BUNCH LIFETIME ANALYSIS BASED ON THE INJECTION INTERVAL AT SuperKEKB

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Abstract
We study the bunch lifetime dependence on the bunch position at the SuperKEKB main ring. The bunch lifetime ratio is evaluated from the injection interval. The lifetime imbalance is observed between the forward and backward of the bunch train at the positron ring. It becomes larger when the beam current becomes larger. The luminosity dependence on the RF-bucket spacing can be explained with the lifetime dependency which we determined in this analysis. The result indicates the existence of the unknown phenomenon which varies the Touschek lifetime with the RF-bucket spacing in the electron ring.

INTRODUCTION
In the multi-bunch operation of the circular accelerator, the difference in the beam condition among the beam bunches sometimes appears. For example, in the case of the KEKB collider, the specific luminosity difference was observed among bunches that have different RF-bucket spacing1 [1]. There is no easy way to optimize the beam condition bunch-by-bunch. Therefore, it may become the limit of the beam commissioning.

At the SuperKEKB collider [3], which is the successor of KEKB, we observed the bunch lifetime dependence among the operation bunches by analyzing the injection counts. In this report, we describe the details of the analysis.

BUCKET DEPENDENCE OF INJECTION
Figure 1 shows the number of injections into the individual RF-buckets of the SuperKEKB main rings. The data from two operation periods are shown. They are from 0:00 a.m. to 9:00 a.m. on December 8th, 2020, and from 0:00 a.m. to 6:00 a.m. on March 28th, 2021. During these periods, we carried out the physics run with the top-up filling operation. We kept the total beam current constant by continuously injecting beam with the filling rule in Ref. [4].

In the top-up filling operation, the single-bunch injection is implemented into the lowest current bunch at the main ring. Besides, we did not implement any beam tuning during these two operation periods. In such a quiet condition, the observed deviation in the number of injections comes from some performance difference related to the beam lifetime.

Figure 1: Number of injections for the individual RF-buckets in two operation periods: the 8 hours of December 2020 data and the 6 hours of March 2021 data for the positron ring are shown with red and pink points, respectively while those for the electron ring are shown with blue and light blue points. The RF-bucket number is sorted with the quotient (left) and the remainder (right) when it is divided by 49.

POSITION DEPENDENCE IN BUNCH TRAIN
In the left plot of Figure 1, we can investigate the influence of the bunch position in the bunch train. The SuperKEKB main rings store the two bunch trains with 300 ns timing gap. Each bunch train has about 390 bunches in these two run periods.

We found a forward-backward imbalance in the number of injections with the bunch train of the positron ring. This behavior may depend on the beam condition since it was observed only in December 2020.

To study in more detail, we analyzed further data sets from the physics runs which were taken from December 13th to December 23rd, 2021. The positron ring was operated with a total current of 900-1050 mA with 1370 stored bunches.

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To evaluate the magnitude of the forward-backward imbalance in the number of injections, the slope parameter is determined with the following procedure: (1) The injection information is accumulated every 5 minutes to be analyzed, separately. (2) The fitting with the linear function is implemented to the quotient plot (the left plot of Figure 1.).

Figure 2 shows the dependence of the four beam parameters, the number of injections every 5 minutes, the slope with the linear function fitting, the beam lifetime measured with the beam current monitor, and the vertical emittance, on the positron beam current.

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1 The definition of RF-bucket spacing is how many RF-buckets the beam bunch is separated from the previous beam bunch.
The slope shown in Figure 2 is normalized with the number of injections every 5 minutes. Therefore, for example, in the “slope = 0.1 \times 10^{-3}” condition, the number of injections on the RF-bucket number $N + 100$ is 1% larger than that on the RF-bucket number $N$.

In the large beam current operation, we observed the steep dependence of this slope parameter. It can be understood that the bunch lifetime becomes shorter in the backward of the bunch train.

This cannot be explained with the current knowledge about the electron cloud effect. In the observation at KEKB, the single-bunch instability caused by the electron cloud makes the bunch size wider in the backward region so that their bunch lifetime becomes longer. Our new result shows the opposite behavior. Therefore, it is a new and unknown phenomenon in the large beam current operation.

One of the concerns related to this phenomenon is the Sudden Beam Loss accident [5]. We suffered from a lot of SBL accidents in the 2022 spring operation with the positron bunch current of around 0.7 mA. The correlation with the slope parameter becomes stronger in such a bunch current. We need to monitor this behavior for the future large current operation at SuperKEKB since it possibly becomes one of the hints to understand the Sudden Beam Loss accident.

### Estimation of Touschek lifetime ratio

As shown in the right plot of Figure 1, the number of injections depends on the RF-bucket spacing. In these operation periods, the bunch trains are constructed with 3, 6, and 7 RF-bucket spacing. Therefore we can discuss the lifetime difference in these three RF-bucket spacing cases.

Figure 3 is a schematic drawing to explain the current behavior of a bunch. Since the injection is implemented into the lowest current bunch, $I_1$, $I_2$, and $I_3$ becomes the same values and they are the same also for all bunches. This condition is realized also for $I'_1$, $I'_2$, and $I'_3$ since the injected current is equivalent in all injections. Only the injection interval, $\Delta t = t_2 - t_1$, $t_3 - t_2$ is different for all operation bunches and it is proportional to the bunch lifetime.

In the injection information archiver of SuperKEKB [6], we record when and which RF-bucket we injected a beam for all injector operations. Therefore we can know the $\Delta t$ value of the individual RF-buckets for all injections. The average of the $\Delta t$ value for three RF-bucket spacing cases is summarized in Table 1. The data are derived from Ref. [2]. It becomes shorter when the RF-bucket spacing becomes larger.

The beam lifetime of SuperKEKB has mainly two components, the Touschek lifetime, $\tau_T$, and the vacuum lifetime, $\tau_V$. Then, the total lifetime, $\tau$ can be explained like $1/\tau = 1/\tau_T + 1/\tau_V$. The ratio, $1/\tau_T:1/\tau_V$, was evaluated to be 0.54:0.46 for the positron ring and 0.79:0.21 for the electron ring in the 2020 December data. Those in the 2021 March data are 0.39:0.61 and 0.81:0.19 for the positron and electron rings, respectively. These ratios were evaluated in the special run at Belle II [7] which is carried out for the understanding of the beam-induced backgrounds.

The Touschek component in the injection interval, $\Delta \tau_T$, was determined with the above ratio and summarized in
Table 1: Summary of injection interval, $\Delta t$, and its Touschek components, $\Delta t_T$; the $\Delta t$ is shown with the standard deviation. All values are shown in the unit of second.

<table>
<thead>
<tr>
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<tbody>
<tr>
<td>$\Delta t$ (sec)</td>
<td>138 ± 19</td>
<td>123 ± 17</td>
<td>198 ± 9</td>
<td>187 ± 32</td>
</tr>
<tr>
<td>3-spacing</td>
<td>128 ± 18</td>
<td>118 ± 17</td>
<td>184 ± 9</td>
<td>182 ± 31</td>
</tr>
<tr>
<td>6-spacing</td>
<td>127 ± 18</td>
<td>114 ± 16</td>
<td>192 ± 9</td>
<td>173 ± 30</td>
</tr>
<tr>
<td>$\Delta t_T$ (sec)</td>
<td>264</td>
<td>153</td>
<td>541</td>
<td>224</td>
</tr>
<tr>
<td>3-spacing</td>
<td>229</td>
<td>145</td>
<td>453</td>
<td>216</td>
</tr>
<tr>
<td>6-spacing</td>
<td>226</td>
<td>139</td>
<td>498</td>
<td>203</td>
</tr>
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Table 1. Note, the $\Delta t_T$ ratio among 3-spacing, 6-spacing, and 7-spacing bunches represents the Touschek lifetime ratio.

Comparison with luminosity ratio

The following relation can be utilized for comparing the $\Delta t_T$ and the luminosity, $L$ [2]:

$$L \propto \frac{I_b \cdot \sigma_{\gamma} \cdot N_b}{\Sigma^*_y} \propto \frac{1}{\sqrt{(\Delta t_{T \text{LER}})^2 + (\Delta t_{T \text{HER}})^2}}.$$  \hspace{1cm} (1)

where $\Sigma^*_y$ 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 $\Sigma^*_y = \sqrt{(\sigma_{\gamma+}^2 + (\sigma_{\gamma-}^2)^2}$. Note, $\sigma_{\gamma+}$ and $\sigma_{\gamma-}$ are the vertical size of the positron and electron bunches at the interaction point. The $\Delta t_{T \text{LER}}$ and $\Delta t_{T \text{HER}}$ are the Touschek lifetime component in the injection interval for the positron and electron rings, respectively. They are introduced instead of the Touschek lifetime since $\tau_T \propto \Delta t_T$.

Besides, the relation between the Touschek lifetime and the vertical beam size in the non-relativistic approximation for the flat beam [8,9] is adopted with the assumption that the horizontal beam size and bunch length are equivalent to all bunches, the Touschek lifetime depends directly on the vertical beam size.

The $1/\Sigma^*_y$ ratio among three RF-bucket spacings was estimated from the $\Delta t_T$ ratio in Table 1. It is compared with the $L$ ratio in Figure 4. The luminosity was measured with the ZDLM detector [10] in the same operation periods. Its uncertainty is 3% and is accurate enough in this discussion.

The two ratios show the same trend and are consistent with each other with one standard deviation of the luminosity measurement. The $L$ ratio becomes smaller when the bunch spacing is smaller. This trend is observed in the KEKB collider [1]. However, the difference in the $1/\Sigma^*_y$ is still within the influence of the standard deviation of the $\Delta t$ distribution. It is omitted for making the plot readable. Therefore, further studies are expected.

The Touschek lifetime dependence on the RF-bucket spacing is observed in both the positron and electron rings. Still, the electron cloud is one of the candidates which made the luminosity difference. The difference at the positron ring can be explained with it. We need the other source which makes the electron bunch wider. One possibility is the excitation of the HOM mode in the superconducting cavity of the electron ring. We observed the heat load dependence of the HOM damper on the RF-bucket spacing in the 2022 run [11]. However, it is fairly taken out with the HOM damper. There is no evidence of its influence on the beam size.

CONCLUSION

The bunch lifetime study is carried out with the injection interval at SuperKEKB. The deviation in the number of injections among the RF-buckets was observed.

The forward-backward imbalance of the number of injections in the bunch train was observed at the positron main ring. The magnitude of the asymmetry depends on the beam current. It is steeply larger in the total current greater than 1000 mA and bunch current greater than 0.7 mA. This condition is the same as when SBL accidents frequently occurred. Therefore, it is worth continuing to study in the future SuperKEKB operation.

The bunch lifetime also depends on the RF-bucket spacing. The Touschek lifetime becomes relatively longer when the RF-bucket spacing is shorter. The same trend is determined in both positron and electron rings. The observed luminosity ratio is consistent with the estimated influence from the vertical beam size ratio which is evaluated from the Touschek lifetime. This behavior is consistent with what we observed in the KEKB project [1].

The result expects further analysis since the $1/\Sigma$ dependence is still within the influence of the standard deviation of the $\Delta t$ distribution. They are interesting and important to succeed in the future SuperKEKB operation.

REFERENCES


