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MODERN ULTRA-FAST DETECTORS FOR ONLINE BEAM DIAGNOSTICS

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Abstract

Synchrotron light sources operate with bunch repetition rates in the MHz regime. The longitudinal and transverse beam dynamics of these electron bunches can be investigated and characterized by experiments employing linear array detectors. To improve the performance of modern beam diagnostics and overcome the limitations of commercially available detectors, we at the institute of data processing and electronics (IPE) have developed KALYPSO, a detector system operating with an unprecedented frame rate of up to 12 MHz [1]. To facilitate the integration in different experiments, a modular architecture has been utilized. Different semiconductor micro-strip sensors based on Si, InGaAs, PbS, and PbSe, with the quantum efficiency optimized at different photon energies, can be connected to the custom-designed low noise front-end ASIC operating at Mega frame rate. The front-end electronics are integrated within a heterogeneous DAQ consisting of FPGAs and GPUs, which allows the implementation of real-time data processing. This detector is currently installed at KARA, European XFEL, FLASH, SOLEIL and DELTA [2]. In this contribution, we present the detector architecture, the performance results, and the ongoing technical developments.

INTRODUCTION

At the KIT storage ring KARA (Karlsruhe Research Accelerator) scientists utilize the synchrotron radiation as a source for THz light with range reaching to lower frequencies from 0.3 to 3 THz. The accelerator can be operated in short-bunch mode where the momentum compaction factor α_c is reduced.This inherently shortens the electron bunch length that results in an interaction of the bunches with their own emitted radiation and thereby forming sub-structures in the longitudinal phase-space. This phenomenon is called the micro-bunching instability [3]. There are several experimental techniques, which allow the study of such an occurrence. Two such experiments include longitudinal bunch size measurements using electro-optical spectral decoding (EOSD) [4] and energy-spread measurements [5].

In this paper the complete detector architecture followed by its applications at KARA is presented.

DETECTOR ARCHITECTURE

The detector system is divided into two parts: First, a front-end card which includes the micro-strip line array sensor, the front-end application-specific integrated circuit (ASIC) and the high-speed ADC (analog-to-digital converter); Second, the back-end data acquisition system which includes the FPGA based read-out card.

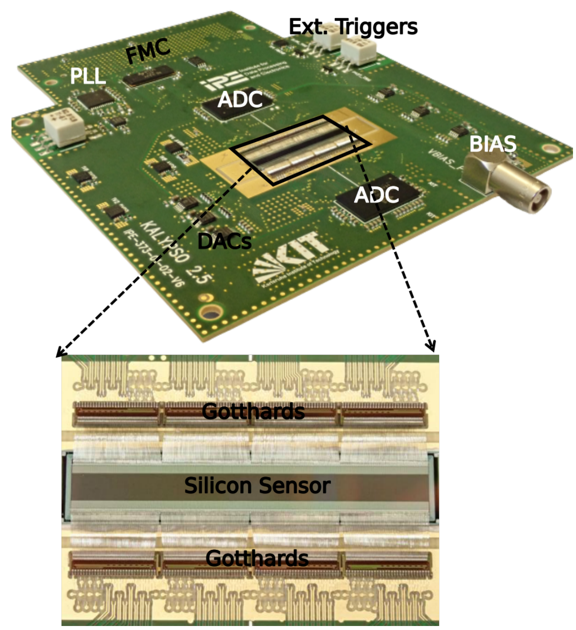

Figure 1: A fully mounted KALYPSO-board based on silicon with 1024 pixels sensitive to the visible light spectrum.

Front-End Card

Micro-Strip Line Array Sensor The front-end card consists of a micro-strip line array sensor connected to 8 front-end ASICs as depicted in Fig. 1. Several sensor semiconductors with different pixel geometries can be mounted on the front-end card, silicon (Si), indium gallium arsenide (InGaAs), lead sulphide (PbS) or lead sellenide (PbSe) as shown in Fig. 2. The silicon sensor has been custom-designed for the front-end card. The design includes user-specific geometries and application of an antireflection coating (ARC) to improve the photon absorption [6]. The ARC has been targeted for the near-ultra violet (up to 350 nm), visible range from 350 nm to 750 nm, and near-infrared range from 750 nm to 1 050 nm [7] for the Si sensors (Fig. 2(a)). For applications that require photon sensitivity beyond 1050 nm, commercially available line array sensors based on InGaAs, PbS, and PbSe with senstivity up to 2 200 nm, 3 000 nm, and 5 000 nm) shown in Fig. 2(b), 2(c) and 2(d), respectively, are used [8]. Figure 3 shows the profile of a 1 560 nm laser beam measured by the three different commercial line arrays. The difference in the amplitude response is explained by the different quantum efficiency region associated with each sensor [9].

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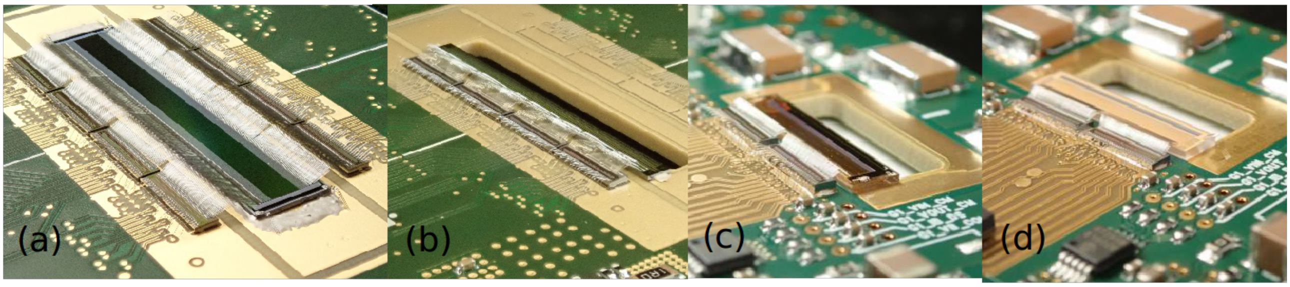

Figure 2: KALYPSO-board mounted with different micro-strip sensors. (a) Si, (b) InGaAs, (c) PbS, (d) PbSe.

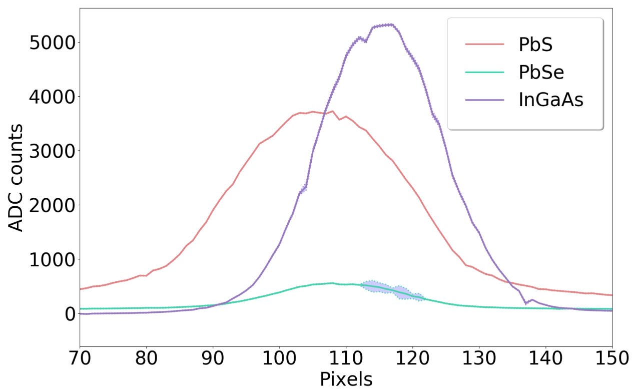

Figure 3: Laser beam profile measured with the infrared sensors.

Front-End ASIC The micro-strip line array sensor is read-out via a high-speed front-end ASIC named GOTTHARD. The ASIC has been designed using UMC 100 nm CMOS technology and is compatible with different semiconductor sensors. There are two versions of this ASIC. First version operates at a maximum frame-rate of 2.7 MHz. It is a modified version of the ASIC described in [10]. The second version operates at a maximum frame-rate of 12 Mfps. This GOTTHARD is developed at KIT. The prototype of the 12 MHz ASIC has been characterised and has noise measurements down to 417 $\pm$ 25 electrons when connected to a sensor capacitance of 1.3 pF. The gain switching stage, which is implemented on the charge sensitive amplifier, allows a wide dynamic range from 125 ke$^-$ up to 2.3 Me$^-$ [11]. Figure 4 shows the complete version of the mentioned ASIC, which features 128 input channels readout by 16 parallel output channels. The ASIC is connected to the sensor via aluminium wedge-to-wedge wire bonding process [12].

The analog output signals from the ASIC are converted to a digital signal using two commercial high-speed ADC ADS52J90. This ADC has a maximum conversion rate of 100 MSPS in 10 bit resolution. The digitized outputs can be serialized either by LVDS or by a 5 Gbps JESD interface. The latter has been implemented in the current version for ease in layout design and also due the limit posed by the number of connections available on the FMC connections for 32 LVDS based outputs. The JESD204b interface enables to serialize digitized data over 4 channels per ADC at high speed [13].

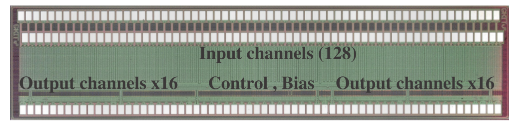

Figure 4: The front-end ASIC GOTTHARD-KIT.

Back-End Data Acquisition System

A dedicated data acquisition system (DAQ) has been developed to connect the detector card to CPU or GPU computation nodes. There are two types of FPGA-based DAQs developed. The first type is based on Xilinx Virtex7 FPGA named Hi-Flex, that is also the current DAQ for KALYPSO. The second type is a novel DAQ system based on Zynq Ultrascale+ MPSoC, which can be used as a standalone system or in combination with MicroTCA via the 12-duplex firefly optical links, see Fig. 5. The data transfer is performed by a custom DMA engine based on PCI Express 3.0 implemented on the FPGA [14]. The performance of the DMA engine compares favorably with the current state-of-the-art, achieving a throughput of more than 14 GByte/s and latency as low as 2 µs. The high throughput as well as the low latency achieved by the DAQ system enables real-time data processing on GPUs or CPUs [15].

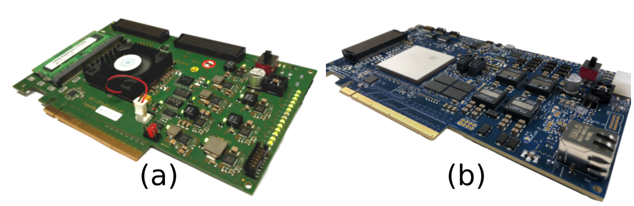

Figure 5: Back-end data acquisition systems developed at KIT, (a) Hi-Flex v1 based on Virtex 7 FPGA with FMC connector, (b) Hi-Flex v2 based on Zynq Ultrascale+ with FMC+ connector.

The FPGA firmware implemented in the DAQ system, in addition to data transfer provides control to the various digital and analog sections on the front-end card. These mainly includes the control of the bias voltages and currents for the optimal ASIC operation, control of the digital and analog power supplies, providing clocks to the ASICs and PLL and also picosecond (ps) phase control over the clocks (see Fig. 6).

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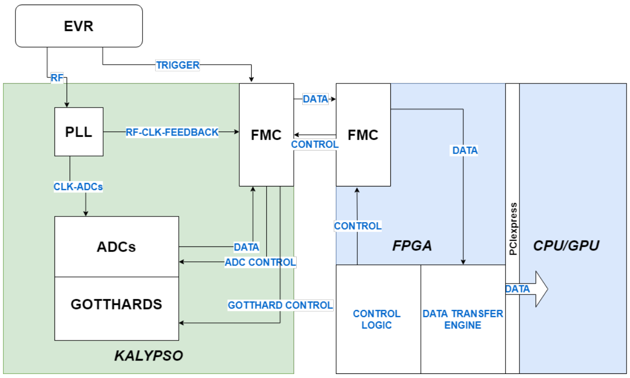

Figure 6: Data and control flow implementation in KALYPSO.

APPLICATIONS AT KARA

EOSD Measurements

KALYPSO has been installed at the EOSD experimental setup at KARA to measure the longitudinal bunch profile of the electron bunch [16]. An ytterbium-doped fiber laser produces fs laser pulses with a wavelength centered at 1050 nm at a repetition rate of 2.7 MHz corresponding to the bunch revolution frequency at KARA. The laser pulses are sent to a gallium phosphide (GaP) crystal located inside the beam pipe of KARA and back to the experimental station for detection with KALYPSO. EOSD is based on the Pockels effect. In the GaP crystal the electrical field of the electron bunch introduces a change of the birefringence, which is proportional to its electric field strength. The birefringence thereby induces a rotation of the laser pulse polarization. Using a chirped laser pulse the time-dependent longitudinal electron density of the bunch is encoded as a wavelength-dependent polarization modulation. Using waveplates and a polarizer, the modulation of the laser spectrum can be turned into an intensity modulation and measured using an optical spectrometer consisting of a grating and KALYPSO. Figure 7 shows the spectrometer and DAQ with KALYPSO currently used in the setup at KARA for EOSD measurements. The data acquired from this experiment can also be used to reconstruct the phase-space density of the electron bunches and its evolution in time [17].

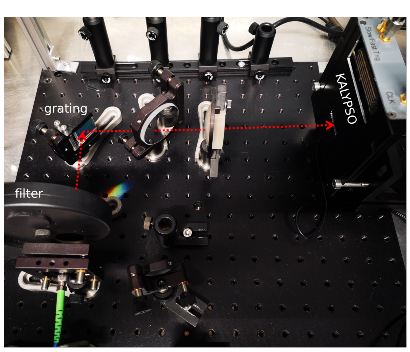

Figure 7: EOSD optical and data acquisition setup at KARA for the measurement of longitudinal bunch profile of the electron beam.

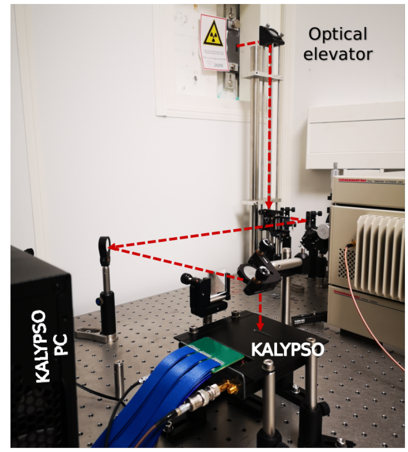

Figure 8: Optical and data acquisition setup for the horizontal bunch measurement for energy spread studies at KARA.

Optical Light Measurements

The energy spread of the electron bunches at KARA is measured at the visible light diagnostics port using the incoherent synchrotron radiation from a 5° port of a dipole magnet. The horizontal bunch size is coupled to the energy spread at the dispersive section of the storage ring as given in Eq. (1). Thus measuring the horizontal bunch size is a method to measure the energy spread of the electron bunch. The wavelength of the radiation emitted is in the range of 400 nm to 550 nm. The single-shot image obtained at the sensor is a convolution of the horizontal bunch size and the filament beam spread function (FBSF). The FBSF is obtained by optical simulations. The current setup shown in Fig. 8 allows for the measurement of the horizontal bunch size with a single-turn precision [5]. Figure 9 shows a preliminary raw data measured at the setup with the beam parameters shown in Table 1.

$$\sigma_\delta = \frac{1}{D}\sqrt{\sigma_x^2 - \beta_x \epsilon_x}. \tag{1}$$

Table 1: KARA Beam Parameters

Energy (E)	1.3 GeV
Beam current (I_b)	0.86 mA
RF frequency (f_{RF})	499.744 MHz
Momentum compaction factor (α_c)	6.63882×10^{-4}

Laser Spectrometer

Stability of the laser spectra is crucial for beam diagnostics. Currently, at KARA also commercial fs lasers are used in THz diagnostics, see Table 2. Since KALYPSO allows for a fairly high repetition rate, it can be used as a tool to analyse the laser spectral stability and assist error corrections in future experiments. This experiment can be performed fairly easily with the help of simple optics. Figure 10 shows a

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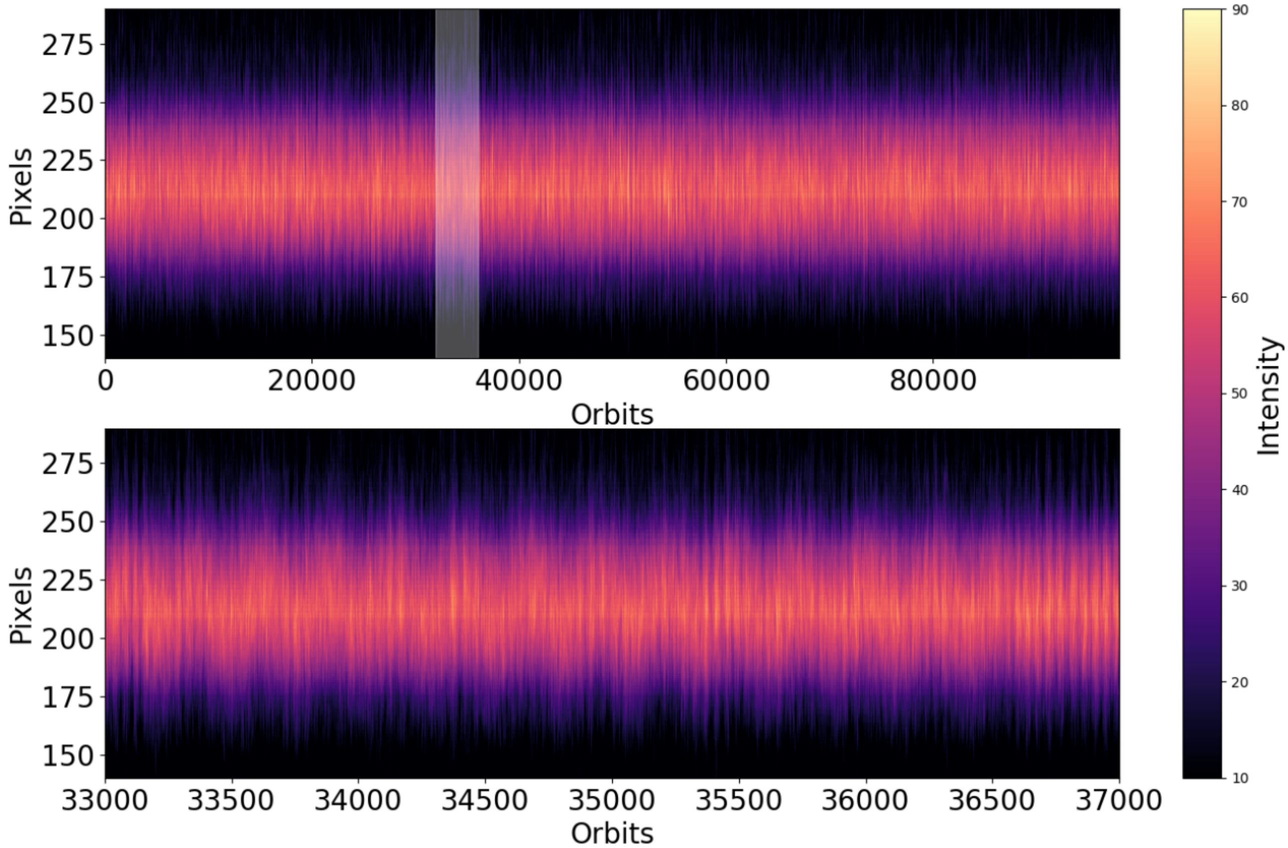

Figure 9: Raw measurement data of the incoherent synchrotron radiation recorded with KALYPSO over multiple turns. The acquisition rate of KALYPSO was set to 2.7 Mfps. Each vertical line corresponds to a single-shot and turn-by-turn measurement. The synchrotron oscillation of the electron bunch is visible on the bottom plot. The full data-set consists of 10^5 turns.

single spectral snapshot of 1560 nm commercial laser, in comparison to the spectral measurements from a commercial spectrometer.

Table 2: Parameters of the Commercial Laser System

Center wavelength (λ_c)	1 560 nm
Spectral width	70 nm
Min. pulse duration (Δ)	90 fs
Average power (P_{avg})	210 mW
Repetition rate	62.5 MHz

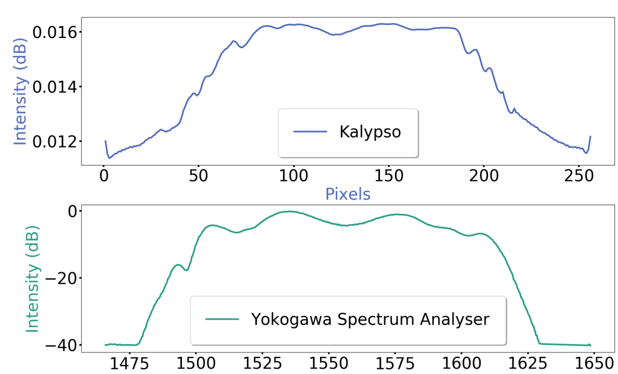

Figure 10: Spectral measurements of a 1 560 nm commercial laser as measured by KALYPSO at a frame rate of 2.7 MHz compared to the measurement with a commercial spectrometer.

OUTLOOK

We have developed KALYPSO, an ultra-fast line array camera, for wide spectral range applications operating with frame rates up to 2.7 MHz. The detector has been installed in several experiments in KARA and other accelerator facilities, for example, European XFEL [18] and FLASH [19]. The detector presented in this paper is the latest version and shows promising improvements compared to its predecessor. The future version of this detector, capable of working up to 12 MHz, is in its final stages and will soon be available for measurements. To further improve the timing resolution of KALYPSO, a system based on a low-gain avalanche detector (LGAD) is under development. LGAD provides an internal gain of more than one order of magnitude [20]. Due to the low charge collection time down to a few ps required by this sensor frame rates up to 500 MHz can be achieved.

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Future works also include developing a dedicated ASIC for high-speed application based on SiGe technology.

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