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Study of innovative LGAD silicon detectors for the ALICE 3 experiment in LHC Run 5 and 6(*)

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Summary. — The ALICE Collaboration has submitted a proposal for a new experimental apparatus - ALICE 3 - built with state-of-the-art silicon technologies, to be installed at the Interaction Point 2 of the Large Hadron Collider (LHC) during Long Shutdown 4, in preparation for Run 5 (2035). In particular, for the Time-of-Flight (TOF) system, which plays a fundamental role in particle identification, a time resolution of 20 ps is required. Several silicon technologies are under investigation for this purpose, and among them, Low Gain Avalanche Detectors (LGADs) have garnered particular interest. The increasingly stringent demands for time resolution by future experiments have spurred an intense R&D campaign aimed at further improving their already excellent performance in terms of timing. Current studies have demonstrated the potential of a thinner LGAD design capable of achieving values very close to the requirements of ALICE 3. In this paper, the results obtained with the first prototypes of very thin FBK LGADs (25 and 35 μm) will be reported. Moreover, the innovative concept of the double-LGAD will be presented and beam test results on three different thicknesses, 25, 35 and 50 μm, will be shown. The results on double-LGAD demonstrated the expected enhancement of input charge for electronics while maintaining a time resolution comparable to or even better than a standard LGAD.

1. – Introduction

1·1. *The ALICE 3 experiment.* – The ALICE Collaboration has proposed a next-generation heavy-ion experiment called ALICE 3, which will be installed at the LHC Interaction Point 2 during Long Shutdown 4, in preparation for Run 5 (2035) and 6 [1]. The experiment will utilize cutting-edge silicon technologies to study heavy-ion collisions with unprecedented impact parameter resolution and collect significantly higher luminosities compared to those collected with the current detector during Runs 3 and 4, in a pseudorapidity region up to $|\eta| < 4$. This apparatus will measure the electromagnetic radiation produced by the Quark Gluon Plasma in a multi-differential way to probe its early stages of evolution. Moreover, it will allow us a better characterization of the production of hadrons with heavy flavours down to very low transverse momenta. Particle

(*) IFAE 2023 - "New Technologies" session identification plays a key role in the proposed physics programme and various techniques are considered: Time of Flight (TOF), Ring Imaging Cherenkov, Muon identification, and Electromagnetic Calorimeter. In particular, the TOF system will consist of an outer and an inner layer placed at 85 cm and 19 cm from the beam pipe, respectively, and of two disks in the forward direction located at 405 cm on either side of the interaction point. The outer layer will enable the identification of electrons and hadrons with transverse momenta up to 500 MeV/c and 2 GeV/c for π and K, respectively. To reach these ranges of PID, an outstanding time resolution of 20 ps is required for the outer layer and detectors capable of sustaining a maximum NIEL of 6.2×10^9 MeV n_{eq}/cm^2/month. Several silicon-based technologies are being evaluated, including Low Gain Avalanche Detectors (LGADs), Silicon Photomultipliers (SiPMs), Monolithic Active Pixel Sensors (MAPS).

1·2. *LGADs R&D motivations.* – LGADs, also referred to as Ultra Fast Silicon Detectors (UFSDs) [2], have undergone extensive R&D in recent years and represent one of the most well-established silicon technologies for timing applications. They are designed to provide an excellent timing performance by introducing a controlled doped gain layer beneath the p-n junction, generating a high electric field at that specific point while maintaining a lower and uniform field throughout the rest of the volume. The resulting moderate internal gain, ranging between 10 and 70, effectively optimizes the signal-to-noise ratio, thereby delivering exceptional timing performance. Thanks to the time resolution they can reach and the possibility to work up to fluences of 2×10^{15} MeV n_{eq}/cm^2 [3], the LGAD technology has been chosen for the timing layers of the ATLAS [4] and CMS [5] Phase II upgrades for High-Luminosity LHC (2026), and represents a good candidate for the ALICE 3 TOF.

2. – Beam test setup and configuration

The results presented in this article come from the data collected at the T10 beamline at CERN's PS facility in 2021 and 2022, using a 10-12 GeV/c hadron beam. The examined detectors, denoted as FBK25 and FBK35, featuring a nominal thickness of 25 and 35 μm, respectively, and an area of 1x1 mm^2, represent the very first production (1) of thin wafers produced by Fondazione Bruno Kessler (FBK). Additionally, a 1x3 mm^2 LGAD with a standard thickness of 50 μm (HPK50), manufactured by Hamamatsu Photonics K.K (HPK), was measured for comparison with the thinner layout. In each run, up to four aligned sensors were measured simultaneously. The 25 and 35 μm samples, as well as those coupled together, were attached to a Santa Cruz read-out board (with a gain of ~ 6) and an additional amplification stage with a gain of 12-13. The reference HPK50 was connected to a front-end board without amplification, followed by a Cividec amplifier with a gain of 190. The complete signal waveforms were recorded using an oscilloscope and an offline analysis was conducted. Data acquisition was triggered by the coincidence of self-triggers from the Devices Under Test (DUTs), with data being collected whenever all signals simultaneously exceeded a predetermined threshold set for each channel. Further details can be found in [6] and [7].

(1) This UFSD production is called EXFLU0 [8].

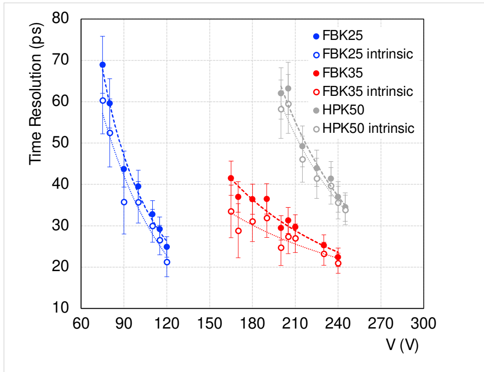

Fig. 1. – The time resolution of FBK25, FBK35, and HPK50 is presented as a function of the applied voltage, with CFD thresholds set at 60%, 20%, and 50%, respectively. The filled circles represent the measured time resolution, while the empty circles denote the intrinsic time resolution.

3. – Main results obtained with very thin LGADs

The first measurements of this study were performed with very thin LGADs, of 25 and 35 μm, produced by FBK were measured for the first time in a test beam setup. Many parameters were extracted, including their time resolution, and compared to the ones of a standard 50 μm LGAD. Before the beam test, a comprehensive electrical characterization was conducted on the samples at the INFN laboratories in Bologna. All the primary extracted parameters, along with all the measurements and results for this new generation of UFSDs, with the full details on the analysis procedure are reported in [6]. The main and most important outcome is presented in fig. 1. Both, the measured and intrinsic time resolutions, at a fixed Constant Fraction Discriminator (CFD), are shown as a function of the applied voltage, for the three different thicknesses. To obtain the time resolution of an individual DUT (single or double-LGAD) at a given voltage and CFD, a system with three sensors and three differences between the arrival times of each pair of detectors was considered. The reference HPK50 yielded a measured time resolution of approximately 34 ps, consistent with previous results, validating the analysis procedure. The two thinner LGADs exhibited, as expected, an improved time resolution due to a reduced Landau term [9]. Measurements of FBK25 and FBK35, while compatible within uncertainties, showed a trend toward better results for FBK35 over FBK25. In particular, FBK35 achieved a time resolution of (22 $\pm$ 2) ps at a bias voltage of 240 V, totally in agreement with the simulations, while FBK25 achieved a time resolution of (25 $\pm$ 3) ps at a bias voltage of 120 V, not indicating an improvement compared to FBK35. The reason lies in FBK25 sensors being manufactured on a highly doped substrate, not optimised for timing measurements. Nevertheless, in summary, the results demonstrate the expected improvement in terms of time resolution achievable by thinner LGAD detectors.

4. – The new double-LGAD concept

The previous study demonstrated that a thinner design of LGAD brings an improvement in the time resolution. However, considering thin detectors, the reduced charge

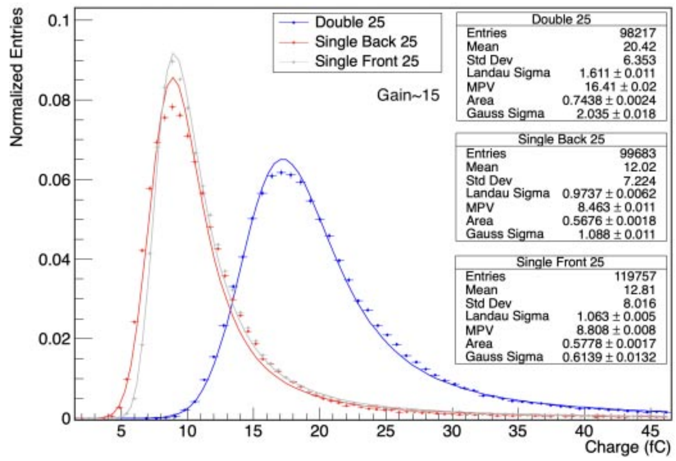

Fig. 2. – Example of the charge distributions for the FBK25 couple at a gain of 15 fitted with a convolution of a Gaussian and a Landau functions. The same behaviour was obtained with all three thicknesses.

generated at the amplifier input can become a challenge, potentially leading to degraded amplifier performances and increased power consumption due to a lower signal-to-noise ratio. To address this concern, the new concept of double-LGAD (d-LGAD) was implemented and tested for the first time at the T10 beamline at PS-CERN in July and November 2022.

4˙1. *Implementation of the new concept for the test beam measurements*. – The double-LGAD (d-LGAD) concept consists of summing up the signals generated by two layers of LGAD using a single front-end amplifier. A sketch of the d-LGAD design is reported in [7]. In the first implementation, signals from two distinct LGADs were merged through a custom PCB design, modified to place one LGAD with thickness t on each side of the board, with the combined output directed to a single shared amplifier, to obtain a double charge at the input of the amplifier. As a consequence, the time resolution for the d-LGAD is expected to be significantly better than that of an equivalent single LGAD with thickness $2t$ and also slightly better than that of a single LGAD with thickness t.

The tests were conducted on couples of sensors with three different thicknesses: 25, 35 and 50 μm. The FBK LGADs with nominal thicknesses of 25 μm and 35 μm are the same ones used for the previous study (see sect. **3**). The HPK sensors with a nominal thickness of 50 μm have an area of 1.3×1.3 mm^2 and come from a very uniform wafer. All measurements were initially performed on the d-LGAD and then repeated under the same conditions with each of the two single LGADs in the couple, allowing for a direct comparison. The noise level between single and double sensors was measured to be consistent for all thicknesses resulting in a higher Signal-to-Noise ratio (S/N) for the d-LGAD (see [7]). The charge distribution at a given voltage is presented, as an example, for the FBK25 couple in fig. 2. The same behaviour was obtained with all the couples [7]; for all thicknesses, the extracted d-LGAD charge MPV is consistently double with respect to both corresponding single sensors, successfully achieving the primary objective of this implementation, *i.e.*, to have increased input charge, consequently enabling the possibility to use less demanding front-end electronics.

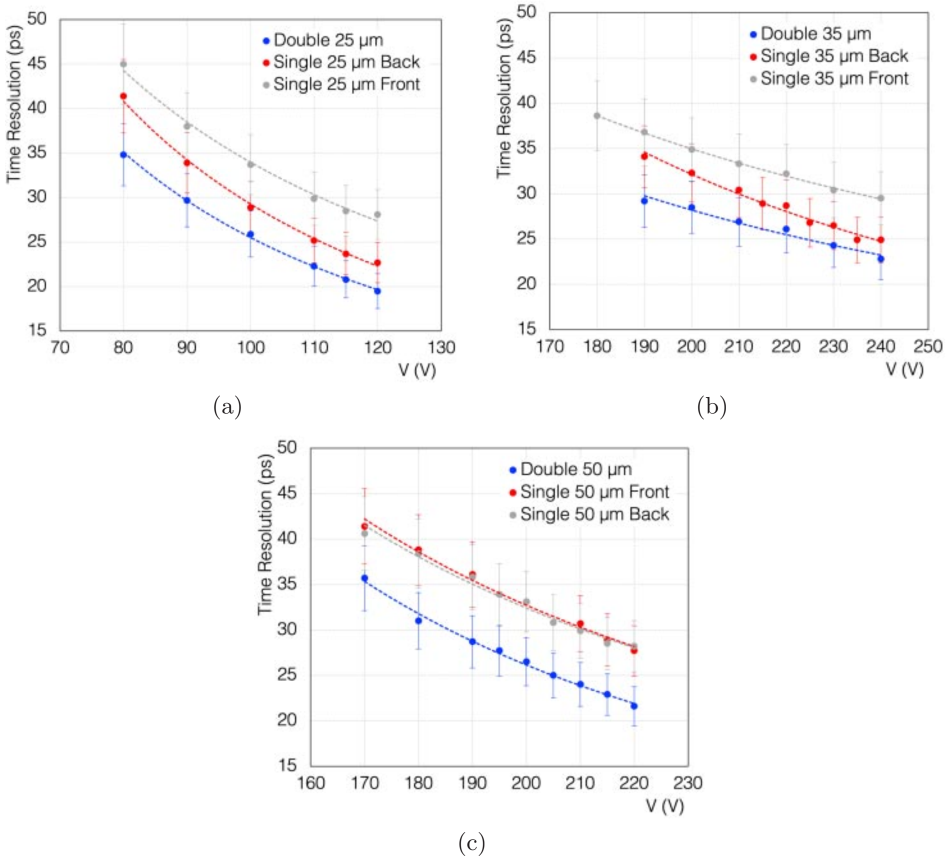

Fig. 3. – Measured time resolution for FBK25, FBK35, and HPK50 couples, as a function of the applied voltage corresponding to CFDs of 50%, 30%, and 30%, respectively.

A comprehensive analysis of the time resolution was conducted using analysis techniques similar to those employed in previous test beams. Specifically, the CFD method was used to derive time resolutions for the DUT, as described in sect. **3**. In fig. 3 the time resolution is reported as a function of the applied voltage for all the couples at a fixed CFD. A very homogeneous time resolution can be noticed for the two single LGADs, only for the 50 μm couple, owing to a more uniform sensor wafer and consequently a more similar gain of the two coupled LGADs. Nevertheless, despite the gain non-uniformities in FBK25 and FBK35 sensors, at a fixed gain, all the single sensors within the couples exhibited a consistent time resolution [7], even when compared with the results obtained in the previous beam test and reported in fig. 1. For all three thicknesses, an improvement in time resolution is observed with the d-LGADs compared to both the single sensors, yielding a final time resolution of approximately 20 ps across all thicknesses. Given these results, possible future productions of 25 and 35 μm sensors with enhanced gain uniformity could potentially push the time resolution of d-LGADs below 20 ps.

5. – Conclusions

In conclusion, a comprehensive investigation of innovative approaches aimed at improving the time resolution of LGAD detectors was conducted. Several measurements on this new generation of very thin LGADs and the ones obtained by the implementation of the d-LGAD concept are reported. The results were obtained using a 10-12 GeV/c beam at CERN PS. Validation of the experimental setup and analysis procedure was achieved through testing an HPK reference LGAD with a standard thickness of 50 μm, yielding results consistent with previous measurements. For the first time in a beam test, 25 μm and 35 μm thick FBK LGAD sensors were measured, reaching respectively a time resolution of $\sim$ 25 ps at a bias voltage of 120 V and $\sim$ 22 ps at a bias voltage of 240 V. Overall results underscore the improvement of the time resolution going from the standard 50 μm to thinner LGADs, as expected. The new concept of double-LGAD was introduced and tested, considering three different thicknesses of sensors. Comparing the performance of the d-LGAD with that of the two single corresponding LGADs, the primary objective of generating a higher (doubled) charge at the input of the amplifier was successfully achieved, resulting in a clear advantage for the electronics, along with a further improvement in terms of timing performance. In particular, results demonstrate a consistent improvement in time resolution for the d-LGAD compared to the single LGADs, reaching a time resolution of $\sim$ 20 ps for all three thicknesses. While the d-LGAD currently stands just as a proof of concept, the prospect of its integration within the detector or electronics board using techniques like TSV presents an exciting avenue for future research and development. In summary, the performance study of a very thin design of LGAD and the innovative d-LGAD concept, gave very promising results in terms of time resolution, in the perspective of both the proposed ALICE 3 apparatus and in general for broader applications in high-energy physics experiments and beyond.

REFERENCES

[1] ALICE Collaboration, *Letter of intent for ALICE 3: A next-generation heavy-ion experiment at the LHC*, https://doi.org/10.48550/arXiv.2211.02491.
[2] Sadrozinski H. F.-W. *et al.*, *Rep. Prog. Phys.*, **81** (2018) 026101.
[3] Kramberger G. *et al.*, *Nucl. Instrum. Methods Phys. Res. Sect. A*, **891** (2018) 68.
[4] ATLAS Collaboration, *Technical Proposal: A High-Granularity Timing Detector for the ATLAS Phase-II Upgrade*, Technical report, CERN, Geneva, CERN-LHCC-2018-023 (2018).
[5] CMS Collaboration, *A MIP Timing Detector for the CMS Phase-2 Upgrade*, Technical report, CERN, Geneva, CERN-LHCC-2019-003 (2019).
[6] Carnesecchi F., Strazzi S. *et al.*, *Eur. Phys. J. Plus*, **138** (2023) 99.
[7] Carnesecchi F., Strazzi S. *et al.*, *Eur. Phys. J. Plus*, **138** (2023) 990.
[8] Sola V. *et al.*, *First results from thin silicon sensors for extreme fluences*, The 37th RD50 Workshop, Zagreb-online Workshop (2020) https://indico.cern.ch/event/896954/contributions/4106324/.
[9] Meroli S. *et al.*, *JINST*, **6** (2011) P06013.