KALYPSO: A Mfps LINEAR ARRAY DETECTOR FOR VISIBLE TO NIR RADIATION

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Abstract

The acquisition rate of commercially available line array detectors is a bottleneck for beam diagnostics at high-repetition rate machines like synchrotron lightsources or FELs with a quasi-continuous or macro-pulse operation. In order to remove this bottleneck we have developed KALYPSO, an ultra-fast linear array detector operating at a frame-rate of up to 2.7 Mfps. The KALYPSO detector mounts InGaAs or Si linear array sensors to measure radiation in the near-infrared or visible spectrum. The FPGA-based read-out card can be connected to an external data acquisition system through a high-performance PCI-Express 3.0 data-link, allowing continuous data taking and real-time data analysis. The detector is fully synchronized with the timing system of the accelerator and other diagnostic instruments. The detector is currently installed at several accelerators: ANKA, the European XFEL and TELBE. We present the detector and the results obtained with Electro-Optical Spectral Decoding (EOSD) setups.

INTRODUCTION

Electro-Optical Spectral Decoding (EOSD) is a well-established technique to measure the longitudinal bunch profile in a non-destructive way [1, 2] and with sub-picosecond spatial resolution [3]. A detailed description of EOSD can be found in [4]. In a typical EOSD setup, a chirped laser pulse is modulated inside an Electro-Optical crystal by the Coulomb field of the electron bunch. In this way the information on the temporal profile of the bunch is contained in the spectrum of the laser pulse. A spectrometer with a linear array detector is commonly used to measure the spectrum and reconstruct the bunch profile. While, in principle, this diagnostic technique allows single-shot measurements over many bunches, the bottleneck of current experimental setups lies in the linear array detector used in the spectrometer.

In particular, the acquisition rate of the detector has to match the bunch repetition rate of the accelerator machine (*e.g.:* 4.5 MHz at the European XFEL, 2.7 MHz during single-bunch operation at ANKA) to obtain single-shot resolution on a turn-by-turn basis. Moreover, the data acquisition system (DAQ) must be able to sustain high data-rates to allow the analysis of the beam dynamics over long time scales (*i.e.*:, a large number of samples). To the best of our knowledge, the line rates of commercial linear detectors reach only a few hundreds of kHz [5, 6].

An alternative approach, based on the method of photonic time-stretch, has been recently implemented by Roussel *et al.* [7] to lift the aforementioned limitation on the acquisition rate. This method enables an unprecedented acquisition rate in EOSD experiments (up to 62.5 MHz, an order of magnitude higher than what can be currently accomplished with linear array detectors) by using an oscilloscope to sample the signal of a fast photodiode. However, because of the finite memory depth of oscilloscopes, only a limited amount of samples can be acquired in a given time frame. This method is therefore not suitable for long observation times or experiments where real-time data analysis and fast-feedback are required.

In order to overcome such limitations, we have developed KALYPSO (KArlsruhe Linear arraY detector for MHz-rePetition rate SpectrOscopy), a novel linear array detector operating at line-rate of up to $2.7 \cdot 10^6$ fps (frames per second). In this contribution, we describe the architecture of the system and its application as beam diagnostic tool in the near-field EOSD setup of ANKA.

DETECTOR ARCHITECTURE

KALYPSO consists of a detector board and an FPGA-based readout card. The detector board mounts the sensor, the front-end amplifier and the Analog-to-Digital Converter (ADC). The sensor is a Si or an InGaAs linear array, with

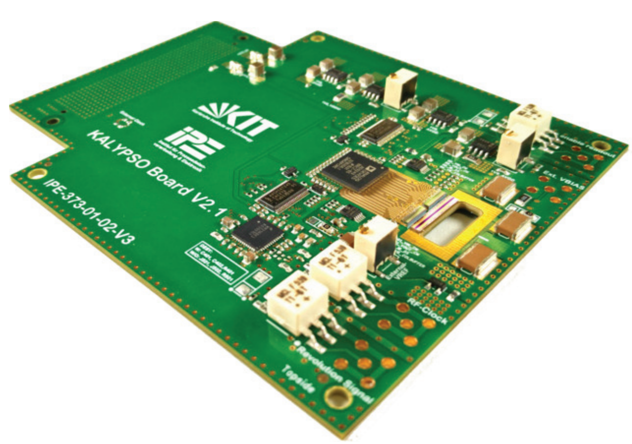

Figure 1: Picture of the KALYPSO detector board with InGaAs sensor.

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256 pixels and a pitch of 50 µm, to detect radiation in the visible and near-infrared spectrum up to wavelengths of 1.7 µm. The sensor is connected to the readout ASIC with high-density gold ball-to-wedge wire-bonds. With respect to the architecture described in [8], a dedicated version of the GOTTHARD chip [9] with an improved output stage has been selected as front-end amplifier. The novel GOTTHARD 1.6 chip, designed at PSI, consists of a charge-sensitive pre-amplifier, a channel buffer and an output buffer. Each output is connected to 16 channels through an analog multiplexer, which has been tested at a switching frequency of 62.5 MHz, therefore limiting the maximum framerate of the system to 2.7 MHz. The analog outputs are digitized by a commercial ADC with 14 bits resolution and a maximum sampling rate of 65 MSPS (AD9249 from Analog Devices). The latency of the detector board when operating at the maximum line-rate is less then 300 ns[1], and it is mainly introduced by the internal pipeline of the ADC. Additional components are also installed on the board to synchronize the detector with the accelerator's timing system and other detectors. The detector card is connected to the back-end card through an FMC connector. A picture of the first prototype mounting an InGaAs sensor is shown in Figure 1.

The readout card used at ANKA is based on a Xilinx Virtex7 FPGA and controls the detector's operation. The data-acquisition (DAQ) system is based on a custom PCI-Express 3.0 Direct Memory Access engine with a maximum throughput of 6.4 GB/s [10], therefore allowing streaming operation at the maximum repetition rate of the detector. Real-time data analysis can be performed inside the FPGA or on a custom processing framework based on Graphical Processing Units (GPUs). While the former solution offers real-time data elaboration without the need of additional hardware, the latter allows for more flexibility in the data evaluation [11], in addition to the possibility to store the raw data and perform off-line data analysis. Thanks to the industry standard connector, the detector card can be easily integrated with different DAQ system, as is the case with the European XFEL: the integration of KALYPSO in a µTCA readout and timing is currently ongoing at DESY.

MEASUREMENTS WITH EOSD SETUP AT ANKA

We performed characterization measurements with the first prototype board mounting an InGaAs sensor at the near-field EOSD setup of ANKA (for which a detailed description can be found in [12])[2].

A Yb-doped laser operating at wavelength of 1050 nm has been used as source. The average power of each laser pulse hitting the detector is 6 pJ. With this incident power, the highest gain mode of the GOTTHARD chip (15 mV/fC) and integration time of 32 ns were choosen to achieve a Signal-to-Noise Ratio (SNR) of around 30. An external reverse bias of 1 V was applied to the sensor. We measured a leakage current of 20 µA, therefore its noise contribution can be considered negligible. These settings were used for all the measurements here reported.

In order to measure the bunch profile, three different measurements have been done: the background signal (recorded when no light is hitting the detector), the un-modulated signal (recorded with the laser pulse, but without the modulation of the electron bunch) and the modulated signal.

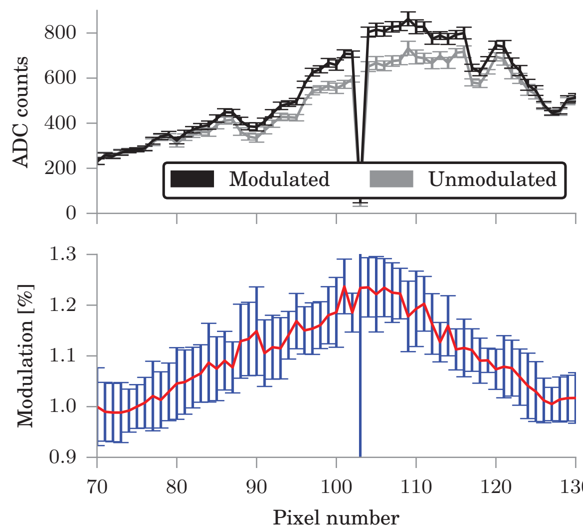

Figure 2: Top: modulated and un-modulated (averaged) signals recorded with KALYPSO. Bottom: relative modulation of the laser pulse (single-shot). In both plots the error bars show the standard deviation.

The background and the un-modulated signal are acquired before the acquisition of the modulated signal, and the average over a large number of samples (> 10^5 samples) is taken as reference. The background is subtracted from both the un-modulated and the modulated signal before calculating the relative modulation, as shown in Figure 2. Because the average modulation of the laser pulse is around 10%, the requirements on the noise detector become particularly challenging: if the modulation has to be measured with a SNR of 10, the SNR of the modulated signal has to be higher than 100. However, even with an incident light power for each laser pulse as low as 6 pJ, the formation of substructures on the bunch profile has been observed successfully, as shown in Figure 3.

CONCLUSION AND FUTURE WORK

We have developed a linear array detector with a frame-rate of 2.7 Mfps. The detector has been developed to upgrade the acquisition rate of existing EOSD setups currently installed at ANKA, the European XFEL and ELBE.

The first prototype of the KALYPSO detector, based on an InGaAs sensor and the new GOTTHARD 1.6 chip, has

[1] The latency is here defined as the time interval between the arrival of the laser pulse and the acquisition of the corresponding digitized value inside the back-end card.

[2] Pixels number 105 and 135 exhibits a higher noise because of a defective wire-bonding.

ISBN 978-3-95450-177-9

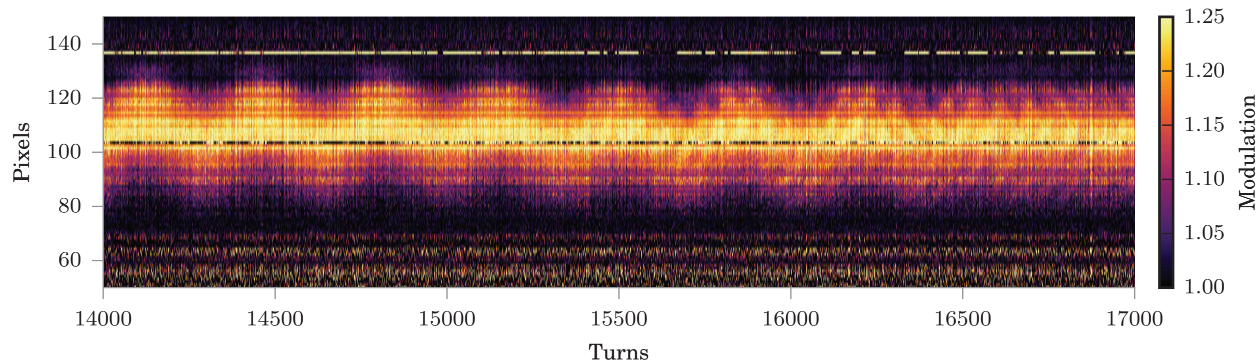

Figure 3: Raw measurement data of the longitudinal bunch profile recorded with KALYPSO over multiple turns. The acquisition rate of KALYPSO was set to 2.7 Mfps, so that each vertical line corresponds to a single-shot and turn-by-turn measurement of the bunch profile. The synchrotron oscillation of the electron bunch is visible on the left side. On the right side, the build-up of substructures on the bunch profile (the so-called microbunching effect) can be observed. The full dataset consists of $5 \cdot 10^5$ turns.

been successfully tested as a beam diagnostic tool in the EOSD setup at ANKA. With an incident light power as low as 6 pJ, the detector achieves a SNR of around 30, which is sufficient to detect the formation of substructures on the bunch profile. When coupled with a high-throughput DAQ system, it enables single-shot and turn-by-turn measurement of the beam longitudinal profile over a large number of turns ($> 10^7$ turns) at the bunch revolution frequency of 2.7 MHz. Moreover, because of the low-latency introduced by the detector board, KALYPSO can be used as diagnostic tool in fast-feedback systems.

Additional measurements are currently ongoing at ANKA and at the European XFEL in order to fully characterize the performance of the system with both InGaAs and Si sensors. In particular, the noise contribution of each component of the system (electronics, laser instabilities, jitter in the timing synchronization) will be studied. In the meantime, maintenance of EOSD setup (in particular, the in-vacuum laser path) is also being carried out at ANKA. With an estimated increase in the incident laser power by a factor of 10, we expect a significant improvement in terms of SNR and a better resolution

Finally, a novel front-end ASIC is being developed at KIT in collaboration with PSI, in order to further improve the frame-rate and the noise performance of the system. A prototype chip, designed in CMOS 0.11 µm technology with a target frame-rate of 5 Mfps has been submitted to the foundry and will be characterized in the next months.

ACKNOWLEDGEMENT

The authors would like to thank Simon Kudella and Pia Steck for their precious help with the wire-bonding process. This work is partially funded by the BMBF contract number: 05K16VKA.

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ISBN 978-3-95450-177-9