IMPEDANCE MEASUREMENTS IN THE KEKB

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Abstract

In the KEKB storage rings, we have measured the current dependence of the betatron tunes and the damping rate to evaluate the broad-band transverse impedance. The measured impedances were cross-checked and exceeded the design value by a factor of more than five. The tranverse mode-coupling instability was observed in LER when chromaticity was reduced. We found that the main impedance source for the instability was caused by the vertical collimators. The impedance of the collimators was investigated by changing their aperture.

1 INTRODUCTION

The coupling impedance is one of the most important issues for B-factories, such as KEKB [1,2], to achieve high beam currents and a high luminosity. KEKB is an asymmetric electron-positron collider with two storage rings, named the low energy ring (LER) and the high energy ring (HER). Approximately 5000 bunches with a 2 ns spacing will be stored in each ring. Basic parameters are listed in Table 1. Note that the momentum compaction α of both rings is small and variable. A small α results in a short natural bunch length (σ_{l0}=4 mm) and a low synchrotron tune (ν_s=0.01). A short bunch length, however, has implications concerning beam dynamics and the machine impedance. The longitudinal coupling impedance of the KEKB storage rings was measured previously [3]. In this note, we focus on the measurement of the tranverse impedance and its effects, in particular, in the LER.

Table 1 Basic KEKB machine parameters.

Parameter	HER	LER
Beam Energy, E(Gev)	8.0	3.5
RF Frequency, f_{rf} (MHz)	508.886	
Revolution Frequency, f_0 (kHz)	99.39	
Harmonic Number, h	5120	
RF Cavity Voltage, V_c (MV)	9.0	4.2 - 5.0
Synchrotron Frequency, f_s (kHz)	1.17 - 1.68	1.14 - 1.62
Momentum Compaction, $\alpha \times 10^{-4}$	1.88 - 3.39	1.06 - 2.42
Momentum Spread, $\delta_\varepsilon \times 10^{-4}$	6.67	7.31
Energy loss/turn, U_0 (MeV)	3.49	1.64

Among the various components of the LER vacuum chamber, the movable collimators are thought to give a big contribution to the transverse impedance. Eight pairs of collimators were installed in order to minimize background noise for the Belle detector. As illustrated in Fig.1 [4], each collimator is a rectangular block that is supported by a stem. Pairs of such collimators are nominally positioned at 4 to 5 mm from the beam orbit, a distance so close that a significant transverse impedance effect can be expected.

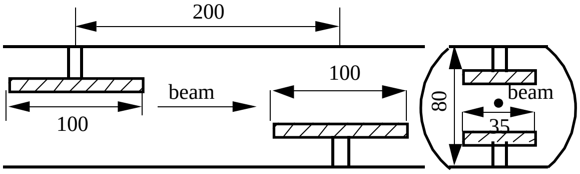

Fig.1 Schematic of one pair of a vertical movable collimator. The left figure shows a longitudinal section, the right one a transverse section. Units are in mm.

2 TRANSVERSE IMPEDANCE

A bunch interacts with a vacuum chamber object and generates wake fields. These wake fields can act back on the bunch itself and affect its beam dynamics. We can estimate these wake fields (or equivalently the machine impedance) by investigating the beam dynamics of the bunch. Analysis of the beam dynamics shows that the machine impedance affects the betatron tune. A bunch oscillates with a tune $\nu = \nu_\beta + m\nu_s$, where ν_β is the betatron tune and $m = 0, \pm 1, \pm 2 \cdots$. The current-dependent, coherent betatron frequency of a bunch for the m=0 mode is given by

$$\frac{\Delta\nu}{I_b} = \frac{\langle\beta\rangle R\{Z_\perp\}}{4\sqrt{\pi}\sigma_l E / e}. \tag{1}$$

Here, I_b is the bunch current, $\langle\beta\rangle$ the average value of the beta function, σ_l the rms bunch length, R the average radius of the machine and $\{Z_\perp\}$ is the effective impedance, defined by

$$\{Z_\perp\} = \frac{\sum_{p=-\infty}^{\infty} Z_\perp(\omega_p) h_m(\omega_p - \omega_\xi)}{\sum_{p=-\infty}^{\infty} h_m(\omega_p - \omega_\xi)}. \tag{2}$$

Here, ω_ξ is the chromatic frequency defined by $\omega_\xi = \xi\omega_0 / \alpha$, where $\xi = \Delta\nu / \Delta p / p$ is the chromaticity and ω_0 the angular revolution frequency. The effective impedance is weighted by the beam power spectrum h_m, after it has been shifted by the chromatic frequency. The chromatic frequency is 4.7GHz, for example, when the chromaticity is 5.0. When the betatron tune shift is on

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the order of the synchrotron tune, a coupling between the m=0 and the m=-1 modes causes an instability. The threshold current for the transverse mode-coupling instability is given by

$$I_{th} \approx \frac{8}{\sqrt{\pi}} \frac{\nu_s \sigma_l E / e}{\langle\beta\rangle R\{Z_\perp\}}. \qquad (3)$$

The instability is a severe limitation on the single bunch current in large storage rings with a low beam energy and a low synchrotoron tune, as is the case for the LER. On the other hand, the short-range wake force enhances the damping of betatron oscillations when the chromaticity is positive. The head-tail damping rate for the m=0 mode is given by

$$\frac{1}{\tau} = \frac{I_b\{Z_\perp\}\langle\beta\rangle}{2\pi E / e} \cdot \omega_\xi. \qquad (4)$$

The damping rate is proportional to the chromaticity and the bunch current. Finally, in a cylindrical chamber, the transverse impedance can be approximated from the longitudinal one by [5]

$$Z_\perp(\omega) = \frac{2R}{b^2}\left|\frac{Z_{II}}{n}\right|. \qquad (5)$$

Here, b is the radius of the beam tube and $n = \omega / \omega_0$.

3 MEASUREMENTS

The synchronous phase and the bunch length were measured as a function of bunch current in ref. [3]. A summary of the results is:

(1) The imaginary part of the impedance was $|Z_i / n|$ = $0.076 \pm 0.006\,(\Omega)$ in the HER and 0.072 ± 0.011 (Ω) in LER, which are five times larger than the value of 0.015 (Ω) calculated in the design report [1]. Note that the collimators were not considered in the report.

(2) The loss factor of both rings was also two to three times larger than the value given in the design report.

The betatron tune of a single bunch was measured in the LER. The chromaticity was set to a lower value than the value normally used, in order to reduce chromatic damping. The measured horizontal and vertical chromaticity were 2.2 and 0.8, respectively. The measured fractional parts of the betatron tune are plotted as a function of the bunch current in Fig.2. Though the tune shift depends on the bunch length, which also depends on the bunch current, the tune decreases almost linearly with current. The bunch length actually increased from 5mm to 7mm as the bunch current was increased from 0.5mA to 1mA [3]. A tune shift of $\Delta\nu / I_b$= -0.0034/mA to -0.0042/mA was obtained in the vertical plane. The corresponding effective impedance is 80.6 to 99.6 $k\Omega$/m at σ_l=5.0mm and is 112.8 to 139.4 $k\Omega$/m at σ_l=7.0mm. The horizontal tune shift was $\Delta\nu / I_b$= -0.0010/mA to -0.0015/mA. These values for both planes are significantly larger than the design value of -0.0004/mA [1], and are consistent with the discrepancy obtained from the longitudinal measurements. Since the LER uses a circular beam tube, the transverse impedances of both planes would be the same if the vacuum chamber components are symmetrical. A candidate for breaking the symmetry is the movable collimators. In order to investigate the effect of the collimators, the measurement was repeated with the collimators fully opened in both directions. The vertical tune shift was reduced to -0.0014/mA, as is shown in Fig.2. Therefore, more than half of the vertical impedance in the LER must be due to the collimators, when they are at their usual settings. The horizontal tune shift, however, did not change significantly. The horizontal collimators were normally opened wider than the vertical ones. Finally, when we approximate the transverse impedance from the longitudinal measured impedance, we obtain $31 \pm 4.8\ k\Omega / m$, a value that is close to the horizontal and the vertical impedances when the collimators are fully opened.

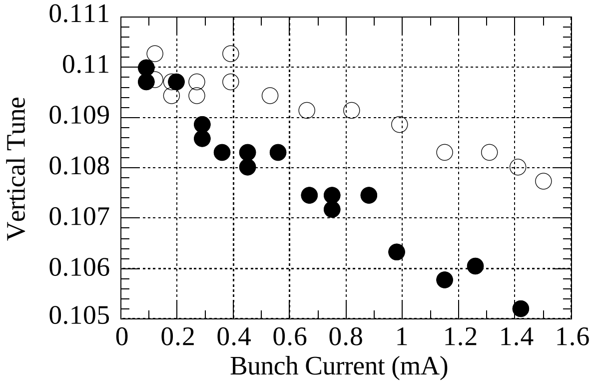

Figure 2: Transverse tune *vs*. bunch current in the vertical plane. Given are results with the collimators at their usual settings (black circles), and with the collimators fully opened (white circles).

The damping rate of betatron oscillations was measured in the LER using a vertical kicker magnet [6]. The amplitude of betatron oscillation was recorded using a turn-by-turn beam position monitor [7] with the collimators at their normal setting. The damping rate increased with bunch current and chromaticity. The effective impedance obtained from the damping rate, when using the data with a low chromaticity, was found to be about 80 $k\Omega$/m, which was consistent with the values obtained from the tune shift measurement.

4 TRANSVERSE MODE-COUPLING INSTABILITY

Since a large tune shift was observed in the vertical plane in the LER, the tune shift was investigated in more detail while varying the rf accelerating voltage. The collimators were set to their normal position. The vertical chromaticity was set at a slightly positive value of 1.27. The two betatron modes: m=0 and m=-1 were observed on a spectrum analyzer. The tune of the m=0 mode decreased with current, while the tune of the m=-1 mode remained almost constant. When the bunch current passed 1 mA, the amplitude of the m=-1 mode rapidly increased. The beam was lost at a current of 1.4 mA, before the tunes of the two modes could merge. We show in Fig.3 the current at which the beam was lost as a function of the synchrotron tune. We find that the threshold current increases in proportion to the synchrotron tune, as is predicted by theory. An estimate of the tune shift at threshold is $\Delta\nu_\beta = 0.6\nu_s$. The threshold current can also be estimated using Eq.(3). Using the measured $\{Z_\perp\}$=95 $k\Omega$/m at σ_l=5.0mm or $\{Z_\perp\}$=133 $k\Omega$/m at σ_l=7.0mm, we obtain the threshold current given by the line in Fig.3. The calculated threshold is consistent with the measured one, which means that the estimated impedance is reasonably accurate.

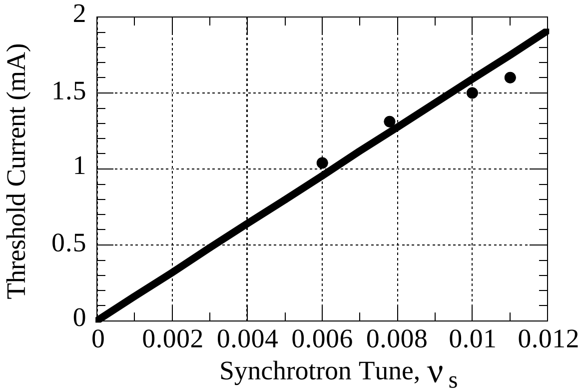

Figure 3: Measured threshold current of the mode-coupling instability as a function of the synchrotron tune. The solid line is a calculated threshold, assuming $\{Z_\perp\}$=95 $k\Omega$/m with σ_l=5.0mm or $\{Z_\perp\}$=133 $k\Omega$/m with σ_l=7.0mm.

5 IMPEDANCE OF COLLIMATORS

Since the vertical impedance is dominated by the collimators (see Fig.2), we decided to investigate their effect in more detail. The tune shift was measured as a function of the aperture of a collimator, while the beam orbit was kept constant. When the aperture was reduced from 2.7 mm to 0.9 mm, the tune shift changed from -0.006/mA to -0.008/mA. The effective impedance of the collimator can be estimated from a change of the tune shift using Eq.(1). Neglecting the effect of the edges, the transverse impedance of a resistive collimator is given, using Piwinski's equation [8], by

$$Z_\perp = \frac{\pi[sgn(\omega)(1-i)]L}{h^3\sqrt{2\omega/(c\mu_r\rho_c Z_0)}} f(\frac{y}{h}), \qquad (6)$$

where L is the length of a collimator, h is the full-aperture, μ_r is the relative permeability, ρ_c the wall resistivity, Z_0 is 377 Ω and $f(y/h)$ is a function that becomes 1 when the beam is centered in the aperture of the collimator. Limiting our interest to the short-range wake effects and letting $\omega \approx c/\sigma_l$, the effective impedance becomes

$$\{Z_\perp\} = \frac{\pi L}{\sqrt{2}h^3}\sqrt{\rho_c Z_0 \sigma_l}, \qquad (7)$$

Figure 4 shows that the impedance obtained from the tune shift agrees with the values obtained by Eq.(7). Note that the impedance will be enhanced when the beam is off-center.

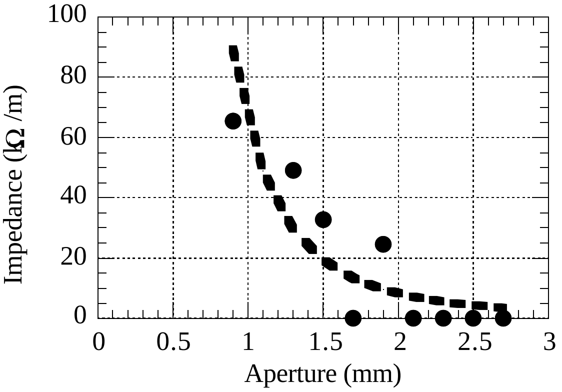

Figure 4: Impedance of the collimator in the LER as a function of its full-aperture. Black circles are the measured impedance and the dashed line is obtained using Eq.(7).

6 SUMMARY

The transverse impedance of the LER was investigated using several measurement methods: the betatron tune shift, the instability threshold, and the head-tail damping rate. The results of these measurement were found to be consistent with each other. The effective vertical impedance was found to be 80 $k\Omega/m$ to 139 $k\Omega/m$ with the collimators at their normal position, and 33 $k\Omega/m$ to 46 $k\Omega/m$ with them fully open. Therefore, the collimators dominate the transverse impedance in the LER. We have shown, in addition, that the effect of the collimators is roughly consistent with Piwinski's analytical resistive-wall formula. Finally, estimating the transverse impedance from the longitudinal one, we have obtained a value close to the measured transverse impedance with the collimators fully opened.

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