

UPGRADE OF THE LHC BUNCH BY BUNCH INTENSITY MEASUREMENT ACQUISITION SYSTEM

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Abstract

The fast beam intensity measurement systems for the LHC currently use an analogue signal processing chain to provide the charge information for individual bunches. This limits the possibility to use higher level correction algorithms to remove systematic measurement errors coming from the beam current transformer and the associated analogue electronics chain. In addition, the current measurement system requires individual settings for different types of beams, implying the need for continuous tuning during LHC operation. Using modern technology, the analogue measurement chain can be replaced by an entirely digital acquisition system, even in the case of the short, pulsed signals produced by the LHC beams. This paper discusses the implementation of the new digital acquisition system and the calculations required to reconstruct the individual LHC bunch intensities, along with the presentation of results from actual beam measurements.

INTRODUCTION

The existing beam intensity measurement system for the LHC was designed some 15 years ago and fully operational at the LHC start-up in 2008. At this time, the available analogue-to-digital (ADC) converters did not have the analogue bandwidth, sampling speed and precision to directly convert short, pulsed signals from LHC beams. Using such ADCs to provide data for the digital integration would have resulted in a much lower measurement accuracy than using analogue integration. Hence the existing system uses an integrator ASIC. The chip integrates the incoming signal at 40 MHz using two integrators working in multiplexed manner. Even if both integrators share the same silicon die, the manufacturing process causes them perform slightly differently when exposed to the same signal. Offset, gain, and the time of integration have to be compensated for each individual integrator. This is done in the FPGA once the integrated data stream has been converted to the digital domain.

Analogue integration also causes a loss of information as the baseline of the signal is integrated together with the beam signal. Once the integrated signal is converted into the digital domain, the algorithm restoring the DC component is unable to separate the baseline from the total integrated value, making it bunch pattern dependent.

The continued progress in ADC technology now enables us to investigate whether fast ADCs can now be used to sample the LHC bunched beam signals, so the complete bunch-by-bunch intensity measurement is performed in the digital domain. This would not only avoid complicated compensation techniques to reduce the problems associated with the integrator ASIC, but it would also allow the use of

more sophisticated base-line restoration methods and bunch apex tracking, making the measurement technique more robust.

Further studies confirmed, that when using two dynamic ranges, an ADC with ENOB better than 10.5 bits and sampling rate greater than 500 MHz is needed to limit single shot digital integration error to 1% when a full scale signal is applied. For circulating beam measurements averaging can be used to reduce the ENOB requirements of the ADC.

IMPLEMENTATION

Hardware Layer

Several requirements have to be satisfied in order to achieve the desired measurement precision:

1. the bandwidth and the impulse response of the measurement device has to be sufficient to fully contain the bunch signal within the 25 ns spacing between LHC bunches (Bandwidth ≥ 800 MHz, Impulse response $\ll 25$ ns),
2. the analogue front-end has to shape the bunch signal such that it entirely fills the 25 ns spacing between LHC bunches, but decaying fully to zero before the next bunch signal arrives,
3. the amplitude of the shaped signal must be adapted to optimally use the ADC dynamic range. This involves injection of an offset voltage V_{ofs} and gain optimisation to increase the measured signal amplitude to cover $\approx 80\%$ of the ADC dynamic range.

The final requirements for this signal shaping can be seen in Fig. 1.

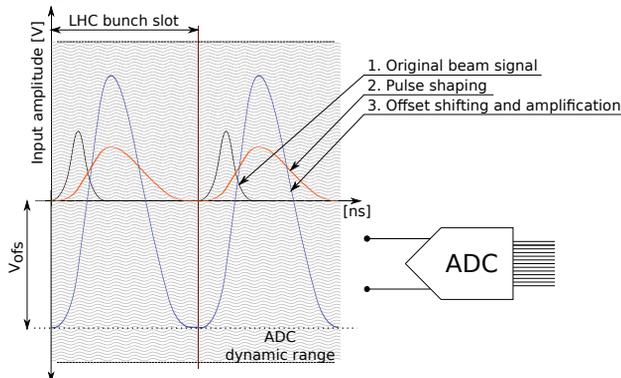


Figure 1: The BCTW signal shaping.

The first condition, concerning the bandwidth and impulse response, could not be satisfied using the original fast beam current transformers (FBCT) installed in the LHC due to the leakage of signal from one bunch into that of a neighbouring bunch slot, and the fact that the signal obtained was position

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dependent [1]. Hence an upgrade of the FBCTs to a CERN developed Wall Current Transformer (BCTW, [2]) was performed during the annual end-of-year CERN shutdown in 2015-2016.

The other signal shaping conditions were satisfied by designing an analogue front-end to the BCTWs. An 8th order 80 MHz Gaussian low-pass filter was used to shape the BCTW signal, and the signal amplitude was adapted to use the same two dynamic ranges as the existing system (full scale of 2×10^{10} and 2×10^{11} ch/b). This also simplified the comparison of measurements performance between the digital and analogue systems. For the time being, the offset voltage V_{ofs} is set to zero and hence the ADC dynamic range is not fully optimised.

The main challenge was in finding a suitable sampling module. The module had to satisfy following criteria:

- an ADC with 10.5 bits ENOB, DC coupled, having an analogue bandwidth greater than 800 MHz and sampling rate ≥ 500 MSPS,
- a high-pin count FMC form factor compatible with the newly developed CERN beam instrumentation group VME motherboard (VFC-HD, [3])

A market survey show, that an FMC module satisfying all those criteria does not currently exist. Lowering the requirements of the ENOB to ≈ 9.5 bits the FMC-1000 module from Innovative Integration could be used. Its two channel 14-bit, 1.25 GSPS, ADC allows parallel data acquisition of both dynamic ranges.

The maximum sampling rate of the FMC-1000 connected to the VFC-HD is 650 MSPS. This limitation comes from the speed of the Arria V (GX) transceivers used in the VFC-HD. For the purpose of the intensity measurements, however, the sampling rate is fully sufficient.

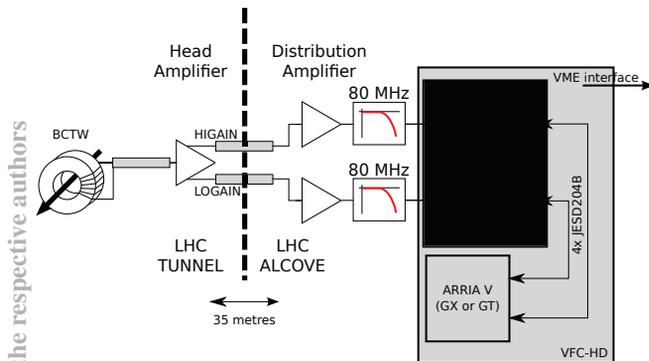


Figure 2: The BCTW analogue front-end overview.

In 2016, three complete acquisition chains (Fig. 2) were installed to measure the intensity of the circulating particle bunches in the LHC. These systems are currently running in parallel with the analogue systems used for the LHC operation.

Firmware Layer

The FPGA data processing flow is shown in Fig. 3. The analogue signal is converted to the digital domain at a rate

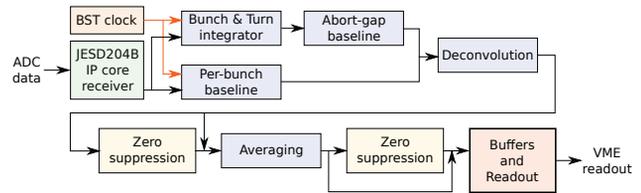


Figure 3: The FPGA data processing flow.

of 650 MSPS. The raw data of both ADC channels are transported to the FPGA through four 6.55 GbPS serial links (VFC-HD equipped with Arria V GX FPGA). An Altera JESD204B IP core is used to de-serialise the data streams on the FPGA side. A successful test was carried out to prove that a 1 GSPS sampling could be used with a custom deserialiser and the VFC-HD equipped with Arria V GT.

An internal 40 MHz clock, synchronous with the beam synchronous timing (BST), is generated, with its phase continuously adjusted using a digital delay such that there is a constant phase shift between the clock's rising edge and a bunch apex. A bunch boundary is then identified by the rising edge of this clock.

Such an implementation allows the system to track the clock frequency changes during the acceleration cycle. Using a peak-finding algorithm, a measurement of one LHC lead ion fill showed that a total phase shift of ≈ 1.5 ns has to be accommodated (Fig. 4). This corresponds to a displacement of the bunch boundary by approximately 1 ADC sample.

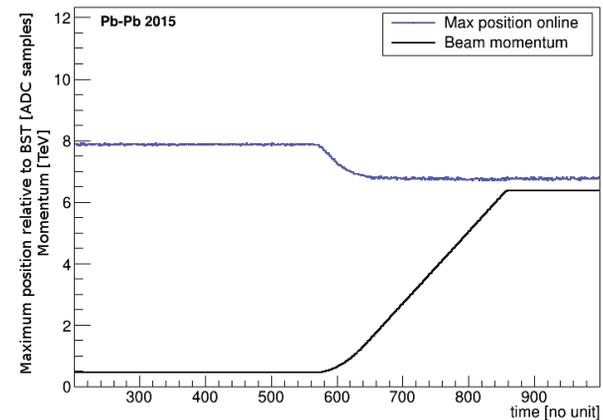


Figure 4: Evolution of the phase between the bunch apex and the BST clock during the acceleration of lead ions in the LHC. The blue trace shows the measured phase while the black trace shows the beam energy.

Once identified the bunch boundaries permit bunch by bunch digital integration to be performed. In addition, a total per-turn integral is provided as the sum of all the bunch intensities within a turn.

Both integrals have to be corrected for a DC component. Two correction algorithms were implemented to compare their performance: baseline correction using extraction kicker abort gap, and a per-bunch baseline correction.

- The abort gap baseline correction uses the $3\mu\text{s}$ LHC abort gap (which in principle does not contain any particles) to estimate the DC value of the beam signal. Each

turn, the *average DC component* of the beam signal can be estimated by calculating a mean value of the integrals of the empty bunch slots in the abort gap. To correct for the baseline, the DC component is added to the bunch and turn integrals at the end of each turn.

- The per-bunch baseline is calculated on the fly as an interpolation of the beam signal captured at two consecutive bunch boundaries. The interpolated bunch baseline is subtracted from each bunch integral individually.

The abort gap baseline correction algorithm is easier to implement compared to the per-bunch algorithm. The average baseline is calculated from the bunch integrals and can hence run at low clock speed (40 MHz). The disadvantage of this algorithm lies in its inefficiency to cope with fast baseline drifts. This is seen in Fig. 5 where the red trace shows a zoom of a typical signal produced by LHC proton bunches, while the blue trace shows the average baseline calculated by the abort gap algorithm.

These baseline drifts are caused by the non-uniform bunch filling pattern, and the only way to eliminate them is to lower the low-frequency cut-off of the BCTW. The difference in the average DC value with respect to the actual one in any given bunch slot might exceed 1% when using the BCTW with a low-frequency cut-off of 500 Hz.

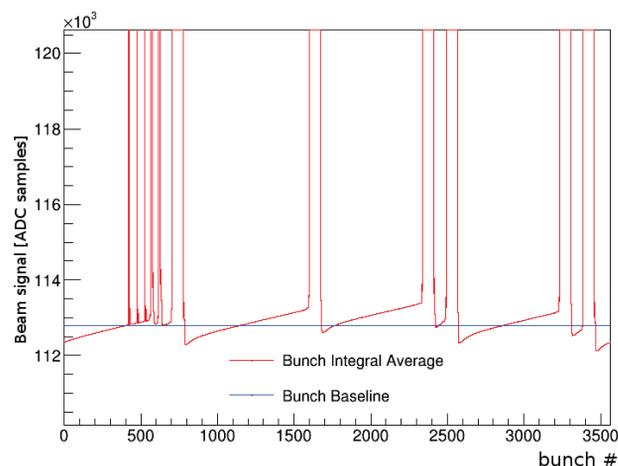


Figure 5: The abort gap baseline reconstruction.

Figure 6 shows an example of the per-bunch baseline restoration performed on 12 LHC proton bunches. The green bars identify the bunch boundaries while the blue trace depicts the raw ADC data and the black trace shows the result of the baseline correction. Compared to the abort gap algorithm, the per-bunch algorithm is more precise as it can calculate the baseline with a higher temporal resolution. The mandatory condition for this algorithm to work is that the analogue signal must return to zero before the start of the next bunch slot. This is a condition which in this particular case was not achieved as these data were taken using a 6th order Gaussian low-pass filter with only a 60 MHz cut-off frequency.

The deconvolution algorithm is applied on the integrated data. It corrects the response of the measurement device

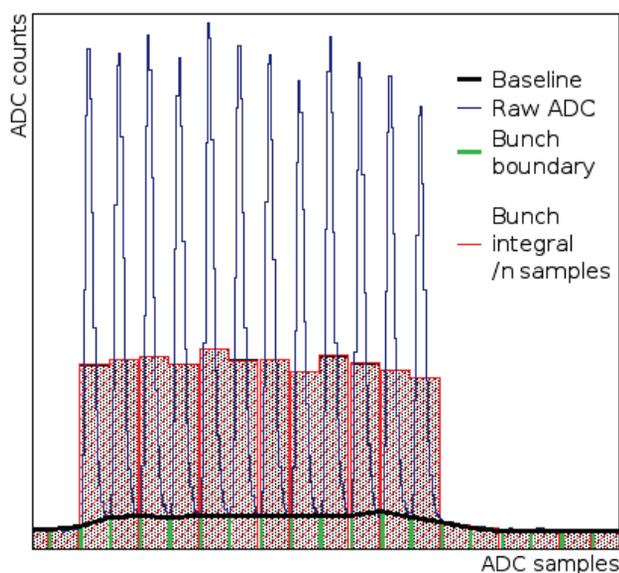


Figure 6: The per-bunch baseline reconstruction.

(BCTW, FBCT) in the case where signal generated by one bunch leaks into the adjacent bunch slot.

The bunch and turn intensities are averaged over 224 turns (20 ms) to improve the rejection of the 50 Hz component in the signal spectra.

To increase the measurement precision of low-intensity beams, two zero-suppression blocks are implemented. They act as noise filters, setting the bunch integral to zero when it is lower than a defined threshold. The first zero-suppression module filters the data at the output of the integrator, while the second one processes the averaged integrals. Both filters can be bypassed.

Software Layer

Integrated data are transported from the internal memory of each sampling system to the operational memory of a MEN A20 CPU using an interrupt-driven DMA VME transfer. The CPU runs the Linux operational system. It is patched to provide a scheduler allowing hard real-time applications to be run. Dedicated real-time and server classes [4] were written to perform the data transport, data processing and calibration, and to expose the measurement device's application interface (API) to the standard CERN controls infrastructure.

Bunch and turn integrals are logged in the CERN logging database. An expert graphical interface (Fig. 7) is available to visualise the measured data in real-time, as well to change the operational parameters of the measurement.

MEASUREMENTS

The digital intensity measurement systems is currently being commissioned and compared in terms of stability and performance to the old analogue and the LHC DC current transformers (DCCT) systems.

One such comparison is shown in Fig. 8. The top graph shows the total beam intensity measurement of the LHC fill number 5076 (beam 1). Three measurement methods are

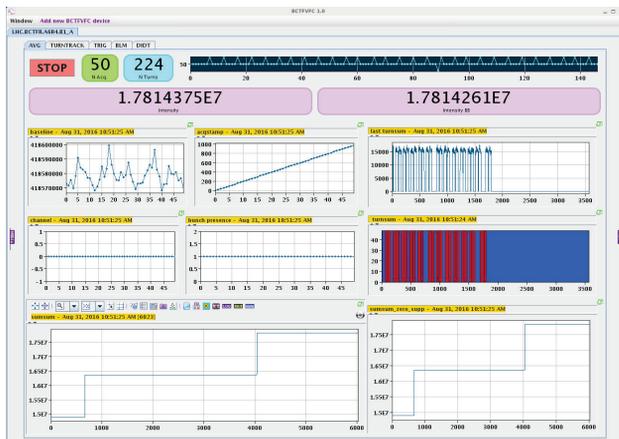


Figure 7: The expert graphical interface captured during the LHC filling with proton bunches.

compared: the digital (VFC), the analogue (DAB), and the DCCT measurements. To highlight the differences, the bottom graph depicts a ratio of the fast intensity measurements (DAB and VFC) to the DCCT measurement. All three measurement methods agree at start of acceleration (where there is no unbunched beam in the machine) within a fraction of a percent. In the figure, the higher ratio at the injection is caused by a slow rise time of the DCCT measurement. Beam debunching is believed to be the source of the increasing deviation of the fast intensity measurements with time as both the bunch by bunch systems deviate from the DCCT measurement in the same way.

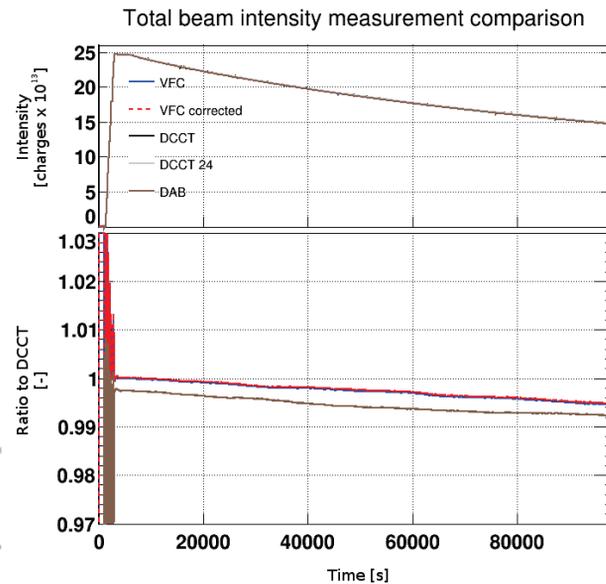


Figure 8: Comparison of the digital intensity measurement method with the DCCT and analogue measurements.

Fig. 9 shows a noise distribution on the total intensity as measured by the three measurement methods. It can be seen, that even when not fully using the ADC's dynamic range ($V_{ofs} = 0$), the digital acquisition system exhibits the same noise performance as the analogue (DAB) measurements.

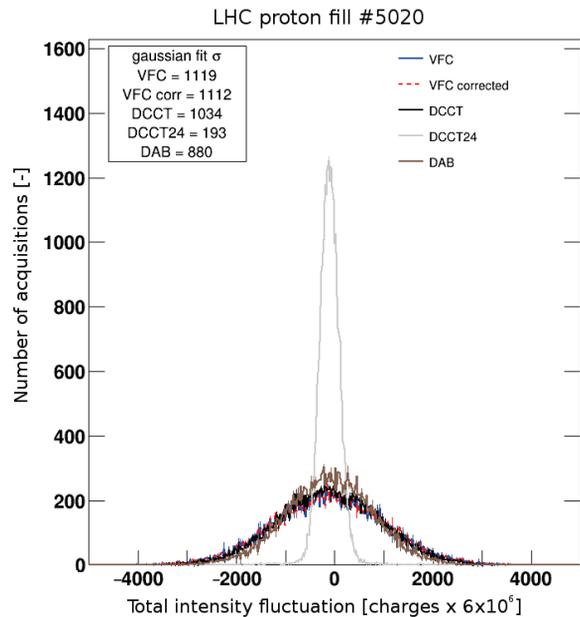


Figure 9: Noise performance of different intensity measurement systems.

OUTLOOK

While still in a commissioning phase, the new digital measurement systems are now fully operational, and for the moment working in parallel to the operational analogue systems. It has been shown that they already provide measurements of the same quality as the old analogue systems, while guaranteeing a more robust functioning, and the possibility for even more advanced signal processing in the future. At the end of the commissioning phase, the digital intensity measurement system will replace the old analogue system, which will permit further optimisation to be performed on the analogue front end.

REFERENCES

- [1] D. Belohrad, M. Gasior, M. Krupa, T. Lefevre, L. Soby, "Summary of LHC MD398: Verification of the dependence of the BCTF measurements on beam position and bunch length", in *CERN Internal Note CERN-ACC-Note-2015-0031*, CERN, Geneva, Switzerland, October 2015.
- [2] M. Krupa, M. Gasior, "The Wall Current Transformer – a new sensor for precise bunch-by-bunch intensity measurements in the LHC", in *Proc. of IBIC16*, Barcelona, Spain, September, 2016.
- [3] A. Boccardi et al., "A Modular Approach to Acquisition Systems for the Future CERN Beam Instrumentation Developments", in *Proc. of ICALEPCS 2015*, Melbourne, Australia, October 2015.
- [4] M. Arruat et al., "Front-End Software Architecture", in *Proc of ICALEPCS07*, Knoxville, Tennessee, USA, March, 2007.