Design and Implementation of On-line System Supervision for Beam Loss Monitoring Systems

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Abstract—**The strategy for beam setup and machine protection of the particle accelerators at the European Organisation for Nuclear Research (CERN) is predominantly based on beam loss monitoring (BLM) systems. These systems were designed to protect the machines against unintended energy deposition by particles lost from the beams and escaping the beam lines, to assist in diagnosing machine faults and to provide feedback of the machine behavior to the control room and other systems.**

The aim of the PhD thesis project related to this paper is to design and implement a process providing a continuous and comprehensive surveillance of the entire beam loss monitoring signal chain from the detector to the processing electronics, with particular emphasis on the connectivity and functionality of the detectors. At present, no particle accelerator features such a procedure.

Sections I-III of this paper elaborate on the background of the project. Section IV summarizes the motivation of the project, briefly reviews the current best implementation and discusses the state of the development. In particular, Section IV-A surveys the hardware features of the system relevant to the development and Sections IV-B and IV-C relate the measurements I conducted to assess the transfer characteristics of the signal chain with the modulation of the high voltage power supply as input. Section V anticipates the next steps of my development work.

I. INTRODUCTION

The particle accelerator complex dedicated to fundamental research in physics at the European Organisation for Nuclear Research (CERN) consists of several distinct accelerators [1]. Specifically, particles are accelerated to increasingly higher energies through a succession of these before being injected into the current flagship particle collider and highest energy machine of the institute, the Large Hadron Collider (LHC). This sequence of accelerators is referred to as the LHC injector complex.

The LHC Injectors Upgrade (LIU) project has been launched to consolidate the aging low energy machines and to meet the ever more stringent requirements in terms of particle beam quality imposed by the LHC. Particle beams with higher energy and intensity[1] will allow to further increase the luminosity[2] of the LHC.

At CERN, beam loss monitoring (BLM) systems deployed at the accelerators are at the core of the strategy for beam setup and machine protection. A continuous supervision of the entire BLM signal chain is therefore essential.

II. BEAM LOSS MONITORING

Beam loss monitoring consists of measuring the shower particles originating from particles lost from the beams and escaping the beam lines. If necessary, the safe extraction of beams and an inhibition of injections is triggered in order to protect the machines against unintended energy deposition, and measurement data are provided for machine calibration and tuning. In particular, for a machine based on superconducting magnets such as the LHC, the fast response of the BLM system is critical for protection against short and intense particle losses, while for longer losses, the quench protection system (QPS) and the cryogenic system provide assistance [2].

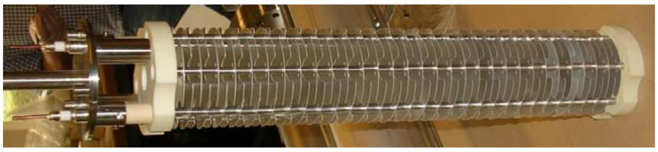

Figure 1. Photograph of an LHC ionization chamber with the cylindrical insulating cover removed [2]. Notice the stack of aluminum electrodes and the ceramic insulation at both ends.

The beam loss monitoring system in operation at the LHC employs mainly ionization chambers, depicted in Fig. 1, as detectors. The particles crossing the chamber create ionization, that is, they liberate electrons from the molecules of the gas filling the volume. The resulting electrons and ions are then separated by a bias high voltage applied to the terminals of the chamber and collected on a stack of conductive electrodes, thereby creating a measurable charge proportional to the total energy deposited in the chamber by the ionizing radiation. The most advantageous locations for the placement of the discrete detectors are determined in advance by simulation.

The output signal of the detectors is connected to the front-end electronics via copper cables for measurement and digitization. The numerical values are then sent to the back-end processing and decision making card over a high-speed serial link. The back-end card computes several moving window integrals of different durations, referred to as running sums (RS), for each channel. These are then compared to their respective predefined abort thresholds in real-time and in case of excess, a beam abort and injection inhibition is triggered.

In order to provide the necessary fail-safety and achieve the expected availability, a large number of additional processes

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[1] The number of particles in the beam or, equivalently, the beam current.

[2] The rate of collisions, more precisely, the ratio of the number of events detected in a certain time to the interaction cross-section.

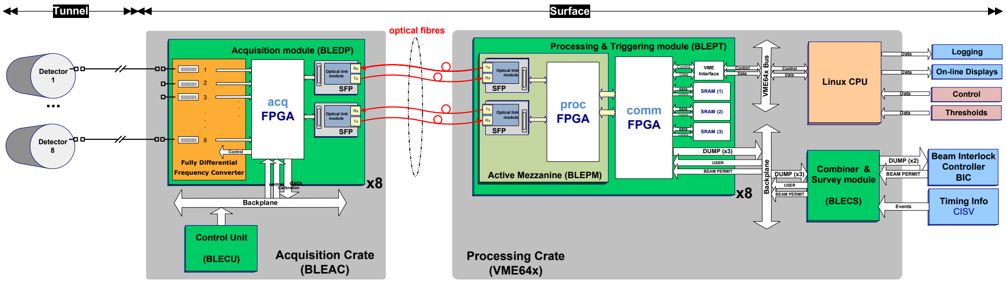

Figure 2. Architecture of the BLM acquisition system for the injector complex at CERN [3].

monitoring the status of the system in real-time have been implemented [4].

The LIU project mandates the development and commissioning of a new BLM system for the injectors. The new system features a higher acquisition frequency and extended dynamic range, and is adapted for the connection of more varied types of detectors as input than its predecessors [3].

III. THE BLM SYSTEM FOR THE INJECTOR COMPLEX

The architecture of the new BLM acquisition system, shown in Fig. 2, has been chosen to make it generic, versatile and highly performant, also taking into consideration the high expectations in terms of reliability and availability. The system makes use of reprogrammable FPGA devices for flexibility and to allow targeting the various requirements of the different injectors. Since the electronics will be installed in protected areas, no radiation tolerance is required.

The acquisition stage has been designed to allow connecting several detector types. In the majority of cases, the use of ionization chambers similar to those employed for the LHC is foreseen, however, other detector types such as secondary emission monitors, diamonds and Cherenkov detectors will also be used in some locations to cover particular cases [3].

The system is in an advanced stage of development. A prototype installation has been set up at the Proton Synchrotron Booster (PSB) accelerator with pre-series front-end cards, in parallel to the previous system currently used for machine protection. The prototype system is used to evaluate performance and gather operational experience.

A. Front-end electronics

An acquisition crate (BLEAC) hosts a maximum of eight acquisition modules along with a control unit (BLECU).

The output current of the detectors is digitized with a new mixed measurement technique based on a fully differential integrator [5], implemented on the new BLEDP acquisition module. It allows the acquisition of input currents ranging from 10 pA to 200 mA, which corresponds to a dynamic range of $2 \cdot 10^{10}$. The measurement range is split into two overlapping ranges covered by two separate circuits: the Fully Differential Frequency Converter (FDFC) operates in the range 10 pA – 10 mA, and the Direct ADC (DADC) in the range 100 μA – 200 mA. The front-end automatically switches between the two modes depending on the magnitude of the input current. The switching thresholds are set by the FPGA of the acquisition module, which is also in charge of collecting and transmitting the digitized data for further processing [6].

Each BLEDP card provides eight input channels. A small, constant offset current is injected into every channel in parallel to the input signal in order to stabilize the circuit. The use of this mechanism to detect whether the channel in question is operational is also foreseen in the future.

B. Back-end electronics

Up to eight processing modules, a Linux-based front-end computer (FEC), accelerator timing receiver cards and a Combiner and Survey module (BLECS) are hosted in a VME64x processing crate.

The processing and triggering (BLEPT) modules feature an active mezzanine card hosting an FPGA. The FPGA is responsible for communicating with the BLEDP cards over an optical link, receiving the acquired data, computing the running sums and comparing them to their respective beam abort thresholds. The information is transmitted to the FPGA on the carrier board, which handles communication with the FEC and the beam interlock lines. This involves publishing processed data and status information on the VME bus, and directing the decision regarding beam injection and circulation.

The BLECS module distributes accelerator timing and status signals to the BLEPT cards and forwards the beam abort requests generated by the BLEPT modules to the Beam Interlock System. It is also responsible for initiating the system sanity check procedures and providing confirmation of their successful execution at regular intervals [3].

IV. CONNECTIVITY CHECKS

At present, no particle accelerator features a procedure providing a continuous and comprehensive supervision of the functionality of its beam loss monitoring system, with particular emphasis on the connectivity and functionality of the detectors. The current best solution operates in the LHC, where among the sanity check procedures mentioned earlier, a connectivity check of each detector channel is enforced every 24 hours. This check can only be executed while the accelerator is not operational.

The primary purpose of this test is to ensure the correct cabling connection of each beam loss monitor. By adding a harmonic modulation to the high voltage supply of the detectors, a corresponding modulation is induced in their output current, which can be detected with the normal signal acquisition chain. If the cable to a detector is missing, disconnected or discontinued for any reason, the harmonic modulation won't be present in the output current. The modulation frequency used in the LHC is on the order of 10 mHz.

This procedure also allows surveying the integrity of the components. Variations in the amplitude and phase of the output current have been found to correspond to various kinds of deterioration in the components of the acquisition chain in the LHC implementation [7].

The present PhD thesis work involves the design, construction, testing and integration of an improved procedure in the injector BLM system. The process should provide a continuous supervision of the entire signal chain from the detectors to the processing electronics as well as the measurement ability of the detectors. However, since the BLM system is mission critical, the processing of the measurement signal should not be altered for the purposes of this test, to avoid introducing new failure cases into the system. Therefore, the error induced by the connectivity checks must either remain within the error margin of the system or the measurement must be done during periods with no beam in the machine, in order to avoid compromising machine protection.

A. *Hardware features of the injector BLMs*

In the injector BLM system, a maximum of 64 ionization chambers are powered in parallel by a pair of high voltage power supplies through a custom-made high voltage distribution box. The two power supplies are connected in parallel through protection diodes, with the secondary set to a voltage about 50 V lower. This way, in normal operation, the secondary is idle, but if the primary fails, it can take over powering the ionization chambers.

As in the case of the LHC system, each ionization chamber has a low-pass filter on its input, which can temporarily take over supplying charges to the chamber in case of high losses and the resulting high current draw. The cutoff frequency of these filters is approximately 0.03 Hz.

The power supplies are from the Heinzinger NCE series, capable of supplying an adjustable DC output voltage of 0−3000 V with a current limited to 20 mA. The output voltage is specified to be proportional to the voltage of 0−10 V applied to the analog setpoint input. The manufacturer provides no additional details about the implementation of the power supply.

The voltage setpoint input of the power supplies is driven by the sum of the voltage output of two 16-bit DAC channels, one for the DC component, the other one for the modulation as required. Their output is subject to analog low-pass filtering, with a cutoff frequency of about 80 Hz. The voltage is capped at 6.8 V with a voltage regulator diode to avoid raising the bias voltage above the high end of the ionization chamber detection region, about 2000 V. In the current configuration, the highest possible modulation amplitude is approximately 250 V_{PP}.

B. *Measurement of the signal chain*

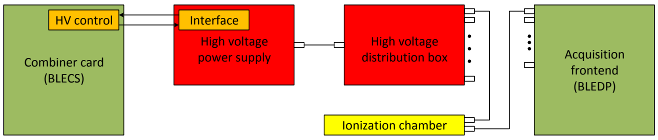

Figure 3. Simplified view of the modulation signal chain.

In order to assess the capabilities of the modulation signal chain, described in Sec. IV-A and illustrated in Fig. 3, a series of measurements was executed.

Measured with an oscilloscope, the step response of the high voltage drive circuitry on the combiner card (BLECS) indeed corresponds to that of a first-order low-pass filter with a cutoff frequency of approximately 80 Hz.

Two measurement methods have been used to characterize the response of the high voltage power supply. First, the device features two analog feedback lines with voltages proportional to the output voltage and the output current, respectively. These are connected to an ADC and can be read by the FPGA of the combiner card. Since the operational firmware only acquires and publishes data at 1 Hz, a signal tap has been implemented in the firmware to access acquisitions at their native frequency of about 530 Hz. Second, a high voltage divider with a ratio of 1 : 1000 can be connected directly to the output of the power supply or to the high voltage distribution box, and its output can be measured with an oscilloscope. The results obtained with the two acquisition methods have proven to be consistent and have been used interchangeably.

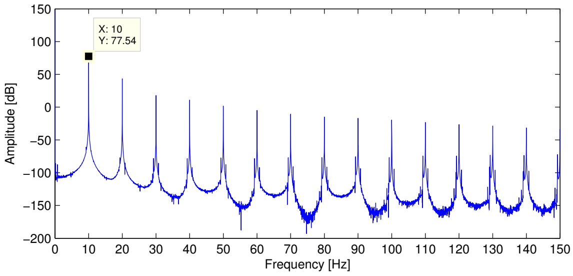

Figure 4. Output spectrum of the high voltage power supply when driven with a 10 Hz modulation of approximately 250 V_{PP} added to a DC level of 1500 V. The waveforms were acquired from the feedback output of the supply. Notice the apparent nonlinear distortion.

With sinusoidal inputs of maximum amplitude and at frequencies up to 5 Hz, a clear sine wave is observed at the output of the high voltage power supply. However, at higher frequencies, distortions become apparent even in the time domain, and the spectrum becomes similar to that shown in Fig. 4, indicating nonlinear effects. Measurements with a square wave excitation suggested a slew rate limitation for voltage decrease, however, the analysis of the step response of the circuit revealed a different behavior. For increases in voltage, the high voltage power supply behaves as a first-order low-pass filter, and for decreases, it exhibits a slow exponential decay with a time constant largely dependent on the loading impedance, typically on the order of 1 s. This behavior is consistent with the power supply actively driving output voltage increases and just letting its output capacitors discharge over the load and an internal parallel resistor for voltage drops. If this limitation is observed, the power supply behaves like a first-order low-pass filter with a cutoff frequency of about 30 Hz.

The high voltage distribution box contains no capacitors and appears to have no significant influence on the frequency response of the system.

C. Data acquisition

A rack hosting an acquisition crate and a processing crate (see Sec. III) along with a single high voltage power supply and a high voltage distribution box is available in the lab. A single ionization chamber was connected to the power supply through the distribution box and its current output was measured through the BLEDP card. The raw data acquired at 500 kHz were transmitted directly to a PC over Ethernet for processing [8]. For this measurement, the amplitude of the modulation needed to be reduced to $1/8$ of the maximum in order to avoid exceeding the magnitude of the offset current, thereby clipping and distorting the signal, since the system can only acquire positive current.

The spectrum of the acquisitions was very flat, with peaks scattered throughout the spectrum due to the operation of the high voltage power supply. At modulation frequencies up to 20 Hz, the corresponding peaks were clearly detectable in the spectrum, at least 20 dB above the noise floor.

Similar acquisitions were made with the prototype system installed in the PSB. This prototype rack features both power supplies, driving a single high voltage distribution box. 32 ionization chambers, mounted onto the accelerator and acquiring actual loss signals whenever there is beam, are connected to the system. Due to the attenuation of the high voltage cables of $60-80$ meters and the presence of multiple detectors, the modulation amplitude was set to the maximum in this case to obtain current amplitudes similar to those in the previous measurement, albeit with more noise.

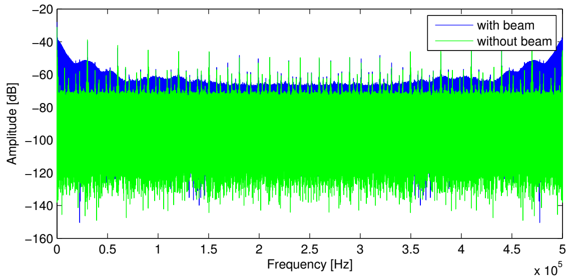

Figure 5. Spectrum of the data acquired in the PSB with and without beam. The frequency axis spans $0-500$ kHz. Notice the scattered peaks due to the operation of the power supply.

The spectra obtained with no beam are remarkably similar to those seen in the lab. However, as shown in Fig. 5, the presence of beam has a considerable effect on the spectrum. Along with an increase in the noise floor, an amplitude roll-off type effect can be observed at frequencies up to $100-150$ kHz. The shape of the roll-off appears to vary from acquisition to acquisition. The low end of the spectrum contains a 0.833 Hz component along with its harmonics, which corresponds to the 1.2 s duration of the basic period[3] of the PSB. Thus, such modulation frequencies should be chosen that the resulting peaks fall between the ones corresponding to the basic period. In this case, even though the magnitude of the peaks created by the modulation doesn't far exceed that of the basic period peaks, the modulation remains detectable up to about 15 Hz. Contrary to previous expectations, without beam, a 20.5 Hz peak is detectable with a margin of about 20 dB. It has to be noted that this signal is no longer detectable in the presence of beam.

V. PERSPECTIVES

Implementation of a prototype algorithm to acquire and identify the modulation is foreseen as the next step. The measurements suggest remarkable performance potential and exploiting a frequency range unused in the LHC implementation seems conceivable. However, the frequency response of the system will need to be studied further in order to implement an integrity survey similar to the LHC system.

Improvements to the simulation model of the signal chain, currently giving good estimates of the discharge time constants of the power supply, are foreseen to feature a more realistic series resistance in the power supply and better predict other parameters such as current consumption.

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[3] One basic period corresponds to an entire beam cycle: injection, acceleration, ejection. This periodicity is therefore characteristic of the entire system.