EXPERIMENTAL EVALUATION OF A DIGITIZER DESIGNED FOR ACCT BEAM CURRENT TRANSFORMERS

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Abstract

To integrate the signals of beam current transformers into accelerator control systems, particle accelerators require high-performance digitizers with optimized bandwidth, sampling rate, and dynamic range. They must be accurate and reliable. And they should be easy to deploy and operate.

A specialized digitizer was developed to interface the Bergoz Instrumentation ACCT sensor and its analog front-end electronics to an accelerator control system. It allows waveform acquisitions preserving the quality of the analog signal. Additionally, it allows controlling the ACCT configuration. Communication is implemented over Ethernet through a simple command protocol and an EPICS soft IOC is provided.

The digitizer was tested with two ACCTs installed at the CHUV Oriatron Linac and a third ACCT at the METAS electron beamline. Results demonstrate improved signal-to-noise ratio, adaptability to multiple beam types, and simplified deployment compared to general-purpose digitizers.

INTRODUCTION

The ACCT from Bergoz Instrumentation is an evolution of the active beam current transformer (BCT) described by Hereward in 1960 [1], which has a lower cutoff frequency compared to conventional BCTs. It is available in a single-range version or with three digitally selectable measurement ranges. The current waveform is provided as an analog output signal.

Various electronics standards are used for acquisition and control across particle accelerators, including VMEbus, CompactPCI, and MicroTCA, each providing high performance but often at the cost of increased integration complexity and required expertise [2].

To address these challenges, a dedicated digitizer was developed to interface ACCT analog signals with accelerator control systems using standard Gigabit Ethernet communication over RJ-45. This approach enables straightforward integration while remaining compatible with existing infrastructures through widely available network interfaces.

Beyond waveform acquisition, the system integrates ACCT electronics range control and on-board data processing, including real-time conversion of voltage waveforms into beam current and pulse charge. This consolidates functionalities typically distributed across multiple hardware modules into a single device.

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Modular Digital Solution

The Modular Digital Solution for ACCT (MDS-ACCT) (Fig. 1) is a dedicated digitizer developed by Bergoz Instrumentation. Its design was guided by three main objectives: preserving the integrity of the analog signal during digitization, ensuring long-term sustainability through the use of high-performance and widely available components, and providing an easy-to-use and quick-to-set-up solution that can adapt to different beam types.

Figure 1: MDS-ACCT in its tabletop chassis.

The MDS-ACCT is based on a 16-bit analog-to-digital converter (ADC) operating at 160 MS/s. The digitized samples are streamed to the programmable logic (PL) of a Zynq UltraScale+ system-on-chip (SoC), where they are processed and stored in multiple circular buffers. Upon trigger detection, after a configurable delay, the acquisition is halted, a trigger counter is incremented, and a local timestamp is recorded.

The processing system (PS) of the SoC performs additional operations on the acquired data, such as the computation of the current waveform and the pulse charge. The processed data is packaged into UDP/IP packets, including both waveform data and associated metadata (timestamp, trigger number...), which are transmitted over Gigabit Ethernet.

In addition, long-term sustainability is enhanced by the ability to update both the PL and the PS, as the firmware is stored on a MicroSD card that can be replaced on-site. This therefore allows for the future implementation of additional functionalities.

CHUV Oriatron Linac

The Oriatron eRT6 Linac from PMB-Alcen is a pulsed electron beam accelerator delivering ~5.4 MeV electrons. The grid tension (100 – 300 V), number of pulses, pulse width (0.05 – 4 µs) and pulse repetition frequency (5 – 250 Hz) can be modified [3]. To assess the dose delivered with the eRT6, two ACCTs have been installed at the exit of the accelerator. Both use the same sensor type (ACCT-S-055), but electronics with different measurement ranges, +1 V / 10 mA and +1 V / 300 mA (ACCT-E-RM-10mA-50R-3M and ACCT-E-RM-300mA-50R-3M).

Output signals of the ACCTs electronics are digitized by two NI PXIe-5114 oscilloscope cards (125 MS/s, 125 MHz bandwidth and 8-bit resolution) installed in a NI PXIe-1071 chassis from National Instruments [4]. This system allows to estimate the dose delivered during operation. However, such digitizing systems are expensive, and a custom LabVIEW virtual instrument needs to be developed decreasing its accessibility.

METAS Beamline

METAS, the Swiss National Metrology Institute, operates a 22 MeV Microtron type electron accelerator from Scanditronix [5] for research and reference measurements in radiotherapy. The accelerator produces electron pulses of 3 µs length and pulse currents of up to 100 mA. Beam energy reaches from 5 to 22 MeV and the repetition rate can be varied from 1 to 250 Hz. The beamline between the accelerator and the experimental end stations is equipped, among other beam diagnostic elements, with an ACCT-S-055. This sensor is connected to its corresponding ACCT-E-RM-150mA electronics with 150 mA measurement range. The electronics, in turn, is attached to a high impedance (1 MΩ) input of a PicoScope 3405D oscilloscope with a bandwidth of 100 MHz. This setup is able to measure the full voltage (±10 V) output of the ACCT electronics.

The combination of an ACCT and such an oscilloscope offers impressive flexibility thanks to the provided software package and the easy setup. Further, the high bandwidth allows for direct visualization of the temporal shape of the electron pulses. Its drawbacks include limited vertical resolution, non-negligible noise and restricted storage capacity and data rate, when measuring at high repetition rates. In addition, integration into a proprietary accelerator control system is difficult.

MEASUREMENTS

We chose to test the MDS-ACCT at the CHUV and METAS for several reasons. First, performing measurements on two different accelerators allows us to validate its operation under distinct conditions in terms of beam structure and noise environment. In addition, both facilities are operated by small teams for whom ease of integration and rapid deployment of digitizers are critical factors.

Qualitative Test Campaign at CHUV

At the CHUV Oriatron Linac, the signal from the ACCT electronics was split using a power divider, allowing simultaneous acquisition with the MDS-ACCT while maintaining normal operation of the accelerator control system using the existing data acquisition system.

The installation of the MDS-ACCT was sufficiently fast to enable 15 measurement series to be performed within half a day. However, for practical reasons, the waveforms from the CHUV control system were not recorded.

The measurement campaign was structured in three parts:

1. Acquisition of arbitrary pulse sequences to verify correct system operation. One of the pulses is shown in Fig. 2, alongside a typical pulse acquired by the CHUV control system a few weeks before this test campaign.
2. Progressive increase of the repetition rate up to the Oriatron limit (250 Hz). The MDS-ACCT was capable of operating at this frequency.
3. Long acquisition sequences to evaluate system stability and reliability over time, with up to 5000 pulses at 25 Hz (Fig. 3). A slight variation in pulse shape is visible, which could be attributed to the accelerator.

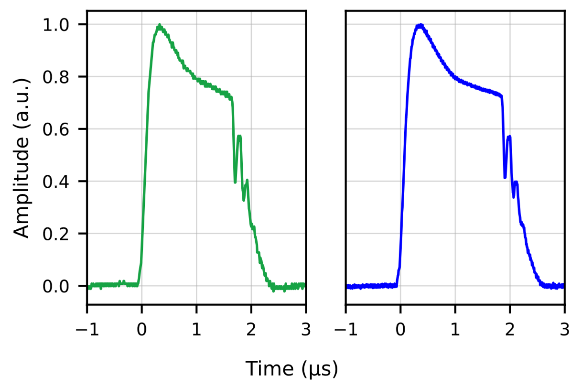

Figure 2: FLASH pulse waveforms acquired by the MDS-ACCT (in blue), showing good agreement with a typical FLASH waveform acquired by the CHUV control system few weeks before the test campaign (in green).

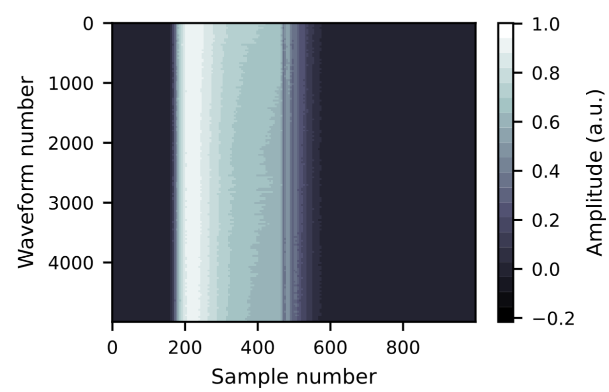

Figure 3: Heatmap of a series of 5000 pulses acquired with the MDS-ACCT at a repetition frequency of 25 Hz. Waveforms were time-aligned and offsets were adjusted.

During long acquisition sequences, missing UDP/IP packets were observed at the receiver side. However, inspection of the received metadata showed matching trigger numbering and packet numbering, even if some packets were missing. This indicated that the MDS-ACCT was not the cause, and the issue was therefore attributed to either the communication link or the receiving software.

For subsequent tests, the Ethernet cable was replaced with a better shielded one, and the Python application was replaced by a compiled C program. After these modifications, no further packet loss was observed.

Comparative Test Campaign at METAS

As for the CHUV campaign, the installation of the MDS-ACCT was completed rapidly, allowing all planned measurements to be carried out within a single morning.

A direct comparison was performed between the MDS-ACCT and the acquisition system used in the METAS control system, based on a PicoScope. A BNC T-connector was used to split the signal from the ACCT electronics to both digitizers. Cable lengths were minimized to reduce signal distortions caused by impedance mismatches.

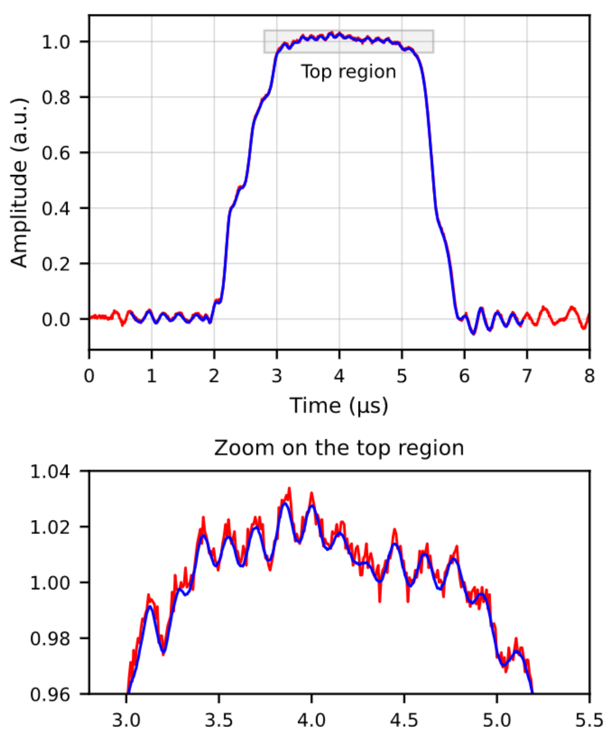

Figure 4: Same pulse acquired with the METAS PicoScope (red) and the MDS-ACCT (blue). The lower plot shows a zoom of the top region.

As shown in Fig. 4, a good agreement is observed between the two digitizers, with a lower noise level for the MDS-ACCT, even though both digitizers have a similar bandwidth.

While the PicoScope provides good performance under standard operating conditions, some limitations were identified in comparison with the MDS-ACCT.

First, the METAS acquisition system based on the PicoScope is limited to short acquisition bursts at the maximum repetition rate of the accelerator (typically 32 waveforms at 50 Hz), whereas the MDS-ACCT is capable of continuous acquisition at repetition rates up to several hundred Hz.

Second, although the PicoScope offers adequate resolution and signal-to-noise ratio for high-amplitude signals, its performance becomes more limited for low-amplitude signals unless the input range is adjusted. In practice, range switching is not always possible because, in some accelerator facilities, unexpected beam conditions may occur rapidly. Pulse trains may exhibit significant amplitude variations that surpass the dynamic range of any chosen oscilloscope input range. In such situations, the higher dynamic range of the MDS-ACCT allows for uncompromised signal acquisitions.

Performance Characterization

A dedicated laboratory test bench was developed to evaluate the intrinsic performance of the MDS-ACCT under controlled conditions.

The test bench's software architecture was built around EPICS, as it has already been done at other facilities [6]. Custom Python-based device drivers were programmed for all test and measurement devices. This approach enabled a clear separation between hardware interfaces and higher-level control logic, while facilitating the development of user interfaces using CS-Studio Phoebus [7]. This architecture also allowed the development and test of a Soft IOC for the MDS-ACCT based on the PvaPy library, which provides a direct pathway for integration into accelerator control environments based on EPICS.

A signal-to-noise ratio (SNR) of at least 72 dB was measured at a sampling rate of 160 MS/s, for input configurations of 50 Ω, ±1 V full scale and high-impedance, ±10 V full scale. The SNR was computed from RMS measurements as $-20\,log_{10}(RMS_{noise}/RMS_{signal})$ where the noise floor was measured with no input signal and the reference signal corresponds to a full-scale sine wave.

The frequency response was found to be flat within ±0.1 dB over the full bandwidth of the ACCT sensor, which has a cut-off frequency of up to 3 MHz. The −3 dB cutoff frequency of the MDS-ACCT was measured at 90 MHz.

In addition, a long-term stability test was conducted over 1000 hours. A temperature dependence <200 ppm/°C was deduced using the internal temperature sensor. No drift due to aging was observed.

CONCLUSION

A dedicated digitizer for ACCT beam current transformers has been developed and experimentally validated. The system integrates signal acquisition and processing as well as measurement range control into a single platform, with a focus on performance and straightforward integration into accelerator control environments.

Tests performed at the CHUV Oriatron Linac and at the METAS electron beamline demonstrated the practical usability of the system in real experimental environments, highlighting its ease of deployment and operation. Additional laboratory characterization enabled the evaluation of key performance parameters such as signal-to-noise ratio and bandwidth flatness.

The results indicate that the chosen dedicated architecture can effectively preserve signal quality while simplifying deployment compared to general-purpose digitizers.

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