ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-WEPG27

REAL-TIME PROCESSING OF LONGITUDINAL SCHOTTKY SIGNALS IN CERN's ANTIPROTON CHAIN

M. Niccolini*, M. E. Angoletta, D. Barrientos, Y. Brischetto, P. Freyermuth, M. Södérén, M. Suminski, CERN, Geneva, Switzerland

Abstract

A low-latency, real-time diagnostic system for the analysis of longitudinal Schottky signals in CERN's antiproton chain has been developed. The system, installed in CERN's Antiproton Decelerator (AD), processes the combined output of two low-noise, wideband AC beam transformers. It uses a GPU and the NVIDIA CUDA Toolkit, exploiting the directly sampled data and hardware features provided by the low-level radio-frequency (LLRF) VMEBus Switched Serial (VXS) system and its companion ObsBox server, to implement the FFT-based multi-harmonic spectral analysis needed to set up and monitor the stochastic and electron cooling processes. Longitudinal beam properties, such as mean momentum and momentum spread, are also derived to evaluate and log the machine performance. This paper describes the implementation of the system and its integration within the CERN control system, achieved using the Front-End Software Architecture (FESA) framework and a graphics co-processor directly installed in the Front-End computer (FEC), running a real-time operating system environment. Preliminary results of its usage in the Extra Low ENergy Antiproton (ELENA) ring and next steps to process bunched beam spectra are also presented.

INTRODUCTION

In CERN's antimatter factory, antiprotons are produced and decelerated to energies as low as 100 keV by alternating bunched and debunched phases of the beam during the deceleration cycles [1]. In this process, the stochastic and electron cooling play a key role that is usually monitored through the analysis of the Schottky signals. This paper presents a novel longitudinal diagnostic system for the Schottky signal observed in the debunched parts of the cycle, with a focus on the AD machine, where it has been operationally deployed.

SYSTEM LAYOUT

The Schottky signal is generated by an alternating current (AC) beam transformer located within the machine. The signal is then subject to amplification prior to being digitized by the LLRF beam (and cavity) controller computer. A Supermicro X11DPU server, that features an Intel Xeon Silver 4216 CPU and a graphic processing unit (GPU), processes the digitized data received from the VXS controller via a fiber-optic link and generates longitudinal diagnostic information. The main system components are presented in Fig. 1.

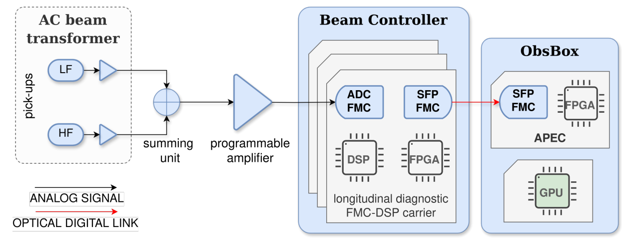

Figure 1: Simplified synoptic of the main hardware components.

Longitudinal Pick-ups

The broad-band AC beam transformer is a device that can measure the beam current within the 20 kHz to 30 MHz range. It consists of two high-Q resonant ferrite-loaded cavities, one for the 20 kHz to 3 MHz frequency range and a second one for the 250 kHz to 30 MHz frequency range. Additionally, it includes two low-noise head amplifiers that operate at ambient temperature [2]. The signal from the two pick-ups is combined in the summing unit through a low and a high pass filter, with a cross-over frequency of 1 MHz [3].

Programmable Amplifier

The amplitude of the signal at the summing unit output varies in amplitude during the cycle. It may drop to -30 dBm during the stochastic and electron cooling phases and rise to 8 dBm during deceleration ramps when the beam is bunched. In order to leverage the dynamic range of the analog-to-digital converter (ADC), a programmable amplifier is employed, allowing to adjust its gain from -13 dB to +23.2 dB. Currently, the gain is set to 0.1 dB during the deceleration segments of the cycle and increased to 15 or 18 dB during the segments in which the beam is debunched, depending on the plateau energy. A dedicated microcontroller unit with Ethernet connectivity controls the gain. Fully integrated in CERN's control system by means of a FESA [4] class, it changes the gain in real-time according to the evolution in the cycle structure and to the requests of machine operators.

VXS Beam and Cavity Controller

The LLRF system controlling the AD is installed in several other CERN machines [5]. In particular, the AD LLRF system [1] is similar to the one installed in ELENA. The system is installed in a VXS crate comprised of multiple carriers hosting a Digital Signal Processor (DSP), two Field Programmable Gate Arrays (FPGA) and FPGA Mezzanine Card (FMC) modules including ADCs and Digital-to-Analog Converters (DACs). In the AD LLRF system, one carrier board is dedicated to beam diagnostics. It hosts 16-bit ADCs with

* marco.niccolini@cern.ch

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-WEPG27

a 122.7 MS/s sample rate, which provide data to a low-pass filter to halve the rate to 61.35 MS/s and preprocesses the data to be sent to the ObsBox. Data are transmitted every 12.5 µs, packaged in frames that contain information such as the revolution frequency, the beam status and a frame counter to allow for the reconstruction of the acquisition context. A small form-factor pluggable (SFP) transceiver module is employed for the optical serial link at 2 Gbps to allow for a high-rate stream from the ADC to an external processing unit, protecting the VME bus from overloading. Further details on this development can be found in [6].

ObsBox

The server operates on the standard CERN operating system, based on CentOS Linux 7 with a real-time kernel patch. It is equipped with an NVIDIA T1000 GPU connected via PCI Express, along with an Advanced PCI-Express Carrier (APEC) card [7], assembled from off-the-shelf components. Custom firmware and a driver were developed at CERN. This card manages the fiber-optic links to the VXS crate through the SFP digital transceivers. Its on-board FPGA is responsible for handling the communication and data transfers via direct memory access (DMA) to a circular buffer in the random-access memory (RAM). The driver can access up to two fiber-optic serial streams through the RAM. Two FESA classes interface with the driver through C++ static libraries to handle the extraction of the ADC data frames from the circular buffer and process the data. More specifically, one FESA class analyzes frames acquired during the bunched part of the cycle in the time domain, computing intensities, bunch length and displaying bunch profiles, as detailed in [6]. The second FESA class, subject of this paper, accumulates frames in order to analyse the signal in the frequency domain. It executes the Fast Fourier Transform (FFT) algorithm on the GPU and computes the statistics for the debunched beam.

DEBUNCHED BEAM DATA PROCESSING

To analyse the Schottky signals and to publish the results of the computation, a FESA class, a C++ static library named *obsboxAPEC* and a C++/CUDA library named *obsboxCUFFT* have been developed. These components constitute a diagnostic system for debunched beam, aimed at optimizing and monitoring the performance of beam cooling phases throughout the cycle. The main conceptual blocks involved in the processing are illustrated in Fig. 2 and detailed in the following sections.

FFT Computation

The *obsboxAPEC* library interfaces with the driver, retrieving and validating ADC frames in order to assemble the samples into a super frame. The length of the super frame is determined by factors such as the requested size of the FFT, the number of FFTs that will be executed in a single transfer to the GPU, and the percentage of overlapping time-domain data. With the intention of keeping the signal processing chain as simple as possible, the sampled signal undergoes direct transformation to the frequency domain without digital downconversion, making the full spectrum up to the 30.67 MHz Nyquist frequency available in the GPU memory. A FFT size of 8388608 samples ensures a frequency resolution of 7.31 Hz per bin across these spectra, needed for precise momentum spread measurements at all energy levels. To enhance time-resolution and capture rapidly evolving beam behaviours, an overlapping mechanism [8] for the ADC data is employed. Each super frame undergoes three FFTs over batches of samples with a 50% time overlap, enabling real-time data publication at around 20 Hz, depending on the processing time jitter. Additionally, a Hann windowing [9] is applied to improve spectral resolution. The *obsboxCUFFT* library manages GPU data loading and initialization for FFT execution using CUFFT, an FFT algorithm implementation within the CUDA v12.0 toolkit [10]. Given the significant overhead of memory transfers between the GPU and the host system, only a portion of the computed spectrum around the relevant revolution frequency harmonic is transferred to the host. This approach simplifies the calculation of the statistics and the publication of the results to the user interface. Despite this, users can still access the entire spectrum and select the desired span and harmonic to be displayed. To further reduce the memory transfer overhead, the conversion of the integer ADC data to floating point numbers is done at the time of the transfer to the GPU using the CUDA callback method [11].

Statistics

In order to compute the statistics, only a portion of the displayed spectrum is used, centered at the selected harmonic of the programmed beam revolution frequency, with a user-selectable span. The distribution moments, including the expectation, variance, and skewness, of the Power Spectral Density (PSD) of the digitised signal are computed over this span. Mean momentum and momentum spread are then derived using the relation detailed in [12]. Additionally, an attempt to measure beam intensity through PSD area integration was made [3], although the low signal-to-noise ratio (SNR) rendered the results inconsistent compared to measurements conducted during the bunched phase of the cycle.

Data Visualization Tool

The FESA class interface was designed to integrate computed spectra and statistics into the CERN control system stack while ensuring compatibility with existing operational software applications. Figure 3 presents data from a typical AD deceleration cycle: Schottky spectra are displayed in a waterfall chart using the Java application “Tiny Schottky” [13]. The high update rate of the displayed data allows for the real-time adjustment of machine parameters, eliminating the necessity of waiting for the cycle to complete.

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-WEPG27

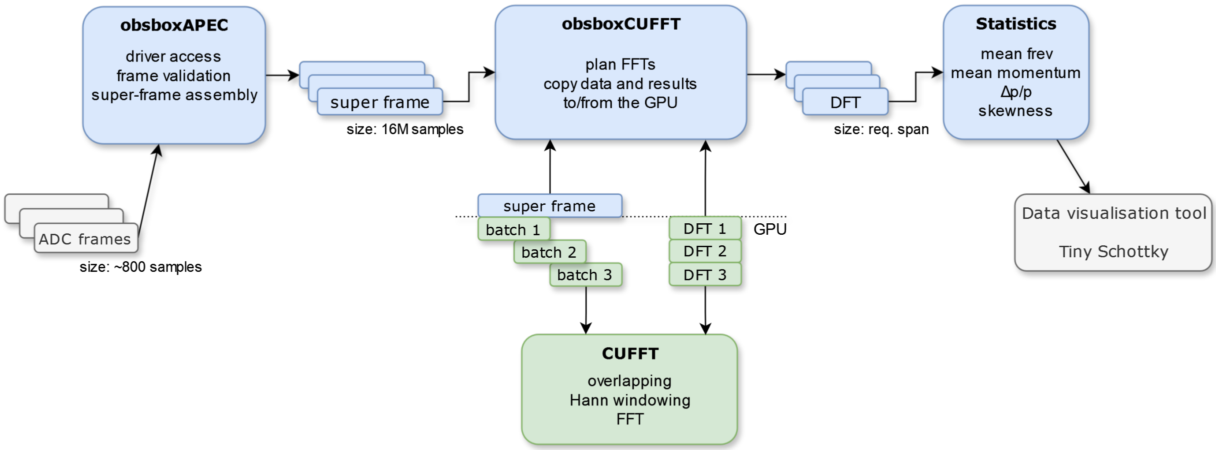

Figure 2: Logical blocks implemented in the ALLObsBoxSchottky FESA class to analyse the Schottky signals.

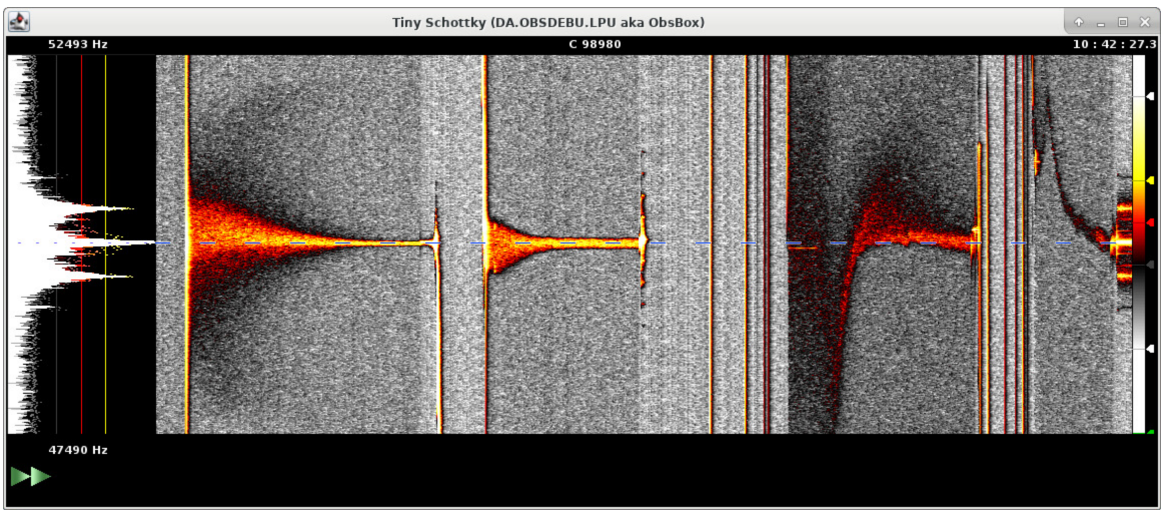

Figure 3: The computed spectra represented in a waterfall display, the stochastic and electron coolings of the four AD plateaux as seen through the Tiny Schottky application [13].

NEXT STEPS AND FUTURE WORKS

The ObsBox system described in this document can also analyze data from recorded files. A second server was installed in order to acquire signals for offline processing for the ELENA machine. In this case, the signal acquisition is carried out via an electrostatic pick-up from the orbit system [14], and an evaluation is underway to determine if the measured signal offers adequate SNR to accurately measure momentum spread reduction. For AD, the future work foreseen is aimed at analyzing the Schottky signal during the bunched phase of the cycle, particularly when the revolution frequency rapidly decreases during the deceleration ramp. This will require the implementation of a demodulation mechanism synchronized with the revolution frequency to track the beam and sufficiently reduce the FFT temporal observation window. Additionally, a mechanism for extracting and saving the spectrogram at key moments in the cycle will be implemented, along with the capability to average multiple spectra to improve the measurement statistics.

CONCLUSIONS

The adoption of static libraries simplifies the portability, reusability, and maintenance of the code developed for the ObsBox system, ensuring compatibility across different systems and facilitating ongoing support. Additionally, the use of a GPU allows for the computation of large FFTs of 2^{23} samples, even on lower-end workstations. The combination of high-rate large FFT computational capabilities, and improved SNR and dynamic range values due to 16-bit ADCs and programmable amplifiers employed in the LLRF system offers excellent spectral and temporal resolution, making the presented solution a suitable candidate for enhancing the existing measurement system. The high update rate of the displayed data allows the machine parameters to be tuned in real-time, in contrast to solutions where publication only occurs at the end of the cycle. In the context of AD, where one machine cycle takes approximately two minutes, this diagnostic system leads to significant time savings and is a valuable asset for commissioning, monitoring, and troubleshooting.

ISBN: 978-3-95450-247-9 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2024-WEPG27

REFERENCES

[1] M. E. Angoletta *et al.*, "Beam Commissioning of the New Digital Low-Level RF System for CERN's AD", in *Proc. IPAC'22*, Bangkok, Thailand, Jun. 2022, pp. 911–914. doi:10.18429/JACoW-IPAC2022-TUPOST025

[2] C. Gonzalez and F. Pedersen, "An Ultra Low Noise AC Beam Transformer for Deceleration and Diagnostics of Low Intensity Beams", in *Proc. PAC'99*, New York, NY, USA, Mar. 1999, paper THAR6, pp. 474–476.

[3] M. E. Angoletta, V. Chohan, M. Ludwig, O. Marqversen, and F. Pedersen, "The New Digital-Receiver-Based System for Antiproton Beam Diagnostics", in *Proc. PAC'01*, Chicago, IL, USA, Jun. 2001, paper WPAH122, pp. 2371–2373.

[4] M. Arruat *et al.*, "Front-End Software Architecture", in *Proc. ICALEPCS'07*, Knoxville, Tennessee, USA, Oct. 2007, pp. 310 – 312.

[5] M. E. Angoletta *et al.*, "Operation and New Capabilities of CERN's Digital LLRF Family for Injectors", in *Proc. IPAC'23*, Venice, Italy, May 2023, pp. 4178–4181. doi:10.18429/JACoW-IPAC2023-THPA094

[6] M. E. Angoletta *et al.*, "A New Longitudinal Diagnostics System for CERN's Antiproton Machines", 2022. doi:10.48550/arXiv.:2212.06793

[7] M. Soderen and D. Valuch, "Low Latency, Online Processing of the High-Bandwidth Bunch-By-Bunch Observation Data From the Transverse Feedback System in the LHC", in *Proc CHEP 2019*, Adelaide, Australia, Nov. 2019.

[8] *Understanding FFT Overlap Processing Fundamentals*, Tektronix INC., 2009. https://download.tek.com/document/37W_18839_1.pdf

[9] A. V. Oppenheim, R. W. Schafer "Discrete-Time Signal Processing", Upper Saddle river, New Jersey, USA: Prentice-Hall inc, 1994, pp. 468-471, 694.

[10] "The API reference guide for cuFFT, the CUDA Fast Fourier Transform library", NVIDIA Corporation, 2024. https://docs.nvidia.com/cuda/cufft/index.html

[11] "The API reference guide for the CUDA Runtime", NVIDIA Corporation, 2024. https://docs.nvidia.com/cuda/cuda-runtime-api/

[12] D. Boussard, "Schottky noise and beam transfer function diagnostics", in *Proc. CAS-CERN Accelerator School: 5th Advanced Accelerator Physics Course*, Rhodes, Greece, Oct. 1993, pp. 749–782. doi:10.5170/CERN-1995-006.749

[13] P. Freyermuth, B. Dupuy and D. Gamba, "Real Time Momentum Spread Measurement of the CERN Antiproton Decelerator Beam", in *Proc. IBIC'23*, Saskatoon, Canada, Sept. 2023, pp. 293–296. doi:10.18429/JACoW-IBIC2023-TUP045

[14] L. Søby *et al.*, "Elena Orbit and Schottky Measurement Systems", in *Proc. IPAC'15*, Richmond, VA, USA, May 2015, pp. 1061–1064. doi:10.18429/JACoW-IPAC2015-MOPTY056