Beam-based measurements in the CERN SPS LLRF

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SPS Upgrade LIU Project

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Abstract

The accurate measurement of beam phase is of utmost importance for optimizing beam control and performance in the CERN Super Proton Synchrotron.

We have three phase pick-ups (PUs) chains in the SPS LLRF:

- The first two chains use PUs resonant at the RF frequency, followed by bandpass filtering to optimize signal to noise ratio. One of these two chains has 20 dB additional gain and is used for beams with very low local intensity
- The third chain (still under development) will provide 5 ns spaced bunch-by-bunch phase measurement. It utilizes a high-speed 5 Gsps ADC and a wideband PU system to monitor individual bunches.

The Beam-Control module receives data streams from these three PU processing chains and seamlessly switch between them if needed during a machine cycle.
This combination of features proves particularly valuable for scenarios such as ions slip-stacking [1], where two beams are independently controlled within the same ring, and for fixed target ions, where an amplified pick-up is employed after de-bunching.

SPS LLRF Architecture

The RF signal processing and the clocks are synchronized within the LLRF system, using the White Rabbit (WR) technology. Hence, signals sampled by different MicroTCA modules can be multiplexed depending on beam types [2,3].

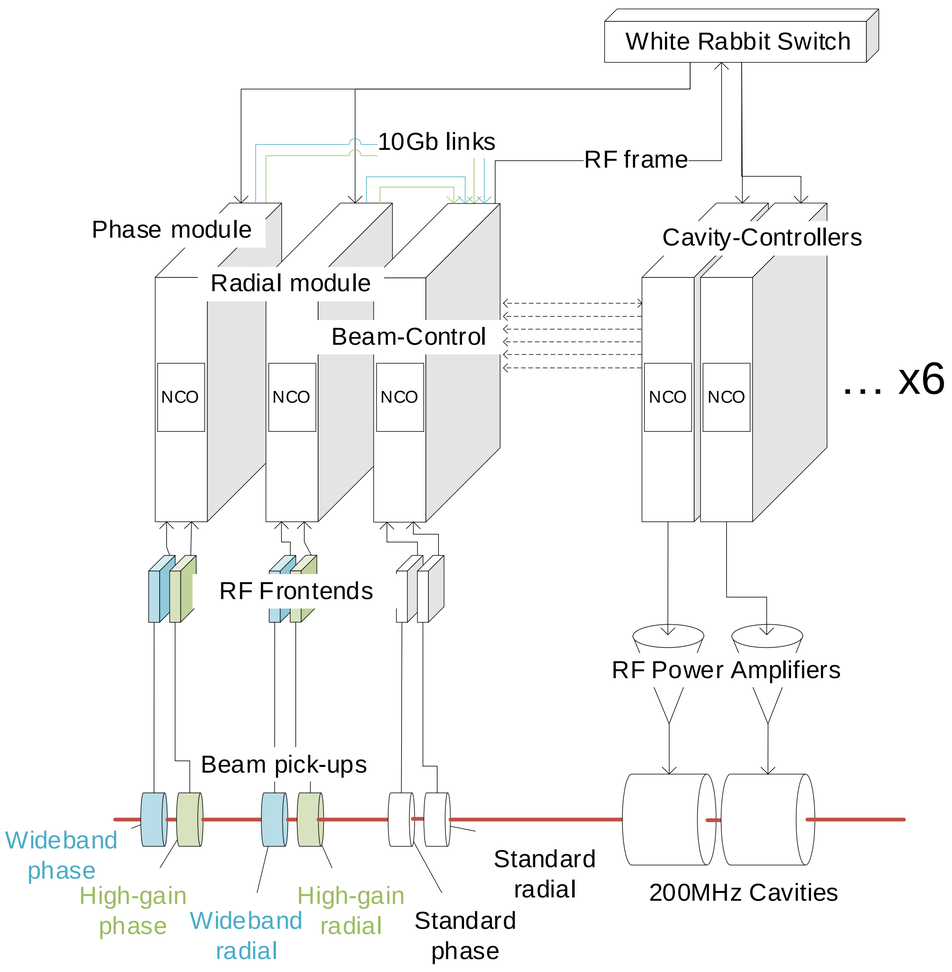

Figure 1 – The Beam-Control module receives digitized beam pick-up signals and cavity voltages via 10 Gb links. It then computes the beam-based loops and frequency program that is transmitter over WR.

5 Gsps bunch profile

The wideband pick-up chain was installed and commissioned for the first time in 2023. The 5 Gsps sampling rate provides ~25 samples per 5 ns bucket.
The bunch phase is extracted by windowing the signal around the bucket and processing an RF-synchronous FFT [4,5]. This requires a high level of parallelization in the FPGA.

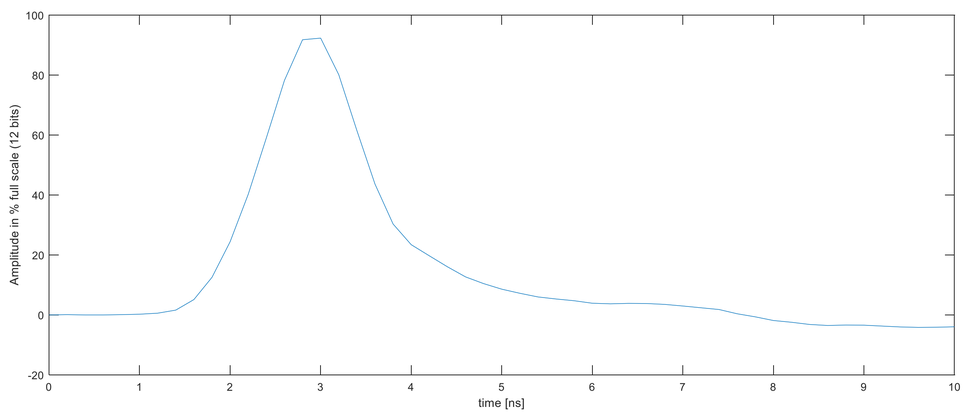

Figure 2 – 5 Gsps acquisition of a proton bunch, 2.8e11 particles per bunch. The longitudinal pick-up bandwidth is 2.5 GHz.

Beam-phase module & synchronization

The Beam-Control module receives two streams of bunch-by-bunch IQ data (200 Msps) from the Beam-Phase module. The synchronizer retrieves the revolution marker (frev) in the streams and aligns the data for further processing. The source (pick-up selection) can be changed during a machine cycle using timings.

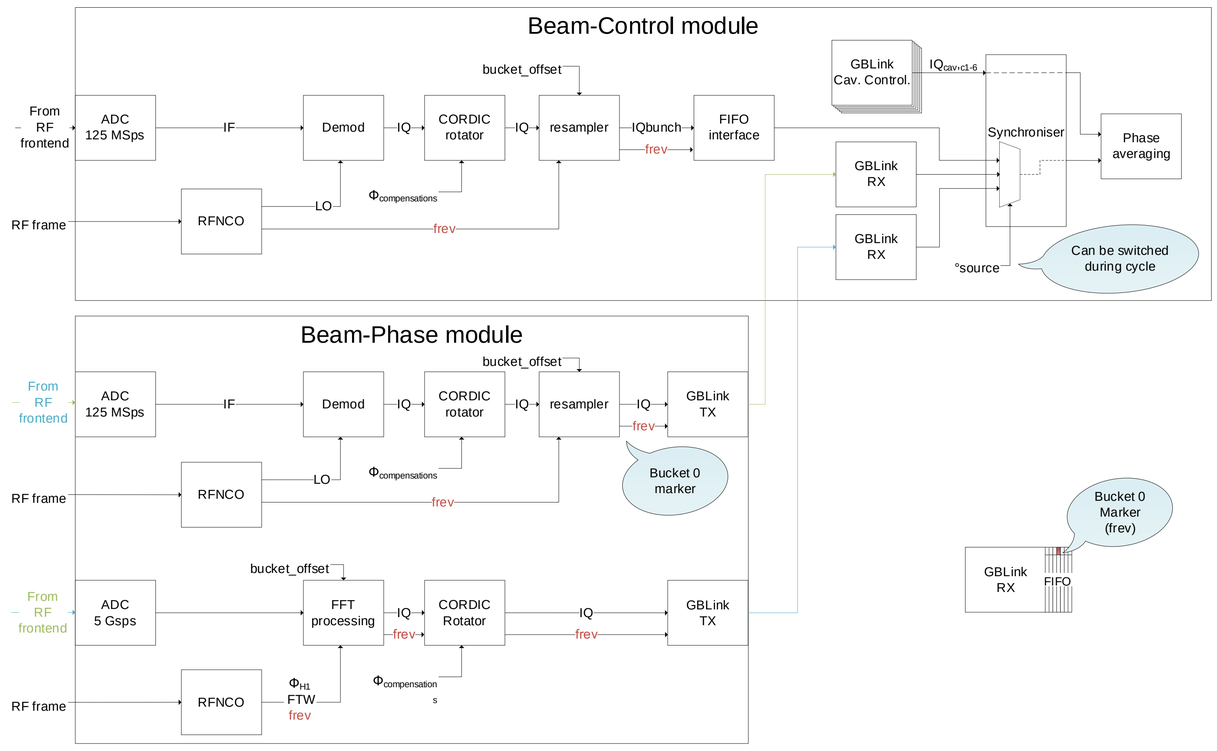

Figure 3 – Signal flow from the Beam-Phase module to the Beam-Control. The bunch-by-bunch data is transmitted over Gblink, a custom protocol that includes the bunch 0 marker.

High-gain / Wideband chains applications

To provide a uniform spill to Lead ions fixed target experiment, a debunching and recapture procedure is applied. The High-gain chain is necessary to compensate for the loss of intensity per bunch (from 4 to 4620).

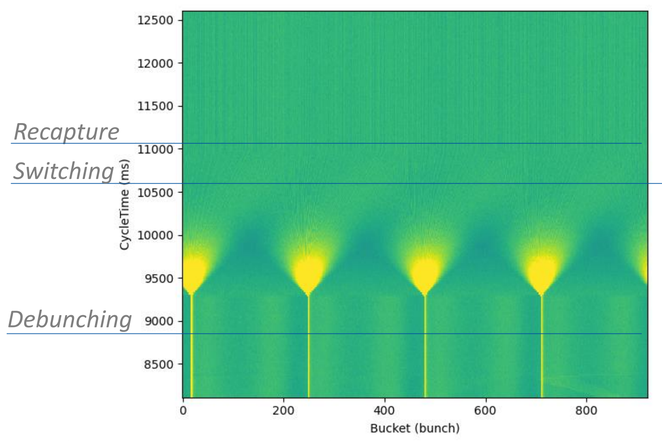

Figure 4 – Debunching and recapture observed with a beam current transformer

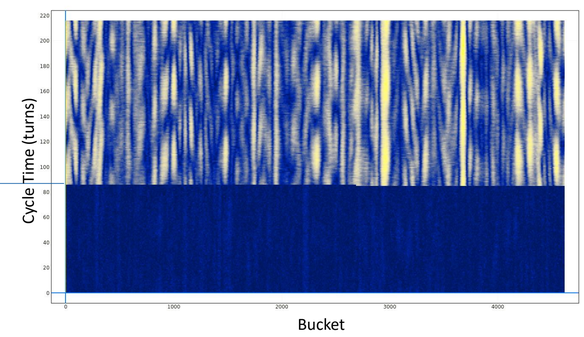

Figure 5 – Bunch-by-bunch amplitude when switching to High-gain pick-up. The longitudinal resonant pick-up has a bandwidth of 3 MHz followed by a band-pass and amplifier. This results in an averaging over a hundred of buckets.

The wideband chain will improve manipulations such as slip-stacking, where a precise masking of individual bunches is necessary.

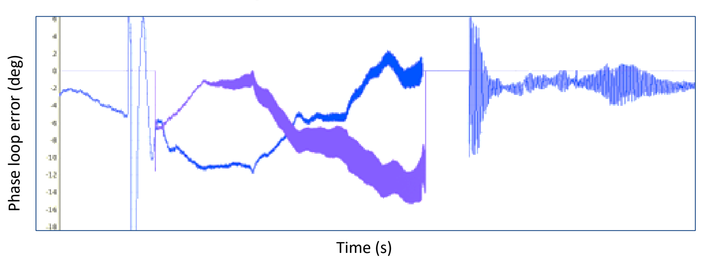

Figure 6 – Phase loop error during slip-stacking using the resonant PU. When beam 1 (blue) gets longitudinally closer to beam 2 (purple), the response of the narrowband PU (500 ns) is polluted by the passage of the other beam. The use of bunch mask improves the situation until there is almost complete overlap and phase loops are then switched off.

Hardware

The Beam-Phase and Radial modules are based on a MicroTCA Advanced Mezzanine Carrier (AMC) with a Zynq UltraScale+ (AFCZ). Two FMCs are attached and a rear Transition Module (RTM) that supports the 10 Gbps links and WR connectivity.

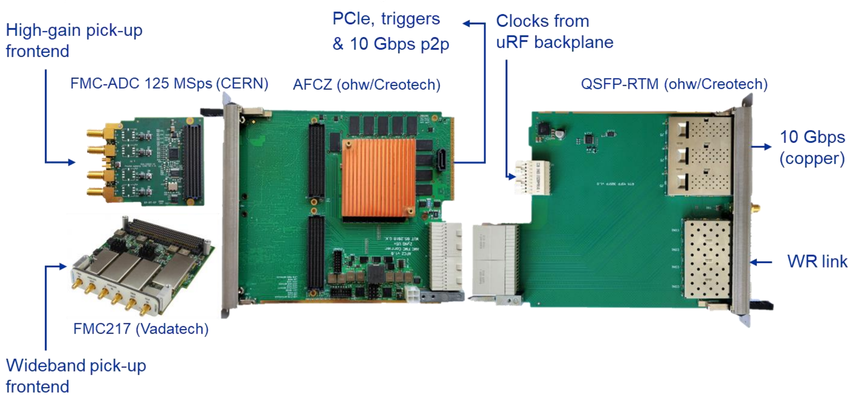

Figure 7 – The three boards (Beam-Control, Beam-Phase and Beam-Radial) sit in the same MicroTCA crate. The backplane point to point and SFP+ links are used to transmit the high-gain and wideband data streams respectively.

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[1] The SPS LLRF Upgrade: Lead ions acceleration, P. Baudrenghien, IPAC2022
[2] The SPS LLRF Upgrade: The Beam Control system, A. Spierer, IPAC2022
[3] The SPS LLRF Upgrade: The Cavity Controller, G. Hagmann, IPAC2022
[4] SPS bunch-by-bunch phase measurement with µTCA AFCZ FMC, R. Borner, LLRF2022, Switzerland
[5] SPS bunch-by-bunch phase measurement in the CERN SPS Low Level RF, R. Borner, IPAC2023