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A low-power LGAD-Timepix dosimeter for biological space radiation monitoring

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Abstract: ALCYONE, an EU-funded project under the Horizon Europe program, addresses the impact of prolonged space exposure on biological systems, which is a critical challenge for future long-duration space missions. The project focuses on the development of a miniaturized on-chip micro-incubator to monitor and control environmental conditions for four types of cell cultures. This contribution outlines the development of a high-resolution dosimeter based on fine-pitch trench-isolated LGADs, coupled with Timepix3 front-end electronics, for accurate radiation monitoring in both space and laboratory environments. The detector is seamlessly integrated into a compact, high-performance system-on-chip platform, enabling real-time processing of radiation fluence and dose.

Keywords: Data acquisition circuits; Dosimetry concepts and apparatus; Hybrid detectors; On-board space electronics

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Contents

1 Introduction

Extending human presence beyond Earth's orbit presents significant biomedical challenges, particularly the effects of prolonged exposure to space radiation, microgravity, and isolation. These factors pose serious health risks, including degenerative pathologies that may compromise astronaut safety and mission success. The ALCYONE project [1], funded under the Horizon Europe program, addresses this issue by developing miniaturized, autonomous systems to monitor biological responses in space. Central to ALCYONE is a novel dosimeter designed for integration into a compact bio-laboratory platform. The system leverages Timepix3 front-end chips, a technology with proven reliability in space missions, and enhances them with newly developed trench-isolated, fine-pitch low-gain avalanche detectors (TI-LGADs) [2] fabricated by FBK [3]. These pixelated sensors are bump-bonded to the Timepix3 chips [4, 5], forming a hybrid detector that offers high spatial and temporal resolution with improved sensitivity. This paper presents the design and implementation of this low-power dosimeter.

2 Advanced lab-on-chip payload for CubeSat

A key innovation of the ALCYONE project is the lab-on-chip integration of thin-film sensors and actuators directly onto the micro-incubator substrate, allowing autonomous operation without external instrumentation while precisely controlling and monitoring local environmental conditions. The lab-on-chip prototype is shown in figure 1. Each chamber is equipped with a miniature thin-film metallic heater and ultra-sensitive hydrogenated amorphous silicon (a-Si:H) temperature sensors for accurate thermal regulation [6]. The system also demonstrates modularity and versatility, accommodating various cell types, including mammalian, yeast, and microbial cultures, and several experimental setups. To overcome the challenges associated with operation in microgravity and weightlessness conditions, a tapered cell culture chamber design has been adopted. This engineered configuration leverages the tendency of liquid to creep into confined spaces on hydrophilic substrates, with the driving force influenced by channel dimensions and taper angle. By ensuring the liquid volume is reliably pinned in the desired location, the tapered chamber aims to enhance the reliability and consistency of experiments conducted within the lab-on-chip device [7].

2026 JINST 21 C02031

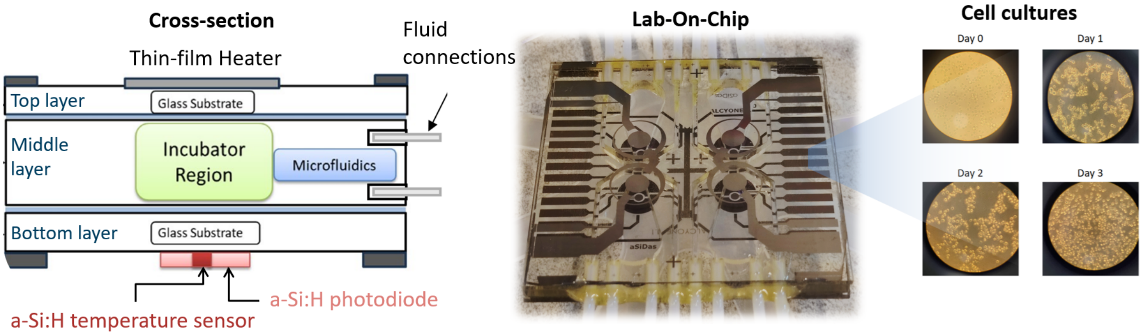

Figure 1. Lab-on-a-chip developed within the ALCYONE project. Left: schematic cross-section of the three-layer structure, comprising a top layer with thin-film heater patterns fabricated by photolithography, a middle layer containing the microfluidic cell incubation chambers, and a bottom layer integrating amorphous-silicon temperature and photodiode sensors. Center: fabricated lab-on-a-chip device. Right: cell culture growing under well-controlled environmental conditions inside the incubator.

Another core aspect is the use of bioluminescence as a real-time analytical tool. Genetically modified prokaryotic and eukaryotic cells carry luciferase-based reporter systems to track stress responses [8, 9]. Bioluminescence sensing is integrated directly on the microfluidic chip, with a-Si:H thin-film photosensors monitoring the optical signal that correlates with cell metabolic activity [10]. This non-invasive approach allows continuous monitoring of cellular responses to microgravity and radiation without interfering with the experiment. As shown in figure 1, the incubators are capable of supporting cell culture growth under well-controlled environmental conditions.

3 Dosimeter architecture

In the ALCYONE setup, the lab-on-chip micro-incubators expose cultured cells to incoming space radiation. To quantify the radiation in terms of energy, dose, and spatial distribution at the cell level, an integrated dosimeter is required. This dosimeter enables direct correlation between the local radiation environment and the observed cellular responses, thereby playing a central role within the ALCYONE project. The ALCYONE dosimetry system is centered around the Timepix3 front-end ASIC, chosen for its high performance, low power consumption, and radiation tolerance, critical requirements for space-based applications. The front-end chip is bump-bonded to a Trench-Isolated Low Gain Avalanche Diode (TI-LGAD) sensor, produced at FBK. Together, they form a compact and robust hybrid detector capable of precise particle and radiation monitoring in deep space environments. The Timepix3 ASIC features a 256×256 pixel matrix, offering over 65,000 independent detection channels. Each pixel can individually register ionizing radiation events with high temporal and energy resolution. The connection to the TI-LGAD sensor is established using an in-house developed high-density flip-chip technology. The bumping on the Timepix3 chip employs InSn bumps by IZM [11], while the under-bump metallization (UBM) layer on the sensor side has been developed by CERN [12]. Space qualification of the bump-bonded assemblies is foreseen through compliance with relevant NASA standards [13], including vibration testing, pull tests, and post-separation optical inspection. Preliminary mechanical tests already demonstrate a high interconnect quality, with measured mechanical strengths exceeding $10\ \mathrm{kg/cm^2}$. The integrated gain layer in the LGAD provides an internal amplification of approximately 10–20, enabling photon-induced signals with collected

2026 JINST 21 C02031

charges of a few hundred electrons to be reliably discriminated above the electronic noise floor of the Timepix3 chip. This intrinsic gain also allows the Timepix3 to operate at reduced power without compromising performance, a critical advantage for space applications such as nanosatellites where strict power and thermal constraints must be met.

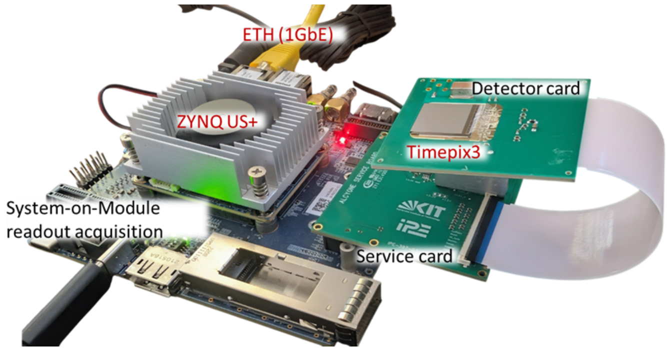

Figure 2. ALCYONE dosimeter system and its key components. The low-noise detector card is connected to the service card using a Zero Insertion Force (ZIF) flip-lock cable. The service card interfaces with the iWave data acquisition system via a VITA-57 FMC+ standard connector.

The dosimeter system is shown in figure 2. The Timepix3 ASIC and TI-LGAD sensor are mounted on a detector card, which provides mechanical support and electrical interfacing. Beneath the detector card lies the service card, responsible for low-noise voltage regulation across analog and digital domains. Designed with a modular architecture, the system allows multiple detector cards to be mounted for extended coverage. The planned integration of TI-LGAD and CdTe sensors will broaden the detectable radiation spectrum, extending the accessible energy range from low-energy charged particles, soft X-rays to hard X- and γ-rays, corresponding to energies from a few keV up to the MeV scale. The scalable DAQ system (iWave [14]) supports high-throughput data acquisition with real-time processing and onboard storage. The acquisition system is built around a Zynq UltraScale+ [15] System-on-Module (SoM), which integrates a high-performance ARM-based processing system with programmable logic (FPGA) in a single device. This architecture enables fully autonomous operation, embedding all data acquisition, real-time processing, and control functionalities directly within the dosimeter system. By eliminating the need for external computing resources, this approach significantly reduces system size, complexity, and power consumption, key advantages for space missions where the budgets for mass, volume, and energy are tightly constrained.

4 FPGA firmware architecture

The FPGA firmware constitutes the core of the ALCYONE dosimeter system, facilitating seamless communication between the Timepix3 chip, the real-time data acquisition chain, and the satellite's control unit. The current implementation of the ALCYONE dosimeter corresponds to a low Technology Readiness Level (TRL) and is intended primarily as a laboratory demonstrator. It is developed within the Vivado design environment, integrating hardware logic and embedded software into a compact and efficient architecture. Radiation tolerance of the programmable logic has been considered for future space deployment, and radiation-tolerant FPGA platforms are under evaluation to support progression toward higher TRL. In particular, the Lattice Certus™-NX-RT FPGA family [16] and the Efinix

Quantum FPGA platform [17] are being considered as candidate solutions, as both provide embedded processor support and enable a smooth migration of the current firmware and software stack, including PetaLinux, toward radiation-tolerant programmable architectures. The current architecture is divided into three main functional sections, performing distinct and complementary roles to guarantee the reliable operation of the dosimeter. The first section, the Timepix3 control and interface block, which includes the modules responsible for configuration, command sequencing, and data readout of the Timepix3 chip. A serial configuration module manages the programming of the internal registers of the Timepix3, while a high-speed readout module handles the rapid serial data stream transmitted by the dosimeter. This module performs data deserialization, integrity verification, and temporary event buffering, ensuring continuous and lossless data transfer to subsequent processing stages. The second section integrates the Embedded ARM Processor and FPGA interface block, implemented on the Zynq UltraScale+ SoC platform. An ARM processing core runs Petalinux, a lightweight and customizable embedded Linux distribution optimized for FPGA-based systems. As a result, the ALCYONE dosimeter operates as a fully autonomous instrument, providing in-situ data processing and closed-loop system control. The third section, the FPGA infrastructure block, encompasses the high-speed internal data handling mechanisms that bridge the Timepix3 logic interface and the processing system. At its core lies the AXI Direct Memory Access (DMA) engine [18], which enables efficient, low-latency data transfer from the FPGA logic to the processor's memory space. This design ensures high-throughput, real-time data availability for processing, visualization, and storage, even under demanding acquisition conditions. The entire firmware follows a modular design philosophy, ensuring flexibility and scalability for future system extensions. This modularity makes the ALCYONE platform highly adaptable and suitable for both laboratory research and space mission environments.

5 SoC platform and PetaLinux integration

The software infrastructure of the ALCYONE dosimeter fully exploits the integrated System-on-Chip (SoC) architecture, ensuring compactness, autonomy, and ease of operation. All essential components run on the embedded ARM processor, under a customized Petalinux OS optimized for ALCYONE. This provides efficient resource management, minimal overhead, and robust hardware-software interaction for both laboratory and space applications. The software stack is shown in figure 3. The FPGA hardware layer implements core logic for Timepix3 control, data acquisition, and internal communication. The AXI interface layer bridges the FPGA logic and ARM processor, enabling reliable, low-latency access to registers, configuration commands, and real-time data streams. The low-level software layer consists of Python drivers using memory-mapped I/O (mmap) [19] to control FPGA registers, orchestrate DMA transfers, and manage Timepix3 signals (reset, shutter, strobe). The top layer of the software stack is a web-accessible graphical user interface (GUI), implemented in Python and served through an embedded Apache server. This interface provides an intuitive and user-friendly platform for controlling the ALCYONE dosimeter, managing acquisition parameters, and visualizing data in real time, all without the need for installing any external software on client machines. To facilitate seamless data exchange, a SAMBA server [20] is integrated, allowing users to transfer files, retrieve measurements, or upload configuration data directly to the system with minimal effort. A dedicated custom server application manages all Ethernet-based remote commands, including powering the dosimeter on or off, configuring Timepix3 parameters, data acquisition, and performing automated calibration routines.

2026 JINST 21 C02031

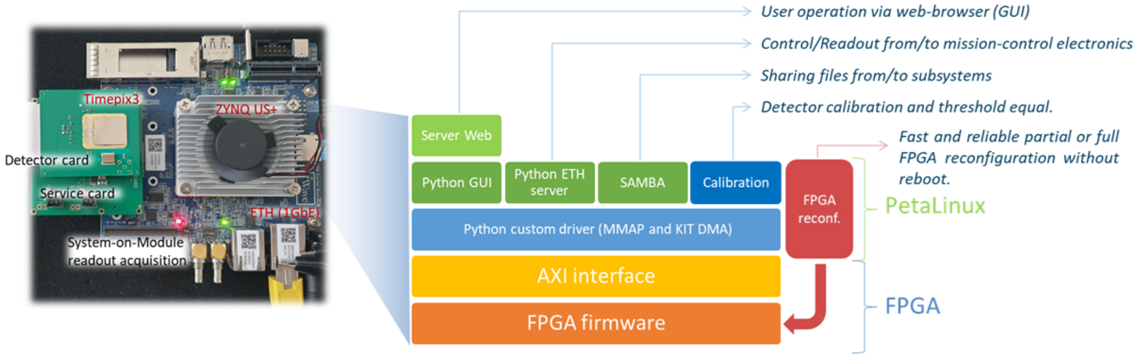

Figure 3. All tier-levels: FPGA, PetaLinux, custom drivers, application layers, and servers, are deployed and executed natively on-device, making it ideal for a compact, standalone dosimeter.

Moreover, the system supports dynamic partial or full FPGA reconfiguration via the Petalinux environment. When a new FPGA bitstream is uploaded from an Earth station using a SAMBA-shared folder, a dedicated Python script automatically programs the FPGA, applies the necessary reset, and seamlessly resumes normal operation without requiring any reboot or power cycle of the SoC. By consolidating all essential software components within the embedded Petalinux environment, the ALCYONE dosimeter achieves a fully self-contained, highly optimized, and autonomous software ecosystem.

6 Conclusion

The ALCYONE project successfully demonstrates the development of fundamental technologies for future long-duration human space missions. Central to the system is the TI-LGAD sensor, which enables a dramatic reduction in Timepix3 power consumption-analog power. The software-defined architecture allows for autonomous operation, real-time data acquisition and processing, onboard calibration, and remote reprogramming without power-cycle interruption. The integration of the dosimeter with the lab-on-chip and its electronics is scheduled for the beginning of 2026. By combining compactness, low power, and intelligent onboard processing, ALCYONE paves the way for next-generation autonomous space-borne radiation detection.

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2026 JINST 21 C02031