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ON-LINE SYSTEM SUPERVISION OF BEAM LOSS MONITORING SYSTEMS WITH SINUSOIDAL EXCITATION

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Abstract - The project related to this paper is aimed at the design and implementation of a process providing a continuous and comprehensive supervision of the beam loss monitoring (BLM) signal chain at the European Organization for Nuclear Research (CERN), a feature no particle accelerator currently has. This paper reports on the background of the project, the current best solution to the problem, the measurements done to lay the foundations of the new implementation and the suggested new setup of the on-line diagnostic process.

Keywords: beam loss monitoring, beam instrumentation, real-time diagnostics, supervision, CERN

1. INTRODUCTION

1.1. Background

At the European Organisation for Nuclear Research (CERN), the particle accelerator chain serving the needs of fundamental physics research comprises several distinct accelerators [1]. In particular, before being injected into the current flagship particle collider of the facility, the Large Hadron Collider (LHC), particles are progressively accelerated to higher and higher energies through a series of accelerators, referred to as the LHC Injector Complex.

The LHC Injectors Upgrade (LIU) project targets the overhaul of the aging accelerators to meet the ever-increasing demands in terms of particle beam quality imposed by the LHC. Higher energy and intensity[1] beams will be required to further increase the luminosity[2] of the LHC.

The strategy for beam setup and machine protection of the particle accelerators at CERN is predominantly based on beam loss monitoring (BLM) systems. The LIU project mandates the development and commissioning of a new BLM system for the injectors. The continouous supervision of the entire BLM signal chain is an essential requirement for this upgrade.

1.2. Beam loss monitoring in general

Beam loss monitoring involves measuring the showers of secondary particles generated by particles lost from the beams and escaping the beam pipes. The measurement data are archived for machine calibration and tuning, and if necessary, the safe extraction of beams can be triggered and further injections can be inhibited to protect the machines from excessive energy deposition. Specifically, the rapid response of the BLM system is vital for protection against short and intense particle losses in accelerators built with superconducting magnets such as the LHC [2].

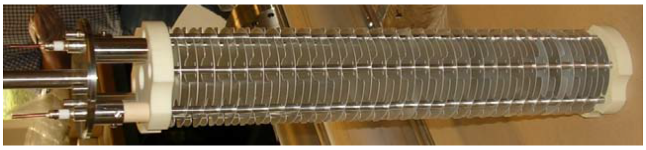

Fig. 1. Photograph of an LHC ionization chamber without the insulating cover [2].

Most of the detectors used in the LHC BLM system are ionization chambers, similar to the one shown in Fig. 1. Electrons and ions are created by the ionizing particles crossing the gas-filled volume of the detector, which are then separated by a bias high voltage connected to the terminals of the chamber and collected on a stack of parallel electrodes. The resulting current signal is measurable and the charge it carries is proportional to the energy deposited in the chamber by the ionizing radiation.

The output current of the detectors is acquired and digitized by the front-end electronics. The digital values are transmitted to the back-end electronics via a high-speed optical link, which computes several moving window averages of different durations for each channel, referred to as running sums (RS). Then, it compares each running sum to its corresponding abort threshold in real-time, and triggers a beam abort and inhibition of injection in case of threshold crossing.

Various additional processes monitoring the status of the system in real-time have been implemented to achieve the required level of fail-safety and availability [3].

1.3. The BLM system of the injector complex

The new BLM system for the injectors mandated by the LIU project, currently in an advanced stage of development, sports an increased acquisition frequency and extended dynamic range. It features reprogrammable FPGA devices for flexibility. The architecture of the new acquisition

[1]The number of particles in the beam.
[2]The rate of collisions, more precisely, the number of events detected in a certain time span divided by the interaction cross section.

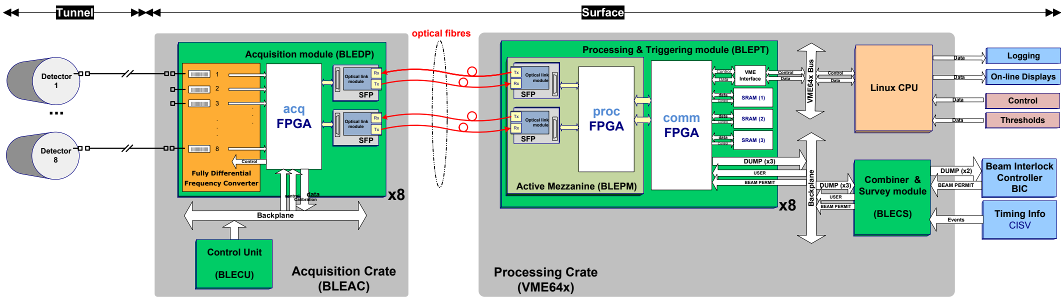

Fig. 2. Architecture of the BLM acquisition system for the injector complex at CERN [4].

system, depicted in Fig. 2, was designed to ensure versatility and high performance and to meet the demanding specifications in terms of availability and reliability.

A maximum of eight front-end acquisition modules (BLEDP) are hosted in an acquisition crate (BLEAC). Each BLEDP card provides eight input channels, whose current is digitized with a new mixed measurement technique based on a fully differential integrator [5]. This method allows the acquisition of currents ranging from 10 pA to 200 mA, that is, a dynamic range of 2×10^{10}. The FPGA of the BLEDP board collects and transmits the data for further processing [6].

A VME64x processing crate hosts up to eight back-end processing and triggering modules (BLEPT), along with accelerator timing receiver cards, a Combiner and Survey module (BLECS) and a Linux-based front-end computer (FEC). The FPGA of the active mezzanine cards accommodated by the BLEPT modules receives the acquired data from the BLEDP cards, calculates the running sums and checks them against their respective abort thresholds, then relays the information to the FPGA of the carrier board. This FPGA broadcasts the data and status information on the VME bus and transmits eventual beam abort requests from the BLEPT module to the Beam Interlock System through the BLECS card. The latter is also responsible for distributing accelerator timing and status signals to the BLEPT modules and for regularly triggering system sanity checks and confirming their successful execution [4].

In most cases, it is foreseen to use ionization chambers for the injectors similar to those used in the LHC system. However, the design of the acquisition stage also allows the connection of more varied kinds of detectors than its precursors. In some locations, other detector types such as diamond detectors, secondary emission monitors and Cherenkov detectors will be used [4].

In order to evaluate performance and collect operational experience, a prototype system has been installed at the Proton Synchrotron Booster (PSB) accelerator. It works alongside the operational system currently ensuring machine protection.

2. CONNECTIVITY CHECKS

There is currently no particle accelerator equipped with a procedure ensuring continuous and comprehensive surveillance of the connectivity and correct operation of its BLM detectors and the functionality of the BLM system as a whole. At present, the best similar process operates in the LHC, enforcing a connectivity check of each detector channel every 24 hours while the accelerator is inactive.

This procedure tests the cabling connection of each beam loss monitor by modulating the bias high voltage and measuring the resulting modulation in the output current of the chambers. In the LHC implementation, the frequency of the modulation is on the order of 10 mHz. The detectability of the modulation at the output depends on the correct operation of the entire signal acquisition chain. Missing, discontinued or disconnected cables will result in the absence of modulation, while variations in the phase and amplitude of the output current have been identified to correspond to various deteriorations of the signal chain. Therefore, the procedure also acts as a survey of the integrity of the components [7].

The design, implementation and integration of an improved process for the injector BLM system is the scope of the present project. It should guarantee a continuous supervision of the whole signal acquisition chain and the measurement ability of the detectors without compromising machine protection. This implies that the processing of the measurement signal must not be modified in order to avoid introducing new failure cases into the mission critical BLM system.

2.1. Hardware features of the injector BLM system

In the injector BLM system, clusters of 64 ionization chambers are powered by a pair of power supplies through a high voltage distribution box. The two power supplies are connected in parallel over protection diodes, and the voltage of the secondary is set about 50 V lower than that of the primary. This way, in normal operation, power is supplied to the chambers by the primary but the secondary can take over in case the primary fails. The DC output voltage of the Heinzinger NCE power supplies can be adjusted from 0 V to 3000 V through an analog voltage setpoint input. Their output current is limited to 20 mA.

The summed output voltages of two 16-bit DACs, controlled by the FPGA of the BLECS module, drive the analog voltage setpoint input of the power supplies. The control voltage, normally in the $0 - 10$ V range, is low-pass filtered with a cutoff frequency of approximately 80 Hz and capped at 6.8 V with a voltage regulator diode to avoid powering the ionization chambers above the upper limit of the ionization chamber detection region, about 2000 V. This configuration yields a maximum modulation amplitude of approximately 250 V_{PP}.

Each ionization chamber has a low-pass filter at its input. The capacitor supplies charge to the detector in case of high output currents resulting from significant losses, thereby overcoming the output current limitation of the power supply.

2.2. Characteristics of the modulation signal chain

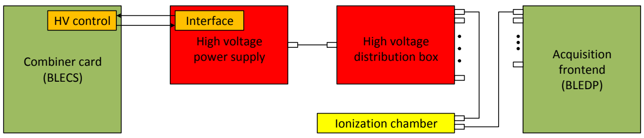

Fig. 3. Simplified overview of the modulation signal chain.

Within the framework of the current project, measurements were executed to assess the capabilities of the modulation signal chain, described in Sec. 2.1 and illustrated in Fig. 3.

The step response of the circuitry on the combiner card (BLECS) driving the voltage setpoint input of the high voltage power supplies was measured with an oscilloscope. It corresponds to that of a first-order low-pass filter with a cutoff frequency of about 80 Hz, as expected.

The response of the high voltage power supply was measured using two different methods. On one hand, the high voltage power supplies feature two feedback outputs whose voltages are proportional to the output voltage and output current, respectively. These outputs are connected to ADCs on the BLECS module. The signals can thus be acquired by the FPGA and extracted with an on-board logic analyzer at their native acquisition frequency of about 530 Hz. On the other hand, a 1 : 1000 ratio high voltage divider can be connected to the output of the power supply or to the high voltage distribution box, and its output can be measured with an oscilloscope. The two methods yield consistent results.

At modulation frequencies up to about 5 Hz with maximum amplitude, the high voltage power supply produces a clear sine wave at its output. However, above this frequency, its output gets distorted similarly to that in Fig. 4. As shown in Fig. 5, a clear sinusoidal spectrum is observed at 5 Hz, while significant nonlinear effects become apparent at 10 Hz. Further investigation of this effect has revealed a behavior consistent with the power supply actively charging its output capacitors for voltage increases and letting them discharge over the load and its internal resistance for voltage drops: it responds to increases in voltage as a low-pass filter, and for decreases, it shows a slow exponential decay with a time constant on the order of 1 s depending on the loading impedance. If this limitation is taken into account, the power supply acts as a low-pass filter with a cutoff frequency of about 30 Hz.

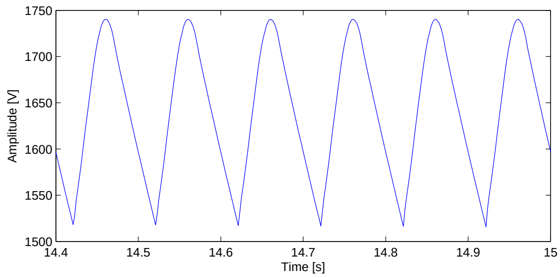

Fig. 4. Distorted output of the high voltage power supply when driven with a 10 Hz sinusoidal modulation of approximately 250 V_{PP} with a DC level of 1500 V.

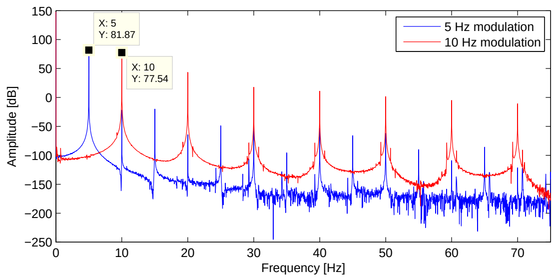

Fig. 5. Output spectra of the high voltage power supply when driven with a high voltage of 1500 V modulated by two different sinusoidal signals of approximately 250 V_{PP}. Notice the apparent nonlinear distortion with 10 Hz modulation.

The frequency response of the system appears not to be substantially influenced by the passive high voltage distribution box.

2.3. Data acquisition with the BLEDP card

In the laboratory, a rack hosting an acquisition crate and a processing crate (see Sec. 1.3) with a high voltage power supply and distribution box is installed. The output current of a single ionization chamber connected to the distribution box was acquired with the BLEDP card at 500 kHz. In order to avoid exceeding the magnitude of the offset current of the system and thereby clipping and distorting the acquired signal, the modulation amplitude was set to $1/8$ of the maximum. The raw data was transmitted from the BLEDP to a PC over Ethernet for further processing [8].

The acquired spectrum was flat with peaks spread out over the spectrum caused by the operation of the power supply. The peaks caused by the modulation were detectable with a margin of at least 20 dB at frequencies up to 20 Hz.

Analogous measurements were made with the prototype system installed in the PSB, featuring two power supplies driving a distribution box with 32 ionization chambers connected. With the modulation amplitude set to maximum, current magnitudes similar to those in the previous measurement were obtained due to the attenuation

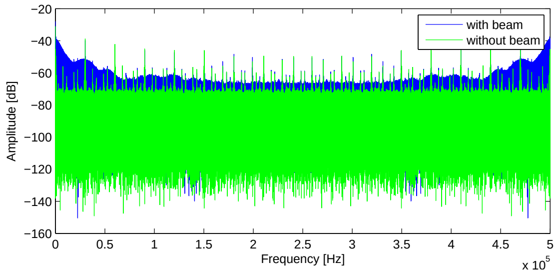

Fig. 6. Spectrum of the data acquired in the PSB with and without beam. The frequency axis spans $0 - 500\,\text{kHz}$. Notice the peaks spread out over the spectrum due to the power supply.

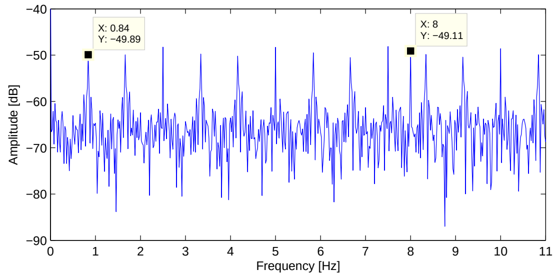

Fig. 7. Spectrum of the data acquired in the PSB with a modulation of 8 Hz of maximum amplitude in the presence of beam. Notice the 0.84 Hz component and its harmonics due to the beam.

of the long copper cables connecting the detectors and the many detectors connected.

The spectra measured in the PSB are similar to those observed in the lab. However, the presence of beam in the machine has a significant influence on the spectrum. Fig. 6 demonstrates a global effect: an increase in the noise floor and an amplitude roll-off at frequencies up to $100-150\,\text{kHz}$. As shown in Fig. 7, a 0.84 Hz component and its harmonics can be observed at the low end of the spectrum, in correspondence with the 1.2 s duration of the basic period[3] of the PSB. Still, the 8 Hz modulation is observable in the signal even in the presence of beam, and the modulation remains detectable up to about 15 Hz. However, in this case, modulation frequencies must be chosen so that the resulting peaks do not coincide with the ones corresponding to the basic period.

Unexpectedly, without beam, a 20.5 Hz peak is detectable with a margin of about 20 dB. Nevertheless, this signal can no longer be recovered in the presence of beam.

3. TOWARDS REAL-TIME SUPERVISION

The measurements suggest that the useful frequency range for modulation can be extended far beyond that used in the LHC implementation, which is essential for a rapid detection of nonconformities in the beam loss monitoring system.

In the LHC system, matched filters are used to identify the modulation in the output signal of the detectors. This method was also considered for the real-time supervision system. Data were acquired in the lab and PSB installations in the presence of modulation, and their cross-correlation to pure sine waves of various frequencies was calculated in Matlab. However, the results obtained were ambiguous. Additionally, methods based on cross-correlation are not particularly suitable for real-time implementation with limited computing resources, thus this approach was abandoned.

The measurements described earlier showed prominent spectral peaks resulting from modulation in the output current of the monitors. Therefore, a frequency-domain approach to detecting the modulation was deemed feasible. In order to prove the suitability of this concept, an autonomous processing and decision making algorithm was implemented in the FPGA of the active mezzanine card of the BLEPT module. This algorithm takes the samples of the running sum of 1 ms duration, decimates them to 1 kHz, then repeatedly calculates the 1024-point FFT of the samples using a manufacturer-supplied fixed-point IP core. It detects the presence of a 10.5 Hz sinusoidal modulation based on the amplitude of the corresponding Fourier coefficient. Tests with the laboratory system have shown this method to work reliably. Even though in the proof-of-concept implementation, all parameters are hard-coded, this approach can easily be extended to other frequencies within the feasible frequency domain.

4. CONCLUSIONS

The characteristics of the system offer very promising perspectives for the implementation of the on-line diagnostic process vital for the adequate protection of the injectors at CERN.

The feasibility of identifying an externally applied sinusoidal modulation using a frequency-domain approach has been demonstrated. Currently, more resource-efficient methods of calculating the relevant Fourier coefficients are being investigated. Later on, the extension of the connectivity check to more complex modulating signals, the implementation of an integrity survey similar to the LHC system and the fusion of signals from different detectors to ensure a more accurate response are foreseen.

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