Possible Methods for Cure of Multi-Bunch Instabilities in the SPring-8 Storage Ring

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1. Introduction

Multi-bunch instabilities are the limiting factors of average current in most light sources. In 6-8 GeV third generation light sources, ESRF, APS and SPring-8, the threshold current of the instabilities by a single cavity are the same order to nominal current and some stabilization scheme is necessary for stable operation. The source of the instabilities are impedance of cavity-like elements and resistive wall impedance of small gap chamber for such as insertion devices.

Multi-bunch instabilities caused by cavity higher-order modes are cured by damping of their impedance or shifting their frequency from resonance of instabilities. In the SPring-8 storage ring, the resonance frequency of higher order modes of the cavities are scattered not to overlap each other by changing their shapes slightly and each cavity has two independent movable tuners to control frequencies of higher order modes not to hit resonance of instabilities while keeping frequency of an acceleration mode.

Except from detuning of higher order modes, there still several methods exist to cure multi-bunch and are analyzed for the SPring-8 storage ring in the following.

2. Multi-Bunch Instabilities in the SPring-8 Storage Ring

Maximum 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 used 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 the simulation and are almost ∴1.5 and ∴2 of those of a single cavity for longitudinal and transverse, respectively.

Table 1. Parameters of the SPring-8 Storage Ring

Parameter		Value
Energy	E_0	8 GeV
Revolution Frequency	f_{rev}	208.8 kHz
Average Current	I_0	100 mA
Energy Loss / turn	U_0	9.2 MV
Radiation Damping Time (Long.)	τ_E	4.1 ms
Radiation Damping Time (Trans.)	τ_x τ_x	8.3 ms
Momentum Compaction Factor	α	1.46×10^{-4}
Betatron Tune (horizontal)	ν_y	51.22
Betatron Tune (vertical)	ν_x	16.16
Beta Function at cavities (x,y)	β	~ 10 m

Table 2. Model impedance for simulation

Average Current	100 mA
Longitudinal Impedance	
R/Q	720 Ω
Q	4000
Frequency	1018 MHz
Transverse Impedance	
R/Q	2308 Ω/m
Q	13000
Frequency	1006 MHz
Beta Function at impedance	10 m
Acceleration Cavity	
R/Q	1855 Ω
Q	1588
Frequency	508.58 MHz
Voltage driven by External Generator	17 MV/turn
Acceleration Voltage at Iave=100mA	14 MV/turn

3. Acceleration Voltage Modulation by Partial-Filling

When a bunch passes a cavity, the bunch is accelerated and extracts energy from RF field in the cavity and reduce its RF voltage. This effect is called beam-loading. 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, which compensate the energy extracted by beam-loading. 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. The acceleration voltage modulated by beam-loading by partial-filling operation can cure longitudinal multi-bunch instabilities and 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[1] developed in the SPring-8 and is shown in Figure 1. Even in 1/2 filling, the amplitude of modulation is more than 0.5MV and resulting synchrotron frequency spread is shown in Figure 2 and is $\Delta f_s \sim 70$Hz. The damping time by this spread is $\tau \sim 1/(2\pi\Delta f_s) = 2.2$ms which is twirce faster than the longitudinal radiation damping time, 4.1ms.

The simulation result, Figure 1-5, 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 In Figure 4 and Figure 5, 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.

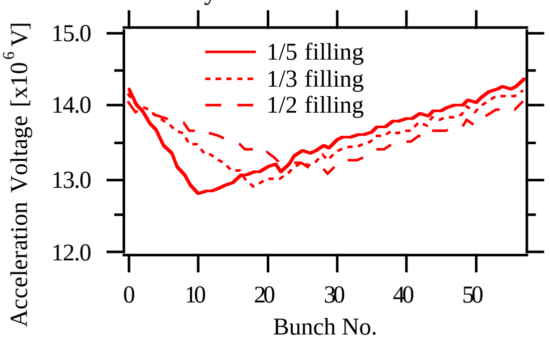

Figure 1. Amplitude of acceleration voltage vs. bunch number. The number of bunch per turn used in the simulation is 59 and first 1/5, 1/3 and 1/2 bunches filled with electrons. At equal filling, acceleration voltage is 13.5 MV

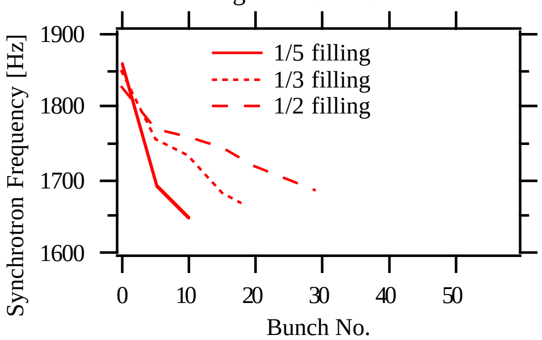

Figure 2. Synchrotron Frequency vs. Bunch Number from simulation result. Only bunchs which have electrons are shown.

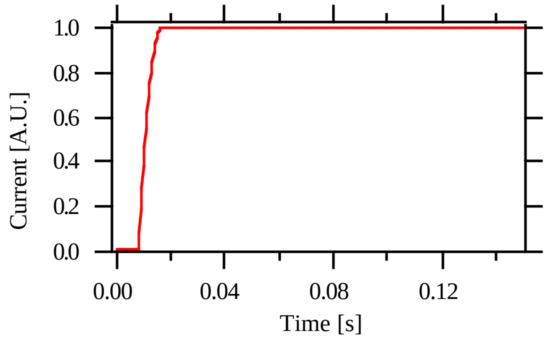

Figure 3. Increase of the current for simulation.

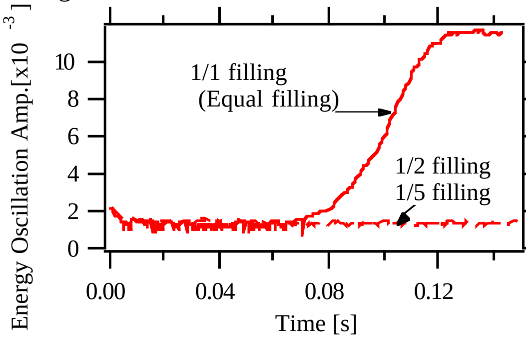

Figure 4. Simulation result for relative energy oscillation amplitude of a bunch for several filling patterns.

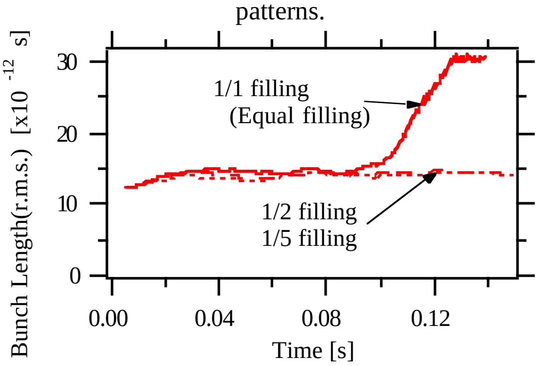

Figure 5. Simulation result for a bunch length for several filling patterns. The growth rate of the instabilities saturated by increase of the bunch length.

4. Add-On Acceleration Systems

$f=f_{acc}+mf_{ref}$, $f_{acc}-mf_{ref}$ Acceleration system

Bunch-by-bunch spread of the synchrotron oscillation can be produced by installation of acceleration system of the frequency $f=f+mf_{acc}$ or $f=f-mf_{acc}$ and is performed in several rings[2]. This acceleration system modulates amplitude of acceleration voltage and produce bunch-by-bunch spread of synchrotron oscillation frequency as in the case of partial-filling.

As in the case of partial filling, 0.5MV of modulation voltage which is the same amount of the case of 1/2 filling is enough to cure instabilities driven by the model impedance.

Higher Harmonic Acceleration system

Such acceleration system introduces non-harmonic potential for synchrotron oscillation and produces amplitude dependent synchrotron tune shift for electrons in a bunch[3]. However in the SPring-8 storage ring, bunch length is so short, 3.5-5mm, and the adjustment of the phase of such acceleration system to introduce non-harmonic potential in this short region is rather hard. Simulation shows that the increase the time gradient of the total acceleration voltage with this acceleration system to increase synchrotron tune is rather effective to decrease the strength of the longitudinal instabilities. In this case, the phase is 180deg. different from the phase to flatten the synchrotron potential to introduce non-harmonic potential.

5. Chromaticity Control

head-tail damping

As the bunch current increases with positive chromaticity, transverse head-tail damping becomes strong and overcomes instabilities. This can be achieved by reducing the number of bunches in the ring. This scheme is applied to several machines, such as KEK TRISTAN[4]. In the SPring-8, this damping is estimated by the simulation by SISR[5,6] to be 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

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

where ξ , σ_δ , ω_s are chromaticty, energy spread and synchrotron frequency, 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 6.

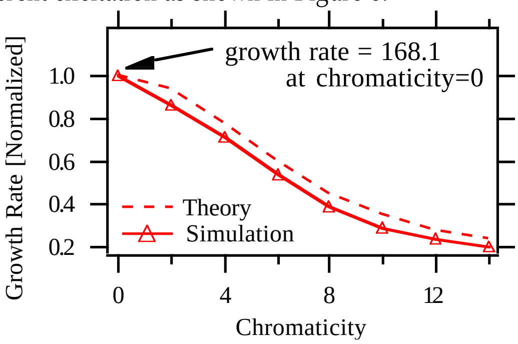

Figure 6. Growth rate of transverse multi-bunch instabilities driven by the model impedance with finite chromaticity.

6. Chromaticity Modulation

Chromaticity modulation[7] by synchrotron frequency produces intra-bunch betatron tune spread and produce de-coherence of the electrons in a bunch.

Because this scheme can produce tune spread inside of a bunch, this scheme is also effective to single-bunch instabilities.

7. Bunch Current Dependent Tune Shift

Betatron tune of a bunch depends on its bunch current by wake field produced by impedance[8]. In the SPring-8 storage ring, this dependence is estimated to be 0.002/(mA/bunch) or 0.4 kHz/(mA/bunch) by the simulation with SISR[5,6]. And single-bunch mode-coupling instabilities occurs and the bunch is lost at 3mA/bunch ~5mA/bunch where this shift is comparable to synchrotron tune 0.010-0.007[5,6]. By distributing the bunch with different bunch current, bunch-by-bunch tune spread can be obtained and the spread of 1mA/bunch is enough to damp the model impedance.

References

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