Status and Upgrade Plans of the Belle Silicon Vertex Detector

H. Aihara[s] T. Arakawa[h] Y. Asano[v] T. Aso[t] A. Bakich[n] M. Barbero[a] T. Browder[a]
M. C. Chang[o] Y. Chao[o] K. F. Chen[o] S. Chidzik[k] A. Chouvikov[k] Y.K. Choi[m] A. Das[p]
J. Dalseno[e] S. Fratina[d] M. Friedl[w] Y. Fujiyama[r] J. Haba[u] K. Hara[f] T. Hara[j] B. Harrop[k]
K. Hayashi[u] M. Hazumi[u] D. Heffernan[j] T. Higuchi[u] T. Hirakawa[r] C. Irmler[w] H. Ishino[r]
N.K. Joshi[p] S. Kajiwara[j] H. Kakuno[s] T. Kameshima[ℓ] T. Kawasaki[h] A. Kibayashi[r]
Y.J. Kim[ℓ] S. Koike[u] S. Korpar[d] P. Križan[d] H. Kurashiro[r] A. Kusaka[s] D. Marlow[k]
H. Miyake[j] G. R. Moloney[e] Y. Nakahama[s] Z. Natkaniec[c] S. Okuno[b] S. Ono[r]
W. Ostrowicz[c] H. Ozaki[u] L. Peak[n] M. Pernicka[w] M. Rosen[a] M. Rozanska[c] N. Sato[u]
S. Schmid[w] J. Schümann[o] S. Stanič[i] H. Steininger[w] K. Sumisawa[u] O. Tajima[u]
T. Takahashi[r] N. Tamura[h] M. Tanaka[u] N. Tani[q] G. N. Taylor[e] K. Trabelsi[u]
T. Tsuboyama[u] K. Uchida[a] K. Ueno[o] Y. Ushiroda[u] G. Varner[a] K. Varvell[n]
Y. S. Velikzhanin[o] C. C. Wang[o] M. Z. Wang[o] M. Watanabe[h] Y. Watanabe[r]
H. Yamamoto[q] Y. Yamashita[g] T. Ziegler[k]

[a] *University of Hawaii, Department of Physics and Astronomy,2505 Correa Road, Honolulu, HI 96822, USA.*
[b] *Kanagawa University,Faculty of Engineering, 3-27-1 Rokkakubashi,Kanagawa-ku,Yokohama,Kanagawa,221-8686, Japan*
[c] *H.Niewodniczanski Institute of Nuclear Physics,Polish Academy of Sciences,ul.Radzikowskiego152,31-342 Krakow, Poland*
[d] *Jožef Stefan Institute, Jamova 39, SI-1000 Ljubljana, Slovenia*
[e] *The University of Melbourne, The School of Physics, Victoria, 3010, Australia*
[f] *High Energy Physics Laboratory,Furou-cho Chikusa-ku Nagoya-shi Aichi, 464-8602, Japan*
[g] *Nihon Dental College, 1-8 Hamaura-cho, Niigata 951-8151, Japan*
[h] *Niigata University, Graduate School of Science and Technology,Niigata 951-8580,Japan*
[i] *University of Nova Gorica,Vipavska 13, POB 301, 5000 Nova Gorica, Slovenia*
[j] *Osaka University,Graduate School of Science,Department of Physics,1-1Machikaneyama,Toyonaka,Osaka 560-0043,Japan*
[k] *Princeton University, Department of Physics, PO Box 708, Princeton, NJ 08544, USA*
[ℓ] *The Graduate University for Advanced Studies, School of High Energy Accelerator Science,1-1 Oho, Tsukuba-shi, Ibaraki-ken 305-080, Japan*
[m] *Sung Kyun Kwan University, Department of Physics, Chunchun-dong 300 Jangan Suwon, Korea*
[n] *University of Sydney, School of Physics, NSW 2006 Australia*
[o] *National Taiwan University, Department of Physics HEP Lab, Taipei 10764,Taiwan, R.O.C.*
[p] *Tata Institute of Fundamental ResearchDepartment of High Energy Physics,Homi Bhabha Road, Mumbai 400005, India*
[q] *Tohoku University, Department of Physics HEP Group, Aramaki,Aoba-ku, Sendai 980-8578, Japan*
[r] *Tokyo Institute of Technology, Department of Physics Group HP, 2-12-1,Oh-okayama, Meguro-ku, Tokyo 152-8551, Japan*
[s] *University of Tokyo, Department of Physics, 7-3-1, Hongo, Bunkyo-ku,Tokyo 113-0033, Japan*
[t] *Toyama National College of Maritime Technology, Toyama, Japan*
[u] *KEK, High Energy Accelerator research Organization, 1-1 Oho, Tsukuba-shi,Ibaraki-ken 305-080, Japan*
[v] *University of Tsukuba, Institute of Applied Physics, 1-1-1 Tenodai,Tsukuba-shi, Ibaraki-ken 305-8573, Japan*
[w] *Institute of High Energy Physics, Austrian Academy of Sciences,Nikolsdorfergasse 18, A-1050 Vienna, Austria*

Preprint submitted to Elsevier Science *13 February 2007*

Abstract

The second generation of Belle silicon vertex detector has been efficiently operated for more than three years. With increasing beam-induced background, a degradation of the detector performance is expected. To avoid such a difficulty, we are planing a next upgrade, the third generation of the silicon vertex detector. Currently, its design is almost finalized.

Key words: Belle; KEKB; Silicon strip detector, APV25

---

1. Introduction

The Belle detector (1) is a large-solid-angle magnetic spectrometer designed to study CP violation in B meson decays. The B mesons are produced in pairs at the KEKB energy asymmetric electron-positron (8 and 3.5 GeV) collider operating at the $\Upsilon(4S)$ resonance with the world highest luminosity of 1.7×10^{34} cm^{-2}s^{-1} . The $\Upsilon(4S)$ is produced with a Lorentz boost factor of $\beta\gamma = 0.425$, and subsequently decays into two B mesons. One of the main goals of the experiment is the precise measurement of the time-dependent CP violating parameters in the neutral B meson system. An accurate determination of the distance between the decay vertices of the two B mesons is a crucial point in these studies. Since the distance between the two vertices is 200 μm on average, the vertex detector must be able to measure the distance between them with a precision better than 100 μm. The Belle Silicon Vertex Detector (SVD) plays a key role in these measurements.

The initial version of the SVD (SVD1 (2)) has been working since 1999. Its very good performance contributed to many important physics results, like the discovery of CP violation in the B sector in 2001 (3). The SVD1 design had, however, several shortcomings, like limited radiation tolerance, non-negligible dead time and sensitivity to the so-called pin-hole effect. To solve these problems, SVD1 was replaced with a new version, SVD2 (4), and since October 2003 it successfully operates in the experiment. Problems associated with SVD1 and a comparison of the performance of SVD1 and SVD2 are described elsewhere (4; 5; 6)

The beam-induced background is gradually increasing as a side effect of the luminosity improvement of the KEKB, and the performance degradation of the SVD is expected. To avoid such difficulties, we are planing a next upgrade, SVD3. In this paper, we describe the status and the upgrade plans of SVD.

2. SVD2

2.1. *Detector configuration*

The schematic view of SVD2 is shown in Fig. 1. The detector is built from 246 AC couple double-sided silicon detector (DSSD) fabricated by Hamamatsu Photonics. Their configurations are summarized in Table 1. The DSSDs are arranged in four layers surrounding the beam pipe. The radii of the four layers are 20, 43.5, 70 and 88 mm. The layers are constructed from 6, 12, 18 and 18 independent ladders consisting of 2, 3, 5 and 6 DSSDs, respectively. To minimize the capacitance of the single readout channel, the ladders are split in halves each of which is read out on the outer end. The SVD2 covers the geometrical acceptance of the drift chamber ($17^\circ < \theta < 150^\circ$ in polar angle).

The SVD2 has in total 110,592 strips, and their signals are read out by the VA1TA chips from IDEAS (7). The VA1TA chip is fabricated using a 0.35 μm CMOS process, and can stand up to 200 kGy irradiation. Four VA1TA chips have been deployed on for each hybrid boards, and they are mounted at both ends of each ladder. The p and n sides of each half-ladder are read out by separate hybrids. A single hybrid board reads out 128 $\times$ 4 = 512 channels with about 800 ns shaping time. The signals are transmitted to a repeater system installed in boxes at the end-plate outside the main detector volume. To avoid the pin-hole effect, the ground of the readout electronics is at level of the detector bias voltage ($\pm$40 V). The decoupling from the ground potential of the rest of the electronics takes place in the repeater system by opto-coupler devices. Amplified signals are transmitted to outside of the Belle detector with 35 m long CAT5 cables. A fast analog-to-digital converter (FADC) system digitize the signals, and the digital data is read out via custom PCI link boards to PCs. Data sparsification, partial event building are performed by the PCs, and the data are transmitted to the Belle data acquisition system.

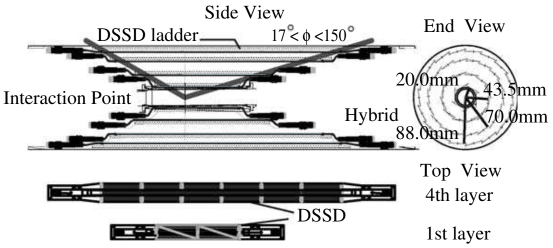

Fig. 1. Mechanical structure of the SVD2 detector.

Table 1
DSSD configuration for SVD2 and SVD3

	SVD2				SVD3	
Layer	1, 2, 3		4		1, 2	
Side	p(z)	n($r\phi$)	p(z)	n($r\phi$)	n(z)	p($r\phi$)
Thickness (mm)	0.3		0.3		0.3	
Strip length (mm)	25.6	76.8	33.3	73.8	26.1	77.7
No. of strips	1024	512	1024	512	1024	1024
Strip pitch (μm)	75	50	73	65	76	25.5
Readout pitch (μm)	150	50	146	65	152	51
Strip width (μm)	50	10	55	12	24	10
Total capacitance (pF)	3.8	22.5	4.6	21.9	4.7	9.4

2.2. *Performance*

During three years of operation, the SVD2 has been operated efficiently. The innermost layer received a dose of approximately 6.5 kGy. Since this is small compared to the maximum exposure dose applied in the radiation test, no significant gain change for the VA1TA is observed due to radiation damage. The signal-to-noise ratios (S/N) have been stable for the third and fourth layers, while the degradation of the first and second layers has been about 20 %. This degradation is mostly due to an increasing shot noise accompanied by an increased leakage current.

The offline analysis shows good matching efficiency of about 98 % which is defined by the probability that the tracks reconstructed in the drift chamber can be extrapolated to the hits in the vertex detector. The typical trigger rate is about 400 Hz and the average detector occupancy is around 3 %. A considerably higher occupancy of 10 % is obtained in the first layer, it drops to 3 % in second layer and to 2 % in the third and fourth layers. The situation of the beam-induced background is occasionally worse than the usual due to the troubles in KEKB such as the leakage of air into the vacuum chamber.

Figure 2 shows the hit efficiency of the first layer as a function of its occupancy, it is obtained from collision data. Here, we require that both p and n sides of the detector have been hit. Almost 90 % detection efficiency is achieved for the first layer, and they are more than 90 % for the outer three layers.

The impact parameter resolutions obtained from cosmic ray data are $\sigma_{d(r\phi)} = 21.9 \oplus 35.5/(p\beta \sin^{3/2}\theta)$ (μm) and $\sigma_{dz} = 27.8 \oplus 31.9/(p\beta \sin^{5/2}\theta)$ (μm), where p is the track momentum in the unit of GeV/c and θ is the dip angle relative to the detector. Figure 3 shows the impact parameter resolutions in the $r\phi$-direction using μ pair events as a function of the first layer occupancy comparing the collision data with the Monte Carlo (MC) data. In the MC, DSSDs are assumed to be perfectly aligned.

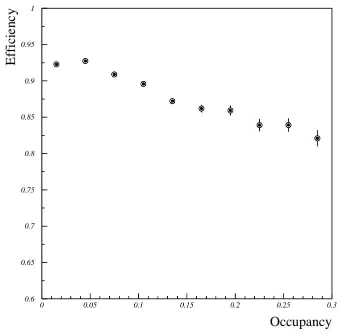

Fig. 2. Hit efficiency as a function of occupancy for the inner most layer of SVD2 using data in collision.

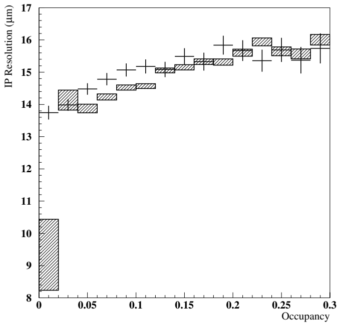

Fig. 3. Impact parameter resolution in $r\phi$ as a function of first layer occupancy using μ pair events. Crosses (boxes) indicate the collision data (Monte Carlo).

2.3. *Future prospects*

With improvement for the luminosity of the KEKB, the beam currents are also increasing gradually. In general, the higher beam currents gives the higher beam-induced background, i.e. the higher occupancy, as well as the higher luminosity. We roughly estimate to have 2 or 3 times higher beam-induced background than now within two or three years later. It corresponds to 20∼30 % occupancy in the first layer, causing about a 10 % degradation of the performances (see Fig. 2 and 3). Monte Carlo studies predict a 17 % degradation on the decay vertex resolution for the decay channel $B^0 \to J/\psi K_S$ (from 86 to 104 μm), no longer fulfilling the detector requirements. To avoid such difficulties, we are planing an additional upgrade, SVD3.

3. SVD3

3.1. *Occupancy reduction*

The high occupancy in the first and second layers causes the performance degradation. Off-timing hits from the beam-induced background increase the occupancy. Readout with the fast shaping time is the solution for the occupancy reduction. By changing the readout chip from the VA1TA to APV25 (8), the SVD3 will realize the low occupancy condition.

The APV25 was developed for the CMS experiment at the LHC. Some nice features are implemented on this chip; an adjustable short shaping time of 50∼200 ns and a 192-cell deep pipeline for each of the 128 channels, where sampled values of the shaper output are stored at 40 MHz (the beam synchronous clock frequency of LHC). We do not use a "deconvolution" method (9), a switched capacitor filter on the chip with synchronizing the LHC bunch crossing timing, since the bunch crossing of the KEKB is almost quasi-continuous. However, the waveform sampling of the detector signal is enabled to readout multi samples of the shaper output spaced by the clock period of 25 ns ("multi-peak" mode).

The short shaping time of the APV25 will provide approximately 1/10 lower occupancy than the VA1TA case. One more order of magnitude on occupancy reduction can be possible with the multi-peak mode operation (10).

3.2. *Status of design and development*

The electric noise related with the detector capacitance ($\propto C/\sqrt{T_p}$) is serious when we use the APV25 chip, where, C is the detector capacitance and T_p is the peaking time. The S/N is 1/4 of current value if we use the same sensor as for the SVD2. Therefore, we developed new DSSD which is optimized for the APV25 readout. Its configuration and the comparison with the SVD2 are summarized in Table 1. To reduce the detector capacitance, the strip pitch or the strip width are modified to be half size (11).

For the prototype single-sided n-strip sensors, we confirmed the 50 ns peaking time operation and the enough $S/N = 34$ by a test with 4 GeV π^+ beam in KEK (11). Three SVD2 spare sensors are also used as telescope. The simultaneous operation like the SVD3, readout with the APV25 for the prototype sensors and readout with the VA1TA for the SVD2 sensors, was also succeeded. With scanning test with infrared laser (980 nm of wavelength) irradiation, we also confirm enough charge collection efficiency for the new DSSD (Fig. 4). The Hamamatsu Photonics will fabricate all sensors by April 2007.

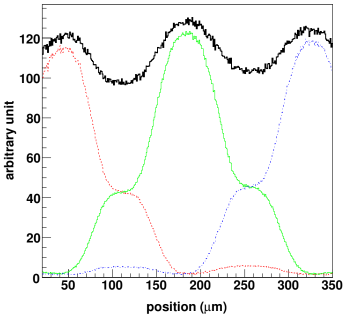

Fig. 4. Charge of readout signals for each strips (thin lines; solid, dashed and dash-dot) and their sum (thick solid line) as a function of irradiated position by infrared layer.

The FADC system for SVD3 is developed. It performs pedestal subtraction and sparsification as well as the digitization of incoming signal. The implementation of the peak time reconstruction algorithm in an FPGA on the FADC board is discussed elsewhere (10). The ladder structure is rearranged since the APV25 chip is about 1 mm wider than the VA1TA chip, and the new design is confirmed by the mock-up test. All the ladders will be prepared by the end of 2007 and will be installed in 2008.

4. Summary

The SVD2 has been operated efficiently during three years of data taking. Its performance degradation is expected with increasing the beam-induced background. The fast readout with the APV25 chip instead of the VA1TA chip is the solution to avoid such a difficulty. The sensors have been re-designed to match the APV25 chip and the production of detectors are started.

5. Acknowledgment

We would like to thank the Belle Collaboration for support. We also thank the KEK mechanical engineering center for their contribution to the SVD construction and installation and the KEK physics department for the ongoing encouragement.

References

[1] A. Abashian, *et al. (Belle Collaboration)*, *Nucl. Instr. and Meth. A* **479** (2002) 117.

[2] T. Kawasaki, *Nucl. Instr. and Meth. A* **494** (2002) 94.

[3] K. Abe, *et al. (Belle Collaboration)*, *Phys. Rev. D* **66** (2002) 071102(R).

[4] Z.Natkaniec *et al. Nucl. Instr. and Meth. A* **560** (2006) 1.

[5] R. Stamen, *et al. Nucl. Instr. and Meth. A* **541** (2005) 61.

[6] H. Ishino, *Nucl. Instr. and Meth. A* **549** (2005) 16.

[7] Ideas ASA, IT Fornebu, Snarøya, Norway. http://www.ideas.no.

[8] M. French, *et al. Nucl. Instr. and Meth. A* **466** (2001) 359.

[9] S. Gadomski, *et al. Nucl. Instr. and Meth. A* **541** (2005) 421.

[10] M. Friedl, *et al.* Obtaining exact time information of hits in silicon strip sensors read out by the APV25 front-end chip, *Nucl. Instr. and Meth. A* (2006), doi:10.1016/j.nima.2006.10.203.

[11] S. Ono, *master thesis* http://www.hp.phys.titech.ac.jp/togasaki/pic/Mthesis_ono.pdf