DETECTOR SIMULATION FOR A POTENTIAL UPGRADE OF THE VERTEX DETECTOR OF THE BELLE II EXPERIMENT*

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We present the results of the first detailed simulations done for an upgraded Belle II vertex detector with a fully pixelated detector and different geometries. We observed that the new designs have better tracking performances compared to the current one, are more robust to the beam-induced background level, and have a lower occupancy. All these improvements will be greatly beneficial as the instantaneous luminosity increases.

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1. Introduction

The SuperKEKB accelerator [1], operating as a B, charm or τ factory, provides electron–positron collisions, which are recorded by the Belle II detector [2]. It consists of two storage rings of 3 km length each, one for the 7 GeV electrons and one for the 4 GeV positrons. Since its start in 2019, Belle II has accumulated physics data corresponding to an integrated luminosity of 90 fb^{-1} and topped the instantaneous luminosity world record with a value of 2.4×10^{34} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$.

The Belle II physics program aims to accumulate a total integrated luminosity of 50 ab^{-1} by 2031, as shown in Fig. 1, which requires a designed peak instantaneous luminosity of SuperKEKB of 6×10^{35} $\mathrm{cm}^{-2}\mathrm{s}^{-1}$, approximately thirty times higher than the current one. To achieve that, a long shutdown is scheduled around 2026 to replace the focusing magnets (QCS), which provides an opportunity to upgrade the tracking detector of Belle II.

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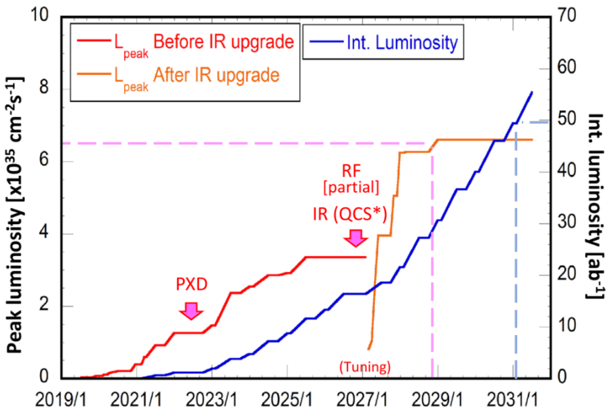

Fig. 1. Current SuperKEKB luminosity projection as a function of time. Two shutdown periods are indicated in 2022 and 2026.

2. Belle II tracking detector requirements

2.1. Current vertex detector

The average track multiplicity in Belle II events is about eleven tracks, mostly composed of $\pi^{\pm}$ (72.8%) and $K^{\pm}$ (14.9%) [3]. They have similar momentum ranges, mostly distributed below 1 GeV$/c$, which implies some multiple scattering and curling tracks effects. In addition, an important source of background comes from the beam-induced parasitic particles from various processes that dominate the occupancy of the vertex detector [4]: Touschek or beam-gas scattering, synchrotron radiation, injection background, radiative Bhabha or two-photon process.

To address these challenges, Belle II has three sub-detectors dedicated to tracking: the Central Drift Chamber (CDC), the four-layer double-sided silicon strip detector (SVD), and the two pixelated layers of the Pixel Detector (PXD). The track finding exploits hits from the CDC and the SVD; the PXD and SVD, also known as VXD for vertex detector, are responsible for the precise vertices measurements [2].

2.2. Vertex detector upgrade

The estimate of the beam-induced background rate at peak luminosity has large uncertainty since various key factors are still unknown. The machine optics needed to reach peak luminosity is not yet confirmed. Also, the interaction region geometry may significantly change. Finally, the background generated during continuous injection has not yet been robustly assessed at low luminosity, hence limiting severely the precision of any extrapolation to higher luminosity. Current simulations with the existing geometry predict that at peak luminosity, occupancies for the various layers of the present VXD get close to or exceed the limit beyond which tracking performance starts to degrade (see Fig. 2).

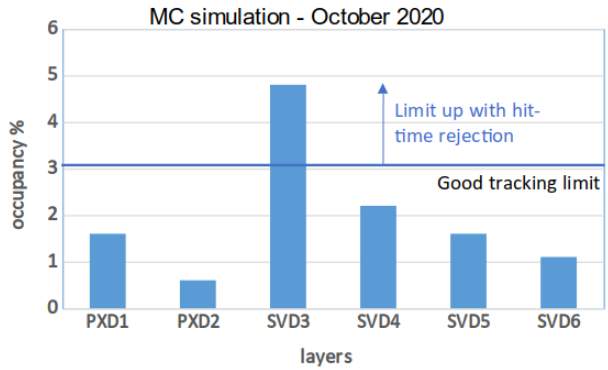

Fig. 2. Occupancy extrapolation at peak luminosity for the current VXD, as of December 2020. The horizontal line indicates the occupancy limit beyond which tracking performance is expected to degrade. However, instrumental and algorithmic effort with the current instrument may push this limit a few percent higher.

The long shutdown planned in 2026 is a good opportunity to upgrade the vertex detector to get better performance and background handling compared to the current VXD. By increasing the granularity of the detector and by reducing the integration time, the occupancy can be greatly reduced. A fast and fully pixelated detector, for instance, based on the CMOS pixel sensor technology [5], to replace the strip and pixel detector is then an appealing solution.

A dedicated team in Belle II was responsible for the implementation of a detailed simulation of the new technology and new geometries in the current Belle II software [6], in order to evaluate the benefits of such an upgraded VXD.

3. Detailed simulation development

3.1. Detector requirements

The new detector should at least match the acceptance of the current one. Its sensitive volume has then to extend from 1.4 cm to 14 cm in radii and from 12 cm to 72 cm in length.

Reducing the occupancy while providing similar or better tracking performance requires a pixel pitch in the range from 30 to 40 μm and an integration time under 100 ns. The material budget should target values of 0.1% of a radiation length (X_0) for the inner layers and 0.3% of X_0 for the outer layers, which implies a small thickness, under 50 μm, and low power dissipation, under 200 mW/cm^2.

These requirements match the capabilities of CMOS. In particular, this paper is based on the TJ-MonoPix1 [7] and TJ-MonoPix2 [8] prototypes that feature pixel size of 40×36 and 33×33 μm^2, respectively, and an integration time of 25 ns.

TJ-Monopix1 already exists and was characterized at the DESY test beam facility. TJ-Monopix2 is being fabricated and its pixel matrix is a good candidate for the sensor needed for the upgrade. It is then necessary to implement the response of these sensors in a so-called digitizer module in order to assess the overall performance of the upgraded VXD.

3.2. Tuning of the digitizer

When a charged particle traverses the sensor, secondary charges are generated by ionization along the particle trajectory within the active thickness of the sensor. The digitizer modules first emulate the collection of these charges over the pixels in the vicinity of the particle hit. Assuming the active volume is fully depleted, charges are randomly spread according to a Gaussian, with a width that depends linearly on the charge depth creation. Then, the digital value of each pixel is decided taking into account an equivalent noise charge, a charge-to-digital conversion factor and, finally, a detection threshold. Only a few parameters are unknown: the transverse diffusion and the hit threshold. Those parameters have been tuned to match a test-beam experiment made at DESY with TJ-MonoPix1 chips.

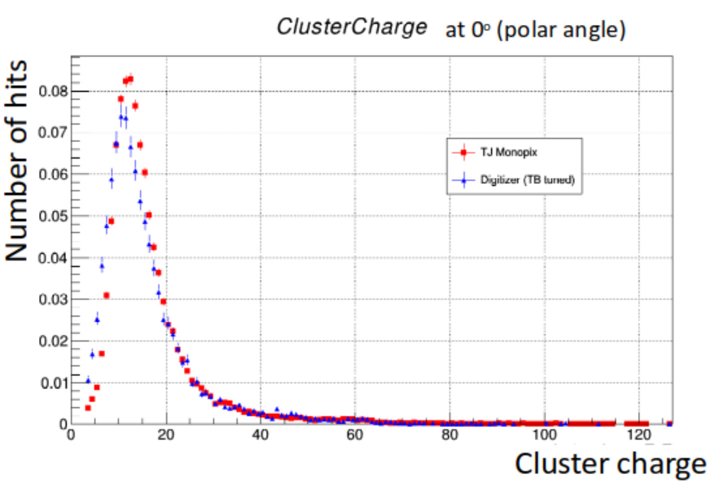

Fig. 3. (Colour on-line) Cluster charge distribution for the test-beam (in grey/red) and the digitizer in the Belle II software (in black/blue) with a normal incidence beam to the detector.

In the end, the tuned digitizer reproduces fairly well the test-beam data. It leads to a good agreement with the cluster size and cluster charge distribution for every test-beam angle (see Fig. 3). Also, the spatial resolution is reproduced within 20%. These results show that the digitizer, in particular the tuned value of the transverse diffusion, is validated for the TJ-MonoPix1, and can be tuned to predict the TJ-MonoPix2, which can then be used for the full simulation presented in the next section.

4. Performance results for two new geometries

Three new geometries based entirely on the predicted TJ-Monopix2 response were developed in the Belle II software. With that, three new geometry designs, called VTX for vertex detector, were implemented and connected to the existing tracking algorithm. All are fully pixelated detectors within the acceptance of the current VXD. One is composed of five layers, one with seven layers and one that is the five-layer design is complemented by two forward disks perpendicular to the beam pipe, which should allow a better measurement of lower momentum tracks. Only results from the first two detectors are presented below, as the third one is still under implementation.

When using a muon particle gun with nominal background predictions from 2019 overlaid, the CMOS five and seven layers have better transverse momentum resolution compared to the current Belle II VXD, in particular at low $p_{\rm t}$, as shown in Fig. 4. Also, the absolute full-track finding efficiency (CDC + VTX) is improved: when averaged on a flat momentum distribution is 2–3% better.

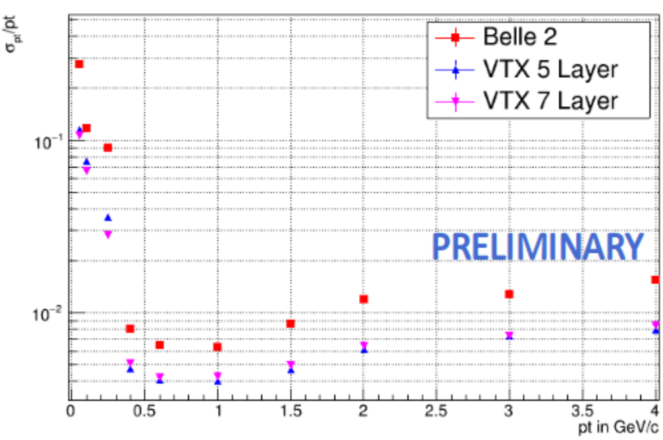

Fig. 4. (Colour on-line) Transverse momentum resolution as a function of $p_{\rm t}$, with in red the current Belle II VXD, in blue the five-layer and in pink the seven-layer geometries.

For the VTX-only figure of merits, the average layer one occupancy is 0.0016%, which is three orders of magnitude lower than the current VXD, due to its pixelated design and its fast integration time. For the absolute tracking efficiency, the five and seven layers are similarly on average 2–3% better at nominal luminosity. Also, the current SVD efficiency drops by 6% on average when the nominal background is multiplied by five as a safety factor. This is not the case for the new geometries. They only drop in absolute tracking efficiency by 0.5% to 1%, which shows that this technology is very robust to the increase of the background.

5. Conclusion

To upgrade the SuperKEKB collider for its peak luminosity, a long shutdown in 2026 is foreseen, which is a good opportunity to to also upgrade the Belle II vertex detector. Current estimates indeed show that its occupancies are close to a limit where its performances can degrade. Three new geometries and a fully pixelated technology were implemented in the Belle II software. The digitizer was tuned to reproduce the TJ MonoPix-1, thus predict the MonoPix-2 performance. Also, according to the first Monte Carlo simulations, the new designs are more robust against a beam-induced background, have a lower occupancy, and have better tracking performances. In the future, the impact of this upgrade on the physics channels will be studied, to further assess the benefits for Belle II from a fully pixelated detector.

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