IMPLEMENTATION OF THE ELECTRONICS CHAIN FOR THE BUNCH BY BUNCH INTENSITY MEASUREMENT DEVICES FOR THE LHC

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Abstract

The fast beam intensity measurements for the LHC are provided by eight Fast Beam Current Transformers (FBCT). Four FBCTs installed in the LHC rings are capable of providing both bunch-by-bunch and total turn-by-turn beam intensity information. A further four FBCTs, two in each of the LHC dump lines, are used to measure the total extracted beam intensity. In addition to providing intensity information the ring FBCTs also send signals to the machine protection system. This increases the complexity of both the RF front-end and the digital acquisition parts of the signal processing chain. The aim of this paper is to discuss the implemented hardware solution for the FBCT system, in particular with respect to the signal distribution, FPGA signal processing, calibration, and interaction of the FBCTs with the machine protection chain.

INTRODUCTION

The fast BCT measurement system consists of a Bergoz type transformer with a bandwidth from 400Hz to 1.2GHz. This is followed by an RF front-end consisting of an RF distributor, analogue integrator and beam circulating flag (BCF) detector, before entry into a 14bit digital acquisition system.

A simplified block schematic of the fast intensity measurement system is depicted in Fig. 2. In order to maintain the compatibility of the CERN-SPS and the LHC FBCT systems it was decided to use a digital processing chain based on the CERN-SPS system. This uses a DAB64x acquisition card developed by TRIUMF (Canada) on which are mounted two Individual Bunch Measurement System (IBMS) mezzanine cards [1]. The mezzanine cards are used to integrate the incoming signal using a 40MHz integrator ASICs developed for the LHCb experiment. The integrated signal is then digitized and processed on the DAB64x card to produce bunch-by-bunch intensity values.

Four channels (2 DAB64x boards) are used to provide measurements in two dynamic ranges: high gain with full scale=2×10^{10} and low gain with full scale=2×10^{11} particles. For each dynamic range the measurements can be acquired with a high bandwidth (HIBW, 200MHz) for bunch to bunch measurements and a low bandwidth (LOBW, 2.5MHz for low gain and 1.5MHz for high gain) for a timing insensitive total intensity measurement.

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SIGNAL DISTRIBUTION

The purpose of the RF distributor is to split the beam signal appearing at the output of the transformer [2] into a total of six outputs. Four of these outputs are used for the measurement, and are connected via appropriate protection circuitry to the IBMS mezzanines. The remaining outputs are used for the BCF detector and an oscilloscope.
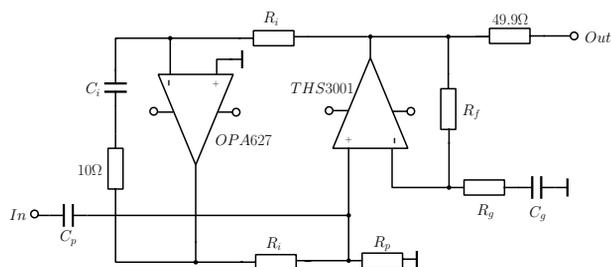
Figure 1: High gain amplifier with offset suppressor.

The signal coming from the transformer is divided by a resistive splitter, is separately amplified and then filtered. The signal amplification for the measurement outputs is dependent on the dynamic range and the bandwidth. Regardless of the bandwidth, the low gain range does not require any amplification as even the LOBW signal creates almost a full scale response at the output of the integrator. An amplification of 30dB and 40dB is required for the HIBW and the LOBW channels respectively for the high gain range.

Maintaining the required bandwidth with high gains is difficult to achieve using voltage feedback operational amplifiers (VFOA). Current feedback operational amplifiers (CFOA) were therefore used. These exhibit higher offset voltages, hence an active feedback to suppress the input offsets was developed (Fig. 1). The implemented method is based on the fact that the measured signal has no DC value. An AC coupled amplifier was designed, and its output actively low-pass filtered, inverted, and injected back to the input of the amplifier. The time constant of the filter is much longer than the one corresponding to the low-frequency cut-off of the measurement transformer.

All filters implemented in the RF distributor are of Gaussian type to ensure that no overshoot occurs in the response to the input signal. The HIBW filters are passive 2nd order LC circuits, and their goal is to reduce the peak amplitude of the incoming beam signal. Fourth order filters consisting of two Sallen-Key blocks were used to implement the LOBW channels.

The entire RF distributor was designed as a VME card. In order to control the impedance of the tracks
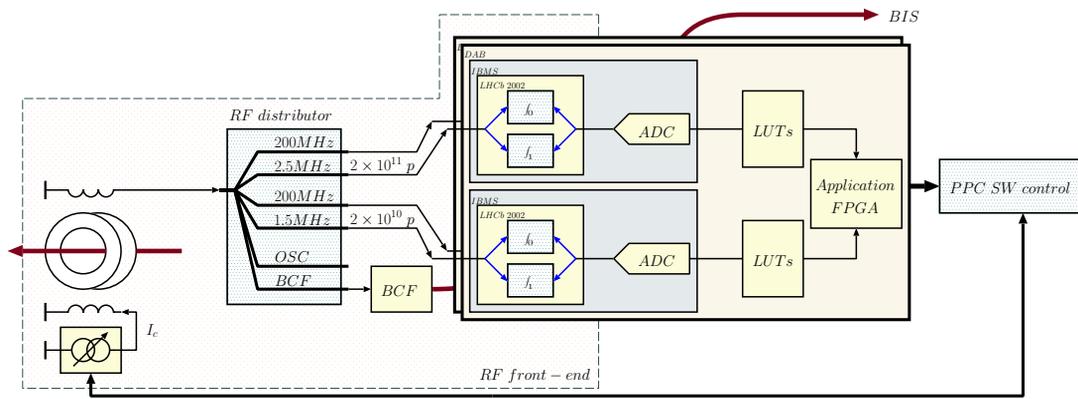
Figure 2: Schematic of the signal processing during the calibration and the intensity measurement.

it was manufactured using four layer composite material. The RF tracks were implemented on a Neltec NY9220 0.256mm thick substrate, which forms the top and the first interior layer of the PCB. The bottom and the second interior layer use standard FR4 material (0.8mm), which is melted by 0.4mm thick prepreg onto the RF substrate. The entire design is protected by a brass shielding. The measured S_{11} using such a configuration was found to be s_{11}=-25dB at 800MHz and s_{11}=-20dB at 1.2GHz.

THE BCF DETECTOR

The LHC Beam Interlock System (BIS) needs the FBCTs to provide information about whether or not there is beam circulating in the LHC. In order to provide this a detection method was implemented using a constant fraction discriminator (CFD) with offset shifting as seen in Fig. 3. By setting the V_{ofs} the threshold at which the CFD triggers can be modified. In order to catch very short pulses appearing at the output of the CFD an ECL flip-flop was connected between the CFD and the processing FPGA. This permits the FPGA, which is clocked at 50MHz, to capture even short signals. The FPGA algorithm for
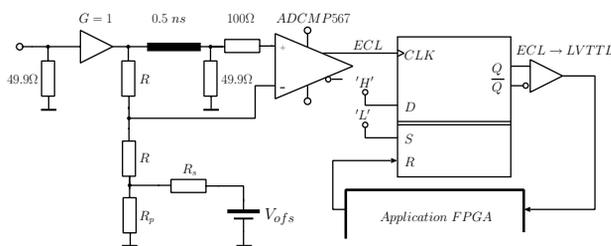
Figure 3: Principal description of the BCF detector for the LHC.

the detection is based on counting the number of events reported by the CFD. A counter value is increased every time the CFD triggers and it is decreased every 100μs. As the LHC turn period is ≈ 89μs, the presence of even a single bunch will slowly increase the value of the counter. By exceeding a given count threshold the presence of circulating beam is presumed and this information is

passed to the BIS. Once the counter is saturated, it stays in the saturation as long as the CFD triggers at least once per 100μs. When the CFD triggers disappear the counter automatically decrements until the threshold value is reached. At this moment the counter value is reset to zero and the BCF detector reports no circulating beam. The value attributed to the beam presence counter threshold will affect the hysteresis of the detector.

For the LHC start-up a four bit counter depth was chosen and the count threshold set to 75% of the maximum value. The V_{ofs} voltage was trimmed to trigger when 2.5×10^9 particles having $\sigma = 680ps$ appear at the input of the CFD. The noise of the electronics limits the CFD threshold to some 2×10^9 particles for this bunch width.

CALIBRATOR

The calibrator for the LHC FBCTs must generate currents to calibrate all four measurement channels. Two point calibration (offset and gain) is used, implying the use of three currents - 750mA, 40mA and 7.5mA. Both HIBW and LOBW channels for the low gain use the 750mA and 40mA, while the HIBW high gain channel uses the 40mA and 7.5mA. The LOBW high gain channel can only use the 7.5mA, with the offset assumed to be zero.

The operation of the calibrator is depicted in Fig. 4. The calibrator consists of a source of high voltage (HV), a variable current sink (I_c) and switches (Q_1, Q_2). The operation of the calibrator is monitored by an ADC, which measures the voltage over the reference resistance R_m and the DC value of the HV. The calibrator functions in the following way. In the idle mode the HV switch is turned on with transistors Q_1 and Q_2 in the off state. This permits the capacitors C_c to charge via the current passing through the path R_c-C_c-R_d as shown in the picture by the orange arrow. Both capacitors are charged at the same moment. When the calibration is triggered a set of timings is generated. Firstly, the HV switch is turned off and Q_1 opens (current flows). The disconnection of the HV is time consuming, and it takes 8μs to switch off the 200V source. Once this is done, switch Q_1 is opened and with the HV disconnected from the R_c, the current starts to

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flow from the lefthand C_c into the current sink I_c (blue arrow). This stabilizes the feedback of the I_c and charges all internal capacitances. Once I_c is stabilized, switch Q_1 is quickly closed while opening Q_2. The current now no longer flows through Q_1 and the dummy resistance R_d, but via the righthand C_c, R_l and the calibration winding L_x (green arrow). As the current sink is already stabilized, concurrent switching of Q_1 and Q_2 provides a very sharp negative current pulse. Under laboratory conditions, using a short cable to connect to a resistive load, a fall time of $4ns$ was measured for a current of $800mA$ (SR=1000V/μs). The calibration cycle is completed by closing switch Q_2 and reconnecting the HV. This permits both capacitors C_c to charge again. The precision with which the current can
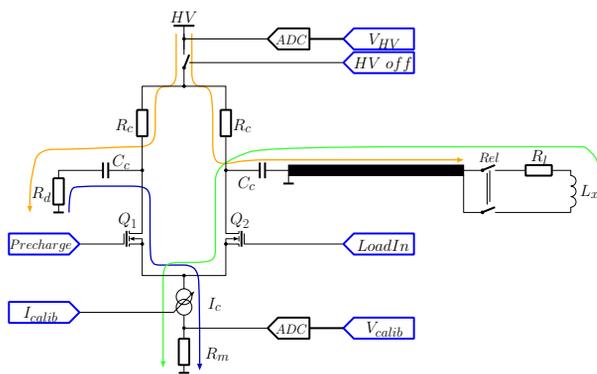
Figure 4: Principle of operation of the LHC BCTF calibrator.

be set is limited by the input offsets of the operational amplifiers (OA) used. As the current sink I_c must quickly react to changes of the load, it is implemented using fast OAs. These limit the uncertainty of the setting of the I_c to $\approx$1.9mA. This value was not acceptable and therefore a measurement of the voltage over a reference resistance R_m was implemeted. By using low offset OAs and a precision component network for this measurement the uncertainty on the knowledge of the actual current generated is limited to 650μA (9% at 7.5mA).

Figure 5 displays the results of the measured linearity error of the complete calibration and acquisition chain. The values are calculated for a single calibration shot per given calibration current. The calibration pulse is measured by LOBW channels on both gain ranges, digitized and passed via look-up tables correcting the offset and gain of the integrator. The error is calculated with respect to the best linear fit. The value of the error increases towards lower calibration currents. This is caused by worsening of the signal to noise ratio and can therefore be partially reduced using statistics, i.e. calculation of an average for each desired current. This is especially true for the high gain LOBW channel which exhibits increased noise due to the heavy amplification. A single VME card houses both the calibrator and the BCF. All settings, including the BCF threshold value, are stored in a local memory and protected

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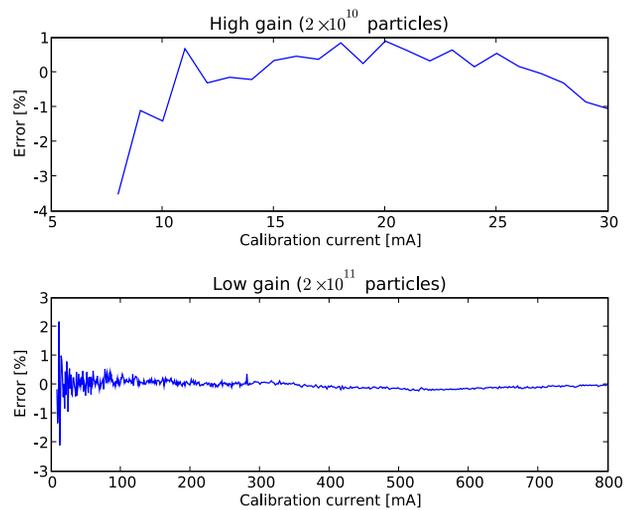
Figure 5: The error of the linearity of the calibration chain for LOBW channels.

against accidental overwrite. The BCF detector connection to the BIS is doubled to ensure redundancy. The calibrator is connected to the calibration turn on the transformer via $\approx$30 metres of 7/8" air-dielectric Heliflex cable. This type of cable is also used to transfer the beam signal to the RF distributor.

LHC START-UP

The FBCT system as described here was installed in the LHC tunnel in time for the start-up in September 2008. Special attention was paid to install the cables and electronics far from any sources of pulsed currents. The first measurements of the FBCTs with circulating beam did not show any perturbation due to neighbouring equipment. The FBCTs for the dumps, however, do acquire noise induced by the extraction kicker magnets. The performance of these monitors will depend on the relative position in time of this signal with respect to the beam signal.

The complete system was tested during the first few days with LHC beam. The acquisition chain, software and implementation of the control system worked flawlessly. Minor problems were detected in the algorithm used for calibration. These issues are now being solved on a test facility using the SPS fast transformer equipped with the same LHC electronics. The functionality of the BCF detector was not tested due to the very small intensity of the beam which was circulating in the LHC.

REFERENCES

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