DEVELOPMENT OF A METHOD FOR CONTINUOUS FUNCTIONAL SUPERVISION OF BLM SYSTEMS

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Abstract

It is of vital importance to provide a continuous and comprehensive overview of the functionality of beam loss monitoring (BLM) systems, with particular emphasis on the connectivity and correct operation of the detectors. At CERN, a new BLM system for the pre-accelerators of the LHC is currently at an advanced stage of development. This contribution reports on a new method which aims to automatically and continuously ensure the proper connection and performance of the detectors used in the new BLM system.

INTRODUCTION

At CERN, the scheme for machine protection and optimization relies heavily on beam loss monitors (BLMs). Therefore, a continuous functional supervision of the BLM system is essential. To our knowledge, no particle accelerator in the world has this feature at present.

Currently, one of the most advanced solutions for supervising the functionality of a BLM system is in operation at the LHC. This method enforces a connectivity check of each detector channel every 24 hours, which can only be executed while the accelerator is offline.

The LHC Injectors Upgrade (LIU) project, presently underway at CERN, is a major accelerator upgrade project targeting the pre-accelerators of the LHC. Among other activities, this program mandates the deployment of an upgraded BLM system with extended functionality in the injectors, which is at an advanced stage of development at the time of writing.

This paper reviews the present state of a project aimed at building on LHC experience to develop a process capable of ensuring an uninterrupted supervision of the entire beam loss monitor signal chain from the detector to the acquisition electronics.

DETECTOR CONNECTIVITY CHECKS AT THE LHC

Ionization chambers are the most frequently used detector type in the LHC BLM system [1]. The bias high voltage applied to the chamber gives rise to an output current proportional to the energy deposited in the volume of the chamber by incident ionizing radiation. This current is acquired and digitized by the front-end electronics [2], then further processed by the back-end electronics [3] responsible for deciding whether the machine is operating under safe conditions. These modules can trigger the safe extraction of circulating beams or inhibit further injections as required.

At the LHC, the method for checking the connectivity of the detectors relies on inducing a sinusoidal modulation at a frequency on the order of 50 mHz in the bias high voltage. The chamber responds as a capacitor and a corresponding sinusoidal signal is generated in its output current, which can then be digitized through the standard signal acquisition chain. The signal is then detected in the time domain using a matched filtering algorithm executed on an FPGA device.

The absence of the modulation in the digitized data stream indicates a defective cabling connection, while variations in the amplitude and the phase of the modulation have been shown to correspond to various other degradations of the signal chain. The connectivity check thus also acts as a component integrity survey [4,5]. Such a check is performed without beam before the start of each physics fill.

SYSTEM SUPERVISION AT THE INJECTORS

System Architecture in Brief

The new BLM system under development will be common to all injectors. These accelerators impose widely varying requirements, thus the acquisition frequency and input dynamic range of the new system must surpass those of its predecessors. In most locations, ionization chambers will be employed but the use of other detector types such as Cherenkov monitors, diamond detectors and secondary emission monitors is also foreseen. Therefore, the system needs to be able to handle all these various types of detectors [6].

These considerations imply that a new acquisition frontend module had to be designed for the new BLM system. It can digitize input currents ranging from 10 pA to 200 mA using a novel measurement method based on a fully differential integrator [7]. The digitized samples are forwarded to the back-end processing and triggering (BLEPT) modules at 500 ksps for further processing. These modules calculate several moving window integrals referred to as running sums for the digitized current of each detector and are responsible for revoking the beam circulation permit if required.

The Suggested Method

For checking the integrity of the main ionization chamber beam loss monitoring system of the injectors, a modulation-based scheme like the one used in the LHC might be a viable option. However, that scheme requires the accelerator to be offline as the checks, lasting about 6 minutes, are executed during the injection preparation phase, i.e. long periods with no beam characterizing the operation of the LHC. In

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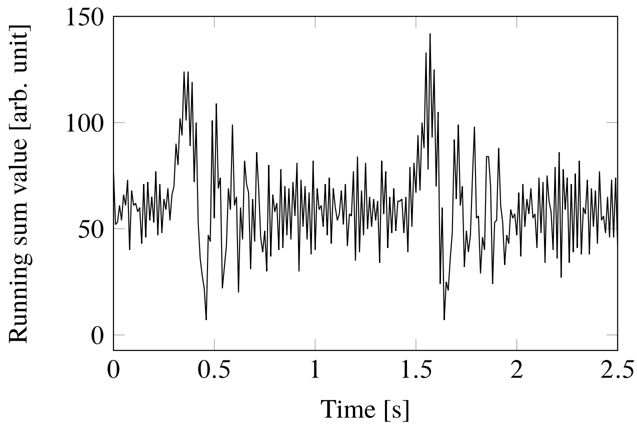

Figure 1: Acquisition made in the PSB system with a linear chirp excitation. Frequency sweep: 0 Hz to 20 Hz. The running sum window length is 10 ms to ensure a good visualization of the features of the signal. Note the reduction in the amplitude of the modulation as the frequency increases, due to the length of the cables connected to the detector.

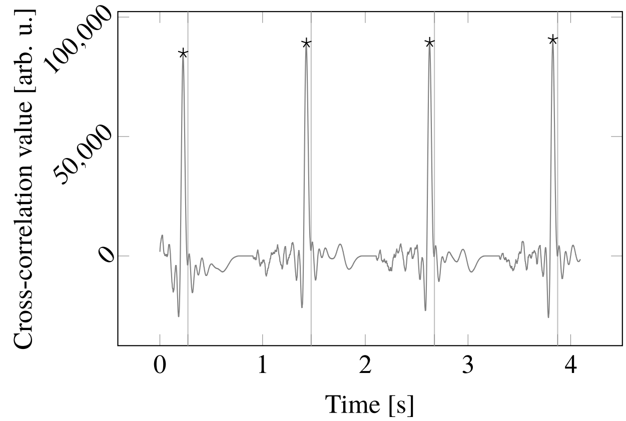

Figure 2: Cross-correlation waveform acquired in the PSB, using the 1 ms running sum with a linear chirp signal sweeping from 0 Hz to 20 Hz. Windowing and average suppression features active. The vertical grid lines represent the moment the Beam In timing strobe signal is asserted. The maxima detected by the logic ($\star$) take place about 50 ms before the strobe signal.

contrast, the operation of the injectors is practically uninterrupted and our goal is to provide continuous supervision. As revealed by previous measurements [8], the frequency range usable for modulation in the new BLM system far exceeds that available in the LHC, due to architectural differences between the two systems. This, combined with the fact that the injectors operate in a pulsed mode, allow us to exploit the gaps between the pulses for the execution of our checks.

At present, two installations of the new system are almost complete, at the Proton Synchrotron Booster (PSB) and LINAC4 accelerators. For both, the basic period of the pulsed operation is 1.2 seconds. In every basic period, there is beam in the LINAC4 for less than 1 ms, and in the PSB for only about 0.7 s, allowing over 0.5 s for checks without beam in both cases.

According to our measurements, by setting up the modulation signal to start and end at the steady-state value of the high voltage, all transients can be avoided when enabling or disabling the modulation. Additionally, the high voltage power supplies providing the bias voltage are capable of producing a swept-frequency modulation. We considered a linear swept frequency sine (chirp) signal, sweeping from 0 Hz to $10 - 100$ Hz. Fig. 1 shows a sample acquisition.

This configuration offers the following advantages:

- The operational measurement and the modulation related to the connectivity checks are executed in distinct time intervals, thus any mutual interference can be avoided.
- The swept-frequency sine signal produces a unique signature and can easily be detected in the time domain by matched filtering, even in noisy environments.

The high voltage power supplies are controlled by an FPGA on the Combiner and Survey (BLECS) module installed in the back-end crate. We developed a firmware for the BLECS card capable of producing arbitrary modulation waveforms of a duration up to 0.5 s. In order to emit the modulation only in periods without beam, the functionality is triggered by the Beam Out signal from the accelerator timing.

The detection of the corresponding signal in the output current of the detectors is done on one of the FPGAs of the BLEPT back-end module. The cross-correlation of the acquired signal to the samples of the excitation signal can be calculated using simple fixed-point arithmetic. Our tests in MATLAB showed that detection is possible using the digitized data at the full sampling rate of 500 ksps, but the resource cost of this implementation would be too high for the FPGA at hand and it is not necessary for the frequency range we are targeting. Instead, we resorted to using the 1 ms running sum readily available in the back-end processing firmware.

Typically, the signal amplitudes related to actual beam loss events are much higher than the amplitude of the modulation. In order to eliminate any disturbing influence in the cross-correlation waveforms, we apply windowing to the input signal: we set all samples to 0 when beam might be present. Since an offset current is injected into the input of the front-end card in order to stabilize it and the steady-state value of the input current is not zero, this manipulation causes abrupt jumps and spurious peaks in the cross-correlation waveform at the edges of the window. In order to mitigate this phenomenon, we calculate the average value of 512 samples in the beam-free part of each basic period by accumulating them and simply applying a bit shift, then subtract the resulting number from all non-windowed sample values. Despite its simplicity and low resource use, this method reduces spurious peaks considerably.

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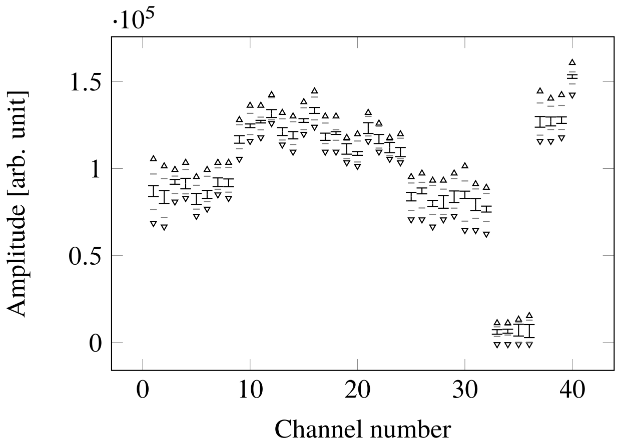
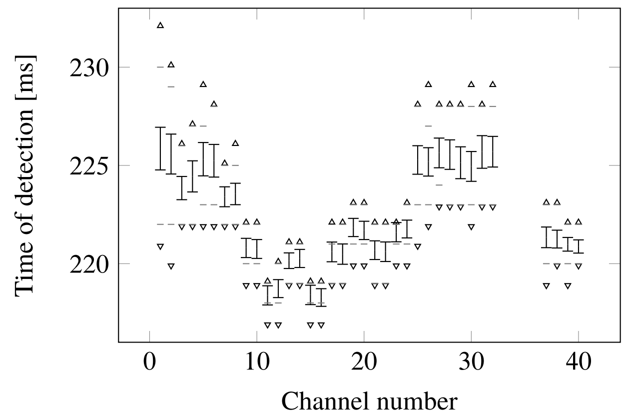


(a) Cross-correlation peak amplitude statistics and acceptance limits per channel. Note that channels with longer cables (channels 1-8, 25-32) tend to have lower amplitudes with higher standard deviations. Disconnected channels (channels 33-36) exhibit amplitudes in a completely separate, lower range.



(b) Cross-correlation peak detection time statistics and acceptance limits per channel. Channels with shorter cables (channels 9-24) tend to have shorter delays with lower standard deviations. The detection time is unpredictable in disconnected channels (channels 33-36), thus these are omitted here.

Figure 3: Cross-correlation peak amplitude and detection time statistics for 1024 contiguous samples (about 20 minutes) acquired in all available channels at the PSB. The mean values and corresponding standard deviations per channel are represented by error bars, while the minima and maxima of these samples are shown by -. ▿ and ▵ represent the low and high acceptance limits, respectively. The acceptance limits are unique per detector and the values shown in the plot were adjusted further with respect to the ones established based on this acquisition, since our subsequent acquisitions over longer time periods showed a non-negligible amount of outlier points.

The maximum of the resulting cross-correlation waveform is identified in each basic period, as demonstrated in Fig. 2. The firmware then checks if the corresponding amplitude and sample number values are within the acceptance window established through calibration, and a decision whether the modulation is present can then be made automatically.

After a series of acquisitions from all 40 detector channels currently available at the PSB accelerator (Fig. 3), we found that the minimum cross-correlation amplitude recorded in presence of the modulation on a correctly working channel is about 4 times higher than the maximum amplitude recorded on an unconnected channel, which provides a satisfactory margin for detection. However, fluctuations in amplitude may be as high as 25-35 %, thus the acceptance windows need to be fairly wide in general. Nevertheless, over a basic period of 1.2 s, the maximum variation in the measured time of the maximum is quite low, at ±10 samples (10 ms).

Failure Cases Covered

In our tests in the laboratory and at LINAC4, this method allowed us to detect all possible cable disconnection scenarios correctly: disconnection of the high voltage or signal cables, either at the acquisition electronics or at the detector.

In the LHC implementation, variations in the value of the filter capacitor at the input of the ionization chambers were found to cause phase shifts in the recorded modulation signal. These variations may reveal faulty soldering or the degradation of the capacitor due to radiation [5]. We tried reproducing this behavior with our implementation, both through simulation by adapting a previous model [9] and laboratory testing. The simulation was intended as a qualitative study of the phenomena. The results, shown in Fig. 4, suggest that in the frequency range we are targeting, changes in the value of the capacitor don't produce phase shifts but result in changes in the amplitude of the output current. This behavior was confirmed by test measurements. However, the acceptance windows currently required to detect disconnection are quite wide in terms of amplitude (see Fig. 3), which results in a reduced sensitivity to the deterioration of the filter capacitance. Nonetheless, sufficiently high variations such as a disconnected filter capacitor remain detectable.

CONCLUSIONS

We presented a promising method for continuous functional supervision of the BLM system currently being developed for the injectors. The procedure takes advantage of the non-presence of beam between injection cycles.

It is desirable to refine the acceptance windows currently used, since narrower windows, especially in terms of amplitude, would improve the sensitivity of the method for the detection of non-conformities.

In the future, we'd also like to assess whether this method can be used to detect other failure cases, such as the connection of a wrong detector type or a leaky ionization chamber.

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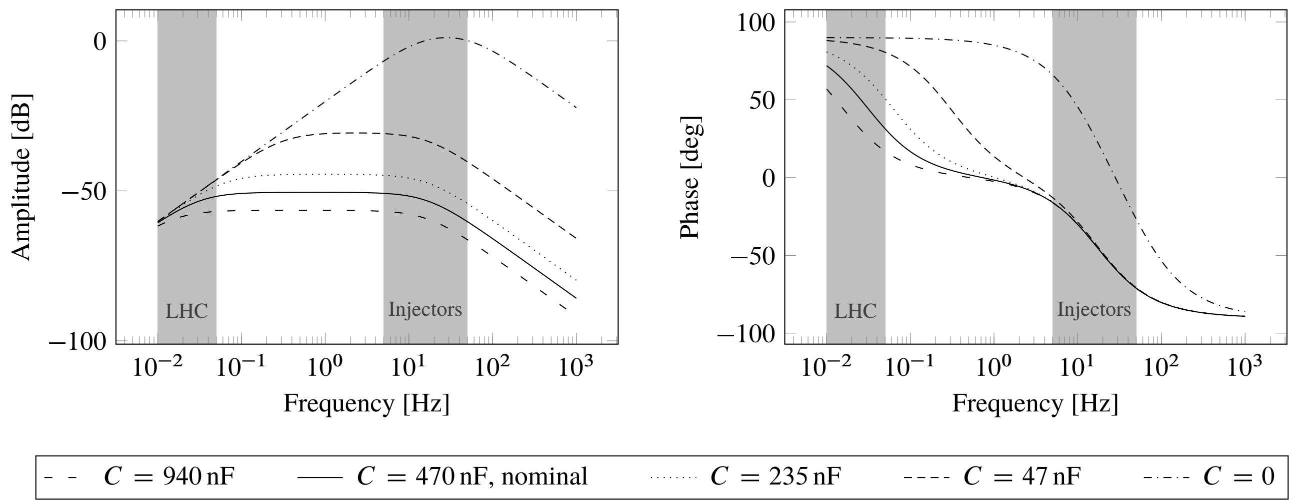

Figure 4: Bode plot of the input current digitized by the front-end card for different values of the filter capacitor at the input of the ionization chamber. The curves were obtained using a simulation model adapted from our earlier work [9], assuming cable lengths of 100 m. The excitation is a sine wave with an amplitude of 5 V superimposed onto a DC component of 1500 V. These simulations underpin that the behavior changes substantially between the frequency ranges targeted in the two systems (highlighted). In the new BLM system, variations in the value of the filter capacitor are to be expected to cause changes in the amplitude of the output signal while having a very limited effect in terms of phase behavior.

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