ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB331

DESIGN CONSIDERATION OF A LONGITUDINAL KICKER CAVITY FOR COMPENSATING TRANSIENT BEAM LOADING EFFECT IN SYNCHROTRON LIGHT SOURCES*

D. Naito†, N. Yamamoto, S. Sakanaka, T. Takahashi, T. Yamaguchi[1]
High Energy Accelerator Research Organization Accelerator Laboratory (KEK), Tsukuba, Japan
[1]also at Department of Accelerator Science, The Graduate University for Advanced Studies (SOKENDAI), Tsukuba, Japan

Abstract

In ultra-low-emittance synchrotron light sources, bunch-lengthening using the combination of main and harmonic cavities is limited by the transient beam-loading (TBL) effect. To manage this effect, we proposed a TBL compensation technique using a wide-band longitudinal kicker cavity. In this paper, we reported our conceptual design of the kicker cavity. We considered the cavity design by assuming the beam parameters of the KEK-LS. We employed the single-mode (SM) cavity concept so that harmful HOMs were damped by rf absorbers on beam pipes. Using this kicker cavity with a double rf system, bunch lengthening by a factor of 4.3 (i.e., 40.9 ps) was expected for the KEK-LS case.

INTRODUCTION

Ultra-low-emittance synchrotron light sources aim at achieving the horizontal beam emittance of less than sub nm-rad. This ultra-low-emittance causes the intra-beam scattering (IBS) which increases the emittance and shortens the Touschek lifetime. To mitigate the IBS, bunch-lengthening using the combination of main and harmonic cavities [1] is an effective solution.

In such a double rf system, the bunch-lengthening performances were limited due to the transient beam-loading (TBL) effect when the large bunch gaps were introduced [2]. To manage this effect, we proposed a TBL compensation technique using a wide-band longitudinal kicker cavity [3]. In this paper, we discuss critical issues concerning the kicker cavity design, and propose a 1.5 GHz, single-mode-type cavity as a promising solution.

TBL COMPENSATION TECHNIQUE USING A KICKER CAVITY

In the previous study and this study, we set our goal to compensate the TBL effect in a planned KEK Light Source (KEK-LS). Parameters assumed in the studies were shown in Tables 1 and 2. Without the compensation, the bunch lengthening using the double RF system was limited by the TBL voltages induced in the main and harmonic cavities. The bunch length was estimated to be 30.5 ps while that without the TBL effect was estimated to be 42.5 ps [3]. To compensate the TBL voltage, we proposed a TBL compensation technique using a wide-band longitudinal kicker cavity [3,4]. In this study, we assumed the kicker cavity having a 3-dB bandwidth of 5 MHz as a time response. The 3-dB bandwidth (Δf) was defined as $\Delta f = f_a/Q_L$. Here, f_a was the resonance frequency and Q_L was the loaded Q of the kicker cavity. The parameters of the kicker cavity assumed in the previous work were shown in Table 3. Assuming these values, the bunch length with the compensation scheme was estimated to be 40.9 ps.

Table 1: Beam Parameters of the KEK-LS without Losses of Insertion Devices [5]

Parameters	Value
Beam energy	3 GeV
Momentum compaction factor	2.2×10^{-4}
Average beam current	0.5 A
RF frequency (fundamental)	500.07 MHz
Harmonic number	952
Number of bunch gaps	2
Number of buckets in a gap	30
Revolution frequency	525 kHz
Synchrotron frequency	2.65 kHz
Longitudinal radiation damping time	22.63 ms
Horizontal radiation damping time	29.25 ms
Vertical radiation damping time	38.28 ms
Natural bunch length	9.5 ps

Table 2: Parameters of the Double RF System [3]

Parameter	Main RF	Harmonic RF
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	875 Ω	386 Ω
Cavity coupling coefficient	3.5	0.27

DESIGN CONSIDERATION OF THE KICKER CAVITY

We investigated a realistic cavity design which could provide the same compensation performance as the previous

* Work supported by JSPS KAKENHI Grant Number 21K17997 and 20H04459.
† daichi.naito@kek.jp

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB331

Table 3: Parameters of the Kicker Cavity Assumed in the Previous Work [3]

Parameter	Value
Resonance frequency	500 MHz
Cavity voltage	45 kV
−3 dB bandwidth	5 MHz
Loaded Q	100
R/Q	175 Ω
Coupling coefficient	399

study. In addition, we had two concerns : cost of the cavity and the higher-order-modes (HOMs) in the kicker cavity. The cost should be as low as possible and the HOMs should be damped sufficiently in order to avoid coupled-bunch instabilities (CBIs).

The considered parameters were listed in Table 4. The kicker cavity should generate the RF voltage which was comparable to the TBL voltages induced in the main and harmonic cavities. The resonance frequency of the kicker cavity should be harmonics of the fundamental radio frequency. We investigated suitable radio frequency among the 1st to 3rd harmonics of the fundamental frequency. The bandwidth of the kicker cavity should be wide enough to compensate a fast variation of the TBL voltage. ΔV_b, which was the subtraction between the maximum and minimum TBL voltage induced in the kicker cavity, should be enough lower than the generator voltage. The above four parameters were essential to achieve the same compensation performance as the previous study.

The cavity input power should be as low as possible for the cost reduction. The low R/Q was essential to employ the single-mode (SM) cavity concept [6]. The SM cavity has a large beam hole so that the HOMs are damped by rf absorbers on beam pipes. Since the SM cavity had no HOM dampers in its outer periphery, this concept enabled us to realize a very compact cavity. In this section, we examined an optimum resonance frequency and R/Q to satisfy the requirement of ΔV_b and input power.

Table 4: The List of Parameters Should be Considered in the Design

Parameter	Value
Generator voltage	50 kV
Resonance frequency	0.5 × n GHz
3 dB bandwidth	5 MHz
ΔV_b	≤5.5 kV
Cavity input power	Minimize
R/Q	≤ 80 Ω

Examine of the ΔV_b

When the TBL voltage was semi-analytically calculated [3], the ΔV_b was approximated to be

$$\Delta V_b \sim \frac{\{1-\exp(-N_g\alpha)\}\{V_0(N_b) - \frac{V_{b0}}{2}\exp(-N_g\alpha)\}}{1-\exp\{-(N_g+N_b)\alpha\}}, \quad (1)$$

where

$$\alpha = \pi \Delta f T_b (1 - j\tan\psi), \quad (2)$$

$$V_{b0} = \pi f_a \frac{R}{Q} q \quad (3)$$

and

$$V_0(N_b) = -\frac{V_{b0}}{2} + V_{b0}\sum_{m=0}^{N_b}\exp(-m\alpha). \quad (4)$$

Here, N_g was a number of buckets in a single gap and N_b was a number of buckets in a single bunch train. T_b was a bunch interval, q was a charge of a single bunch. ψ was a tuning angle of the kicker cavity and set to be 0 in this study. From Eqs. (1)-(4), ΔV_b was proportional to $f_a R/Q$. Figure 1 showed the correlation between ΔV_b and R/Q. To make ΔV_b less than the upper limit shown in Fig. 1, $f_a R/Q$ should be smaller than 87.5 GHz·Ω.

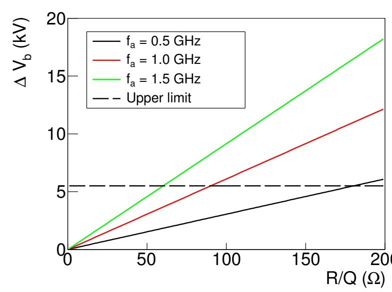

Figure 1: The correlation between ΔV_b and R/Q with 50 kV of V_g and 5 MHz of Δf.

Examine of the Input Power

The input power of the cavity was described as

$$P_g = \frac{(1+\beta^2)}{4\beta R}V_g^2 \sim \frac{\Delta f}{4 f_a}\frac{1}{R/Q}V_g^2 \quad (5)$$

[7] since RF coupling of the kicker cavity, which was defined as β, was large as shown in Table 3. Here, V_g represented the generator voltage of the kicker cavity. From Eq. (5), P_g was inversely proportional to $f_a R/Q$ while ΔV_b was proportional to $f_a R/Q$. Figure 2 showed the correlation between P_g and R/Q. R/Q should be as small as possible to reduce the cost. Hence, $f_a R/Q$ should be equal to 87.5 GHz·Ω.

The best values of R/Q for each resonance frequency was shown in Table 5. Only at the resonance frequency of the 1.5 GHz, the value of R/Q was smaller than 80 Ω. We decided to employ 1.5 GHz as the resonance frequency of the kicker cavity.

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB331

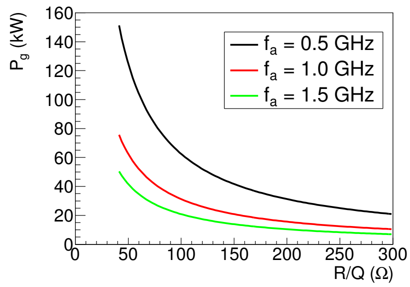

Figure 2: The correlation between P_g and R/Q with 50 kV of V_g and 5 MHz of Δf.

Table 5: The Best Values of the R/Q for Each Resonance Frequency

Resonance frequency	**Value of R/Q**
500 MHz	175 Ω
1.0 GHz	88 Ω
1.5 GHz	58 Ω

DESIGN OF THE KICKER CAVITY

We scaled down the original shape of the SM cavity at first. Then, we optimized the shape of the kicker cavity using 3D electromagnetic simulation(CST [8]). Figure 3 showed the 3D view of the kicker cavity after the optimization. The TM010 mode was resonated as the longitudinal kick field and the kicker cavity was a normal conducting cavity. We employed the Pillbox shape of the cavity to reduce the R/Q from the original paper. We also optimized the shape of waveguides, the position and material of the absorber. At the top and bottom of the cavity had large through hole (48 mm×55.7 mm) to realize large RF coupling. The absorber was made of ferrite(IB-004). The power loss at the absorber was estimated to be 250 W with 50 kV of V_g. We estimated the parameters of the cavity using eigenmode and frequency domain solver as shown in Table 6 and compared two results. Two results agreed well each other and satisfied our requirements of the TBL compensation.

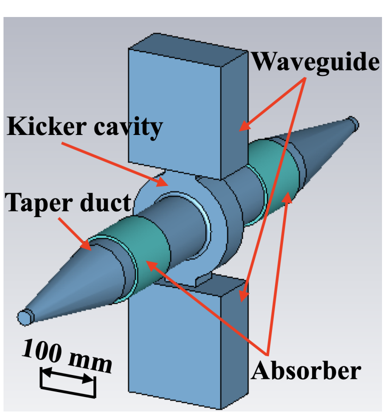

Figure 3: 3D view of the kicker cavity.

Table 6: Parameters of the Designed Kicker Cavity Under V_g =50 kV

Parameter	**Eigenmode**	**Frequency domain**
Frequency	1.50001 GHz	1.50003 GHz
R/Q	59.23 Ω	59.54 Ω
Q	16853	16814
Q_L	296	291
P_c	2.52 kW	2.53 kW
Max power density	26.6 W/cm^2	25.1 W/cm^2

We also evaluated the coupling impedance of the kicker cavity using the CST. Figure 4 showed the frequency dependence of the coupling impedance. Left figure showed the coupling impedance in the longitudinal direction and right figure showed that in the transverse direction. Red lines showed the threshold of the coupled bunch instability calculated from the radiation damping ratio shown in Table 1. In the left figure, the coupling impedance of the TM010 mode was bigger than the threshold. This peak could not become a problem since a growth rate calculated from this peak was almost zero. The residual peaks were smaller than the threshold and the kicker cavity was expected to work stably.

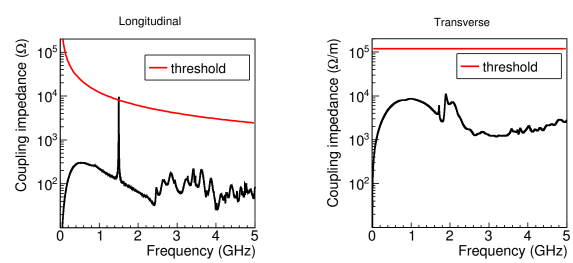

Figure 4: Frequency dependence of the coupling impedance.

CONCLUSION

We designed a wide-band longitudinal kicker to compensate the TBL voltage induced in the main and harmonic cavity. In the consideration of the design, we investigate the requirements of the resonance frequency and the R/Q against the ΔV_b and the P_g. We employed the single-mode cavity concept so that harmful HOMs were damped by rf absorbers on beam pipes. At the KEK-LS case, the resonance frequency of 1.5 GHz was found to be suitable in order to satisfy our requirements and employ the single-mode cavity concept. We optimized and evaluated the design of the kicker cavity using 3D electromagnetic simulation. The designed cavity satisfied our requirements and the coupling impedance of the cavity was estimated to be enough small at the KEK-LS case.

REFERENCES

[1] A. Hofmann and S. Myers, “Beam dynamics in a double rf system”, in *Proc. 11th Int. High-Energy Accelerators Conf.*

ISBN: 978-3-95450-214-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2021-MOPAB331

(HEACC'80), Geneva, Switzerland, 1980, pp. 610-614.

[2] N. Milas, L. Stingelin, *et al.*,"Impact of filling patterns on bunch length and lifetime at the SLS", in *Proc. 1st Int. Particle Accelerator Conf. (IPAC'10)*, Kyoto, Japan, 2010, paper THPE084, pp. 4719-4721.

[3] N. Yamamoto, T. Takahashi, and S. Sakanaka, "Reduction and compensation of the transient beam loading effect in a double rf system of synchrotron light sources", *Phy. Rev. Accel. Beams*, vol. 21, p. 012001, Jan. 2018. doi:10.1103/PhysRevAccelBeams.21.01200

[4] N. Yamamoto, T. Takahashi, and S. Sakanaka, "Beam loading compensation for optimal bunch lengthening with harmonic cavities", in *Proc. Coherent Beam Instabilities (MCBI'19)*, Geneva, Switzerland, 2019, pp. 96-100. doi:10.23732/CYRCP-2020-009.96

[5] T. Honda, "Concept of a New Generation Synchrotron Radiation Facility KEK Light Source", in *Proc. 8th Int. Particle Accelerator Conf. (IPAC'17)*, Copenhagen, Denmark, 2017, pp. 2687-2690. doi:10.18429/JACoW-IPAC2017-WEPAB047

[6] T. Weiland, "Single mode cavities", DESY, Hamburg, Germany, Rep. DESY-83-073, Sep. 1983.

[7] P. B. Wilson, and J. E. Griffin, "High energy electron linacs; application to storage ring RF systems and linear collider", *AIP Conf. Proc.*, vol. 87, pp. 486-495, 1982. doi:10.1063/1.33620

[8] 3DS, https://www.3ds.com