PROCEEDINGS OF SCIENCE

R&D on MAPS Pixel Detectors for Linear Collider Applications *

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CMOS-MAPS (Monolithic Active Pixel Sensors) are one possible technology which may fulfill the stringent requirements of a precision vertex detector at a future e^+e^- Linear Collider. Progress on the work on physics simulation, layout optimization, design of the mechanical structure and cooling, sensor simulation, radiation hardness, as well as results from measurements of sensors of 3.5 cm^2 area with 1 million pixels using photons from an ^{55}Fe source and 6 GeV electrons, are reported. The results confirm the excellent performance of MAPS for precision particle tracking.

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*Most of the work presented is documented in the PhD thesis of D. Contarato [1].
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1. Physics Simulations and Layout Optimization

The aim of this work was to characterize different vertex detector geometries by evaluating the performance with respect to a number of benchmark physics reactions. For this purpose a fast simulation program SGV [2] was adapted for an ILC vertex detector simulation. In particular it was necessary to interface SGV to the ZVTOP [3] package, the standard heavy flavour indentification software used for ILC studies. The program was validated with respect to the full simulation program BRAHMS [4] which is based on GEANT-3 [5].

For the layout optimization a baseline configuration with 5 sensor layers arranged in a barrel-type geometry at radii of 15, 26, 37, 48 and 60 mm was used. Sensors were assumed to be 50 μm thick with a point resolution of 2 μm. The statistical errors of the measurement of Standard Model Higgs branching fractions into charm and beauty where evaluated for three modifications of the baseline configuration:

- removal of the inner layer at 15 mm,
- worsening of the position resolution from 2 to 10 μm, and
- increase of the sensor thickness from 50 to 300 μm.

The results are shown in Fig. 1. They demonstrate the importance of the inner layer for the measurement of the $c\bar{c}$ branching ratio, in particular if the spatial resolution is 10 μm or worse.

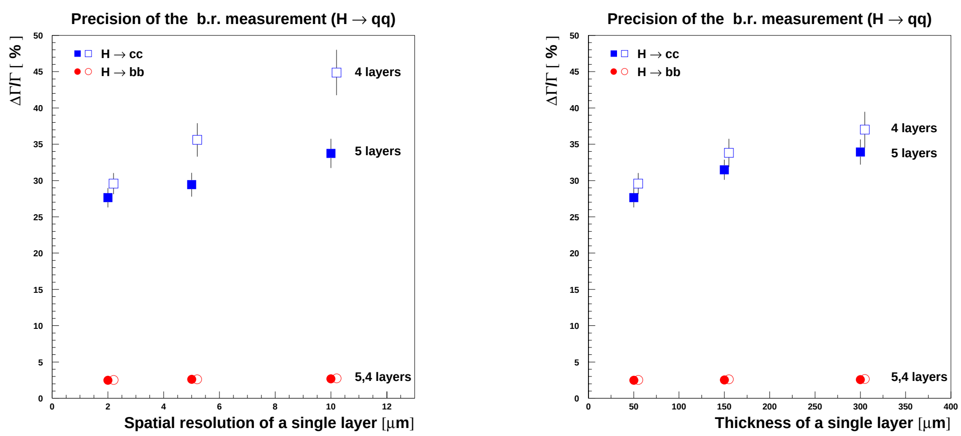

Figure 1: Precision of the BR(Higgs $\longrightarrow c\bar{c}$ and $b\bar{b}$) measurement as function of the **a.** single sensor resolution, **b.** sensor thickness.

2. Mechanical Design, Cooling and Power Cycling

A first order mechanical design, including cooling with evaporative C_3F_8 in 600 μm diameter capillaries has been designed. Measurements in a test set-up operating at -12°C, which uses 30 μm glass plates with evaporated aluminum resistors, have been performed. A detailed finite element simulation has been set up to interpret the measurements. In parallel the performance of a full size MAPS with power cycling is being investigated. For a bunch structure as foreseen for the ILC, the power of ~1 kW for a complete vertex detector could possibly be reduced by a factor of up to 100.

3. MAPS Simulation

The detector used in the tests is a MIMOSA-5 prototype developed by IReS/LEPSI, Strasbourg. For details of the design we refer to [6]. The sensor is manufactured in AMS 0.6 μm CMOS technology [7] on a low ohmic substrate with a 14 μm epitaxial layer. A module consists of 4 independent sensors with 510$\times$512 square pixels of 17 μm pitch. Two layouts have been implemented with different areas of charge collecting diodes: "large" with 4.9$\times$4.9 μm^2 and "small" with 3.1$\times$3.1 μm^2.

The ISE-TCAD software [8] has been used for a 3-dimensional simulation of the response of 3$\times$3 pixels to a minimum ionizing particle passing through the center of a pixel. Fig. 2.a shows the simulated time dependence of the charge collection of 1, 2$\times$2 and 3$\times$3 pixels for a "small" diode. 9 pixels collect a cluster charge of 740 electrons, with $\sim$60 % in the central pixel. About 90 % of the charge is collected within 100 ns. The results for "large" diodes are similar.

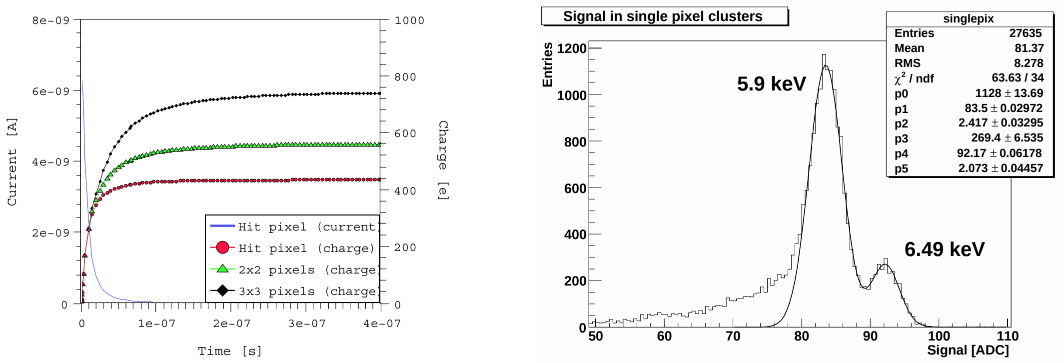

Figure 2: **a.** Simulation of charge collection in MIMOSA-5; **b.** ^{55}Fe spectrum for single pixel clusters.

4. Source and Beam Test Results, and Radiation hardness

To determine the charge-to-voltage conversion, the sensors have been illuminated by the 5.90 and 6.49 keV X-rays from an ^{55}Fe source. Fig. 2.b shows the pulse height response for single pixel clusters. The two peaks, corresponding to the two X-ray energies, are well separated. They provide a precise calibration of the conversion from ADC channels to charge in units of electrons. From the pedestal width an equivalent noise charge of 21-22 electrons for the "small" and of 25-27 electrons for the "large" diodes at an operating temperature of -10°C is determined. The measured widths of the peaks imply an upper limit of 2-3 % for the non-uniformity of the response of the individual pixels over the sensor.

Detailed performance measurements have been made in the DESY-II test beam set-up, which consists of an electron beam of up to 6 GeV from the DESY-II synchrotron, two small scintillation counters for triggering and timing, and a silicon-strip detector telescope with 3 pairs of orthogonal detectors with intrinsic resolutions of about 2.8 μm. The MAPS detectors are installed in a temperature controlled box and can be cooled down to -10°C. Most results refer to this temperature.

Fig. 3.a shows the cluster charge as function of the pixel multiplicity, with the pixels ordered by increasing distance from the impact position of the particle reconstructed in the MAPS using the

center-of-gravity algorithm. Most of the charge is collected in 9 pixels. For events reconstructed within 3 μm of the pixel center, the measured cluster charges are compared to the simulation in Table 1. The agreement is fair.

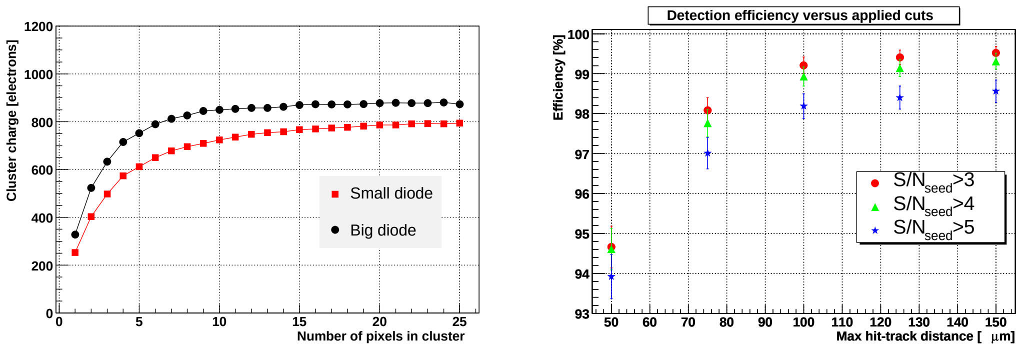

Figure 3: a. Cluster charge as function of the pixel multiplicity in the cluster for 6 GeV electrons at -10°C; **b.** detection efficiency for 6 GeV electrons as function of the maximum hit-to-track distance for different signal-to-noise requirements for seed pixels.

Cluster size number of pixels	Cluster charge sim. "small" electrons	Cluster charge meas. "small" electrons	Cluster charge sim. "large" electrons	Cluster charge meas. "large" electrons
1	430	370	490	480
2×2	560	530	620	640
3×3	740	730	790	830

Table 1: Comparison between simulated and measured charges in 1, 4 and 9 pixel clusters

The determination of both spatial resolution and efficiency of the MAPS is limited by the multiple scattering of the 6 GeV electrons. As illustration, Fig. 3.b shows the efficiency as function of the difference between the position reconstructed in the MAPS and the one predicted by the telescope for different requirements on the signal-to-noise ratio S/N of the seed pixel. For cuts larger than 100 μm an efficiency of $\sim$99.5% is reached. Using data at different beam energies to correct for multiple scattering, a MAPS resolution of 3.6 ± 1.1 μm is estimated. This estimate is well compatible with the accuracy of 1.7 ± 0.1 μm reported in [9].

MIMOSA-5 chips have been irradiated with 9.4 MeV electrons up to a fluence of 10^{13} cm^{-2} at the superconducting S-DALINAC at Darmstadt. This corresponds to the dose expected at the inner layer of an ILC vertex detector for 5 years of operation. As expected, a significant increase in dark current approximately proportional to the dose, has been found. A preliminary analysis of the data shows that the degradation seen can all be attributed to the increase in dark current.

5. Summary

A short status report of the work of the Hamburg - Łódź/Warsaw Collaboration towards the design and performance study of an ILC vertex detector using MAPS sensors has been given.

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