# Towards a New Generation of Monolithic Active Pixel Sensors

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## Abstract

A new generation of Monolithic Active Pixel Sensors (MAPS), produced in a 65 nm CMOS imaging process, promises higher densities of on-chip circuits and, for a given pixel size, more sophisticated in-pixel logic compared to larger feature size processes. MAPS are a cost-effective alternative to hybrid pixel sensors since flip-chip bonding is not required. In addition, they allow for significant reductions of the material budget of detector systems, due to the smaller physical thicknesses of the active sensor and the absence of a separate readout chip.

The TANGERINE project develops a sensor suitable for future Higgs factories as well as for a beam telescope to be used at beam-test facilities. The sensors will have small collection electrodes (order of µm) to maximize the signal-to-noise ratio, which makes it possible to minimize power dissipation in the circuitry. The first batch of test chips, featuring full front-end amplifiers with Krummenacher feedback, was produced and tested at the Mainzer Mikrotron (MAMI) at the end of 2021. MAMI provides an electron beam with currents up to 100 µA and an energy of 855 MeV. The analog output signal of the test chips was recorded with a high bandwidth oscilloscope and used to study the charge-sensitive amplifier of the chips in terms of waveform analysis. A beam telescope was used as a reference system to allow for track-based analysis of the recorded data.

*Keywords:* Silicon, CMOS, monolithic active pixel sensors, MAPS, particle detection, test beam, Allpix2, TCAD

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## 1. Introduction

The Tangerine (Towards Next Generation Silicon Detectors) project pursues the goal of developing a monolithic active pixel sensor (MAPS) using a 65 nm CMOS imaging process. The sensor will be optimized for the requirements of e.g. future lepton colliders, so the project aims for a spatial resolution below 3 µm, temporal resolution below 10 ns, and a total thickness below 50 µm.

To optimize the sensor design, the project employs a chain of simulation tools predicting the performance of a specific sensor design in a tracking application. The first step is the detailed calculation of the electric fields, starting from a generic doping profile. To do so, the Poisson equations are numerically solved, using Synopsys Technology Computer Aided Design (TCAD) software [1]. These electric fields are used in Allpix$^2$ [2] for charge transport simulations. The energy deposition by charged particles is simulated via an interface to Geant4 [3].

The simulated performance is compared for different sensor designs, emphasizing sensor volume modifications as introduced in [4, 5] for sensors produced in a 180 nm CMOS imaging process. Also, the pixel pitch, the biasing conditions, the width of the p-well opening and the width of the gap in the n-blanket are varied. More details on the sensor layout and the simulation procedure are given in [6].

This paper addresses the characterization of a first test chip featuring Krummenacher type charge sensitive amplifiers (CSA) [7], received in October 2021. The main feature of the amplifier is a continuous reset, well suited for time over threshold (TOT) measurements. The CSA test chip features two CSAs with different feedback capacitances (1.5 and 2 fF), which can be investigated via test-pulse injection. It also hosts a $2 \times 2$ pixel matrix with a pitch of 16.3 µm. The output signal of these pixels is amplified with the same type of CSA (2 fF) and an additional operational amplifier before they are recorded with a high-bandwidth oscilloscope (4 GHz, 10 Gs/s per channel) in edge-trigger mode.

## 2. Sensor Testing

First tests of the CSA test chip were performed in the laboratory using an $^{55}$Fe source. They were followed by a campaign of test-beam measurements at the DESY II Test Beam facility [8], CERN SPS, and at the Mainzer Mikrotron (MAMI) facility [9], using a EUDET-type [10], a Timepix-based [11], and a compact ALPIDE-based [12] beam telescope, respectively. The acquired waveforms were analyzed in terms of a pulse shape analysis. For an analysis including track reconstruction, the Corryvreckan software [13] was used. Data were recorded

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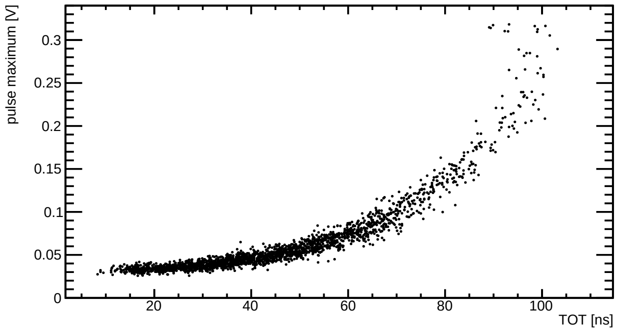

Figure 1: Baseline-corrected maximum of the amplified pulses as a function of TOT, measured with a CSA test chip at the MAMI facility. The applied threshold corresponds to about 27 mV.

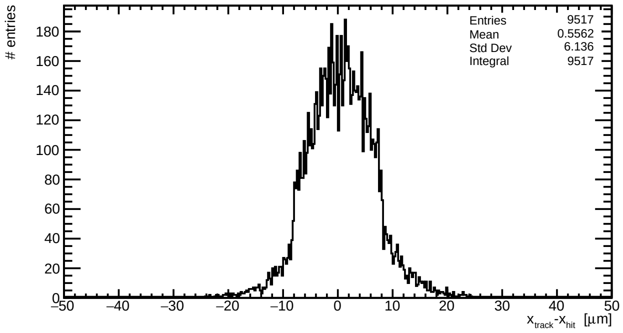

Figure 2: Residual distribution between the position measurement of the CSA test chip and the reference track reconstructed with the beam telescope. The measurements were carried out at the MAMI facility.

with trigger rates on the order of 0.001 Hz, 0.01 Hz and 1 Hz at DESY, SPS and MAMI, respectively. This is about two orders of magnitude lower than expected for the active area of the chip and attributed to an issue in the sensor design, leading to low detection efficiencies everywhere but under the read-out electrodes.

MAMI provides a beam of electrons with an energy of 855 MeV and beam currents up to 100 μA. The waveforms recorded at MAMI were analyzed and figure 1 shows the maximum of the pulse, after subtraction of the baseline, as a function of the TOT. The small slope for TOT $<$ 50 ns is not desired, as a small slope makes the TOT less sensitive to signal variations in this region, which contains the signal expected for a minimum ionizing particle. Improvements are foreseen for the next version of the front-end amplifier by reducing the circuit's slew-rate dependence on the amplitude. The rise time of the output pulses is limited by the operational amplifiers. It was found to be in the range of 4 to 9 ns, depending on the investigated sample and the operational parameters of the CSA test chip.

The track-based analysis of the data acquired at CERN delivered further evidence for the low efficiencies mentioned above. Despite this, the data taken at MAMI made it possible to reconstruct residuals between the intersection of the reconstructed electron track with the CSA test chip ($x_{track}$), and the chips own position measurements ($x_{hit}$), presented in figure 2. The residual width (Std Dev) is dominated by the interpolation error of the beam telescope, which is on the order of 5 μm for the 855 MeV electrons and the spacing of 20 mm between all adjacent planes. It should be mentioned that the position resolution of the CSA test chip is artificially enhanced by the small sensitive area. Still, this figure proves that the test chip is successfully integrated with the reference system and works as a detector for charged particles.

## 3. Conclusion and Outlook

These results present the first successful operation of 65 nm CMOS sensors developed at DESY. This sensor is dedicated to a first characterization of the new CSA design, which will be improved in terms of TOT linearity for future sensors. The rise time of the output pulses of the CSA is found to be in the range of 4 to 9 ns, limited by the operational amplifiers, so that time resolutions on the order of ns are expected to be achievable. A flaw in the pixel design, leading to an efficient region of only a few μm around the readout electrode, has been identified and fixed for future submissions.

A second generation of test chips is expected for the beginning of 2023 and will include an upgraded version of the CSA test chip and a fully integrated chip with 64 × 16 square pixels of 35 μm pitch and an 8 bit counter per pixel. In the meantime a set of Analogue Pixel Test Structures (APTS) [14, 15], featuring pitches of 15, 20 and 25 μm and the standard, n-blanket and n-gap design, will be characterized. The results will be used to validate the simulation procedure and improve its predictive power for the optimization of the final TANGERINE sensor design.

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