BUNCH-BY-BUNCH PHASE PICK-UP SYSTEM IN THE SPS

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Abstract

As part of the High-Luminosity LHC (HL-LHC) project, the Super Proton Synchrotron (SPS) Low-Level RF (LLRF) system has undergone a major upgrade during the machine shutdown in 2019-20 to meet the performance requirements of the LHC ion program and high-intensity proton beams. A key development in this context is the implementation of a bunch-by-bunch measurement chain, designed to provide high-resolution diagnostics and bunch-by-bunch phase feedback capability.

This tool is particularly valuable for the ion slip-stacking RF manipulations where precise bunch-masking is required. In addition, it serves as a diagnostic tool to investigate beam loading effects by directly comparing the cavity voltage with the phase evolution of individual bunches. The system is implemented on the MicroTCA platform and employs 5 Gsps digitization of the beam signal from a wall current monitor (WCM).

This paper presents the operational results and commissioning challenges of the new acquisition and phase loop system.

INTRODUCTION

The SPS LLRF upgrade for the HL-LHC era aims to support increasingly demanding beam conditions, including high-intensity proton beams and complex ion manipulation schemes such as slip-stacking. These scenarios impose stringent requirements on longitudinal diagnostics and feedback systems.

The operational narrowband phase measurement system, based on a 200 MHz resonant pick-up and undersampling at 125 Msps, provides averaged phase measurements but lacks the temporal resolution required to resolve individual bunch dynamics.

To address this limitation, a wideband bunch-by-bunch acquisition system has been developed, based on direct digitization at 5 Gsps of a WCM signal that provides the longitudinal bunch profile of the ~3 ns long bunches.

The wideband system overcomes the ~100 ns time constant limitation of the narrowband system, which averages over multiple bunches for 5 ns or 25 ns spacing. However, for low bunch count beams, the absence of resonant averaging reduces phase sensitivity.

It also improves the bunch mask resolution, which is essential for ion slip-stacking operations [1], allowing both phase loops to remain active during ion beams overlap.

Additionally, the system increases the effective bandwidth of the longitudinal damper, now limited primarily by the RF cavity response (~2 MHz).

As a diagnostic tool, it enables:

- Observation of longitudinal instabilities (dipolar and quadrupolar), bunch-by-bunch and turn-by-turn
- Direct comparison of beam phase and cavity voltage
- Improved time-alignment of signals from cavities and pick-up

SYSTEM IMPLEMENTATION

The wideband phase acquisition system is implemented on a MicroTCA platform using an AFCZ board (Ultrascale+™ MPSoC) and Vadatech® FMC217 mezzanine board, synchronized via White Rabbit. The beam signal is acquired from a WCM and digitized at 5 Gsps, with 12 bit resolution. It integrates with the Beam-Control LLRF [2]. The phase and amplitude of the 200 MHz RF component of the individual bunch profiles are transmitted over a 10 Gigabit link, as shown in Fig. 1.

Signal Processing

Phase extraction is performed using a custom FFT algorithm. Only the complex bin corresponding to the RF frequency is computed, equivalent to IQ demodulation but optimized for parallel processing.

The input stream is sliced into 32-sample windows centered on each bunch using a beam-synchronous Numerically Controlled Oscillator (NCO) interpolated to the 5 Gsps data rate. The data is tagged such that the first bunch can be detected and synchronized. For additional details on the signal processing and hardware, refer to [3].

For ion slip-stacking, the processing chain is duplicated to track two RF systems running at different frequencies during a part of the cycle. To merge the two streams, two FIFO interfaces store the samples arriving at different rates, while the read logic waits for data to be available on both channels. A multiplexer selects which RF system a bucket belongs to. The output stream is then used by the two beam-phase loops, which average on their respective bucket ranges. Figure 1 shows the data-flow.

COMMISSIONING CHALLENGES

Calibration and Delay Compensation

The signal propagation delay of 1.4 us between the pick-up and the ADC introduces frequency-dependent phase shift. This must be compensated prior to slicing to maintain alignment with the bunch profile. The phase shift is automatically compensated by the RFNCO, which computes a phase correction in real time using the instantaneous RF frequency.

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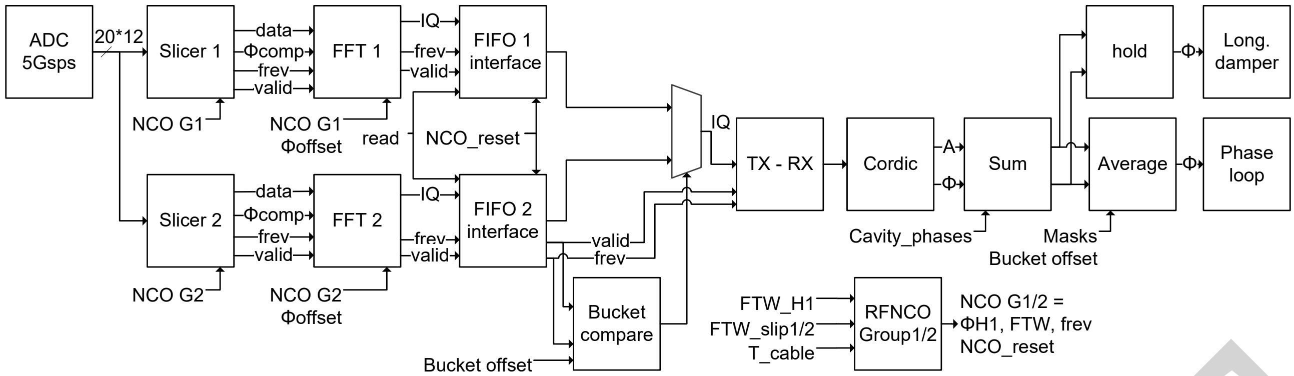

Figure 1: Overview of the bunch-by-bunch acquisition and processing system.

Ion Cycle Issues

During ion acceleration, RF frequency modulation within a turn introduces phase discontinuities due to the fixed-clock NCO. This can lead to de-synchronization of the slicing process if an additional bucket is falsely detected.

As a cure, an algorithm has been implemented to detect such events. While this proved effective in the laboratory, in operational condition, a slow drift of the bunch position with respect to the revolution marker was still observed. This might be due to additional perturbations in frequency.

The stability of beam phase-loop and synchro-loop is also affected by the difference of their respective processing latencies. While stable configurations exist for narrowband and wideband systems independently, switching between them during operation is challenging. To use the wideband system only during the slip-stacking phase (and avoid the previously mentioned issue), a delay of a turn must likely be added to one processing chain only.

Adaptation for Longitudinal Damper

The SPS longitudinal damper acts via phase modulation of the accelerating cavities. Its bandwidth is around 2 MHz. Since the wideband system produces phase values for filled buckets only, a hold mechanism was implemented to maintain compatibility with the narrowband system, see Fig. 2. The phase value is held for 50 buckets or until a change, to match the behavior of the narrowband chain.

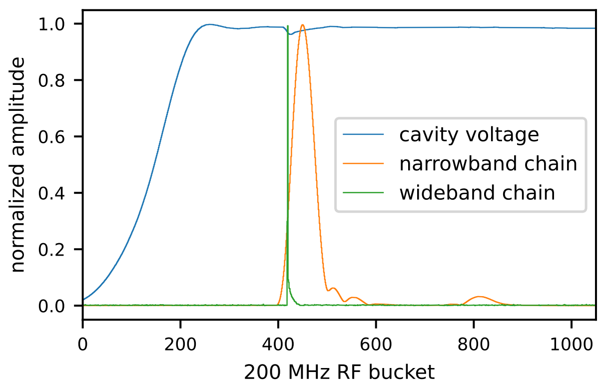

Figure 2: Comparison between wideband and narrowband systems with a single bunch.

Windowing Effects

The FFT is computed bunch-by-bunch with 32 samples per bunch at 5 Gsps. This 6.4 ns window slightly exceeds the 200 MHz RF bucket length. This has no detrimental effect for LHC beam with bunch spacing of 25 ns or more. For fixed-target beam with 5 ns bunch spacing, a too large window creates a phase error due to bunch leakage. Zero-padding can be applied to reduce edge effects. Figure 3 shows the sampled pick-up signal on which the window is applied.

Applying a windowing function (e.g., Tukey) could further improve phase accuracy by reducing bunch leakage and distortions due to non-zero window edges.

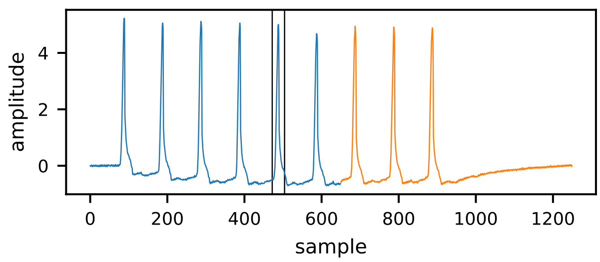

Figure 3: Bunch profile sampled at 5 Gsps. Only the first (blue) and last (orange) bunches of a batch are displayed. The black lines show the 32 samples wide window.

RESULTS

The system has been successfully commissioned in the SPS.

The results demonstrate:

- Good agreement with our most accurate measurement performed with a 10 Gsps oscilloscope and offline analysis. Figure 4 shows a comparison of the bunch-by-bunch phase measurement from the two systems, where the phase discrepancy does not exceed 3 degrees at RF (42 ps). The measurements are superposed with the cavity voltage measured by the LLRF. The cavity phase is subtracted from the bunch phase for the phase loop.
- Enhanced diagnostics, available for all bunches, through the cycle and without complex configuration. A typical acquisition is shown in Fig. 5.

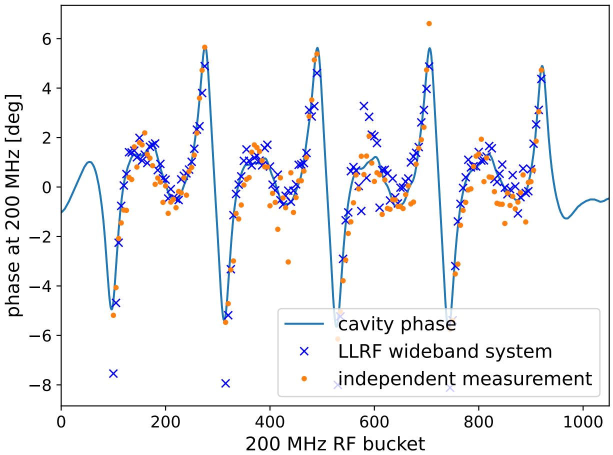

Figure 4: Bunch-by-bunch phase compared to cavity voltage and an independent measurement. Train of 4x36 bunches with 1.6e11 protons per bunch, 25 ns bunch spacing.

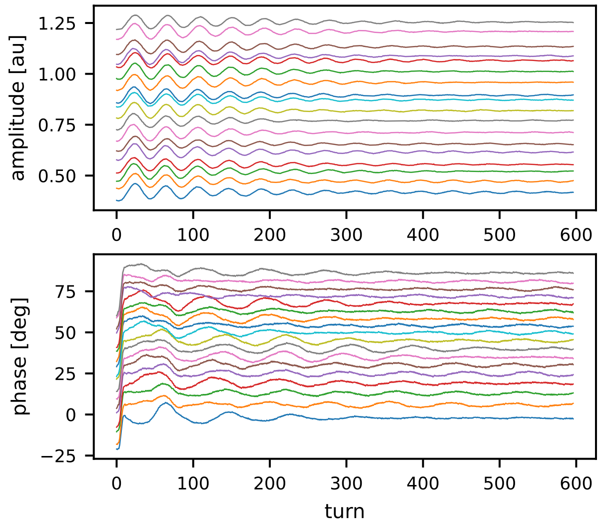

Figure 5: Bunch-by-bunch amplitude and phase variation at injection, caused by quadrupole and dipole oscillations respectively. 16 out of 36 bunches from the batch are shown, translated in amplitude and phase for display purpose.

- Accurate bunch-by-bunch phase measurement, with an increase of the broadband noise by 10 dB for a single bunch beam compared to the narrow band system. Preserved phase noise within the SPS synchrotron frequency range (200 Hz to 2 kHz). The bunch-by-bunch chain uses a 2 GHz BW pick-up and direct sampling at 5 Gsps. The narrowband chain uses a resonant pick-up (~2 MHz BW) followed by an analog band-pass filter of 4 MHz bandwidth. The noise band affecting the two systems are therefore much different: around 200 MHz for the wideband and 2 MHz for the narrowband system. This explains the more noisy phase detection (Fig. 6).
- Enhanced time-resolution compared to the narrowband system, useful for the calibration of feedback loops and year-by-year reference for injection alignment.

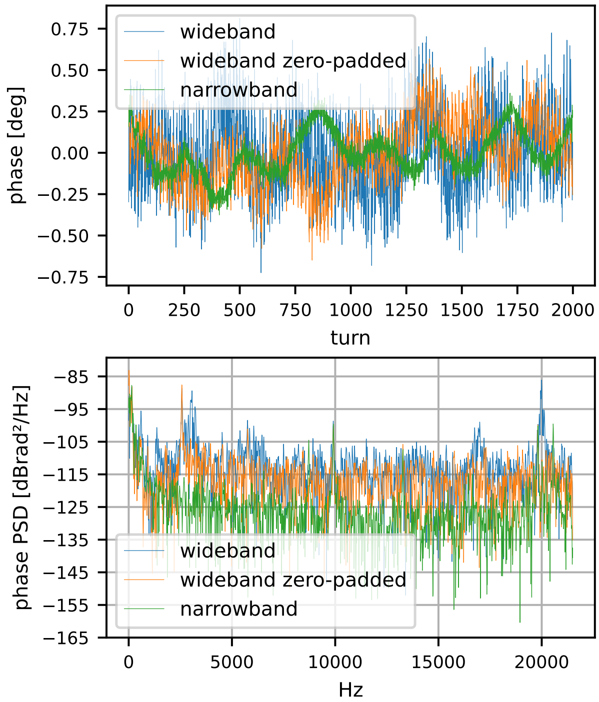

Figure 6: Phase loop error signal for a single bunch beam and the associated power spectral density. The sampling rate corresponds to the SPS revolution frequency of 43 kHz.

CONCLUSION

A wideband bunch-by-bunch phase measurement system has been successfully developed and deployed in the SPS LLRF framework. The system significantly enhances diagnostic capabilities and enables advanced beam control strategies required for HL-LHC operation.

With the growing availability of fast sampling ADCs and RF System on Chip (RFSoC), highly parallel processing becomes necessary. The approach presented can be adapted to a wide range of operating frequencies and constraints.

Remaining challenges include improving robustness for ion cycles, particularly regarding latency control and RF frequency modulation effects.

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