Software-Defined Radio Based Feedback System for Beam Spill Control in Particle Accelerators

Philipp Niedermayer, René Geißler, Rahul Singh P.NIEDERMAYER@GSI.DE
GSI Helmholtzzentrum für Schwerionenforschung GmbH, Darmstadt, Germany

Abstract

Controlling stored beams in particle accelerators requires specially designed RF signals, such as needed for spill control via transverse excitation. The software-defined radio (SDR) technology is adopted as a low cost, yet highly flexible setup to generate such signals in the kHz to MHz regime. A feedback system is build using a combination of digital signal processing with GNU Radio and RF Network-on-Chip (RFNoC) on a Universal Software Radio Peripheral (USRP). The system enables digitization of signals from particle detectors and direct tuning of the produced RF waveforms via a feedback controller – implemented on a single device. To allow for triggered operation and to reduce the loop delay to a few ms, custom OOT and RFNoC blocks have been implemented. This contribution reports on the implementation and first test results with beam of the developed spill control system.

1. Introduction

A typical operation scenario of a circular particle accelerator such as a synchrotron is to inject, accelerate and extract a beam of particles. The method of resonant slow extraction (Hereward, 1961) is commonly applied to extract particles at a constant rate over the course of several seconds or longer while slowly emptying the synchrotron storage ring. The extracted particles, referred to as *spill*, are thereby delivered to target stations, experiments or treatment rooms.

In order to extract the particles in a controlled manner, the beam is being excited by means of transverse electromagnetic RF fields (Hiramoto & Nishi, 1992). The excitation system consists of an RF signal generator, RF amplifiers, and *stripline units* inside which the RF fields act on the beam. In this process, the signal generator is the central element by which the particle beam, and thus the spill, can be influenced in a controlled manner.

Proceedings of the 13^{th} GNU Radio Conference,

The primary goal here is to maintain a constant spill rate, that is, to extract an equal number of particles per time. To reach this goal, two complementary strategies exist: On timescales above about $50\,\mathrm{ms}$, the signal amplitude is controlled by a complex function or a feedback system based on measured spill rates (Schömers et al., 2015). On smaller timescales, the signal waveform is optimized to reduce statistical fluctuations (Niedermayer et al., 2023).

The SDR technology and the GNU Radio ecosystem are chosen to implement the signal generator and feedback in a single device, since they offer all necessary tools while providing the required flexibility to change and adopt complex signal waveforms online and in real-time. With SDRs being adopted by an increasing number of users in the accelerator community (Feldmeier et al., 2022; Steinhagen et al., 2023; Kühteubl et al., 2023), collaboration and sharing of algorithms between institutes is easily possible.

2. System Design

The excitation signal generator is realized with a USRP X310 (fig. 1) equipped with low frequency daughterboards working in the frequency range from DC to $30\,\mathrm{MHz}$. The signal processing is implemented with GNU Radio and RFNoC (Braun et al., 2016) as described in the following.

2.1. Generation of Excitation Signals

The frequencies required for the excitation of stored particle beams in a circular accelerator are in the order of a few MHz or less, such that they can be produced with GNU Radio in direct synthesis at a sampling frequency of $f_{s,\mathrm{signal}} = 10\,\mathrm{MHz}$. The excitation signal can generally consist of multiple bands at different carrier frequencies. Thereby, each band is produced by one of the following

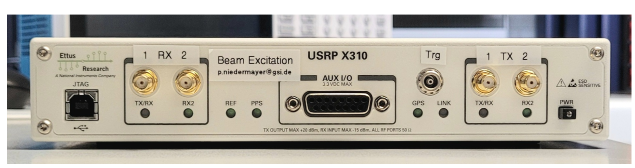

Figure 1. USRP X310

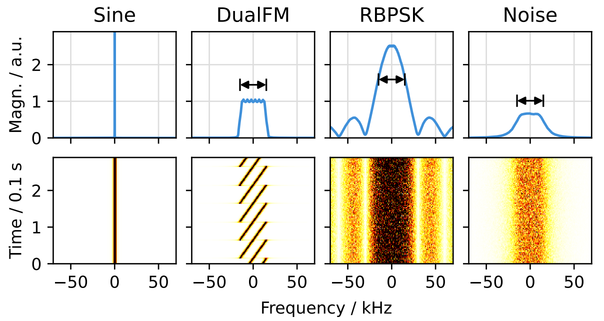

Figure 2. Spectra of the different excitation signal types used. In the upper plots, the bandwidth is indicated.

signal types:

- Sine: Sinusoidal waveform with fixed frequency
- DualFM: Two sine waves whose frequency is modulated by a sawtooth pattern (Noda et al., 2002)
- RBPSK: Random sequence encoded with binary phase-shift keying (BPSK) (Feldmeier et al., 2022)
- Noise: White noise filtered by a Butterworth filter

Figure 2 shows the spectra of these signals. For each band, the carrier frequency, bandwidth and signal amplitude can be controlled individually. More signal types can easily be added to the GNU Radio flow graph as desired.

It is necessary that the excitation signal can be started at a defined time and lasts for the specified duration within the accelerator machine cycle. This is achieved by means of start-of-burst (SOB) and end-of-burst (EOB) stream tags in the GNU Radio flow graph, which mark the beginning and end of the excitation. These tags are generated by a custom out-of-tree (OOT) block listening to one of the general purpose input/output (GPIO) pins of the USRP, which receives a trigger from the accelerator timing system.

2.2. Processing of Spill Detector Signals

The USRP is not only used to generate signals, but also to process signals from a particle detector. This provides the spill rate required for the feedback, and at the same time allows for an online-evaluation of spill fluctuations, which enables the automatic optimization described below.

Common spill detectors produce a pulse for each particle, which, if counted in user-defined time intervals, directly yields the spill rate. For current based detectors, which output an electric current proportional to the spill rate, current-to-frequency converters (IFCs) exist to generate compatible signals (Reeg, H., 1999). The pulse width is typically in the order of 20 ns to 200 ns, which requires processing of the signals at $f_{s,\mathrm{adc}} = 200\,\mathrm{MHz}$ on the field-programmable gate array (FPGA) using the RFNoC technology.

A custom RFNoC *Pulse Counter* block discriminates the detector signals with two thresholds and counts the positive flanks. Using two thresholds in hysteresis hardens the implementation against noisy signals. The block outputs the number of pulses in a defined time interval, thereby decimating the sampling rate to $f_{s,\mathrm{detector}} = 200\,\mathrm{kHz}$ so that it can be streamed to the host and processed by GNU Radio.

2.3. Feedback

Figure 3 shows a schematic of the feedback loop consisting of the SDR based feedback and excitation system and the accelerator components. A custom OOT block named

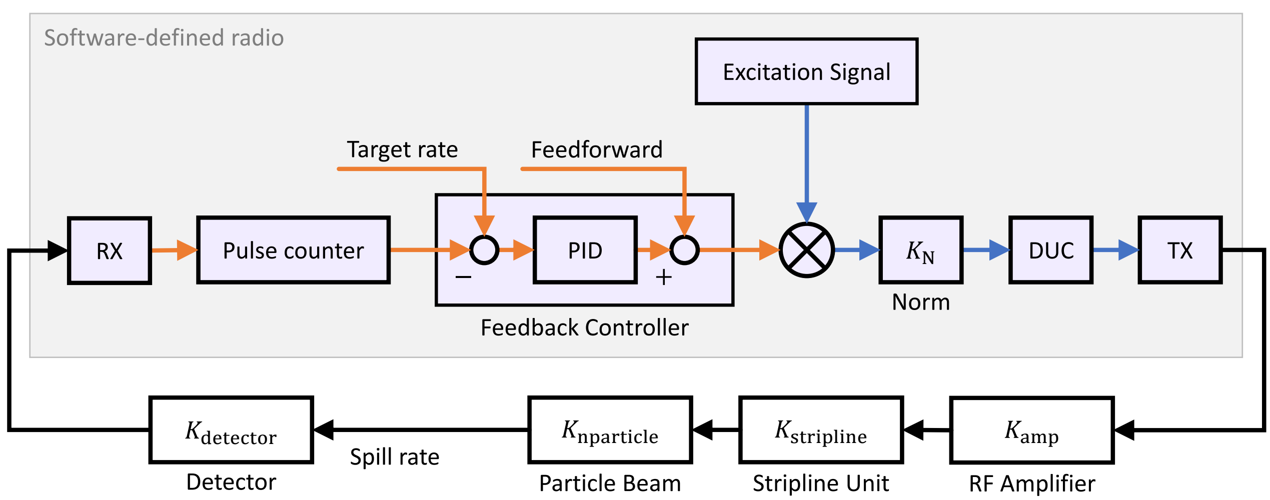

Figure 3. Schematic of the feedback loop with components of the SDR (top) and accelerator (bottom). The excitation signal is adjusted with a PID controller based on the spill rate received (RX), digitally up converted (DUC) and finally transmitted (TX) to the accelerator.

Feedback Controller with a C++ implementation of a proportional–integral–derivative (PID) controller is used to realize the feedback logic in GNU Radio. It receives the spill rate from the *Pulse Counter* as input and produces an output value that is used to scale the excitation signal amplitude. A normalization factor $K_N \propto 1/K_{\mathrm{nparticle}}$ is introduced to adjust the signal amplitude and to allow for compensation of the variable gain in the accelerator, most notably the number of particles stored in the synchrotron $K_{\mathrm{nparticle}}$.

The *Feedback Controller* block features an optional feedforward mode which can be used in cases where a detector signal is not permanently available. The feedforward value can either be a constant value, which is useful for setting up the extraction process. Or it can be a playback of the recorded feedback controller output, averaged over multiple bursts. The latter mode relies on the reproducibility of the process if the accelerator settings are not changed.

2.4. Minimization of System Delay

For a feedback system to operate fast and stable, it is crucial to minimize the loop delay and avoid dead times as much as possible. Therefore, the SDR system has to be real-time capable and the delay between receiving the input signal and transmitting the output signal must be minimized. The flexibility gained from digital signal processing (DSP) in software naturally comes with the tradeoff of increasing the system delay by introducing buffers, transmitting the data between USRP and PC and processing it on the CPU.

To reduce the system delay, the following steps are taken. The triggered operation mode is exploited, which allows flushing buffers before each burst with the *Trigger Switch* OOT block described by Niedermayer & Singh (2022), thereby reducing the accumulated buffer delay to a minimum. Furthermore, the GNU Radio flow graph is optimized by using real-time scheduling and limiting the maximum output buffer of the *RFNoC Rx Streamer* block, which streams the data from the USRP to the PC, to 64 samples. It is executed on an industrial PC equipped with an 8 core 2.1 GHz CPU and 32 GB RAM running Ubuntu 20.04, USRP hardware driver 4.4 and GNU Radio 3.10. The USRP X310 is connected via PCI Express (PCIe), which reduces the delay of the system by a factor of two compared to the Ethernet connection.

As a result of these measures, a delay of $1.28(33)$ ms between the RF in- and outputs of the SDR based feedback system was achieved.

2.5. Automatic Waveform Optimization

A key aspect of the presented spill control system is the optimization of excitation signal waveforms in order to reduce statistical fluctuations on timescales below about 50 ms down to 10 µs, which are not accessible by spill feedback systems.

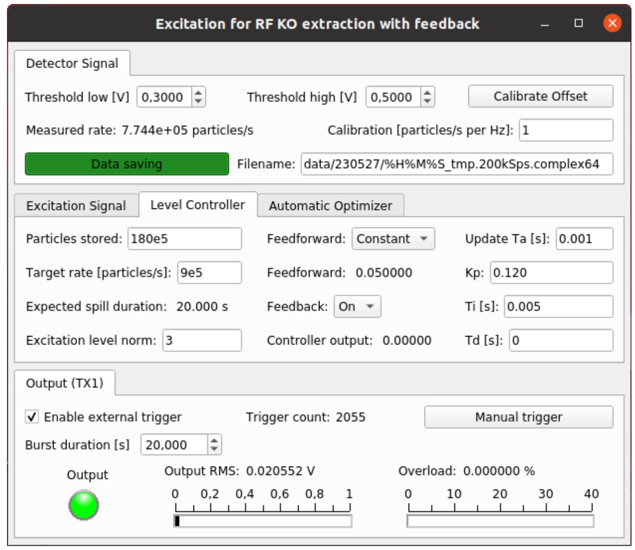

Figure 4. GNU Radio based user interface for control of the excitation, feedback and spill control system.

The automatic optimization is implemented by means of two OOT blocks: A *Burst Evaluate* block uses the detector signal to calculate a loss function proportional to the spill fluctuations and emits a message in regular intervals. An *Optimizer* block receives this message, calls the underlying optimization algorithm, and then updates a number of flow graph variables that control the generated excitation signal. The variables used for the optimization can be configured at runtime, and the changes made by the algorithm are visible to the operator on the graphical user interface (GUI).

The block uses bound optimization by quadratic approximation (BOBYQA) by Powell, M.J.D. (2009) as the underlying optimization algorithm, with the Py-BOBYQA implementation provided by Cartis et al. (2022). This is a robust, derivative-free global optimizer, which – in our tests – minimized the spill fluctuations in less than 100 iterations.

3. Commissioning at COSY Accelerator

The spill control and feedback system (fig. 4) was commissioned in the course of a beamtime in May 2023 at the Cooler Synchrotron (COSY) accelerator in Jülich. For spill detection, a Low Gain Avalanche Detector (LGAD) developed by Pietraszko et al. (2020) for the High Acceptance Di-Electron Spectrometer (HADES) was used, which was being tested by the HADES LGAD group at COSY during the same beamtime.

Figure 5 shows a 20 s spill recorded with the developed system. Excitation with a constant level (set by the feed-

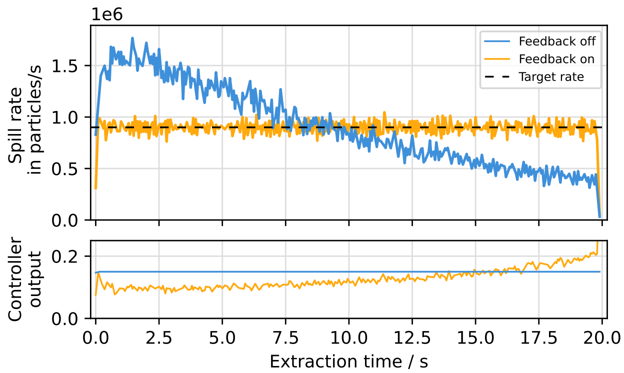

Figure 5. Measured spill rate and controller output with and without active feedback. Plot resolution: 50 ms.

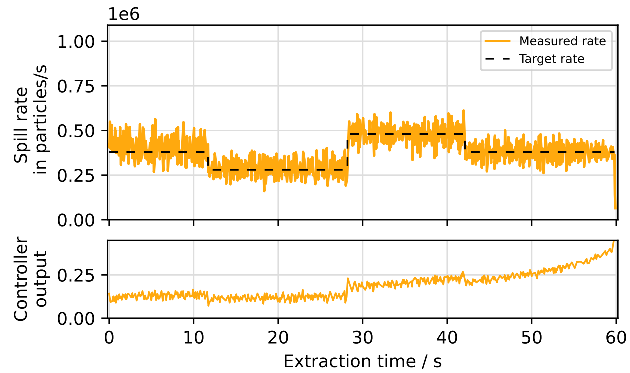

Figure 6. Measured spill rate and controller output for stepwise changed target rate. Plot resolution: 50 ms.

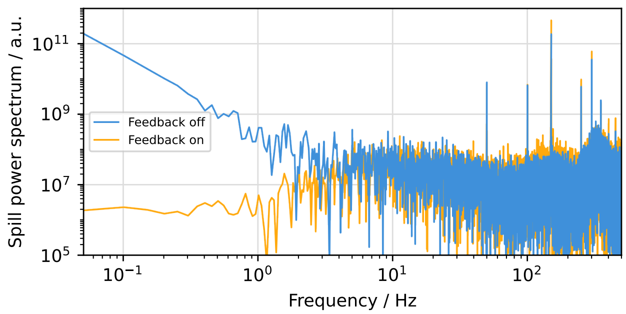

Figure 7. Power spectrum of measured spill rates with and without active feedback (compare fig. 5). The feedback system is able to suppresses fluctuations up to about 5 Hz.

forward mode) shows – as expected for this kind of slow extraction – a significant drift of the achieved spill rate over the course of the extraction. The feedback system, if switched on, is able to adjust the excitation level such as to maintain a constant spill rate on the detector. Likewise, it is able to follow arbitrary changes in the target rate (fig. 6).

Figure 7 shows the spectrum of the measured spill, revealing the spectral composition of the fluctuations dominating the extraction process. The feedback system suppresses low frequent fluctuations up to about 5 Hz. Fluctuations of higher frequency, in particular the dominant harmonics of the 50 Hz power line frequency, are not accessible by the presented feedback system. Instead, these can be reduced by optimizing the excitation waveforms with the automatic optimizer (results not presented in this paper).

4. Conclusions

An excitation, feedback and spill control system was developed and commissioned at COSY Jülich. Based on GNU Radio and realized with an USRP X310, the device does not only generate the required excitation signals to extract stored particles, but also processes the signal of a spill detector monitoring the extraction process. A feedback controller adjusts the excitation signal amplitude, thus maintaining a constant spill rate and suppressing fluctuations up to about 5 Hz. Higher frequency fluctuations are addressed by an automatic optimization algorithm tuning the excitation signal frequencies, bandwidths and related parameters.

The custom functionality required to realize the SDR based system in a particle accelerator environment is implemented in an OOT module comprising several custom GNU Radio and RFNoC blocks (Niedermayer, 2022-2023). The modular nature of the GNU Radio ecosystem makes it possible to easily use and adopt the developed blocks and flow graphs. For example, it appears straightforward to adopt the system for the method of longitudinal stochastic extraction – where the spill rate is controlled by the excitation frequency instead of its amplitude – simply by incorporating a single block known as *Voltage Controlled Oscillator* into the flow graph, which turns the multiplication with the feedback controller level into a respective frequency shift.

5. Outlook

At the time of writing, only the *Pulse Counter* block is implemented on the FPGA, while all other blocks are processed on the host PC. To further improve the performance of the system, two approaches appear obvious: First, the whole feedback loop should be moved onto the FPGA. Second, the upcoming GNU Radio 4.0 should be considered, which promises a significant performance improvement (Morman, 2022).

Acknowledgements

The authors would like to express our gratitude to the whole team of the COSY accelerator in Jülich for their support during the preparation and execution of the beamtime.

We are very thankful to Jerzy Pietraszko and the HADES LGAD group for providing us with an excellent detector signal. Bastian Bloessl and Eike Feldmeier are thanked for their support with GNU Radio and advice on SDRs. Finally, we acknowledge support by the beam instrumentation department of GSI.

References

Braun, M., Pendlum, J., & Ettus, M. (2016). RFNoC: RF Network-on-Chip. *Proceedings of the 6th GNU Radio Conference, 1(1)*. https://pubs.gnuradio.org/index.php/grcon/article/view/3

Cartis, C., Roberts, L. & Sheridan-Methven, O. (2022). Escaping local minima with local derivative-free methods: a numerical investigation. *Optimization, 71:8, pp. 2343-2373*. https://doi.org/10.1080/02331934.2021.1883015

Feldmeier, E., Cee, R., Cortés García, E.C., Galonska, M., Haberer, T., Hun, M., Peters, A., Scheloske, S. & Schömers, C. (2022). Upgrade of the Slow Extraction System of the Heidelberg Ion-Beam Therapy Centre's Synchrotron. *Proceedings of the 13th International Particle Accelerator Conference, IPAC2022, Bangkok*. https://doi.org/10.18429/JACOW-IPAC2022-THPOST029

Hereward, H.G. (1961). The possibility of resonant extraction from the C.P.S.. *Report No. AR/Int. GS/61-5. CERN*. https://cds.cern.ch/record/297121

Hiramoto, K. & Nishi, M. (1992). Resonant beam extraction scheme with constant separatrix. *Nucl. Instrum. Methods Phys. Res., Sect. A, vol. 322, pp. 154-160*. https://doi.org/10.1016/0168-9002(92)90023-W

Kühteubl, F., Renner, E., Adler, L., Fischl, L., German, X., Guidoboni, G., Holzfeind, K., Kurfürst, C., Maderböck, C., Pivi, M.T.F., Plassard, F., Prokopovich, D.A., Rizzoglio, V., Strasik, I., Schmitzer, C., Wastl, A., Arrutia Sota, P.A., & Fraser, M.A. (2023). Investigating alternative extraction methods at MedAustron. *Proceedings of the 14th International Particle Accelerator Conference, IPAC'23, Venice*. https://doi.org/10.18429/JACOW-IPAC2023-TUPM091

Morman, J. (2022). Further Evolving GNU Radio 4.0. *GNU Radio Blog*. https://www.gnuradio.org/blog/2022-12-03-low_level_api

Niedermayer, P.J. & Singh, R. (2022). Novel beam excitation system based on software-defined radio. *Proceedings of the 11th International Beam Instrumentation Conference, IBIC2022, Krakow*. https://doi.org/10.18429/JACOW-IBIC2022-MOP36

Niedermayer, P.J. (2022-2023). Software Radio Beam Exciter. *GSI git repository*. https://git.gsi.de/p.niedermayer/exciter

Niedermayer, P.J., Singh, R., Franchetti, G., Cortés García, E. C., Feldmeier, E. & Haberer, T. (2023). Investigation of micro spill in RF KO extraction using tailored excitation signals. *Proceedings of the 14th International Particle Accelerator Conference, IPAC'23, Venice*. https://doi.org/10.18429/JACOW-IPAC2023-TUPM094

Noda, K., Furukawa, T., Shibuya, S., Uesugi, T., Muramatsu, M., Kanazawa, M., Takada, E., & Yamada, S. (2002). Advanced RF-KO slow-extraction method for the reduction of spill ripple. *Nucl. Instrum. Methods Phys. Res., Sect. A, vol. 492, pp. 253-263*. https://doi.org/10.1016/S0168-9002(02)01319-0

Pietraszko, J., Galatyuk, T., Kedych, V., Kis, M., Koenig, W., Koziel, M., Krüger, W., Lalik, R., Linev, S., Michel, J., Moneta, S., Rost, A., Schemm, A., Schmidt, C. J., Sumara, K., Träger, M., Traxler, M. & Wendisch, Ch. (2020). Low Gain Avalanche Detectors for the HADES reaction time (T_0) detector upgrade. *Eur. Phys. J. A, 56:183*. https://doi.org/10.1140/epja/s10050-020-00186-w

Powell, M.J.D. (2009). The BOBYQA algorithm for bound constrained optimization without derivatives. *Report No. DAMTP 2009/NA06. University of Cambridge*. https://damtp.cam.ac.uk/user/na/NA_papers/NA2009_06

Reeg, H. (1999). A current digitizer for ionisation chambers/SEMS with high resolution and fast response. *Proceedings of the 4th European Workshop on Diagnostics and Instrumentation for Particle Accelerators, DIPAC 1999, Chester*. https://cds.cern.ch/record/911736

Schömers, C., Feldmeier, E., Naumann, J., Panse, R., Peters, A. & Haberer, T. (2015). The intensity feedback system at Heidelberg Ion-Beam Therapy Centre. *Nucl. Instrum. Methods Phys. Res., Sect. A, vol. 795, pp. 92-99*. https://doi.org/10.1016/j.nima.2015.05.054

Steinhagen, R., Kretz, M., Krimm, A., Cukic, I., Osterfeld, F., Kozel, D. & Morman, J. (2023). GNU Radio 4.0 for real-time signal-processing and feedback applications at FAIR. *Proceedings of the 14th International Particle Accelerator Conference, IPAC'23, Venice*. https://doi.org/10.18429/JACOW-IPAC2023-THPL099