15th International Particle Accelerator Conference,Nashville, TN JACoW Publishing
ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-THPG33

EXPERIMENTAL RESULTS ON LONGITUDINAL RF BEAM PHASE FEEDBACK IN THE HEAVY-ION SYNCHROTRON SIS18

B. Zipfel, D. Lens, GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany
R. Balß, K. Gross, M. Hardieck, H. Klingbeil[1], U. Laier, S. Schaefer, C. Thielmann, K. G. Thomin,
GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany
[1]also at Technische Universität Darmstadt, Darmstadt, Germany

Abstract

In the SIS18 heavy-ion synchrotron at GSI, RF beam phase feedback systems are developed and tested with beam for the damping of coherent longitudinal bunch oscillations. In particular, a Bunch Phase Control system (BPC) is currently commissioned for the damping of longitudinal dipole oscillations. The feedback system has to cope with both, a large RF frequency span (400 kHz to 5.4 MHz) and synchrotron frequencies of up to 6 kHz. It has to be compatible with several beam manipulation schemes such as dual-harmonic operation, bunch merging, and bunch compression. The system relies on recent upgrades of the SIS18 LLRF topology including a newly developed multi-purpose DSP system that is used for the RF cavity synchronization as well as for RF beam feedback. This paper describes the LLRF concept of the RF beam phase feedback at SIS18 and presents results from machine experiments with beam where an adaptive feedback filter for damping longitudinal dipole oscillations during the whole SIS18 machine cycle was realized and successfully applied.

EXPERIMENTAL SETUP

Dynamic Control Parameter f_S

It is well known that longitudinal beam instabilities lead to longitudinal bunch oscillations with oscillation frequencies that depend on the synchrotron frequency f_S [1]. In heavy-ion synchrotrons, the synchrotron frequency $f_S(t)$ may change considerably during the acceleration ramp, but its development over time is predictable. $f_S(t)$ can be calculated in advance of the machine cycle. The formula to estimate the synchrotron frequency f_S as a ramped parameter is:

$$f_{S,0} = f_R \sqrt{-\frac{\eta_R\ Q \hat{V}\ h\ \cos\varphi_R}{2\pi W_R \beta_R^2}} \quad . \tag{1}$$

$f_{S,0}$ denotes the synchrotron frequency for small oscillation amplitudes, f_R the revolution frequency, h the harmonic number, $\hat{V}$ the applied RF-amplitude function, Q the particle charge, W_R the total particle energy, β_R the normalized relativistic velocity, φ_R the synchronous phase of the bunch and η_R the phase slip factor [2].

Since the synchrotron frequency is a fundamental parameter for the beam phase control (BPC) [3], it is provided directly via a front end controller (SCU & DAC) of the central control system (CCS) to the Low-Level Radio Frequency system for the heavy-ion synchrotron SIS18 at GSI. Via optical direct link (ODL) these streaming control data are fed into the Digital Signal Processor (DSP) system [4] that is used for the data processing of the beam phase control to modify parameters of the control loop in real time or to switch the control loop in real time on and off.

Control Loop Setup

The topology shown in Fig. 1 is designed to apply bunch phase control to damp coherent longitudinal dipole oscillations with any combination of different cavities in SIS18 [4]. Signals coming from the Direct Digital Synthesis Modules (DDS) for RF reference generation, Cavity Gap Monitors and Fast Beam Current Transformer (FCT) are routed via an RF switch matrix to the dedicated control loops based on the DSP system.

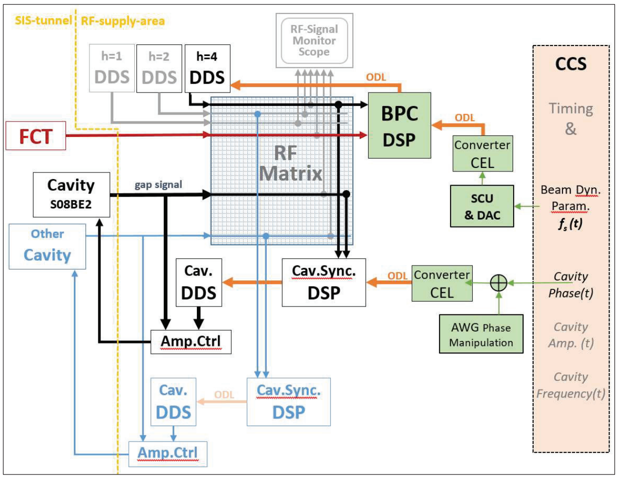

Figure 1: Implementation of the beam phase feedback control loop and the intentional stimulation of bunch phase oscillations.

The streaming data output of the BPC-DSP is used to control the Group-DDS module on which the SIS18 Cavities are synchronized by supplementary DSP-Systems. In the machine development experiments, described in the following, only Group-DDS h=4 was controlled by phase corrections of the BPC and only one cavity named S08BE2 was used for particle acceleration.

Signal Processing Chain

Signal processing is performed by a dual DSP system which includes an FPGA. Input signals are routed via an RF Switch Matrix and identical line delays from FCT and Group-DDS. Preprocessing includes noise recognition, automatic gain control, up mixing to intermediate frequency and digitizing with sub-sampling. A CORDIC-algorithm on an FPGA converts the signals into two paired phase and amplitude data streams. The DSP performs the data processing [5]:

- Phase difference calculation and phase data validation
- Read optical control parameter input stream ($f_{S,0}$ via ODL)
- Applying appropriate 3 tap FIR filter [3] on phase difference signal with a passband frequency that scales with f_S
- Adjust feedback gain by proportional scaling as a function of f_S
- Streaming control data output (ODL) to Group-DDS

The fiber optical streaming rate at the ODL output of the DSP system is about 310 kHz, since processing of one loop cycle takes about 3µs.

Bunch Phase Oscillation Stimulation

Intentional periodic phase jumps of the cavity RF over the complete acceleration cycle excite bunch oscillations for testing the beam phase control loop (Fig. 2). Therefore, a step function was added to the regular cavity phase ramp signal coming from the center control system (see also Fig. 1), converted in an ODL stream and fed in the cavity phase control DSP.

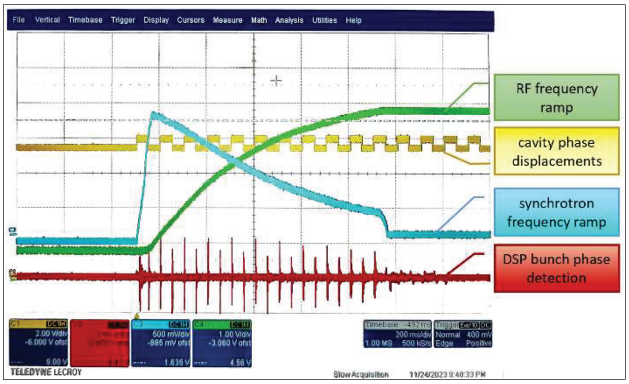

Figure 2: Repetitive bunch phase oscillation stimulation.

On an analog output of the DSP the stimulated bunch phase oscillations were monitored and the response of the bunch was assessed.

EXPERIMENTAL OBSERVATIONS

Assessment of Results

Evaluation criteria to classify a BPC can be the amount of particle loss, amplitude of oscillations, emittance conservation, noise free flatness of the bunch phase signal, stable short bunches as an indicator of a well-preserved phase space distribution, damping rates of an induced collective excitation and more. Depending on the application, the focus and the priority of these criteria differ. Here we concentrate primarily on the criteria of minimizing beam loss on fast current transformer monitors and only secondarily on emittance and oscillation damping rate.

There are two main parameters available to adjust the Beam Phase Control Loop. The first parameter is the feedback gain K_p, which represents the strength of the effect on the phase correction of the cavity voltage. The second parameter is the passband frequency f_{pass}, which determines the frequency range for the BPC. It depends on the linear synchrotron frequency. The passband of the BPC is important in order not to suppress slow adjustments of accelerating phase of the bunches and not to destroy the natural phase focusing effect. During the acceleration process, the synchrotron frequency varies considerably. For SIS18, the synchrotron frequency may vary from less than 100 Hz up to a few kHz. For simplification and normalization, the center frequency of the passband is sometimes given in multiples of the synchrotron frequency of the bunches. The strength of the effect also scales linearly with the applied frequency, so it is useful to normalize this with the synchrotron frequency as well. If this is done in this way, the stability range for the two parameters is always similar for different cycle parameters such as the ion species or the particle energy [3]. Since the central control system is now able to supply the control parameter f_S to the BPC in real time, the aim of the experiment here was to find and set the correct universal proportionality factors passband per f_S and gain per f_S.

Online Observation of Effectiveness

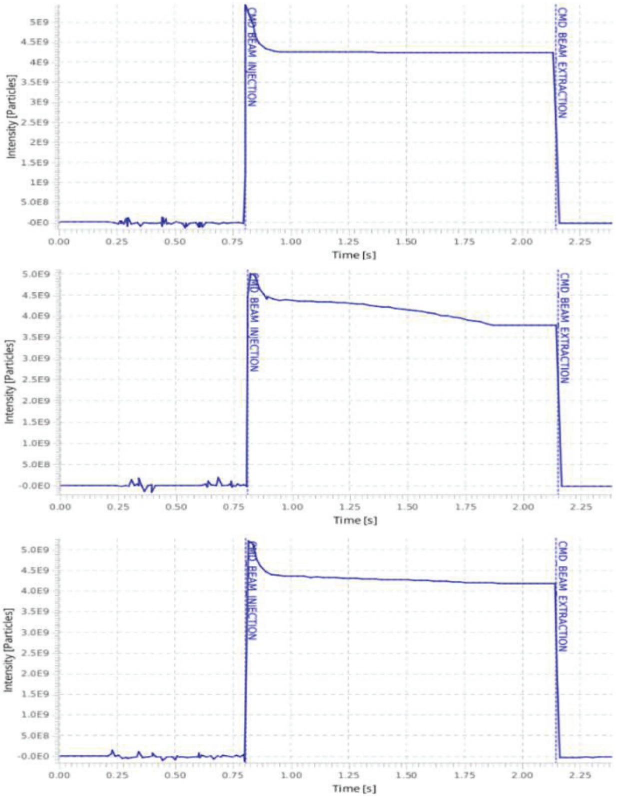

Figure 3: DC beam current of different machine cycles. Top: normal machine cycle, almost no beam loss. Middle: stimulation active and BPC inactive, significant beam loss. Bottom: Stimulation and BPC active, low beam loss.

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-THPG33

The direct evaluation of the functionality was carried out via the fast beam current monitor. Usually, after the injection process, a well-adjusted machine cycle shows almost no particle loss over the entire acceleration ramp (Fig. 3 top). To the given machine cycle the repeated excitation of the bunch oscillations was adjusted until significant beam losses could be observed on the current monitor (Fig. 3 middle). The BPC is able to heal almost all beam losses caused by the excessive phase manipulation of the cavities (Fig. 3 bottom). It is expected that the damping of slowly increasing instabilities will be even more effective.

Table 1 summarizes the machine parameters during the experiment. Please note, that the RF-frequency swing and the synchrotron frequency band extends over several octaves.

Table 1: Beam Parameters SIS18 at 24 November 2023

Ion species	$^{14}\mathrm{N}^{7+}$
Beam current	1-10 mA
Kinetic particle energy	11.4 MeV/u – 1 GeV
RF frequency	0.857 – 4.847 MHz
Used cavity, harmonic number	S08BE2, h=4
Particles per machine cycle	3×10^9
Sync.frq $f_{S,0}$	100 – 1800 Hz

Offline Evaluation of Beam Dynamics

In addition to direct observation via the beam current monitor, the recorded data were analyzed. Careful adjustment of feedback parameters and machine cycle parameters was required when acceleration reaches flat top and the RF voltage became very low to hold the bunches. Because of the low RF voltage, the synchrotron frequency was very low and within the bandwidth of the natural synchronous phase movement. The control loop has switched off automatically on flat top.

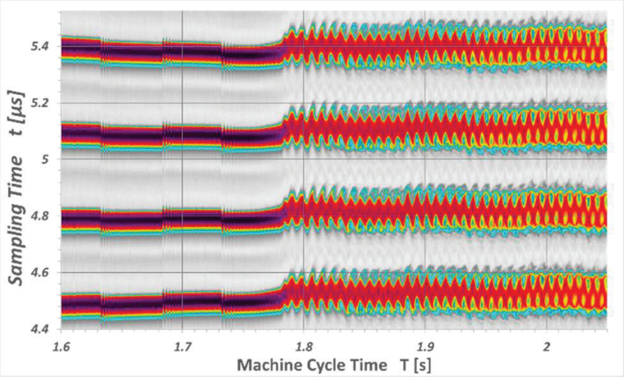

Figure 4: Comparison BPC active (during acceleration left side) and inactive (at flat top right side).

Nevertheless, this is a good example to demonstrate the effect of bunch phase control compared with BPC inactive (Fig 4). From the time of switch-off, there was no further damping of the oscillation at all.

Overall Results

The main goal of the experiment was to find out the two appropriate scaling factors for the dynamic input parameter $f_{S,0}(t)$ used to set the filter bandwidth and the corresponding feedback gains. Another procedure was to check the stable parameter range of the BPC and find one general parameter set which can be applied for all possible machine cycles. The results of the evaluation of the beam current monitor over the entire machine cycle are shown in Fig. 5. The best performance is by using a feedback gain K_p=-g×$f_{S,0}(t)$ with a scaling factor g=0.004. The pre-configured calculation of the filter index was i= $f_{S,0}(t)$×0.02, almost accordingly to $f_{pass}\cong f_{S,0}$. The tried and tested 50Hz discretization between the 127 stored filter settings gives the best effect.

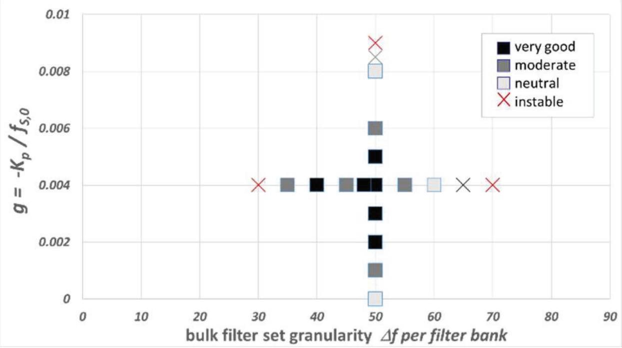

Figure 5: Stability plot of scaling factors for the ramped control parameter proportional to synchrotron frequency.

CONCLUSION

The experiments show that after new revisions of hard- and software and some minor updates in the LLRF topology the BPC works as expected. Damping was effective, instabilities did not occur and there were no significant particle losses due to the active BPC.

The introduction of the universal and predictable control parameter $f_{S,0}(t)$ has the advantage, that the system automatically adapts to a wide range of operating modes for different ions and different experimental machine cycles [3]. Overall, this was an important step towards standard operation and dual harmonic bunch phase control [6].

REFERENCES

[1] F. J. Sacherer, "A longitudinal stability criterion for bunched beams", *IEEE Trans. Nucl. Sci.*, vol. NS-20, no. 3, pp. 825–829, Jun. 1973. `doi:10.1109/TNS.1973.4327254`

[2] H. Klingbeil, U. Laier, D. Lens, *Theoretical Foundations of Synchrotron and Storage Ring RF Systems*, Springer Cham, 2014. `doi:10.1007/978-3-319-07188-6`

[3] H. Klingbeil, B. Zipfel, M. Kumm and P. Moritz, "A digital beam-phase control system for heavy-ion synchrotrons", *IEEE Trans. Nucl. Sci.*, vol. 54, no. 6, p. 2604, `doi:10.1109/TNS.2007.909666`

[4] H. Klingbeil, U. Laier, K. P. Ningel, S. Schäfer, C. Thielmann, and B. Zipfel, "New digital low-level rf system for heavy-ion synchrotrons", *Phys. Rev. Spec. Top. Accel Beams*, vol. 14, no. 10, Oct. 2011, `doi:10.1103/PhysRevSTAB.14.102802`

[5] H. Klingbeil, “A fast DSP-based phase-detector for closed-loop RF control in synchrotrons”, *IEEE Trans. Instrum. Meas.*, vol. 54, no. 3, pp. 1209-1213, Jun. 2005. `doi:10.1109/TIM.2005.847138`

[6] J. Grieser *et al.*, “A digital beam-phase control system for a heavy-ion synchrotron with a dual-harmonic cavity system”, *IEEE Trans. on Nucl. Sci.*, vol. 61, no. 6, pp. 3584-3591, Dec. 2014. `doi:10.1109/TNS.2014.2367911`