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NEW GENERATION OF VERY LOW NOISE BEAM POSITION MEASUREMENT SYSTEM FOR THE LHC TRANSVERSE FEEDBACK

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Abstract

Recent studies showed that the transverse feedback system noise floor in the Large Hadron Collider (LHC) must be reduced by at least factor of two in order to operate the machine with large beam-beam tune shift as foreseen in the High Luminosity (HL) LHC. Also, the future feedback system foreseen to suppress the LHC Crab Cavity noise relies on improved noise performance of the beam position measurement system. An upgrade program was launched to lower the LHC transverse feedback system noise floor during the LHC Long Shutdown II. A new generation, very low noise beam position measurement module was developed and tested with beam. Innovative methods in the RF receiver, digital signal processing, thorough optimization of every element in the signal chain from pickup to the kickers allowed to achieve a significant reduction of the system noise floor. This unprecedented noise performance opens also new possibilities for auxiliary instruments, using the position data from the transverse feedback. The paper presents the new system, notable implementation details and measured performance.

TRANSVERSE FEEDBACK IN LHC

The Large Hadron Collider (LHC) relies on a transverse feedback (TFB) to suppress coupled bunch instabilities and to damp injection oscillations conserving the injected beam emittance. Apart of these primary functions, the TFB in the LHC provides a large number of auxiliary functions, for example all kinds of beam excitation for abort and injection gap cleaning [1, 2], controlled transverse emittance blow-up for aperture and collimation measurements [3], or controlled transverse losses for special measurements [4].

During LHC Run I, the LHC TFB system started to provide very valuable bunch-by-bunch, turn-by-turn beam position data for diagnostics purposes. The data quickly became the second most important ”commodity” delivered by the transverse feedback. A high performance computing system, called ADTObsBox was introduced [5] to collect and analyze these data in real time, allowing for example a real time detection of transverse instability onset, assisted tune measurements, collimator impedance measurements and many more. The beam position measurement quality is equally important also for this secondary application.

The beam position is sensed by four stripline type pickups in the arc around LHC point 4. Symmetrically at both sides of the former interaction point. The pickups are referenced as Q9 and Q7 (by the quadrupole magnets they belong to), Q8 and Q10 respectively. Signals of both pickup electrodes (referenced as electrode A and B) are transported to the surface. A and B signals are combined by a 180-degree, hybrid coupler to produce the analogue Σ and the delta Δ signals. These raw, impulse like signals are then feeding the Beam Position Measurement module (BeamPos), which downconverts and digitizes them. A normalized bunch position is calculated digitally by a field programmable gate array (FPGA). One data point per bunch per turn is sent over an optical link to Digital Signal Processing Unit where all feedback related calculations are performed. An analogue correction/excitation signal is sent back to the tunnel, amplified by tetrode amplifiers to a peak amplitude of up to 10 kV and fed to electric field kickers.

PERFORMANCE OF THE OLD SYSTEM

Though the TFB performance during the LHC Runs I (2009-2013) and II (2013-2018) was greatly sufficient for the LHC operation, recent studies showed that the TFB noise floor in the LHC must be reduced by at least factor of two in order to operate the machine with large beam-beam tune shift as foreseen in the High Luminosity (HL) LHC [6] and suppress the risk of loss of Landau damping by noise [7]. Improvement by factor of 4 is required to recover an emittance growth rate in the order of 2% per hour as in the present LHC. Also, the future feedback system foreseen to suppress the LHC Crab Cavity noise in HL-LHC [8] relies on improved noise performance of the upgraded TFB.

With the majority of the signal processing chain of the LHC TFB being digital, the beam position measurement subsystem is considered to define the noise performance of the whole LHC TFB system, therefore the effort to lower it focuses on improving the beam position measurement subsystem. The noise floor of the TFB system can be determined only indirectly: either beam based by measurement of transverse emittance blow-up [6], or by analysis of the beam position measurement hardware [9].

For latter, a complete numeric model of the receiver and the signal processing chain was constructed. The model was fed by a noiseless input signal corresponding to a full scale bunch position. Then a real BeamPos module in LHC was set to nominal operating conditions, but without beam and noise from the analogue to digital converters was measured. The signal was superimposed to the ideal position data and processed by the model. Distribution of the measured position was recorded.

Noise floor of the LHC TFB beam position measurement system used in the Run I/II was found to be 1.03-1.40 μm_{RMS}, depending on pickup, settings and operating conditions.

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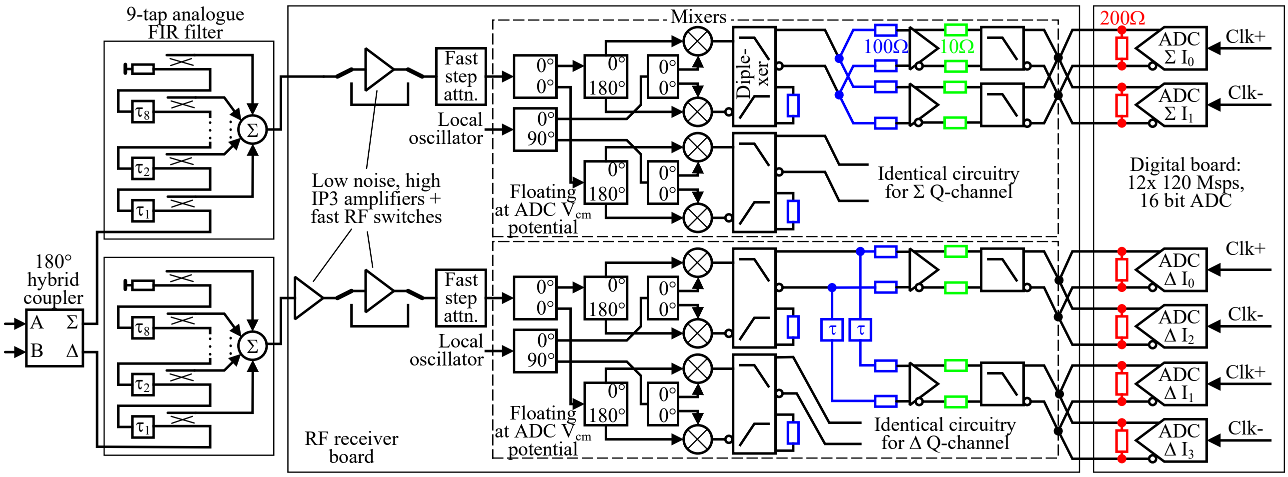

Figure 1: Diagram showing the new receiver topology, with important sub-circuits which influence the overall noise performance. Black lines are 50 Ω characteristic impedance, blue elements and lines are 100 Ω.

NEW BEAM POSITION MODULE

The Beam Position Measurement module used by LHC TFB for Runs I and II [10] was developed within the first large scale digital low-level RF project at CERN, circa 2006. Very little was known about how could it be used beyond the basic feedback loop functionality, or what should be the optimal electrical parameters. No special optimization was done for noise performance, or operational flexibility at the time. For development of the new Beam Position Module, the noise performance and the operational flexibility were the primary design parameters. Thermal stability, or accuracy of absolute position measurements are not of a large concern. A multi-domain simulation model of the complete system was created starting with the beam-pickup interaction (Particle studio), transmission line system and signal processing in the RF domain (Microwave office), downconverters and intermediate frequency amplifiers (SPICE), digitization, noise and digital signal processing (Python).

Four different position measurement methods, compatible with the existing system were evaluated:

1) direct sampling of the A and B signals by high speed digitizers. The pickup electrode signals are typically a 1 ns long pulses with not more than a 2 dB difference in amplitude for a full scale bunch position movement. Effective number of bits (ENOB) of currently available multi-Gsps digitizers is too low for our application.

2) direct sampling of a band-pass filtered A and B signals by high resolution, medium speed digitizers. At the time of development, state of the art analogue to digital converters were delivering 13-14 bits ENOB, at a sampling frequency of low hundreds Msps. Noise performance of this method was found to be about the same as the old system.

3) direct sampling of a band-pass filtered Σ and Δ signals by high resolution, medium speed digitizers. The bunch repetition frequency in LHC is 40 MHz. Convenient frequencies to measure would therefore be integer multiples of the bunch repetition frequency, e.g. 200, or 400 MHz. The LHC TFB uses a bunch synchronous sampling and data processing. Convenient data rates would be 40, or 120 MHz. Theoretical analysis of this option showed, that if a 200 MHz wavelet is generated by the analogue FIR filter, and it is sampled at 240 Msps, an improvement of noise floor of factor of 2 to 3 might be in reach. This option was implemented and successfully tested in LHC towards end of Run II [11]. Though the method was successfully tested, the aim of the upgrade project was to obtain the best possible noise performance with the technology available to date.

4) continue using the super-heterodyne principle and high resolution, medium speed digitizers similar to the old beam position measurement system, but "super-optimize everything possible". Every component of the signal chain was modelled, or measured, thoroughly analyzed and optimized for the ultimate noise performance. It was possible to connect up to six, 16-bit, 125 Msps dual analogue to digital converters (ADCs [12]) to the Artix7 FPGA used by the LHC TFB modules, setting the baseline for this option.

New Concept of a Fully Differential RF Receiver

The new generation beam position measurement module [13] [14] profits from a high signal power available from the pickup. Ideally the whole signal chain from the pickup to the ADC could be completely passive. This required development of a fully differential, quadrature RF receiver. The result is shown in Figure 1. The wavelet forming analogue FIR filter was designed as a fully fused, 4-layer printed board made on microwave substrate. A very tight electrical parameter control was possible, all 40 produced filters were identical without any need of tuning. Broad side coupled directional couplers with progressively increasing coupling extract most of the energy at the frequency of interest (400 MHz) from the through line, forming a 9-RF period wavelet with very clean and flat impulse response. ADCs typically use a differential input, we have designed the whole RF receiver as fully differential to use all the available signal power.

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The input RF signal is split to 0°/180° (differential) components and downconverted by two Level 13 mixers using a local oscillator signal split to 0°/0° (common mode). High LO-IF isolation of the mixer, together with the common mode rejection of the IF amplifier and the ADC suppresses the LO leakage below the ADC resolution. The main noise contribution comes from the IF amplifier. Thanks to available high IF output voltage from the mixers, its gain could be kept at the very minimum (3-6 dB), contributing not more than 0.5 LSB (least significant bit) to the ADC noise floor.

Majority of the RF receiver is floating at a common mode potential of ADC (0.9 V) to prevent back-biasing of the mixers through the differential IF amplifiers. Many "analogue" tricks are implemented in the new receiver allowing to form e.g. delay lines, pulse responses, or IF amplifier paralleling with the aim not to waste any signal power in termination resistors.

Interleaved Sampling and ADC Noise Floor

Each of the IF signals is sampled by multiple ADCs. The Δ signal is unique for each bunch and each passage, so we have to treat it as a single shot phenomena. Four interleaved ADCs are used to sample it at a total rate of 4x120=480 Msps. Two of the ADCs are drive by non-inverted and the other two by inverted clock. A further interleaving is obtained by time-delaying two of four input analogue signals by quarter of a sampling period. The Σ signal is not expected to change much withing few turns, so only two ADCs are used providing a sampling frequency of (240 Msps). More Σ samples can be acquired from successive turns and averaged. A total of 12 ADCs is used. The datasheet ADC transition noise is specified at 3.4 LSB_{RMS}. IF amplifiers were designed to contribute not more than 0.5 LSB_{RMS}. As the real ADC performance was found a bit better, the achieved total ADC noise floor (including the drivers) is about 3.6 LSB_{RMS}.

FINAL NOISE PERFORMANCE

Using the same method as for the old module (numerical model plus superimposed real noise data), the noise floor of the new generation beam position module was determined to be 0.22 μm_{RMS}, with Gaussian distribution as shown in Figure 2. An improvement by more than factor 6 with respect to the first generation. From Run III (2022-), the LHC TFB will also use four pickups instead of two, further lowering the overall TFB system noise floor. The obtained noise performance is close to the limit of available technology. There is still a bit of potential to further lower the noise floor by digital signal processing of the Σ signals. The new module supports bunch by bunch gain control which is transparent for operation. For ultimate performance, the receiver gain can closely follow the machine cycle, e.g. large acceptance for injected bunch train, increase after the injection transient is damped, and compensate for lost bunch intensity during collisions. The new system also allows to run at optimal gain for circulating bunches with very different intensities, e.g. for machine development sessions.

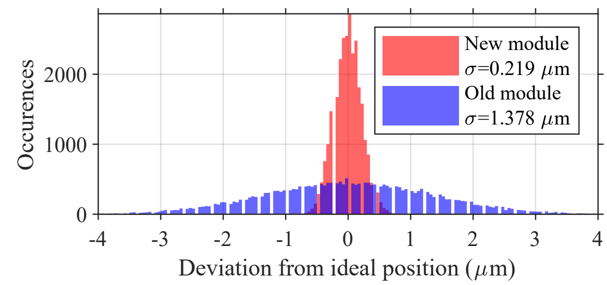

Figure 2: Comparison of position measurement quality for the old and new BeamPos modules (27000 samples). Same operating conditions, such the performance can be directly compared.

To validate the technology, one prototype of the new generation beam position module per beam per plane was installed to LHC for the beam test in October 2021. LHC was operated with upgraded TFB during the whole two week period. Figure 3 shows an injection transient captured by the old and new beam position measurement modules.

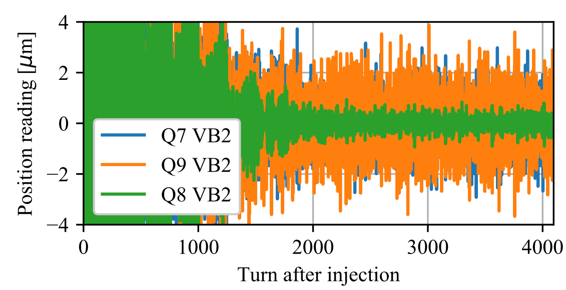

Figure 3: Injection into LHC captured by the old (Q7,Q9) and new (Q8) beam pos. meas. module. Data are notch filtered and β-normalized, so they can be directly compared.

CONCLUSION

For Run III, the LHC TFB was upgraded with a new generation, very low noise beam position measurement modules. The measurement subsystem noise floor was lowered by more than a factor 6 with respect to the old modules. Together with the doubled number of pickups and more advanced operation possibilities it is expected the overall TFB noise floor will improve even further.

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