A Grazing Angle Technique to Measure the Charge Collection Efficiency for CMOS Active Pixel Sensors

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OUTLINE

- Charge Collection Efficiency
- Test Setup Description
- Method Description
- Results
- Conclusions

Charge Collection Efficiency

The use of CMOS Active Pixel Sensors as radiation detectors has been already established.

- Excellent spatial resolution
- High SNR
- Efficiency close to 100%

One important parameter to be analyzed is the **Charge Collection Efficiency (CCE) as a function of the distance from the pixel surface.**

Knowing this parameter is possible to understand the sensor sensibility when the electron/hole pairs are generated at different depths from the pixel surface and predict the pixel response.

How to measure CCE Profile ?

The most direct way to accomplish the measure of the Charge Collection Efficiency is to generate a known amount of electron/hole pairs at a given depth and then to measure the sensor signal → difficult task.

Various methods have been proposed (mainly for microstrip devices) among which:

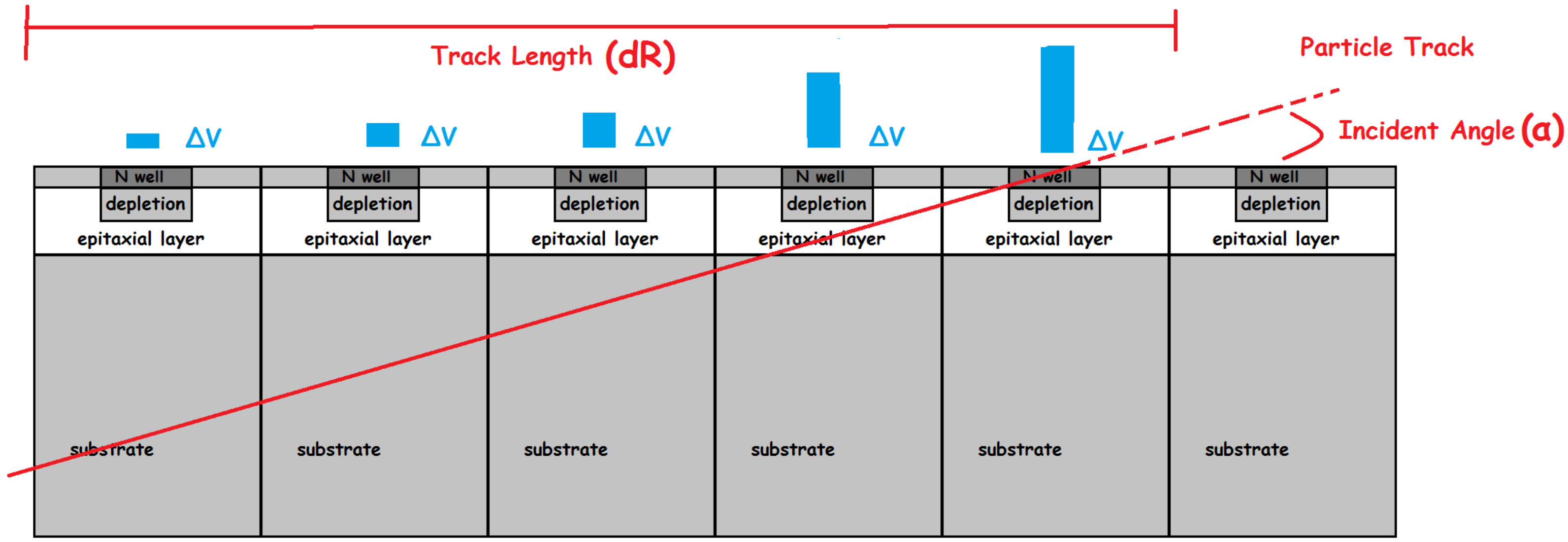
- an IR laser entering from a polished side of the silicon and focused at different depths under the relevant sensible element (strip or pixel);

- a charged particle beam incident at a small angle (grazing angle) on the sensor surface (our starting point).

In all cases one of the problems is the obtainable spatial confinement for the charge generation (several microns at best).

Introduction to the Grazing Angle Method

Using the "grazing angle" method, the charged particle crosses several pixels, each one at a different depth, with **the same average energy deposited in each pixel.**



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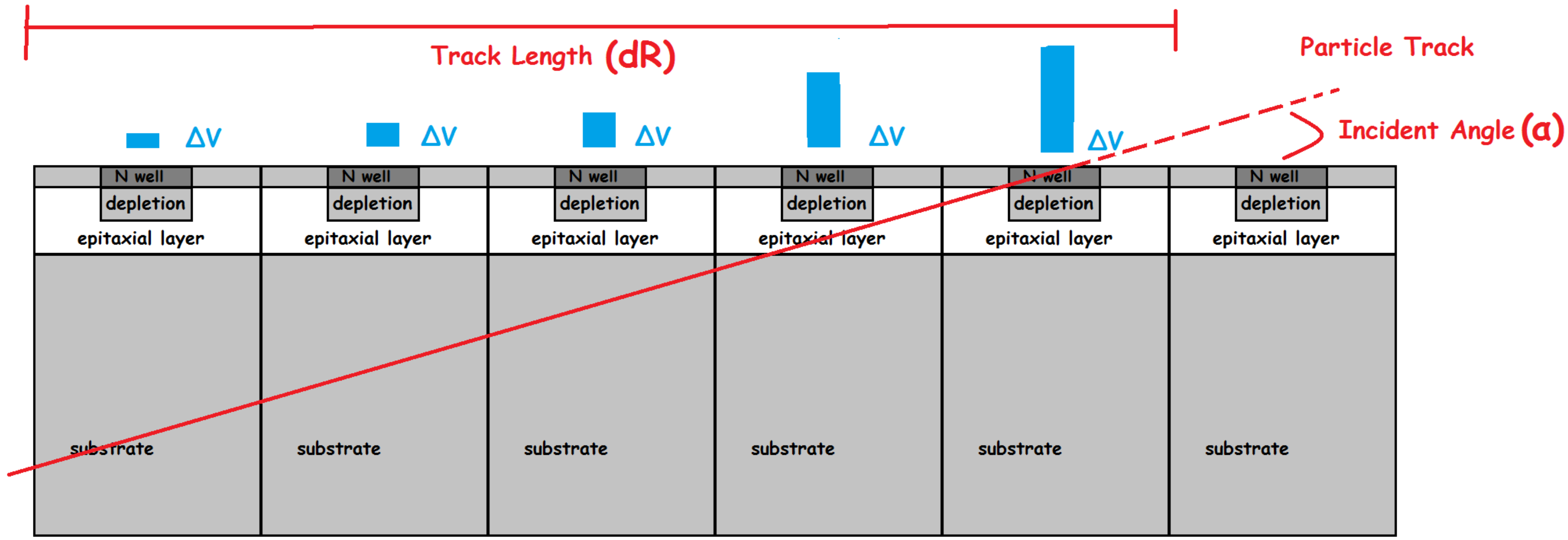


The incidence angle is correlated to the measurement of the track length.
dR= **d**/tan(α) **d** is the sensible layer of the sensor (most often unknown).

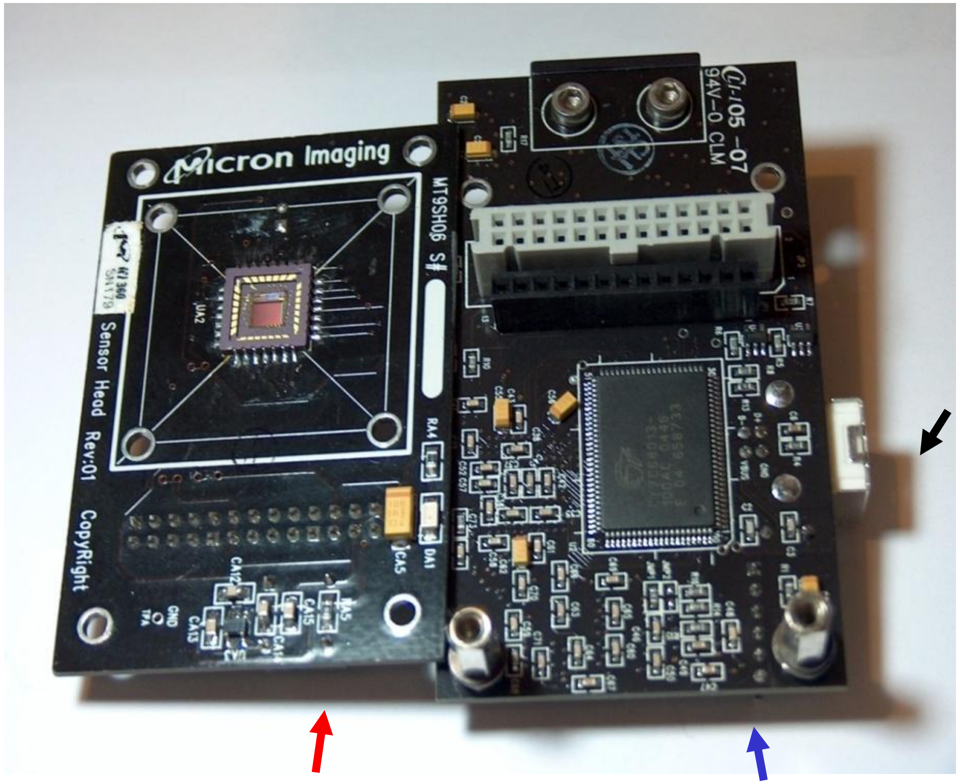
n-th pixel in the track is always crossed by the incident particle at the same depth ➔ controlled depth for electron/hole generation.

CMOS Active Pixel Sensor

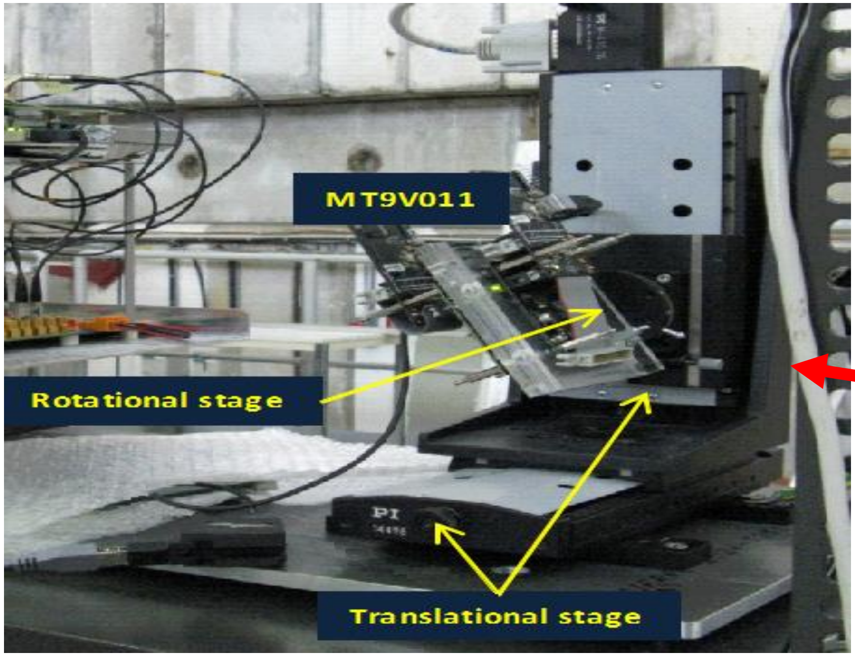
To perform this test a commercial sensor has been used

MT9V011 Micron Sensor

- 640x480 pixels (VGA)
- **5.6x5.6μm pixel size**
- **4.0 μm epitaxial layer**
- No microlenses and colour filter
- 10-bit ADC
- Adjustable gain from 1 to 15.88



Test Setup



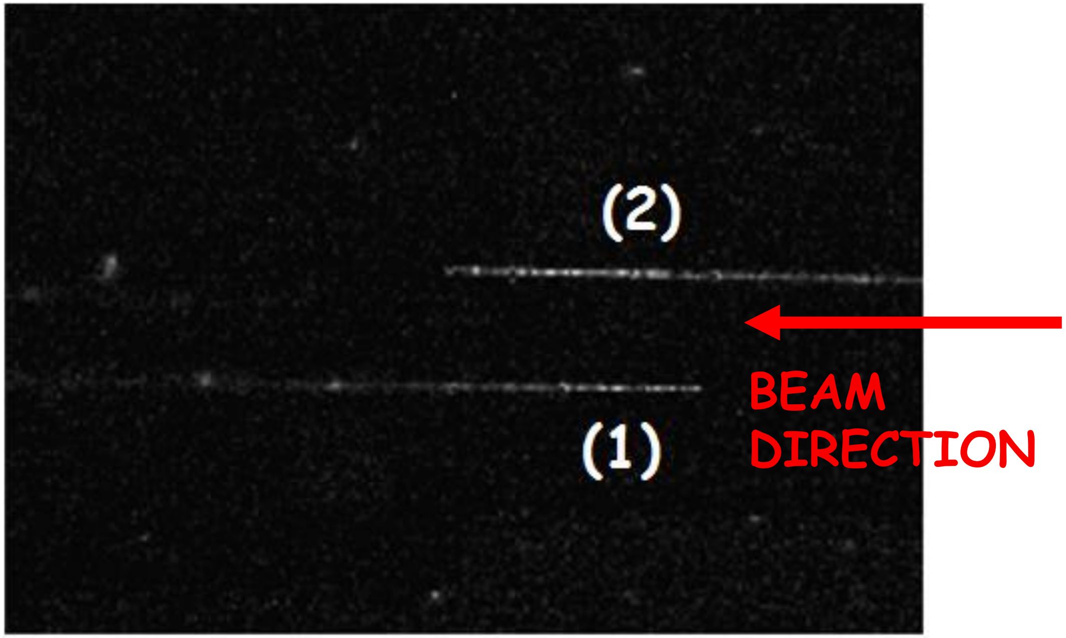
BEAM DIRECTION

The sensors were exposed to:
100 MeV electrons at Laboratori Nazionali di Frascati;
12 GeV protons at CERN ProtoSynchrotron.

To have track length up to 100 pixel, given the sensor geometrical constraints

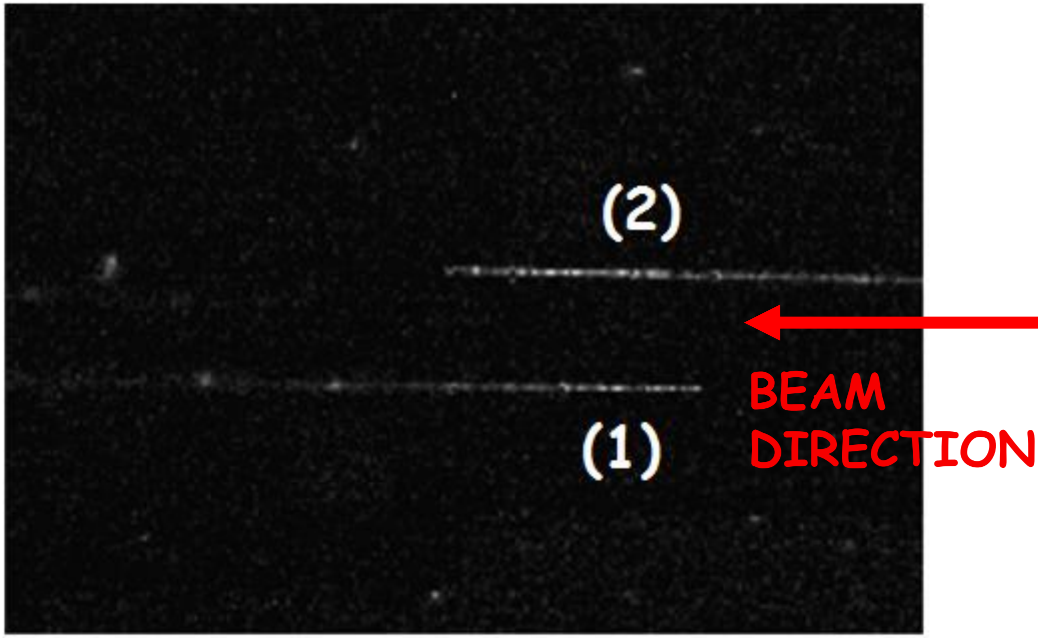
➔ **incident angle ranging from -5° to +5°.**

Test Setup



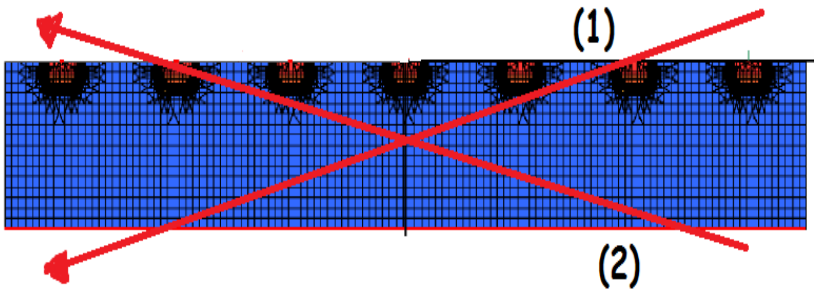
Online display of two simultaneous tracks.

Test Setup

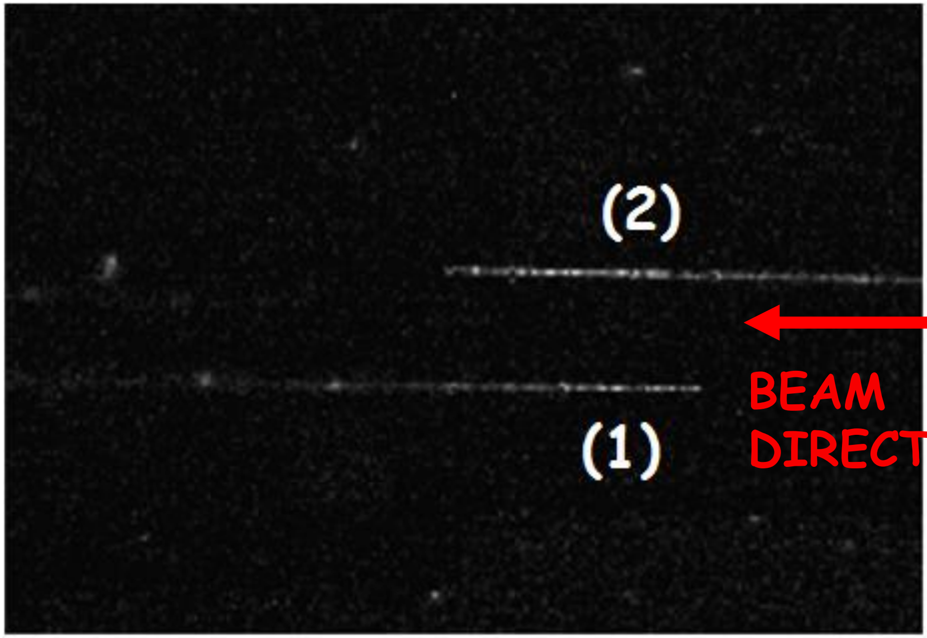


Online display of two simultaneous tracks.

Due to the beam divergence the tracks hit the sensor from opposite sides



Test Setup



BEAM DIRECTION

Online display of two simultaneous tracks.

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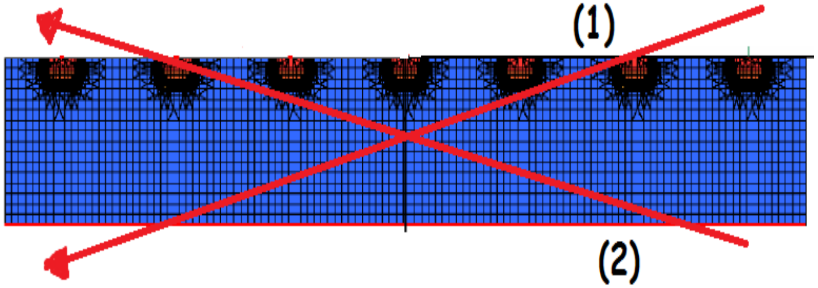


(1)Track entering from sensor surface
→ the first part of the track shows a higher pixel response respect to the tail which tends to be confused with the background noise

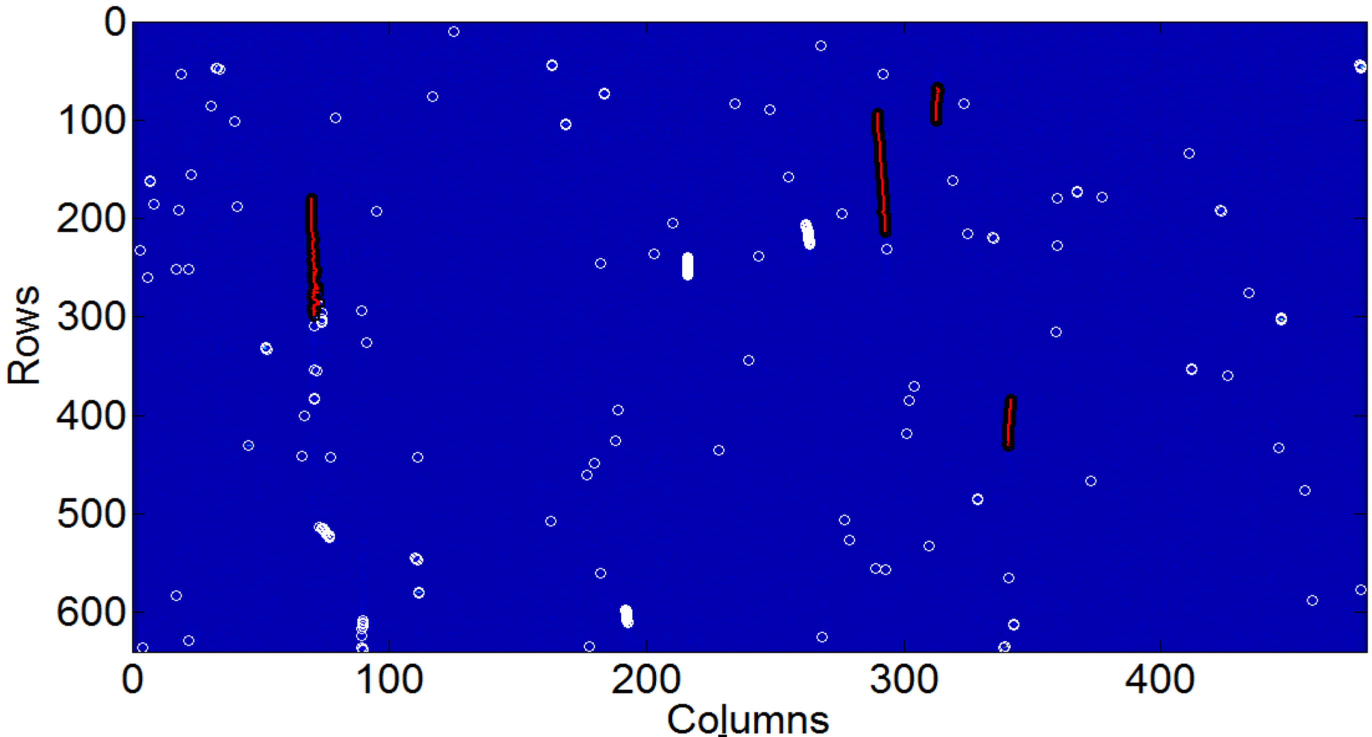
(2) Track entering from sensor back
→ Symmetric respect to track 1 behaviour

➔ **CMOS Sensors capability to distinguish the two track types.**

Track Finding Algorithm

A track finding algorithm has been implemented in order to select "good" tracks and to reject background signals (noisy pixels, short track).

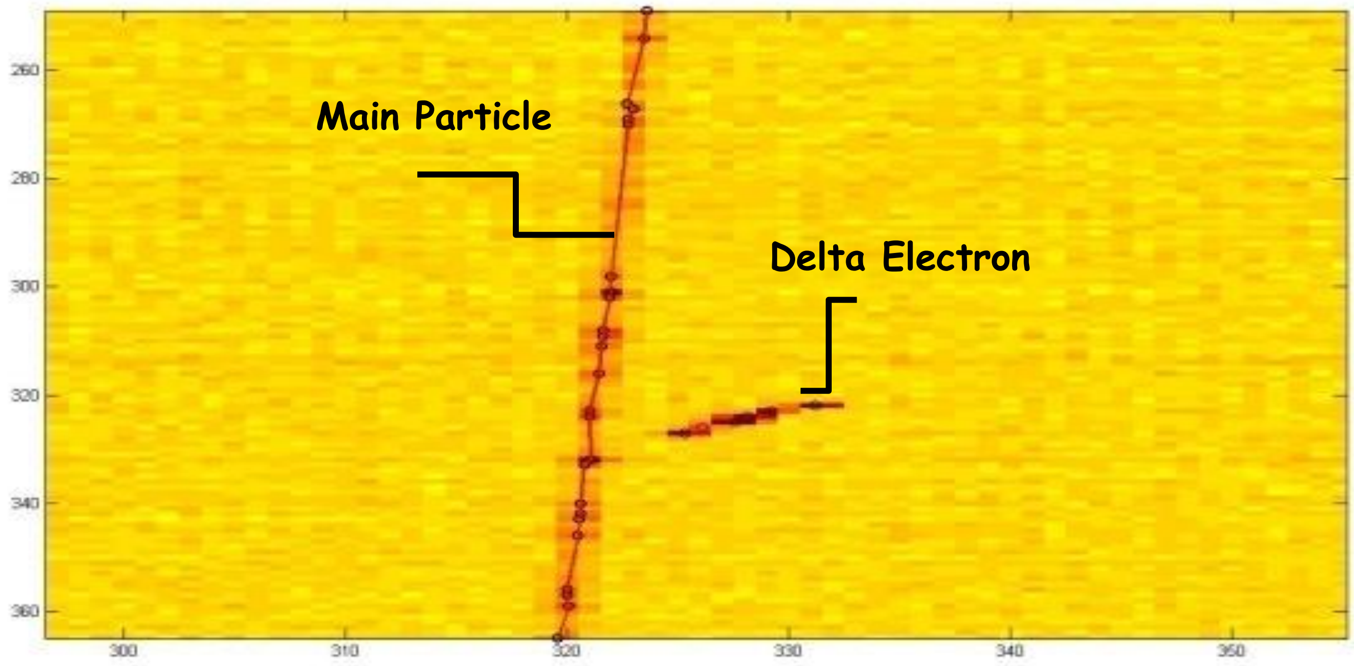
For each hit pixel pertaining to a row orthogonal to the beam direction its neighbors are tested: if their signals are greater than a defined threshold (2 times the pixel noise), the pixels are included in the track.



Track Finding Algorithm

Very good separation capabilities between different tracks have been obtained.

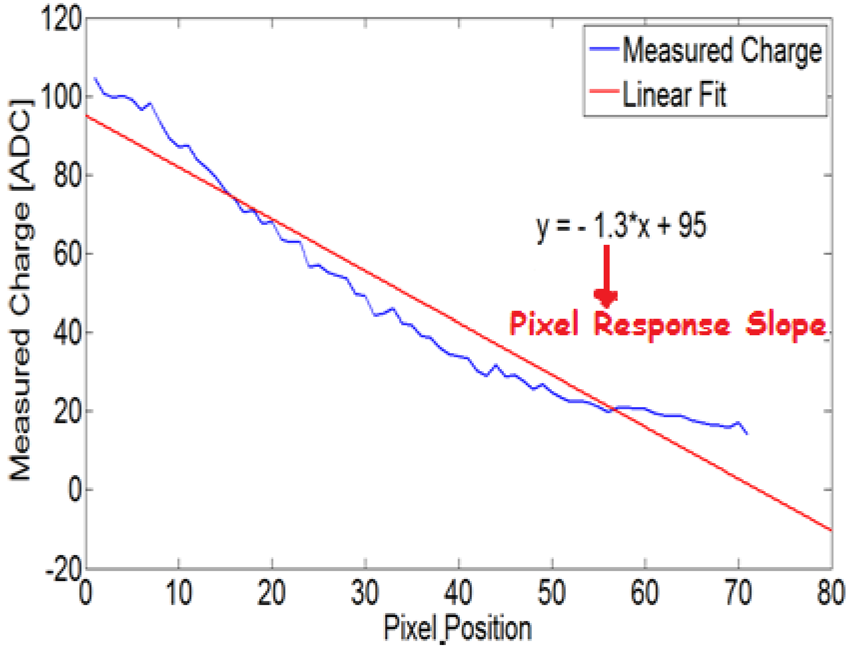
Two different tracks with only few separation pixels, can be defined.

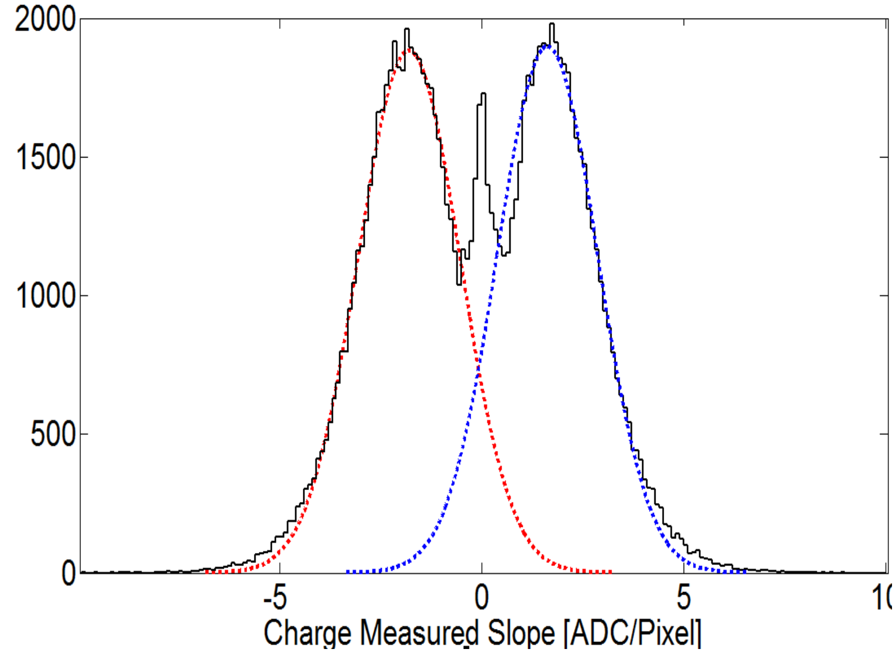


This is mandatory to select clean tracks for the analysis and to reject tracks with secondary emissions.

Grazing Angle Method

• To distinguish tracks entering from the sensor surface respect to the ones entering from the back the variation of pixel response along the track has been used.



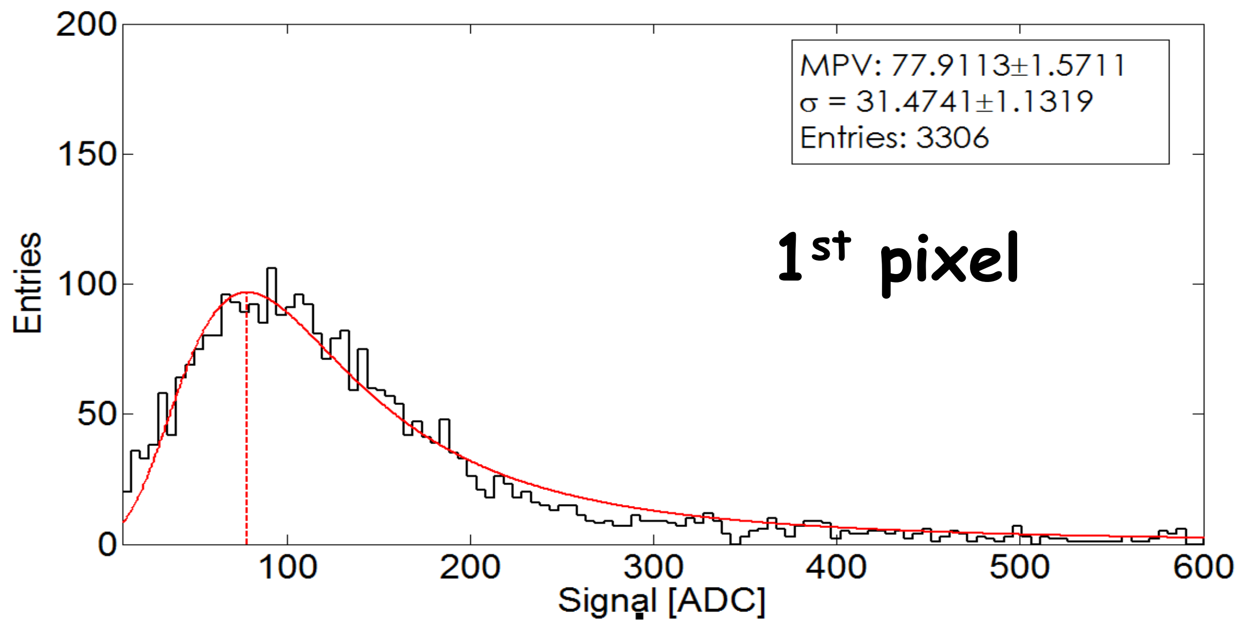


In the rigth figure the distribution of the pixel response slope along the beam direction is plotted.
Tracks entering the surface have negative slope because the pixel response begins high and decreases to zero.

Grazing Angle Method

• Select tracks entering from the sensor surface with the same length (for instance with a length of 100 pixels).

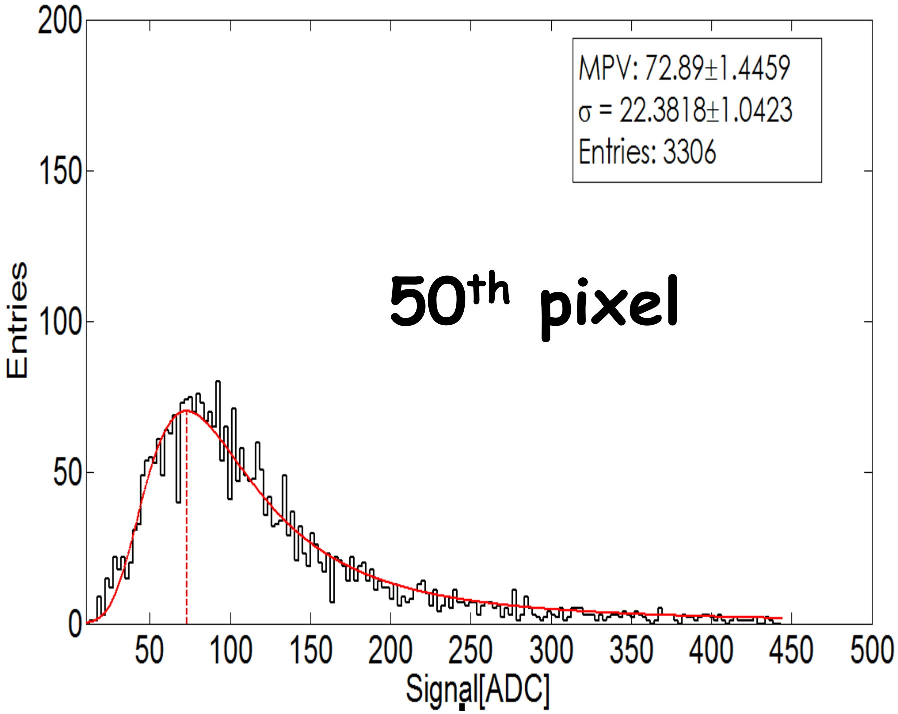
• Take the first pixel for all collected tracks and built a signal distribution.

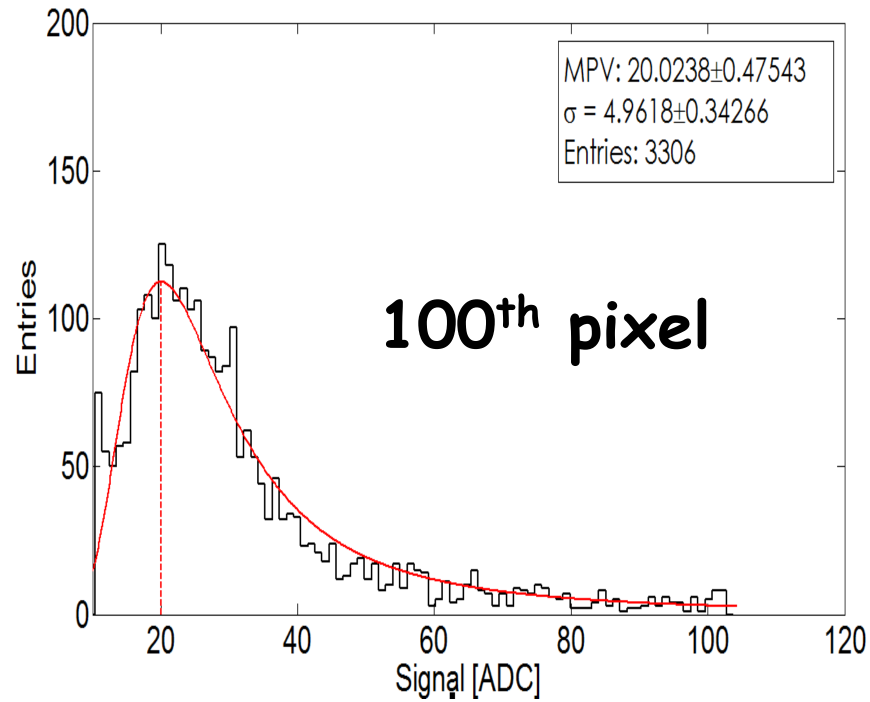


The signal distribution is well modeled by a Landau-Vavilov distribution.

Grazing Angle Method

After the first pixel we build the signal distributions for each pixel position.

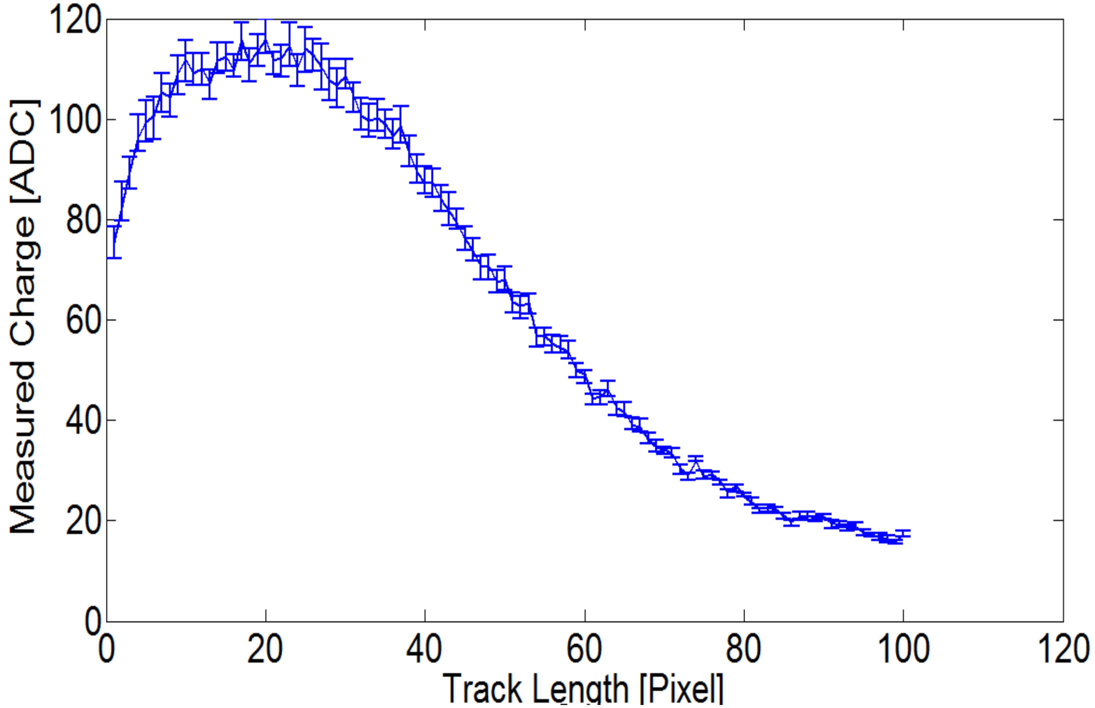




→ For each pixel position we take the MPV of the signal distribution

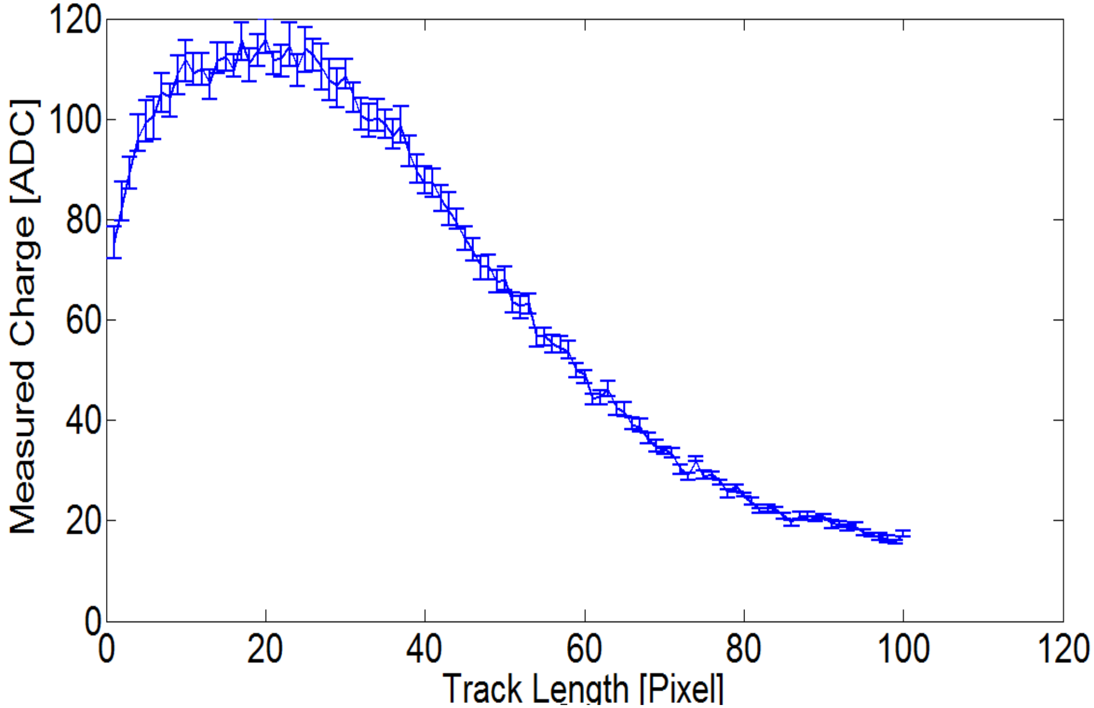
CCE Profile

The most probable values (MPV) for each pixel can be plotted as a function of pixel position along the track.



CCE Profile

The most probable values (MPV) for each pixel can be plotted as a function of pixel position along the track.

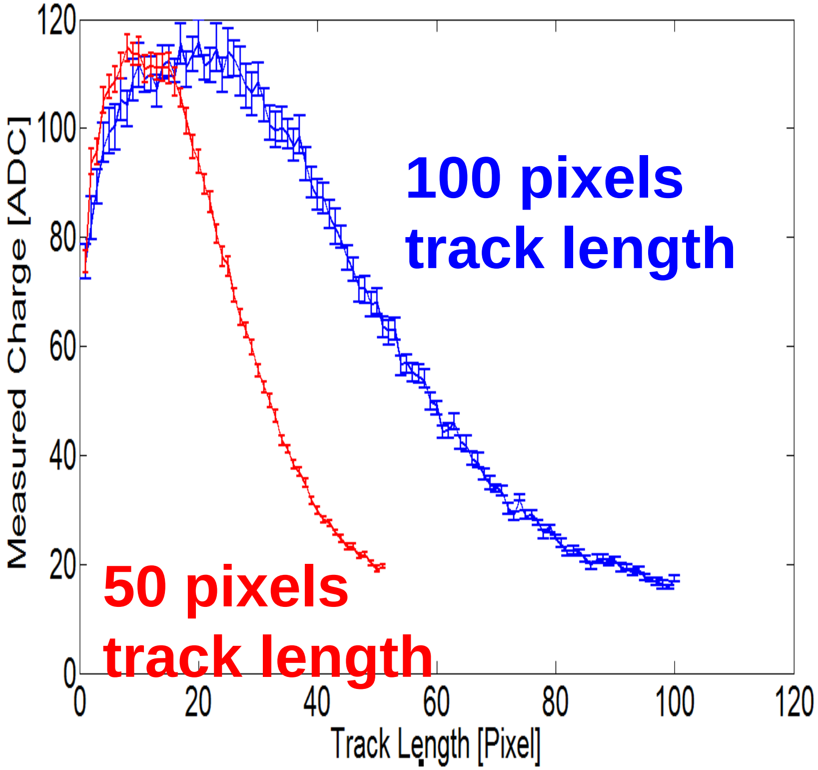


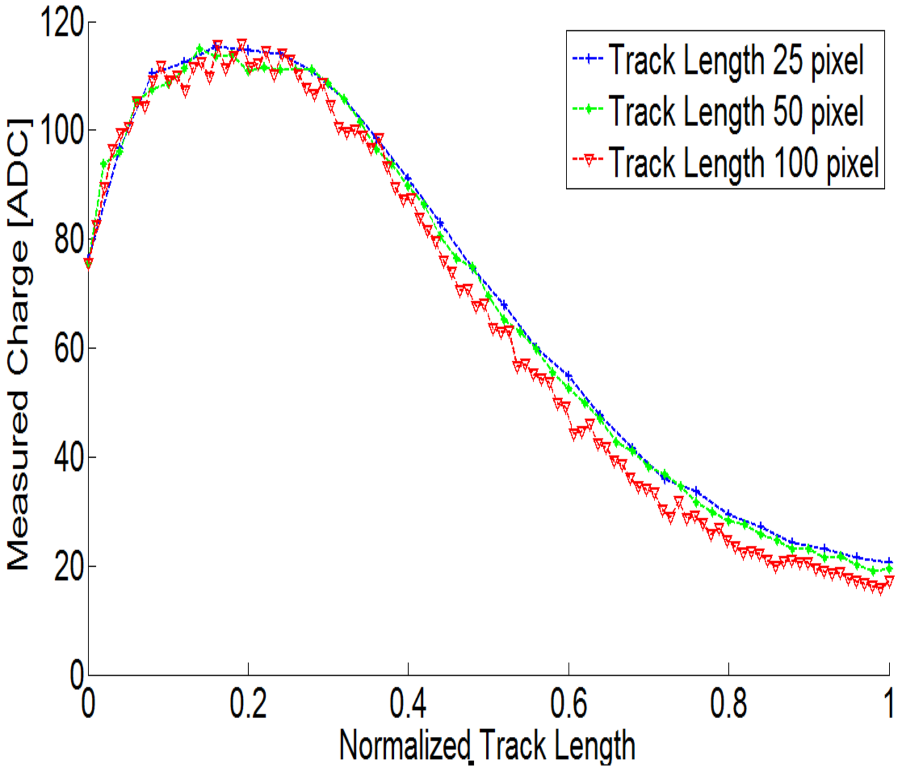
Position 0 is the track start (point closest to the surface) and position 100 is the track end (point farthest to the surface).

It is evident the modulation of the response as a function of the pixel position.

CCE Profile

Varying the track lengths different profiles are obtained:

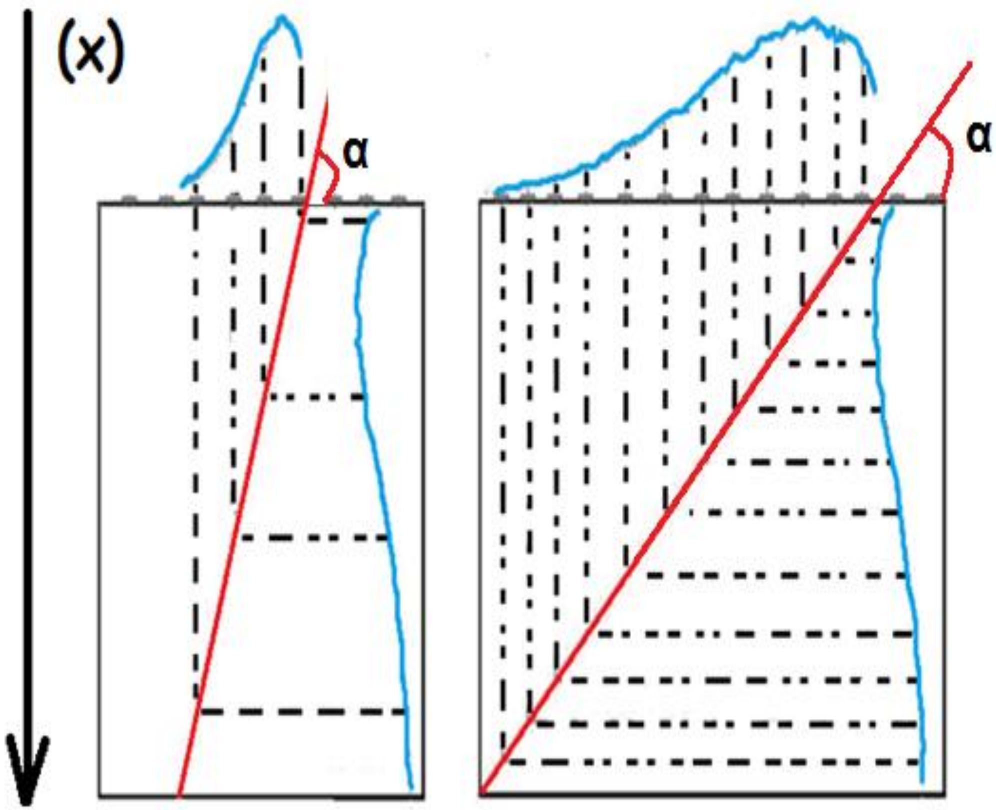




Normalizing the profiles to track length, the curves overlap.
The shape of the profiles are very similar. The only difference is the curve sampling.

Grazing Angle Method: scale normalization

The last step is translate the horizontal scale unit from pixel units to length units (micrometers).
→ need **α** to extract the depth scale of CCE profile.



The average total charge released by an inclined track is described by:

$$Q_{tot} = \frac{1}{\sin\alpha}\int_0^d Q(x)\,p(x)\,dx$$

Q(x) is the charge released at distance x from the surface;
p(x) is the CCE profile function;
α is the track incident angle on the sensor surface;
d is the maximum depth at which the function ***p(x)*** is measured.

Grazing Angle Method: scale normalization

$$Q_{tot} = \frac{1}{\sin\alpha}\int_0^d Q(x)p(x)dx$$

For orthogonal tracks α = 90° the average total charge is the MPV of the Landau-Vavilov fit.

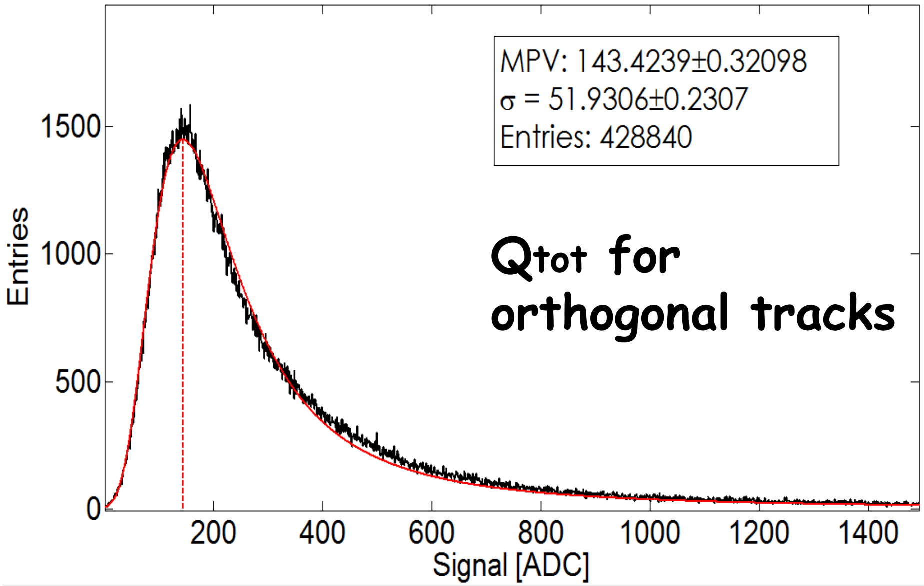
$$Q_{tot} = Q_{ort} = \int_0^d Q(x)p(x)dx$$

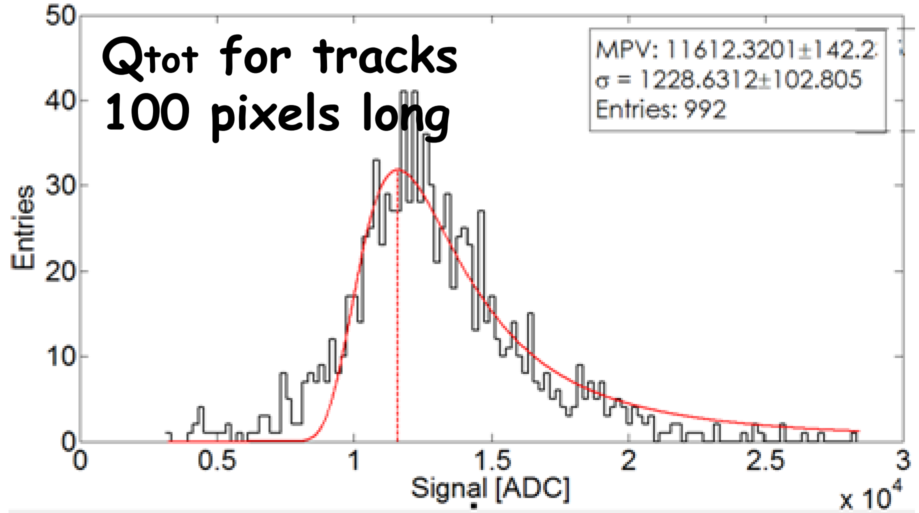
Defined the value of integral is very simple to measure the incident angle of the other tracks.

$$\frac{Q_{ort}}{Q_{tot}} = \sin\alpha$$

➔ we could extract **α**.

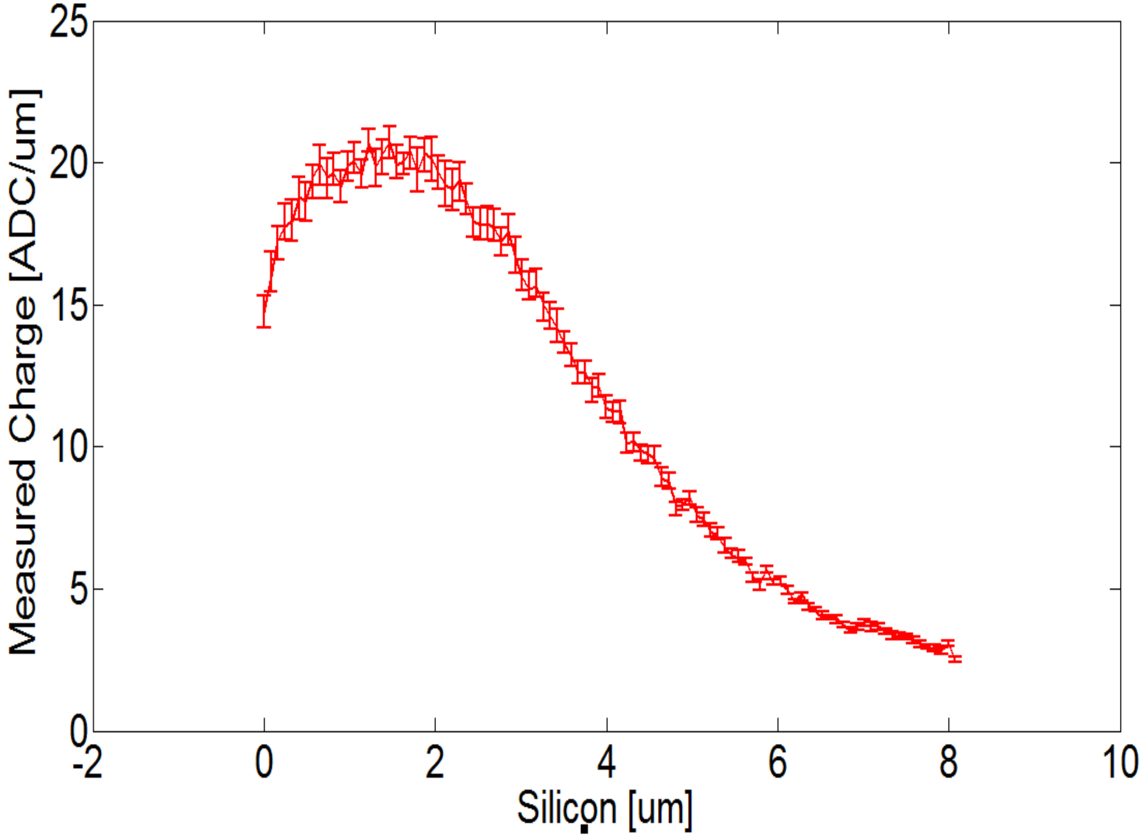
➔ the **depth scale** is extracted from **α** and the **track length**





MT9V011 Profile

The result for sensor MT9V011 (4 um epi-layer) is shown in figure.
In the vertical scale is reported the signal per unit track length.
The horizontal scale starts from 0 (silicon surface) and goes toward negative values (silicon bulk).



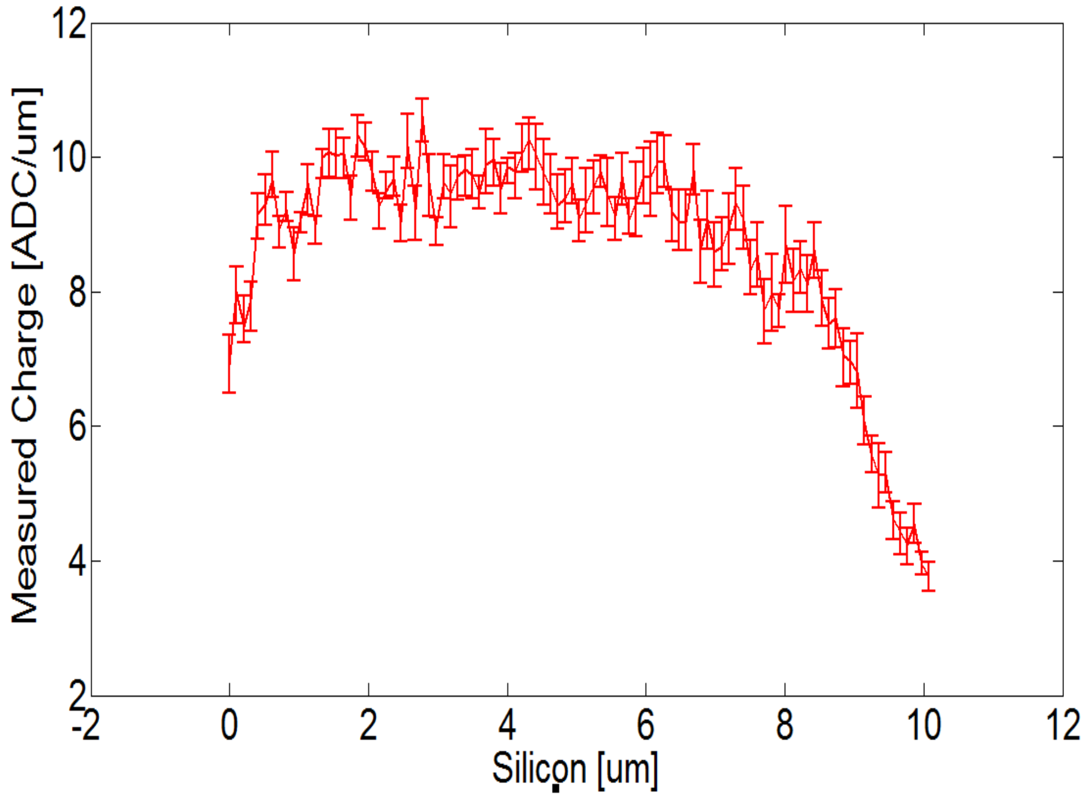
first 0.5 um:
charge collection efficiency is not complete
→ **CMOS electronic regions**

from 0.5 to 2.5 um:
plateau in efficiency
→ **presence of 4 um epitaxial layer**

from 2.5 to 8 um:
efficiency decreases
→ **increasing distance of the charge creation region from the photodiode**

MT9V032 Profile

Another sensor MT9V032 with different epi-layer thichness (12 μm) has been tested and preliminary results are shown in figure.



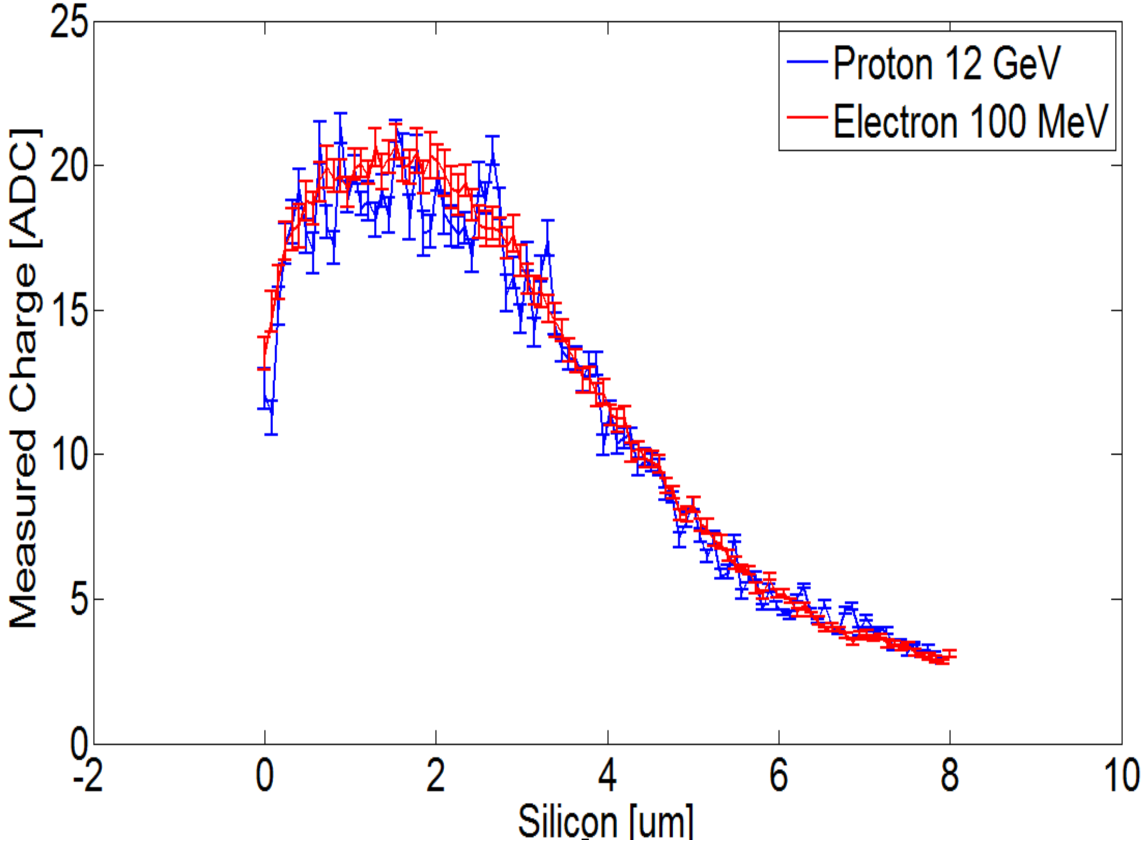
first 0.5 um:
charge collection efficiency is not at maximum
→ **CMOS electronic region**

from 0.5 to 9 um:
plateau in efficiency → **presence of 12 um epitaxial layer**

from 9 um:
efficiency decreases
→**increasing distance of the charge creation region from the photodiode**

CCE Profile

In figure are reported two profiles of MT9V011 sensor obtained using 100 MeV electrons (BTF at LNF) and 12 GeV protons (PS at CERN).
No difference is visible in all the measured domain.



This result is important because it allows either high or medium energy facilities to be used for the charge collection efficiency profile measurement.

Conclusions

• Is possible to measure the charge collection efficiency profile for CMOS pixel sensors in great detail **(80 nm sampling granularity already achieved).**

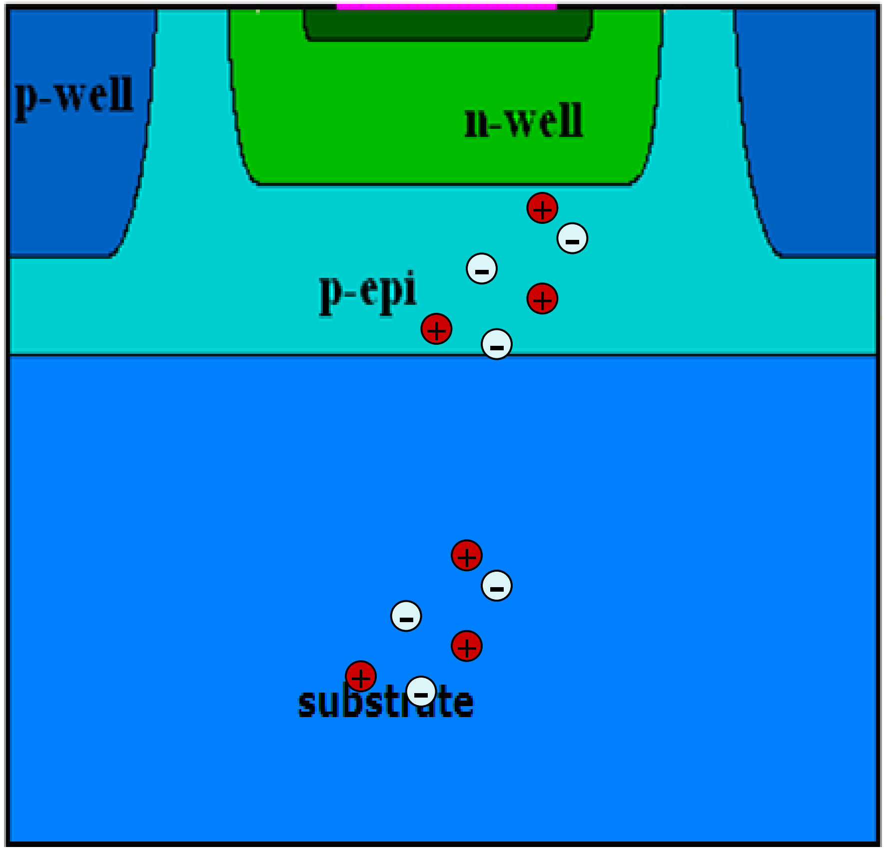
• Only one sensor with sufficient segmentation (> 32x32 matrix) is required.

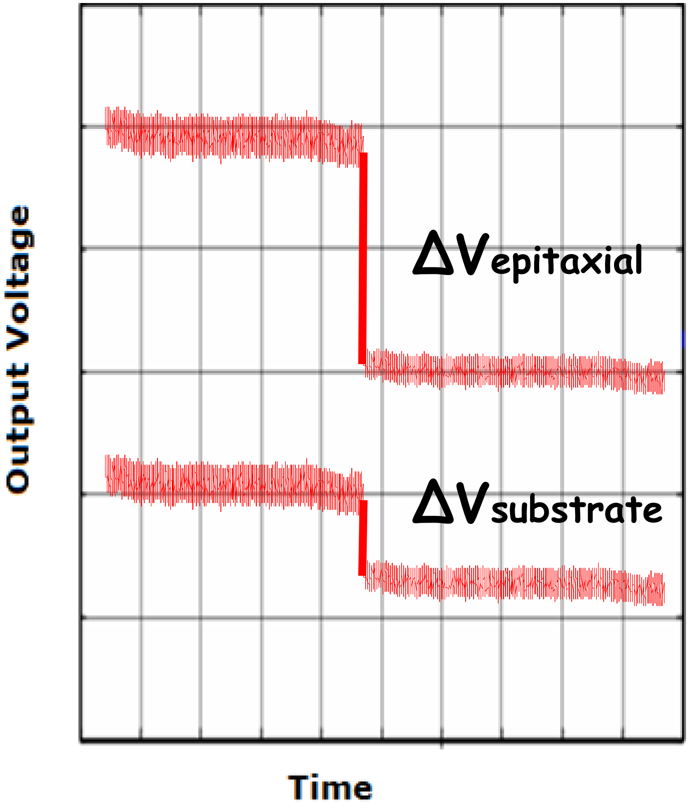
•There is no need for external informations.

•Medium energy accelerators (100 MeV electrons or even less) could be used, extending considerably the number of available facilities.

Backup

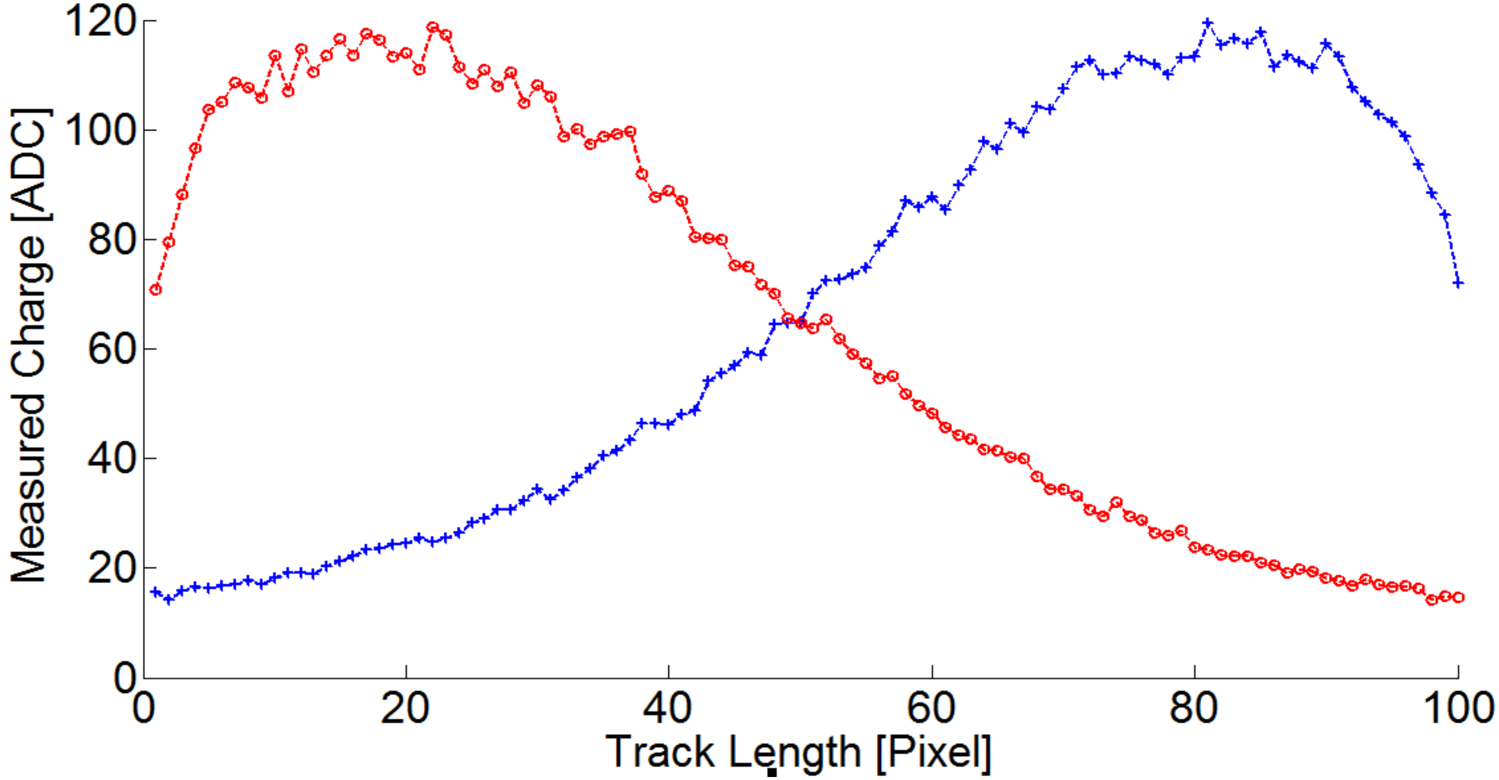
Charge Collection Efficiency





CCE Profile

In this figure there are two profile obtained using the tracks coming from the sensor surface and from the back.



The high symmetry shows that the track finding algorithm is working very well.