BUNCH LENGTHENING IN TAIWAN PHOTON SOURCE USING HARMONIC CAVITY*

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Abstract

A higher harmonic RF cavity is usually considered as an important tool to control the bunch length in the storage rings. In this article we study the effects of third active harmonic cavity on bunch length in the 3 GeV Taiwan Photon Source (TPS). We present the procedure, the simulation and the formulae to analyze the effects of third harmonic cavity on the rms bunch length while the main accelerating RF system was operated in 3 MV. It is shown that the longitudinal rms electron bunches will lengthen up to 7.9 times for the optimum operation of the harmonic system.

INTRODUCTION

The typical rms bunch length in the storage rings can be manipulated by the main RF gap voltage. Increasing voltage in the storage rings generates a reduction in bunch length. In addition to the bunch length, it affects the lifetime issue in the ring. The beam lifetime in the storage rings is usually dominated by large angle intrabeam (Touschek) scattering in which elastic collision of electrons [1, 2] have a finite probability of transferring enough longitudinal momentum to each electron such that they no larger are within the momentum acceptance of the storage ring and therefore are lost. As a result, for the light sources with high density of electrons, a very short bunch produces strong parasitic losses and short Touschek lifetime.

The harmonic cavity is one of the solutions to lengthen the bunch and recovering the lifetime in the light sources. Curing beam instabilities and damping coherent instabilities [3] such as the longitudinal coupled bunch instabilities through an effect known as Landau damping are the other benefits. Another advantageous is that the harmonic phase can be adjusted such that the bunch length is shortened. This mode of operation may be of interest to a selected group of users for whom lifetime is not the primary concern. In spite of the benefits, considering higher harmonic RF systems in the storage rings at the lengthening mode has some unwanted effects. Beam current reduces when the rms electron bunch is lengthened. Moreover, in the presence of X-ray pulse compressing system consists of a pair of transverse deflecting RF cavities (crab cavity) [4, 5] in the storage ring operating higher RF systems causes transverse emittance of electron bunch degrades greatly and the intensity of photons in beam line will be reduced. Since a pair of superconducting deflecting structures in the quadruple-bend achromat (QBA) lattice of TPS has been investigated for ultra shot X-ray pulses production, it motivated us to find how much the electron bunch could be lengthened in TPS.

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HIGHER HARMONIC RF SYSTEMS

The double RF system in the storage rings allows shaping the accelerating voltage at the time of passage of the synchronous particles and bunch lengthening is achieved by reducing the slope of accelerating voltage in the vicinity of electron bunch. A. Hofmann [6-9] has described the RF conditions for a double RF system that yields bunch lengthening. The voltage slope seen by every bunch at each turn changes and longitudinal bunch size is obtained without considerably affecting the RF acceptance as follows

$$\sigma_l \propto \sqrt{\frac{\alpha_c \gamma^3}{dV_{RF}/dz}} \tag{1}$$

where the α_c is the momentum compaction factor and γ is the relativistic factor. The total RF voltage seen by the beam at presence of higher RF system is given by

$$V = V_{RF}\left[Sin(\varphi+\varphi_s) + kSinN(\varphi+\varphi_n)\right] \tag{2}$$

where k is the ratio of the harmonic voltage to the main RF one, N denotes the nth harmonics, V_{RF} is the peak voltage and φ_s and φ_n are synchronous and relative harmonic phases, respectively. For optimum bunch lengthening, slope of accelerating voltage has to be horizontal in the electron bunch and the voltage should not be curved at this point. It means that the first and second derivatives of voltage must vanish.

$$Cos\varphi_s = -kNCosN\varphi_n \, , \, Sin\varphi_s = -kN^2 SinN\varphi_n \, . \tag{3}$$

Since the energy loss per turn for both single ($U_0 = eV_{RF} Sin\varphi_{s0}$) and double RF systems ($U_0 = eV_{RF}\left[Sin\varphi_s + kSinN\varphi_n\right]$) due to synchrotron radiation is fixed, the synchronous phase for double RF system reduces comparing with single RF system. This phase condition is presented in Fig. 1. The difference in synchronous phase in single and double RF system is explained in terms of parameters of harmonic cavity such as voltage and phase as below

$$Sin\varphi_{s0} = Sin\varphi_s + kSinN\varphi_n \tag{4}$$

where φ_{s0} and φ_s are synchronous phases in single and double RF systems, respectively. The conditions lead to finding harmonic parameters for optimum bunch lengthening. The parameters are computed as following

$$k = \frac{1}{N}\sqrt{1 - \frac{N^2}{N^2-1}\left(\frac{U_0}{eV_{RF}}\right)^2} \tag{5}$$

$$\varphi_s = Sin^{-1}\left(\frac{N^2}{N^2-1}\left(\frac{U_0}{eV_{RF}}\right)\right) \tag{6}$$

$$\varphi_n = \frac{1}{N}\tan^{-1}\left(-\frac{N\left(\frac{U_0}{eV_{RF}}\right)}{\sqrt{(N^2-1)^2 - N^4\left(\frac{U_0}{eV_{RF}}\right)^2}}\right) \tag{7}$$

Operating the RF systems in the optimum parameters for bunch lengthening is shown in Fig. 2.

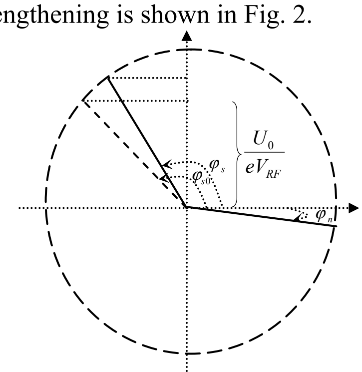

Figure 1: The synchronous phases for single and double RF systems, $\varphi_s < \varphi_{s0}$.

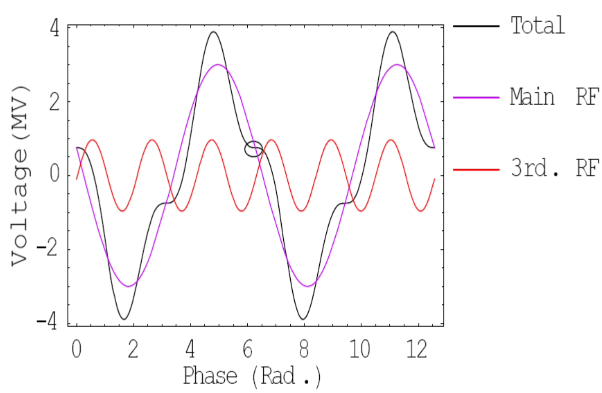

Figure 2: The electron bunch position in the wave form with double RF system. The phase and voltage of harmonic system are adjusted to lengthen the electron bunch.

It is assumed that the main RF cavity and the third harmonic system were operated in 3 and 0.964 MV respectively. The phase of main and third harmonic cavity were adjusted to 163.657 and 358.139 respectively. Fig. 2 shows the wave form of single and third RF systems are cancelled each other at bunch position and near the bunch center, the restoring force of RF voltage is linear and leads to lengthening electron bunch. In this scheme, the peak charge density decreases while the energy distribution is unaffected.

BUNCH LENGTH

The synchrotron equations of motion for an electron in the bunch are given by

$$\dot{\varphi} = \frac{\alpha_c \omega_{RF}}{E}\varepsilon \tag{8}$$

$$\frac{d\varepsilon}{dt} = \frac{eV(t) - U_0}{T_0} \tag{9}$$

where ε is the energy deviation from the beam energy, T_0 is the revolution time and U_0 is the energy loss per turn. The motion of an electron described by the previous equations is similar to that of a particle in a potential well $U(\varphi)$.

$$U(\varphi) = \frac{\alpha_c \omega_{RF} eV_{RF}}{ET_0}[(1-\frac{1}{N^2})(Cos\varphi_s - \varphi Sin\varphi_s) - Cos\varphi_s(Cos\varphi - \frac{CosN\varphi}{N^2}) + Sin\varphi_s(Sin\varphi - \frac{SinN\varphi}{N^3})] \tag{10}$$

For small phases, it changes as following

$$U(\varphi) = \frac{\alpha_c \omega_{RF} eV_{RF}}{ET_0}\frac{N^2-1}{24}\varphi^4 Cos\varphi_s. \tag{11}$$

Since the equilibrium beam profile follows the shape of the potential well, a higher harmonic cavity can provide a longer bunch. By manipulating the potential well, one can change correspondingly the longitudinal distribution of the particles in the bunch. For a fixed total energy, the potential well in the double RF system provides a large range of oscillations for each non-synchronous particle. The effective potential well for single RF system and double RF system including a third harmonic cavity and main accelerating cavity are plotted in Fig. 3. Having in mind the effective potential well of a single RF system is written as,

$$U(\varphi) = \frac{\alpha_c \omega_{RF} eV_{RF}}{ET_0}\left(\frac{Sin\varphi_s}{6}\varphi^3 - \frac{Cos\varphi_s}{2}\varphi^2\right). \tag{12}$$

Thus the flat region of potential well is longer for the double RF system. It means that the electron bunch is expected to be longer in long flat region of double RF system.

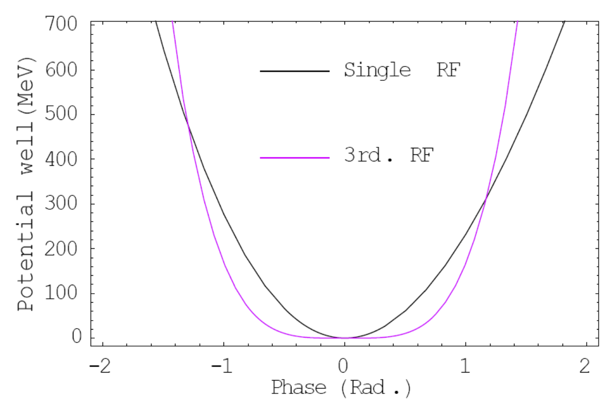

Figure 3: Potential well for single and third harmonic RF system.

Therefore the kinetic energy of electrons in the flat region is maximized and can be written as follows

$$\frac{\dot{\varphi}^2}{2} + U(\varphi) = \frac{\dot{\varphi}_m^2}{2} \tag{13}$$

where $\dot{\varphi}_m$, the phase velocity of an electron with highest energy deviation from nominal energy, is equal to $\frac{\alpha_c \omega_{RF}}{E}\varepsilon_m$. The longitudinal Gaussian density distribution for the electrons in a bunch is determined by the energy distribution in the potential well formed by the total RF voltage. The electron density distribution for double RF system is given by

$$\rho(\varphi) = \rho_0 e^{-\frac{1}{\alpha_c \sigma_\varepsilon^2}\frac{\omega_{RF} e V_{RF}}{E T_0}\frac{N^2-1}{24}\varphi^4 Cos\varphi_s} \quad (14)$$

where ρ_0 is the normalization constant such that $\int \rho(\varphi) d\varphi = 1$. The calculated bunch distribution for the main RF voltage and with the third harmonic voltage adjusted according to Eq. (5), 6) and (7) are shown in Fig. 4. It indicates that the longitudinal rms bunch length increases while the density of electrons has been unaffected.

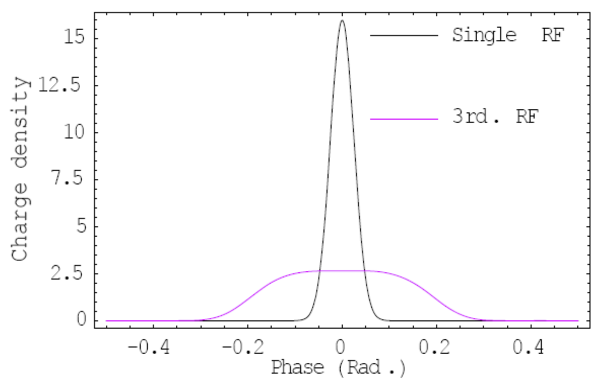

Figure 4: Longitudinal distribution for single and third harmonic system with 3MV gap voltage.

The longitudinal rms bunch length in TPS is around 3 mm of the operation of 3 MV accelerating RF cavity. An external generator is applied and resonant frequency of second RF system is utilized to be third times of the main RF frequency to produce the harmonic voltage in TPS. It is modelled by the RFCA routine of ELEGANT [10, 11] as a program code. We decrease the synchronous phase of main accelerating cavity up to 163.657 degrees. The harmonic cavity is adjusted to optimum RF phase which is 358.139 degrees and the gap voltage is scanned for various voltages. We observed that the maximum bunch length is available for the optimum calculated voltage from Eq. (5).

Normalized bunch length for 3 MV gap voltage is plotted in Fig. 5. It is seen that when $k \to 0$ it goes to unity. By increasing harmonic voltage that is determined by k, the slopes of main and harmonic system better cancelled each other and bunch length increased automatically. It indicates that adjusting phase and voltage of harmonic system, the maximum bunch lengthening are around 7.9 times for third harmonic systems.

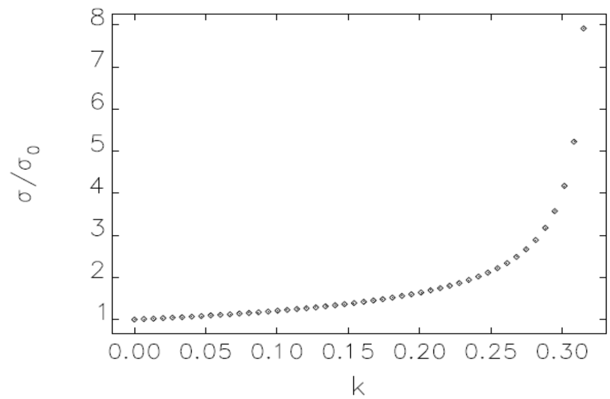

Figure 5: Normalized bunch length versus $k(k = V_{HRF}/V_{RF})$ for third harmonic RF systems. The main gap voltage is 3 MV.

CONCLUSION

A harmonic cavity in TPS is an approach to give additional degree of freedom to control the bunch length. Using ELEGANT tracking code, we have examined a proposed third harmonic RF system for TPS. Although the third harmonic cavity causes unwanted effects such as reduction of beam current but we find that the longitudinal bunch could be lengthened up to 7.9 times for third harmonic while the main RF cavity is operated in 3 MV.

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