Upgrade of the LHC Bunch by Bunch Intensity Measurement Acquisition System

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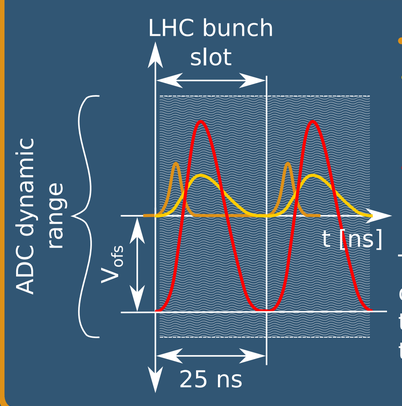
ABSTRACT

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 a 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.

MEASUREMENT METHOD EXPLAINED

Analogue front-end signal shaping



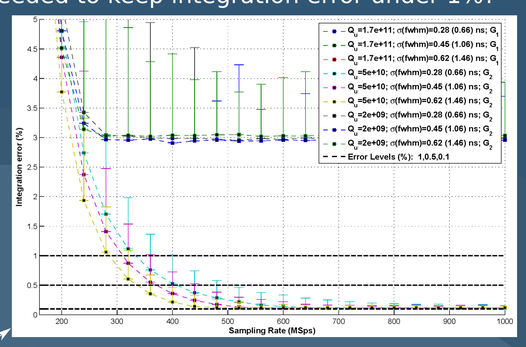
- Original beam signal
- The original signal is stretched to fully extend over the LHC bunch slot, while still decaying to the baseline
- The amplitude of the shaped signal for both dynamic ranges (1×10^{10}, 1.5×10^{11} ch./b) must be set to optimally use the ADC dynamic range

The amplitude shaping involves an injection of the offset voltage V_{ofs} and gain optimisation to increase the measured signal amplitude to cover ≈80% of the ADC dynamic range.

2

ADC FMC module

What sampling frequency and ENOB is needed to keep integration error under 1%?



- Sample simulation result for 11 bits ADC (75% FS)

Needed:
- ADC with 10.5 bits ENOB, **DC coupling**
- analogue bandwidth > 800 MHz,
- sampling rate minimum 500 MSPS

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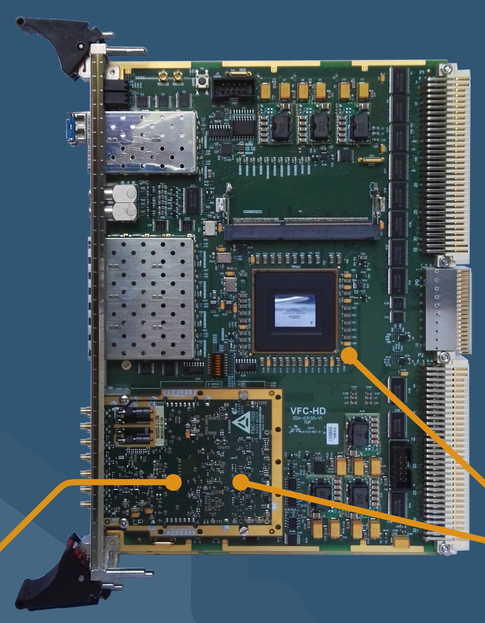

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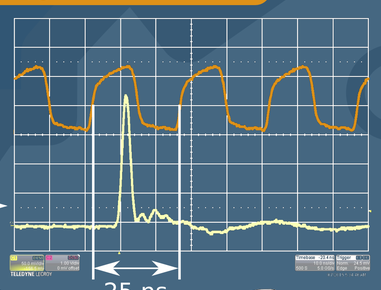
BCTW

Needed:
- bandwidth > 1 GHz
- impulse response much shorter than 25 ns to fit the signal into a single LHC bunch slot
- Figure shows the LHC bunch measured by the FBCT, signal is not satisfactory for the digital acquisition system.
- LHC FBCTs removed, installed new Wall Current Transformer (BCTW, **see WEAL02, or Wed contributed talk**)



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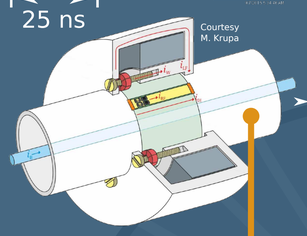
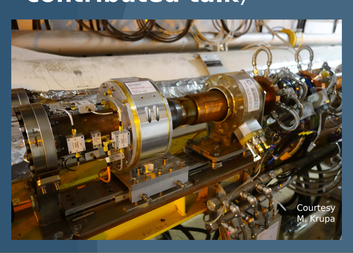
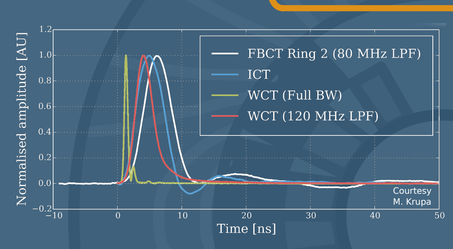






Head Amplifier → HIGAIN / LOGAIN → Distribution Amplifier → 80 MHz → 80 MHz

LHC TUNNEL | LHC ALCOVE

35 meters

5

VME interface

channel #1 — ADC 650 MSPS

channel #2 — ADC 650 MSPS

FMC-1000

4x JESD204B

ARRIA V (GX or GT)

VFC-HD

VME carrier board:
- one FMC high pin count slot
- 6 SFP slots, 2 of them dedicated to CERN timing and Ethernet
- *Standard:* equipped with Arria V GX
- *Custom:* Arria V GT having 10GbPS transceivers

In combination with **FMC-1000** from Innovative Integration a sampling system was constructed:
- FMC-1000 allows up to 1.25 GSPS sampling, however:
- VFC-HD with Arria V GX can only go up to 650 MSPS
- Successful tests carried with Arria V GT version and custom deserialiser to run at 1 GSPS

FMC-1000 is two-channel 14-bit DC coupled with ENOB of 9.5 bits, however 10.5 bits is required for single shot measurements. → For circulating beams averaging is used to reduce these requirements.

VFC-HD IS AN OPEN HARDWARE: www.ohwr.org/projects/vfc-hd

SIGNAL PROCESSING IN THE FPGA

In the de-serialised data a **bunch boundary** is identified. Internal 40 MHz clock is generated. Its phase is adjusted on fly using digital delay.

Clock → BST clock → Internal clock

Serial ADC → JESD204B receiver

This keeps a constant phase between the internal clock and the bunch apex.

Two **integrals** are provided:
- a bunch by bunch integral: sum of all the samples within a bunch slot, defined as space between two bunch boundaries
- a turn integral: sum of all the bunches intensities within a turn

Two **baseline** corrections:
- abort gap: estimation of per-turn baseline from an average integration of 'no-beam'
- per-bunch: interpolation of the beam signal at two consecutive bunch boundaries

Bunch & Turn integrator → Abort-gap baseline → Deconvolution → Zero suppression → Averaging → Zero suppression → Buffers and Readout

Per-bunch baseline → Deconvolution

Zero suppression uses a settable threshold to filter the bunch integrals. Applied on raw or averaged integrals.

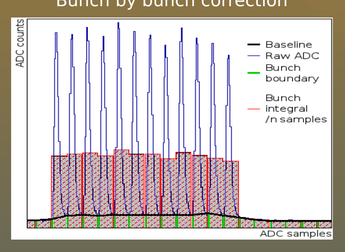
The calculated bunch and turn integrals are averaged over 224 LHC turns (≈20 ms) to improve the rejection of the 50 Hz component in the signal spectra.

VFC-HD

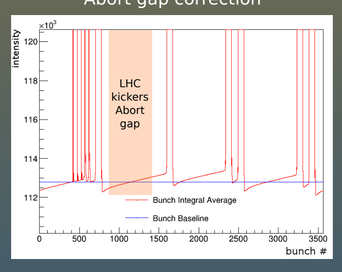
MEASUREMENT RESULTS

Comparison of the baseline correction methods

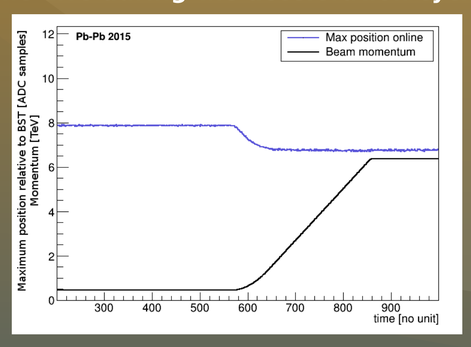
Bunch by bunch correction



Abort gap correction

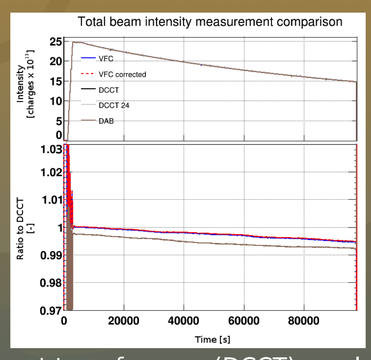


Tracking the clock frequency changes in the LHC during the acceleration cycle



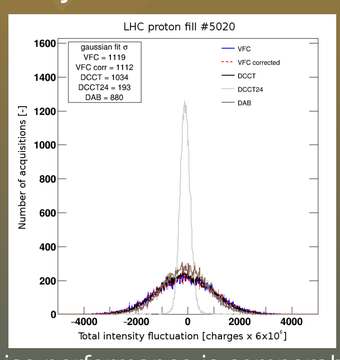
- Using a peak-finding algorithm, a measurement of one LHC lead ion fill showed, that a total phase shift of 1.5 ns has to be accommodated.
- This corresponds to a displacement of the bunch boundary by 1 ADC sample
- LHC proton beam in the SPS: a total phase shift of up to 12.5 ns was observed

Comparison of three beam intensity measurement methods for the LHC



- DC current transformers (DCCT), analogue system (DAB) and the digital system (VFC)
- Agree at start of acceleration where there is no unbunched beam in the machine
- Higher ratio at injection: slow rise-time of the DCCT measurement
- Beam de-bunching causes increasing deviation from the DCCT measurement

Noise performance of different intensity measurement methods



- The noise performance is comparable to the old analogue system
- DCCT measurements shown using 16-bit and 24-bit acquisition systems. 24-bit system outperforms other measurements when significant beam circulates (1×10^{14} charges), but does not provide bunch by bunch measurements

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