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Simulation study on luminosity feedback for horizontal beam stabilization at SuperKEKB

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Abstract. The SuperKEKB $e^+ e^-$ collider uses highly focused ultra-low emittance bunches colliding every 4 ns to reach a very high luminosity of $8 \times 10^{35} \text{cm}^{-2} \text{s}^{-1}$. It is essential to have an orbit feedback system at the Interaction Point (IP) to maintain the optimum overlap between the colliding beams in the presence of ground motion disturbances. For the horizontal motion, a luminosity monitoring system, based on measuring the rate of the Bhabha process at vanishing scattering angle, is developed as input signal to the feedback system. The relative precision needed for this monitor is studied in detail, for the different successive stages of luminosity operation, based on a full simulation of this system, including the detector, DAQ, lock-in amplifier, and feedback control.

1. Introduction

Particle colliders with small beam sizes require maintenance of strict control over the beams to ensure optimum beam collision condition that maximizes the luminosity. SuperKEKB uses highly focused ultra-low emittance bunches colliding every 4 ns to reach a very high luminosity of $8 \times 10^{35} \text{cm}^{-2} \text{s}^{-1}$. In the presence of horizontal ground motion, the offset between beams can become large compared to the horizontal beam size, due to the slow Ground Motion (GM), thereby significantly degrading the luminosity.

The horizontal beam orbit stabilization at SuperKEKB uses a dithering feedback system similar to that operated in the past at PEP-2 [1, 2]. The luminosity signal used as input comes from detectors which measure the Bhabha scattering at zero degrees downstream of the Interaction Point (IP) on both sides. The system then computes the horizontal beam offset corresponding to the measured variations of the luminosity and provides a signal to upstream kickers, which steer the beam toward the nominal trajectory to achieve optimum overlap between the colliding beams.

In this paper, based on the simulated radiative Bhabha signal sequences in a diamond detector (one of the kinds of sensors used for fast luminosity monitoring at SuperKEKB, the others being Cherenkov and scintillator sensors [3]) located in the Low Energy Ring (LER)[4], the train integrated luminosity signal is simulated and used as input to the feedback system, then the feedback control process is simulated using MATLAB. The performance of the feedback system is estimated and the relative precision needed luminosity monitoring is discussed.



2. Preparation of feedback simulation

2.1. Luminosity Loss with Beam-Beam Offset

The calculation of the loss due to a horizontal beam-beam offset is very complicated at SuperKEKB because of its large crossing angle, extremely small vertical beta function at the IP, smaller than the bunch length, as part of the 'nano beam collision scheme' [5], and beam blow-up from non-linear beam-beam effects. To simplify the simulation, the luminosity reduction factor due to horizontal beam-beam offsets for head-on collision mode is used here as a conservative and reasonable approximation to the real dependence for the case of the nominal luminosity [6].

$$L=L_0 \times R=L_0 \exp\left[-\frac{(q+psin(2\pi ft))^2}{4\sigma_x^2}\right] \quad (1)$$

Here, q is the beam-beam offset, p is dithering amplitude, f is dithering frequency, and the horizontal beam sizes of two beams, σ_x , are assumed to be the same.

2.2. Train Integrated Luminosity Monitoring

Thanks to the large cross-section of Bhabha process at vanishing scattering angles, and to a custom made window shaped beam pipe at the location of our monitor in the LER [4], the luminosity can be measured at 1kHz with a very good relative precision. Once the luminosity is reduced due to an offset between the beams, Equation (1) can be used to infer its value.

2.3. Lock-In Amplifier Model

SuperKEKB uses an analog lock-in amplifier bought from Ametek Advanced Measurement Technology to extract the Fourier component of the luminosity signals at the dithering frequency with the frequency of orbit correction [7]. Here a two-phase lock-in amplifier model is built to process the simulated luminosity signals [8], as shown in Equations (2-4), R is the magnitude, V_i is the luminosity signal amplitude, f is dithering frequency. The output of the lock-in amplifier R is proportional to the beam-beam offset

$$R = \sqrt{X^2 + Y^2} \quad (2)$$

$$X = \sum V_i \times \cos(2\pi ft_i) \quad (3)$$

$$Y = \sum V_i \times \sin(2\pi ft_i) \quad (4)$$

for values not exceeding than the beam size, and reaches a minimum when beams overlap perfectly. The control algorithm uses the Newton method to calculate the needed corrections every second, based on the slopes obtained for the Fourier components at the dithering frequency with respect to the successive corrective moves. The sign ambiguity resulting from the evenness of the luminosity dependence with offset in Equation 1 is resolved by comparing the phase of the magnet current modulation used to dither the beam orbit with that of the resulting luminosity modulation.

3. Orbit feedback simulation

The nominal beam parameters of SuperKEKB are summarized in Table 1. The orbit dithering frequency is 77 Hz, and due to some hardware and network issue, correction frequency at 1 Hz was assumed presently, and can be changed in the future if necessary [2, 7]. The lock-in amplifier model processes the last 1 s simulated luminosity signals at 1 Hz. For dithering amplitude, $0.1\sigma_x$ is used here. The maximum horizontal offset which can be created by the planned orbit bumps at the IP is about $50 \mu m$, which corresponds to $5\sigma_x$.

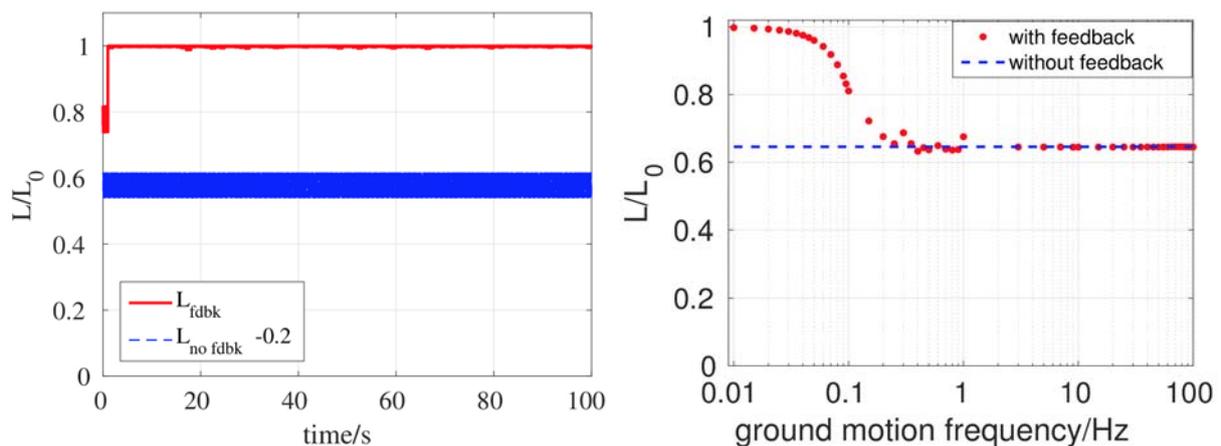
3.1. Feedback Performance

To investigate the performance of horizontal orbit feedback, an initial offset of σ_x is introduced to test the ability of recovering and later maintaining the luminosity at a stable level, based on

Table 1. Main Nominal SuperKEKB Beam Parameters

Parameter	LER / HER	Units
Energy	4 / 7.007	GeV
Luminosity	8×10^{35}	$\text{cm}^{-2}\text{s}^{-1}$
beam current	3.60 / 2.62	A
σ_x^* at IP	10 / 11	μm
σ_y^* at IP	48 / 56	nm
Number of bunches	2500	

simulated measurements at 1 kHz with relative precision of 1%. The result is shown in Figure 1 (l.h.s). The luminosity is reduced to 80% without and fully recovered with feedback. The frequency response of the feedback is then studied by introducing sinusoidal with amplitude of $2\sigma_x$ with varying frequencies, see Figure 1 (r.h.s). As shown in Figure 1, for corrections at a frequency of 1 Hz, the feedback can recover the luminosity to better than 95% if the GM frequency is about 20 times lower than the correction frequency. For higher frequencies, the feedback can not correct the orbit anymore.

**Figure 1.** feedback algorithm test (l.h.s) and its response as function of ground motion frequency (r.h.s)

3.2. Feedback Simulation for a Realistic GM Spectrum

The Power Spectral Density (PSD) measured in the past [9, 10, 11, 12, 13], was used as input to an inverse Fast Fourier Transform, to generate a set of statistically independent GM data sequences in time domain to represent the beam-beam offset in the feedback simulation. Figure 2 and 3 show the simulated luminosity ratio over time and beam-beam offset distribution, with and without feedback, respectively. It is shown that the feedback can recover the luminosity in the presence of typical GM effects in the horizontal plane at SuperKEKB, and maintain the RMS value of beam-beam offsets within $1.25 \mu\text{m}$, which corresponds to a luminosity loss of less than 0.5%.

Good performance is obtained for a correction frequency at 1 Hz due to the small magnitude of horizontal GM relative to the horizontal beam size at frequencies above 0.05 Hz. Relative

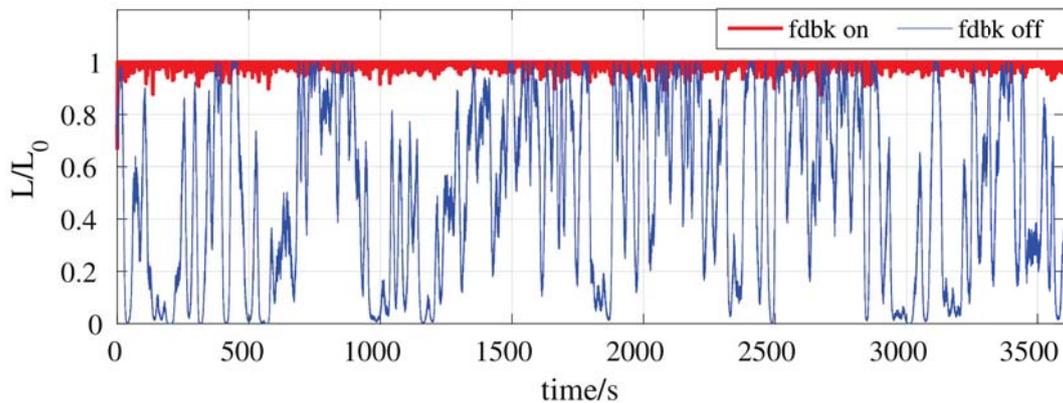


Figure 2. Luminosity ratio with and without feedback as function of time

precision of 1% at 1 kHz for ideal luminosity were assumed, with the change of luminosity due to beam-beam offset, the relative precision also changes with the rule of $1/\sqrt{N_{Bhabha}}$.

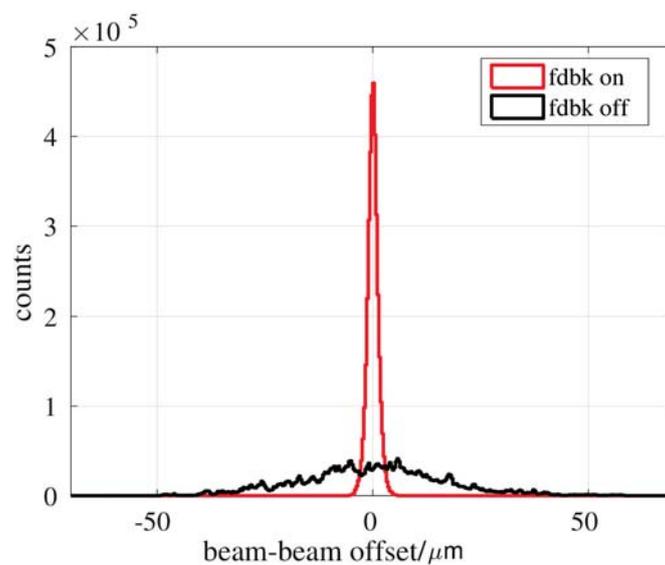


Figure 3. Beam-beam offset due to GM with and without feedback

3.3. Dependence on Luminosity Signal Relative Precision

The relative precision of the luminosity monitoring signal needs to be good enough to accurately compute the size and sign of the beam-beam offsets with above described method in the lock-in amplifier. If the relative precision is too bad, e.g. which covers the signal change due to the dithering, the correct sign information can for instance become more difficult to obtain, resulting in a potentially compromised corrections. Confusion from poor precision can in principle be mitigated by increasing the amplitude of dithering, however that will also reduce the average luminosity. To investigate the impact of the luminosity signal relative precision, signals with different relative precision were used as input to the simulation model, all other conditions being equal. The results are shown in Figure 4. It's obvious that the beam-beam offsets are smaller (corresponding to a better luminosity under the same condition) with better relative precision.

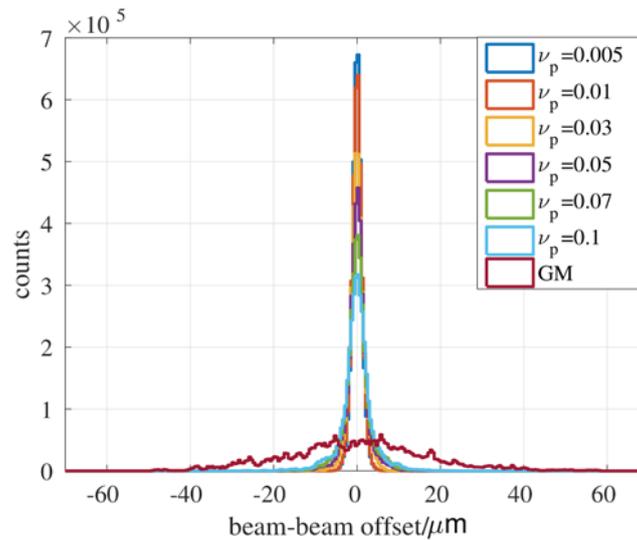


Figure 4. Residual beam-beam offset with feedback for different relative luminosity precisions

Figure 5 shows the RMS values of the beam-beam offsets (l.h.s) and the luminosity ratio with feedback (r.h.s) as a function of the relative precision of the luminosity signal. The results show that the performances are almost proportional to the luminosity signal relative precision. For example, with a relative precision of 5% at 1kHz, the RMS offset can be kept as small as $2.5 \mu\text{m}$, which corresponds to the luminosity loss of 1.5%, and for a relative precision of 1% at 1kHz, the RMS offset and luminosity loss are $1.25 \mu\text{m}$ and 0.5%, respectively.

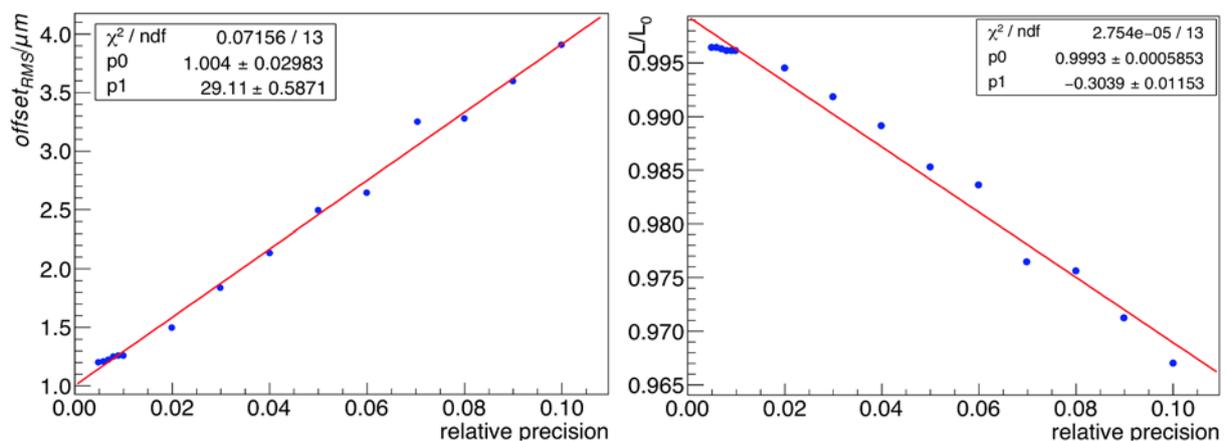


Figure 5. RMS offset (lhs) and ratio of luminosity with feedback with respect to ideal luminosity (rhs) as a function of luminosity signal relative precision

3.4. Results for Phase 2

For Phase 2 of SuperKEKB, the $\beta_{x,y}$ will initially be 4 and 8 times larger than nominal values in both horizontal and vertical planes, so the luminosity is less sensitive to beam-beam offsets from GM. Here the feedback algorithm is simulated for Phase 2 with relative precision of 1% at 1kHz and $\beta_{x,y}$ 8 times larger than nominal. The luminosity dependence of beam-beam offset is provided by [14] with realistic numerical simulation. The results are shown in Figure 6 and 7,

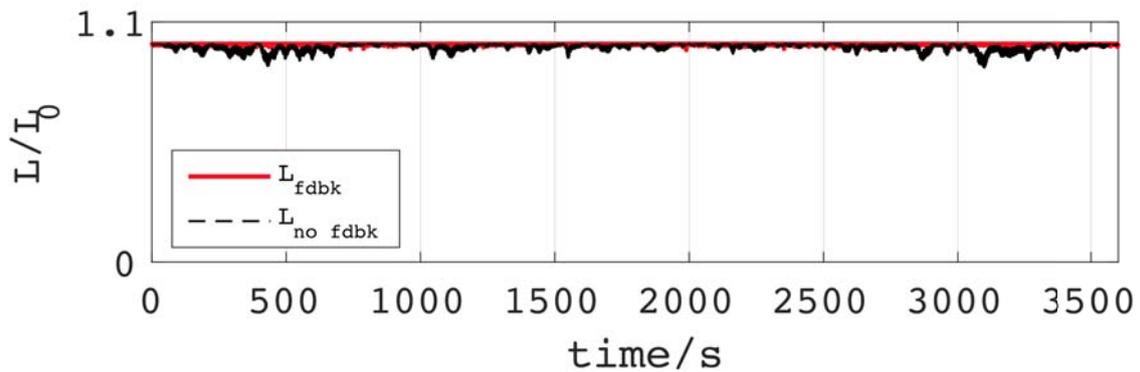


Figure 6. Luminosity ratio with and without feedback for Phase 2 as function of time

The luminosity loss due to GM without feedback is only about 0.7%, which could be ignored. With feedback, the luminosity loss due to horizontal GM is reduced to less than 0.1%, and the residual the RMS offset is about $6.5 \mu\text{m}$, which indicates the feedback algorithm still works well and can be tested in Phase 2.

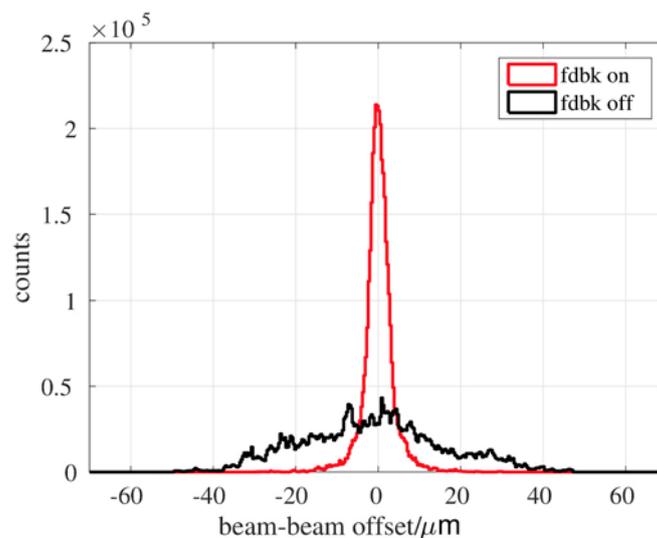


Figure 7. comparison of beam-beam offset due to ground motion with and without feedback for Phase 2

4. Conclusion

An initial simulation study of the horizontal IP feedback system based on luminosity monitoring has been presented, showing that horizontal orbit stabilization can be achieved to recover and maintain the beams in collision. Due to its slow correction frequency, it doesn't work with fast GM. However, the GM at high frequency is very small compared to the beam size in the horizontal plane, and so can basically be ignored. The relative precision of the luminosity monitoring was also studied. With 1% at 1kHz, the feedback system can maintain the RMS beam-beam offset within about $1.25 \mu\text{m}$ for nominal machine parameters, and the luminosity loss is less than 0.5%, which is good enough. For a 5% luminosity precision at 1 kHz, the luminosity loss is increased to about 1.5%.

In this study, only the horizontal plane was investigated, and the only source of luminosity loss considered were from GM induced beam-beam offsets, other external factors being ignored. To increase the realism of these simulations, more factors must be considered in a step-by-step process, such as non-linear beam-beam effects, spatial coherence of the GM impacting the relative motion of the beams, etc. Further studies will expand upon the limited conditions of this simulation, and will also include other ground motion models.

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