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THE CERN SPS LOW LEVEL RF: THE CAVITY-CONTROLLER

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Abstract

This paper is the second of a series of three on the Super Proton Synchrotron (SPS) Low Level RF (LLRF) upgrade. It covers the 200MHz Cavity-Controller part, that is responsible for the regulation of the accelerating field in a single SPS cavity. When the SPS is used as Large Hadron Collider (LHC) proton injector, the issue is the high beam loading that must be compensated to guarantee longitudinal stability and constant parameters over the bunch train. That calls for strong One-Turn Delay Feedback (OTFB) and Feed-Forward (FFWD). The SPS is also accelerating Lead ions (Pb). There the issue is Frequency-Modulation (FM) and Amplitude-Modulation (AM) over the turn (so called Fixed Frequency Acceleration - FFA) plus RF gymnastics for the new ions slip-stacking. The paper reviews the functional requirements, presents the block diagram, then gives details on the signal processing, firmware and hardware. Finally results from the first year of beam commissioning are presented (2021).

MOTIVATIONS NEW FUNCTIONALITIES

The SPS was restarted in April 2021 after a Long-Shutdown (LS2, 2019-2020) during which the LLRF system was upgraded to achieve the beam performance required for the SPS as High Luminosity LHC (HL-LHC) injector [1].

Bunch Intensity

For protons, the SPS bunch intensity will double during run 3 to reach 2.3e11 p+/bunch at extraction to the LHC [2, 3]. The new LLRF has improved the compensation of the beam loading to reduce the cavity impedance and prevent longitudinal coupled-bunch instabilities that have limited the bunch intensity to 1.4e11 p+/bunch in the SPS before LS2 [2].

For LHC high intensity beam and AWAKE single bunch beam, the RF voltage required, exceeds the average power of the amplifiers. Therefore, the LLRF now operates with 100% AM to exploit the maximum RF peak power.

Complete renovation of the FFWD and Longitudinal Damper (LD) was required to integrate the new architecture. The old FFWD implementation proved very noisy, and the old LD design did not effectively follow the change of optics resulting in the increase of synchrotron frequency.

Ions Slip-stacking

For ions, the target is a doubling of the LHC beam intensity with 50 ns bunch spacing [4]. The new LLRF must implement momentum slip-stacking to produce 50 ns spacing from two batches of bunches at 100 ns spacing [5]. Moreover, the One-Turn Delay Feedback (OTFB) is now operational for ions with FM and 100% AM over the turn.

Obsolescence

The upgrade of the entire SPS LLRF was motivated by: the critical obsolescence of the electronics where some modules were designed in the late 70's; the lack of LLRF control required to produce the new proton and ion beams; the installation of two additional 200 MHz travelling wave cavities.

ARCHITECTURE

Figure 2 shows the SPS LLRF architecture [1] based on the White-Rabbit network (WR) and on Numerically Controlled Oscillators (RFNCO) to synchronize all RF stations. The Beam-Control [6] computes the Frequency Tuning Word (FTW) for harmonic h=1 (revolution frequency) and sends it over WR to the Cavity-Controllers. The Cavity-Controllers (one instance per cavity) regulate the cavity field and reduce the beam loading by measuring the cavity voltage and the beam current to produce the correcting RF drive to the power amplifier.

RF Feedback

The RF feedback is the core of the Cavity-Controller. It contains two branches as shown in Fig. 1. The low-pass branch, switched on before injection, is a classic RF feedback regulating the cavity voltage with a 1 kHz bandwidth centered at the RF frequency.

The high pass branch is a One-Turn Delay Feedback with gain on the revolution frequency sidebands. It compensates the transient beam loading and prevents longitudinal instabilities linked to the impedance on the synchro-revolution sidebands. A triple comb filters is implemented [1] and operates at a fixed processing clock. The biquad structure of the comb filters and the loop delay both include a variable fractional delay tracking the changing revolution period during the acceleration.

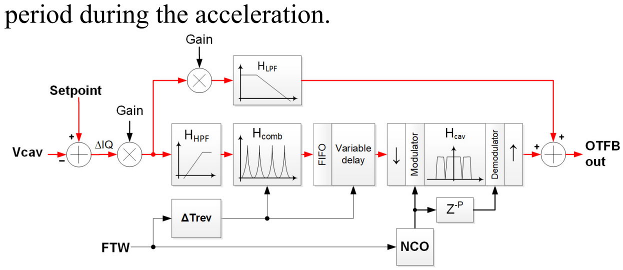

Figure 1: RF Feedback and One-Turn Delay Feedback.

As shown in Fig. 2, the cavity voltage (Vcav) cable and power amplifier introduce a delay and therefore a phase shift that varies with the RF frequency. The FIFO on the IQ demodulator local oscillator at ω_0 cancels this phase shift. As this delay is different amongst the cavities and because

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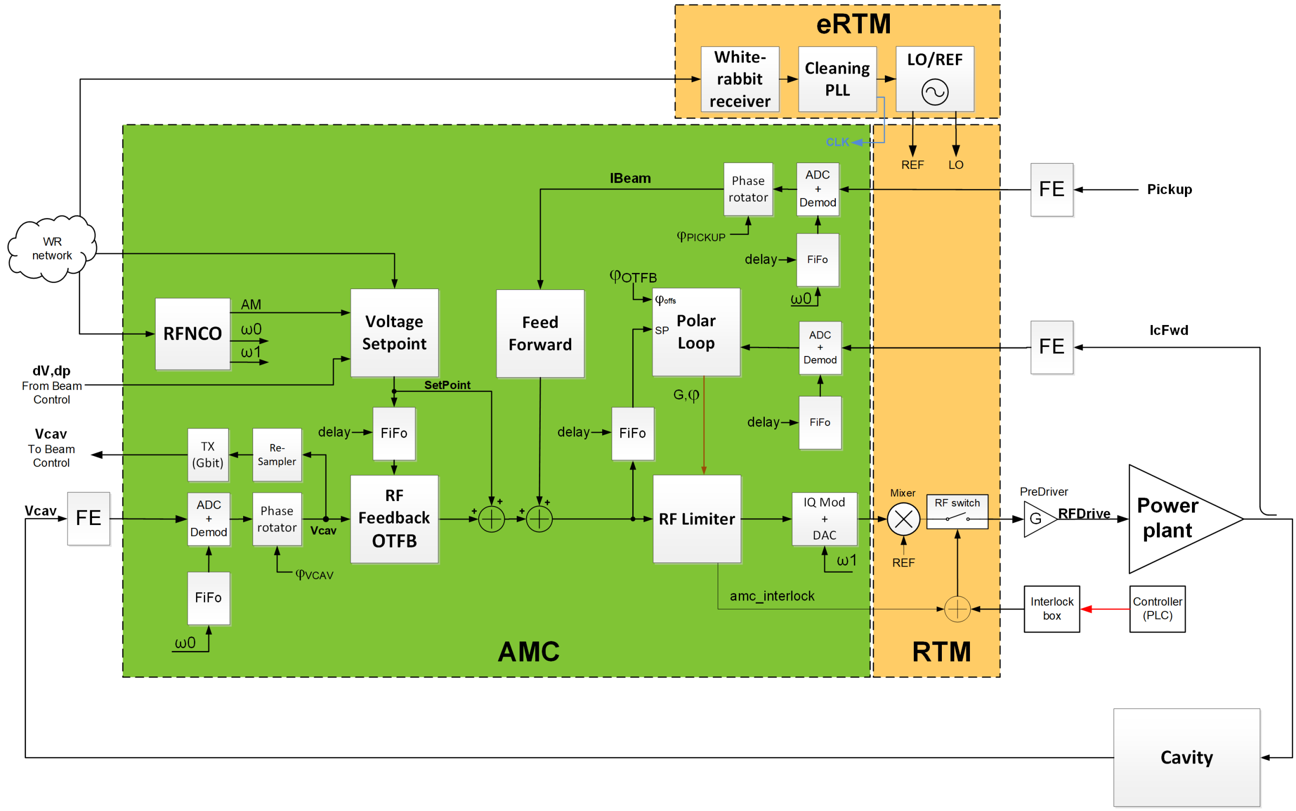

Figure 2: SPS 200 MHz Cavity-Controller.

the Beam-Control needs the voltage seen by the beam to compute the vector sum of all cavities, only the delay from the cavity to the LLRF must be compensated. Therefore, the phase rotator after the demodulator re-injects the phase shift due to the delay between the modulator and the cavity. Moreover, for FFA operation, the rotator acts as a velocity compensation phase shifter. The OTFB is switched on only after injection, one turn after the FFWD. This prevents a transient with double compensation on the second turn.

Feed-Forward

Together with the OTFB, the FFWD [7, 8] compensates the transient beam loading in the cavity. As shown in Fig. 3, it measures the RF component of the beam current from a wideband pickup. This signal is then processed by a digital filter (H_{FFWD}) to generate a drive that will best compensate for the beam induced voltage. The digital filter is implemented as a 32 taps Finite Impulse Response (FIR). The filter coefficients are calculated from the cavity model. As the demodulation is synchronous to the RF frequency ω_0 and not to the cavity center frequency ω_c, the FIR is inserted between a modulator and demodulator at $\Delta\omega_0 = \omega_0 - \omega_c$, so that the FFWD response does not change with the RF frequency.

The FFWD reuses the OTFB architecture. The FIFO depth is set to get a fraction of one turn as the azimuthal position of the pickup and the cavity are different. The variable delay keeps the compensation synchronous to the beam during the acceleration.

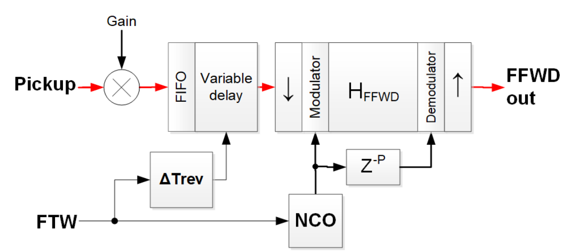

Figure 3: SPS Feed-Forward.

Voltage Setpoint

Figure 4 shows the Voltage Setpoint core. The amplitude and phase setpoint are received over the WR link from the Beam-Control with one turn granularity. This allows great flexibility for the RF gymnastics [6].

The Cascade Integrator Comb (CIC ,16 µs response) interpolates the voltage steps, thereby reducing RF peak power demand. The LD contributions (amplitude dV, phase dp) received over a dedicated point-to-point serial link, are added vectorially to the amplitude and phase setpoints. In AM operation, the amplitude setpoint is modulated by the trapezoidal waveform of the AM shaper synchronized within the turn by the RFNCO.

The CORDIC translates the setpoint (amplitude, phase) to cartesian coordinates (I,Q) before the (possible) excitation noise is added. The noise feature is used for controlled emittance blow-up [9].

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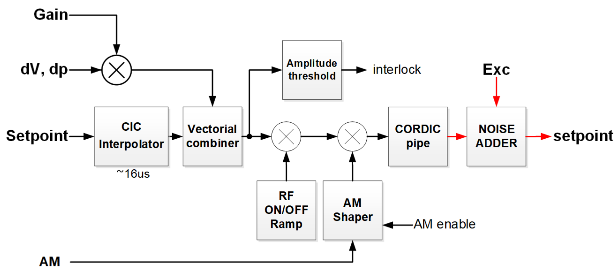

Figure 4: Voltage Setpoint.

PolarLoop

The PolarLoop (see Fig. 2), developed for the LHC RF first [10], compensates for the power amplifier drifts in gain and phase shift. It measures the cavity forward power (IcFwd) from a coupler in the RF power line and keeps it equal to the OTFB (plus FFWD) output used as setpoint. The cable and amplifier delay create a phase shift with the RF frequency. The FIFO on the IQ demodulator ω_0 cancels this phase shift so that the baseband IcFwd vector is phase invariant with the RF frequency. The gain and phase loops of the PolarLoop are switched on in the RF ON sequence before the OTFB is closed. This restores the OTFB open-loop phase in case of amplifier drifts. It also compensates for the power amplifier gain non-linearity and reduces its amplitude and phase noise, caused by the ripples in the high-voltage supply, in a small 1 kHz band.

Delay Compensation Mechanism

For 100% AM and FM operation, the feedback loops must operate only part of the turn when the RF voltage is pulsed. Inside the Cavity-Controller, the input signals to the PolarLoop and OTFB are time aligned with FIFOs on the setpoint inputs to compensate for the digital processing, cables and amplifier delays inside the loops.

HARDWARE

The 200 MHz Cavity-Controller shown in Fig. 2 is implemented on a MicroTCA platform with all six 200 MHz cavities in a single crate. For each cavity, a pair of Advanced Mezzanine Card (AMC) and Rear Transition Module (RTM) are used. The AMC hosts the analog-digital converters, one FPGA, the WR interface and the 10 Gbits point-to-point interface. The RTM receives the 200 MHz RF inputs, applies analog processing and sends the signals to the AMC for direct sampling at a fixed frequency clock of 125 MHz. After sampling, the RF appears around 50 MHz (2x125 MHz-f_{RF}) and finally it is digitally down-modulated to baseband. Before the Digital-to-Analog Conversion (DAC), the baseband RF drive is digitally up-modulated to an Intermediate Frequency (IF) around 23.5 MHz (ω_1). Then the analog IF is up-modulated back to 200 MHz with a fixed frequency local oscillator (REF) at 223.5MHz.

The RF switch is controlled by the LLRF from the FPGA and by the RF power controller (PLC) on charge of protections. The Fiber-To-Copper Interface (FTCI) converts the optical interlock received from the PLC to an electrical signal connected on the RTM.

The enhanced Rear Transition Module (eRTM) reconstructs the sampling and processing clocks from the WR serial data stream, by means of a very low noise Phase-Locked-Loop (PLL), filtering the WR master oscillator [11]. It also generates the local oscillator for the up-modulator mixer (REF) and optional down-modulator mixers (LO). The external analog front ends provide signal switching and attenuation for LLRF calibration and independent loop measurements.

RESULTS AND CONCLUSION

The new SPS LLRF was successfully commissioned in 2021 and the pre-upgrade performances were quickly exceeded. The OTFB, longitudinal damper and RF blow-up are in operation. The LHC proton beam (25 ns bunch spacing, 72 bunches per batch, bunch length below 1.65 ns) was accelerated to top energy with one batch of 1.85e11 p/bunch, and four batches of 1.4e11 p/bunch. AWAKE single bunch reached an intensity of 3e11 p/bunch and 1 ns bunch length at extraction. To achieve the target HL-LHC beam intensity of 2.3e11 p/bunch, the LLRF will exploit amplitude modulation to reach the amplifier peak power (maximum RF voltage) and the Feed-Forward.

A test Lead ion beam was also accelerated in 2021 using the fixed-frequency acceleration and the momentum slip-stacking to 50 ns bunch spacing with injected batches at 100 ns bunch spacing [5].

The SPS LLRF is the first operational system on the MicroTCA platform in the CERN accelerator complex. The problems faced during 2021 commissioning such as CPU erratic crashes, cooling issues and RF phase non-reproducibility have all been solved. The platform has shown major benefits over the former VME systems, such as a drastic increase of the bus bandwidth which allows fast and long acquisition buffers. The compactness, embedded diagnostics tools, hot-swap capability and power supply redundancy are very useful.

The LLRF architecture and the fixed frequency clocking bring a level of modularity which allows the commissioning of the Cavity-Controllers independently of the Beam-Control. The RF phase noise injected by the LLRF was a critical specified parameter for the system and no visible effect on the beam has been seen. The recovery of the sampling clock from the WR data stream has proven to achieve excellent performances.

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