ISBN: 978-3-95450-236-3 ISSN: 2673-7027 doi:10.18429/JACoW-eeFACT2022-WEXAT0101

BEAM-BEAM INTERACTION IN SuperKEKB: SIMULATIONS AND EXPERIMENTAL RESULTS

D. Zhou*, K. Ohmi, Y. Funakoshi, Y. Ohnishi, KEK, Tsukuba, Japan
Y. Zhang, IHEP, Beijing, China

Abstract

The beam-beam interaction is one of the most critical factors determining the luminosity performance of SuperKEKB. Simulations and experimental results from SuperKEKB have shown that a complete understanding of the beam-beam effects demands reliable models of 1) the nonlinear beam-beam interaction at the interaction point, 2) the one-turn lattice transfer map with machine imperfections, and 3) other intensity-dependent collective effects. The interplay of these factors makes it difficult to predict the luminosity performance of SuperKEKB via simulations.

INTRODUCTION

This paper continues the authors' previous work to discuss the beam-beam effects on luminosity in SuperKEKB [1]. SuperKEKB commissioning had three phases: Phase-1 [2, 3] (February - June 2016, without installation of the final focusing superconducting QCS magnets and roll-in of Belle II detector), Phase-2 [4] (February - July 2018, with QCS and Belle II, but without the vertex detector), and Phase-3 [5] (from March 2019 until present with the full Belle II detector). Beam commissioning without collisions in Phase-1 achieved small vertical emittances of less than 10 pm for both beams, which is essential for high luminosity. Machine tuning with collisions in Phase-2 confirmed the nano-beam collision scheme [6], i.e., collision with a large crossing angle and vertical beta function β_y^* at the IP much smaller than bunch length σ_z. However, without the CW, the beam-beam (BB) driven vertical emittance blowup was severe, causing degradation of specific luminosity (L_{sp}) as bunch currents increased.

The uncontrollable blowup in vertical emittances sets a severe limit on the luminosity performance and motivated the installation of the CW in SuperKEKB [7]. Beam commissioning with the CW at SuperKEKB has been successful with $\beta_y^* = 1$ and 0.8 mm [7]. Experiments have shown that the CW effectively suppresses vertical blowup and allows larger beam currents to be stored in the rings [8]. On Jun. 22, 2022, a luminosity record of 4.71×10^{34} cm^{-2}s^{-1} was achieved at SuperKEKB with $\beta_y^* = 1$ mm and total beam currents $I_+/I_- = 1.46/1.145$ A [9].

LUMINOSITY PERFORMANCE WITH CRAB WAIST

Since April 2020, the crab waist (CW) has been implemented at SuperKEKB to suppress beam-beam resonances [10, 11]. Luminosity performance has been improving with the following observations (see Refs. [7, 8] for reviews): 1) Luminosity performance became closer to the predictions of simulations; 2) Balanced collision (i.e., $\sigma_{y+}^* \approx \sigma_{y-}^*$, the vertical beam sizes at the IP are close to each other) was achieved with careful tuning knobs; 3) The fractional working point could be set around the design values (.53, .57); 4) The total beam currents were not limited by BB blowup, but by injection power and by machine failures of sudden beam losses (SBLs, their sources are unclear so far); 5) There still exists an unexpected degradation of L_sp vs. product of bunch currents (see Figs. 1 and 4). In particular, increasing the beam current does not give large increases in luminosity.

Figures 1, 2 and 3 compare the L_{sp} and transverse beam sizes at the IP from strong-strong BB simulations and measurements using X-ray monitors (XRMs). The machine parameters of 2022.04.05 in Table 1 are used for BB simulations. Optics functions at the IP and the XRMs calculated from a lattice model are used to estimate the beam sizes at the IP in measurements. In both simulations and experiments, the luminosity is sensitive to the vertical beam sizes at the IP. With the standard settings of 40% and 80% CW strengths in the experiments, respectively, for HER and LER (40% CW strength was set for HER due to a technical constraint), the decrease of L_{sp} in strong-strong BB simulation is mainly attributed to bunch lengthening due to the longitudinal wakefields and weak vertical blowup of HER beam due to insufficient CW strength. However, experimental results showed a much faster L_{sp} decrease as bunch currents increase. The sources of luminosity degradation are discussed in the next section. The plots also show simulations with the CW strengths varied. It is seen that the L_{sp} drop in simulations correlates with BB-driven blowup in the positron beam because its vertical fractional tune .589 is close to the 5th-order BB resonances.

Figures 4, 5 and 6 show a comparison of simulations and measurements with machine conditions of 2021. One can see that the machine operation after April of 2022 showed gradual beam-size blowup as the bunch currents were increased (see Figs. 2 and 3); while in 2021, the beam-size blowup was severe for both e+ and e- beams. At that time, it was difficult to achieve a balanced collision (i.e., $\sigma_{y+}^* \approx \sigma_{y-}^*$). A "flip-flop" blowup appeared when the bunch-current product $I_{b+}I_{b-} \gtrsim 0.4$ mA^2: When one beam was tuned to have a small vertical beam size at IP, another beam blew up severely. This severe blowup at high bunch currents was believed to be related to the "-1 mode instability" of the positron beam, which was driven by the interplay of vertical impedance (dominated by small-gap collimators) and the bunch-by-bunch (BxB) feedback (FB) system as discussed in detail in

* dmzhou@post.kek.jp

ISBN: 978-3-95450-236-3 ISSN: 2673-7027 doi:10.18429/JACoW-eeFACT2022-WEXAT0101

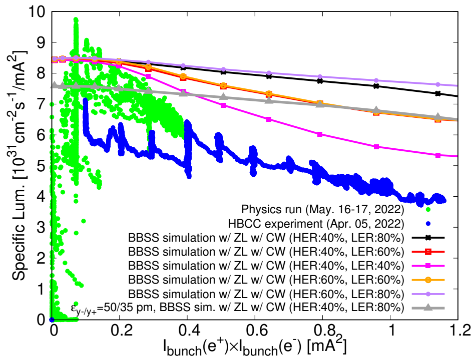

Figure 1: L_{sp} predicted by BBSS [12] simulations with the inclusion of longitudinal impedances and from experiments of high-bunch current collision (HBCC) machine study (blue dots) and physics run (green dots) in 2022. During the HBCC machine study, the collision for $I_{b+}I_{b-} < 0.4$ mA^2 was not optimized, resulting in lower L_{sp} than the physics run.

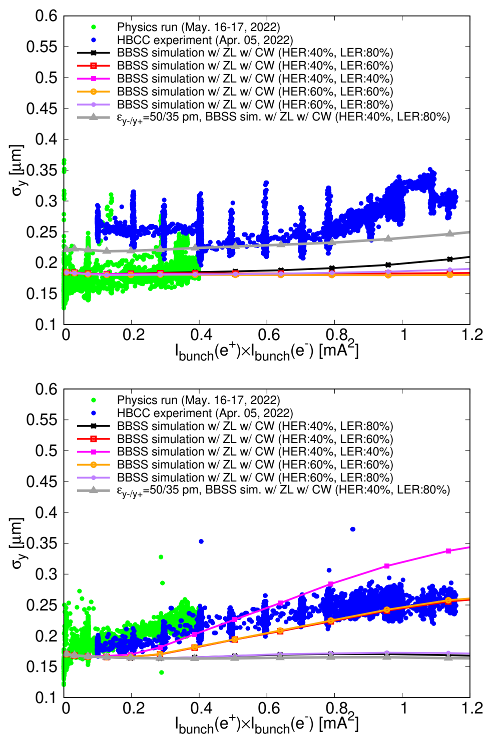

Figure 2: Vertical beam sizes of electron (upper) and positron (lower) beams at the IP (corresponding to Fig. 1) predicted by BBSS simulations compared with experiments. The dots and lines with the same colors in the upper and lower plots correspond to the same machine conditions.

Ref. [13]. After fine-tuning the BxB FB system in March of 2022, the "-1 mode instability" was suppressed significantly, and the beam-size blowup became less severe as shown in Figs. 2 and 3.

During physics runs or machine studies, the horizontal blowup in both beams has been observed in qualitative agreement with BB simulations. Machine tunings showed the horizontal blowup was sensitive to the horizontal tune and affected the injection efficiency. This can be explained as

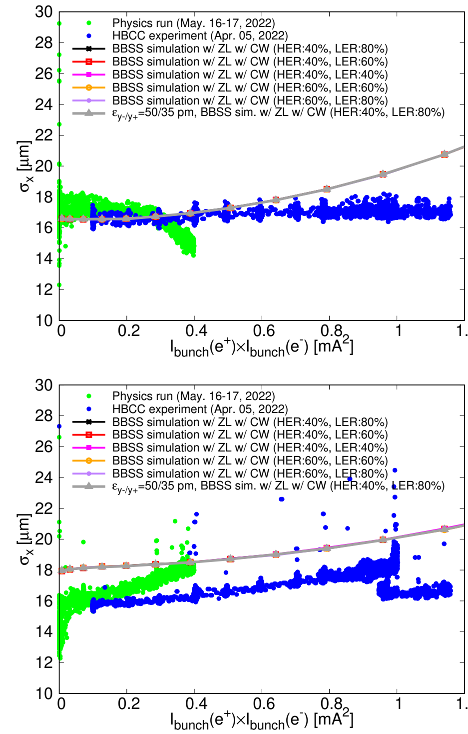

Figure 3: Horizontal beam sizes of electron (upper) and positron (lower) beams at the IP (corresponding to Fig. 1) predicted by BBSS simulations compared with experiments. The dots and lines with the same colors in the upper and lower plots correspond to the same machine conditions. The green dots in the upper figure are unreliable because of failure in the XRM. The horizontal tune of the e+ beam was changed during the HBCC study, resulting in a decrease of σ_x for $I_{b+}I_{b-} > 0.95$ mA^2.

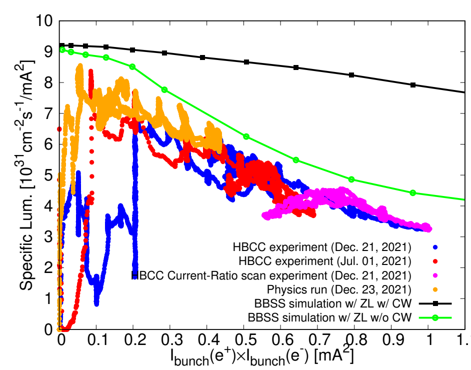

Figure 4: L_{sp} predicted by BBSS simulations with the inclusion of longitudinal impedances and from experiments of HBCC machine studies (blue, red, and magenta dots) and physics run (orange dots) in 2021.

follows: After installing the CW, both LER and HER have been operated with the horizontal tunes between the synchro-betatron resonances $\nu_x - \nu_s = N/2$ and $\nu_x - 2\nu_s = N/2$ (see Table 1). The beams' footprints spread in the tune space because of beam-beam, impedance effects, and lattice nonlinearity. When the tune footprint touches the resonance lines, the beam lifetime reduces, and extra beam losses appear in the injected bunches.

ISBN: 978-3-95450-236-3 ISSN: 2673-7027 doi:10.18429/JACoW-eeFACT2022-WEXAT0101

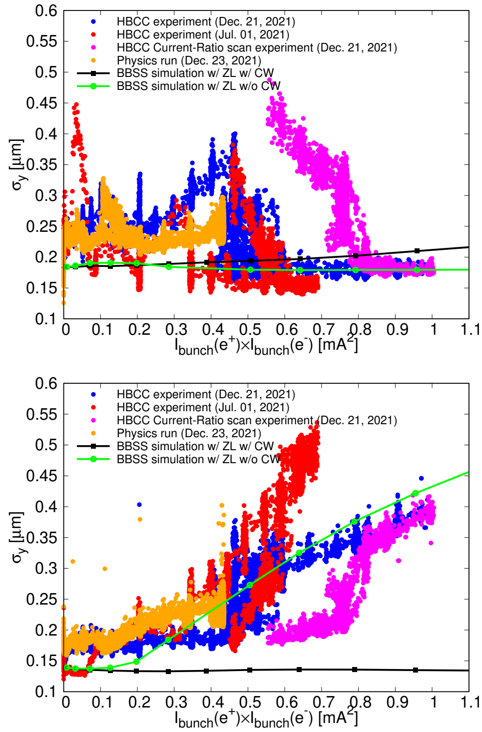

Figure 5: Vertical beam sizes of electron (upper) and positron (lower) beams at the IP (corresponding to Fig. 4) predicted by BBSS simulations compared with experiments. The dots and lines with the same colors in the upper and lower plots correspond to the same machine conditions.

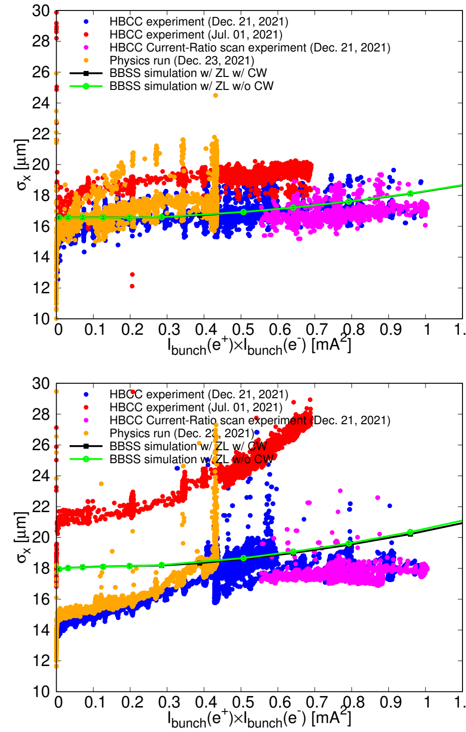

Figure 6: Horizontal beam sizes of electron (upper) and positron (lower) beams at the IP (corresponding to Fig. 4) predicted by BBSS simulations compared with experiments. The dots and lines with the same colors in the upper and lower plots correspond to the same machine conditions. For $I_{b+}I_{b-} \geq 0.4$ mA^2, the horizontal tune of the positron beam was tuned to suppress the horizontal blowup, which helped improve the injection efficiency.

Table 1: SuperKEKB machine parameters for machine operation on Dec. 21, 2021, and on Apr. 5, 2022, respectively. The vertical emittances are values measured by X-ray monitors without collisions.

Parameter	2021.12.21		2022.04.05	
	LER	HER	LER	HER
I_b (mA)	1.0	0.8	0.71	0.57
ϵ_x (nm)	4.0	4.6	4.0	4.6
ϵ_y (pm)	20	35	30	35
β_x (mm)	80	60	80	60
β_y (mm)	1	1	1	1
σ_{z0} (mm)	4.6	5.0	4.6	5.1
ν_x	44.524	45.53	44.524	45.532
ν_y	46.589	43.572	46.589	43.572
ν_s	0.023	0.027	0.023	0.027
Crab waist ratio	80%	40%	80%	40%
N_b	393		1174	

SOURCES OF LUMINOSITY DEGRADATION

Known Sources

Simulations and experiments have identified the known sources of luminosity degradation: 1) Bunch lengthening driven by longitudinal impedance. The scaling law of specific luminosity shows $L_{sp} \propto 1/\sqrt{\sigma_{z+}^2 + \sigma_{z-}^2}$. Simulations using impedance models predict $\sigma_z(I_b) = \sigma_{z0} + A \cdot I_b$ with I_b the bunch current and A about 1 mm/mA for both rings, while measurements using streak cameras showed A to be about 2 mm/mA. The sources of discrepancy in simulated and measured bunch lengthening are under investigation. Nevertheless, the bunch lengthening is expected to cause a loss of geometric luminosity by order of 10% at the bunch current product of $I_{b+}I_{b-} = 1$ mA^2. 2) Chromatic couplings. Their effects on luminosity were recognized at KEKB [14]. For SuperKEKB, rotatable skew-sextupoles are installed in LER, and dedicated skew-sextupoles are installed in HER to control the global chromatic coupling (see Ref. [15]). Simulations showed that chromatic couplings from the nonlinear IR can cause remarkable loss if they are not well suppressed in the case of $\beta^*_{y+}/\beta^*_{y-} = 0.27/0.3$ mm (final design configuration of SuperKEKB). For the case of $\beta^*_y = 1$ mm (This is the achieved β^*_y in 2021 and 2022), simulations with measured chromatic couplings showed a few percent of luminosity loss. 3) Beam oscillation excited by the injection kickers of LER. It was found that the injection kickers in the LER were not perfectly balanced. This causes a leakage kick to the beam in the horizontal direction during the injection. Due to the global coupling of the lattice, the vertical oscillation is also excited. From the waveform of the kickers' field, roughly 20% of the stored

ISBN: 978-3-95450-236-3 ISSN: 2673-7027 doi:10.18429/JACoW-eeFACT2022-WEXAT0101

beam will be excited. The BxB FB system can damp the dipole oscillations in less than 200 turns (Compared with the radiation damping time of about 4500 turns). A simple estimate shows it will cause a loss rate of about 1% to the luminosity. 4) Vertical blowup in the LER driven by the interplay of vertical impedance and feedback system. The problem was well suppressed by fine-tuning the feedback system (see Ref. [13, 16]). But this interplay can remain a source of vertical blowup, especially when the vertical small-gap collimators were severely damaged [17], generating extra vertical impedances. 5) Injection background. The

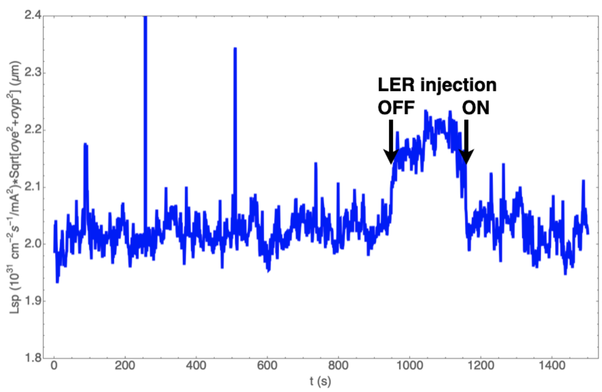

Figure 7: The weighted luminosity $L_{sp}\sqrt{\sigma_{y+}^{*2}+\sigma_{y-}^{*2}}$ synchronized with LER injection during the physics run on Jun. 2, 2022.

electromagnetic calorimeter (ECL) [18] has been used to measure the online luminosity at Belle II. The luminosity data provided by ECL is the most important reference for machine tunings and online optimizations. In this paper, the beam-beam simulations are compared only with the luminosity of ECL. It was identified that the ECL luminosity had a clear correlation with the LER injection [19]. Figure 7 shows an example of this correlation. When the LER injection was intentionally turned off or on, a sudden change in L_{sp} was observed. The following investigations showed that the luminosity measurement by ECL was affected by the injection background during the LER's beam injection [20]. Quantitatively, the luminosity measured by ECL dropped by <5% during LER injection while luminosity measured by ZDLM (Zero Degree Luminosity Monitor [21]) did not [20]. Further investigations are ongoing to understand the correlation between ECL luminosity and the background from LER injection.

Sources to be Investigated

There are sources of luminosity degradation to be investigated through simulations and experiments: 1) Imperfect CW and insufficient CW strengths. The nonlinear optics and optics distortion (its sources include machine errors, current-dependent orbit drift, etc.) around the IR might reduce the effectiveness of CW in suppressing BB resonances. In 2022, it was identified that the synchrotron radiation (SR) heating caused drift of closed orbit (COD) at SuperKEKB [9]. The small horizontal offset at the strong sextupoles for local chromaticity correction generates a significant beta-beat in the rings. Figures 1 and 4 show luminosity degradation by insufficient CW strengths. The CW strength of HER has been 40% due to technical constraints. Beam-beam simulations showed that this is insufficient to suppress the 5th-order BB resonances and can be a source of vertical blowup in the e- beam and consequent luminosity degradation. 2) BB-driven incoherent synchro-betatron resonances. Currently, the working point of SuperKEKB is between $\nu_x - \nu_s = N/2$ and $\nu_x - 2\nu_s = N/2$, which are strong due to the BB interaction [10] and nonlinear chromatic optics. The tune space in this region might not be large enough to hold the footprint of the beams. Note that collective effects and machine nonlinearity stretch the tune footprint. 3) Interplay of BB, longitudinal and transverse impedances, and BxB FB system. The interplay of transverse impedances and BxB FB system is discussed in Refs. [13, 16]. To simulate the interplay of all these three factors, it is necessary to construct a realistic model of FB system, taking into account the realistic settings of the FB parameters, the environment noises, etc. 4) Interplay of BB and nonlinear lattices. This was identified as important for the final design of SuperKEKB configurations but should not be for the case of β_y^* =1 mm [22]. On this issue, the machine errors are unknown sources of lattice nonlinearity. The CW, which was not counted in the final design, introduces additional nonlinearity to the lattices. 5) Coupled bunch instabilities (CBI) with large bunch numbers and high total currents. With 2151 bunches and total beam currents of 1.4/1.12 A achieved in LER/HER, L_{sp} degradation due to CBI has not been seen. As shown in Fig. 8, machine tunings with different numbers of bunches for collisions led to the same best luminosity. This indicates that CBI, which is always suppressed by the BxB FB system, should not be a source of L_{sp} degradation in the current phase. Furthermore, the ZDLM luminosity data showed flat BxB luminosity [23], and CBI driven by electron cloud was not observed for the cases shown in Fig. 8.

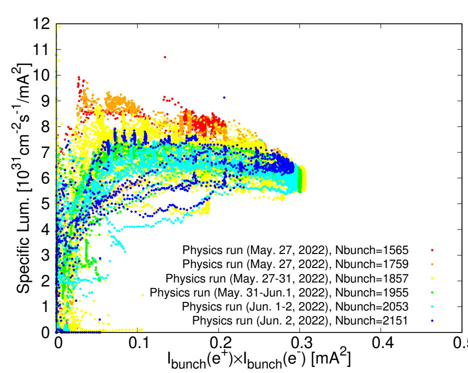

Figure 8: Measured L_{sp} as a function of bunch current product with the different numbers of bunches during the physics runs in 2022. Machine tunings were routinely done to achieve the best luminosity performance around $I_{b+}I_{b-} \approx$ 0.3 mA^2.

ISBN: 978-3-95450-236-3 ISSN: 2673-7027 doi:10.18429/JACoW-eeFACT2022-WEXAT0101

SUMMARY

Since April 2020, the CW has been incorporated with the nano-beam collision scheme at SuperKEKB and has proved decisive in suppressing nonlinear BB effects. The interplay between beam-beam and single-bunch impedance effects is critical at SuperKEKB. Especially the longitudinal monopole and vertical dipole impedances are essential in affecting machine performance. The intense interplay of bunch-by-bunch feedback and vertical impedance in LER has been a strong limit of luminosity performance until April 2022. After fine-tuning the feedback system, this problem was relaxed but remained a possible source of mild vertical emittance blowup.

ACKNOWLEDGEMENTS

We thank the SuperKEKB team and the Belle II team for their constant support of our work. The author D.Z. thanks S. Uehara and K. Matsuoka for fruitful discussions on luminosity measurements at Belle II.

REFERENCES

[1] D. Zhou, Y. Funakoshi, K. Ohmi, Y. Ohnishi, and Y. Zhang, "Simulations and Measurements of Luminosity at SuperKEKB", in *Proc. 13th Int. Particle Accelerator Conf. (IPAC'22)*, Bangkok, Thailand, Jun. 2022, pp. 2011-2014. doi:10.18429/JACoW-IPAC2022-WEPOPT064

[2] Y. Ohnishi *et al.*, "Commissioning of the Phase-I SuperKEKB B-Factory and Update on the Overall Status", in *Proc. 2nd North American Particle Accelerator Conf. (NAPAC'16)*, Chicago, IL, USA, Oct. 2016, pp. 32-36. doi:10.18429/JACoW-NAPAC2016-MOB3IO01

[3] Y. Funakoshi *et al.*, "Beam Commissioning of SuperKEKB", in *Proc. 7th Int. Particle Accelerator Conf. (IPAC'16)*, Busan, Korea, May 2016, pp. 1019-1021. doi:10.18429/JACoW-IPAC2016-TUOBA01

[4] Y. Ohnishi, "Highlights from SuperKEKB Phase 2 Commissioning", in *Proc. 62nd ICFA Advanced Beam Dynamics Workshop on High Luminosity Circular e^+e^- Colliders (eeFACT'18)*, Hong Kong, China, Sep. 2018, pp. 1-6. doi:10.18429/JACoW-eeFACT2018-MOXAA02

[5] A. Morita *et al.*, "Status of Early SuperKEKB Phase-3 Commissioning", in *Proc. 10th Int. Particle Accelerator Conf. (IPAC'19)*, Melbourne, Australia, May 2019. doi:10.18429/JACoW-IPAC2019-WEYYPLM1

[6] Y. Ohnishi *et al.*, "Accelerator design at SuperKEKB", *Progress of Theoretical and Experimental Physics*, vol. 2013, no. 3, p. 03A011, Mar. 2013. doi:10.1093/ptep/pts083

[7] Y. Ohnishi *et al.*, "SuperKEKB operation using crab waist collision scheme", *Euro. Phys. J. Plus*, vol. 136, p. 1023, 2021. doi:10.1140/epjp/s13360-021-01979-8

[8] Y. Funakoshi *et al.*, "The SuperKEKB Has Broken the World Record of the Luminosity", in *Proc. 13th Int. Particle Accelerator Conf. (IPAC'22)*, Bangkok, Thailand, Jun. 2022, pp. 1–5. doi:10.18429/JACoW-IPAC2022-MOPLXGD1

[9] Y. Ohnishi, "SuperKEKB luminosity quest", in *Proc. 65th ICFA Advanced Beam Dynamics Workshop on High Luminosity Circular e^+e^- Colliders (eeFACT'22)*, Frascati, Italy, Sep. 2022, paper MOXAT0103, this workshop.

[10] P. Raimondi *et al.*, "Beam-Beam Issues for Colliding Schemes with Large Piwinski Angle and Crabbed Waist", arXiv:physics/0702033, 2007.

[11] M. Zobov *et al.*, "Test of "Crab-Waist" Collisions at the DAΦNE Φ Factory", *Phys. Rev. Lett.*, vol. 104, p. 174801, 2010. doi:10.1103/PhysRevLett.104.174801

[12] K. Ohmi, "Simulation of beam-beam effects in a circular e^+e^- collider", *Phys. Rev. E*, vol. 62, p. 7287, 2000. doi:10.1103/PhysRevE.62.7287

[13] K. Ohmi *et al.*, "Study for -1 mode instability in SuperKEKB low energy ring", in *Proc. 65th ICFA Advanced Beam Dynamics Workshop on High Luminosity Circular e^+e^- Colliders (eeFACT'22)*, Frascati, Italy, Sep. 2022, paper WEXAT0102, this workshop.

[14] D. Zhou *et al.*, "Simulations of beam-beam effect in the presence of general chromaticity", *Phys. Rev. Spec. Top. Accel. Beams*, vol. 13, p. 021001, 2010. doi:10.1103/PhysRevSTAB.13.021001

[15] M. Masuzawa *et al.*, "Chromatic X-Y Coupling Correction by Tilting Sextupole Magnets in the SuperKEKB Positron Ring", presented at the 13th Int. Particle Accelerator Conf. (IPAC'22), Bangkok, Thailand, Jun. 2022, paper TUOZSP2, unpublished.

[16] S. Terui *et al.*, "The Report of Machine Studies Related to the Vertical Beam Size Blow-Up in SuperKEKB LER", in *Proc. 13th Int. Particle Accelerator Conf. (IPAC'22)*, Bangkok, Thailand, Jun. 2022, pp. 2169–2172. doi:10.18429/JACoW-IPAC2022-WEPOTK050

[17] T. Ishibashi *et al.*, "Status and Experiences of the vacuum system in the SuperKEKB main ring", in *Proc. 65th ICFA Advanced Beam Dynamics Workshop on High Luminosity Circular e^+e^- Colliders (eeFACT'22)*, Frascati, Italy, Sep. 2022, paper THXAS0102, this workshop.

[18] F. Abudinen *et al.*, "Measurement of the integrated luminosity of the Phase 2 data of the Belle II experiment", *Chin. Phys. C*, vol. 44, no. 2, p. 021001, 2020. doi:10.1088/1674-1137/44/2/021001

[19] D. Zhou, "Specific-luminosity degradation correlated with LER injection", presented at the 6th SuperKEKB commissioning meeting, Jun. 17, 2022.

[20] K. Matsuoka, "Luminosity degradation by the beam injection", presented at the 12th SuperKEKB commissioning meeting, Oct. 14, 2022.

[21] T. Hirai *et al.*, "Real-time luminosity monitor for a b-factory experiment", *Nucl. Instrum. Methods Phys. Res. A*, vol. 458, pp. 670-676, 2001.

[22] D. Zhou *et al.*, "Interplay of Beam-Beam, Lattice Nonlinearity, and Space Charge Effects in the SuperKEKB Collider", in *Proc. 6th Int. Particle Accelerator Conf. (IPAC'15)*, Richmond, VA, USA, May 2015, pp. 2413-2417. doi:10.18429/JACoW-IPAC2015-WEYB3

[23] S. Uehara, Private communication.