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# Tuning of 3-tap bandpass filter during acceleration for longitudinal beam stabilization at FAIR

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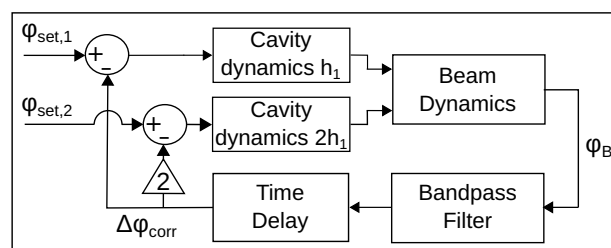
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**Abstract.** During acceleration in the heavy-ion synchrotrons SIS18/SIS100 at GSI/FAIR longitudinal beam oscillations are expected to occur. To reduce longitudinal emittance blow-up, dedicated LLRF beam feedback systems are planned. To date, damping of longitudinal beam oscillations has been demonstrated in SIS18 machine experiments with a 3-tap filter controller (e.g. [1]), which is robust in regard to control parameters and also to noise. On acceleration ramps the control parameters have to be adjusted to the varying synchrotron frequency. Previous results from beam experiments at GSI indicate that a proportional tuning rule for one parameter and an inversely proportional tuning rule for a second parameter is feasible, but the obtained damping rate may not be optimal for all synchrotron frequencies during the ramp. In this work, macro-particle simulations are performed to evaluate, whether it is sufficient to adjust the control parameters proportionally (inversely proportionally) to the change in the linear synchrotron frequency, or if it is necessary to take more parameters, such as bunch-length and synchronous phase, into account to achieve stability and a considerable high damping rate for excited longitudinal dipole beam oscillations. This is done for single- and dual-harmonic acceleration ramps.

## 1. Introduction



**Figure 1.** Control loop

Figure 1 shows the simplified topology of the beam phase control loop used in the machine and in the macro particle simulations. Starting from beam dynamics the beam phase  $\varphi_B$  is measured with respect to a reference signal from a direct digital synthesizer (DDS). The beam phase is processed by a finite impulse response (FIR) filter, which is realised as bandpass filter and followed by an integrator. The correction signal  $\Delta\varphi_{\text{corr}}$  is subtracted from a set value  $\varphi_{\text{set},1}$ ,

or doubled and subtracted from a set value  $\varphi_{\text{set},2}$  for the double harmonic cavity. The result is forwarded to the cavity dynamics, which model the phase response of the cavities including the so-called cavity synchronisation loop. They are modeled as first order low-pass transfer functions. In single-harmonic operation only the cavity with  $h_1$  and  $T_1 = 10\mu\text{s}$  is active. In dual-harmonic operation a second cavity with  $T_2 = 20\mu\text{s}$  and doubled frequency  $h_2 = 2h_1$  is added. The sample time of the DSP-system is  $T_S = 3.22\mu\text{s}$  and the transport delay time is  $T_D = 10\mu\text{s}$ .

## 2. FIR Filter configuration

The FIR filter used in the parameter analysis is introduced in [1] and is given by:

$$y_p = -\frac{1}{4}x_p + \frac{1}{2}x_{p-m} - \frac{1}{4}x_{p-2m} \quad (1)$$

Due to its symmetric form and zero-sum of coefficients, it is a bias free digital bandpass filter. The index  $p$  corresponds to the actual measurement. The spacing  $m$ , to take values from the past, is given by

$$m = \frac{f_R}{f_{\text{syn}} \cdot \chi} \quad (2)$$

where  $f_R$  is the revolution frequency of the particles,  $f_{\text{syn}}$  the linear synchrotron frequency and  $\chi$  one of the two tuning parameters in the parameter analysis. It shifts the center frequency of the bandpass filter.

After filtering, the value  $y_p$  can be applied as frequency shift  $\Delta\omega_{\text{corr}}$  to the cavities, or it can be summed up and be applied as phase shift  $\Delta\varphi_{\text{corr}}$  as it is treated in the simulation. The phase shift  $\Delta\varphi_{\text{corr}}$  is multiplied by a gain factor  $K$ , which is given by

$$K = -2\pi \cdot f_{\text{syn}} \cdot T_S \cdot k \quad (3)$$

where  $k$  is the second tuning parameter for the parameter analysis.

## 3. Simulation setup

For most experiments the synchrotron is designed to obtain a high throughput of particles. Therefore, the cycle time of acceleration ramps have to be short, and particle buckets should be filled to a maximum amount of ions. The requirements can introduce a source of longitudinal dipole excitation. The main goal is to keep longitudinal RMS-emittance low, which is the type of emittance this work always refers to. Another constraint is a fast damping rate, which in

**Table 1.** Parameter specifications for parameter scan.

	Single harmonic	Dual harmonic
Range of $k$	[0.0,0.4]	[0.0,0.2]
Stepsize $\Delta k$	0.02	0.01
Range of $\chi$	[0.05,1.2]	[0.05,1.0]
Stepsize $\Delta\chi$	0.05	0.05
Initial	115°, 160°,	141°, 177°
Bunch-width ( $4\sigma$ )	200°, 239°	203°, 230°
Types of Ramps	7 [2, 3]	3 [3]

some cases has led to a higher increase in RMS-emittance in the simulations of this work. This observation is particularly relevant in case beam oscillations are excited continuously throughout the ramp.

To cover all the different working conditions of the ramps under investigation, each ramp was divided into multiple sections. The sections are 3 linear synchrotron oscillations apart and 6 synchrotron oscillations long, so that neighbouring sections overlap each other. At the beginning of each section a parameter scan according to Table 1 was carried out, which is more than 400 simulations per section.

The RMS-emittance per particle is recorded before the distortion is applied and also taken a second time after 6 synchrotron oscillations. To obtain a more interpretable result, the emittance increase of every measurement is compared to the emittance increase without feedback. Negative relative emittance increase is possible when there is particle loss and relatively more particles on the edge of bunches are lost so the bunch size shrinks as a whole.

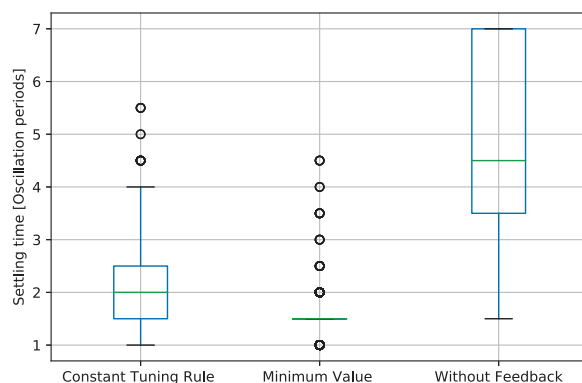
A gap voltage phase shift of  $10^\circ$  is used as distortion. The settling time is reached, when the beam-phase stays within an interval of  $\pm 1.25^\circ$  in single harmonic operation and within  $\pm 2^\circ$  in double harmonic operation. The settling time result of the simulation is discretized in steps of 0.5 oscillation periods.

The plots for RMS-emittance increase (Fig. 2 and 4) and settling times (Fig. 3 and 5) show a summary over all ramp-sections with all four bunch sizes. The "Constant Tuning Rule" results have the same  $\chi$  and  $k$  over the acceleration ramp. For the "Minimum Value" results, the best result of each parameter scan was used. The parameters change over the acceleration ramp and are often different for emittance increase and settling time in one ramp section.

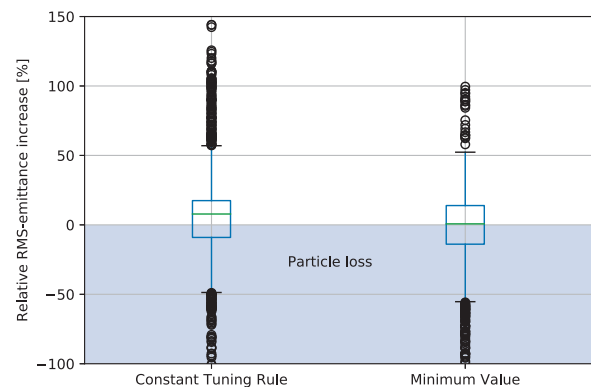
The emittance increase for the case without feedback is always 100% and is therefore not shown. The summarized results are diagrammed as boxplots with whiskers of a maximum length of 1.5 times the interquartile range.

#### 4. Tuning rule for single harmonic operation

For the single-harmonic case, a constant tuning rule with  $k = 0.32$  and  $\chi = 1.0$  was chosen. The parameter regions for lowest emittance gain and a small settling time share the same parameter regions. As shown in Fig. 3, the median of the RMS-emittance is around 10%, which indicates



**Figure 2.** Settling time for single harmonic operation: On the left is the constant tuning rule, in the middle are minimum settling times and on the right results without feedback.



**Figure 3.** Relative RMS-emittance increase for single harmonic operation in relation to operation without feedback: On the left is the constant tuning rule, on the right the minimum emittance increase obtained.

that the controller is often fast enough, so that only minor filamentation occurs. Sometimes there is also particle loss. The values above 100% belong to the two larger bunch sizes at the beginning of the ramps, where ramp parameters are changing fast and particles get lost. Nevertheless the controller does not get unstable. The median for the minimum values obtained is only about 10% lower. Thus the performance of the controller is reasonable.

The median of the settling time shown in Fig. 2 is about 1.5 to 2 oscillation periods. Most values are 0.5 oscillation periods larger than the minimum value obtained. Compared to the case without feedback, the settling often is more than halved.

The tuning parameters are similar to the parameters of a linear quadratic controller for linear bunches [4] ( $k_{\text{opt,stat}} = 0.32$  and  $\chi_{\text{opt,stat}} = 0.97$ ), which indicates that a bunch on a ramp shows linear behaviour regarding bunch phase feedback.

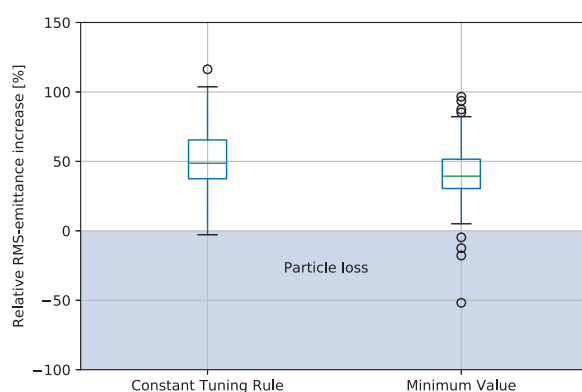
## 5. Tuning rules for dual harmonic operation

In dual harmonic operation, the parameter regions for reduced emittance increase and low settling time tend to be the same for larger bunch lengths. For small bunch lengths a smaller gain modification  $k$  leads to smaller settling times, but larger emittance increase. As a compromise the parameter set  $[\chi, k] = [0.6, 0.15]$  is chosen in favour of larger bunches.

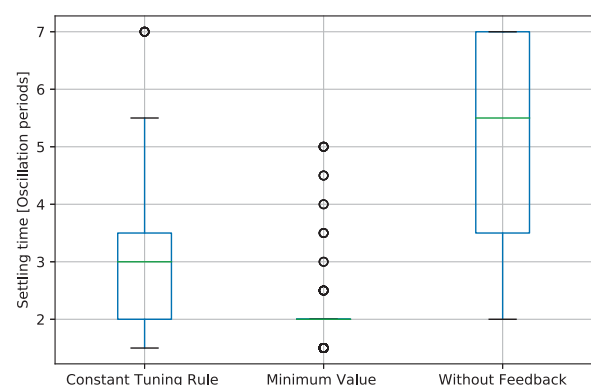
Applied on all 3 ramps, with all bunch lengths, Fig. 4 shows that the median of emittance increase is halved compared to the case of no feedback. Almost all values are between 0% and nearly 100%. The median of minimum emittance increase is about 10% lower. The constant tuning rule is a reasonable result.

Fig. 5 shows the settling time of the bunch barycenter. The constant tuning rule approximately halves the settling time, compared to the case without feedback. There are filter configurations that even lead to better results of about one oscillation period. Nevertheless, the parameter configurations for an improved settling time usually also show a higher emittance increase.

Compared to [5], where optimal simulation parameters for stationary operation are given by  $\chi_{\text{opt,stat}} \approx 1.0$  and  $k_{\text{opt,stat}} \approx 0.3$ , the parameters are reduced by 40% for  $\chi$  and 50% for  $k$  respectively.



**Figure 4.** Relative RMS-emittance increase for dual-harmonic case in relation to operation without feedback: On the left is the constant tuning rule, on the right the minimum emittance increase obtained.



**Figure 5.** Settling time for dual harmonic case: On the left is the constant tuning rule, in the middle are minimum settling times and on the right results without feedback.

## 6. Additional notes

Most importantly the controller design has to provide stability throughout a whole acceleration cycle, which is the case for all studied ramps.

The constant tuning rules for  $k$  and  $\chi$  imply a proportional tuning rule for  $K$  and an inversely proportional tuning rule for  $m$  regarding the linear synchrotron frequency  $f_{\text{syn}}$ .

A further remark is that the distortion can be considered a worst case for this type of FIR filter and will typically be much smaller. It is chosen to investigate the damping potential of the controller. But it also introduces an oscillation with a high amplitude ( $\pm 10^\circ$ ). The controller needs about one oscillation period to unfold its full performance. A slowly increasing oscillation amplitude of less than  $2^\circ$  per oscillation should lead to even better results for the FIR filter.

The simulations also show that without feedback, every distortion leads to bunch-phase damping through filamentation, which will cause emittance-growth. With feedback, oscillations can be damped with nearly no emittance increase when the oscillation amplitude stays below  $3^\circ$ .

## 7. Conclusions and outlook

The FIR filter implemented as bandpass-filter can be used to strongly damp beam-phase oscillations. This holds for single- and dual-harmonic operation. A constant tuning rule for  $\chi$  and  $k$  is sufficient for stable operation, although the separatrix and therewith the shape of the bunch changes in different ways from ramp to ramp. Despite of the differences, additional parameters like bunch-length and synchronous phase are not necessary to get reasonable results. In the future the results of the simulations have to be tested in experiments.

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