Measurement of Longitudinal Coupling Impedance at KEKB

Takao IEIRI*, Kazunori AKAI and Nobumasa AKASAKA
KEK, High Energy Accelerator Research Organization
Oho 1-1, Tsukuba, Ibaraki 305-0801, Japan

Abstract

We have measured current dependence of the synchronous phase and the bunch length in order to evaluate the longitudinal coupling impedance at KEKB. A real part of the impedance can be estimated from a variation of the synchronous phase. An imaginary part of the impedance is derived from bunch lengthening. Measured loss factor indicated from two to three times as large as a design value. Measured impedance exceeded a design value by a factor of five.

1 Introduction

The coupling impedance is one of the most important issues for B-factories, such as KEKB [1,2], to achieve high beam current and a high luminosity. Problems of bunch lengthening and parasitic wall loss give us a severe condition to perform design values. KEKB is an asymmetric electron and positron collider with two storage rings, named LER and HER. About 5000 bunches will be stored with a 2 ns spacing in each ring. The total current is designed to be 2.6 A in LER and 1.1 A in HER. Basic parameters are listed in Table 1.

Table 1
Basic parameters of KEKB used in this measurement

Parameter	HER	LER
E Beam Energy	8.0	3.5 (Gev)
f_{rf} RF Frequency	508.886 (MHz)	
f_0 Revolution Frequency	99.39 (kHz)	
h Harmonic Number	5120	
V_c RF Cavity Voltage	8.0	4.0 (MV)
f_s Synchrotron Frequency	1.17	1.14 -1.18 (kHz)
α Momentum Compaction	1.88	1.41 -1.53 $\times 10^{-4}$
δ_ε Energy Spread	6.67	7.31 $\times 10^{-4}$
U_0 Energy Loss/Turn	3.49	0.85 (MeV)

2 Longitudinal Beam Parameters

Longitudinal beam parameters represented by the synchrotron frequency, the synchronous phase and the bunch length of a bunch are coupled with each other. The synchrotron frequency is given by

$$f_s = \sqrt{\frac{\alpha f_{rf} e V_c |\cos\varphi_s|}{2\pi E T_0}} \tag{1}$$

where φ_s is the synchronous phase and T_0 is revolution period. The synchrotron frequency is proportional to $\sqrt{\alpha V_c |\cos\varphi_s|}$ in a storage ring and a measure of the momentum compaction, when total cavity voltage is fixed. The cavity voltage in a storage ring gives a circulating bunch electric energy to compensate for the radiation loss. The synchronous phase is determined by the energy balance between the rf voltage and the radiation loss. A bunch loses more energy due to resistive impedance of a vacuum chamber. This additional energy loss represented by the loss factor, $k(\sigma)$ depending on the bunch length, is compensated by an appropriate shift in the synchronous phase, which is given by

$$V_c \sin(\varphi_{s0} + \Delta\varphi_s) = \frac{U_0}{e} + k(\sigma) T_0 I_b. \tag{2}$$

Here, φ_{s0} is the synchronous phase for a very small beam current and I_b is beam current when a single bunch is assumed. Assuming $\Delta\varphi_s$ is small enough, the loss factor is obtained by

$$k(\sigma) = \frac{V_c \cos\varphi_{s0}}{T_0} \frac{\Delta\varphi_s}{I_b}. \tag{3}$$

The loss factor is also related to the resistive impedance and it is given for a Gaussian bunch by

$$k(\sigma) = \frac{1}{\pi} \int_0^\infty Z_r(\omega) e^{-(\omega\sigma)^2} d\omega, \tag{4}$$

where $Z_r(\omega)$ is a real part of the impedance and σ is rms bunch length. The natural rms bunch length is given by

$$\sigma_{L0} = \frac{c\alpha\delta_\varepsilon}{2\pi} \frac{1}{f_s}, \tag{5}$$

where c is the velocity of light. The natural bunch length is inversely proportional to the synchrotron frequency. The coefficient is determined by the momentum compaction and the energy spread.

As the beam current increases, an effect of the coupling impedance appears. An inductive or capacitive impedance changes the bunch length due to the potential-well distortion. When a purely inductive impedance is assumed, the bunch lengthening for a Gaussian bunch is analytically derived [3] and given by

$$\begin{aligned}
\left(\frac{\sigma}{\sigma_{L0}}\right)^3 - \left(\frac{\sigma}{\sigma_{L0}}\right) &= \frac{\sqrt{\pi} I_b}{2hV_c \cos\varphi_s} \left(\frac{R}{\sigma_{L0}}\right)^3 \left(\frac{Z_i(\omega)}{n}\right) \\
&= \frac{e\alpha I_b}{4\sqrt{\pi}\gamma_s^2 E} \left(\frac{R}{\sigma_{L0}}\right)^3 \left(\frac{Z_i(\omega)}{n}\right) \\
&= \frac{\Gamma}{4\sqrt{\pi}}.
\end{aligned} \tag{6}$$

Here, R is average radius of a ring, n is integer given by $n = \omega / \omega_0$ and γ_s is the synchrotron tune and Γ is a dimensionless parameter introduced by K. Bane [4]. An inductance is given by $\omega_0 L = |Z_i / n|$, where ω_0 is the angular revolution frequency. The bunch lengthening using Eq. (6) agrees with a numerical calculation using the Haissinski equation within 1% up to Γ=40 [5].

When the bunch lengthening is small enough at a very low current, the bunch length is given by

$$\sigma = \sigma_{L0} + \frac{ecLI_b}{8\sqrt{\pi}\alpha\delta_\varepsilon^2 E}. \qquad (7)$$

It is noted that the second term is independent of the bunch length and the synchrotron tune.

3 Measuement

Measurement was performed with a single bunch at both LER and HER, where wiggler magnets at LER were not excited. A longitudinal position was detected using a turn-by-turn monitor [6] which can detect a beam phase from a ratio of orthogonal components of a beam at 509 MHz. An averaging method improves a resolution of measurement. Measurement reproducibility of less than 0.3 deg. was achieved in a short term. The synchronous phase was measured as a function of the cavity voltage when the bunch current was around 0.3 mA and 0.4 mA. When the cavity voltage is changed under a constant beam current, the $\Delta\varphi_s$ in Eq.(3) would be almost constant, because the cavity voltage and the loss factor similarly varies for a change in the bunch length. The $\Delta\varphi_s$ was actually 1.1 ± 0.1 deg. using measured data described later. Thus we can evaluate the cavity voltage from measurement of the synchronous phase. Measured phase was shifted so as to match it with a calculated synchronous phase. The best agreement was achieved by shifting the phase by 147 deg. and by multiplying the V_c by 1.05 at LER. This result means that the mesured V_c is lower than that in calculation by 5% at LER. An error in the V_c was only 2% at HER. The synchrotron oscillation was excited and its frequency was measured as a function of the V_c on a spectrum analyzer. The best fit of the f_s with a calculation including the error of the V_c was a condition of using the $\alpha = 1.50 \times 10^{-4}$ at LER.

On the other hand, the bunch length can be obtained from the beam spectrum. When we detect two frequency components, ω_1 and ω_2, in the beam spectrum under the condition of $\omega\sigma < 1$, an amplitude ratio of these components gives an rms value of a bunch shape. This method is applicable to even an asymmetric distribution of a bunch. Thus, amplitudes of two frequency components at 0.5 GHz and at 2.5 GHz were detected using a beam signal from a button electrode. A common electronics circuit was used for detecting both beams of LER and HER. Since it is difficult for this method to determine an absolute value of the bunch length, the calculated natural bunch length at zero beam current is used as a reference value. In order to calibrate the monitor, the bunch length was plotted as an inverse function of the f_s as shown in Fig. 1. The slope of measured bunch length was 5.95 ± 0.1 mmkHz at HER, which agrees with a calculation with 5.97 mmkHz. The measured bunch length has an offset of about 0.8 mm for the calculated natural bunch length, which may be due to the potential-well effect shown in Eq.(7). The measured bunch length agrees with an absolute value within ± 1 mm considering a gain error of the detector.

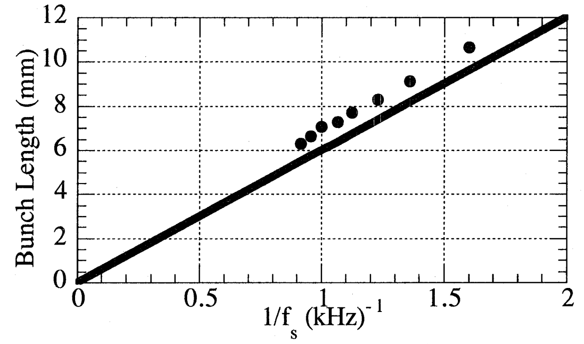

Fig. 1 Measured bunch length shown in dots vs. 1/fs. Solid line is the calculated natural bunch length.

The loss factor can be obtained from a slope of a synchronous phase as a function of the beam current using Eq.(3). The bunch length was also measured as a function of the I_b as described in the next paragraph. Figure 2 shows the loss factor for HER and Fig. 3 for LER as a function of the bunch length . The loss factor at the design bunch length of 4 mm was not measured because the natural bunch length was longer than 4 mm. The loss factor of both rings are changed as $\sigma^{-1.6\pm0.2}$ at HER and $\sigma^{-2.9\pm0.3}$ at LER as a function of the bunch length. When we extrapolate the loss factor at the bunch length of 4 mm from measured data, the loss factor would be 67 ± 16 V/pC at HER 87 ± 30 V/pC at LER. The measured data suggest that the resistive impedance at LER has a little stronger frequency dependence than that at HER.

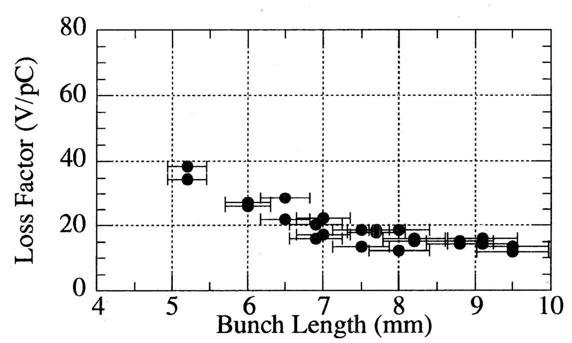

Fig.2 Loss factor vs. bunch length at HER. The error bars are due to ambiguity of the bunch length depending on the beam current.

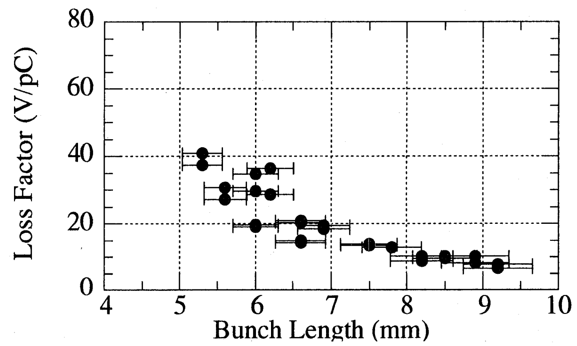

Fig.3 Loss factor vs. bunch length at LER.

Figure 4 shows bunch lengthening as a function of the bunch current at HER. The natural bunch length is 5.5 mm. The bunch length measured using a streak camera is also plotted [7]. The streak measured fwhm/2.354 of a bunch. There seems to be a disparity in the measured bunch length between the streak and the spectrum at higher current above 1 mA. The streak indicated a parabolic distribution [7] rather than a Gaussian at the higher current. The deformation was remarkable as the beam current increased. The disparity should be caused by the deformation of a bunch shape. A fitting curve using Eq. (6) agrees with the measured rms bunch length, where $|Z_i / n| = 0.076\ \Omega$ is used. On the other hand, bunch lengthening at LER is shown in Fig. 5. A fitting curve ia also shown, where $|Z_i / n| = 0.075\ \Omega$ is used. However, the fitting is not so good as that in HER. One possible reason for the poor fitting at LER may be a limit of using a purely inductive impedance model. It was observed that the synchronous phase shifted to more than one standard deviation of the natural bunch length as the bunch current increased up to 1 mA at LER.

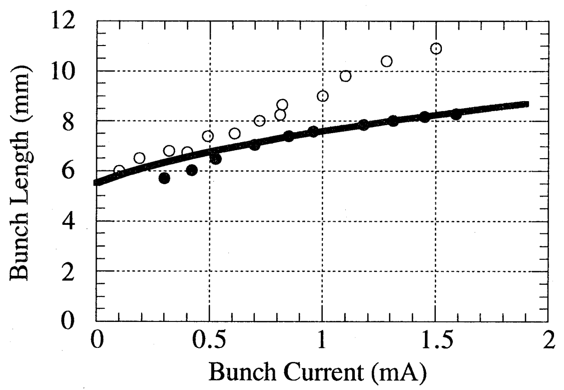

Fig. 4 Bunch length vs. bunch current at HER. Dots are bunch length by a spectrum method and circles are by a streak camera. Solid line is calculated bunch length.

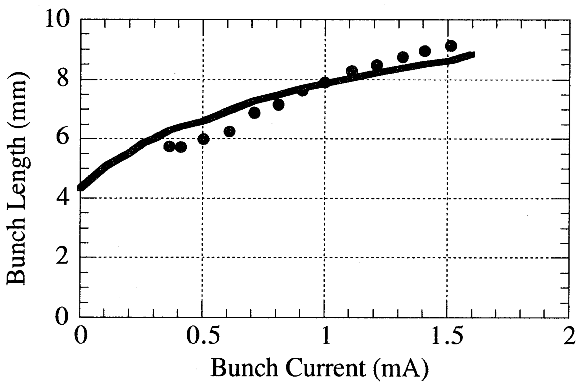

Fig.5 Bunch length vs. bunch current at LER, where the natural bunch length is 4.3 mm. Solid line is calculated bunch length.

4 Summary

We have measured the loss factor and the imaginary part of the longitudinal impedance at both rings. The results are listed in Table 2, where design values are also shown for comparison. Measured loss factors are from two to three times as large as the design values of about 28 V/pC at σ_L=4.0 mm. On the other hand, measured impedance is about 5 times as large as the design value in both rings. We notice a big disparity between the actual machine and the designed values. Vacuum chambers have been modified especially in the interaction region and unexpected components added since the design note was published in 1995. A remaining issue is to evaluate those components.

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Table 2
Measured impedance together with designed values. The loss factor is a value at the bunch length of σ=4mm.

HER	measurement	designed
k (V/pC)	67±16	28
$\|Z_i / n\|$ (Ω)	0.076±0.006	0.015
LER	measurement	designed
k (V/pC)	87±30	25
$\|Z_i / n\|$ (Ω)	0.072±0.011	0.015

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* e-mail : takao.ieiri@kek.jp