

# Advanced Diagnostic Detectors for Rogue Phenomena, Single-Shot Applications

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## ABSTRACT

The detection of rapid dynamics in diverse physical systems is traditionally very difficult and strongly dominated by several noise contributions. Laser mode-locking, electron bunches in accelerators, and optical-triggered phases in materials are events that carry important information about the system from which they emerge. 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 and electron beams in synchrotron and free-electron laser (FEL) accelerators open up. This contribution focuses on the latest developments of real-time, single-shot, high-repetition-rate detectors and data acquisition systems, with a special focus on emerging technologies and new possibilities in the diagnostics of rogue optical signals.

**Keywords:** Photonic time-stretch, femtosecond time resolution, silicon sensor, electron bunches in accelerators, single-shot measurement, ZYNQ-RFSoc, time-interleaving ADC, real-time data processing

## 1. INTRODUCTION

Electronics and sensor developments have supported and enabled various aspects of photon science physics. Current detector technologies compare in complexity with the most challenging developments in the industry. Modern detectors rely on a wide range of technologies, from novel silicon and terahertz (THz) sensors, nanoscale integrated circuits, to recent programmable devices with analog radio frequency electronics and embedded artificial intelligence (AI) engines integrated into single devices. In the past years, novel electro-optical spectral decoding (EOSD) and Photonic Time-Stretch (PTS) schemes have been developed, enabling continuous ultra-fast single-shot spectroscopy,<sup>1</sup> imaging,<sup>2-5</sup> digitization of electric fields evolution with THz bandwidth<sup>6</sup> and other measurements at refresh rates of trillions of consecutive frames per second (see Ref.<sup>7</sup> for a review). These technologies have opened up new frontiers in measurement science: in nonlinear dynamics of optical rogue waves,<sup>8</sup> acoustic shock waves,<sup>9</sup> mode-locked lasers,<sup>10-17</sup> parametric oscillators,<sup>18</sup> relativistic electron bunching,<sup>6,19</sup> as well as in applications to cancer cell identification,<sup>20,21</sup> optical coherence tomography (OCT),<sup>22,23</sup> material pump-probe spectroscopy,<sup>24</sup> and LIDAR.<sup>25</sup>

To satisfy the ever-increasing demands on high-performance detectors for future physics experiments, at Karlsruhe Institute of Technology (KIT) several new detector technologies and systems are continuously developed in close collaboration with beam physics scientists of Karlsruhe Research Accelerator (KARA),<sup>26</sup> DESY<sup>27</sup> and Lille University.<sup>28</sup> The research activities span from the development of sensors and application-specific integrated circuits (ASIC), high-performance data acquisition, high-density interconnection technologies and packaging,

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advanced data processing and fast control algorithms for accelerators based on AI. Within this framework, two detector systems have been developed and commissioned at several accelerators and research centers, Karlsruhe Pulse Taking Ultra-Fast Readout Electronics (KAPTURE)<sup>29</sup> and Karlsruhe Linear array detector for MHz rePetition rate SpectrOscopy (KALYPSO).<sup>30</sup>

Along with the most apparent aspects, future experiments will require a technological jump toward the new generation of detector technologies, which enables the acquisition of unprecedented frame rates in continuous readout mode with excellent time and energy resolution. The paper is divided into seven sections. After the introduction, the evolution of the KALYPSO line array and its components for future EOSD experiments is presented. The third section focuses on the development of wideband detectors and front-end electronics for terahertz applications. The fourth section presents a fast digitizer, the so-called THERESA (TeraHertz REadout SAMpling) system for photonic time-stretch applications. In section five, a common data acquisition infrastructure based on new generation of programmable devices, like *RFSoc* family from Xilinx<sup>31</sup> and the *Versal*<sup>32</sup> is discussed. The sixth section describes the hardware integration and AI algorithms for fast real-time feedback for controlling the beam parameters at modern synchrotron accelerators, summary and conclusions.

## 2. EVOLUTION OF AN ULTRA-FAST LINE ARRAY DETECTOR FOR REAL-TIME IMAGING

To capture rare events in laser dynamics occurring on short-time scales, fast real-time measurements are essential. 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 synchrotron beams and lasers open up. KALYPSO is an ultra-fast line-array detector that operates with framerates of up to 12 Mfps in continuous readout mode. When combined with an EOSD system, KALYPSO provides a shot-to-shot reconstruction of the longitudinal bunch profile of an electron beam at circular or linear accelerators with femtosecond time resolution. Figure 1 shows the general design of the corresponding setup (for a detailed description of the setup refer to<sup>33</sup>).

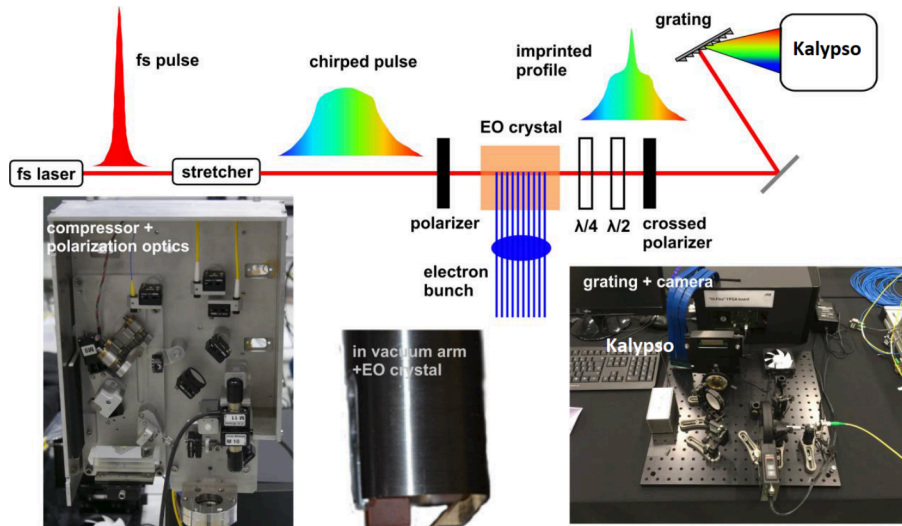


Figure 1: A sketch of the EOSD setup to measure electron bunch profiles on a turn-by-turn basis (see<sup>33</sup> for details). Implementation of the compressor (built to adjust the width of the laser pulses) with the polarization optics (below, on the left). Redesigned in vacuum arm with the EO crystal (center) and photo (on the right) visualizes an implementation used for information decoding of the bunch profiles with KALYPSO.

The KALYPSO detector has been successfully commissioned at several accelerator facilities like KARA,<sup>33</sup> FLASH,<sup>34</sup> EuXFEL,<sup>35</sup> SOLEIL,<sup>36</sup> ELBE<sup>37</sup> and DELTA.<sup>38</sup> The high versatility of both sensor and front-end ASIC of KALYPSO allows it to be employed for various scientific applications, including near- and far-field Electro-Optical (EO) setup,<sup>39,40</sup> transverse beam diagnostics,<sup>41</sup> shot-to-shot laser<sup>42</sup> or FEL<sup>43</sup> diagnostics, material science and medical imaging.

Despite the successes of the KALYPSO detector, future EO applications require high-granularity single-shot measurements acquired with excellent and uniform sensor efficiency at several hundred Mfps. The two most important limitations in high-granularity, high-speed imaging applications are the limited number of photons collected by a single small sensor element and the response time of the sensor. In traditional silicon sensors, the small amount of charge signals collected limits the Signal-to-Noise Ratio (SNR) and the charge collection time, which is typically around a few tens of ns and, therefore, limits the maximum frame rate.

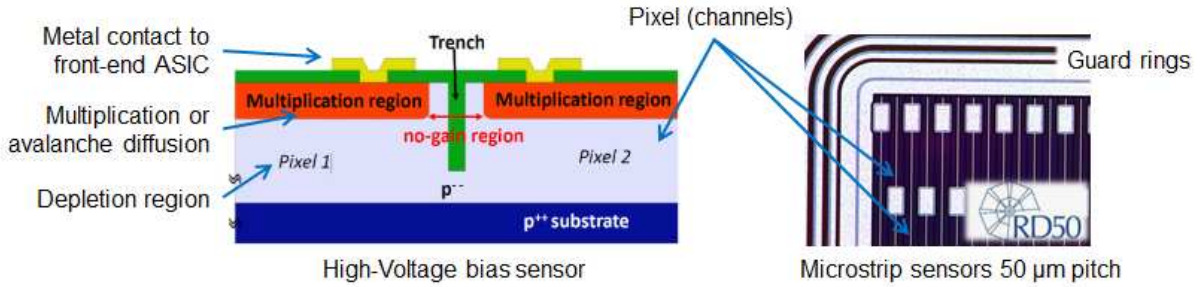


Figure 2: Cross-section scheme (not in scale) of a TI-LGAD sensor, see<sup>44</sup> for details (left). silicon microstrip sensor based on TI-LGAD developed and fabricated within the framework of RD50 collaboration (right).

To overcome the rate limitation as well as the low sensitivity of conventional silicon detectors while maintaining high spatial resolution, novel fine-channel segmentation, high-gain uniformity, and high fill-factor Trench-Isolated Low-Gain Avalanche Detectors (TI-LGAD) have been designed and fabricated by FBK<sup>45</sup> and integrated into KALYPSO. The TI-LGAD is an evolution of Low Gain Avalanche Diodes (LGAD) sensors. LGAD has gained great interest in particle tracking and timing applications for the excellent timing resolution down to  $\sim 30$  ps, which makes LGAD a promising technology for timing detectors for particle physics and photon science applications. As shown in Figure 2 (left), TI-LGAD employs shallow trench isolation (STI) to isolate the individual channels (microstrips) of the sensor. In that way, it is possible to produce fine-segmented microstrip sensors with intrinsic signal gain of a few tens and total charge collection time down to a few nanoseconds. Figure 2 (right) shows the first prototype of TI-LGAD line-array sensor that has been designed for the KALYPSO detector. The top metal layer has been minimized to reduce the photons reflectivity, which is crucial in photon sciences experiments.

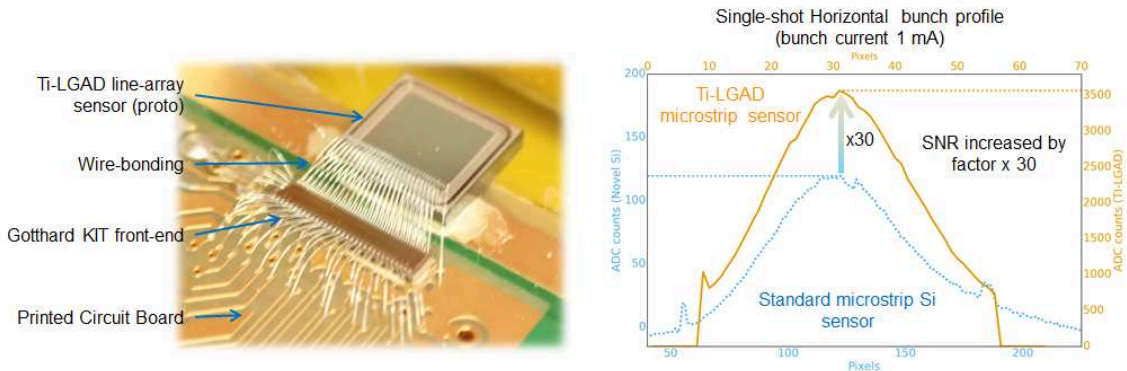


Figure 3: KALYPSO detector and its main components, the TI-LGAD line array sensor, the Gotthard-KIT front-end ASIC and the aluminium wire-bonding interconnections (left). Single-shot measurement of the horizontal bunch profile at KARA and comparison between a standard line-array and the TI-LGAD line-array obtained with the same bunch current conditions and channel pitch (right).

The TI-LGAD line array has been integrated with the new version of the front-end ASIC<sup>46</sup> on the KALYPSO detector. A detailed view of KALYPSO detector equipped with a TI-LGAD sensor and connected to the front-end ASIC is shown in Figure 3 (left). The electrical tests and the beam characterization has been performed

at the Visible Light diagnostics (VLD) port at KARA.<sup>41</sup> The VLD port has been optimized for shot-to-shot measurements of the energy spread of the electron bunches at high frame rates. In Figure 3 (right) a single-shot measurement acquired with both a standard silicon line-array (dash line) and the line-array based on TI-LGAD technology (solid line) is shown. Thanks to the intrinsic gain of the TI-LGAD sensor, which is estimated to be a factor of 15 times higher than standard silicon sensors, and the additional gain with a factor of 2 implemented in the new charge-sensitive amplifier integrated into the new Gotthard front-end, the new KALYPSO exhibits a significant SNR improvement compared to the previous generation. The higher SNR combined with the fine-pitch sensor channels and the fast charge collection time, open up new possibilities in the detection and study of beam dynamics even at very low bunch charges (down to 20 pC) operating in high frame rate conditions. The energy spread of short electron bunches is crucial for understanding microbunching instabilities. There exists a bursting current threshold beyond which this instability starts to occur. At KARA, this threshold can be around 2.5 mA depending on the various other parameters during the operation. The energy spread is indirectly studied by measuring the horizontal bunch size of the incoherent synchrotron radiation at a filtered wavelength of 450 nm. KALYPSO-LGAD allows the measurement of the bunch profile even below the bursting threshold, previously limited by the sensitivity of the sensor.

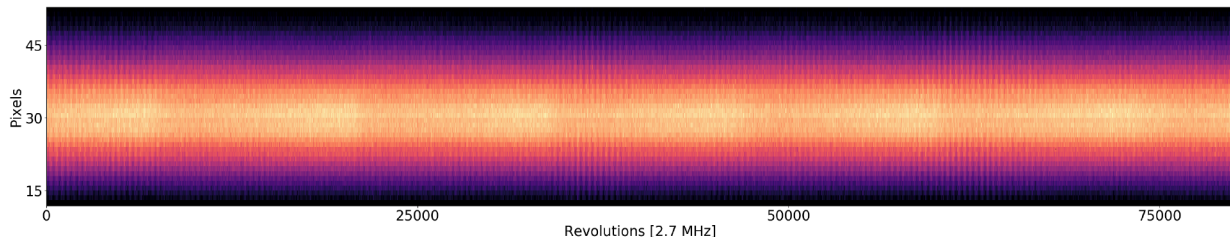


Figure 4: Horizontal bunch profile raw data acquired by KALYPSO-LGAD at the VLD port of KARA during short bunch operation mode, with an acquisition rate of 2.7 MHz. The periodicity seen in the figure coincides with the short bursts of THz radiation.

The single-shot measurement shown in Figure 3 (right) is part of a large dataset recorded at 2.7 MHz, which reveals turn-by-turn effects. Thanks to the high-data throughput acquisition, KALYPSO is able to measure over 10 million uninterrupted subsequent revolutions. A fraction over 75000 consecutive single-shots is shown Figure 4 that corresponds to less than 30 milliseconds of data.

### 3. TERAHERTZ DETECTOR TECHNOLOGIES

The terahertz ‘gap’ is a well-worn expression used to describe a region of the electromagnetic spectrum lying above microwaves and below infrared light in frequency. ‘The gap’ refers to the absence of technology appropriate to the terahertz spectral region in contrast to the sophisticated electronic and optical technologies available in other spectral regions. Coherent synchrotron radiation (CSR) in the terahertz frequency range is produced by synchrotron accelerators when the length of the bunches is in the range of a few millimetres and below. The high-intensity CSR in the THz range emitted by electron bunches has attracted the interest of the scientific community in recent years. These THz sources open up a new range of research fields in both industry and scientific community. At KARA, low momentum compact ( $\alpha_c$ ) mode is employed to produce short electron bunches that generate a high-intensity THz emission.<sup>47</sup> To measure and study the THz radiation, the ultrafast digitizer KAPTURE has been developed. KAPTURE<sup>48</sup> is a broadband picosecond sampling system for ultra-short pulses operating at a pulse rate of up to 1 GPulse/s. KAPTURE is able to acquire and sample ultra-short pulses with a local sampling rate that exceeds 300 GS/s. Up to 8 parallel sampling channels are integrated into one system, which is used to digitize each pulse with 8 sampling points. KAPTURE is used extensively at KARA to study the microbunching instability. For example, it enables the turn-resolved analysis of multibunch effects.<sup>49</sup> The measurement time to analyze beam current dependent effects could be drastically reduced by using KAPTURE with the help of a special filling pattern in the accelerator, where each bunch has a different charge and is read out individually.<sup>50</sup> Thus, the determination of the so-called bursting threshold and the recording of

a beam current dependent spectrogram can be reduced from several hours to less than one second, which has enabled large-scale systematic studies.<sup>51,52</sup> The 8 sampling points per channel are used for pulse reconstruction to extract the intensity, length and arrival time of the bunches.<sup>53</sup> Another possible configuration mode is to read out several detectors synchronously with a single sampling point each. We have used this with narrow-band detectors, sensitive in different frequency ranges to measure single shot spectra with a repetition rate of 500 MHz.<sup>54</sup> By sharing the same readout framework, KAPTURE and KALYPSO measurements can be synchronized and combined for unprecedented turn-by-turn details of the electron bunches.<sup>55</sup>

As an evolution of the KAPTURE system, a pixelated THz detector for 6-dimensional measurements is currently under development at KIT. TeraHertz pixelated SpectRAL detector (THESTRAL) is a large-area monolithic pixelated THz detector where the THz antennae and the front-end electronics are tightly integrated into a unique substrate. The first demonstrator, which integrates a THz antenna and the related readout electronics, is currently under development. To benefit from the most recent available technologies, the readout electronics will be developed in the recent sub-micrometer 130 nm BiCMOS SiGe technology provided by IHP foundry,<sup>56</sup> which allows combining high-frequency circuits with a large voltage swing. To exploit the potential of this novel detector, a first multi-spectral prototype with a matrix of 8x8 THz sensors will be developed and tested at the THz beamline at KARA. The aim of the demonstrator is to design the first THz detector that combines spatial, spectral, timing, and polarization measurements in a unique compact detector operating in very high frame rate conditions, over 500 Mfps in continuous readout mode. Figure 5 shows the idea of the first THESTRAL THz detector and the related features.

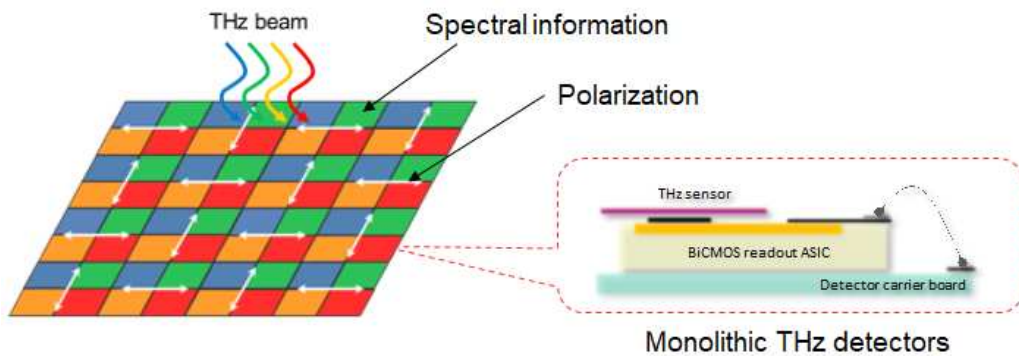


Figure 5: Architecture of the integrated chip with 8x8 pixels, each pixel integrates a high-efficiency narrow-band antenna, at different detection frequencies, with the front-end electronics (left). Cross-section of the monolithic pixel architecture, the on-chip antenna are implemented using the top metal layer

The choice of a front-end architecture which can be scaled to a large number of pixels is critical with respect to its sensitivity, scalability and power dissipation. A down-converting architecture with harmonic mixing provides a low noise performance due to matched-filter receiver architecture but poses several challenges such as routing of LO, maintaining phase coherence to all pixels, large silicon area and excessive power consumption. Therefore, scaling a down-converting architecture to a high-resolution THz detector with many pixels is not possible. A direct detection scheme with an integrated antenna and associated baseband circuitry is a prominent solution for large and high-granularity THz cameras. Several antenna topologies are under investigation, such as ring antennas<sup>57,58</sup> or antennas with quartz superstrate/external silicon lenses. For the first prototype, a standard rectangular differential patch antenna was chosen, because of simple and scalable implementation and front-side irradiation. As the on-chip antenna suffers from low gain and poor efficiency, the microstrip patch antenna uses lower metal layers of the technology stack as a ground to shield the electromagnetic fields from the lossy silicon substrate. This approach results in a very small bandwidth of less than 10%, whereas we consider this to be sufficient for initial investigations. The core of the pixel front-end electronic is shown in Figure 6 (left). It is based on a pair of transistors with differential input in a common emitter configuration.<sup>57-59</sup> The differential structure is more commonly used for the detectors design as it is effective in suppressing common-mode noise. Especially, it is expected that the cross-talk influence from the adjacent pixels can be suppressed. The direct

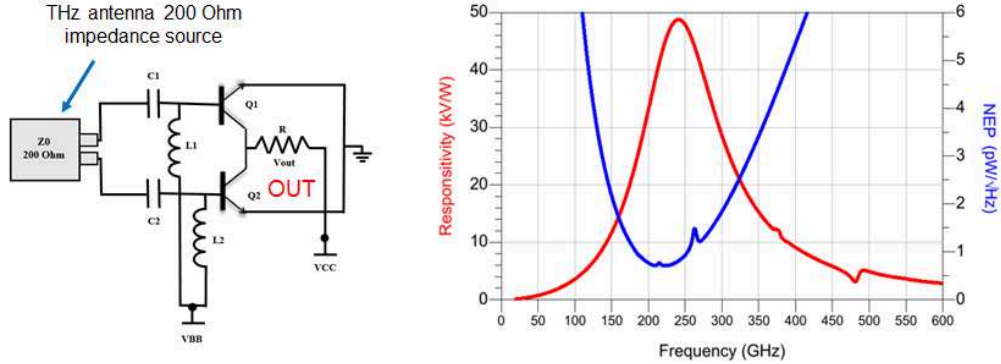


Figure 6: Schematic of the THz detector (left). Simulation results of THz detector (right)

detection scheme converts the incoming RF signal from the antenna (antenna modelled as a 200 Ohm source in Figure 6 (left)) to DC signal directly, and the rectified collector currents are converted to voltage across a high resistive load  $R$ . The circuit was implemented using Electromagnetic simulation software (ADS Momentum) and the results for Responsivity and NEP are shown in Figure 6 (right). At the design frequency of 240 GHz, the obtained values are 48.7 kV/W and 0.79 pW/ $\sqrt{\text{Hz}}$  for responsivity and NEP, respectively. By combining such narrow-band detectors tuned at multiple frequencies, it's possible to realize broadband detection, as shown in.<sup>60</sup>

#### 4. FAST READOUT ACQUISITION FOR PHOTONIC TIME-STRETCH EXPERIMENTS

The photonic time-stretch technology is nowadays used in many applications. Along with most apparent aspects, the real potential of this technique, to enable continuous ultra-fast acquisition with recordings spanning trillions of consecutive frames, is still not completely exploited. To utilize the potential of this powerful technique, a high-speed digitizer architecture for continuous sampling of ultra-fast analog signals has been developed. THERESA (TeraHertz REadout SAMpling) is this fast digitizer that benefits from the new Xilinx ZYNQ-RFSoc family technology to speed up the sampling rate and acquire time-stretched signals continuously. The whole system, including the optical setup, the THERESA digitizer system and its components for the sampling of THz radiation emitted by relativistic electron bunches in modern accelerators, is shown in Figure 7.

A chirped carrier laser pulse is fed through an electro-optical device which modulates the ultra-fast (THz or electrical) pulse under investigation onto the laser pulse. The modulated laser pulse is then stretched in time using a long dispersive fiber until their duration is in the order of nanoseconds (see Figure 7). The encoded time-stretched signal coming from the optical path is fed into a photodetector that converts the optical pulse into an electrical signal. The photodetector signal is then replicated sixteen times by a wideband active power divider. All signals are sampled in parallel by the THERESA sampling card, which integrates up to sixteen sampling channels. Each channel contains a wideband Track-and-Hold Amplifier (THA) and a programmable delay that controls the THA sampling time in steps of 11 ps. The sampling card is connected to the ZCU216 evaluation board from Xilinx, which is equipped with the latest generation of ZYNQ UltraScale+ Radio Frequency System-on-Chip (RFSoc). A comprehensive description of THERESA and its components including the data acquisition and firmware architecture has been reported in.<sup>61</sup>

A preliminary characterization of the first digitizer demonstrator was performed with a periodical pulse train with an amplitude of 1 V and a pulse rate of 125 MHz. The clock of the sampling channels was set to 1 GHz such that one sample of the fast-pulse was followed by 7 samples of the baseline. The peak of pulse was sampled by an appropriate setting of the picosecond delay chip. Input and output signal are shown in Figure 8. The Xilinx RF Data Converter Evaluation GUI was used to display the sampled signals by the RF-ADCs implemented within the Zynq RFSoc. The GUI enables the online visualization of the sampled signal, as shown in Figure 9 (left), but also gives the possibility to perform a Fast Fourier Transform on the sampled signal, as shown in Figure 9 (right).

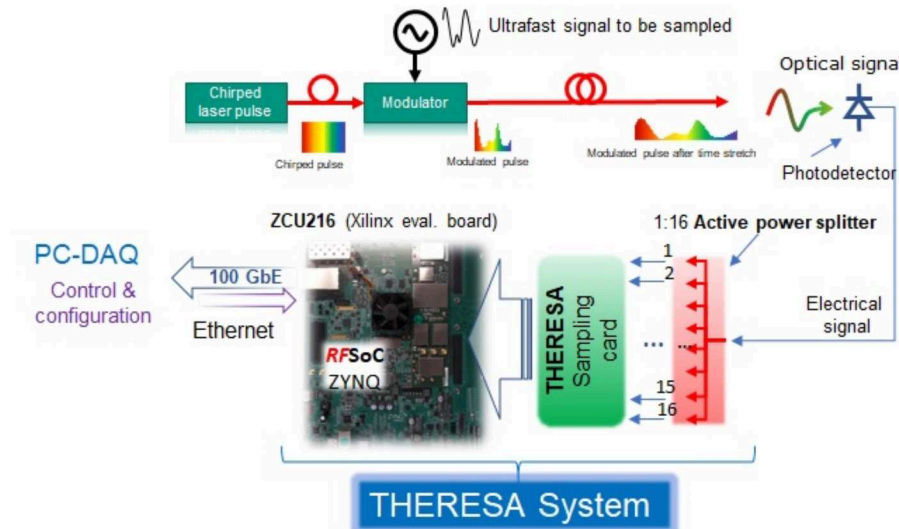


Figure 7: PTS system and readout architecture. It consists of an optical time-stretch setup, a fast photodetector and the THERESA sampling system. The system contains the wideband front-end electronics, the THERESA sampling card and the data acquisition system based on the recent ZYNQ-RFSoc.

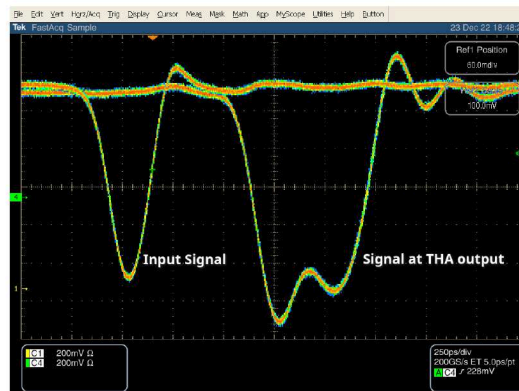


Figure 8: Input and output signals of the THA.

The first estimation of the Signal-To-Noise Ratio (SNR) of the sampling channels result in values of the order of 65 dB. Therefore, the Effective Number of Bits (ENOB) can be estimated to be 10 bits. To improve the SNR and enable the sampling of coherent detection using balanced photodetectors, a fully differential sampling channel architecture will be implemented in the final version of the THERESA card. It is planned to improve the overall system performance obtained with the demonstrator in final design by detection of differences in power between two optical input signals and thus largely suppress fluctuations in the input signal.

## 5. HIGH DATA-THROUGHPUT DATA ACQUISITION SYSTEM

Data acquisition and analysis are the essential components at the heart of any scientific experimental application. The produced data rates by photon sciences detectors increase significantly, as the technology of the photon sources evolves. Modern high-performance detectors for photon science applications are able to produce a deluge of data with a throughput in the range of several hundreds of Gbps. THESTRAL and THERESA, with throughputs that go up to 400 Gbps, are good examples of these classes of advanced detectors. Transferring, manipulating and processing such data streams in real-time is a challenge. For new projects and experiments high availability, bandwidth, throughput and scalability, along with intelligent platform management are essential. Scalability implies modular design and flexibility in interconnections between modules, while availability requires redundancy and intelligent management for the platform hardware and software. To satisfy scalability and

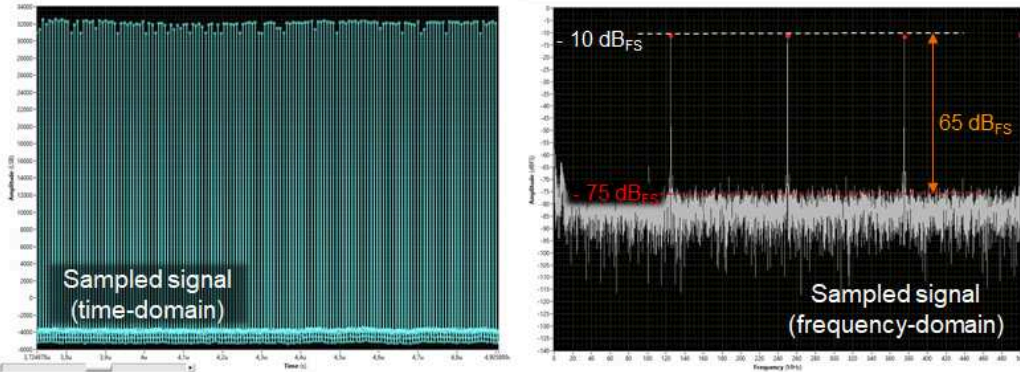


Figure 9: Sampled pulse train in ADC counts versus time (left). In the frequency-domain the pulse harmonics are visible as multiples of 125 MHz, which corresponds to the pulse train frequency. The average noise floor is around -75 dBFS while the harmonic signal is -10 dBFS (right)

availability several accelerator facilities have started to adopt industrial open standards such as Advanced Telecom Computing Architecture (ATCA) and  $\mu TCA$  (also written as MTCA or microTCA),<sup>62</sup> while others employ custom architectures.<sup>63</sup>

Sufficient data transfer rates can be realized by recent Ethernet link. IP blocks provided by the FPGA vendors allow the integration of 100 GbE, or even 600 Gb Ethernet or Interlaken networks.

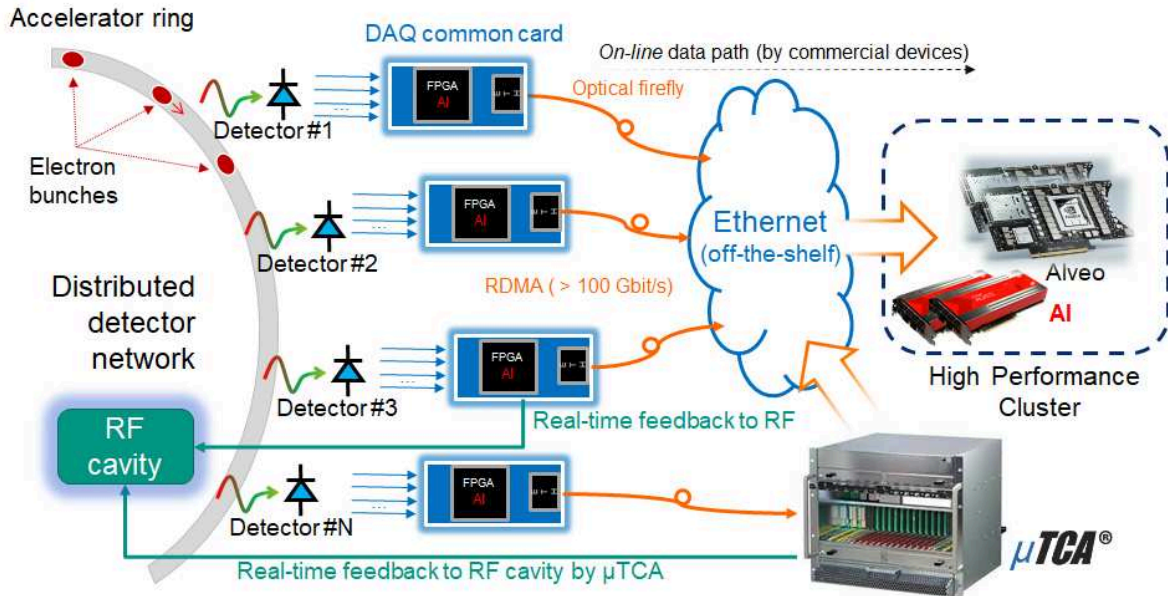


Figure 10: Proposed readout architecture for distributed detectors around the storage ring. On line data path is covered by off-the-shelf devices, which dramatically reduce the custom electronics, optimize cost and effort and ensure seamless incremental upgrades of individual subsystems with technological progress.

To deal with such stringent detector requirements, common development and implementation of reusable hardware and firmware components that can be applied to different kinds of detector devices and facilities are under development. As shown in Figure 10, the key feature of this common DAQ framework is the use of remote direct memory access (RDMA) for fast data transfer from the detector electronics. RDMA realizes the transfer of data from the memory of one host or device into that of another one without any CPU intervention, allowing high throughput. We are exploring the advantage offered by recent Ethernet standards, which are nowadays available RoCE (RDMA over Converged Ethernet)<sup>64</sup> and iWARP.<sup>65</sup> In particular, the RoCE standards offer

several advantages: it is a non-complex UDP/IP protocol based on the Infiniband, higher RDMA performance over 100G, direct implementation on modern FPGA by the Xilinx Embedded Target RDMA enabled NIC (ETRNIC) IP-Core.<sup>66</sup> It will enable a direct connection to the high-performance computing (HPC) system for fast data processing including edge AI technology. The latest generation of the NVIDIA EGX™ GPU<sup>67</sup> and Xilinx Alveo<sup>68</sup> cards, could directly be integrated within the on-line data path to scale up the ability to handle and process more data as the size of the data from detector grows. The key idea of the proposed architecture is its scalability, which allows integrating a single device, operating stand-alone, as well as supporting many detectors with several channels in a simple plug-and-play mode. The key-hardware component of the proposed architecture is the so-called “DAQ common card”, which consists of an FPGA-based card responsible for the local readout and control of the detector. It interfaces the detector mezzanine card, by an FMC/FMC+<sup>69</sup> connector, to the ETH/HPC and/or (ATCA) and  $\mu TCA$  mainframes system by optical fibers. The “DAQ common card” is joint-force development between KIT and DESY and is considered to be a key component for the integration of current and future detector instrumentation at several accelerators in DESY, KIT, SOLEIL and DELTA. As shown in Figure 10, fast feedback to control the fast dynamic of the beam is possible by conventional or AI algorithms deployed on the programmable logic of the “DAQ common card” or by more complex and distributed ATCA and  $\mu TCA$  devices.

## 6. A REAL-TIME FEEDBACK SYSTEM FOR ELECTRON BEAM CONTROL WITH AI ALGORITHMS

The dynamically changing substructures that appear in the longitudinal phase space of the bunch, characteristic of the micro-bunching instability, yield a fluctuating CSR power<sup>70</sup> that limits the use of the emitted THz radiation by experiments. The goal is to stabilize the CSR emission and control the power output, improving the reproducibility of THz experiments.

Machine Learning (ML) based on Reinforcement Learning (RL) is proposed to control the CSR micro-bunching instability. Reinforcement learning algorithms are able to generate an optimal sequence of actions that maximize the expected reward by interacting with the environment of the control problem. In contrast to conventional supervised learning algorithms, RL algorithms can learn purely from interaction with a real environment. Compared to the currently available classical controller designs for the CSR stabilization,<sup>71</sup> the RL approach is expected to perform better and be applicable to a wider range of conditions.

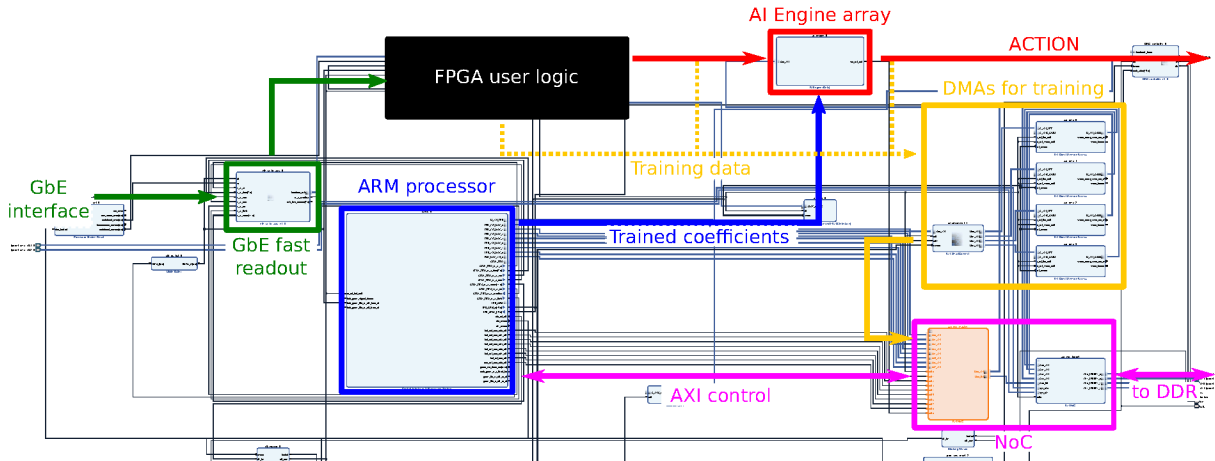


Figure 11: Block design of the feedback platform.<sup>72</sup> The different blocks of the Xilinx Versal platform are clearly visible and are all used.

Stringent latency constraints, in the order of tens of microseconds, are dictated by the timescale of the longitudinal beam dynamics and need to be satisfied by the feedback loop, including the inference time of the RL algorithm. Moreover the integration of the algorithm with both the detector systems (KAPTURE, KALYPSO, THERESA, and THESTRAL) and the accelerator feedback (Bunch-By-Bunch kicker and Low-Level RF systems) is of utmost importance. One promising technical platform for this is the novel Xilinx Versal

Adaptive Compute Acceleration Platform (ACAP). Such a system combines several different computational components: ARM processor, FPGA, and AI Engine Array. The latter is particularly designed for ML models as it has the capability to perform floating-point multiplications on an array of Reduced Instruction Set CPU (RISC) that are deeply interconnected among themselves, the FPGA, and the ARM processor. These submodules are linked together using a high-throughput low-latency Network-on-Chip (NoC), allowing the shared use of DDR memory and resources. An intriguing possibility is the ability to implement low latency floating-point precision models, in this way allowing the trivial deployment of solutions already developed using the commonly available ML frameworks. The design of such a system is shown in [Figure 11](#). The data is readout by a Gigabit Ethernet interface, pre-processed in custom FPGA IPs, and fed into the AI Engine array for feature extraction and ML model inference. The action is then transferred as analog signal to the machine control system. The ARM processor, running a Linux operating system, is used for the slow-control of the infrastructure and for the monitoring of the feedback loop, thanks to a series of DMAs automatically transferring training data to the DDR memory through the NoC. A more in-depth description of the system is provided in.<sup>72</sup>

## 7. CONCLUSION AND OUTLOOK

Innovations in electronics have often enabling breakthroughs in experimental techniques in photon sciences, particle physics and novel detectors. Sensor and front-end electronics are core components of any detector system. They define its properties and fulfil the task of collecting, amplifying, storing and processing signals coming from the sensor and transferring information to the back-end electronics for further digital processing. During the past years the ultrasfast line camera KALYPSO and the intelligent sampling system KAPTURE have been developed for the needs of the beam physics community. Both systems are in regular use in various facilities to explore beam properties with continuous measurements. Recently, a new generation of ultra-fast detectors that are suitable to measure the spectral, position and time with very high accuracy in the order of tens  $\mu\text{m}$  and tens picoseconds and are driving progress in photon sciences. Thanks to the well-established network between beam scientists of KARA, DESY and University of Lille, and electronics engineers at KIT, several novel detector systems are under development to satisfy the ever-increasing demand for shot-to-shot high-granularity and precise timestamp detectors spanning from THz to X-ray and operating at high frame rate.

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