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The DMAPS upgrade of the Belle II Vertex Detector

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Abstract

The SuperKEKB collider will undergo a major upgrade at the end of the decade to reach the target luminosity of 6×10^{35} cm^{-2}s^{-1}, offering the opportunity to install a new fully pixelated vertex detector (VTX) for the Belle II experiment, based on depleted-MAPS sensors. The VTX will be more granular and robust against the expected higher level of machine background and more performant in terms of standalone track finding efficiency. The VTX baseline design includes five depleted-MAPS sensor layers, spanning radii from 14 mm to 140 mm, with a material budget ranging from 0.2% to 0.8% X/X_0 per layer. All layers will be equipped with the same OBELIX sensor, designed in the TowerJazz 180 nm technology, with the pixel matrix derived from the TJ-Monopix2 sensor originally developed for the ATLAS experiment. The paper will describe the proposed VTX structure and review all project aspects: tests of the TJ-Monopix2 sensor, OBELIX-1 design status, ladder prototype fabrication and tests.

Keywords: Belle II, Vertex detector, VTX, Upgrade, CMOS Pixel Sensor, Depleted Monolithic Active Pixel Sensor, DMAPS, Particle tracking detectors.

1. Belle II and Vertex Detector Upgrade Motivations

The Belle II experiment [1] is dedicated to exploring physics beyond the Standard Model at the second generation B-factory,

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the SuperKEKB [2] e^+e^- asymmetric collider, running at the $\Upsilon(4S)$ resonance, situated in Tsukuba, Japan. The experiment aims to collect an integrated luminosity of $50\,\mathrm{ab}^{-1}$, facilitating a broad range of measurements and searches. SuperKEKB employs very high beam currents and a nanobeam scheme to reach a target luminosity of $6 \times 10^{35}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$, which also imposes challenging background conditions on the detector [3].

To ensure precise track reconstruction near the interaction point, Belle II is equipped with a low-mass silicon vertex detector (VXD), shown in figure 1. VXD consists of two layers of DEPFET pixel sensors (PXD) [4], with very small pitch of $50-70\,\mu$m, but long integration time of $20\,\mu$s, and four layers of double-sided strip sensors (SVD) [5], that on the contrary have an excellent hit time resolution of 3 ns but relative long strips, up to 6 cm long. The VXD offers a spatial resolution of about $10-25\ \mu$m in the various layers, it provides a coverage over a polar angle range of $17-150$ degrees, spanning radii from 14 mm to 140 mm, with an average material budget per layer between 0.25% to 0.75% of a radiation length.

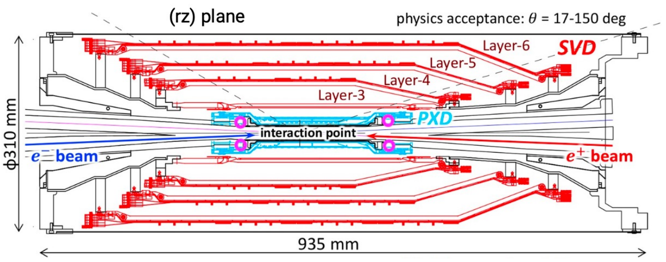


Figure 1: Layout of the current Belle II Vertex Detector.

During the Run 1 data-taking period (2019-2022), SuperKEKB achieved a world record peak luminosity of $4.7 \times 10^{34}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$ and the VXD was operated effectively, under low background conditions, showing excellent performance, although with the second pixel layer only partially equipped.

Throughout the Long Shutdown 1 (LS1, 2022-2023), several machine and detector improvements were implemented, including the installation of a complete VXD with two fully populated new PXD layers on a new beam pipe, while retaining the existing SVD.

Run 2 machine operation began in January 2024: the refurbished VXD confirmed the full functionality as the accelerator nearly restored its pre-LS1 performance levels.

Looking ahead, SuperKEKB plans to boost peak luminosity by more than an order of magnitude, increasing beam currents and reducing beam sizes, which will exacerbate background conditions in the detector. This objective will require significant upgrades to the accelerator complex, potentially including a redesign of the Interaction Region (IR), which could impact the VXD envelope. The current VXD provides excellent tracking capabilities but has limitations in handling the very high background rates expected from beam background extrapolation [3], potentially degrading tracking performance and the overall robustness of the detector.

The upcoming Long Shutdown 2 (LS2), projected around 2029, presents an ideal opportunity for a vertex detector upgrade. Due to uncertainties in background predictions and potential modifications in the accelerator environment, a new more robust vertext detector (VTX) is proposed, described in the Belle II Detector Upgrades Framework Conceptual Design Report [3].

With respect to the current detector, the VTX will have higher spatial and time granularity in all layers to cope with the harsh background conditions, provide a larger safety margin for higher luminosity operations, and enhance overall physics performance. Additionally, preparing the technology for the new VTX would be prudent in case of IR envelope changes or to safeguard against component failures and beam-related incidents.

2. Vertex detector requirements

To address the anticipated challenges, the new VTX must meet stringent requirements, that take into account Belle II physics needs, background extrapolation at target luminosity, including safety margins, flexibly and reduced services to easily adapt the design to possible modifications of the machine-detector boundaries. The key requirements are:

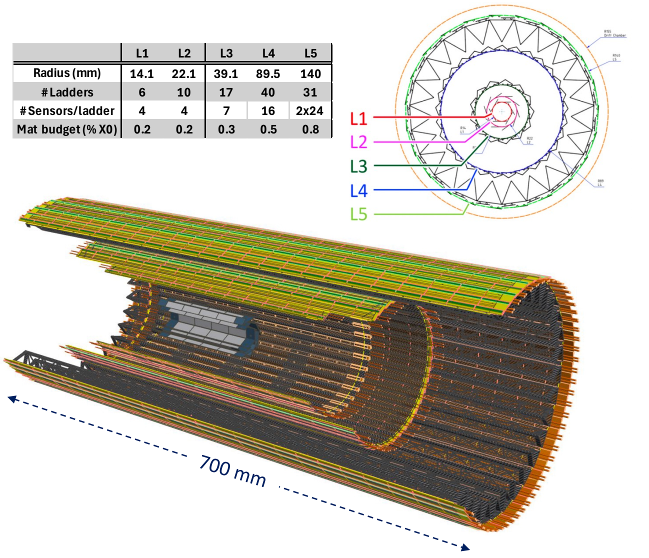
- **Spatial Resolution:** better than 15 μm requiring pitches between $30-40\ \mu$m.
- **Low Material Budget:** in the range of 0.2% - 0.8% X/X_0 per layer for the inner-outer layers
- **Hit Rate Capability:** as high as 120 MHz/cm².
- **Fast Timestamping:** 50-100 ns.
- **Radiation Tolerance:** TID up to 100 Mrad and NIEL fluence of $5 \times 10^{14}\ \mathrm{n}_{eq}/\mathrm{cm}^2$ in the innermost layer.
- **Power Dissipation:** at or below $200\,\mathrm{mW/cm}^2$ to minimize the material budget and services for the cooling.

These specifications align well with the core features of the Depleted Monolithic Active Pixel Sensors (DMAPS) developed to meet the ATLAS ITk outer layers requirements [6], and in particular with the TJ-Monopix2 sensor [7], produced using the TowerJazz 180 nm process.

3. VTX baseline design

In order to match the requirements described in the previous section, the VTX consists of straight detection layers, all equipped with the same DMAPS monolithic pixel sensor, the Optimised BELle II monolithic pIXel sensor (OBELIX) chip, developed starting from the TJ-Monopix2 sensor, with new features described in the next sections. The new VTX will have higher space and time granularity in all layers, with 33 um um pitch and 50-100 ns timestamping, will be operated at room temperature allowing also lower material budget, reduced services and an easier geometry more adaptable to potential future changes of the interaction region.

In figure 2 a schematic view of the VTX baseline design with 5 detection layers is shown, whose details have been described in [3]. A version with 6 layers is now also under evaluation,



	L1	L2	L3	L4	L5
Radius (mm)	14.1	22.1	39.1	89.5	140
#Ladders	6	10	17	40	31
#Sensors/ladder	4	4	7	16	2x24
Mat budget (% X0)	0.2	0.2	0.3	0.5	0.8

Figure 2: Schematic view of the VTX baseline layout with 5 detection layers.

with potential advantages for detection efficiencies for K_S reconstruction.

VTX Performance studies

To validate the performance of the proposed VTX design, simulation studies on benchmark physics channels have been conducted. To take into account the large uncertainty due to the future machine evolution, different background scenarios have been considered. Results described in [3] confirmed that the proposed 5 layers fully pixelated VTX, with finer granularity both in space and in time, will improve track finding, tracking efficiency, especially at low momentum, and vertex reconstruction capabilities, preserving the boosted performance even in the high background scenarios. As an example figure 3 shows

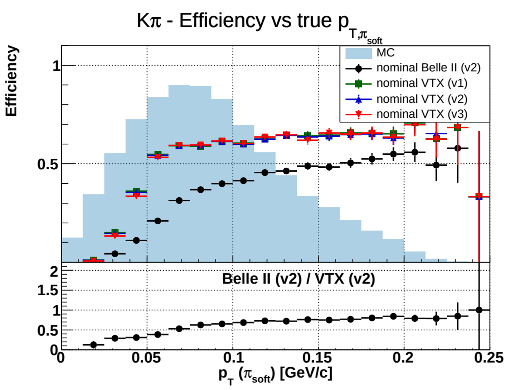


Figure 3: Reconstruction efficiency for the decay $B^0 \rightarrow D^{*-} l^+ \nu_l$ as a function of the transverse momentum of the $\pi^-_{\rm soft}$ from the $D^{*-} \rightarrow D^0\pi^-$ decay (with $D^0 \rightarrow K^-\pi^+$). The current Belle II detector with the VXD (black) is compared with performance achieved with the upgraded VTX. To consider operation at high luminosity different background scenarios are overlayed to the signal hits: optimistic (v1), intermediate (v2), conservative (v3).

the improvement in the reconstruction efficiency for the benchmark channel $B^0 \rightarrow D^{*-} l^+ \nu_l$ as a function of the transverse momentum of the $\pi^-_{\rm soft}$ from the $D^{*-} \rightarrow D^0\pi^-$ decay (with $D^0 \rightarrow K^-\pi^+$). A significant improvement (of almost a factor 1.7) in the reconstruction efficiency for the VTX geometry is visible over the nominal Belle II detector with VXD, and performance are very stable for increasing background levels. Performance study of the alternative 6 layers design are now underway.

VTX Ladder concept

The inner VTX (iVTX) will have 2 layers, at 14 and 22 mm, featuring an "all-silicon ladder" design, targeting a material budget below 0.2% X/X_0 per layer. Starting with a block of 4 adjacent OBELIX chips from the same wafer, a post-process redistribution layer (RDL) for the interconnections among chips will be implemented, followed by a selective thinning of the backside of the silicon block down to about 50 μm, except in some border area 400 μm thick, needed to ensure the ladder stiffness. Air cooling is now being evaluated for the iVTX to evacuate the average power of 200 mW/cm2, also including the eventual contribution of thin cooling pipes at the edge of the ladders, to better evacuate the higher power density in the chip periphery. A schematic view of the iVTX ladder is shown in figure 4.

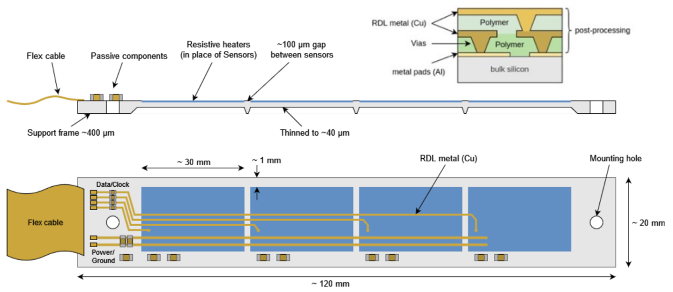


Figure 4: iVTX ladder concept.

The first demonstrator, built from a silicon wafer and the redistribution layer that implements dummy heater structures, instead of sensors, has been fabricated at IZM-Berlin and it will allow the evaluation of the electrical, mechanical, and thermal properties of the iVTX concept.

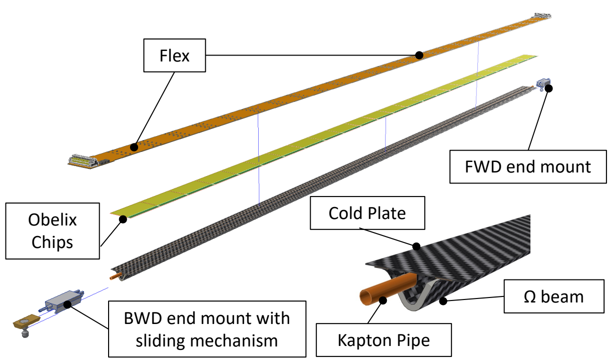


Figure 5: Exploded view of the oVTX ladder components with the new omega shape carbon support used for the truss.

The outer VTX (oVTX) will span radii up to 140 mm, with 3 or 4 additional layers designed with a more conventional structure, inspired to the ALICE ITS design. Each ladder is made of a light carbon fiber support structure, truss, with triangular shape, a cold plate including pipes for liquid coolant circulation with a row of sensors glued on the cold plate, the flex circuits connecting each half-ladder to a connector. The material budget with for the ladders with the triangular truss support, visible in the r-phi view of figure 5, is up to 0.8% X/X_0 per layer. Mechanical and thermal characterization of a 70 cm long oVTX prototype ladder, with the triangular truss structure, already confirmed good results, well within specifications [8].

To further reduce the material budget and radial dimensions, a new low mass carbon fiber support is proposed, sandwiching Rohacell foam with of two carbon fiber sheets in an omega-shaped structure. The oVTX ladders with the omega-shape truss will have a reduced material budget of less than 0.45% X/X_0, are expected to give even better mechanical stability and will allow to have up to 4 layers in the oVTX region. An exploded view of the oVTX ladder based on the new omega-beam support is shown in figure 5. A prototype featuring the new proposed omega-shape support is now under construction for further evaluation.

4. TJ-Monopix2: evaluation of the foreruner

The OBELIX sensor, designed for the Belle II VTX upgrade, inherits the matrix of the TJ-Monopix2 CMOS DMAPS sensor [7], developed in the Tower 180 nm imaging technology, with a modified process to improve radiation hardness [9]. The cross section of the small collecting electrode DMAPS pixel, implemented in both sensors, is shown in figure 6.

The signal released by a Minimum Ionizing Particle (MIP) in the thin active sensor volume is only about 2500 e- (MPV). Operation with low detection threshold and signal reduction due to bulk damage effects are then particularly critical for these CMOS MAPS sensors.

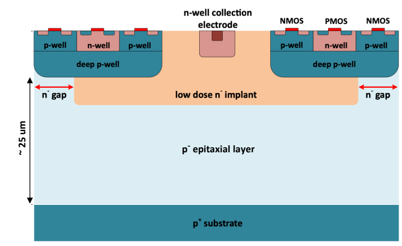


Figure 6: Cross section of the DMAPS pixel in the Tower 180 nm process modified to improve radiation hardness: a low-dose n-type implant is used to implement a planar junction and deplete the p-epitaxial layer over the full pixel area. Lateral electric field at the pixel corner is also enhanced with the additional n-gap modification.

TJ-Monopix2 is a large matrix of 512 × 512 pixels, with 33 × 33 μm pitch, 25 ns timestamping, 7 bit Time over Threshold (ToT) analog information and 3 bit for the in-pixel threshold tuning. Four different front-end version are implemented in the chip. The matrix is organized in double-columns, with a column-drain readout architecture able to transmit hits to the chip periphery, coping efficiently with hit rates up to 600 MHz/cm^2 [7]. These core features match the VTX requirements, but the chip has a triggerless readout with no memories in the periphery, and a new digital periphery was developed in OBELIX to match Belle II needs.

Extensive tests of TJ-Monopix2 have been conducted to validate the key performance relevant for the OBELIX design, with characterization in laboratory and in beam test campaigns, [3].

Laboratory tests confirmed stable TJ-Monopix2 operation was achievable with threshold at about 250 e-, threshold dispersion of about 15 e- and noise of 8 e-. In the first test beam campaign [10] [11] held in July 2022 with the DESY 3-5 GeV electron beam, hit efficiency above 99% and position resolution of 9 um have been measured for un-irradiated sensors.

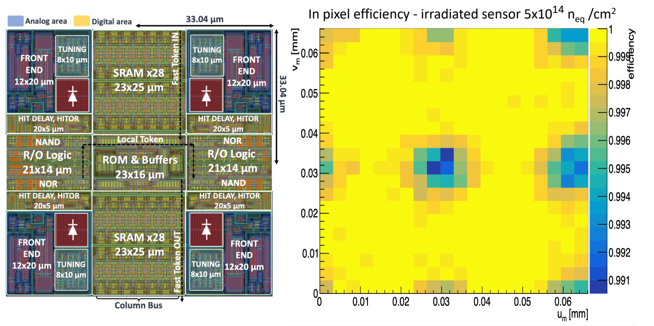


Figure 7: Layout of the 2x2 superpixel cell of TJ-Monopix2 (left) [7]. In pixel efficiency on irradiated sample with 24 MeV protons up to 5×10^{14} $\mathrm{n_{eq}/cm^2}$ (right) [11], for one of the four front-end versions: DC-Normal Front-end.

Similar good performance have been also confirmed on an irradiated sample with 24 MeV protons, up to 5×10^{14} $\mathrm{n_{eq}/cm^2}$, in the July 2023 DESY beam test campaign. The irradiated device was operated with thresholds ranging from 200 to 300 e-, depending on the front-end version and the bias applied. The same good position resolution as for un-irradiated sensor was confirmed. High efficiency of 98-99.9% was achieved in all the front-end versions, increasing the bias to compensate for the radiation damage effects. An example of the in-pixel efficiency distribution, is illustrated in figure 7 [11]. Only a small reduction of the efficiency is visible at the pixel corners, far from the collecting electrode, as expected from the layout of the cell. Further performance study on irradiated samples (both with TID up to 100 Mrad and with NIEL up 5×10^{14} $\mathrm{n_{eq}/cm^2}$) will be conducted in new beam test in July 2024.

5. The OBELIX chip for Belle II

The OBELIX design adopted the same TJ-Monopix2 matrix and double column readout architecture, with a new digital periphery developed for the application in Belle II [12]. The floor plan and dimensions of the OBELIX chip is shown figure 8. The full size matrix has 47 ns time-stamping, 7 bit Time over Threshold and a 3 bit register for the in-pixel threshold tuning, with an increased range of threshold compensation.

Pitch	33μm
Signal ToT	7 bits
Time stamping	50 to 100 ns
Fine time * stamping	~ 5 ns for hit rate < 10 MHz/cm²
Hit rate max for 100% effi	120 MHz/cm²
Trigger handling	30 kHz with 10 μs latency
Trigger * output	~10 ns resolution with low granularity
Power (with hit rate)	120 to 200 mW/cm² (1 to 120 MHz/cm²)
Bandwidth	1 output 320 MHz

* optional features for outer layes

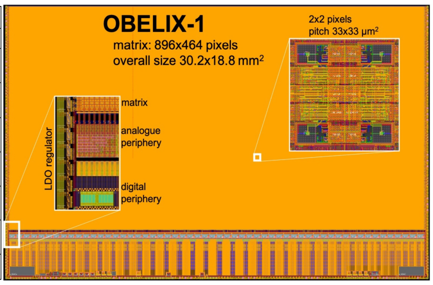


Figure 8: Floorplan of the OBELIX chip.

OBELIX has a triggered readout architecture implemented in the digital periphery (TRU module) with the trigger logic and the needed memories to be operated up to 30kHz trigger rate, with a fixed latency up to 10 μs, a maximum average hit rate of 120 MHz/cm^2 and able to sustains a peak hit-rate up to 600 MHz/cm^2, that could be reached for very short time during SuperKEKB continuous injections. With the foreseen short acquisition window of about 100 ns, the data throughput of 320 Mbps is adequate at the target hit rate expected. Extensive simulations validated the performance of the TRU showing that at the design hit rate and trigger latency, data loss of less than 0.02% [12] are achieved.

Two additional new features are implemented in OBELIX, both exploiting the column-wise HitOr lines from the pixel matrix and elaborating these fast and asynchronous signals from aggregate pixel regions in the matrix periphery.

The track trigger transmission module (TTT) is developed to provide a coarse but fast information to the Belle II trigger system. The chip is divided into a small number of macropixels (configurable from 2 to 8) and the HiTOr signal of a macropixel, sampled with a 33.9 MHz clock, is trasmitted off matrix with low latency. Only the outer layers of VTX can be used for the trigger contribution. In fact in the inner layers the higher hit rates could cause pile up at the available granularity, and in addition there are tight power dissipation budget constraints for iVTX layers.

The periphery time to digital module (PTD) has been developed for precision timing of the pixel hits in the external layer. The clock available in pixel provides only a 47 ns timestamping for the all hits, but the HitOR of a column can be sampled in the periphery with a faster clock (x16). According to measurements performed with TJ-Monopix2, an accuracy of 3 ns can be expected on time measurements based on the HitOr, after corrections are applied to account for time walk and HitOr position dependent delay [12]. If more than one hit is detected within one column and the same timestamp, the association of the PTD-time to the hit is not possible. To avoid ambiguities the reconstruction of the precision timing is possible at low hit rates $\lesssim$ 10 MHz/cm^2, which is the case for the outer layers of VTX. This feature will allow to attach to the tracks some hits with a finer time resolution and will be beneficial to improve the rejection of off-time background tracks, without increasing the main timestamp resolution, and consequently the power consumption.

6. Summary and Outlook

SuperKEKB will undergo a second shutdown around 2028-2029 to prepare the accelerator complex for the target high luminosity operation. The proposed DMAPS upgrade of the Belle II VTX represents a significant step forward in preparing the experiment for the challenges of high-luminosity operations. With its enhanced performance and robustness, the new VTX will play a crucial role in achieving the scientific goals of Belle II.

The framework Conceptual Design Report [3] provides detailed insights into the design and expectations for the new VTX. While the first full-scale prototype chip of the OBELIX sensor is expected to be submitted for fabrication in Autumn 2024, research and development and engineering activities are continuing to prepare the VTX Technical Design Reports.

The VTX collaboration is growing, bringing together expertise from various fields to tackle the numerous challenges ahead.

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