

Design and low-power measurement of the broadband kicker cavity used to compensate the transient beam-loading effect in synchrotron light sources

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The issue of concern in ultralow-emittance synchrotron light sources is the growth of emittance and the shortening of the Touschek lifetime as a result of intrabeam scattering (IBS). One of the most reliable methods for mitigating these IBS effects is to lengthen the bunches using fundamental and harmonic cavities. In such double rf systems, the effect of bunch lengthening is limited by the fluctuation of the fundamental and harmonic rf voltages. In particular, the voltage fluctuations caused by gaps in the bunch filling pattern critically influence the bunch lengthening. To mitigate such a transient beam-loading (TBL) effect, a compensation method using a broadband cavity has been proposed. In this paper, we present a conceptual design of a broadband “kicker” cavity that can be used to compensate for the TBL effect. We then report the manufacture of a low-power model cavity and the results of our evaluation of its performance to confirm the design of the kicker cavity. The measured external- Q value of the cavity was sufficiently low to achieve the requisite broad bandwidth and was in agreement with simulation results. We also confirmed that the rf absorbers sufficiently damp the harmful higher-order modes.

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I. INTRODUCTION

Ultralow-emittance synchrotron light sources [1,2], which aim to achieve sub-nm-rad horizontal beam emittance, are essential for the advancement of x-ray science [3]. With such ultralow beam emittance, emittance growth and a shortening of the Touschek lifetime are induced by intrabeam scattering (IBS) [4] (i.e., the collisions of electrons within a beam bunch). To mitigate the IBS effects, bunch lengthening using fundamental and harmonic cavities [5] is a key technology, especially in the context of medium-energy synchrotron light sources.

With such a double rf system, the bunch lengthening is sensitive to any changes in either the fundamental or the harmonic rf voltage because the slope of the total rf voltage at the center of the bunches is set to be zero. In particular, the cavity voltages fluctuate substantially when bunch gaps, which are often introduced to avoid ion trapping, pass through the cavities. This fluctuation in the rf voltage, which is due to the transient beam-loading (TBL) effect, can substantially limit the effect of bunch lengthening [6,7]. In addition, the TBL effect can influence the machine's

operating processes, such as the longitudinal injection procedure [8], which requires high stability of the rf voltages.

To mitigate the TBL effect, it is important to reduce the total R/Q factor of the harmonic cavities because the TBL voltage is positively correlated with this factor [7]. To reduce the total R/Q factor, two approaches are typically used: using a superconducting (SC) cavity as the harmonic cavity [9] and using TM020 normal-conducting (NC) harmonic cavities [10]. For example, assuming the machine parameters of the proposed KEK Light Source (KEK-LS) [11,12] with two bunch gaps of 60 ns each, we expected to lengthen the bunches by a factor of approximately three with either the SC or the NC option [13]. However, when longer bunch gaps are introduced into the bunch trains, such double rf systems cannot lengthen the bunches sufficiently. In such cases, the compensation of the residual TBL-induced voltage fluctuations can effectively recover the bunch-lengthening performance.

The simplest method of the TBL compensation is to use the fundamental and harmonic cavities. However, to satisfactorily recover the bunch-lengthening performance, the generator power of these cavities should be increased by several hundred kW. This is because the bandwidth of these cavities is several tens kHz, while the required bandwidth is more than 1 MHz. In addition, most of increased power is reflected at the input coupler of the cavities. Such large reflected power is not acceptable in the rf system. Instead of these cavities, we proposed the TBL compensation

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technique [13] in which a kicker cavity with a bandwidth of several megahertz is used and can provide an rf voltage of several tens of kilovolts.

In a previous study, we reported the optimal parameters and a practical design of the broadband kicker cavity used to compensate for the TBL effect, where we used the machine parameters of the KEK-LS as an example fourth-generation light source [14]. We also briefly reported on the manufacturing of the low-power model cavity and the results of its performance tests to confirm the design of the kicker cavity [15]. In the performance tests, the properties of the accelerating mode, as well as the damping effect of higher-order modes (HOMs) by rf absorbers, were measured. In the present paper, we present the details of the aforementioned studies and fully discuss the optimal design of the kicker cavity and its performance. We then discuss the feasibility of operating the kicker cavity in synchrotron light sources.

II. TBL COMPENSATION TECHNIQUE USING THE BROADBAND CAVITY

A. Parameters of the KEK-LS and its rf system

The KEK-LS parameters used in the present study are shown in Table I. The energy of the stored electron beam is 3 GeV. The nominal beam current is 500 mA. All rf buckets, except for two bunch gaps, are filled with electrons; the ring is filled with two bunch trains having 446 bunches each, and each bunch gap consists of 30 empty buckets.

To mitigate the IBS, a double rf system consisting of fundamental and third-harmonic rf systems is used.

TABLE I. KEK-LS parameters used in the present study [12,13].

Parameter	Symbol	Value
Beam energy	E_0	3 GeV
Momentum compaction factor	α_c	2.19×10^{-4}
Average beam current	I_{av}	0.5 A
Charge per bunch	q_b	1.07 nC
Bunch interval	τ_b	2 ns
Radio frequency (fundamental)	f_{rf}	500.07 MHz
Harmonic number	h	952
Number of bunch gaps		2
Number of buckets in a gap	N_g	30
Revolution frequency	f_{rev}	525 kHz
Synchrotron frequency ^a	f_s	2.65^b (2.75) ^c kHz
Synchrotron radiation loss per turn	U_0	851^b (298) ^c keV
Horizontal betatron tune	ν_x	48.58
Vertical betatron tune	ν_y	17.62
Longitudinal damping time	τ_s	7.0^b (22.6) ^c ms
Horizontal damping time	τ_x	12.0^b (29.3) ^c ms
Vertical damping time	τ_y	13.3^b (38.3) ^c ms

^aWithout harmonic cavities.

^bIncluding insertion devices.

^cWithout insertion devices.

TABLE II. Parameters of the double rf system [13].

Parameter	Symbol	Fundamental	Harmonic
		(ss = f)	(ss = h)
Resonant frequency	$f_{a,ss}$	500 MHz	1.5 GHz
rf voltage	$V_{c,ss}$	2.5 MV	777 kV
Synchronous phase	ϕ_{ss}	1.178 rad	-1.708 rad
Tuning angle	ψ_{ss}	-0.962 rad	1.433 rad
Total R/Q^a	$R_{ss}/Q_{0,ss}$	875 Ω	386 Ω
Total shunt impedance	R_{ss}	35 M Ω	14.48 M Ω
Coupling coefficient	β_{ss}	3.5	0.27

^aShunt impedance is defined as $R = V_c^2/P_c$, where P_c is the dissipated power on the cavity wall.

The principal parameters of the rf system are shown in Table II. In the double rf system, the accelerating voltage is described by

$$V_c(\phi) = V_{c,f} \cos(\phi + \phi_f) + V_{c,h} \cos(3\phi + \phi_h). \quad (1)$$

Here, $V_{c,f}$ and $V_{c,h}$ are the fundamental and harmonic rf voltages, respectively, ϕ is the phase angle of the particle with respect to the fundamental rf wave, and ϕ_f and ϕ_h are the synchronous phases with respect to the fundamental and harmonic rf voltages, respectively. To lengthen the bunches, the first and second derivatives of the rf voltages are set to be zero at the center of the bunches.

When the beam-loading voltages are induced in the fundamental and harmonic cavities, the total rf voltage of the m th bunch is expressed by [13,16]

$$\begin{aligned} \tilde{V}_c(m) &= \tilde{V}_{c,f}(m) + \tilde{V}_{c,h}(m) \\ &= \tilde{V}_{g,f}(m) + \tilde{V}_{b,f}(m) + \tilde{V}_{g,h}(m) + \tilde{V}_{b,h}(m), \end{aligned} \quad (2)$$

with

$$\begin{aligned} \tilde{V}_{b,ss}(m) &= -2k_{ss}q_b \frac{e^{\alpha_{ss}}}{1 - e^{\alpha_{ss}}} \\ &\times \left\{ \frac{1 - e^{N_g \alpha_{ss}}}{1 - e^{(N_g + N_t) \alpha_{ss}}} e^{(N_g + m - 1) \alpha_{ss}} + 1 - e^{(m - 1) \alpha_{ss}} \right\} \end{aligned} \quad (3)$$

and

$$\alpha_{ss} = -\frac{t_b}{\tau_{f,ss}} (1 - i \tan \psi_{ss}). \quad (4)$$

Here, $\tilde{V}_{c,f}(m)$ and $\tilde{V}_{c,h}(m)$ are the fundamental and harmonic cavity voltages, respectively, $\tilde{V}_{g,f}(m)$ and $\tilde{V}_{g,h}(m)$ are the generator-induced voltage of the fundamental and harmonic cavities, respectively, and $\tilde{V}_{b,ss}(m)$ is the beam-induced voltage immediately before the m th bunch. The subscript of each parameter, ss, represents the type of cavity: ss = f, ss = h, and ss = k represent the

fundamental cavity, the harmonic cavity, and the kicker cavity, respectively. Parameters N_t and N_g are the number of bunches in a bunch train and the number of buckets in a gap, respectively. At the KEK-LS, $N_t = 446$ and $N_g = 30$. In this calculation, we assumed that each bunch has the same charge of q_b . We also assumed that all bunches pass through the cavities with the same interval of τ_b , where we ignored the shifts of the bunch positions caused by the voltage fluctuations. Parameter k_{ss} is the loss factor of the cavity, q_b is the bunch charge, ψ_{ss} is the tuning angle, t_b is the bunch interval, and $\tau_{f,ss}$ is the filling time of the cavity. Because the beam-induced voltages change, the total rf voltage changes as a function of the bunch index m ; this fluctuation then changes the first and the second derivatives of the rf voltages at the center of the bunches. As a result, the effect of the bunch lengthening is degraded. Semianalytical calculations have indicated that the average of the rms bunch lengths should be 30.5 ps with bunch gaps of 60 ns each, whereas the bunch length should be 41.8 ps without bunch gaps [13].

We found that we could recover the performance degradation of the bunch lengthening with the bunch gaps by applying an additional rf voltage that compensates for the fluctuation of the total rf voltage [16]. To compensate for the rf voltage, we assumed that a bunch was accelerated in the kicker cavity at the on-crest phase. We then assumed that the kicker cavity compensates for the real part of the TBL voltage; that is, we assumed that its voltage $[\tilde{V}_{c,k}(m)]$ for the m th bunch can be expressed as

$$\text{Re}[\tilde{V}_{c,k}(m)] = -\text{Re}[\tilde{V}_{c,f}(m) + \tilde{V}_{c,h}(m)] + U_0/e. \quad (5)$$

Under the assumption that the tentative parameters of the kicker cavity are as described in Table III, we expected that the compensation voltage, $\tilde{V}_{g,k}(m)$, could be applied to the beam as shown in Fig. 1. When calculating the $\tilde{V}_{g,k}(m)$ shown in Fig. 1, we assumed that the bandwidth of the driving rf wave was limited to less than 3.15 MHz; we then considered the response of the kicker cavity, as described elsewhere [13]. Assuming the compensation voltage in Fig. 1 is applied in the KEK-LS case, the average bunch length over the bunch trains is expected to be 40.9 ps [13],

TABLE III. Tentative parameters of the kicker cavity [13].

Parameter	Symbol	Value
Frequency	$f_{a,k}$	500 MHz
Synchronous phase	ϕ_k	0 rad
Tuning angle	ψ_k	0 rad
Loaded Q	$Q_{L,k}$	100
R/Q	$R_k/Q_{0,k}$	175 Ω
Coupling coefficient	β_k	399
Generator voltage	$\tilde{V}_{g,k}$	53 kV
3 dB bandwidth of the cavity	$2 \times f_{1/2}$	5 MHz

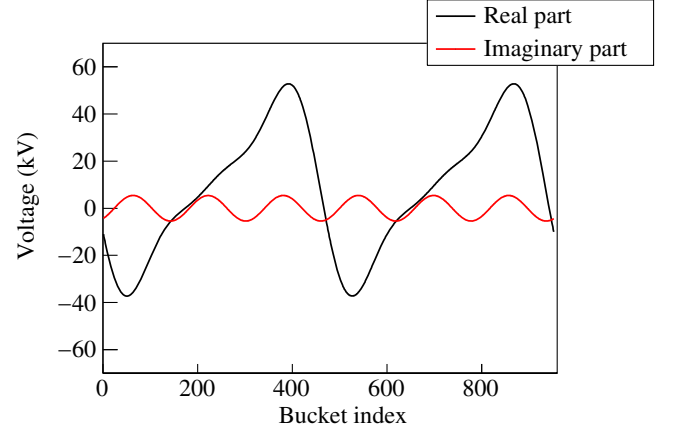


FIG. 1. Generator voltage for the kicker cavity. The horizontal and vertical axes show the bucket index and the generator voltage, respectively. The black and red lines show the real and the imaginary parts, respectively. In this figure, the values of negative and positive peaks at the real part of the generator voltage are asymmetric because of the TBL voltage induced in the kicker cavity. The imaginary part of the generator voltage fluctuates at a frequency close to 3.15 MHz (bandwidth of the driving rf wave) because of the effect of the frequency response of the kicker cavity to an input rf wave.

which is close to the rms bunch length of 42.5 ps obtained under the ideal condition without any bunch gaps. In the present study, we show that the compensation for the real part of the TBL voltage can effectively improve the effect of the bunch lengthening. An alternative method in which both the real and imaginary parts of the TBL voltage are compensated will be discussed in Sec. VI.

III. INVESTIGATION OF THE OPTIMAL PARAMETERS OF THE KICKER CAVITY

We investigated the optimal parameters for a realistic design of the kicker cavity. To provide the required rf voltage assumed in Sec. II, the four parameters shown in Table IV are essential. First, the kicker cavity is required to generate an rf voltage comparable to the TBL voltages induced in the fundamental and harmonic cavities. Second, the resonant frequency of the kicker cavity should be a harmonic of the fundamental rf. Third, the bandwidth of the kicker cavity should be sufficiently broad to compensate for rapid changes in the TBL voltage. Fourth, $\Delta V_{b,k}$, which is the difference between the maximum and minimum of

TABLE IV. Essential parameters of the kicker cavity.

Parameter	Value
Generator voltage	53 kV
Resonant frequency	$0.5 \times n$ GHz
3 dB bandwidth	> 5 MHz
$\Delta V_{b,k}$	≤ 5.5 kV

the TBL voltage induced in the kicker cavity itself, should be sufficiently lower than the kicker-cavity voltage. Keeping these issues in mind, we first investigate the optimal value of $R_k/Q_{0,k}$ to consider the shape of the kicker cavity. We determine the upper limit of $R_k/Q_{0,k}$ from the viewpoint of the voltage induced by the TBL effect. We also determine the lower limit of $R_k/Q_{0,k}$ from the viewpoint of the cavity generator voltage. The optimal parameters are thus determined.

A. Fluctuation of the beam-induced voltage in the kicker cavity

We investigated the fluctuation of the rf voltage in the kicker cavity, which is induced by the TBL effect. The fluctuation occurs when the bunch gap passes the kicker cavity. Using Eqs. (3) and (4), we can write the expression for $\Delta V_{b,k}$ as

$$\begin{aligned} \Delta V_{b,k} &= \text{Re}[\tilde{V}_{b,k}(N_t)] - \text{Re}[\tilde{V}_{b,k}(1)] \\ &= -2k_k q_b \frac{e^{\alpha_k}}{1 - e^{\alpha_k}} \frac{(1 - e^{N_g \alpha_k})(1 - e^{(N_t-1)\alpha_k})}{1 - e^{(N_g+N_t)\alpha_k}}. \end{aligned} \quad (6)$$

Because the loss factor can be written as

$$k_k = \frac{2\pi f_{a,k}}{4} \frac{R_k}{Q_{0,k}}, \quad (7)$$

$\Delta V_{b,k}$ is proportional to the product of the resonant frequency and $R_k/Q_{0,k}$. Figure 2 shows $\Delta V_{b,k}$ as a function of $R_k/Q_{0,k}$. We assume that the fluctuation of the kicker-cavity voltage should be lower than approximately 10% of the maximum kick voltage; that is, $\Delta V_{b,k}$ should be less than 5.5 kV. The upper limit of $f_{a,k} \cdot R_k/Q_{0,k}$ is then found to be 87.5 (GHz Ω) from Fig. 2.

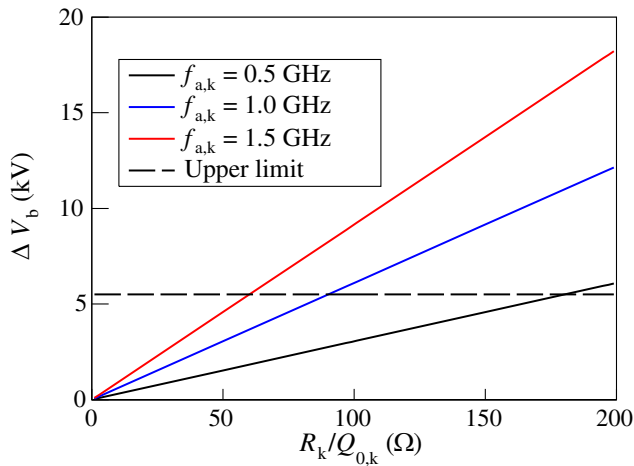


FIG. 2. $\Delta V_{b,k}$ as a function of $R_k/Q_{0,k}$ with the parameters of the KEK-LS. The horizontal and vertical axes show $R_k/Q_{0,k}$ and $\Delta V_{b,k}$, respectively. Black, blue, and red lines show $\Delta V_{b,k}$ for resonant frequency of 0.5, 1, and 1.5 GHz, respectively.

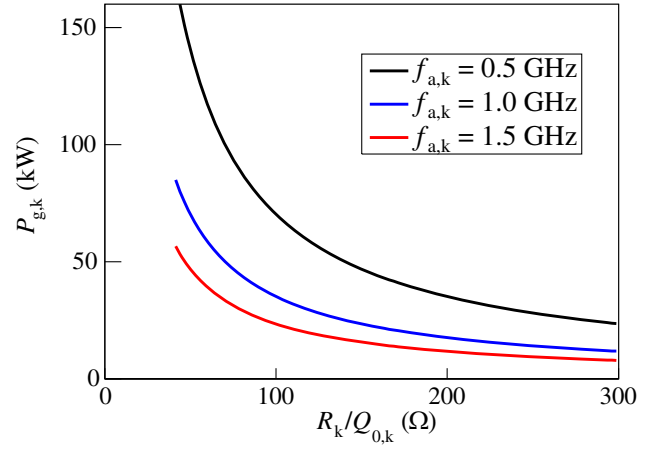


FIG. 3. $P_{g,k}$ as a function of $R_k/Q_{0,k}$ with $|\tilde{V}_{g,k}| = 53$ kV and $2 \cdot f_{1/2} = 5$ MHz. The horizontal and vertical axes show $R_k/Q_{0,k}$ and the generator power, respectively. Black, blue, and red lines represent the $P_{g,k}$ values corresponding to the resonant frequencies of 0.5, 1, and 1.5 GHz, respectively.

B. Generator power for the kicker cavity

Here, we investigate the generator power required for the kicker cavity. To achieve low cost and low power consumption, lower generator power is desirable. The generator power, which is defined as $P_{g,k}$, is described as [17]

$$P_{g,k} = \frac{(1 + \beta_k)^2}{4\beta_k R_k} |\tilde{V}_{g,k}|^2 \sim \frac{f_{1/2}}{2f_{a,k}} \frac{1}{R_k/Q_{0,k}} |\tilde{V}_{g,k}|^2. \quad (8)$$

In this calculation, β_k is approximated as

$$\beta_k \sim 1 + \beta_k = 2Q_{0,k} \frac{f_{1/2}}{f_{a,k}}, \quad (9)$$

because β_k is on the order of 10^2 , as shown in Table III. Figure 3 shows $P_{g,k}$ plotted as a function of $R_k/Q_{0,k}$. Here, we assume that $|\tilde{V}_{g,k}|$ is 53 kV and $2 \cdot f_{1/2}$ is 5 MHz. From Eq. (8) and Fig. 3, the product $f_{a,k} \cdot R_k/Q_{0,k}$ should be as large as possible to reduce $P_{g,k}$. However, $f_{a,k} \cdot R_k/Q_{0,k}$ has an upper limit to limit $\Delta V_{b,k}$. As a result, the optimal value of $R_k/Q_{0,k}$ is uniquely determined, as shown in Table V. In this table, the optimal value of the loaded Q ($Q_{L,k}$) is also uniquely determined because it is defined as

TABLE V. Optimum values of $f_{a,k} \cdot R_k/Q_{0,k}$, $R_k/Q_{0,k}$, and $Q_{L,k}$ for the kicker cavity.

Resonant frequency $f_{a,k}$	$f_{a,k} \cdot R_k/Q_{0,k}$ (GHz Ω)	$R_k/Q_{0,k}$ (Ω)	$Q_{L,k}$
500 MHz	87.5	175	100
1.0 GHz	87.5	87.5	200
1.5 GHz	87.5	58.3	300

$Q_{L,k} = f_{a,k}/(2f_{1/2})$. With these optimal values, $P_{g,k}$ is determined to be 40 kW.

IV. DESIGN OF THE KICKER CAVITY

We consider the single-mode (SM) cavity concept [18] as the cavity shape. The SM cavity has the two following advantages. First, the mechanical design of the absorbers for damping HOMs is straightforward; the SM cavity has a large beam hole so that the HOMs can be damped by rf absorbers on the beam pipes. This design enables us to damp the HOMs effectively without interfering with the waveguides used to input rf power. Second, the SM cavity has a small R/Q factor, indicating that it is suitable for use as the kicker cavity. Therefore, we expect that the SM-type cavity is the most suitable for the kicker cavity used for TBL compensation.

Among the sets of the parameters shown in Table V, we selected the cavity parameters with the third-harmonic rf because the corresponding cavity size is the smallest among the cavity sizes in the three sets of parameters. The cavity size should be as small as possible because the available space for the installation of the kicker cavity is limited in ultralow-emittance synchrotron light sources. In addition, among the cavity shapes in the three sets of parameters, the SM cavity shape is the easiest to realize using the parameters of the third harmonics because it has a small R/Q factor.

We used the CST 3D electromagnetic (EM) simulation software [19] to optimize the design of the kicker cavity to not only satisfy the required cavity parameters but also maintain a coupling impedance lower than the upper limit to avoid coupled-bunch instabilities (CBIs). For the optimization of the cavity shape and investigation of the power and voltage distributions, we used the eigenmode solver. For the optimization of the loaded Q , we used the frequency-domain solver. For the evaluation of the coupling impedance, we used the time-domain solver.

3D and schematic views of the optimized cavity are shown in Figs. 4 and 5, respectively. The TM010 mode provides the rf voltage needed to compensate for the TBL

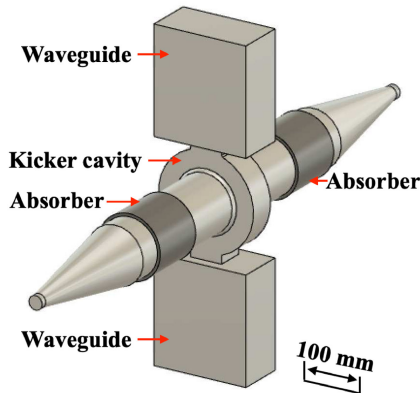


FIG. 4. 3D view of the kicker cavity.

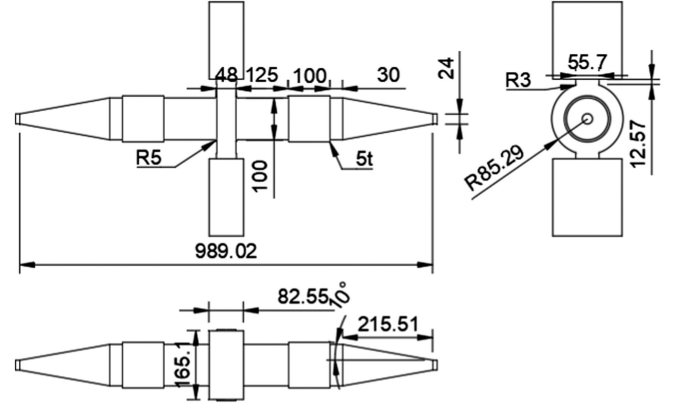


FIG. 5. Drawing showing the inner dimensions of the kicker cavity. All units of the dimensions are in millimeters.

voltage. The kicker cavity consists of a normal-conducting cavity equipped with two input waveguides, two silicon-carbide (SiC) absorbers, and tapered beam pipes. The rf power is fed into the cavity from the two waveguides through large coupling holes; this design is effective for achieving a small loaded Q of the accelerating mode. We investigated the position, length, and material of the absorbers from the viewpoint of the availability and damping performance of the CBIs. We then used a silicon carbide, CERASIC-B [20], as the absorbing material [15]. The typical complex permittivity of the CERASIC-B is $21.5-18i$ at a frequency of 2 GHz.

Figure 6 shows the coupling impedances calculated using the CST software. The upper and lower subfigures show the longitudinal and transverse coupling impedances, respectively. The black lines show the coupling impedance, whereas the green lines indicate the upper limits required to avoid the CBIs using the parameters of the KEK-LS. When the longitudinal coupling impedance is defined as $Z_{\parallel}(f_a)$ and the transverse coupling impedance is defined as $Z_{\perp}(f_a)$, each upper limit is given by

$$\text{Re}[Z_{\parallel}(f_a)]_{\text{th}} = \frac{2f_s E_0}{e\alpha_c I_{\text{av}} f_{\text{rev}} \tau_s f_a}, \quad (10)$$

$$\text{Re}[Z_{\perp}(f_a)]_{\text{th}} = \frac{4\pi\nu_y E_0}{ecI_{\text{av}}\tau_y}, \quad (11)$$

respectively [21]. Here, f_a represents the resonant frequency of each resonated mode and the other parameters are as defined in Table I. We found that the SiC absorbers reduced the coupling impedances sufficiently, with values one order of magnitude smaller than the CBI threshold. Therefore, the kicker cavity can be used even if the synchrotron frequency and the threshold of the CBI are changed by the TBL effect. Since the TBL-induced voltage in the fundamental and harmonic cavities is less than 2% of their cavity voltages, the synchrotron frequency variation is

expected to be less than 0.5% when a small amplitude of the synchrotron oscillation is assumed.

We also investigate the power loss in the cavity caused by the HOMs using the CST software. We calculate the power losses when the HOMs frequencies overlap the beam spectrum and the resonant buildup [17] occurs. Even in such a worst case, the maximum value of the power loss is estimated to be 1.1 kW, which is induced by the HOM around 2 GHz in lower subfigures of Fig. 6. We conclude that the power losses induced by the HOMs are acceptable.

The parameters related to the performance of the kicker cavity, which was evaluated via EM simulations, are shown in Table VI. Among these parameters, the expected value of the loaded Q , which determines the performance of the TBL compensation, is approximately the same as the target value shown in Table V. Our kicker cavity design is expected to be effective for TBL compensation.

As shown in Table VI, the power loss in the cavity is relatively low (approximately 2.6 kW) and most of the power will be reflected back from the cavity. Consequently, the power consumption is concentrated at the aperture between the cavity and the waveguide. The maximum power density and the power consumption within the aperture are expected to be 21.7 W/cm² and 81.8 W, respectively, at the peak generator power of 49.5 kW. This level of power density will be managed by applying a suitable cooling technique similar to that developed for the PEP-II damped cavity [22], where the maximum power density was 120 W/cm² around the slots for HOM damping. However, an rf window used to feed the high rf power is a remaining issue to be investigated.

Finally, we investigate the multipacting of the kicker cavity. The narrowest gap in the cavity is 48 mm, and the

TABLE VI. Parameters of the kicker cavity [15], as estimated using EM simulations.

Parameter	Value
Resonant frequency	1.50006 GHz
R/Q	60.38 Ω
Q_0	17937
Q_L	292.41
Synchronous phase	0 degree
Generator voltage	53 kV
Cavity voltage	44.2 kV
Generator power	49.5 kW
Power loss in cavity	2.59 kW
Reflecting power	15.7 kW
Maximum power density	21.7 W/cm ²
Power loss in absorbers	101.9 W

maximum voltage induced within the gap is 174.7 kV at the peak generator power of 49.5 kW. The product of the resonant frequency and the minimum gap is 7200 MHz cm. In this case, an rf voltage between the minimum gap may fall within a multipacting zone of 9/2 cycle [23] when the kicker-cavity voltage is increased from 0 to 44.2 kV. Because multipacting will be weak in this zone, the multipacting will be sufficiently mitigated by the cavity conditioning.

V. MANUFACTURING AND TESTS OF A LOW-POWER MODEL

To demonstrate the design of our kicker cavity, we fabricated a model cavity made of aluminum alloy and subsequently measured the properties of the accelerating mode as well as the HOM damping performance using rf absorbers. Figure 7 shows a photo of the model cavity. The cavity is composed of two blocks assembled into a single block via four bolts. At the large beam duct part of the cavity, two small ports are provided to enable the fields of HOMs to be probed using loop antennas. The rf signal is fed through the two WR-650 waveguides. Two cylindrically shaped rf absorbers made of the commercial SiC product CERASIC-B are installed inside large beam ducts

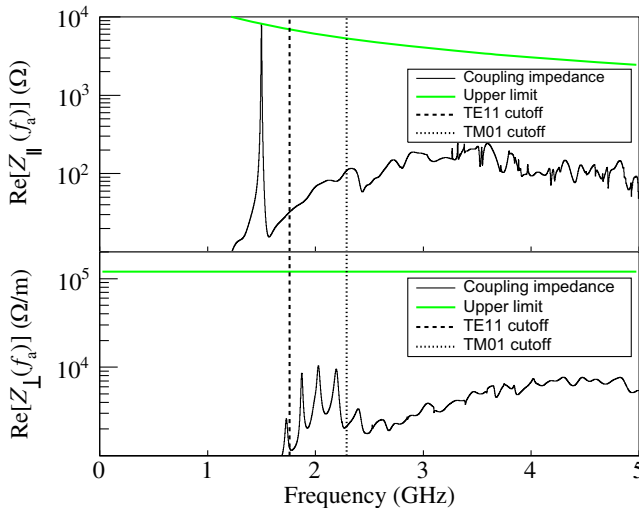


FIG. 6. Real part of the coupling impedance plotted as a function of the frequency. The solid dashed line shows the cutoff frequency of TE11 mode for a 100 mm diameter beam pipe. The dashed line shows the cutoff frequency of the TM01 mode for a 100 mm diameter beam pipe.

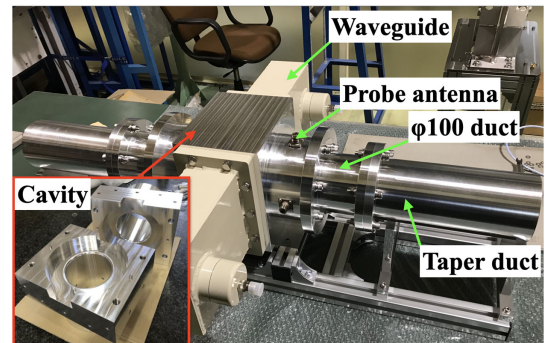


FIG. 7. Photo of the low-power model [15].

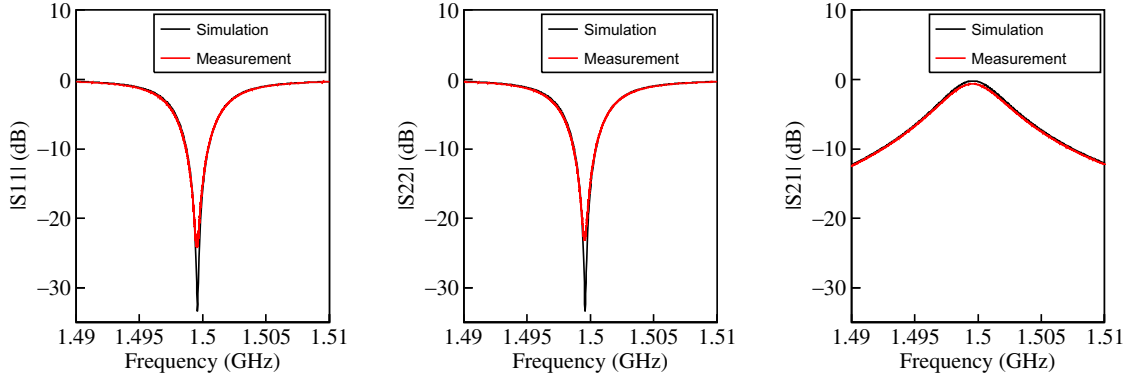


FIG. 8. Comparison between measurements and simulations of the S-parameters associated with the TM010 mode.

with an inner diameter of 110 mm, beside the cavity body. The thickness, inner diameter, and length of the absorbers are 5, 100, and 100 mm, respectively. To conduct comparative testing, we also prepared beam ducts (inner diameter: 100 mm) without rf absorbers. After the manufacturing process, we measured the dimensions of all of the components and found that the manufacturing errors were within $\pm 5 \mu\text{m}$.

A. Measurement of the TM010 mode properties

We measured the properties of accelerating (TM010) mode by connecting the network analyzer to waveguides through waveguide-coaxial transformers. Figure 8 shows the S-parameters of the TM010 mode. The black and red lines show the S-parameters estimated by the CST simulation and those measured using a network analyzer, respectively. The left, center, and right figures show the S11, S22, and S21 parameters, respectively. The measured and calculated properties of the TM010 mode are compared in Table VII. Except for the unloaded Q , all parameters from the measurement agree with the simulation results. The discrepancy in the unloaded Q is attributable to nonideal electrical contact between the cavity parts. This poor contact will not be an issue in future high-power models because the cavity parts will be well connected by brazing. The measured external Q agrees with the calculated value. The bandwidth deduced from the measured external Q was 5.32 MHz, which is sufficiently wide for

our application. These measurements show that the accelerating mode of the kicker cavity demonstrates adequate performance.

B. Measurement of HOM properties

To check the performance of HOM damping using real rf absorbers, we measured the properties of HOMs with and without the rf absorbers. For this purpose, two loop antennas were inserted into the probe ports, as shown in Fig. 7, and the S-parameters were measured using these probes. In this measurement, the side and top port of the probe antennas in Fig. 7 were defined as port 1 and port 2, respectively. In particular, HOMs with resonant frequencies of 1.916, 2.066, and 2.247 GHz were important because they were expected to have large transverse coupling impedance according to Fig. 6.

Figure 9 shows the measured S21 curve, together with that obtained from the CST simulation, relevant to the three

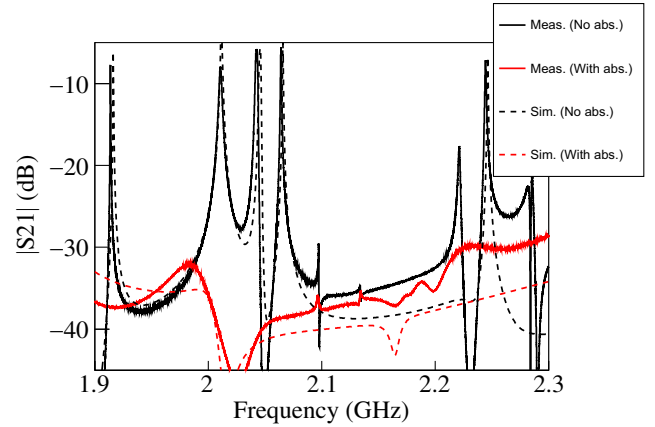


FIG. 9. Comparison of the S21 values between the measurement and the simulation. The HOMs with the resonant frequencies of 2.012 and 2.046 GHz, which were not observed in the EM simulation results shown in Fig. 6, were observed. On the basis of the detailed EM simulation that includes the probe ports, these peaks are expected to be strongly coupled with the probes and to not affect the coupled-bunch instabilities.

TABLE VII. Comparison between measurements and simulations of the parameters of the TM010 mode.

Parameter	Measurement	Simulation
Resonant frequency	1.49955 GHz	1.4996 GHz
3 dB bandwidth	5.32 MHz	5.15 MHz
Loaded Q	282	291
Coupling coefficient	14.2	45.6
Unloaded Q	4273	13555
External Q	302	297

aforementioned HOMs. The black solid and dashed lines represent the measured and calculated S21 values, respectively, in the absence of absorbers. The red solid and dashed lines represent the measured and calculated S21 values, respectively, in the presence of the absorbers. The three HOMs were heavily damped when the absorbers were present; the peaks due to these HOMs could not be observed with the loop antennas. Although we could not measure the loaded Q values of these HOMs, reasonable agreement between the measurement and simulation indicated that the three HOMs were effectively damped by the absorbers, as expected from the simulation.

VI. DISCUSSION

In this section, we first discuss the TBL compensation performance when the designed kicker cavity is used and longer bunch gaps are introduced. The effect of detuning the kicker cavity is also examined. Second, we discuss the bunch-lengthening performance when an additional compensation of the imaginary part of rf voltage is introduced. Finally, we briefly introduce the schematic of the TBL compensation in the LLRF system.

A. Cases of longer bunch gaps

In Sec. II, we showed that our kicker cavity can compensate the TBL voltages well when two bunch gaps of 60 ns each are introduced in the KEK-LS. In this case, the required rf voltage for the kicker cavity was 53 kV. In this subsection, we discuss other cases, where longer bunch gaps are introduced. We assume that the bunches are lengthened using a double rf system in conjunction with the TBL compensation technique using our designed kicker cavity. Here, we do not limit the required power for the kicker cavity. For each bunch-gap length assumed, we evaluate the bunch-lengthening factor of each bunch by applying a semianalytical calculation [13]. Here, we define the bunch-lengthening factor (BLF) as the ratio of the rms bunch length of each bunch to the natural bunch length without third-harmonic cavities.

Figure 10 shows the estimated BLF with and without the TBL compensation, plotted as a function of the bunch gap. The black and green points show the average BLF over all bunches with and without the TBL compensation, respectively. When the bunch gaps are introduced, the BLF varies from bunch to bunch. We next marked the maximum and the minimum BLF values among the stored bunches as error (top and bottom) bars in Fig. 10. In Fig. 10, the minimum BLF exceeds 2.4 under all of the investigated configurations of bunch gaps when TBL compensation is applied. As the bunch gaps increase, the difference of the average BLF between with and without the TBL compensation becomes larger and the TBL compensation becomes more effective.

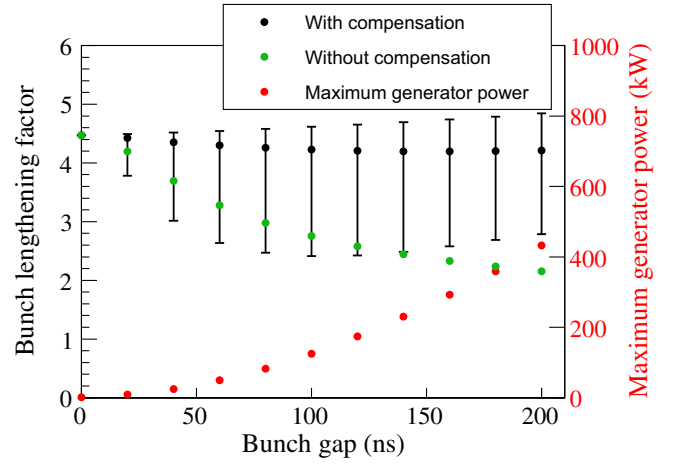


FIG. 10. Bunch-lengthening factor and maximum generator power as functions of the bunch gaps. These estimations were performed using the semianalytical calculation method described in [13].

Figure 10 also shows the power required for the kicker cavity, plotted as red circles. The power is defined as the total generator power supplied to two waveguides when the kicker voltage reaches its maximum value among all bunches. When the bunch gaps exceed 150 ns, the generator power per waveguide exceeds 100 kW. With such high-input power, achieving sufficient cooling of the cavity body and sufficient power-handling capability of the input rf windows can be challenging.

To apply our TBL compensation technique in cases of long (150 ns or longer) bunch gaps, two solutions are available. One solution is to mitigate the TBL voltage induced at the harmonic cavity. For this purpose, the SC cavity can be used as a harmonic cavity for the following reasons. The R/Q factor of the SC cavity is smaller than that of the NC cavity. In addition, the total number of cavities used for the bunch lengthening is reduced because the voltage of a single SC cavity is greater than that of a single NC cavity. From the discussion in Sec. III A, a smaller R/Q factor leads to a smaller TBL voltage. The other solution is to use the first harmonic frequency (500 MHz) for the kicker cavity. As discussed in Sec. III, the value of $f_{a,k} \cdot R_k / Q_{0,k}$ is set to be constant. In this configuration, the rf coupling aperture is more than 10 times larger because of the decrease in both the resonant frequency and the loaded Q . In addition, the required power for the kicker cavity does not depend on the resonant frequency of the cavity. As a result, heat concentration is expected to be substantially mitigated. If large space for installation is acceptable, the lower (fundamental) frequency for the kicker cavity can be a possible solution for longer bunch gaps. Furthermore, the performance of the bunch lengthening could be improved by changing the fill pattern of the bunches [7]. The combination of our

compensation method and the bunch charge modulation is worth considering.

Finally, we mention other concerns in cases of long bunch gaps. In general, the synchrotron frequency of the double rf system is proportional to the amplitude of the synchrotron oscillation [24]. In addition, the synchrotron frequency of each bunch is shifted by the TBL effect when the bunch gaps are introduced. As longer bunch gaps are introduced, the bunch-by-bunch variation of the synchrotron frequency is expected to be increased. It leads to the bunch-by-bunch variation of the longitudinal feedback performance and the design of the feedback system will be complicated. We consider that the TBL compensation using the kicker cavity is also useful to mitigate bunch-by-bunch variation of the longitudinal feedback performance.

B. Effect of tuning errors

As shown in Figs. 4 and 5, the kicker cavity is not equipped with a tuning plunger because its 3-dB bandwidth is almost 5 MHz and very wide. In this section, the influence of cavity detuning is investigated to determine whether the kicker cavity should be tuned. Cavity detuning is mainly caused by manufacturing errors or thermal deformation of the cavity. First, the amount of cavity detuning caused by each effect is estimated. Second, the change of the compensation performance caused by the detuning is evaluated. Third, the changes of the CBIs caused by the detuning are estimated.

We used an EM simulation to estimate the amount of detuning caused by manufacturing errors. In the EM simulation, the radius of the cavity is changed by manufacturing errors and the resonant frequency of the accelerating mode is compared with that without the manufacturing error. The manufacturing errors of the cavity are expected to be less than $\pm 10 \mu\text{m}$, which corresponds to changes of $\pm 170 \text{ kHz}$ in the resonant frequency.

The amount of detuning caused by thermal deformation is roughly estimated from our experience with water cooling of the other cavity [25]. The temperature of the cavity surface is expected to increase by less than 10°C when the power loss of the cavity surface is 2.59 kW. This increase of the surface temperature corresponds to a resonant frequency change of -250 kHz . Considering both the manufacturing error and the thermal deformation, the amount of the detuning is estimated to range from $+170$ to -420 kHz .

On the basis of the EM simulation, when the cavity is detuned by $+170$ and -420 kHz , the dissipated power in the cavity is expected to be reduced by -0.02 and -0.11 dB , respectively. The required power for the TBL compensation will then increase by 0.47% and 2.5% , respectively. The phase of the kicker voltage is also shifted by 3.93° and 9.10° , respectively. Because the kicker cavity will be set to be the on-crest phase and the phase of the

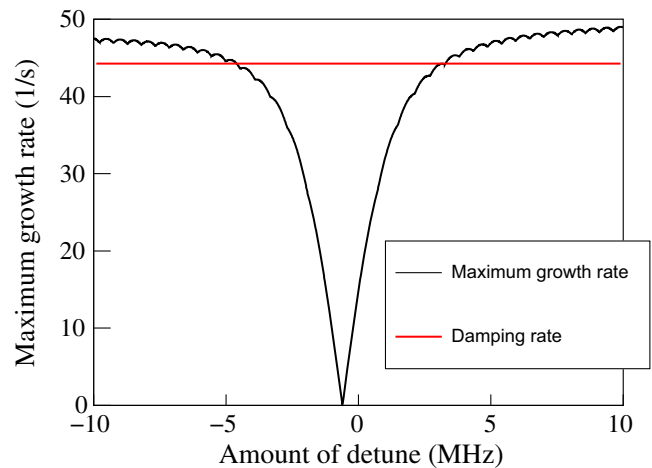


FIG. 11. Maximum growth rate as a function of the detuned frequency.

kicker need not be changed by the increase in the beam power, these changes in the kicker voltage are acceptable. Notably, the shift of the kicker voltage phase can be easily corrected by a low-level rf system.

The effect of detuning of accelerating mode on the coupled-bunch instability induced by the accelerating mode was calculated via an analytical calculation [21]. The maximum value of the growth rate among all coupled-bunch modes is shown in Fig. 11. Here, the horizontal and vertical axes show the shift of the resonant frequency and the maximum growth rate at each frequency, respectively. The black and red lines show the maximum growth rate and the longitudinal damping rate, respectively, for the KEK-LS case. As shown in Fig. 11, even if the kicker cavity is detuned by $+170$ or -420 kHz , the growth rates are sufficiently lower than the damping rate. From the perspective of the CBIs, the kicker cavity can be left to be tuned even if it is not used.

When the kicker cavity is not used, the power reflected from it should be considered. From the EM simulation, the loss factor of the kicker cavity is estimated to be $7.53 \times 10^{11} \text{ V/C}$. The power loss of the beam is then expected to be 377 W at the maximum beam current of 500 mA in the KEK-LS case. The power loss in the cavity is negligibly small, and almost all of the power will exit the cavity. This reflected power is acceptable, and the kicker cavity can be left in the storage ring when it is not being used.

C. Additional compensation for an imaginary part of the rf voltage

In Sec. II, we assumed that the kicker-cavity voltage compensates the fluctuation of only the real part of the rf voltage, as indicated in Eq. (5). In this subsection, we investigate whether we can improve the performance of the bunch lengthening by an additional compensation of the

TABLE VIII. Comparison of bunch-lengthening performance for two cases: (1) compensation with the real part of the rf voltage and (2) compensation with the real and imaginary parts of the rf voltage. The parameters of KEK-LS with two bunch gaps of 60 ns each were assumed.

Parameter	Case (1)	Case (2)
Generator power	49.5 kW	51.3 kW
Maximum BLF	4.55	4.52
Average BLF	4.30	4.30
Minimum BLF	2.64	2.64

imaginary part of the rf voltage. To this end, we assume that the kicker cavity produces an additional rf voltage given by

$$\text{Im}[\tilde{V}_{c,k}(m)] = -\text{Im}[\tilde{V}_{c,f}(m) + 3 \times \tilde{V}_{c,h}(m)], \quad (12)$$

which indicates that $V'(0) = 0$ at the center of the m th bunch. Using an analytical calculation described elsewhere [13], we estimated the bunch-lengthening performance (Table VIII). Although the required generator power for the kicker cavity increases by a factor of 1.04 with the aforementioned rf voltage compensation, the BLF remains almost the same as under the original compensation scheme, where only the real part of the rf voltage was compensated.

For reference, Fig. 12 shows the imaginary part of the kicker cavity voltage. The black and red lines show the imaginary part of the kicker voltage for the cases of compensation for the (1) real part and (2) the real and imaginary parts of the rf voltage. In Fig. 12, the dashed

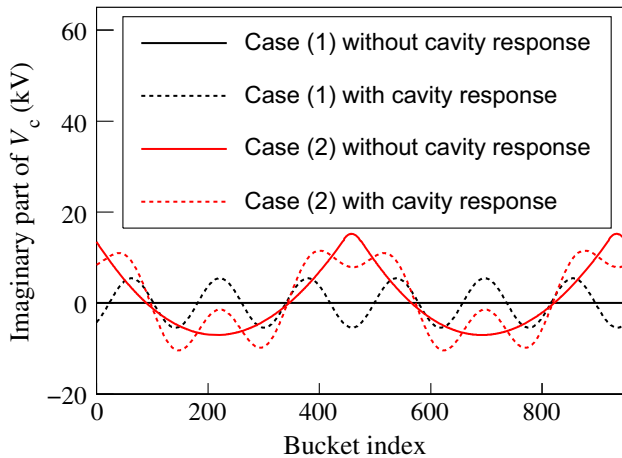


FIG. 12. Imaginary part of the kicker cavity voltage for two cases. In case (1), without the cavity response, the imaginary part of V_c is equal to zero.

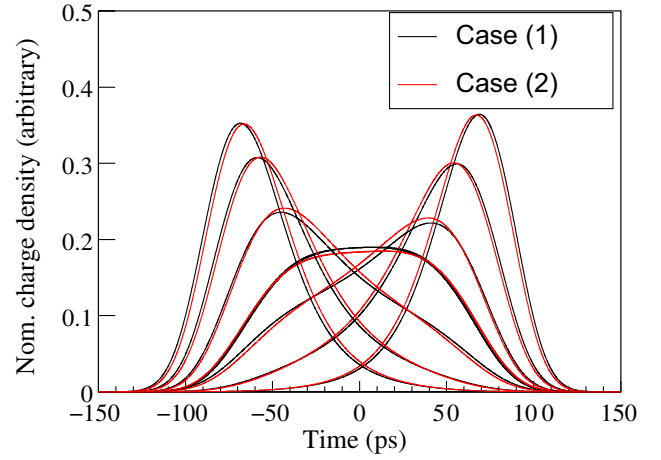


FIG. 13. Bunch shapes with compensation for cases (1) and (2). From left to right, the 1st, 11th, 21st, 213th, 223rd, 233rd, 426th, 436th, and 446th bunches are illustrated.

lines represent results corresponding to the solid lines after modification by the cavity response. The difference in the imaginary part between cases (1) and (2) then becomes small. Figure 13 shows the bunch shapes with the compensation for cases (1) and (2). In Fig. 13, the performance improvement of the bunch lengthening with case (2) was limited. The present study shows that the additional requirement given by Eq. (12) does not substantially improve the bunch-lengthening performance, at least in the case of the assumed parameters of the KEK-LS. To improve the compensation performance, the speed of the cavity response should be increased.

D. Schematic of the TBL compensation in the LLRF system

Figure 14 shows our proposed schematic of the TBL compensation in the low-level rf (LLRF) system. In this system, the generator voltage of the kicker cavity is modulated by a feedforward pattern. The bunch phase from the signal of button type pickup is monitored by the LLRF system synchronized with the revolution frequency. We plan to apply the newly developed digital LLRF system for the KEK PF 2.5 GeV ring [26]. The bunch phase is calculated by a special firmware of the digital LLRF system [27]. It enables us to measure the average bunch phase within several ms with a small error. The generator voltage can be modulated according to an arbitrary modulation pattern and added to the rf output of the digital LLRF system [28]. We have performed the experimental demonstration of the TBL compensation at the KEK-PF 2.5 GeV ring [28]. The details of the experimental demonstration will be published in other papers. The details of the LLRF system for the kicker cavity are under consideration.

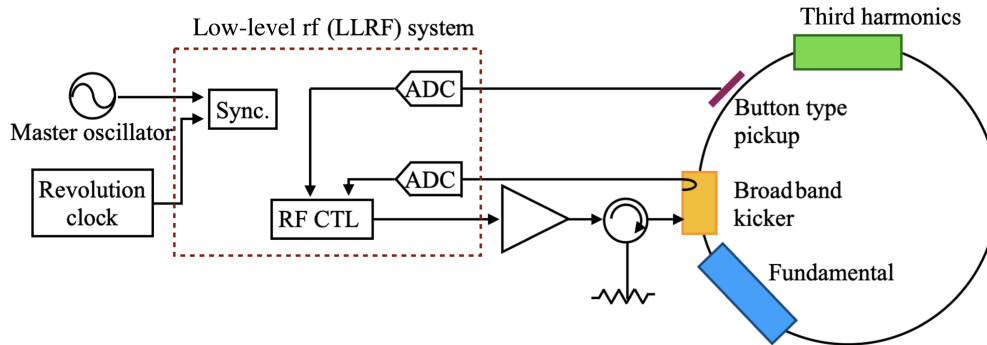


FIG. 14. Schematic of the TBL compensation in the LLRF system.

VII. CONCLUSION

We investigated the optimum parameters of the kicker cavity used to compensate the TBL effect in a double rf system. We showed that the product $f \cdot R/Q$ should be small to reduce the TBL voltage in the kicker cavity itself, whereas a high R/Q is desirable for minimizing the required drive power for the cavity. An optimum value of $f \cdot R/Q$ has been determined. Considering the required cavity bandwidth and the space needed for the cavity installation, we chose the third-harmonic frequency as a resonant frequency of the kicker cavity and then determined the optimal values of R/Q and loaded Q .

To realize a kicker cavity having these optimum parameters, we designed a cavity based on the single-mode cavity concept. To obtain low external Q , the rf power is fed with two waveguides connected to the cavity through large coupling holes. The power associated with harmful HOMs escapes through large beam holes and is consumed by the rf absorbers. According to EM simulations, the designed cavity has an R/Q factor of 60.4Ω and a loaded Q of 292 at a resonant frequency of 1.500 GHz, which meets the requirements. To produce the required rf voltage of 53 kV, a power of 49.5 kW is input to the cavity, whereas the power dissipated in the cavity is 2.6 kW. The EM simulation also showed that the longitudinal and transverse coupling impedances due to the HOMs can be sufficiently reduced using an SiC for rf absorbers.

To confirm the performance of the kicker cavity, we manufactured a low-power model of the cavity and evaluated the properties of the TM₀₁₀ mode and HOMs. The measured properties of the TM₀₁₀ mode agreed with the simulated properties. The bandwidth of the kicker cavity was determined to be 5.32 MHz, which satisfies the requirement. We also investigated three resonant peaks predicted to have high transverse coupling impedance without rf absorbers. We observed that the three peaks in the S₂₁ curves almost disappeared when SiC absorbers were installed, indicating that these HOMs were sufficiently damped by the SiC absorbers. From the aforementioned results, we confirmed the designed performance of

the kicker cavity. Through these works, we have established a basic EM design for the kicker cavity.

According to the discussion in Sec. VI, this kicker cavity could be used under a bunch gap as long as 150 ns if the cavity can withstand a high-input power of approximately 200 kW. To reduce the maximum power density on the cavity wall in such an extreme case, we showed that choosing a fundamental (500 MHz) resonant frequency is advantageous.

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DATA AVAILABILITY

The data that support the findings of this article are not publicly available upon publication because it is not technically feasible and/or the cost of preparing, depositing, and hosting the data would be prohibitive within the terms of this research project. The data are available from the authors upon reasonable request.

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