PROCEEDINGS OF SCIENCE

# Upgrade of the Belle II Vertex Detector with monolithic active pixel sensors

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The Belle II experiment at the SuperKEKB accelerator in Japan is dedicated to exploring physics beyond the Standard Model by performing high-precision measurements of heavy-flavor processes. The SuperKEKB will undergo a major upgrade during LS2 to achieve the target luminosity of $6{\times}10^{35}$ cm$^{-2}$s$^{-1}$. The vertex detector is a critical component of Belle II, responsible for precise tracking and vertexing near the interaction point. To enhance performance and address challenges from increasing luminosity, the current vertex detector is being upgraded to a fully pixelated vertex detector (VTX), based on Monolithic Active Pixel Sensors (MAPS). The VTX will consist of five layers of DMAPS sensor, called OBELIX, with radii from 14 mm to 140 mm and a material budget ranging from 0.2-0.8% $X/X_0$ per layer. The OBELIX sensor is derived from the TJ-Monopix2 sensor, originally developed for the ATLAS experiment. Sensor has been designed under TowerJazz 180 nm technology and will be submitted to foundry at the end of year 2024. This paper discusses the design, implementation, and expected performance of the VTX, highlighting the technical advances brought by MAPS technology, which offer significant advantages in terms of material budget, radiation hardness, and spatial resolution. The motivation for this upgrade, the design considerations, and the expected performance improvements are analyzed.

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## 1. Introduction

The Belle II [1] is an intensity frontier collider experiment at the SuperKEKB [2] accelerator facility in Japan. The primary goal of the Belle II experiment is to search for new physics in the flavor sector and to improve the precision measurements of Standard Model (SM) parameters [3]. The SuperKEKB is an asymmetric electron-positron collider, which reached a world record instantaneous luminosity of 4.7 $\times 10^{34}$cm$^{-2}$s$^{-1}$ in Run 1 data taking period (2019-2022). However, it has not yet reached its target luminosity of 6 $\times 10^{35}$ cm$^{-2}$s$^{-1}$. To achieve the desired luminosity, SuperKEKB 49 needs an upgrade, which is thoroughly explained in [5].

The Belle II Vertex Detector (VXD) is crucial in reconstructing decay vertices with high precision. The current VXD consists of two layers of Pixel Detector (PXD) in the inner region and four layers of Silicon Vertex Detector (SVD) in the outer layers. The PXD uses a pixel sensor based on DEPFET technology with a pitch of 50-70 $\mu$m and 20 $\mu$s integration time while SVD uses a double-sided strip detector (DSSD) with an excellent time resolution of about 3 ns but relatively longer strip length of 6 cm. In the current state, where the background is low, the VXD shows excellent performance. The accelerator complex will be upgraded to achieve target luminosity which will require a re-design of the Interaction Region (IR). The background condition will become worse at higher peak luminosity. The performance of the current VXD is constrained by the high background levels, as anticipated from previous extrapolations [5]. This could potentially impair the tracking capabilities and overall performance of the detector, making an upgrade necessary. The planned Long Shutdown (LS2), expected around 2029, presents an opportunity to implement an upgrade to the VXD. A new vertex detector concept, VTX, has been proposed, where five layers of fully pixelated MAPS sensor, called Optimised BELle II monolithic pIXel (OBELIX), will be employed [5].

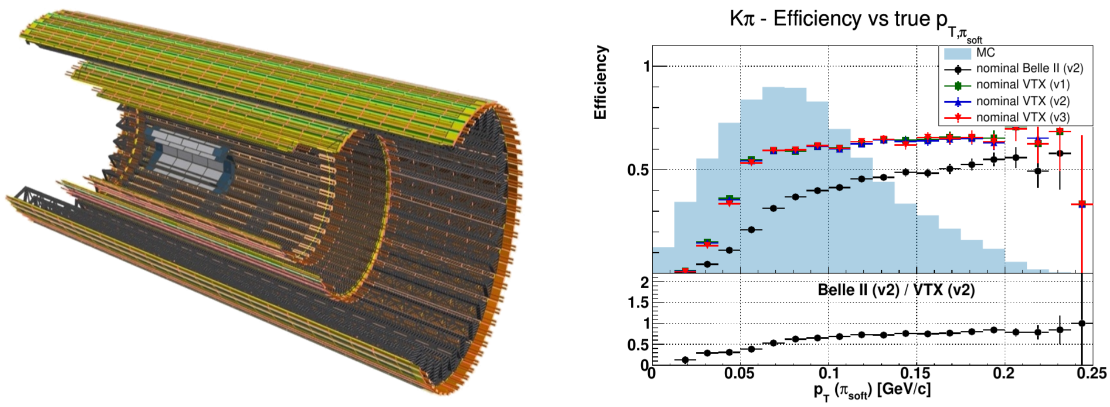


**Figure 1:** Left: 3D cut view of the VTX. Right: VTX performance at three background scenarios. Black dots: nominal Belle II detector, v1: optimistic background scenario-1, v2: intermediate scenario-2, v3: conservative scenario-3. The bottom plots show the ratio between nominal Belle II and nominal VTX in the intermediate background scenario-2

The VTX will provide higher spatial and time resolution in all layers to cope with harsh background conditions in addition to the current VXD. MAPS technology offers a promising solution, as it integrates sensor and readout electronics on the same silicon wafer, improving granularity and reducing material budget.

The structure of the paper is organized as follows: Section 2 discusses the VTX requirements, while Section 3 presents the VTX structure and its simulation performance. A brief overview of the TJ-Monopix2 sensor, its role as a forerunner, and its characterization is provided in Section 4. Section 5 covers a discussion of the OBELIX sensor, and finally, the summary is presented in Section 6.

| **VTX requirements** | |
|---|---|
| Spatial Resolution | <15$\mu$m |
| Hit Rate | 120MHz/cm$^2$ |
| Material Budget (per layer) | 0.1-0.8% X/$X_0$ |
| Trigger frequency | 30kHz |
| Temporal resolution | <100 ns |
| Trigger latency | 10$\mu$s |
| Power dissipation | 200 mW/cm$^2$ |
| TID | 1 MGy |
| NIEL fluence | 5×10$^{14}$ $n_{eq}$cm$^{-2}$ |

**Table 1:** Requirement for VTX detector of Belle II experiment

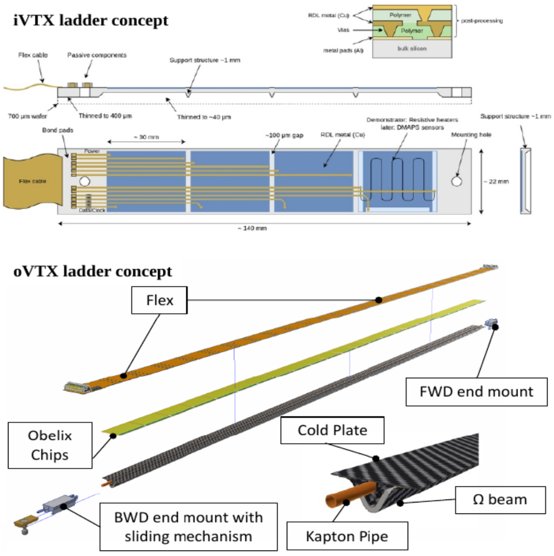


**Figure 2:** Top: iVTX ladder concept. Bottom: oVTX ladder concept with omega-shaped carbon support

## 2. VTX requirements

Given the anticipated challenges at high luminosities, the VTX requirements are outlined in Table 1. These requirements were evaluated based on background extrapolations at the target luminosity, incorporating appropriate safety margins. Monolithic Active Pixel Sensors (MAPS) offer several advantages over traditional hybrid pixel detectors, including high spatial resolution (with 15$\mu$m achievable at a pixel pitch of 30-40$\mu$m), thin sensors that contribute to a reduced material budget, radiation tolerance, low power consumption, and simplified mechanical design.

The key features of the Depleted Monolithic Active Pixel Sensor (DMAPS), specifically TJ-Monopix-2 [8, 9], developed for the ATLAS ITk outer layers, align well with the VTX requirements presented in the table.

## 3. VTX structure and simulation performance

The VTX is divided into two sections: the inner VTX (iVTX) and the outer VTX (oVTX), based on their radii relative to the interaction point. A 3D cutaway view of the VTX is shown on the left side of Figure 1. The iVTX will consist of 2 layers at 14 and 22 mm, using an “all-silicon ladder“ design with a material budget below 0.2% $X/X_0$ per layer. A post-process redistribution layer (RDL) will connect 4 OBELIX chips, followed by selective thinning of the silicon block to ~50 $\mu$m, leaving a 400 $\mu$m border for stiffness. A schematic is shown on the right side of Figure 2 (top). Air cooling and thin pipes are being evaluated for heat dissipation. The oVTX will feature up to 4 layers at radii up to 140 mm, with a carbon fiber triangular truss or a new omega-shaped structure, reducing the material budget to 0.45% $X/X_0$. Prototypes of both structures are being evaluated for performance. Schematic of an omega-shaped carbon support is shown on the right of side of Figure 2(bottom).

Simulation studies, conducted using the Belle II software framework, demonstrate enhanced tracking efficiency, particularly at low momentum, with the introduction of new MAPS layers, as depicted on the right side of Figure 1. These simulations were carried out under three different background scenarios: v1 (optimistic), v2 (intermediate), and v3 (conservative).

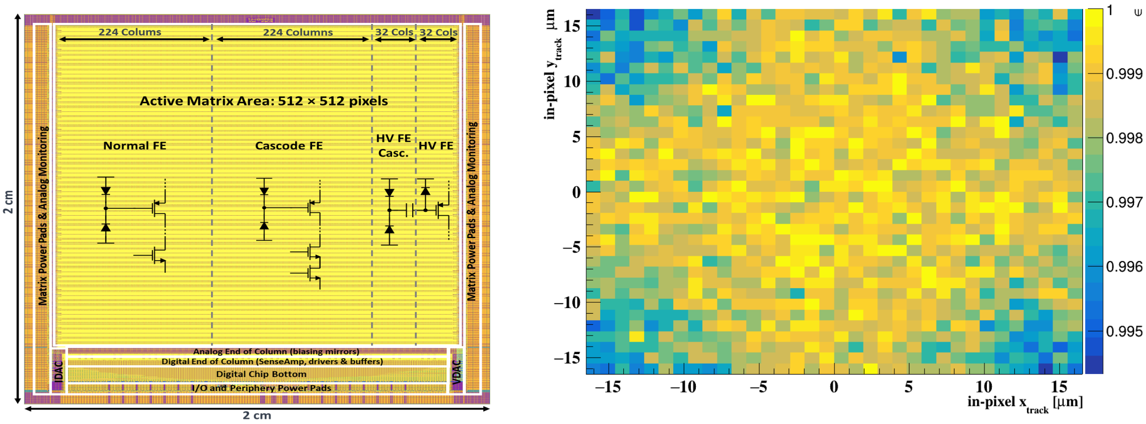


**Figure 3:** Left: Matrix arrangement of TJ-Monopix2 sensor showing four flavors, namely, Normal Front-End, Cascode Front-End, HV FE, and Cascode HV FE respectively. Right: in-pixel efficiency for Cascode FE of irradiated TJ-Monopix2 sensor. Efficiency is greater than 99%, even in the corner of the pixel. The analysis is performed using Corryvreckan Software [17]

## 4. TJ-Monopix2 sensor

The TJ-Monopix2 sensor was chosen as the baseline for the OBELIX matrix, which features four variants ("flavors") as shown on the left side of Figure 3. The matrix comprises 512 rows and 512 columns, with further details available in [9, 12]. Extensive characterization of both non-irradiated and irradiated sensors has been conducted in laboratory and test beams at DESY [10] to validate the sensor's performance. Early results indicate that the sensors meet key performance criteria, such as pixel readout speed, radiation hardness, and spatial resolution [11–14].

One such result, shown on the left side of Figure 3, demonstrates the in-pixel detection efficiency for a sensor irradiated with 24 MeV protons up to a fluence of $5\times10^{14}$ $n_{eq}/cm^2$ in the DC Cascode sub-matrix, obtained during the July 2024 beam test. As shown in the figure, the sensor achieved over 99% detection efficiency, with only a slight reduction (still above 99%) observed at the pixel corners. Additional parameters such as spatial resolution and time resolution were also studied, showing consistently strong performance [12]. A second sensor, irradiated with X-rays up to a dose of 100 Mrad, was also tested during the same beam test, with preliminary results indicating good performance. Ongoing analysis of the July 2024 test beam data is focused on evaluating the effect of temperature on sensor performance.

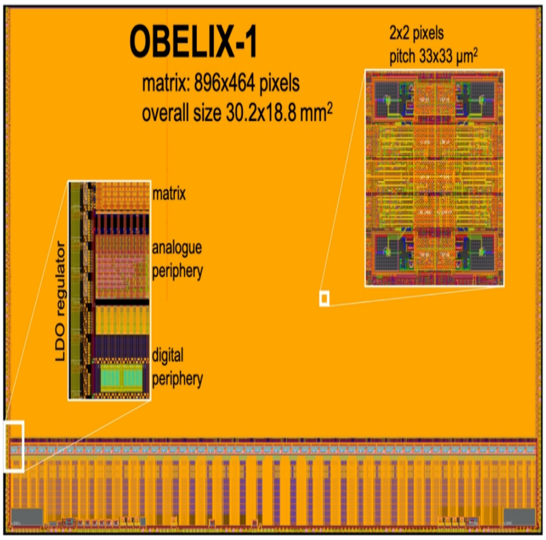


**Figure 4:** Floorplan of the OBELIX-1 chip

| | |
|---|---|
| Pitch | 33$\mu$m |
| Signal ToT | 7 bits |
| Time stamping | 50-100 ns |
| Fine time stamping | ~5 ns for hit rate <10 MHz/cm$^2$ |
| Hit rate max for 100% eff. | 120 MHz/cm$^2$ |
| Trigger handling | 30 kHz with 10 $\mu$s latency |
| Trigger output | ~10 ns resolution with low granularity |
| Power | 120-200 mW/cm$^2$ |
| Bandwidth | 1 output 320 MHz |

**Table 2:** Specification of OBELIX-1 sensor. The optional features are shown in blue color

## 5. OBELIX sensor for Belle II

All layers of VTX will be equipped with an OBELIX sensor, which is under design phase. The pixel matrix and the double-column readout architecture are inherited from the TJ-Monopix2 sensor with a new digital periphery [14]. The size of the sensor is about 3 cm $\times$ 2 cm and the pitch of about 33$\mu$m, respectively. It has a 47 ns time-stamping and 7-bit Time over Threshold (ToT) resolution. In addition to this, there is a 3-bit register for the in-pixel threshold tuning. The floorplan of the OBELIX-1 sensor is shown on the left side of Figure 3 and its detailed specifications are given in Table 2. The additional features of OBELIX are shown in blue.

The digital processing system incorporates a trigger memory to buffer hit data with a configurable latency of up to 10 $\mu$s and can operate at hit rates of up to 120 MHz/cm$^2$ [14].

## 6. Conclusion

The upgrade of the Belle II vertex detector with monolithic active pixel sensors represents a significant technological advancement, poised to meet the challenges of higher luminosities and event rates at SuperKEKB. The expected improvements in spatial resolution, material budget reduction, and radiation tolerance will enhance Belle II's ability to probe physics beyond the Standard Model. The integration of OBELIX sensors into the Belle II detector requires careful consideration of mechanical, thermal, and electronic aspects, but the anticipated benefits to the experiment's physics reach make this upgrade a critical step forward.

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## References

[1] T. Abe, et al., Belle II Technical Design Report (TDR) (2010).

[2] K. Akai, et al., SuperKEKB collider, Nucl. Instrum. Meth. A 907 (2018)188–199.

[3] E. Kou, et al., The Belle II Physics Book, Progress of Theoretical and Experimental Physics, 2019, 12, 2019, 123C01.

[4] F. Forti, Snowmass Whitepaper: The Belle II Detector Upgrade Program, 2022.

[5] H. Aihara, et al., The Belle II Detector Upgrades Framework Conceptual Design Report, 2024.

[6] P. Avella, DEPFET sensors development for the pixel detector (PXD) of Belle II, JINST 9 (2014) C01057.

[7] K. Adamczyk, et al., The design, construction, operation and performance of the Belle II silicon vertex detector, JINST 17 (2022) P11042.

[8] C. Bespin, et al., DMAPS Monopix developments in large and small electrode designs, Nucl. Instrum. Meth. A 978 (2020) 164460.

[9] K. Moustakas, Design and Development of Depleted Monolithic Active Pixel Sensors with Small Collection Electrode for High-Radiation Applications, Ph.D. thesis, Bonn U., 2021.

[10] R. Diener, et al., The DESY II test beam facility, Nucl. Instrum. Meth. A 922 (2019) 265-286.

[11] S. Bettarini, et al., The DMAPS upgrade of the Belle II vertex detector, JINST, 2024, 19, C02060.

[12] M. Schwickardi, Characterisation of CMOS Sensors for the Belle II Vertex Detector Upgrade, Ph.D. thesis, Georg-August-Universität Göttingen, 2024.

[13] M. Schwickardi, et al., Upgrade of Belle II vertex detector with CMOS pixel technology, JINST 19 (2024) C01054.

[14] M. Babeluk, et al., The DMAPS upgrade of the Belle II vertex detector, Nucl. Instrum. Meth. A 1064 (2024) 169428.

[15] M. Babeluk, et al., The OBELIX chip for the Belle II VTX upgrade, Nucl. Instrum. Meth. A 1067 (2024) 169659.

[16] T.H. Pham, et al., Design of the OBELIX monolithic CMOS pixel sensor for an upgrade of the Belle II vertex detector, 2024 JINST 19 C04020.

[17] D. Dannheim et al., “Corryvreckan: a modular 4D track reconstruction and analysis software for test beam data”, J. Instr. 16 (2021) P03008.