ISBN: 978-3-95450-210-3 doi:10.18429/JACoW-FEL2019-WEP081

DESIGN AND DEVELOPMENT OF HIGH-SPEED DATA ACQUISITION SYSTEM AND ONLINE DATA PROCESSING WITH A HETEROGENEOUS FPGA/GPU ARCHITECTURE

M. Bawatna†, J. Deinert, O. Knodel, S. Kovalev
Helmholtz-Zentrum Dresden-Rossendorf (HZDR), Dresden, Germany
R. Spallek, Institut für Technische Informatik, Technische Universität, Dresden, Germany.

Abstract

The superradiant THz sources at TELBE facility is based on the new class of accelerator-driven terahertz (THz) radiation sources that provide high repetition rates up to 13 MHz, and flexibility of tuning the THz pulse form. The THz pulses are used for the excitation of materials of interest, about two orders of magnitude higher than state-of-the-art tabletop sources. Time-resolved experiments can be performed with a time resolution down to 30 femtoseconds (fs) using the novel pulse-resolved Data Acquisition (DAQ) system. However, the increasing demands in improving the flexibility, data throughput, and speed of the DAQ systems motivate the integration of reconfigurable processing units close to the new detectors to accelerate the processing of tens of GigaBytes of data per second. In this paper, we introduce our online ultrafast DAQ system that uses a GPU platform for real-time image processing, and a custom high-performance FPGA board for interfacing the image sensors and provide a continuous data transfer.

INTRODUCTION

TELBE THz facility is performing ultra-fast pump-probe experiments by providing a unique combination of high pulse energies and high repetition rates. In this type of experiment, the electric or magnetic field in the THz pump pulse acts as the excitation of dynamics in the matter. This dynamic in turn is then probed by ultra-short (light) pulses, typically with the sub THz cycle resolution as in [1]. A pulse resolved DAQ system has been developed at TELBE user facility as in [1] to allow the performance of time-resolved THz spectroscopy measurements with sub 30 fs Full-Width Half Maximum (FHWM) time resolution with excellent dynamic range up to 120 dB as in [2]. However, the high-speed commercial cameras used at TELBE user facility have several drawbacks in terms of data transfer, recording time, and data processing. Currently, most of the operating time is spent on the data transfer, rather than the data acquisition. Images are stored in the camera's internal buffer before being sent further. New data acquisition is only possible when all data is transferred. Therefore the commercial cameras are usually not able to provide online data processing.

The dominant technology used in the visible light detectors is the Charge Coupled Device (CCD) as in [3] due to its sensitivity and low noise performance. However, the high frame rate of the current imaging detectors is limited by the pixel access time. Therefore, commercially available imaging detectors decrease the number of pixels while increasing the frame rate.

Another drawback is that the firmware that interfaces the visible light detectors is not available to the developers, with a few parameters available for optimization. Therefore optimization of the camera's functionality to the application requirements is not possible.

Recently, there is an increased performance in large-scale real-time data processing using massively parallel architectures such as Graphics Processing Units (GPU) and Field Programmable Gate Arrays (FPGAs).

Accelerating the image processing using FPGAs or GPUs is not a new concept. Although GPUs can provide better performance than the FPGAs for applications where the data processing can be implemented with no inter-dependency in the data flow, the FPGAs are more suitable for applications that require many control operations and parallel processing. FPGAs not only provides flexibility in developing the desired algorithms, but also the ability for parallel data processing.

In this paper, we will present an online DAQ system for applications capable of providing both high data throughput and real-time data processing.

The paper is organized as follows: the first section introduces the requirements for the pulse-resolved DAQ system at TELBE. The second section presents the online pulse-resolved DAQ system, the implemented signal processing techniques, and the implemented firmware. The third section presents the arrival time information measurements. After summarizing the results, foreseeable future development and upgrades are discussed.

REQUIREMENTS FOR THE PULSE RESOLVED DAQ SYSTEM AT TELBE

Femtosecond level diagnostic and control of sub-picosecond electron bunches is an essential topic in modern accelerator research. At the ELBE user facility, there are two available electron injectors in use [4] as in Fig. 1. The thermionic injector, which supports repetition rates up to 13 MHz and bunch charges up to 100 pC, and the Super Radio Frequency (SRF) photo-cathode injector, which is used for experiments that may require lower emittance or higher bunch charges of up to 1 nC as in [4]. Moreover, the SRF injector at ELBE also has a maximum repetition rate of 13 MHz with different macro pulse modes of operation.

† m.bawatna@hzdr.de

39th Free Electron Laser Conf. FEL2019, Hamburg, Germany JACoW Publishing
ISBN: 978-3-95450-210-3 doi:10.18429/JACoW-FEL2019-WEP081

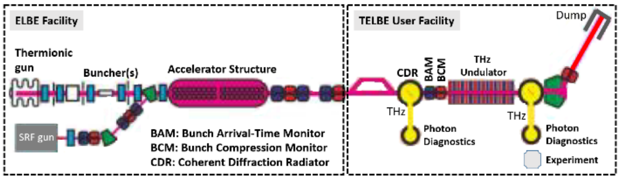

Figure 1: ELBE accelerator beamlines for THz radiation production.

However, the timing jitter of electron bunches as in Fig. 1 is affected by the bunch compression. The measurements of timing jitter for different bunch compression shows that the thermionic injector has a jitter up to 2 picoseconds (ps) and the SRF injector has much lower jitter up to 1 ps as shown in Fig. 2.

Accurate timing of an accelerator to an external laser system can be accomplished in several ways. One method is the Bunch Arrival time Monitor (BAM) system that based on RF pickups installed in the electron beam pipe, and the signal caused by the Coulomb field of the passing bunch can be used to derive an arrival time concerning an external laser. The BAM system is installed between the diffraction radiator and the undulator sources of the TELBE facility, as shown in Fig. 1.

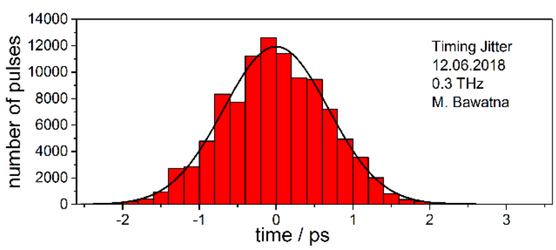

Figure 2: Histogram of the pulse-to-pulse arrival time jitter. Data were taken at the full 101 kHz repetition rate.

However, at TELBE user facility, the more accurate time resolution is required to utilize the transient THz fields as a novel highly selective excitation for non-linear dynamics. These dynamic processes are typically studied using pump-probe experiments as shown in Fig. 3, on few ten fs FWHM timescales involving synchronized external laser systems.

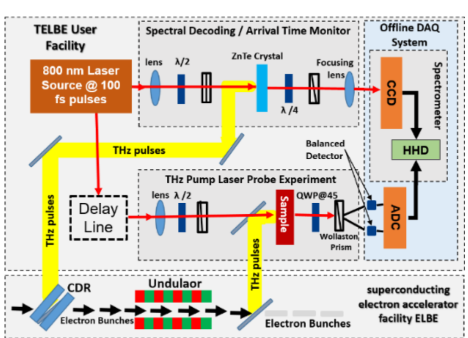

Figure 3: Schematic of the pulse-resolved DAQ system developed in TELBE This diagram shows how the arrival-time monitors are integrated into the experimental setup.

The current DAQ system at TELBE, as shown in Fig. 3, is capable of recording up to eight experimental data channels per pulse at a maximum repetition rate of 100 kHz. After the acquisition, the data is immediately written to disk, where it can be processed later.

Several digital signal processing operations need to be done on the measured arrival time information to achieve an excellent time resolution and performance accuracy of a few ten fs. The three offline signal processing operations as in [5] are: subtracting the pixels form the background noise, then applying the zero-phase filter on these pixels to reduce noise, and then calculating the location of the maximum peak.

Presently no data can be taken while writing to disk and the writing process is slower than the data acquisition by a factor of about 3. The system hence, currently has a duty cycle of about 25%. Therefore, we implemented an FPGA architecture close to the camera to achieve the necessary speed to process data between pulses, as well as improving the transfer rate of data to storage as in [5].

Online Pulse-resolved DAQ System

The online DAQ system enables continuous data acquisition at the highest speed and offers real-time data analysis, which provides opportunities for new experiments. The arrival time information for each THz pulse is recorded as a vector of 256 pixels using a KALYPSO linear array detector [6,7] due to its unprecedented MHz line rate. The measure photon energy at each pixel of the size of 50 µm x 3 mm is converted into a digital value with 12-bit resolution as in Fig. 4.

By applying a threshold level to the recorded vector, only the samples rise above the threshold are processed. If the number of samples above the threshold is below four, then they are considered as glitches. The arrival time information of each THz pulse is calculated based on the location of the maximum value.

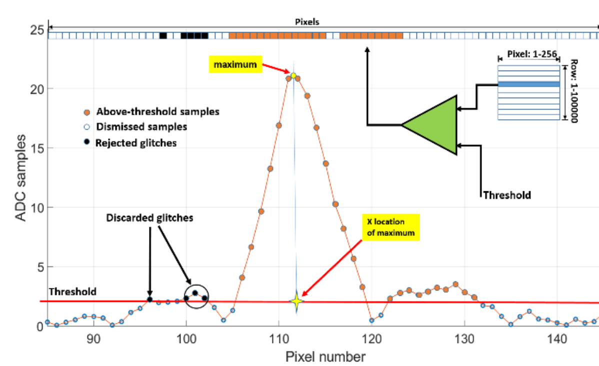

Figure 4: A vector containing the arrival time information of the THz pulse. Data were taken at 100 kHz repetition rate.

Firmware

The architecture of the DAQ system as shown in Fig. 5 is divided into three main parts: KALYPSO front-end, a Xilinx Virtex-6 FPGA ML605 evaluation board and a GUI used for controlling the parameters such as the image exposure time, noise threshold, as well as, storing the raw data and performing the online signal processing. The KALYPSO front-end is connected to the FPGA board by an FPGA Mezzanine Card (FMC) connector.

When the exposure or integration time is provided to the sensor, and the FPGA issues a frame request command, the image is stored in the pixel-matrix. The pixel values are digitized. These values are transferred using Low Voltage Differential Signal (LVDS) channels. Each LVDS channel is responsible for a group of adjacent columns of the pixel matrix.

A standard PCI Express (PCIe) connection is used to transfer the data from the camera directly either to NVIDIA GPU card or to the main computer memory to avoid the bottleneck between data acquisition and the limitation of the camera's internal buffers.

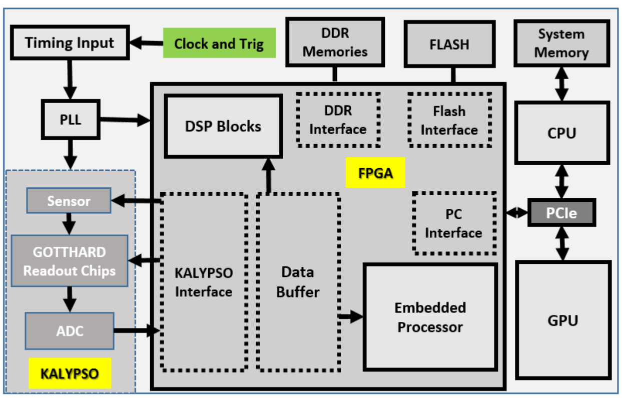

Figure 5: Block Diagram of the Heterogeneous FPGA/GPU DAQ and Processing System.

The DDR memory device is used for both temporary frame data storage and image processing algorithms.

EVALUATION

The Electro-optic sampling system is most commonly used to measure the time-domain form of THz pulses. They work by altering the polarization of a probe beam that propagates through the electro-optic crystal co-linear with a THz pulse an as in [5]. This effect is quasi-simultaneous and can be used to detect signals on femtosecond timescales.

For ZnTe crystal, the condition is met for THz pulses by using an 800 nm probe pulse as in Fig. 3. The undulator was tuned to 1 THz, and the beam was guided through the whole beamline. The laser pulse length was two picoseconds, the bunch charge was 200 pC, and the beam energy was 25.8 MeV.

A raw data of 300 frames at 100 kHz repetition rate, as shown in Fig. 6 has been recorded at TELBE.

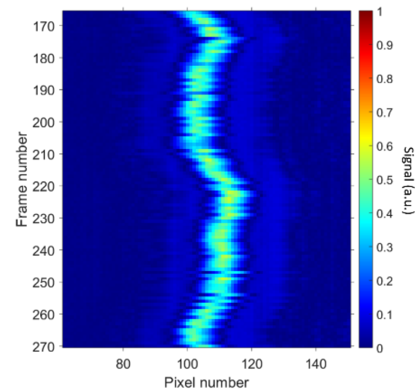

Figure 6: Raw data measurements recorded by the FPGA-Based DAQ System at TELBE.

CONCLUSION AND FUTURE WORK

The real-time DAQ system and online data analysis is still under development and evaluation. The results will be presented in a full article. The arrival time information of THz pulses can be recorded and processed by the developed real-time DAQ system at TELBE. As future work, interfacing ultra-high-speed ADC of 1000 MSPS with the FPGA shall be implemented to improve the SNR of our experimental data. The real-time signal processing shall be implemented inside the GPU card.

REFERENCES

[1] S. Kovalev *et al.*, "Probing ultra-fast processes with the high dynamic range at 4th-generation light sources: Arrival time and intensity binning at unprecedented repetition rates," *Structural Dynamics*, vol. 4, no. 2, p. 024301, 2017. Doi:10.1063/1.4978042

[2] M. Bawatna *et al.*, "Pulse-resolved Data Acquisition System for THz Pump Laser Probe Experiments at TELBE using Super-radiant Terahertz Sources", 2019 IEEE MTT-S International Microwave Workshop Series on Advanced Materials and Processes for RF and THz Applications (IMWS-AMP), Bochum, Germany, 2019, pp. 142-144.

[3] P. Magnan, "Detection of visible photons in CCD and CMOS: A comparative view," *Nucl. Instr. and Meth in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment*, vol. 504, no. 1, pp. 199–212, 2003. doi:10.1016/S0168-9002(03)00792-7

[4] J. Teichert *et al.*, "Experiences with the SRF Gun II for User Operation at the ELBE Radiation Source", in *Proc. IPAC'18*, Vancouver, Canada, Apr.-May 2018, pp. 4145-4147. doi:10.18429/JACoW-IPAC2018-THPMF040

[5] M. Bawatna *et al.*, "Towards Real-time Data Processing using FPGA Technology for High-speed Data Acquisition System at MHz Repetition Rates," presented at the SRF'19, Dresden, Germany, Jun.-Jul. 2019, paper THP029.

[6] L. Rota *et al.*, "KALYPSO: A Mfps Linear Array Detector for Visible to NIR Radiation," in *Proc. IBIC'16*, Barcelona, Spain, Sep. 2016, pp. 740-743. doi:10.18429/JACoW-IBIC2016-WEPG46

[7] M. Caselle *et al.*, "A high-speed DAQ framework for future high-level trigger and event building clusters," *Journal of Instrumentation*, vol. 12, no. 03, p. C03015, 2017. doi:10.1088/1748-0221/12/03/C03015