Minimization of Emittance Increase in the Diffraction-Limited Storage Ring by Improving the Performance of the Harmonic Radio Frequency System

For future diffraction-limited synchrotron light sources, it is important to study the beam dynamics for longitudinal bunch shaping by adding harmonic radio-frequency (rf) fields to the main accelerating one to realize ultralow emittance beams with long lifetimes. In particular, it is important to mitigate the transient beam loading effect, which originates in the unoccupied rf buckets in the fill pattern, since it causes the rf fields to fluctuate and disturbs the bunch shaping. We numerically demonstrated the promising performance of a new harmonic rf system based on TM020 resonant mode. Further improvements in performance are expected by using our proposed active compensation techniques.

A current trend in the design of next-generation synchrotron storage rings is to achieve horizontal beam emittance of <100 pm.rad with a high beam current. In such rings, it is essential to mitigate the increase in emittance due to intrabeam scattering in order to provide high-brightness photons to beamlines [1]. The short Touschek lifetime is also a serious concern for stable top-up operation and radiation issues.

Longitudinal bunch lengthening by canceling the beam focusing force of the main accelerating field, which can be realized by adding harmonic radio-frequency (rf) fields (see **Fig. 1**), is considered to be a promising measure to mitigate the emittance increase and short Touschek lifetime. However, the zero-focusing condition, i.e., "flat potential" condition [2], is easily affected by disturbances of the fields, and the bunch lengthening performance is also limited. In most cases, this limitation is caused by the transient beam loading effect.

When unoccupied rf buckets, i.e., bunch gaps, are introduced in the fill pattern of the stored beam, the bunch gaps induce considerable variations in both the main and harmonic voltages. In this situation, the total rf potential for the electron bunch fluctuates along the bunch train, and the bunches are largely influenced.

We confirmed by numerical investigations that the transient beam loading effect could be reduced by using rf systems having a small total *R/Q*. Theoretically, the voltage fluctuation increases exponentially with the total *R/Q* of the rf system (for details, see Fig. 7 in reference [3]).

Following this result, we proposed a harmonic cavity (HC) based on the TM020 resonant mode, which was pioneered by Ego et al. as accelerating cavities for the upgraded SPring-8 storage ring [4]. The estimated *R/Q* for the TM020 normal conducting (NC) HC was 77 Ω. This value is about one half compared to existing NC cavities [5–7]. Moreover, the unloaded-Q of the TM020 cavity is a factor of 1.5–3 times higher, and so the total *R/Q* can be reduced to less than 30% in the KEK-LS case [8]. Assuming the bunch gap of 30 buckets for KEK-LS, we expect an average rms bunch length of 31 ps. This is three times longer than the natural one and is longer than those obtained with the existing HCs by a factor of 1.8.

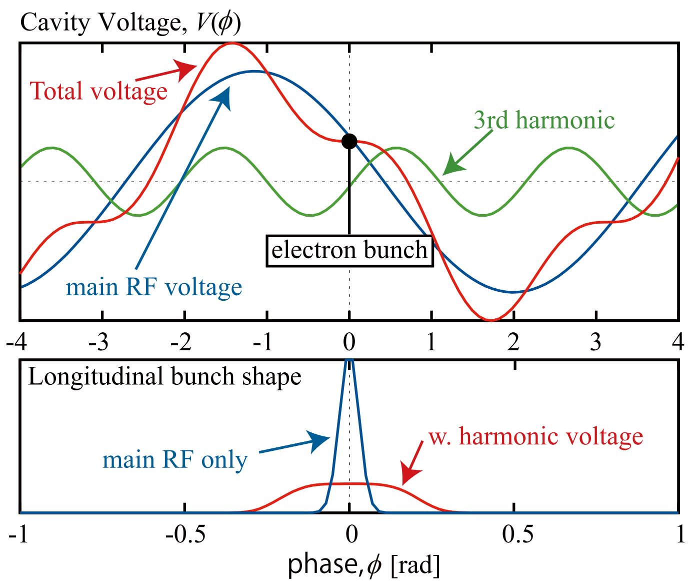

Figure 1: (upper) Voltages as a function of the main rf phase of the main and third harmonic cavities are shown in blue and green, respectively. The total voltage is shown in red. The "flat potential" condition is obtained at the position of the electron bunch, which is defined as the zero phase position. **(lower)** The electron distribution in the bunch is shown with (red) and without (blue) harmonic voltages as a function of the main rf phase.

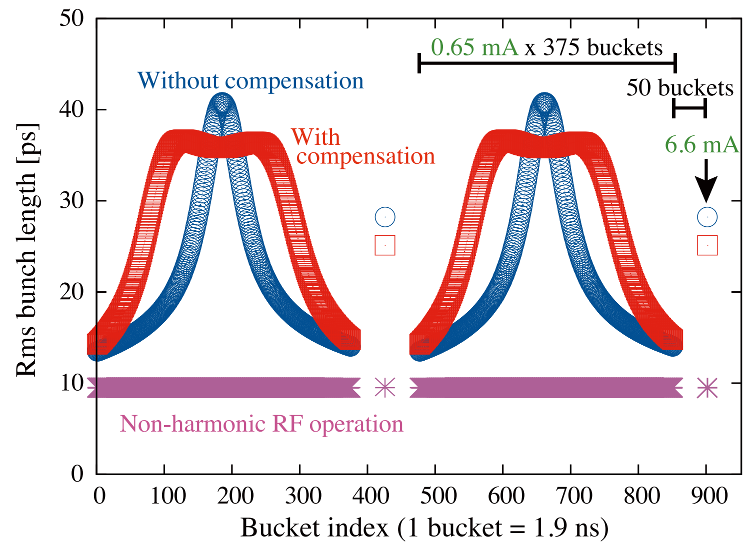

Figure 2: Rms bunch lengths as a function of the index of the buckets with compensation **(red)** using a kicker cavity compared to those without compensation **(blue)**. For reference, the natural bunch lengths are also plotted in magenta. We assumed a stored current of 500 mA and a hybrid fill pattern, where there are two single bunches with bunch gaps of 50 buckets. The bunch current for each single bunch is set to be 6.6 mA, which is ten times higher compared to the other bunches.

If the transient fluctuations can be reduced by using the TM020-HCs, we can further reduce the transient beam loading effect by using an active compensation technique. In our previous paper [3], we investigated its performance based on two measures: (a) compensation on the main and harmonic cavities, and (b) compensation using a separate kicker cavity.

A cavity for this purpose should provide an rf voltage that is comparable to the fluctuating rf voltages in the main and harmonic cavities. When the fluctuation is as small as a few percent for the voltage of several MV, the amplitude of the compensation rf signal for the cavity is estimated to be several tens of kV. The generator power required to induce such voltage with an adequate temporal structure strongly depends on the cavity bandwidth.

The advantage of compensation method (b) is that we can freely tune the cavity bandwidth. This is expected to achieve more effective compensation performance compared to method a), while keeping the required generator power at a modest level. In addition, it can also be applied for the superconducting system and multiple harmonic system which aims at the simultaneous operation of long and short bunches in the same train [9].

As a calculation result of method (b), we examine the bunch length along one turn for the KEK-LS ring. We assume a single high-charge filled bucket separated by two sets of 50-empty buckets from the other 375 filled buckets in the half revolution. In one turn, there are two single bunches each with a current of 6.6 mA, which is ten times larger charge compared to the other filled buckets. In **Fig. 2**, the averaged rms bunch length with the kicker cavity (red) was 25.0 ps, which is 2.6 times longer than that obtained without HCs. The required voltage for the compensation is ~57 kV, while the peak generator power for the 3 MHz-bandwidth kicker cavity is ~49 kW. These parameters for the kicker cavity are technically feasible.

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