BEAM LIFETIME DEPENDENCE ON BUNCH SPACE AT SuperKEKB

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Abstract

We study the injection performance with respect to the bunch position in the SuperKEKB operation. The number of injections to the individual operation bunches, with using a method to equalize the current of all bunches, clearly depends on their bunch spacing. It indicates the beam lifetime dependence on the bunch spacing. In the assumption that the difference of the beam lifetime comes from the difference of the vertical beam size, the comparison between the Touschek lifetime ratio and the bunch luminosity ratio shows agreement. It suggests the existence of the inter-bunch effect that blows up the vertical beam size.

INTRODUCTION

The SuperKEKB collider [1] is one of the most important scientific projects in the world. This electron-positron collider is expected to reveal the true figure of the universe. The accelerator has been operated since 2016. The first physics result was published in 2020 [2, 3]. The world's luminosity record is updated successively and is achieved to be 3.1×10^{34} cm^{-2}s^{-1} in the 2021 spring run. The further beam commissionings and studies are ongoing together with the stable physics run for realizing the design luminosity of 8×10^{35} cm^{-2}s^{-1}.

We report the beam lifetime dependence on the bunch spacing in both the SuperKEKB electron ring (High Energy Ring, HER) and positron ring (Low Energy Ring, LER). The method to determine the lifetime ratio which is based on the sophisticated timing system [4] is explained. Then, the results from two data sets taken in 2020 and 2021 are shown and discussed.

BUCKET DEPENDENCE OF INJECTION

Figure 1 shows a number of injections to the individual RF-buckets of HER. The entries are accumulated from 0:00 a.m. to 9:00 a.m. on December 8th, 2020. The difference of entries indicates some performance differences of the individual operation bunches. In this section, we analyze the injection performance dependence on the beam bunch position.

Data condition

Two data sets in the SuperKEKB operation are selected for the injection performance analysis. One is from 0:00 a.m. to 9:00 a.m. on December 8th, 2020. The other is from 0:00 a.m. to 6:00 a.m. on March 28th, 2021. SuperKEKB carried out stable physics runs during the above operation periods. We did not implement any beam tuning, so that the data are suitable to understand the beam property.

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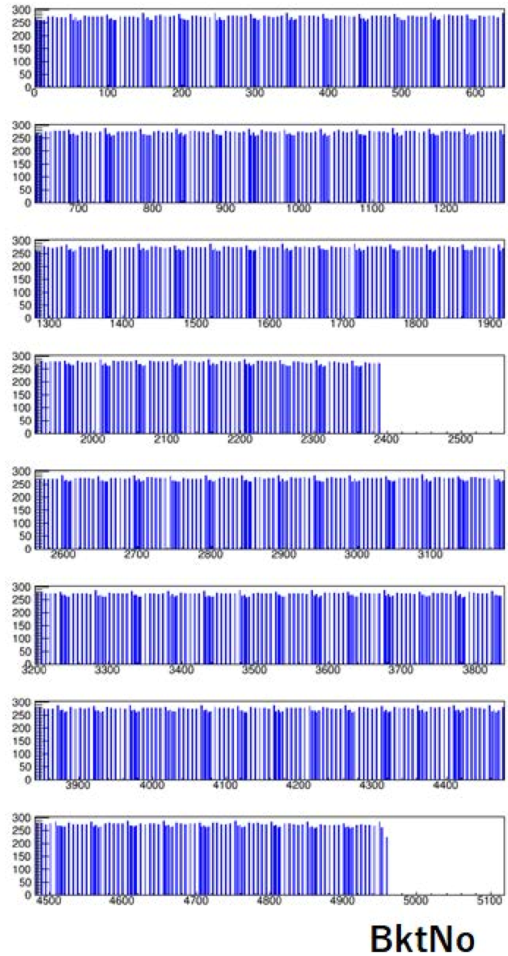

Figure 1: The number of injections to the RF-bucket at HER: The injections to the individual RF-buckets are counted for 9 hours.

The total beam currents for LER and HER are 480 mA and 450 mA, respectively, in the 2020 December data. They are 550 mA and 440 mA in the 2021 March data. The beam optics were SuperKEKB's typical collision optics. The horizontal beta functions of LER and HER at the interaction point, β_x^*, were 80 mm and 60 mm, respectively. The vertical beta function, β_y^*, was 1 mm for both rings.

The two bunch trains with a total of 978 beam-bunches were stored for both LER and HER. In each train, the bunches are stored in the cyclic pattern of 3, 6, 7 RF-bucket spacing[1].

The injector linac [5] performed the single bunch injection toward the smallest current bunch with the injection rate from 6.25 Hz to 25 Hz. It is also an important condition for

[1] Note, the RF frequency of SuperKEKB is 508.9 MHz. Therefore, the one RF bucket corresponds to 1.96 ns period.

this analysis. If the injection efficiency and beam lifetime are equal to all operation bunches, the number of injections to individual bunches should be equal. However, if one bunch has a relatively smaller injection efficiency or lifetime, the injection should be implemented more frequently.

Bunch Train analysis

In Fig. 2, the accumulation of the injection-current, ΣI_{INJ}, the number of injections, N_{INJ}, the average injection-current, $<I_{\mathrm{INJ}}>$, and the average charge at the end of beam transport, $<Q_{\mathrm{BT}}>$, are plotted as a function of the quotient when the bucket number are divided by 49, **BktNo/49**. This view is suitable to overlook the entire view of the filling pattern. The two trains with two abort gaps are seen.

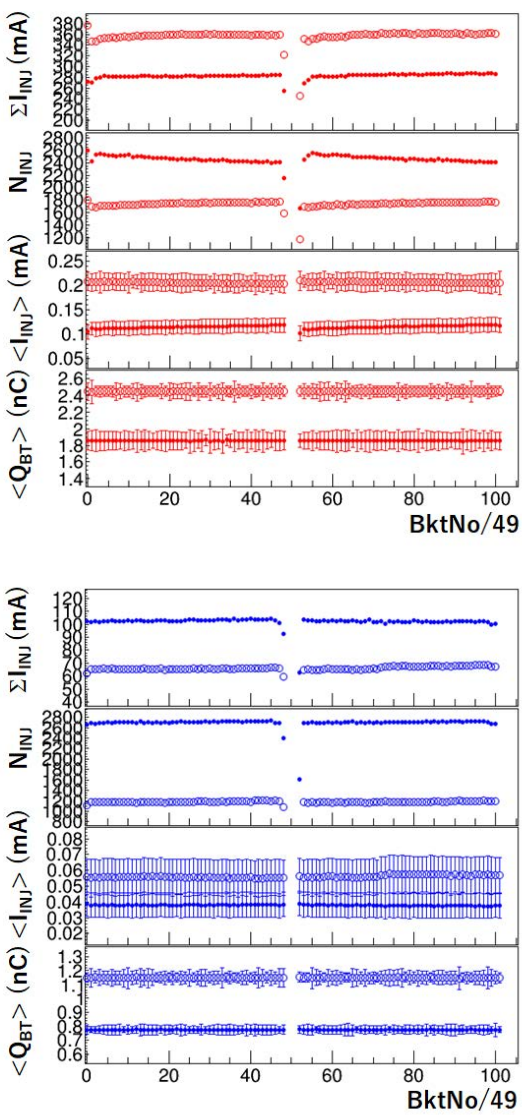

Figure 2: Four injection-related variables as a function of **BktNo/49**: the red and blue plots are the results at LER and HER, respectively. The closed (open) circles indicate the December 2020 (March 2021) results.

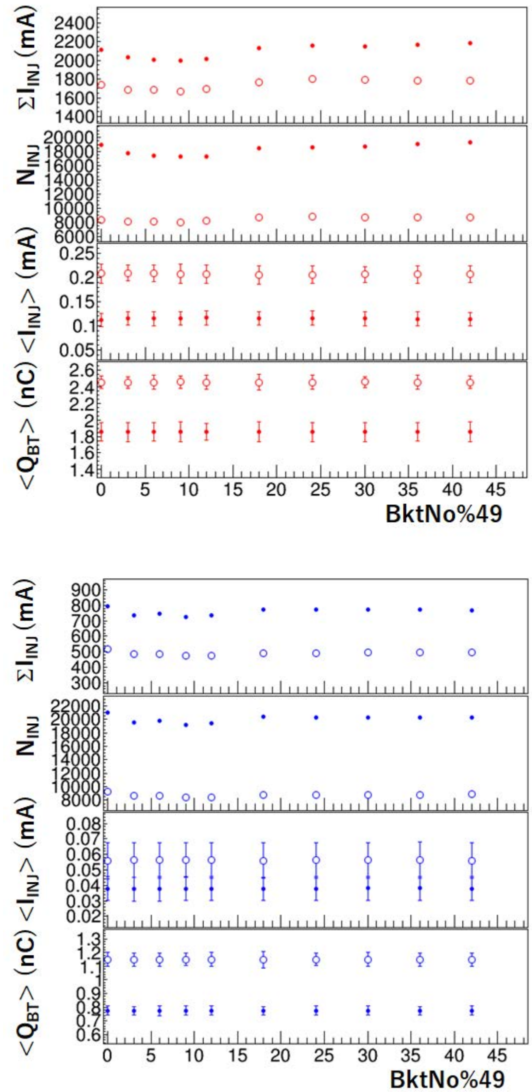

Figure 3: Four injection-related variables as a function of **BktNo%49**: the specifications of the color and marker type are the same as those in Fig. 2.

The accumulation or average is implemented for the entire data range. The upper figure with the red points and the lower figure with the blue points show the result from LER and HER, respectively. The results from two data sets are plotted on the same figure.

In the LER data of March 2021, even though there is no bunch position dependence of the $<I_{\mathrm{INJ}}>$ and $<Q_{\mathrm{BT}}>$, the N_{INJ} becomes larger in the backward of the bunch train. Consequently, ΣI_{INJ} becomes larger, too. There is the beam lifetime difference from the single bunch instability, for example, caused by the electron cloud effect. That behavior is not observed in the December 2020 data. Therefore, it depends on the machine parameters or beam conditions.

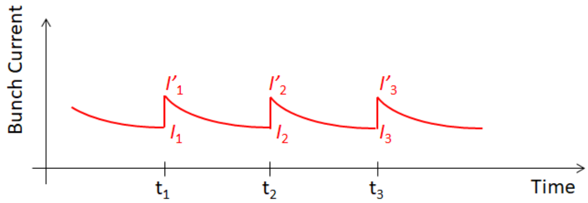

Figure 4: Schematic view of the injection information: the archived data for one operation bunch is summarized. The I_1, I'_1, and t_1 indicate archived data from the same injection. The I_2, I'_2, and t_2 are the same for another injection and so on.

bucket spacing analysis

In Fig. 3, four parameters discussed in the previous section are shown as a function of the remainder when the bucket number is divided by 49, **BktNo%49**. The bunch position of the SuperKEKB beam has a 49-folded pattern. Therefore, in this view, we can study the bunch space dependence. Three kinds of bunch spacings exist in the SuperKEKB operation during two data periods. The data points appear in the 3, 6, and 7 horizontal distances. Note, the first point (**BktNo%49** = 0) has 7 bucket distance from the last point (**BktNo%49** = 42). From the second point to the fifth point have 3 bucket distance. And the remainings have 6 bucket distance.

The bunch space dependence is observed in both LER and HER and both the December 2020 and March 2021 data. In all cases, $\Sigma I_{\rm INJ}$ and $N_{\rm INJ}$ are smaller when the bunch spacing is small. There is no significant difference in $<I_{\rm INJ}>$ and $<Q_{\rm BT}>$. Therefore, the most reasonable interpretation of this behavior is as follows: there is a beam lifetime dependence on the bunch spacing. The beam lifetime becomes longer when the bunch spacing becomes smaller. Fewer injections are necessary for the operation bunches with short bunch spacing.

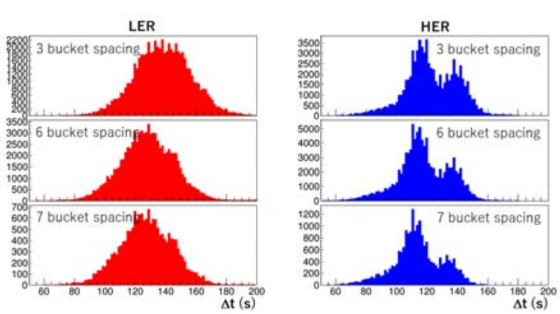

Figure 5: Δt distribution: the Δt distribution is shown for each bucket spacing. The December 2020 results are shown for LER (left) and HER (right).

Table 1: Summary of Injection Interval in the December 2020 Data: the values listed in the Δt region are the mean and the r.m.s of the Δt distribution. Those listed in the $\Delta t_{\rm T}$ are the evaluation of the Touschek components. All values are shown in the unit of second.

	LER	**HER**
Δt (s)		
3-spacing	138 ± 19	123 ± 17
6-spacing	128 ± 18	118 ± 17
7-spacing	127 ± 18	114 ± 16
$\Delta t_{\rm T}$ (s)		
3-spacing	264	153
6-spacing	229	145
7-spacing	226	139

Table 2: Summary of Injection Interval in the March 2021 Data: the specification of values is the same as those in Table 1.

	LER	**HER**
Δt (s)		
3-spacing	198 ± 9	187 ± 32
6-spacing	184 ± 9	182 ± 31
7-spacing	192 ± 9	173 ± 30
$\Delta t_{\rm T}$ (s)		
3-spacing	541	224
6-spacing	453	216
7-spacing	498	203

BEAM LIFETIME ESTIMATION

Beam lifetime raito

In the injection method of both data periods, the operation bunch with the smallest bunch current is selected and injected one after another. This method is implemented to equalize the bunch current of all operation bunches.

In this situation, the beam lifetime has a relation to the injection interval, Δt. The lifetime ratio among individual operation bunches equals the Δt ratio.

The injection information archiver [4] records the bunch current before injection, I, that after injection, I', and injection time, t, for every injection together with the injection RF-bucket number. If we take notice of one operation bunch, the archived data are summarized like Fig. 4. Then, in this figure, Δt becomes "$t_2 - t_1$" or "$t_3 - t_2$".

Figure 5 is the Δt distribution for the operation bunches with the 3, 6, and 7 bunch spacings. The histograms are made with the December 2020 data. The mean of the Δt distribution for each bunch spacing case is summarized with r.m.s. in Tables 1 and 2. The Δt distribution is shifted to be smaller direction when the bunch spacing becomes larger. The result is consistent with the discussion in the previous section.

Estimation of Touschek lifetime

The beam lifetime of SuperKEKB has mainly two components. They are the Touschek lifetime, τ_T, and the vacuum lifetime, τ_V [2]. The Touschek lifetime can be estimated from the following relations:

$$1/\tau = 1/\tau_T + 1/\tau_V, \quad (1)$$

where τ is the total lifetime.

The ratio between the $1/\tau_T$ and $1/\tau_V$ components is estimated from Belle's special run carried out on December 16th, 2020 for the understanding of the beam-induced backgrounds. It is estimated for two data sets, individually, since it depends on the total beam current and the bunch current. In the case of the December 2020 data, the ratio is estimated to be 0.54:0.46 for LER and 0.79:0.21 for HER. Those for the March 2021 data are 0.39:0.61 for LER and 0.81:0.19 for HER. The Touschek component of Δt which is denoted to be Δt_T is estimated with these ratios and summarized in Tables 1 and 2. These Touschek lifetime ratios can be compared with the bunch luminosity. It is discussed in the next section.

COMPARISON WITH LUMINOSITY

According to the non-relativistic approximation of the Touschek lifetime for the flat beam [6, 7], τ_T has the following relation to the bunch profile:

$$1/\tau_T \propto \frac{I_b}{8\pi\sigma_x\sigma_y\sigma_l\gamma^3}, \quad (2)$$

where σ_x, σ_y, and $_l$ are the vertical beam size, horizontal beam size, and the bunch length, respectively. The γ is the Lorentz factor. The I_b is the bunch current.

The following relation can be utilized for comparing the Δt and the luminosity:

$$L \propto \frac{I_{b+}I_{b-}N_b}{\Sigma_y^*} \propto \frac{1}{\sqrt{(\Delta t_T^{LER})^2 + (\Delta t_T^{HER})^2}}, \quad (3)$$

where Σ_y^* is the parameter that explains the vertical beam size at the interaction point. It is calculated with the vertical beam size of two beams to be $\Sigma_y^* = \sqrt{(\sigma_{y+}^*)^2 + (\sigma_{y-}^*)^2}$. The $^*_{y+}$ and σ_{y-}^* are the vertical size of the positron and electron bunches at the interaction point. Note, the inverse proportion between L and Σ_y^* is a normal condition for the particles' collider. The relation between Σ_y^* and $\sqrt{(\Delta t_T^{LER})^2 + (\Delta t_T^{HER})^2}$ is derived from the Eq. (2). In the assumption that the horizontal beam size and bunch length are equivalent to all bunches, the difference of the Touscheck component, Δt_T, comes from the difference of the vertical beam size. Therefore, the Σ_y^* ratio can be estimated from the Δt_T ratio.

Figure 6 shows the number of hits from the radiative Bhabha scattering in the SuperKEKB collision. It was measured at 3:03 a.m. December 8th, 2020, by ZDLM [8]. Thanks to its good time resolution, the rate can be detected for individual operation bunches. This hit rate is utilized to evaluate the luminosity. In the case of this analysis, the hit ratio can be directly regarded as the luminosity ratio after a correction for the deadtime effect among the bunches.

[2] Note, the vacuum lifetime is the parameter to explain the beam loss caused by the beam-gas scattering.

The comparison of the luminosity ratio and the $1/\Sigma_y^*$ ratio is carried out for both December 2020 data and March 2021 data in Fig. 7. Both ratios are evaluated among three bunch spacings. They show the same trend and are consistent with each other within the statistical error of the luminosity ratio. The ratio becomes smaller when the bunch spacing is smaller.

Actually, the same trend in the luminosity had been observed in the KEKB collider [9]. The electron cloud effect was considered as the reason at that time. However, this analysis provides new knowledge. Since the lifetime dependence is observed at both LER and HER, this inter bunch effect cannot be explained with the electron cloud.

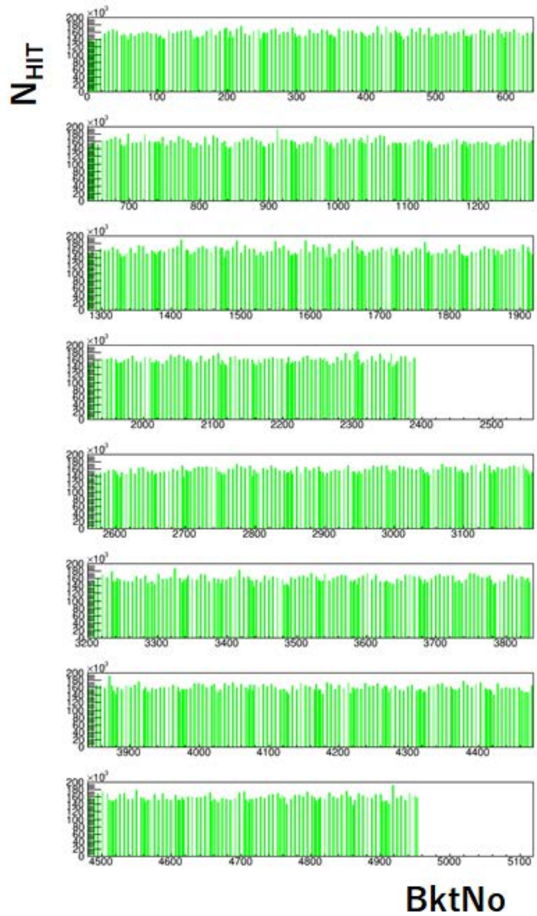

Figure 6: Rate of the radiative Bhabha scattering from the individual colliding bunches: the vertical axis shows the number of hits during 32 seconds of the measurement. The measurement was implemented at 3:03 on December 8th, 2020, by the ZDLM detector of Belle II.

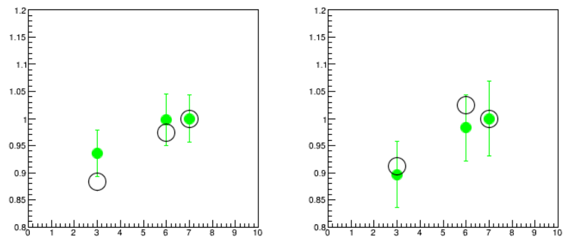

Figure 7: Luminosity ratio of December 2020 (left) and March 2021 (right) data: the luminosity ratio among 3, 6, and 7-bucket spacing are shown with the green closed circle. The $1/\Sigma_y^*$ ratio which is evaluated from Δt_T^{LER} and Δt_T^{HER} is plotted with the open black circle for the comparison.

CONCLUSION

The bunch position dependence of the injection performance at SuperKEKB is studied. In the bunch train view, the position dependence along the bunch train is observed in the March 2021 LER data. This phenomenon may depend on the operation parameters since it is not shown in the December 2020 data. Therefore, it is suggested that this kind of analysis should be checked online during the operation.

On the other hand, the bunch space dependence of the beam lifetime is determined in both run periods and both rings. It suggests the existence of the inter bunch effect which has not been understood. Under the assumption that lifetime difference comes from its Touschek component, we estimate the Touschek lifetime ratio among three bunch spacings. The Touschek lifetime ratio is consistent with the luminosity ratio.

The studies and understandings should be continued since SuperKEKB plans to be operated with the further shorter bunch spacing in the design luminosity. The degradation of the luminosity becomes larger for that condition. The absence of systematic uncertainties must be revised in future analysis. For example, the ratio between τ_T and τ_V has a systematic uncertainty and it is not considered in this analysis. The deadtime deference among the bunch locations affects the evaluation of the luminosity ratio by ZDLM. It should be estimated as a systematic uncertainty.

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