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SINGLE-SHOT LONGITUDINAL BEAM PROFILE AND TERAHERTZ DIAGNOSTICS AT MHz- TOWARDS GHz-RATES WITH HIGH-THROUGHPUT ELECTRONICS

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Abstract

Accelerators with high bunch-repetition rates require high-throughput detector electronics to diagnose each individual bunch. KALYPSO with a 256-pixel detector line-array integrated in an fs laser-based electro-optical set-up allows longitudinal bunch profiling with sub-ps resolution as demonstrated at the storage ring KARA for single-bunch mode operation at 2.7 MHz and also at the European XFEL with a 4.5-MHz micro-bunch train. Improvements will enhance fs-time accuracy, reduce noise, and increase frame-rate. A custom front-end with an application-specific integrated circuit (ASIC) has been developed to operate with 10-MHz frame-rates at low noise. Several linear arrays with up to 1024 pixel and smaller pixel pitch were submitted for production. The development of a low-gain avalanche diode (LGAD) sensor will further improve the time resolution. Detector data is transmitted in the DAQ framework to external GPU-based clusters and processed in real-time at 7 GBytes/s with a few µs latency. For beam dynamics studies we also develop KAPTURE capable to analyze terahertz detector pulses at GHz-repetition rates. These developments open new possibilities in beam diagnostics of modern accelerators.

INTRODUCTION

The investigation of bunch-to-bunch interactions and beam dynamics during micro-bunching poses several challenges to both accelerator physicists and detector developers [1, 2]. The short bunch lengths and the dimension of substructures on the bunch profile impose tight requirements in the temporal resolution of detectors and front-end electronics technologies. Furthermore, if beam diagnostics setups require single-shot measurements on a turn-by-turn basis for long observation times, the front-end electronics and the Data Acquisition (DAQ) system must be able to sustain data rates of several GBytes/s.

At the Karlsruhe Institute of Technology (KIT), we are developing new experimental techniques and detector systems to meet the requirements of modern accelerators and enable ultra-fast beam diagnostics at high repetition rates. The development of new technological components is carried out in close cooperation with the accelerator facilities of KARA (Karlsruhe Research Accelerator) [3] and soon FLUTE (Ferninfrarot Linac- und Test-Experiment) [4], where the novel detectors systems are fully characterized and tested in a real accelerator environment, before their commissioning at other research centers.

In this paper we report about recent developments on two detector systems which have been developed for time-resolved beam diagnostics. The first system is KALYPSO, an ultra-fast camera developed for turn-by-turn longitudinal and transverse beam profile measurements. The second one is KAPTURE, a detector system which has been widely employed in the investigation of the fluctuations of terahertz (THz) Coherent Synchrotron Radiation (CSR) by micro-bunching instability (bursting). Both detectors have been integrated in a custom DAQ framework for real-time data processing based on Field Programmable Gate Arrays (FPGAs) and Graphic Processing Units (GPUs), in order to achieve high data throughput with low latency.

KALYPSO

KALYPSO (Karlsruhe Linear Array Detector for MHz repetition rate spectroscopy) is an ultra-fast 1D camera with a continuous frame rate of 2.7 Mfps [5]. KALYPSO has been originally developed for the upgrade of the Electro-Optical Spectral Decoding experimental setups at KARA and at the European XFEL. The front-end electronic components are mounted on the detector mezzanine card shown in Figure 1. Two types of semiconductor linear arrays can be employed, depending on the specific application. The first one is a Si microstrip sensor, originally developed at the Paul Scherrer Institute (PSI) for charge integrating X-ray

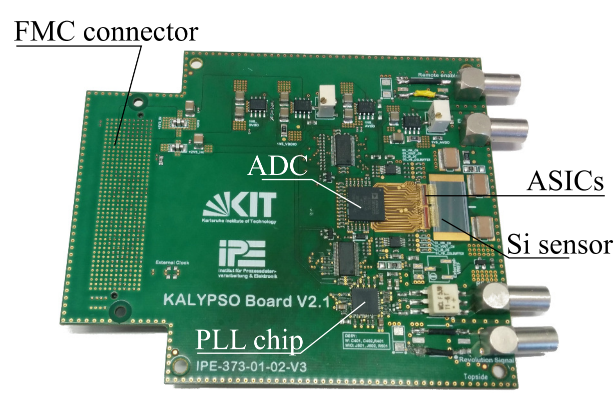

Figure 1: Photograph of the KALYPSO mezzanine board.

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detectors. The second one is an InGaAs linear array from Xenics. The former is used in applications where visible light must be detected, while the latter is employed with near-infrared radiation. The current version of the detector, named KALYPSO II, is based on a modified version of the GOTTHARD front-end ASIC [6] and achieves a maximum frame-rate of 2.7 MHz. In the current version, two GOTTHARD chips are connected to a linear array sensor with 256 pixels and 50 µm pixel pitch. A commercial analog-to-digital converter (ADC) converts the analog samples with a sampling rate of 65 MS/s and 14-bit resolution. When connected to the DAQ system described below, KALYPSO sustains continuous data taking at the maximum repetition rate.

New Si Microstrip Sensors

As described above, the Si sensor employed in the current version of KALYPSO is not optimized for the detection of visible light and near-IR radiation. To improve the quantum efficiency at different wavelengths, we have designed a new Si sensor optimized for imaging applications. The new sensor features an optimized geometry, with a pixel pitch of 25 µm and a variable number of pixels (from 512 to 2048). A smaller pitch improves the spatial resolution while, at the same time, decreases the capacitance of each photodiode, resulting in a higher readout speed and lower noise. Moreover, different Anti-Reflective Coatings (ARC) will be applied to the sensor during the production phase. In particular, three different ARCs will be applied, optimized respectively for visible light, near-ultraviolet (300 nm to 400 nm) and near-infrared (up to 1.1 µm). With respect to a monolithic approach based on CMOS processes, a hybrid solution allows us to cover a wide range of experimental applications with a unique detector system. The final layout of the sensors has been completed and is shown in Figure 2. The sensors will be produced by FBK in the third quarter of 2017.

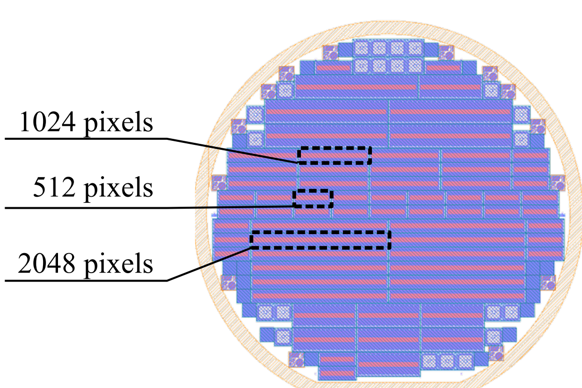

Figure 2: Layout of the wafer containing the new Si sensors for KALYPSO. The different versions of the sensor are shown.

KALYPSO III: Towards 10 MHz Repetition Rates

To further increase the frame rate of KALYPSO, we are currently developing a new front-end Application Specific Integrated Circuit (ASIC) in collaboration with PSI. Moreover, by optimizing the front-electronics with respect to the electrical proprieties of the new Si sensors described above, the noise performance can be improved despite the higher frame rate. A higher frame rate is nececssary to meet the requirements of different facilities (*e.g.,* the European XFEL with a repetition rate of 4.5 MHz) and further improve the temporal resolution of beam diagnostic applications. A prototype chip, designed in a commercial 110 nm CMOS technology and consisting of 48 channels, has been submitted in late 2016. The prototype is fully functional and achieves a frame rate of 12 MHz. After the submission of the final version of the chip, the production of KALYPSO III will start in early 2018.

High-speed Imaging with Ultra-fast Detectors

An important limitation in high-speed imaging applications is the response time of the semiconductor detector. With traditional Si sensors, the time required to collect the charges generated by the incoming radiation is typically around a few tens of ns, therefore limiting the maximum frame rate. When exposed to an incoming radiation with an higher repetition rate, the sensor would quickly saturate. While it is possible to install a gating-intensifier stage in front of the detector, such as the ones used in intensified CCD (ICCD) cameras, these can degrade the resolution and the uniformity of the detector.

In high-speed imaging detectors, Avalanche PhotoDiodes (APDs) are widely employed. Typically they are operated in linear mode, meaning that the intensity of the generated signal is proportional to the intensity of the incoming radiation. A device based on APDs for beam diagnostics applications is described in [7], where 16 pixels are operated with a maximum frame-rate of 50 MHz. However, several technological challenges hinder the possibility to realize APD linear arrays with a large number of channels. Therefore, this makes them unsuitable for many beam diagnostics applications demanding high spatial resolution, such as Electro-Optical Spectral Decoding.

In order to overcome the rate limitation of conventional Si detectors while maintaining high spatial resolution, we are currently evaluating the integration of KALYPSO with Low-Gain Avalanche Detectors (LGAD). LGADs have been recently proposed in the literature for 4D tracking applications in high energy physics detectors [8]. With respect to conventional APDs, LGADs feature a moderate internal gain, thus enabling the fabrication of finely-segmented microstrip and pixel detectors, while achieving charge collections times as low as 3 ns [9]. This would ensure that the sensor is not saturated by the incoming radiation, even if exposed to pulses with repetition rates of a few hundreds of MHz. The production of a prototype LGAD microstrip array for the

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KALYPSO detector with a pixel pitch of 50 μm is currently planned for the end of 2017.

KAPTURE

KAPTURE (KArlsruhe Pulse Taking Ultra-fast Readout Electronics) [10] is a wide-band front-end electronics system for sampling ultra-short pulse signals generated by ultra-fast detectors. The wide-dynamic range at the input enables an high-compatibility with many fast detectors, *e.g.,* YBCO THz detectors [11], HEB [12], room-temperature Schottky diodes, Beam Position Monitors (BPMs) and diamond detectors. KAPTURE is able to digitize pulse shapes with a sampling time down to 3 ps and pulse repetition rates up to 500 MHz. The combination with ultra-fast THz detectors, also designed and produced at KIT [13], offers a complete detector and readout system for the measurement of CSR intensity in the THz region to the scientific community.

A second version of the KAPTURE board [14] has been designed and produced to overcome these limitations. The KAPTURE-2 mezzanine card is shown in Figure 3. KAPTURE-2 makes use of the latest advantages of the best components on the market. In particular, of a new generation of ultra high-speed ADCs and an ultra low-noise clock jitter cleaner with dual-loop PLL. The new fast ADC offers several advantages: a sampling rate up to 2 GS/s and voltage reference, offset and analog gain adjustable channel-by-channel by 15 bits. This last option is useful to compensate the gain mismatch between different sampling channels. The dual-loop PLL architecture is capable of 111 fs rms jitter which is 4 times less compared with the first KAPTURE version. The PLL provides an excellent clock distribution through two fully configurable delay logic, one coarse delay from 2.25 ns up to 261 ns with a time step of 500 ps and an analog fine delay from 0 to 475 ps with time resolution steps of 25 ps. The flexible and accurate time distribution allows an easy synchronization between the detector pulse and the sampling time system. The selected PLL synchronizes the distributed signal clocks, with a fixed and known phase relationship, between two or more PLL devices located on different KAPTURE boards. This special feature allows us to synchronize the sampling times of two or more KAPTURE boards, extending the sampling points beyond four samples. The comparison between the pulse sampling strategies of the first version of KAPTURE and the new version are shown in Figure 4.

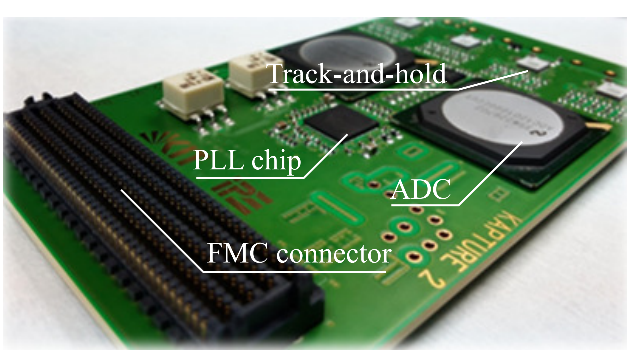

Figure 3: Photograph of the KAPTURE mezzanine board.

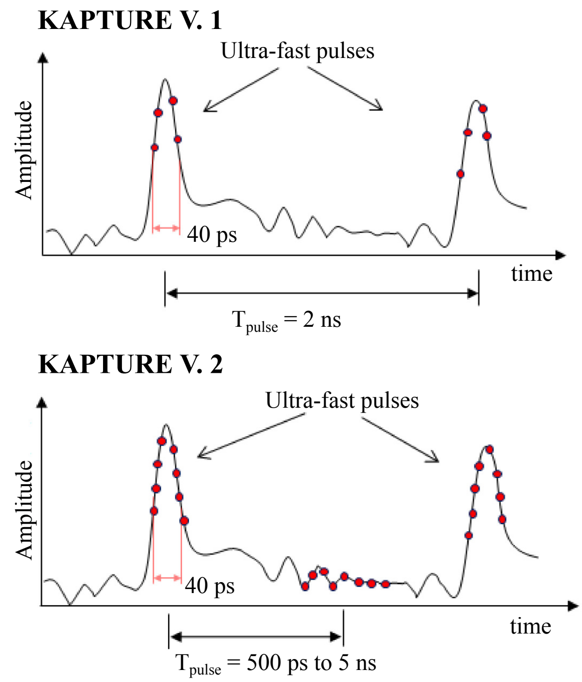

Figure 4: Comparison of the sampling strategies between the first (top) and second (bottom) KAPTURE versions. The sampling points are indicated by the red circles.

With the new version, two KAPTUREs can be connected together for direct sampling of detector pulses with up to eight sampling points with a pulse repetition rates of up to 2 GHz. Optionally, the system can be programmed to sample both the detector pulse and the baseline between two pulses with a constant pulse rate of up to 1 GHz. The FPGA will receive both the pulse amplitude and the baseline so that only the corrected amplitude will be sent to the GPU for data processing. The expand and flexible pulse repetition rate from 0.2 to 2 GHz makes the new design compatible with many synchrotron accelerator machines. The flexibility includes also the option of parallel detectors for acquisition. The system can digitize up to eight detectors in parallel with one sample point located at the peak amplitude of each detector pulse.

HIGH-THROUGHPUT DAQ SYSTEM

The front-end electronics of both systems have been developed as mezzanine cards based on the VITA FMC standard. In this way, the mezzanine cards are compatible with a large number of FPGA readout cards, thus allowing external users to integrate them within an existing DAQ system.

At KIT, the detectors have been integrated in a custom high-performance and heterogeneous DAQ system consisting of FPGAs and GPUs directly connected via PCI-Express. The different cards hosting the front-end electronics are connected to a custom FPGA board, named "High-Flex" [15].

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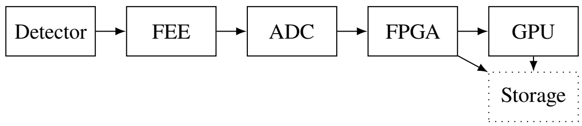

Figure 5: Data flow of the heterogeneous DAQ system based on FPGAs and GPUs.

The data flow in the DAQ system is shown in Figure 5. Data produced by the front-end electronics (FEE) on the mezzanine cards are acquired by the FPGA board, where they are pre-processed and temporarily stored in a local DDR3 memory. Data are then transmitted to external storage or computing nodes. A custom GPU-based processing framework enables user-friendly and on-line monitoring of the data produced by the detector systems [16]. As demonstrated in [17], our architecture allows scientists to develop high-performance processing algorithms without requiring specific knowledge of the underlying hardware architecture. Moreover, the low-latency performance of the DAQ system meets the requirements of fast feedback systems. With specific optimization of the data processing software components, a latency as low as a few microseconds has been achieved [18].

EXPERIMENTAL RESULTS AT KARA

Turn-by-turn Bunch Profile Measurements

The KALYPSO detector system has been installed at the near-field EOSD setup at KARA. A detailed description of the experimental setup can be found in [19]. Preliminary measurements have been performed at the maximum repetition rate of 2.7 MHz. Single-shot and turn-by-turn measurements of the longitudinal bunch profile have been achieved for long observation times, as reported in previous publications [20]. Due to improvements in both the detector system and the experimental setup, in particular with the commissioning of a new EO arm, a much higher sensitivity when observing sub-structures on the bunch profiles is expected [21]. KALYPSO is also installed as diagnostic tool at the EO setup of the European XFEL. The detector is connected to a custom FPGA readout card, developed at DESY, to ease the integration of the detector with the μTCA (Micro Telecommunications Computing Architecture) infrastructure of the European XFEL.

At KARA, a dedicated Visible Light Diagnostics (VLD) beamline hosts a fast gated intensified camera (FGC) to study the horizontal bunch profile and thus the energy spread [22, 23]. However, with the current setup the bunch profile can be measured only once every 6 turns, and only a limited number of profiles can be acquired in one measurement. To lift this limitation, a KALYPSO detector equipped with a Si sensor has been recently installed at the VLD port. Preliminary measurements have shown that the low-noise performance of the detector allows us to measure the horizontal bunch profile, even without employing an intensifier stage. Similar to the EOSD setup, turn-by-turn monitoring has been achieved for long observation times. However, the optimization of both the detector system and the optical setup at the VLD port are currently ongoing.

Far-field THz Diagnostics

KAPTURE has been integrated as a permanent diagnostic tool at KARA. Several studies have already been conducted with KAPTURE, such as the investigation of the emission of THz radiation in the bursting regime [1, 24] and the evolution of micro-bunching instabilities in multi-bunch environments [2]. With the quasi-simultaneous acquisition of bunches covering the full bunch current range, a spectrogram can be created from just one dataset. KAPTURE thus offers a way to quickly scan the beam behavior over several machine parameters and gain new insights into the behavior of different thresholds and the change of the spectrograms as recently shown in [25]. Moreover, the four sampling channels can be connected to different THz detectors, each one tuned to a specific frequency band, thus revealing the spectral proprieties of CSR [26].

Synchronized Measurements

KAPTURE and KALYPSO can be installed at different experimental stations and synchronized via the accelerator timing system. The synchronization procedure and the first experimental results obtained with both systems have been described in [22, 27]. After the upgrade and the optimization of the EOSD and VLD setups, further measurement campaigns will be carried out in the next months.

SUMMARY AND OUTLOOK

Two detector systems, KALYPSO and KAPTURE, have been developed for beam diagnostics requiring high temporal resolution and repetition rates in the MHz range. The current status and the major improvements planned for both systems have been described. Both systems are currently installed at different experimental setups at the KARA storage ring, such as the near-field EOSD monitor, the VLD port and the THz beamlines. Moreover, the commissioning of KALYPSO at the European XFEL is ongoing. With respect to other solutions, KAPTURE and KALYPSO achieve high repetition rates for long observation times, allowing scientists to study the beam behaviour over a wide range of time-scales.

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