Operational experience and commissioning of the Belle II vertex detector

27th Vertex, 21-26 October 2018

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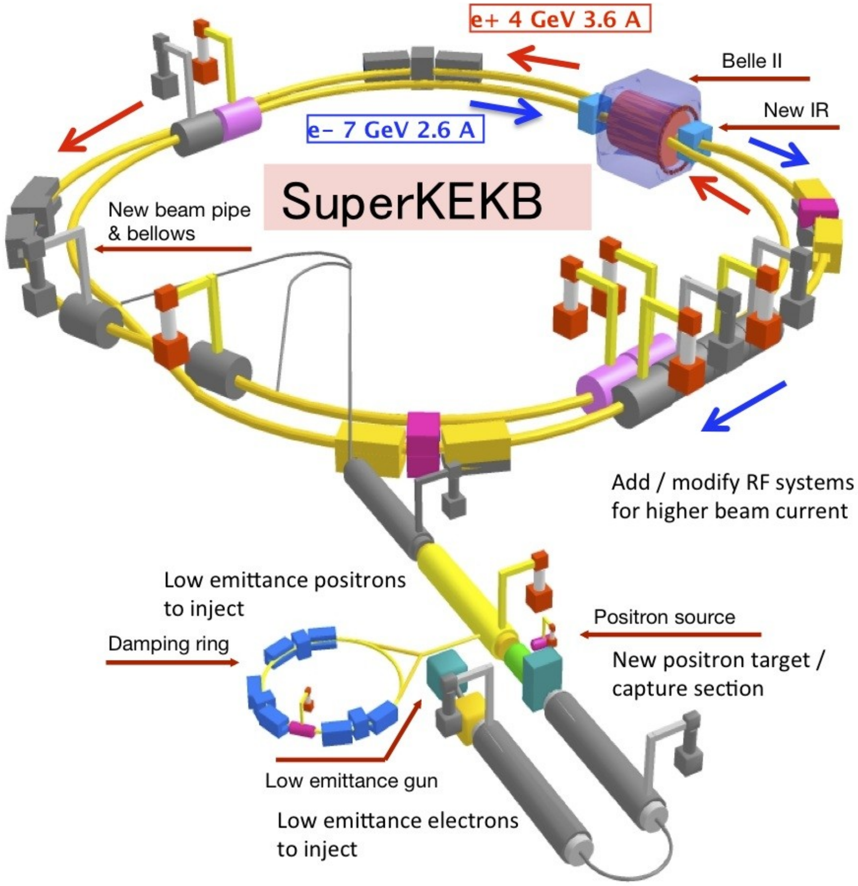
GEORG-AUGUST-UNIVERSITÄT GÖTTINGEN

Outline

- SuperKEKB and Belle II experiment
- The Belle II vertex detector for Phase 2
- Operation and calibration during first data taking
- Background measurements

SuperKEKB @ Tsukuba, Japan



- SuperKEKB: New Super Flavor factory in Tsukuba, Japan
- Asymmetric e+e- collider @ $E_{cm} = 10.58\text{GeV} = m(Y(4S))$
- Peak luminosity $L = 8 \times 10^{35}\ cm^{-2}\ s^{-1}$, 40 times higher than KEKB machine
- Nano beams: Beam spot size reduction (x1/20) and 2x higher currents

The Belle II detector

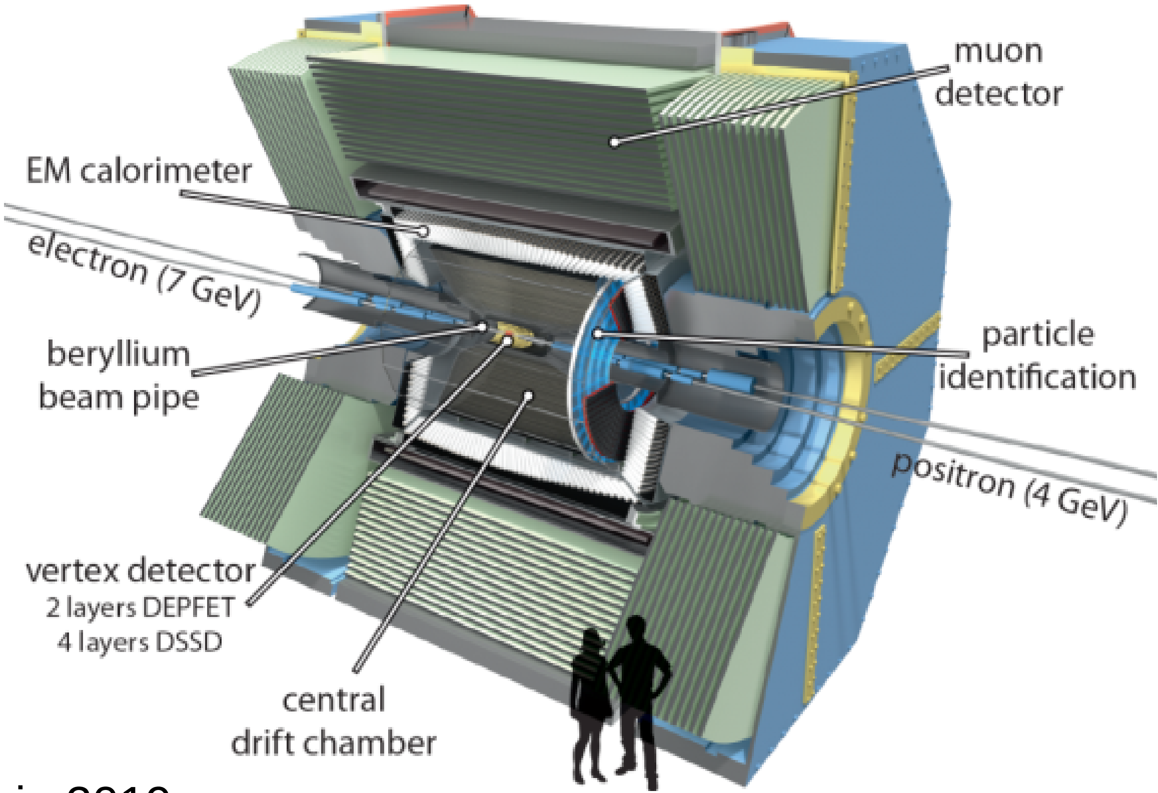
- Experiment needs excellent vertexing and tracking down to low-p_t

- Very low material budget for innermost layers

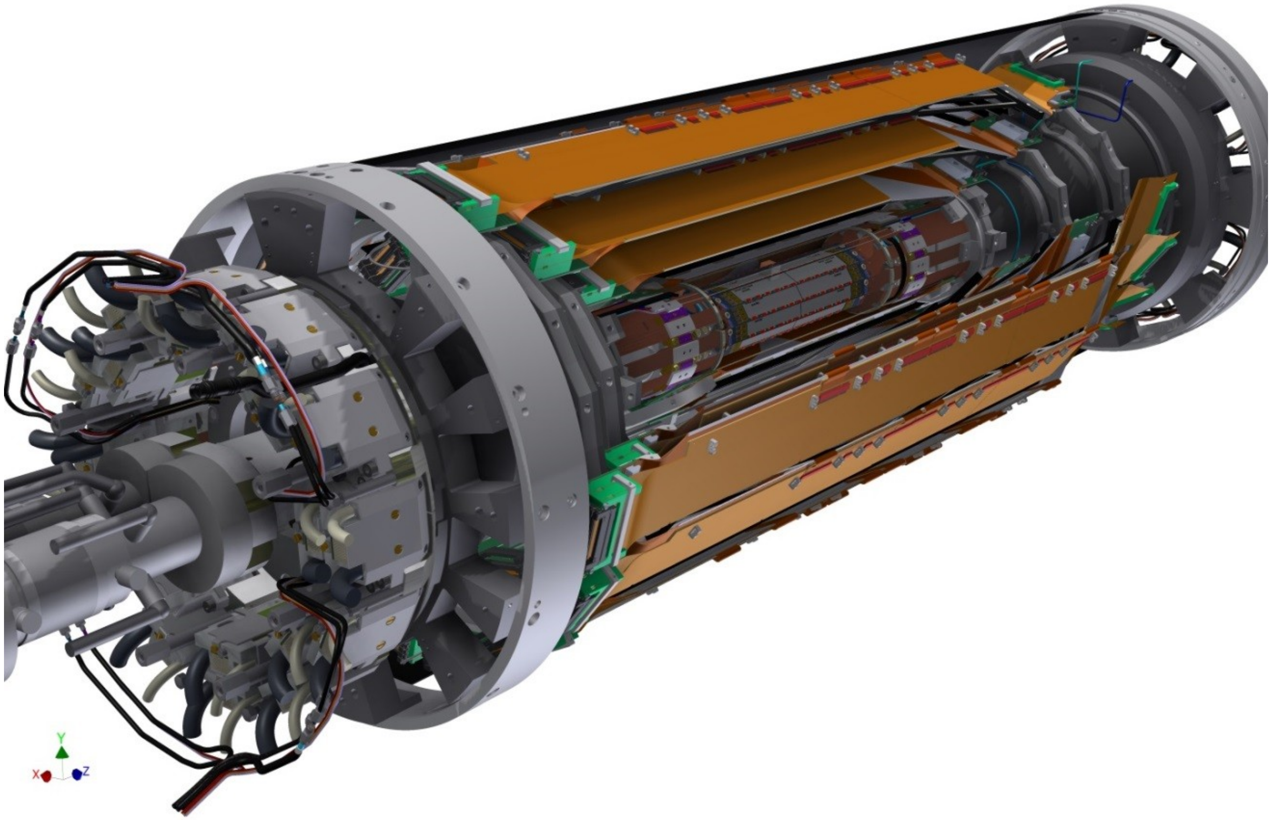
- Innermost pixel layer 14mm away from beam line

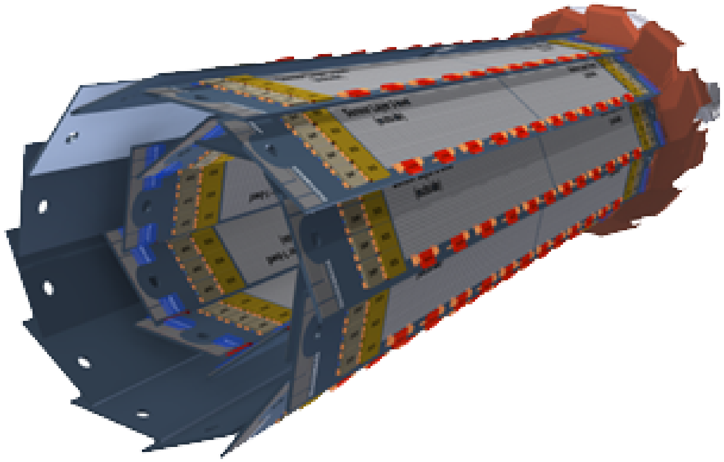
- Fast readout to operate in high background environment

- First physics data taking with full detector in 2019



The Belle II vertex detector





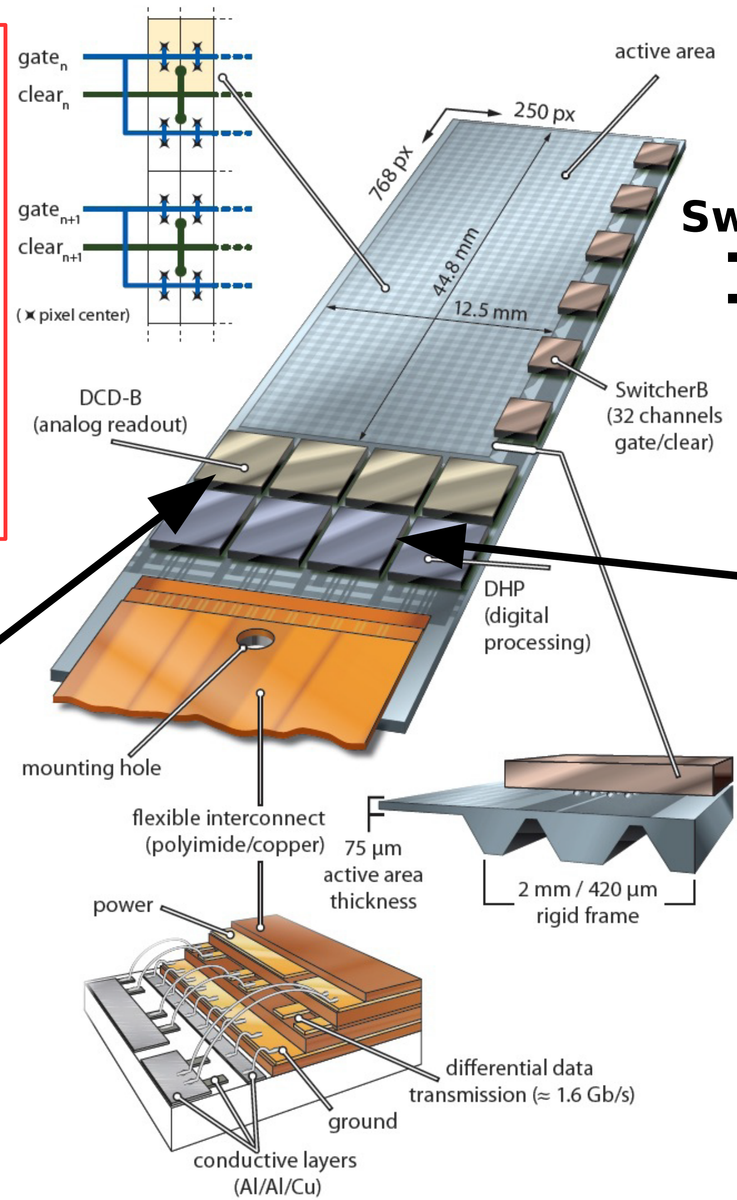
- **Pixel Detector (PXD)**
2 layers of DEPFET pixels
r = 1.4 cm, 2.2 cm
L = 12 cm
~ 0.027 m^2

- **Silicon Vertex Detector (SVD)**
4 layers of DSSD
r = 3.9 cm, 8.0 cm, 10.4 cm, 13.5 cm
L = 62 cm
~ 1 m^2

The PXD module: Sensor and readout

- PXD with DEPFET active pixels
- 75µm thick sensors
- 40 sensors, 250x768 pixels each

- 3% occupancy limit (DHP)
- L1: 1% occupancy with nominal bg
- Trigger rate of up to 30kHz
- Sensor and ASICSs rad. hard for 20MRad in ten year operations



SwitcherB - Row Control

- Gate and Clear signal
- Rad. hard proved (36 Mrad)

DHP - Data Handling Processor

- Common mode and pedestal correction
- Data reduction (zero suppression)
- Timing and trigger control
- Rad. Hard proved (100 Mrad)

DCDB - Drain Current Digitizer

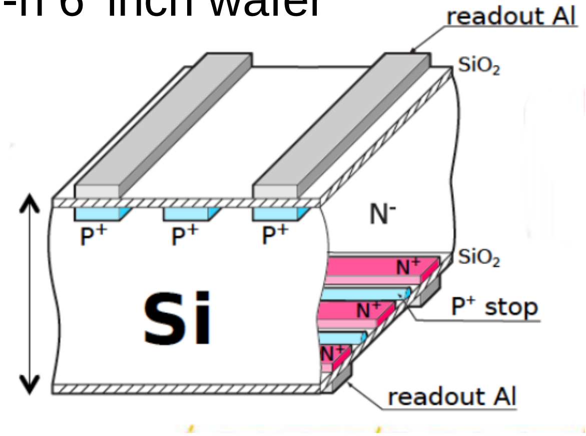
Amplification and digitization of DEPFET signals.

- 256 input channels
- 8-bit ADC per channel
- 92 ns sampling time
- Rad. hard proved (10 Mrad)

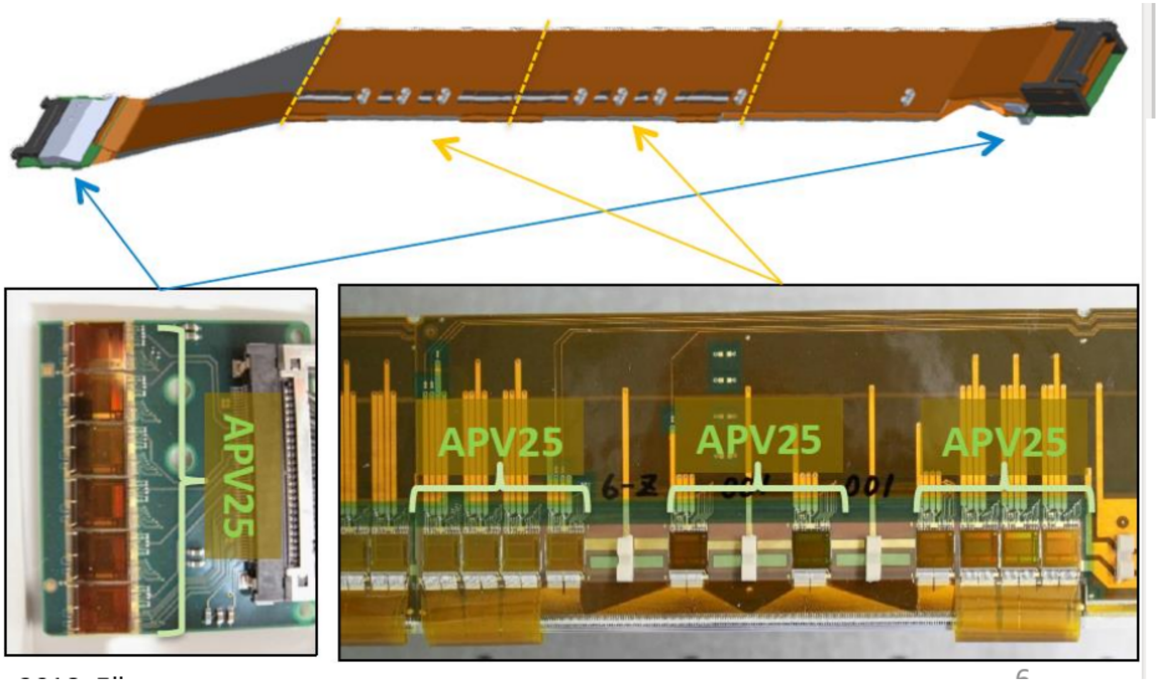
The SVD module: Sensor and readout

300-320µm thick double sided silicon micro-strip detector (DSSD)

p-in-n 6' inch wafer

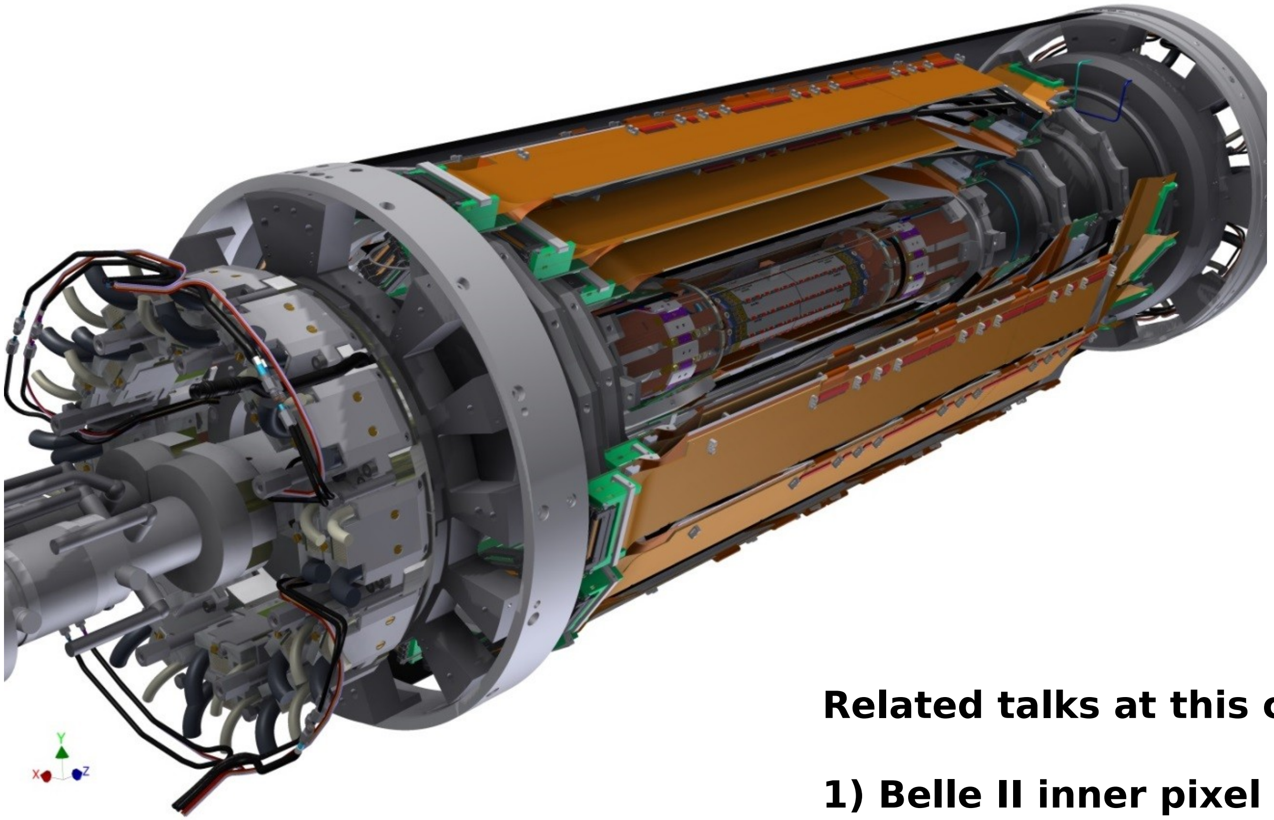


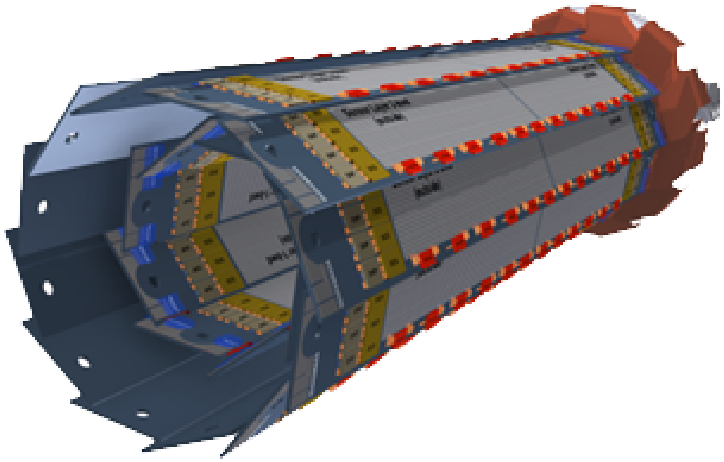
- Sensors and chips are rad. hard for 10MRad in 10 years of operation
- Optimal tracking performance for SVD for occupancy <2-3%.
- L3: 1.3% average occupancy with nominal bg



APV 25 chip (developed for CMS)
- Shaping time 50ns
- 128 input channels per chip
- Chips thinned down to 100µm to reduce material
- Central DSSD's → Origami chip on sensor concept to reduce cap. noise

The Belle II vertex detector





Related talks at this conference:

1) **Belle II inner pixel detector upgrade**
   (C. Koffmane, Tuesday, 15:30)

2) **Belle II silicon strip detector upgrade**
   (T. Higuchi, Tuesday, 16:30)

3) **Tracking and vertexing in Belle II**
   (B. Scavino, Wednesday, 16:30)

Commissioning of Belle 2 vertex detector

3 commissioning phases:

- **Phase 1**: no Belle II detector, no final focus system, no collisions, accelerator commissioning. Done

- **Phase 2**: Belle II in final position, final focusing in place, VXD volume installed with BEAST II detectors (including 1/10 of final design Belle II vertex detector and 1/10 of its readout). Done

- **Phase 3**: full Belle II detector, physics runs.

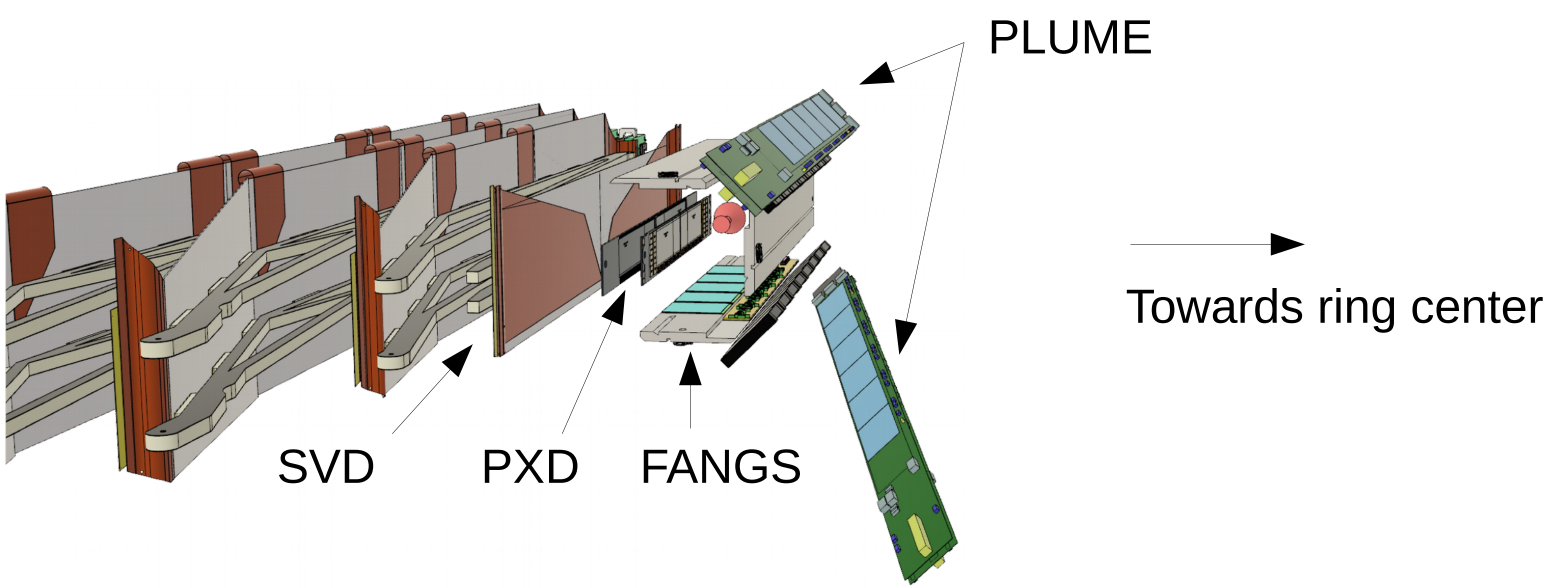
Goals for Phase 2:

- SuperKEKB: Demonstrate increase of specific luminosity in regime $\beta^*_y < \sigma_z$

- Radiation safe environment for installing final Belle II vertex detector (measure background components using BEAST II detectors)

- First physics data taking of the (Phase 2) vertex detector with the outer detectors of the Belle II experiment.

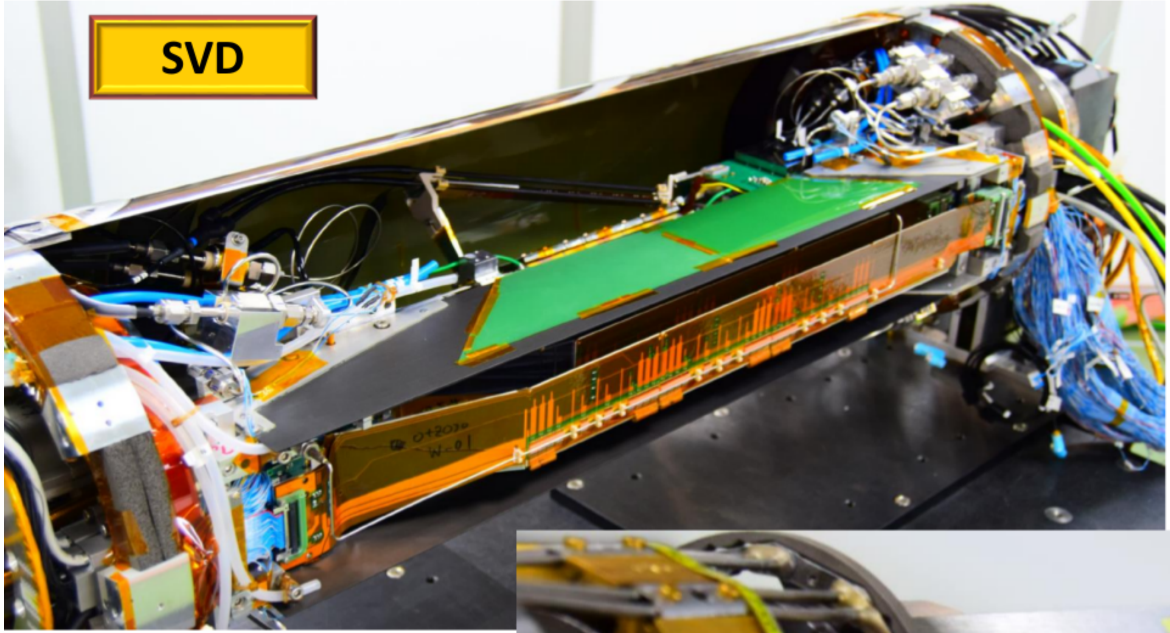
Phase II detectors in VXD volume



PXD + SVD form 6 layers in final Belle II geometry. Only one ladder per layer in +X. All ladder will be replaced for final Belle 2.

- FANGS: Hybrid silicon pixel detector with FE-I4 front end (ATLAS)
- CLAWS: Plastic scintillators with SiPM readout (ILC)
- Plume: Double sided CMOS pixel detector (STAR)
- Diamond sensors for total ionizing dose measurement and for beam abort system (not shown)
- ^{3}He detector for thermal neutron flux measurement (not shown)
- TPC for fast neutron flux measurement (not shown)

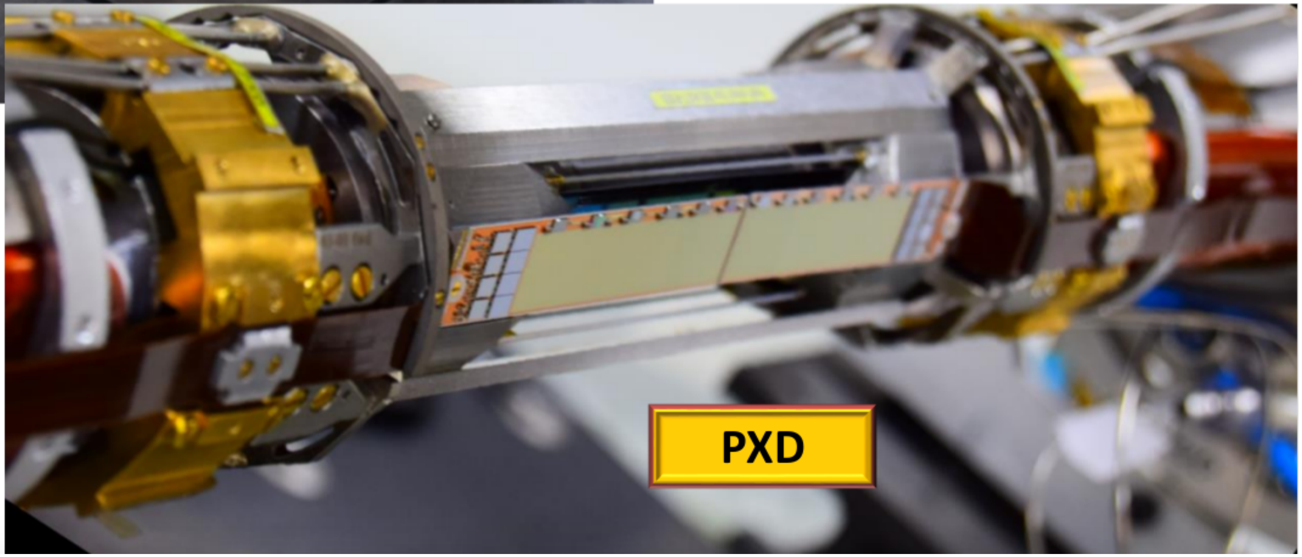
Phase II installation and schedule



PXD+SVD modules sent to Japan until September 2017

Attached to beam pipe and integrated with rest of BEAST II in Sep-Nov 2017

Insertion into Belle II in mid. Nov 2017



Global cosmic run 14.2

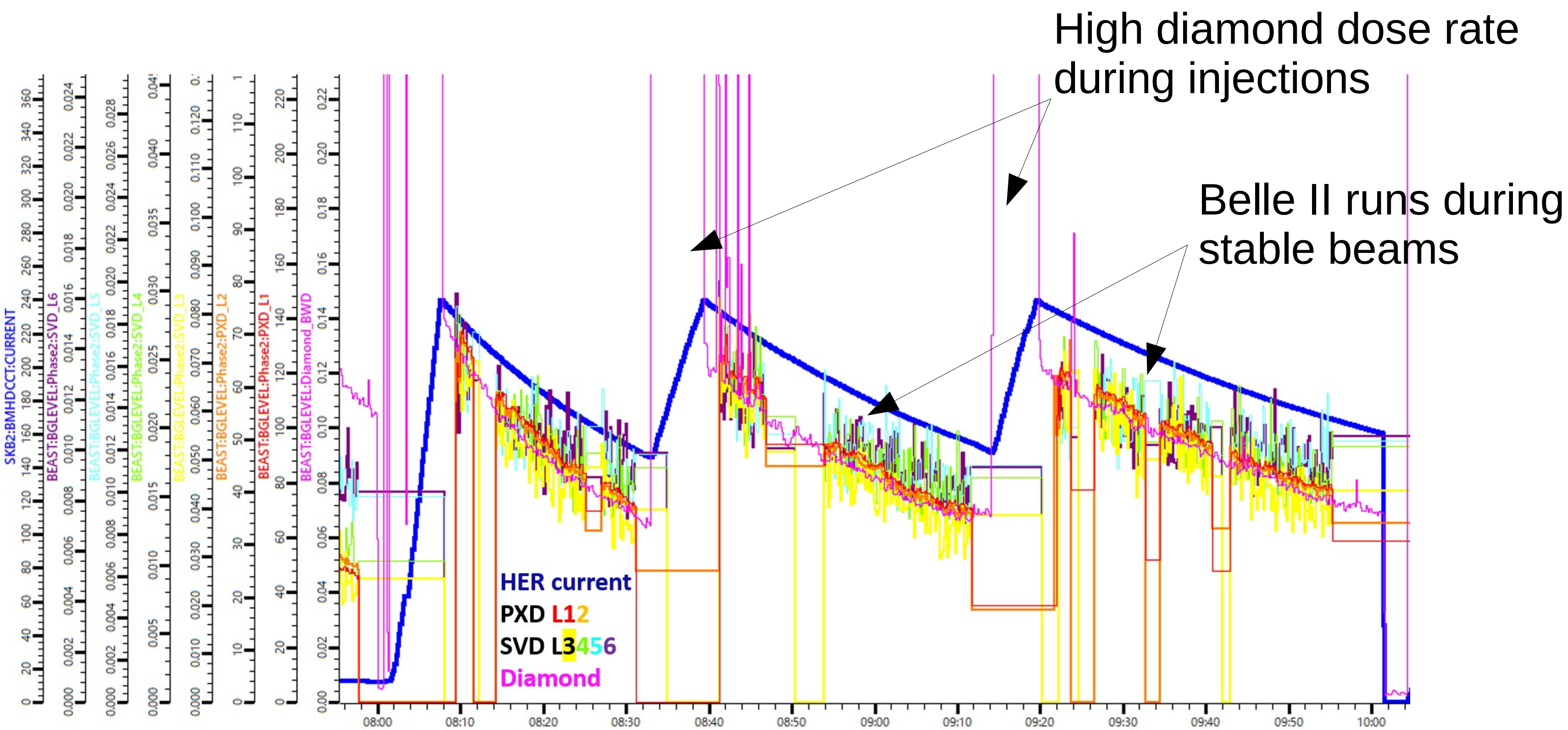
First beams mid March

First collisions 26.4

End of Phase 2 on 18.7 (on schedule)

Operational aspects of Phase 2

- BEAST II detectors always running from start to end of Phase 2
  - Provided 1Hz background rates to Belle II and accelerator control room
- PXD and SVD fully integrated in Belle 2 DAQ, run control and HV control.
  - HV switched ON only after stored beams were declared stable and OFF before new filling

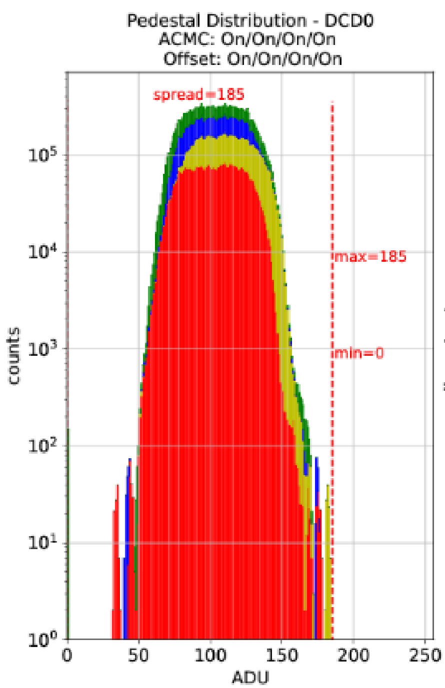


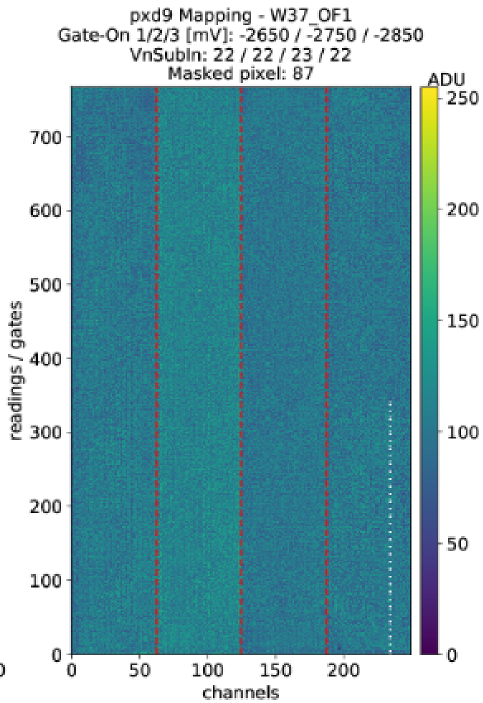
PXD calibration and optimization

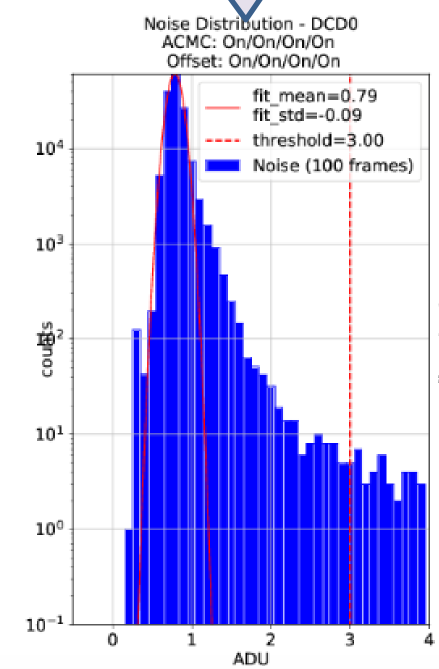
- PXD modules were characterized and optimized before installation
- Analog common mode correction essential to compensate drift of drain currents over time
- Switchable current sources at input of Drain Current Digitizer used to compress spread of drain currents from sensor.

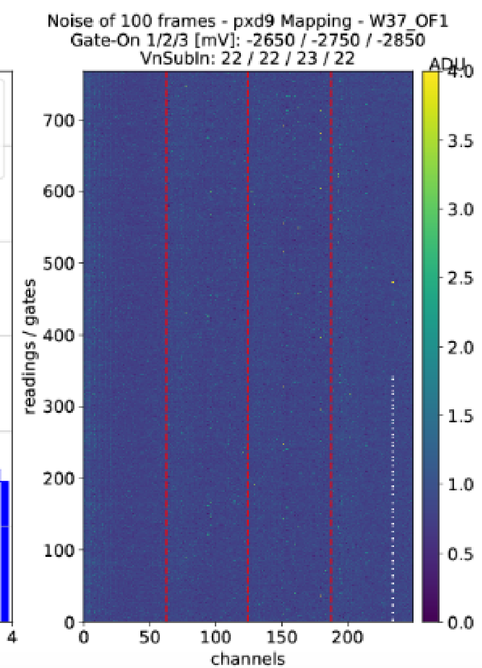
Narrow and stable pedestals on sensors

Noise ~0.8ADU (~100e ENC) over sensor

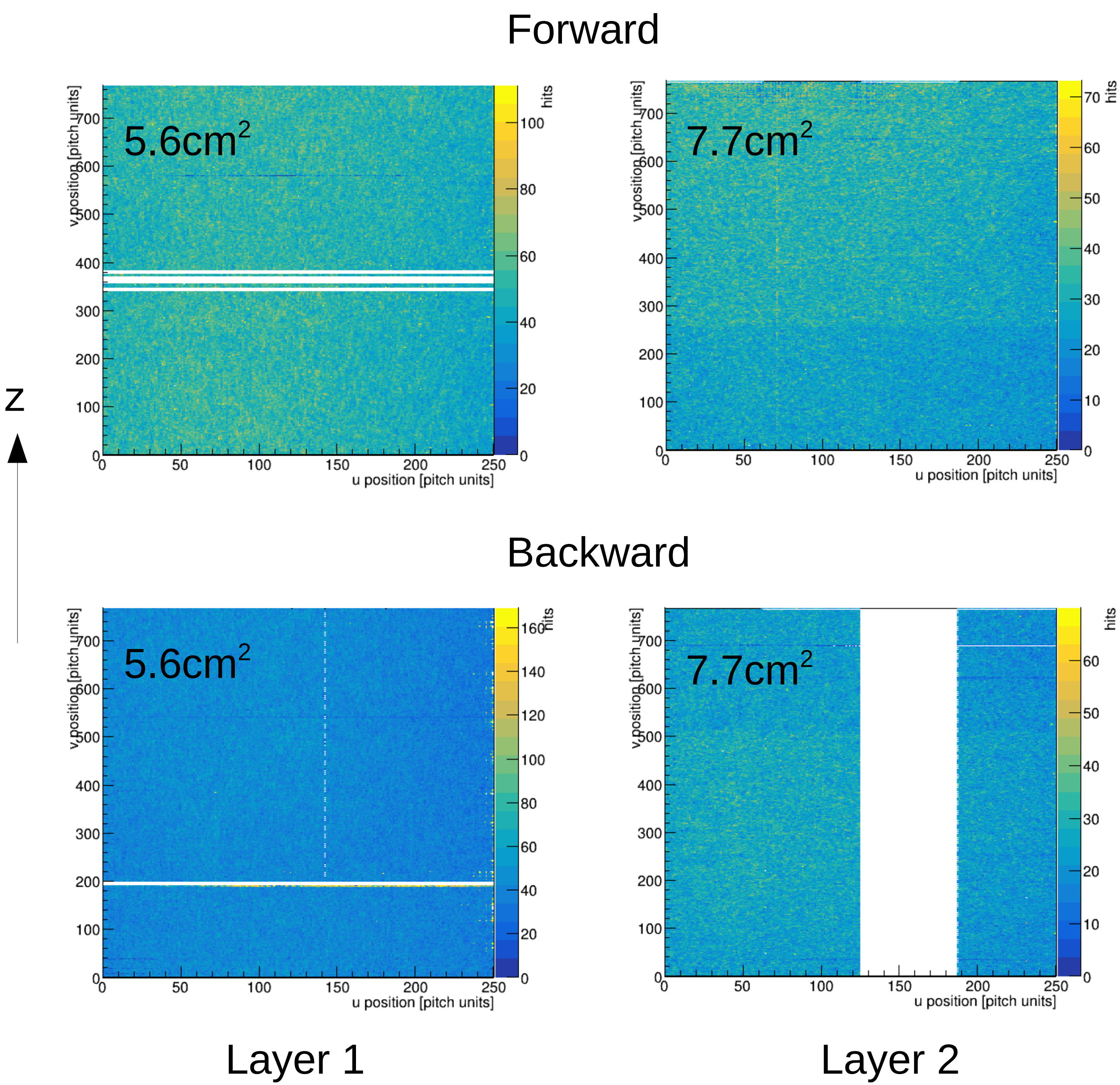








PXD hit maps during phase 2



Physics run after first collisions

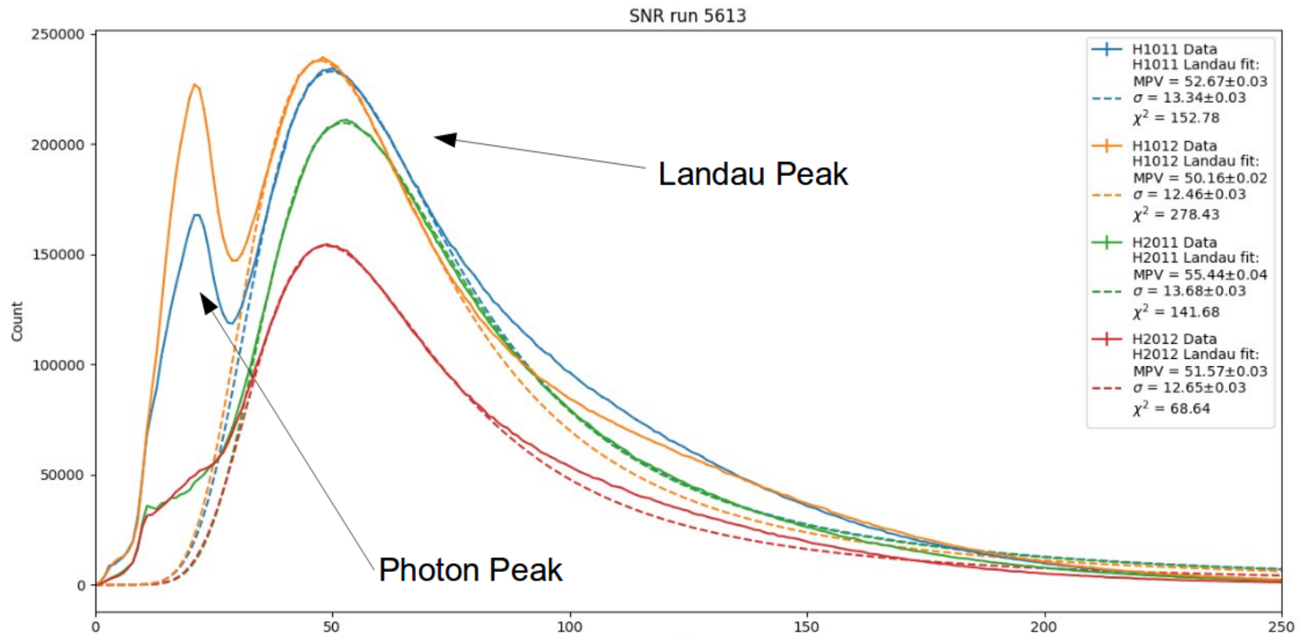
Flat hit profile seen for all four PXD sensors.

B-grade PXD modules with few masked channels and broken metal lines

Lost optical connection for one DHP in Layer 2 BWD sensor

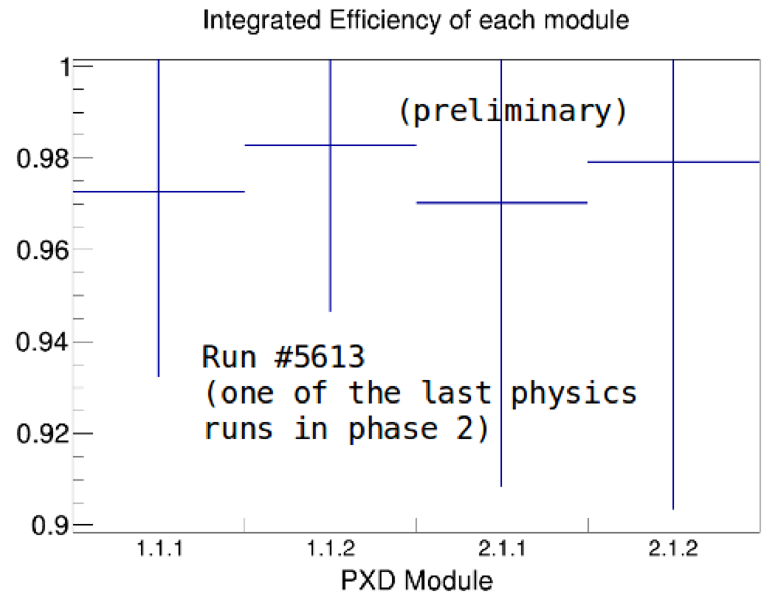
- Connection re-established in tests after de-installation of Phase 2
- Add strain relief for optical fibers at PXD dock box

PXD SNR and hit efficiency



- Cluster S/N ratio distribution (including bg clusters)
- Landau fit gives most probable SNR ~50 for all sensors
- Unexpected low energy peak on inner layer (→ later discussed in background part)

- PXD hit efficiencies estimated using sample of high momentum ($p_T > 4$ GeV/c) CDC tracks having at least 3 SVD hits
- Tracks extrapolated near dead pixels are excluded

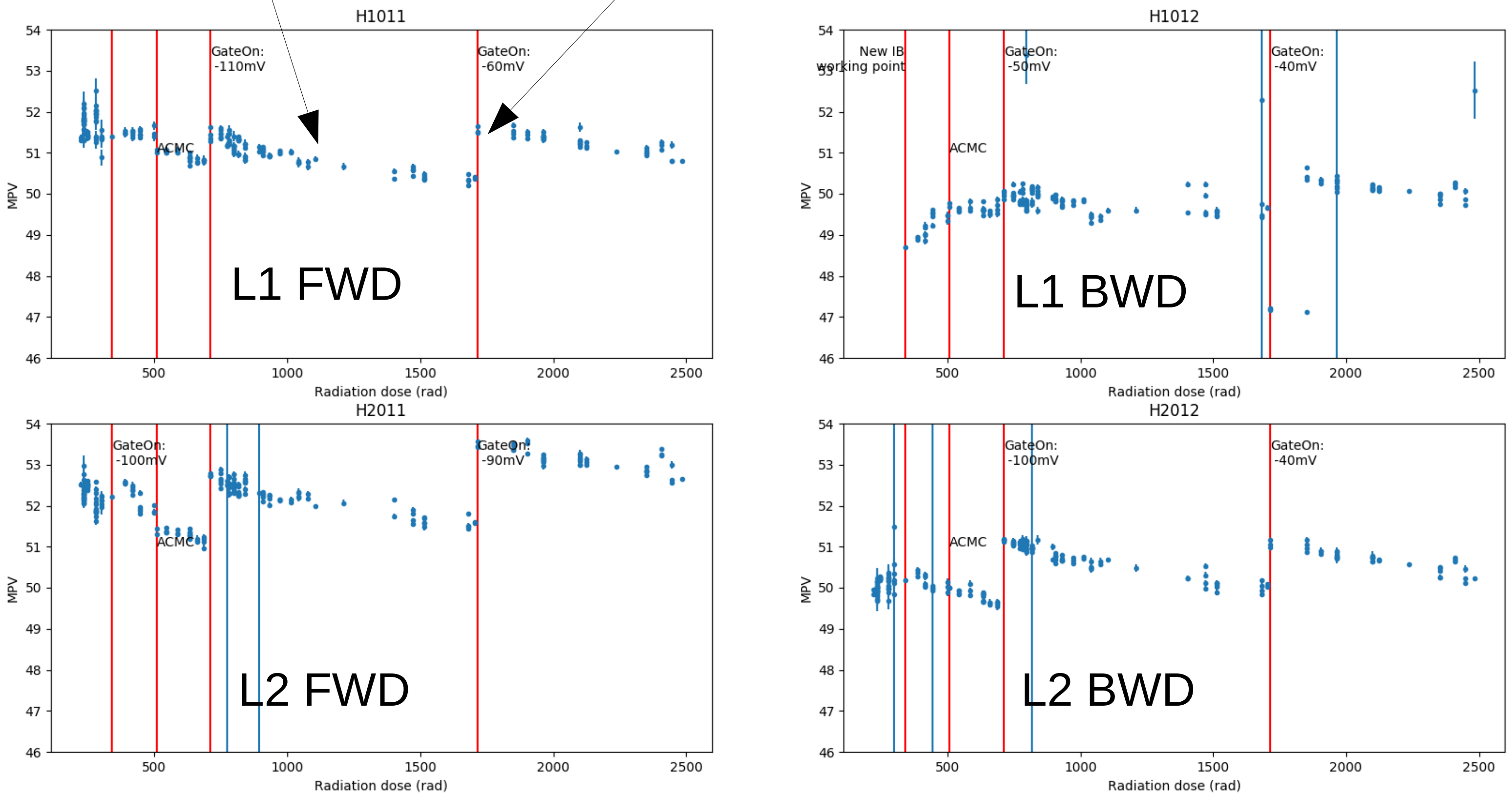


Evolution of PXD gains in Phase 2

Small drift of gains with TID due to shift of threshold voltage

Gain loss is recovered by adjusting Gate-On voltage

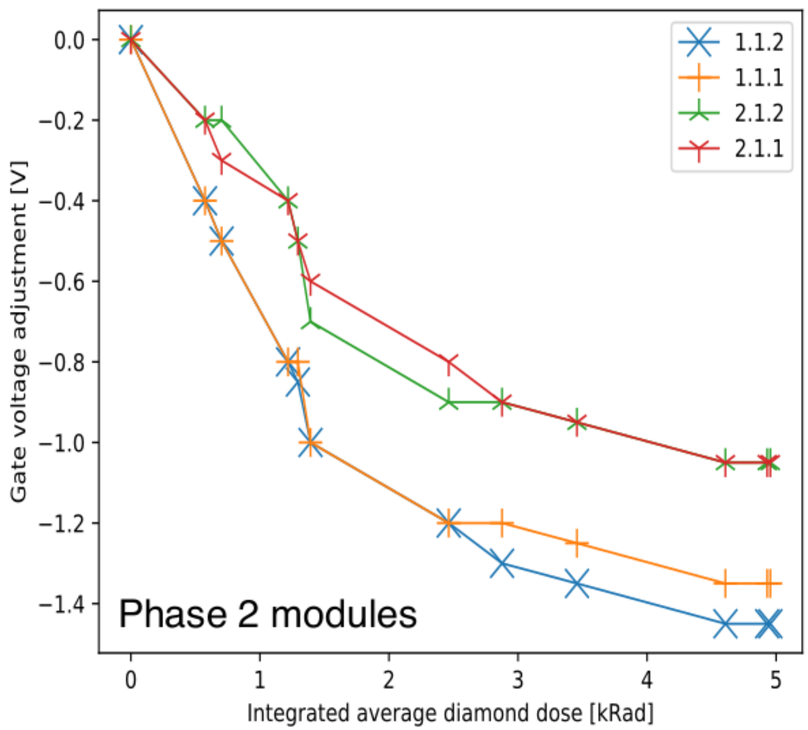
Most probable cluster charge (as proxy for gain)

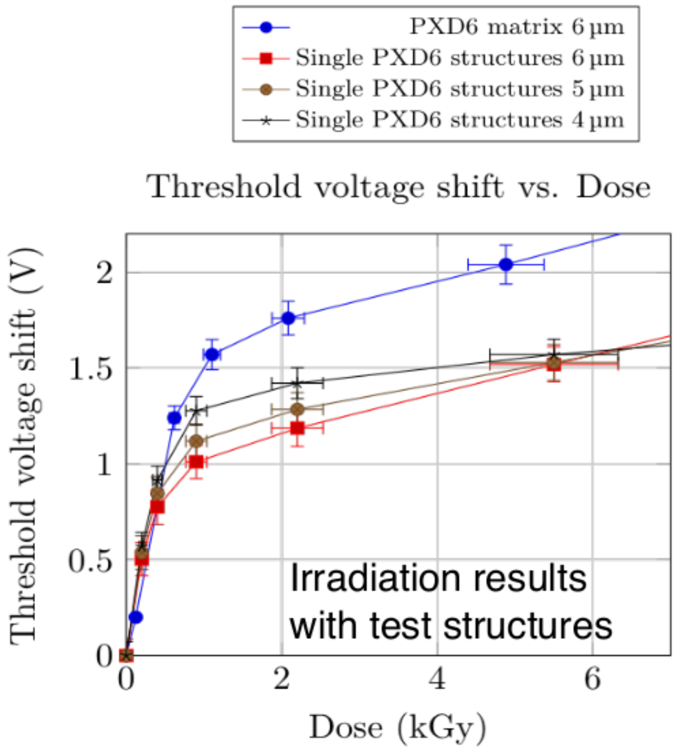


Integrated Diamond dose [rad]

$$MPV \sim g_q \sim \sqrt{I_D} \sim (U_{Gate} - U_{Threshold})$$

Total ionizing dose for PXD



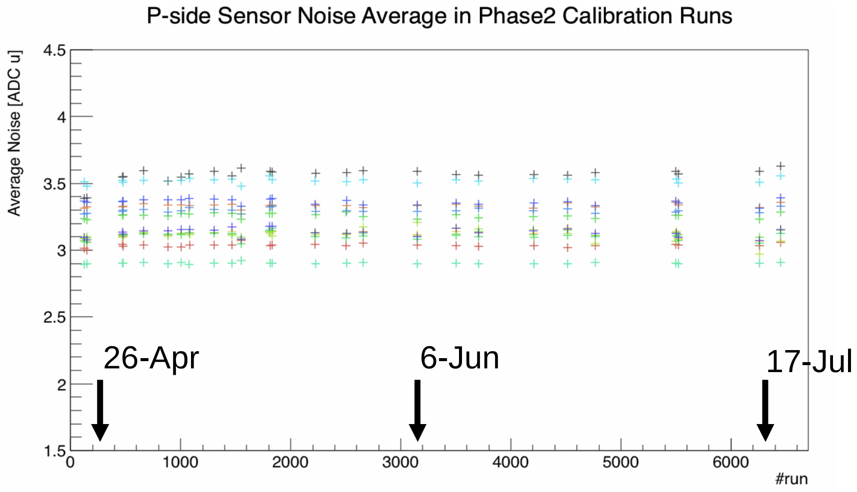


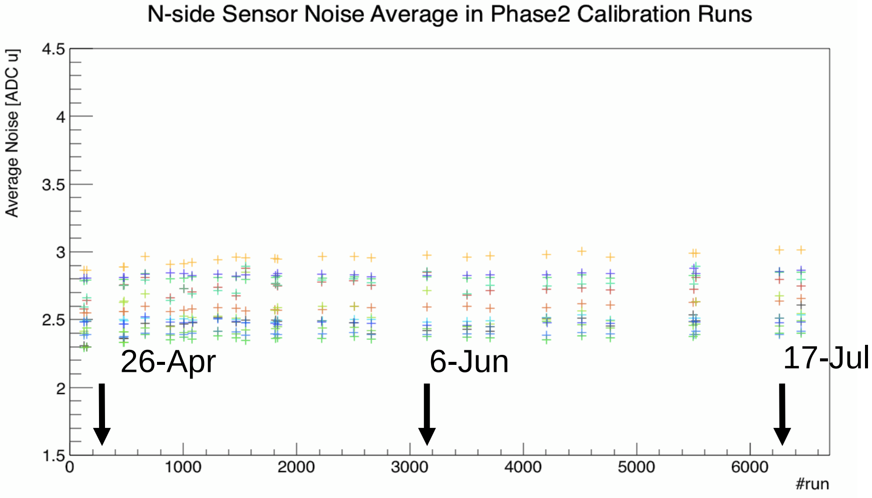
- Estimated TID from threshold voltage shift: ~ 2-5 kGy
- Factor 50-100 larger than estimate from diamonds
  - diamonds have only little sensitivity to ~10keV photons
  - different location on beam pipe in z and rϕ

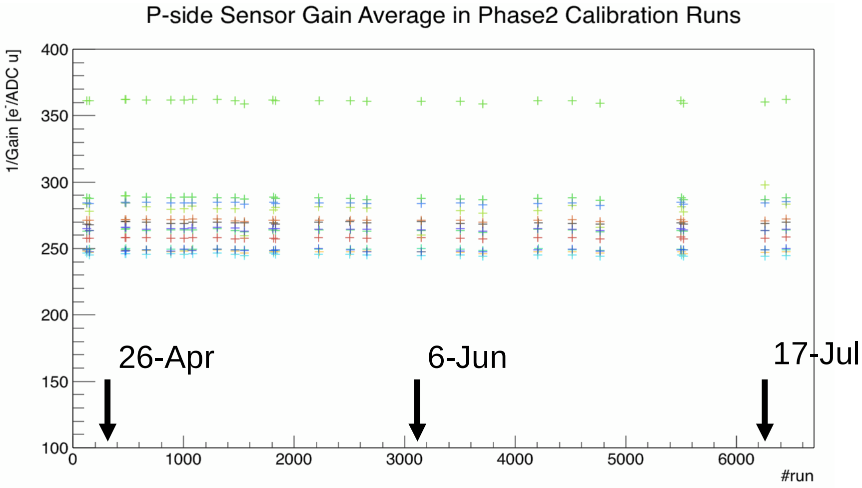
- Radio-chromic foils @ diamonds see factor 5-10 higher dose than diamonds and a soft radiation component (<100keV)
- Ratio of PXD dose rate (sens. Si volume) to diamond dose rate gives factor 10-100 depending on run condition

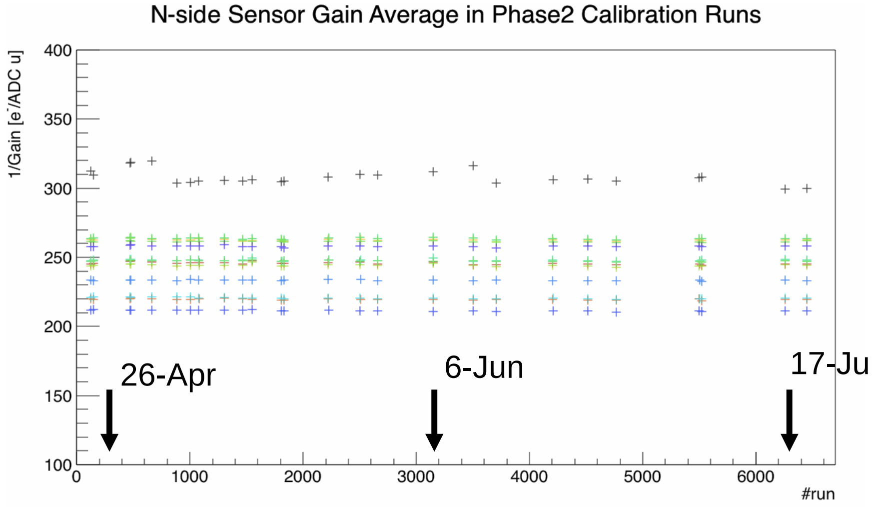
SVD calibration

Very stable calibration constants (noise, gain) during Phase 2 run



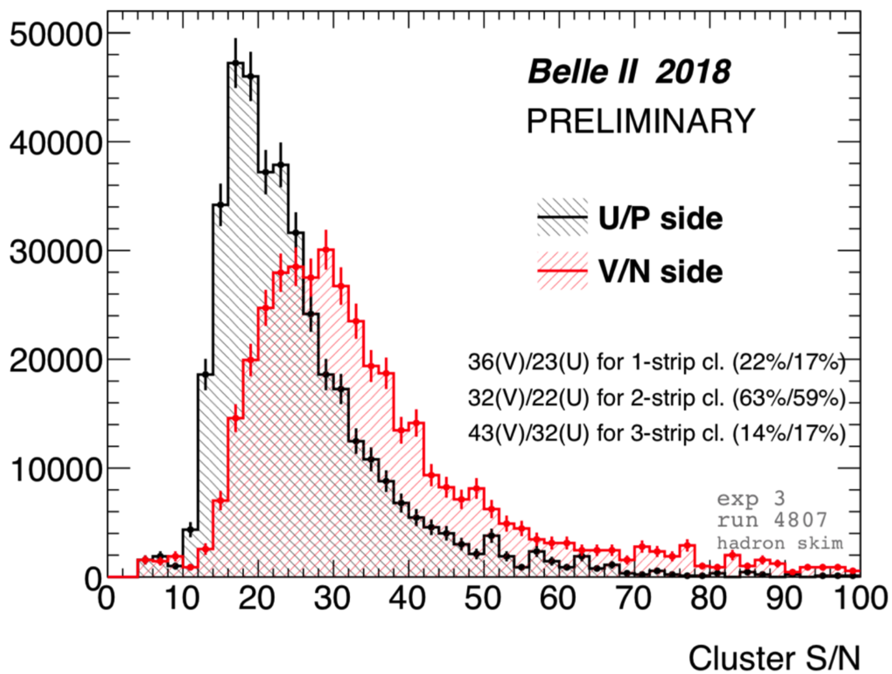




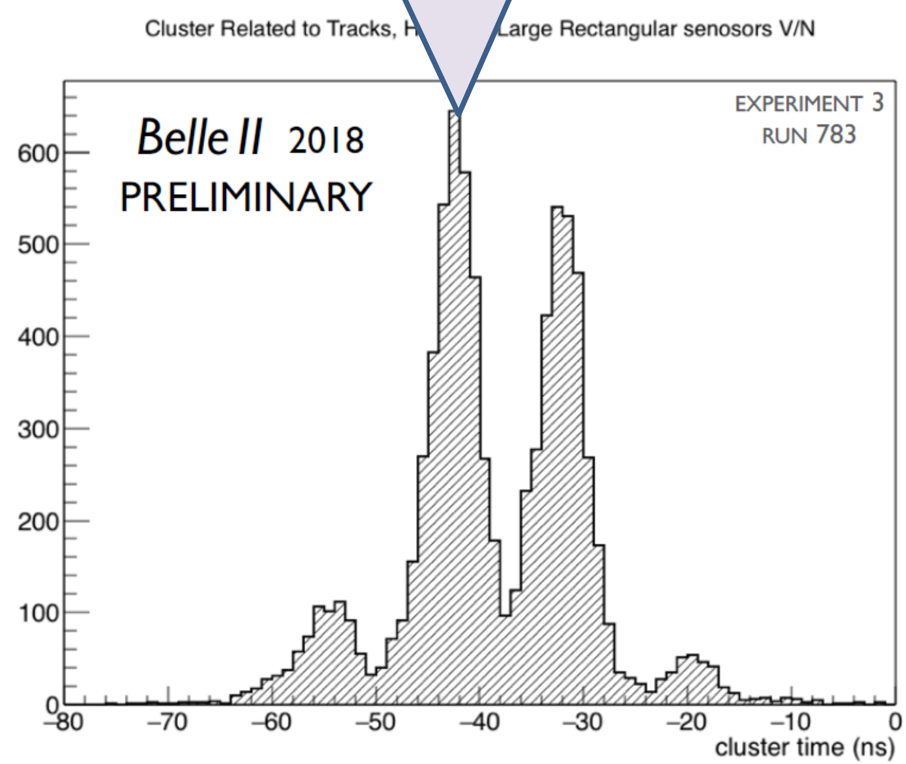


SVD performance in Phase 2
Highlights from first data

Cluster S/N Ratio Distribution for Clusters Related to Tracks

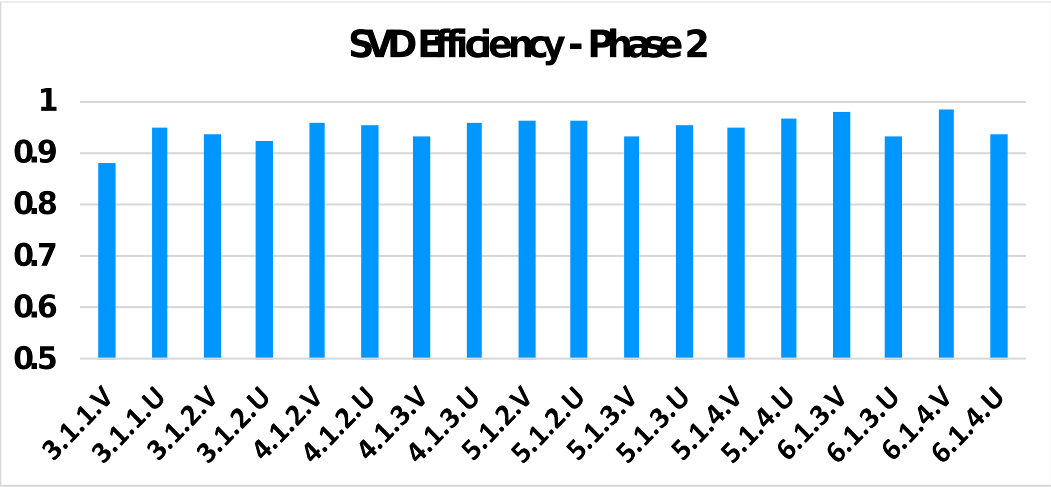


The filling pattern of the machine with different bunches separated by ~10 ns



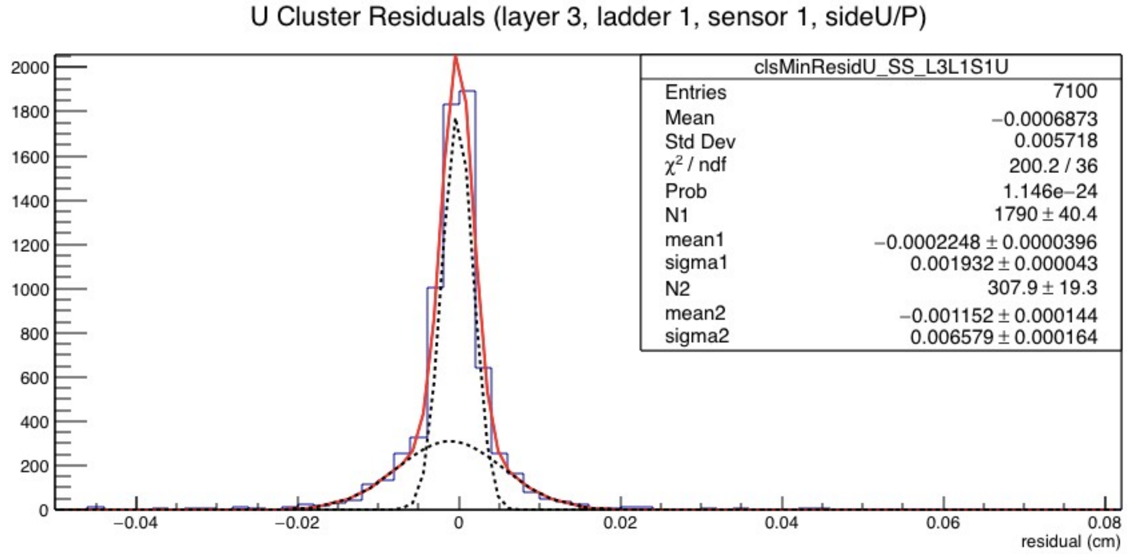
Cluster Time Distribution for Clusters Related to Tracks

SVD efficiency and residuals



- 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.

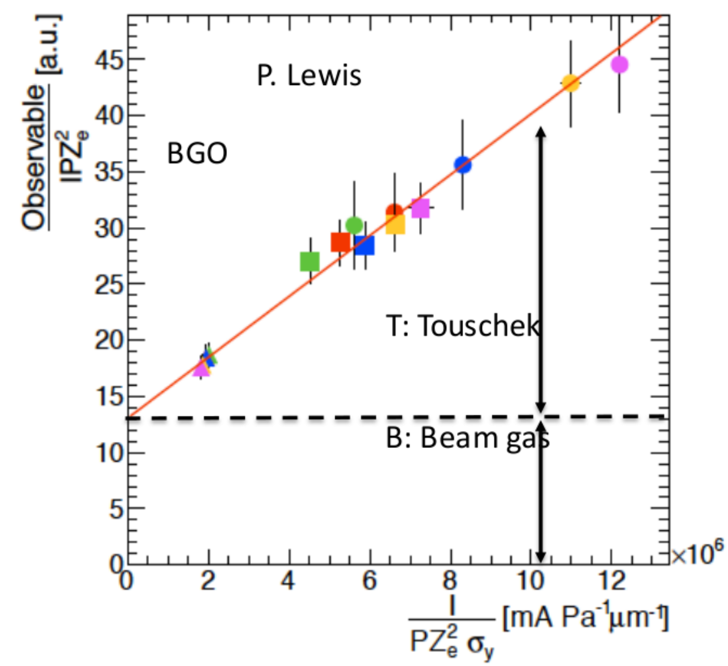


Estimating backgrounds from data

Background sources

Touschek scattering: single Coulomb scattering event. Phase 1: measured, consistent with simulation.	$R_{Tou} \propto \frac{1}{\sigma} E^3 n_b I_{beam}^2$
Beam-gas scattering: Coulomb scattering with residual gas atoms and bremsstrahlung. Phase 1: measured, more than predicted in simulation but	$R_{bg} \propto IP$
Synchrotron radiation: photon emission from beam particles. Phase 1: not measured.	$R_{sr} \propto E^2 B^2$
Radiative Bhabha: neutron production from emitted photons; particle loss because of too much ΔE wrt nominal energy. Phase 1: not measured.	$R_{RB} \propto L$
Two photons process: low momentum e⁺e⁻ pairs hitting VXD. Phase 1: not measured.	$R_{tp} \propto L$
Injection background: injected bunch is perturbed, resulting in particle losses. Phase 1: measured (time structure and energy of radiation produced)	

Example data from Phase I

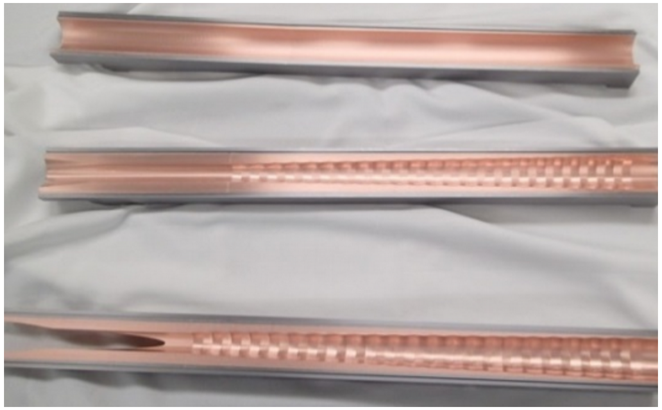


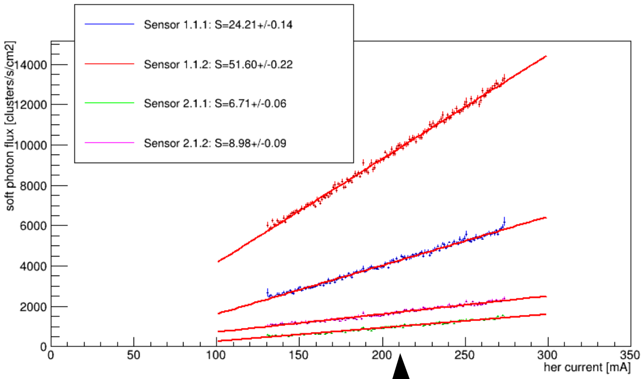
- Single beam studies with different beam sizes σ_y (by varying ε_y)
- Measure detector rate at 1Hz to follow pressure p and ring current I
- Fit B, T from scaling law to data and compare with MC
- Use ratios B_{data}/B_{MC} and T_{data}/T_{MC} to correct MC rate for Phase 3

$$Rate = T\frac{I^2}{\sigma_y n_b} + BZ_{eff}^2 Ip$$

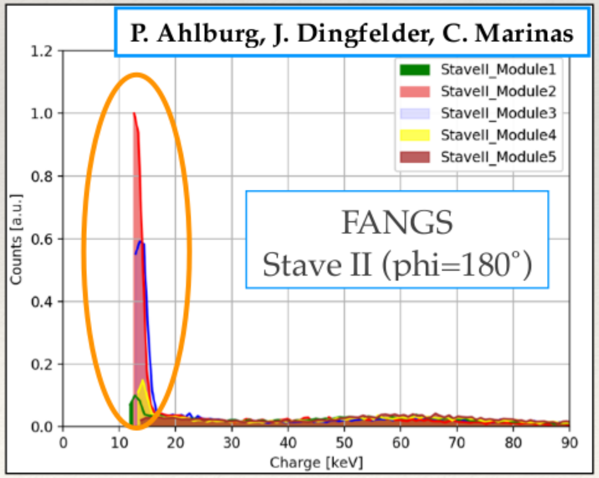
SR radiation background in Phase 2

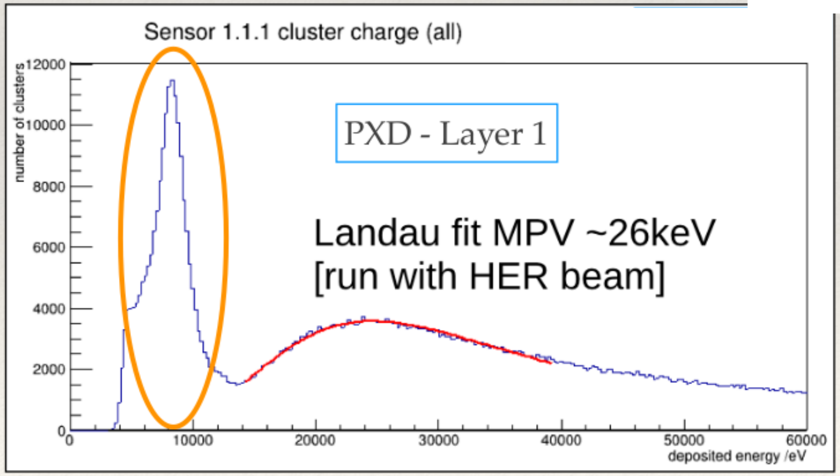
- $R_{sr} = E^2B^2$ → dominant contribution expected from HER
- Energy of SR photons expected to be from few keV to tens of keV
- Inner surface of beryllium beam pipe coated with Au layer to absorb SR photons
- Ridge structures of incoming pipes to avoid hits from forward reflected SR photons in beam pipe
- Direct hits stopped by tappered shape of incoming beam pipes
- PXD (+X) and FANGS (-X) observed soft photon peaks for both beam around 6-10keV
- “Postdicted” in new MC simulations with more precise Geant4 physics list





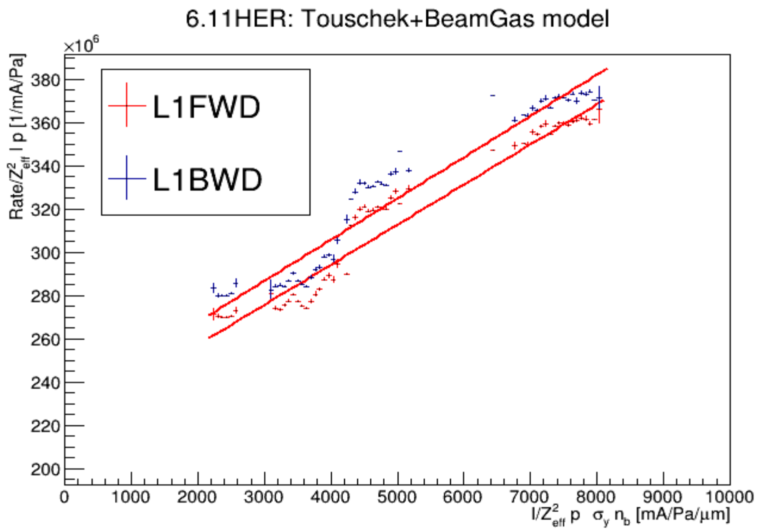
Rate of soft photon hits in PXD scales just with current + offset





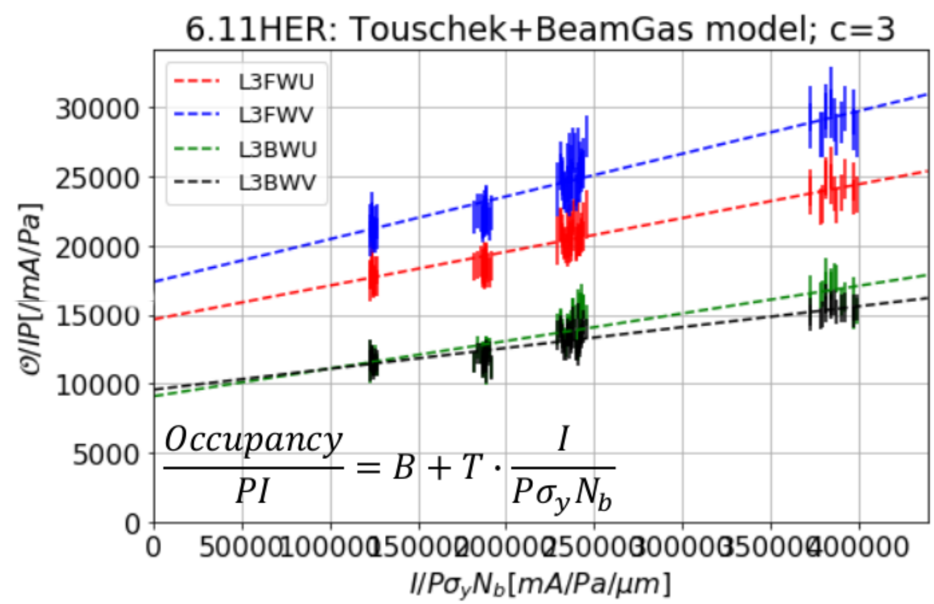
VXD occupancy from backgrounds

- Single beam study for LER and HER rings with β^*_y=3mm (→ start of Phase 3)
- Occupancy for PXD+SVD follows B,T scaling law for LER and HER studies
- Data compared to run specific MC (optics, collimators)
- Reasonable Data/MC agreement for LER studies
- Huge Data/MC discrepancy for HER studies



Data/MC

	PXD Layer 1 (June 11,12)	SVD Layer 3 (June 11,12)
HER Coulomb	480-510	270-610
HER Touschek	360-370	260-350
LER Coulomb	15-16	11-13
LER Touschek	2.4-2.5	2.3-2.9



Similar pattern in PXD and SVD. Scaling background MC for full Phase 3 with Data/MC ratios gives too high occupancy (need to reduce by factor x10)

Summary

- All BEAST II detectors operational and provided valuable online feedback for machine commissioning and safe operation of Belle II
- Phase 2 VXD readout in final readout chain design (1/10 of final VXD)
- Phase 2 VXD has regularly participated in Phase II runs since first collisions
  - Many lessons learned for organizing shifts for 24/7 operation
- SVD key operation features like S/N and cluster timing are within or exceeding TDR expectation
- PXD demonstrated stable operation of 4 large, thinned sensors at low threshold (<1000e-) with excellent S/N ratio
- Background from soft photons observed in PXD, FANGS and radio-chromic foils
  - Qualitative agreement with simulation of synchrotron radiation after removing low energy cuts in Geant4
- Run specific simulations for backgrounds (Touschek, Coulomb) for LER and HER ring with β^*_y =3mm (→ start of Phase 3)
  - LER: ~< 15xMC
  - HER: ~600xMC for SVD+PXD and factor 10x for outer detectors
  - For early Phase 3 (half beam currents), SVD L3 occupancy (1.4-3.0%) could be close to limit for good tracking

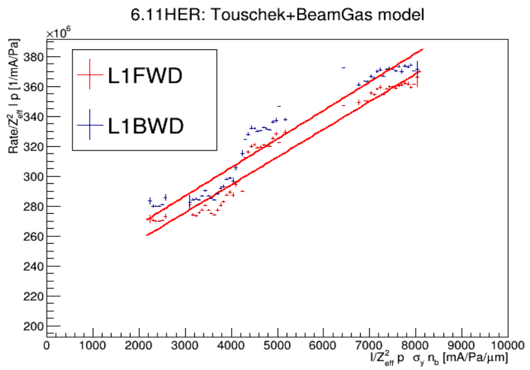
Summary

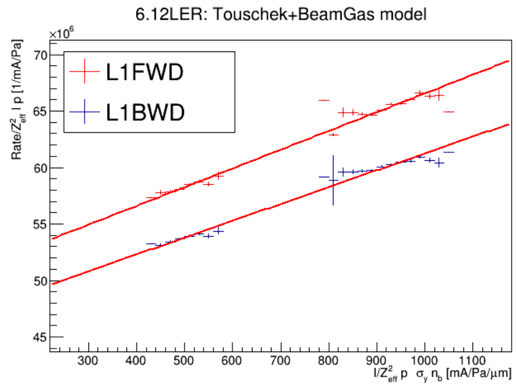
- Phase 2 run confirmed that the full VXD could be safely installed for Phase 3
- At the beginning of Phase 3, background improvements will be further pursued (tuning SuperKEKB, installation of new collimators, ...)

Thanks

backup

PXD and Beam Background





- Full Phase3 background MC for Target luminosity (MC campaign 16)
- Rescaled by Data/MC ratios from Phase2 (for Coulomb /Touschek)
- Dose to high by x4 (no injections bg)
- Occupancy to high x2 (DHP limit)

	PXD L1 occupancy Phase 3 MC	Data/MC Max value	PXD L1 occupancy Scaled Phase 3 MC
HER Coulomb	0.01%	510	5.1%
HER Touschek	<0.005%	370	<0.2%
LER Coulomb	0.03%	16	0.5%
LER Touschek	0.05%	2.5	0.12%
twoPhotons	0.84%	x1	0.84%
	~1%		6.6%

	PXD L1 dose Phase 3 MC [Gy/sma]	Data/MC Max value	PXD L1 dose Scaled Phase 3 MC [Gy/sma]
HER Coulomb	90	510	46000
HER Touschek	<1	370	<370
LER Coulomb	458	16	7300
LER Touschek	760	2.5	1900
twoPhotons	19270	x1	19270
Sum	20000		75000

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 is 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

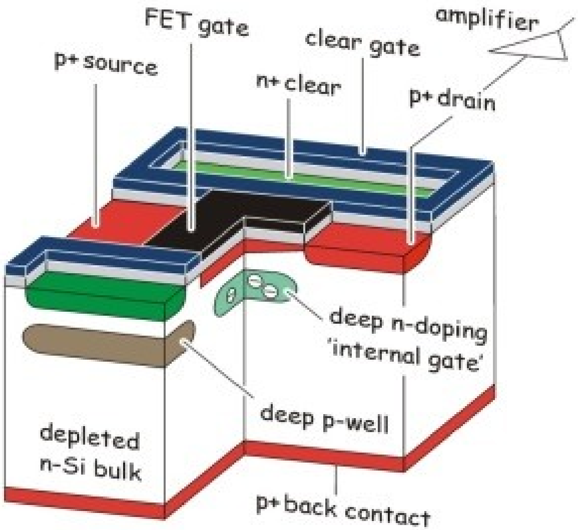
Machine parameters - SuperKEKB

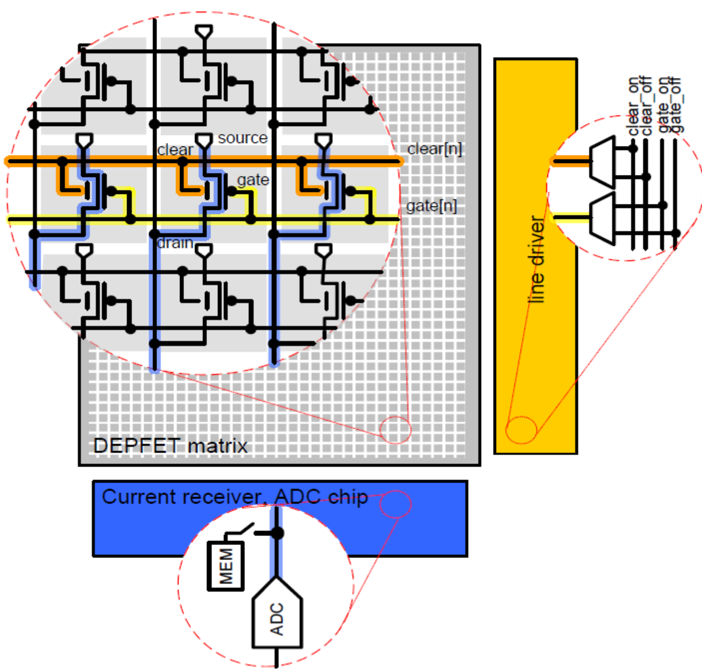
2017/September/1	LER	HER	unit	
E	4.000	7.007	GeV	
I	3.6	2.6	A	
Number of bunches	2,500			
Bunch Current	1.44	1.04	mA	
Circumference	3,016.315		m	
$\varepsilon_x/\varepsilon_y$	3.2(1.9)/8.64(2.8)	4.6(4.4)/12.9(1.5)	nm/pm	():zero current
Coupling	0.27	0.28		includes beam-beam
β_x^*/β_y^*	32/0.27	25/0.30	mm	
Crossing angle	83		mrad	
α_p	$3.20\text{x}10^{-4}$	$4.55\text{x}10^{-4}$		
σ_δ	$7.92(7.53)\text{x}10^{-4}$	$6.37(6.30)\text{x}10^{-4}$		():zero current
V_c	9.4	15.0	MV	
σ_z	6(4.7)	5(4.9)	mm	():zero current
ν_s	-0.0245	-0.0280		
ν_x/ν_y	44.53/46.57	45.53/43.57		
U_0	1.76	2.43	MeV	
$\tau_{x,y}/\tau_s$	45.7/22.8	58.0/29.0	msec	
ξ_x/ξ_y	0.0028/0.0881	0.0012/0.0807		
Luminosity	$8\text{x}10^{35}$		$cm^{-2}s^{-1}$	

Machine Design Parameters

parameters		KEKB		SuperKEKB		units
		LER	HER	LER	HER	
Beam energy	E_b	3.5	8	4	7.007	GeV
Half crossing angle	ϕ	11		41.5		mrad
# of Bunches	N	1584		2500		
Horizontal emittance	ε_x	18	24	3.2	4.6	nm
Emittance ratio	κ	0.88	0.66	0.27	0.25	%
Beta functions at IP	β_x^* / β_y^*	1200/5.9		32/0.27	25/0.30	mm
Beam currents	I_b	1.64	1.19	3.6	2.6	A
beam-beam param.	ξ_y	0.129	0.090	0.088	0.081	
Bunch Length	σ_z	6.0	6.0	6.0	5.0	mm
Horizontal Beam Size	σ_x^*	150	150	10	11	μm
Vertical Beam Size	σ_y^*	0.94		48	62	nm
Luminosity	L	2.1×10^{34}		8×10^{35}		$cm^{-2}s^{-1}$

DEPFET's in a nutshell

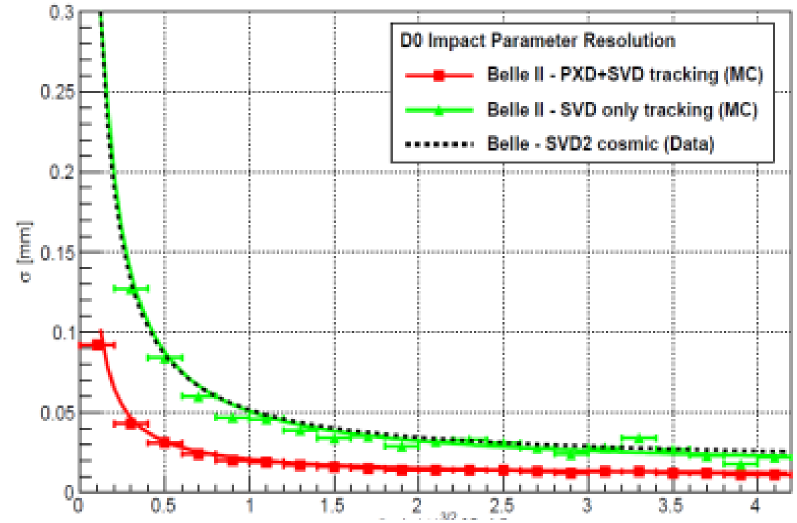


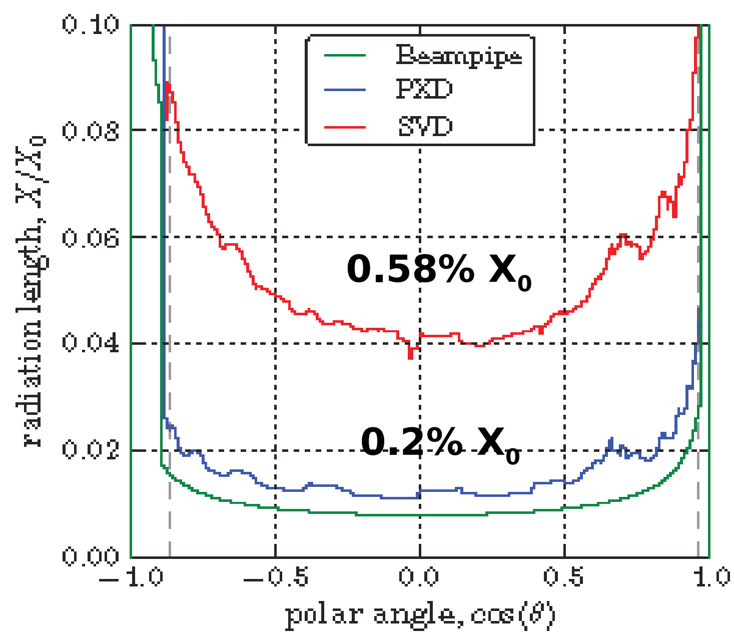


- **fully depleted sensitive volume**
  - fast signal rise time (~ns), small cluster size
- In-house fabrication at MPS Semiconductor Lab
  - **Wafer scale devices possible**
  - **Thinning to (almost) any desired thickness**
  - no stitching, 100% fill factor
- no charge transfer needed
  - faster read out
  - better radiation tolerance
- **Charge collection in "off" state, read out on demand**
  - potentially low power device
- **internal amplification**
  - charge-to-current conversion
  - r/o cap. independent of sensor thickness
  - **Good S/N for thin devices ▯ ~40nA/µm for mip**

Belle II vertexing requirements

	Belle II PXD
Radiation	2 Mrad/year
	$2 \cdot 10^{12}$ 1 MeV n_{eq} per year
Duty cycle	1
Frame time	20 µs
Momentum range	50 MeV < p < multi GeV
Acceptance	17°-155°
Material budget	0.2% X_0

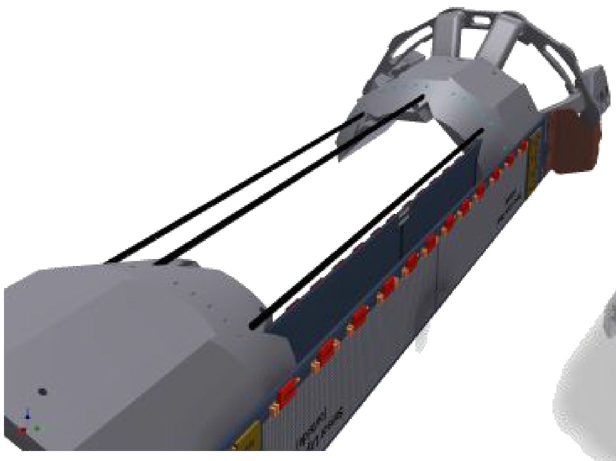


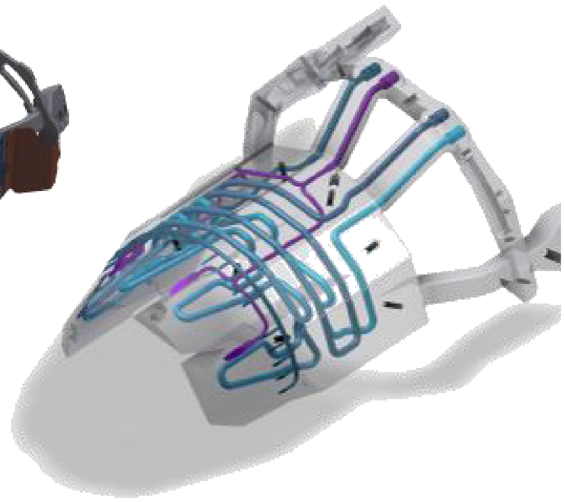


- Modest impact paramter resolution (15 µm), dominated by multiple scattering → pixel size (50 x 75 µm²)
- Lowest possible material budget (0.2% X)
  - Ultra-transparent detectors
  - Lightweight mechanics and minimal services

VXD cooling schema

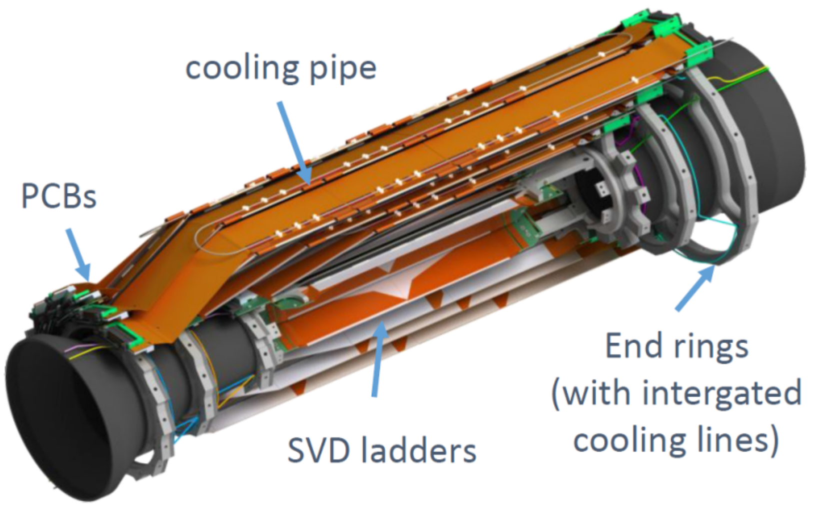
Cooling PXD





Support Cooling Block (SCB), manufactured using 3D printing technology, with CO_2 and N_2 channels inside

Cooling SVD



Requirements

- PXD: Sensor < 25 °C to minimize shot noise due to leakage current; ASICs < 50 °C to avoid risk of electro-migration
- SVD: APV25 readout chips surface@~0 °C for SNR improvement
- Power consumption: PXD 360W; SVD 700W, together with the heat load through 9m of vacuum isolated flex lines; required cooling capacity of 2-3kW
- VXD needs to be thermally isolated against CDC and beam pipe. Room temperature at the inner surface of CDC is required for stable calibration and dE/dx performance

PXD DAQ Overview

Huge data amount (240Gb/s from PXD) sent to ONSEN
Need to be reduced by 1/30 (by HLT trigger & ROIs)