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Full Length Article

Towards a 20 ps timing detector with hybrid and CMOS monolithic LGADs for the future ALICE 3 experiment at LHC☆

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ABSTRACT

In the context of the future ALICE 3 experiment, planned for installation at the CERN-LHC during LS4 in 2034-35, an intensive research program is actively addressing the challenge of identifying a 20-picosecond sensor technology for the Time-Of-Flight detector. Key results and next steps in the development of both traditional and monolithic Low Gain Avalanche Detectors (LGADs and CMOS-LGADs) are presented. Comprehensive studies conducted on progressively thinner LGAD highlighted the potential of a thinner design for improved timing performance, and a resolution below 20 ps was achieved. To address the challenge of a small signal at the input of the front-end electronics, the novel double-LGAD concept was introduced and tested for the first time. Extending the LGAD concept to a CMOS technology has the potential to offer a transformative path forward, combining precise timing and full-area coverage in a monolithic approach, offering a simpler and cost-effective assembly. The first CMOS-LGAD prototypes, produced in the third ARCADIA engineering run using the 110 nm technology of LFoundry, were tested for the first time and the most recent production reached an intrinsic sensor time resolution of 75 ps in line with simulations. Efficiency and in-pixel time resolution are presented together with the first studies on irradiated sensors and next steps towards the 20-ps goal are discussed.

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1. Introduction

The ALICE experiment at the CERN Large Hadron Collider (LHC) is dedicated to the study of strongly interacting matter under extreme energy-density conditions. Several key physics topics – including measurements of heavy quarks, low-momentum dileptons, and rare electromagnetic probes – cannot be fully addressed without a new experimental apparatus. To meet these scientific challenges, the ALICE Collaboration has proposed ALICE 3 [1], a next-generation, all-silicon heavy-ion experiment envisioned for LHC Run 5.

ALICE 3 is designed as an ultra-light detector based on thin, high-granularity silicon layers, providing excellent tracking, vertexing, and particle-identification capabilities. The detector will offer nearly continuous spatial and timing coverage over the pseudorapidity range $|\eta| < 4$. Particle identification will rely on several dedicated subsystems, among which the Time-of-Flight (TOF) detector plays a central role. The TOF system consists of an inner and an outer barrel layer located at radii of 19 and 85 cm from the beam line, respectively, as well as two forward disks positioned at ± 3.7 m from the interaction point. Overall, the TOF detector will cover a total active area of approximately $45\,\mathrm{m}^2$, with a material budget of 1–3% X_0 and a power density below $200\,\mathrm{mW/cm}^2$. To achieve the physics objectives of ALICE 3, the TOF system must provide a time resolution of approximately 20 ps. Existing state-of-the-art silicon timing technologies provide different trade-offs between timing performance, radiation tolerance, integration level, and fabrication complexity. AC-LGADs [2] and 3D silicon sensors [3] typically achieve time resolutions of about 30–50 ps, offering respectively excellent spatial granularity and radiation tolerance above 10^{16} neq/cm^2, while monolithic CMOS [4] timing detectors provide a high level of integration and reduced production costs at the expense of a more modest timing performance, currently in the range of ∼50–100 ps. Therefore, none of the available technologies was able to simultaneously satisfy the stringent ALICE 3 TOF requirements, motivating a dedicated R&D program on LGAD and CMOS-LGAD technologies.

Reaching this ambitious performance has motivated an extensive R&D program focused on advanced silicon timing technologies. Low Gain Avalanche Detectors (LGADs) currently represent the most mature solution, as their internal gain layer enables rapid signal formation and an excellent time resolution approaching 20 ps. R&D efforts, described in Section 2, included the development of sensors with thinner active regions, the introduction of the novel double-LGAD concept, and detailed studies of detector performance for non-perpendicular particle incidence.

Building on the excellent performance of LGADs, current R&D activities have increasingly focused on fully depleted CMOS sensors with internal gain (CMOS-LGADs, see Section 3,). These devices constitute a promising monolithic alternative and have been selected as the baseline technology for the ALICE 3 TOF system. By integrating the active sensor and the front-end electronics on the same substrate, CMOS-LGADs offer the potential for substantial reductions in material budget and production costs, together with a simplified detector assembly. Although further optimization is required to reach the target time resolution of 20 ps, recent prototype devices incorporating dedicated gain layers have demonstrated encouraging improvements in timing performance.

To assess the suitability of both LGAD and CMOS-LGAD technologies for the ALICE 3 TOF detector, a comprehensive beam-test campaign was conducted between 2021 and 2025 at the CERN PS T10 beamline, using hadrons with momenta of 10–12 GeV/c, at CERN SPS beamline with 120 GeV/c hadrons and at the DESY test-beam facility with 4–5 GeV/c electrons. These measurements provide essential information on charge-collection properties and, in particular, on the timing performance of LGAD and CMOS-LGAD devices, enabling a detailed evaluation of their potential to meet the stringent requirements of the ALICE 3 TOF system.

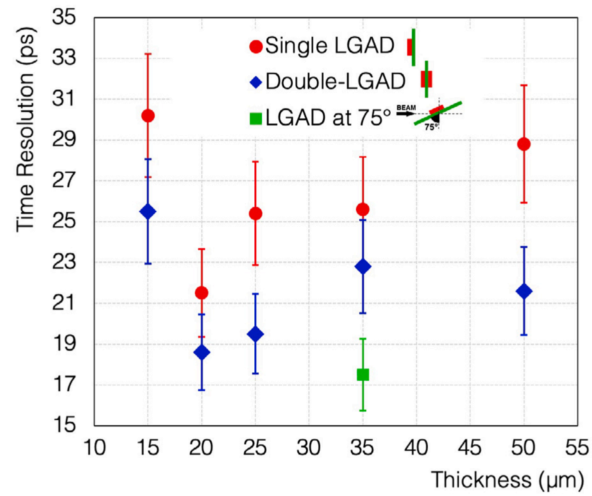

Fig. 1. Time resolution measured with the constant fraction discrimination (CFD) technique at the highest applied voltage for each tested thickness (15, 20, 25, 35, and 50 μm), for single and double-LGADs. The CFD threshold providing the best time resolution is 60%, 60%, 40%, 30%, and 30% for the double-LGADs, and 60%, 60%, 50%, 30%, and 30% for the single LGADs, respectively, from 15 to 50 μm. The time resolution of the LGAD at the maximum incidence angle for a fixed CFD threshold of 40% is also reported.

2. Towards 20 ps with hybrid LGADs

An extensive beam-test program was conducted to characterize the timing capabilities of thin LGAD sensors developed at FBK. The study included devices from the EXFLU0 production [5], featuring nominal active thicknesses of 25 and 35 μm and a sensitive area of 1×1 mm^2. In addition, sensors from the EXFLU1 production [6] were tested for the first time in a beam environment, extending the investigation to ultra-thin devices with active thicknesses of 15 and 20 μm and an area of 1.3×1.3 mm^2. Standard 50 μm-thick LGADs manufactured by Hamamatsu Photonics K.K. (HPK) were also included as reference devices.

All sensors were integrated on a V1.4-SCIPP-08/18 SantaCruz front-end board, hosting a 2 GHz low-noise inverting trans-impedance amplifier of 470 Ω. The experimental setup allowed the simultaneous readout of at least three sensors mounted side-by-side aligned to the beam. Signal waveforms were acquired using a high-bandwidth oscilloscope and subsequently processed offline to extract the timing information. The measurements were carried out during multiple beam-test campaigns between 2021 and 2024 at the CERN PS T10 beamline, employing a 10 GeV/c positive hadron beam predominantly composed of protons and pions.

After a comprehensive characterization performed at the INFN laboratories in Bologna, the first beam-test results focused on the 25 and 35 μm-thick LGADs. Their timing performance was benchmarked against that of a standard 50 μm HPK sensor, used to validate both the experimental setup and the analysis methodology. The procedures adopted to extract the timing resolution are described in detail in [7]. The HPK50 reference device achieved a time resolution of approximately (34 ± 3) ps at a bias voltage of 245 V, in agreement with previous studies. In contrast, the thinner FBK sensors exhibited a marked improvement, primarily attributed to the reduction of Landau fluctuations [8]. In particular, the 35 μm LGAD reached a time resolution of (22 ± 2) ps at 240 V, consistent with simulation predictions, while the 25 μm sensor achieved (25 ± 3) ps at 120 V. The investigation was subsequently extended to LGADs with even smaller active thicknesses of 20 and 15 μm. A global comparison among all tested thicknesses (15, 20, 25, 35, and 50 μm) showed that devices thinner than the standard

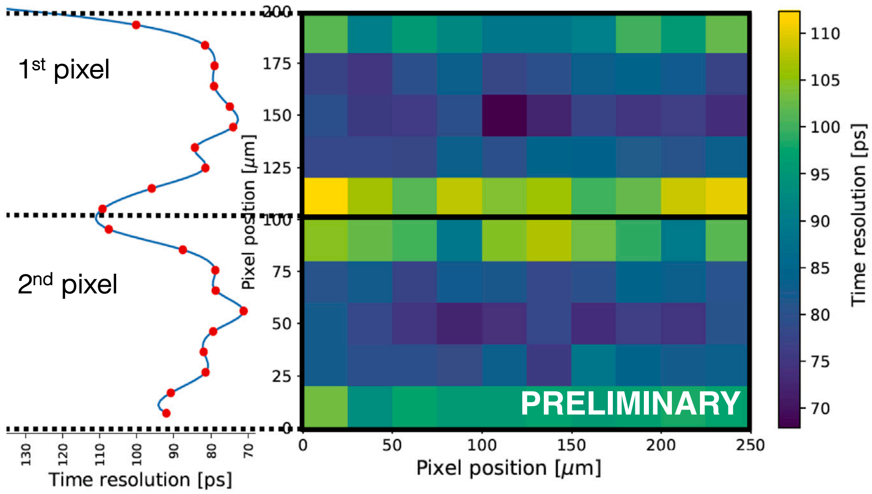

Fig. 2. In-pixel time-resolution map of two adjacent CMOS-LGAD pixels. For each horizontal slice, the corresponding mean time-resolution value is indicated on the left panel.

50 μm LGAD systematically achieve a better timing performance, down to the 20 ps required by the experiment. These measurements clearly demonstrate the benefit of reducing the active sensor thickness [7].

The only deviation from this trend was observed for the 15 μm sensors, whose performance appears to be limited by the front-end electronics, not optimized for the extremely fast and low-amplitude signals produced by such thin devices. As the sensor thickness decreases, the electronics term increasingly dominates the overall time resolution. This observation underlines that further progress requires not only sensor optimization but also an improved signal-to-noise ratio (S/N). To address this limitation, a novel double-LGAD concept was proposed and experimentally validated [9]. While the implementation would require a double sensor already in the production phase, to prove the concept, two LGAD sensors with identical nominal thickness were mounted on opposite sides of a dedicated PCB, so that their signals are summed at the input of a shared amplifier. This design, effectively increases the collected charge by nearly a factor of two, leading to a significant enhancement of the S/N and allowing excellent timing performance with less stringent front-end requirements. Beam tests were performed on double-LGAD assemblies with thicknesses ranging from 15 to 50 μm, using both FBK and HPK sensors. For each assembly, the timing performance was directly compared to that of the corresponding single sensors operated under identical conditions. As reported in [9,10], the double-LGAD configuration consistently demonstrates an increase in collected charge and S/N, typically by a factor between 1.3 and 2, translating into a clear improvement in time resolution. Across the full range of investigated thicknesses, double-LGADs achieved time resolutions close to 20 ps, including the 50 μm devices, demonstrating the effectiveness of this approach also with a more standard and mature technology. For the thinnest sensors, the observed improvement is slightly reduced, mainly due to non-uniformities in the first production batches, likely originating from variations in acceptor activation, gain layer thickness, and diffusion effects during implantation and annealing steps, which are more critical in ultra-thin substrates. This suggests that further optimization of implantation uniformity, thermal budget control, and wafer-to-wafer reproducibility is expected to mitigate these effects and unlock the full benefit of the double-LGAD configuration, indicating that additional improvements are expected from future, more homogeneous sensor productions. A summary plot of the best time resolution found with d-LGADs compared to single LGADs is summarized in Fig. 1.

In addition, dedicated measurements were carried out to study the dependence of the timing performance on the particle incidence angle [11]. A 35 μm LGAD was tested at angles of 0°, 30°, 45°, and 75° relative to the sensor normal. Increasing the incidence angle leads to a longer particle path within the sensitive volume, resulting in higher collected charge and a modest improvement in time resolution. These results demonstrate that LGAD sensors exposed to inclined tracks preserve timing performance compatible with the requirements of the ALICE 3 TOF detector. Further investigations using LGAD arrays and tracking telescopes should allow potential edge effects, such as partial charge loss and position-dependent resolution, to be studied in details.

In summary, the beam-test results presented here show that hybrid LGAD detectors can meet the stringent timing requirements of the ALICE 3 Time-of-Flight system. A broad set of measurements covering multiple sensor thicknesses, detector configurations, and track incidence angles confirms that thin LGADs can achieve time resolutions approaching 20 ps. The double-LGAD concept provides an additional performance enhancement through improved signal-to-noise ratio, with further improvements expected from future sensor and electronics developments.

3. CMOS-LGADs: a monolithic solution for precision timing

For hybrid LGAD detectors we demonstrated their capability to satisfy the stringent timing requirements of the ALICE 3 Time-Of-Flight (TOF) system. Building on this experience, the monolithic CMOS-LGAD approach represents a natural evolution, offering further advantages such as a reduced material budget, lower production costs, and a simplified detector assembly. For these reasons, CMOS-LGADs have been selected as the baseline technology for the ALICE 3 TOF, while an active R&D program is ongoing to achieve the target time resolution.

Conventional Monolithic Active Pixel Sensors (MAPS) collect charge by drift or diffusion in a depleted epitaxial layer, with the readout electronics integrated in the same substrate. Although this architecture is attractive in terms of cost and integration, the limited signal amplitude and the presence of slow diffusion components typically restrict the achievable time resolution to the nanosecond scale [12]. The CMOS-LGAD address these limitations by fully depleting the epi-layer (using a large collection electrode design) and by introducing a p+ gain layer beneath the n+ collection electrode, drastically improving the signal rise time and S/N. This combines the advantages of CMOS technology with the timing capabilities of LGAD sensors.

The first prototype of a Monolithic CMOS Avalanche Detector PIXelated (MadPIX) sensor with internal gain was developed within the ARCADIA project [13], using LFoundry's 110 nm CMOS imaging process, which allows full integration of the sensing element and the front-end electronics on the same substrate. The device features an active thickness of 48 μm and can be fully depleted via backside biasing (V_{bottom} between −20 and −40 V), while a separate topside voltage (V_{top} between 45 and 65 V) controls the gain. The prototype comprises eight pixel matrices, each one with 64 pixels of size, each with a size of $250\,\mu\text{m} \times 100\,\mu\text{m}$. Each pixel integrates a cascoded common-source front-end followed by a differential stage and an output buffer to drive the PCB lines, with an average power consumption of 0.18 mW per channel [12].

The first engineering run of the ARCADIA project (ER-3.0) exhibited a lower-than-expected gain of about 2–3 due to a fabrication issue. Despite this limitation, these devices successfully demonstrated the feasibility of integrating a gain layer within a monolithic CMOS sensor [12]. Subsequent process optimization focused on tuning the gain implant dose through dedicated short-loop productions. The ER-3.2 production resulted in functional devices with internal gain values between 11 and 14, depending on the applied bias. Further improvements are foreseen in future productions featuring thinner active regions, for which the target timing performance is expected at gain values between 20 and 30.

The timing performance of ER-3.2 CMOS-LGAD prototypes was evaluated in beam-test campaigns at the CERN Proton Synchrotron using 10 GeV/c positive hadron beams. For the latest ER-3.2 devices, a time resolution of 88 ps was measured for the combined sensor and front-end electronics at $V_{\text{bottom}} = -25$ V and $V_{\text{top}} = 67$ V, with a front-end power consumption of 0.18 mW per channel. This corresponds to an intrinsic sensor contribution of approximately 75 ps. A detailed presentation of the timing results, including their dependence on gain and operating conditions, is reported in [14].

Thanks to the use of a tracking telescope, the time resolution as a function of the particle impact position within the pixel was also studied. The in-pixel time resolution map at a bias voltage $V_{\text{top}} =$ 67 V is shown in Fig. 2. The best performance is achieved at the pixel center, where a more uniform electric field results in improved charge collection dynamics and a time resolution below 70 ps. After subtracting the electronics jitter in quadrature, the intrinsic sensor time resolution reaches values around 60 ps. Moving towards the pixel edges, a degradation of the electric field uniformity is observed, leading to a corresponding deterioration of the timing performance.

In addition to timing studies, the detection efficiency of CMOS-LGAD sensors was investigated at the DESY Test Beam Facility using 4–5 GeV/c electrons and a high-resolution telescope [15]. The global detection efficiency was evaluated by correlating reconstructed tracks with pixel hits in the Device Under Test, using an association window accounting for the telescope resolution and pixel geometry. For thresholds set just above the cross-talk and noise contributions, the global detection efficiency reaches values greater than 95%, representing a conservative lower bound due to residual tracking uncertainties. The corresponding efficiency curves and their dependence on threshold and biasing conditions are discussed in [14].

Finally, the radiation tolerance of the sensors was assessed through irradiation campaigns carried out at the TRIGA Mark II reactor of the Jožef Stefan Institute (JSI) in Ljubljana, Slovenia [16], reaching fluences up to 10^{15} $n_{\text{eq}}/\text{cm}^2$. Following irradiation, the sensors were tested at the CERN SPS using the ALTAI tracking telescope with a 120 GeV hadron beam. These measurements allow to investigate irradiation-induced defects in the silicon bulk, which introduce trapping centers and reduce the collected charge. In LGAD-like structures, the dominant effect is the progressive degradation of the gain layer: acceptor removal in the multiplication region reduces the effective doping concentration, weakening the electric field and lowering the impact ionization probability. This results in a reduction of the internal gain and signal amplitude (MPV) with increasing fluence, directly impacting the signal-to-noise ratio and timing performance. Fig. 3 shows the global detection efficiency, as a function of the threshold applied to the signal amplitude distribution for a sensor irradiated at 10^{13} $n_{\text{eq}}/\text{cm}^2$, which corresponds to the maximum fluence expected for the ALICE 3 TOF detector. The measurements were performed at $V_{\text{bottom}} = -25$ V and $V_{\text{top}} = 65$ V. Comparison with a non-irradiated sample [14] shows no degradation of the detection efficiency after irradiation, which remains above 95% across the explored threshold range.

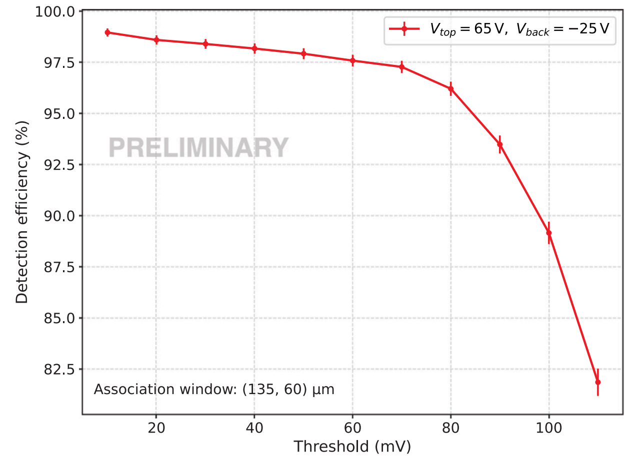

Fig. 3. Global detection efficiency evaluated considering three adjacent pixels on the same column as a function of the threshold applied to the signal amplitude distribution for a sensor irradiated at (10^{13} $n_{\text{eq}}/\text{cm}^2$). The measurement for both sensors was obtained with $V_{\text{bottom}} = -25$ V and $V_{\text{top}} = 65$ V.

Overall, these results demonstrate the strong potential of CMOS-LGAD technology as a monolithic solution for precision timing in the ALICE 3 TOF detector. While the current prototypes do not yet achieve the target time resolution of 20 ps, the observed performance trends are totally in line with TCAD simulations for the current sensor layout and thinner sensors with a higher intrinsic gain are expected to provide improved timing performances towards meeting the ALICE 3 requirements. A new engineering run is planned for the first half of 2026, including 15 and 20 μm thick sensors with modified termination geometries, including an increased n-termination-pwell distance to enable operation at higher bias voltages. At the sensor level, a time resolution of about 25 ps is foreseen for 20 μm thick CMOS LGAD devices, while an intrinsic timing resolution of approximately 20 ps is expected for 15 μm thickness.

4. Conclusions

Overall, the R&D program has shown that hybrid LGAD detectors are capable of meeting the 20 ps timing requirement of the ALICE 3 TOF, establishing them as a reliable back-up option for the detector. The introduction of the double-LGAD concept further enhances the timing performance while simultaneously relaxing the constraints on the front-end electronics. In addition, studies with inclined tracks demonstrated that the time resolution remains largely insensitive to the particle incidence angle, with a modest improvement observed at larger angles.

Extending the LGAD concept to a monolithic implementation, CMOS-LGAD sensors provide significant advantages in terms of reduced material budget, lower production costs, and simplified detector assembly, and have therefore been selected as the baseline technology for the ALICE 3 TOF. The first CMOS-LGAD prototypes have achieved a time resolution of about 75 ps, representing a remarkable result for monolithic sensors with internal gain, together with an in-pixel detection efficiency exceeding 95%. These experimental results are consistent with simulation studies, which indicate that devices with an active thickness of 15 μm and a gain of approximately 20 could allow to reach a timing performance better than 20 ps. Although the reduced primary charge expected for 15 μm sensors increases the impact of the front-end electronics noise, dedicated optimization also for the monolithic readout electronics is currently under investigation to preserve the required signal-to-noise ratio and fully exploit the timing potential of these devices. New sensors matching this layout requirements be produced in the first part of this year, with the expectation of a further improvement of the timing resolution towards the ALICE 3 performance target.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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