Use of standard CMOS imagers as position detectors for charged particles.

L. Servoli\textsuperscript{(1)}, D. Biagetti \textsuperscript{(1,2)}, S. Meroli \textsuperscript{(1,3)}, P. Placidi \textsuperscript{(1,2)}, D. Passeri \textsuperscript{(1,2)}, P. Tucceri \textsuperscript{(1)}

\textsuperscript{(1)} Istituto Nazionale di Fisica Nucleare Sez. di Perugia - Italy
\textsuperscript{(2)} Dip. di Ingegneria Elettronica e dell'Informazione Università degli Studi di Perugia - Italy
\textsuperscript{(3)} Dip. di Fisica Università degli Studi di Perugia - Italy
Outline

- Why standard CMOS imagers;
- The MT9V011 imager;
- Calibration with X-ray;
- Test with 180 GeV protons;
- Conclusion;
Standard Commercial CMOS Imagers

• Are made using standard CMOS processes;
• Mass production (tens of million of pieces);
• High quality;
• Optimized for collecting visible light;
• Advanced technological nodes (130 nm or lower).
Standard Commercial CMOS Imagers

- Are made using standard CMOS processes;
- Mass production (tens of million of pieces);
- High quality;
- Optimized for collecting visible light;
- Advanced technological nodes (130 nm or lower).

Are they usable for ionizing radiation detection?
Standard Commercial CMOS Imagers

- Are made using standard CMOS processes;
- Mass production (tens of million of pieces);
- High quality;
- Optimized for collecting visible light;
- Advanced technological nodes (130 nm or lower).

Are they usable for ionizing radiation detection?

Work made in collaboration with: Micron

Work made in collaboration with: Aptina
Micron MT9V011 Sensor (now Aptina)

- 640x480 pixels (VGA)
- 300k pixels
- 5.6x5.6µm pixel size
- 4.0µm epitaxial layer
- No microlenses
- No colour filter
- 10-bit ADC
- Rolling shutter
- Adjustable integration time from 56µs to 267ms
- Adjustable gain from 1 to 15.88
MT9V011: characterization without signal

Very good pixel homogeneity across all the ~ 300k pixels
MT9V011: characterization without signal

Very good pixel homogeneity across all the ~ 300k pixels

Pedestal
$41 \pm 0.8$ ADC
MT9V011: characterization without signal

Very good pixel homogeneity across all the ~ 300k pixels

\[ \langle \text{Noise} \rangle = 2.5 \text{ ADC} \]

Pedestal
\[ 41 \pm 0.8 \text{ ADC} \]
MT9V011: characterization without signal

Very good pixel homogeneity across all the ~ 300k pixels

<Noise> = 2.5 ADC

Pedestal
41 ± 0.8 ADC

all pixels < 6 * Noise
MT9V011: characterization with X-ray

Sensitivity to a single $^{55}$Fe photon has been proved.

The response to a single photon is limited to few pixels (3x3 submatrix) with an average signal collection of more than 95%.
MT9V011: characterization with X-ray

Sensitivity to a single $^{55}$Fe photon has been proved.

The response to a single photon is limited to few pixels (3x3 submatrix) with an average signal collection of more than 95%.

The signal sharing among adjacent pixels is quite small; 2/3 concentrated on seed pixel.
A two-threshold clustering algorithm has been used: one threshold for seed pixel, another one for topologically connected adjacent pixels.
MT9V011: characterization with X-ray

A two-threshold clustering algorithm has been used: one threshold for seed pixel, another one for topologically connected adjacent pixels.

The pixels belonging to the cluster on average are 5-6.

Localization of signal (< 100-200 µm²)
MT9V011: characterization with X-ray

The response depends on the photoelectron production position on the pixel surface and also on the photon interaction depth.
The response depends on the photoelectron production position on the pixel surface and also on the photon interaction depth.

Only events in the mono pixel region will be used for absolute sensor calibration.
**MT9V011: characterization with X-ray**

- Approximated model of the signal distribution
- Fit of the measured data with the model

Both peeks are clearly visible
The sensor shows a very good energy resolution
FWHM = 227 eV
Commercial spectrometer shows rather similar values
Energy Calibration with X-ray sources

Using an X-Ray tube and $^{55}$Fe source the response to different deposited energies has been investigated. The sensor shows a good linearity up to 24 keV (Gain = 1).

From the slope we obtain:
- $7.0 \pm 0.1$ ADC/keV (Gain = 1)
- $139 \pm 15$ ADC/keV (Gain = 15.88)

In terms of electrons:
- $39.7 \pm 0.6$ [e-/count] (Gain = 1)
- $2.0 \pm 0.2$ [e-/count] (Gain = 15.88)
MT9V011: minimum sensitivity to X-ray

Detector response to $^{55}\text{Fe}$ photons.

**Sensitivity to released energy:**

1 keV.
MT9V011: response to 180 GeV protons

The device has been put on the SPS 180 GeV proton beam line. Again low occupancy for proton crossing (~ 5 pixels).
MT9V011: response to 180 GeV protons

The device has been put on the SPS 180 GeV proton beam line. Again low occupancy for proton crossing (~ 5 pixels).

<p>| | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>2.0%</td>
<td>6.7%</td>
<td>2.5%</td>
</tr>
<tr>
<td>6.5%</td>
<td>57%</td>
<td>7.5%</td>
</tr>
<tr>
<td>2.3%</td>
<td>7.3%</td>
<td>2.5%</td>
</tr>
</tbody>
</table>

Charge sharing among adjacent pixels: **57% in seed; 94% in the 3x3 submatrix.**

**Average number of pixels in a cluster:** 4.4
**MT9V011: response to 180 GeV protons**

Cluster charge using double threshold algorithm:

Using calibration constant we obtain:

\[ \text{MPV} = 405 \, \text{e}^- \]

In good agreement with 5 µm equivalent collection region (compared with 4 µm nominal thickness of epitaxial layer).
MT9V011: response to 180 GeV protons

\[
\frac{\text{Signal}}{\text{Noise}} = \frac{405}{6.5} / \sqrt{\text{number pixels in cluster}}
\]

\[S/N = 29.7 \pm 0.6\]
MT9V011: response to 180 GeV protons

Signal / Noise = 405 / 6.5 / √<number pixels in cluster>

S/N = 29.7 ± 0.6

Using the event by event Signal / Noise distribution for the seed:

S/N = 34.7 ± 1.0
MT9V011: Detection efficiency

From cluster and noise distribution a detection efficiency vs fake hit probability could be derived:

@ 6σ cut
> 99% efficiency

and a fake hit probability of 4 × 10^{-5}
MT9V011: summary for charged particle

• **Equivalent Electron Pixel Noise**
  - 36.0 ± 3.6 electrons (unitary gain);
  - 6.5 ± 0.7 electrons (maximum gain);

• **Charge collection capability**
  The MT9V011 collects 405 ± 10 e⁻ for 180 GeV proton.

• **Charge sharing**
  The seed pixel collects 57% of the total charge.

• **Signal over noise ratio for MT9V011**
  29.7 ± 0.6 at maximum gain (two-threshold cluster);
  34.7 ± 1.0 at maximum gain (seed pixel);
A new method to extract the intrinsic spatial resolution for a single device has been used:

**Grazing angle technique:**

A particle at small angle, almost parallel to the sensor surface. Many pixels “hit” by the same particle ➔ tracks!
Spatial resolution with grazing angle method

A new method to extract the intrinsic spatial resolution for a single device has been used:

**Grazing angle technique:**

A particle at small angle, almost parallel to the sensor surface. Many pixels “hit” by the same particle ➔ tracks!
Spatial resolution with grazing angle method

Setup at SPS beam line (protons or electrons @ 180 GeV)
Spatial resolution with grazing angle method

Reconstructed tracks
Spatial resolution with grazing angle method

• Select a track and reconstruct the spatial coordinates.

• **Fit with a line** and find best parameters and associated errors.

• Extract the spatial resolution from the distributions of the errors on the slope parameters.
Spatial resolution with grazing angle method

At SPS we got tracks spanning on average 15 pixels (± 2.2 due mainly to beam divergence)
Spatial resolution with grazing angle method

At SPS we got tracks spanning on average 15 pixels (± 2.2 due mainly to beam divergence)

Slopes are also well defined (28 mrad with 20 mrad opening angle)
Spatial resolution with grazing angle method

The average error on the slope of the track is: 7.4 mrad
Spatial resolution with grazing angle method

The average vertical error on the points of the track is:

\( 0.11 \pm 0.03 \) * pixel size.

The upper limit to the intrinsic spatial resolution for 5.6 mm pixel size is:

\( 0.62 \pm 0.18 \mu m \)
Conclusions (1)

• The suitability of CMOS Standard Imagers as Ionizing Particle detectors has been demonstrated for MIP and soft X-ray.

• Lower limit to detect "soft" X-ray: about 1 keV.

• Dynamic range up to 4.5 and 20 MIP (max and min gain settings) with good linearity.

• Small average pixel multiplicity (4-5), for the detection of charged particles.

• S/N ratio for MIP ~ 30;

• Detection efficiency for charged particles close to 100% with small fake hit rate.
Conclusions (2)

• An innovative method for extracting spatial sensor resolution with particle at grazing angle has been used.

• A 600 nm upper limit to the intrinsic spatial resolution has been measured.

Standard CMOS imagers could be used as particle detectors in specific applications.
BACKUP SLIDES
The signal definition is quite independent from the algorithm (cluster or 3x3 submatrix).

Events with charge shared among pixels are losing part of the collected charge.
The pixels belonging to the cluster on average are 4-5.

→ Localization of signal ($< 100-200 \, \mu m^2$)
Spatial resolution with grazing angle method

There is room for improvement (in principle)? Yes! Longer tracks will yield better track definition.

Here is a frame taken at LNF 100 MeV electron Beam.

Track length > 100 pixels