BUNCH LENGTHENING EFFECTS BY UTILIZING A THIRD HARMONIC CAVITY IN CONJUNCTION WITH DEFLECTING CAVITIES IN TPS†

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Abstract

The effects of utilizing a third harmonic RF cavity in the lengthening mode have been investigated on quality of the electron beam and the emitted photons in the deflecting RF structures for TPS. For the obtained optimum synchronous and relative harmonic phases and harmonic voltage of 0.7 MV, the equilibrium horizontal and vertical emittances blow up as much as 13% and 97%, respectively. In addition, the intensity of the emitted X-ray pulses with 0.54 ps FWHM reduces by 30%.

INTRODUCTION

The typical rms bunch length in a storage ring is usually about several tens of picoseconds (ps). Many efforts have been made to produce shorter X-ray pulses in synchrotron radiation facilities [1,2]. As a third generation light source, the 3 GeV Taiwan Photon Source (TPS) would produce about 10 ps-long (rms) X-ray pulses by operating the accelerating radio frequency (RF) cavity at 3 MV. The TPS proposed design is made of six super-periods, each consisting of two Quadruple-Bend Achromat (QBA) cells [3] and a pair of crab cavity investigated in TPS for generating short X-ray pulses [2]. However, in order to decreasing the parasitic losses, reducing of current loss rate and improving of the beam lifetime for TPS, we have utilized a third harmonic RF cavity in the lengthening mode in our simulation [1] in conjunction with the crab cavities and studied the effects of the electron bunch lengthening. The higher harmonic RF system has some undesired effects in presence of the deflecting structures.

The double RF system in storage rings allows shaping the accelerating voltage at the time of passage of the synchronous particles and bunch lengthening is achieved without considerably affecting the RF acceptance by reducing the slope of accelerating voltage in the vicinity of electron bunch [4,5]. The total RF voltage seen by the beam in presence of a higher RF system is given by

$$V = V_{RF}(\sin(\varphi+\varphi_s) + k\sin N(\varphi+\varphi_n)) \qquad (1)$$

where V_{RF} is the peak RF voltage, k is the ratio of the harmonic voltage to the main RF ($k = V_{HRF}/V_{RF}$), N denotes the nth harmonic, φ_s and φ_n are synchronous and relative harmonic phases, respectively. For the optimum bunch lengthening, the slope of the accelerating voltage has to be horizontal in the electron bunch and the voltage should not be curved at this point. This condition gives the following optimum harmonic RF parameters

$$\varphi_s = \sin^{-1}\left(\frac{N^2}{N^2-1}\left(\frac{U_0}{eV_{RF}}\right)\right) \qquad (2)$$

$$\varphi_n = \frac{1}{N}\tan^{-1}\left(-\frac{N\left(\frac{U_0}{eV_{RF}}\right)}{\sqrt{(N^2-1)^2 - N^4\left(\frac{U_0}{eV_{RF}}\right)^2}}\right) \qquad (3)$$

$$k = \frac{1}{N}\sqrt{1-\frac{N^2}{N^2-1}\left(\frac{U_0}{eV_{RF}}\right)^2} \qquad (4)$$

where e is the electron charge and U_0 is the energy loss per turn and equal to 0.75 MeV for TPS. These equations indicate that for the optimum bunch lengthening in TPS with V_{RF}=3 MV, the third harmonic system must be operated in 0.96 MV (k=0.32) and the calculated optimum synchronous and relative harmonic phases are 163.66 and 358.14 degrees, respectively. For the various harmonic voltages and fixed phases as given above, the normalized bunch length is shown in Fig. 1.

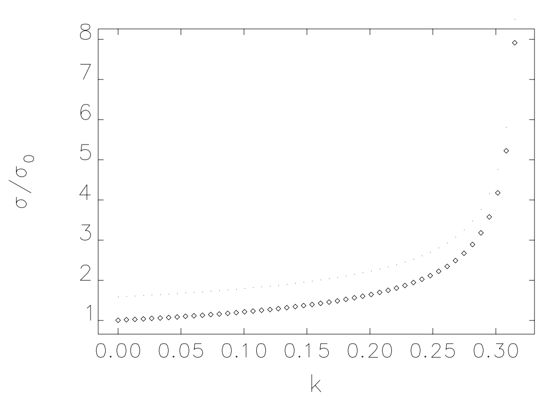

Figure 1. The normalized bunch length as a function of k for the third harmonic RF system in TPS. The main RF gap voltage is fixed at 3 MV (φ_s=163.66, φ_n=358.14 degrees and E=3 GeV).

As expected, when k approaches zero the normalized bunch length goes to unity as well and by increasing harmonic voltage determined by k, the slopes of the main

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and third harmonic RF systems cancel each other better and the bunch length increases. This figure indicates for the obtained optimum harmonic parameters the electron bunch can be lengthened to around 7.9 times of its nominal value. It is seen that for k=0.23 (V_{HRF} =0.7 MV) the electron bunch will be lengthened around twice as much and in turn improves the beam lifetime sufficiency. Since a low beam emittance degradation, a sup-picosecond duration of the X-ray pulses with an acceptable intensity for the users and a sufficient lifetime are desired simultaneously in TPS, in the remainder of our studies the third harmonic cavity with the obtained optimum synchronous and relative harmonic phases is set to operate at 0.7 MV.

BEAM EMITTANCE

To produce a large vertical kick and a rapid angular variation regarding the quantum lifetime limitation the crab cavities are set at 6 MV and 8th harmonic prior to the electron tracking. For 10 ps and 19 ps electron bunches generated by the single and double RF (main RF cavity + third harmonic cavity) systems, the vertical slopes of around 0.95 mrad and 0.5 mrad are obtained respectively. As the deflecting parameters are fixed, the sinusoidal formation of the vertical kick would be clear for the third harmonic RF system and thus the vertical amplitude of the electrons for the main RF system becomes smaller than for longer bunch which could be helpful for the interior sextupoles. Therefore we expect lower emittance for double RF system in TPS. The equilibrium transverse emittance on successive passes through the ring for both single and double RF systems is shown in Fig. 2. Tracking of electrons with deflecting voltage (V_d) of 6 MV and without deflecting voltage are included.

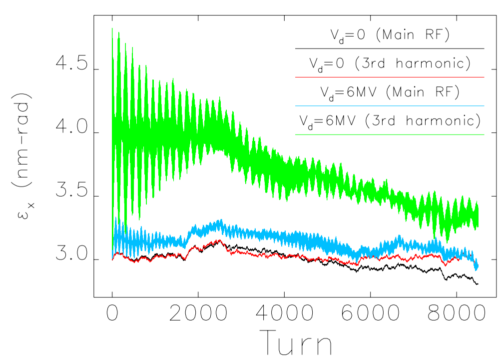

Figure 2(a): Horizontal emittance degradation on successive passes for the both main and 3rd harmonic RF systems in TPS.

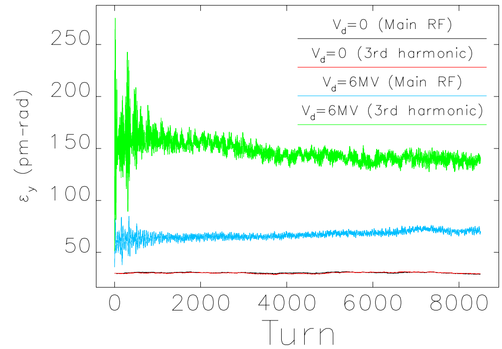

Figure 2(b): Vertical emittance degradation on successive passes for the both main and 3rd harmonic RF systems in TPS.

As presented, degradation of the horizontal emittance for the main RF operation even for 6 MV deflecting voltage is small but for the third harmonic system the eventual horizontal emittance blows up from 3 nm-rad to around 3.4 nm-rad. Moreover, the eventual vertical emittance for the single and double RF systems with crab cavities at 6 MV and 8th harmonic increases from the nominal value of 30 pm-rad to around 70 pm-rad and 138 pm-rad, respectively. In other words, the eventual vertical emittance for the single RF operation becomes half as much as compared to the third harmonic operation with the harmonic voltage at 0.7 MV. The main reason for this large discrepancy is the higher charge density near the bunch center for the single RF system. As a consequence, the electron bunch would has been a lower beam emittance.

X-RAY

The radiated photons are tracked in the TPS photon beamline which is composed of a 60 m long drift space, a slit and an asymmetrically cut crystal. The radiated photons after drifting the 60 m distance are cut by the slit in the photon beamline and the minimum duration of the radiated pulses for V_d=6 MV and h=8 is achieved by optimizing the parameter of crystal. Transmission of the radiated pulses versus the slit size for both single and double RF systems is plotted in Fig. 3. As far as the duration of radiated pulses of the reflected photons from the crystal is concerned, the photon transmission versus the FWHM is obtained and presented in Fig. 4. The recent figures indicates that for the extreme operation mode of crab cavities (6 MV and h=8), the minimum FWHM of the radiated pulses for a small slit size is around 0.42 ps. They also show that when the slit size is 100 mm, a 62% photon transmission with the FWHM of around 0.5 ps for double RF system can be achieved while around 90% transmission with FWHM of 0.48 ps is obtained for the single RF cavity in TPS. They further indicate that for the single RF operation and slit size of 140 mm associating to FWHM of 0.54 ps, the photon transmission is approximately 30% more than the double RF system operation. Moreover, for a complete photon transmission a difference of around 500 fs FWHM between the main RF and third harmonic systems is observed. Since the characteristics of the radiated photons from the ID are associated with the electron beam characteristics, the density of the photons at a fixed distance from the bunch center for the single RF is more than the double RF system operation. Moreover, divergence of the photons emitted from the longer electron bunch is relatively larger than the shorter bunch and for a fixed slit size the number of photons pass the slit in the single RF is much more than the double RF system operation and thus a higher transmission of radiated photons is observed for the single RF operation.

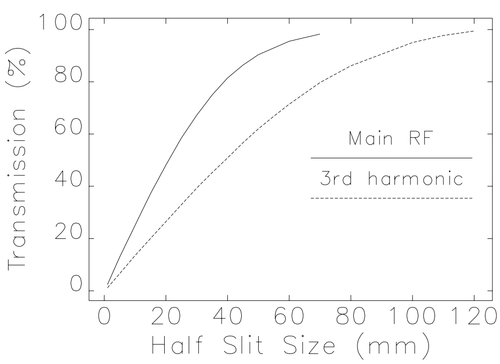

Figure 3. Transmission of the photons through the slit in the TPS photon beamline versus the half slit size, for the main and 3rd harmonic RF systems.

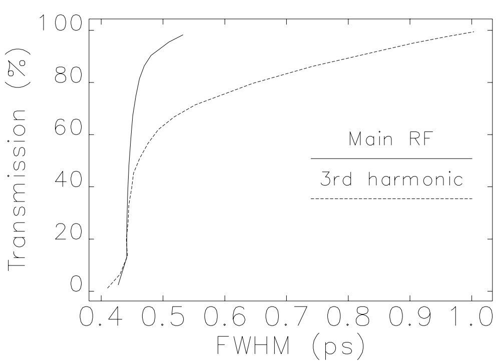

Figure 4. Transmission of the photons through the slit in the TPS photon beamline as a function of the FWHM of the X-ray pulses, for the main and 3rd harmonic RF systems.

CONCLUSION

In operation of the double RF system as compared to the single RF system for the extreme operation mode of the crab cavities, the eventual horizontal emittance blows up from 3 nm-rad to around 3.4 nm-rad, and the equilibrium vertical emittance blows up to around twice as much, 138 pm-rad, where its degradation is no longer negligible. It is noteworthy to mention that although the sub-picosecond X-ray pulses were achieved for both main and third harmonic RF systems but at around 0.54 ps pulse duration, the intensity of the emitted photons for the single RF cavity is around 30% more than double RF cavity in TPS. Consequently, the harmonic parameters should be set according to the desired experimental requirements. When the beam emittance, transmission and duration of the radiated pulses are crucial, it is beneficial to set the harmonic voltage to the lower values. However, when the beam lifetime is in focus, the harmonic voltage should be set at higher values.

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