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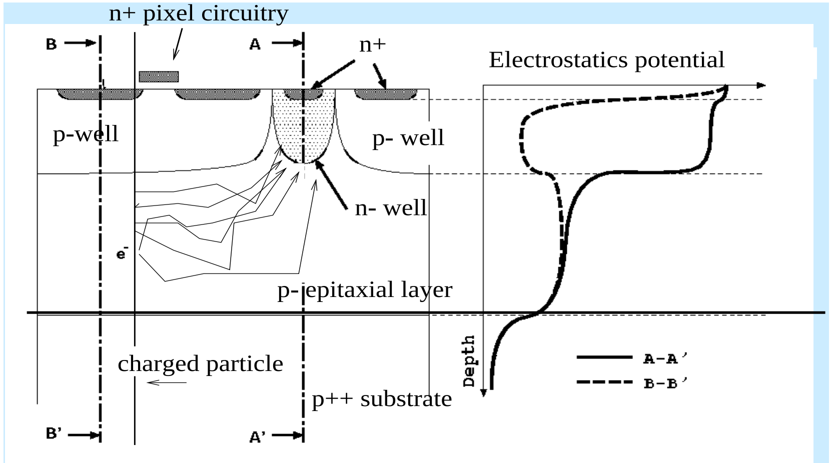
Monolithic CMOS Pixel Detectors for Radiation Imaging

From digital still and video cameras to particle tracking device

Twin - tub (double well), CMOS process with epitaxial layer



- The effective charge collection is achieved through the thermal diffusion mechanism,
- The 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,
- The active volume is underneath the readout electronics allowing a 100% fill factor.

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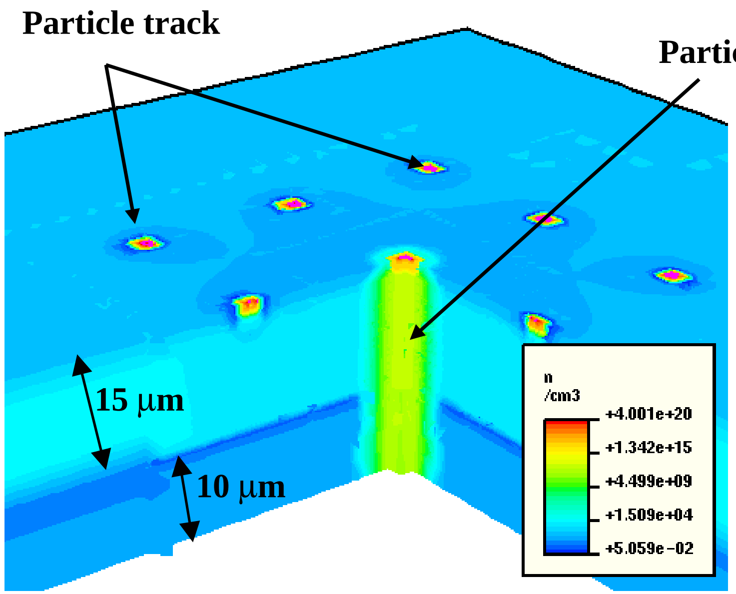
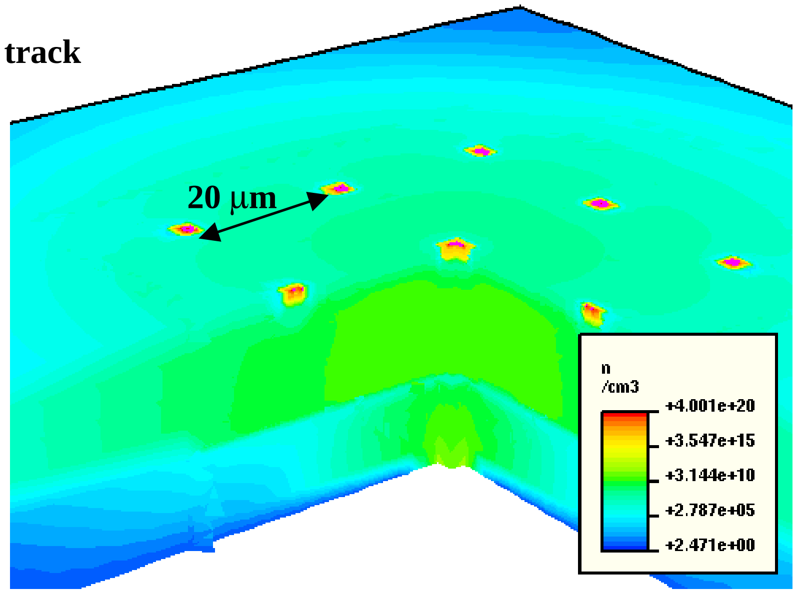
Monolithic Pixel CMOS Sensor for Particle Tracking

☑ Simulation of physics process





$\tau = 0$ ns — **Carrier concentration** — $\tau = 25$ ns

- The charge collection efficiency examined using the mixed mode device and circuit simulator DESSIS-ISE from the ISE-TCAD package,
- The charge collection is traced as a relaxation process of achieving the equilibrium state after introducing an excess charge emulating passage of the ionising particle
- The device is described in three dimensions by a mesh generated using the analytical description of doping profiles and the boundary definition corresponding to the real device,
- Different detector parameters, including the thickness of the epitaxial layer, the size of a pixel and collecting diodes and number of diodes per pixel, were investigated.

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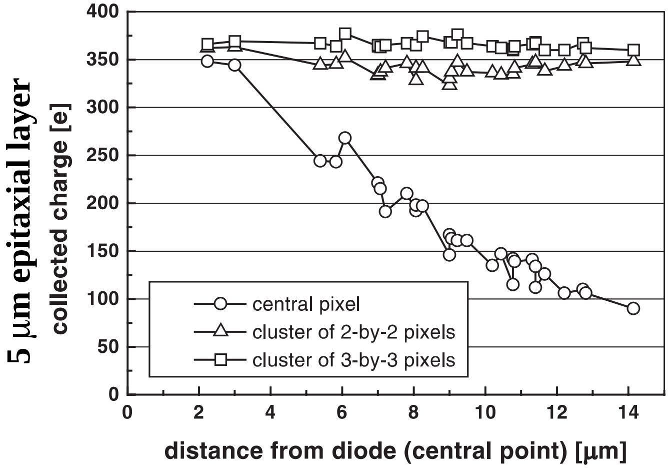
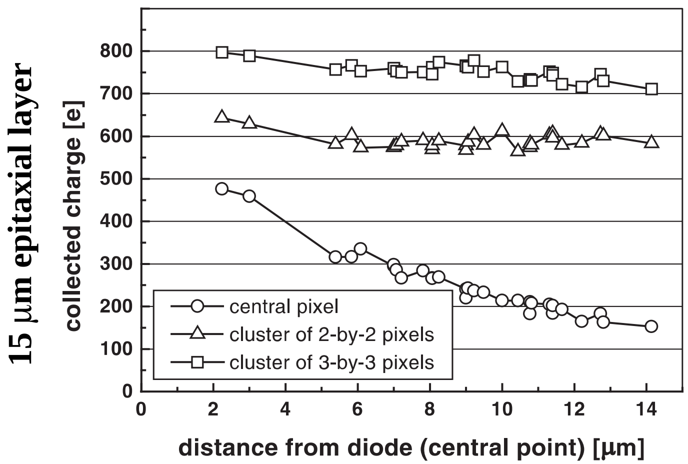
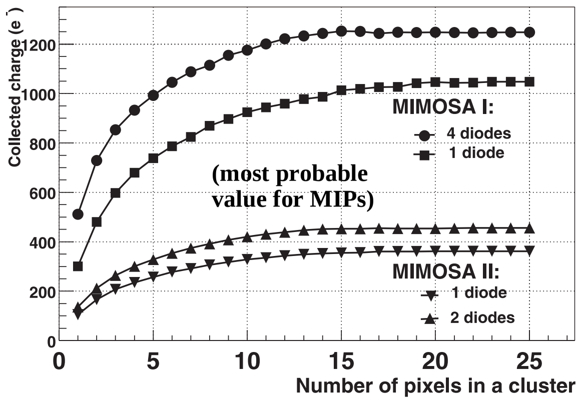
Monolithic Pixel CMOS Sensor for Particle Tracking

☑ Simulation of physics process

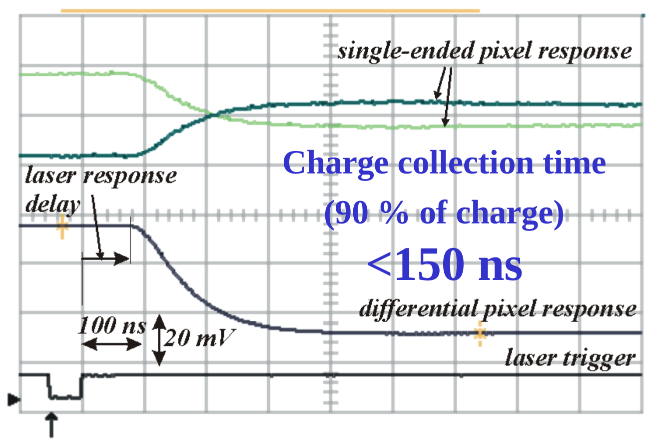




• **Experimental verification:**



The measured collected charge for two chips having 14 μm and less then 5 μm, the pitch of 20 μm



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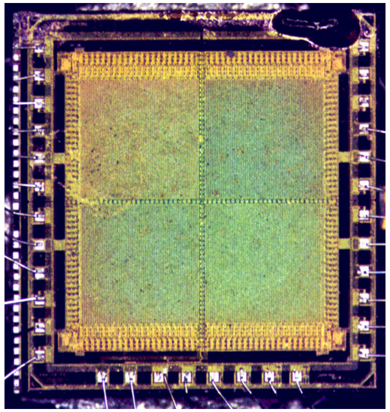
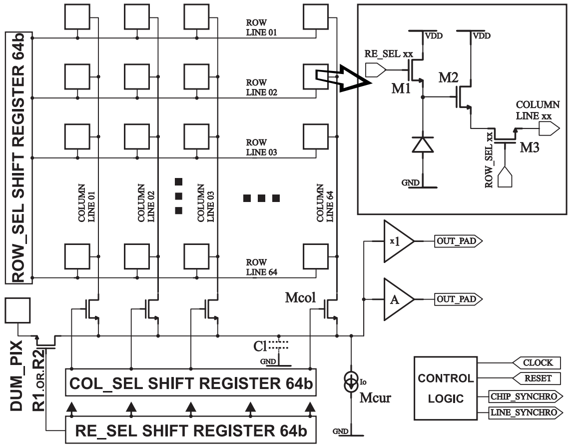
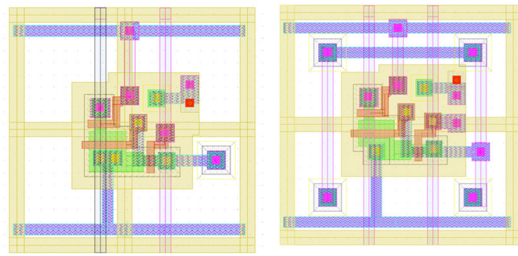
Monolithic Pixel CMOS Sensor for Particle Tracking

☑ **Prototype chips - MIMOSA I (*Minimum Ionising Particle MOS Active Pixel Sensor*)**



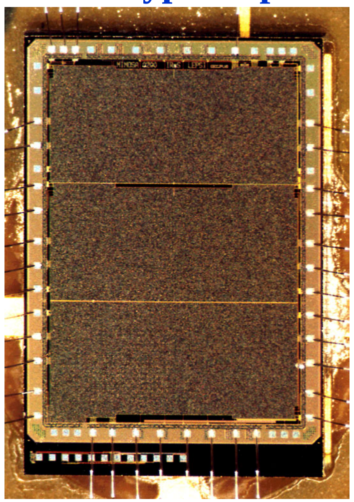
die size 3.6x4.2 mm^2

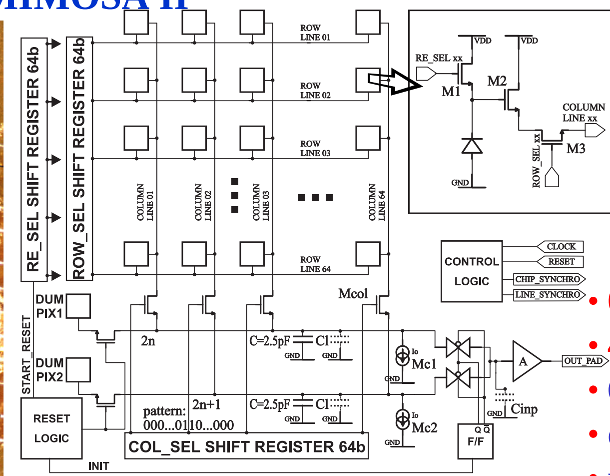




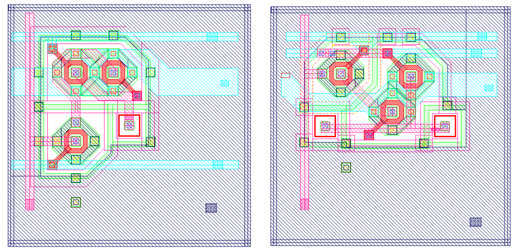
- 0.6 µm CMOS (t_{ox}=12.7 nm)
- 14 µm thick EPI layer (10^{14} cm^{-3})
- 4 arrays 64x64 pixels, pitch 20x20 µm^2
- diode (nwell/p-epi) size 3x3 µm^2 - 3.1 fF

☑ **Prototype chips - MIMOSA II**





die size 4.9x3.5 mm^2



- 0.35 µm CMOS (t_{ox}=7.4 nm)
- 4.2 µm thick EPI layer (10^{15} cm^{-3})
- 6 arrays 64x64 pixels, pitch 20x20 µm^2
- diode (nwell/p-epi) size 1.7x1.7 µm^2 - 1.65 fF
- radiation tolerant transistor design

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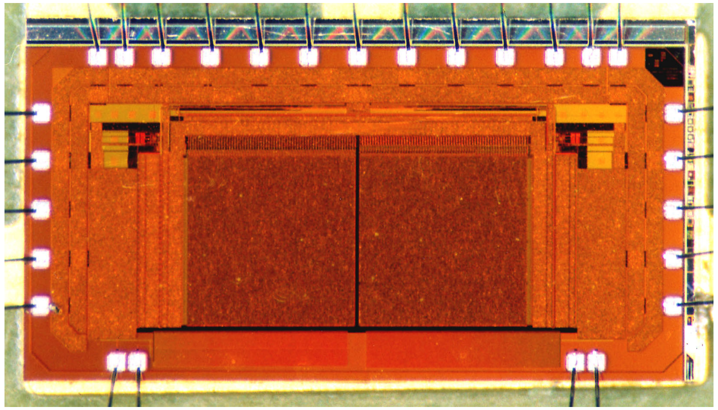
Monolithic Pixel CMOS Sensor for Particle Tracking

☑ Prototype chips MIMOSA III

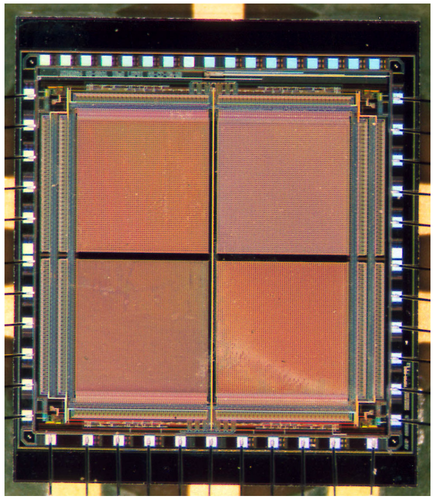
- **Collaboration with Microelectronics Group of CERN - MIMOSA III**



- **standard 0.25 μm CMOS (tox=5.84 nm)**
- **2 μm thick EPI layer (~10^{15} cm^{-3})**
- **2 arrays 128x128 pixels, pitch 8x8 μm^2**
- **diode (nwell/p-epi) size 1x1 μm^2 - 2.1 fF**
- **radiation tolerant transistor design**
- **optimisation for low noise ~6 e^- @ 20MHz**

die size 4.0x2.0 mm^2

☑ Prototype chips - MIMOSA IV



- **0.35 μm CMOS (tox=7.5 nm)**
- **p-substrate process (~10^{14} cm^{-3})**
- **4 arrays 64x64 pixels, pitch 20x20 μm^2**
- **diode (nwell/p-epi) size 2x2 μm^2 - 1.8 fF**
- **radiation tolerant transistor design**
- **charge collection from non epitaxial substrate**
- **new structures of charge sensing elements:**
  - **charge spill-gate,**
  - **current mode pixel,**
  - **self-biasing diodes**

die size 3.7x3.8 mm^2

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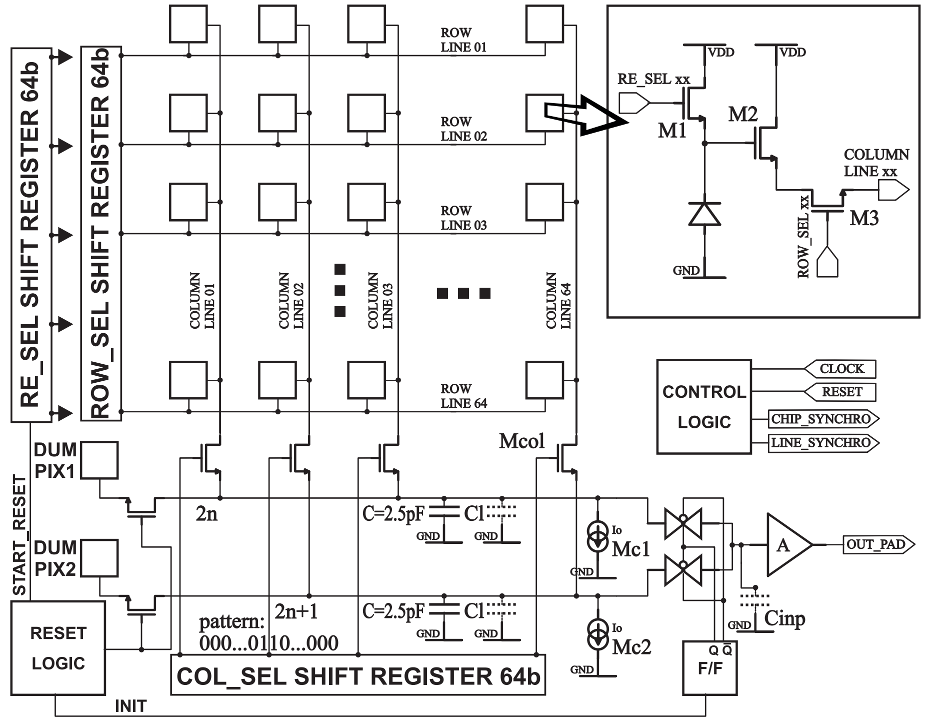
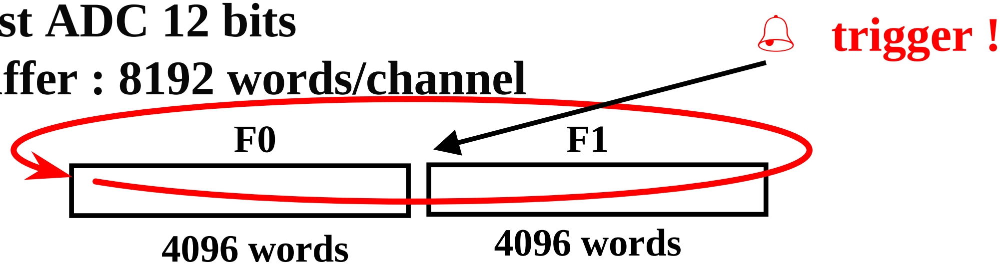
Monolithic Pixel CMOS Sensor for Particle Tracking

☑ **Present readout and data processing**



Fast ADC 12 bits

Buffer : 8192 words/channel



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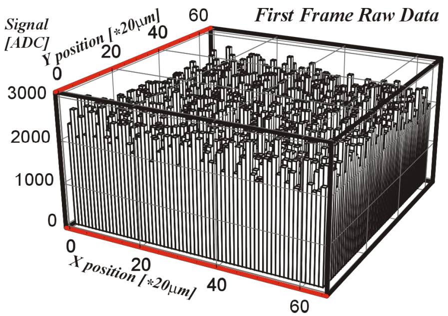
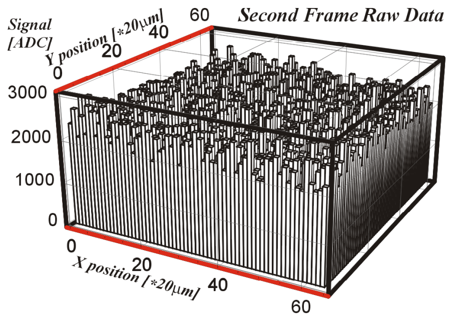
Monolithic Pixel CMOS Sensor for Particle Tracking

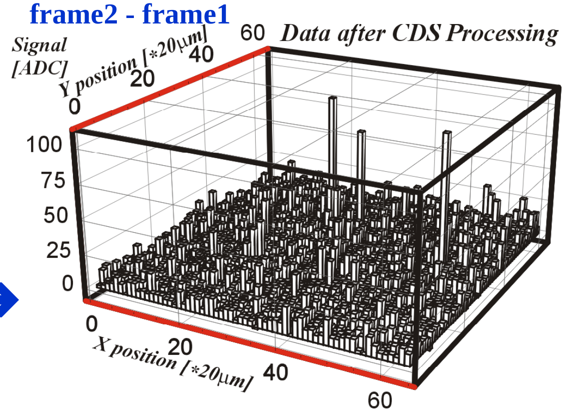
☑ Present readout and data processing

- **Off-line CDS:**

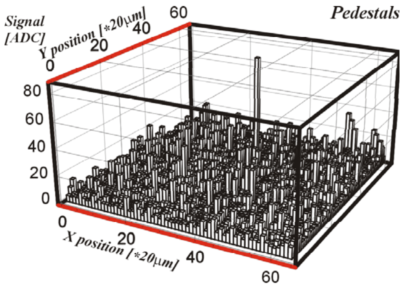




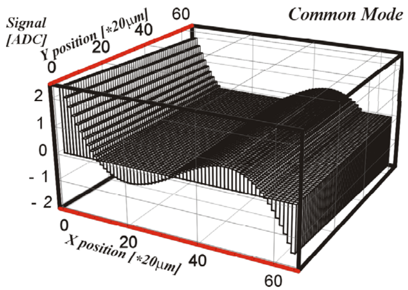
frame2 - frame1

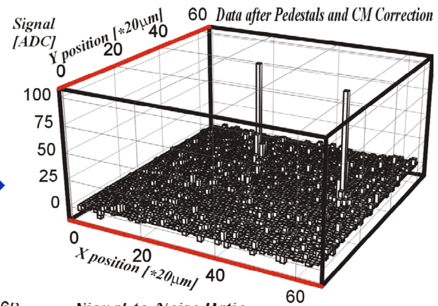


- **CDS Pedestals:**

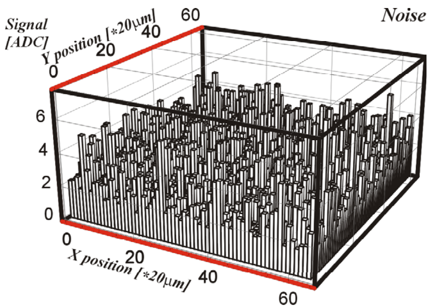


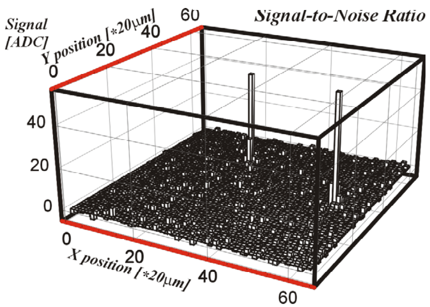
- **Common Mode:**





- **Temporal noise distribution:**





- **Signal-to-noise ratio evaluated for considered event**

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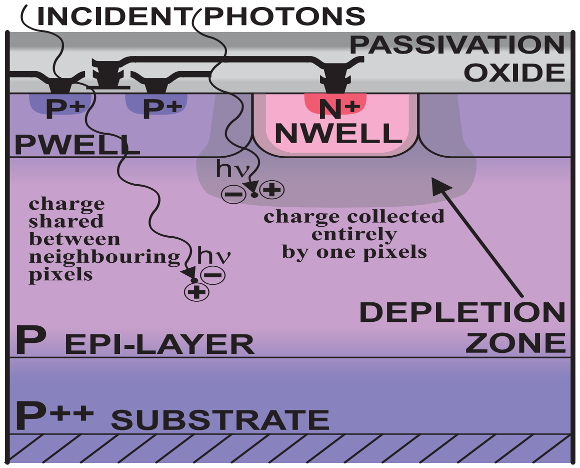
Monolithic Pixel CMOS Sensor for Particle Tracking

☑ Calibration of the conversion gain - with soft X-rays

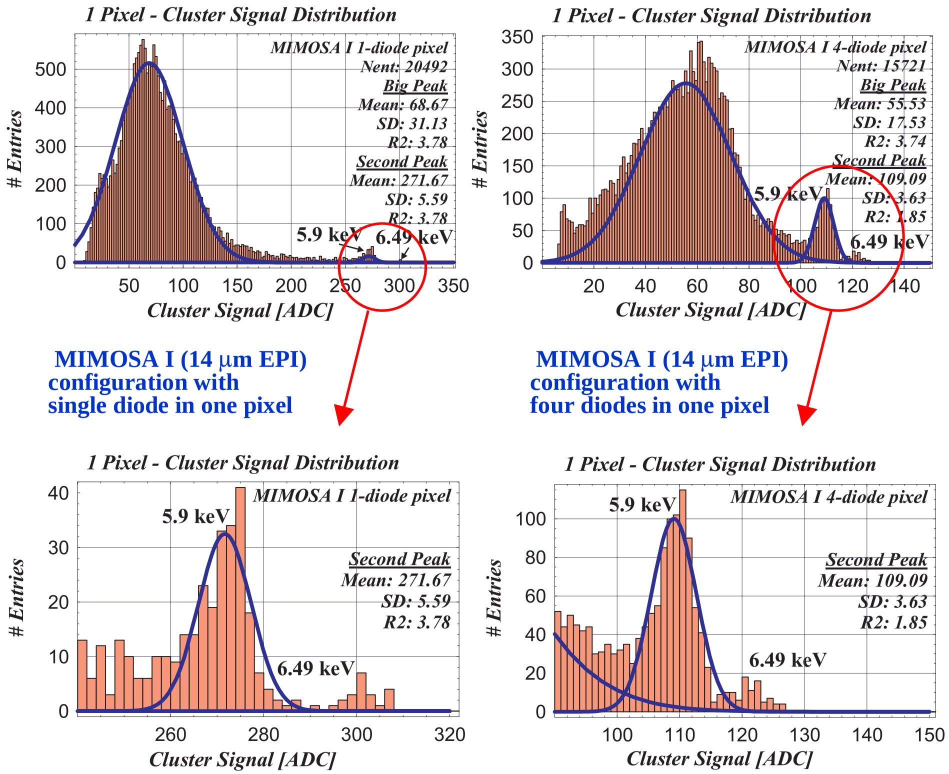
• Calibration methods:

Emission spectra of a low energy X-ray source e.g. iron ^{55}Fe emitting 5.9 keV photons.

very high detection efficiency even for thin detection volumes - μ =140 cm²/g, constant number of charge carriers about 1640 e/h pairs per one 5.9 keV photon



The ' warmest ' colour represents the lowest potential in the device



MIMOSA I CMOS 0.6 μm	1 diode – 14.6 μV/e⁻ ENC = 14 e⁻ @1.6 ms f. rate	4 diode – 6.0 μV/e⁻ ENC = 30 e⁻ @1.6 ms f. rate
MIMOSA II CMOS 0.35 μm	1 diode rad. tol.– 22.9 μV/e⁻ ENC = 12 e⁻ @0.8 ms f. rate	2 diode rad. tol.– 17.5 μV/e⁻ ENC = 14 e⁻ @0.8 ms f. rate

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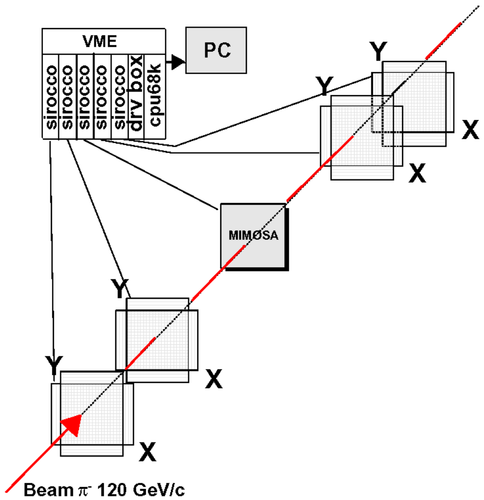
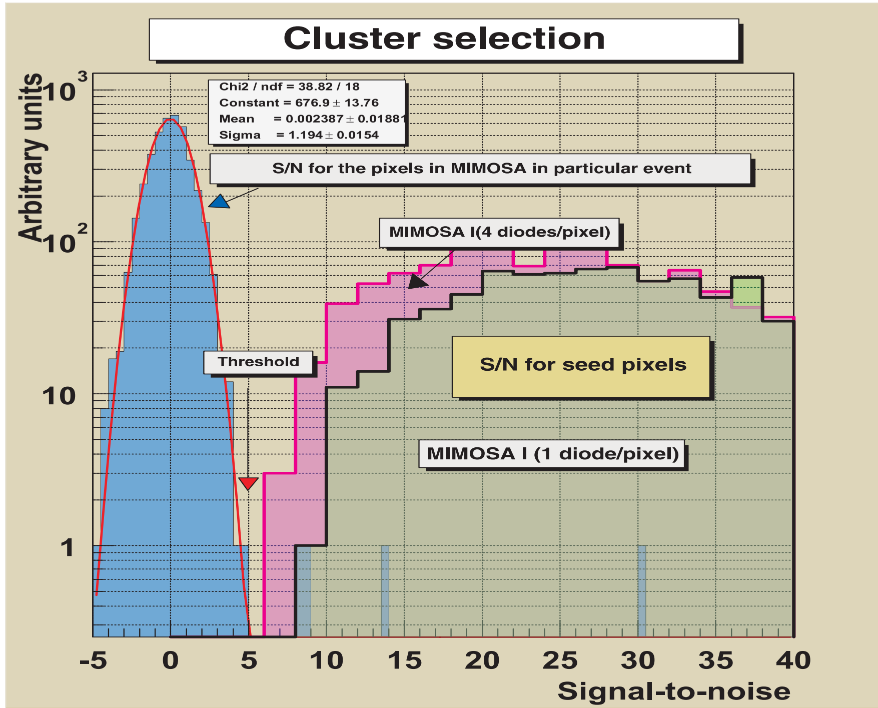
Monolithic Pixel CMOS Sensor for Particle Tracking

☑Beam tests results



… the track position in the middle of the telescope is predicted with the precision of ~1 µm



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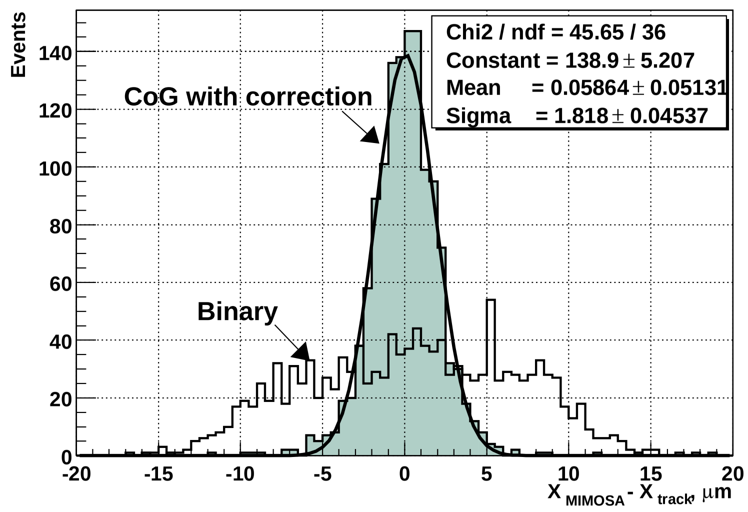
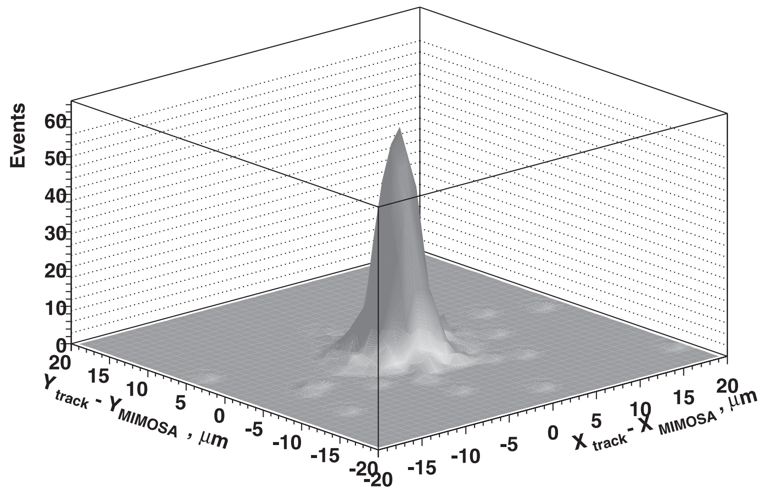
CMOS Monolithic Pixel Sensor: MIP particles tracking tests





ENC<10 electrons
S/N>30

Efficiency (5σ S/N seed cut):
$\varepsilon_{\text{hits} < 20\,\mu m} = 99.5\ \%$

Spatial resolution:
$\sigma = 1.4\ \mu m$

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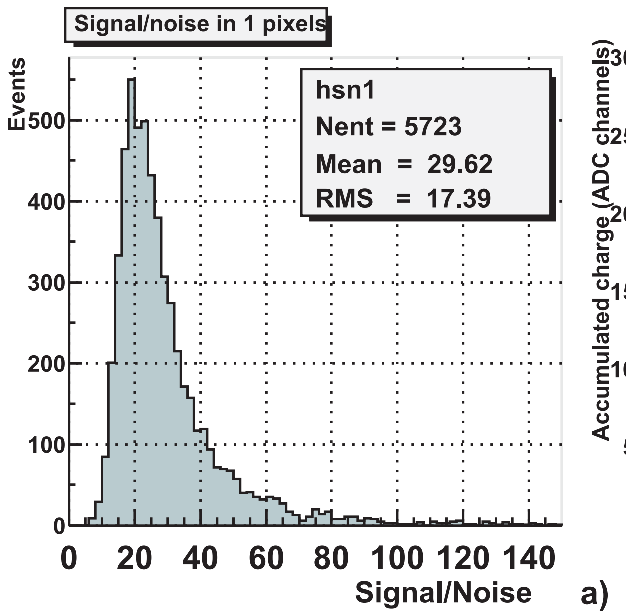
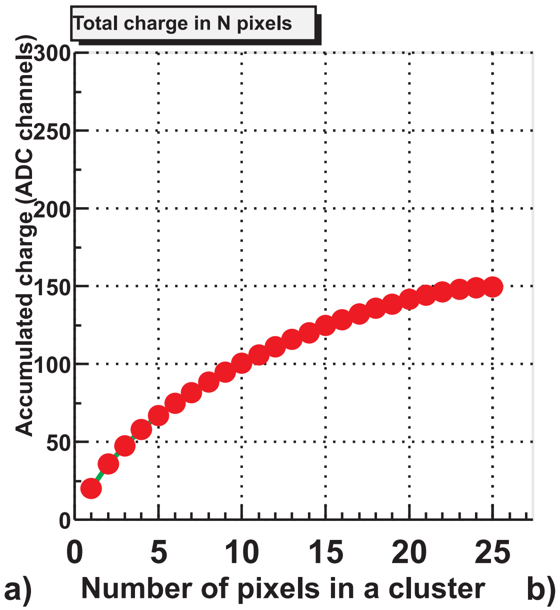
MIMOSA-4 test results:

0.35 mm AMS process without epitaxial layer but with low doping (resistivity) substrate





Observed performances with 120 GeV/c p- at CERN-SPS:
- Detection efficiency ~99.7%
- S/N ~30 but charge is wider spread
- Spatial resolution ~4 μm (20 μm pitch)

Technology without epitaxial layer seems worth investigating and optimizing

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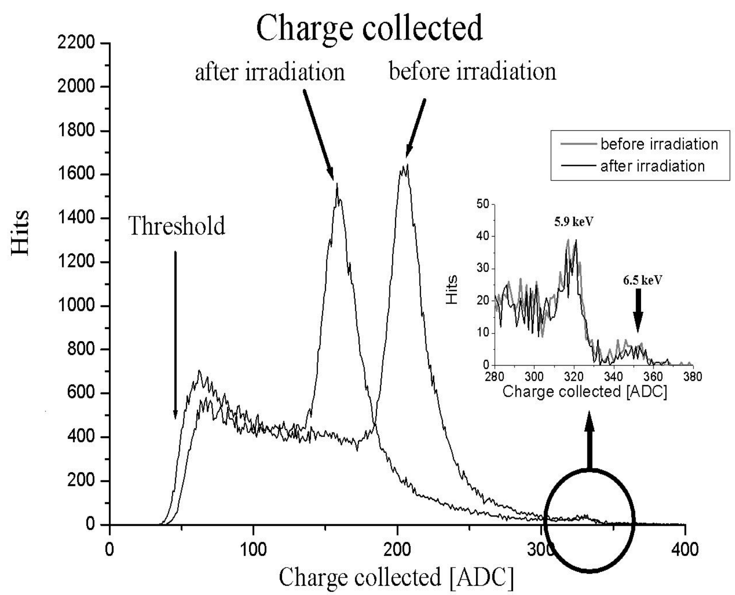
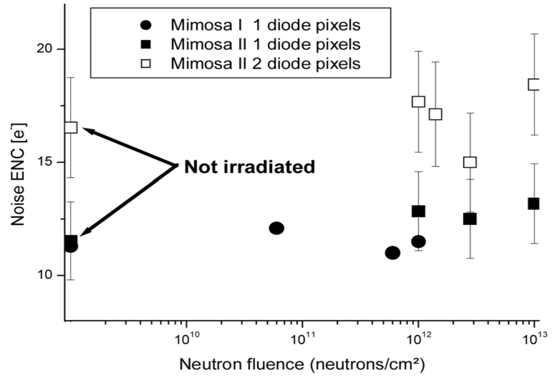
Neutron radiation tolerance

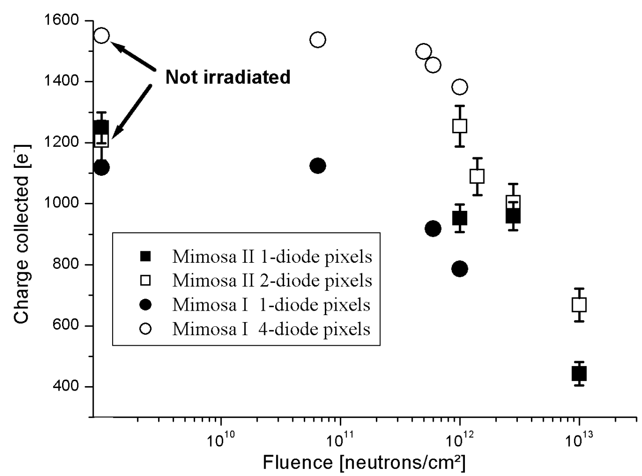
Chips irradiated with neutron sources at JINR and CEA-Saclay reactors were tested with Fe^{55} X-ray source.



Noise as a function of fluence:



Observed charge loss as a function of fluence:



Charge loss is observed only for fluences $>10^{11}$ n/cm^2 what is 2 orders of magnitude more than it is expected for TESLA!

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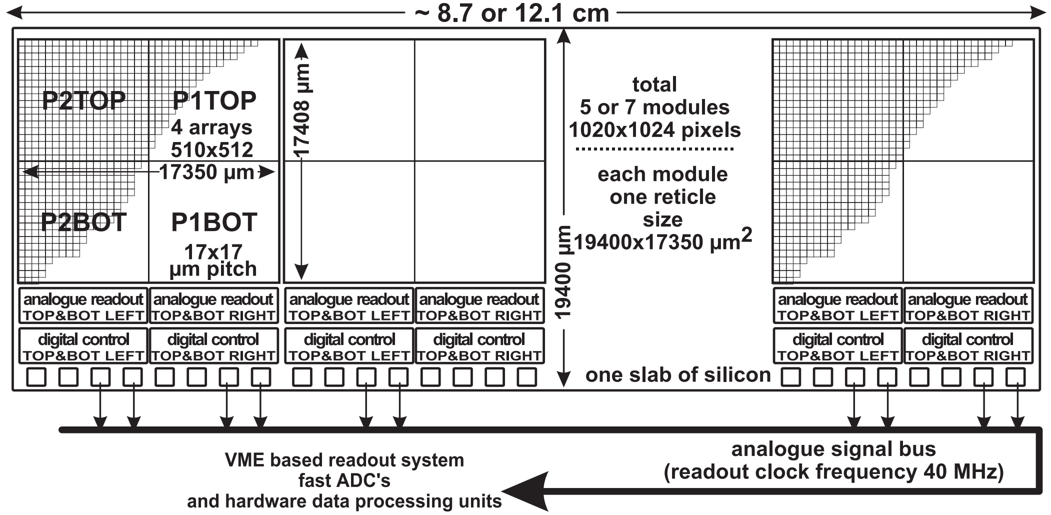
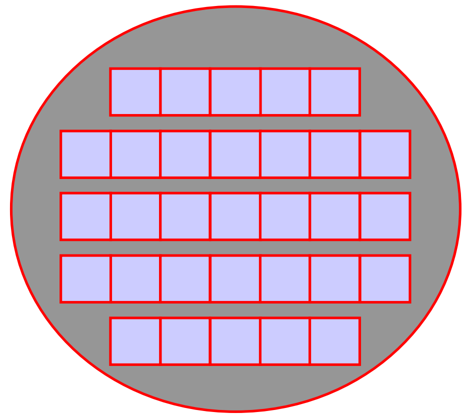
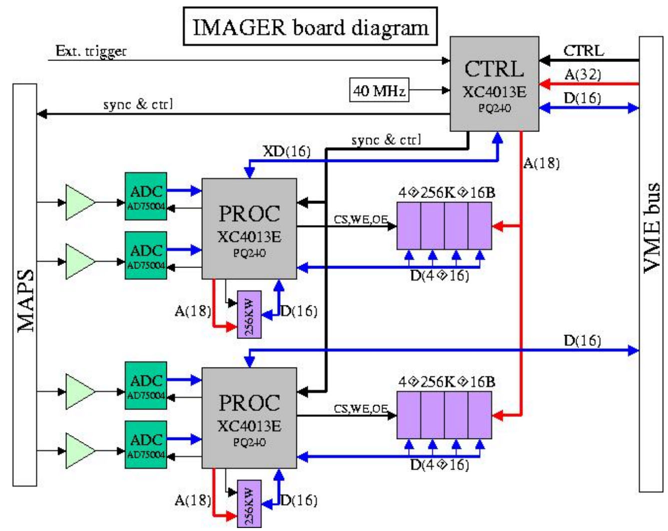
Monolithic Pixel CMOS Sensor for Particle Tracking

☑ MIMOSA V - wafer scale detector





- ☑ stitching: coarse - 100 µm + scribeline, option:precise - 1 µm
- ☑ normal readout: 6ms/frame, fast sampling readout: 100 µs/frame
- ☑ 0.6 µm with 14 µm epitaxial layer
- ☑ lot of six 6’’ wafers 44 kEuro
- ☑ analogue readout - with hardware processing
- ☑ acquisition board with hardware processor - pedestal subtraction, CDS, S/N analysis, sparsification on-line.



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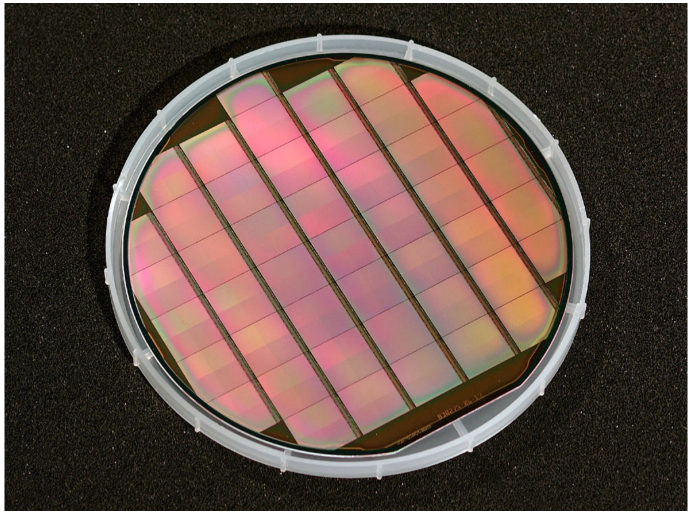

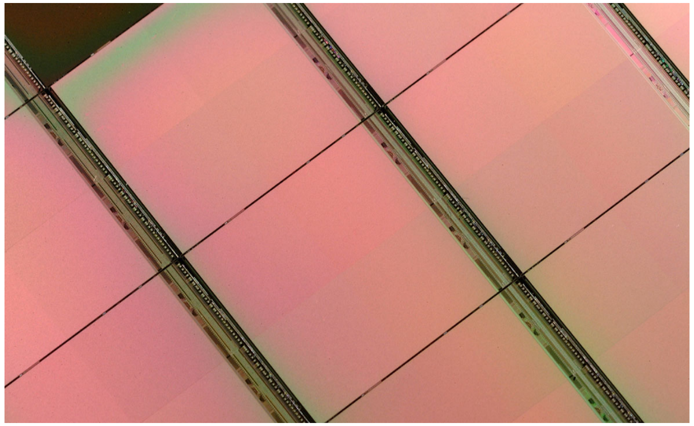

Mimosa-5 status

- 6 wafers delivered by AMS
- 1 wafer back-thinned (down to 120μm) and sliced
- prober tests of all wafers in progress: first estimation of yield ~30%
- 4 corner chips send to Barcelona for fine back-thinning
- beam tests at CERN: results as expected

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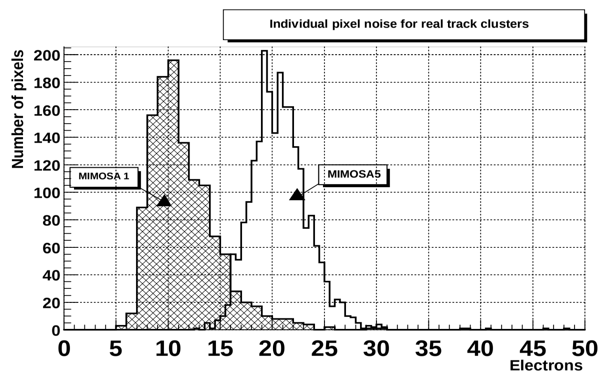
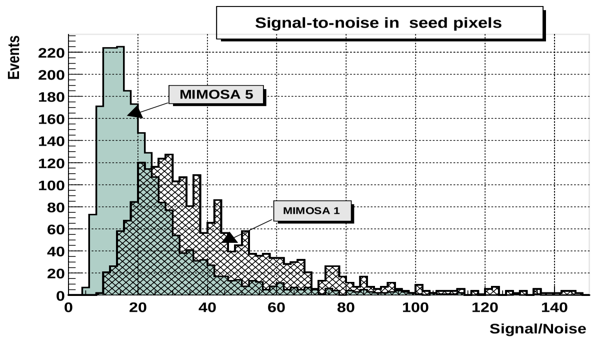
MIMOSA-5 tests

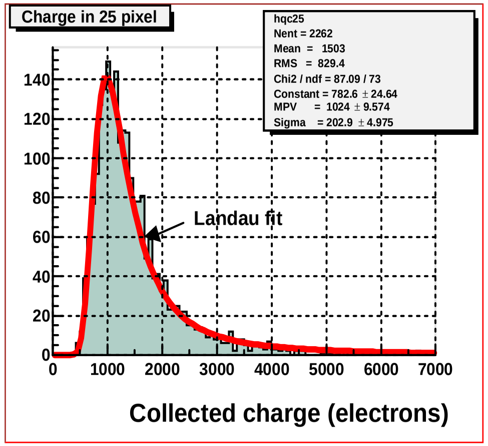
The chip (4 matrices of 512×512 pixels (17x17 μm²)
0.6 μm AMS process, etched down to 120 μm
exposed to 120 GeV/c π^- beam at CERN-SPS

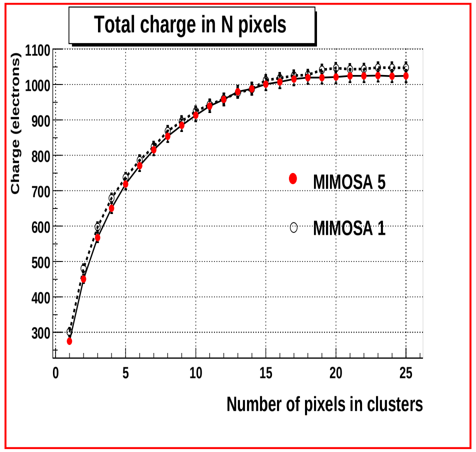
The same process as MIMOSA-1 _ the same performances expected?

Larger noise relative to M1 (different serial r.o.architecture)









Epitaxy layer ~14 mm _ charge ~1000e⁻

Preliminary results:
ε ~99.3%,
σ_{sp} ~1.7mm,
$\sigma_{gain} \leq$ 2-3%

close to those of MIMOSA-1

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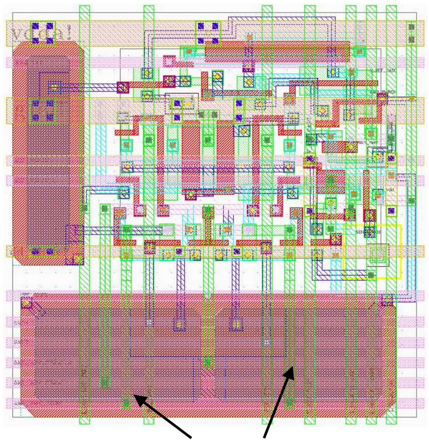
MIMOSA-6 – first sensor with integrated functionality

0.35 MIETEC technology (same as MIMOSA-2)
IReS-LEPSI/DAPNIA collaboration

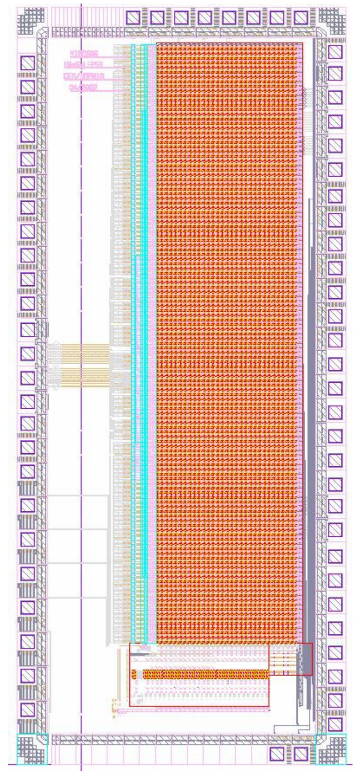
- **24 column readout in parallel**
- **128 pixels per column**
- **5MHz effective readout frequency**
- **Amplification (x5.5), <u>Correlated Double Sampling on pixel</u>**
- **<u>Discriminator integrated on chip periphery</u> (1 per column)**
- **Power dissipation ~500 μW per column**



Charge storage capacitors

Pixel layout:
28x28 μm²

29 transitstors



Chips are back from foundry this days.
Test results by the end of 2002.

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Monolithic Pixel CMOS Sensor for Particle Tracking

☑ **Good performance of CMOS pixels successfully demonstrated with small scale prototypes ε~99%, S/N~20-40, σ~1.5-2.5 µm @ 20x20 µm^2 pixels ,**

☑ **First wafer scale chip - works according to expectation!**

☑ **Access to processes with epitaxial layer (e.g. TSMC CIS 0.25 µm with 8 µm p-type epitaxial layer - optimised for CMOS imagers),**

☑ **Cost effective solution (1900 USD/ 8'' wafer ⇨ 9 USD/cm^2 comparable to simple strip detectors),**

☑ **directions to investigate:**

- **fabrication of a large size chip - even of very simple architecture,**
- **for latter - estimation of yield, thinning to 20-50 µm, on-wafer stitching,**
- **data processing on-a-chip,**
- **radiation hardness (fairly good... hundreds kRad and 10^{12} n/cm^2 - *preliminary*),**
- **optimisation of the sensitive element - alternative charge sensing structures.**

☑ **R&D programme on CMOS MAPS TESLA VD in a collaboration with several other centres – aim for the detector design by 2004 -2005**

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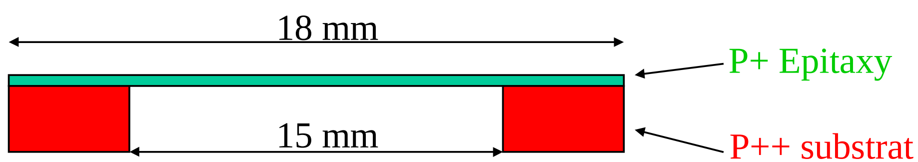
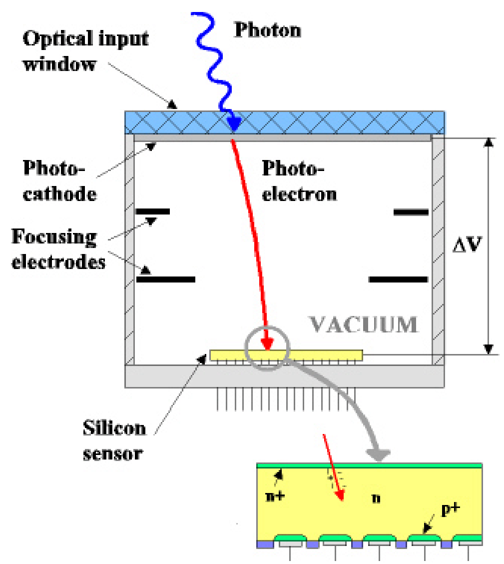
Monolithic CMOS Pixel Detectors for Radiation Imaging? A lot still to be done!

1. Visible light: first and the most important commercial application!
2. X and γ imaging: not very appropriate (except dental imagers using scintillating converter)
3. α and electron (β) imaging/dosimetry
4. Neutron imaging (using Be or Ga converter foils)



Back - thinning for low energy electrons imaging



Hybrid Photo Diode (HPD) ---> single photon imaging

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SUCIMA* European collaboration (F - G - I - Pl - CH) backed by EU grant since last year

Two different development lines :

- sensor for TERA beam monitor

- sensor for radioactive source imaging and dosimetry

*** Silicon Ultra Fast Cameras for Electrons and Gamma sources in Medical Application**

My acknowledgement to LEPSI and IReS teams working since 3 years on that project!

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