

The Silicon Vertex Detector of the Belle II Experiment

Antonio Paladino^{*†}

INFN - National Institute for Nuclear Physics and University of Pisa

E-mail: antonio.paladino@pi.infn.it

K. Adamczyk^s, H. Aihara^o, C. Angelini^{h,i}, T. Aziz^g, V. Babu^g, S. Bacher^s, S. Bahinipati^d, E. Barberio^a, Ti. Baroncelli^a, To. Baroncelli^a, A. K. Basith^e, G. Batignani^{h,i}, A. Bauer^b, P. K. Behera^e, T. Bergauer^b, S. Bettarini^{h,i}, B. Bhuyan^f, T. Bilka^c, F. Bosiⁱ, L. Bosisio^{j,k}, A. Bozek^s, F. Buchsteiner^b, L. Bulla^b, G. Casarosaⁱ, M. Ceccantiⁱ, D. Červenkov^c, S. R. Chendvankar^g, N. Dash^d, G. De Pietro^{h,i}, S. T. Divekar^g, Z. Doležal^c, D. Dutta^g, F. Forti^{h,i}, M. Friedl^b, K. Hara^p, T. Higuchi^l, T. Horiguchiⁿ, C. Irmiler^b, A. Ishikawaⁿ, H. B. Jeon^q, C. W. Joo^l, J. Kandra^c, K. H. Kang^q, E. Katoⁿ, T. Kawasaki^{m,B}, P. Kodyš^c, T. Kohriki^p, S. Koike^{p,A}, M. M. Kolwalkar^g, P. Kvasnička^c, L. Lanceri^{j,k}, J. Lettenbicher^b, T. Lueck^{h,i}, M. Maki^p, P. Mamminiⁱ, S. N. Mayekar^g, G. B. Mohanty^g, S. Mohanty^{g,C}, T. Morii^l, Z. Natkaniec^s, K. Negishiⁿ, N. K. Nisar^g, Y. Onuki^o, W. Ostrowicz^s, A. Paladino^{h,i}, E. Paoloni^{h,i}, H. Park^q, F. Piloⁱ, A. Profetiⁱ, I. Rashevskaya^{k,D}, K. K. Rao^g, G. Rizzo^{h,i}, M. Rozanska^s, J. Sasaki^o, N. Sato^p, S. Schultschik^b, C. Schwanda^b, Y. Seino^m, N. Shimizu^o, J. Stypula^s, J. Suzuki^p, S. Tanaka^p, K. Tanida^r, G. N. Taylor^a, R. Thalmeier^b, R. Thomas^g, T. Tsuboyama^p, S. Uozumi^q, P. Urquijo^a, L. Vitale^{j,k}, S. Watanukiⁿ, I. J. Watson^o, J. Webb^a, J. Wiechczynski^s, S. Williams^a, B. Würkner^b, H. Yamamotoⁿ, H. Yin^b, T. Yoshinobu^p, L. Zani^{h,i}. (Belle II SVD Collaboration)

- ^a*School of Physics, University of Melbourne, Melbourne, Victoria 3010, Australia*
- ^b*Institute of High Energy Physics, Austrian Academy of Sciences, 1050 Vienna, Austria*
- ^c*Faculty of Mathematics and Physics, Charles University, 121 16 Prague, Czech Republic*
- ^d*Indian Institute of Technology Bhubaneswar, Satya Nagar, India*
- ^e*Indian Institute of Technology Madras, Chennai 600036, India*
- ^f*Indian Institute of Technology Guwahati, Assam 781039, India*
- ^g*Tata Institute of Fundamental Research, Mumbai 400005, India, ^C also at Utkal University, Bhubaneswar 751004, India*
- ^h*Dipartimento di Fisica, Università di Pisa, I-56127 Pisa, Italy*
- ⁱ*INFN Sezione di Pisa, I-56127 Pisa, Italy*
- ^j*Dipartimento di Fisica, Università di Trieste, I-34127 Trieste, Italy*
- ^k*INFN Sezione di Trieste, I-34127 Trieste, Italy, ^D presently at TIFPA - INFN, I-38123 Trento, Italy*
- ^l*Kavli Institute for the Physics and Mathematics of the Universe (WPI), University of Tokyo, Kashiwa 277-8583, Japan*
- ^m*Department of Physics, Niigata University, Niigata 950-2181, Japan, ^B presently at Kitasato University, Sagami-hara 252-0373, Japan*
- ⁿ*Department of Physics, Tohoku University, Sendai 980-8578, Japan*
- ^o*Department of Physics, University of Tokyo, Tokyo 113-0033, Japan*
- ^p*High Energy Accelerator Research Organization (KEK), Tsukuba 305-0801, Japan, ^A deceased*
- ^q*Department of Physics, Kyungpook National University, Daegu 702-701, Korea*
- ^r*Department of Physics and Astronomy, Seoul National University, Seoul 151-742, Korea*
- ^s*H. Niewodniczanski Institute of Nuclear Physics, Krakow 31-342, Poland*

The Belle II experiment at the SuperKEKB flavour factory will operate at an unprecedented luminosity of $8 \times 10^{35} \text{cm}^{-2} \text{s}^{-1}$, which is about 40 times larger than its predecessor KEKB. The Vertex Detector is composed of a two-layer DEPFET PiXel Detector (PXD) and a four-layer double sided silicon strip detector (SVD). To achieve a precise vertex position determination and an excellent low-momentum tracking, even under the high background and high trigger rate of 10kHz, the SVD employs several innovative techniques. In order to reduce the occupancy and to minimise the parasitic capacitance in the signal path, 1748 APV25 ASIC chips, which read-out signals from 224k strip channels, are directly mounted on the ladders with the novel Origami concept. The analog signals from APV25 are digitised by an FADC system and sent to the central DAQ. An online tracking system based on SVD hits provides the Regions Of Interests to PXD in order to reduce the data size to achieve the required bandwidth and data storage space. In this talk, we present the design principles and construction status of the Belle II SVD, together with preliminary results on sensors performances.

*38th International Conference on High Energy Physics
3-10 August 2016
Chicago, USA*

*Speaker.

†On behalf of the Belle II SVD group

1. Introduction

The Belle II collaboration [1] has a comprehensive program in precision measurements of the B meson sector, including CP violation in decays, in mixing and in the interference between mixing and decays. Studies will be also performed in the D meson sector, rare τ decays, quarkonium states, exotic hadrons and dark sector [2].

The experiment will be performed at the SuperKEKB asymmetric e^+e^- collider [3] now under construction at the KEK laboratory (Tsukuba, Ibaraki Prefecture, Japan). SuperKEKB is a major upgrade of the KEKB collider, aiming to reach an unprecedented instantaneous luminosity of $8 \times 10^{35} \text{ cm}^{-2}\text{s}^{-1}$, that will be reached reducing the vertical beta function at the interaction point (IP) by a factor 20 and increasing the beam current to twice that of KEKB, while keeping the same vertical beam-beam parameter. Within the actual schedule such a high luminosity will be reached by 2022 and will allow Belle II to collect up to 15 ab^{-1} of data per year, or 50 ab^{-1} of data within the end of 2024. The SuperKEKB accelerator is based on two separated rings, with 7 GeV energy for the electron beam and 4 GeV for the positron beam, corresponding to a center of mass energy of $\sim 10.58 \text{ GeV}$, around the $\Upsilon(4S)$ resonance. The $\Upsilon(4S)$ will thus be produced with a sizeable relativistic boost in the laboratory frame ($\beta\gamma = 0.28$), although significantly reduced with respect to KEKB ($\beta\gamma = 0.425$).

All the Belle II sub-detectors have been redesigned to improve the performances with respect to Belle and to cope with the expected increase of luminosity. The sub-detector nearest to the IP is the VerteX Detector (VXD), which is fundamental for the measurement of the impact parameters of charged tracks and for the reconstruction of primary and secondary B and D mesons decay vertexes. It consists of two inner layers (1 and 2) of a silicon PiXel Detector (PXD) followed by four layers (from 3 to 6) of a Silicon Vertex Detector (SVD), which is composed by double sided silicon strips sensors. The whole VXD is immersed in a 1.5 T magnetic field parallel to the beam axis. The CAD design of the VXD is shown in Fig. 1.

A description of the SVD will be given, with particular attention to the Origami concept, in section 2; in section 3 some preliminary results on sensors performance and data reduction system for PXD will be shown, while in section 4 the status of the production and the next important milestones will be presented.

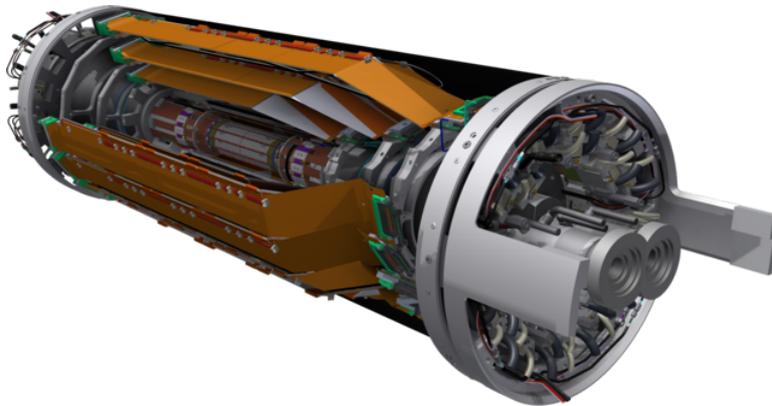


Figure 1: Layout of the Belle II VerteX Detector (VXD)

2. SVD description and the "Origami" concept

The Belle II SVD is made by 4 layers of double sided silicon strip detectors (DSSD) organised in a barrel geometry with a polar angle coverage from 17° in the forward region to 150° in the backward region and with a radius going from 39 mm for the inner layer to 140 mm for the outer layer. In the forward region slanted trapezoidal sensors are used to optimise the angular coverage and the particle incidence angle. Only three different kind of sensors, fabricated on 150 silicon wafers and with n-type substrate of $300\ \mu\text{m}$ thickness, are used, two rectangular and one trapezoidal. The list of strip pitches can be found in Fig. 2. The two rectangular sensors are made by Hamamatsu Photonics K.K. (Japan) and are both around 120mm long, the larger one being 60 mm wide, the other one 39 mm wide. The trapezoidal sensors are made by Micron Semiconductor Ltd. (UK) and are around 120 mm long, with the largest edge around 60 mm wide and the shortest edge around 39 mm wide. More details on the sensors can be found in Ref. [4] [5]. Sensors are longitudinally organised in *ladders*, which are made of 2, 3, 4, 5 sensors for layer 3, 4, 5, 6 respectively. In Fig. 2 the longitudinal layout of the SVD is shown. From the inner to the outer layer 7, 10, 12, 16 ladders will be used to build the barrel shape of every layer.

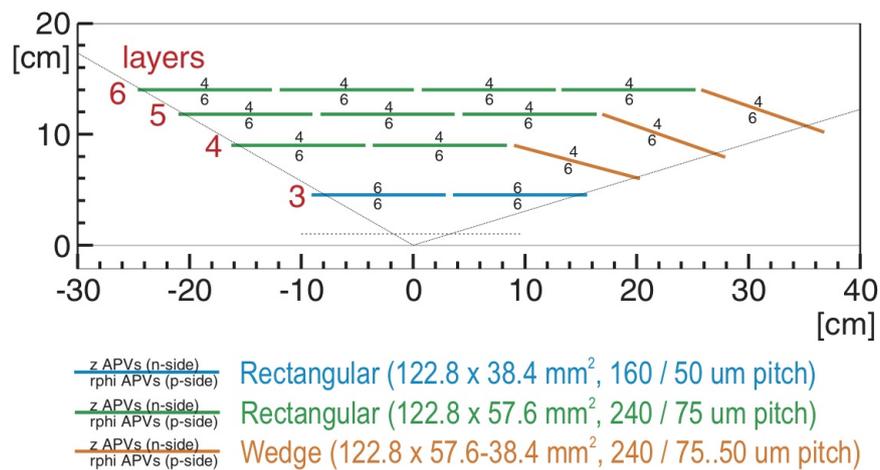


Figure 2: Longitudinal structure of SVD. The origin of the reference system represents the nominal interaction point.

The peripheral sensors in the forward and backward region of the ladders will be read-out by front end electronics placed on hybrid circuits located outside of the SVD active region. In order to reduce the occupancy of the strips and to minimise the capacitive load on the front end electronics, keeping high the signal-to-noise ratio, it was decided to read-out sensors individually. This means that the read-out electronics for the inner sensors in layer 4, 5 and 6 must be placed inside the active area of the SVD. These reasons introduced some constraints for the read-out electronics: it must have a short shaping time, must be radiation hard and its material budget should be as small as possible. The chip that fulfils this requirements is the APV25 [6], which is tolerant to high radiation doses (more than 100 MRad) and the combination of short shaping time (50 ns) and the online pulse shape processing will keep the occupancies below the 1% level even under the severe background conditions at the SuperKEKB design luminosity. APV25 chips to be used for the inner

sensors have been thinned from the original $300\ \mu\text{m}$ thickness down to $100\ \mu\text{m}$ and placed on top of the sensors using the so called "*Origami*" chip-on-sensor concept [7] [8].

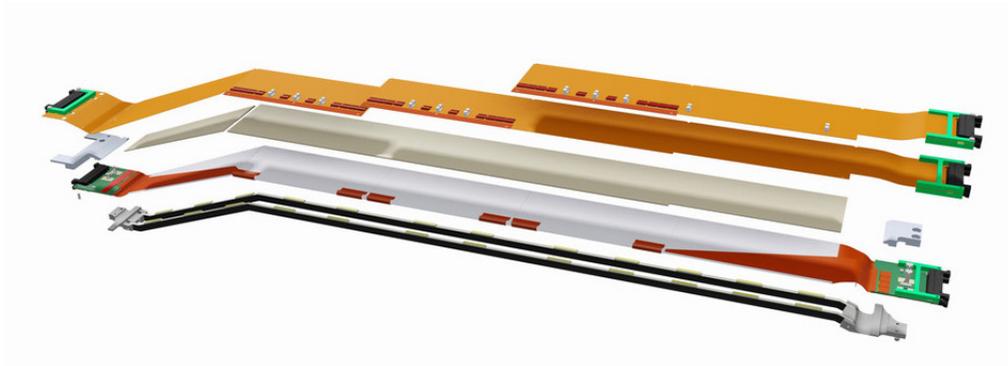


Figure 3: Structure of a layer 6 ladder. From bottom to top: carbon fiber ribs, peripheral sensors with hybrid board attached and inner sensors, airex sheet, Origami flex circuits with APV25 chips on top.

The Origami is a three layer kapton hybrid circuit on which all APV25 read-out chips of one sensor are placed and aligned. The Origami is then glued on the top side of the sensor, with a 1 mm thick layer of Airex in between, to ensure electrical and thermal insulation. The sensor top side strips will be connected to the APV25 chips through a planar flexible pitch adapter circuit, while the bottom side strips will be routed to the other side of the sensor, toward the electronics, wrapping two different pitch adapters around the sensor edge, above the top side wire bondings. Two carbon fiber ribs are used as a support structure for the ladder. The structure of a layer 6 ladder (the longest one in the SVD) is shown in Fig. 3. The alignment of APV25 chips on top of the Origami allows the use of just one cooling channel, that consists of a 1.6 mm diameter pipe with CO_2 flowing inside. This ensure efficient read-out electronics cooling keeping low the material budget, that is in average 0.6% of a radiation length.

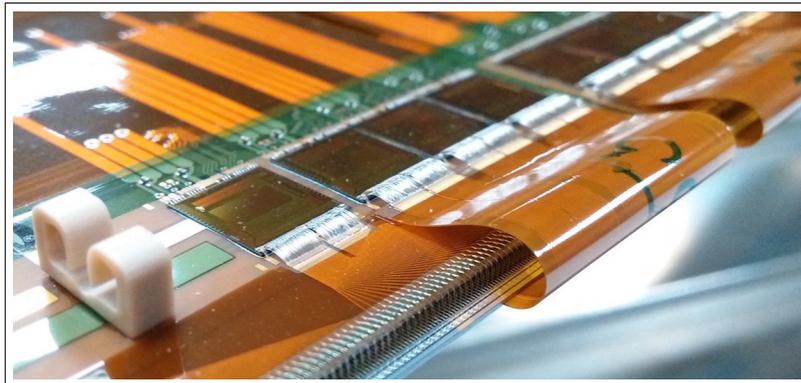


Figure 4: Pitch adapter wrapped from bottom to top side of an inner sensor, over the top side wire bondings, to connect bottom side strips to the read-out electronics.

The analog outputs from the APV25 chips are transmitted to the Flash Analog-to-Digital Converter (FADC). An FADC board receives up to 48 APV25 analog outputs and performs flash analog- to-digital conversion with 31.8 MHz clock to obtain the digitised DSSD signals that are

then decoded and processed on an FPGA, and propagated to a Finesse Transmitter Board (FTB). The FTB sends the data to the Common Pipelined Platform for Electronics Read-out (COPPER), which is a Belle II DAQ interface through an optical fiber. In the Belle II experiment, 48 FADC boards and 48 FTBs will be installed. A full description of the read-out electronics can be found in Ref. [9] [10] [11].

3. SVD performance

In April 2016 the SVD group, together with the PXD group, worked in a beam test at the DESY facility in Hamburg (Germany) to evaluate the performance of the sensors. In this occasion for the first time a slice of the VXD that included all layers was assembled and tested with an electron beam of energy $2 \div 5$ GeV and a solenoid magnetic field up to 1 T. The main tasks of the beam test were to integrate PXD and SVD systems, to verify the full DAQ chain and to evaluate sensors efficiency and resolution.

3.1 Sensors efficiency

For the efficiency study, the data sample was taken with electron beam of energy 5 GeV and a magnetic field of 1 T. Only the four SVD layer data are used to evaluate the efficiency: once that the layer under study is fixed, the other three layers are used as a reference, requiring one hit per layer and fitting a track passing through all 3 reference layers. The fitted track is used to estimate the position of the hit point on the fourth layer, then the number of hits within $300 \mu\text{m}$ from the estimated hit point is counted. The efficiency ε is evaluated as the ratio between the number of counted hits and the number of fitted tracks. In the following plots the inefficiency η is shown:

$$\varepsilon = \frac{\#hits}{\#tracks} \quad \eta = 1 - \varepsilon \quad (3.1)$$

Only tracks coming from high momentum particles are selected: $2 < p_{\text{fit}} < 4$ GeV. In the plots of Fig. 5 the inefficiencies for a layer 4 sensor on both ϕ and z sides are shown. The efficiency is above 99.5% in both directions. The same study was performed on the sensors of the other layers and the efficiencies show similar results for both ϕ and z strip directions.

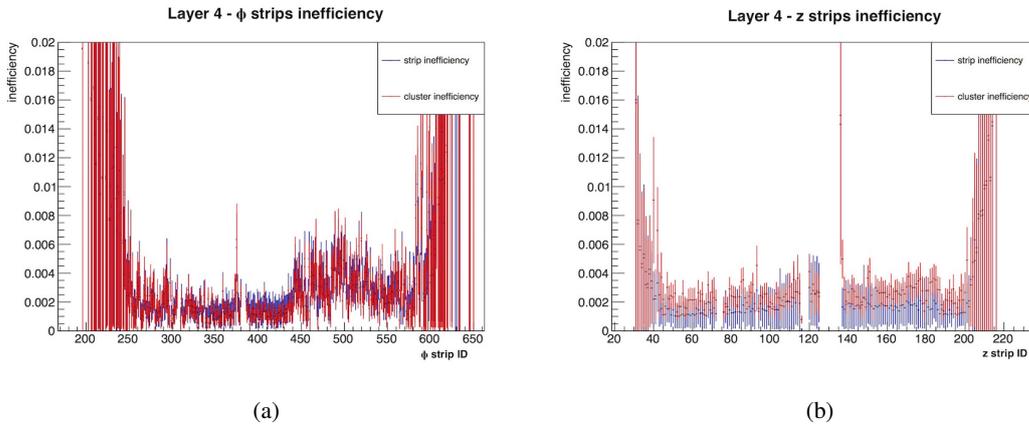


Figure 5: Inefficiencies for layer 4 sensor on ϕ -direction (a) and z -direction (b).

3.2 Sensors resolution

For the resolution evaluation, in addition to the four SVD layers, also the 2 PXD layers and 6 layers of the EUDET telescope, three downstream and three upstream, are used, to avoid a biased estimation of the resolution. So a total of twelve layers were traversed by particles. The tracks used to evaluate the resolution are required to have at least 10 hits in the eleven layers used as a reference. The residuals for the sensor under investigation is calculated as the difference between the position of the extrapolated track and the hit on the sensor, on both ϕ and z directions. In Fig. 6 the residuals distributions for the layer 4 sensor are shown. The obtained resolution estimation is compatible with the digital resolution: $R_{dig} = pitch/2\sqrt{12}$.

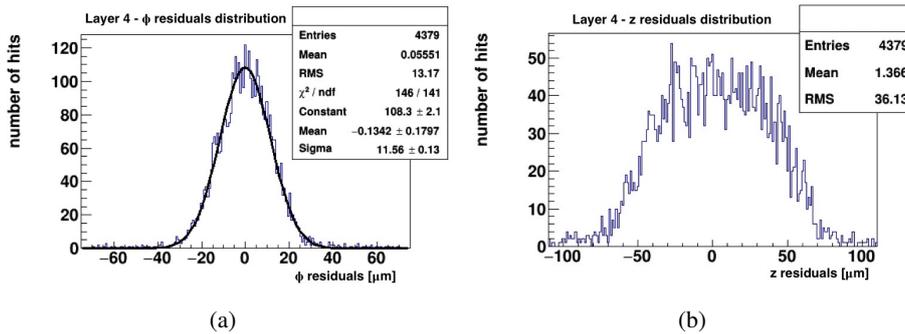


Figure 6: Resolutions for layer 4 sensor on phi-direction (a) and z-direction (b).

3.3 PXD Regions Of Interest (ROI)

Another important task of the DESY beam test was the verification of the data reduction system for the read-out of the PXD. Due to the high instantaneous luminosity of SuperKEKB a very high rate of events will be produced, that means for the PiXeL Detector a huge amount of data to be handled. A large fraction of data can be rejected by defining a set of Regions Of Interest (ROI) [12] on the PXD sensors and then recording just the data from the pixels inside the ROI. The ROIs are defined on an event by event basis by extrapolating back onto the PXD the charged tracks detected in the SVD. The tracks are reconstructed in real time on the High Level Trigger (HLT) and the pixel detector is then read out based on the ROI information. The beam test has shown that this method is successful and that can be used as an effective method to reduce PXD data.

4. Conclusions

The Belle II VerteX Detector is now under construction. The assembly procedures, despite all the challenges, are well defined and all SVD assembly sites have started ladder mass production. Moreover, performance evaluation of the sensors in a beam test was done with excellent results on the efficiency, that is higher than 99.5% for all sensors tested, and on the resolution, that is comparable with the digital one. Given that the SVD assembly requires that two half-shells are produced separately and then combined together, the assembly of the first shell can start before the completion of all ladders, so the ladder mount for the first half-shell of the SVD is foreseen to start in February 2017. The following important milestone will be the SVD commissioning, which is

foreseen in October 2017. Finally the first physics runs with the full Belle II detector are foreseen in fall 2018.

References

- [1] T. Abe et al., Z. Doležal and S.Uno (editors), *Belle II Technical Design Report*, KEK Report 2010-1, arXiv:1011.0352; see also <http://belle2.org/>
- [2] P. Urquijo, *Physics prospects at the Belle II experiment*, Nuclear and Particle Physics Proceedings, Volumes 263-264, June-July 2015, Pages 15-23.
- [3] Y. Ohnishi et al., *Accelerator design at SuperKEKB*, Prog. Theor. Exp. Phys. (2013) 03A011; see also <http://www-superkekb.kek.jp/>
- [4] T. Bergauer et al., *Recent progress in sensor- and mechanics-R&D for the Belle II Silicon Vertex Detector*, Nucl. Instr. Meth. A 718 (2013) 279-282.
- [5] T. Bergauer, *The Silicon Vertex Detector of the Belle II Experiment*, PoS(EPS-HEP 2013)487.
- [6] M. French et al., *Design and results from the APV25, a deep sub-micron CMOS front-end chip for the CMS tracker*, Nucl. Instr. Meth. A 466 (2001) 359-365.
- [7] M. Friedl et al., *The Origami Chip-on-Sensor Concept for Low-Mass Readout of Double-Sided Silicon Detectors*, TWEPP-08, CERN-2008-008 (2008), 277-281.
- [8] C. Irmler, *Origami chip-on-sensor design: progress and new developments*, TWEPP-12, 2013 JINST 8 (TWEPP 2012 conference), C01014.
- [9] M. Friedl et al., *The Belle II Silicon Vertex Detector Readout Chain*, JINST 8 (TWEPP 2012 conference), C02037.
- [10] M. Friedl et al., *First Results of the Belle II Silicon Vertex Detector Readout System*, JINST (TWEPP 2014 conference).
- [11] K. Nakamura et al., *Development of a Data Acquisition System for the Belle II Silicon Vertex Detector*, Proceedings of Science (TIPP 2014 conference), 198.
- [12] T. Bilka et al., *Demonstrator of the Belle II Online Tracking and Pixel Data Reduction on the High Level Trigger System*, arXiv:1406.4955v2, 2 Apr 2015.