INTERACTION OF RF PHASE MODULATION AND COUPLED-BUNCH INSTABILITIES AT THE DELTA STORAGE RING*

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Abstract

Analyzing the interaction of RF phase modulation and coupled-bunch instabilities requires a method to determine damping rates of coupled-bunch modes at presence of RF phase modulation. This paper shows, that the common way of using exponential fits to determine damping rates is not viable for high modulation amplitudes. It presents a new method, which is capable of acquiring damping rates of coupled-bunch modes for phase shifts up to 5°, using a bunch-by-bunch feedback system. For this purpose a specific mode is excited by the feedback system and the saturation value, i.e. the maximum excitation, is measured to calculate the damping rate.
With this new method, the modulation amplitude of the RF phase modulation is swept from 0° to 5° and it can be shown, that the damping rate is proportional to the square of the modulation amplitude.

INTRODUCTION

The effects of RF phase modulation in circular accelerators date back to the early 1990's [1] [2]. Besides of its effect on the longitudinal phase space [3] [4], it is also able to suppress the excitation of coupled-bunch instabilities [5]. The modulation leads to a tune spread inside the electron bunches forcing the electrons to oscillate in different synchrotron frequencies and suppressing resonant excitations of modes. In 2008, an RF phase modulation system [6] had been applied at the 1.5-GeV electron storage ring DELTA operated by the Technical University of Dortmund (see Fig. 1 and Tab. 1). During user operation, the RF phase modulation is routinely in operation suppressing coupled-bunch instabilities and increasing beam lifetime by up to 20 % due

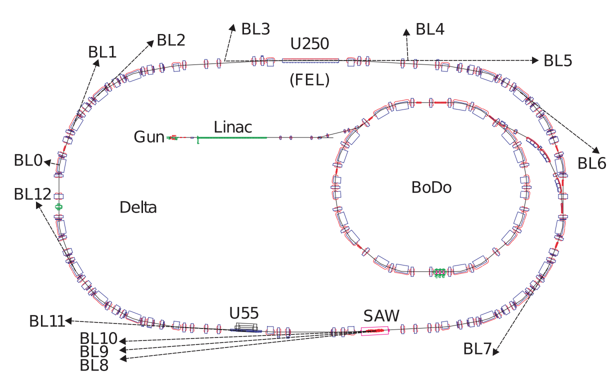

Figure 1: Overview of the DELTA facility including the storage ring and its booster snychrotron BoDo.

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to a reduction of the mean electron density and, thus, the rate of Toushek scattering [7] [8]. Since 2011, a digital bunch-by-bunch feedback system [9] is installed at DELTA for beam diagnostic purposes [10]. This system is used to determine the damping rates of coupled-bunch modes and to analyze the interaction of RF phase modulation with coupled-bunch instabilities [11].

Experimental Setup

In order to analyze longitudinal coupled-bunch instabilities, the bunch-by-bunch feedback system uses the sum signal of a beam position monitor. After digitizing, a 24-tap FIR filter is applied on consecutive input data to create output signals which are getting converted to analog signals driving the power amplifiers and the corresponding kicker structures. In addition, the processing units include a frequency generator, which allows to send a dedicated RF signal, called *drive-signal*, to the beam, for example to excite a specific mode. The appearance of coupled-bunch instabilities depends on the beam current. Since the growth rate $1/\tau$ of the oscillation amplitude is proportional to the number of electrons [12] [13], while the damping mechanisms, like synchrotron radiation damping, are independent of the beam current, there is a certain threshold for the beam current above which instabilities occur. The instability threshold for DELTA is at $I_{\text{th}} \approx 50 \pm 6\,\text{mA}$ [10], if the superconducting wiggler is switched off, what is the case for all studies in this paper. The RF phase modulation is applied by an external system mainly consisting of electrical phase shifters and a signal generator with variable amplitude and frequency [6]. The signal modulation of the DELTA cavity voltage is given by

$$U_{\text{RF}}(\omega) = U_0 \sin\left(\omega_{\text{RF}} t + \varphi_0 \cdot \sin(\omega_{\text{m}} t)\right)$$

with the RF amplitude U_0, the RF frequency ω_{RF}, the modulation amplitude or phase shift φ_0 and the modulation frequency ω_{m}.

Table 1: Storage Ring Parameters

parameter	**value**
revolution frequency	2.6 MHz
RF frequency	500 MHz
nominal RF power loss	25 kW
maximum beam current (multibunch)	130 mA
bunch length rms	100 ps / 18° at RF
synchrotron frequency	15.2 - 16.4 kHz
instability threshold (SAW off)	50 ± 6 mA
harmonic number	192

ISBN 978-3-95450-147-2

The modulation frequency can be set directly while the phase shift is set via an input voltage U_{m} with an amplitude up to 3 V resulting in a phase shift of up to 10°. The standard settings during user operation are $U_{\mathrm{m}} \approx 0.7\,\mathrm{V}$, $\varphi_0 \approx 1.1°$ and $\omega_{\mathrm{m}} \approx 2 \cdot \omega_{\mathrm{s}}$, with the synchrotron frequency $f_{\mathrm{s}} = \omega_{\mathrm{s}}/2\pi$.

DETERMINATION OF DAMPING RATES

In order to determine the damping rate of a specific coupled-bunch mode, it is excited by the drive-signal of the bunch-by-bunch feedback system, while the beam current is far below the instability threshold [11]. After the excitation is switched off, the beam damps down and the damping rate can be obtained with an exponential fit as shown in Fig. 2.

Analysis of RF Phase Modulation

Since instability damping rates are current-dependent, the measured data has to be normalized to the beam current or the beam current has to be constant during the measurement. Due to the fact that the beam current has to be far below the instability threshold, it was chosen to be around 40 mA where the beam lifetime is more than 20 hours, making the assumption of a constant beam current reasonable. In fact, the current decreases by less than 1 % during an entire measurement. To analyze the effect of RF phase modulation on damping rates, a specific mode is measured as shown in the previous section for several phase shifts φ_0 (see Fig. 3). The saturation value decreases with increasing phase shift, but the shape of the signals change for $\varphi_0 \gtrsim 0.7°$. This can be explained by the fact, that the manipulation of the longitudinal phase space by the RF phase modulation leads to an oscillation of the center of mass of every bunch. The bunch-by-bunch feedback system can only measure the center of mass and the obtained result is a convolution of damping and oscillation. Fitting an exponential curve to these signals is inappropriate [11]. A new method to determine damping rates with RF pahse modulation is shown in the next section.

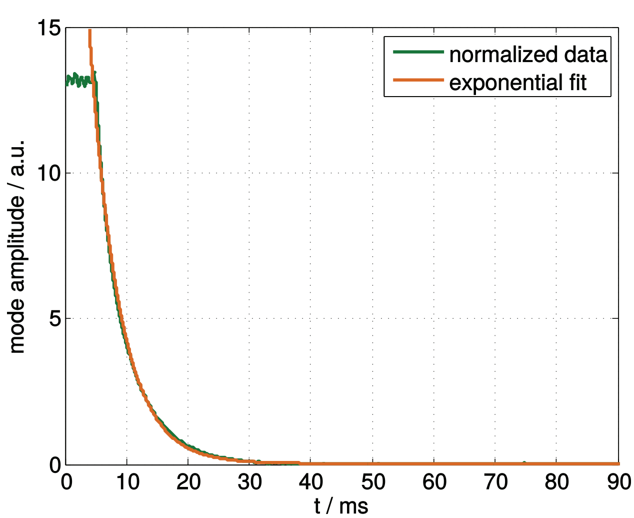

Figure 2: Exponential fit to determine damping rate of the most unstable mode of DELTA (no. 12) at a beam current of 39.3 mA to $1/\tau = 0.207\,\mathrm{ms}^{-1}$

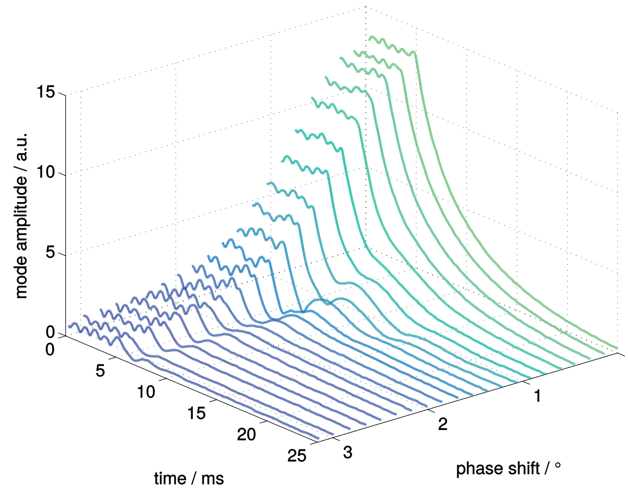

Figure 3: Mode signals of mode 12 at approx. 39 mA while the modulation amplitude is swept. Different modulation amplitudes are color coded increasing from green to blue.

Saturation Method

When an excited beam starts damping at $t = 0$, the exponential damping of the oscillation can be expressed by

$$x(t) = \begin{cases} 0 & \text{for } t < 0 \\ -ie^{\delta t} & \text{for } t \geq 0 \end{cases} \text{with } \delta = i\omega_0 - \lambda \text{ for } \lambda \geq 0$$

with the oscillation frequency ω_0 and the damping rate λ. The beam is excited by the frequency generator of the feedback system, which can be switched on and off. The switch is realized by a rectangular function which leads to

$$a(t) = A_0 \cdot rect\,(t/T) \cdot e^{i\omega_1 t}$$

with the excitation frequency ω_1, the total excitation time T and the excitation amplitude A_0. To reconstruct the measured signal, $x(t)$ and $a(t)$ has to be convolved, which is accomplished by multiplication of the Fourier transformations $X(\omega)$ and $A(\omega)$. Then, the reconstructed mode signal $Y(\omega)$ can be written as

$$Y(\omega) = A_0 \cdot \frac{1}{\omega_0 - \omega + i\lambda} \cdot \frac{\sin\{T(\omega - \omega_1)\}}{T(\omega - \omega_1)}.$$

If the excitation time is very long, this can be simplified to

$$Y(\omega) = \underbrace{A_0 \cdot \frac{1}{\omega_0 - \omega + i\lambda} \cdot \delta(\omega - \omega_1)}_{\text{for } T \to \infty}.$$

With the assumption, that the beam is excited resonantly with the mode frequency $\omega_1 = \omega_0$, the saturation value can be described with

$$|Y(\omega)| = A_0 \frac{1}{\lambda}.$$

This shows, that the damping rate can be obtained by measuring the saturation value with a known excitation amplitude A_0. For this purpose, A_0 has to be extracted from a

ISBN 978-3-95450-147-2

calibration measurement. This is done without RF phase modulation granting the possibility to use an exponential fit to determine the damping rate. Together with the saturation value from the same measurement, A_0 can be defined and used for further measurements since it does not depend on RF phase modulation parameters.

Results

With the new method, presented in the previous section, it is possible to determine the damping rates of a specific coupled-bunch mode for all RF phase modulation amplitudes. To analyze the interaction of RF phase modulation and damping rates of coupled-bunch modes, the phase modulation amplitude was swept from 0 V (0°) to 3 V (≈5°) and the damping rate of the most unstable mode (no. 12) was obtained by both the fitting and the saturation method. To ensure that the excitation time T is large compared to the damping time, seperated measurements are done for the saturation value and the damping rate. The beam is excited for at least 100 ms acquiring the saturation value by the mean of the mode signal. Afterwards, the excitation is switched off and the damping part is measured for another 100 ms as shown in Fig. 2. This also helps to obtain decent statistics when averaging the saturation value. The results in Fig. 4 show, that fitting exponential curves to the mode signals is inappropriate for $\varphi_0 \gtrsim 0.7°$ (orange curve), as indicated by Fig. 3. On the other hand, the new saturation method shows a nice smooth curve up to 5° (blue curve), which indicates that it is working properly. Fitting a second order polynomial curve to the damping rates gathered from the saturation method reveils a quadratic correlation of damping rates and phase shifts (see Fig. 5). Another indicator supporting the saturation method is the fact, that the damping rates for small modulation amplitudes acquired by both methods match.

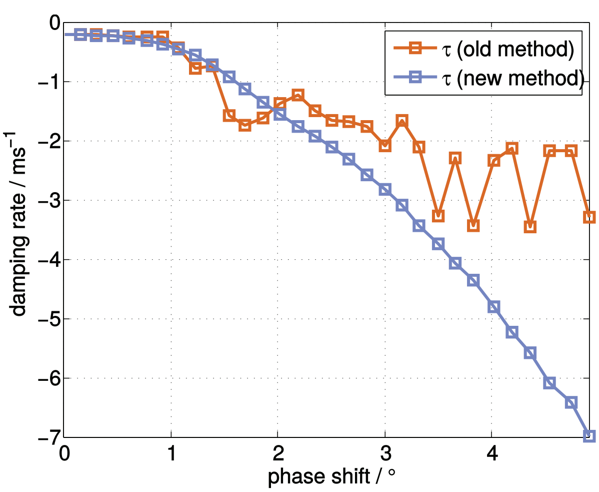

Figure 4: Damping rate of mode 12 as a function of the phase shift of the RF phase modulation at a beam current of around 39 mA. The old method, using exponential fits (orange curve), only works for small phase shifts. The new method, using the saturation value (blue curve), works for the whole regime.

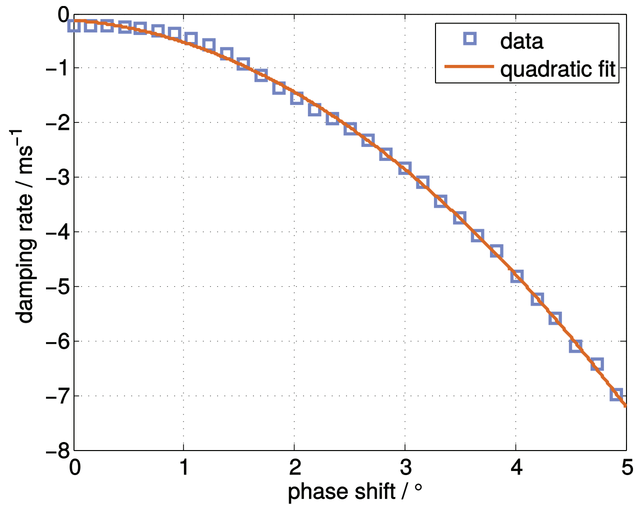

Figure 5: Using a second order polynomial fit shows a quadratic correlation of the damping rate to the modulation amplitude.

CONCLUSION AND OUTLOOK

Suppressing the excitation of coupled-bunch instabilities in a circular accelerator with RF phase modulation could be succesfully achieved. Obtaining the damping rate via exponential fitting is only viable for small modulation amplitudes, while this method is inappropriate for phase shifts greater than ≈ 0.7° at DELTA. A new measurement and analysis method has been developed to determine damping rates of coupled-bunch instabilities for any modulation amplitude using the saturation value of an excited mode. While $\varphi_0 < 0.7°$ the damping rates acquired by the new method match the results of exponential fitting, indicating that it works properly. For higher phase shifts, it shows that the damping rates are proportional to the square of the phase shifts. The analysis with a bunch-by-bunch feedback system is limited to the center of mass motion of the electron bunches. Unfortunately, RF phase modulation manipulates the center of mass motion making the feedback measuring a convolution of damping and the impact of the phase modulation. Measurements with a streak camera could gather additional information about the incoherent motion. Additionally, a deeper understanding of the behaviour of the convolved measured signal could be another step to explain the interaction of RF phase modulation and coupled-bunch instabilities completely.

ACKNOWLEDGEMENT

It is a pleasure to thank all our colleagues at DELTA for the continuous support. In addition, we want to thank everyone for the fruitful discussions we had, which helped a lot to complete this work succesfully and also the BMBF for the financial support.

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ISBN 978-3-95450-147-2