BELLE2-NOTE-TE-2019-011
DRAFT Version 1.0
June 25, 2019

Initial requirements for an upgraded VXD in Belle II

L. Andricek*

HLL, Munich, Germany

J. Baudot†

Universit de Strasbourg, CNRS, IPHC UMR 7178, Strasbourg, France

F. Forti and G. Rizzo‡

INFN and University of Pisa, Pisa, Italy

A. Ishikawa, K. R. Nakamura, S. Tanaka, and T. Tsuboyama

High Energy Accelerator Research Organization (KEK), Tsukuba-shi, Japan

C. Marinas

University of Bonn, Bonn, Germany

C. Niebuhr

Deutsches Elektronen-Synchrotron(DESY), Hamburg, Germany

C. Schwanda

Institute of High Energy Physics, Austrian Academy of Sciences, Vienna, Austria

(The Belle II Collaboration)

Abstract

This short note reviews the basic requirements on the detection layers which may compose an upgraded version of the vertex detector (VXD) of the Belle II experiment . The grounding hypothesis for such a new VXD assumes operation at an upgraded version of the SuperKEKB collider, featuring ×5 increase in instantaneous luminosity up to 40×10^{35} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

Numbers provided here stem from a rather crude projection of background rates, starting from the full MC simulation at the nominal SuperKEKB luminosity and the knowledge acquired during the early data taking with the present VXD in 2018 and 2019, at a much lower luminosity. Hit rates and radiation tolerance are the main drivers to elaborate the requirements, together with some basic specifications on resolution and low mass design, inherited from the current VXD detector to match the required physics performance. These requirements should be considered as an initial guidance to select potential adequate candidate technologies. They do not represent a comprehensive or final set of specifications obtained by a detailed analysis of the current data or simulated data with potential new geometries.

---

[*] Electronic address: lca@hll.mpg.de

[†] Electronic address: jerome.baudot@iphc.cnrs.fr

[‡] Electronic address: giuliana.rizzo@pi.infn.it

Contents

1. INTRODUCTION

This short note reviews the basic requirements on the detection layers which may compose an upgraded version of the vertex detector (VXD) of the Belle II experiment [1]. The grounding hypothesis for such a new VXD assumes operation at an upgraded version of the SuperKEKB collider, featuring ×5 increase in instantaneous luminosity up to 40×10^{35} $\text{cm}^{-2}\text{s}^{-1}$.
Numbers provided here stem from a rather crude projection of background rates, starting from the full MC simulation at the nominal SuperKEKB luminosity and the knowledge acquired during the early data taking with the present VXD in 2018 and 2019, at a much lower luminosity. Hit rates and radiation tolerance are the main drivers to elaborate the requirements, together with some basic specifications on resolution and low mass design, inherited from the current VXD detector to match the required physics performance. These requirements should be considered as an initial guidance to select potential adequate candidate technologies. They do not represent a comprehensive or final set of specifications obtained by a detailed analysis of the current data or simulated data with potential new geometries.

Section 2 introduces the current design of the VXD. Section 3 shows the method used to derive beam background related requirements for an upgraded VXD. Preliminary requirements are finally summarized in the last section 4 before conclusion.

2. THE CURRENT VXD

The current vertex detector of Belle II fulfils two major tasks for the experiment: extrapolates tracks toward the interaction point for precision tracking and vertexing measurements and provides standalone tracking for low-momentum charged particles (down to a few tens of MeV) that cannot be measured by the central drift chamber. It also contributes to particle ID with dE/dx measurement. Given the low momentum of the tracks produced at the $\Upsilon(4S)$, the material budget reduction plays a central role in the design of the VXD, especially in the first sensitive layers. Employing a first layer very close to the IP (14 mm), a low mass design (0.2-0.7% X_0 per layer) and a hit resolution of about 10 μm, the current VXD matches the requirements set by physics performance. The VXD acceptance corresponds to a full azimuthal (ϕ angle) coverage and a polar range restricted to $\theta \in [17, 150]$ degrees.

The current VXD, shown in figure 1, is a six layers system built from two different silicon sensor technologies. DEPFET pixel sensors make the two innermost layers (PXD1 and PXD2) or PXD system [2]. While the SVD system [3] adds four layers (SVD3, SVD4, SVD5, SVD6) equipped with double sided silicon strip detectors.
Both systems, described in some details in the following two subsections, have been designed to cope with the relatively high hit rates produced by beam related background at the design SuperKEKB luminosity. An additional constraint arises from operation in continuous injection mode.
Due to the relatively short beam lifetime at SuperKEKB, a continuous refill is required, typically every 20 ms. The newly injected bunch crosses the detector every $10\,\mu$s, 1 revolution, each time producing very high background in the detector. This new bunch remains "noisier" than older bunches for several turns, typically for $400 \times 10\,\mu\text{s} = 4$ ms. A short trigger veto ($\sim 2\,\mu$s) is then applied in this 4 ms time window every $10\,\mu$s, to avoid an impact of this so called "injection noise" effect on the data stream.

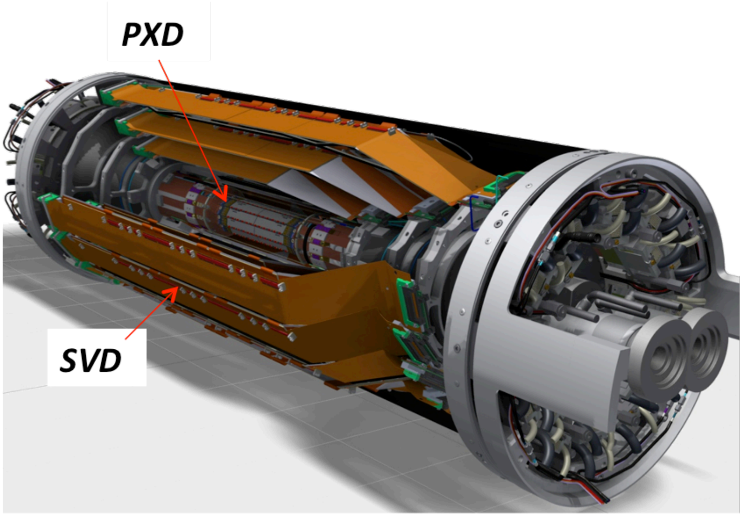

FIG. 1: The Belle II VXD.

2.1. Current PXD

The basic building block of the Belle II PXD is a module. Each module consists of pixel matrix with 250 columns, along the z direction and 768 rows, along R-phi. Pixel size in the inner layer (R-ϕ × z) is $50\,\mu m \times 55\,\mu m$ for the 256 pixels closest to the interaction region, $50\,\mu m \times 60\,\mu m$ for the pixels further out. In the second layer the pixel dimensions are $50\,\mu m \times 70\,\mu m$ and $50\,\mu m \times 85\,\mu m$, respectively. The pixels are smaller (in z) in the central region close to the interaction point. Here tracks are crossing the detector essentially at normal incidence. Hence charge generated by ionization are usually collected in a single pixel and the resolution is binary, demanding the smallest pixel size. Further out tracks are more inclined and the charge is distributed over two or more pixels. Hence the resolution is improved applying a center of gravity algorithm and the pitch can be chosen larger without compromising resolution. This way the total number of pixels in z can be reduced. In fact, the number of rows has been chosen so that, given the fixed readout time per pixel given by the readout electronics, the time to readout a complete frame can be achieved within 20 μs. Hence the readout can be phase locked to the SuperKEKB revolution time of 10 μs. The "injection noise" effect introduced earlier features a period of 10 μs, shorter than the DEPFET integration time of 20 μs driven by the read-out architecture of such sensors. However, a special gating mode has been implemented to blind the sensors during the passage of the noisy bunches, without loosing the signal previously integrated and not yet read-out.

Two modules are assembled into ladders and arranged as two cylindrical layers around the interaction point, as depicted in figure 2 and detailed in table I.

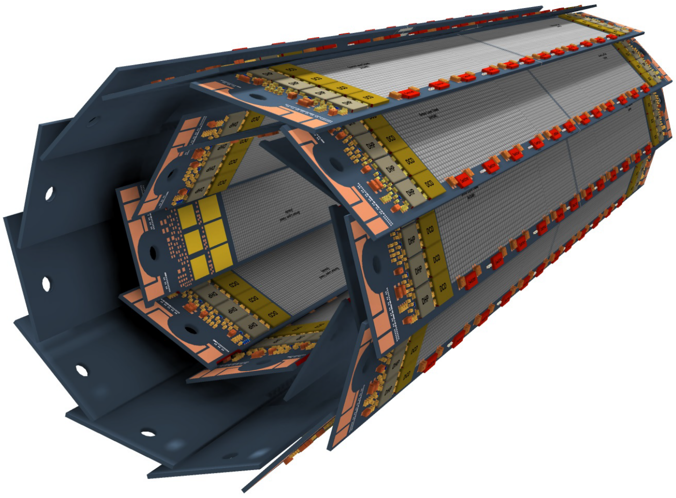

FIG. 2: Current PXD layout.

2.2. Current SVD

The SVD is composed by 4 layers (SVD3, SVD4, SVD5, SVD6) of double-sided silicon microstrip detectors (DSSD) read-out with the APV25 chips [4] and organized in ladders, as described in table II. The longitudinal schematic view of the current SVD is shown in figure 3. A picture of the SVD is shown in figure 4.

The main feature of the three types of SVD silicon sensors are reported in table III. The small rectangular sensors are used for layer SVD3. Ladders of layers SVD4, SVD5 and SVD6 are composed of two to four large rectangular sensors with a slanted trapezoidal sensors used in the forward region to minimize the material and the instrumented surface

layer	PXD1	PXD2
radius (mm)	14	22
nb of ladders (modules)	8 (16)	12 (24)
sensitive thickness (μm)	75	
pixels/module	768×250	
pixel size (μm)	50×55 and 50×60	50×70 and 50×85
total nb of pixels	3072000	4608000
frame and row rate	50 kHz and 10 MHz	
sensitive area per module (mm^2)	44.8×12.5	61.44×12.5
power consumption (W)	24 (sensors) + 124 (ladder-end)	36 (sensors) + 180 (ladder-end)

TABLE I: Current PXD details. Regarding power dissipation, while the sensor area is air-cooled, evaporative CO2 cooling is used at the ladder-end.

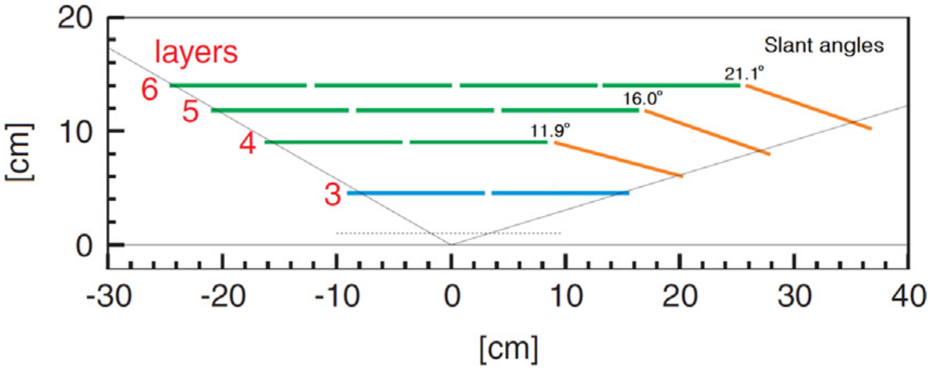

FIG. 3: Current SVD layout.

while still covering the largest angle, featuring a lantern shape.
For an efficient background suppression, the APV25 read-out chip is adopted, which has 50 ns peaking time and matches the capacitive load of the strips to provide a signal-over-noise ratio above 15 for all the layers. In the layers 4-5-6 the central DSSDs are individually read out by a novel Origami chip-on-sensor concept. In this scheme, thinned (down to 100 μm) APV25 chips are placed on flexible circuits, glued on top of the sensors. Thanks to flexible pitch adapters, which are wrapped around the edge of the sensors, the strips of both sides of the DSSDs are read out from top. This feature allows to minimize the analog path length for capacitive noise reduction. By optimizing the ladder design and support structures, as well as using an evaporative CO2 cooling system, an average material budget of 0.7% of radiation length has been achieved.

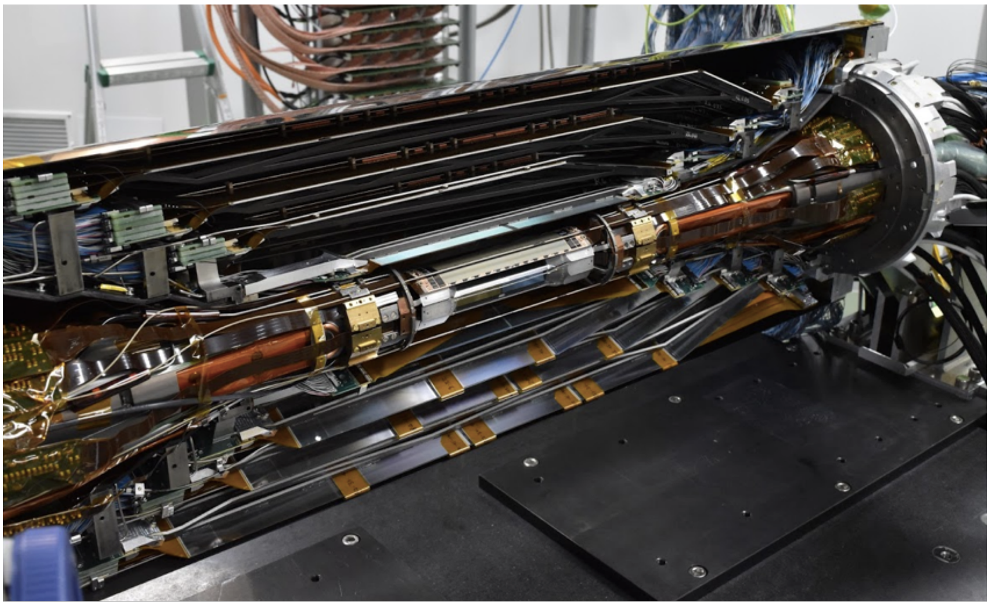

FIG. 4: Photograph of the Belle II vertex detector during the integration of the PXD with the SVD. The SVD ladders assembled in two halves are coupled with the PXD mounted on the beam pipe. Only one half of the SVD is present in the picture, the four layers are all visible, while the PXD is visible in the middle of the picture.

layer	SVD3	SVD4	SVD5	SVD6	total
radius (mm)	39	80	104	135	
nb of ladders	7	10	12	16	45
nb and type of sensors/ladder	2 small	2 large + 1 trapezoidal	3 large + 1 trapezoidal	4 large + 1 trapezoidal	14 small + 120 large + 38 trapezoidal
nb of APV25 chips	168	300	480	800	1748
power consumption (W)	69	124	198	330	721

TABLE II: Current SVD details.

2.3. Current known VXD limits

As stated earlier, the current VXD system was designed to operate at the nominal SuperKEKB luminosity taking into account various aspects, the prominent ones including the hit rate, the trigger rate, the sustainable bandwidth, the radiation level, as well as tracking performances.
Table IV provides a snapshot of the known current system limits with respect to these factors. The occupancy limit originates not only from hardware limitations, but also from tracking performances, especially reconstruction efficiency, which deteriorates beyond the quoted values. The quoted occupancy limits for the 4 SVD layers are in fact due to tracking performance limitations and are obtained using the background occupancy ratios between the layers. At the moment it is not known which SVD layer determines the most severe

	Small Sensor	Large Sensor	Trapezoidal Sensor
Readout strips (p/R-ϕ/U)	768	768	768
Readout strips (n/Z/V)	768	512	512
Readout pitch (p/R-ϕ/U)	50 μm	75 μm	75-50 μm
Readout pitch (n/Z/V)	160 μm	240 μm	240 μm
Sensor Active area (mm^2)	122.90 x 38.55	122.90 x 57.72	122.76 x (57.59-38.42)
Sensor Thickness	320 μm	320 μm	300 μm

TABLE III: Details of the double-sided silicon strip sensor types used in the SVD. All sensors have one intermediate floating strip among two readout strips.

limit on tracking efficiency.

layer	PXD1	PXD2	SVD3	SVD4	SVD5	SVD6
radius (mm)	14	22	39	80	104	135
trigger rate (kHz)	30		30 with 6 APV25 samples 70 with 3 APV25 samples			
occupancy (%)	3		2.6	0.8	0.6	0.4
hit rate (MHz/cm^2)	52.2	33.9	2.8	0.9	0.4	0.2
TID (MRad)	> 20		10	10	10	10
NIEL $\times 10^{12}$ (cm^{-2})	100		10	10	10	10

TABLE IV: Limits of the current VXD system, encompassing both technical and physics-driven performances.

3. BEAM RELATED BACKGROUND AND EXTRAPOLATION TO HIGHER LUMINOSITY

VXD layers are enclosed within a radius of 150 mm. In this area close to the beams, particle rates induced by various single-beam or beam-beam effects (known as beam-backgrounds) largely dominate the rate produced by elementary collisions (physics). SuperKEKB being a continuous machine (bunches are separated by 4 ns), this background hit rate can be considered as constant.
Extrapolating such hit rates requires knowledge of the scaling laws and factors for each background type. However in the VXD region, beam-beam effects, "luminosity" background terms resulting from the electromagnetic interactions between the electron and positron beams, generate rates almost one order of magnitude larger than the single-beam processes (Touschek effect, beam-gas interactions, synchrotron radiation). Consequently the extrapolation used here is simplified by a scaling with the instantaneous luminosity, taking as a reference the hit rate (r_{nom}) evaluated from simulated events at the nominal instantaneous

luminosity ($\mathcal{L}_{\rm nom}$), according to:

$$r_{\rm new} = \frac{\mathcal{L}_{\rm new}}{\mathcal{L}_{\rm nom}} \, r_{\rm nom}. \tag{1}$$

Since there are large unknowns on how single beam background will scale in the upgraded SuperKEKB machine we add a scenario with a safety factor of 5 in the next section.

Of course the additional background stemming from newly injection bunches, as described above as "injection noise", will still be present with an upgraded SuperKEKB. The amplitude of the effect, producing spikes of occupancy every $10\,\mu$s during a time span of about 4 ms after bunch injection, is not known and we assume it will also scale with luminosity.

4. REQUIREMENTS

An upgraded VXD should fulfill the following requirements:

- match the main specs of the current VXD, in terms of resolution, low material budget and geometrical acceptance, summarized in table V; note that the number of layers are not specifically constraint but of course should be on the one hand high enough for track reconstruction and on the other hand low enough not to exceed the current total VXD material budget (3.2 % X_0);
- satisfies the additional constraints imposed by the higher beam background conditions in terms of sustainable hit rate, TID and equivalent neutron fluence, as summarized in table VI, for different background extrapolation scenarios;
- be robust against high local ionization effects that might lead to latch-up;
- be operable with a trigger rate of 150 kHz (we apply here the same simple luminosity scaling as for the background, hence 5×30 kHz, without a detailed study supporting this number);
- integration time $< 1\,\mu$s is desirable. Such short integration time is driven by various considerations. First, it is needed to reduce the occupancy to acceptable level, for good tracking performance, and to control the bandwidth load, given the high hit rate and trigger rate. Then, the trigger veto strategy to mitigate the SuperKEKB "injection noise" described above, introduces some data taking inefficiency, related to the integration time, approximately given by: $duration_{trigger-veto}/10\,\mu\text{s} \times 4\text{ms}/20\text{ms}$, where the trigger veto length cannot be shorter than the integration time (unless a specific sensor read-out mode like the DEPFET gating is introduced).

5. CONCLUSION

We re-state as a conclusion that the above requirements should be taken as guidelines rather than strong or absolute numbers. Nevertheless, it is clear that any proposal for an upgraded VXD should address all requirements at once and for each layer. In addition, sufficient inputs should be provided to implement a full simulation of the proposed geometry and evaluate its performances with respect to tracking

layer	PXD1/2	SVD3	SVD4/5/6
resolution (R-ϕ/U-Z/V μm)	10	10 /24	13 /36
material budget % X0	0.2	0.7	0.7
acceptance	$\theta \in [17, 150]$ degrees		

TABLE V: Basic requirements on resolution, material budget (including cooling, power and data transmission), and acceptance for the VXD.

Finally and though the timeline of such an upgrade is not yet clearly defined, the technical aspects of the proposal should be complimented by a coarse roadmap to actually reach an operating detector.

[1] T. Abe, Belle II Collaboration, *Belle II Technical Design Report*, `arXiv:1011.0352 [physics.ins-det]`.

[2] F. Luetticke, DEPFET, *The ultralight DEPFET pixel detector of the Belle II experiment*, Nucl. Instrum. Meth. **A845** (2017) 118–121.

[3] K. Adamczyk et al., *The silicon vertex detector of the Belle II experiment*, Nucl. Instrum. Meth. **A824** (2016) 406–410.

[4] M. J. French et al., *Design and results from the APV25, a deep sub-micron CMOS front-end chip for the CMS tracker*, Nucl. Instrum. Meth. **A466** (2001) 359–365.

		nominal luminosity 8×10^{35} cm^{-2}s^{-1}			upgraded luminosity 40×10^{35} cm^{-2}s^{-1}					
					nominal background			background $\times 5$		
layer	radius (mm)	hit rate (MHz/ cm^2)	TID (MRad/smy)	NIEL $\times 10^{12}$ (cm^{-2}/smy)	hit rate (MHz/ cm^2)	TID (MRad/smy)	NIEL $\times 10^{12}$ (cm^{-2}/smy)	hit rate (MHz/ cm^2)	TID (MRad/smy)	NIEL $\times 10^{12}$ (cm^{-2}/smy)
PXD1	14	22.6	2	10.0	113	10	50	565	50	250
PXD2	22	11.3	0.6	5.0	56	3	25	280	15	125
SVD3	39	1.41	0.1	0.2	7	0.5	1	35	2.5	5
SVD4	80	0.29	0.02	0.1	1.5	0.1	0.5	8	0.5	2.5
SVD5	104	0.22	0.01	0.1	1.1	0.05	0.5	6	0.25	2.5
SVD6	135	0.15	0.01	0.1	0.8	0.05	0.5	4	0.25	2.5

TABLE VI: Requirements in terms of hit rates and radiation tolerance. See text for a discussion of the requirements on the integration time.