

COUPLED-BUNCH INSTABILITY SUPPRESSION USING RF PHASE MODULATION AT THE DELTA STORAGE RING*

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Abstract

In this paper, a feedback-based method to measure the damping rates of multibunch modes at the 1.5-GeV electron storage ring DELTA operated by the TU Dortmund University is presented and the influence of an RF modulation on these damping rates is analyzed. For this purpose, the amplitude as well as the frequency of the modulation was varied. The suppression of coupled-bunch instabilities could be observed with a modulation frequency slightly below twice and three times the synchrotron frequency. However, the determination of damping rates for high modulation amplitudes using the presented method is problematic. In addition, the decrease of beam quality using RF phase modulation was investigated and the increase of bunch length was measured as a function of the modulation amplitude.

INTRODUCTION

The upcoming upgrade of BESSY II, called BESSY-VSR [1], involves the utilization of superconducting multicell RF-resonators to provide short and long bunches simultaneously. The residual impedances of the cavities may cause collective multibunch instabilities at the frontier of stability available from current bunch-by-bunch feedback systems. Hence, other damping methods have to be considered, e.g. a modulation of the radio frequency (RF) of the accelerating cavity. The effects of RF phase modulation in circular accelerators date back to the early 1990's [2] [3]. In 2008, a modulation had been applied at the 1.5-GeV electron storage ring DELTA operated by the TU Dortmund University (see Fig. 1 and Table 1) in order to suppress longitudinal instabilities [4] [5]. In 2011, a digital bunch-by-bunch feedback system [6] was installed for beam diagnostics purposes [7]. This system is able to suppress the aforementioned instabilities successfully, without the application of the RF phase

modulation. During user operation, the RF modulation is routinely in operation to increase the beam lifetime by up to 20% due to the reduction of the mean electron density and, thus, the rate of Touschek scattering [8]. To get a deeper understanding of the suppression of instabilities by RF phase modulation, the bunch-by-bunch feedback system is used to determine the damping rates of all coupled-bunch modes.

Experimental Setup

To extract the horizontal, vertical and longitudinal position of every bunch, a combination of a beam position monitor and a hybrid network is used. The horizontal and vertical differential signals as well as the sum signal are sent to the feedback frontend, where they are filtered, attenuated and digitized. By applying a 24-tap FIR filter on consecutive input data, the output signals are created, which are 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 to the beam, for example to excite a specific multibunch mode [9].

The modulation of the RF phase of the accelerating cavity is realized by an external system. It mainly consists of electrical phase shifters and a signal generator with variable frequency and amplitude (for detailed information see [5]). The signal modulation of the DELTA RF master generator is given by

$$U_{RF}(\omega) = U_0 \sin(\omega_{RF}t + a \cdot \sin(\omega_{mod}t))$$

with the amplitude U_0 , the RF frequency ω_{RF} , the modulation amplitude a and the modulation frequency ω_{mod} . At the signal generator, the modulation frequency $f_{mod} = \omega_{mod}/2\pi$ can be set directly and the modulation amplitude a can be set via input signal U_{mod} from 0 V up to 3 V. The standard settings for user operation are $U_{mod} = 0.7$ V and $\omega_{mod} \approx 2 \cdot \omega_s$, with the synchrotron frequency $f_s = \omega_s/2\pi$.

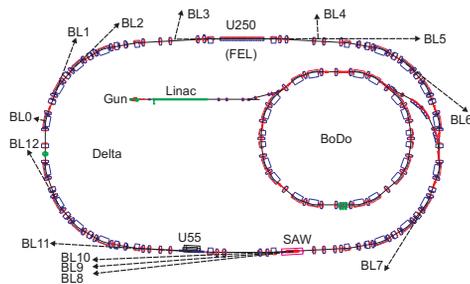


Figure 1: Overview of the DELTA facility including the storage ring and its booster synchrotron BoDo.

Table 1: Storage Ring Parameters

parameter	value
revolution frequency	2.6 MHz
RF frequency	500 MHz
nominal RF power loss	26 kW
maximum beam current (multibunch)	130 mA
maximum beam current (single bunch)	20 mA
synchrotron frequency	15.2 - 16.4 kHz
fractional horizontal tune	0.10 - 0.20
fractional vertical tune	0.20 - 0.30

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DAMPING TIMES OF COUPLED-BUNCH MODES

In a first step, a method was developed to measure the damping rates of all $h = 192$ multibunch modes at DELTA. Below the instability threshold, a specific coupled-bunch mode is excited by the frequency generator of the bunch-by-bunch feedback system while the longitudinal bunch positions are recorded. In between, the excitation is switched off for a few milliseconds and the oscillation is damped. This measurement, called grow-damp measurement, is repeated for every multibunch mode while the damping rates are obtained by exponential fits. In Fig. 2, a measurement for mode no. 20 is shown in time domain (a), frequency domain (b) and with an exponential fit to obtain the damping rate (c). The resulting damping rates of all 192 modes are shown in (d). As expected from analytical calculations, the pairs of modes μ and $h - \mu$ show an anti-correlated behaviour. While one mode damps slower, the other has a higher damping rate than the zero-current value. For further information see [7] [9] [10].

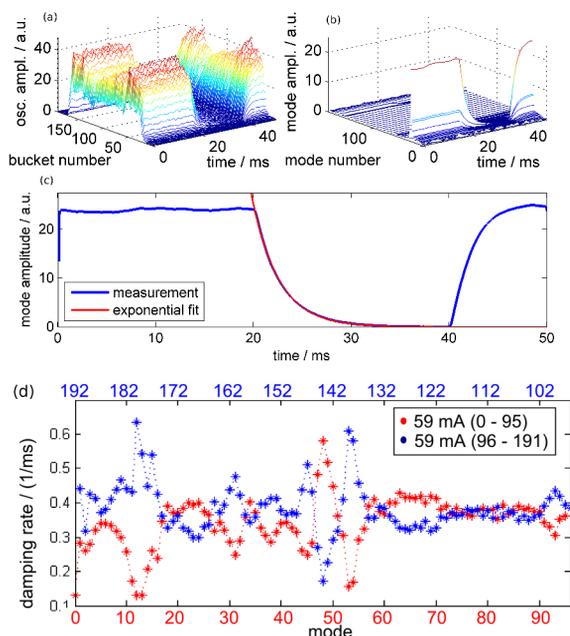


Figure 2: Bunch oscillation amplitudes in time domain (a) and mode amplitudes in frequency domain (b). The excitation is switched off for several milliseconds while the damping rate is obtained by an exponential fit (c). Observed damping rates for all longitudinal modes (d) are plotted in red (modes 0-95) and blue (modes 96-191).

COUPLED-BUNCH INSTABILITY SUPPRESSION BY RF MODULATION

In order to analyze the influence of the RF phase modulation on the damping rates of all multibunch modes, the method shown in the previous section is used. Since the RF phase is modulated in the kHz regime, the accelerating

gradient varies in the same regime as the synchrotron frequency. Therefore, the longitudinal accelerating gradient of every electron changes, which leads to slightly different synchrotron frequencies for every single particle. This results in an incoherent motion of the electrons in every bunch. In consequence, the coherent excitation of coupled-bunch modes is suppressed. This takes effect for every longitudinal mode and is observable also for horizontal modes due to dispersion. As seen in Fig. 2, the most unstable longitudinal mode (with the lowest damping rate) at DELTA is mode 12. In Fig. 3, this mode is under investigation while the generator voltage was varied from 0 V to 1.3 V in 0.05 V steps (see Fig. 3). The frequency generator of the bunch-by-bunch feedback system was used at a frequency of $f_{12} = 31216$ kHz on all bunches to excite the longitudinal mode 12. The excitation started at 7 ms and was switched off 3 ms later. With a beam current of 34.5 mA at the beginning of the measurement, the beam was far below the instability threshold and, therefore, damped. The total acquisition time amounted to 50 ms. This process was repeated for variable amplitudes of the modulation at a frequency of $f_{\text{mod}} \approx 2 \cdot f_s = 31.8$ kHz. During the whole measurement, the beam current decreased by less than 0.05 mA and its deviation was, therefore, negligible. While determining the damping rates via exponential fit worked fine for small modulation amplitudes, the shape of the measured curve changed for modulation amplitudes higher than 0.5 V. Above this value, exponential fits are no longer accurate for the description of the measured data. While this effect gets even worse for higher modulation amplitudes up to the maximum of 3 V, the maximum oscillation amplitudes decrease. This shows, that the excitation of mode 12 is suppressed depending on the amplitude of the RF phase modulation. However, to determine the damping rates of coupled-bunch modes under the influence of an RF phase modulation, the used method is not applicable and a new analysis method is necessary.

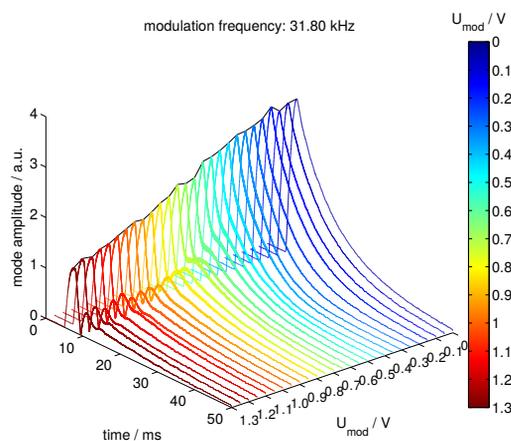


Figure 3: Grow-damp measurements for different amplitudes of the RF phase modulation with a modulation frequency of $f_{\text{mod}} \approx 2 \cdot f_s = 31.8$ kHz. Exponential fits to determine the damping rate are not viable for amplitudes above $U_{\text{mod}} = 0.5$ V.

Frequency Dependence

The modulation frequency f_{mod} is another important parameter for the influence of the RF phase modulation on the instability suppression. The influence is investigated by the same grow-damp measurements as used before with a fixed generator voltage $U_{\text{mod}} = 1.5 \text{ V}$. As can be seen in Fig. 4, the modulation frequency has to be set slightly below twice the synchrotron frequency. With $f_s = 16.05 \text{ kHz}$, the maximum suppression of the longitudinal mode 12 is reached with a modulation frequency of $f_{\text{mod}} = 31.8 \text{ kHz}$. A deviation of the modulation frequency of $\pm 1.5 \text{ kHz}$ from the optimal value extinguishes the suppression effect.

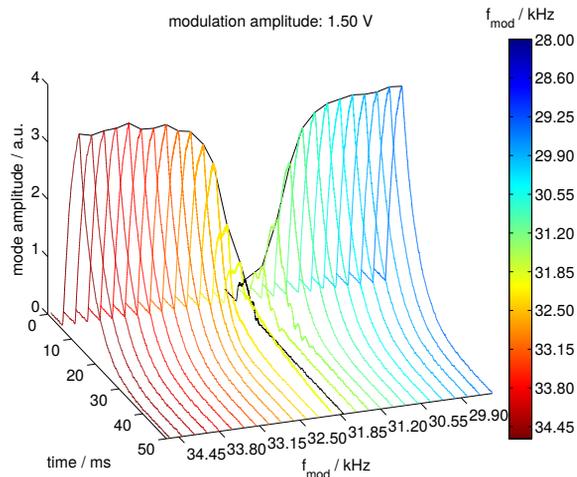


Figure 4: Grow-damp measurements for variable modulation frequencies f_{mod} with the synchrotron frequency $f_s = 16.05 \text{ kHz}$. The suppression of multibunch mode 12 is maximized for $f_{\text{mod}} = 31.8 \text{ kHz}$ (black curve).

Another method to analyze the frequency dependence of instability suppression is obtaining the spectral power at the mean synchrotron frequency of all bunches. For this purpose, grow-damp measurements were repeated for variable modulation frequencies from 28 kHz to 54 kHz. As can be seen in Fig. 5, previous results are confirmed, since the maximum instability suppression is obtained at $f_{\text{mod}} = 31.8 \text{ kHz}$. In addition, instability suppression could also be detected at $f_{\text{mod}} \approx 3 \cdot f_s = 47.7 \text{ kHz}$, as expected from previous works [3]. Here, a deviation of $\pm 0.5 \text{ kHz}$ already extinguishes the suppression effect.

Beam Quality Decrease

Next to the suppression of coupled-bunch instabilities and the increase of beam lifetime, the modulation of the RF phase also has a negative influence on the beam quality. Due to the excitation of incoherent motion inside the bunches, the bunch length increases depending on the modulation amplitude. To investigate this phenomenon, a streak camera was used for the determination of the bunch length while the generator voltage was varied from 0 V to 3 V. The results show that in normal user operation, with $U_{\text{mod}} = 0.7 \text{ V}$, the bunch length increase is less than 20%. With a modulation

amplitude of 1 V, the bunches get prolonged by approx. 35%. With 2 V, the effect increases to circa 85% and with the maximum modulation amplitude of 3 V, the bunch length increases by about 120%. In addition, the longitudinal phase space changes. For high modulation amplitudes, the number of stable islands in the phase space increases, which leads to sub-bunches revolving around the center of mass. For detailed information see [3] [5] [11] [12].

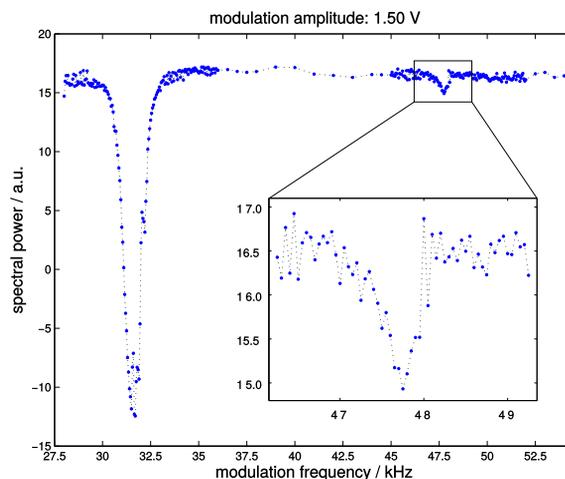


Figure 5: Spectral power at the synchrotron frequency $f_s = 16.05 \text{ kHz}$ of all bunches for variable modulation frequencies. Coupled-bunch instability suppression is maximized for $f_{\text{mod}} = 31.6 \text{ kHz}$ and also achievable for $f_{\text{mod}} = 47.8 \text{ kHz}$.

CONCLUSION AND OUTLOOK

With a new measurement method where every multibunch mode is preexcited by the frequency generator of the bunch-by-bunch feedback system, it is possible to determine the damping rate of every mode in a circular accelerator. Suppressing coupled-bunch modes with an RF phase modulation can be detected by decreasing maximum amplitudes in grow-damp measurements depending on the modulation amplitude. However, determination of damping rates by exponential fit is problematic. Using a frequency dependent measurement, it can be shown that the modulation frequency has to be set slightly below a multiple of the synchrotron frequency. However, streak camera measurements demonstrates that the bunch length increases the higher the modulation amplitude is set. The use of an RF modulation could be an option for the BESSY-VSR project to add more stability at the cost of a slightly reduced brilliance and a bunch length increase.

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