COMMISSIONING AND FIRST PERFORMANCE OF THE LHC BEAM CURRENT MEASUREMENT SYSTEMS

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Abstract

CERN's Large Hadron Collider (LHC) is equipped with three distinct types of intensity measurement systems: total intensity measurement using DC transformers (DCCTs) with a bandwidth up to a few kHz; total intensity measurements on a turn-by-turn basis for lifetime measurements using AC-coupled fast transformers (fast BCTs); bunch-by-bunch intensity measurements with a bandwidth up to a few hundred MHz also using the fast BCTs. In addition to providing intensity information these devices are part of the machine protection system, indicating whether or not there is beam circulating, transmitting intensity for evaluation of safe beam conditions and capable of triggering a beam dump if fast losses are detected. This paper reports on the commissioning of all these systems and their initial performance.

INTRODUCTION

The LHC beam intensity measurement needs to cover individual bunch intensities from as low as 1×10^{9} c* up to 1.7×10^{11} c (ultimate p^+ bunch) and total beam currents from a few µA to 850 mA with sufficient time resolution [1]. The measurement of the total circulating current is performed by the **D**irect-**C**urrent-**C**urrent-**T**ransformer system (**DCCT**), while the individual bunch intensities and the total of the bunched beam are acquired by the fast AC-coupled BCTs in the rings (**fast ring**) and similar systems in the dumps (**fast dump**) for both beams.

The DCCT system [2] acquires four gain ranges simultaneously to cover the entire dynamic range of the beam intensity. These are sampled by a 12-bit ADC and acquired at 50Hz.

The fast ring system [3] integrates the current of each individual bunch at 1/10 f_{RF}† inside a synchronised integration window, continuously giving 40 MHz bunch charges (in bits) in the first stage. The second stage implements data treatment in an FPGA in four measurement modes.

In the **turn-sum** mode the integrated intensities in each bucket are summed up over each individual turn ($f_{rev}\approx11$ kHz). The low bandwidth (LOBW, 1.5 MHz high gain, 2.5 MHz low gain) [3] signal does not depend on gate synchronisation, and the turn-sums are further averaged over 225 turns to provide whole bunched beam intensities at 50 Hz for comparison with the DCCT. The turn-sums of the high bandwidth (HIBW, 200 MHz) signal are available with a turn-by-turn resolution and updated each second, depending on the configuration.

The **bunch-average** mode averages each individual bunch over many turns, using the HIBW channel, giving an update of all individual bunch intensities at several Hz (i.e. 12.5 Hz for 900 turns).

The **capture** mode provides a complete snapshot of selected individual bunches over a sufficient number of turns to study fast phenomena at injection and for machine development needs. While the turn-sum and bunch-average measurements of the rings are continually updated, the capture mode is set up and triggered for each single measurement according to operational needs.

In order to measure the beam intensity in the beam dump lines, where an acquisition trigger typically arrives later than the beam, a **circulating post-mortem** FIFO-buffer is used. This rolling buffer is continuously filled, stores 1024 consecutive turn-sums and it is frozen and read-out following a dump-kicker trigger.

DCCT MEASUREMENTS

The expected accuracy depends on the selected gain range, and the resolution of the DCCT is limited by magnetic and electronic noise only for the highest gain setting. All other less sensitive gain channels are dominated by the quantisation noise of the 12 bit ADC. The Fig. 1 shows the measurement accuracy (expected intensity error / true intensity in %) with respect to circulating charges: for small beams up to 5×10^{11} c the most sensitive range 4 is used, the following less sensitive ranges are selected at 5×10^{12} c and 5×10^{13} c. For a beam of 10^{10} c the accuracy is 10%, and for beams above 3×10^{11} c is it 0.6% or better for all successive ranges.

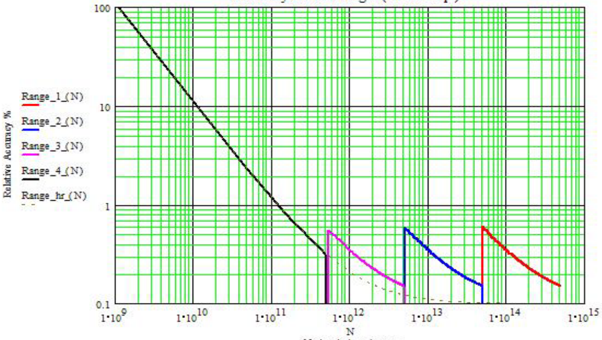

Fig. 1: Expected measurement accuracy depending on signal and gain range, temperature induced drifts ignored.

* Number of charges, abbreviated unit for the whole text

† f_{RF}=400789650 Hz. A “bucket” refers to 10 RF periods and is 25 ns long, as commonly measured by the observation systems of the LHC.

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A calibration set (scale and offset) for each of the four gain ranges is obtained by playing a sequence of calibration pulses which takes a few seconds, called quick calibration. Quick calibrations are automatically invoked before any first injection into the LHC to validate the DCCT acquisition chain. At the start of the sequence an analogue signal offset is readjusted to restore any drift of the base line. These quick calibration sets are compared to previously obtained precision sets, and if found to be out of tolerance any first injections are blocked and machine protection alarms are raised.

Results

Fig. 2 shows the intensity evolution of beam 1 over a period of 24 hours as measured by the DCCT and the fast BCT LOBW 225-turn-sum averages, both averaged over 1 second from initially 20 ms time resolution. The rms noise amplitude of the DCCT for highest gain (range 4) is 9.2×10^{8} c giving a noise floor of 1.7 μA in agreement with the expected resolution. A DCCT offset drift of a few 10^{9} is observed during this time span.

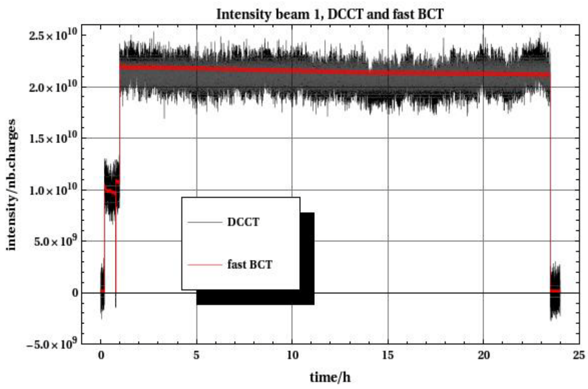

Fig. 2: Intensity evolution measured by the DCCT and the fast BCT during 24 hours. The first bunch has 1×10^{10} c; the second bunch injects another 1.2×10^{10} c.

The DCCT intensity is transmitted to the LHC machine protection system in order to calculate limits for safe beam conditions [4] and to retransmit beam intensity information as a generally available beam parameter for all other LHC systems.

Open issues

A scoring algorithm selects the optimum gain range each second with the following criteria: avoid saturation, be insensitive to noise-spikes and provide best possible resolution for a given intensity. This algorithm still has to be confirmed under operational conditions for intensities above 5×10^{11} c. The gain selection must be compatible with all dependent applications and the machine protection system.

The DCCT signal offset has been measured to vary over a range of $\pm3\times10^{9}$ charges corresponding to ±5.4 μA. This is slightly worse that the foreseen performance of ±1 μA. The main cause of this drift is thought to be due to temperature variations in the electronics and the BCT coil, magnetic and electronic noise, and potentially any other external source. Even though presently these drifts are only significant with low beam intensities, in order to understand their origin it is planned to measure and long-term record the signal offsets and temperatures.

The safety relevant intensity transmission to the machine protection system depends on instrumentation software running on top of a LynxOS/VME architecture, whereas most other safety relevant components are realized in the electronics directly.

Future plans

Presently signals are digitized using a 12 bit ADC, and using the most sensitive range 4 for up to 5×10^{11} c leads to quantisation noise of 2.44×10^{8} c (2.4×10^{9} c, 2.4×10^{10} c and 2.4×10^{11} c for ranges 3, 2 and 1). Therefore the resolution of three of the four gains is currently limited by quantisation noise. It is therefore planned to use a 24-bit system capable of covering the whole intensity range. This should allow a quantisation noise of $<3\times10^{8}$ c covering all intensities, which is well below the BCT noise. Then the calibration can be simplified for one single gain and the gain selection will be suppressed.

FAST BCT MEASUREMENTS

The calculation of the turn-sums and the bunch-averages from the HIBW channel permits to have an intensity reading with time-resolution of an individual turn (updated at 1 Hz). The summing-up of empty buckets has to be avoided by setting a minimum beam threshold; otherwise the turn-sums will be dominated by a non-zero mean value of the restored base-line. For the base-line restoration (BLR) the lowest integrated intensity of all buckets in one turn is used as offset correction for the next turn, relying on the fact that always empty buckets are present in each turn, at least for the 3 μs abort gap, to restore the base line. The lowest measurable turn-sum and bunch-average intensity is then given by the noise suppression peak threshold, which is as low as 10^{8} c for high gain and 5×10^{8} c for low gain for both bandwidths.

Detailed intensities from both beams are required as input for the post-mortem system to analyse the causes of machine protection triggered beam dumps. The fast BCT ring system provides frozen copies of LOBW 225-turn-sum averages during the last 30 seconds, HIBW turn-sums and HIBW bunch-averages during the last second to the post-mortem. For the dump systems the turn-sums of the LOBW channel are kept in the post-mortem buffer without any base-line restoration.

Results

The fast BCT LOBW channel provides turn-sums which are averaged over 225 consecutive turns (to suppress noise at 50 Hz) and are continuously updated for operational displays. Fig. 3 shows the beam evolution during set-up MD sessions, initially injecting and dumping single bunches per beam followed later by 2 bunch operation. Losses caused by missing orbit feedback occur around 4 hours, followed by bigger beam losses crossing resonances during optics adjustements. Small losses of a few 10^8 c are resolved in sufficient detail, so that an adaptive beam-lifetime calculation based on these turn-sum averages has successfully been used for the measurement of lifetimes of several hundred hours within a few minutes.

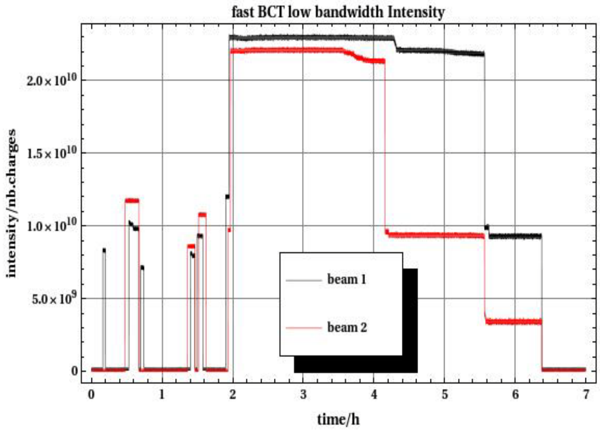

Fig. 3: LOBW 225-turn-average intensity evolution. The losses after 3 h are caused by optics adjustment (betatron squeeze) studies at 3.5TeV.

The fast BCT HIBW summing mode provides individual turn intensities with a time resolution of one turn (89 μs) and an rms noise of 8.5×10^7 c. This measurement is repeated every 900 turns (80 ms) and also delivers individual bunch-averages for all bunches during this period. The HIBW summing runs continuously and the results are updated each second, logged into a long-term storage system and are then available for further off-line analysis of fast losses.

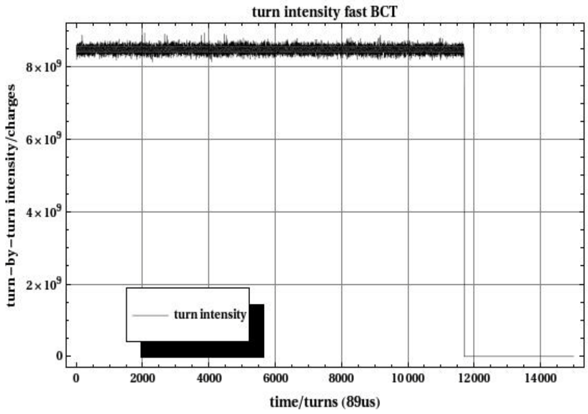

Fig. 4: Turn-by-turn intensity from the HIBW high-gain channel of the fast BCT during ~1 second (11 k turns).

Fig. 5 shows the intensity evolution of one pilot bunch at injection, captured using the HIBW, high gain channel. Losses of about 1.4×10^6 protons (~2.5%) coming both from the injection process and the capture efficiency of the RF system are clearly visible over the first 2000 turns. The rms noise on the measurement was calculated to be equivalent to 1.5×10^7 protons.

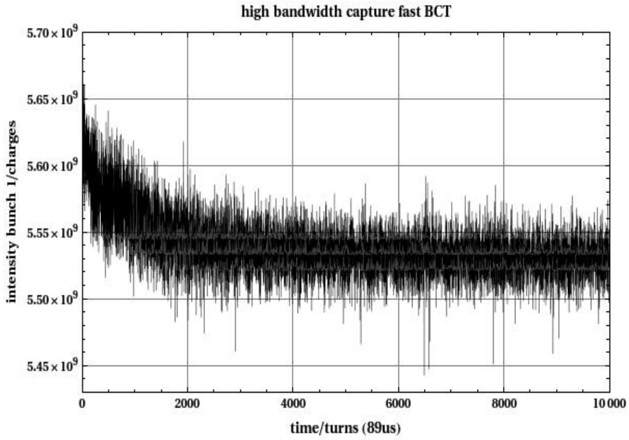

Fig. 5: HIBW capture of a single LHC pilot bunch for 10000 turns, triggered by an injection.

Open Issues

The present calibration system limits the accuracy of the absolute intensity reading of the fast BCT systems to ~5% provided that the phase between the integration interval and the bunch, offset suppression and scaling factors are adjusted using a full calibration routine [5]. Calculation of the LOBW average turn-sums depends strongly on the beam threshold, causing distortions below 10^{10} c. Improvements in the BLR algorithm should help to decouple the noise rejection from the summing.

CONCLUSION

The large number of client programs requesting intensity data from all BCT systems requires an intermediate proxy software layer which fans out data while minimizing low-level system loads: this has permitted both systems to gain the required stability. The current requirements for normal operations are met, including the smoothly running lifetime calculation, and further improvements concerning calibration, precision and noise suppression are under way.

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