INVESTIGATION OF THE COMPENSATION SCHEME USING THE BROADBAND KICKER CAVITY TO MITIGATE THE TRANSIENT BEAM-LOADING EFFECT IN SYNCHROTRON LIGHT SOURCES*

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Abstract

The bunch lengthening technique is the most reliable method to mitigate the intrabeam scattering in synchrotron light sources. However, the performance of the bunch lengthening can be degraded by the transient beam-loading (TBL) effect, which increases when long gaps are introduced in the bunch filling pattern. To mitigate the TBL effect, we have proposed a compensation method using a broadband kicker cavity, and carried out the performance tests of the low-power model cavity. In this presentation, the performance of the TBL compensation using the kicker cavity is discussed in detail, based on the results of these tests. As an example, the TBL compensation at the KEK PF 2.5 GeV ring is investigated using semianalytical calculations.

INTRODUCTION

At storage-ring light sources, the bunch-lengthening technique using a combination of fundamental and harmonic cavities is useful to mitigate the harmful effects of intrabeam scattering [1]. When large gaps are introduced in the fill pattern of the bunch train, the performance of the bunch-lengthening can be degraded by the transient beam loading (TBL) effect [2]. To mitigate the TBL effect, we have proposed a compensation method using a broadband cavity [3]. We have also investigated the conceptual design of the kicker cavity, and carried out performance tests of a low-power model cavity that can be used to compensate for the TBL effect [4]. In this paper, as an example of the TBL compensation, we investigate the performance of the TBL compensation at the KEK Photon Factory (PF) 2.5 GeV ring [5] based on semianalytical calculations. At first, we evaluate the performance of the bunch lengthening using a double RF system, which is under consideration at the PF ring. Second, the strategy of the TBL compensation at the PF ring is discussed. Finaly, the performance of the TBL compensation using the kicker cavity is investigated.

BUNCH LENGTHENING AT THE PF RING

Table 1 shows the beam parameters assumed in this paper. In the PF ring, there are two operation modes: multi-bunch mode and hybrid mode. The fill pattern of the hybrid mode consists of 129 bunches, 91 gaps, a single bunch and 91 gaps. The beam current of the multi bunches and the single bunch are 0.4 A and 0.05 A, respectively. Table 2 shows the RF parameters of the fundamental and harmonic cavities. At present, the harmonic cavities are not installed in the PF ring, and they are under consideration for the bunch lengthening. In this paper, we investigate the bunch lengthening using two or three harmonic cavities, which are defined as Cases A and B, respectively. In Table 2, the values allocated to Cases A and B are denoted by two values separated by ''/''. The operation of the harmonic cavities are assumed to be the passive. The parameters of the fundamental and harmonic cavities are based on those of the cavity installed in the PF ring and the TM020 cavity developed by our group, respectively [6].

Table 1: Beam Parameters of Hybrid Mode

Parameter	Value
Total beam current	0.45 A
Number of multi bunch	129
Number of gaps	91 × 2
Harmonics	312
Bucket interval	2 ns
Beam energy	2.5 GeV
Momentum compaction	0.0064
Energy loss per turn	399 KeV
Energy spread	7.28e-4

Table 2: RF Parameters for the Bunch Lengthening at the PF Ring

Parameter	Fundamental	Harmonic
Number of cavity	4	2 / 3
Frequency	500.1 MHz	1500.3 MHz
Total R/Q[1]	697.4 Ω	136 / 204Ω
Unloaded Q	39000	31400
Coupling factor	3.5	0.5
Total cavity voltage	1.7 MV	320 / 480 kV
Synchronous phase	1.29 / 1.26 radian	−1.82 radian
Tunning angle	−0.99 radain	1.32 radian

The performance of the bunch lengthening at the PF ring is evaluated using a semianalytical calculation, the details of which are described in reference [3]. In this calculation, we assumed that the bunch charge in multi bunches is uniform and that the bunch shape is gaussian. Figures 1 shows the bunch length calculated by semianalytical calculations. In Fig. 1, the horizontal and vertical axises show the bucket index and the longitudinal bunch length for each bunch,

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[1] $R = V_c^2/P_c$

respectively. The black, red and green points show the results obtained with the fundamental cavity alone, Case A and B, respectively. The bunch length is improved by 1.4 times and twice at Cases A and B, respectively. However, the fluctuation of the bunch length in the multi bunches increases by the TBL effect as the number of the harmonic cavities is increased. It is desirable to mitigate the fluctuation of the bunch length. For this purpose, we investigate the TBL compensation using a broad band kicker.

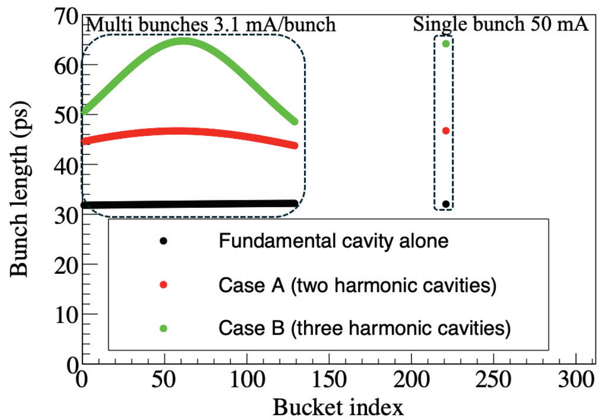

Figure 1: The longitudinal bunch length at the each RF bucket.

TBL COMPENSATION USING THE KICKER CAVITY

At first, the required voltage to compensate for the TBL effect is discussed. Second, the method and performance of the TBL compensation using the kicker cavity are discussed, based on the semianalytical calculations.

An arbitrary cavity is assumed to provide the additional voltage required for the TBL compensation in ideal conditions. Its cavity voltage is defined as $|\tilde{V}_{\rm add}(m)|e^{iN_{\rm add}\phi_{\rm add}(m)}$. Here, $N_{\rm add}$ is the harmonic number of the RF frequency for the cavity. $|\tilde{V}_{\rm add}(m)|$ and $N_{\rm add}\phi_{\rm add}(m)$ are the amplitude and the synchronous phase of the cavity voltage, respectively, just before the mth bunch. The real and the imaginary parts of the cavity are given by [7]

$$\mathrm{Re}[\tilde{V}_{\rm add}(m)] = \frac{U_0}{e} - \mathrm{Re}[\tilde{V}_{\rm c,f}(m) + \tilde{V}_{\rm c,h}(m)], \quad (1)$$

$$\mathrm{Im}[\tilde{V}_{\rm add}(m)] = -\frac{\mathrm{Im}[\tilde{V}_{\rm c,f}(m) + N_h\tilde{V}_{\rm c,h}(m)]}{N_{\rm add}}, \quad (2)$$

respectively. Here, $\tilde{V}_{\rm c,f}(m)$ and $\tilde{V}_{\rm c,h}(m)$ indicate the cavity voltage of the fundamental and harmonic cavities, respectively, just before the mth bunch. U_0 and $N_{\rm h}$ are the energy loss per turn and the harmonic number of the RF frequency for the harmonic cavity, respectively. In our case, $N_{\rm h} = N_{\rm add} = 3$ and the kicker cavity is used to provide the additional voltage. In this work, the parameters of the kicker cavity are assumed based on the performance tests of the low-power model cavity [4]. The kicker cavity is a normal conducting cavity and its shape is a single-mode cavity type [8]. RF power is fed into the kicker cavity through two small-external Q RF couplers to achieve a wide bandwidth of 5.32 MHz.

To mitigate the fluctuation of the bunch length, the required voltage of the kicker votage shoud be

$$\tilde{V}_{\rm c,k}(m) = \tilde{V}_{\rm add}(m) - \langle\tilde{V}_{\rm add}\rangle \quad (3)$$

Here, $\langle\tilde{V}_{\rm add}\rangle$ indicates the mean value of $\tilde{V}_{\rm add}$ during the bunch train. Figure 2 shows the required voltage of the kicker cavity to fully compensate for the TBL effect. The horizontal and vertical axes show the bucket index and cavity voltage, respectively. The black and red curves show the real and imaginary parts of the required voltage, respectively, obtained from Eq. (3) at case A. The green and blue curves show the real and imaginary parts of the required voltage, respectively, obtained from Eq. (3) at case B. In Fig. 2, the imaginary parts of the required voltage remain almost constant during the bunch train. It is not necessary to compensate for the imaginary parts of the accelerating voltage in order to mitigate the fluctuation of the bunch length. On the other hand, the real part of the required voltage of the kicker cavity periodically fluctuates during the bunch train. Consequently, to mitigate the fluctuation of the bunch length, it is reasonable to apply the amplitude modulation to the cavity voltage using a cosine wave with on-crest acceleration.

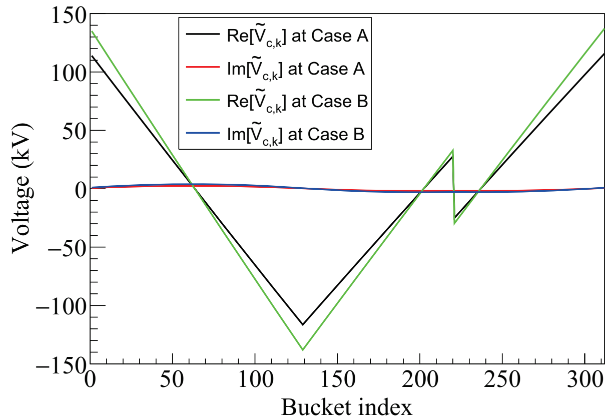

Figure 2: Required voltage of the kicker cavity to compensate for the TBL effect.

To modulate the cavity voltage of the kicker cavity, the modulation of the generator voltage is investigated. The cavity voltage can be written as

$$\tilde{V}_{\rm c,k}(m) = \tilde{V}_{\rm g,k}(m) + \tilde{V}_{\rm b,k}(m). \quad (4)$$

Here, $\tilde{V}_{\rm g,k}(m)$ and $\tilde{V}_{\rm b,k}(m)$ indicate the generator voltage and the beam-induced voltage just before the mth bunch, respectively. The generator voltage can be modulated by modulating the generator current, which can be written as

$$\tilde{i}_{\rm g,k}(m) = i_{\rm g,mod}\cos\left(2\pi\frac{m}{h}\right) + \theta_{\rm delay}. \quad (5)$$

Here, $i_{\rm g,mod}$, $\theta_{\rm delay}$ and h indicate the amplitude and phase delay of the modulation, and ring harmonics, respectively.

Taking into account the frequency response of the cavity, the effective generator voltage can be written as [9]

$$\tilde{V}_{g,k}(t) = \left[\tilde{V}_{g,k}(-\infty) + k\int_{-\infty}^{t} \tilde{i}_{g,k}(t') e^{\frac{\tau_b}{\tau_f}t'} dt'\right] e^{-\frac{\tau_b}{\tau_f}t}. \quad (6)$$

Here, k and τ_f indicate the loss factor and the filling time of the kicker cavity, respectively. τ_b indicates the bucket interval. The value of $i_{g,mod}$ is determined so that the maximum value of the generator voltage is 53 kV per cavity. This is the maximum voltage that can be guaranteed by the design in the previous study [4]. Using the semianalytical calculations, the optimal parameter of θ_{delay} is determined.

Figure 3 and Table 3 show the cavity voltage and RF parameters of the kicker cavity, respectively, with the optimal parameters of the amplitude modulation. Figure 4 shows the bunch length with and without the TBL compensation. A comparison of Figs. 2 and 3 shows that the bucket index of the downward peak in Fig. 2 corresponds to the upward peak in Fig. 3. The peak amplitudes at Cases A and B in Fig. 3 are 35.6 kV and 73.3 kV, respectively, while the peak amplitudes of the required voltage in Fig. 2 are 116.4 kV and 138.0 kV, respectively. However, increasing the modulation amplitude does not significantly reduce the fluctuation of the bunch length. This is because the shape of the required voltage differs from a cosine wave. Applying the TBL compensation improves bunch length fluctuations during the bunch train by factors of 2.7 and 3.5 in Cases A and B, respectively.

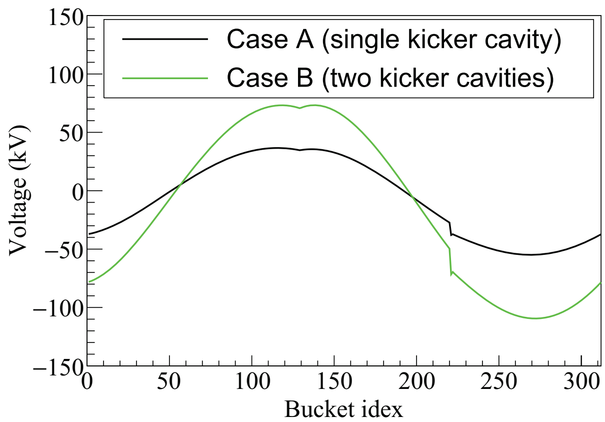

Figure 3: The cavity voltage of the kicker cavity as a function of the bucket index to mitigate the TBL effect. The black and green curves show the cavity voltage for Cases A and B, respectively.

SUMMARY

To further investigate the performance of the TBL compensation using a broadband kicker cavity, the TBL compensation at the KEK PF 2.5 GeV ring was examined via semianalytical calculations. Bunch lengthening using the combination of the fundamental and third harmonic cavities is under consideration at the PF ring. During operation in hybrid mode, fluctuation of the bunch length during the bunch train is expected to be large due to the large beam-induced voltage in the cavities. To compensate for the induced voltage, it is reasonable to apply the amplitude modulation to the kicker cavity using a cosine wave with on-crest acceleration. Applying the amplitude modulation to the kicker cavity, the fluctuations of the bunch length during the bunch train was expected to be improved by factors of 2.7 and 3.5 in Cases A and B, respectively.

Table 3: RF Parameters of the Kicker Cavity to Compensate for the TBL Effect at the PF Ring

Parameter	**Value**
Resonant frequency	1500.3 MHz
Number of cavity	1 / 2
R/Q per cavity	60 Ω
Unloaded Q	17937
Coupling factor	60.3
Synchronous phase	0 radian
Tuning angle	0 radian
Generator voltage per cavity	53 kV
Modulation delay (θ_{delay})	1.36 / 1.31 radian
Mean generator power per cavity	28.1 kW
Mean power loss in each cavity	1.1 kW
Mean reflecting power per cavity	30.5 kW

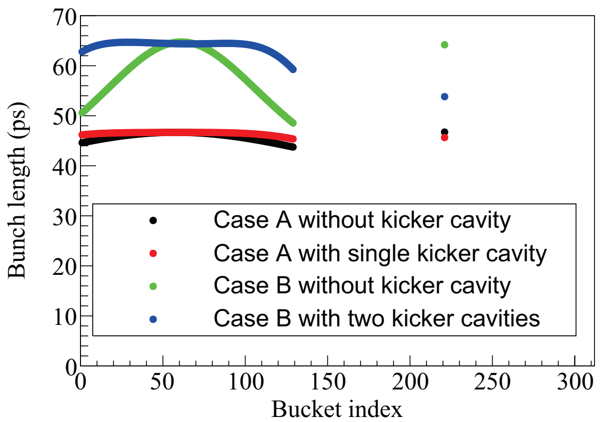

Figure 4: The bunch length with and without the TBL compensation. The black and red curves show the bunch length without and with the TBL compensation at Case A, respectively. The green and blue curves show the bunch length without and with the TBL compensation at Case B, respectively.

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