ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-TUPOST021

THE CERN SPS LOW LEVEL RF: THE BEAM-CONTROL

A. Spierer†, P. Baudrenghien, J. Egli, G. Hagmann, P. Kuzmanovic, I. Stachon, M. Suminski, T. Wlostowski, CERN, Geneva, Switzerland

Abstract

The Super Proton Synchrotron (SPS) Low Level RF (LLRF) has been completely upgraded during the CERN long shutdown (LS2, 2019-2020). The old NIM and VME based, mainly analog system has been replaced with modern digital electronics implemented on a MicroTCA platform. The architecture has also been reviewed, with synchronization between RF stations now resting on the White Rabbit (WR) deterministic link. This paper is the first of a series of three on the SPS LLRF upgrade. It covers the Beam-Control part, that is responsible for the generation of the RF reference frequency from a measurement of the magnetic field, and beam phase and radial position. It broadcasts this frequency word to the RF stations, via a White Rabbit network. The paper presents the architecture, gives details on the signal processing, firmware, hardware and software. Finally, results from the first year of beam commissioning are presented (2021).

OVERVIEW OF THE LLRF UPGRADE

The CERN LHC Injectors Upgrade (LIU) project plans doubling the proton intensity extracted from the Super Proton Synchrotron (SPS) for injection into the Large Hadron Collider (LHC), therefore requiring a major upgrade [1]. Also planned is the doubling of the Lead ion beam intensity in the LHC, using a slip-stacking scheme in the SPS [2]. The Beam-Control has been upgraded along with the 200 MHz Cavity-Controllers [3,4] and the high level RF system. The two additional RF cavities (now six in total) and the need to control them individually called for a new architecture. The transition from a mostly analog to a digital system allows for new RF manipulations and an improvement of the beams' characteristics. In addition, parts of the system were aging and were difficult to maintain.

After the long shutdown (January 2019 - March 2021), the SPS commissioning with beam started in mid-April 2021 and the first proton beam was accelerated to 450 GeV/c by mid-May. During the year proton beams were delivered to the following experiments: Fixed Target, AWAKE and HiRadMat. From October to December, tests were conducted with the SPS Lead ion beam and with low intensity protons extracted to the LHC transfer lines. The first quarter of 2022 was dedicated to beam intensity increase and fine tuning of the different beams for the start of physics.

ARCHITECTURE

The new architecture relies on the White Rabbit (WR) technology [5] to synchronize the RF generation in different nodes. As shown in Figure 1, the newly developed LLRF devices are all connected to the same WR network and reconstruct their clocks for sampling and signal processing from the WR data stream.

The Beam-Control computes and broadcasts an ethernet RF frame on the WR network. It contains Frequency Tuning Words (FTW, among which the instantaneous revolution frequency) that are inputs for the distributed Numerically Controlled Oscillators (RFNCO). To generate the RF synchronously in every node, we use the fixed latency feature of the WR streamers [5]. The RFNCO core also provides frequency and amplitude modulation signals used for ions Fixed Frequency Acceleration (FFA) [6].

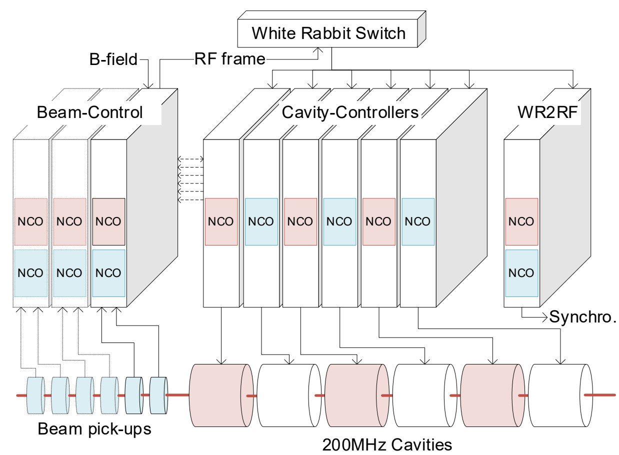

Figure 1: The SPS LLRF architecture.

The MicroTCA platform is used to host the Beam-Control and Cavity-Controllers' boards, providing controls and high bandwidth over PCIe for data acquisition.

THE BEAM-CONTROL SYSTEM

A Zynq System on Chip (SoC) is used to implement the digital signal processing and interfaces. The processing is balanced between the ARM CPU (turn by turn update) and the programmable logic for RF pre-processing (see Fig. 2).

The output of the Beam-Control is a set of FTWs and setpoints sent at the revolution frequency (~43 kHz). The FTW format allows for a 2 mHz resolution at 200 MHz.

Table 1: The WR RF Frame Content

Fields	Size in bits
FTW [main, on (FFA), program]	3*48
ΔFTW slip-stacking [group 1, 2]	2*32
Controls [modulation rate, resets]	1*16
Cavity setpoints [1..6][Amp., Phase]	6*32

For slip-stacking, a separate frequency ramp is provided for each of the two cavity groups (ΔFTW in Table 1), to let the two batches slip toward each other [6].

† arthur.spierer@cern.ch

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-TUPOST021

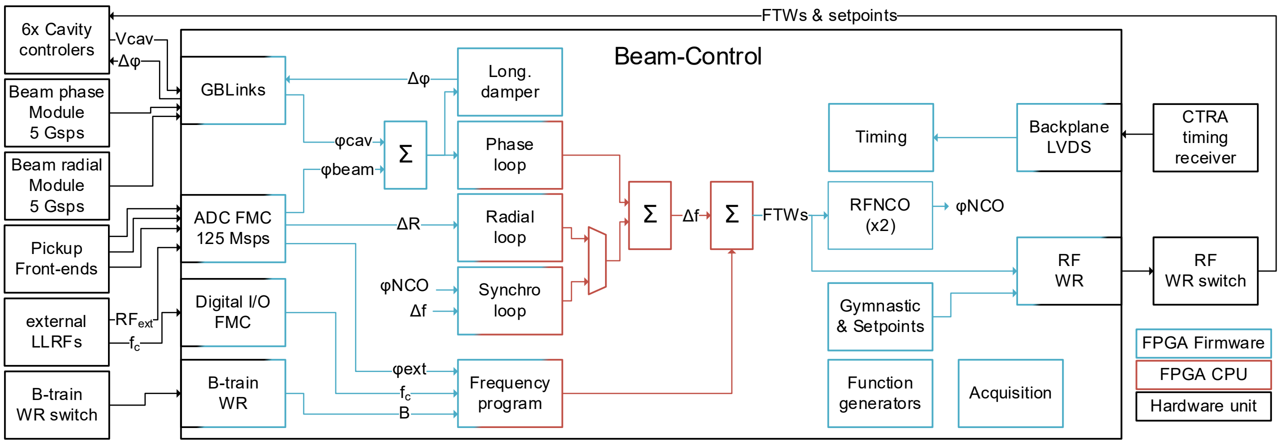

Figure 2: The Beam-Control processing flow.

Frequency Program

The Beam-Control receives a measurement of the bending field (B-train) from a dedicated WR network and computes the RF frequency program with a precision better than 10 mHz at 200 MHz.

For the LHC and AWAKE beams, rephasing to external reference signals (common frequency) must take place at flat top before extraction. The reference signals are sampled at 1.25 GHz using an FPGA serializer, and the beam is rephased to be extracted in the correct position.

Beam Based Feedback Loops

When completed, the new LLRF will use signals from three radial and three phase pick-ups (PU). Among these, one radial and one phase processing chain will use wideband PUs (2.5 GHz bandwidth) with signals digitized at 5 Gsps, followed by processing resulting in a bunch per bunch measurement. These chains (beam phase and beam radial position modules, Fig. 2) are presently being designed. They should be commissioned in summer 2022.

So far, we have used narrow-band acquisition chains, consisting in a resonant 200 MHz PU or a wideband PU followed by a 200 MHz Band-Pass filter. These narrowband beam signals are direct-sampled and processed with a fixed 125 MHz clock. The SPS RF frequency sweeps during acceleration and is regenerated digitally by the RFNCO, to be used for Direct Down Conversion (DDC). The obtained base band signal is resampled [7] from the fixed 125 MHz sampling to an RF-synchronous ~200 MHz sampling, resulting in bunch-by-bunch measurements with reduced bandwidth (averaged over ~50 RF buckets).

The phase loop error is the phase difference between the beam pickup signal and the sum of the cavity voltages. The latter is computed from a bunch-by-bunch stream coming from the six Cavity-Controllers (see GBLink in the Hardware section).

The narrow band radial loop error is obtained from the two electrodes of a transverse pickup fed to a 200 MHz bandpass filter and a 90° hybrid. Thanks to the hybrid, the measured phase difference between the two channels is then proportional to the position of the beam. The same processing can thus be used as for the phase measurement.

For the synchro loop error, which locks the beam on the frequency program, we use the phase difference between two outputs of the RFNCO: One with the loops contributions and one with the frequency program only (main and program in Table 1). The phase loop is always active and the beam energy is regulated by using either the synchro loop or the radial loop, as is classic in hadron synchrotrons [8].

To generate *optimal* loop gains along the accelerating ramp, we use the Linear Quadratic Regulator (LQR) formalism. It is based on a state space model that includes the longitudinal beam dynamics (synchrotron oscillation) and the feedback variables. Two matrices govern the speed of the regulation: The error weighting matrix Q and the regulation cost R. The larger the elements of Q versus R, the faster the regulation. Given the state space model and the Q and R matrices, we obtain feedback gains resulting in a stable regulation for the synchro/phase and radial/phase loop systems, see Fig. 3. These feedback gains configure floating point biquadratic filters that output a correction to the RF frequency, as shown on Fig. 2.

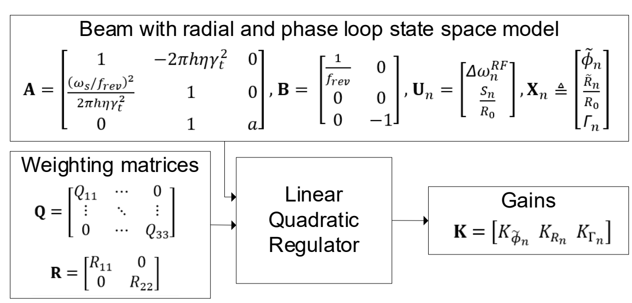

Figure 3: LQR optimal gains for the radial and phase loop, with ω_s the synchrotron frequency in rad/s and the state variables: $\tilde{\phi}_n$ the phase error, $\tilde{R}_n/R_0$ the relative radial displacement and Γ_n its integrated version.

The loop errors are computed once per turn and are the result of averaging over a certain range of bunches. With a masking system, we can select which bunches are counted in the average. This system allows to track individual groups of bunches and to implement two separate phase loops during the ions slip-stacking manipulations [6].

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-TUPOST021

To damp injection phase or energy errors during the injection of successive batches, and to prevent dipole-mode coupled bunch instabilities, we have implemented a longitudinal damper that applies a phase modulation in quadrature with the detected oscillation. From the beam pickup signal, after filtering with an IIR filter matched to the synchrotron tune, the 10 MHz bandwidth damping signal $\Delta\phi$ is sent over the GBLink to the cavities phase setpoint.

Fast RF Manipulations

The Beam-Control can manipulate the six 200 MHz cavities phase and amplitude independently, within a beam revolution. The setpoints are sent over WR along with the FTWs. This is used for bunch rotation, to either increase the momentum spread for slow extraction (Proton Fixed Target physics) or to shorten the bunch for the AWAKE experiment. In the first case, the beam is shortly put on the unstable RF phase so that the bunch lengthens, then the RF jumps back to the stable phase and the bunch rotates in phase space. When the momentum spread is largest the total voltage is reduced to zero by full counter-phasing and the beam is slowly extracted via a quadrupole driven 2/3 integer resonance. In the second case, the voltage is first adiabatically reduced creating a long bunch and then increased rapidly resulting in bunch rotation. It is extracted when the length is the smallest.

For ions slip-stacking, the interleaved bunches are recaptured by a rapid voltage increase and 100% amplitude modulation is applied within the turn [6,9]. A real-time measurement of the batch displacement allows to precisely time the recapture.

Finally, a pre-calculated phase noise waveform can be sent for controlled longitudinal emittance blow-up [10].

HARDWARE

The Beam-Control is based on a MicroTCA Advanced Mezzanine Carrier (AMC) with a Zynq UltraScale+ (AFCZ). Two FMCs are attached: A 4-channel 125 Msps 14 bits ADC and a 32 Digital I/O interface. The Rear Transition Module (RTM) supports up to sixteen 10 Gb links among which we use two for WR. The four boards are shown on Figure 4. We use commercially available components, apart from the ADC FMC that is developed at CERN. The boards are under open hardware license and available from Creotech. The same hardware is used for the 5 Gsps sampling modules by replacing one of the FMCs with the Vadatech FMC217.

Figure 4: Beam-Control hardware, from left to right, the two FMCs, the AFCZ carrier and the QSFP-SFP RTM.

We use the 10 Gb links over copper to transmit either 200 Msps beam-synchronous tagged data (Cavity voltages) or fixed latency 125 Msps clock synchronous data (Longitudinal Damper). The developed GBLink protocol relies on Xilinx Aurora streaming channels and WR for synchronization and tagging. The links between Beam-Control and Cavity-Controllers are depicted in Figure 1.

CONTROLS

To configure the hardware for several types of accelerating cycles and beams, the settings are managed through the LHC Software Architecture (LSA). The settings and functions (settings varying during the cycle) are automatically generated using either conditional values or computed ones from higher-level physics parameters (momentum, bucket area, …). The settings are archived to allow exploration and roll-back. For remote observation and diagnostic, several Megabytes of bunch-by-bunch and turn-by-turn data are extracted at each cycle.

ISSUES

Although the beam commissioning was rather quick, we suffered reliability issues of some of the MicroTCA commercial products, such as power supplies, Front End CPU or crate management boards. We also have a strong dependency on the WR technology and complex clocking schemes, which resulted in the loss of RF alignment after crashes/reboots. Most of these issues are solved now.

With the use of LQR generated gains, we have observed instabilities at high energy that might be explained by discrepancies between the beam/machine model and reality. We hope that reducing the processing delay (not included in the model) will help in this regard, as for now the phase loop aggressiveness must be reduced at high energy.

RESULTS

A series of beams were accelerated on schedule with the new LLRF system and fine-tuned for experiments and machine developments: LHC beams extracted with rephasing at 450 GeV/c; AWAKE runs with 1ns long bunches using a voltage jump at extraction; Fixed Target beams with slow extraction RF manipulations; Lead ion beams with Fixed Frequency Acceleration (FFA) and slip-stacking on a 300 GeV/c intermediate plateau, to reduce spacing from 100 to 50 ns. In addition, the LLRF is so far accepting the intensity increase towards HL-LHC, with the longitudinal damper in operation.

ACKNOWLEDGEMENT

The beam commissioning and operation was greatly simplified thanks to F. Follin and K.S.B. Li with the implementation of high-level controls and applications. We also thank I. Karpov, G. Papotti and the SPS operation team for their support, as well as our colleagues from the RF power. We thank the developers of the different sub-systems: J. Galindo for the resampler, G. Kotzian for the PU frontends and signal processing, M. Lipinski for the B-train over WR. We are grateful for the work and availability of the real-time software developers K. Adrianek, B. Bielawski and S. Novel Gonzalez.

ISBN: 978-3-95450-227-1 ISSN: 2673-5490 doi:10.18429/JACoW-IPAC2022-TUPOST021

REFERENCES

[1] J. Coupard *et al.*, "LHC Injectors Upgrade, Technical Design Report, Vol. I: Protons", Tech. Rep. CERN-ACC-2014-0337 CERN, Geneva, Switzerland, 2014.

[2] J. Coupard *et al.*, "LHC Injectors Upgrade, Technical Design Report, Vol. II: Ions", Tech. Rep. CERN-ACC-2016-0041, CERN, Geneva, Switzerland, 2016.

[3] G. Hagmann *et al.*, "The CERN SPS Low Level RF upgrade Project", in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 4005-4008. doi:10.18429/JACoW-IPAC2019-THPRB082

[4] G. Hagmann, P. Baudrenghien, J. Egli, A. Spierer, M. Suminski, and T. Wlostowski, "The CERN SPS Low level RF: The Cavity-Controller", presented at the 13th International Particle Accelerator Conf. (IPAC'22), Bangkok, Thailand, Jun. 2022, paper TUPOST023, this conference.

[5] M. Lipiński *et al.*, "White Rabbit Applications and Enhancements", 2018 IEEE International Symposium on Precision Clock Synchronization for Measurement, Control, and Communication (ISPCS), 2018, pp. 1-7. doi:10.1109/ISPCS.2018.8543072

[6] P. Baudrenghien, J. Egli, G. Hagmann, A. Spierer, T. Wlostowski., "The SPS LLRF Upgrade: Lead Ions Acceleration", presented at the 13th International Particle Accelerator Conf. (IPAC'22), Bangkok, Thailand, Jun. 2022, paper TUPOST022, this conference.

[7] J. Galindo Guarch, P. Baudrenghien, J. M. Moreno Arostegui, "An Architecture for Real-Time Arbitrary and Variable Sampling Rate Conversion With Application to the Processing of Harmonic Signals", *IEEE Trans. Circuits Theor.*, vol. 67, pp. 1653-1666, 2020. doi:10.1109/TCSI.2019.2960686

[8] P. Baudrenghien, "Low-level RF - Part I: Longitudinal dynamics and beam-based loops in synchrotrons", CERN Accelerator School: Specialized Course on RF for Accelerators, Ebeltoft, Denmark, Jun 2010, pp. 341-367, doi:10.5170/CERN-2011-007.341

[9] T. Argyropoulos, T. Bohl, A. Lasheen, G. Papotti, D. Quartullo, and E. N. Shaposhnikova, "Momentum Slip-Stacking in CERN SPS for the Ion Beams", in *Proc. IPAC'19*, Melbourne, Australia, May 2019, pp. 3184-3187, doi:10.18429/JACoW-IPAC2019-WEPTS039

[10] D. Quartullo, H. Damerau, I. Karpov, G. Papotti, E. Shaposhnikova, C. Zisou, "Controlled Longitudinal Emittance Blow-Up for High Intensity Beams in the CERN SPS", in *Proc. 64th ICFA ABDW*, Batavia, IL, USA, Oct. 2021. doi:10.18429/JACoW-HB2021-MOP11