SYNCHRONIZED DEMULTIPLEXING OF A BEAM CURRENT SIGNAL FOR A BUNCH-BY-BUNCH LONGITUDINAL FEEDBACK SYSTEM

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Abstract

High-intensity operation of the new SIS100 synchrotron is expected to be sensitive to coupled-bunch and single-bunch instabilities [1]. To counter these effects, a Bunch-By-Bunch Longitudinal Feedback System is currently in development. Operating this feedback system during acceleration and for arbitrary revolution frequencies presents several challenges. Thereby, this article focuses on the timing regarding the processing of a beam current signal provided by a Fast Current Transformer. This signal is utilized as main input for the feedback system in order to detect longitudinal beam oscillations of individual bunches. Therefore, it is demultiplexed into a sequence of segments, each containing the beam current signal of a single bucket. Afterwards, those segments are processed to extract potential oscillation components. The timing of the demultiplexing is controlled via harmonic RF reference signals that must be calibrated. The functionality of this demultiplexing process has been verified through measurements during a machine experiment with beam in July 2025.

INTRODUCTION

In order to counter longitudinal coupled-bunch and single-bunch instabilities during operation of the synchrotron SIS100 currently constructed at the GSI Helmholtz center for heavy-ion research in Germany, a Bunch-By-Bunch Longitudinal Feedback System is in development. A schematic showing the basic topology of the system is provided in Fig. 1.

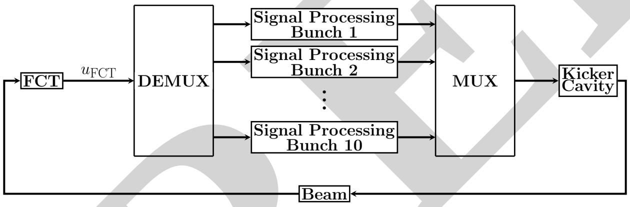

Figure 1: Schematic visualizing the basic topology of the Bunch-By-Bunch Longitudinal Feedback System.

In general, the system utilizes a beam current signal u_FCT provided by a Fast Current Transformer (FCT) to detect longitudinal oscillations of individual bunches. An example for u_FCT is given on the left-hand side of Fig. 2. This signal is distributed among several, identical signal processing units using a demultiplexer (DEMUX). Thereby, each of these units receives only parts of the FCT signal associated with one specific bunch resulting in signals like $u_\mathrm{FCT,b1}$ shown on the right-hand side of Fig. 2. This separation enables an individual monitoring of the single bunches in the ring by their dedicated signal processing units which, in case longitudinal bunch oscillations are detected, generate corresponding feedback signals to damp these oscillations. All feedback signals are combined to one final RF kicker signal by a multiplexer (MUX) which is then applied on the beam through a kicker cavity.

This contribution focuses on the demultiplexing of the beam current signal with a special focus on the synchronization of this process with the synchrotron operation. Thereby, the functionality of this system independent of the current RF frequency is ensured. Further information regarding the working principles of the complete Bunch-by-Bunch Longitudinal Feedback System can be found in [2–4].

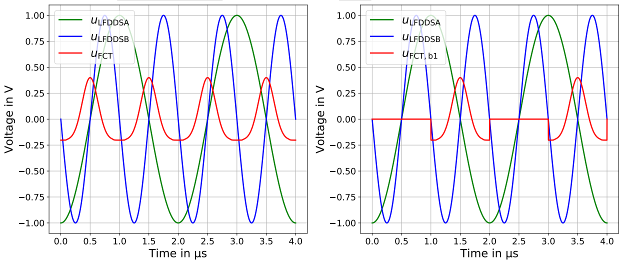

Figure 2: The diagram on the left-hand side shows a schematic of a beam current signal u_FCT provided by an FCT and corresponding RF reference signals u_LFDDSA and u_LFDDSB. Thereby, a harmonic number of $h = 2$ is assumed. The diagram on the right-hand side illustrates a demultiplexed beam current signal $u_\mathrm{FCT,b1}$ for bunch one.

SETUP FOR THE DEMULTIPLEXING OF THE BEAM CURRENT SIGNAL

Figure 3 shows a simplified block diagram of the setup used for the demultiplexing of the beam current signal. It includes the DDS modules Longitudinal Feedback DDS A (LFDDSA) and Longitudinal Feedback DDS B (LFDDSB) for the generation of the harmonic reference signals u_LFDDSA and u_LFDDSB visualized in Fig. 2 using Direct Digital Synthesis (DDS). Additionally, the system includes two Calibration Electronics Modules (CEL) to adjust the phase of the reference signals, a demultiplexer module (DEMUX) to forward the FCT signal to various output ports and, finally, a Trigger Unit to control the switching of the demultiplexer. Various other components like amplifiers, splitters, short coaxial transmission lines, etc. between the main blocks have been omitted for the sake of simplicity.

The demultiplexing process is controlled by the two harmonic RF reference signals u_{LFDDSA} and u_{LFDDSB}. Such signals are utilized as references for various purposes all over the facility, e.g. to generate synchronized gap voltages in all cavities. Their correct timing is ensured by the Bunch-phase Timing System BuTiS [5,6] and the White Rabbit System [7,8]. The signals u_{LFDDSA} and u_{LFDDSB} oscillate with the revolution frequency f_{R} and the RF frequency $f_{\mathrm{RF}} = h \cdot f_{\mathrm{R}}$ respectively. For a synchronized demultiplexing of the beam current signal it is desired that, in case of a synchronous phase of $\varphi_{\mathrm{R}} = 0$, the phase relations illustrated in Fig. 2 between all signals hold at the point they enter the Feedback System indicated by the green, dashed line in Fig. 3. Then, the number of the active output port of the demultiplexer can be incremented during every negative zero crossing of u_{LFDDSB} to send only one pulse of a single bunch in the FCT signal to each signal processing unit. This is also valid for $\varphi_{\mathrm{R}} \neq 0$ as the negative zero crossing of u_{LFDDSB} represents the boundary between two RF buckets. After each revolution, the number of the active output port of the demultiplexer is reset using the positive zero crossing of u_{LFDDSA}, enabling the creation of signals like $u_{\mathrm{FCT,b1}}$. This control algorithm is implemented in the Trigger Unit which enables/disables the output ports of the demultiplexer accordingly with TTL signals.

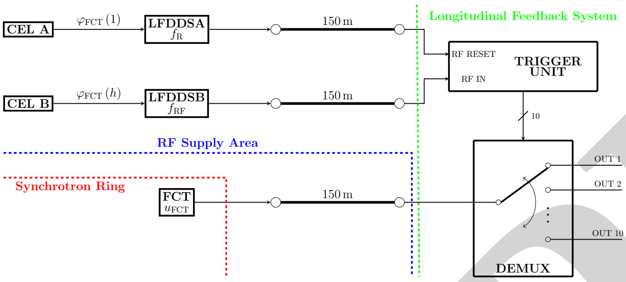

Figure 3: Block diagram of the network utilized for the synchronized demultiplexing of the beam current signal. The FCT is located at the synchrotron ring while all other components are located in the RF supply area. The lengths of the transmission lines are valid for the synchrotron SIS18 where the setup is currently tested. The lengths for SIS100 may vary.

In order to ensure that the phase relations at the green line in Fig. 3 do not depend on the RF frequency, the delays of all three signals have to be equal at this point. As the FCT signal originates at the ring, it must be sent to the demultiplexer via a 150 m long transmission line. Thus, although the modules LFDDSA and LFDDSB are located in proximity to the demultiplexer, their signals are also delayed using 150 m long transmission lines to adapt their delay accordingly. Of course, there are further delays which have to be taken into account for the overall process, e.g. the processing delay introduced by the Trigger Unit within the Longitudinal Feedback System, but those are compensated locally through the insertion of transmission lines in the parallel signal paths.

PHASE CORRECTIONS FOR THE RF REFERENCE SIGNALS

Since fixed, frequency-independent phase differences between u_{LFDDSA}, u_{LFDDSB} and u_{FCT} will be present (due to installation positions in the ring) and such phase differences cannot be compensated by delays that are included in the setup for the demultiplexing, the introduction of additional phase offsets is required to align all signals according to Fig. 2. The harmonic reference signals refer to the azimuthal position θ_{ref} in the ring illustrated in Fig. 4 corresponding to an RF phase of 0 ° assuming a harmonic number of $h = 1$. To ensure that signals can be compared, e.g. for a phase measurement, they have to refer to the same position in the ring, in this case the position of the FCT θ_{FCT}. Thus, considering a beam circulating in clockwise direction and the basic description

$$u_{\mathrm{DDS}}(t) = \hat{V} \sin\left(h\omega_{\mathrm{R}} t - \varphi^{*}\right)$$

for the harmonic reference signals with an optional phase offset φ^{*}, they have to be shifted according to

$$\begin{aligned} u_{\mathrm{DDS}}(t) &= \hat{V} \sin\left(h\omega_{\mathrm{R}} t - h\left(\theta_{\mathrm{FCT}} - \theta_{\mathrm{ref}}\right)\right) \\ &= \hat{V} \sin\left(h\omega_{\mathrm{R}} t + \varphi_{\mathrm{FCT}}(h)\right) \end{aligned}$$

with

$$\varphi_{\mathrm{FCT}}(h) = -h\left(\theta_{\mathrm{FCT}} - \theta_{\mathrm{ref}}\right).$$

Considering the harmonic numbers associated with u_{LFDDSA} and u_{LFDDSB}, their required phase corrections $\varphi_{\mathrm{FCT}}(1)$ and $\varphi_{\mathrm{FCT}}(h)$ are stored in CEL A and CEL B to shift these reference signals accordingly. It should be noted that a clockwise circulation direction of the beam has been assumed in this example as this applies for the synchrotron SIS18 at GSI where the setup is tested in the current development stage. In the new synchrotron SIS100 the beam will circulate counter-clockwise but the main principles do not change.

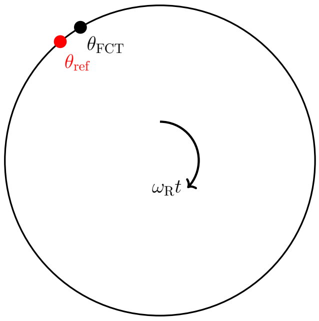

Figure 4: Diagram indicating the reference position θ_{ref} for RF reference signals in the ring, the FCT position θ_{FCT} and a beam circulating in clockwise direction with a revolution frequency of ω_{R}.

EXPERIMENTAL VERIFICATION OF THE DEMULTIPLEXING

The functionality of the demultiplexing of the beam current signal independent of the current RF frequency has been confirmed in a machine experiment with beam in July 2025. In this experiment, the Longitudinal Feedback System was used to damp longitudinal dipole oscillations of individual bunches during operation with a harmonic number of $h = 2$. A measurement result from this experiment presented in Fig. 5 visualizes the successful separation of the single pulses in the signal. As desired, the active output port of the demultiplexer is switched during every negative zero crossing of u_{LFDDSB} and the single bunch pulses are located at their reference positions defined by the current synchronous phase $\varphi_{\mathrm{R}} \approx 2.5\,°$. Another measurement shown in Fig. 6, which has been recorded two weeks earlier during preparations for the experiment, demonstrates the functionality of this process by providing a waterfall diagram of a demultiplexed beam current signal over a whole acceleration cycle. In this plot, regions of the demultiplexed signal containing the beam pulses of a single bunch can easily be separated from the light blue regions indicating $u_{\mathrm{FCT}} = 0$ in which u_{FCT} was forwarded to different output ports of the demultiplexer. As this measurement was taken during experiments of other GSI departments, the harmonic number is different compared to the measurement shown in Fig. 5.

CONCLUSION

The system for the demultiplexing of the beam current signal within the Bunch-by-Bunch Longitudinal Feedback System for SIS100 has been described. It is crucial for monitoring longitudinal beam oscillations of individual bunches as it distributes corresponding signal parts to dedicated processing units. In order to operate the system independent of the RF frequency, the influence of signal delays had to be taken into account by inserting additional transmission lines for delay compensation. Furthermore, a phase correction for the reference signals controlling the process was determined to ensure a correct timing regarding the switching events of the demultiplexer. These measures used to synchronize the demultiplexing with the synchrotron operation proved to be reliable in measurements.

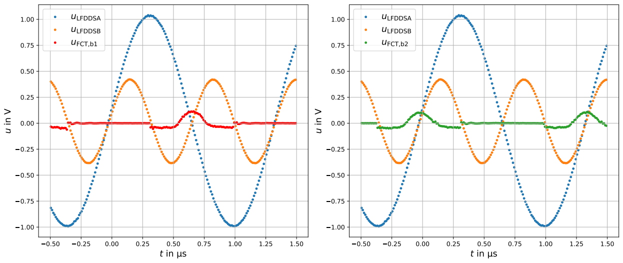

Figure 5: Measurement results showing the successful demultiplexing of a beam current signal during operation with a harmonic number of $h = 2$ and a synchronous phase of $\varphi_{\mathrm{R}} \approx 2.5\,°$.

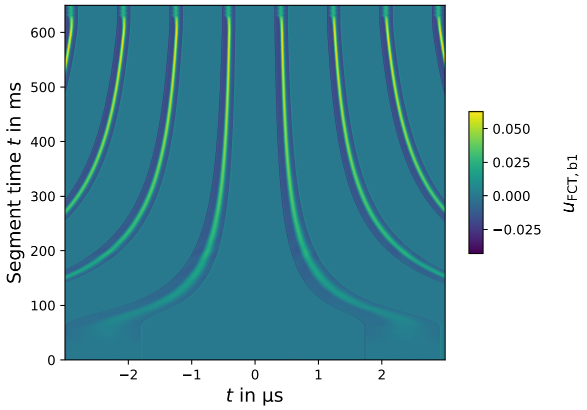

Figure 6: Waterfall diagram of a demultiplexed beam current signal over a whole acceleration cycle during operation with a harmonic number of $h = 4$. Although the position of the observed bunch within the corresponding RF bucket changes with the synchronous phase φ_{R} over the cycle, the entire signal of the bunch was captured without distortions or interruptions.

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