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 a second long shutdown to achieve the target luminosity of 6×10^{35} cm^{-2}s^{-1}. The vertex detector is a critical component of Belle II, responsible for precise tracking and vertexing near to the interaction point. The current vertex detector will be upgraded to a fully pixelated vertex detector (VTX) based on Monolithic Active Pixel Sensors (MAPS) technology to enhance performance and address challenges from increasing luminosity. The VTX will consist of five layers of depleted MAPS 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 under TowerJazz 180 nm for the ATLAS experiment. 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] detector 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 [4, 5].

The Belle II Vertex Detector (VXD) is crucial in reconstructing decay vertices with high precision. The current VXD is made up of two layers of Pixel Detector (PXD) [6] positioned in the inner region and four layers of Silicon Vertex Detector (SVD) [7] located in the outer region. The PXD employs pixel sensors based on DEPFET technology, featuring a pitch of 50-70 μm and an integration time of 20 μs. In contrast, the SVD utilizes double-sided strip detectors (DSSD), offering an impressive time resolution of approximately 3 ns but with relatively longer strip lengths of 6 cm. In the current state, where the background is low, the VXD shows excellent performance. Nevertheless, the background conditions will be 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].

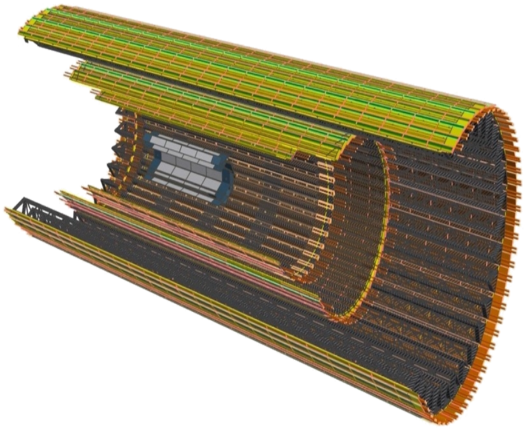

Figure 1: 3D cut view of the VTX

VTX requirements	
Spatial Resolution	$<15\mu$m
Hit Rate	120MHz/cm^2
Material Budget (per layer)	0.2-0.8% X/X$_0$
Trigger frequency	30kHz
Temporal resolution	<100 ns
Trigger latency	10μs
Power dissipation	200 mW/cm^2
TID	1 MGy
NIEL fluence	5$\times 10^{14}$ n$_{eq}$cm^{-2}

Table 1: Requirements for VTX detector of Belle II experiment

2. VTX requirements and structure

The VTX requirements that are needed to tackle high luminosity conditions are outlined in Table 1. These requirements were evaluated based on background extrapolations at the target

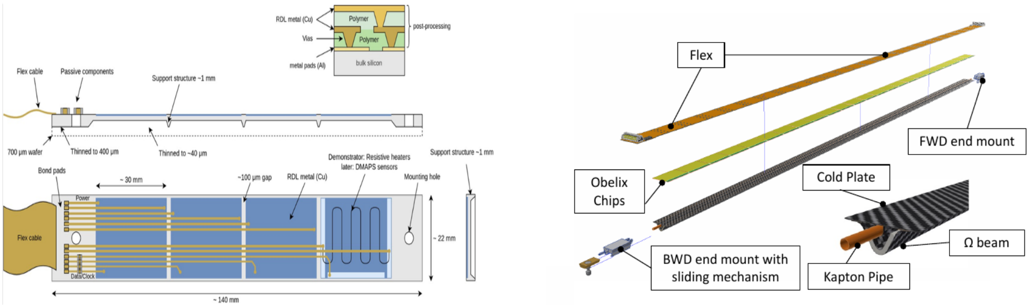

Figure 2: Left: iVTX ladder concept. Right: oVTX ladder concept with omega-shaped carbon support

luminosity, incorporating appropriate safety margins. Monolithic Active Pixel Sensors (MAPS) offer several advantages over traditional hybrid pixel detectors, including high spatial resolution (with 15μm achievable at a pixel pitch of 30-40μm), 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.

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 in Figure 1. The iVTX will consist of two 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 μm, leaving a 400 μm border for stiffness. A diagram of the iVTX ladder is shown in Figure 2 (left). 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. A Schematic of an omega-shaped carbon support is shown in Figure 2 (right).

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 described in detail in [5].

3. TJ-Monopix2 sensor

The TJ-Monopix2 sensor was chosen as the baseline for the OBELIX matrix, which features four variants ("flavors"), namely, Normal FE, Cascode FE, HV FE, and HV FE Cascode respectively. The matrix comprises 512 rows and 512 columns, with further details available in [9, 10]. Extensive characterization of both non-irradiated and irradiated sensors has been conducted in laboratory and test beams at DESY [11] 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 [12–14].

One such result, shown in Figure 3, demonstrates the in-pixel detection efficiency for a sensor irradiated with 24 MeV protons up to a fluence of $5{\times}10^{14}$ n_{eq}/cm^2 in the Cascode FE sub-matrix,

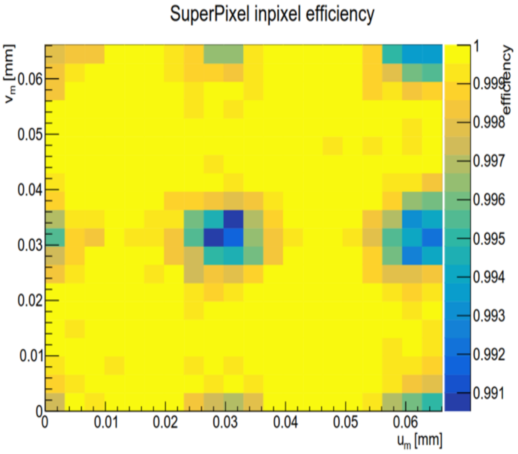

Figure 3: in-pixel efficiency for Cascode FE of irradiated TJ-Monopix2 sensor.

Pitch	33μm
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 μs 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

obtained during the July 2023 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 and time resolutions were also studied, showing consistently expected performance [10]. The sensors were operated at room temperature (about ~33°C). During the beam test in July 2024, we conducted tests on irradiated sensors across a range of temperatures and thresholds. The objective was to explore the optimal operating conditions in terms of threshold and temperature. If the sensors can function reliably at higher temperatures, air cooling could be sufficient for the iVTX modules. A detailed analysis of these measurements is currently in progress.

4. 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 [15, 16]. The size of the sensor is about 3 cm × 2 cm and the pitch of about 33μm, 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 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 μs and can operate at hit rates of up to 120 MHz/cm^2 [15].

5. 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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