LONGITUDINAL BEAM STABILIZATION AT FAIR BY MEANS OF A DERIVATIVE ESTIMATION*

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Abstract

During acceleration in SIS18/SIS100 at GSI/FAIR longitudinal beam-oscillations are expected to occur. To reduce emittance blow-up, dedicated LLRF beam feedback systems are planned. To date longitudinal beam oscillations have been damped in machine experiments with a finite-impulse-response (FIR) filter controller with 3 filter taps[1]. An alternative approach implementing the FIR filter as a derivative estimator controller is simulated and tested. This approach shares the same controller topology and can therefore be easily integrated in the system. It exploits the fact that the sampling rate of the feedback hardware is considerably higher than the frequency of the beam oscillations. It is therefore capable of damping oscillations without overshoot *within* one oscillation period.

INTRODUCTION

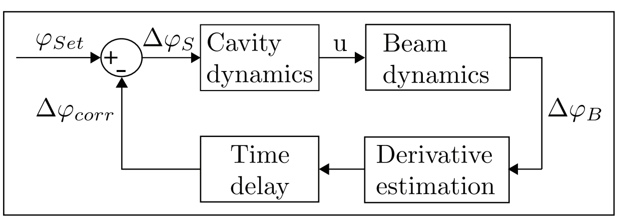

Figure 1: Control loop.

Figure 1 shows the simplified topology of the beam phase control loop used in the experiment and in the macro particle simulations. Starting from beam dynamics the beam phase $\Delta\varphi_B$ is measured with respect to a reference DDS signal. The phase of this DDS signal is not influenced by the feedback. In this paper, the measurement noise will be modeled as white noise. The beam phase is processed by an FIR filter, which is realised as delayed derivative estimator. In addition, there is a transport delay from the processing DSP system to the cavity. In Fig. 1, the correction signal $\Delta\varphi_{corr}$ is subtracted from a set value $\Delta\varphi_{set}$. The result is forwarded to the block cavity dynamics, which models the phase response of the cavity including the so-called cavity synchronisation loop. A first order low-pass transfer function with a time constant of $T_1 = 20\,\mu s$ is used to model this block. The sample time of the DSP-system is $T_S = 3.22\,\mu s$ and the transport delay time is $T_D = 10\,\mu s$. The range of frequencies of the beam phase oscillations range from $f_{syn,min} = 10\,Hz$ to $f_{syn,max} = 6000\,Hz$.

FIR FILTER AS DERIVATIVE ESTIMATOR

The applied derivative estimation approach in this paper is a discrete first order delayed derivative. The current measurement value, as well as past values are needed.

The filter is designed with 10 consecutive taps. The derivative estimation approach proposed in [2] implements the filter to perform a linear regression. The derivative estimation with a FIR filter with current measurement value i, filter length $N \geq 2$ and N measurement values $r_{i-N+1}, \ldots, r_i$ is obtained by

$$x_i = \frac{\sum_{n=1}^{N}(-N+2n-1)\cdot r_{i-N+n}}{T_s \sum_{n=1}^{N}\frac{n(n-1)}{2}},$$

where the sum in the numerator is the actual filter and the sum in the denominator is a normalizing factor depending on the filter length. There is a delay of $T_d = \frac{N-1}{2}\cdot T_s$, as one estimates the derivative in the middle of a series of measurements.

Simulations of the filter on a constant signal with white noise show a noise level dependence proportional to about $N^{-1.5}$. Larger filters regard more measurement points for derivative estimation which increases statistics as well as a larger time window which increases the signal to noise ratio. On the downside there is additional delay time and errors due to not estimating nonlinearities correctly.

PARAMETER STUDIES FOR CONTROL PERFORMANCE

In this section an estimation is given on how strong a mismatch for the feedback gain influences the control performance. In stationary operation an ideal reference particle is at the zero crossing of the RF-cavity voltage in the longitudinal phase space. Particles only oscillating in close distance (small phase deviations) of the zero crossing, experiencing only the linear part of the accelerating voltage behave as harmonic oscillators. The corresponding frequency is the linear synchrotron frequency. Particles oscillating in a larger distance experience also the nonlinear parts of the accelerating voltage and perform slower oscillations which is called nonlinear synchrotron frequency. The linear synchrotron frequency is an upper limit of the nonlinear synchrotron frequency. If there are coherent oscillations, such as dipole

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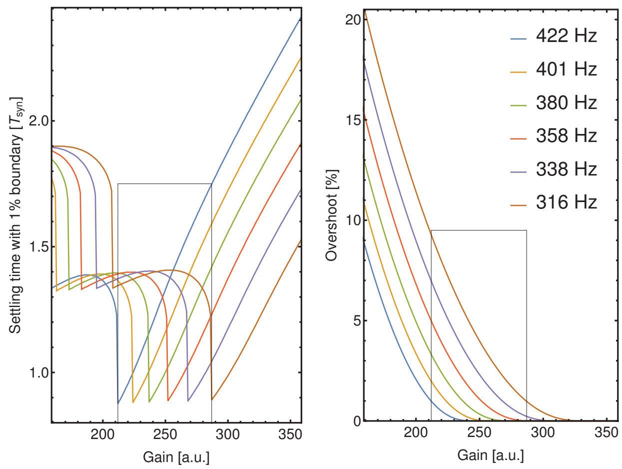

Figure 2: Single particle simulation of beam phase control loop with an initial excitation of 10° for different frequencies.

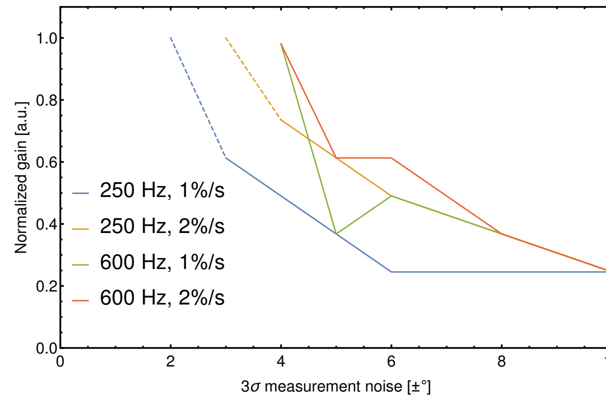

Figure 3: Macro particle simulation to obtain borders for critical normalized gain which leads to certain RMS-emittance growth at a given frequency while using a filter with N = 9 filter coefficients.

oscillations, the different oscillation frequencies lead to a dephasing, also known as filamentation. This leads to a natural damping of the beam phase $\Delta\varphi_B$ and also to an increase in RMS-emittance. The frequency of the coherent dipole oscillation will be referred to as coherent synchrotron frequency and is lower than the linear synchrotron frequency.

For the estimation of the dynamics in the experimental setup where $f_{syn,lin} = 422$ Hz, a single particle simulation is performed for the control loop. Typical macro particle simulations show a coherent synchrotron frequency in the range of 75 % to 90 % of the linear synchrotron frequency depending on the bunch size. Figure 2 shows the results of the single particle simulation with linear synchrotron frequencies 422 Hz, 401 Hz, 380 Hz, 358 Hz, 338 Hz and 316 Hz from bottom to top in the right picture (color code is the same in the left part). In the left part is the settling time of the beam phase, in the right part the overshoot time against the gain. The black borders mark the gain values for aperiodic behaviour for the frequencies of 422 Hz and 317 Hz, which is a gain interval from 212 to 287. There are steps in the left picture when the gain value is below threshold for aperiodic behaviour because there are oscillations around the set value. Each half oscillation leaving the 1% boundary around the set value leads to an additional step.

Tuning for higher synchrotron frequencies would lead to overshoot, whereas tuning for lower synchrotron frequencies would lead to supercritical behaviour and therefore longer settling times. Nevertheless, 10 % overshoot or 1.75 oscillation periods is still a very good performance.

In this simulation, an undamped harmonic oscillator was used as a model for the beam phase dynamics. Damping tends to result in lower synchrotron frequencies and some predamping of the beam phase. Damping requires less gain for aperiodic behaviour whereas a lower synchrotron frequency requires more gain. The uncertainties cancel out each other partially.

Parameter uncertainties have an impact on the control performance. Nevertheless the whole plotted range in Fig. 2 shows reasonable results with settling times below 2.5 oscillation periods and overshoots of about 20 % maximum for large gain mismatches, compared to about 40 % overshoot in [1].

NOISE LIMITATIONS FOR CONTROL PERFORMANCE

Another important point to consider is measurement noise. The use of the derivative estimation controller should not decrease the beam quality, if there is only measurment noise but no distortion. Macro particle simulations indicate that an output noise of the cavity below a threshold of $3\sigma_{cav} = \pm 5°$ does not increase the RMS-emittance of the beam.

Figure 3 shows at which gain value - dependend on the noise level - a given emittance growth rate in the macro particle simulation is exceeded. The normalized gain value is the gain for aperiodic behaviour for an undamped harmonic oscillator at the linear synchrotron frequency $f_{syn,lin}$. Critical values below the normalized gain 1 are plotted. The dashed extensions of the curves are worst case assumptions, as the growth rate limit has not been exceeded at gain 1.

The frequencies of 600 Hz and 250 Hz enclose the expected synchrotron frequency in the experiment. As the experiment has a measurement noise of about $3\sigma = \pm 0.5°$ which is four times lower than the critical noise of the blue curve for the normalized gain of 1, there should be an emittance growth much lower than $\frac{1\%}{s}$.

SIMULATION AND EXPERIMENTAL RESULTS

In this section the measurement data of a beam experiment which took place on October 18th 2014 is compared to the results of a macro particle simulation with the same derivative estimation controller and the former used 3 tap filter approach. The beam was accelerated to a kinetic beam energy of $E_{kin} = 300\ \frac{\text{MeV}}{\text{u}}$ and a dipole oscillation was intentionally excited by shifting the gap voltage by $\varphi_{set} = 2°$. The

Table 1: Parameter Specifications for Simulation and Experiment

Parameter	Value
Ion type	$^{238}U^{73+}$
Number of ions	ca. $4 \cdot 10^8$
Kinetic energy	$300\,\frac{MeV}{u}$
Gap voltage	2.18 kV
Linear synchrotron frequency	422 Hz
Phase shift for dipole oscillation	2°
Harmonic number	h = 2

open-loop operation is shown in Fig. 4, while the results in the closed-loop case are shown in Fig. 5. The acceleration was done in open-loop mode, whereas the feedback-loop was closed as soon as flattop was reached. Table 1 gives an overview over the parameter specifications in the experiment and the simulations.

Figure 5 shows that both the experimental measurement (blue) and the macro particle simulation with the FIR filter as derivative estimator (red) are in good agreement. The excited dipole oscillation is damped *within* one oscillation period and there is almost no overshoot. The gain is 186, which is lower than the estimated interval from 212 to 287. Figure 4 shows that there is damping in open-loop case, which leads to less required gain for aperiodic behaviour in the closed-loop case. For comparison there is also the simulated case where the FIR filter is used as a bandpass filter [1]. An overshoot occurs and the oscillation can be considered as damped after at 4.875 s.

This measurement is a proof of principle. The good agreement of experimental measurement data and the macro particle simulation indicates that there are no major effects missing in the modeling of the whole control loop.

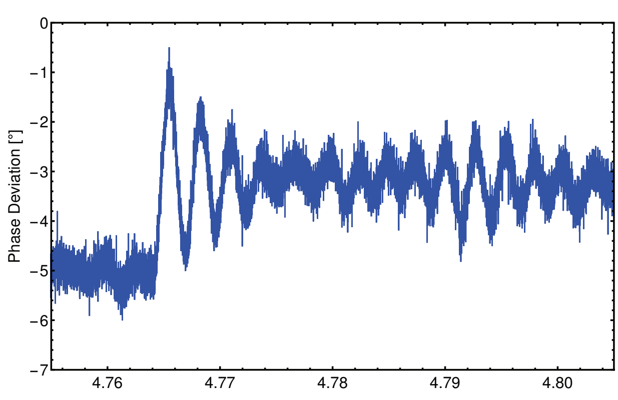

Figure 4: Phase shift φ_{set} applied in the experiment in the open-loop case.

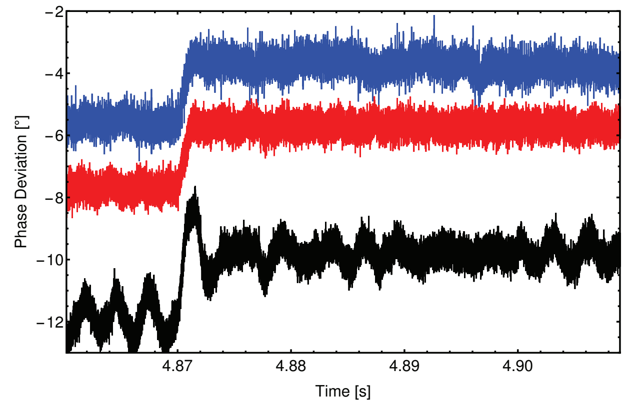

Figure 5: Phase shift φ_{set} applied in experiment and simulations with arbitrary offsets: Derivative estimation experiment, Derivative estimation simulation, 3 tap FIR bandpass simulation.

CONCLUSION AND OUTLOOK

Theoretical studies of a derivative estimation feedback approach as well as macro particle simulations regarding performance limitations caused by measurement noise for synchrotron frequencies around 400Hz were performed. It was demonstrated in an experiment that longitudinal dipole oscillations can be damped *within* one oscillation period with nearly no overshoot by using an FIR filter feedback controller implemented as derivative estimator. The beam behaviour in the closed-loop case is simulated accurately. Further studies also show that the controller should be usable with either more noise or higher synchrotron frequencies up to $f_{syn,lin} = 6$kHz and a measurement noise level up to $3\sigma = \pm 10°$ regarding the measurement precision of the beam phase. Future work will consider beam phase control also during acceleration of the beam, as well as for dual-harmonic operation.

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REFERENCES

[1] H. Klingbeil, B. Zipfel, M. Kumm, P. Moritz, “A Digital Beam-Phase Control System for Heavy-Ion Synchrotrons”, *IEEE Transactions on Nuclear Science*, vol. 54, no. 6, pp. 2604-2610, Dec. 2007.

[2] P. Mai, C. Hillermeier, “Least Squares based Derivative Estimation: Theory and Tuning Rules for the Practical Application”, *at-Automatisierungstechnik*, vol. 56, no. 10, pp. 530-538, Oct. 2008.

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