Ultra-fast Detector for wide range spectral measurements

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ABSTRACT

KALYPSO is a novel detector operating at line rates above 10 Mfps. The detector board holds a silicon or InGaAs linear array sensor with spectral sensitivity ranging from 400 nm to 2600 nm. The sensor is connected to a cutting-edge, custom designed, ASIC readout chip which is responsible for the remarkable frame rate. The FPGA readout architecture enables continuous data acquisition and processing in real time. This detector is currently employed in many synchrotron facilities for beam diagnostics and for the characterization of self-built Ytterbium-doped fiber laser emitting around 1050 nm with a bandwidth of 40 nm.

Keywords: line array detector, microstrip detector, soft X-ray spectrometer, ultra-fast imaging, high data throughput readout, machine learning for photon science, artificial intelligent.

1. INTRODUCTION

To capture rare events in laser dynamics occurring on short time scales, fast real-time measurements are essential. A possible application could be mode-locked lasers, which offer a large variety of operational regimes featuring complex dynamics. By detecting single-shot spectra with high repetition rates over long time scales, new possibilities and applications to diagnose, control and tailor the spectral dynamics of lasers open up. KALYPSO (Karlsruhe Linear arraY detector for MHz rePetition rate SpectrOscopy) an ultra-fast linear array detector working up to 12 Mfps overcomes the limitations of conventional detectors. In contrast to commercial cameras, KALYPSO offers the opportunities for fast online processing in its FPGA architecture and thus provides the means for bunch-by-bunch diagnostics, feedback methods and accelerator control. InGaAs or Si sensors are used to detect a wide range of spectral regimes from near-ultraviolet (NUV) to near-infrared (NIR). Connected to the sensor is a custom-made, high performance ASIC which is responsible for the unprecedented frame rate in continuous mode. An FPGA based readout connected to a high performance PCI-express datalink enables continuous data acquisition and real time data processing. The applications of such a detector extend from laser characterization and transients, beam diagnostics to microscopy for classification of biological cells. In this contribution we describe the overall architecture and its application as a tool for spectral characterization at MHz repetition rates.

2. KALYPSO DETECTOR

KALYPSO has originally been developed for the upgrade of the Electro-Optical Spectral Decoding experiments at KIT's synchrotron light source and the Karlsruhe Research Accelerator (KARA) [1]. Later KALYPSO was also used at the

European XFEL [2] and FLASH [3]. The detector system employed at KARA synchrotron light source is shown in figure 1. It consists of a modular architecture that includes 3 main components: the KALYPSO mezzanine detector board, the readout card equipped with a Field Programmable Gate Array (FPGA) for data acquisition and processing, and the heterogeneous DAQ system consisting of FPGAs and GPUs connected via PCI-Express.

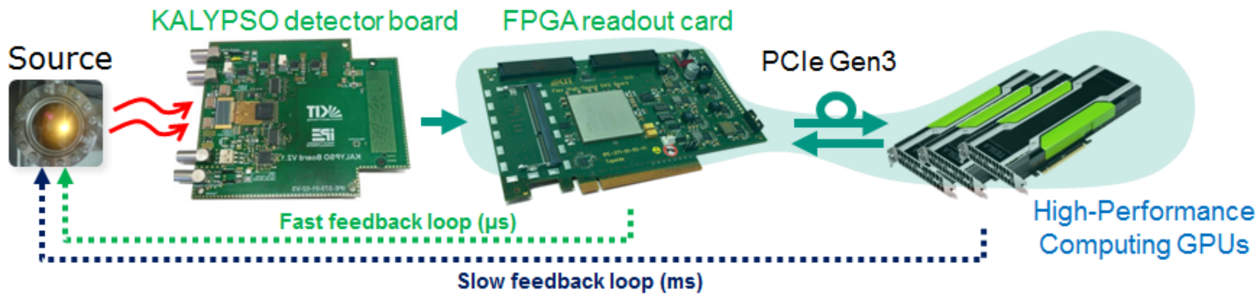

Figure 1. Picture of the KALYPSO system at KIT, the detector board is connected to a heterogeneous FPGA – GPU system for the real-time data processing.

The detector system employed at both EuXFEL and FLASH is shown in Figure 2. It consists of 3 main components: the KALYPSO mezzanine detector, the carrier for the KALYPSO mezzanine card equipped with a Field Programmable Gate Array (FPGA) for data acquisition and processing, and the FLASH front-electronics in MTCA.4 standard for integration into the control system and synchronization to the FLASH timing system.

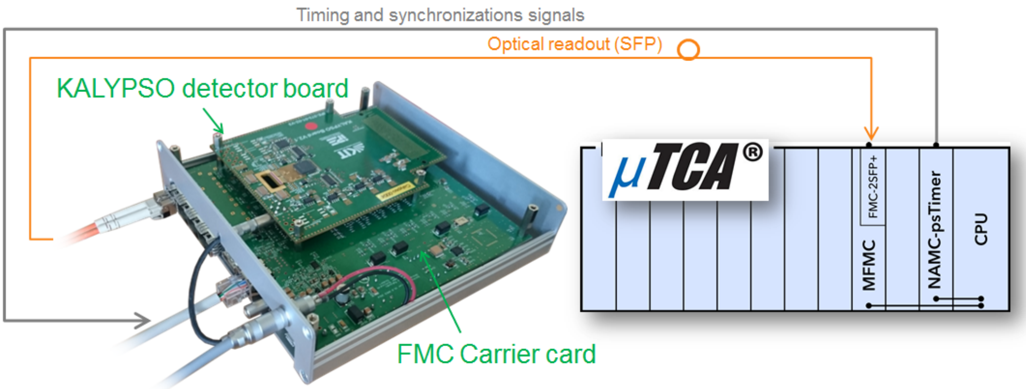

Figure 2. Picture of the KALYPSO system at DESY, the detector board is mounted on a FMC carrier card. The FMC carrier is connected to the FLASH front-end electronics in MTCA.4 standard via optical fibers (data) and twisted-pair cables (timing signals).

The KAYLPSO detector board, developed at KIT, is exactly the same for both systems. It is equipped with a linear array sensor connected by high-density wire-bonding interconnections to an application-specific integrated circuit (ASIC) front-end readout. Two versions of semiconductor linear arrays sensors technologies can be employed, depending on the specific application. The first one is a silicon microstrip sensor developed at KIT; the second one is an InGaAs linear array purchased from Xenics [4]. The original version of KALYPSO is based on a slightly modified design of the GOTTHARD front-end ASIC [5] and achieves a maximum frame-rate of 2.7 MHz with 256 pixels. In the new version, several improvements have been included: up to eight GOTTHARD chips are connected to a wider linear array sensor with up to 1024 pixels at pixel pitch of 25 µm. Two multichannel, low-power and high-speed ADCs (Analog-to-Digital Converter) convert the analog samples, with a sampling rate up to 100 MS/s and 14-bit resolution, to digital data which are then processed by the FPGA. In both systems, the detector board is connected to an FPGA readout card by an FMC (FPGA Mezzanine Card) connector. For the KIT, the FPGA is designed to perform data processing and transmission via PCIe [6]; whereas for the DESY, via quad Multi-Gigabit optical link comprising Small Form-factor Pluggable (SFP) transceivers. The continuous low-latency data readout of the detector system enables the integration into fast feedback applications. Low-latency fast feedbacks to the experimental system are fundamental in order to correct the beam properties in real-time. Therefore, both systems have been designed to generate feedback signals with a total latency of only few microseconds. When connected to the DAQ system, KALYPSO sustains continuous data taking at the maximum repetition rate.

3. EXPERIMENTAL SETUP AND RESULTS AT KARA

The method of fs-laser based on electro-optical spectral decoding (EOSD) to investigate the Coulomb field of electron bunches by investigating their near-fields was first employed in the world at a storage ring in 2013 [7] at the KIT. Figure 3 displays the general design of the corresponding setup (for a detailed description we refer to [8]). The challenge for storage rings is the high repetition rate of electron bunches, ranging from 2.7 MHz for single-bunch to 500 MHz for multi-bunch operation.

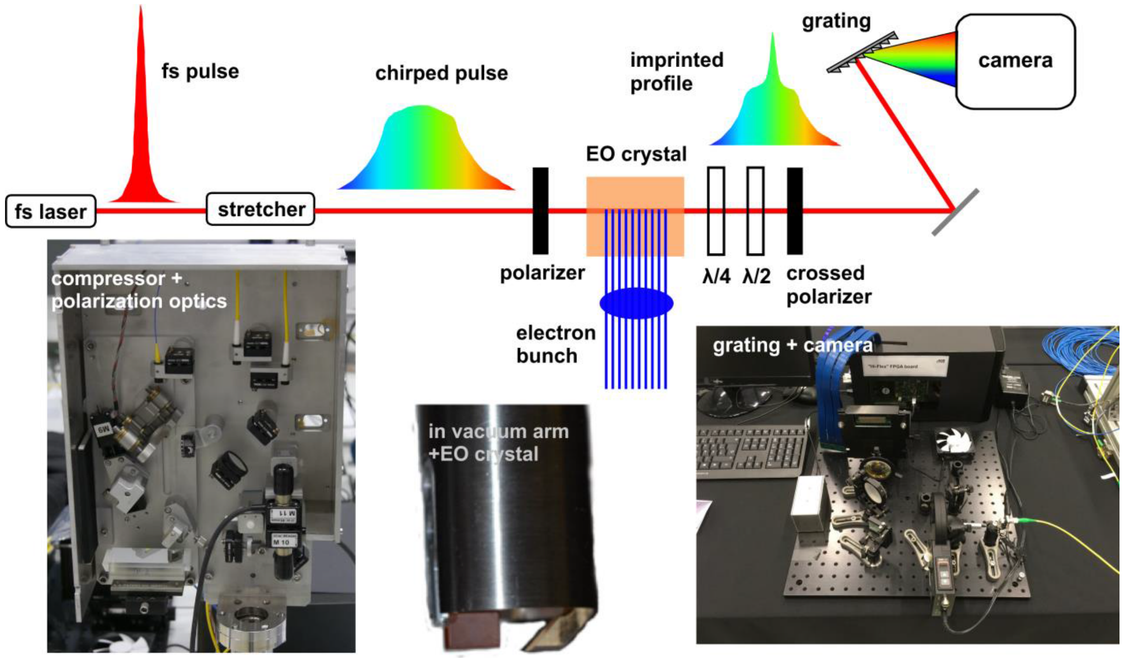

Figure 3. A sketch of the EOSD setup to measure electron bunch profiles on a turn-by-turn basis (see [8] for details, upper part). Implementation of the compressor (built to adjust the width of the laser pulses) with the polarization optics (below). Redesigned in vacuum arm with the EO crystal and the photo on the right side visualizes an implementation used for information decoding of the bunch profiles with KALYPSO (center).

In 2013, commercial line cameras could not cope with the high rates especially for laser frequencies in the 1030 nm range which demands line-cameras with framerates of at least 2.7 megaframes per second. The upper part of Figure 4 displays a stacking of bunch profile measurements with a commercial camera. The used 14 Hz frame rate is too slow to follow the slow synchrotron oscillation of the electron bunches. In July 2015, the first tests of KALYPSO with electron beam were carried out at the KIT synchrotron, which were followed by detailed studies in September 2015 continuously retrieving electron bunch profiles at a framerate of 0.9 megaframes per second (see Figure 4 middle part). In single-bunch operation, we could thus record every third turn while the 110-meter length of the storage ring leads to a repetition rate of about 2.7 MHz. Here, the synchrotron oscillation can be observed.

The close proximity of the Institute for Data Processing and Electronics (IPE), responsible for developing the line-camera, and of the Institute for Beam Physics and Technology (IBPT), responsible for developing the fs-laser based diagnostics and operating the KIT storage ring, as well as the Karlsruhe Research Accelerator (KARA), ultimately enables rapid prototyping on-site. In addition, it fosters the quick dissemination of hardware and software to other research partners such as the European XFEL, which demonstrated in February 2016 the electro-optical bunch length detection at its injector with a 1 MHz bunch rate.

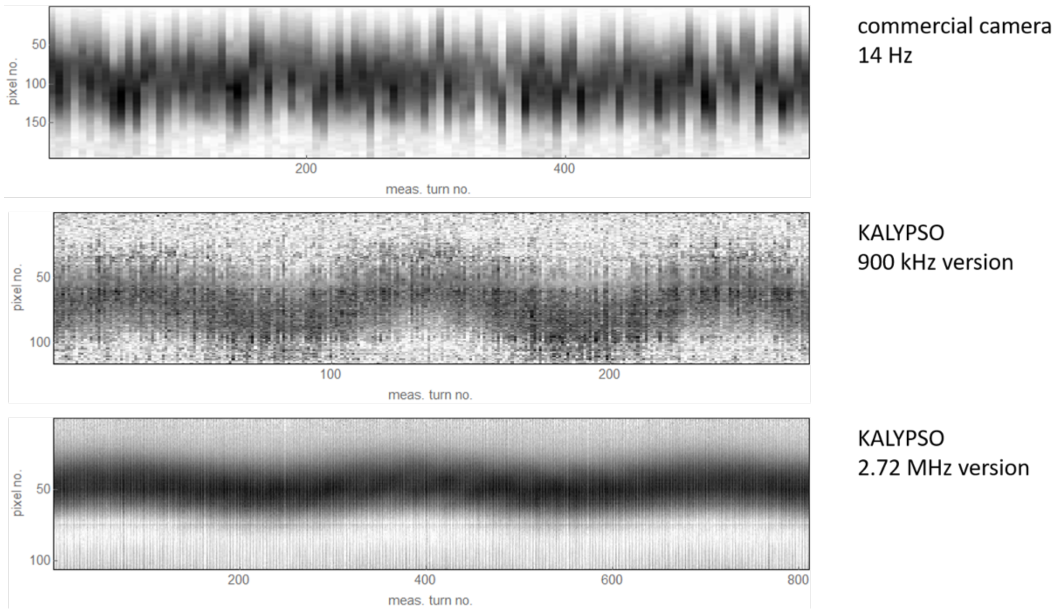

Figure 4, Performance evolution of the EOSD measurement. Displayed are measured electron bunch profiles stacked from left to right. The grayscale encodes the value of the measured charge density (see [2]) . The top diagram displays an early measurement with a commercial camera at 14 Hz repetition rate. The data on the middle diagram was measured at a repetition rate of 900 kHz using KALYPSO. Here, the synchrotron oscillation of the bunch profiles can indeed be observed. The diagram on the bottom shows a recent measurement with the 2.72 MHz KALYPSO version. Here the electron bunch profile is measured for during every turn.

In addition, limitations were imposed by the then used pickup, the in-vacuum electro-optical (EO) probe arm. This first EO-probe arm design at KIT was derived from linear accelerators operating at much lower repetition rates in the macro-pulse in the range of a few tens of hertz. Subsequently, the EO-probe arm was redesigned to minimize the wakefields [9] and, thus, the heating of the probe arm in multi-bunch operation. The redesign of the EO-probe further improved the signal-to-noise ratio. A recent measurement with the improved arm and a new KALYPSO version, which enables the detection of a single bunch during every revolution at a repetition rate of 2.72 MHz, is shown in Figure 4 at the bottom. Here, not only the synchrotron motion can be observed, but also the dynamics of the microstructuring of the charge density.

4. KAYLPSO AT FLASH

At the FLASH facility [10], the two FEL beamlines FLASH1 and FLASH2 are driven by one super-conducting linear accelerator that operates in burst mode at 10 Hz repetition rate with electron beam energies of up to 1.25 GeV [11]. Every burst, also denoted as bunch train, can have a maximum of 800 bunches at maximum repetition rate of 1.0 MHz. FLASH1 is a single-pass FEL based on the self-amplified spontaneous emission (SASE) process and generates soft X-ray laser pulses in the wavelength range 4.2 nm to 52 nm. Since the exponential amplification process in a SASE FEL starts from spontaneous emission (shot noise) in the electron bunch, the SASE FEL radiation is inherently of stochastic nature, i.e. individual radiation pulses differ in intensity, spectral distribution and temporal structure. Hence, photon diagnostic tools that operate in a non-destructive way with single-pulse resolution are of fundamental importance for the optimization of the FEL radiation as well as evaluation of measurement results obtained in user experiments.

The KALYPSO detector has been installed at the variable line spacing (VLS) grating spectrometer [12] in the FLASH1 FEL beamline [13]. The VLS spectrometer is equipped with two gratings for which the blaze angles are optimized for 0^{th} order of diffraction such that the main part of the FEL radiation is transmitted to the user experiment, while approximately 1 – 10 % of the FEL radiation intensity is dispersed into 1^{st} order for the online measurement of FEL spectra (figure 5 (left)). The 1st order diffraction is focused onto a Ce:YAG crystal located in the focal plane of the VLS spectrometer. The visible fluorescence light of the Ce:YAG crystal is imaged onto the Si microstrip sensor of the KALYPSO detector. By this, the spectral distribution of the incident FEL pulses is converted into signal intensities of the 256 pixels of the Si microstrip sensor.

A carrier board [14] for the KALYPSO detector has been developed that is used for the data acquisition, processing, and transmission to the FLASH front-end electronics in MTCA.4 standard [15] to be fully integrated into the accelerator control system. The clock and trigger signals of the FLASH timing system are used for the photon pulse synchronous recording of all pulses in a pulse train at 1 MHz readout rate.

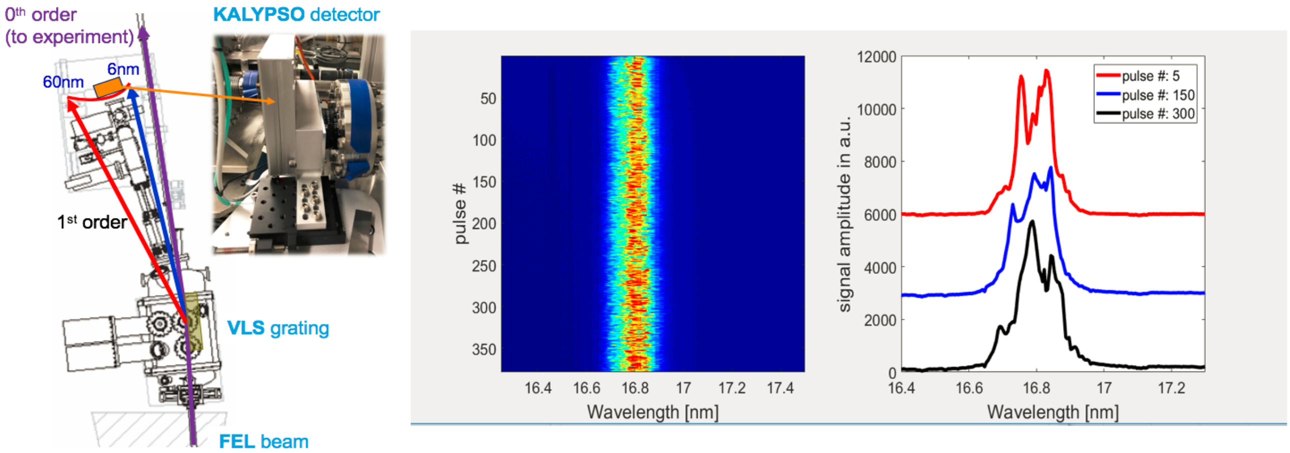

Figure 5. Schematic of the VLS spectrometer: Most of the intensity of the FEL beam is reflected in the 0th order to the user experiment while about 1 – 10% of the intensity in the 1st order is used for the online measurement of FEL spectra (left). The image represents the FEL spectra of a pulse train with 380 pulses. The three individual spectra for the pulse numbers 5, 150, and 300 have been offset vertically for better distinction (right).

Figure 5 (right) depicts the pulse-resolved FEL spectra of a pulse train with 380 pulses measured with the KALYPSO detector at a repetition rate of 1.0 MHz as well as three individual spectra for the pulse numbers 5, 150, and 300. FLASH operators use this online measurement of the FEL spectra for accelerator tuning to keep the FEL pulses along the pulse train within a wavelength bandwidth of about 1% which is inherent to the FEL radiation. The information about the spectral shape of individual pulses can be used in user experiments to improve the spectral resolution.

5. KAYLPSO DETECTOR AT EU-XFEL

The super-conducting linear accelerator for the European X-Ray Free Electron Laser (E-XFEL) [16] operates at a beam energy of up to 17.5 GeV and delivers femtosecond electron bunches with a repetition rate of up to 4.5 MHz in bursts of up to 2700 bunches every 100 ms which can be distributed into three different undulator beamlines. The corresponding femtosecond X-ray laser pulses are generated at wavelengths between 0.05 nm and 6 nm and can be delivered to three experimental stations in parallel.

To measure the longitudinal bunch profile of the electron bunches, a detection system based on the electro-optical spectral decoding technique [2] is currently being commissioned which has been installed after the 2nd electron bunch compressor at an electron energy of 700 MeV. It utilizes a Gallium Phosphide (GaP) crystal that is installed in the electron beampipe. This electro-optic active GaP crystal becomes birefringent in the presence of the Coulomb field of an electron bunch passing by. The induced birefringence is sampled with a chirped laser pulse from an Ytterbium fiber laser [17] which is synchronized to the radio frequency of the E-XFEL accelerator. When a laser pulse passes through the crystal in parallel with the Coulomb field of an electron bunch, the laser polarization is modulated. This polarization modulation is transferred after a polarizer to an amplitude modulation in the laser spectrum. The laser spectrum after the GaP crystal is measured with a spectrometer utilizing a KALYPSO detector equipped with an InGaAs microstrip sensor. An identical KALYPSO readout system has been used as in the case of the VLS spectrometer at FLASH as described above. The detector and readout system are capable of recording individual longitudinal bunch profiles of all bunches in a bunch train with sub-picosecond resolution at a bunch repetition rate of 1.1 MHz.

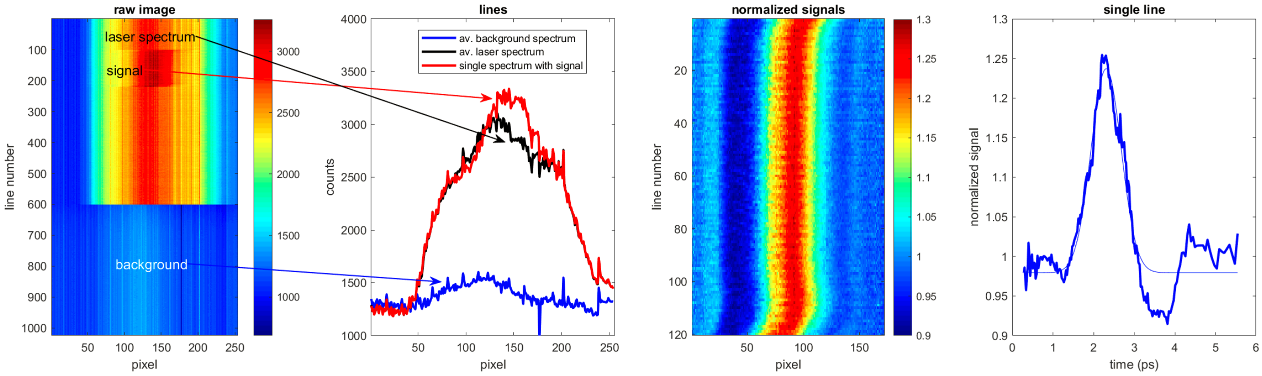

Figure 6. (left) The image represents 1000 consecutive KALYPSO frames around one electron bunch train of the E-XFEL. The profiles correspond to the unmodulated laser spectrum (black), one laser spectrum modulated by an electron bunch (red), and averaged background signal (blue). (right) Normalized signals calculated for the 120 electron bunches of the data-set on the left, and the resulting longitudinal profile of one bunch together with a Gaussian fit.

Figure 6 (left) shows the recorded data from a single bunch train. The recording of the detector starts 100 frames (at 1.1 MHz) before the first electron bunch to acquire unmodulated laser spectra, followed by laser spectra that have timing overlap with the electron bunches and are modulated by the Coulomb field, and a number of frames without laser pulses present to measure the detector background. The averaged background (blue line) and averaged unmodulated laser spectrum (black line) are used to calculate from the laser spectra modulated by the electron bunches (red line as example) the normalized signals which are shown in figure 6 (right). The normalized signal of a single electron bunch (blue line), i.e. the longitudinal bunch profile, is depicted together with a Gaussian fit with a width (rms) of 330 fs. In addition to the longitudinal bunch profile, arrival times of entire bunch trains with single-bunch resolution can be measured as well as jitter and drift for consecutive bunch trains. The short readout latency of the KALYPSO readout system of below 1 µs is a prerequisite to establish a fast intra-bunch train feedback for the stabilization of the longitudinal bunch profile.

6. NOVEL KALYPSO DETECTOR SYSTEM

Complex dynamics are crucial to understand numerous optical processes, including laser dynamics, white light generation and beam filamentation. Mode-locking is a phenomenon where a large number of laser modes are locked together to form ultrashort femtosecond pulses down to a single optical cycle. Conventional measurements generally fail to probe rapid non-repetitive changes over long time intervals, thus making direct studies of mode-locking transitions difficult or even impossible. The major physical and electrical limitations of the current system reside in both the front-end electronics and the used fast commercial ADCs. Novel KALYPSO detector, optimized high rate, is under current development. The novel system will combine a wide field-of-view, over 2.5 cm, high spatial resolution sensor with novel readout electronics capable to operate with a framerate over 30 Mfps at full resolution. The sensor module will use an InGaAs or silicon line array sensor with pixel pitch of 25 in order to ensure good quantum efficiency at different spectral regimes combined with a high spatial resolution. The key feature of the new system is the unprecedented frame rate. To obtain this outstanding performance, a new generation of front-end readout chip based on emerging low-cost SiGe-130nm technology provided by IHP foundry [18] will be developed. Compared to other CMOS sub-micrometer technologies, the SiGe-130nm technology shows excellent analog bandwidth over 100 GHz with wide analog dynamic range over 3V. The frontend chip will collect the charges generated in the InGaAs or silicon sensor and will convert them to a voltage signal proportional to the total charges collected by a high-bandwidth and low-noise charge-sensitive amplifier. A 64:1 analog multiplexer connects 64 readout channels to a differential output driver which will transfer the voltage output to external ADCs. In this way, 16 high-speed analog serial outputs will readout up to 1024 pixels.

The readout electronics will be based on the FPGA Ultrascale+ family that combines a multi-giga-sample RF ADCs with high-speed digital logic cells based on 16 nm FinFET technologies in a unique device [19]. The new FPGA family, so-called "RFSoC ZYNQ", integrates radio-frequency analog circuitries that includes an array of 16 ADCs each operating of 2 or 4 GS/s. In the new readout scheme the front-end chips will be connected directly to the ADC arrays in the FPGA. Each ADC will handle 64 multiplexed pixels with a sampling rate of 2 GS/s. In the proposed scheme, each front-end chip, with 128 readout channels each, will be readout by 2 ADCs. In order to cover 1024 pixels, eight front-ends are necessary and therefore 16 fast ADCs on FPGA will be employed. The proposed architecture will result in a well-integrated compact detector system to probe rapid non-repetitive changes of laser dynamic with a frame rate that will exceed 30 Mfps. A fast operation mode is foreseen by using only half of the field-of-view. In this case the ADC arrays operate with 4 GS/s, which will result in a frame rate that exceeds 60 Mfps for 512 pixels at full occupancy.

7. CONCLUSIONS

Modern photon science detectors require many cutting-edge technologies: custom ASIC and semiconductor design and fabrication, low-noise analog circuits, high-density interconnect technologies and high-throughput readout electronics combined with advanced real-time data processing. KALYPSO is the result of a close collaboration between engineering, accelerator physicists and beam line scientists. The collaboration has produced one of the fastest line-camera available in scientific communities; it is considered one of the fundamental tools for understanding the beam dynamics of ultra-short bunches in accelerators and required diagnostics for synchrotron and free-electronic laser light sources and photon science applications. The KALYPSO detectors have been successfully installed and are in use at several accelerator facilities. KALYPSO is an essential part of several detector systems, which are daily in use: the electro-optical spectral decoding (EOSD) experimental setups at the storage ring KARA (Karlsruhe Research Accelerator) at KIT; the bunch arrival and bunch shape detectors at the 3.4-km linear accelerator European XFEL and the photon light source FLASH, both at DESY; the High-Field High-Repetition-Rate Terahertz facility TELBE at the linear accelerator ELBE located at the Helmholtz-Zentrum Dresden-Rossendorf (HZDR); and DELTA (Dortmunder ELekTronenspeicherring-Anlage, electron storage ring at Dortmund) at the TU Dortmund University.

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