COMPENSATION OF TRANSIENT BEAM LOADING WITH DETUNED CAVITIES AT BESSY II*

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Abstract

This paper presents operational experience and use cases of cavity operation at the synchrotron light source BESSY II, where a cavity is operated at another harmonic number. In this case, the distortion of the different longitudinal phase space is periodic with the revolution, which allows for the compensation of fill pattern induced transient beam loading. Measurements at BESSY II are presented with active and passive operation of the detuned cavity, reducing the phase transient and increasing the beam life time. Calculations depicting the application of this scheme for the future project BESSY VSR [1, 2] are presented.

INTRODUCTION

The studies in this paper are motivated by the lifetime improvement which results from a compensation of transient beam loading. The question of lifetime is relevant for the synchrotron light source BESSY II and especially BESSY VSR [1–3].

At BESSY II, the Landau cavities are normally operated in lengthening mode to increase the bunch length and in turn the life time of the stored beam. One significant feature of this operation is the strong effect of transient beam loading, appearing as a result of the gap in the fill pattern in combination with the use of Landau cavities in lengthening mode and a relatively low main cavity RF voltage, see [3, 4]. The strong phase transient reduces the effectiveness of the Landau cavities, as only some bunches are properly elongated, thus reducing the Touschek lifetime.

BESSY II is equipped with four normal conducting active RF cavities and four normal conducting third harmonic passive Landau cavities, see Table 1 [5]. All cavities can be controlled individually and due to their large tuning ranges, a high degree of freedom is reached in manipulating the longitudinal phase space. The harmonic number of BESSY II is $h = 400$ and the revolution frequency $f_{\mathrm{rev}} = 1.25\,\mathrm{MHz}$. If a cavity is operated at another harmonic number, e.g. 401, it creates a distortion of the longitudinal phase space that is synchronous to the revolution but different for each bunch in the fill pattern. We call V_0, V_1, and V_2, the voltage oscillating at f_{rev} times h, $h+1$ and $h+2$.

Table 1: BESSY II RF Systems

Parameter	Main RF	Landau
Quantity	4	4
Type	active	passive
RF frequency	500 MHz	1.5 GHz
Maximum voltage	500 kV	60 kV
Normalized shunt impedance *	115 Ω	62 Ω
Quality factor	29 600	13 900
Coupling parameter	≈ 2.7	-
Tuning range	> 3 MHz	> 6 MHz

* Given in circuit definition.

LIFETIME IMPROVEMENT AT BESSY II

The phase transient over the complete bunch train was extracted from streak camera measurements. Figure 1 left depicts the phase transient similar to the one observed in BESSY II standard operation at 300 mA with all Landau cavities in lengthening mode and a 100 ns gap in the fill pattern, compare [3].

The experiments shown in Figure 1 depict how the phase transient can be reduced (increased) by means of one passive $h+1$ main cavity, increasing (reducing) the average bunch length and in turn the lifetime of the stored beam.

In this example, the beam lifetime is increased from 6.6 h to 7.7 h if the $h+1$ cavity is tuned to the upper side of the resonance at $f \approx 401.04 f_{\mathrm{rev}}$. If tuned to $f \approx 400.97 f_{\mathrm{rev}}$ a lifetime reduction to 6.3 h is observed.

Note, it would have been possible to detune a Landau cavity to the 1201 harmonic to achieve a similar effect. The main cavities were chosen because of their higher quality factor, better diagnostics, control system integration, and the attempt to demonstrate maximum bunch lengthening.

DEMONSTRATION OF ACTIVE CAVITY OPERATION

In a separate experiment, the active operation of a cavity at $h+1$ or $h+2$ has been demonstrated. As the Landau cavities were removed at that time, the previous experiment could not be repeated. For convenience, a homogeneous fill pattern (no gap) has been chosen for all experiments with active cavities.

Clock Synchronization

In order to actively operate one cavity at a different frequency, the RF amplifier of that cavity needs to be fed by a second, phase locked frequency generator with a well defined frequency relation. For the case of $h+1$, $f_1 = \frac{401}{400} f_0$ must hold. This was experimentally realized by two R&S®SMA 100 signal generators using a mutual 10 MHz input reference and externally calculating and setting the correct frequencies.

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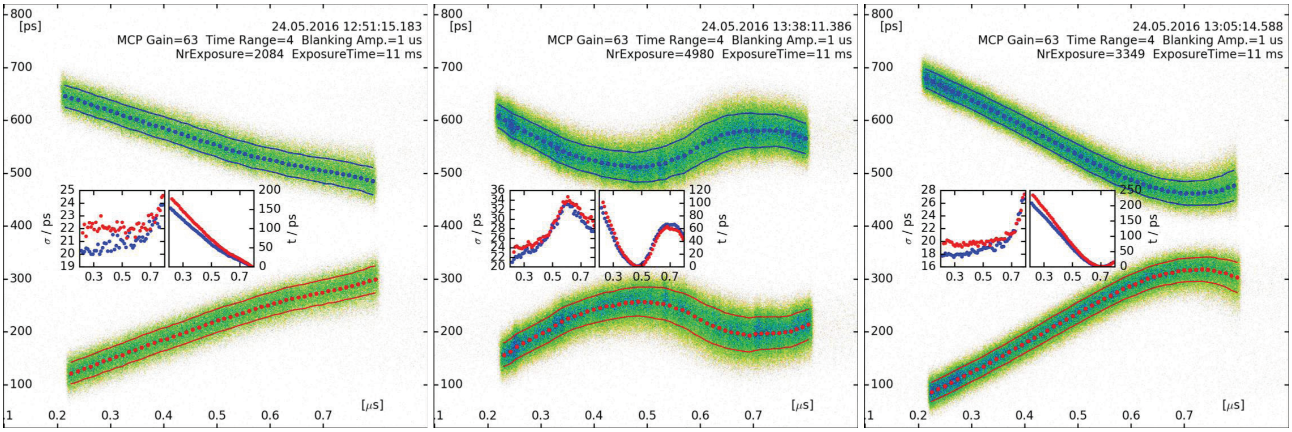

Figure 1: Streak camera images, photon counting, of high current operation with 100 ns gap in fill pattern. One main cavity in passive operation at $h + 1$, with the resonance frequency tuned to $f \approx 400.5 f_{\text{rev}}$ (left), $f \approx 401.04 f_{\text{rev}}$ (center) and $f \approx 400.97 f_{\text{rev}}$ (right).

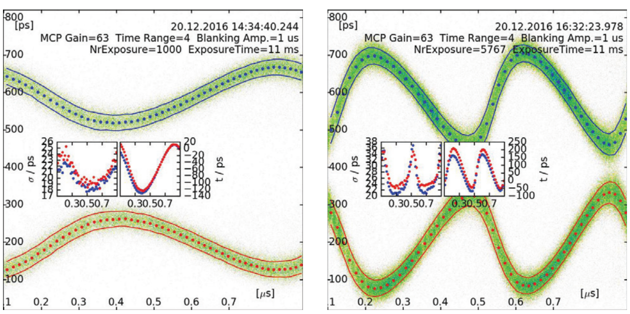

Figure 2: Low current operation with $V_0 = 1000\,\text{kV}$, $V_1 = 217\,\text{kV}$ (left) and $V_0 = 730\,\text{kV}$, $V_2 = 273\,\text{kV}$ (right). Streak camera images, photon counting.

Note that phase stability requires the fraction of f_1 to f_0 to be exact, i.e., the signal generators must derive these frequencies by integer multiplication from their smallest internal frequency increment. For the devices used in this experiment, this is 1 mHz, i.e. f_1 to f_0 need to be a multiple of 1 mHz.

With this requirement fulfilled and the reference clock set to 10 MHz accurate down to the mHz scale, the phase stability was given over the entire course of experiments.

Low Current Experiments

Figure 2 shows examples of one cavity operated at $h + 1$ and $h + 2$ respectively in a low current situation with even fill. The variation in synchronous phase and bunch length is a consequence of the detuned cavity. For example, the synchronous position for the $h + 2$ can easily be calculated by finding the solutions to the equation for the accelerating voltage:

$$
\begin{aligned}
E_{\text{loss}} &= V_2 \sin((h+2) \cdot t\omega_{\text{rev}}) + V_0 \sin(h \cdot t\omega_{\text{rev}}) \\
250 &= 273 \sin(402 \cdot t\omega_{\text{rev}}) + 730 \sin(400 \cdot t\omega_{\text{rev}})
\end{aligned}
$$

with ω_{rev} the angular revolution frequency and assuming synchrotron radiation losses of about 250 keV per turn.

High Current Experiments

In high current operation, the question of multibunch instabilities becomes relevant. In general, a longitudinal multibunch instability of mode 1 (399) is driven if the real part of the impedance of the $h + 1$ cavity is large at the positive (negative) synchrotron sideband of the $h + 1$ harmonic. In this experiment, this is the case as it is necessary to tune the resonance frequency of the $h + 1$ cavity close to the revolution harmonic in order to be able to obtain reasonably large fields. However, in active operation, the detuning of the cavity can be set, to some degree, independently of the frequency, phase and operation voltage of the cavity, which helps avoiding the instability. The appearance of this instability is further reduced by strong Landau damping stemming from the bunch-to-bunch spread in synchrotron frequency, see [3].

The example in Figure 3 shows unstable operation where a longitudinal multibunch instability is driven (left) and stable operation where the instability is suppressed (right). More detailed studies about the stable operational range need to be conducted.

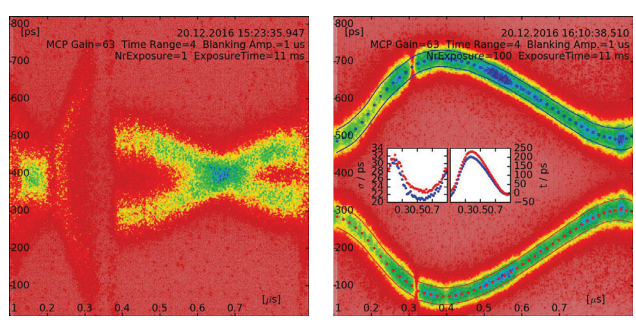

Figure 3: Streak camera images of high current operation with active $h + 1$ cavity. Left: Unstable behavior. Right: Stable behavior at $I = 250\,\text{mA}$, $V_0 = 830\,\text{kV}$, $V_1 = 280\,\text{kV}$

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PREDICTION FOR BESSY VSR

The baseline fill pattern in BESSY VSR leads to transient beam loading and thus potential lifetime issues. This is explained in [3] with additional explanation of the theory and software in [4]. The transient beam loading is dominantly determined by the two gaps, which suggests that a cavity with a detuning by two is most suitable to achieve a good compensation. As there is an asymmetry between the two gaps in the baseline fill pattern, i.e. one gap is occupied by a high current long single bunch and the other by a low current short bunch, the transient beam loading from the baseline fill pattern is also slightly asymmetric between the first and second gap [3, 4]. If this asymmetry is reduced, the effectiveness of a h-2 cavity to achieve bunch lengthening is even greater. Thus, for the purpose of demonstration, the fill pattern presented here is different from the baseline fill pattern. It is obtained after a small modification, namely the length of the high current single bunch gap is slightly increased while the length of the low current single bunch gap is reduced. As expected, the resulting beam generally becomes more symmetric, comparing the effect of the first and second gap. A large value of average bunch lengthening can be achieved. It should be noted, that a change in the gap lengths is not required for the aforementioned optimization. For instance, small adjustments to the bunch current over the bunch trains could be used to achieve a similar effect. Figure 4 shows how variation of the gap length and active operation of the normal conducting main RF cavities at $h-2$ with 80 kV at a suitable phase can be used to decrease the phase transient. A significant general elongation of the long bunches is predicted. In this simulation, the average bunch length of the long bunches increases from 10.3 ps to 18.9 ps for the same fill pattern. Note that other lengthening effects, such as coherent synchrotron radiation and machine impedance are not included.

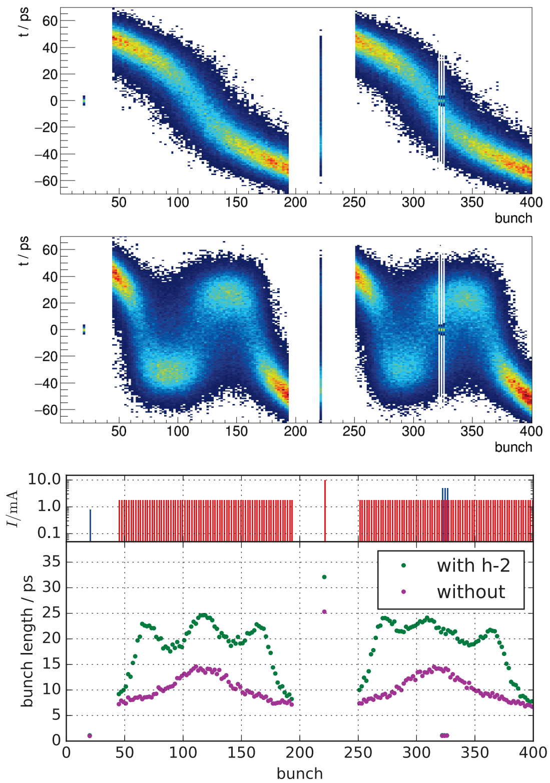

Figure 4: Simulation of phase transient and bunch length in BESSY VSR. Top: Without $h-2$ cavity. Center: With $h-2$ cavity. Bottom: Fill pattern and comparison of bunch lengths.

CONCLUSION

Active and passive $h+1$ or $h+2$ cavity operation has been demonstrated at BESSY II at low and high currents. The application of this method to a high current scenario with 100 ns gap in the fill pattern, i.e. like in the standard operation mode, has shown an increase of the beam lifetime by 15%. For BESSY VSR, the benefit from a $h-2$ cavity could be significant, considering a predicted bunch length increase of more than 50% for the long bunches, ignoring other impedance effects.

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