THE CERN SPS LOW LEVEL RF UPGRADE PROJECT

G. Hagmann*, P. Baudrenghien, J. D. Betz, J. Egli, G. Kotzian, M. Rizzi,
L. Schmid, A. Spierer, T. Wlostowski, CERN, Geneva, Switzerland
F. J. Galindo Guarch, UPC, Barcelona, Spain

Abstract

The High Luminosity LHC project (HL-LHC) calls for the doubling of the beam intensity injected from the Super Proton Synchrotron (SPS). This is not possible with the present RF system consisting of four 200 MHz cavities. An upgrade was therefore launched, consisting of the installation of two more cavities during the machine shutdown in 2019-2020 (LS2). Installation of more cavities requires the installation of extra Low Level RF (LLRF) electronics. The present LLRF system consists of the original equipment installed in the 1970s, plus some additions dating from the late 1990s when the SPS was commissioned as LHC injector. The High-Power RF upgrade has motivated a complete renovation of the LLRF during LS2; use of a MicroTCA platform, use of a digital deterministic link for synchronization (the so-called White Rabbit), use of an absolute clock for the processing, new algorithms for reducing the cavity impedance, and a complete re-design of the beam control loops and slip-stacking.

OVERVIEW OF THE SPS RF UPGRADE AS HL-LHC INJECTOR

Motivation

The demanding beam performance requirements of the High Luminosity LHC (HL-LHC) project translate into a set of requirements for the SPS as HL-LHC injector which are not possible with the current RF system:

- Protons [1]: Doubling of the present bunch intensity to 2.3×1011 p+/bunch at extraction to LHC [2], 25 ns bunch spacing, up to four batches of 72 bunches.
- Lead ions [3]: 2.1×108 ions/bunch extracted to LHC (2.2×108 achieved in 2018), bunch spacing of 50 ns (75 ns and 100 ns achieved in 2018 [4]), 48 bunches accumulated by 12 injections during the 39.6 s long injection plateau, 100 ns bunch spacing at injection reduced to 50 ns by slip stacking [5].

In addition, the need for new electronics to control the additional two cavities has motivated a complete renovation of the entire LLRF system.

RF Upgrade

The SPS is equipped with two travelling wave cavity systems, one at 200 MHz [6] and a second at 800 MHz used as Landau damping cavities. After the upgrade, the SPS will have two additional 200 MHz cavities by re-arranging the sections of the existing cavities and by using two spare sections. In total the machine will include four three-sections cavities (32 cells) and two four-sections cavities (43 cells) at 200 MHz, as shown in Fig. 1.

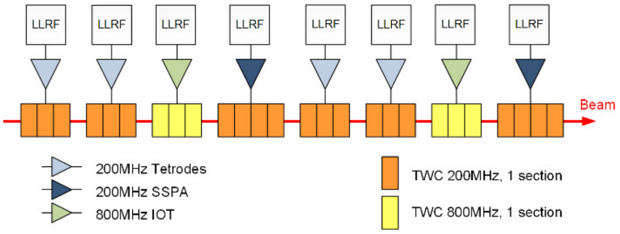

Figure 1: SPS RF systems after LS2.

Shortening the cavities and adding two more RF amplifiers will increase the ratio of total RF voltage to beam-loading voltage, thereby improving stability with high intensity proton beam [1]. For ions, the new LLRF will implement the Fixed Frequency Acceleration (FFA) developed in the late nineties [7], with the new momentum slip stacking gymnastic [5]. The 800 MHz RF system (two cavities) was upgraded during the 2013-2014 shutdown with two new power plants and LLRF systems implemented on a VME platform.

THE LOW-LEVEL RF UPGRADE

New Functionalities

For protons, to cope with twice the present day beam intensity, the LLRF upgrade must improve the compensation of beam loading in order to reduce the cavity impedance at the fundamental and prevent longitudinal coupled-bunch instabilities that are presently limiting the bunch intensity at 1.4×10^{11} p/bunch [1]. The classic RF feedback is not an option in the SPS because the amplifiers are installed at the surface resulting in a long loop delay (> 2 μs) limiting the feedback bandwidth to less than one revolution frequency (43 kHz). A One-Turn Delay Feedback (OTFB) was therefore installed in 1985 and upgraded since to reduce the beam-induced voltage at the fundamental (f_{RF}) and on the revolution frequency sidebands (f_{rev}) [8-10]. To counteract coupled-bunch instabilities the feedback must have gain on the synchrotron sidebands (f_{s}) of the revolution frequency lines (m=1 for dipole mode):

$$f_{\mathrm{RF}} \pm (k \cdot f_{\mathrm{rev}} \pm m \cdot f_{\mathrm{s}}), \qquad k, m \in \mathbb{N}. \tag{1}$$

To achieve this performance, the OTFB will be implemented with a triple comb filter tracking the revolution frequency lines plus the two synchrotron sidebands (m=1) as explained below.

For ions, the LLRF must implement the momentum slip-stacking to increase the number of ion bunches for LHC beams. The SPS injection chain cannot produce 50 ns bunch spacing. In order to create this bunch spacing in the SPS at extraction, two batches are injected with 100 ns bunch spacing at two azimuthal positions.

---

*gregoire.hagmann@cern.ch

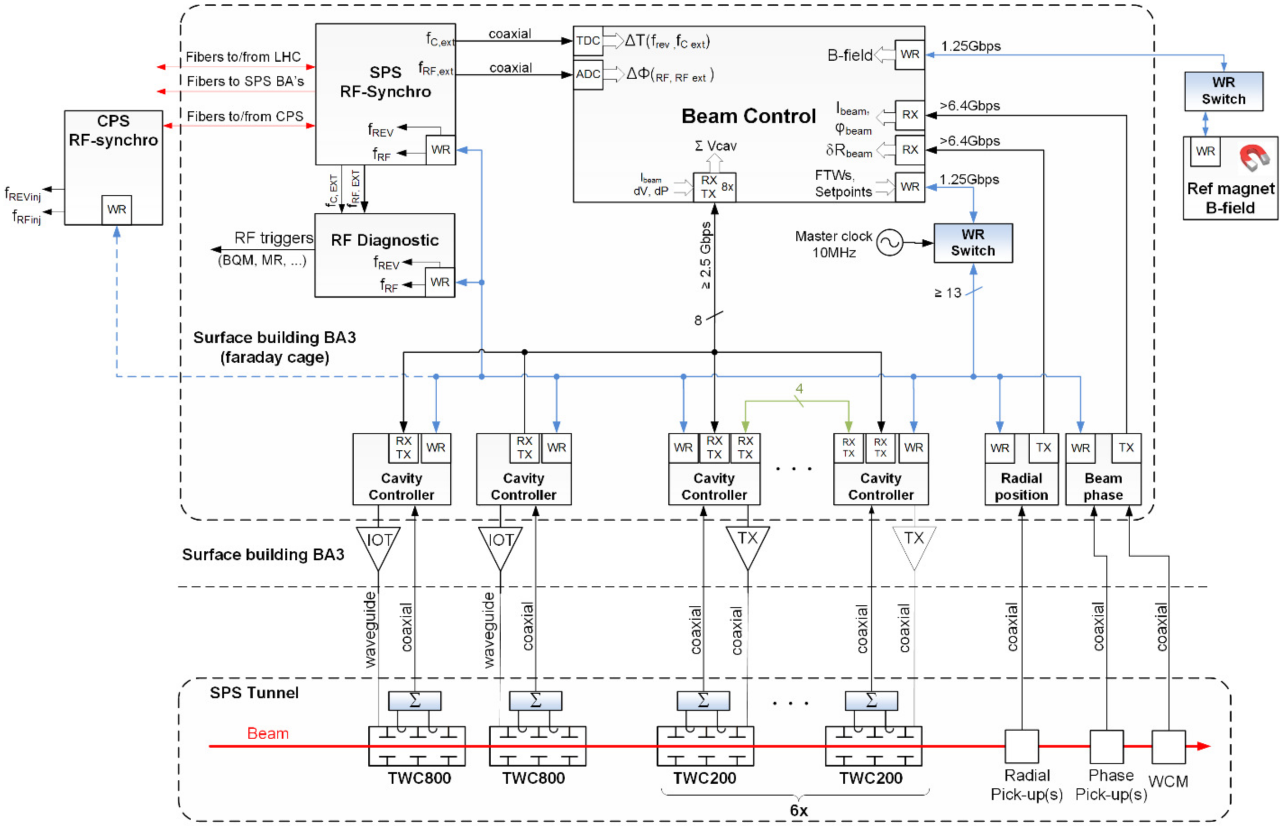

Figure 2: SPS low level architecture.

Two groups of cavities controlled by two independent master RF signals capture the two batches. At some energy plateau during the ramp, the two batches are azimuthally moved in opposite directions along the ring until they are interleaved. Subsequentially they are re-captured by all cavities to get a single batch with 50 ns bunch spacing [5].

In addition, we aim for individual measurements of each bunch phase, intensity and radial position, for both diagnostics and beam-based feedback loops. These bunch-by-bunch measurements must be possible for any bunch spacing multiple of the 200 MHz RF wavelength. Finally, it is expected that modern digital electronics, remote controls, embedded diagnostic and flexibility will ease the day-to-day operation and maintainability.

New Architecture

Figure 2 outlines the low level RF system, indicating three distinct main sub-systems: The *Beam-Control,* the *Cavity-Controllers*, and the *RF-Synchro*. The *Beam-Control* and the *200 MHz Cavity-Controllers* will be upgraded on a MicroTCA platform.

Unlike the previous SPS system, the Master RF will not be distributed in analog, but as a numerical data represented by the Frequency Tuning Words (FTWs, duplicated to allow slip stacking), transmitted over a deterministic serial link, the White Rabbit (WR) [11]. A similar method is implemented in BNL [12] and GSI [13]. The WR will also transmit machine-wide synchronization triggers. In addition, the sampling and processing clock is reconstructed from the WR serial link as described in the following section. Our new architecture uses a fixed clock, a move motivated by the very disappointing past experiences with sweeping frequency clocks for FPGAs.

The *Beam-Control* receives the measured B-field transmitted over a second WR network and, via dedicated point-to-point serial links, the cavity voltage measurements with fine time granularity, plus the bunch-by-bunch phase, intensity and radial position measurements. Based on a system-on-chip architecture, the *Beam-Control* computes two FTWs plus corrections from the usual beam-based feedback loops (Phase loop, Synchro loop and Radial loop). To cope with any bunch spacing multiple of the 200 MHz RF wavelength, the bunch-by-bunch measurements are based on direct digitization of wideband pick-ups signal (< 3 GHz) at constant sampling rate.

The *Cavity-Controllers* (one per cavity), regulate the cavity voltage and reduce the beam loading. Their core is an OTFB first introduced in 1985 [8] and since then using a digital comb filter clocked at a multiple of the beam revolution frequency [8-10]. The new system will use a fixed 62.5 MHz processing clock at half the sampling frequency (125 MHz). In addition, we now decouple its two tasks: Transient beam-loading compensation that calls for regulation on the revolution frequency sidebands, and longitudinal stability linked to the impedance on the synchro-revolution sidebands, Eq. (1). The result is the *Triple Comb* filter shown in Fig. 3.

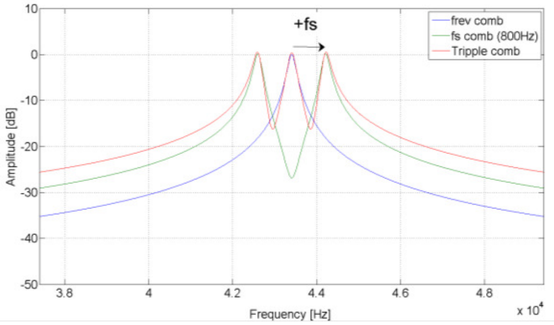

Figure 3: OTFB – Biquads (IIR) response.

The filter consists of two Biquads in parallel: The first one implements the comb at the exact multiple of the revolution frequency, whereas the second one covers the synchrotron sidebands. Equation (1) shows the Biquad z-transform H_{comb}.

$$H_{\mathrm{comb}} = \frac{b_0 + b_1 \cdot z^{-(N+n)} + b_2 \cdot z^{-2(N+n)}}{1 + a_0 \cdot z^{-(N+n)} + a_1 \cdot z^{-2(N+n)}} \tag{1}$$

The coefficients $\{b_0, b_1, b_2, a_0, a_1\}$ are changed to track the synchrotron frequency during acceleration and $N+n$ represents one machine turn [14-15]. While N is kept constant, the delay n, called variable delay, must be reduced during acceleration by 220 ns to cover an RF frequency span of 2 MHz for the fixed-target ions acceleration in the SPS. The intended RF feedback bandwidth is ±5 MHz, covering ±116 revolution frequency harmonics. This requires 27 ps delay resolution to achieve an alignement better than 5 Hz up to the last revolution harmonics. The variable delay is made of two components, a variable integer delay to cover fourteen sampling clock periods and a fractional delay to reach the 27 ps precision. The fractional delay is realised with a fourth order Lagrange polynomial interpolation with a FIR architecture whose coefficients are also changed during acceleration [16]. As the interpolator introduces gain larger than one for higher frequencies, it is followed by a low pass filter to keep the Biquad stable as shown in Fig. 4, [17].

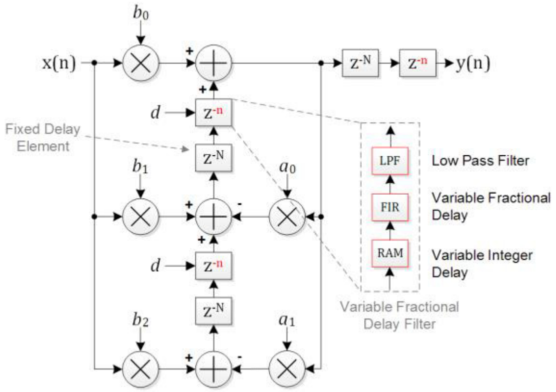

Figure 4: OTFB – Biquad (IIR) with fractional delay FIR filter.

The *RF-Synchro* receives external RF references for beam alignment at extraction to the LHC (rephasing). It also generates and distributes SPS RF references for synchronization of the transfers (injection and extraction) and for beam observation and diagnostics. As a possible improvement at a later stage, the distribution of the RF references and the re-synchronization between accelerators could be done through the WR network.

REFERENCE CLOCK RECOVERY

Unlike the architecture used at BNL [12] and GSI [13], our sampling and processing clocks are reconstructed from the WR serial data stream, in each node of the network, by means of a very low noise phase-locked-loop (PLL), filtering the WR master oscillator. WR brings the benefit of link stabilization against temperature [18] and gives us a system where synchronization between various cavities is made easy, and that can be scaled up with the WR network topology. Our first tests have shown discrete phase jumps of the reconstructed clock by up to ±40 ps (±3 deg at 200 MHz) after the WR link is restarted. Such a jitter is incompatible with the SPS needs as an absolute phase reference.

These jumps have been found to originate from a serial-to-parallel clock divider and from the phase alignment logic inside the Gigabit transceiver of the FPGA. The WR core was thereafter optimized, keeping the jitter within ±5 ps after numerous link restarts (~2500 restarts within a period of 19 hours) at constant room temperature.

CONCLUSION

The new SPS LLRF is based on a fixed processing clock and the use of the White Rabbit (WR) for data and clock transmission. The latter was made possible thanks to the improved phase stability of the clock reconstruction. Operating modern FPGAs at a fixed frequency allows for best exploitation of their potential. The authors' experience of using FPGAs with varying and occasionally interrupted clocks has been disappointing. The use of the White Rabbit makes synchronization between various cavities very easy. Transmission of key RF information, such as the RF frequency, via a deterministic numerical link, instead of a classic analog distribution, makes the system very scalable: addition of new cavities only calls for new WR links. Where beam-synchronous processing is required, such as the One Turn Delay Feedback (OTFB), a new algorithm has been designed that implements an integer plus fractional variable delay, with the fixed processing clock.

ACKNOWLEDGEMENT

We thank our CERN BE-RF colleague T. Bohl for sharing his knowledge and experience in the SPS RF system. We are gratefull to our CERN BE-CO colleagues J. Serrano, M. Vanden Eynden and S. Pamelard for their support and encouragements in the use of the WR and MicroTCA. We also thank our BNL colleagues K. Smith, K. Mernick, T. Hayes and F. Severino for their advices on the deterministic digital links and for sharing their expertise on LLRF systems.

REFERENCES

[1] LHC Injector Upgrade, Technical Design Report, Vol. I: Protons, edited by J. Coupard, H. Damerau, A. Funken, R. Garoby, S. Gilardoni, B. Goddard, K. Hanke, A. Lombardi, D. Manglunki, M. Meddahi, B. Mikulec, G. Rumolo, E. Shaposhnikova, M. Vretenar, CERN-ACC-2014-0337 (CERN, Geneva, 2014).

[2] E. Metral *et al.*, "Update of the HL-LHC operational scenarios for proton operation", Jan 19th, 2018, pp. 11-12, CERN-ACC-NOTE-2018-0002.

[3] LHC Injector Upgrade, Technical Design Report, Vol. II: Ions, edited by J. Coupard, H. Damerau, A. Funken, R. Garoby, S. Gilardoni, B. Goddard, K. Hanke, D. Manglunki, M. Meddahi, G. Rumolo, R. Scrivens, E. Shaposhnikova, CERN-ACC-2016-0041 (CERN, Geneva, 2016).

[4] H. Bartosik *et al.* "Recent beam performance achievements with the pb ion beam in the sps for lhc physics runs", presented at the 10th Int. Particle Accelerator Conf. (IPAC'19), Melbourne, Australia, Mai. 2019, paper MOPGW069, this conference.

[5] D. Quartullo, T. Argyropoulos, and A. Lasheen, "Momentum Slip-Stacking Simulations for CERN SPS Ion Beams with Collective Effects", in Proc. 61 ICFA ABDW on High-Intensity and High-Brightness Hadron Beams (HB'18), Daejeon, Korea, June 2018, pp. 174-179. `doi:10.18429/JACoW-HB2018-TUP2WA02`

[6] G. Dôme, "The SPS Acceleration System Travelling Wave Drift-Tube Structure for the CERN SPS", in *Proc. 1976 Proton Linear Accelerator Conf. (LINAC'76)*, Chalk River, Canada, Sep. 1976, paper C06, pp. 138-147.

[7] D. Boussard, T. Bohl, T. Linnecar, and U. Wehrle, "Non Integer Harmonic Number Acceleration of Lead Ions in the CERN SPS", in *Proc. 16th Particle Accelerator Conf. (PAC'95)*, Dallas, TX, USA, May 1995, paper FAE10, pp. 1506-1508.

[8] D. Boussard, "Control of Cavities with High Beam Loading", in *Proc. 11th Particle Accelerator Conf. (PAC'85)*, Vancouver, Canada, May 1985, pp. 1852-1857.

[9] P. Baudrenghien, G. Lambert, "Reducing the impedance of the Travelling Wave Cavities, Feed-Forward and one turn Delay-Feedback", *Xth Workshop on LEP-SPS performance*, Chamonix, Jan. 17-21, 2000, CERN-SL-2000-007-DI, pp. 94-101.

[10] P. Baudrenghien, G. Lambert, "Control of strong beam loading. Results with beam", *XIth Workshop on LHC performance*, Chamonix, Jan. 15-19, 2001, CERN-SL-2001-003-DI, pp. 63-72.

[11] J. Serrano *et al.*, "The White Rabbit Project", in *Proc. 2nd Int. Beam Instrumentation Conf. (IBIC'13)*, Oxford, UK, Sep. 2013, paper THBL2, pp. 936-942.

[12] T. Hayes, F. Severino, and K. S. Smith, "A Deterministic, Gigabit Serial Timing, Synchronization and Data Link for the RHIC LLRF", in *Proc. 24th Particle Accelerator Conf. (PAC'11)*, New York, NY, USA, Mar.-Apr. 2011, paper MOP282, pp. 642-644.

[13] H. Klingbeil *et al.*, "New digital low-level rf system for heavy-ion synchrotrons", Phys. Rev. ST Accel. Beams 14, 102802 – Published 6 October 2011. `doi:10.1103/PhysRevSTAB.14.102802`

[14] G. Hagmann *et al.*, "The SPS LLRF upgrade project", LLRF17 workshop, Barcelona, Spain, Oct. 16-19, 2017, Poster P-92.

[15] G. Hagmann, P. Baudrenghien, "LLRF System upgrade in the CERN SPS", LLRF15 workshop, Shanghai, China, Nov. 15, 2015.

[16] F.J. Harris, "Resampling filters", in *Multirate Signal Processing for Communication Systems*, Prentice Hall PTR, Ed. New Jersey, NY, USA: Pearsen, 2004, pp. 153-200.

[17] L. Schmid *et al.*, "Implementation of a One-Turn Delay Feedback with a Fractional Delay Filter (PDF)", LLRF17 workshop, Barcelona, Spain, Oct. 16-19, 2017, Poster P-77.

[18] P. Boven, "DWDM stabilized optics for white rabbit WR link stabilization link", in *Proc. 2018 European Frequency and Time Forum (EFTF)*, Torino, Italy, April 10-12, 2018, pp. 213-216. `doi:10.1109/EFTF.2018.8409035`