Estimation of Beam Instabilities and Its Cure in the SPring-8 Storage Ring

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1 Introduction

Single-bunch and multi-bunch instabilities in the SPring-8 storage ring were estimated and the possible scheme to cure them were studied using the simulation code SISR[1] and CISR[2], respectively. SISR can simulate single-bunch instabilities driven by broad-band impedance and CISR can do multi-bunch instabilities driven by narrow-band impedance.

2 The SPring-8 Storage Ring

The parameters of the ring is shown in Table 1.

Table 1. The parameters of the SPring-8 storage ring.

Parameter		Value	Unit
Energy	E_0	8	GeV
Revolution Frequency	T_0	208.77	kHz
Energy Loss per Turn	U_0	9.2	MeV
Momentum Compaction Factor	α	1.46×10^{-4}	
Radiation Damping Time (Long.)	τ_E	4.1	ms
Radiation Damping Time (Trans.)	τ_x , τ_x	8.3	ms
Betatron Tune (horizontal)	ν_y	51.22	
Betatron Tune (vertical)	ν_x	16.16	

Broad-band impedance of the ring[3] are estimated using the code MAFIA and the estimated values of the longitudinal broad-band impedance, the broad-band transverse impedance of small discontinuities and localized transverse broad-band impedance of cavities are

$$Z^{\parallel} = -9.68\times10^{-8}\,\omega\, i + 400 + 1.49\times10^{8}\frac{1+i}{\sqrt{\omega}} \quad [\Omega]\,, \quad (28)$$

$$\langle \beta_{BB} Z^{\perp}_{BB} \rangle = 17.3\times\left(-2.13\times10^{5} + 5.98\times10^{14}\frac{1}{\omega}\right) \quad [\Omega] \quad (29)$$

and

$$\langle \beta_{Cav} Z^{\perp}_{Cav} \rangle = 10.0\times 4.2\times10^{19}\,\frac{1+i}{\omega\sqrt{\omega}} \quad [\Omega] \quad (29)$$

, where β_{BB} = 17.3m and is the averaged value of the beta functions at the small discontinuities and β_{Cav} is the value of the beta function at the cavities. Transverse instabilities are estimated only for y direction which has larger transverse broad-band impedance caused by smaller aperture of the beam pipe.

3 Single-Bunch Instabilities

Longitudinal Instabilities

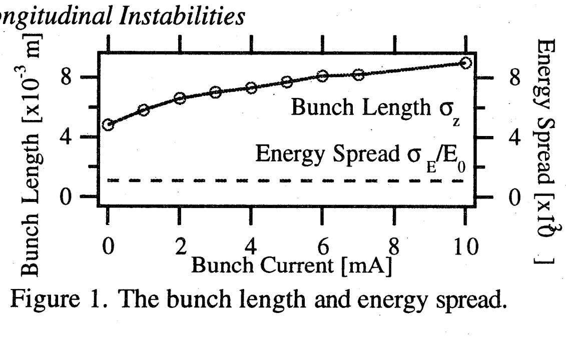

Figure 1. The bunch length and energy spread.

Figure 1 shows the dependence of the bunch length and the energy spread σ_E/E on the bunch current I_b. Because this ring is rather inductive compared to colliders which have a lot of cavities, the potential-well distortion lengthen the bunch length and the threshold of microwave instabilities can not be seen until the threshold current of the transverse instabilities which is shown later.

Transverse Instabilities

Figure 2 shows the bunch current increase vs. time used in the simulation. Figure 3 and Figure 4 show the amplitude of betatron motion of the bunch vs. time and the spectrum of betatron oscillation for chromaticity ξ=0, respectively.

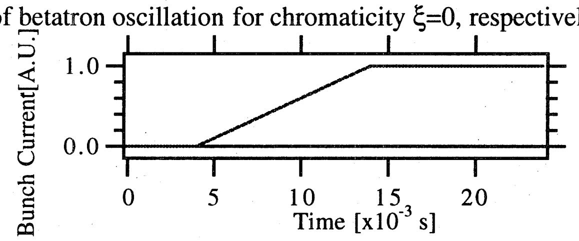

Figure 2. bunch current shape vs. time

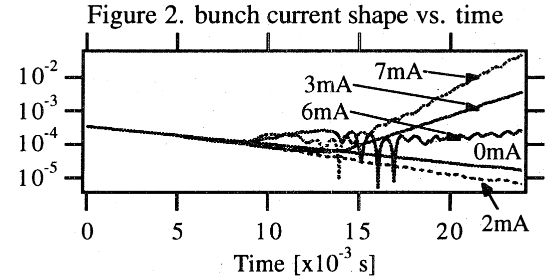

Figure 3. Amplitude of the betatron motion vs time (ξ=0).

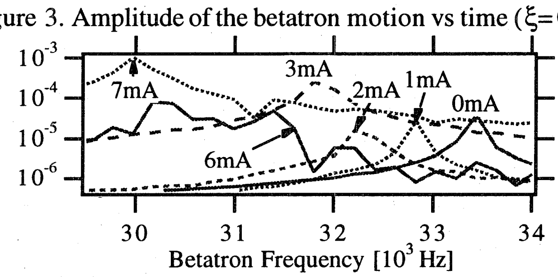

Figure 4. Spectrum of the betatron motion (ξ= 0).

From Figure 4, the shift of the frequency of m=0 mode is comparable to the synchrotron frequency, 1.5kHz at I_b =3mA and 2x1.5kHz at I_b=7mA. These instabilities seems to be a mode-coupling instability of m=0 and m=1 at I_b =3mA and that of m=0 and m=2 occurs at I_b=7mA

In Figure 5 and Figure 6, which are for ξ=4, No instabilities occurs near I_b=3mA, but the instabilities with m=0 and m=2 mode-coupling growths up at I_b=10mA. The difference between ξ=0 and ξ=4 seems to be from the effect of the head-tail damping, which can be seen at the beginning of the bunch current increase at time ~ 5ms in Figure 5 and it is much faster than radiation damping seen at I_b=0mA.

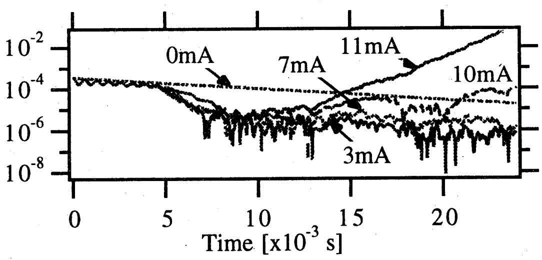

Figure 5. Amplitude of the betatron motion vs. time (ξ=4).

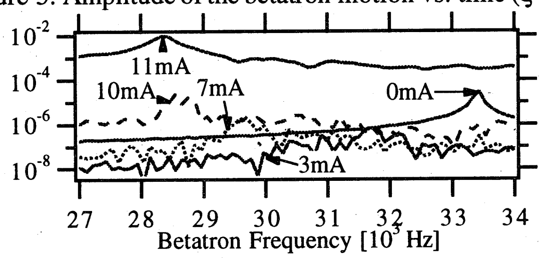

Figure 6. Spectrum of the betatron motion (ξ= 4).

4 Multi-Bunch Instabilities

Maximum allowable values of impedance to get the average current 100mA, which is the nominal current of the SPring-8 storage ring, are $f_{HOM} R^{\parallel} < 1.4$ [MΩ·GHz] for longitudinal and $\beta R^{\perp} < 92$ [MΩ] for transverse, where f_{HOM} are frequency of impedance and β is beta function at impedance. The sources of the multi-bunch instabilities in the SPring-8 storage ring are expected to be resonator impedance of higher order modes of acceleration cavities and resistive wall impedance of the narrow-gap undulators. In this report, the instabilities caused by resonator impedance is focused.

The calculated impedance of the single-cell cavities installed in the SPring-8 storage ring is ~1.5MΩ at 900 MHz for longitudinal and 14MΩ/m at beta function 10m for transverse. The parameters in Table 2 are model impedance used in simulation of multi-bunch instabilities and are almost 1.5 and 2 times larger values of those of a single cavity for longitudinal and transverse, respectively.

Table 2. Model impedance for simulation with average current 100mA

Longitudinal Resonator Impedance	
R/Q	720 Ω
Q	4000
Frequency	1018 MHz
Transverse Resonator Impedance	
R/Q	2308 Ω/m
Q	13000
Frequency	1006 MHz
Beta Function at impedance	10 m
Acceleration Mode	
R/Q	1855 Ω
Q	15880
Frequency	508.58 MHz
Voltage driven by External Generator	17 MV/turn
Acceleration Voltage at Iave=100mA	14 MV/turn

5 Acceleration Voltage Modulation by Partial-Filling

While a bunch train passes acceleration cavities, RF voltage decreases by beam-loading. After the bunch train passes, RF power supplied to the cavity re-fills RF energy in the cavity until the bunch train comes again. The bunches at the head of the train feel larger amplitude of acceleration voltage and execute faster synchrotron oscillation and the bunches in the tail feel lower amplitude of acceleration voltage and do slower oscillation. This causes bunch-by-bunch spread of synchrotron frequency and lead to de-coherence of the oscillation of instabilities and cease it. This scheme was successfully applied to the ESRF with 1/3 filling. 1/5 filling is easily achieved in the SPring-8 storage ring because extracted beam from the SPring-8 booster synchrotron has 1 micro second duration which is one fifth of the revolution period of the storage ring.

The modulation of the amplitude of acceleration voltage by beam-loading of bunch train is obtained by the simulation code CISR and is shown in Figure 7. Even in 1/2 filling, the amplitude of modulation is more than 0.5MV and resulting synchrotron frequency spread is $\Delta f_s \sim$ 70Hz as is shown in Figure 8. The damping time by this spread is $\tau \sim 1/(2\pi\Delta f_s) = 2.2$ms which is twice faster than the longitudinal radiation damping time, 4.1ms.

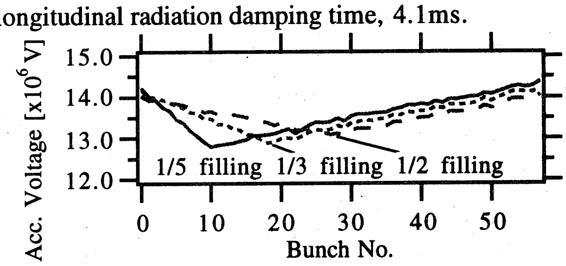

Figure 7. Amplitude of acceleration voltage vs. bunch number. The number of bunch per turn used in the simulation is 59 and first 1/5, 1/3 and 1/2 bunches filled with electrons.

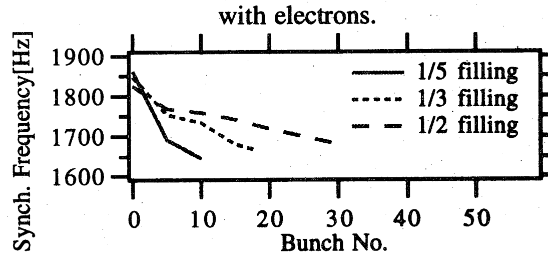

Figure 8. Synchrotron Frequency vs. Bunch Number from simulation result.

The simulation result, Figure 9-11, shows that no longitudinal instabilities occurs in 1/2,1/3,1/5 filling and this amplitude modulation is enough to cure the instabilities driven by the model impedance. For 1/1 filling(equal filling) shown in Figure 10 and Figure 11, instabilities saturates at some amplitude of bunch motion and the bunch length become longer then. This is because of the filamentation caused by the nonlinearity of the acceleration potential and resulting tune spread in the bunch, which was observed and analyzed in ALS and ELETTRA.

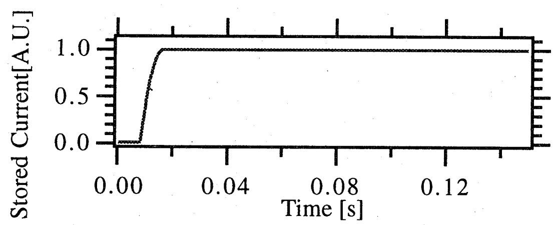

Figure 9. Increase of the current to their maximum values used in simulation

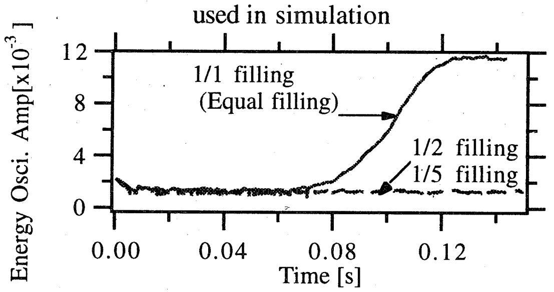

Figure 10. Simulation result for relative energy oscillation amplitude of a bunch.

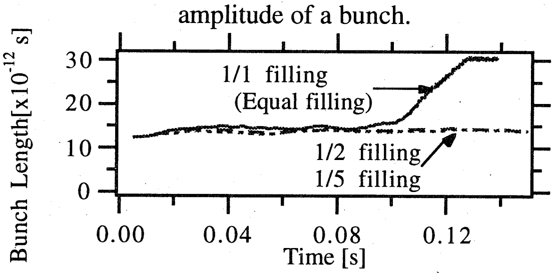

Figure 11. Simulation result for a bunch length(rms). The growth of the instabilities was saturated as increase of the bunch length.

6 Chromaticity Control

head-tail damping

As the bunch current increases with positive chromaticity, transverse head-tail damping becomes strong and overcomes instabilities. This scheme was applied to several machines such as KEK TRISTAN[4]. In the SPring-8, this damping is estimated by the simulation by SISR and is comparable to radiation damping at 0.2-0.3mA/bunch for chromaticity is 4.

tune modulation effect

Each electron with non-zero amplitude of synchrotron oscillation executes non-harmonic betatron oscillation. This is caused by the betatron frequency modulation by chromaticity and the energy oscillation by synchrotron motion. This reduce the effect of harmonic force of wake field which impedance source produces on the electrons. The reduction factor is

$$\int_0^\infty J_0^{\,2}\left(\left(\frac{\omega_{HOM}}{\omega_s}\eta+\frac{\xi}{\omega_s}\right)\hat{\delta}\right)\frac{1}{\sigma_\delta^{\,2}}\,e^{-\frac{\hat{\delta}^2}{2\sigma_i^2}}\,\hat{\delta}\,d\hat{\delta}$$

where ξ, σ_δ, ω_s, and h are chromaticity, energy spread, synchrotron frequency and momentum compaction factor, respectively. This factor reduces the effect of the force on bunch and affects the motion like electron energy increase because this increase the rigidity of the bunch to coherent excitation as shown in Figure 12.

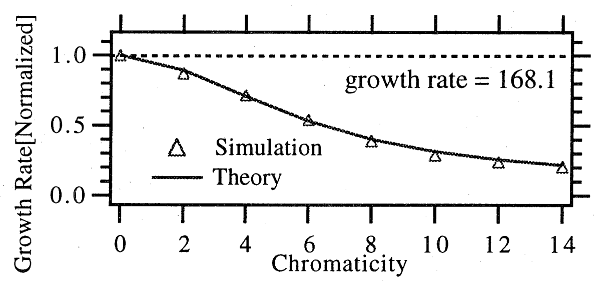

Figure 12. Growth rate of transverse multi-bunch instabilities by the model impedance vs chromaticity.

7 Chromaticity Modulation

Chromaticity modulation[5] by synchrotron frequency produces intra-bunch betatron tune spread and cause de-coherence of the electrons in a bunch and cure transverse instabilities. Because this scheme can produce tune spread inside of a bunch, this scheme is also effective to single-bunch instabilities.

8 Bunch Current Dependent Tune Shift

Betatron frequency of a bunch depends on its bunch current by wake field produced by impedance and this shift is estimated to be 0.4-0.5 kHz/(mA/bunch) as shown in Sec.1. And single-bunch mode-coupling instabilities occurs and the bunch is lost where this shift is comparable to synchrotron tune 1.5kHz~2kHz at 3mA/bunch ~5mA/bunch. By distributing the bunch with different bunch current, inter-bunch tune spread can be obtained to cure transverse multi-bunch instabilities and the spread of 1mA/bunch is enough to cure it for the model impedance.

9 Coclusion

Using simulation codes, the strength and characteristics of the instabilities of the storage ring is estimated and the effects of the possible scheme to cure of them were studied. The result shows that the storage ring can store design value of their current, average current 100mA and 5mA/bunch.

References

[1,2,3,5] Refer SPring-8 Annual Report 1995 and 1996.

[2] T. Nakamura, "The Simulation Study of the Single-Bunch Instabilities in the SPring-8 Storage Ring," The Fifth European Particle Accelerator Conference, Sitges(Barcelona), June 1996, p1102.

[3] T. Nakamura, "Broad-Band Impedance of the SPring-8 Storage Ring," The Fifth European Particle Accelerator Conference, Sitges(Barcelona), June 1996, p1099.

[4] K.Akasaka, S.Kamada, "Experimental Study of Head-Tail Damping and Nonlinear Filamentation Based on Precise Analysis of Coherent Betatron Oscillations in Electron Storage Rings," Proc. of The Fifth European Particle Accelerator Conference, Sitges(Barcelona), June 1996, p1141.

[5] T. Nakamura, "Cure of Transverse Instabilities by Chromaticity modulation," Proc. of the 1995 Particle Accelerator Conference, Dallas 1995, p3100.