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FAST LUMINOSITY MONITORING FOR THE SuperKEKB COLLIDER (LumiBelle2 PROJECT)

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Abstract

LumiBelle2 is a fast luminosity monitoring system prepared for SuperKEKB. It uses sCVD diamond detectors placed in both the electron and positron rings to measure the Bhabha scattering process at vanishing photon scattering angle. Two types of online luminosity signals are provided, Train-Integrated-Luminosity signals at 1 kHz as input to the dithering feedback system used to maintain optimum overlap between the colliding beams in horizontal plane, and Bunch-Integrated-Luminosity signals at about 1 Hz to check for variations along the bunch trains. Vertical beam sizes and offsets can also be determined from collision scanning. This paper will describe the design of *LumiBelle2* and report on its performance during the Phase-2 commissioning of SuperKEKB.

INTRODUCTION

SuperKEKB uses the so-called *nano-beam scheme* to reach a very high instantaneous luminosity of $8 \times 10^{35}\,\mathrm{cm^{-2}\,s^{-1}}$ [1]. It consists of using a large crossing angle at the interaction point (IP) to enable colliding 2500 ultra-low emittance bunches with very small beam sizes (design value σ_y ~50 nm). The luminosity is very sensitive to beam-beam offsets, e.g., caused by vibration of mechanical supports induced by ground motion. In order to maintain the optimum beam collision condition, orbit feedback systems are essential at the IP [2]. At SuperKEKB, the beam-beam deflection method is used for orbit feedback for the vertical plane, while for the horizontal plane, a dithering orbit feedback system using the luminosity as input, similar to that operated in the past at PEP-II, has been adopted [3, 4].

For this purpose, a fast luminosity monitor based on sCVD diamond detectors, named *LumiBelle2*, was developed and tested during the Phase-2 commissioning of SuperKEKB. By measuring the rate of Bhabha events on each side of the IP at vanishing photon scattering angle, *LumiBelle2* can provide both Train-Integrated-Luminosity (TIL) signals and Bunch-Integrated-luminosity (BIL) signals simultaneously, over a large range of luminosities. TIL signals are needed by the dithering orbit feedback system at 1 kHz, with relative precisions better than 1 % [5]. BIL signals are important to probe potential luminosity differences between the numerous bunches along the trains. Another luminosity monitoring system named Zero Degree Luminosity Monitor (ZDLM) is also installed in the immediate vicinity. It uses Cherenkov and scintillator detectors [6], providing important complementary measurements. In addition, the Electromagnetic Calorimeter Luminosity On-line Measurement (ECL-LOM) is operated in the backward and forward end-caps of the Belle II detector, measuring the coincidence rates of back-to-back Bhabha events in the opposite sectors, with the ability to provide absolute values of the luminosity after proper internal calibration [7].

In this paper, we describe the design of *LumiBelle2*, including results of detector tests with a Sr-90 electron isotope source, the experimental set-up and the DAQ based on an FPGA, and the report on obtained luminosity monitoring performances, based on simulation and measurements pursued during the Phase-2 commissioning period, both with colliding beams, and with single beams, for background evaluations.

DESIGN AND LAYOUT

The placement of the *LumiBelle2* detectors was carefully studied with respect to signal rates and background contamination, resulting in choosing locations 10 and 29 m downstream of the IP in the Low Energy Ring (LER) and High Energy Ring (HER), to measure, respectively, Bhabha scattered positrons and photons [8]. To increase the rate of extracted positrons, a custom made beam pipe section with a depression of 15 mm and 45° inclined windows is used in the LER, see Figure 1. A Tungsten radiator with an effective thickness of 4 Radiation Lengths (1RL=3.5 mm) was added to enhance the electromagnetic showers and boost the detection efficiency [9].

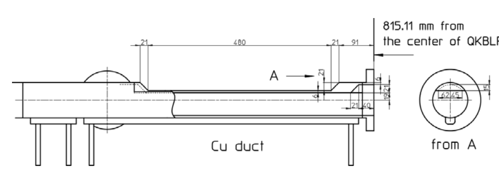

Figure 1: Designed window shape beam pipe.

The RF of SuperKEKB is about 500 MHz, with bunches stored nominally almost every other bucket (so called quasi 2-bucket fill pattern), which implies collisions every 4 ns. For BIL monitoring at high counting rate, signals from neighbouring bunches must be separated. A new diamond detector with a thickness of 140 µm, coupled with a broadband 2 GHz 40 dB current amplifier from CIVIDEC [10] at the front-end, are used for this purpose. Low attenuation half-inch HELIAX coaxial cables are used to avoid signal broadening

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during the transfer to the data acquisition system in the Belle II Electronic Hut located about 100 m away.

Diamond Detector Test

Signal amplitudes and charges in the diamond detector were compared using data acquired with an oscilloscope, integrating the signal peaks to determine the charge, see Figure 2. The good observed linearity makes it possible to sum signal amplitudes turn by turn to evaluate integrated relative Bhabha scattering rates for each bunch crossing.

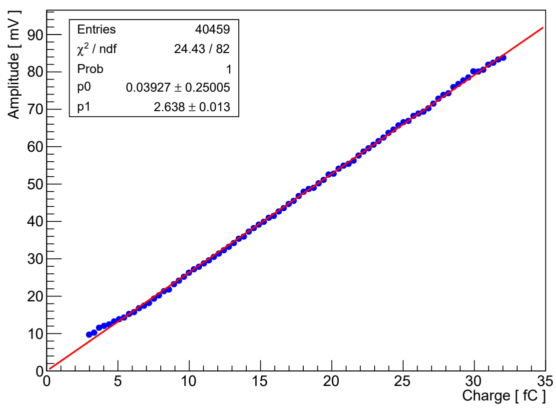

Figure 2: Relationship between signal amplitude and charge generated in diamond detector.

The Constant Fraction Discrimination (CFD) method was used to study the timing performance of the diamond detector, using a fraction of 5 %. As can be seen in Figure 3, the signal rise time peaks at 0.88 ns, and most signals (more than 98 %) are within 4 ns. The small impact from these partially overlapping pulses is at present neglected, but could in principle be taken into account as a correction.

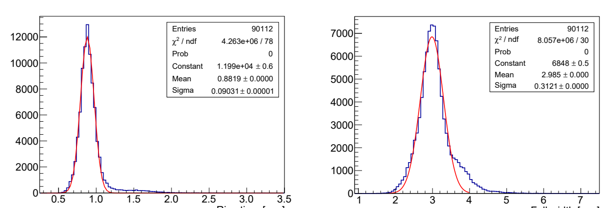

Figure 3: Distribution of rise time (l.h.s) and full width (r.h.s) of the signal in the diamond detector.

Mechanical Set-up

The experimental layout for luminosity monitoring during the Phase 2 commissioning is shown in Figure 4. It consists of pillars supporting three *LumiBelle2* diamond detectors and the ZDLM counters in both rings [6]. One of the *LumiBelle2* diamond sensor in each ring has a remotely controlled motor to enable scans in the horizontal plane over a range of 25 mm.

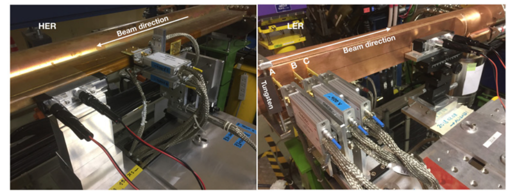

Figure 4: Experimental layout of *LumiBelle2* and ZDLM sensors in both ring (left: HER, right: LER).

Data Acquisition System

The DAQ developed for *LumiBelle2* is located in the Belle II Electronics Hut. A functional diagram is shown in Figure 5. Four among the six provided signals are selected by connecting the corresponding cables to a GSPS 10-bit AC-coupled ADC board (FMC126, 4 DSP), requiring a clock at 1 GHz (twice the RF frequency). The four ADC digital outputs are then fed to a VIRTEX-7 FPGA board (VC707, Xilinx), which calculates the Train Integrated Luminosity (TIL), Bunch Integrated Luminosity (BIL), COUNT (event rate) and RAW SUM (direct summing all of samples) in real time, at a rate of up to 1 kHz, simulataneously for the four incoming inputs. The DAQ includes also a 16-bit DAC, providing eight analog outputs with 1 kHz bandwidth, that can be configured independently to convert to any TIL, BIL, COUNT or RAW SUM values, from any of the four input channels.

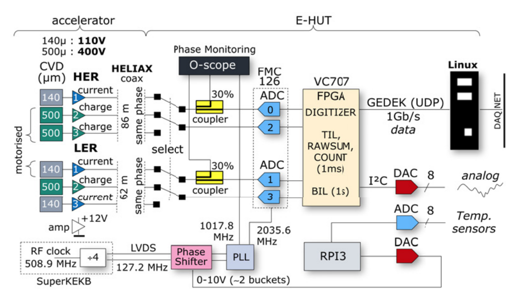

Figure 5: *LumiBelle2* DAQ function diagram.

The DAQ was initially designed to handle a maximum rate of one bunch every 2 ns, corresponding to train patterns with all or almost all buckets filled. It makes use of two principles: (1) the luminosity is proportional to the amplitudes and rates of signal peaks, and (2) the pulses and RF clock are synchronous, to enable sampling all peaks simultaneously. As the ADC is AC-coupled, the mean value of the pulse train is always centered at 0 V, requiring therefore to sample also the pedestals between subsequent pulses. For bunches separated by 2 ns, this implies sampling at twice the RF frequency. As illustrated in Figure 6, the current amplifiers used for the Phase 2 commissioning are fast enough only for the 4 ns bunch spacing used nominally at SuperKEKB. One sample (1) is then positioned on the peak (using the Phase Shifter shown on Figure 5 to find the optimum timing) and the pedestal is obtained from the third sample (+3). The luminosity process integrates over 1 ms the sum

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of all differences `Diff(n)` between these samples above a defined threshold to provide the TIL value. The same process provides 5120 sums each 1 second corresponding to the BIL value for each bucket. The COUNT value gives the total number of pulses during 1 ms, and therefore the ratio TIL/COUNT gives the mean pulse amplitude. The RAW SUM value calculates the sum of all samples above a defined threshold and is intended for some channels which use Charge Amplifiers with a 10 ns FWHM, and that cannot be handled easily in terms of TIL and BIL. All the real time data are uploaded to a Linux machine through the GEDEK protocol (ALISE) over a UDP link at 1 GB/s, then converted into *n*-Tuple files and saved together with a number of related relevant machine parameters available through the EPICS protocol and important for the offline analysis. A subset of the *LumiBelle2* data were also uploaded to EPICS at a rate of about 1 Hz, for continuous display in the accelerator and Belle II control rooms. Moreover, for the purpose of the IP dithering orbit feedback, analog information from the DAC based on the 1 kHz TIL data was directly fed to the lockin amplifier used by that system.

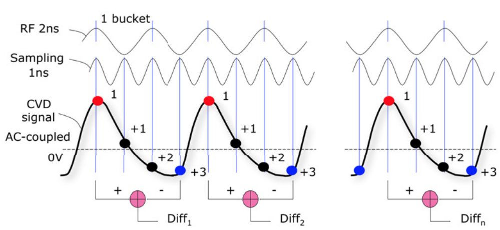

Figure 6: Illustration of DAQ signals processing for 4 ns bunch spacing.

RESULTS IN PHASE-2

The Phase 2 commissioning of SuperKEKB started with single beam testing and tuning in March 2018. Beam collisions were first achieved on April 25, 2018, followed by luminosity and background tuning and studies until July 17, 2018.

Background

During single beam operation, *LumiBelle2* measured single beam loss rates, mainly resulting from Bremsstrahlung accompanying scattering of beam particles on the nuclei of the residual gas in the straight section upstream of the sensors, and from Touschek scattering [11]. Figure 7 gives an example of background rates measured by *LumiBelle2* together with the beam currents and pressures during successive fills in both rings.

Good correlation was found between the measured background rates and key machine parameters in each ring. A detailed simulation of single beam loss rates was developed based on generating the basic processes and tracking final state particles with SAD, followed by modeling the signal collection in the detectors using GEANT4. Rather realistic estimates of the vacuum profile along the relevant parts of

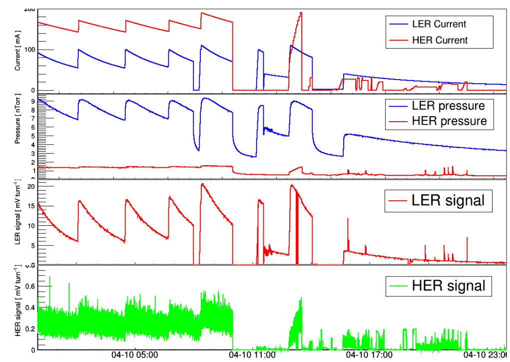

Figure 7: Example of background rates in *LumiBelle2* during single beam testing in 2018.

the interaction region, obtained by reweighting the measured vacuum levels using a detailed vacuum simulation [12], were obtained and used for the Bremsstrahlung process. Comparisons between simulation and *LumiBelle2* measurements as function of the product of current and pressure in each ring are shown in Figure 8. The simulation overestimates the loss rates in both rings by about 10 % to 20 %. This bias can be explained by the imperfect knowledge of the exact vacuum pressure in the narrow 1 cm radius beam pipe used at the IP, where most of the Bremsstrahlung scatters which can reach *LumiBelle2* sensors are produced. Also, the thresholds for signal detection used for the real and simulated data were not yet fully calibrated. The linear dependence in Fig-

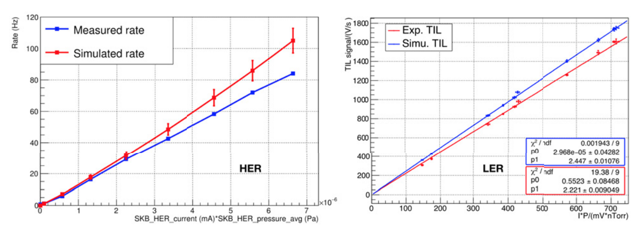

Figure 8: Comparison between the simulation and measurement in LER (l.h.s.) and HER (r.h.s.).

ure 8 indicates that the Bremsstrahlung process dominates the background loss rates in *LumiBelle2* in both rings. A dedicated 'Touschek study' was pursued at the end of the Phase 2 commissioning period, consisting of taking single beam loss data as a function of the vertical emittance (with $\beta_x^* = 200/100$ mm for LER/HER and $\beta_y^* = 3$ mm) to enable convenient extraction of the Touschek component from the background signals [11]. The Touschek and Bremsstrahlung processes represented 87 % and 13 % fractions of the measured *lumiBelle2* single beam loss rates in this experiment, respectively, consistent with the prediction from the simulation.

Train Integrated Luminosity Monitoring

LumiBelle2 and ZDLM luminosity monitors observed Bhabha scattering signals in both LER and HER when beams were collided for the first time on April 26, 2018 [6]. The

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luminosity monitors were then used for machine tuning and luminosity optimization during the entire commissioning.

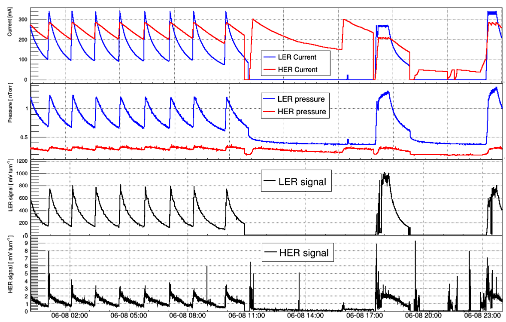

Figure 9: Example of measured *LumiBelle2* luminosity signals together with beam currents and pressures in both rings.

While the Train-Integrated-Luminosity signal integrates the signals' amplitude at 1 kHz to meet the requirements of the dithering feedback system, integrating and recording this luminosity signal at 1 Hz provides relative luminosity information which is quite useful for collision tuning and studies in the accelerator control room. Figure 9 gives an example of the *LumiBelle2* luminosity signals, together with the beam currents and pressures in both rings. In general, the luminosity signals follow the changes in the product of beam currents in both rings.

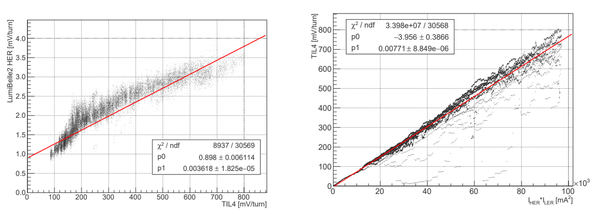

Figure 10: Luminosity signals in HER vs that in LER (l.h.s.) and LER luminosity signal as function of product of beam currents in both rings.

Thanks to the custom made beam pipe section with a depression of 15 mm and 45° inclined windows installed on the LER side, the corresponding Bhabha scattering positron signal collection was much more efficient than for the photons in the HER, see Figure 10 (l.h.s.), while still reasonably proportional to each other. The LER signals were typically proportional to the product of the beam currents, as illustrated in Figure 10 (r.h.s.), although vertical beam offsets at the IP can have a major impact large, e.g. due to ground motion or other effects.

Luminosity signals from ZDLM and ECL-LOM were compared with *LumiBelle2* in the LER, see Figure 11, showing good overall consistency. The ECL-LOM measurement has poor statistics because of much lower Bhabha rates at finite scattering angle. Studying the short term fluctuations in the 1 kHz TIL data, the statistical precision for the luminosity measurement in the LER was found to be 2.27 % for a luminosity of 1.85×10^{33} cm^{-2} s^{-1}. A relative precision of 1 % can thus be expected when luminosities reach

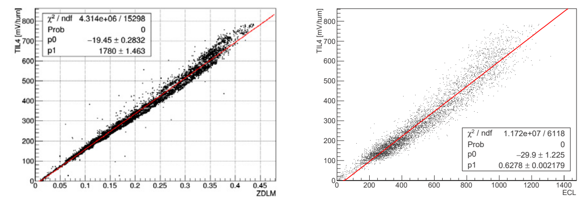

Figure 11: Comparison between luminosity signals from different monitors: *LumiBelle2* vs ZDLM (l.h.s.) and *LumiBelle2* vs ECL (r.h.s.).

1×10^{34} cm^{-2} s^{-1}. The 1 kHz relative luminosity signal were also used to test the performance of the dithering orbit feedback system, by deliberately introducing a horizontal beam-beam offset. The results show that the feedback system can correct the beam orbit at the IP. Details can be found in [13].

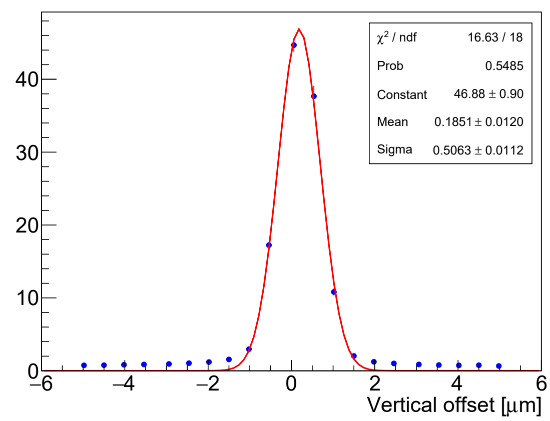

Figure 12: Relative luminosity signals against the vertical offset of e^- beam.

Based on the variation of TIL signal when scanning the vertical position of one beam across the other, averaged vertical beam size information and optimum collision position can be estimated. Figure 12 gives an example of *LumiBelle2* luminosity signal when scanning the vertical position of the electron beam. Fitting a Gaussian function, the optimum vertical offset was 0.19 µm while the second moment of the distribution was $\Sigma_y = 0.51$ µm. Assuming both beams have Gaussian charge distributions and equal vertical beam sizes, and that beam blow-up from the beam-beam interaction can be neglected, then the vertical beam size could be evaluated as $\sigma_y = \Sigma_y/\sqrt{2}$. This latter assumption is only valid for very low beam intensities, and beam blow-up from the beam-beam interaction should in general be taken into account. The vertical beam offset scans enable also the SNR to be estimated by comparing the signal at peak position with that when the two beams are completely separated. During the above scan, the maximum luminosity provided by ECL-LOM was 1.3×10^{32} cm^{-2} s^{-1} and the observed SNR was 65. From simulation, the SNR was estimated as 42 under the same conditions. Some overestimation of the simulated

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background may explain this difference, while it still needs to be studied in detail.

Bunch Integrated Luminosity Monitoring

The number of bunches circulating in each ring is nominally 2500. Variations in the bunch transverse positions and sizes are in principle possible, through a variety of effects, and should be monitored, just like the bunch currents. The *LumiBelle2* BIL signal prepared for this purpose is illustrated in Figure 13 for the beam conditions at the end of the Phase 2 commissioning, when the instantaneous luminosity was about 1.6×10^{33} cm^{-2} s^{-1}, with 395 bunches circulating in each ring, separated by 32 ns (corresponding to sixteen RF buckets). The observed spread in bunch integrated luminosity signals was about 9.3 %, dominated by the measured spread in the product of bunch currents, which was found to be about 8.7 % using the bunch-by-bunch current monitor [14]. In comparison, the relative precision in the corresponding 1 kHz TIL data was 2.35 %, from which the average relative precision of BIL signals at 1 Hz could be estimated at the level of 1.5 % (by simple scaling in the assumption of uniform bunch current and alignment of the bunches along the trains in both rings).

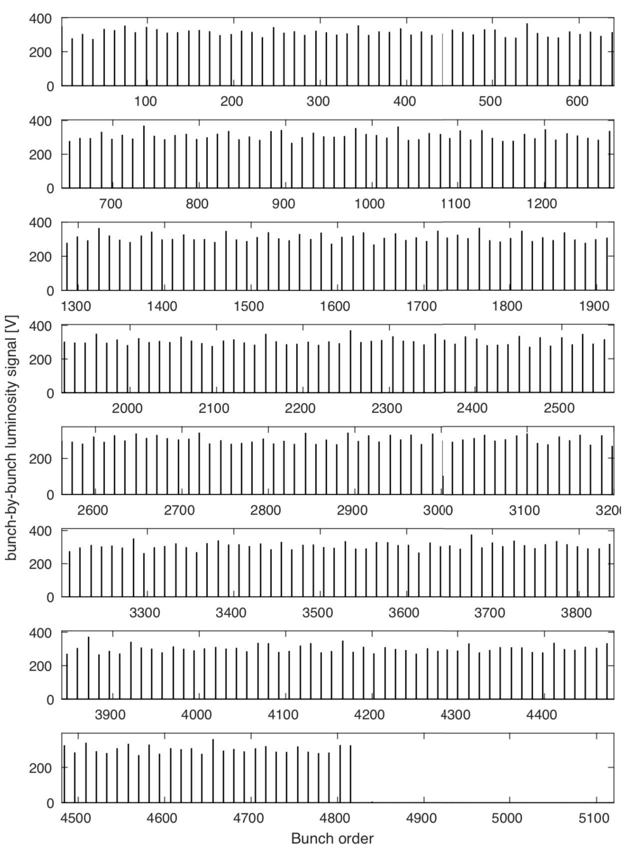

Figure 13: Bunch-by-bunch relative luminosity signals from *LumiBelle2* for 395 bunches circulating in each ring and colliding.

CONCLUSION AND NEXT PLANS

Fast luminosity monitoring based on diamond sensors was developed and employed during the Phase 2 commissioning of SuperKEKB. With several months' operational experience in both single and colliding beam modes, good general performance and reliability were found. With the increase in luminosity and evolution of the machine in future years, some additional studies are needed, such as optimising the arrangement of sensors and amplifiers, both their combination and positions, to cover a large luminosity dynamic range while ensuring sufficient relative precision and minimizing accumulated radiation doses, shielding to mitigate activation of the beam pipe and radiator, upgrading the DAQ, etc. The dithering orbit feedback system was tested successfully and more tests are needed to ensure continuous operation in the future when beam sizes become much smaller. Potential variations in luminosity along the bunch trains from collective effects or other mechanisms can be studied using the provided bunch-by-bunch luminosity signals together with existing bunch current data in both rings.

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REFERENCES

[1] Y. Ohnishi *et al.*, "Accelerator design at SuperKEKB", *Prog. Theor. Exp. Phys.*, vol. 2013, pp. 03A011, 2013. doi:10.1093/ptep/pts083

[2] Y. Funakoshi *et al.*, "Orbit feedback system for maintaining an optimum beam collision", *Phys. Rev. ST Accel. Beams*, vol. 10, pp. 101001, 2007. doi:10.1103/PhysRevSTAB.10.101001

[3] A. S. Fisher *et al.*, "Commissioning the fast luminosity dither for PEP-II", Stanford Linear Accelerator Center, Stanford, CA 94309, USA, Rep. SLAC-PUB-12608,July 2007, http://www.slac.stanford.edu/cgi-wrap/getdoc/slac-pub-12608.pdf

[4] Y. Funakoshi *et al.*, "Interaction point orbit feedback system at SuperKEKB", in *Proc. 6th Int. Particle Accelerator Conf. (IPAC'15)*, Richmond, VA, USA, May 2015, pp. 921–923. doi:10.18429/JACoW-IPAC2015-MOPHA054

[5] C.G. Pang *et al.*, "Simulation study on luminosity feedback horizontal beam stabilization at SuperKEKB", in *Proc. 9th Int. Particle Accelerato Conf. (IPAC'18)*, Vancouver, Canada, May 2018, pp. 2250–2253. doi:10.18429/JACoW-IPAC2018-WEPAL037

[6] C.G. Pang *et al.*, "First tests of SuperKEKB fast luminosity monitors during 2018 Phase-2 commissioning", in *Proc. 9th Int. Particle Accelerato Conf. (IPAC'18)*, Vancouver, Canada, May 2018, pp. 2254–2257. doi:10.18429/JACoW-IPAC2018-WEPAL038

ISBN: 978-3-95450-201-1 doi:10.18429/JACoW-IBIC2018-MOPA13

[7] Belle-ECL *et al.*, "Electromagnetic calorimeter for Belle II", *J. Phys.: Conf. Ser.*, vol. 587, pp. 012045, 2015. doi:10.1088/1742-6596/587/1/012045

[8] D. El Khechen *et al.*, "First Tests of SuperKEKB Luminosity Monitor During 2016 Since Beam Commissioning", in *Proc. 7th Int. Particle Accelerator Conf. (IPAC'16)*, Busan, Korea, May 2015, pp. 81–83. doi:10.18429/JACoW-IPAC2016-MOPMB006

[9] C. G. Pang *et al.*, "Preparation of CVD diamond detector for fast luminosity monitoring of SuperKEKB", in *Proc. 8th Int. Particle Accelerator Conf. (IPAC'17)*, Copenhagen, Denmark, May 2017, pp. 135–138. doi:10.18429/JACoW-IPAC2017-MOPAB027

[10] CIVIDEC, https://cividec.at

[11] D. El Khechen, "Fast Luminosity Monitoring Using Diamond Sensors for SuperKEKB", PhD thesis, Université Paris-Sud, Orsay, France, 2016.

[12] M. Ady, "Monte-Carlo simulation of ultra high vacuum and synchrotron radiation for particle accelerators", PhD thesis, école polytechnique férérale de Lausanne (EPFL), Lausanne, Switzerland, July 2016.

[13] M. Masuzawa *et al.*, "Early Commissioning of the Luminosity Dither Feedback for SuperKEKB", presented at IBIC'18, Shanghai, China, Sep. 2018, paper TUPC13, this conference.

[14] M. Tobiyama *et al.*, "Beam comissioning of SuperKEKB rings at phase 1", in *Proc. Int. Beam Instrumentation Conf. (IBIC'16)*, Barcelona, Spain, 2016, pp. 6–10. doi:10.18429/JACoW-IBIC2016-MOAL03