BUNCH-BY-BUNCH FEEDBACK SYSTEMS AT THE DELTA STORAGE RING USED FOR BEAM DIAGNOSTICS*

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Abstract

At the 1.5-GeV electron storage ring DELTA operated by the TU Dortmund University, a bunch-by-bunch feedback system was installed in 2011. Since then, it is in operation for different beam diagnostic purposes. A fast analysis of bunch-position data allows a real-time multibunch mode analysis during machine operation. In addition, the data analysis can be triggered by external events, e.g. beam losses or the injection process. In this paper, a feedback-based method to measure the damping times of multi-bunch modes is presented. Furthermore, a chromaticity-dependent single-bunch instability is analyzed. Finally, the use of the feedback system in the presence of an RF-phase modulation is presented.

INTRODUCTION

In 2011, a digital bunch-by-bunch feedback system [1] was installed at the 1.5-GeV electron storage ring DELTA (Fig. 1, Table 1) for beam diagnostics purposes [2, 3] and to suppress longitudinal and transverse coupled-bunch instabilities. The system comprises processing units for the longitudinal, horizontal and vertical plane as well as a common frontend and backend. In user operation, ~144 out of 192 buckets are filled with a beam current up to 130 mA (3/4 filling pattern). Longitudinal coupled-bunch modes show up above a current threshold of ~75 mA, while transverse instabilities are rarely observed. A modulation of the RF phase is routinely applied [4, 5] to suppress longitudinal instabilities and to improve the beam lifetime by reducing the mean electron density and thus the rate of Touschek scattering.

Ultrashort radiation pulses in the VUV and THz regime are generated since 2011 by an interaction of femtosecond laser pulses with an electron bunch of enhanced current [6]. For this purpose, the storage ring is either filled with a single bunch during dedicated machine shifts or with a hybrid filling pattern (an additional bunch in the gap of the 3/4 filling pattern). One purpose of the longitudinal feedback system is to suppress longitudinal oscillations of the bunch interacting with the laser pulses.

In addition, the feedback system is used to provide post-mortem data on the bunch motion preceding beam losses [3] and to study the beam dynamics under various circumstances. One example is to record the bunch motion during the injection process [2, 3], other more recent examples are descibed below.

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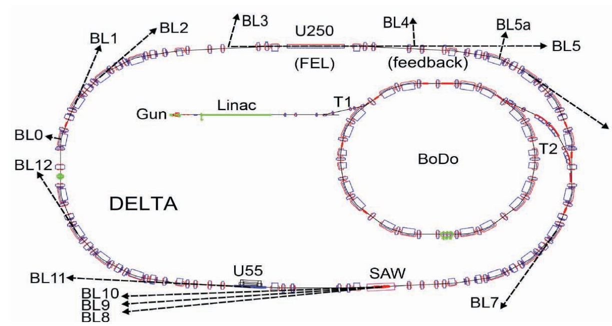

Figure 1: Overview of the DELTA facility including the storage ring and its booster synchrotron (BoDo).

Feedback Setup

To extract the horizontal, vertical and longitudinal position of every single bunch, the signals from a beam position monitor with four symmetrically arranged buttons are combined in a hybrid network to extract the horizontal and vertical differential signal as well as the sum signal. The three resulting signals are stretched using a two-cycle comb-filter in the feedback frontend and are mixed with a 1.5-GHz reference signal. The resulting signals are filtered by a low-pass filter. Using phase shifters and attenuators, the mixed signals can be adjusted to be either phase sensitive (longitudinal position) or amplitude sensitive (transverse position). Finally, the signals are digitized by 12-bit ADCs in the feedback processing units. 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 [7]. In the longitudinal plane, the output signal is mixed up to 1.5 GHz in the feedback backend before being sent to the amplifier. In addition to an FIR-filter, the processing units include a frequency generator, which allows to send a dedicated RF signal to the beam, e.g. to excite specific multibunch modes, as shown in the next section.

Table 1: Storage Ring Parameters

parameter	value
revolution frequency	2.6 MHz
RF frequency	500 MHz
nominal RF power	25 kW
maximum beam current (multibunch)	130 mA
maximum beam current (single bunch)	20 mA
synchrotron frequency	15.7 kHz
fractional horizontal tune	0.10
fractional vertical tune	0.28

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DAMPING TIMES OF COUPLED-BUNCH MODES

To determine the damping rates of all $h = 192$ multibunch modes at DELTA, the following measurement scheme was applied [8]. Below the instability threshold, i.e. well below 75 mA, all bunches are excited by the feedback drive signal corresponding to a dedicated multibunch mode. Then the excitation is switched off for a few milliseconds and the oscillation is damped. The measurement was repeated for all multibunch modes. From an exponential fit to the damping time of each multibunch mode, its respective damping rate can be obtained. Figure 2 shows one example measurement for mode no. 20 in time domain (a), in frequency domain (b) and the resulting damping rates of all 192 modes (c). As expected from analytical calculations, the pairs of modes μ and h μ show an anti-correlated behaviour. While one mode is damping slower, the other is damping faster than the zero-current value. This can be understood by calculating the multibunch growth rate for two example modes following the analytical expression given by [9]

$$\frac{1}{\tau_\mu} = \frac{hNe^2\eta}{2\omega_s E T_0^2} \sum_{p=\ \infty}^{\infty} \omega(p)\mathrm{Re}Z_\parallel \ \ \omega(\mathrm{p})) \qquad (1)$$

with $\omega(p) = ph\omega_0 + \mu\omega_0 + \omega_s$, the revolution frequency ω_0, the synchrotron frequency ω_s, the number of electrons in each bunch N, the electron charge e, the slippage factor η, the beam energy E and the revolution time T_0. For a narrowband impedance $Z_\parallel$ with center frequency $\mu\omega_0$, as an example, the growth rate for multibunch mode μ is positve, while the growth rate of mode h μ is negative, while all other multibunch modes are not effected by the impedance. Since several narrowband impedances, e.g. higher-order modes of the accelerating cavity, interact with the beam, many of the multibunch modes are affected and are damping faster or slower than the zero-current value.

Beam Current Dependence

To study the current dependence of the damping rates, the measurements shown above were repeated for different beam currents below the instability threshold. The damping rates of several modes with high or low damping rates are plotted as a function of the beam current in Fig. 3. Linear fits for each mode allow to extrapolate to the zero-current damping rate, which should be identical for all multibunch modes. The resulting zero-current damping rate of about $1/\tau = 0.4/\mathrm{ms}$ differs from the synchrotron radiation damping rate of $1/\tau = 0.23/\mathrm{ms}$. This might be explained by the fact that the feedback system is only capable to detect the center-of-mass motion, which damps faster than the incoherent motion. This effect can also be seen by comparing the feedback data with data from a streak camera, which is discussed in the next section.

Comparison With Streak Camera Data

In addition to studying the bunch dynamics with the feedback system, the longitudinal bunch oscillation can be observed with a streak camera. In this measurement, the beam is stabilized by negative feedback and only excited by positive feedback for a time interval of 8 ms. The resulting oscillation is observed with the streak camera and the feedback system simultaneously, both being are triggered by a common clock signal. In Fig. 4a, the streak camera image is shown where the abscissa extends over several ms, while the ordinate shows the bunch length on a scale of several 100 ps. When the positive feedback is enabled, the bunches start to oscillate longitudinally. The actual oscillation of the bunches is not resolved on the given timescale, but results in a broadening of the apparent bunch length. In Fig. 4b, the rms value of a Gaussian fit to the bunch profile is plotted on the same time scale together with the amplitude of longitudinal bunch oscillations observed by the feedback system. There is a good general agreement between the position data

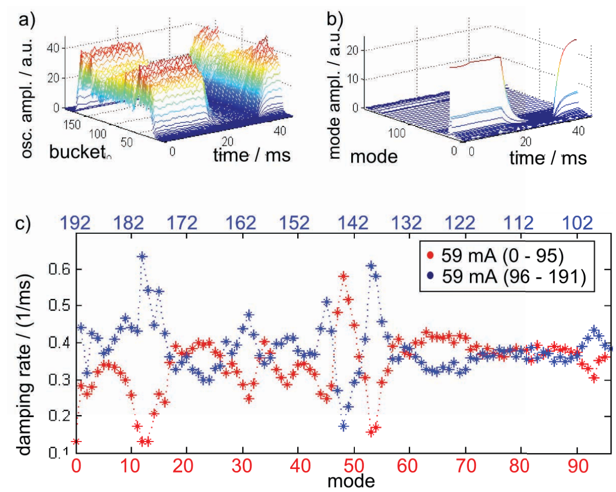

Figure 2: Bunch oscillation amplitudes for one example mode in time domain (a) and frequency domain (b). The excitation is switched off for several ms. The observed damping rates (c) of all longitudinal coupled-bunch modes are plotted in red (modes 0-95) and blue (modes 96-191).

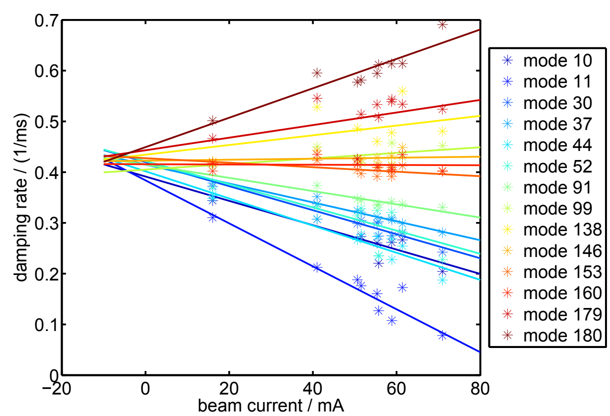

Figure 3: Damping rates of selected coupled-bunch modes as function of the beam current. Linear fits to the data points of each mode allow an extrapolation to the zero-current damping rate.

taken with these two different tools except for the difference in the rising and falling slope of the signals which can be explained by the fact that the feedback system detects only the bunch centroid, while the streak camera images the whole charge distribution (e.g. [10]). Since the bunch centroid is damped faster, the slopes are steeper in the feedback data than in the streak camera curve.

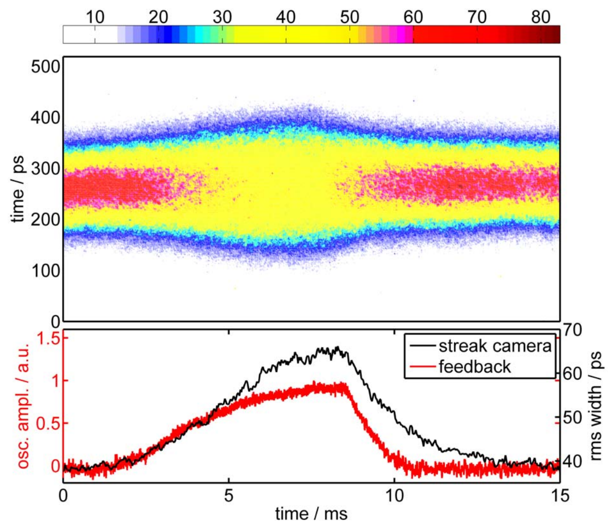

Figure 4: Streak camera image of a temporarily excited beam (top) with color-coded light intensity. The width of the apparent bunch length from the streak camera image and the oscillation amplitudes obtained by the feedback system are plotted on a common scale (bottom, see text for details).

SINGLE-BUNCH INSTABILITY

Besides using the bunch-by-bunch feedback system to study multibunch effects, it was used to observe the bunch oscillation during single-bunch operation. In this example, the chromaticity of the DELTA storage ring was varied by reducing the strength of sextupol magnets to excite single-bunch instabilities. The chromaticity was measured by changing the RF frequency by several kHz and detecting the change of the betatron tune $Q_{x,y}$. From a linear fit to the extracted data, the chromaticity can be determined according to

$$\xi_{x,y} = -\alpha \cdot f_{RF} \cdot \frac{dQ_{x,y}}{df_{RF}} \qquad (2)$$

with the momentum-compaction factor α and the RF frequency f_{RF}. While the chromaticities at DELTA are typically slightly positive $\xi_y \sim 2$ and $\xi_x \sim 3$, with reduced sextupoles they are reduced and the vertical chromaticity becomes negative, which gives rise of an oscillation of the single bunch. By reducing the sextupole strength further, the negative vertical chromaticity is increased, which leads to an increase of the the growth rate of the single-bunch oscillation. In Fig. 5a-d, two example measurements for different chromaticities and the corresponding exponential fits are plotted. Figure 5e shows the linear dependence of the growth rate on the chromaticity $\frac{1}{\tau} \sim -\xi$.

The growth of the oscillation saturates at a certain level due to the dependence of the betatron frequency on the oscillation amplitude, which leads to a collapse of the oscillation. As the growth rate increases, the periodicity of the single bunch oscillations becomes shorter because the saturation level is reached earlier. The linear dependence of the observed single-bunch growth rate on the chromaticity, can be interpreted as head-tail instability. For a negative chromaticity, the head-tail mode zero which can be detected by a centroid motion of the bunch has a positive growth rate (e.g. [9]).

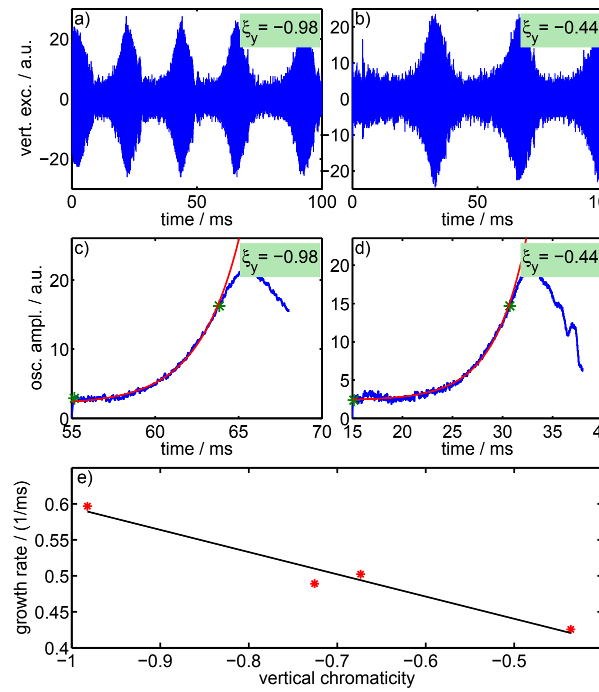

Figure 5: Vertical oscillation of a single bunch plotted in time domain for two different vertical chromaticities (a/b). The signal was high-pass filtered to suppress slow orbit fluctuations and the DC offset. An exponential fit to the envelope of the oscillation within the green marks yields the growth rate (c/d). The growth rate shows a linear dependence on the chromaticity (e).

FEEDBACK DURING RF-PHASE MODULATION

The DELTA short-pulse facility, based on the Coherent Harmonic Generation principle (CHG) [6] was constructed in 2011. Here, femtosecond laser pulses interact with a short slice within an electron bunch to create ultrashort, coherent VUV radiation pulses. In addition, coherent THz radiation is created [11]. During machine studies, ultrashort pulses are generated in single-bunch mode. In order to operate the short-pulse facility during multibunch user mode, a hybrid fill pattern was tested, injecting a high-current single bunch into the gap of the multibunch fill. Furthermore, an RF-phase modulation is routinely employed in user operation to

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increase the beam lifetime. The high-current single bunch is not only disturbed by this modulation but also performs center-of-mass oscillations due to coupled-bunch instabilities. Therefore, the longitudinal bunch-by-bunch feedback was used to stabilize the single bunch without acting on the other bunches. To study the influence of the RF-phase modulation and the bunch-by-bunch feedback on the beam lifetime and the laser-induced THz and CHG signal, these parameters were observed over several minutes for different configurations. If the RF phase is not modulated and the feedback system is switched off, the laser-induced signals are relatively high, while the beam lifetime is about 11 hours (see Fig. 6). If the RF-phase modulation is switched on, the beam lifetime is improved but the laser-induced signals are reduced by up to 30%. Finally, stabilizing the high-current single bunch using the longitudinal bunch-by-bunch feedback unit, does not affect the beam lifetime, but brings the laser-induced signals to their optimum level. Even though the signal fluctuations are slightly increased, the feedback system allows to generate ultrashort pulses during user operation without compromising the beam lifetime. As shown in Ref. [12], a synchronization of the laser to the RF-phase modulation can even increase the laser-induced signal.

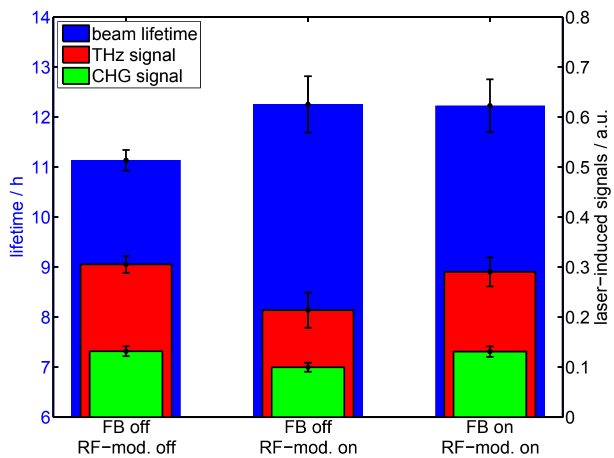

Figure 6: Laser-induced THz radiation (green), laser-induced CHG radiation in the VUV regime (red) and beam lifetime (blue) for different feedback and RF-phase modulation configurations: without feedback and RF-phase modulation (left), with phase modulation (center) and with both, feedback and phase modulation (right). The error bars indicate the fluctuation of the respective value during a time interval of several minutes.

SUMMARY AND OUTLOOK

The bunch-by-bunch feedback system is a powerful tool to study coupled-bunch and single-bunch instabilities. A beam-current-dependent measurement of the damping time of all coupled-bunch modes was performed and shows a linear dependence on the beam current. The measured damping rates indicate the relative strength and frequency of longitudinal impedance contributions folded into the baseband of the RF-frequency. The use of the longitudinal bunch-by-bunch feedback system in hybrid filling mode yields promising results to achieve a mode of operation, with a high beam lifetime while generating laser-induced VUV and THz radiation with optimum intensity.

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