Mitigation of the Single-Bunch Current Limit by Using Higher Harmonic Cavities for PF Hybrid Filling Mode

A hybrid filling operation mode with a high-current single bunch and a train of low-current bunches allows for simultaneous operation of high intensity and time-resolved experiments. At KEK-PF, the single-bunch current is limited to 30 mA owing to beam-duct heat problems and beam instabilities. These effects are potentially mitigated by introducing higher harmonic cavities and realizing bunch-lengthening operation. Accordingly, the impact of harmonic cavities and the ring impedance on the PF hybrid operation mode is numerically investigated using a multi-particle tracking code. Consequently, improvement of the single-bunch current limit is expected thanks to the bunch-lengthening.

Simultaneous operation of high current intensity and time-resolved experiments can be achieved by using a beam operation mode with a high-current single bunch and a train of low-current bunches, which is called “hybrid filling operation.” This operation mode has been adopted at KEK-PF for one month a year since FY2012. However, for the last several years, the single-bunch current has been limited to 30 mA because of beam-duct heat problems and shortening of the beam lifetime caused by single and multi-bunch instabilities [1].

A longitudinal bunch-lengthening operation can potentially mitigate this problem. By applying a higher harmonic voltage to cancel the longitudinal focusing force of the main accelerating voltage, the longitudinal bunch size is lengthened and synchrotron tune spread is also introduced. The maximum bunch length is obtained when the focusing force is perfectly canceled. In this so-called “flat potential condition,” the bunch-lengthening factor of 2.4 to the natural bunch length is expected if the uniform bunch fill pattern is employed [2]. Therefore, we carried out a more practical investigation for the PF hybrid filling mode.

It is considered that the inductive component of the ring impedance also contributes to bunch-lengthening when the single-bunch current is large. Therefore, we evaluated the ring impedance for the present PF ring by measuring bunch lengths as a function of bunch current and comparing with numerical calculations. The bunch lengths were measured with a streak camera (Hamamatsu, C5680 M5675 M5679) and the error bars were determined as a standard deviation of bunch lengths derived from twenty images (see red circles of **Fig. 1**). The measured bunch lengths with the bunch current of up to 30 mA are well-reproduced by both the analytical formula (Zotter’s law) and the multi-particle simulation code MBTRACK [3], and the inductive component of the ring impedance is evaluated as 0.87 Ω.

To evaluate the efficiency of bunch-lengthening, existing impedances in the ring and bunch fill pattern should be taken into account. For this purpose, the MBTRACK code was used instead of analytical evaluations. Concerning the existing impedance, cavity impedances are also assumed in addition to the inductive component of the ring impedance. The impact of ring impedance varies as a function of bunch current and its

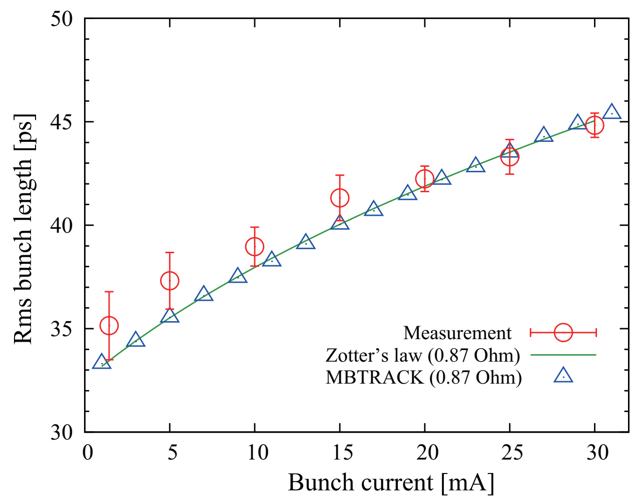

Figure 1: Bunch length as a function of bunch current. The measurement values are plotted by red circles together with the predictions by analytical formula (Zotter’s law) (green line) and MBTRACK code (blue triangles).

Table 1. Assumed parameters for main and harmonic cavities.

Parameter	Main rf	3rd Harmonic rf
Cavity number	4	1/2
R/Q, $R = V_c^2 / P_c$	174 Ω	80 Ω
Unloaded Q	39000	37500
Coupling factor	3.5	0
Total cavity votage	1.7 MV	160/ 298 kV
Synchronous phase	1.304 rad	-1.770 / -1.731 rad
Detuning frequency	-44.1 kHz	146 / 152 kHz

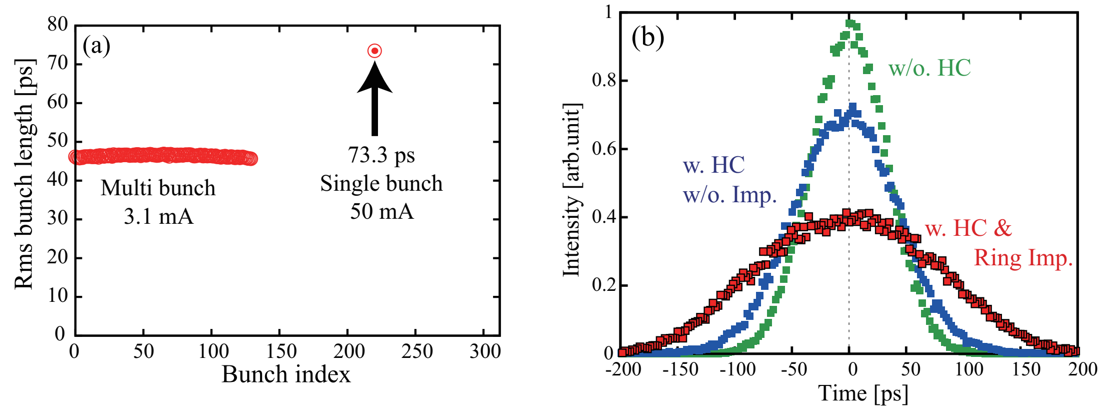

Figure 2: (a) Bunch length vs. bunch index and **(b)** longitudinal bunch profile of the single bunch having 50 mA with/without the harmonic cavity and ring impedance. The use of two harmonic cavities is assumed. The natural bunch current is 32.5 ps.

distribution. On the other hand, total accelerating voltages of main and harmonic cavities for each bunch are periodically perturbed according to both the bunch fill pattern and the cavity impedance properties, which are resonant frequency, Q-value and shunt impedance [4]. Thus, the multi-particle tracking simulation becomes a powerful tool to investigate the electron bunch dynamics in such a complex situation and evaluate the efficiency of bunch-lengthening.

The bunch fill pattern with a bunch train of 130 bunches and an isolated single bunch was assumed, and the bunch currents for each component were 3.1 and 50 mA, respectively, where the total current was calculated to be 450 mA. **Table 1** shows the parameters of the main and 3rd harmonic cavities. One or two 3rd harmonic cavities were assumed. For the harmonic cavity, the voltage, phase and detuning frequency were decided to maximize the single-bunch length while the dissipation power per cavity was kept within 10 kW.

The bunch length along the bunch index for the two harmonic cavities case is shown in **Fig. 2 (a)**. The bunch lengths of 46 and 73 ps, where bunch-lengthening factors were 1.4 and 2.3, were obtained for the bunch train and single bunch, respectively. This means that a bunch length almost equal to the ideal case can be achieve for the high-current single bunch thanks to the harmonic cavity and the ring impedance.

The single-bunch charge distribution calculated with the ring impedance and harmonic cavity is compared with those of the other cases (**Fig. 2 (b)**). It is confirmed that the ring impedance strongly affects the bunch lengthening performance.

Furthermore, the case of one harmonic cavity was also investigated, and the bunch lengthening factor of 2.0 for the single bunch was obtained. Even in this case, a certain effect regarding the beam-duct heat and beam-instability problems can be expected.

As a final remark, the fundamental design of the 3rd harmonic cavity for the PF ring has already been finished, and proof-of-principle measurements have been under way since FY2020, using a low-level model cavity made of aluminum alloy [5].

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