THE LHC FAST BEAM CURRENT CHANGE MONITOR

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Abstract

The modularity of the Large Hadron Collider's (LHC) machine protection system (MPS) allows for the integration of several beam diagnostic instruments. These instruments have not necessarily been designed to have protection functionality, but MPS can still use them to increase the redundancy and reliability of the machine. The LHC fast beam current change monitor (FBCCM) is an example. It is based on analogue signals from fast beam current transformers (FBCT) used nominally to measure the LHC bunch intensities. The FBCCM calculates the magnitude of the beam signal provided by the FBCT, looks for a change over specific time intervals, and triggers a beam dump interlock if losses exceed an energy-dependent threshold. The first prototype of the FBCCM was installed in the LHC during the 2012-2013 run.

The aim of this article is to present the FBCCM system and the results obtained, analyse its current performance and provide an outlook for the final system which is expected to be operational after the long LHC shutdown.

SYSTEM DESCRIPTION

Fig. 1 depicts the FBCCM system. The FBCCM uses a beam signal provided by the LHC FBCTs to calculate the magnitude of the beam signal's strongest component at 40 MHz. It evaluates its change over a specific time interval and triggers the beam dump interlock if the losses are not acceptable.

The beam signal is first filtered by an active 6^{th} order low pass Bessel filter, then sampled at 160 MHz by a 16-bit analogue to digital (ADC) converter (ADS5485). The filter's gain is set so that the ADC reaches full scale at 3×10^{11} charges per bunch.

The data stream is further filtered using a 256-tap band-pass FIR filter ($f = 40 \pm 2.5\ MHz$) followed by an IQ demodulator calculating the signal magnitude on the fly using Eq. 1.

$$M = \sqrt{I^2 + Q^2} \quad (1)$$

The ADC is clocked by a 160 MHz sine wave derived from the 40 MHz bunch synchronous timing (BST) provided by the LHC timing system [1]. The 160 MHz square wave is produced by a PLL (Si5326), which reduces the overall jitter of the BST (300 ps_{rms}) to below 50 ps_{rms}. An additional 160 MHz low-pass filter installed between the Si5326 and the ADC reduces the amount of clock harmonics and improves SNR by 4.5dB to ≈75 dBFS, which is in good accordance with the manufacturer's specifications.

The signal magnitude provided by the IQ demodulator is then fed into a set of moving averagers. Six averagers are implemented, having window lengths of 1, 4, 16, 64, 256 and 1024 turns to cover a range of loss rates. Each averager produces a value every one-sixteenth of its length. Hence the 1-turn averager provides a value every 222 (or 223) bunch slots out of 3564 total, whereas the 1024-turn averager provides a value every 64 turns. The use of such treatment is to speed up detection of very high losses.

Each sample provided by any of the moving averagers is individually compared to the previous sample from the same window. If the difference between the two successive samples exceeds a pre-defined threshold, a flag is raised, indicating that the loss rate detector requests the beam to be dumped. This signal is sent to the beam interlock system [2].

The loss thresholds are a critical parameter for the system's operation. They are defined for each window individually, as is the case for the Beam Loss Monitors (BLM) of the LHC. The threshold is energy dependent [3] and the energy value is taken from the LHC telegram or from the BST. Currently the system implements 4 energy dependent thresholds for each window. To avoid corruption of the threshold tables they are hard-wired in the FPGA. Hence a change of these thresholds requires the FPGA code to be recompiled.

Data Logging

The quality of the data is analysed on-line on a statistics basis. This is done by using statistics modules, which observe the data over a 10 s time interval, and calculate the data average, minimum and maximum values. Two such modules for each moving averager were implemented in the FPGA. The first one reports statistics on the magnitude provided by the output of the averager, the second one reports statistics on the data presented to the threshold comparator. The latter's maximum value corresponds to the maximum losses presented to the comparator. In case of a 'normally' operating machine this value sets the lowest limit on the threshold that should not cause false beam dump requests.

For further debugging and post-mortem analysis the 1-turn moving averager data are also exported. The FPGA on-chip memory can store two 8192-turn magnitude buffers. Each buffer covers ≈720 ms observation time. Both buffers alternate, and thus provide a continuous stream of turn by turn data.

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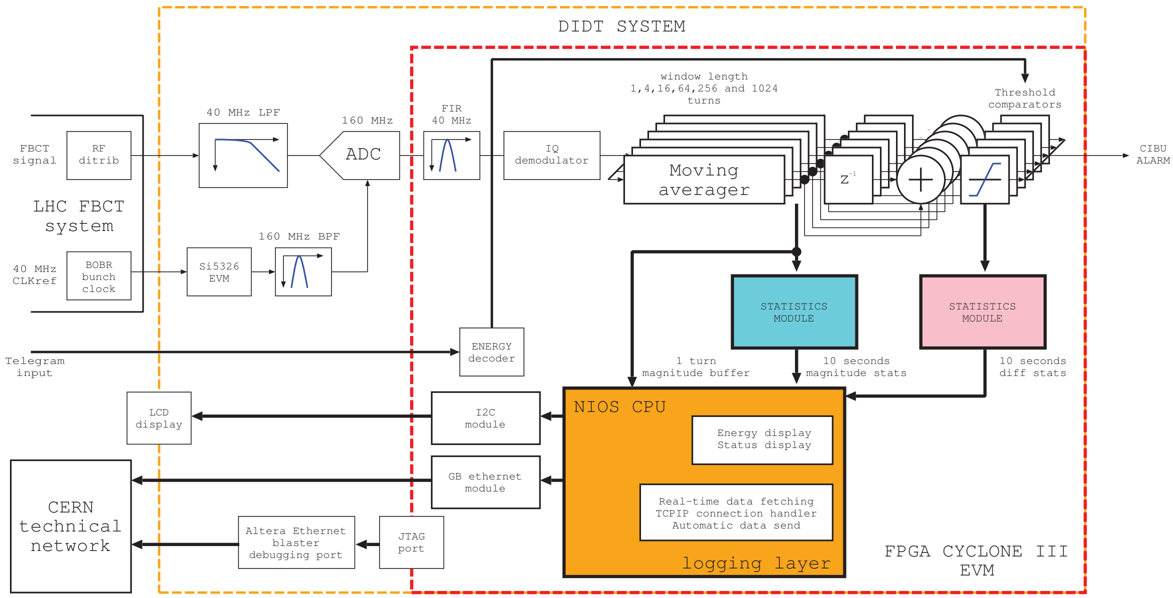

Figure 1: The FBCCM system description.

PHYSICAL IMPLEMENTATION

Hardware Layer

The FBCCM is implemented as a standalone 1U×19" rack-mounted unit. As a first approach, to speed up the development time, several evaluation modules were connected together to build the system. The FPGA processing is performed using a Cyclone III 3C120 development board. The board is equipped with two high speed mezzanine connectors (HSMC), which permit the connection of user hardware. One connects to the ADS5485 200 MSPS ADC evaluation module, the other is equipped with custom circuits providing a user interface and connection to the machine protection system.

The beam synchronous timing is fed to the Si5326 evaluation module, which is set up to generate a 160 MHz single-ended clock signal used to drive the clock input of the ADC evaluation board. The ADC produces a data-ready signal, which is synchronous to the data stream and is used by the FPGA to clock the incoming data. This source-synchronous data treatment minimises problems related to clock domain crossing inside the FPGA as the entire core uses a single clock source.

The FBCCM communicates using a 100 MBit Ethernet connection. The Ethernet physical layer is provided by the Cyclone development board. The TCP protocol was preferred over UDP. The TCP protocol cannot be easily implemented in hardware due to the complexity of the connection management. However it provides a reliable, error-checked and ordered transmission to a connected client. The IP stack is implemented in the soft-core NIOS CPU residing in the same FPGA chip as the core hardware. The CPU is responsible for fetching the data provided by the statistics modules and turn buffers, and for publishing them over Ethernet.

The IP implementation and the data processing represent a significant load to the CPU. Hence the number of TCP connections is limited to two, reserving one for the official data communication, and one for debugging purposes. Communication with the FBCCM is unidirectional to avoid possible security risks. Data are sent to the client as soon as the TCP connection is successfully established. Statistics data are sent over the channel in small packets (300 bytes) every 10 seconds. Every 720 ms a 32 kiB data block containing turn-buffer data is also sent. The average throughput is less than 50 kiB per FBCCM device per connection.

An Altera Ethernet blaster is installed in the unit and connected to the Cyclone development board. The Ethernet blaster provides a bridge between the Altera Quartus compiler and the JTAG interface of the FPGA. This permits to develop and improve the algorithms directly on the device installed in the LHC tunnel, and remote observation of the FPGA registers.

Software Layer

The software that allowed debugging of the FBCCM system during the initial commissioning consists of a FESA class which makes a TCP connection to the tunnel electronics and listens to messages being sent continuously. The header information on the TCP data is extracted and used to decode the type of data sent in order to determine the structure. The statistics information sent every 10 seconds is normalised using static base-line offsets and calibration factors for easier cross-correlation with intensity values from other LHC measurement devices. The off-line analysis is simplified through the implementation of standard LHC logging variables [4]. The higher frequency turn-by-

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turn data are normalised similar to the statistics data and an expert application was developed to visualise the results on-line. The data produced following beam dump requests are stored in the post-mortem repository allowing data from several systems to be correlated [5], in order to identify the most likely causes for the beam dump.

The expert application allows the data from both LHC beams to be observed. Each measurement consists of the statistics and the turn buffer data. The latter is implemented using a rolling buffer with a settable time span. This permits short-event disturbances to be caught on a larger time span. The buffer values are displayed along with their minimum and maximum traces.

FIRST MEASUREMENTS

The FBCCM was installed in the LHC in 2012 and connected to a masked LHC machine interlock channel. This allows observing the FBCCM's dump requests in the MPS logger, and thus to verify the entire FBCCM transmission link.

The FPGA code constantly evolved right up to the end of the LHC run in February 2013. The following measurements show a short analysis of the last 4 days of measurement.

Magnitude Measurements

The magnitude measurements are provided by the statistics module at the output of the averagers (cyan block in Fig. 1). In theory, the data provided by the FBCCM's statistics module should follow the FBCT measurements. Analysing the measured data confirms that this is the most common behaviour. However differences can be seen in the details, as shown e.g. in Fig. 2.

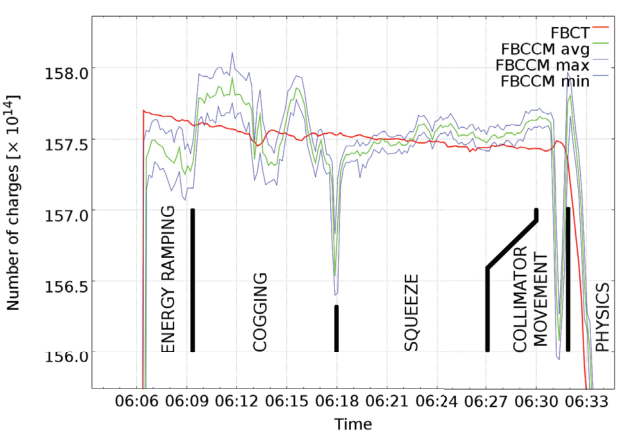

Figure 2: 1024-turn moving averager data compared to FBCT measurements on the flat-top of one of the LHC fills.

This figure shows the data provided by the FBCCM for one of the LHC beams during preparation of the machine for the physics run (flat-top). The red trace shows a measurement of the beam intensity using the FBCT, the set of blue traces identify the FBCCM minimum and maximum measured values in a 10 second interval, and the green trace corresponds to the average value. As can be seen, the FBCCM shows larger variations than the FBCT. Measured FBCCM data also show regions of positive slope. This effect is caused by a position dependency of the current transformer [6], which is of the order of 1 % per millimetre of beam displacement. It is also visible in the data, that the current transformers of the FBCCM and the FBCT are oriented in opposite directions as they react in an opposite manner to such position changes.

The fact that the FBCTs are less sensitive to the position is caused by the processing method: While the FBCTs integrate the 200 MHz bandwidth beam signal, the FBCCM uses only the 40 MHz component, and calculates its amplitude. As the FBCT toroids exhibit strong beam position dependency for all spectral lines above ≈30 MHz, the FBCCM is affected more than the FBCT. As this effect is very slow, having a time constant much longer than the longest (1024-turn) averager, it is not an issue for detecting fast current changes.

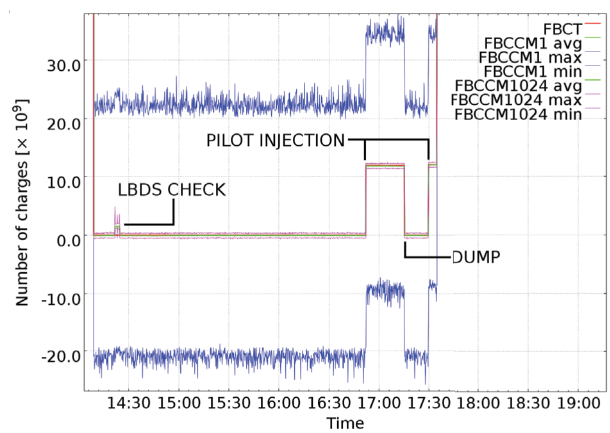

Figure 3: Comparison of the 1-turn and the 1024-turn moving averager performance on the LHC pilot (1×10^{10} charges in a single bunch).

Fig. 3 compares the noise levels of the 1-turn and the 1024-turn averagers. The noise floor for the 1-turn window is $\approx 2.2 \times 10^{10}$ charges and $\approx 4 \times 10^{8}$ for the 1024-turn averager, and it increases only by a few per-cent for a high-intensity beam. The noise adds to the signal thus even the magnitude of the low-intensity beams, such as the LHC pilot, is still visible in the max, min and average values of the 1 turn averager. The figure also shows an effect of the LHC Beam Dump System (LBDS) automatic check. This consists of modifying the RF clock frequency of 400 MHz by 1 kHz. As the RF frequency is directly used in the BST to generate the 40 MHz bunch clock, the effect is visible on the FBCCM measurements as well. This operation is performed without beam and hence is not an issue.

Differential Measurements

While the magnitude measurements are used to validate the IQ demodulation algorithm, the real information for

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the machine protection is contained in the rate of change. The derivative is calculated in the FPGA by simple subtraction of successive samples generated by each averager. Published loss data are generated by the FBCCM's second statistics module (shown pink in Fig. 1). Typical data, normalised to 1-turn, can be seen in Fig. 4.

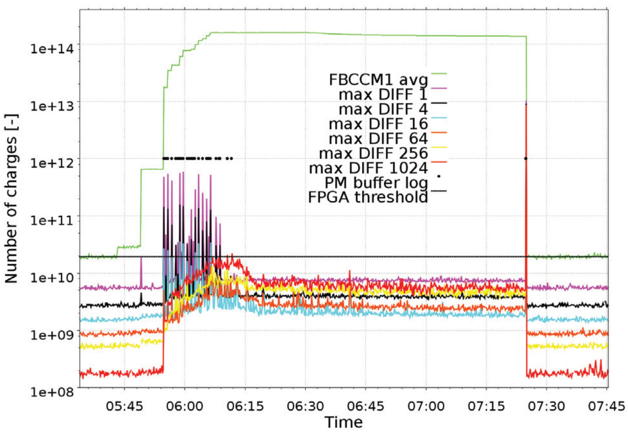

Figure 4: Multiple injections and dump as seen by the threshold comparators depicted in Fig. 1.

The graph shows multiple injections, followed by a dump, and it is taken from the same data set as Fig. 2. During the injection the FBCCM shows significant, non-physical losses of the order of 6×10^{11} charges. The effect is not yet fully understood, however it is believed that the cause of this is a combined effect of an injection oscillation and the position dependency of the FBCT's toroid. This measurement was performed while injecting nominal bunches (1.7×10^{11} ch./b.). For lower per-bunch intensities the peaking is proportionally less, and hence the threshold of 6×10^{11} charges per turn at 450 GeV sets the limits on the FBCCM performance. During the physics part of the cycle (starting at 06:30), the signal is free of any disturbances, and the threshold can be lowered.

For the purpose of testing, the FBCCM dump threshold was set to the same value for all windows. It was set intentionally low (1.9×10^{10} ch./turn) to see how the system behaves during injection and physics at 3.5 TeV. Fig. 4 shows the measured loss rates ($\mathrm{DIFF}_{1,max} \ldots \mathrm{DIFF}_{1024,max}$) and overlays the MPS post-mortem buffer log (black dots). These indicate real dump requests generated by the FBCCM, and sent to the MPS system. It is important to note, that even with the threshold set to 1.9×10^{10} charges/turn, the physics run does not contain any false trigger until the beam is dumped.

In general the FBCCM behaves correctly, but within the 4-day data set, 3 dump events were detected without clear evidence in the loss rate data. A possible cause of these false dumps could be re-programming of the FPGA. This is under investigation.

System Resolution

The resolution of the FBCCM is given by the noise floor of the loss rate signal. The combined effects of the noise on the loss rate signal, and the asynchronous sampling at one-sixteenth of the window length implies that the loss rate needs to be at least $4 \times DIFF_{noise,max}$ to be sure that it represents a true loss.

The 'average' noise levels for each averager can be read from Fig. 4. The single turn window background noise corresponds to 5.5×10^9 charges/turn, for the 1024-turn averager, the noise floor decreases to 2×10^8 charges/turn. Hence the system is able to detect 2.2×10^{10} charges lost in a single turn, or 8×10^8 charges lost in 1024 turns. This corresponds to 0.011 % of the total intensity for the single turn averager. Currently, the threshold at 450 GeV is dictated by the beam position dependency of the FBCT toroids.

CONCLUSIONS AND OUTLOOK

The FBCCM presented in this paper is new equipment, currently in its commissioning phase. Although it was installed in the LHC in 2012, there is not enough data to resolve all the issues described in this paper. During the LHC long shutdown the main work concentrates on the replacement of the FBCTs with another technology, which would minimise the beam position dependency.

The FBCCM is now being finalised with the evaluation modules re-designed as a single PCB. One of the major issues for debugging is the asynchronous fast sampling, which impairs the cross-check of the loss rate and the intensity values during dump and injection events. The final version will use turn-synchronous sampling to fix this issue.

It is foreseen that the LHC will start back up in 2015 with fast beam current change monitors installed on both beams.

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