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NUMERICAL ANALYSIS OF EXCITATION PROPERTY OF PULSE PICKING BY RESONANT EXCITATION AT BESSY II*

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Abstract

The pulse picking by resonant excitation (PPRE) method is applied at BESSY II to provide pseudo single bunch operation by separating the radiation from one horizontally enlarged bunch from the light of the multi-bunch filling. The bunch is enlarged by an excitation with an external signal close to the tune resonance. The variation of the beam size depends strongly on the frequency and amplitude of the excitation signal. In this paper we show the properties of the PPRE bunch studied by analytical modeling and numerical calculations using Elegant. The simulation results are compared with beam size measurements using a new interferometry beam size monitor at BESSY II.

INTRODUCTION

Since July 2015 BESSY II has been providing a new bunch filling pattern in Top-Up mode [1]. It consists of a Hybrid (Chopper) bunch of 4 mA in the center of a 200 ns wide ion cleaning gap, followed by a Pulse Picking by Resonant Excitation (PPRE) bunch for the single bunch science driven user community. Surrounding these is the standard multi-bunch mode each of 1 mA current separated by 2 ns. The remaining Slicing bunches deliver photons daily to the ultra-fast experiments at the Femtoslicing facility [2].

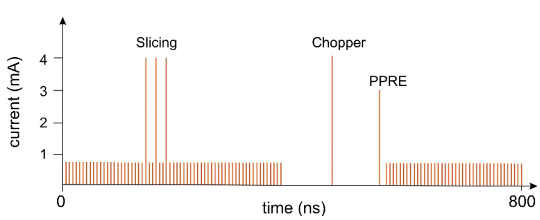

Figure 1: Standard filling pattern consists of Camshaft (Chopper) bunch, PPRE-bunch, usual multibunch filling, and the three slicing bunches.

The pulse picking by resonant excitation (PPRE) method which is based on an increased horizontal emittance of a single bunch by a quasi-resonant incoherent excitation it provides a pseudo single bunch signal for applications relying on time-of-flight schemes [3]. The first synchrotron sideband of the betatron oscillation frequency is excited using the bunch-by-bunch feedback system and diagnostic stripline kicker [4]. The amplitude and frequency of the excitation signal are optimized for high suppression ratio of signals from multi-bunch to PPRE bunch which is positioned near the end of the dark gap [5]. The exact position is chosen such that the bunch is outside the chopper window on technically separated from others.

ANALYTICAL MODEL

The PPRE method is based on transverse beam heating through an RF field provided by a stripline kicker. The amplitude and angle variation due to the kicker can be obtained approximately by using the transfer matrix, because the equation of the motion can be linearized. The transverse kicks the particle in the phase-space position (x_{n-1}, x'_{n-1}), and the particle position after one turn is given by [6]

$$\begin{pmatrix} x_n \\ x'_n \end{pmatrix} = M \begin{pmatrix} x_{n-1} \\ x'_{n-1} \end{pmatrix} + M \begin{pmatrix} 0 \\ \theta_m \end{pmatrix}, \tag{1}$$

where $M = \begin{pmatrix} \cos\Phi + \alpha\sin\Phi & \beta\sin\Phi \\ -\gamma\sin\Phi & \cos\Phi - \alpha\sin\Phi \end{pmatrix}$, α, β, and γ are Twiss parameters, Φ is the betatron phase advance, $\theta_m = \theta_k\cos(2\pi m q_k + \phi_j)$, ϕ_j is the initial phase of the excitation pulse, $q_k = f_k/f_{ref}$, f_k is the excitation frequency and f_{ref} is the revolution frequency. Assuming a linear transverse motion the total betatron phase advance as function of the number of turns n is given by $2\pi Q_x n + \Delta\phi_x(n)$, where $\Delta\phi_x(n)$ is the phase shift due to chromaticity expressed as the derivative of the tune with respect to the relative momentum deviation. It is expressed for a particle with initial phase space coordinates z and δ as [7] :

$$\begin{aligned} \Phi(n) &= \int_0^n dN 2\pi \left(Q_x + \xi_x\delta\cos(2\pi Q_s N)\right. \\ &\qquad \left. + z\frac{\xi_x Q_s}{\eta R}\sin(2\pi Q_s N)\right) \\ &= 2\pi\left(Q_x n + \frac{\xi_x\delta}{2\pi Q_s}\sin(2\pi Q_s n)\right. \\ &\qquad \left. - \frac{\xi_x z}{2\pi\eta R}(\cos(2\pi Q_s n) - 1)\right), \end{aligned} \tag{2}$$

where Q_x and Q_s are the horizontal betatron and synchrotron tunes, respectively, ξ_x is the horizontal chromaticity, R is the machine radius, and η is the slippage factor.

The evolution of the transverse coordinate is given by summing the previous quantity over the particle distribution. For the particles with small initial amplitude and angle, x_0 and $x'_0 \ll \theta_k$, the transverse coordinate as a function of the number of turns is obtained as

$$\begin{aligned} x_n = \beta\sum_m^{n-1}\theta_m \int\int d\delta dz \frac{1}{2\pi\sigma_z\sigma_\delta}\sin\Phi(n \\ - m)e^{-\delta^2/(2\sigma_\delta^2)}e^{-(z-z_0)^2/(2\sigma_z^2)}, \end{aligned} \tag{3}$$

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where σ_δ is the rms energy spread, σ_z is the rms bunch length and z_0 is the longitudinal offset.

By solving the double integral in Eq. (3) and using $\sigma_\delta = \sigma_s Q_s/\eta R$ for a bunch matched to its bucket [7, 8], the transverse position can be driven. Finally the emittance after n-turns is given by inserting the transverse position and momentum component into the Courant-Snyder invariant, $\epsilon = \beta x^2 + 2\alpha x x' + \gamma x^2$, i.e :

$$\epsilon_x(n) = \frac{\beta\theta_k^2}{4\pi^2}\sum_l \left(\frac{I_l\left(\left(\frac{\sigma_\delta \xi_x}{Q_s}\right)^2 - i\frac{z_0}{\sigma_z}\frac{\sigma_\delta \xi_x}{Q_s}\right)}{\pi(q_k - q_x - l q_s)} \right)^2 e^{-\left(\frac{\sigma_\delta \xi_x}{Q_s}\right)^2} \times \sin^2(\pi(q_k - q_x - l q_s)(n-1)), \quad (4)$$

where $I_l(x)$ is the modified Bessel function of order l, q_x and q_s are the decimal part of the tune Q_x and Q_s, respectively.

The emittance is independent of the initial phase of the excitation signal. Since the beam size is expressed by $\sigma_x \sim \sqrt{\beta\epsilon_x}$, the beam size is linearly proportional to the deflecting angle and betatron function at the kicker position. Using the typical operation condition, the growth rate of the horizontal beam size, $d\sigma_x/dn$, is about 0.11 μm/turn/μrad. The horizontal beam size as a function of the excitation frequency and number of turns is calculated with chromaticity of 2.5, the energy spread of 0.18%, a kick angle of 5 μrad and decimal part of horizontal betatron and synchrotron tunes of 0.84 (1.06 MHz) and 0.00632 (7.9 kHz). The result is shown in Fig. 2.

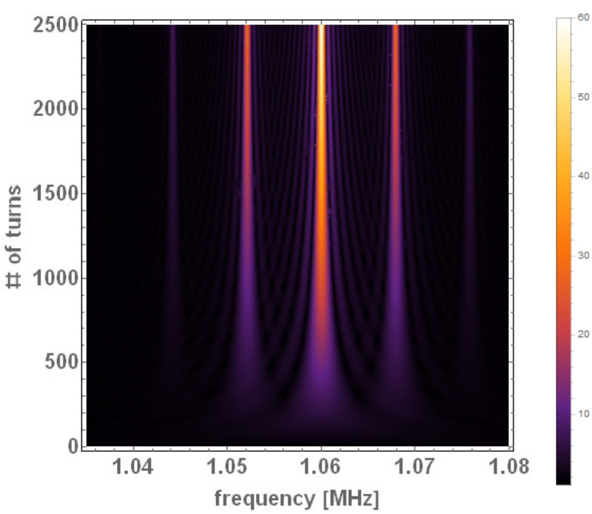

Figure 2: Normalized beam size (σ_x/σ_{x0}) as function of excitation frequency and number of turns with chromaticity of 2.5, energy spread of 0.18 %, θ_k of 5 μrad and q_x and q_s of 0.84 (1.06 MHz) and 0.00632 (7.9 kHz). The color code represents the normalized beam size.

Since the effects of radiation damping, quantum excitation and higher order aberrations are not considered in the model, there is no quasi-equilibrium state and the beam size continuously increases. The beam size growth ratio of the betatron frequency to the first synchrotron sideband is about 40 %.

NUMERICAL CALCULATION

In order to estimate the effects of quantum excitation, radiation damping, and higher order aberrations, a macro-particle simulation is performed using the Elegant code [9]. The lattice functions are established based on a LOCO (Linear Optics from Closed Orbit) measurement and the accelerator components such as undulators, superconducting multipole wiggler (MPW), and superconducting wavelength shifter which cause strong non-linear aberrations are excluded. The initial coordinates of the 2k particles were generated based on the equilibrium-state of the storage ring. The beam properties as a function of excitation frequency and time (number of turns) are calculated. The variation of normalized horizontal beam size as a function of excitation frequency and number of turns is shown in Fig. 3.

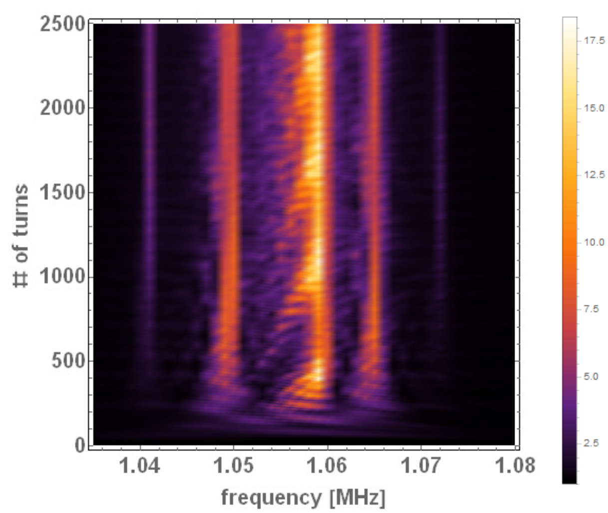

Figure 3: Normalized beam size (σ_x/σ_{x0}) as function of excitation frequency and number of turns from numerical calculation including the effect of radiation damping, quantum excitation, and up to second-order component. The color code represents the normalized beam size.

As shown in Fig. 3, the bandwidth behavior in early stage are similar to the analytical results but the beam size growth and bandwidth reduction converge after around 600 turns (0.5 ms). The bandwidth and amplitude properties are asymmetric and the first negative synchrotron sideband has much broader bandwidth than the positive sideband. In the calculation, the beam distribution reaches a quasi-equilibrium state which is not varied significantly during the excitation process within 2500 turns (2 ms). The frequency response of the simulated horizontal beam size is compared to the analytical expression, which is shown in Fig. 4.

The betatron frequency computed using Elegant is slightly lower than the theoretical value calculated under symplectic conditions and the positive synchrotron sideband closes to the betatron frequency. The beam size ratio of the betatron

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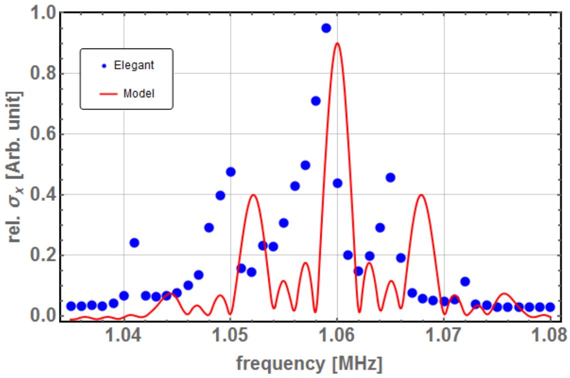

Figure 4: Relative beam size as function of excitation frequency calculated by analytical model (after 600 turns) and numerical method (after 2000 turns).

frequency to the first synchrotron sideband is about 48 % and the amplitude of the second negative synchrotron sideband is over 20 % of the baseband.

EXPERIMENTAL MEASUREMENT

Two hard X-ray pinhole systems, PINH3 and PINH9, are installed at BESSY II to monitor a transverse phase-space information [10]. Since the hard X-ray pinhole camera is not suitable for bunch resolved analysis which is significant request for the future BESSY VSR upgrade [11], an optical interferometry beam size monitor (IBSM) has been developed [12, 13]. The PINH3, PINH9, and IBSM are placed in different positions of the storage ring. The amplitudes of the betatron oscillation at the PINH3, PINH9, and IBSM are 0.40 m, 0.46 m, and 0.39 m, respectively. Since the excitation properties of the PPRE strongly depend on the bunch current, it is measured in the beam current range of 2mA to 3 mA. The measurement is performed at the first negative synchrotron sideband of 1.0556 MHz. The numerical calculation result is compared with the result of the measurements by the pinhole monitors and the IBSM, which is shown in Fig. 5.

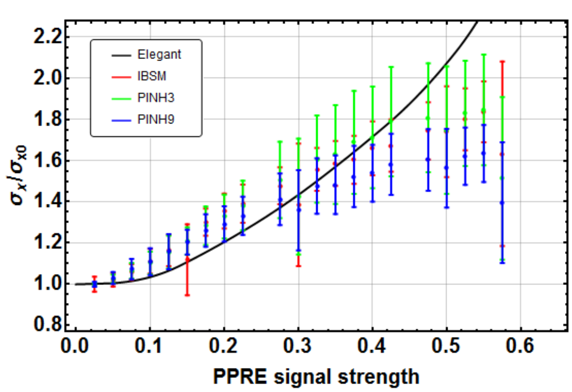

Figure 5: Normalized beam size (σ_x/σ_{x0}) as function of excitation amplitude. It is measured using two pinhole cameras (PINH3 and PINH9) and the IBSM in bunch current range of 2mA to 3 mA.

Since the beam size is normalized by the minimum beam size of each device, the slope is proportional to the square root of beta-function at the kicker position. From Eq. 4, a linear response on the kick angle is expected, which is well visible in the measurement. The elegant simulation results show qualitative agreement with the measurement, although the measurements has large deviations.

SUMMARY

Analytical expressions for the PPRE method have been derived describing the emittance growth as a function of frequency and amplitude of the excitation signal. Since the quasi-equilibrium state is determined by nonlinear effects and radiation damping processes, the model is not suitable to describe the saturated emittance but it can provide the relation between the phenomenon and knobs such as chromaticity, energy spread, beta-function, and kick angle. Also a numerical calculation is performed using Elegant and it shows qualitative agreement with the measurement which is measured by two pinhole cameras and IBSM.

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