SIMULATION OF LONGITUDINAL BEAM DYNAMICS WITH THE THIRD HARMONIC CAVITY FOR SSRF PHASE II PROJECT

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Abstract

Longitudinal beam dynamics especially transient beam loading effects of a passive superconducting third harmonic cavity which will be installed in the SSRF storage ring in phase II project are simulated with a self-developed code. The harmonic phase shifts along the bunch train is found which will reduce the bunch lengthening effect. The synchrotron tune spread is also be evaluated in the paper.

INTRODUCTION

Shanhgai synchrotron radiation facility (SSRF) is a third generation light source which consists of a 150 MeV linac, a 3.5 GeV booster with 180 m in circumference, a 432 m, 3.5 GeV storage ring and phase-I seven beamlines. The storage ring gets 20 double-bend-achromat cells, four 12 m long straight sections and sixteen 6.5 m standard straight sections. The nature emittance of the storage ring is 3.9 nmrad. The light source has been opened to users since April 2009. During the last five years, 6 beam lines have been built. Among them, 5 beamlines are dedicated to protein sciences within the program of National Facility for Protein Sciences [1].

SSRF phase-II project has been proposed since 2011. In phase-II project 16 beam lines will be built and the electron storage ring will be upgraded. The storage ring upgrade plane consists of adding a passive superconducting 3rd harmonic cavity to stretch the bunch length; a superconducting wiggler for hard X-ray production; a 650W 4.2K cryogenic system to support more cryogenic devices; two cells' bending magnets will be replaced by super-bends to create short straight sections and provide hard X-ray radiations from the super-bends.

The main purpose of the 3rd harmonic cavity is to increase the Touschek lifetime which will operate in stretching mode, the sketch of superconducting cavity module is shown in Figure 1. It can also provide Landau damping in longitudinal plan to increase the longitudinal single bunch current threshold. The cavity will operate in passive mode which will make the system simple and economy. However the beam dynamics will be more complex. Among them transient beam loading effects should be studied carefully which will great effects the lengthening effects. In this paper a self-developed time domain iterative tracking code is developed to explore the transient loading effect and a preliminary solutions has been found.

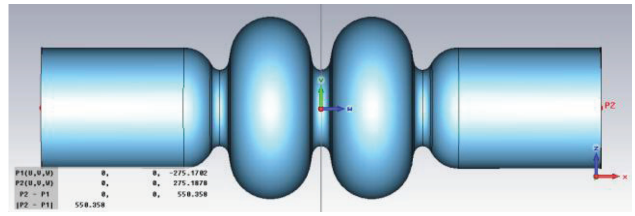

Figure 1: Preliminary design of a two cell 3rd harmonic cavity, operate at temperature 2K, provide1.5GHz, 1.4MV voltage.

TRACKING METHOD

For the passive cavity, the RF voltage inside is excited by the wakefields of the beam passing through the cavity. The wakefields excited by the bunch passing through can be written under here [2],

$$V(\Delta t) = -2kqe^{(\omega\sigma_l)^2/2}e^{[j\omega-(\omega/2Q)]\Delta t}, \tag{1}$$

where Δt is the time between the previous bunch pass through the cavity and the witness bunch pass through the cavity, $\Delta t > 0$. ω, Q are the resonance angular frequency and quality factor of the 3rd harmonic cavity respectively. q is the bunch charge excites the wakefield. $k = \omega R/(2Q)$, R is the shunt impedance of the cavity. σ_l is the bunch RMS length. For Δt=0, the bunch experiences the self-excited wakefield should be:

$$V(0) = -kqe^{(\omega\sigma_l)^2/2}, \tag{2}$$

The total voltage in the cavity is the sum of all the wakefields exited by the preceding bunches passing through the cavity and the witness bunch self-excited wakefield.

$$V_{total} = \sum_{\Delta t=0}^{\infty} V(\Delta t). \tag{3}$$

The longitudinal motion of the bunch can be tracked using difference equations under here,

$$\varphi^{n+1} = \varphi_s + \omega_{rf}\Delta\tau^n, \tag{4}$$

$$\Delta U = 2\varepsilon^n T_0/\tau_s, \tag{5}$$

$$\varepsilon^{n+1} = \varepsilon^n - U_0 + V_{rf}\cos(\varphi^{n+1}) - \Delta U + V_{total}^{n+1}, \tag{6}$$

$$\Delta\tau^{n+1} = \Delta\tau^n + \alpha * \varepsilon^{n+1} * T_0/E_0, \tag{7}$$

where φ_s is the synchrotron phase, ω_{rf}, V_{rf} are the angular frequency and voltage of the main RF system, T_0

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is the revolution period, τ_s is the longitudinal radiation damping time, U_0 is the radiation loss per turn, α is the momentum compaction factor, E_0 is the beam energy, ε is the relative beam energy deviation.

For a superconducting cavity, the quality factor Q is usually bigger than 10^8, it is impossible to record the wakefield within $10^8/H$ turns (where H is the harmonic number of the ring) of hundreds bunches in the ring. As indicated in [3] a reduction of Q will not change the tracking result. So it is reasonable to reduce the Q to 10^4~10^5 which will greatly reduce the number of turns that wakefields need to be recorded for tracking and reduce the turns for convergence of the longitudinal oscillations.

The code is written in Matlab. Although it is slow in 'for' loop, it is convenient for coding and speedy for array manipulation and also friendly for post process of tracking results.

TRACKING OF TRANSIENT LOADING

The main parameters of SSRF storage ring and of the 3rd harmonic cavity is listed in Table 1. In the tracking, the quality factor of the 3rd harmonic cavity is reduced to 1.5×10^5 and wakefields within 200 turns are take into account for voltage build up which make the simulation end up in a reasonable time($720\times200\approx1.5\times10^5$).

Table 1: Main Parameters of SSRF Storage Ring and 3rd Harmonic Cavity

Parameters	Value
Electron energy (GeV)	3.5
Circumference (m)	432
RF frequency (MHz)	500
Harmonic number	720
RF voltage (MV)	4.0
Beam current (mA)	300
Energy loss per turn (MeV)	1.44
Momentum compaction	4.2e-4
Bunch length (mm)	4.0
Longitudinal damp time (ms)	3.5
R/Q of 3rd harmonic cavity (Ω)	180
Q of 3rd harmonic cavity	1e10

The detuning frequency of the 3rd harmonic cavity is +63KHz at which point the voltage excited in the 3rd harmonic cavity is about 1/3 of the main RF voltage and the Robinson instability can be damped by the radiation damping for the uniformly filled storage ring. However most of the storage rings are partially filled. The empty gaps are used to cleaning ions to avoid ion related instabilities [4]. The partially filling pattern is the source of the transient loading effects: the 3rd harmonic RF voltage and the phase will vary along the bunch train which makes the bunch lengthening effect deviate from theoretical value. For SSRF, a practical filling pattern is a 500-bunch train filled in the storage ring, leaves a 220-bucket empty gap. The tracking results of the voltage, harmonic phase and the lengthening factor is shown in Figure 2, 3 and 4. The average lengthening factor is 2.3 which is smaller than optimized lengthening factor 3.7 (Bunch length is characterized in full width at half maximum).

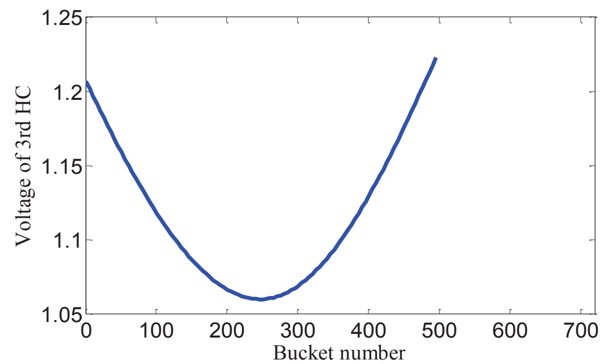

Figure 2: Tracking result of the voltage in the 3rd harmonic cavity along the bunch train.

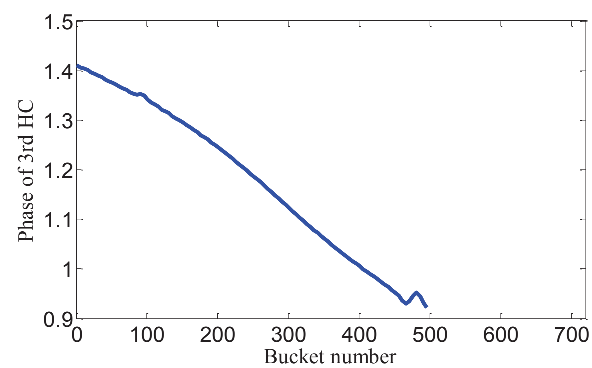

Figure 3: Tracking result of harmonic phase in 3rd harmonic cavity along the bunch train.

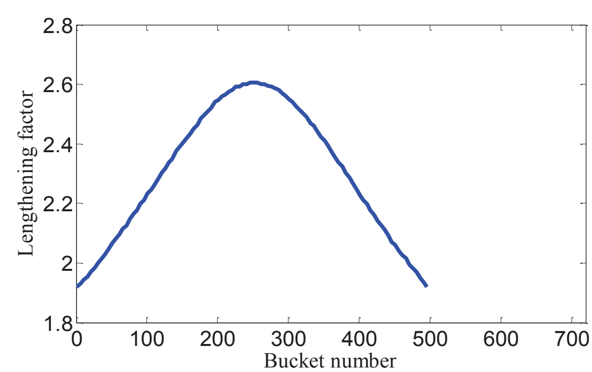

Figure 4: Tracking result of lengthening factor along the bunch train.

In order to reduce the transient effects, multi bunch-trains has been tried. Five bunch trains each contains 100 bunches separated by 44 empty buckets makes the filling more uniform. The tracking result is as shown in Figure 5, the average lengthening factor is 4.3, much bigger than a long bunch train. In this case, bunches are a little bit over stretched to bi-Gaussian shape which makes the lengthening factor even grate than optimized value. In this

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tracking the detuning frequency is kept constant with long bunch train case +63KHz. If detuning frequency gets bigger the over stretch can be avoided which will benefit for instability aspect because the impedance see by the beam will be much smaller.

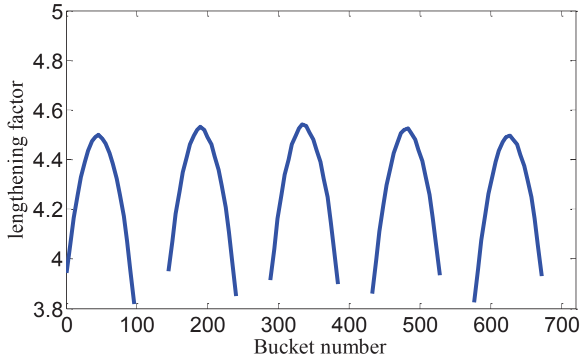

Figure 5: Tracking result of lengthening factor for multi bunch-trains.

The bunch lengthening benefits beam lifetime is more importance for single bunch operation or a hybrid operation mode. For them, the high single bunch charge will greatly reduce the single bunch lifetime. For single bunch operation mode, it will be a uniform filling, the transient loading will be neglected. However for hybrid mode, the transient loading effect will be a big problem. Figure 6 shows the bunch lengthening factor for a big bunch fills at different place in an empty-buckets-train. It is clear that the single bunch at the middle of the empty-bucket-train gets the optimal harmonic phase and gets the biggest lengthening effect.

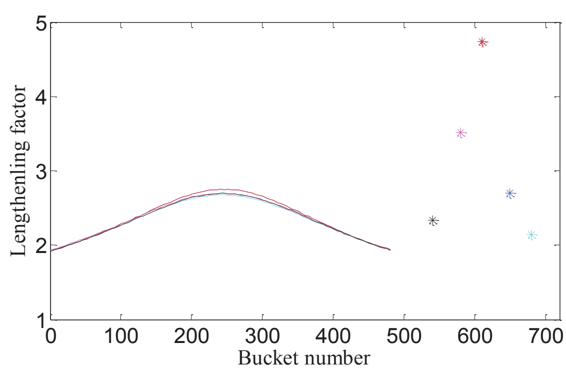

Figure 6: Tracking results of lengthening factor for hybrid filling patterns. The single bunch is represented by a star with bunch current 9mA.

EVALUATE SYNCHROTRON FREQUENCY SPREAD

The synchrotron frequency including a 3rd harmonic cavity can be evaluated both by analytical method [5] and tracking method. Figure 7 shows the synchrotron frequency distribution at different 3rd harmonic voltages. When 3rd harmonic voltage approaches the optimized value, the frequency gets a wide spread which will greatly benefit suppression longitudinal instabilities as Landau damping rate increases.

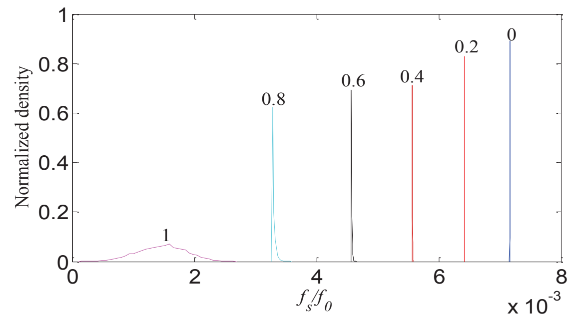

Figure 7: Synchrotron frequency distribution at different 3rd harmonic voltages (The number indicates $V_{3rd}/V_{3rd\text{-}optimized}$).

When 3rd harmonic voltage above optimized value, the bunch will distorted to bi-Gaussian shape as shown in Figure 8. The synchrotron frequency will split into 3 parts as shown in Figure 9. The blue and the red one is the frequency of particles sit in the two valley of the potential well as show in Figure 8. where two density peaks appear. And the pink one is the particles that with higher energy which oscillate pass through both valleys

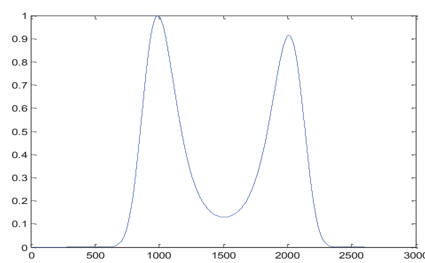

Figure 8: Bi-Gaussian shape of a over stretched bunch.

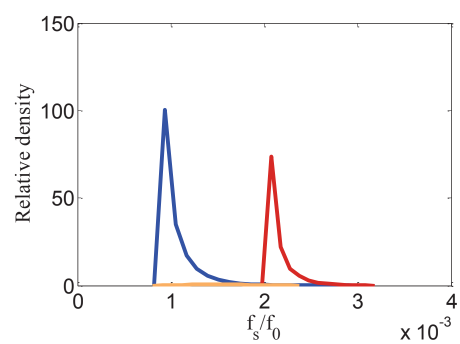

Figure 9: Frequency distribution of bi-Gaussian bunch.

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