SIMULATION STUDY OF NORMAL-CONDUCTING DOUBLE RF SYSTEM FOR THE 3-GeV KEK LIGHT SOURCE PROJECT

N. Yamamoto*, S. Sakanaka, T. Takahashi, KEK, Tsukuba, Japan

Abstract

Feasibility of a 1.5-GHz harmonic radio frequency (rf) system in a proposed KEK Light Source (KEK-LS) project was investigated numerically. In the harmonic rf system, we will use normal conducting (NC) cavities which are operated with the TM020 resonant mode instead of the conventional TM010 mode. By using the TM020 mode having low R/Q and high unloaded Q, transient beam-loading effect resulting from bunch gaps can be reduced drastically. In addition, remaining small variations in the rf voltage can be compensated by an active compensation technique. As a result, we can expect the bunch lengthening performance that is comparable to the one obtained with a superconducting (SC) cavity under typical KEK-LS parameters.

INTRODUCTION

Recently, quasi diffraction-limited synchrotron radiation (SR) rings with a bare emittance of a few hundred pm-rad have been constructed or proposed. For the extremely low emittance rings with low-to-medium energy such as a proposed 3 GeV KEK-LS [1,2], reduction of bunch charge densities is required since the equilibrium 6D emittance and the beam lifetime are strongly dominated by intrabeam scattering [3].

The longitudinal bunch lengthening by using a harmonic radio frequency (rf) system [4] is one of the solutions to mitigate the intrabeam scattering effect. In order to operate the harmonic rf system effectively, the transient beam loading effects should be considered. Bunch gaps are introduced in stored beams to avoid problems caused by ions. However, the bunch gaps cause such harmful effects as the transient voltages in the cavities. The transient becomes severer as increasing the resonant frequencies of the cavities due to smaller stored energies.

The transient effects of 1.5-GHz harmonic cavities (HCs) were reported by Byrd *et al.* [5]. They pointed out an advantage of SC cavities over the NC ones. In fact, several successful operations with the SC HCs are reported [6–8], while only limited performances with NCs were reported [9, 10] at the 1.5-GHz range. Due to recent development in rf technologies, however, we have got to consider that the NC cavities are also promising for the higher harmonic system. Then we studied a feasibility of a full NC double rf system consisting of 500-MHz main cavities (MCs) and 1.5-GHz HCs for the use in the KEK-LS storage ring.

In this paper, we estimate numerically the dependences of the transient effects as a function of the total R/Q of the cavities. We then propose a HC which is based on the TM020 resonance mode and investigated its performances. In addition, further improvements of bunch lengthening performance is investigated by using an active compensation for beam induced rf voltage.

TRANSIENT EFFECT

The transient beam loading effects resulting from the absences of electron bunches for a storage ring were studied by Byrd *et al.* [5] using a beam tracking simulation. They showed that high unloaded-Q and low R/Q for an rf structure are the key parameters to reduce the effects. For the purpose to clarify the R/Q dependences on the effect numerically, we carried out a semi-analytical calculation to evaluate a fluctuation of cavity voltage along the bunch train.

The voltage fluctuation was numerically calculated as $\Delta V_c/|V_c| = \frac{|\widetilde{V}_{c,\max} - \widetilde{V}_{c,\min}|}{<|\widetilde{V}_c|>}$. The $\widetilde{V}_c$ denotes the complex cavity voltage, the subscripts max and min represent the maximum and minimum voltage in the bunch train, and <> denotes the average over the bunch train. The calculation was conducted assuming the optimum passive condition [4] for the KEK-LS storage ring [1,2] with a bunch gap duration of 60 ns. The principal parameters of the KEK-LS are listed in Table 1.

The estimated voltage fluctuations as a function of total R/Q for the KEK-LS case are shown in Fig. 1. Open circles in Fig. 1 indicate the calculation results for the cases of NC cavities. To derive these results, both typical cavity R/Qs and several possible unloaded-Qs were assumed at first. Once the required voltage and maximum dissipation power were given, the number of needed cavities was derived uniquely. Then the total R/Q was derived as a product of the number and the cavity's R/Q. Finally, the voltage fluctuations were numerically calculated by using these parameters.

On the other hand, open triangles indicate calculation results for the SC cavities. The difference with the case of NC

Table 1: The Principal Parameters of the KEK-LS

Parameter	Unit	Value
Beam energy	GeV	3.0
Storage current I	mA	500
Rf frequency	MHz	500.07
Harmonic number	-	952
Revolution frequency	kHz	525
Total radiation loss per turn	keV	957
Main rf voltage	MV	2.5
Optimum 3rd HC rf voltage	MV	0.78
Natural energy spread	-	7.3e-4
Momentum compaction	-	2.19e-4

---

[*] naoto.yamamoto@kek.jp

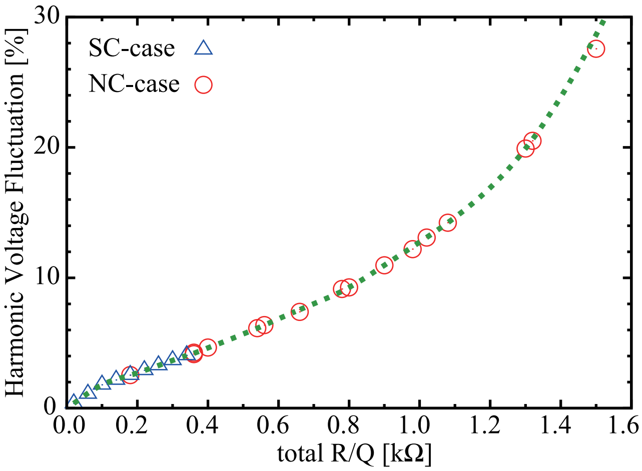

Figure 1: Fluctuations in harmonic cavity voltage which were estimated for the KEK-LS with 60 ns bunch gaps.

cavities is the numbers of cavities. The shunt impedance of an SC cavity is enough large due to its fairly large unloaded-Q. Then the number of installed cavities can be set to unity for the KEK-LS case.

The dashed line in Fig. 1 represents an approximated curve for the results. It was found that the approximated curve can be shared with both the NC and SC cavities for the KEK-LS case. Figure 1 shows that the fluctuation curve largely depends on the total R/Q. Then the reduction of the total R/Q is one of the most effective measures to mitigate the transient effect.

From the above-mentioned estimation, we can see that the fairly high unloaded-Q for a SC cavity is not always necessary for reducing the transient. In the case of extreme low emittance rings with low-to-medium energy such as the KEK-LS, the main and the harmonic rf voltages required are a few megavolts and a sub megavolt, respectively. Then in spite of the fairly high unloaded-Q for the SC cavity (typically 10^8 as compared to 10^4 of NC cavities), the ratio of total R/Q of SC cavities to that of NC cavities is at most a factor of ten. This means that there are some potentials for the NC harmonic cavities by using small R/Q cavities.

PERFORMANCE WITH NORMAL CONDUCTING TM020 CAVITY

An rf structure having high unloaded-Q and low R/Q should be chosen to realize low total R/Q. For this purpose, we propose to employ an rf structure based on the TM020 resonant mode. A TM020 cavity with HOM damped structure was originally proposed by Ego *et al.* [11, 12] as a beam-accelerating cavity to realize a high Q and a sufficient shunt impedance. We consider that the TM020 cavity is very suitable for the harmonic cavities as compared with conventional TM010 cavities due to its large stored electromagnetic energy.

The calculation for a 1.5 GHz TM020 cavity was carried out to estimate the cavity parameters by several electromagnetic field simulation codes. The unloaded-Q and R/Q of the TM020 mode were estimated to be 37500 and 77 Ω [13]. As compared to existing NC-cavities [9, 10, 14] which are based on the TM010 resonant mode, an unloaded-Q is higher by a factor of $1.5 \sim 3$, and R/Q is about a half.

Transient Reduction by TM020-Cavity

For the KEK-LS, the main rf voltages of 2.5 MV is required as listed in Table 1. The optimum 3rd HC voltage is calculated to be 827 kV in the situation that the slope and the curvature of the total rf voltage are both set to zero at the synchronous phase [4]. In this case, the optimum voltage can be produced with five TM020 cavities with a dissipated rf power of 9.1 kW per each cavity. With a total R/Q of 385 Ω, the voltage fluctuation is estimated to be 4.5 %.

For a comparison, we consider a BESSY-type NC TM010 HC [10]. Each cavity has the unloaded-Q and R/Q of 13900 and 124 Ω, respectively. Then the total R/Q was determined to be 1488 Ω and the voltage fluctuation was estimated to be 27.2 %, which is larger by a factor of six as compared to that of the TM020 cavities.

In case of the SC HC cavity for the SLS [7], each cavity has the unloaded-Q and R/Q of 2×10^8 and 176 Ω, respectively. The total R/Q was determined to be 176 Ω and the voltage fluctuation was estimated to be 2.5 %. This is only a slight improvement as compared with the NC TM020 cavity. The fluctuation has a linearly dependence on the total R/Q in this range and the slope is small as shown in Fig. 1

Evaluation of Bunch Lengthening

The bunch lengthening performance were estimated by semi-analytical calculation. For the semi-analytical calculations, the cavity parameters, such as cavity coupling, rf phases and average cavity voltage, are determined by the static optimum condition [4] for the KEK-LS parameters in Table 1. Then a longitudinal charge distribution for each bunch was derived numerically with the potential well using numerically calculated cavity voltages $\widetilde{V}_c$. Note that we conducted another macro-particle simulation on the same problem and found a good agreement with the semi-analytical calculation.

To estimate the charge distribution and the bunch length in the double rf operation, the KEK-PF type rf structure [15] was tentatively employed as a 500 MHz main accelerating rf structure. The unloaded-Q and R/Q of the KEK-PF cavity are 40000 and 175 Ω, respectively. The required rf voltage is realized with five cavities and the coupling factor of 3.5 is assumed. The voltage fluctuation for the MCs was estimated to be 1.7% for the bunch gap of 60 ns. This transient effect in the MCs also affects the bunch length.

The root-mean-square (rms) bunch lengths along the bunch train, which were calculated by semi-analytical method, are shown in Fig. 2. In Fig. 2, open circles represent bunch lengths calculated by using the TM020 HCs and PF-type MCs, and the solid and dashed lines are those without bunch gap and without HC, respectively. The upper

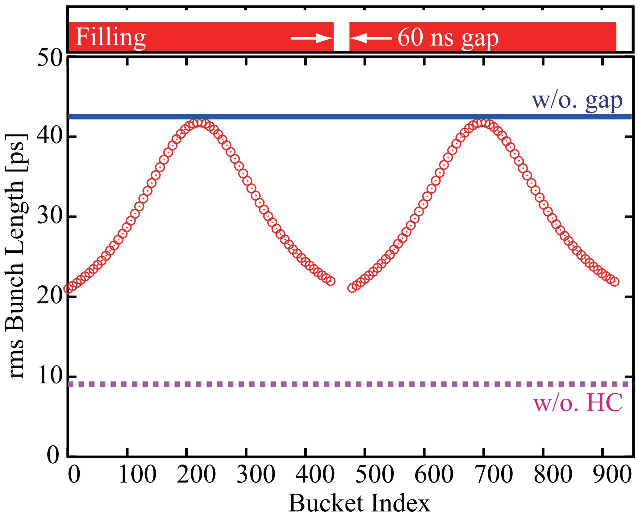

Figure 2: Bunch lengths along the bunch train. Open circle represents bunch length calculated by using TM020 HCs and PF-type MCs. The solid and dashed lines are those of without bunch gap and without HC. The upper inset indicates the filling pattern in one revolution period.

inset shows the assumed filling pattern in one revolution period. The bunch length without bunch gaps and HCs were estimated to be 42.5 and 9.5 ps, respectively.

The average bunch length over the bunch train was approximately 31.1 ps for the NC TM020 cavity. On the other hand, that for the NC TM010 cavity was estimated to be 17.1 ps. It showed a clear advantage of the NC TM020 cavity as compared to the NC TM010 cavity. As a reference, an average bunch length for the SC TM010 cavity was estimated to be 35.0 ps. This is only a slight improvement as compared with the NC TM020 case.

COMPENSATION OF TRANSIENT VOLTAGE

To improve the bunch lengthening further, we investigated to compensate the transient rf voltages in both rf cavities. We investigated two measures: A) compensation of rf voltages by using feedforward technique for both MCs and HCs, and B) compensation by using a separate rf cavity.

The compensation of the rf voltage is possible by changing the generator-induced voltage in such a way to cancel the beam loading. The numerical calculations were carried out for some realistic cases.

We assumed the bunch gap of 60 ns and an 1.1 MHz bandwidth of the generator voltage for both cavities. By applying the feedforward technique, an estimated average bunch length improved from 31.1 ps to 34.9 ps. The bunch length of 34.9 ps was close to that with the SC TM010 HC case.

Concerning the generator power, it strongly depends on the cavity bandwidth and the voltage fluctuation to be canceled. Since the beam loading effect can be suppressed small by using the TM020 cavities, the required generator power becomes realistic in spite of the narrow bandwidth of the cavities. For the MCs, the peak power increased from 131 to 149 kW per cavity. For the HCs, the required generator power increased from zero to ∼3 kW, and instantaneous reflected power increased from 4.6 to 9.8 kW per cavity. These are acceptable for practical beam operation.

If a single separate cavity dedicated to the transient compensation is installed, further improvement in the bunch lengthening is expected since the cavity bandwidth can be freely tuned. We assumed a separate KEK-PF-type 500 MHz cavity with an input coupling factor of 399, where the cavity bandwidth became 5 MHz, and an active compensation bandwidth of 3 MHz. Then, the resulting average bunch length was estimated to be 40.9 ps, which is close to the one under no bunch-gap condition. It is worth noting that the bandwidth of 3 MHz is realistic for an rf source using a solid-state amplifier.

CONCLUSION

An advantage of a NC 1.5 GHz-TM020 cavity for the transient effect was demonstrated by calculating the cavity voltage fluctuation and expected bunch lengthening with some realistic assumptions. By using such cavities for the KEK-LS case with the bunch gap of 60 ns, an expected bunch length is longer by a factor of 3.3 than a natural one.

Since the voltage fluctuation in the NC TM020 cavity was reduced to be small (4.5%), further improvement is expected by using the feedforward compensation techniques. In case of the compensation in both MC and HC, bunch lengthening by a factor of 3.7 (to the natural bunch length) was estimated with realistic generator powers. In the other case of using a single separate cavity for compensation, the bunch lengthening by a factor of 4.3 will be achieved.

ACKNOWLEDGEMENT

This work was supported by JSPS KAKENHI Grant Number JP17K05131.

REFERENCES

[1] K. Harada, M. Adachi, N. Funamori, T. Honda, Y. Kobayashi, N. Nakamura, K. Oide, H. Sakai, S. Sakanaka, and K. Tsuchiya, "The HMBA lattice optimization for the new 3 GeV light source," in *Proc. 7th Int. Particle Accelerator Conf. (IPAC'16)*, Busan, Korea, May 14-19 2016, pp. 3251–3253, paper THPMB012.

[2] T. Honda, "Concept of a new generation synchrotron radiation facility KEK light source," presented at the 8th Int. Particle Accelerator Conf. (IPAC'17), Copenhagen, Denmark, May 14-19 2017, paper WEPAB047, this conference.

[3] S. C. Leemann, "Interplay of Touschek scattering, intrabeam scattering, and rf cavities in ultralow-emittance storage rings," *Phys. Rev. ST Accel. Beams*, vol. 17, p. 050705, May 2014.

[4] A. Hofmann and S. Myers, "Beam dynamics in a double rf system," in *11th International Conference on High-Energy Accelerators*. Springer, 1980, pp. 610–614, CERN-ISR-TH-RF-80-26.

[5] J. M. Byrd, S. De Santis, J. Jacob, and V. Serriere, “Transient beam loading effects in harmonic rf systems for light sources,” *Phys. Rev. ST Accel. Beams*, vol. 5, p. 092001, Sep 2002.

[6] M. Pedrozzi, J.-Y. R. W. Gloor, A. Anghel, M. Svandrlik, G. Penco, P. Craievich, A. Fabris, C. Pasotti, I. E. Chiaveri, R. Losito *et al.*, “SLS operational performance with third harmonic superconducting system,” in *Proc. of 11th SRF workshop*, Lübeck/Travemünder, Germany, 2003, pp. 91–94, paper MOP25.

[7] P. Bosland, P. Brédy, S. Chel, G. Devanz, M. L. C. S. France, P. Craievich, G. Penco, M. Svandrlick, M. Pedrozzi, W. Gloor *et al.*, “Third harmonic superconducting passive cavities in ELETTRA and SLS,” in *Proc. of 11th SRF workshop*, 2003, pp. 239–243, paper TUO06.

[8] G. Penco and M. Svandrlik, “Experimental studies on transient beam loading effects in the presence of a superconducting third harmonic cavity,” *Phys. Rev. ST Accel. Beams*, vol. 9, p. 044401, Apr 2006.

[9] J. Byrd, S. Santis, M. Georgsson, G. Stover, J. Fox, and D. Teytelman, “Commissioning of a higher harmonic RF system for the advanced light source,” *Nucl. Instr. Meth. A*, vol. 455, no. 2, pp. 271–282, 2000.

[10] W. Anders and P. Kuske, “HOM damped NC passive harmonic cavities at BESSY,” in *Proc. of the 2003 Particle Accelerator Conf.*, vol. 2, 2003, pp. 1186–1188, paper TPAB004.

[11] H. Ego, J. Watanabe, S. Kimura, and K. Sato, “Design of a HOM-damped rf cavity for the SPring-8-II storage ring,” in *Proc. 11th Annual Meeting of Particle Accelerator Society of Japan (PASJ2014)*, 2014, pp. 237–241, paper MOOL14.

[12] “SPring-8-II conceptual design report,” Nov. 2014.

[13] T. Takahashi, S. Sakanaka, and N. Yamamoto, “Design study of damped accelerating cavity based on the TM020-mode and hom couplers for the KEK light source project,” presented at the 8th Int. Particle Accelerator Conf. (IPAC’17), Copenhagen, Denmark, May 14-19 2017, paper THPIK036, this conference.

[14] M. Georgsson, W. Anders, D. Krämer, and J. Byrd, “Design and commissioning of third harmonic cavities at BESSY II,” *Nucl. Instr. Meth. A*, vol. 469, no. 3, pp. 373–381, 2001.

[15] M. Izawa, T. Koseki, S. Sakanaka, T. Takahashi, K. Hass, S. Tokumoto, and Y. Kamiya, “Installation of new damped cavities at the photon factory storage ring,” *JSR*, vol. 5, no. 3, pp. 369–371, May 1998.