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SIMULATIONS AND MEASUREMENTS OF LUMINOSITY AT SuperKEKB

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Abstract

The interplay of beam-beam interaction, machine imperfections, and beam coupling impedance makes it difficult to predict the luminosity performance of SuperKEKB. Since 2020, the crab waist scheme was introduced to SuperKEKB to suppress beam-beam resonances. The coherent beam-beam head-tail instability and beam-beam driven synchro-betatron resonances due to large crossing angle can drive horizontal blowup, which cannot be suppressed by the crab waist. The longitudinal impedance modulates the synchrotron motion and therefore affects beam-beam instability. In this paper, we compare simulations and measurements of luminosity and discuss the challenges and direction toward developing a predictable luminosity simulation model for SuperKEKB.

INTRODUCTION

SuperKEKB [1] commissioning had three phases: Phase-1 [2, 3] (February - June 2016, without installations 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 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 interaction point (IP) much smaller than bunch length σ_z. However, without the crab waist (CW) the beam-beam (BB) driven vertical emittance blowup was severe, causing degradation of specific luminosity (Lsp) as bunch currents increased. This situation continued until April 2020 when the crab waist scheme [7] was adopted. The CW suppresses the beam blowup significantly and beam commissioning with CW has been successful [8], while luminosity performance has been worse than predictions of simulations.

OVERVIEW OF LUMINOSITY AND BEAM-BEAM EFFECTS AT SUPERKEKB

The specific luminosity $L_{sp} = L/(N_b I_{b+} I_{b-})$ for SuperKEKB with nano-beam collision scheme can be well approximated by

$$L_{sp} \approx \frac{e^{-\frac{\Delta^2}{2(\sigma_{y+}^{*2}+\sigma_{y-}^{*2})}}}{2\pi e^2 f \sqrt{\sigma_{y+}^{*2}+\sigma_{y-}^{*2}}\sqrt{\sigma_{z+}^2+\sigma_{z-}^2}\tan\frac{\theta_c}{2}} \quad (1)$$

Here N_b is the number of bunches, $I_{b\pm}$ is the bunch current, f is the revolution frequency, θ_c is the full crossing angle, $\sigma_{y\pm}^*$ and $\sigma_{z\pm}$ are the beam sizes at IP in the vertical and longitudinal directions, respectively. The quantity Δ indicates the relative vertical orbit offset of the colliding beams at IP. The incoherent BB tune shifts can be calculated from the BB kick [9], and are given by the approximate formulae

$$\xi_{x+}^i \approx \frac{r_e}{2\pi\gamma_+}\frac{N_-\beta_{x+}^*}{\sigma_{z-}^2\tan^2\frac{\theta_c}{2}+\sigma_{x-}^{*2}}, \quad (2)$$

$$\xi_{y+}^i \approx \frac{r_e}{2\pi\gamma_+}\frac{N_-\beta_{y+}^*}{\sigma_{y-}^*\sqrt{\sigma_{z-}^2\tan^2\frac{\theta_c}{2}+\sigma_{x-}^{*2}}} \quad (3)$$

for the positron beam. Exchanging the +/- by -/+ gives the formulae for the electron beam. Equations (1) to (3) are the basis of discussions on luminosity and BB effects in this paper.

Table 1: SuperKEKB machine parameters for β_y^*=2 mm on Jul.1, 2019 and β_y^*=1 mm on Apr. 5, 2022, respectively.

Parameters	2019.07.01		2022.04.05	
	LER	HER	LER	HER
I_b (mA)	0.51	0.51	0.71	0.57
ϵ_x (nm)	2.0	4.6	4.0	4.6
ϵ_y (pm)	40	40	30	35
β_x (mm)	80	80	80	60
β_y (mm)	2	2	1	1
σ_{z0} (mm)	4.6	5.0	4.6	5.1
ν_x	44.542	45.53	44.524	45.532
ν_y	46.605	43.583	46.589	43.572
ν_s	0.023	0.027	0.023	0.027
Crab waist ratio	0	0	80%	40%

Table 1 shows the typical machine parameters from operation without the CW (2019.07.01) and with the CW (2022.04.05). Using these parameters, the BB induced footprints of the LER beam are plotted in Fig. 1 with solid lines indicating the important resonances. The linear and chromatic coupling resonances $\nu_x - \nu_y + k\nu_s = N$ are driven by machine imperfections. The resonances at $\nu_x \pm n\nu_y = N$ are excited by BB interaction with a large crossing angle. The synchro-betatron resonances $2\nu_x - k\nu_s = N$ can be excited by both machine imperfections and BB interaction. Here the incoherent betatron and synchrotron tunes are used to describe the resonances. Transverse coupling impedances and BB effects can cause shifts of the incoherent betatron tunes, and potential-well distortion from longitudinal impedance

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can cause shift of the incoherent synchrotron tune. Therefore, as bunch currents change, the positions of relevant resonant lines also shift dynamically in the tune space. The rule of thumb is to find a working point to avoid obvious overlap between the beam's footprint and harmful resonances [10].

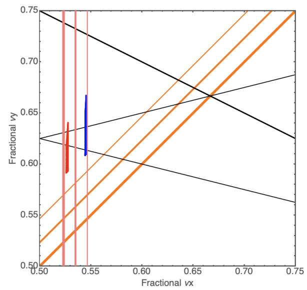

Figure 1: Beam-beam driven footprint of LER beam in the tune space with parameters of Table 1. The blue and red footprints represent 2019.07.01 and 2022.04.05, respectively.

With $\beta_y^* \geq 1$ mm, it was expected that interplay of BB and lattice nonlinearity at SuperKEKB should have a negligible impact on luminosity [11,12]. In Phase-2 commissioning without the CW, it was found that linear x-y coupling and dispersion at IP can severely degrade luminosity [13]. The source of linear coupling was traced to unwanted skew-quadrupole components in the final focusing superconducting magnets (the so-called QCS magnets). It was suspected that nonlinear chromatic and betatron couplings should be the next sources to explain the luminosity degradation. However, it was also suggested that nonlinear optical aberrations at the IP have to be extremely large, which was inconsistent with optics measurements [13]. Coherent beam-beam head-tail instability (BBHTI) [14, 15], which cannot be suppressed by the CW, is potentially harmful to luminosity performance. However, beam commissioning shows that the BBHTI was observed in early Phase-2 [16] but was not seen in Phase-3 when β_y^* was squeezed to 1 mm with careful optics tunings. Without the CW, strong-strong BB simulations showed that BB resonances were the most likely sources of luminosity degradation. This will be addressed later.

The uncontrollable blowup in vertical emittances set a severe limit on the luminosity performance and motivated the installation of the CW in SuperKEKB [8]. Though it would severely reduce the dynamic aperture and lifetime of the SuperKEKB rings with optics of $\beta_{y\pm}^* = 0.27/0.3$ mm [17], design studies showed that the CW is tolerable if $\beta_y^* \geq 0.6$ mm [18]. Beam commissioning with the CW at SuperKEKB has been very successful with $\beta_y^* = 1$ and 0.8 mm [8]. Experiments have shown that the CW effectively suppresses vertical blowup and allows larger beam currents to be stored in the rings [19].

STATUS OF BEAM-BEAM SIMULATIONS

Beam-beam simulations for SuperKEKB have been intensively done since the design stage. Simulation codes include BBWS, SAD [20], BBSS [21,22] and IBB [23]. BBWS and BBSS were developed by K. Ohmi at KEK, and IBB was developed by Y. Zhang at IHEP. BBWS simulations use a weak-strong model for the BB interaction, one-turn matrix for lattice transformation, perturbation maps for linear and nonlinear machine imperfections, ideal CW, longitudinal and transverse beam coupling impedances, etc. SAD simulations use the weak-strong BB model of BBWS and allows loading full lattice, perturbation maps, etc. BBSS simulations use a strong-strong model for BB interaction and all features of BBWS. IBB is a MPI-based parallel strong-strong code developed by Y. Zhang and has similar features of BBSS.

SAD simulations are used to investigate the interplay of BB and lattice nonlinearities [11]. BBWS simulations have been frequently used for fast estimates of luminosity performance and tune scan. BBSS and IBB simulations are used for investigating the interplay of BB, impedances and machine imperfections.

LUMINOSITY PERFORMANCE

Luminosity Performance Without Crab Waist

From March 2018 to March 2020, SuperKEKB was operated with collisions but without a crab waist. During that time, many challenges were experienced: 1) Peak luminosity much lower than predictions of simulations; 2) Easy vertical blowup of single beams; 3) Small area in tune space for good luminosity; 4) Unexpectedly high backgrounds in Belle II; 5) No or small gain of luminosity via squeezing $\beta_{x,y}^*$; 6) Hard to approach the design working point (.53, .57).

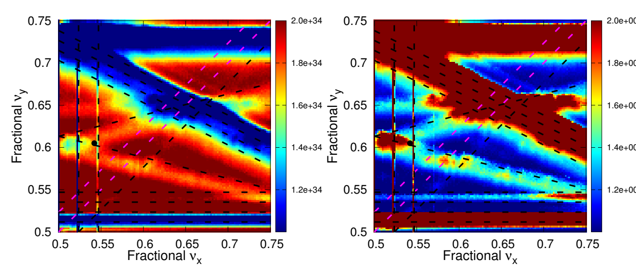

Figure 2: Tune scan of luminosity (left) and vertical beam size (normalized by σ_{y0}) for the parameter set of 2019.07.01 with the LER as the weak beam in the BBWS simulation. Important resonant lines are plotted, and the black dot indicating the working point for machine operation.

In addition to linear optics aberrations at IP [13], the BB driven resonances $\nu_x \pm 4\nu_y + \alpha = N$ have a large impact on the above observations and consequently limit the luminosity performance. Here the parameter α scales as the vertical BB tune shift and determines the widths of BB resonances. A luminosity tune scan shows that these 5th order resonances can be easily excited and their widths scale as vertical BB tune shift (see Fig. 2). According to Eq.(3), ξ_{yi} is proportional to $\sqrt{\beta_y^*/\epsilon_y}$, assuming $\beta_{y+}^* = \beta_{y-}^*$ and $\epsilon_{y+} = \epsilon_{y-}$.

Luminosity Performance With Crab Waist

Since April 2020, the CW has been implemented at SuperKEKB to suppress beam-beam resonances [24,25]. Luminosity performance has been improving with the following

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observations (see Ref. [19] for a review): 1) Luminosity performance became closer to the predictions of simulations; 2) Balanced collision (i.e. $\sigma^*_{y+} \approx \sigma^*_{y-}$) was achieved with careful tuning knobs; 3) The working point could be set around the design (.53, .57); 4) The total beam currents were not limited by BB blowup, but by injection power and hardware issues; 5) There still exists an unexpected degradation of Lsp vs product of bunch currents (Fig. 3). In particular, increasing the beam current does not give large increases in luminosity.

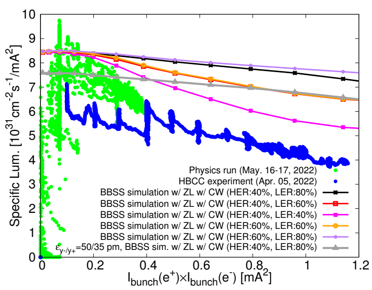

Figure 3: Lsp predicted by BBSS simulations with inclusion of longitudinal impedances and from experiments of high-bunch current collision (HBCC) machine study and physics run.

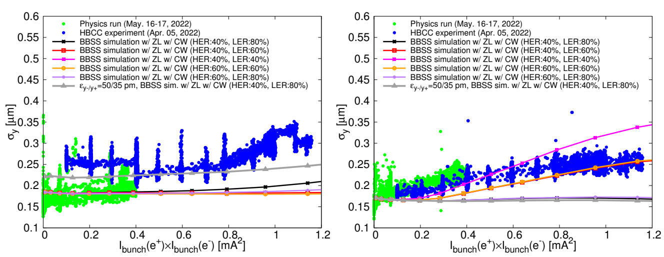

Figure 4: Vertical beam sizes of electron (left) and positron (right) beams at the IP predicted by BBSS simulations compared with experiments.

As shown in Figs. 3 and 4, with 40%/80% CW strength of HER/LER, the decrease of Lsp in strong-strong BB simulation is mainly attributed to bunch lengthening due to longitudinal wakefields and weak vertical blowup of HER beam due to insufficient CW strength. However, experimental results showed a much faster Lsp decrease as bunch currents increase. The sources of luminosity degradation are discussed in next section.

SOURCES OF LUMINOSITY DEGRADATION

Known Sources

The known sources of luminosity degradation have been identified by simulations and experiments: 1) Bunch lengthening driven by longitudinal impedance. From Eq.(1), the scaling law is $L_{sp} \propto 1/\sqrt{\sigma^2_{z+} + \sigma^2_{z-}}$. 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. 2) Chromatic couplings. Their effects on luminosity were recognized at KEKB [26]. 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. [27]). 3) Beam oscillation excited by the injection kickers of LER. These cause loss of Lsp on the order of 10% (see Ref. [28]). 4) Vertical blowup in the LER driven by the interplay of vertical impedance and feedback system. The problem was eliminated by fine tuning of the feedback system(see Ref. [29]).

Sources to be Investigated

There exist other sources to be investigated through simulations and experiments: 1) Imperfect crab waist. 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. Figure 3 shows luminosity degradation by weaker CW strength. 2) BB driven incoherent synchro-betatron resonances [28]. 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 [24]. The tune space in this region might not be large enough to hold the footprint of the beams. 3) Interplay of BB, longitudinal and transverse impedances, and feedback system. 4) Interplay of BB and nonlinear lattices. This was identified to be important for the final design of SuperKEKB configurations [11]. 5) Coupled bunch instabilities (CBI) with large bunch number and high currents. With 2151 bunches and total beam currents of 1.4/1.12 A achieved in LER/HER, so far Lsp degradation due to CBI has not been seen [28].

The sources listed above define the challenges and direction toward developing a predictable model of luminosity simulation.

CONCLUSION AND OUTLOOK

With progress in machine tunings, the measured luminosity of SuperKEKB is approaching predictions of BB simulations. Meanwhile, sources of luminosity degradation in collisions with the crab waist are better understood through investigations of simulations and experiments. Improving models for BB simulations are required in the future when beam currents become higher and β^*_y is squeezed further. Further discussions will be presented in Ref. [28].

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