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DAMPING OF QUADRUPOLE OSCILLATIONS WITH BUNCH-BY-BUNCH LONGITUDINAL RF FEEDBACK FOR FAIR

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Abstract

To damp undesired longitudinal oscillations of bunched beams, the main synchrotron SIS100 of FAIR (Facility for Antiproton and Ion Research) will be equipped with a bunch-by-bunch longitudinal feedback (LFB) system. It will consist of new broadband kicker cavities and a dedicated low-level RF (LLRF) system. The LFB helps to stabilize the beam, to keep longitudinal emittance blow-up low and to minimize beam losses via damping dipole and quadrupole oscillations for up to 10 bunches individually. The topology of the LLRF signal processing is validated in closed loop with beam in the heavy-ion synchrotron SIS18 at GSI for future integration into SIS100. In a recent SIS18 machine development experiment (MDE) with two bunches at flattop, quadrupole oscillations were excited for one bunch and then damped with a prototype setup of the LFB system using an existing magnetic alloy cavity as dedicated kicker cavity. This paper presents the test setup, the results of this experiment, and the proposed LLRF topology of the closed-loop LFB system. This validates a core part of the final SIS100 system. Finally, the current status of the longitudinal feedback system for FAIR is summarized.

INTRODUCTION

In hadron synchrotrons, longitudinal bunch instabilities represent a major limitation to high beam intensities, cf. [1,2]. To overcome this, mode-by-mode or bunch-by-bunch feedback is commonly used for damping these oscillations. For electron machines, the feedback for (usually dipole mode) bunch instabilities is widespread [3–5]. For hadron machines, mode-by-mode (e.g. [6]) and bunch-by-bunch systems (e.g. [7]) exist. As stated in [7], the LFB design in hadron machines has the additional challenge that the emittance of the beam is sensitive to any noise-exitation due to the missing synchrotron radiation damping. For the heavy-ion synchrotron SIS100 [8], such a system has to deal with harmonic numbers of up to 10, fast ramp rates, a large frequency swing, and RF frequencies in the lower MHz range [9]. In [10], a first concept for the SIS100 LFB system and first results on damping of quadrupole modes in the existing synchrotron SIS18 were presented. However, the feedback was not yet bunch-by-bunch, i.e. acted on all bunches in the same way. In [11], the LLRF topology was detailed, using a time-domain approach with a dedicated kicker cavity, and a bunch-by-bunch damping of longitudinal dipole oscillations was demonstrated using a prototype LFB setup in SIS18 on flattop with a ferrite cavity as kicker cavity. In an MDE in 2023, it was demonstrated that the prototype LFB system in SIS18 is able to damp quadrupole oscillations in a bunch-by-bunch manner on flattop. Our results from this experiment are summarized in this paper.

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SETUP

Scenario

For the experiment, SIS18 was operated at h=2 and one of two bunches was excited to perform quadrupole oscillations on flattop by RF manipulations. These oscillations were detected and damped by the LFB prototype using a magnetic alloy (MA) cavity as kicker cavity. The second (non-disturbed) bunch was used to verify that the feedback was indeed acting in a bunch-by-bunch manner, i.e. only affecting one bunch. The main parameters for the experiment are summarized in Table 1.

Table 1: Main Parameters of the Experiment

Ion species	$^{238}U^{73+}$
Particles at injection	$3 \cdot 10^8$
Injection energy	11.4 MeV/u
Flattop energy	300 MeV/u (Dec. 2nd, 2023)
	600 MeV/u (Dec. 10th, 2023)
Revolution freq.	904.8 kHz (at 300 MeV/u)
	1.098 MHz (at 600 MeV/u)
Beam current (flattop)	3 mA
Main harmonic number	h=2

On flattop, ferrite cavity BE2 was used at h=2 to bunch the beam. Two MA cavities were used for the excitation (BE3 at h=1 and BE4 at h=2) and a further MA cavity was used as kicker cavity (BE5). All reference signals for the cavities and for the LFB were based on the topology generated by four group DDS Modules (A,B,C,D), cf. [12].

LFB Topology

The topology of the LLRF setup is shown in Fig. 1. The analog beam current signal from a fast current transformer (FCT) is de-multiplexed (DEMUX) in the time domain into multiple signals, where signal n only contains the information of bunch n and is zero elsewhere. Each de-multiplexed signal is digitized and processed by a dedicated DSP system [13]. This includes the I/Q detection and the feedback filter for the quadrupole modes cf. [14]. The DSP output is used to construct the analog RF correction signal that is needed

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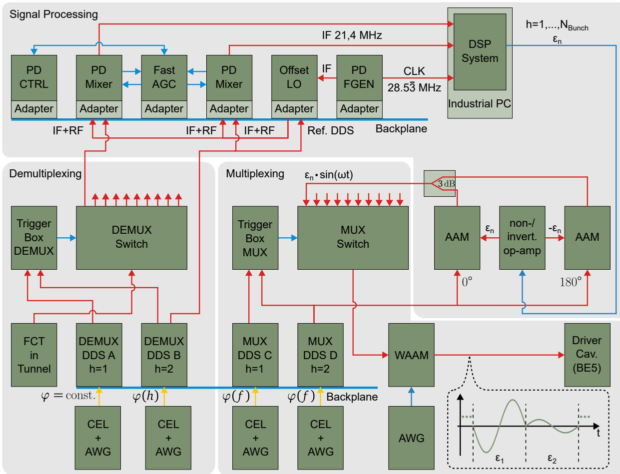

Figure 1: Longitudinal Feedback LLRF topology for the experiment cf. [11].

for bunch n. All correction signals are time-multiplexed (MUX) into one kicker input signal that is amplitude modulated by the target amplitude and used as a driver signal of the kicker cavity.

For the timing synchronization of DEMUX, MUX, and kicker cavity, signal delays were adjusted for the fixed flattop frequency in a manual way using constant phase shifts that were generated by arbitrary waveform generators (AWG) and dedicated calibration electronic modules (CEL). For the DEMUX part, a constant phase shift compensated for the installation position of the FCT. For MUX, reference signals C and D were phase shifted such that the gap voltage of kicker cavity BE5 was in phase with the other cavities. This was necessary since the kicker cavity was operated in an open-loop mode, whereas all other cavities were operated in closed-loop mode.

In the final setup of the LFB system, the phase-shifting and delay adjustment will be realized such that all signal phases are automatically adjusted during the frequency ramp. This will include a phase calibration of the kicker cavity system. In future, it is planned to use extra, dedicated DDS modules for the longitudinal feedback system. This will enable an automatic adjustment of the necessary phases for the de-multiplexing, the multiplexing, and the kicker cavity.

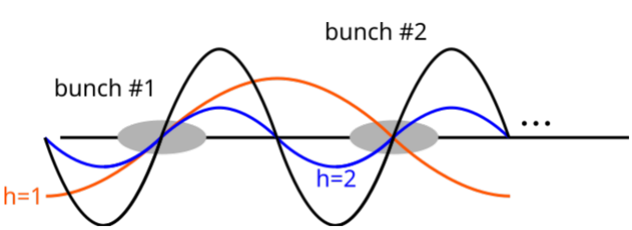

Figure 2: Quadrupole mode excitation: Main gap voltage at h=2 (black, BE2), additional gap voltages at h=2 (blue, BE4) and at h=1 (orange, BE3).

Excitation of Quadrupole Oscillations

Quadrupole oscillations were intentionally induced for one bunch by increasing the gap voltages of BE3 and BE4 adiabatically to the setup shown in Fig. 2. For bunch 1, the additional gap voltages with h=1 and h=2 increase the main gap voltage, whereas the additional voltages approximately cancel for bunch 2, leaving this bunch unaffected. To start the oscillations, the gap voltages of BE3 and BE4 were reduced to zero as fast as possible. Selected ramps of the pattern are shown in Fig. 3. The amplitude of BE4 (not shown) was half of the amplitude of BE3.

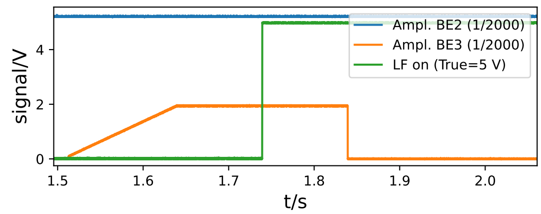

Figure 3: Target values (measurement 030, Dec. 10th).

With the abrupt reduction of voltage for bunch 1, its length increased, whereas the amplitude of the beam current decreased and performed oscillations with about twice the synchrotron frequency, cf. [14]. The oscillations are damped due to filamentation, leading to a (small) emittance increase for bunch 1. These RF manipulations were used in combination with a rather low beam intensity to systematically investigate the feedback behavior. Of course, the final LFB system will be operated with high SIS100 beam intensities.

Feedback and Damping

For each bunch, a dedicated DSP system detected phase and amplitude. The measured amplitude was then processed by an FIR-filter, followed by an integration. For details on the filter and the closed-loop stability for quadrupole modes, we refer to [14]. The feedback was switched on shortly before the rapid decrease of the excitation gap voltages of BE4 and BE3.

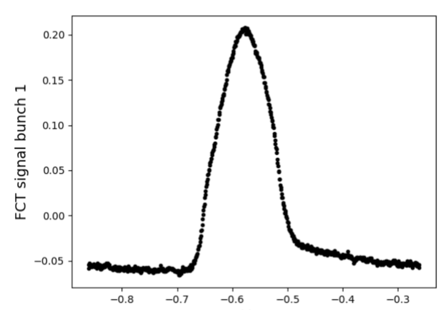

Figure 4: Typical bunch shape of bunch 1 before reducing the additional voltages (measurement 023, Dec. 10th).

Figure 4 shows the bunch signal of bunch 1 directly before the voltage reduction. Its bunch length is about $4\sigma_t \approx 4 \times 43$ ns $= 172$ ns. The RF frequency was $f_{\mathrm{RF}} = 1.81$ MHz. According to [14] and assuming a Gaussian distribution, the amplitude of the RF harmonic is

$$I_1 = 2I_0 e^{-0.5\times(2\pi f_{\mathrm{RF}}\sigma_t)^2}, \quad (1)$$

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where I_0 is the DC current. For measurement 023, the voltage amplitudes were 11.7 kV (BE2, h=2), 2 kV (BE4, h=2) and 4 kV (BE3, h=1). For the bunching at h=2, the effective amplitude of BE3 is $4 \times \frac{1}{2}$ kV = 2 kV. With these values and assuming a Gaussian distribution, the new bunch length for an adiabatic change of the gap voltages would be

$$\tilde{\sigma}_t = \left(\frac{\widehat{U}_{\text{before}}}{\widehat{U}_{\text{after}}}\right)^{\frac{1}{4}} \sigma_t = \left(\frac{15.7\text{ kV}}{11.7\text{ kV}}\right)^{\frac{1}{4}} \sigma_t \approx 46\text{ ns} \tag{2}$$

The corresponding beam current amplitude is equal to

$$\tilde{I}_1 = 2I_0 e^{-0.5(2\pi f_{\text{RF}} \tilde{\sigma}_t)^2} \tag{3}$$

For the given parameters, the ratio is $\tilde{I}_1/I_1 \approx 0.99$. Because the voltage reduction is non-adiabatic, the ratio will in general be smaller due to filamentation, i.e. $\tilde{I}_1/I_1 < 0.99$. It is expected that feedback damps oscillations and mitigates filamentation: $(\tilde{I}_1/I_1)_{\text{LFB off}} < (\tilde{I}_1/I_1)_{\text{LFB on}} < 0.99$. The excitation was small (beam current amplitude variations in the order of one percent), but realistic for testing emerging instabilities.

RESULTS

Figure 5 shows a waterfall plot of the FCT signal for the excitation of bunch 1 with feedback off. As desired, quadrupole oscillations are excited for bunch 1 only and bunch 2 remains unaffected. The frequency of the quadrupole oscillations is about 1.8 kHz. Figure 6 shows the FCT amplitude with feedback off and on, respectively. The feedback damps the oscillation within 2 to 3 synchrotron periods. The ratio $\tilde{I}_1/I_1$ is roughly between 0.98 to 0.99. This is in good agreement with the theoretical value of 0.99, which does not include filamentation.

The signal of the DC beam current is shown in Fig. 7. To remove a disturbance at 150 Hz, the analog signal was post-processed by using a simple moving average (SMA) filter with a window length of 20 ms. The result shows no significant beam losses during excitation and feedback.

CONCLUSION AND OUTLOOK

The experiment successfully realized the bunch-by-bunch damping of quadrupole oscillations as a further proof-of-principle validation for the concept of the SIS100 LFB system. The recorded data of the parameter scans are a good starting point for further investigations, since the optimal parameters (gain and filter frequency) were determined for multiple machine settings. The next steps for the LLRF part of the LFB system will be the operation during ramping and the automatic gain adjustment of the individual bunch signals. A major topic will be the development and production of the SIS100 broadband cavities for the LFB with a sufficient bandwidth that will have to be considerably higher than the bandwidth of the SIS18 MA cavities.

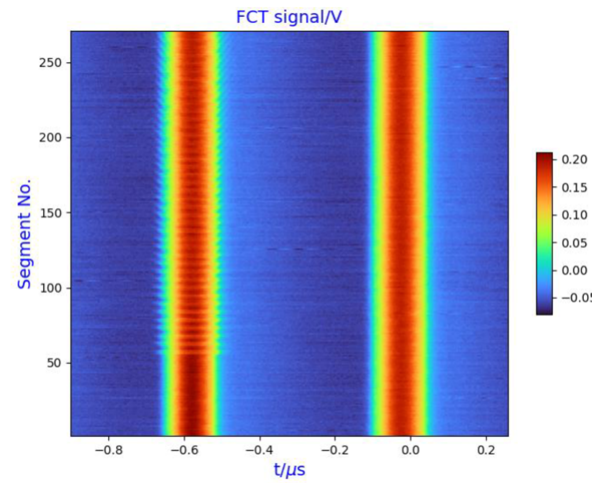

Figure 5: Waterfall plot of FCT signal, excitation of bunch 1, feedback off (measurement 023, Dec. 10th).

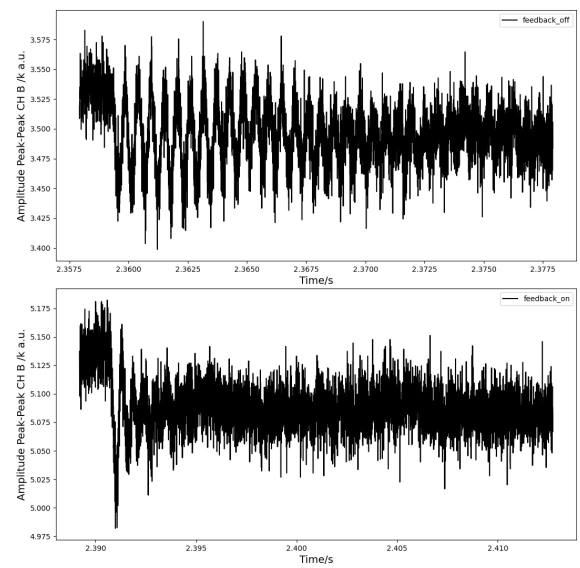

Figure 6: FCT amplitude (at h=2) of bunch 1, top: LFB off (meas. 023), bottom: LFB on (meas. 030).

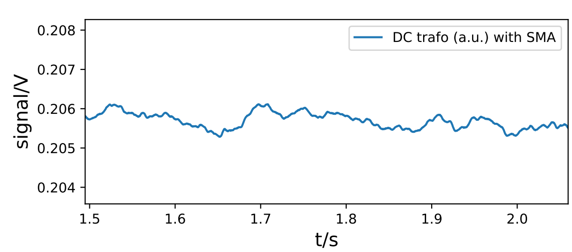

Figure 7: DC trafo signal on flattop (meas. 030, Dec. 10th) after SMA filtering, identical time frame compared to Fig. 3.

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