INFLUENCE OF TRANSIENT BEAM LOADING ON THE LONGITUDINAL BEAM DYNAMICS AT BESSY VSR*

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Abstract

BESSY VSR, a scheme where 1.7 ps and 15 ps long bunches (rms) can be stored simultaneously in the BESSY II storage ring has recently been proposed [1]. The strong longitudinal bunch focusing is achieved by superconducting high gradient RF cavities. If the bunch fill pattern exhibits a significant inhomogeneity, e.g. due to gaps, transient beam loading causes a distortion of the longitudinal phase space which is different for each bunch. The result are variations along the fill pattern in synchronous phase, synchrotron frequency and bunch shape. This paper presents investigations of transient beam loading and depicts the consequences on bunch length, phase stability and longitudinal multi-bunch oscillations for the projected setup of BESSY VSR.

INTRODUCTION

The upgrade proposal BESSY VSR [2] is based on the idea that the superposition of the voltage of two different higher harmonic cavity systems will allow to store short and long bunches simultaneously. In order to separate the synchrotron radiation from single bunches by means of a mechanical chopper, they need to be placed in the center of gaps in the bunch fill pattern. Therefore, the fill pattern is proposed to have two 100 ns gaps as depicted in Fig. 2, which gives rise to potentially strong transient beam loading.

TRACKING CODE

A tracking code written in C++ has been developed which uses one macro-particle per bunch for the calculations presented here. The cavity-bunch interaction is calculated by means of phasor addition and active cavities are controlled by a feedback loop which does not act within a revolution but acts quickly from one revolution to another. This simplified method is sufficient to evaluate the effects of beam dynamics discussed in this paper. Related studies, with a focus on RF control are given in [3].

Experimental Verification at BESSY II

Transient beam loading can readily be observed at BESSY II as it is typically operated with a 200 ns gap in the fill pattern and the 1.5 GHz Landau cavities set to bunch lengthening mode. Figure 1 shows an example of measurements at BESSY II compared to simulations performed with the tracking code used in this paper. Both, the data of the synchronous phase position of each bunch, measured in ps with respect to the nominal equidistant bucket reference, and the individual synchrotron frequencies was taken by the diagnostics of bunch-by-bunch feedback systems [4].

The agreement of simulation and measurement can be considered satisfying. Despite some deviation, all major features, such as magnitude of phase transient, magnitude and shape of the synchrotron frequencies are predicted by the simulation. The deviations are expected to stem from uncertainties from both the measurements and the input parameters to the simulation, such as quality factors Q, the shunt impedances R_s^c and the tuning settings. Investigations towards identification and improving the accuracy are ongoing.

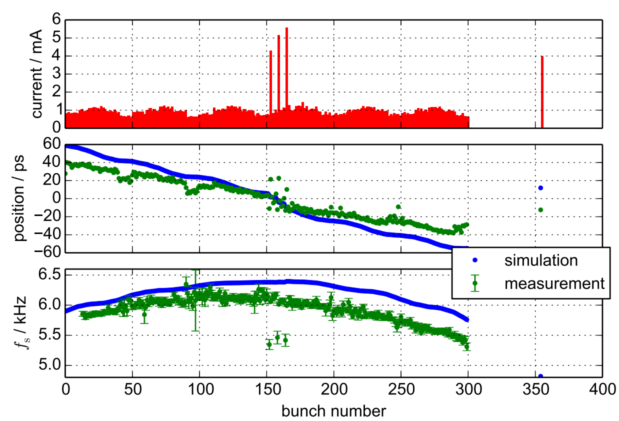

Figure 1: Comparison between simulation and measurements of synchronous phase position of each bunch (center), measured in ps w.r.t. the nominal equidistant bucket reference, and synchrotron frequency (bottom) at BESSY II for a given fill pattern (top). Error bars show a statistical error only.

BESSY VSR SETUP

In BESSY VSR, the storage ring will be equipped with four 5-cell SC cavities, two at 1.5 GHz and two at 1.75 GHz. In this simulation, the normalized shunt impedance[1] is set to $R_s^c/Q = 250\,\Omega$ per cavity. In order to accelerate the approach of the equilibrium state in this simulation, the quality factor of the cavities is set to $Q = 4 \times 10^5$ and the radiation damping time to $\tau = 4 \times 10^{-4}$ s. The 1.5 GHz and 1.75 GHz system are tuned to $\Delta f = -11.3$ kHz and $\Delta f = 15.3$ kHz respectively to compensate for the average

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[1] Given in circuit definition: $R_s^c = V_{acc}^2/(2P_{diss})$ with V_{acc} the maximum effective accelerating voltage and P_{diss} the dissipated power.

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beam loading. However, as the generator power is not limited in this simulation, precise tuning is not necessary. The NC 500 MHz system has a combined shunt impedance of R_s^c = 12.4 MΩ and Q = 26700 and is tuned to Δf = −45 kHz. The target values for the feedback controlled cavities are set to 1.5 MV, 20 MV and 17.5 MV, for the 500 MHz system, the 1.5 GHz system and the 1.75 GHz system respectively.

Those numbers are an outcome from an optimization that maximizes the average bunch length of the long bunch while ensuring that there is no net energy transfer between the 1.5 GHz and 1.75 GHz systems. The numbers are valid only for the BESSY VSR baseline fill pattern shown in Fig. 2.

The energy loss due to incoherent synchrotron radiation per turn is set to 178 keV for the long bunches. Short bunches loose additional energy by coherent synchrotron radiation. The total synchrotron radiation loss for the single short bunch is set to 689 keV and for the short bunches in the train to 603 keV [2]. Additional parameters can be found in Table 1.

Table 1: Basic Machine Parameters

Parameter	Value
Energy E	1.7 GeV
Momentum compaction factor α	$7.1 \cdot 10^{-4}$
Total beam current I	300 mA
Revolution period	800 ns
Longitudinal radiation damping time τ_z	8 ms

RESULTS

The variation of the relative deviation of the voltage amplitude and the phase of all three cavity systems is shown in Fig. 2 center and bottom.

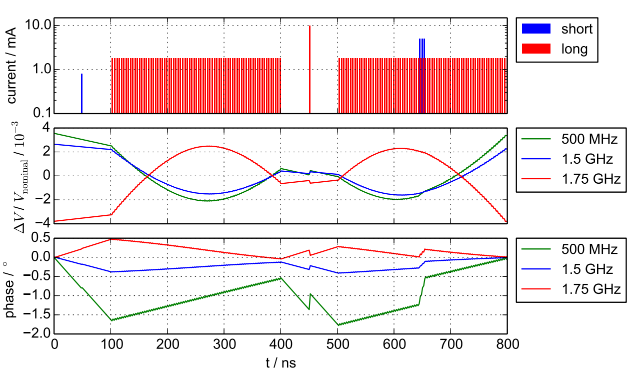

Figure 2: Simulation of transient beam loading in BESSY VSR with the baseline fill pattern (top). The time variation of the relative deviation of the voltage amplitude (center) and the phase (bottom) are shown for all three cavity systems.

All cavities are of high quality factor and operated at rather high fields close to zero-crossing where beam loading primarily acts as a phase shift. Therefore, the variations of the relative voltage are small, see Fig. 2 center.

For the same reason, the variation in phase are more pronounced and relate directly to the bunch charges of the fill pattern, i.e. each bunch adds a certain value to the phase, proportional to its charge. Empty buckets cause a phase shift in opposite direction given by the detuning which is set to compensate the average beam loading. Furthermore, for the 1.75 GHz system, the sign depends on the bucket type, long or short, because of the 180° phase difference. Still, the variation in phase is below 0.5° for all SC cavities.

Synchronous Phase and Bunch Shape

The variation in phase and amplitude of the involved cavity systems mean that the time-behavior of the total voltage is different at each bucket position. For even buckets (short bunches), where all contributions sum up with the same sign to achieve a high gradient, the relative effect is expected to be small. At the buckets of the long bunches however, the contributions of the SC cavities are supposed to cancel each other, thus relative variations are amplified. The majority of the current is placed in long bunches which cause the cavity phases to shift in opposite directions for the 1.5 GHz and the 1.75 GHz system.

Figure 3 depicts the time-behavior of the total voltage in the vicinity of the nominal bucket positions for three selected bunches. The constant synchrotron radiation loss has been subtracted so that the synchronous phase position is to be found at $V = 0$. It can be seen in Fig. 3, that small

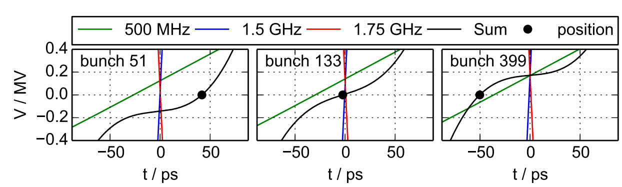

Figure 3: Time-behavior of the individual contributions and the total voltage in the vicinity of the nominal bucket position for three selected bunches. Black circles indicate the synchronous phase positions.

changes in the phases of the SC cavity systems are enough to significantly shift the zero-crossing of the total voltage, i.e. the synchronous phase position. In turn, the slope of the total voltage is different for each bunch which changes its synchrotron frequency and bunch length.

The synchrotron phase position, the synchrotron frequency f_s and the normalized zero-current bunch length is shown in Fig. 4. A peak-to-peak phase transient of approx. 80 ps is visible for the long bunches while the short bunches are barely affected by the transient beam loading. The synchrotron frequency and analogously the bunch length show a variation of a factor of about two and exhibit their extrema approximately in the center of the bunch trains.

Touschek Lifetime

The over-all beam lifetime at BESSY VSR will be Touschek dominated. Despite their high electron density, hence

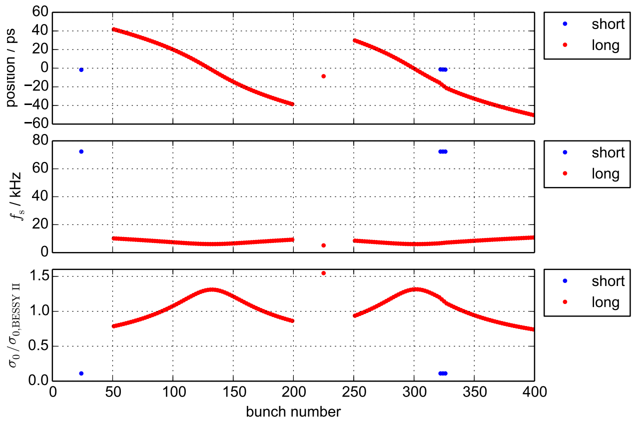

Figure 4: Simulated synchronous phase position (top), synchrotron frequency (center) and zero-current bunch length scaled to the nominal BESSY II value of 10 ps (bottom) for the BESSY VSR baseline fill pattern shown in Fig. 2.

poor lifetime, the electron loss rate of the short bunches is expected to be manageable as their total current is rather low. As the number of long bunches halves in BESSY VSR compared to BESSY II, the bunch charge doubles and an elongated long bunch would be desirable.

Unfortunately, these simulations show that the effect of transient beam loading prevents a significant average elongation of the long bunches. While decreasing the amplitude of the 1.5 GHz cavity system or increasing the amplitude of the 1.75 GHz cavity system increases the bunch length for a small number of long bunches, the majority of bunches becomes shortened, consequently lowering the Touschek lifetime, see Fig. 5. The elongation of a single long bunch is limited by the non-linear behavior of the potential, resulting in a bunch no longer than approximately 2.5 times the nominal BESSY II value and has been taken into account in the averaging in Fig. 5 right panel.

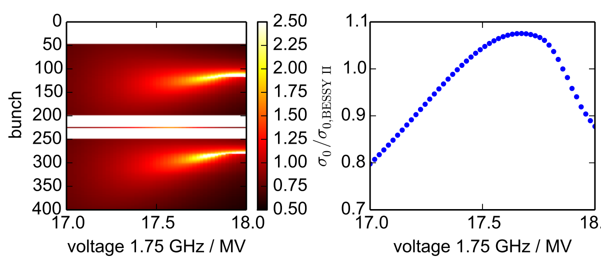

Figure 5: Scaled bunch lengths (color code) vs. voltage of the 1.75 GHz cavity system for all bunches (left) and averaged over all bunches (right).

Landau Damping

Significant progress in the development of higher order mode damped SC cavities has been made [5]. Yet the issue of higher order mode driven coupled bunch instabilities in BESSY VSR, as discussed in [6], may continue to be a challenge and the question whether a mitigation by means of Landau damping is possible remains of interest.

The Landau damping for an arbitrary, discrete distribution can be evaluated by means of a dispersion relation [7, Eq. 2.12, Eq. 2.18], $d(\omega) = I\omega_r Z$, where the dispersion function d contains all machine parameters, the f_s distribution and the (radiation) damping time τ.

In Fig. 6 right panel, d is drawn at the threshold for the given f_s distribution (left panel) and for comparison for a case with constant f_s. Both cases assume $\tau = 8$ ms.

The damping performances can be read out from the radius of the $I\omega_r Z$-circle intersecting with d. In this case, Landau damping increases the damping performance by a factor of 14.7 compared to radiation damping. This is about 50% more than the present bunch-by-bunch feedback performance of BESSY II [4] and could intentionally be further increased by small changes in the tuning of the SC cavity systems. However, the latter comes along with a reduction of the Touschek lifetime.

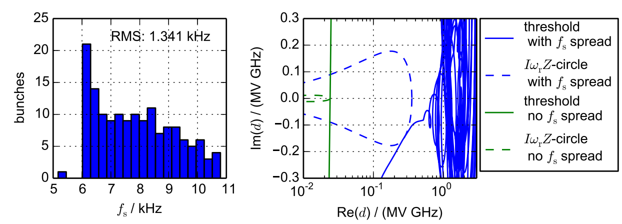

Figure 6: Left: Distribution of the synchrotron frequency of the long bunches. Right: Complex plane of the dispersion function at the instability threshold (solid lines) and $I\omega_r Z$-circles (dashed lines) indicating the maximum current.

CONCLUSIONS

The calculations in this paper have shown that transient beam loading is significant in BESSY VSR. It poses a limit on the maximum achievable elongation of the long bunches which limits their Touschek lifetime. On the other hand, if necessary, transient beam loading could be used to obtain Landau damping to mitigate coupled bunch instabilities, however, only as a trade-off to lifetime.

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