Simulation of Multibunch Instabilities in the Damping Ring of JLC

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Abstract

Multibunch instabilities due to higher order modes of RF cavities in the damping ring of JLC (Japan Linear Collider) were studied by tracking simulations. Both transverse and longitudinal motions, with monopole and dipole modes in the RF cavities, were considered. Bunch motions were found stable in the condition of low Q-values of higher order modes of Q=100 and bunch to bunch betatron tune spread of $\Delta\nu=1\times10^{-3}$.

I. INTRODUCTION

The bunch configuration of the damping ring of JLC is shown in Fig.1 schematically. There are ten bunch trains in the ring and each bunch train contains ten bunches. The number of particles in a bunch is designed to be 2×10^{10}. The spacing between bunch trains are about 60 nsec and the spacing between bunches is 1.4 nsec in each train. There are two sections for RF cavities. Because of the large number of bunches and high current, multibunch instabilities due to higher order modes of RF cavities may be serious problems.

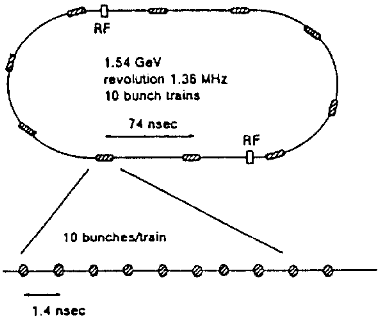

Fig. 1. Bunches in the JLC damping ring.

In section II and IV, each bunch was treated as a single charged particle (rigid bunch). Transverse instabilities (section II) and longitudinal instabilities (section IV) were simulated separately. In each case, only one higher order mode was considered. In section III, each bunch was assumed to consist of several macroparticles.

General parameters of the ring are as follows[1].

Beam energy	1.54 GeV
Revolution frequency	≈1.4 MHz
RF frequency	1.428 GHz
Number of particle/bunch	2×10^{10}
Number of bunch/train	10
Number of train in a ring	10
Beam current	≈0.4 A
Injection(extraction) rate	200 Hz
Radiation loss	0.47 MeV/turn
Radiation damping time	5 msec (transverse)
Betatron tune	≈21.2
Betatron wave length β	5 m (RF sections)
$d\beta/ds$	0 (RF sections)
Momentum compaction α	0.003

II. TRANSVERSE MOTION (RIGID BUNCH)

A. Simulation steps and parameters

The simulation consists of four steps as follows.
1) A higher order mode (dipole mode) in RF cavities are excited when bunches pass at the RF sections.
2) Each electron is kicked at RF sections.
3) The higher order mode oscillates and damps exponentially.
4) Each bunch takes place betatron oscillation and radiation damping through the ring.

The following parameters were used.

Frequency of the mode	≈2.3 GHz
(R/Q) of the mode	10 KΩ/m/RF section
Injection error	0.1 mm

Note that one train (10 bunches) is injected (extracted) at a time. Injection rate is 200 Hz and number of train is 10, then each train stays in the ring for 50 msec. In our simulation, the first train was injected in an empty ring and the following trains were injected every 5 msec. After 50 msec, the first train was extracted and the next train was injected where the other trains were circulating. Motions of first injected train and those of trains which take the place of it (11th, 21th etc.) were observed. It was assumed that all bunches have the same transverse offset at the injection. Betatron tune was chosen not to be a simple fraction of any integers. The loaded Q-value of the dipole mode was varied to estimate the required value.

B. Low Q-value case

As examples, Fig. 2 shows offset of the last bunch of 10 bunches in a train vs. turn number for (a) Q=5 and (b) Q=10. It shows that Q=5 is low enough, but Q=10 is too high.

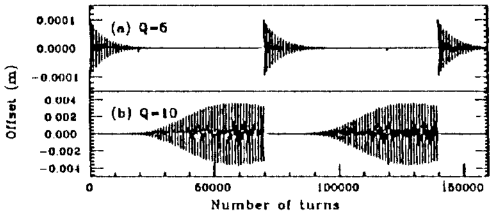

Fig. 2. Offset of 10th bunch in a train vs. turn number, (a) Q=5 (b) Q=10.

To see how bunches are stable (or unstable) for various conditions, we observed 'emittance of bunch center' defined as

$$\varepsilon=(x^2+v_x{}^2\beta^2)/\beta.$$

where x is transverse offset and $v_x=dx/ds$. For simplicity, we will observe only ε of the last(tail) bunch in a train because the last bunch will take place the largest oscillation in unstable cases. Fig. 3 shows ε vs. turn number for Q=5, 6, 7, 8, 10, 14, 50 and 100. In the case Q=50 and Q=100, oscillation is growing rapidly and never damped. For Q=8, 10, and 14, damping begins after growing but not enough. This result shows that Q=5 is low enough but Q=6 is not clearly good.

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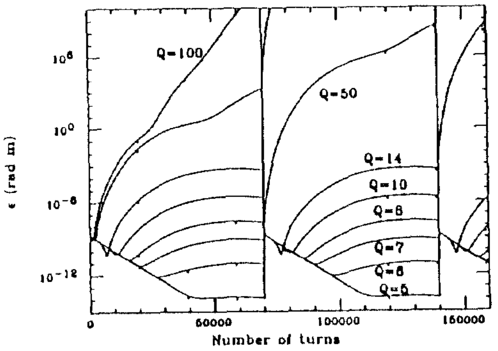

Fig.3. ε vs. turn number for Q=5, 6, 7, 8, 10, 14, 50 and 100.

To achieve such extremely low Q-value is very difficult and $Q \approx 100$ seems to be reasonable even applying 'damped cavity'.

Assuming that the damping is exponential, it was estimated how fast the damping should be for a certain Q value. It was found that the damping time should be smaller than 1 msec if Q=100. This damping rate can not be achieved by only radiation damping. The other damping mechanism were proposed[2] and these effects were simulated in section III.

C. Bunch to bunch tune distribution

Let's introduce another cure, 'bunch to bunch tune difference'. If bunches in a train have different betatron tune values, coherent oscillation between bunches is expected to be suppressed. Here, we introduce linear spread Δv as shown in Fig. 4. The spread $\Delta v \approx 1\text{x}10^{-3}$ is expected to be obtained in the JLC damping ring by RF quadrupole[3].

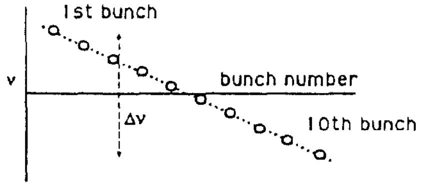

Fig.4. Definition of Δv.

In Fig. 5, ε vs. turn number is shown for $\Delta v = 3\text{x}10^{-4}$ and $1\text{x}10^{-3}$ in the case Q=100. $\Delta v=1\text{x}10^{-3}$ is enough. Fig. 6 shows results in the case $\Delta v=1\text{x}10^{-3}$, for Q=100, 150, 200 and 300. If $\Delta v=1\text{x}10^{-3}$, Q=150 is low enough but Q=300 is too high.

Some severer cases were studied. With higher R/Q of 20 KΩ/m/RF, it was simulated that Q=100 is low enough for $\Delta v=1\text{x}10^{-3}$. It was also checked that longer damping time, about 10 msec, could be accepted with $\Delta v=1\text{x}10^{-3}$, R/Q=10 KΩ/m/RF section and Q=100. In another simulation, the number of bunches/train was increased form 10 to 20, with the same charge/bunch, bunch to bunch spacing and train to train spacing (revolution frequency 1.14 MHz). If R/Q=10KΩ/m, Q=100 and $\Delta v=1\text{x}10^{-3}$, it was seen that the bunches were stable.

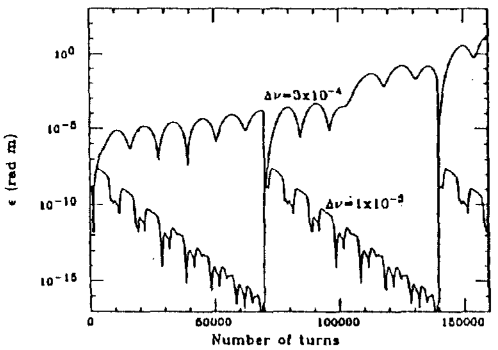

Fig. 5. ε vs. turn number for $\Delta v=3\text{x}10^{-4}$ and $1\text{x}10^{-3}$(Q=100).

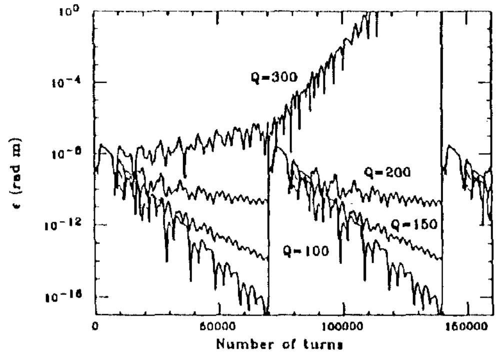

Fig. 6. ε vs. turn number for Q=100,150,200 and 300 ($\Delta v=1\text{x}10^{-3}$)

III. TRANSVERSE (WITH MOTIONS IN A BUNCH)

Two damping effects were studied in this section, which can be expected from motions of many particles in a bunch. To simulate these effects, each bunch was divided into several macroparticles. For simplicity, all particles were assumed to take place synchrotron oscillation with the same amplitude and frequency, and their phase to be uniformly distributed. The following parameters were used.

Synchrotron frequency	25 KHz
Energy spread ($\Delta E/E$)	0.08% (equilibrium)
Energy spread ($\Delta E/E$)	0.6%(at injection)

$\Delta E/E$ was assumed to be damped to 0.08% exponentially after injection. Injection and extraction were treated in the same ways as section II. Δv was set to be zero and Q-value of the dipole mode was fixed as Q=100. The other parameters were the same as those in section II.

If the chromaticity of the ring is not 0, the particles in a bunch have different betatron tunes corresponding to different energies. This tune spread will cause damping of the center of mass of the bunch. From simulations for chromaticity $\xi=1$, 5 and 10, it was observed that the effect would not suppress the transverse motion with reasonable value of chromaticity because of the rapid damping of the energy spread.

Another effect is due to short range wake field within a bunch. If chromaticity is positive, the head-tail effect can damp betatron oscillations of the bunch center.

To consider head-tail effect, wake function within each bunch was assumed to be constant, the strength (W_{short}) was changed as a parameter and the wake field was assumed to be localized at the RF sections. Chromaticity was fixed at $\xi=5$ and the number of macroparticles was 8/bunch. From analytic calculations with the hollow bunch model[4], the damping time of the zero mode oscillation is proportional to W_{short}^{-1} and estimated to be about 20 msec for W_{short}=1 V/pC/m^2 in our case. Fig. 7 shows the results (ε vs. turn number) for W_{short}=0, 1, 3, 6 ,10 and 30 V/pC/m^2. The head-tail effect could slow down the growth up to W_{short}=6 V/pC/m^2, but in the case of larger W_{short}, the rapid growth was observed. This growth can be regarded as a result of higher order motion in each bunch. This means also growth of the emittance of each bunch and it is not acceptable. It may be too optimistic to expect the effect damps transverse motion so rapidly compared with the radiation damping.

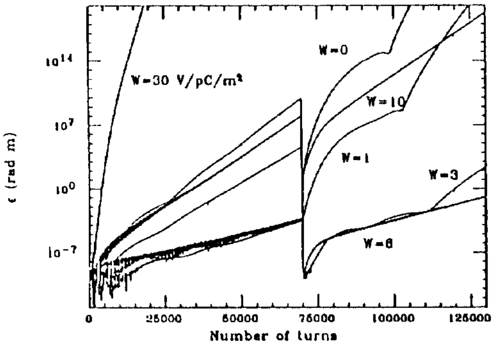

Fig. 7. ε vs. turn number for W_{short}=0, 1, 3, 6, 10 and 30 V/pC/m^2 (Q=100, ξ=5).

IV. LONGITUDINAL MOTION

A. Simulation steps and parameters

In our simulation, there are three field components in an RF cavity.

i. Field of the fundamental mode (accelerating mode), generated by power source.

ii. Wake field of the fundamental mode.

iii. Wake field of a higher order mode.

The strength and phase of the first field was fixed. The second one and the third one were simulated in the same way as the transverse wake field described in the previous section.

1) The fundamental mode and a higher order mode (monopole mode) in RF cavities are excited when bunches pass at the RF sections.

2) Each electron is accelerated at the RF sections.

3) The fields oscillate and damp exponentially.

4) Each bunch loses its energy through the ring (radiation loss) proportional to square of its energy.

5) Each bunch reaches to the next RF section with time delay depending on its energy.

The following parameters of the RF cavity were used.

Cavity voltage	0.6 MV/RF section
Impedance (fundamental)	10 MΩ/RF section
Q (fundamental)	≈5350
Frequency (fundamental)	1.428 GHz
(R/Q) (higher order)	100 Ω/RF section
Frequency (higher order)	2.4 GHz.

Note that, radiation damping time was about 2.5 msec corresponding to the radiation loss 0.47 MeV/turn. Initial state was chosen as 10 mm displacement for the first bunch in each train and 0 for other bunches and E=E_0 for all bunches. Q-value of the higher order mode was varied as a parameter.

B. Result

The results for Q= 100, 200, 300 and 500 are shown in Fig 8. Each figure shows the time delay of the tenth bunch in a bunch train vs. number of turns. The figure shows that Q=100 is low enough to suppress the longitudinal instabilities. Because of the low Q-values, the resonance frequency is not an important parameter. Even in the case R/Q=150 Ω/RF section, it was checked that Q=100 is low enough.

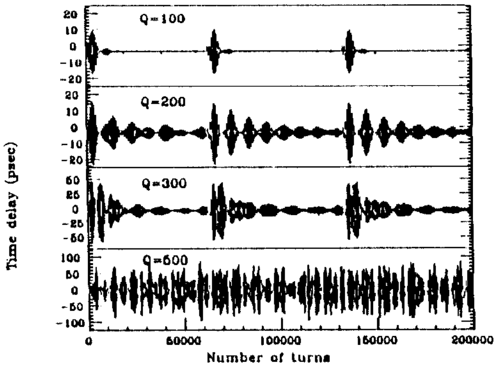

Fig.8. Time delay of 10th bunch, for Q= 100, 200, 300 and 500.

There may be higher modes with low R/Q and high Q-values. To see their effect, a simulation was performed for R/Q=20 Ω/RF section. Q=500 was checked to be low enough.

To study in the case of slower radiation damping, radiation loss/turn was changed as a parameter. Damping time of 4 msec (loss of 0.295 MeV/turn) is acceptable with R/Q=100 Ω/RF section and Q=100.

V. SUMMARY

Multibunch motion due to wake field of higher order mode in RF cavities for the JLC damping ring was simulated.

It was shown that with bunch to bunch tune spread $\Delta\nu=1\times10^{-3}$ and low Q-value of the dipole mode Q=100, transverse multibunch motion is stable. With low Q-value of the monopole higher order mode Q=100, the longitudinal motion is also stable. It was found that some severer design parameters are acceptable. The effect of bunch internal motion was considered preliminary.

VI. REFERENCES

[1] J. Urakawa et al. Linear Accelerator Conference, 1990, Albuquerque.
[2] K. A. Thompson and R.D. Ruth, SLAC-PUB-4962.
[3] S. Sakanaka, private communication.
[4] A.W. Chao, AIP Proc. 105(1983), p 353.