

SINGLE-BEAM COLLECTIVE EFFECTS IN THE KEK B-FACTORY

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Abstract

In this paper, we deal with the issues of single-beam collective effects (the bunch lengthening and the transverse mode-coupling instability) and coupled-bunch beam instabilities due to RF cavities and the resistive-wall beam pipes in the KEK B-factory. The transit ion problem and coupled-bunch instabilities due to photo-electrons will be discussed in other publications.

I. INTRODUCTION

The KEK B-factory (KEKB) is an electron-positron collider with unequal beam energies (8 and 3.5 GeV) for study of B meson physics[1]. The dominant issues in the KEKB in terms of beam instabilities are the very high beam current (2.6 A in the low energy ring (LER) and 1.1 A in the high energy ring (HER)) to achieve the high luminosity of $10^{34}\text{cm}^{-2}\text{s}^{-1}$, and a short bunch ($\sigma_z = 4$ mm) to avoid a degradation of the luminosity by the hour-glass effect. Since the charges are distributed over many (5120) bunches, the bunch current is not unusually high. As a consequence, single-bunch effects are expected to be relatively moderate: their stability limits are beyond the design values with comfortable margins. The main concern, in turn, is on coupled-bunch instabilities due to high-Q resonant structures such as RF cavities and the transverse resistive-wall instability at very low frequency (lower than the revolution frequency).

II. SINGLE-BUNCH COLLECTIVE EFFECTS

In this section, we review our predictions of single-bunch collective effects, namely, the bunch lengthening and the transverse mode-coupling instability. As mentioned in the introduction, these instabilities are expected to impose no fundamental limitation on the stored current, since the bunch current is relatively low compared with other large electron rings. However, the requirement of the short bunch ($\sigma_z = 4$ mm) demands a careful attention at any possible causes for deviation from the nominal value.

A. Bunch lengthening

There are two mechanisms to alter the bunch length from the nominal value. One is the potential-well distortion of the stationary bunch distribution due to the longitudinal wake potential. The deformed bunch distribution can be calculated by solving the Haissinski equation. The bunch can be either lengthened or shortened depending on the type of the wake potential. Another mechanism is the microwave instability and has a clear threshold current for the onset of the instability.

Oide and Yokoya have developed a theory to include both the potential-well distortion effect and the microwave instability[2]. A program is now available to compute the bunch length according to their theory. Figure 1 shows the calculated bunch length in the LER as a function of the number of particles in a bunch,

N_p . As can be seen, there is a constant bunch lengthening due to the potential-well distortion and the microwave instability takes off at $N_p = 1.2 \times 10^{11}$, which is about three times larger than the proposed number of particles per bunch. At the design intensity, the bunch is lengthened only by 20%.

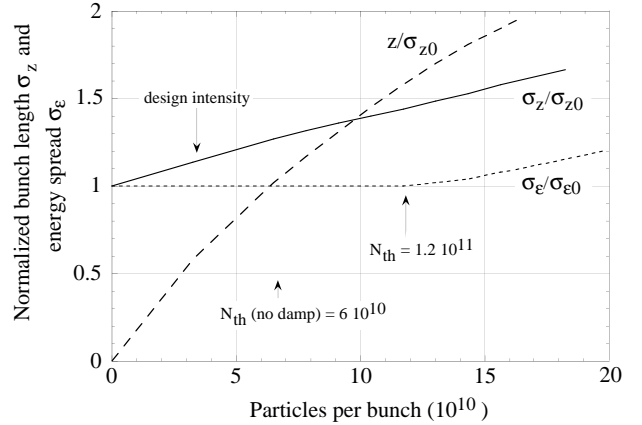


Figure 1. Bunch length and energy spread in the LER.

B. Transverse mode-coupling instability

The transverse mode-coupling instability is known to be responsible for limiting the single-bunch current in large electron rings such as PEP[3] and LEP. This instability takes place when two head-tail modes ($m=0$ and $m=-1$ modes in most cases) share the same coherent frequencies. In a short bunch regime where the KEKB will be operated, the coherent frequency of the $m=-1$ mode keeps almost constant as a function of the bunch current, while that of the $m=0$ mode keeps descending until it meets with the $m=-1$ mode. Using the estimated transverse wake potential and the averaged beta function of 10 m, we found that the coherent tune shift of the $m=0$ dipole mode is only ~ -0.0002 at the design bunch current. This value is much smaller than the design value of the synchrotron tune (~ 0.017). Thus, the transverse mode-coupling instability will not impose a serious threat on the performance of the KEKB.

III. COUPLED-BUNCH INSTABILITIES

As mentioned earlier, the coupled-bunch instabilities due to high-Q structures such as RF cavities and the resistive-wall beam pipes are the main concerns in the KEKB rings because of the unusually large beam current. We have adopted the so-called damped-cavity-structure to sufficiently lower the Q-values of higher-order parasitic modes, typically less than 100. As a result, the growth time of the fastest-growing mode in the LER (HER) becomes about 60 msec (150 msec) longitudinally and 30 msec (80 msec) transversely. They are longer than or comparable to the radiation damping time of 20 msec (longitudinally) or 40 msec

(transversely) in the two rings (with wiggler in the LER). More details on the calculation results will be available in ref. [1]. In this section, we focus on the transverse coupled-bunch instability due to the resistive-wall impedance and coupled-bunch instabilities (both transverse and longitudinal) excited by the crabbing mode of the crab cavity.

A. Transverse resistive-wall instability

The growth rate of the instability in terms of the rigid particle model is given by

$$\tau_{\text{RW}}^{-1} = -\frac{\beta_{\perp}\omega_0 I_b}{4\pi E_b/e} \sum_{p=-\infty}^{\infty} \text{Re}[Z_{\text{RW}}(\omega_{p,\mu,\nu_{\beta}})], \quad (1)$$

where

$$\omega_{p,\mu,\nu_{\beta}} = (pM + \mu + \nu_{\beta})\omega_0. \quad (2)$$

Here, β_{\perp} is the averaged beta function over the ring, ω_0 is the angular revolution frequency, $\text{Re}[Z_{\text{RW}}]$ is the real part of the resistive-wall impedance, I_b is the beam current, E_b is the beam energy, ν_{β} is the betatron tune, μ is the mode number of the coupled-bunch oscillation and M is the number of bunches in the beam. In the above formula, it is assumed that the RF buckets are uniformly filled with the equal number of particles (we ignore effects of the gap in the bunch filling which may be necessary to suppress the ion trapping).

In Figs. 2 and 3, the growth time of the most unstable mode in the LER and HER, respectively, are shown as a function of the betatron tune. In the current design of the LER (HER), the horizontal and vertical tunes are 45.52 (46.52) and 45.08 (46.08), respectively. The most unstable mode (5074 mode) in the LER has the growth time 5.9 and 8.1 msec at these tunes, respectively. On the other hand, the most unstable mode in the HER is the 5073 mode, and has the growth time of 4.0 and 5.6 msec at the horizontal and vertical tunes, respectively. Conversely, we plot the growth time as a function of the coupled-bunch mode number at the tunes 45.52 and 46.52 for the LER and the HER in Figs. 4 and 5, respectively

One possible cure for this instability is a bunch-by-bunch feedback system. The growth rates obtained in the above are, however, close to the limit of design capability of our feedback system. Fortunately, the coherent frequencies of the unstable modes

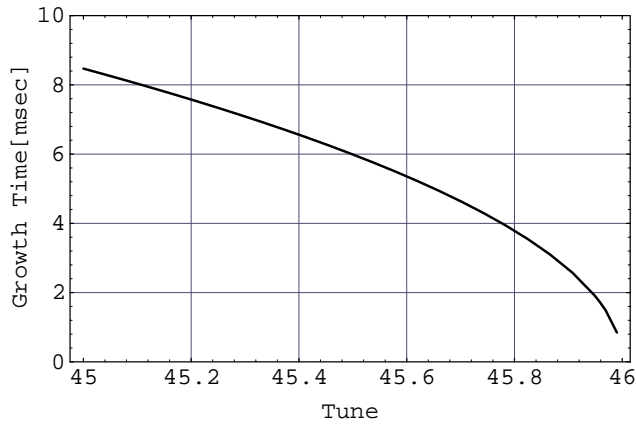


Figure 2. Growth time of the resistive-wall instability as a function of betatron tune in the LER.

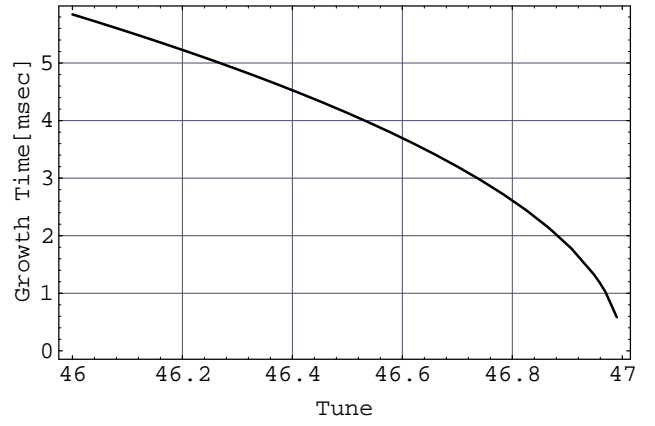


Figure 3. Growth time of the resistive-wall instability as a function of betatron tune in the HER.

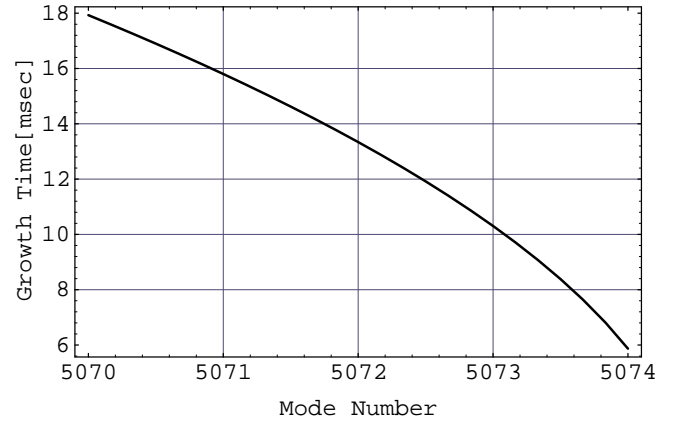


Figure 4. Growth time of the resistive-wall instability as a function of the mode number at the betatron tune of 45.52 in the LER.

stay in a narrow frequency range at low frequency, and thus these modes may be stabilized by a narrow-band mode feedback system rather than a wide-band bunch-by-bunch feedback system. If the bunch-by-bunch feedback system can perform at the damping time of 10 msec, the mode feedback system must cover only one unstable mode in the LER and three modes in the HER, as seen from Figs. 4 and 5. Then, the combination of the two feedback system is expected to provide a damping time of 1 msec for the fastest-growing modes.

B. Coupled-bunch instability by crabbing mode

In this section, we deal with only the instability due to the impedance of the crabbing mode. The instability due to the HOMs can be treated in a similar manner to those in accelerating cavities. The transverse coupling-impedance of a deflecting crabbing mode is expressed as

$$Z_{\perp}(\omega) = \frac{\omega_r}{\omega} \cdot \frac{\frac{R_{\perp}}{Q_0} Q_L}{1 + i Q_L \left(\frac{\omega}{\omega_r} - \frac{\omega_r}{\omega} \right)}, \quad (3)$$

where ω_r is the resonant frequency of the crabbing mode, R_{\perp} is the transverse shunt impedance, Q_0 is the unloaded Q-value

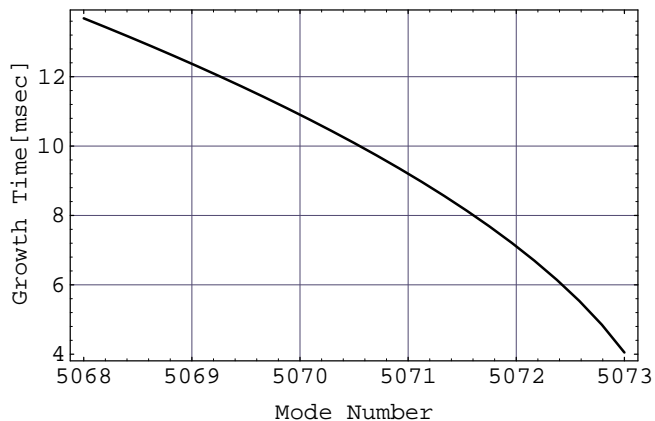


Figure 5. Growth time of the resistive-wall instability as a function of the mode number at the betatron tune of 46.52 in the HER.

and Q_L is the loaded Q-value. The most characteristic feature of the crabbing mode is that it operates at the same frequency as the accelerating mode unlike the HOMs. This feature renders this mode harmless by cancellation between the two betatron sidebands in both sides of the impedance peak, just like for the fundamental accelerating mode of a cavity. Unlike the accelerating mode which must be detuned by a large amount of frequency to compensate the heavy beam loading, we need not detune the crabbing mode. The growth rate of all coupled-bunch modes then almost vanishes as far as the resonant frequency of the crabbing mode is kept near the accelerating frequency. The main parameters of the crab cavity together with some machine parameters of LER are summarized in Table 1. The growth time of the most unstable mode (the 5074 mode for positive detuning, and the 5075 mode for negative detuning) in the LER is depicted in Fig. 6 as a function of the detuning frequency. In this figure, the radiation damping time (40 msec, with wiggler) is shown by the thick solid line. From this figure, it is clear that all modes are stable in the wide range of detuning from -6.5 kHz to 6.5 kHz. The growth time in the HER is even longer than in the LER. We can therefore conclude that the transverse coupled-bunch instability due to the crabbing mode will cause no serious problem as far as its frequency is well controlled.

Another problem may arise when the beam orbit has some offset at the cavity. In this case, longitudinal wake fields are excited which may cause a longitudinal coupled bunch instability. Even so, this type of instability can be stabilized by the fundamental mode of the accelerating cavities or by detuning the crab cavities to the lower frequency.

IV. SUMMARY

We have seen that neither bunch lengthening nor the transverse mode-coupling instability will impose a significant limitation on the stored bunch current. The luminosity performance of the KEKB is rather affected by the couple-bunch instabilities due to RF cavities (longitudinally) and the resistive-wall instability (transversely). Our carefully designed damped-cavity-structure helps to reduce the longitudinal growth to a manageable level. Even the most unstable mode has the growth time (60 msec)

Table I
Main parameters of the crab cavity in the LER.

Beam energy	3.5 GeV
Beam current	2.6 A
Horizontal beta-function at crab cavities	100 m
Horizontal betatron tune	45.52
Number of crab cavities	2
Accelerating frequency	508.88 MHz
Harmonic number	5120
R_{\perp}/Q_0	277.4 Ω/m
Q_L	1×10^6

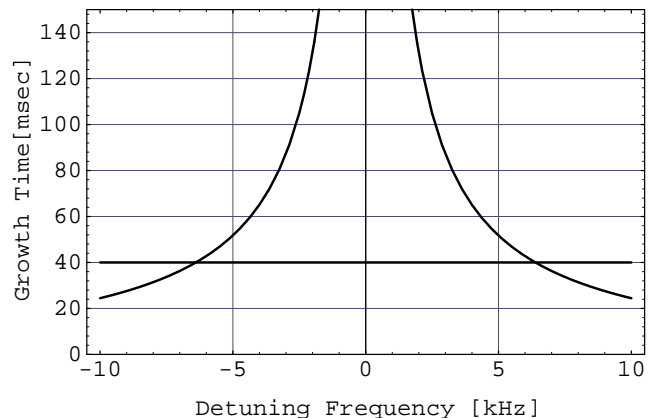


Figure 6. Growth time of the coupled bunch instability due to the crabbing mode in the LER versus the detuning frequency.

longer than the radiation damping time of 20 msec in the LER with wiggler. Transversely, however, the growth time of the resistive-wall instability (~ 5 msec) is far shorter than the radiation damping time of 40 msec. The design of the fast feedback system which can deal with the remaining growth is one of the most challenging problems for the KEKB.

References

- [1] *The KEKB Design Report* in preparation.
- [2] K. Oide and K. Yokoya, KEK Preprint 90-10 (1990).
- [3] M. S. Zisman et. al., *Study of Collective Effects for the PEP Low-Emittance Optics*, LBL-25582 and SSRL ACD Note-59 (1988).