Journal of
Instrumentation

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To cite this article: M.M. Patil *et al* 2025 *JINST* **20** C01006

Jinst
Published by IOP Publishing for Sissa Medialab
Received: *November 3, 2024*
Accepted: *December 13, 2024*
Published: *January 10, 2025*

Topical Workshop on Electronics for Particle Physics
University of Glasgow, Scotland, U.K.
30 September–4 October 2024

KALYPSO LGAD — a MHz repetition rate line camera based on trench isolated low gain avalanche detector

M.M. Patil[a,*] **M. Caselle,**[a,*] **E. Bründermann,**[a] **S. Chilingarayan,**[a] **A. Kopmann,**[a] **G. Niehues,**[a] **J.L. Steinmann,**[a] **S. Stankov,**[a] **C. Widmann,**[a] **A.-S. Müller,**[a] **G. Borghi,**[b,1] **G. Paternoster,**[b] **M. Centis Vignali**[b] **and M. Boscardin**[b]

[a] *Karlsruhe Institute of Technology, Karlsruhe, Germany*
[b] *Fondazione Bruno Kessler, Trento, Italy*

E-mail: meghana.patil@kit.edu, michele.caselle@kit.edu

Abstract: Designed for accelerator beam diagnostics and photon science applications, KALYPSO is a line array camera that stands out for its high-speed performance with the ability to operate at rates up to 12 Mfps in continuous readout mode while maintaining full occupancy. In this contribution, the KALYPSO system with sensor based on TI-LGAD is presented. The latest version of this system is employed as a beam diagnostic imaging sensor to measure radiation profiles of the particle beam at the KIT accelerator, KARA. The system's key features will be presented, including its linearity, sensitivity, and dynamic range.

Keywords: Accelerator Applications; Instrumentation for synchrotron radiation accelerators; Front-end electronics for detector readout; Data acquisition concepts

*Corresponding author.
[1] Now at Politecnico di Milano, Italy.

https://doi.org/10.1088/1748-0221/20/01/C01006

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1 Introduction

KALYPSO (KArlsruhe Linear arraY detector for MHz rePetition-rate SpectrOscopy) is an ultra-fast line array camera capable of operating at MHz frame-rates, continuously [1]. This camera has been used extensively in the field of beam diagnostics for research in accelerator physics. It has been used to study the micro-bunching instability which occurs due to the compression of electron bunches, which also results in short bursts of THz radiation [2]. KALYPSO has been used to measure the longitudinal bunch profile [3, 4] and the transverse bunch profile of the electron bunch [5]. As a sensing element, it uses a semiconductor microstrip sensor connected to a low-noise custom-designed ASIC (Application Specific Integrated Circuit). The sensor can be of several materials including Si (Silicon), InGaAs (Indium Gallium Arsenide), PbS (Lead Sulphide) or PbSe (Lead Selenide). Although this gives a wide spectral sensitivity, one of the main drawbacks is the low intensity performance of KALYPSO, especially with the Si microstrip sensor, which results from the synchrotron radiation emitted at low bunch charges (around 368 pC) that make the bunch profile indistinguishable due to detector noise. Hence, in order to overcome this drawback, a Si microstrip sensor based on TI-LGAD (Trench-Isolated Low Gain Avalanche detector) has been used. This contribution presents the architecture and performance of KALYPSO-LGAD, followed by initial experimental results obtained at the Visible Light Diagnostic (VLD) port of the Karlsruhe Research Accelerator (KARA) at KIT.

2 TI-LGAD

LGADs are a type of Si sensors with an additional implant below the standard implant which contributes to an internal gain of 10–30 depending on the reverse voltage bias and geometry of the sensor. The gain is mainly attributed to the high electric field $3 \times 10^5\ \mathrm{V\,cm^{-1}}$ at the junction of the additional implant. However, since the field is below the breakdown field of Si, it is fairly easy to control the avalanche mechanism, as well as the gain. Another advantage is that due to the low gain, quenching mechanism as used in SiPMs (Silicon Photomultipliers) is not needed, which in turn leads to easier implementation of readout electronics. A cross-section of such a sensor in comparison to a typical Si microstrip is shown in figure 1.

The main disadvantage of this sensor is the presence of an additional region adjacent to the implant called the JTE (Junction Termination Extension) which introduces a large no-gain region between adjacent implants. The JTE is applied in order to curb very high electric fields at the edge of the implants. Due to this the segmentation pitch of the sensor cannot be improved beyond 100 µm.

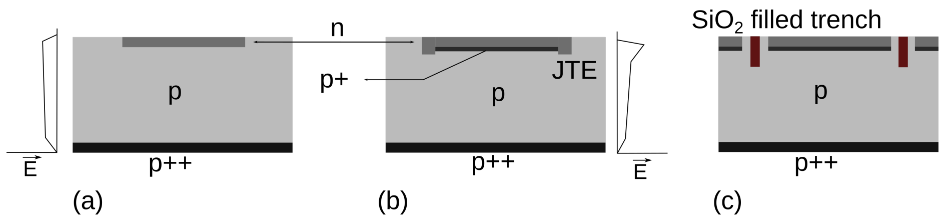

Figure 1. Schematic depicting the internal structure of a (a) silicon microstrip (b) Low Gain Avalanche Detector (LGAD) (c) Trench Isolated Low Gain Avalanche detector (TI-LGAD).

Applications involving imaging of photons or charged particles require a minimum pitch of 50 µm, hence an LGAD based on trench isolation has been fabricated by FBK laboratories. The comparison between traditional LGAD and TI-LGAD can be seen in figure 1.

In TI-LGAD, the implant region is the same as the traditional LGAD but the JTE is replaced with a deep and narrow trench ($<$ 1 µm wide and few microns deep) filled with SiO_2 (silicon dioxide) [6]. The trench acts as a physical barrier providing electrical and optical isolation between implants. With this sensor, the no-gain region between implants has been reduced and hence improves the segmentation pitch.

As a part of the RD50 collaboration [7] several designs were fabricated in order to test and evaluate the performance. Both micro-strips and pixels were a part of the design and KIT received the micro-strips sensors with 50 µm and 100 µm pitch with an area of 2.1×2.1 mm^2 and 4.2×4.2 mm^2.

The IV characteristic of the bare sensor was measured. For the connected 30 channels, it shows a low leakage current in the order of a few pA per channel with a breakdown voltage of 200 V.

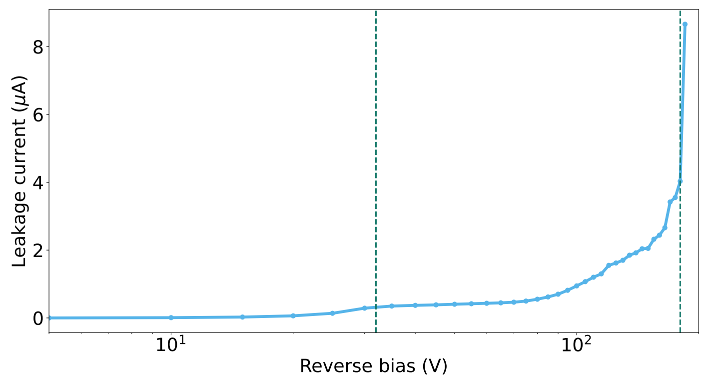

Figure 2. Dark IV measurement of the complete TI-LGAD sensor. The first vertical line depicts depletion and the second line depicts breakdown.

3 KALYPSO-LGAD

A TI-LGAD sensor has been mounted on KALYPSO card. The 48 channels of the sensor are wire-bonded to a custom-made ASIC Gotthard-KIT [8], see figure 3. The first stage of the ASIC is a charge sensitive amplifier (CSA) with a synchronous reset and with modular feedback capacitances at C_f, $4C_f$, $20C_f$ with C_f equal to 33 fF. This allows the tuning of the gain of the CSA. The CSA is followed by a Correlated Double Sampling (CDS) stage which is used for removing undesired

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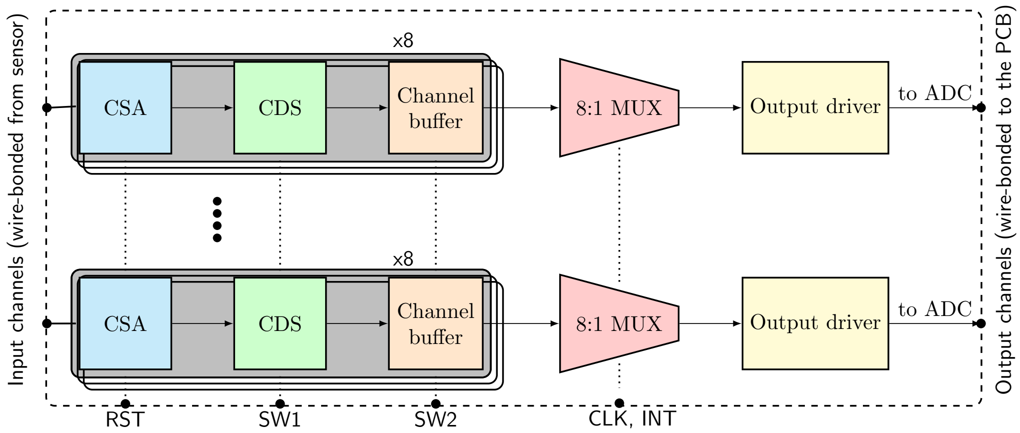

Figure 3. Overall architecture of the Gotthard-KIT ASIC.

KT/C noise contribution. The CDS is followed by the channel buffer which samples and hold the CDS output while the previous sample is being read. The channel buffers are coupled to an analog multiplexer in groups of 8 input channels, which is followed by a high-speed output driver. The digital signals RST, SW1, SW2, CLK, INT are responsible for the control of the individual blocks shown. The output drivers are connected directly to an Analog to Digital converter (ADC) AD9681 capable of sampling rates up to 125 MHz. The LVDS outputs of the ADC are then routed directly via an FMC connector to the FPGA. In order to synchronize the card with an external reference clock, a jitter-cleaning PLL LMK03001CISQ is mounted. The readout is performed by a Virtex-7-based FPGA card called the High-Flex PCIe readout card [9]. The DAQ interface is realized by PCI express interface. Figure 4 shows the KALYPSO card with the TI-LGAD sensor.

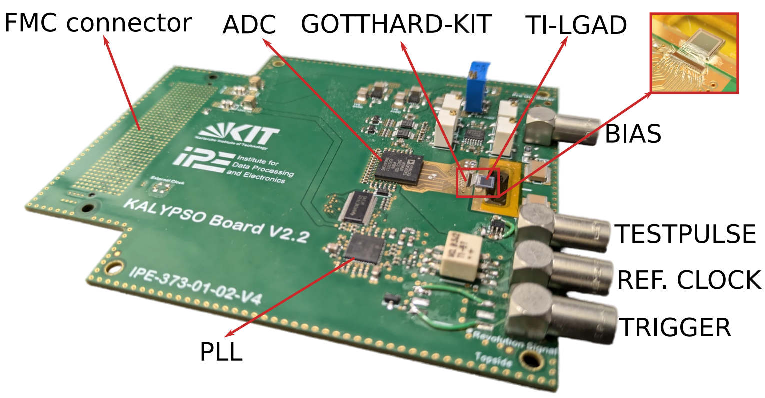

Figure 4. KALYPSO detector card mounted with a TI-LGAD sensor wire-bonded to Gotthard-KIT ASIC.

The system response to different exposure times at the three gain regions has been studied and has been shown in figure 5. A uniform source of wavelength 450 nm has been used to illuminate the complete sensor area. The exposure time was increased from 4 ns to 68 ns in increments of 4 ns. The system exhibits linear behavior for integration times up to approximately 60 ns. For integration times greater than 60 ns, non-linearity is observed due to the limitations of the readout process at a 2.7 MHz frame rate. If an integration time greater than 60 ns is used, the framerate of the system

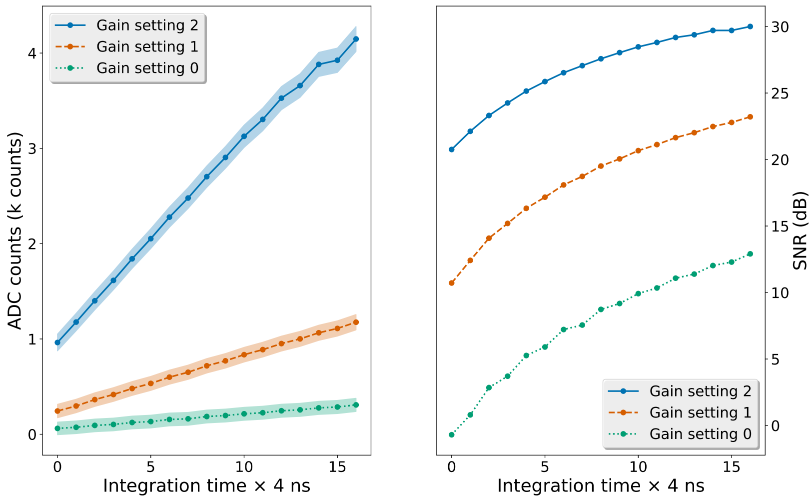

Figure 5. Linearity and SNR measurements for the TI-LGAD KALYPSO performed at three gain settings, with gain setting 2 being the highest.

needs to be reduced. The dynamic range of the system has been calculated using the photon transfer method at an exposure time of 16 ns to be 63.23 dB.

4 First beam time measurements

The energy spread of an electron bunch is an essential parameter in order to study the micro-bunching instability. The micro-bunching instability occurs in very short electron bunches (RMS longitudinal bunch length around 4.5 ps) due to the self-interaction of the bunch with its own emitted radiation. This results in bunch charge dependant periodical bursts of THz radiation (the periodicity of the bursts depends on the machine operating conditions and ranges between 200 Hz to 400 Hz). At KARA, a dedicated VLD port has been installed in order to study the energy spread of the electron bunch during short bunch operation mode [10]. This port is located at a dispersive section of the accelerator and here the energy spread is coupled to the horizontal bunch size of the electron bunch. KALYPSO based on Si has been installed and has proven to be a good candidate for such a study due to its high repetition rate and continuous data acquisition. However, the version of KALYPSO with a standard Si sensor posed a problem at very low bunch charge around 368 pC as the noise floor of the detector was overpowering the radiation intensity that had to be measured. The measurements at low bunch charges are a key to study the onset of the THz bursting behavior. The measurements revealing the onset has been reported in [11].

Figure 6 shows the evolution of horizontal bunch profiles over a bunch current range of 1 mA to 0.1 mA. Even at lower bunch current levels, when signal amplitudes usually decrease, accurate profile measurement is possible due to the application of TI-LGAD technology. Because of the improved sensitivity of the LGAD, the bunch shape's fine details can be preserved with the least amount of signal degradation. The peak structure is clearly visible throughout the current range, indicating how well LGADs preserve measurement accuracy in low-current scenarios.

Figure 7 shows the evolution of consecutive single shot bunch profile over a period of 7.4 ms acquired at a rate of 2.7 MHz. The detailed analysis of the data in perspective to beam diagnostics has been reported in [11, 12].

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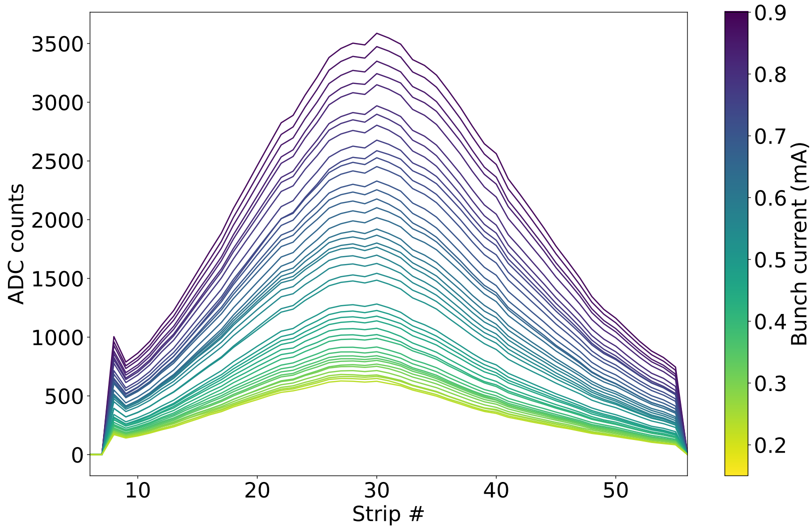

Figure 6. Horizontal bunch profile measurements taken at regular intervals of a decaying bunch current.

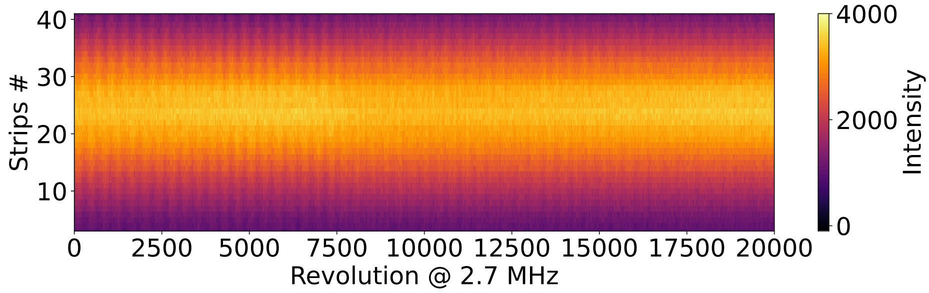

Figure 7. Evolution of a dataset acquired by KALYPSO, showing 20,000 consecutive bunch profile measurements over successive revolutions at 2.7 MHz.

5 Conclusion

The TI-LGAD sensor has been successfully integrated with the KALYPSO card. The KALYPSO-LGAD has been characterized and shows significant improvements regarding signal sensitivity, dynamic range and noise. The system has also been installed in the visible light diagnostics port at KARA to measure incoherent synchrotron radiation for energy spread studies. The gain tuning capability of TI-LGAD in combination with the Gotthard-KIT ASIC has led to exploring beam dynamics at very low bunch current. To improve the resolution of the bunch profile measured, an engineering run is planned with larger microstrip TI-LGADs.

Acknowledgments

M.M.P. acknowledges the support by the DFG-funded Doctoral School "Karlsruhe School of Elementary and Astroparticle Physics: Science and Technology". The work is in part supported by the BMBF (German Federal Ministry of Education and Research) project 05K22VKB and 05K22VK2 and by the RD50 collaboration.

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