

# DETERMINATION OF THE ELECTRON BUNCH LENGTH WITH THIRD HARMONIC CAVITY FOR THE TAIWAN PHOTON SOURCE

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## Abstract

The Taiwan Photon Source (TPS) is a modern 3 GeV low emittance light source with RMS bunch lengths of about 3 mm at a beam current of 500 mA and operating gap voltage of 3.2 MV. With a higher harmonic cavity, we could increase the Touschek lifetime and lower the heat load of in-vacuum undulators by lengthening the bunch lengths. Preliminary studies show that for full and uniform fill patterns, the bunch lengths could be increased by a factor of four. However, this calculation ignores phase transient effects and may overestimate the effect of harmonic cavities. A multi-bunch, multi-particle tracking method has been developed to determine the bunch lengths for non-uniform fill patterns, which also takes phase transient effects into account and the expected maximum bunch lengthening factor for different TPS operation conditions are discussed.

## INTRODUCTION

The Taiwan Photon Source (TPS) is a 3 GeV third generation, low emittance light source located at the NSRRC, Taiwan [1]. The 24 cell double-bend achromat (DBA) lattice generates an emittance of 1.6 nm-rad. The RMS bunch length is about 3 mm at a beam current of 500 mA and operating gap voltage of 3.2 MV. Table 1 shows the TPS design parameters.

Table 1: TPS Parameters

Beam Energy	3 GeV
RF frequency	499.65 MHz
Beam current	500 mA
Circumference	518.4 m
Harmonic number	864
RF Voltage	3.2 MV
Energy loss per turn (bending)	853 keV
Momentum compaction	$2.4 \times 10^{-4}$
Longitudinal damping time	6.07 ms
$Q_0$ of main SRF cavity	$1.8 \times 10^9$
$Q_L$ of main SRF cavity	$6.6 \times 10^4$
R/Q of main SRF cavity	47.5
Number of main SRF cavities	2 or 3
Natural energy spread	$8.86 \times 10^{-4}$
Natural RMS bunch length @ 3.2 MV	3.0 mm

Short bunch lengths cause short Touschek lifetimes and high parasitic losses at in-vacuum insertion devices (ID).

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Installation of a higher harmonic cavity (HC) could increase the Touschek lifetime and lower the heat load by bunch lengthening [2]. The effect of a third harmonic cavity in the TPS and the expected bunch lengthening factor were reported in a previous note [3]. Without a double-hump bunch shape theoretical calculations give a maximum bunch lengthening factor of four for a TPS operating at 3.2 MV gap voltage. However, this calculation only considers full and uniform bunch fill patterns, while ignoring phase transient effects, thus overestimating the effectiveness of the HC. A multi-bunch, multi-particle tracking method has been developed to determine the bunch length for non-uniform fill patterns, which takes phase transient effects into account. In this paper, we discuss the tracking method and results for the bunch length elongation factor with phase transients. The expected maximum elongation factor for the TPS under different operating conditions are discussed as well.

## PARTICLE TRACKING METHOD

A multi-bunch, multi-particle tracking method is used to determine the bunch lengths. A difference equation to track the motion of individual electrons in each bunch can be written as [4]:

$$\Delta E_{n+1} = \Delta E_n \cdot \left(1 - 2 \frac{T_0}{\tau_s}\right) + e \cdot \sum (V_{g,l} + V_{b,l}) \quad (1)$$

$$-U_0 + 2 \frac{\sigma_E}{E} E_0 \sqrt{\frac{T_0}{\tau_s}} R$$

$$\Delta z_{n+1} = \Delta z_n + \alpha \cdot c \cdot \frac{T_0}{E_0} \Delta E_{n+1} \quad (2)$$

where  $\Delta E$  is the energy and  $\Delta z$  the phase difference with respect to the synchronous particle. A positive phase difference indicates that the particle is behind the synchronous particle.  $T_0$  is the revolution period,  $\tau_s$  the damping time,  $U_0$  the radiation loss per turn,  $\alpha$  the momentum compaction factor and  $\sigma_E/E$  the nominal RMS energy spread.  $R$  is a random number with normal distribution centered at zero and RMS one. The sum of generator  $V_{g,l}$  and beam-induced voltages  $V_{b,l}$  from all electrons in the  $l^{\text{th}}$  cavity are defined by:

$$\tilde{V}_{b,n,l} = \tilde{V}_{b,n-1,l} \cdot \exp(i\omega_r \Delta t - \frac{\omega_r \Delta t}{2Q_L}) - 2k_{0,l} \cdot q \quad (3)$$

$$\tilde{V}_g = I_{g0} R_L \cos \phi_Z e^{i(\phi_s + \theta_L + \phi_Z)} e^{i\omega_g t_m} \quad (4)$$

$$V_{b,n,l} = \text{Re}(\tilde{V}_{b,n,l}) \quad (5)$$

$$V_g = \text{Re}(\tilde{V}_g) \quad (6)$$

where  $\omega_r$  is the cavity resonance frequency,  $Q_L$  the loaded quality factor,  $\omega_g$  the RF generator frequency,  $q$  the bunch charge and  $k_0 = (R/Q)\omega_r/2$ . The time difference between the current and previous bunch is expressed by  $\Delta t$ . In eq.

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(4),  $R_L$  is the loaded shunt impedance,  $\varphi_s$  the synchronous phase,  $\theta_L$  the loading and  $\varphi_Z$  the tuning angle of the main cavity. The tuning angle can be written as:

$$\tan \phi_{Z,i} = -Q_{L,i} \left( \frac{m_i \cdot \omega_g}{\omega_{r,i}} - \frac{\omega_{r,i}}{m_i \cdot \omega_g} \right) \quad (7)$$

where  $m_i = 1$  for the main cavity and  $m_i = 3$  for the HC. The resonance frequency of the HC can be obtained from the tuning angle. The tuning angle for the main cavity is

$$\tan \phi_Z = -Y \sin \phi_s + \tan \theta_L (1 + Y \cos \phi_s) \quad (8)$$

which can be determined by operational conditions. The steady state generator current  $I_{g0}$  can be written as:

$$I_{g0} = \frac{V_c}{R_L} \sqrt{(1 + Y \cos \phi_s)^2 + (\tan \phi_Z + Y \sin \phi_s)^2} \quad (9)$$

where  $Y = 2I_{DC}R_L/V_c$ . To reduce the number of turns for the simulation, the initial beam-induced voltage for the main cavity is assumed to be already at its steady state without HC expressed by:

$$V_{b,0} = -2I_{DC}R_L \cos \phi_Z \exp(i\phi_Z) \quad (10)$$

For the HC, the initial beam-induced voltage is zero. Because a reduction of the quality factor  $Q$  for the superconducting HC will not affect the tracking results [5], the  $Q$  value for the HC in our simulation is limited to  $10^6$  to reduce the required turns for convergence of the longitudinal oscillation [6]. There are two HCs and their  $R/Q$  are set to be 44.2 in the tracking simulation.

The particle tracking code was developed with MATLAB. The number of particles in each bunch is 600 and the number of turns in the simulation is 40,000. The initial distributions of  $\Delta E$  and  $\Delta z$  for each bunch have a Gaussian distribution with one standard deviation of the natural energy spread and natural bunch length, respectively.

## TRACKING RESULTS

The bunch length and phases are obtained by calculating the standard deviation and mean values of  $\Delta z$  from all particles in a bunch. Figure 1, 2 and 3 show the tracking results for different fill patterns. In these results, the detuning frequency for the HC is +60 kHz, which is the optimized value without double-hump bunch shape calculated in the previous study [3]. The buckets of address 151 to 750 are filled like in the normal fill pattern. Conversely, 500-bunch train and a single bunch are used for the hybrid mode, which both can be used for time resolved and general users. The time difference between the bunch train and the single bunch for the hybrid mode is 200 ns, which corresponds to 100 buckets. The charge of each bunch in the hybrid mode is the same as for current operation. The maximum relative synchronous phase of the bunch train is about 33 degrees for normal fill and is close to zero for the full fill pattern.



Figure 1: Tracking results for the HC phase distribution along the bunch train for different fill patterns.

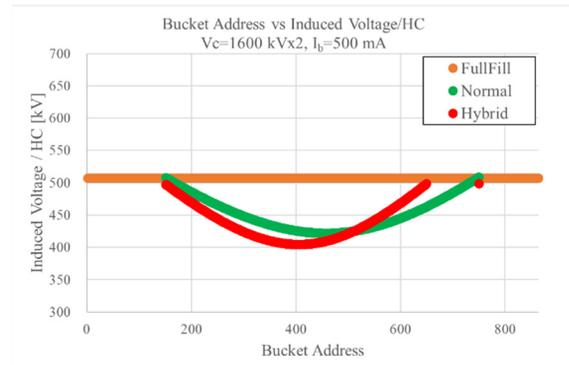


Figure 2: Induced voltage in each HC along the bunch train for different fill patterns.

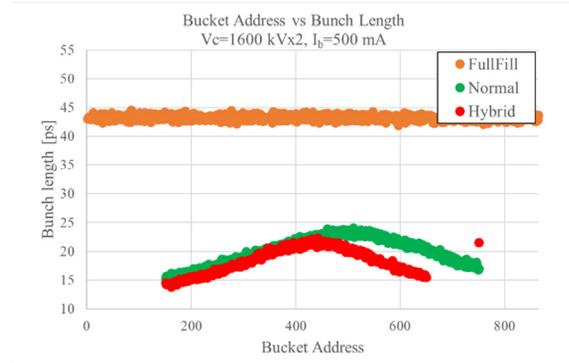


Figure 3: Bunch lengths along the bunch train for different fill patterns.

The total induced voltage and bunch length for full fill patterns are about 1020 kV and 43 ps, respectively. These results are consistent with theoretic calculation [3]. Figure 4 shows the average elongation factor for different HC detuning and operation modes. For hybrid operation, the bunch length of a single bunch and bunch train are shown separately. Due to phase transient effects, the average elongation factor is about two for +60 kHz detuning with a 70% fill pattern (normal fill), which is much lower than the full fill pattern. For the hybrid operation, the optimized HC detuning is different for a single bunch or a bunch train. The operational settings can be adjusted according to requests from users.

For future TPS operation with more beam lines and IDs, the radiation loss will increase. To support enough beam power for high beam current operation, an additional RF system is required. Figure 5 shows the average bunch length for different operating conditions with three SRF modules. The radiation loss from IDs is assumed to be 30% to 60% of that from bending magnets.

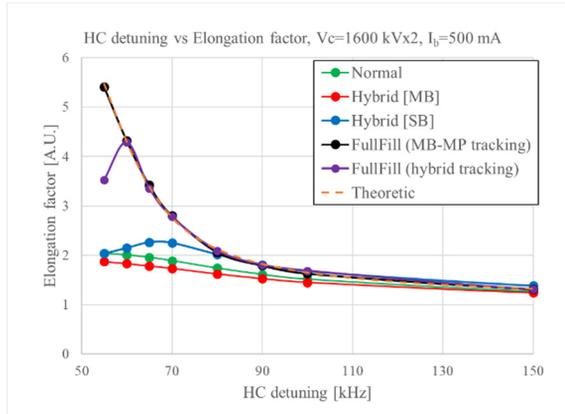


Figure 4: Average elongation factor for different operation modes as a function of HC detuning.

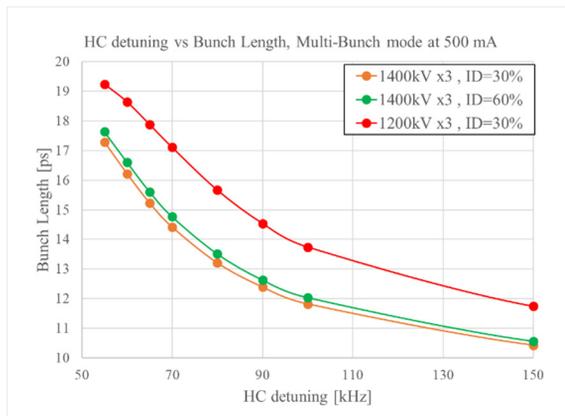


Figure 5: Average bunch length for different operation conditions with three SRF modules as a function of HC detuning.

## HYBRID TRACKING SIMULATION

A fast simulation, using a hybrid tracking method, has been tested. In this tracking method, we use many particles in a selected bucket but only one macro-particle in all the other bunches. The bunch length is calculated from the particle distribution in the selected bucket. All equations are similar to the multi-bunch, multi-particle tracking method given in the previous section. Information from macro particle bunches are ignored in the hybrid tracking method. The results from hybrid tracking are consistent with multi-bunch, multi-particle tracking for most of the cases except for small detuning and full fill patterns, as shown in Fig.4 and 6. For small HC detuning, intra-bunch effects can't be ignored due to the double-hump bunch shape causing therefore a difference between hybrid tracking and multi-bunch, multi-particle results. Although hybrid tracking is

not suitable for small detuning, it still can be used for cases without double-hump bunch shapes, thus saving significant computation time.

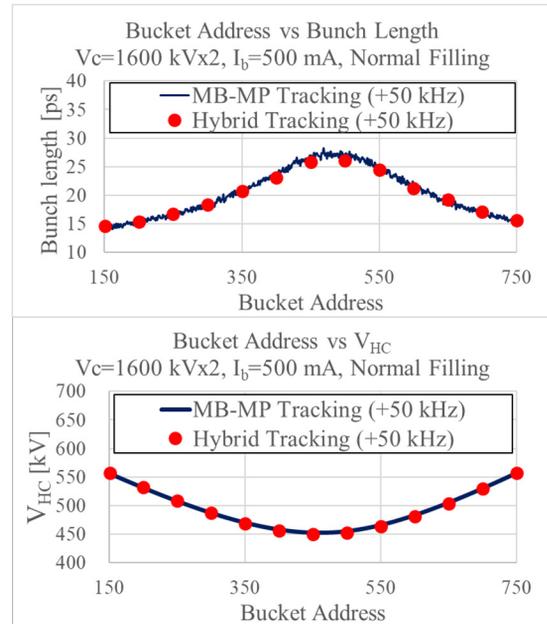


Figure 6: Comparison between multi-bunch, multi-particle tracking and hybrid tracking for +50 kHz HC detuning.

## CONCLUSION

To determine bunch lengths, one should include phase transient effects. A multi-bunch, multi-particle tracking method has been developed to determine bunch lengths for non-uniform fill patterns. A fast simulation, using the hybrid tracking method, is discussed as well. This hybrid tracking method is useful for cases without double-hump bunch shapes and would save significant computation time. For a full fill pattern, the tracking results are consistent with theoretical calculation. When phase transient effects become important, the elongation factor turns out to be lower than for the full fill pattern. The average elongation factor is about two for +60 kHz detuning with a 70% fill pattern for different operation conditions.

## REFERENCES

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