BEAM LOADING COMPENSATION FOR OPTIMAL BUNCH LENGTHENING WITH HARMONIC CAVITIES

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Abstract

Emittance growth and short beam lifetime due to intra-beam scattering in extremely low emittance storage rings can be mitigated if harmonic rf cavities are used for the purpose of lengthening the longitudinal bunch size. The "flat potential condition" can be achieved with harmonic cavities, lengthening the bunch by a factor of ~ 5. However, the performance is limited by the transient beam-loading effect in the rf cavities, which is induced by gaps in the ring fill pattern. As a counter-measure of this effect, we have proposed the active compensation techniques by using a single kicker cavity having a bandwidth of several times the revolution frequency. The transient effect can be compensated when the kicker cavity voltage is determined to suppress bunch phase shifts along the train.

INTRODUCTION

Extremely low emittance storage rings, which aim at achieving the beam emittances of < 100 pm-rad, are being actively designed as future ring-based synchrotron light sources. In such rings, emittance growth and short beam lifetime due to intrabeam scattering are of serious concern. To mitigate such adverse effects, a harmonic radio-frequency (rf) system [1] is used to lengthen the beam bunches, so that the particle density at the core of the bunch can be reduced.

Harmonic rf systems have been successfully operated to lengthen beam bunches in several light sources [2–9]. However, in some of them, the bunch-lengthening performance was limited due to the transient beam-loading (TBL) effect when the large bunch gaps are introduced [3–5]. It was reported [10] that the reduction of a total R/Q of rf cavities is essential to alleviate such transient effects.

The voltage fluctuations due to the TBL effect can be reduced when rf cavities having a small total R/Q are employed as shown in Fig. 7 in reference [11]. When the remaining variation of cavity voltages is kept smaller than several tens kV, we can further improve the bunch lengthening performance using a single kicker cavity within technical feasibility. In reference [11], we proposed two measures for active compensation techniques: compensation on the fundamental and harmonic cavities, and compensation using a separate kicker cavity.

As a next step of this work, feasiblity studies of the active compensation techniques using a separate kicker cavity were made. In this paper, we present numerical calculation results after the details of the compensation techniques are described.

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Table 1: Main parameters of the KEK-LS without harmonic rf systems, including insertion device losses.

Parameter	Value
Nominal beam energy	3.0 GeV
Stored beam current	500 mA
RF frequency (fundamental)	500.07 MHz
Harmonic number	952
Revolution frequency	525 kHz
Unperturbed synchrotron frequency	2.65 kHz
Synchrotron radiation loss per turn	851 keV
Main rf voltage	2.5 MV
Natural relative energy spread (rms)	7.3×10^{-4}
Momentum compaction factor	2.2×10^{-4}
Longitudinal radiation damping time	7.0 ms
Natural bunch length (rms)	9.5 ps

Table 2: Parameters of the KEK-LS rf systems used in calculations at the beam current of 500 mA. For the fundamental and third harmonic cavities, the PF-type cavity and the TM020 cavity were assumed, respectively. The synchronous phases are shown in the cosine definition.

Parameter	Fund. rf	Harmonic rf (3rd)
Rf voltage	2.5 MV	777 kV
Synchronous phase	1.178 rad	-1.708 rad
Tuning angle	-0.962 rad	1.433 rad
Total R/Q ($R = V_c^2/P_c$)	875 Ω	386 Ω
Total shunt impedance	35 MΩ	14.48 MΩ
Cavity coupling	3.5	0.27
Cavity detuning amount	-40.3 kHz	185 kHz

KEK-LS STORAGE RING

As an example of the extremely low emittance storage rings for feasibility study of the TBL compensation, we assumed the KEK light source (KEK-LS) [12]. Table 1 shows the main parameters of the KEK-LS. The KEK-LS has a design based on the hybrid multi-bend achromatic lattice. Although the natural emittance of 0.13 nm-rad is expected with zero beam current, the emittance affected by the intra-beam scattering is estimated to be 0.31 nm-rad at the nominal beam current of 500 mA. Then we have planned to introduce the harmonic cavities to mitigate the impact of the intra-beam scattering.

The assumed parameters for the fundamental and harmonic rf system are summarized in Table 2. The existing Photon Factory (PF) type cavities [13] are assumed for the fundamental cavity. A typical total RF voltage of 2.5 MV is

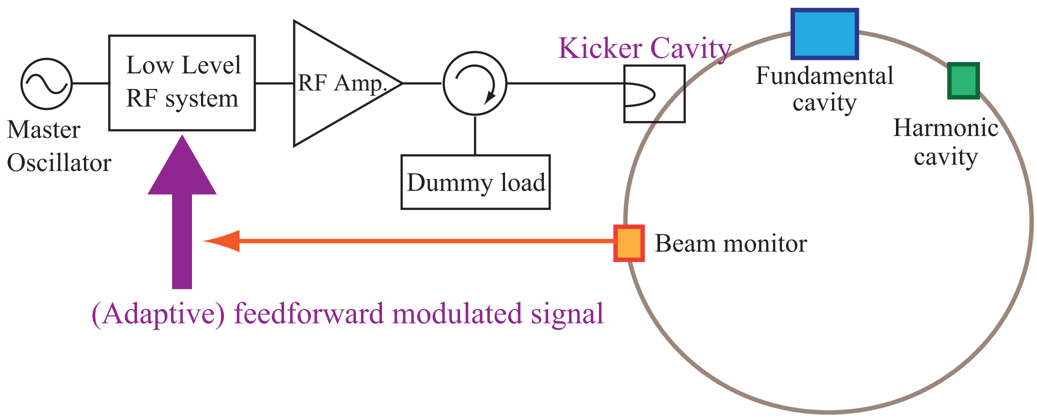

Figure 1: A Schematic of active compensation for transient beam loading effect.

produced by five cavities, where each cavity has an unloaded Q of 40,000 and R/Q of 175 Ω.

Concerning harmonic rf cavities for the KEK-LS, the candidate is a normal conducting TM020 cavity having the resonant frequency of 1.5 GHz, which is the third harmonic of the fundamental frequency, since lower R/Q and higher unloaded Q, as compared to the conventional TM010 cavity are expected [14, 15]. In this investigation, R/Q of 77.2 Ω and unloaded Q of 37,500 are expected for one 1.5 GHz-TM020 cavity. At nominal stored current of 500 mA, the "flat potential condition", which means that the voltage slope and the first derivative of the slope become zero, is satisfied with the cavity coupling of 0.27 and detuning amount of 185 kHz. At these conditions, the input power of the harmonic cavities ideally becomes zero, that is to say, passive cavity operation.

ACTIVE COMPENSATION SYSTEM

The schematic of an active compensation system using a separate kicker cavity is shown in Fig. 1. We have considered to use a kicker cavity having the wide bandwidth, a solid state amplifier and a feedforward low level rf (LLRF) control.

For the bandwidth of the feedforward signal, we consider the frequency range of about several megahertz, covering multiples of the repetition frequency of the fill pattern for typical synchrotron sources.

Kicker cavity

A single kicker cavity is the key equipment of this system. The cavity parameters shown in Table 3 are assumed for the feasibility studies. The summarized parameters are based on that of the PF-type 500-MHz cavity [13]. The cavity coupling is changed to realize the adequate cavity bandwidth. The 3dB full bandwidth of 5.0 MHz, which is given by $(1+\beta)/Q_0 \times f_r$, is expected if the cavity coupling (β) is set to 199 for a cavity having the resonant frequency (f_r) of 500 MHz and unloaded Q (Q_0) of 40,000, respectively.

Solid state amplifier

In order to compensate the transient voltages, the bandwidths of rf generators should be wider than the bandwidths of feedforward signal. Then as a high power rf amplifier for the active compensation system, a solid state amplifier is preferred option due to the intrinsic advantage of the wider bandwidth as compared to a klystron-based amplifier. As a result of feasibility test, we obtained a 1-dB full bandwidth of about 10 MHz with our prototype 1-kW, 500-MHz solid-state amplifier.

Table 3: Assumed parameters for a single cavity of the compensation system.

Parameter	Value
Resonant frequency	500.07 MHz
R/Q	175 Ω
Unloaded Q	40,000
Cavity number	1
Cavity coupling coefficient	199
-3dB full bandwidth	5.0 MHz

Adaptive feedforward LLRF system

The LLRF system should provide an rf signal including a fast feedforward pattern to compensate the transients while stabilizing both amplitude and phase of rf voltage on average using some feedback loops. We believe that both the feedforward and the feedback should be realized compatibly if they have much different response time.

At this moment, we have not determined the practical design of the feedforward LLRF system. A possible solution is reading both fill pattern and beam current in the system, calculating necessary feedforward pattern, and outputting the desired rf signal from the LLRF system.

COMPENSATION USING SINGLE KICKER CAVITY

In this section, we explain how to obtain the feedforward signal of a single kicker cavity in case that the voltage fluctuations along the bunch train for the fundamental and harmonic cavities are given. Then, the calculation results obtained in the KEK-LS case are shown as an example of the transient compensation.

The voltage fluctuations are anticipated numerically by using analytical [11] or tracking [16] tools if the operation parameters of the ring, including the bunch fill pattern , are known. For practical cases, it is considered that we can measure the fluctuations through rf cavity pickups experimentally.

Feedforward signal

Once cavity voltage fluctuations are caused by TBL effect, synchronous phases of bunches are varied according to the location in the bunch train. The amount of the phase shift is larger in the bunch lengthening operation mode compared to the other operation modes because of the nonlinearity of the harmonic rf voltage. The feedforward signal for a kicker cavity should be determined to minimizing these phase shifts.

When in the complex plane, voltages of both the fundamental and n-th harmonic cavity are represented by $\tilde{V}_{c,1}(m)$ and $\tilde{V}_{c,n}(m)$ as functions of the bucket number m, the kicker cavity voltage $\tilde{V}_{c,k}(m)$ should satisfied the following requirement for canceling the bunch phase shift,

$$\mathrm{Re}[\tilde{V}_{c,k}(m)] = -(\mathrm{Re}[\tilde{V}_{c,1}(m) + \tilde{V}_{c,n}(m)] - U_0/e), \quad (1)$$

where U_0 is the radiation loss per turn, e is the electron charge and $\mathrm{Re}[\tilde{V}_c]$ is the accelerating voltage seen by the beam. If the resonant frequency of the kicker cavity is exactly the same or integer multiple of the ring rf frequency, the amplitude of the kicker cavity voltage is represented by

$$|\tilde{V}_{c,k}(m)| = \mathrm{Re}[\tilde{V}_{c,k}(m)]/\cos\phi_{s,k}, \quad (2)$$

where $\phi_{s,k}$ is the cavity synchronous phase of the kicker cavity in the cosine definition.

Then using the beam induced voltage in the kicker cavity $\tilde{V}_{b,k}(m)$, we obtain the required generator voltage

$$\tilde{V}_{g,k}(m) = \tilde{V}_{c,k}(m) - \tilde{V}_{b,k}(m). \quad (3)$$

The generator current can be calculated using the kicker cavity response given in Eq. (25) of Ref [11]. Consequently, we deduce the input signal for the LLRF system after some band-limiting treatments to keep the peak generator power technically feasible.

Analytical simulation for KEK-LS case

In a standard operation of the KEK-LS ring, all rf buckets will be equally filled with electrons, except for the bunch gaps. To avoid ion trapping, we introduce several bunch gaps symmetrically in the ring. The number and duration of the gaps are tentatively 2 and 60 ns, respectively.

With the bunch gaps assumed, the amplitude of cavity voltages for both the fundamental and 3rd harmonic cavities are evaluated as shown in Fig. 2. For the harmonic cavity driven mainly by the beam induced power, the amplitude decreases at the head part of the bunch train, then increases as the number of the bunch passing through the cavity increases.

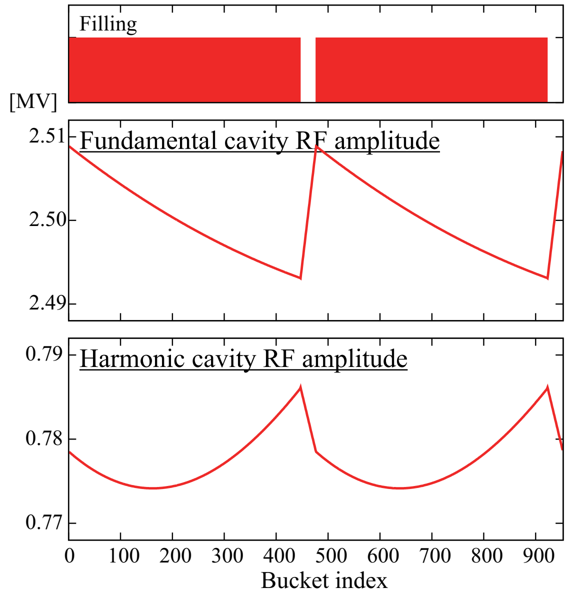

Figure 2: Amplitude variations in the fundamental and harmonic voltage due to bunch gap. A beam current of 500 mA with the standard fill pattern of the KEK-LS, where the number and duration of the gaps are 2 and 60ns respectively, is assumed.

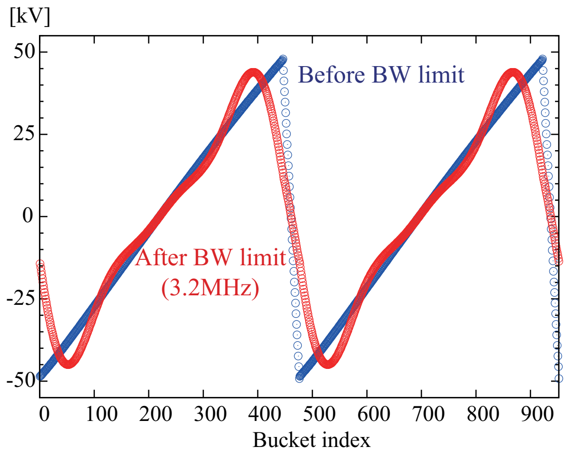

Figure 3: Required amplitude signal of the kicker cavity with assumption of the standard fill pattern of the KEK-LS. The red circles represent the band-limited signal with the bandwidth of 3.2 MHz for the primary signal shown in blue circles.

The amplitude of the kicker cavity voltage calculated by Eq. (1) is plotted by blue circles in Fig. 3, where $\phi_{s,k}$ is assumed to be zero. It is preferred that the bandwidth of the feedforward signal for the kicker cavity is limited to keep the generator power technically feasible. By omitting the frequency components above 3.2 MHz (frequency which is slightly higher than three times the repetition frequency of bunch train) in the Fourier series of the generator cur-

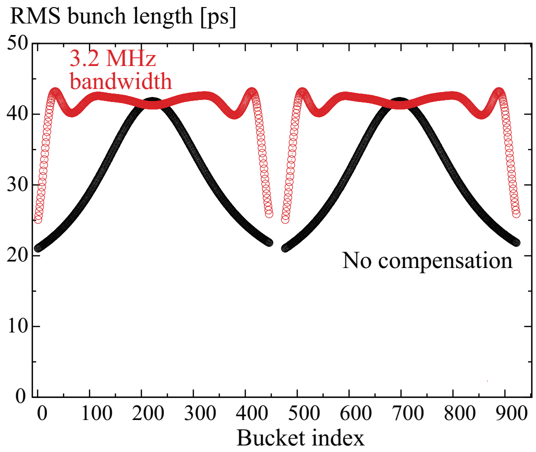

Figure 4: Rms bunch length versus the bucket index with (red) and without (black) the kicker cavity. The feedforward modulated signal with the frequency components below 3.2 MHz is assumed.

rent and re-calculating the generator voltage in the cavity, the feedforward signal indicated by red circles in Fig. 3 is obtained.

The rms bunch length with the kicker cavity is also calculated by using the semianalytical measure detailed in Ref. [11], where each longitudinal bunch distribution along the train is numerically calculated by considering the rf-potential shape at each bunch location, and is compared to the length obtained without the kicker cavity. In the Fig. 4, the red and black circles indicate the rms bunch lengths with and without the kicker cavity, respectively. The average bunch length with the active compensation over the bunch trains is 40.9 ps, which is close to that (42.5 ps) obtained under ideal conditions without any bunch gaps. Note, that the average bunch length without the kicker cavity is estimated to be 31.1 ps.

To confirm its technical feasibility, the voltage required for the kicker cavity is plotted together with the dissipated, generator and reflected powers as a function of bunch index in Fig. 5. These values are calculated using the cavity parameters listed in Table 3. The cavity voltage required for this compensation scheme is ~ 45 kV, while the peak generator power is ~ 50 kW. Both of them are technically feasible.

CONCLUSION

To mitigate the impact of the TBL to the bunch lengthening operation in extremely low emittance storage ring, we have proposed the feedforward compensation technique using a single kicker cavity. The kicker cavity having the band width around several megahertz allows us to minimize the phase shifts of the stored beam, and as a consequence, to recover the bunch lengthening performance degraded by the TBL effect.

In the case of the KEK-LS standard operation, the bunch lengthening factor can be improved from 3.3 to 4.3 by using the 500-MHz kicker cavity and the feedforward modulated

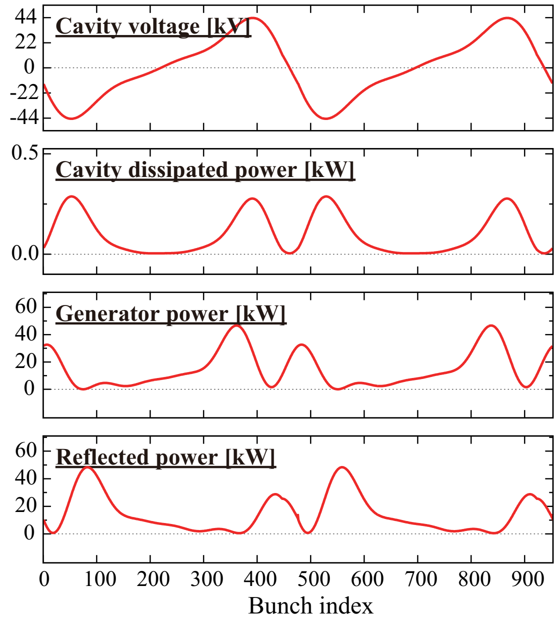

Figure 5: Cavity voltage required for the kicker cavity and comparison of the dissipation, generator and reflected powers as a function of bunch index when the cavity voltage indicated by red circles in Fig. 3 is produced in the assumed kicker cavity.

signal having 3.3-MHz frequency components. In that case, the average and peak generator powers are estimated to be 14.7 and 46.7 kW, respectively.

In addition, it is considered that this technique can be applied even to a passive harmonic system consisted of superconducting (SC) harmonic cavities. By using SC cavities, the total R/Q can be reduced. However, the large bunch phase shifts and degradation of the rms bunch length due to the TBL effect were reported when the large bunch gap is introduced for hybrid operation mode [5]. Even in such case, the compensation technique described in this paper can be applied, and expected to mitigate them.

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