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THE CERN SPS LOW LEVEL RF: LEAD IONS ACCELERATION

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Abstract

This paper is the third of a series of three on the Super Proton Synchrotron (SPS) Low Level RF (LLRF). Its focus is the upgrade concerned with the acceleration of Lead ions for injection into the LHC. Lead ions are far from relativistic at injection into the SPS. Therefore, the classic acceleration scheme at constant harmonic number (h=4620) does not work as the RF frequency swing does not fit within the cavity bandwidth. Fixed Frequency Acceleration (FFA) is therefore used. The upgraded LLRF uses a completely new implementation of the FFA, based on a Numerically Controlled Oscillator (NCO) implemented as an FPGA IP in the Controller of each cavity. In addition, the 2022 scheme for LHC ions filling calls for slip-stacking of two families of bunches, 100 ns spacing, to generate a 50 ns spacing after interleaving. The paper presents the key components for FFA and ions slip-stacking as implemented in the new system, together with successful first tests performed in Autumn 2021.

MOTIVATION

The LHC Injector Upgrade project (LIU) aims at the doubling of the total intensity of the Lead ion beam in the LHC with 50 ns bunch spacing [1]. The SPS injector (CPS) cannot provide the 50 ns spacing; the nominal scheme therefore calls for injection of several batches of 100 ns spaced bunches in the SPS and reduction of the bunch spacing to 50 ns using momentum slip-stacking in the SPS to interleave bunches from the several batches [2].

THE SPS LEAD ION CYCLE

The new SPS ion cycle for LHC filling was tested in November 2021. Figure 1 shows the cycle used: Momentum in red color (from 17 Z GeV/c to 450 Z GeV/c with a slip-stacking plateau at 300 Z GeV/c), DC beam current in yellow. The test cycle included the injection of two batches, each containing four bunches spaced by 100 ns. In 2022 the operational LHC filling cycle will include the injection of up to fourteen four-bunches batches from the CPS, with 150 ns gap between batches. The SPS flat bottom will therefore be much longer.

Fixed Frequency Acceleration

All SPS proton beams are accelerated with a fixed harmonic number h=4620. The bandwidth of the six 200 MHz accelerating cavities (Travelling Wave type) covers the required frequency range [3, 4]. With Lead ions, on the other hand, the required frequency variation exceeds the cavity bandwidth, if the harmonic number is kept constant. A solution was proposed in the late eighties and made operational, the Fixed Frequency Acceleration (FFA): Given that the beam fills less than half the circumference, and thanks to the small filling time of the cavities, we can apply 100% Amplitude Modulation (AM) during a turn with the RF ON during beam passage only. Frequency Modulation (FM) is applied in synchronism, with a fixed frequency chosen within the cavity bandwidth during the RF ON segment, and a variable frequency during the rest of the turn, adjusted to have a fixed 4620 RF periods during one revolution [5].

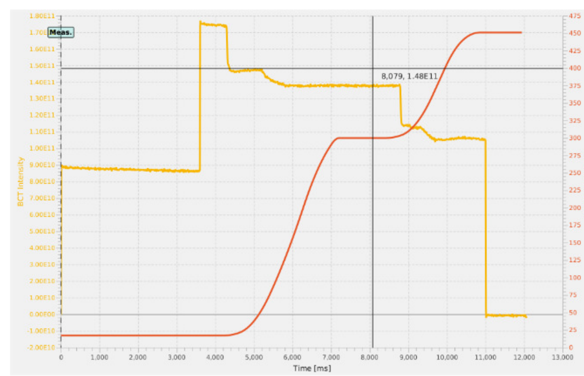

Figure 1: The SPS short ion cycle used in 2021 for setting-up momentum slip-stacking.

As explained in two companion papers [6, 7] the new LLRF architecture relies on the White Rabbit (WR) to keep the RF stations in synchronism [8]. The WR is a deterministic network, with fixed latency, distributing numerical data including Frequency Tuning Words (FTW) in our application, and providing a reset timing, at the start of each cycle. The clock of all digital electronics is recovered from the WR data stream [8, 9]. The RFNCO IP core is implemented in each station (see Fig. 2). Thanks to the WR architecture, different instances of the RFNCO will generate the exact same RF waveform at distant locations.

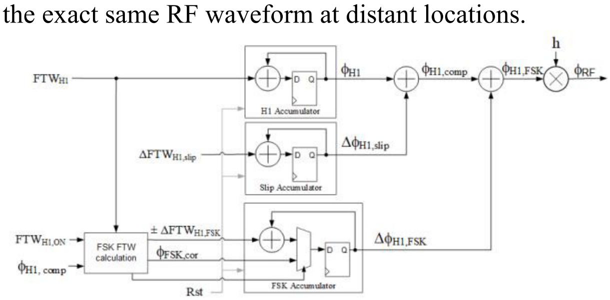

Figure 2: The RFNCO IP core.

The WR transmits the FTW_{H1} that corresponds to the revolution frequency, and the $FTW_{H1,ON}$ that encodes the RF ON frequency reduced to harmonic 1. It generates the instantaneous RF phase ϕ_{RF} (sawtooth), after multiplication by h=4620, and addition of a sawtooth $\Delta\phi_{H1,FSK}$ (for

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Frequency Shift Keying) that has a positive slope during the RF ON segment and negative during the rest of the turn. The FPGA clock is a fixed 125 MHz. Without special care this would result in an unacceptable jitter of the RF ON phase with respect to the bunch passage at each new turn. The block marked *FSK FTW calculation* computes a (small) phase correction, applied at each turn, to restore the constant RF ON phase at the bunch passage. Also indicated is the Reset signal (Rst) coming from the WR and applied at the beginning of the cycle with constant latency to all stations. Recall that the 125 MHz clock is also recovered from the WR and therefore identical at all nodes. The scheme therefore guarantees identical RF phase wave-forms $_{RF}$ at all stations through the cycle. The RFNCO also provides the toggling for the 100% AM modulation (not indicated in the figure).

The LLRF implements beam-based loops, as is classic in Hadron machines [6]. During filling (17 Z GeV/c, =7) we use a combination of Phase and Synchro loop. The RF ON frequency is set at the exact harmonic 4653 (divisible by 11) to allow locking the CPS for bunch into bucket transfer with the 1:11 CPS:SPS ratio of radii. After filling (only two injections in the test cycle of Fig. 1) and before ramping, the RF ON frequency is moved to 200.1 MHz that is the center of the 200 MHz cavity band [4]. The ramping is per-formed with Phase and Radial loop. The use of a Radial loop is classic for transition crossing.

Transition Crossing and Stabilization

With the RF ON kept at 200.1 MHz, the RF OFF frequency will increase as the average remains equal to 4620 times the revolution frequency. The two frequencies become equal at some time, before transition ($_{tr}$=22.77). From then on, the FSK is switched off (no more FM modulation) and acceleration proceeds with fixed harmonic number h=4620. But the 100% AM modulation is kept. Measurements carried out in 2018, with the old LLRF, have shown that longitudinal instability occurs after transition crossing. It was proposed to stabilize the beam with the two 800 MHz harmonic cavities [2]. The 800 MHz LLRF has been renovated in 2015, and it was not intended to use it for the ions' acceleration then. So, it cannot be used during FFA, nor during transition (fast jump of stable phase). With modifications to the firmware, we could switch it on after transition. As it will remain operational through the slip-stacking gymnastic, with two groups of 200 MHz cavities at different frequencies, we dedicate one 800 MHz to each group and regulate its phase to the vecto-rial sum of the corresponding three 200 MHz cavities. Fig-ure 3 shows the bunch peak line density from the start of the acceleration ramp to the end of the 300 Z GeV/c plateau where the beam was dumped during this test. The spike marks the transition crossing. Signs of instability are clearly visible thereafter. Comparing the red and blue traces we see that the resulting peak line density after tran-sition is almost doubled with the 800 MHz ON. This is in good agreement with the simulations [2].

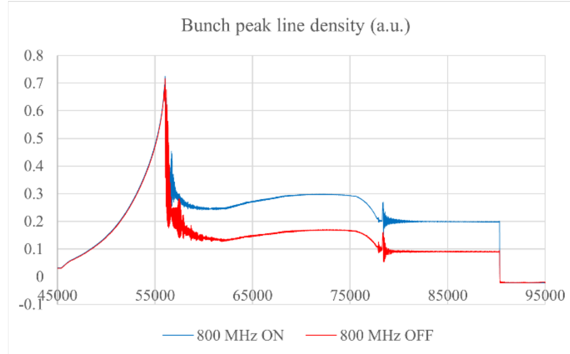

Figure 3: Stabilization after transition crossing. Bunch peak line density without (red) and with 800 MHz (blue).

Momentum Slip-Stacking Plateau

Upon arrival on the plateau, we switch the Radial loop OFF and replace it with the Synchro loop, to keep precise registration of the phase of the two beams during the slip-page [6]. We now have one phase loop per beam, looking at the relevant bunches only. To identify these, we use a bunch mask per beam, that is continuously updated to dis-regard overlapping locations [6]. Figure 4 shows the four successive steps. It displays the bunches of the two beams (blue and red) in momentum versus time. At the top we have the situation when arriving at the plateau, with 100 ns between bunches. As indicated by the arrows the blue beam is pushed towards the positive momentum while the red beam sees its momentum reduced. That results in the situ-ation on the second trace. The slippage is piloted by the RFNCO (Fig. 2): The frequency offset $FTW_{H1,slip}$ is re-ceived from the WR frame and will create the two RF fre-quency bumps (in opposite directions).

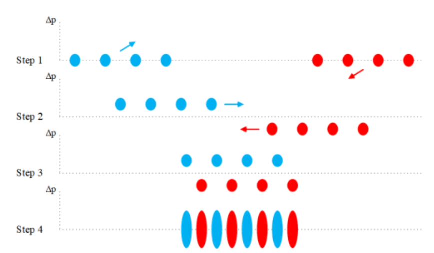

Figure 4: The steps of slip-stacking from top to bottom.

Figure 5 (top) shows the AM modulation before slip-stacking starts. All cavities are pulsing in synchronism, during (almost) half the turn, providing a 9000 ns long flat portion well sufficient for both beams (3000 ns maximum per beam and a 2000 ns gap in between).

To ensure a stable motion of the bunches inside their buckets we need to minimize the perturbation from the other unsynchronized group of RF cavities. The closer the two beams are in frequency (energy) the stronger the per-turbation is. We therefore need to take extra care at the be-ginning of the slip-stacking process when we start to sepa-rate the two beams (step 1 in Fig. 4). For that reason, am-plitude modulation on the two groups of RF cavities is ap-plied during the slip-stacking process: Only one group is switched on when the corresponding beam passed by

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(Fig. 5, bottom two traces).

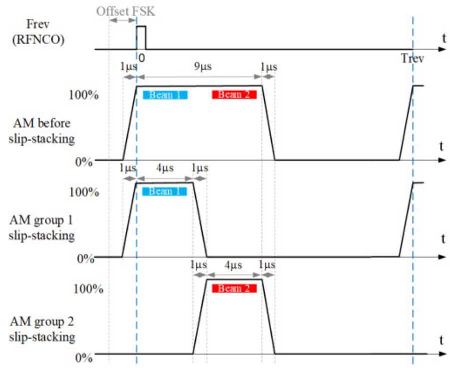

Figure 5: AM modulation before and during slip-stacking.

The two beams now drift closer as they follow opposite frequency bumps (step 2 in Fig. 4) and will eventually superpose partially. But the energy separation is now maximal, set at a value that minimizes the disturbance between the two buckets. The second group of cavities is invisible [2]. Overlap is not a problem for the Beam based Phase loop either, thanks to the masking policy: We disregard the buckets where the Pick-Up signal contains disturbance from the other beam. The Beam Control contains two RFNCOs, configured to track the two beams. When the dif-ference is equal to 50 ns (ten RF buckets at 200 MHz), it sends a trigger, via the WR, that nulls the frequency bump and rises the voltage, thereby merging the buckets of the two groups of cavities [6] (steps 3,4 in Fig. 4).

Ramping up to 450 Z GeV/c

The acceleration from 300 Z GeV/c to 450 Z GeV/c pro-ceeds with Synchro and Phase loop active. The Phase loop now includes measurements from all bunches. On flat top the beam is rephased to the LHC references and extracted.

RESULTS

Figure 1 shows the results achieved with a test cycle in November 2021. Refer to the DC beam current (yellow trace). We have two injections of a four-bunches batch with 100 ns spacing (in each batch). We lose about 15 % of the intensity at the start of the ramp, due to capture losses. An-other 5% is lost in the first portion of the ramp at transition crossing. After the 300 Z GeV/c slip-stacking gymnastic we lose another 15% caused by the insufficient RF voltage. The RF cavities had been moved out of the tunnel, opened, and re-installed during the 2019-2020 shutdown. In 2021 re-conditioning was very lengthy. In addition, two stations (TX-Cavity) were limited in power due to arcing in the power lines. The cause was discovered during the 2021 End-of-Year break only. It has now been cured. So, we are confident that performances will improve in 2022 as addi-tional voltage will be available.

Figure 6 shows the time evolution of the individual bunch intensity. Each horizontal trace plots bunch intensity in a portion of a turn (6.25 µs). Cycle time runs Cycle time run from top (injection) to bottom. At the top left we see the injection of the first batch of four bunches. Then, 3.6 seconds later, the second batch is injected with a 5000 ns turn offset. During the slip-stacking we see the two beams moving closer until the bunches are interleaved resulting in eight bunches spaced by 50 ns. Although some intensity is escaping, due to the insufficient voltage when merging the buckets (step 4 in Fig. 4), the implementation works.

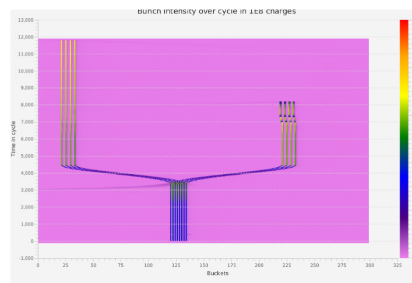

Figure 6: 2-D color-coded plot of the beam intensity. The horizontal axis is the position in the turn (samples spaced by 25 ns), the vertical axis is the cycle time with injection at the top.

CONCLUSIONS

Little time (two weeks) was available in 2021 for the test cycle. Yet the results are very encouraging: The upgraded RF has proven capable of all gymnastics required to produce the 50 ns bunch spacing. The fixed latency RFNCO, together with the WR link, allow for precise complex RF phase and amplitude manipulations as required for FFA and slip-stacking. In 2022 more RF voltage will be available and transmission will improve. The first ions will be available to the SPS on October 3rd. We then have three weeks to make the cycle operational in the SPS, followed by two weeks when ions will not be available. We must be ready for the LHC ions transfer with 50 ns bunch spacing on Nov 10th.

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