Summary

New experiments must be conceived to exploit the capabilities of the High-Luminosity upgrade of the Large Hadron Collider at CERN. ALICE 3 is a future experiment designed with this goal in mind. It will be installed during the Long Shutdown 4 (2034 - 2035), with the data taking starting in 2036 (run 5). The experiment target is to fully exploit the heavy-ion physics potential achievable at LHC, bridging the gaps left by the current ALICE experiment.

To reach all its intended goals, ALICE 3 requires a detector capable of identifying particles down to very low transverse momenta: the Time-of-Flight system (TOF). This detector should provide a 20 ps time resolution over a 40 m^2 area, requirements that place it among state-of-the-art systems. Experimental studies demonstrated that such performance can be met using Low-Gain Avalanche Diode sensors (LGAD), silicon devices in which a gain layer is implemented in the pn junction to achieve a controlled charge multiplication. However, the costs and production complexity associated with the hybrid approach (sensor and electronics produced on separate substrates) suggest that LGADs are a suboptimal choice for ALICE 3.

Monolithic CMOS sensors enable better integration, robustness, and assembly, while reducing material budget and costs; therefore, they are an attractive option also due to the low data rate ($< 200\,\mathrm{kHz/cm^2}$) and modest radiation environment expected in ALICE 3. However, although their excellent tracking capabilities have been demonstrated, timing optimization has only recently been explored, and a large-area demonstrator in a commercial process, achieving sub-100 ps MIP time resolution is not yet available. Therefore, the TOF group has started an R&D campaign to reach the 20 ps target by introducing a gain layer into a commercial CMOS process, thereby creating the CMOS LGAD.

This work presents the CMOS LGAD design and the results obtained with a prototype developed to demonstrate the feasibility of gain layer implantation in a standard CMOS CIS process. The work builds upon the sensor technology developed at INFN by the ARCADIA project, which features a fully depleted monolithic sensor. In the last engineering run of ARCADIA (beginning of 2023),

the CMOS LGAD prototype, named MadPIX, was manufactured.

MadPIX (Monolithic CMOS Avalanche Detector) is a pixelated ASIC divided into eight matrices of 64 pixels each. The sensor is based on an n-collection electrode implanted on a 48 μm n-type epitaxial layer grown on a p^+ substrate. Deep p-wells host the electronics and prevent charge collection from the n-weel of the PMOS transistors. A p^+-gain layer is implanted beneath the collection electrodes.

The in-pixel front-end is AC-coupled to the collection electrode, and is based on a trans-impedance amplifier followed by a differential buffer working in the 1.2 V domain. The analog signals are then buffered off-chip with 3.3 V buffers placed in the periphery. The first production demonstrated full substrate depletion and internal charge multiplication. However, the measured gain was three times lower than expected, impacting the time resolution.

A second production (beginning of 2024) followed the characterization campaign, which guided the tuning of the gain-layer implant to better match simulations and measurements. A total time resolution of 72 ± 1 ps was achieved in beam tests, including contributions from electronics jitter and intrinsic sensor resolution. Test beam measurements performed with a tracking telescope showed a detection efficiency of 95 % and a time resolution of 58 ps measured considering only the pixel centre. MadPIX performances was mainly limited by the sensor design due to its thickness ($48\,\mu$m) and sub-optimal pixel size ($250 \times 100\,\mu\text{m}^2$). Monte Carlo simulations matched with experimental measurements stated that the 20 ps target can be achieved by increasing the pixel size and reducing the active thickness to $15\,\mu$m.

The results obtained with MadPIX demonstrate that the CMOS LGAD technology is robust and represents the most promising candidate for the ALICE 3 TOF system. A third production is expected for mid-2026 and will feature thin active sensors ($15\,\mu$m) targeting the 20 ps timing goal.