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HIGH-RESOLUTION BUNCH PROFILE MEASUREMENTS FOR ENHANCED LONGITUDINAL BEAM DIAGNOSTICS

Y. Brischetto*, T. Argyropoulos, H. Timko, CERN, Geneva, Switzerland

Abstract

Efficient operation of the Large Hadron Collider (LHC) relies on accurate longitudinal beam measurements to diagnose beam instabilities and verify the correctness of bunch-shaping techniques. To achieve this goal, a diagnostic system was developed to perform high-resolution measurements of longitudinal bunch profiles. High-performance oscilloscopes, synchronised to precise accelerator events, are employed to carry out the measurements, acquiring data from wide-band wall-current monitors installed in the machine. This paper provides details on the implementation of the system, illustrating its current and future applications that will play a key role in increasing beam intensity in the LHC.

INTRODUCTION

The LHC is the world's largest and most powerful particle accelerator, designed to collide high-energy particle beams to help scientists explore fundamental questions in particle physics [1]. It is a complex machine requiring thorough control and characterization of beam parameters. Understanding the longitudinal dynamics of the particle beams is essential for optimizing luminosity, minimizing beam losses, and ensuring the safe operation of the machine. The main challenges of LHC and High-Luminosity (HL-)LHC [2] operation in the longitudinal plane are associated with beam instabilities [3, 4] and large radio-frequency (RF) power requirements due to strong beam-induced voltage in the RF cavities [5, 6]. All these motivate the development of a high-resolution beam profile measurement system, from which many longitudinal beam parameters, such as bunch length, emittance and energy mismatch at injection can be derived, and thus allow for a detailed analysis of beam behavior during different acceleration phases.

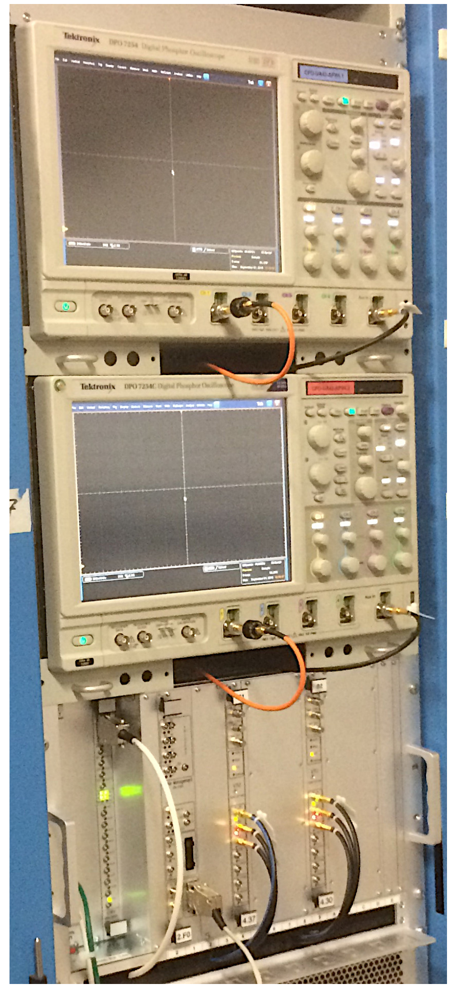

Figure 1: The two VTU modules installed in the VME crate (bottom) in the RA43 tunnel and the oscilloscopes (top). One VTU-oscilloscope pair serves one beam.

SYSTEM ARCHITECTURE

Two wall-current monitors, each dedicated to one beam, are installed in the LHC tunnel near the RF cavities. These monitors, referred to as APWL [7], are longitudinal wide-band pick-ups of the coaxial type, based on a design from the 1970s [8]. Wall-current monitors are employed to analyze the beam current and are commonly used to acquire longitudinal bunch profiles. Each pick-up is connected to a 40 GS/s high-performance oscilloscope, which is triggered by a VME Trigger Unit (VTU) [9] module. The VTU receives the 400 MHz RF frequency and revolution frequency signals from the low-level RF system and generates RF-synchronous pulses to trigger data acquisition on the oscilloscope. The system is installed in a underground service gallery and receives RF signals from the low-level RF system installed in another underground gallery. The acquisition system is shown in Fig. 1. A schematic of the signal distribution is presented in Fig. 2.

SOFTWARE ARCHITECTURE

Remote Control

A socket-based C++ library was developed to provide the remote control of the oscilloscopes, as they implement the LXI (LAN eXtensions for Instrumentation) standard [10], which allows for their control through Ethernet. The library is based on SCPI (Standard Commands for Programmable Instruments) [11]. The supervision of the VTU boards follows CERN's standard guidelines for controlling electronic modules. A hardware interface definition, commonly referred

* ylenia.brischetto@cern.ch

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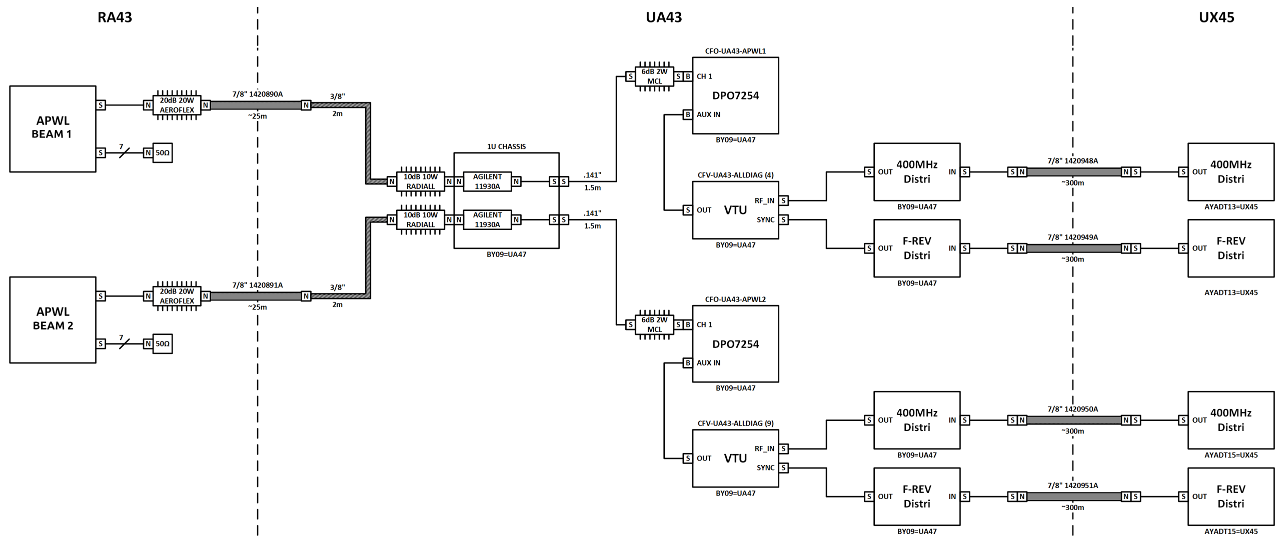

Figure 2: Schematic of the signal distribution among the devices that are part of the diagnostic system and are installed in three separate LHC underground galleries.

to as a memory map, was defined for these cards by the hardware designer, which was used to build a Linux driver and a C++ library to access the hardware. This process was automated thanks to the use of Reksio [12], a dedicated tool that helps streamline such tasks and was developed within the RF group.

Control Software

The control software responsible for supervising the equipment and data acquisition is implemented as a FESA class [13]. It oversees both the oscilloscopes and the VTU through the LXI library and a second dedicated FESA class, respectively. An overview of the control stack is shown in Fig. 3. When the software receives the start acquisition trigger, which can be a central timing event, a timer, or a manual trigger sent by the user depending on the acquisition mode, a sequence unfolds. In this sequence, the software is establishing a connection with the scope and VTU, setting up both instruments, arming the scope, and waiting to receive the acquired data. After receiving the settings, the VTU starts generating triggers to synchronize the scope's data acquisition with the RF signals. The data acquired is then made available for real-time monitoring and stored in CERN's accelerator logging system, NXCALS [14], for later extraction and further analysis.

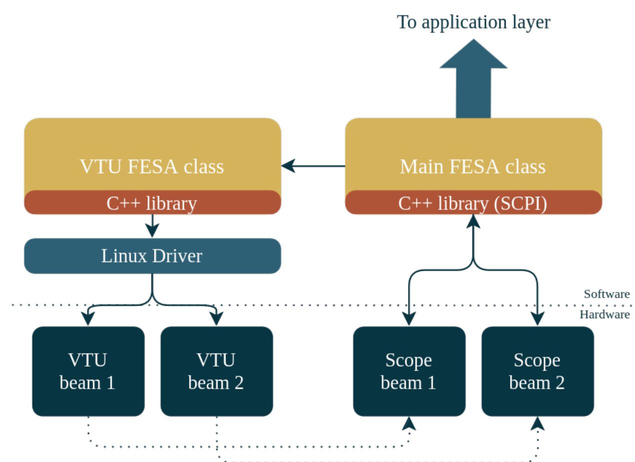

Figure 3: Overview of the software control stack.

Measurements

The control software has been designed with three data acquisition modes to cater to different measurement requirements, namely injection, full-turn, and manual mode. Each mode has different start triggers and allows for the configuration of various parameters, such as the bucket selector, the number of samples to be taken per trigger, and the number of turns to record, in order to fully utilize the hardware capabilities and provide extensive customization options to the user. The product of the number of samples per trigger and the number of turns to record represents the number of points that will be acquired. For instance, the measurement of an RF bucket, which contains a single bunch, requires 100 points, and for the measurement of a complete set of 144b physics bunch trains, around 160000 points are acquired. As a last example, one complete turn measurement acquires 35640 × 100 points. All parameters can be easily customized to accommodate the LHC's various filling schemes. The following section presents the measurement configurations offered by the diagnostic system.

Injection measurement The injection measurement mode allows to capture the beam profile of every bunch that is injected in the LHC. The injection bucket number is automatically retrieved from the injection warning timing event that is generated one second before the injection takes place. User-specified information, such as the number of turns to record or the number of samples per trigger, is used

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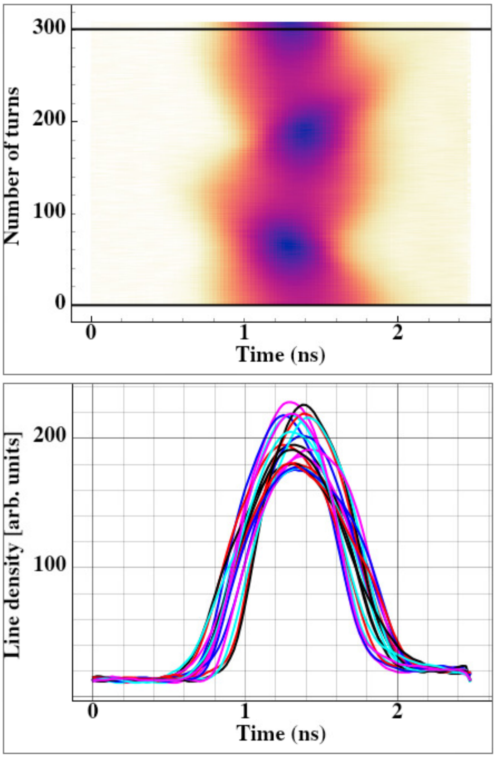

Figure 4: Measurement of a single bunch for 300 turns just after LHC injection, illustrated as a waterfall plot (top) and overlaid bunch profiles (bottom).

to set up both the VTU and the oscilloscope. Once the VTU receives the injection trigger from the accelerator timing system, it starts triggering the oscilloscope that locks onto the selected bunch and acquires the profiles. This measurement is the basis of the machine-learning (ML) tomography [15] that computes the longitudinal beam parameters, such as phase and energy errors, and bunch length, at injection and reconstructs the phase-space distribution of each of the injected bunches. Fig. 4 presents an example of a single bunch measured[1] at the LHC injection during operation in 2024. Additionally, the beam profiles are stored in the logging system for later extraction, as mentioned previously.

Full-turn measurement The full-turn measurement configuration enables the equipment to acquire the profiles of all bunches that are circulating in the accelerator for one complete turn. This measurement is automatically triggered with a periodic cadence, typically every 10 minutes. It allows the LHC operations team to monitor the beam profiles and ensure the quality, shape and stability of the circulating beams. Especially in collisions, the beam shape is changing over time and thanks to this measurement the change can be accurately taken into account in luminosity estimates. Similarly to injection measurements, these profiles are logged and stored for future reference and studies.

[1] The observed quadrupole oscillations of the bunch are due to the RF voltage mismatch at the LHC injection.

Manual measurement The manual measurement mode provides the user with greater control over the acquisition process, allowing for the tailoring of the acquisition parameters to meet specific measurement needs. Additionally, this mode offers the flexibility of triggering measurements manually or automatically through external software. Its ability to provide customization and flexibility ensures that the acquisition process is optimized for any specific measurement. This configuration is being widely used in machine development (MD) measurement sessions for beam diagnostics.

CONCLUSION

The implementation of a high-resolution longitudinal beam profile measurement system is a major milestone in ensuring the efficient operation of the LHC. By taking advantage of high-performance equipment, this system enables the accelerator's operators to monitor the quality and stability of the beam with very high precision. Additionally, it allows experts to study and address beam instabilities while validating the bunch-shaping techniques that are critical to maintaining optimal beam intensity. The diagnostic system allows to perform detailed analysis of longitudinal beam characteristics that serve the current operational needs of the LHC. It will continue to be instrumental in optimizing beam parameters and supporting the future evolution of the world's largest particle accelerator.

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