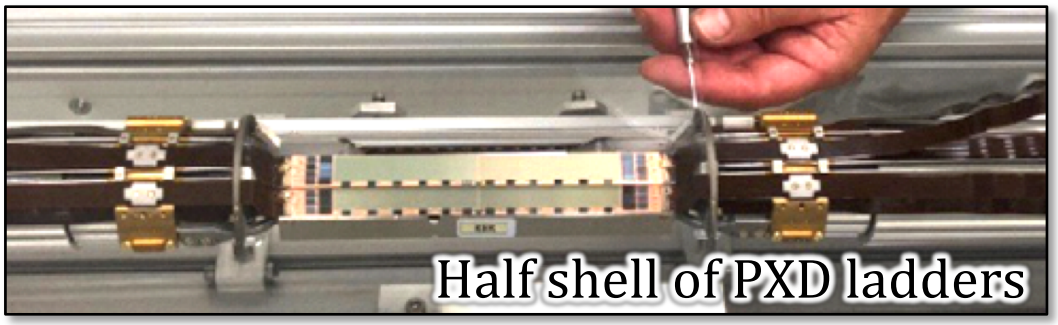
- **Monolithic silicon sensor**

Thickness = 75μm
# of pixels = 768 x 256
Pixel size 50×(55…80)μm²

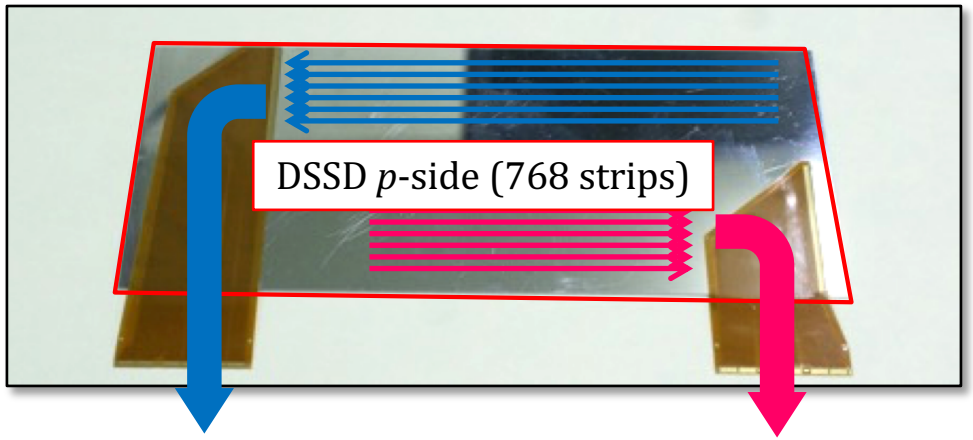


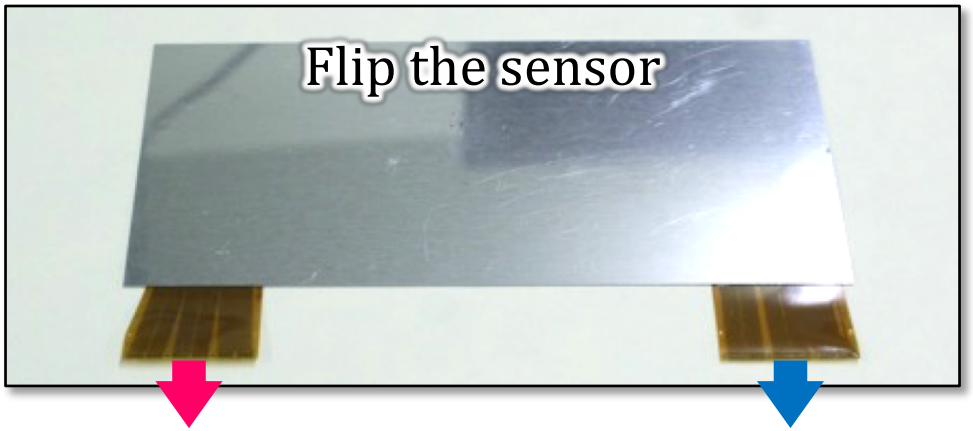
- **Readout ASIC functions**
  - FET array switching.
  - Drain current digitization.
  - Zero suppression.

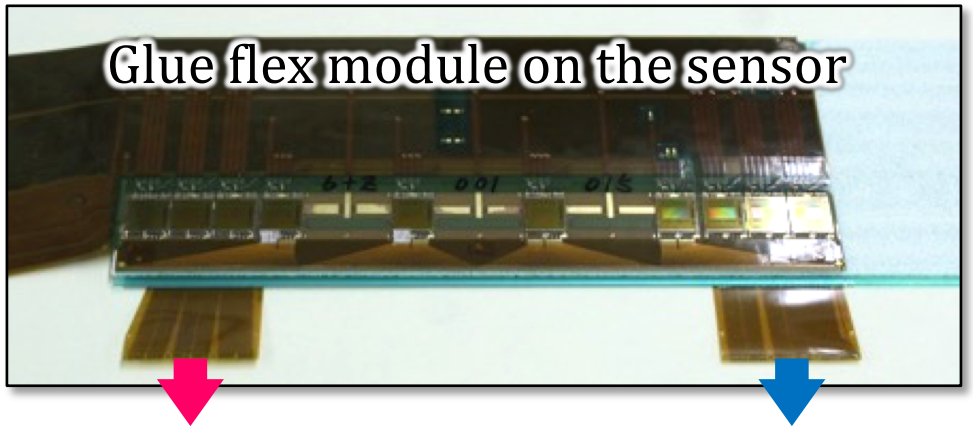
- **Status of the PXD**
  - 10 PXD ladders have been mounted on the PXD structure.
  - The PXD is under commissioning at KEK.

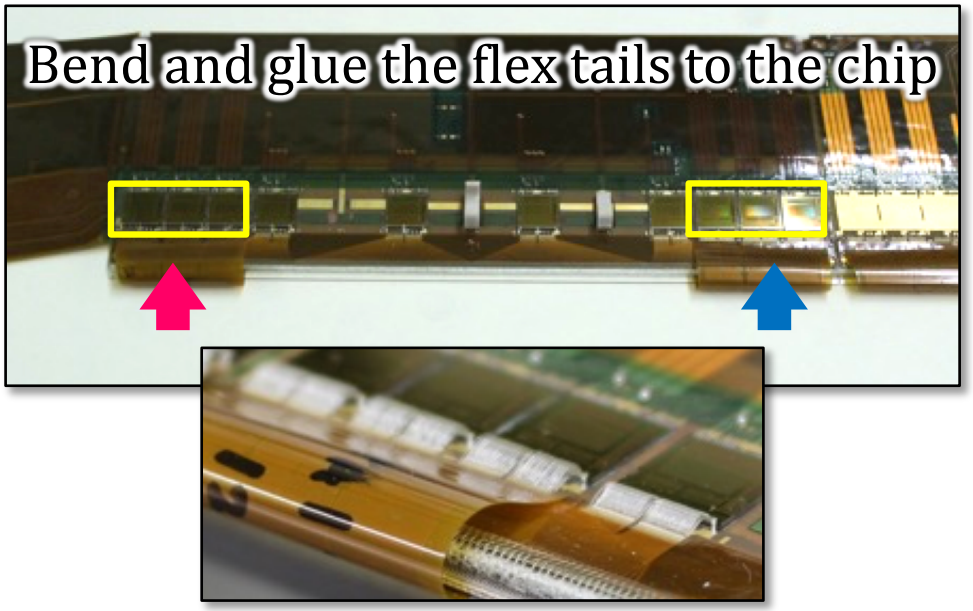


Origami Concept



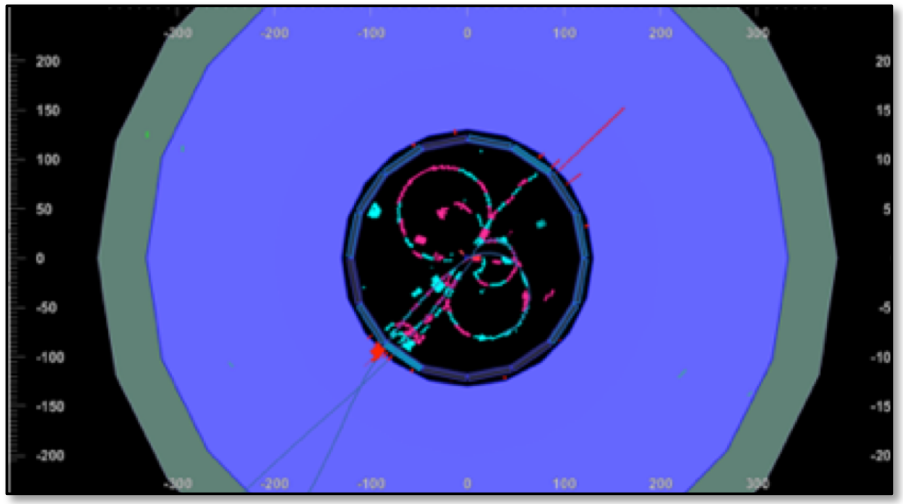


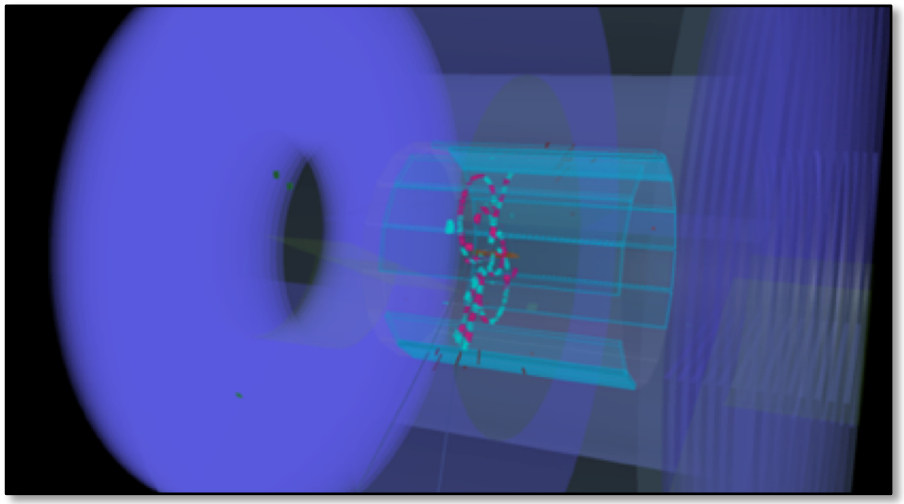




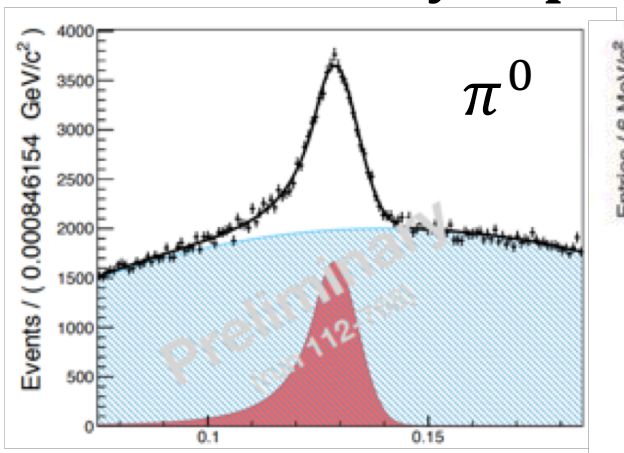
SuperKEKB + Belle II

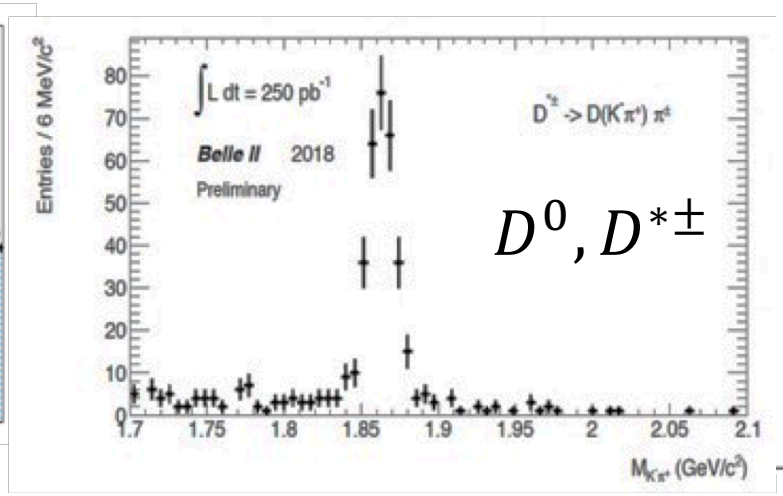
Event display (2D and 3D):

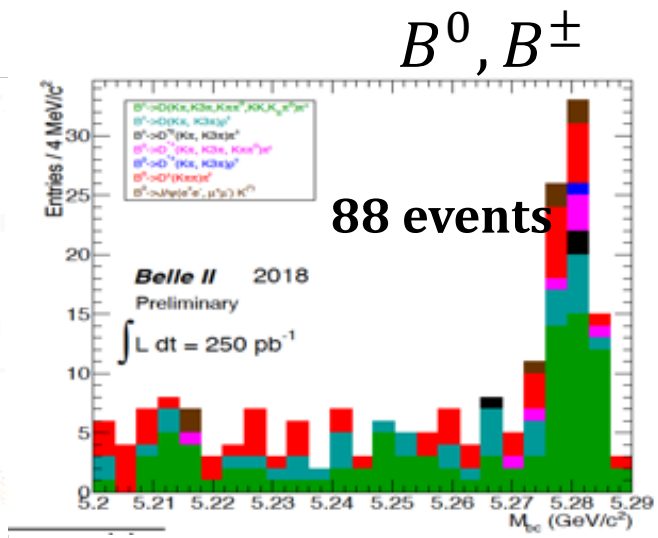




Re-discovery of particles:







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

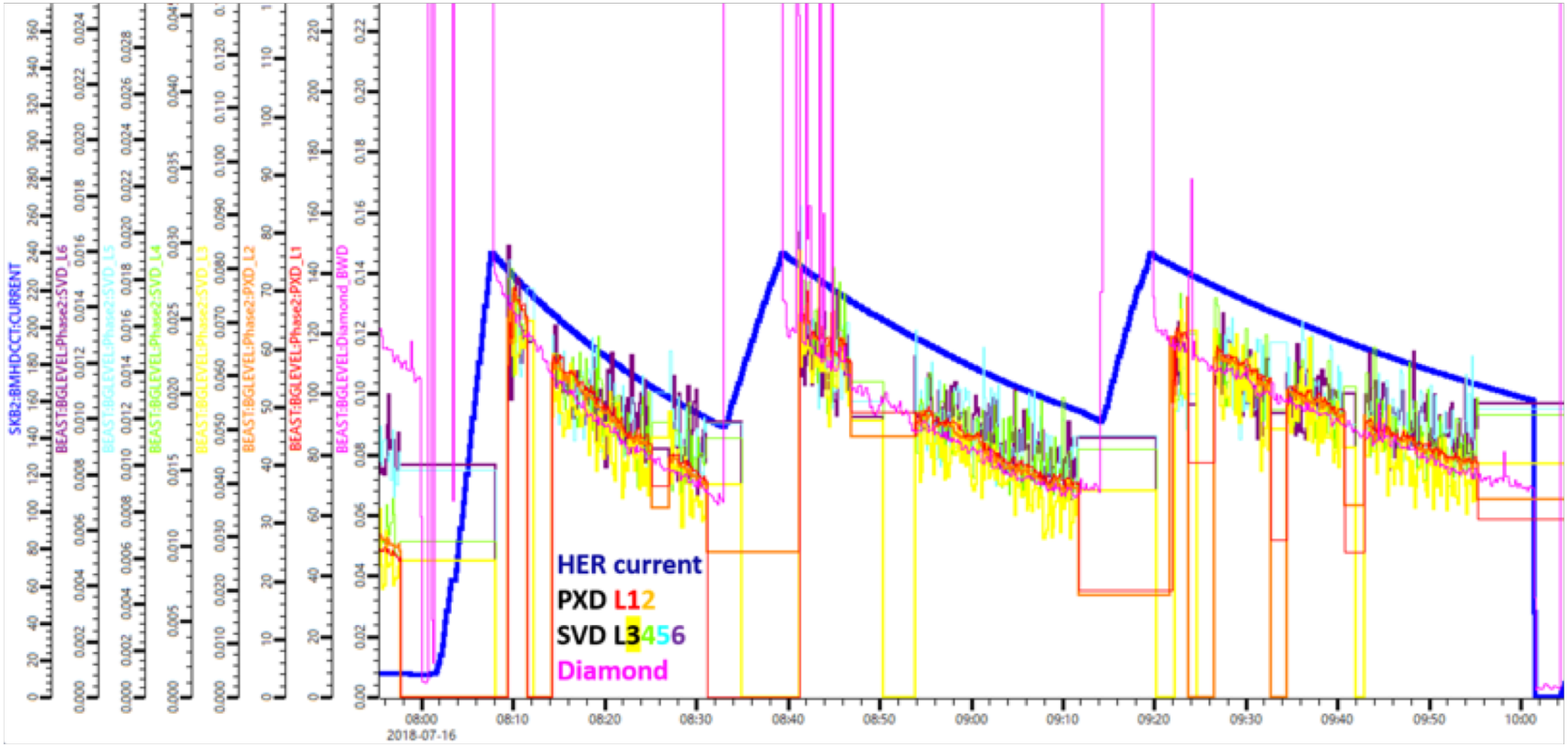
→ Extrapolation to final Phase 3 conditions gives x10 discrepancy with MC prediction

→ 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

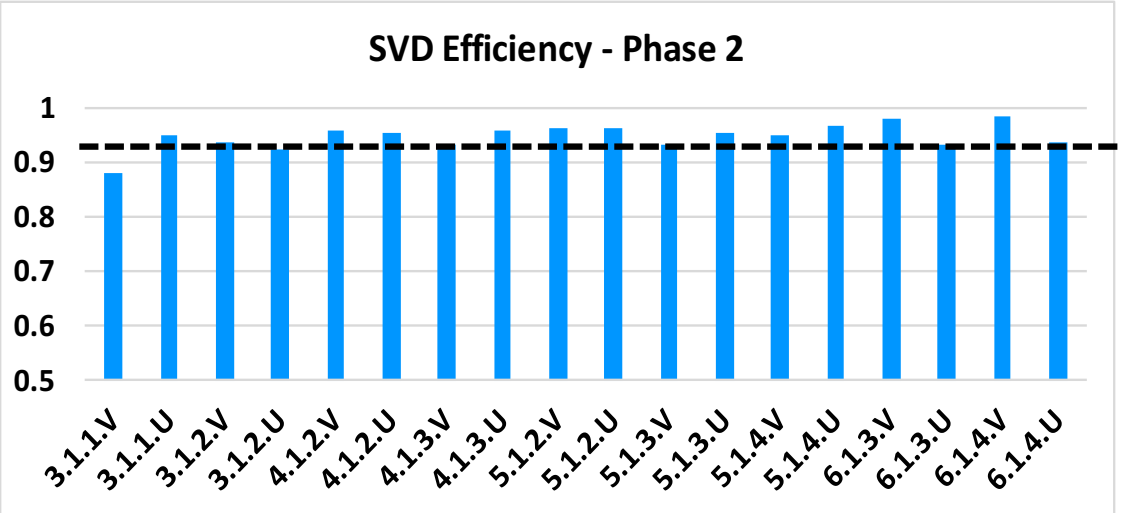
At the beginning of Phase 3 background improvement will be further pursued tuning SuperKEKB parameters and the new collimators installed

VXD Backgrounds in Phase 2

- Example of background levels measured for PXD/SVD & diamonds during Phase 2 background studies campaign

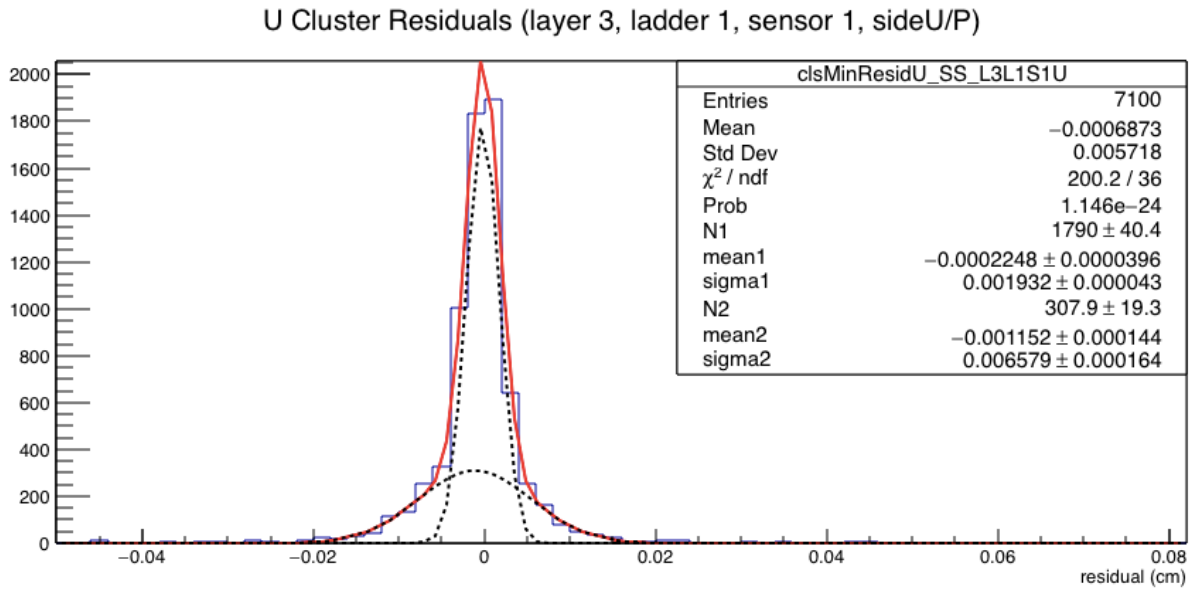


Efficiency and Residuals (Phase 2)



- 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

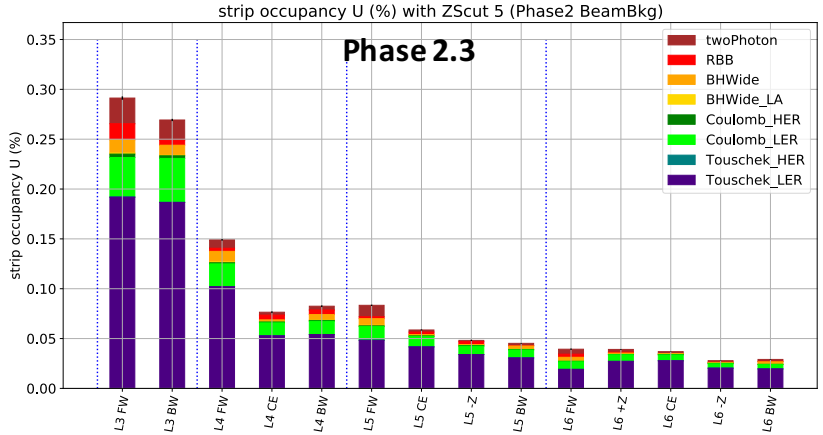
- Good efficiencies ≥ 95%, considering lower quality sensors installed
- Nice gaussian residuals, cluster position resolution not quoted yet, work in progress to estimate contribution from track extrapolation.



SVD Occupancy in background simulation

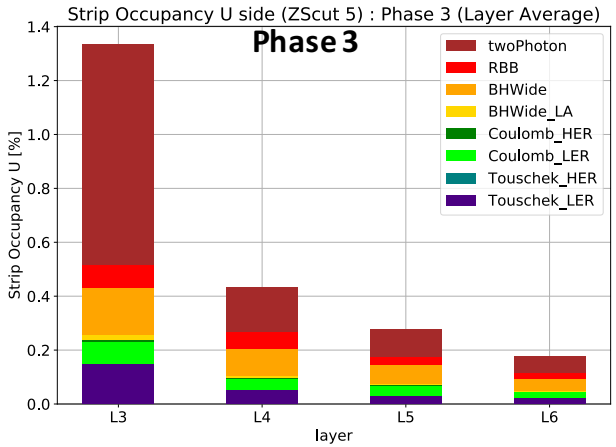
Phase 2.3

- 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