Simulation of Influence of a Bunch Gap in TRISTAN-II

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Abstract

A bunch gap, which is introduced in electron storage rings in order to avoid the ion-trapping, modulates the cavity voltage and the bunch phase. This modulation can cause serious problems in extremely high-luminosity colliding accelerators, such as TRISTAN-II. We calculated the modulation due to the bunch gap by two different methods; (1) by calculating a change of the cavity voltage due to the bunch phase modulation and a change of the bunch phase due to the cavity voltage modulation alternatively until they converge, and (2) by utilizing the transfer function of the beam-cavity system. The results of the two methods are in good agreement. We also simulated possible measures to compensate the modulation caused by the gap in order to avoid luminosity degradation or any other harm.

1. INTRODUCTION

TRISTAN-II (KEKB) is an asymmetric two-ring electron-positron collider for B-physics, comprising an 8 GeV electron storage ring (HER) and a 3.5 GeV positron storage ring (LER), which will be constructed in the existing TRISTAN Main Ring tunnel at KEK[1]. In order to achieve the final design luminosity of 1×10^{34} $cm^{-2}s^{-1}$, stored current in the HER and LER should be 1.1 A and 2.6 A, respectively, which is much higher than that in any existing electron-positron colliders.

The ion-trapping is one of the problems arising from the high electron beam current. In storage rings, some part of residual gas molecules are transformed to ions due to the collision with stored beams. The ions can be trapped around the beam orbit by the potential well of the electron beam. The trapped ions can (1) shorten the beam life time due to collisions, (2) give rise to two-beam instability, and (3) affect the betatron tune.

In order to prevent the ion trapping, several methods have been proposed. Among them, introducing a bunch gap is the most attractive solution for KEKB. In this method, beams are filled partially in the ring instead of being filled uniformly. The ions escape from the beam orbit to the duct wall when they encounters the bunch gap. Other methods are less attractive; for example, a method using clearing electrodes increases the ring impedance or give rise to local heat problems. Thus a bunch gap will be introduced in the HER of KEKB.

The bunch gap, however, modulates the amplitude and phase of the accelerating field in the cavity, since the beam-induced field is modulated by the non-uniformly filled beams. The modulation of accelerating field then changes the synchronous phase of bunches. Since this effect is different from one bunch to another, the synchronous phase differs accordingly, which results in not-equally-spaced bunches. Then the successive collisions of electrons and positrons occur at different locations in the longitudinal direction. Furthermore, the longitudinal displacement makes a relative transverse displacement of both beams at the collision point, if a finite crossing angle is adopted. The luminosity can be reduced by (1) the displacement of the collision point from the optimum point where the β-function is minimum and (2) the transverse displacement of both beams at the collision point. Furthermore, beam-beam effect of the transverse displacement at the collision point is so far unknown. Thus the bunch gap may deteriorate the machine performance significantly.

In this paper we present the calculation of the modulation of accelerating field and the synchronous phase of each bunch due to a bunch gap by use of two independent methods described above. We also simulated possible measures to compensate the modulation.

2. MODULATION DUE TO THE BUNCH GAP

2.1 Direct calculation

The first method is by calculating a change of the cavity voltage due to the bunch phase modulation and a change of the bunch phase due to the cavity voltage modulation alternatively until they converge. We are concerned with the steady state where every physical quantity differs from bunch to bunch but is independent of every revolution. In this case, when the accelerating voltage seen by the m-th bunch ($V_{c,m}$) is given, the arrival time delay of this bunch (δ_m) that gives the bunch the same energy as one turn loss is calculated. On the other hand, when δ_m is given, $V_{c,m}$ is calculated. The real values of δ_m and $V_{c,m}$ should satisfy both relations at the same time. The solutions for δ_m and $V_{c,m}$ can be obtained in an iterative way, namely, by repeating the calculations until they converge.

2.2 Transfer function

The second method is by utilizing the transfer function of the beam-cavity system, which has been developed by F. Pedersen.[2,3] As far as the system is operated satisfying the Robinson stability criterion, real part of every pole in the transfer function of the beam-cavity system is not positive. The transient response related with a pole that has a negative imaginary part is damped. Since we are concerned with the steady state in the sense mentioned above, the gap transient response is calculated from pure imaginary poles.

2.3 Results

Since the analysis with a transfer function is based upon a linearized theory, it is not clear whether the analysis gives a correct answer when the beam current is extremely high. One can, on the other hand, expect that the direct calculation method gives a correct answer even if the beam current is extremely high, as far as the solution converges.

In order to examine that, results from the two methods were compared. Figure 1 shows modulation of the bunch phase and the accelerating voltage for the case of 10 % gap in the HER with normal conducting 2-cell damped cavities.[4] Table 1 shows the bunch phase modulation for three types of cavities under development for KEKB. It is seen that the results obtained from the two methods are in good agreement up to 1.1 A for any type of cavity except the 2-cell normal conducting cavity. In the case of 2-cell normal conducting cavity, the results are also in good agreement up to 0.77 A, above which the solution of the direct calculation method was hard to converge due to the large amount of modulation. We thus conclude that either method gives a quantitatively correct answer as far as the solution of the direct calculation method converges. When the solution of the direct calculation diverges, we adopt the transfer function method.

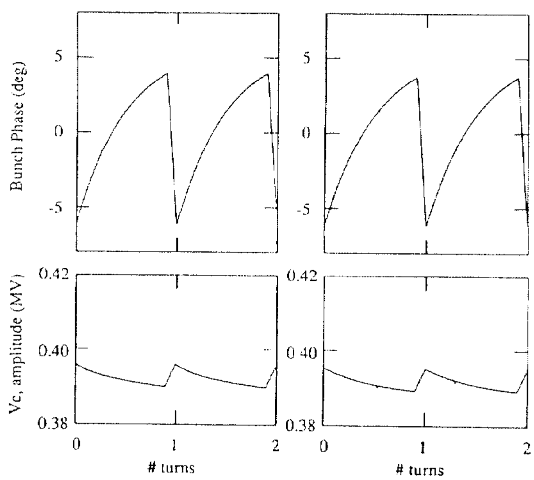

Figure 1. Modulation of the bunch phase and the cavity voltage due to the bunch gap calculated by two different methods; (left) direct calculation in an iterative way and (right) utilizing the transfer function.

Table 1 Comparison of the results of the two methods to calculate the bunch phase modulation

Cavity	Current(A)	Δφ (deg) direct cal.	Δφ (deg) transfer function
NC(2-cell)	0.22	9.9	9.8
	0.77	34.6	34.3
	1.1	*	48.9
ARES[5]	1.1	2.5	2.5
SC[6]	1.1	4.1	4.1

A 10% gap in the HER of KEKB is assumed.
* does not converge.

3. COMPENSATION FOR THE MODULATION

A bunch phase modulation of ±3 degrees corresponds to a longitudinal displacement of $1\sigma_z$ (=5mm) in KEKB. Since a finite crossing angle of ±10mrad will probably be adopted, this modulation will cause a transverse displacement of 50μm at the collision point, which is about 1/3 of σ_x^*. A much larger bunch phase modulation will probably decrease the luminosity significantly. Furthermore, beam-beam effect of this transverse displacement has not been simulated so far.

Since it is not clear at this stage which type of cavity to be used in the HER and the length of the necessary gap to cure the ion trapping, the seriousness of its influence can not be evaluated quantitatively. Nevertheless, we believe we need to develop in advance possible cures to solve the problem caused by the bunch gap. In order to compensate for the bunch gap transient we examined several methods, which are classified into two categories; (1) compensation gap in the positron ring,[3] and (2) modulating cavity input rf power.

3.1 Compensation gap in the positron ring

The first method is introducing an appropriate gap in the positron ring (LER) so that it makes a similar gap transient response in the LER to that in the HER. If one can control every bunch charge accurately enough, the relative bunch phase between both rings can be minimized. The effect of the compensation gap was simulated by use of the transfer function. Figure 2 shows a typical result of the relative bunch phase modulation as a function of the bunch charge in the compensation gap in the LER. The relative phase is reduced from 12.8° (no compensation gap) to 2.8°. Table 2 summarizes the relative bunch phase for different types of cavities with and without the compensation gap. The advantage of this method is its simplicity. However, The compensation is not perfect since the operation condition such as cavity voltage, loaded Q, etc. is different in both rings. Furthermore, the compensation effect may be reduced by inaccurate bunch current distribution caused either through injection or due to the different life of positrons and electrons.

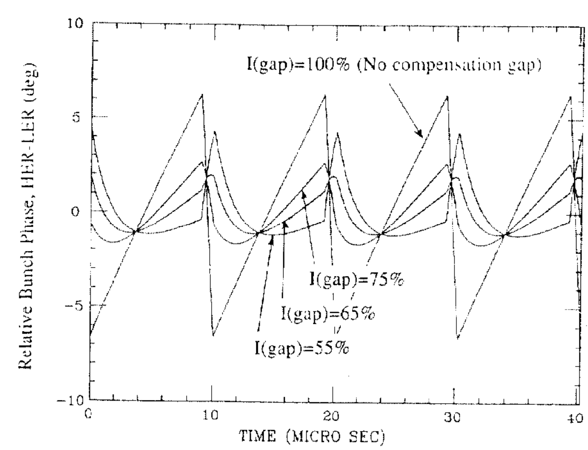

Figure 2. Effect of the compensation gap in the positron ring (LER) in the case of SC with the Low-α optics.

Table 2 Effect of a compensation gap in LER

Optics	Cavity	I(gap)/I (in LER)	$\Delta\varphi$(HER)-$\Delta\varphi$(LER) w/o (deg)	w/gap(LER) (deg)
Normal-α*	NC(2cell)	54%	48.9	2.5
Normal-α	NC(ARES)	60%	2.4	<0.5
Normal-α	SC	60%	4.8	<0.5
Low-α*	SC	65%	12.8	2.8

A 10% gap in the HER of KEKB is assumed.
* The design of optics in KEKB has two options related with the momentum compaction factor (α).

3.2 Modulating the cavity input power

By modulating the cavity input power so that it compensates the beam loading modulation, the gap transient is reduced. We examined two methods to realize this compensation; (i) feedback with parallel band pass filters, each of which is adjusted at the revolution side band (Figure 3) and (ii) feed-forward correction with a pulse modulation (Figure 4). If the generator power is such that it perfectly compensates for the beam loading, the gap transient is perfectly eliminated. In a real machine, however, a finite bandwidth or a group delay of klystrons or others will reduce the effect of the compensation. We simulated the effect of this compensation using the direct calculation method taking a finite bandwidth (system(i)) or a group delay (system(ii)) into account. The result of an example for KEKB (Figure 5, right) showed that if the system has a bandwidth of about 5 times revolution frequency (system(i)) or a group delay of less than about 1/3 of the gap width (system(ii)), the bunch phase modulation is well compensated. The disadvantage of this method is that a large amount of peak power is needed, as shown in Figure 5 (left). In order to ease the requirement for the peak power, we also simulated another scheme in which only the phase of the input power is modulated, while the amplitude is not. As shown in Figure 5(d), this method also helps to reduce the bunch phase modulation, although the effect is smaller than the method modulating both of the phase and amplitude.

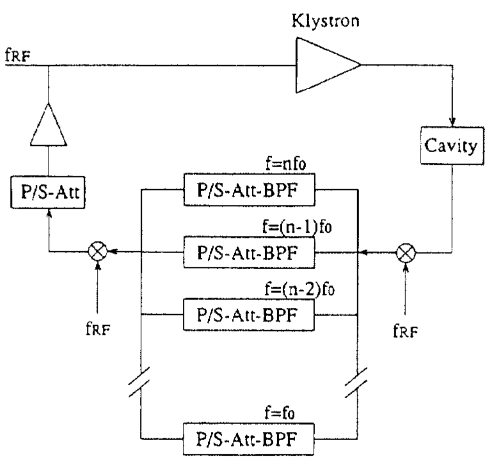

Figure 3. Gap transient compensation system modulating the cavity input power with revolution side bands.

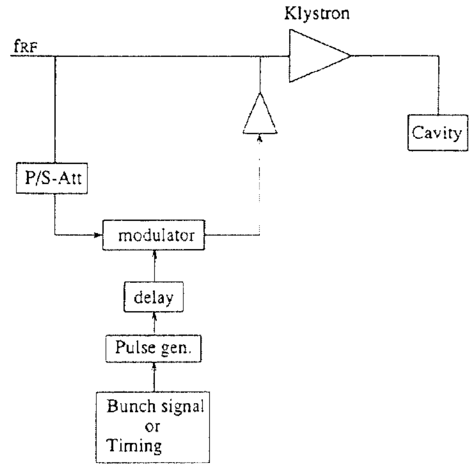

Figure 4. Gap transient compensation system modulating the cavity input power with a pulse corresponding to the gap.

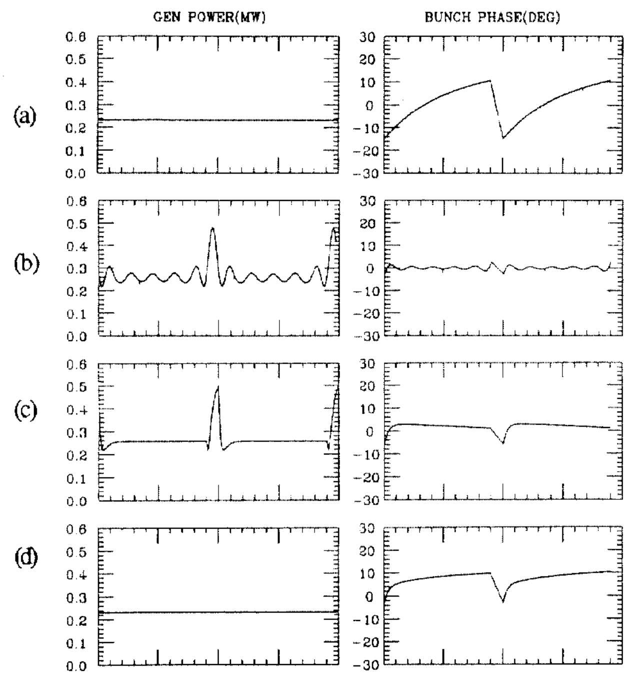

Figure 5. Simulation results of gap transient compensation modulating the rf power; (left) generator power and (right) the bunch phase modulation. From top to bottom is shown; (a) without any modulation of input power, (b) with revolution side bands, (c) with a pulse modulation for the phase and amplitude, and (d) with a pulse modulation only for the phase. The bandwidth of ±5 times revolution frequency in (b) and the group delay of 1/3 of the gap width in (c) and (d) is assumed.

4. REFERENCES

[1] "Accelerator Design of the KEK B-Factory", KEK Report 90-24 (1991).
[2] F. Pedersen, IEEE Trans. Nucl. Sci., NS-22, p.1906 (1975).
[3] F. Pedersen, SLAC-400, pp.192-207 (1992).
[4] M. Suetake et.al., KEK Report 90-24, p.85 (1991)
[5] Y. Yamazaki et.al., KEK Preprint 93-15, (1993)
[6] S. Mitsunobu et.al., KEK Proceedings 93-7, p.140 (1993).