BEAM-BASED FEEDBACKS FOR FAIR – PROTOTYPING AT THE SIS18

Ralph J. Steinhagen, J. Fitzek, H. Hüther, H. Liebermann, R. Mueller, D. Ondreka,
H. Reeg, B. R. Schlei, P. Spiller, GSI, Darmstadt, Germany

Abstract

The 'Facility for Anti-Proton and Ion Research' (FAIR) presently under construction, extends and supersedes GSI's existing infrastructure. Its core challenges include the precise control of highest proton and uranium ion beam intensities, the required extreme high vacuum conditions, machine protection and activation issues while providing a high degree of multi-user mode of operation with facility reconfiguration on time-scales of a few times per week.

To optimise turn-around times and to establish a safe and reliable machine operation, a comprehensive suite of semi-automated measurement applications, as well as fully-automated beam-based feedbacks will be deployed, covering the control of orbit, Q/Q', spill structure, optics, and other machine parameters.

These systems are based on the LSA settings management framework, code-shared with and also used at CERN. The concepts, software architecture and first prototype beam tests at the SIS18 in 2016 are presented. As an initial proof-of-concept, a cycle-to-cycle orbit and macro-spill feedback, as well as a semi-automated magnetic quadrupole- and sextupole-centre measurement tool have been selected.

INTRODUCTION

In addition to the existing UNILAC [1], SIS18 [2], and ESR [3], the FAIR accelerator complex will supersede and extend the existing GSI infrastructure by a dedicated anti-proton production target, the Super Fragment Separator for the production of rare isotope beams (RIBs) and five new accelerators [4, 5]: a dedicated high-intensity proton linac [6], the SIS100 synchrotron [7], as well as the experimental CRY, CR and HESR storage rings [8, 9]. Some of the noteworthy FAIR features include:

- the control of a wide range of proton, anti-proton, primary and RIBs, with targeted design intensities ranging from $3 \cdot 10^{13}$ ppp (particles-per-pulse) for protons at 29 GeV/u up to $5 \cdot 10^{11}$ ppp for $^{238}U^{28+}$ at 2.7 GeV/u – a factor 100 higher than similar existing facilities at those energies,
- the flexibility to quickly reconfigure the facility to provide these beams to about 4 to 5 experiments in parallel, with many of these experiments lasting often only 5 to 6 days (N.B. median duration), as well as
- the resulting operational complexity increase (presently: $\mathcal{O}(n^2)$, FAIR: $\mathcal{O}(n^5)$) due to the larger facility, longer accelerator chains, and especially more precise beam and machine parameter control that is required at the targeted intensities and energies:
  - excellent XHV vacuum conditions (e.g. SIS100: vacuum $< 10^{-12}$ mbar) and the precise control of dynamic-vacuum or other beam loss mechanism,
  - emittance preservation, control of space-charge, transverse and longitudinal beam dynamics starting in the primary beam pre-injectors, as well as
  - adequate machine protection and minimisation of machine activation (ALARA-principle: 'As Low As Reasonably Achievable').

BEAM-BASED CONTROL STRATEGY

To optimise turn-around times, to establish a safe and reliable machine operation, and to improve the beam parameter qualities, a shift from a presently predominantly manual 'analog' to an automated 'fully digital' control and operation paradigm is in progress. The aim is to automate routine tasks to minimise inadvertent errors (i.e. 'poka yoke' principle), to aid the frequent machine (re-) set up, to control beam-parameters to a higher precision, and to minimise unnecessary strain on operating crews in order that their talents are optimally utilised and focused on more important tasks that cannot be automated.

Thus a comprehensive suite of semi-automated measurement applications, as well as fully-automated beam-based feedbacks (FBs) is being prepared, and will be deployed as generic tools across all FAIR accelerators. These cover a wide range of beam parameters ranging from beam transmission, trajectory, orbit [10], tune and chromaticity [11, 12], machine optics, emittance preservation and manipulations, fast turn-by-turn feedbacks, as well as specialised machine-specific feedbacks. For example, for the optimisation of multi-turn-injection process, slow resonant extraction, as well as diagnostics to aid the set up of injection energy, stochastic and electron cooling methods.

Generic Cycle-to-Cycle Feedback Topology

A generic, Java-based and distributed framework is being developed for this wide scope of targeted beam-based feedback implementation in order to minimise the heterogeneity, to optimise the reliability, as well as long-term code maintainability. Focus is laid on the use of common standards, off-line testability of the individual sub-components.

The framework, based on a distributed three-tier architecture, implements the controls- and device-interfaces common to all feedbacks, and relies upon the LSA settings management framework and the low-level FESA-based front-end software architecture [13–18]. Both provide an abstraction between the physical device hardware and measured beam parameters.

This provides a very low threshold for accelerator experts to write custom beam-physics-centric and -encapsulated modules with minimal prior Java knowledge requirements, while the framework takes care of the control system specific aspects: central handling of device specific interfaces, hardware limits and consistency checks, traceability of machine settings modification, parameter hierarchy and interdependencies, and archiving of the measurement and settings data. This opens basically all accelerator parameters for feedbacks that are modelled in LSA, provided they fulfil the basic control theory criteria [19]:

1. *Stability*: the parameter should be reproducible and stable above targeted feedback bandwidth (here: cycle-to-cycle, with kHz-range in-cycle bandwidths, discussed below).
2. *Controllability*: an affine (but not necessarily linear) dependence between observable effect and given control actuator.
3. *Observability*: ability to measure the targeted parameter reliably, notably with low systematic biases and measurement noise.

EXPERIMENTAL RESULTS WITH BEAM

As a proof-of-concept, a selected limited set of automated beam parameter measurement and feedback systems have been tested as early prototypes at the SIS18 during the machine development studies in 2016: a new beam transmission monitoring system, an automated beam parameter scanning application, and a cycle-to-cycle orbit- as well as a macro-spill feedback.

SIS Machine Reproducibility

The quasi-periodic operation and consequently reproducibility of the accelerators chain is an important property these beam-based feedbacks rely upon [20]. While the parameters may (and often do) vary largely within a given sub-cycle-segment, these in-cycle structures are in most cases reproducible from cycle-to-cycle (see e.g. [12]). While some limited low-order parameters such as turn-by-turn trajectory, orbit and tune can be measured and corrected on time-scales up to a few kHz. Most other higher-order parameters and processes, important to the operation of FAIR, cannot be corrected on these fast time-scales, or at least not with the required precision (e.g. slow-extraction, emittance manipulations, optics, beam vacuum, etc.). The latter must thus rely on the inherent machine reproducibility.

A combined orbit and beam position monitor (BPM) measurement reproducibility at the SIS18 is shown in Fig. 1.

While the orbit at the given pick-up changes by up to 10 mm during the energy ramp, the variation around the average orbit changes from cycle-to-cycle over an eight hour period by only about 100 µm r.m.s. For comparison, the horizontal (vertical) BPM aperture is 200 mm (70 mm). This is sufficient for most operational aspects such as multi-turn-injection, fast- and slow-extraction at the SIS18. The few outliers are believed to be related to non-periodic conditions where the SIS18 needed to wait at its injection plateau for beam from the UNILAC. The larger variations during the start of the ramp may be related to this, but require further detailed investigation.

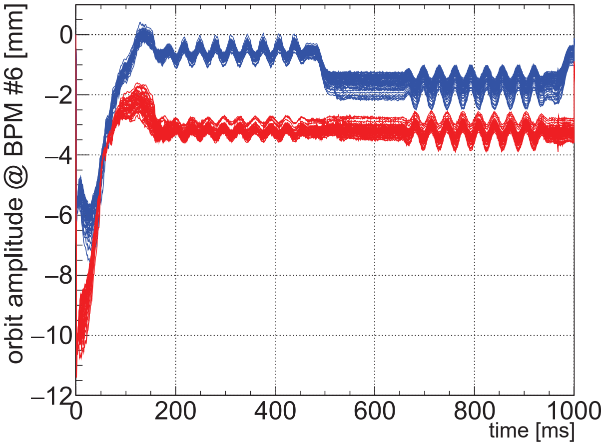


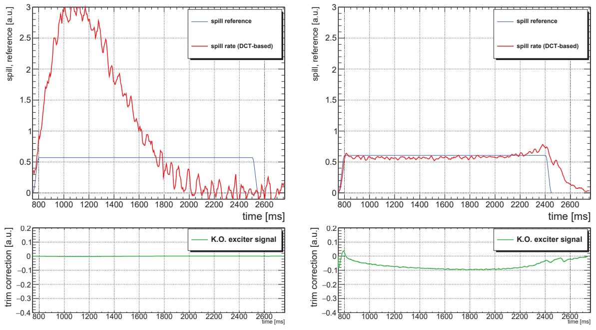
Figure 1: Cycle-to-cycle orbit stability over an eight hour period for the horizontal (blue) and vertical plane (red) at injection ($t = 0$ ms), during the ramp ($t = 0 - 170$ ms), and throughout two flat tops with different optics are shown for a selected BPM. The sinusoidal oscillations are caused by deliberately driven lattice sextupole-strength modulations.

Macro-Spill Prototype Feedback

Providing slowly extracted ion beams is a particularly important operational mode of SIS18 and SIS100. Traditionally this type of extraction is commonly steered using tune shifts rather than changes of the lattice sextupole strengths. In recent years, the resonant slow-extraction using controlled transverse or longitudinal emittance blow-up became more popular using so-called knock-out (k.o.) exciters [21,22]. It's spill rate depends on the specific transverse and longitudinal emittances, which may vary depending on the multi-turn-injection set up or other pre-injector conditions. Thus the tune or k.o. exciter strength commonly needs to be adjusted for every new experiment. At SIS18, this is presently done manually using dedicated particle counters in the extraction channel or the derivative of the ring DC current transformers (DCCTs) and a qualitative macro-spill reference.

A prototype feedback loop has been developed that automates this process, using the numeric time-derivative of the DCCT and LSA-based reference function and either the k.o. exciter strength, tune shift, or sextupole strengths settings as an actuator. Example measurements with the feedback being 'off' and 'on' are shown in Fig. 2.

For the first tests, a very crude linear model and simple PI-regulator have been used, which nevertheless provided sufficiently flat macro-spill structures. The macro-spill structure was reproducible within the DCCT measurement noise floor and – similar to the cycle-to-cycle orbit observation – showed only few outliers, as described above. An in-cycle bandwidth of 1 kHz could be established, primarily limited



(a) Spill-FB ’off’ (b) Spill-FB ’on’

Figure 2: SIS18 macro-spill structures without and with FB. Relative FB corrections are indicated below.

by the DCCT’s limited number of acquisition data points for the the given spill length. The DCCT DAQ is presently being upgraded, and is expected to provide a maximum sampling of up to 20 kHz, which should improve the spill resolution. The numeric differentiation enhances some of the DCCT’s measurement noise related to the low sampling and high signal offsets in the ADC. An analog differentiation of the signal and amplification prior to being digitized is being investigated.

To demonstrate the flexibility and fine-control of such a feedback, an arbitrary user function has been programmed as feedback reference as shown in Fig. 3.

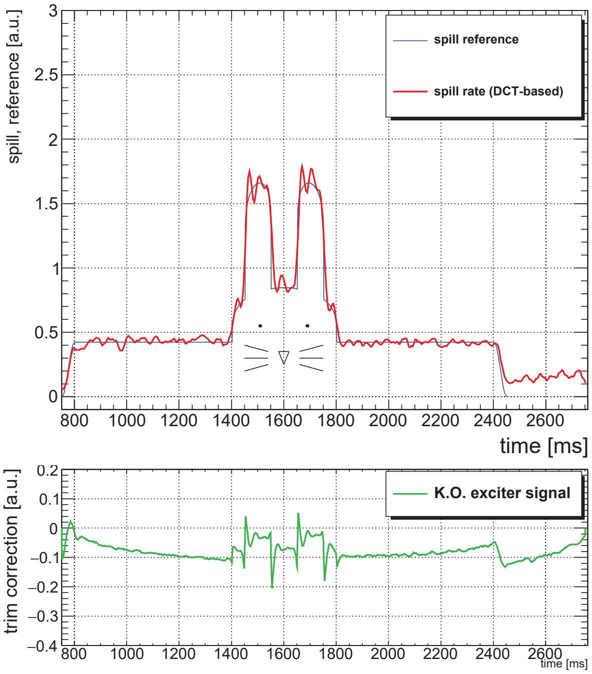


Figure 3: Macro-spill structure with feedback ’on’ and user-defined arbitrary FB reference function.

Using particle counters in the extraction channel or the DCCT in the ring are basically equal from a feedback point of view. However, using the DCCT as input provided some advantages with respect to signal integrity, absolute calibration, and decoupling of other slow-extraction parameters that impact the actual rate of particles through the transfer-line (e.g. orbit or trajectory steering at the extraction septa). Future iterations will aim at combining the different beam diagnostics and parameter dependences, provided the issues related to decoupling, robustness, and interdependencies are handled in an operationally robust fashion.

Automatic Beam Parameter Measurement Tool

An LSA-based automatic beam parameter measurement tool has been developed that allows the parametric variation of any user-defined parameters modelled in LSA, while recording intensity, life-time and orbits. This tool has been used to measure the magnetic central ’golden orbit’ through the lattice sextupoles in the SIS18, which is more relevant the for slow-extraction optimisation at SIS18/100 rather than the more common quadrupole-centre measurement. An example is shown in Fig. 4.

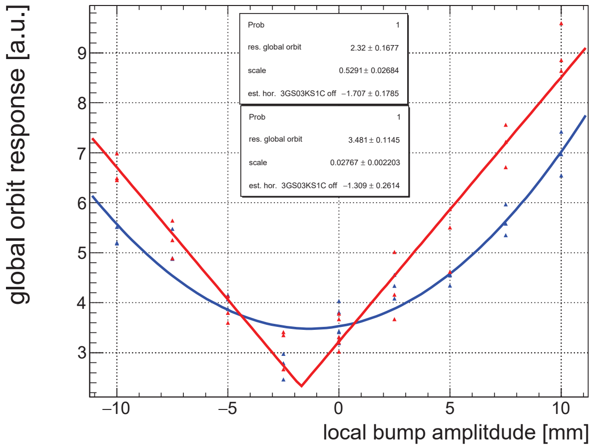


Figure 4: Automated mag. sextupole centre measurement.

The measurement has been done without any human intervention and demonstrates the ease and convenience provided by the new control system framework, by supporting tools to perform about 700 fully autonomous otherwise very tedious measurements.

CONCLUSION

First beam-based feedback and automatic measurement prototype systems for FAIR have been successfully tested with beam at the SIS18. The measured stability was sufficient down to the residual measurement noise of the beam instrumentation, provided SIS18 is operated in its quasi-periodic booster mode. In-cycle bandwidths up to 1 kHz and cycle-to-cycle bandwidths in the order of a few cycles have been demonstrated. Some improvements for online pre-analysis, controls integration of these systems, and instrumentation upgrades are still needed prior to their day-to-day operational use. These early prototypes are important steps toward a more (semi-) automated beam-based measurement and control suite for FAIR.

REFERENCES

[1] L. Groening et al., “Upgrade of the Universal Linear Accelerator UNILAC for FAIR”, IPAC’16, Busan, Korea, 2016.

[2] B. Franczak, “SIS18 Parameterliste”, GSI, Darmstadt, Germany, September 10, 1987.

[3] B. Franzke, “The Heavy Ion Storage and Cooler Ring Project ESR at GSI”, NIMA 287 (1987) 18

[4] H. H. Gutbrod (ed.) et al., “FAIR Baseline Technical Report”, GSI, Darmstadt, Germany, 2006.

[5] O. Kester et al., “Status of the FAIR Accelerator Facility”, IPAC’14, Dresden, Germany, 2014.

[6] R. Brodhage et al., “Status of the FAIR Proton Linac”, IPAC’15, Richmond, VA, USA, 2015.

[7] P. Spiller, “Status of the FAIR Synchrotron Projects SIS18 and SIS100”, IPAC’14, Dresden, Germany, 2014.

[8] Michael Lestinsky et al, “CRYRING@ESR: A study group report”, GSI, Darmstadt, Germany, July 26, 2012.

[9] H. Danared et al. “LSR Low-Energy Storage Ring Technical Design Report”, Stockholm University, Sweden, 2011.

[10] B. Schlei et al, “Closed Orbit Feedback for FAIR - Prototype Tests at SIS18”, these proceedings

[11] R. J. Steinhagen, “Tune and Chromaticity diagnostics”, Proc. of CAS, Dourdan, CERN-2009-005, 2008.

[12] R. J. Steinhagen, “Real-Time Beam Control at the LHC”, PAC’11, New York, NY, USA, 2011.

[13] G. Kruk et al. “LHC Software Architecture (LSA) – Evolution toward LHC Beam Commissioning”, ICALEPCS’07, Knoxville, Tennesse, USA, 2007.

[14] R. Mueller et al., “Evaluating the LHC Software Architecture for Data Supply and Setting Management within the FAIR Control System”, ICALEPCS’09, Kobe, Japan, 2009.

[15] D. Ondreka et al., “Settings Generation for FAIR”, IPAC’12, New Orleans, Louisiana, USA, 2012.

[16] M. Arruat et al., “Front-End Software Architecture (FESA)”, ICALEPCS’07, Knoxville, Tennessee, USA, 2007.

[17] S. Matthies et al., “FESA3 Integration in GSI for FAIR”, PCaPAC’14, Karlsruhe, Germany, 2014.

[18] V. Rapp and W. Sliwinski, “Controls Middleware for FAIR”, PCaPAC’14, Karlsruhe, Germany, 2014.

[19] R. J. Steinhagen, “Feedback Control for Particle Accelerators”, PCaPAC’16, Campinas, Brazil, 2016.

[20] H. Hüther et al., “Realization of a Concept for Scheduling Parallel Beams in the Settings Management System for FAIR”, ICALEPCS’15, Melbourne, Australia, 2015.

[21] S. Van der Meer, “Precooling in the Antiproton Accumulator”, CERN/PS/AA 78-6, CERN, 1978.

[22] M. Kirk et al., “Status - SIS-18 Slow Extraction”, GSI SCIENTIFIC REPORT, PHN-SIS18-ACC-24, GSI, Darmstadt, Germany, 2012.