**Abstract**-- A Monolithic Active Pixel Sensor (MAPS) for charged particle tracking based on a novel detector structure has been proposed, simulated, fabricated and tested. This detector is inseparable from the readout electronics, since both of them are integrated on the same, low-resistivity silicon wafer standard for a CMOS process. The individual pixel is comprised of only three MOS transistors and a photodiode collecting the charge created in the thin undepleted epitaxial layer. This approach provides a low cost, high resolution and thin device with the whole detector area sensitive to radiation (100% fill factor).

Detailed device simulations using the ISE-TCAD package have been carried out in order to study the charge collection mechanism and to validate the proposed idea.

Two prototype chips were successively fabricated using 0.6 μm and 0.35 μm CMOS processes. Special radiation tolerant layout techniques were used in the second chip design. Both chips have been tested and fully characterised. The pixel conversion gain has been calibrated using 5.9 keV photons and both prototypes have been exposed to a 120 GeV/c pion beam at CERN. Test results are reviewed, preceded by general design ideas and simulation results.

I. INTRODUCTION

This paper presents a novel position sensitive device for charged particles tracking and imaging - the Monolithic Active Pixel Sensor (MAPS) - which integrates on the same substrate the detector element and the processing electronics. The baseline architecture of the proposed device is similar to a visible light CMOS camera, emerging recently as a substantial competitor to standard CCD's for digital photography and video applications [1]. Up to now, several attempts were made to combine detector and electronics onto the same substrate [2,3], but all of them used high resistivity silicon as the fully depleted active volume. This approach is optimised for the charge collection efficiency, but complicates the detector design since a dedicated fabrication process must be used. Charge collection can also be achieved when a lightly doped undepleted epitaxial layer is used as an active volume [4,5]. The epitaxial layer is available in numerous modern VLSI processes featuring twin tubs, where it is grown on a highly, usually p-type, doped substrate. The presented solution takes advantage of the epitaxial layer and, unlike the previously proposed monolithic tracking devices, the new device can be fabricated using a standard, cost-effective and easily available CMOS process. The charge generated by the impinging particle is collected by the n-well/p-epi diode, created by the floating n-well implantation reaching the epitaxial layer. This structure forms a potential well trapping electrons. The active volume is underneath the readout electronics allowing a 100% fill factor, as required in tracking applications.

In order to validate these ideas, two prototype chips were fabricated using 0.6 μm and 0.35 μm CMOS processes. The design principle is reviewed in the next section and physics device simulations are discussed in the consecutive part. The last section gives an overview of the experimental results with the emphasis on the beam tests data analysis.

II. DETECTOR ARCHITECTURE

A. General Design Guidelines

Two prototype MIMOSA (Minimum Ionising particle MOS Active pixel sensor) chips, following the presented idea, were fabricated in two different processes. The first device, MIMOSA I, was fabricated in a 0.6 μm process featuring an epitaxial layer of about 14 μm and the second chip, MIMOSA II, was fabricated in a 0.35 μm process with less than 5 μm of this layer. Both chips contain several (four and six in the case of MIMOSA I and MIMOSA II, respectively), independent arrays of active elements having slightly different design. Each array is made of 64 by 64 square pixel elements, laid down with a pitch of 20 μm in both directions. The individual pixel is comprised of only three MOS transistors and a floating diffusion photodiode. Because the n-well implantation areas form the collecting diodes, the design is limited to NMOS transistors only at the pixel level, whereas both types of
transistors are used on the chip periphery. Chips are equipped with a serial, analogue readout requiring only two digital signals to operate. The schematic diagrams of MIMOSA I and II are presented in figure 1. The transistor M1 resets the photodiode to reverse bias, the transistor M2 is a source follower combined with the current source Mcur, which is common for the entire column, while the transistor M3 combined with Mcol is used to address the pixel for readout. Periodically, the floating diffusion of the collecting diode has to be reset to remove the collected charge and to compensate the diode leakage current. This procedure superimposes thermodynamic fluctuations onto the signal described statistically by the equipartition theorem:

$$\frac{1}{2}C_d\langle V^2_d \rangle = \frac{1}{2}kT$$

(1)

where $C_d$ is a node capacitance, $k$ is the Boltzman constant and $V_d$ represents the noise voltage.

This type of noise dominates the contributions from other sources and is known as the kTC noise. It can be removed applying correlated double sampling signal processing (CDS) [6]. For both circuits, the CDS operation is performed by software during off-line data processing [5], and the useful signal is calculated as the difference between two consecutive frames taken after the reset. The detector operated in this mode is a charge-integrating device with an integration time equal to the readout time of one full frame, given by:

$$\tau = N_p(f_{clk})^{-1}$$

(2)

where $N_p$ is the total number of pixels connected to one serial output line and $f_{clk}$ is the readout clock frequency. Two 64 bit long shift registers, selecting rows and columns, are used for pixel addressing. This simple scheme was implemented and the analogue information is readout with consecutive clock cycles. The entire array is reset in 64 clock cycles, when the reset shift register selects the entire row at a time.

In order to improve the noise performance, the bias current of the on-pixel source follower is reduced, decreasing the cut-off frequency of the latter. Because the limited bandwidth of the source follower reduces the maximum possible readout speed, a special technique to overcome this problem was implemented in MIMOSA II. Two separate readout lines with two current sources inside the chip are switched alternatively to the output amplifier by two transmission gates. All even columns are connected to the first line and all odd columns to the second one. When a given column is selected for readout, the neighbouring one is being prepared by connecting the bias current. Both readout lines are loaded with additional capacitance of 2.5 pF, limiting the bandwidth of the source follower and improving the noise performance. The input capacitance of the output amplifier is small enough to be charged shortly after the transfer gate is activated. This technique, combined with an optimised design of the output amplifier, allows increasing the readout frequency up to 25 MHz, to be compared to 5 MHz in the case of MIMOSA I.

**B. Design Details**

The basic configuration for both chips features one collecting diode per square pixel with all transistors designed in a standard rectangular form. This default topology is depicted in figure 2(a). The second characteristic configuration of MIMOSA I is a design with four collecting diodes placed close to each pixel corner. This configuration reduces the charge collection time and the charge spreading among neighbouring pixels, at the expense of increased noise due to the higher node capacitance and of a decreased charge-to-voltage conversion gain.

There are two new features implemented in MIMOSA II. In order to optimise the signal-to-noise ratio for reconstructed clusters, a staggered pixel layout was introduced, where every other row is shifted by half the pixel pitch. In this way each pixel has only six closest neighbours, reducing the number of pixels in a reconstructed cluster.

Since the radiation environment of many applications will be harsh, the radiation hardness of the new devices is an important issue. Therefore, array configurations shown in figures 2(c), 2(d) and also the second version of 2(a) were designed in radiation tolerant geometry with enclosed NMOS transistors [7]. The charge collection efficiency of four collecting diodes was traded for a better charge-to-voltage conversion factor. A configuration with two diodes instead of four diodes was implemented in MIMOSA II.
Figure 2: Main pixel configurations in MIMOSA I a), b) and in MIMOSA II a), c), d).

C. Noise Performance

The primary sources of pixel readout noise are kTC reset noise, and amplifier (from the pixel source follower and the output voltage amplifier) thermal and flicker (1/f) noise. The dark current shot noise becomes important only at higher detector temperatures, while below 0°C it is completely dominated by the other sources of noise. The estimated kTC reset noise is $32e^{-}$ and $62e^{-}$ according to the lowest and the highest detector capacitance in table 1. The pixel thermal and flicker noise spectrum density can be estimated by fitting the SPICE simulated curves with the following expression:

$$S(f) = S_0 \left(1 + \frac{f}{f_c}\right)^2$$

where $S(f)$ is the total spectral noise density referred to the input, $S_0$ is the fitting coefficient and $f_c$ is the flicker noise corner frequency. In order to remove the kTC noise, the CDS signal processing technique was used with the temporary noise sampled twice after the pixel reset. The CDS processing suppresses the low frequency noise components, at the expense of increased thermal noise contributions. The noise spectral density after CDS is given by the following formula:

$$S_{\text{out}}(f) = 4 \left[ \sin \left( \frac{\pi f \tau_{\text{in}}}{\tau_{\text{int}}} \right) \right]^2 \sum \left[ S_n \left(f - \frac{n}{\tau_{\text{int}}} \right) \right]$$

where $S_{\text{out}}(f)$ is the output noise power spectral density before CDS processing. It is a product of the pixel noise spectrum density at the input of the readout amplifier and its transfer function $H_{\text{amp}}(f)$, that can be expressed by:

$$S_n(f) = S(f) \times |H_{\text{amp}}(f)|^2$$

The r.m.s. value of the noise expressed in equivalent number of electrons (ENC) depends on the DC voltage gain $G_v$ of the readout amplifier and on $G_c$, the charge-to-voltage conversion gain of the pixel. It is then calculated by:

$$\text{rmsNoise} = \sqrt{\int S_{\text{out}}(f) \text{df}}$$

where $q$ is the elementary electronic charge. Figure 3 shows the noise power spectral densities for both MIMOSA chips, where sampling frequencies of 0.625, 1.25, 2.5, 5 and 10 MHz were examined. For the sake of later measurements, only the four lowest (four highest) sampling frequencies were considered in the case of MIMOSA I (MIMOSA II). The ENC values of the noise presented in this figure were obtained by a numerical integration of power spectral density distributions.

The radiation tolerant design demands a compromise with respect to noise optimisation, since the dimensions of the transistors cannot be chosen freely. The standard non-radiation tolerant design gives an ENC 10 to 20% better than the design with all transistors enclosed. The noise bandwidth of MIMOSA II, because of the increased speed of the output amplifier, is wider than the one of the predecessor and thereby the noise behaviour could be worse. The pixel source follower was thus loaded in MIMOSA II with an additional capacitance $C=2.5pF$, decreasing the ENC by 10% with respect to the initial value. The r.m.s. value of the noise after CDS processing of the output amplifier referred to its input was estimated to be 46 $\mu$V and 72 $\mu$V for MIMOSA I and II, respectively.

The main parameters of both prototypes are summarised in table 1. The numbers presented were found doing analytical calculations and post-layout simulations with the spectreS
The drift-diffusion model, used to study the charge collection mechanism, is based on three equations, i.e. the Poisson equation and two continuity equations for electrons and holes. The specific design of the detector prevents the holes from giving a significant contribution to the total collected charge. In addition, the density of the charge created in any part of the detector at room temperature is negligible compared to the density of the ionised atoms of impurities. The last feature simplifies the right-hand side of the Poisson equation, given by:

\[ \varepsilon \nabla^2 \psi = -q \left( p - n + N_D^+ - N_A^- \right), \]  

where \( \varepsilon \) is the electric permittivity, \( \psi \) is the electrostatic potential, \( q \) is the elementary electronic charge, \( n \) and \( p \) are the electron and hole densities, \( N_D^+ \) and \( N_A^- \) are the densities of ionised donors and acceptors. Equation 7 depends now only on the densities of ionised donors and acceptors. Because the density of the generated excess charge is negligible compared to the densities of the ionised impurities the distribution of the electric field does not depend on it, justifying the use of the steady state solution for the electrostatic potential during the transient analysis. Taking into account the aforementioned arguments, the transient charge transport mechanism was analysed by solving only the continuity equation for electrons. The collected charge was obtained by a straightforward integration of transient currents on the collecting diode contacts. The potential of contact nodes remained constant and contact electrodes were biased from the 3 V voltage source.

An appropriate set of dependencies and physics models having a significant impact on the charge collection mechanism was chosen. The doping dependent mobility of the charge carriers was modelled according to Masetti et al. [8]. For all the simulations, a uniform device temperature of \( T=300K \) was assumed and the high field saturation model according to Canali et al. [8] was chosen. For the net recombination rate, required for the drift diffusion model, only the contribution due to Schockley-Read-Hall (SRH) mechanisms was taken into account. The minority SRH carrier lifetimes, from the doping concentration, were determined by the Scharfetter relation [8]. As necessary parameters for this model, default values for silicon were used. The doping dependent electron lifetimes were estimated to 10 ns, 10 \( \mu \)s and about 1 \( \mu \)s in the substrate, in the epitaxial layer and in the p-well, respectively. The carrier lifetime is a crucial parameter for the charge collection in the MAPS device. The very short carrier lifetime in the substrate, combined with the degraded mobility due to the high doping level, limits the charge spreading possibility in this region. This fact reduces the substrate contribution to the total charge that is collected in a pixel cluster.

The active volume of the detector is the epitaxial layer, since most of the collected charge originates in it. The thickness of this layer, which is a characteristic feature for a given fabrication process, was used as a parameter. Simulations were performed for three different thickness:

### III. CHARGE COLLECTION SIMULATIONS

The charge collection efficiency of the MAPS device was verified using the ISE-TCAD package [8]. The device geometry, as described by a mesh generated by the MESH-ISE program using the boundary definition and doping information, was examined by DESSIS-ISE, a multidimensional, mixed-mode device and circuit simulator. The mesh was generated using the analytical description of doping profiles inside the detector. This doping information, was examined by DESSIS-ISE, a program using the boundary definition and doping geometry, as described by a mesh generated by the MESH-ISE program.

In the computations that were carried out, DESSIS-ISE was used to solve the semiconductor device equations for the drift-diffusion carrier transport model in three dimensions. The \textit{alpha-particle} model, available for transient simulations, was used to describe an excess charge due to a single passage of an ionising particle. A uniform charge distribution along the particle track with a value of 80 e/hm\(^{-2}\) was assumed. The radial charge distribution was gaussian with a width \( \sigma=0.75 \) \( \mu \)m. The maximum simulated volume of the detector was 122x122x40 \( \mu \)m\(^3\), filled with a generated mesh of up to 125000 vertices. The thickness of the simulated structure was varied according to the considered thickness of the epitaxial layer. The highly doped substrate was described by a constant thickness of 15 \( \mu \)m for all analyses. Using a thicker substrate layer is of no significance for the collected charge, since the substrate contribution is shown to be limited to the first 10 \( \mu \)m of its depth [9]. This fact is invoked later in this section, where a rough estimation of the substrate contribution is presented. The simulated structure, comprising nine adjacent pixels, was prepared in a way allowing to overcome limitations of the reflective boundary conditions (a default option in DESSIS-ISE) and to keep the simulation time as short as possible. Pixels were laid down with a pitch of 20 \( \mu \)m in a square array of 3-by-3 elements.

#### TABLE 1
MAIN ESTIMATED ELECTRICAL PARAMETERS OF MIMOSA CHIPS

<table>
<thead>
<tr>
<th>MIMOSA I</th>
<th>1 diode n-radtol.</th>
<th>1 diode radtol.</th>
<th>2 diodes radtol.</th>
</tr>
</thead>
<tbody>
<tr>
<td>total node capacitance @ 3.2 V</td>
<td>10.9 fF</td>
<td>26.2 fF</td>
<td></td>
</tr>
<tr>
<td>diode capacitance @ 3.2 V</td>
<td>3.1 fF</td>
<td>4x3.1 fF</td>
<td></td>
</tr>
<tr>
<td>conversion factor (after SF*)</td>
<td>13.9 ( \mu )V/e</td>
<td>5.8 ( \mu )V/e</td>
<td></td>
</tr>
<tr>
<td>diode leakage current @ 27°C</td>
<td>5 fA</td>
<td>4x5 fA</td>
<td></td>
</tr>
<tr>
<td>noise (CDS 1.25 MHz)</td>
<td>15 e(^{-})</td>
<td>32 e(^{-})</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>MIMOSA II</th>
<th>1 diode n-radtol.</th>
<th>1 diode radtol.</th>
<th>2 diodes radtol.</th>
</tr>
</thead>
<tbody>
<tr>
<td>total node capacitance @ 2.5 V</td>
<td>6.2 fF</td>
<td>7.1 fF</td>
<td>9.4 fF</td>
</tr>
<tr>
<td>diode capacitance @ 2.5 V</td>
<td>1.65 fF</td>
<td>1.65 fF</td>
<td>2x1.65 fF</td>
</tr>
<tr>
<td>conversion factor (after SF)</td>
<td>25.7 ( \mu )V/e</td>
<td>22.6 ( \mu )V/e</td>
<td>16.9 ( \mu )V/e</td>
</tr>
<tr>
<td>diode leakage current @ 27°C</td>
<td>0.25 fA</td>
<td>0.25 fA</td>
<td>2x0.25 fA</td>
</tr>
<tr>
<td>noise (CDS 2.5 MHz)</td>
<td>11 e(^{-})</td>
<td>13 e(^{-})</td>
<td>17 e(^{-})</td>
</tr>
</tbody>
</table>
5 µm, 15 µm and 25 µm. The main geometrical parameters of the simulated structures are summarised in table 2. These parameters define the detector geometry, which corresponds roughly to both MIMOSA chips architectures.

| TABLE 2 |
| GEOMETRICAL SIMULATION PARAMETERS |
| --- | --- |
| single pixel size | x=20 µm, y=20 µm |
| number of diodes per pixel | one |
| diode size | 3x3x3.2 µm³ |
| diode position | centre pixel |
| substrate thickness | 15 µm |
| epitaxial layer thickness | 5 µm, 15 µm, 25 µm |
| simulated structure size | 3-by-3 pixels |

For each thickness of the epitaxial layer, 33 separate analyses, each devoted to a single event at fixed impact point of the ionising particle, were performed. Two characteristic parameters, i.e. the charge collection efficiency and the collection time, were determined for each point. The impact positions were chosen randomly using the Design-of-Experience (DOE) option available when running the GENESIS-ISE environment. The charge collection efficiency and the collection time were analysed for three different cluster configurations depending on the distance between the impact position and the centre of the collecting diode in the central pixel. The results, presented in figure 4, show the charge collection efficiency (expressed as the number of collected electrons) and the collection time for the three values of the epitaxial layer thickness.

Figure 4: Simulated charge collection efficiency (expressed as the number of collected electrons) and collection time as a function of the distance between the impact position and the centre of the pixel for a): 5 µm, b): 15 µm and c): 25 µm thick epitaxial layers, and a 15 µm thick substrate layer.
Three cluster definitions were considered, comprising either only the central pixel, or the four pixels exhibiting the highest signals, or all nine pixels closest to the impact position.

Figure 4 shows that the charge spreading among neighbouring pixels increases with the epitaxial layer thickness. For a thickness of 5 µm nearly all the collected charge is located in a cluster of 2-by-2 pixels. The charge collected on the central pixel depends strongly on the hit position: it is minimal when the impact position is at equal distance from the four closest pixel centres (corner hit), regardless the epitaxial layer thickness. The charge collected in this case is less than a quarter of the total charge found in a cluster of 3-by-3 pixels. The charge collected on the central pixel first increases with increasing thickness of the epitaxial layer and then starts saturating when the epitaxial layer thickness gets comparable to the pixel pitch. The growth of the collected charge with the epitaxial layer thickness is weaker for the central pixel than for clusters of 2-by-2 or 3-by-3 pixels.

The collection time, which is defined as the time after which 90% of the total charge is collected, increases as well with the epitaxial layer thickness and depends also on the impact position: the shortest collection time is observed for the central hit, i.e. when the impinging particle passes through the collecting diode. In this case nearly all the available charge is collected on the central pixel. The longest collection time occurs for corner hits and intermediate cases exhibit a nearly linear dependence on the hit distances from the middle point of
the central pixel.

Figure 5 shows simulation results where the substrate thickness is reduced close to 0. This figure allows evaluating charge collection efficiency and collection time for electrons originating only in the epitaxial layer. In this way, the relative contribution of the highly doped substrate to the total charge collected is estimated. This contribution increases with decreasing thickness of the epitaxial layer. For 5 μm thick epitaxial layer and a pixel pitch of 20 μm, the substrate contribution is estimated at 30% of the total charge in the 3-by-3 pixels cluster. It decreases with thicker epitaxial layer, reaching 15% and 10% for 15 μm and 25 μm thickness, respectively.

IV. EXPERIMENTAL RESULTS

Both MIMOSA I and MIMOSA II chips were extensively tested with ionising radiation. All tests were performed with the specific data acquisition system based on an OS9 processor. The individual pixels were addressed in consecutive clock cycles and an external 12-bit ADC unit was used to digitise the raw analogue signals. Data from two consecutive frames (8092 samples) were kept in a circular buffer memory. The acquisition was stopped after trigger (particle) arrival, with a delay corresponding to the readout time of one frame. The CDS signal processing was performed by calculating a difference between the data in two consecutive frames i.e. before and after the trigger arrival. Figure 6a-6c illustrates the effect of such an operation on raw data. After CDS, the signal generated by the particle interaction could easily be extracted, being only superimposed on a fixed voltage offset (pedestal) from the leakage current. The first 250 events of each run were used to derive the pedestal and its fluctuation (temporal noise), needed for further steps of the signal extraction. Figure 6e shows that very few channels are subject to large fluctuation, i.e. large temporal noise. The latter may fake real signal hits in the detector since they can survive CDS and pedestal subtraction (figure 6d). Such fake hits vanish once the pattern recognition comes to the selection of pixels on the basis of their signal-to-noise ratio (S/N), as shown on figure 6f.

Most of the MIMOSA I prototype measurements were done at a temperature near –10 °C (beam tests), using 1.25 and 2.5 MHz readout clock frequencies. The major motivation for cooling was to increase the time interval between consecutive reset cycles. The diode leakage current modifies the voltage of the charge-collecting node and if the leakage current is too high, this voltage (still amplified on the chip) moves rapidly out of the dynamic range of the ADC. The cooling reduced the leakage current and the reset cycle could be slowed down to a few Hz only. This feature is important for beam tests, where the triggers are randomly distributed in time and not synchronised with the pixel resetting.

In the case of MIMOSA II, a higher readout frequency was used (10 MHz) and since the diode reverse current was an order of magnitude lower due to the different fabrication process (table 1), most of the measurements were performed at room temperature.
Figure 6. The response of the matrix of 64x64 pixels for one event recorded with the test beam (ADC counts)

a) Signal in pixels: frame 1 (before trigger)
b) Signal in pixels: frame 2 (after trigger)
c) Signal in pixels after CDS
d) Signal in pixels after CDS and pedestal subtraction
e) Noise distribution entering the S/N calculation
f) S/N distribution used for pattern recognition

A. Device Calibration Using Soft X-rays

The major goal of the calibration performed with a $^{55}$Fe 5.9 keV photon source was to measure the conversion gain, which is needed for further parameterisation, in absolute units, of the device performance. Such photons undergo photoelectric interaction inside the active detector volume and generate a quasi-constant number of charge carriers of 1640 e/h pairs in the silicon. This gives rise to a characteristic peak in the signal amplitude distribution. For detectors having close to 100% charge collection efficiency, the position of this peak can be directly used for measurements of the conversion gain. This is not the case of the present device, where the carrier transport mechanism is dominated by thermal diffusion, leading to
charge losses. The charge is also naturally spread among several pixels. However, the assumption of fully efficient charge collection is justified for a small sub-sample of photons converted inside the depleted volume of the collecting diode p-n junction. This can explain the presence of the second, smaller peak visible in the central pixel photon spectrum shown in figure 7. The position of this particular peak was used to measure the conversion gain and consequently other basic electrical parameters (table 3).

**B. Properties of the Signal Generated by Minimum Ionising Particles**

The response of the MIMOSA chips to minimum ionising particles (MIP) traversing a CMOS sensor was studied using 120 GeV/c pion beam from the CERN SPS accelerator. For these tests, pixel detectors were mounted inside a high precision beam telescope. A small scintillation counter was delivering a trigger and it was adapted to match the physical dimension of the tested device. Both MIMOSA prototypes were successfully tested and the detailed data analysis is in progress. The present paper gives an overview of the data analysis result of MIMOSA I.

The description of the beam test set-up and the methodology of the data analysis can be found elsewhere [10]. The distribution of the individual pixel noise, defined as a fluctuation of the signal (after CDS processing) around its pedestal value, is shown in figure 8. The mean ENC was found to be equal to 12 and 25 electrons for the 1 diode and 4 diode pixel configurations, respectively. These values are in good agreement with prior calculations and measurements.

![Figure 8: Individual pixel noise distribution.](image)

The response of the pixels not affected by the particle impact has a gaussian distribution with a standard deviation of about 1.2, whereas the seed pixels and its neighbours exhibit a S/N value well above 5 (figure 9).

![Figure 9: Signal-to-noise distribution for all the pixels in single event (same event as on fig.6), in linear and logarithmic (window) scale.](image)

**Table 3**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>MIMOSA I 1 diode</th>
<th>MIMOSA I 4 diodes</th>
</tr>
</thead>
<tbody>
<tr>
<td>conversion factor (after ADC)</td>
<td>6.1 e^-/ADC</td>
<td>14.9 e^-/ADC</td>
</tr>
<tr>
<td>conversion factor (after SF)</td>
<td>14.6 µV/e^-</td>
<td>6.0 µV/e^-</td>
</tr>
<tr>
<td>total node capacitance @ V_DD=5V</td>
<td>10.9 fF</td>
<td>26.6 fF</td>
</tr>
<tr>
<td>noise (CDS 1.25 MHz @ T=-20°C)</td>
<td>15 e^-</td>
<td>31 e^-</td>
</tr>
</tbody>
</table>

**MIMOSA II**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>1 diode rad-tolerant</th>
<th>2 diodes rad-tolerant</th>
</tr>
</thead>
<tbody>
<tr>
<td>conversion factor (after ADC)</td>
<td>5.1 e^-/ADC</td>
<td>6.7 e^-/ADC</td>
</tr>
<tr>
<td>conversion factor (after SF)</td>
<td>22.9 µV/e^-</td>
<td>17.5 µV/e^-</td>
</tr>
<tr>
<td>total node capacitance @ V_DD=5V</td>
<td>7.0 fF</td>
<td>9.1 fF</td>
</tr>
<tr>
<td>noise (CDS 2.5MHz @ T=+20°C)</td>
<td>16 e^-</td>
<td>18 e^-</td>
</tr>
</tbody>
</table>

![Figure 10 displays the signal-to-noise ratio for the central pixel of a cluster for minimum ionising particles. The central pixel was identified by requesting an individual signal-to-noise ratio above five and taking the pixel with the highest signal value within a cluster of neighbouring pixels. The variation of the collected charge as a function of the cluster size is plotted](image)
in figure 11. Pixels were successively added to the cluster in decreasing order of their signal amplitudes. The charge spread appears to be limited to about 16 pixels per cluster for both pixel configurations, the absolute amount of the collected charge being about 20% larger for the 4-diode design. The variation of the cluster signal-to-noise ratio with their size (figure 12) exhibits better performances for one diode per pixel. The mean value of the signal-to-noise ratio reaches 43 in this case. The cluster noise was taken here as the average single-pixel noise times the square root of the cluster multiplicity.

\[
\text{Cluster noise} = \text{Average single-pixel noise} \times \sqrt{\text{Cluster multiplicity}}.
\]

**Figure 10:** Signal-to-noise distribution for the cluster central pixel.

**Figure 11:** Collected charge (most probable value) as a function of the cluster size.

**Figure 12:** Signal-to-noise (mean value) as a function of the cluster size.

**Figure 13:** Correlation between the track positions given by the reference telescope and by the pixel sensor data using the centre of gravity of a 3x3 pixel cluster.

\[
\begin{align*}
\text{Chi}^2/\text{ndf} &= 45.65/36 \\
\text{Constant} &= 138.9 \pm 0.05131 \\
\text{Mean} &= 0.05864 \pm 0.04537 \\
\text{Sigma} &= 1.818
\end{align*}
\]

**Figure 14:** Residue distribution of a track position measured by the 1-diode pixel MIMOSA I sensor using two different algorithms, i.e. binary and centre of gravity with the non-linear correction.

\[
\begin{align*}
\text{Chi}^2/\text{ndf} &= 45.65/36 \\
\text{Constant} &= 138.9 \pm 5.207 \\
\text{Mean} &= 0.05864 \pm 0.05131 \\
\text{Sigma} &= 1.818 \pm 0.04537
\end{align*}
\]

C. Tracking Performance of MIMOSA I Prototype

In order to determine the pixel detector spatial resolution, the track parameters extracted from the reference beam telescope were compared to the position calculated from the pixel device data using two different methods. In the first method (digital resolution), the track position is given by the center of the pixel with the highest signal in the cluster. In the second method (CoG), the track position is taken as the centre of gravity of the charge within a 3x3 pixel cluster. Using the second method, a gaussian fit to the residuals exhibited a standard deviation of 2.2 µm. This result could still be improved using a non-linear correction to the CoG algorithm. The s-shaped correction function was derived from the correlation between the track position given by the reference telescope and that given by the pixel sensor data using the CoG method (figure 13).

After this correction the standard deviation of a gaussian fit to the residual was found to be 1.8 µm (figure 14). Taking into account the estimated precision of the telescope (1 µm), the spatial resolution of the 1-diode pixel configuration of MIMOSA I, based on the centre of gravity position determination algorithm, was estimated to be 1.6 ±0.1 µm in both directions.
Figure 15 shows the distribution of the distance between the track position at the pixel plane (measured by the reference telescope) and all clusters reconstructed by the pixel sensor. For most of the tracks, a cluster was found within the distance of 20 µm. The detection efficiency of the 1-diode pixel sensor was therefore determined to be 99.5 ± 0.2%, applying a 5σ cut to the seed cluster signal-to-noise ratio.

VI. REFERENCES