Study of a CMOS pixel sensor based high spatial resolution beam telescope

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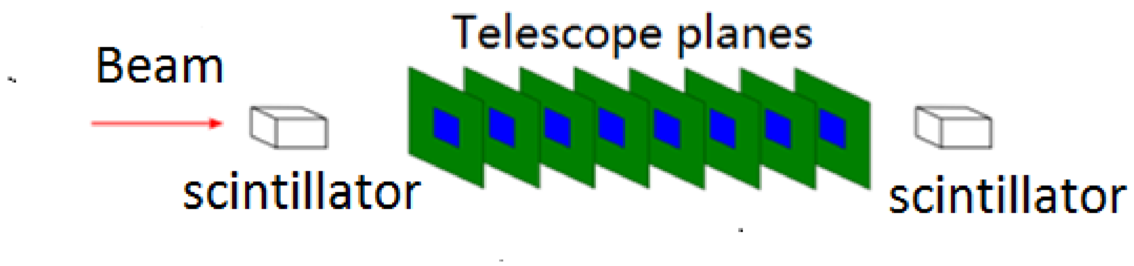
Outline

- Introduction of the beam telescopes
- Motivation
- Conceptual design
  - Pixel sensor
  - Telescope module
  - Readout
  - Mechanics and services
  - Reconstruction and alignment
- Simulation
- Summary

Beam telescopes

Beam telescopes tracking charged particles to determine the spatial resolution and the detection efficiency have been proven to be a useful tool for the characterization of the position sensitive detectors.
The devices under test range from pixel sensors and micro-strip sensors to GEM and medical applications, among others.

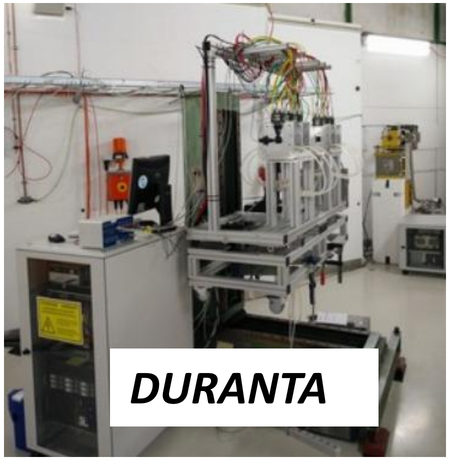


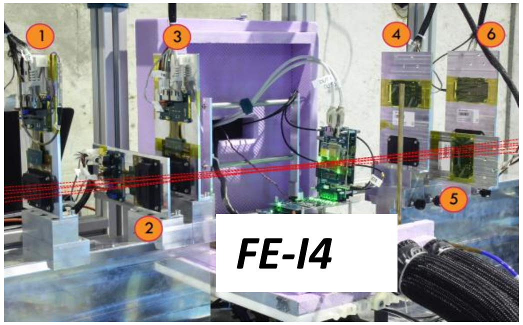
The figure of merit of a beam telescope is the **track resolution**. It defines the precision with which a particle trajectory can be determined for a biased (unbiased) track.

Key parameters:
- Spatial resolution of telescope reference planes
- Material budget of telescope planes and DUT
- Plane spacing
- Energy of particles

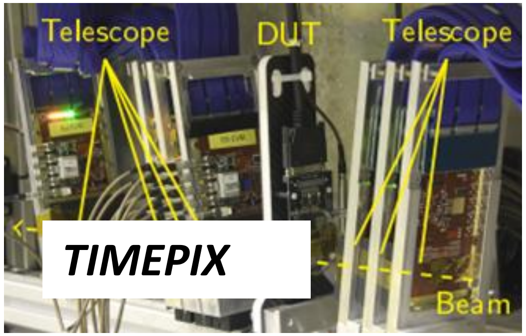
Telescopes family

- EUDET, MIMOSA-26 based, 7 built in DESY
  - AIDA, commuting between DESY and CERN SPS-H6.
  - ANEMOME (6-MIMOSA+1-FEI4+2), Bonn-ELSA.
  - ACONITE, copy for ATLAS used at CERN-SPS-H6, DESY, SLAC.
  - DATURA, copy for DESY, at the TB21 area.
  - CALADIUM, ESA, SLAC, USA
  - DURANTA, copy for DESY, at the TB22 area
  - AZALEA, used at the CERN PS





- LHCb&CLIC-TIMEPIX @ CERN-SPS-H8
- Geneva FEI4 @ CERN-SPS-H8
- Mu3e-MuPix @ CERN-SPS-H6
- ALICE-Alpide @ CERN-PS
- KarTel (Ljubljana, EUDET family) @ CERN-SPS-H6
- Strasburg Telescope @ CERN-SPS-H6
- The LYCORIS strip telescope @ DESY



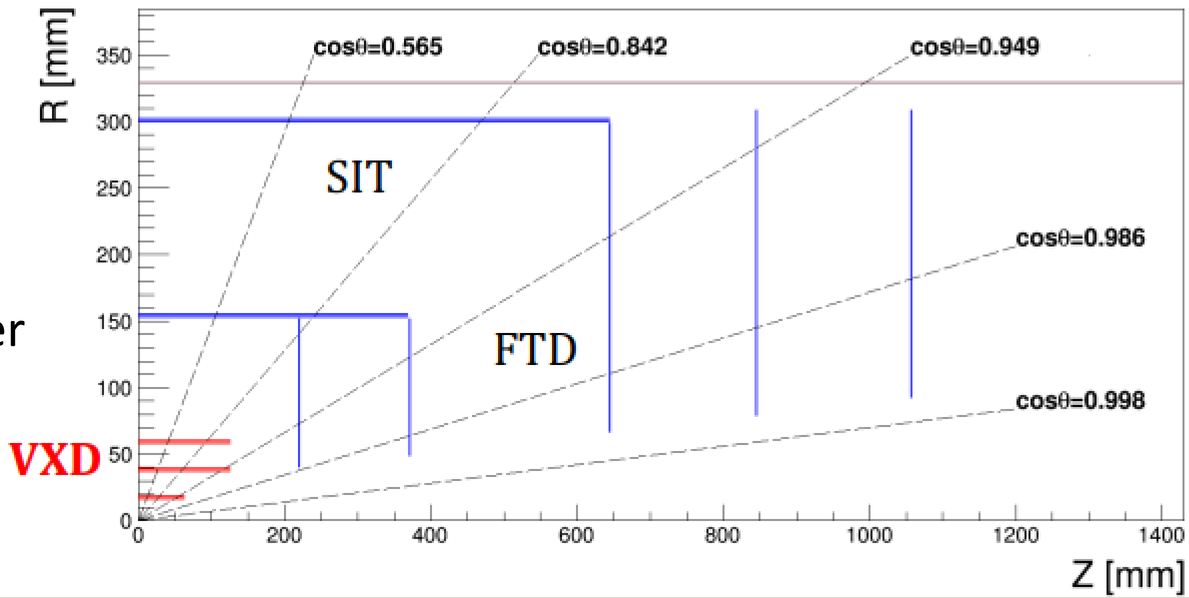
Motivation

The position requirements for the next generation collider experiments will reach a level of a few microns, for instance,

- ILC(<4 μm),
- CLIC(3 μm vertex, 7 μm tracker),
- CEPC(3-5 μm)

CEPC Vertex detector (VXD):

- ILD-like layout
- σ_{SP}=2.8 μm, inner most layer
- σ_{SP}=4 μm, outer layer

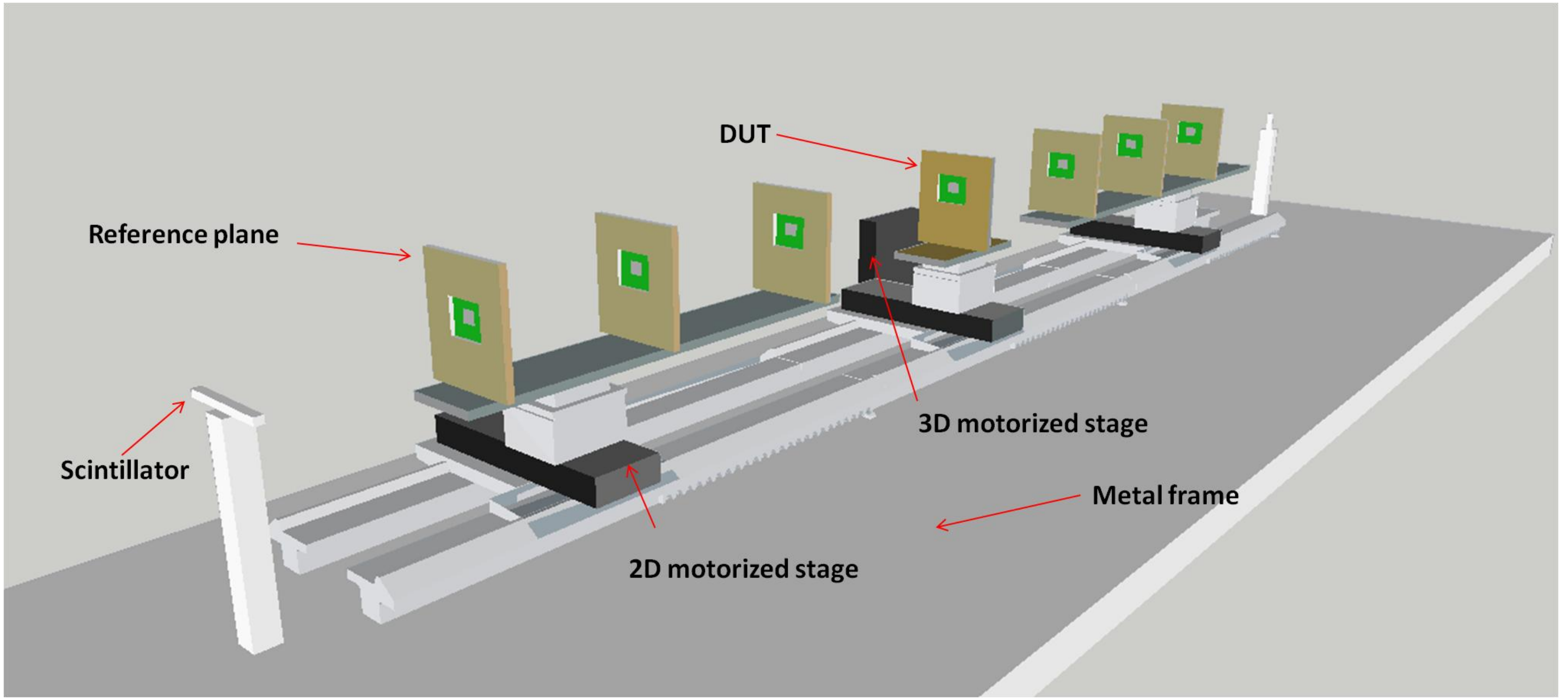


A new beam telescope which could offer the spatial resolution of 3 μm with a 1.5 GeV electron test beam (BEPC test beam) is under R&D.

Conceptual design

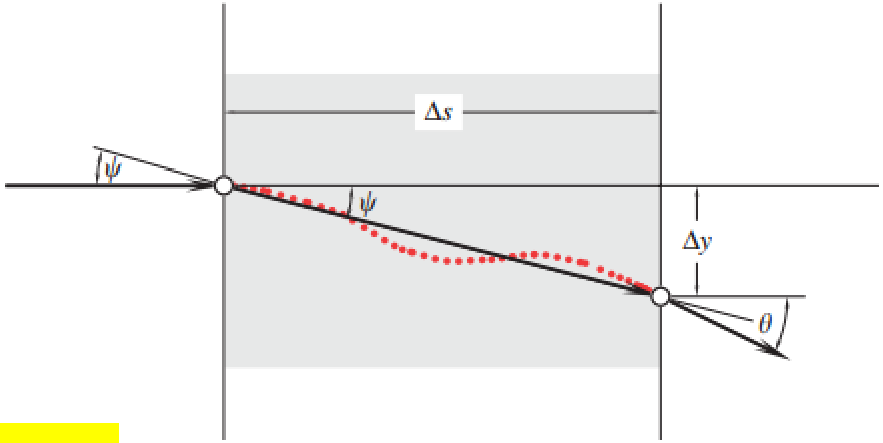
The telescope mainly consists of:

- Two arms, each hosting 3 reference planes
- One or four high spatial resolution CMOS pixel sensors on each plane
- DUT mounted between the two arms
- Crossed scintillators for trigger
- DAQ



Analytical verification (1/4)

Angular deflection of charged particles would be caused by the multiple Coulomb scattering (MS). The distribution of the angle is approximately Gaussian. The width of the distribution is estimated by the formula:



$$\Delta\Theta = \frac{13.6\ \mathrm{MeV}}{\beta cp} z \sqrt{\frac{dx}{X_0}} \left[1 + 0.038 \ln\left(\frac{dx}{X_0}\right)\right]$$

- βc: particle velocity
- z: charge of particle
- X_0 : radiation length
- p : momentum of particle

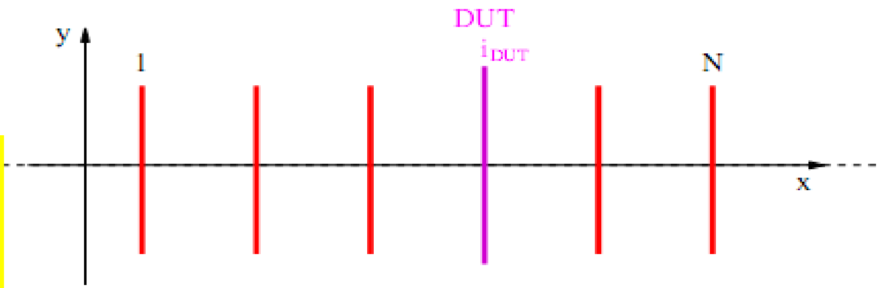
Lower energy particles have higher scatter probability.

$X_0 = 9.36$ cm for silicon

Analytical verification (2/4)

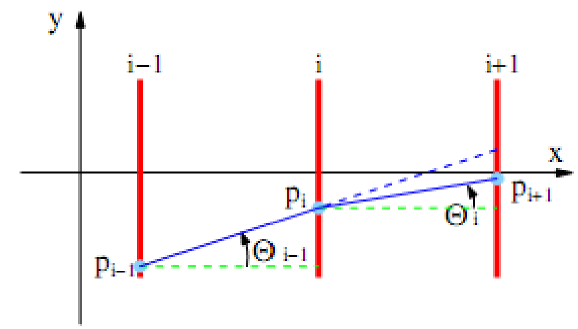
- Taking in to account the MS, Chi[2] for plane i can be written as:

$$\Delta\chi_i^2 = \left(\frac{y_i - p_i}{\sigma_i}\right)^2\Big|_{i\neq i_{DUT}} + \left(\frac{\Theta_i - \Theta_{i-1}}{\Delta\Theta_i}\right)^2\Big|_{i\neq 1,N}$$



- The angle can be calculated as:

$$\Theta_i = \frac{p_{i+1} - p_i}{x_{i+1} - x_i}$$



- N-1 measured positions, and no scattering term for the first and the last plane.

- Summing over all the planes:

$$\chi^2 = \sum_{i=1}^{N}\varepsilon_i(y_i - p_i)^2 + \sum_{i=2}^{N-1}\left(\frac{(a_i + a_{i-1})p_i - a_{i-1}p_{i-1} - a_i p_{i+1}}{\Delta\Theta_i}\right)^2$$

$$\varepsilon_i = \begin{cases} 1/\sigma_i^2 & \text{for } i \neq i_{DUT} \\ 0 & \text{for } i = i_{DUT} \end{cases}$$

$$a_i = \frac{1}{x_{i+1} - x_i}$$

Analytical verification (3/4)

- Minimize the Chi² to find the most probable particle positions:

$$\frac{\partial \chi^2}{\partial p_i} = 0,\ i = 1, \ldots, N$$

- p_i can be determined by solving a matrix equation:

$$\sum_i A_{ij} p_j = \varepsilon_i y_i$$

$$A_{ij} = \frac{1}{2} \frac{\partial^2 \chi^2}{\partial p_i \partial p_j}$$

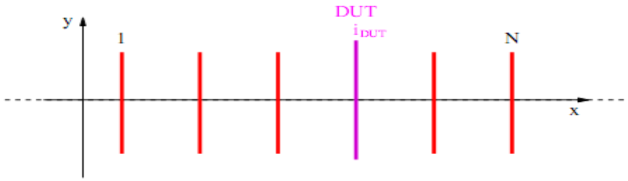
- Find the inverse matrix:

$$S = A^{-1}$$

$$p_i = \sum_j S_{ij} \varepsilon_j y_j$$

- Error on the plane i:

$$\tilde{\sigma}_i = \sqrt{S_{ii}}$$



Assume six reference planes have the same spatial resolution and the same interval. Note:

$$c = \varepsilon,\ b = \left(\frac{a}{\Delta\Theta}\right)^2$$

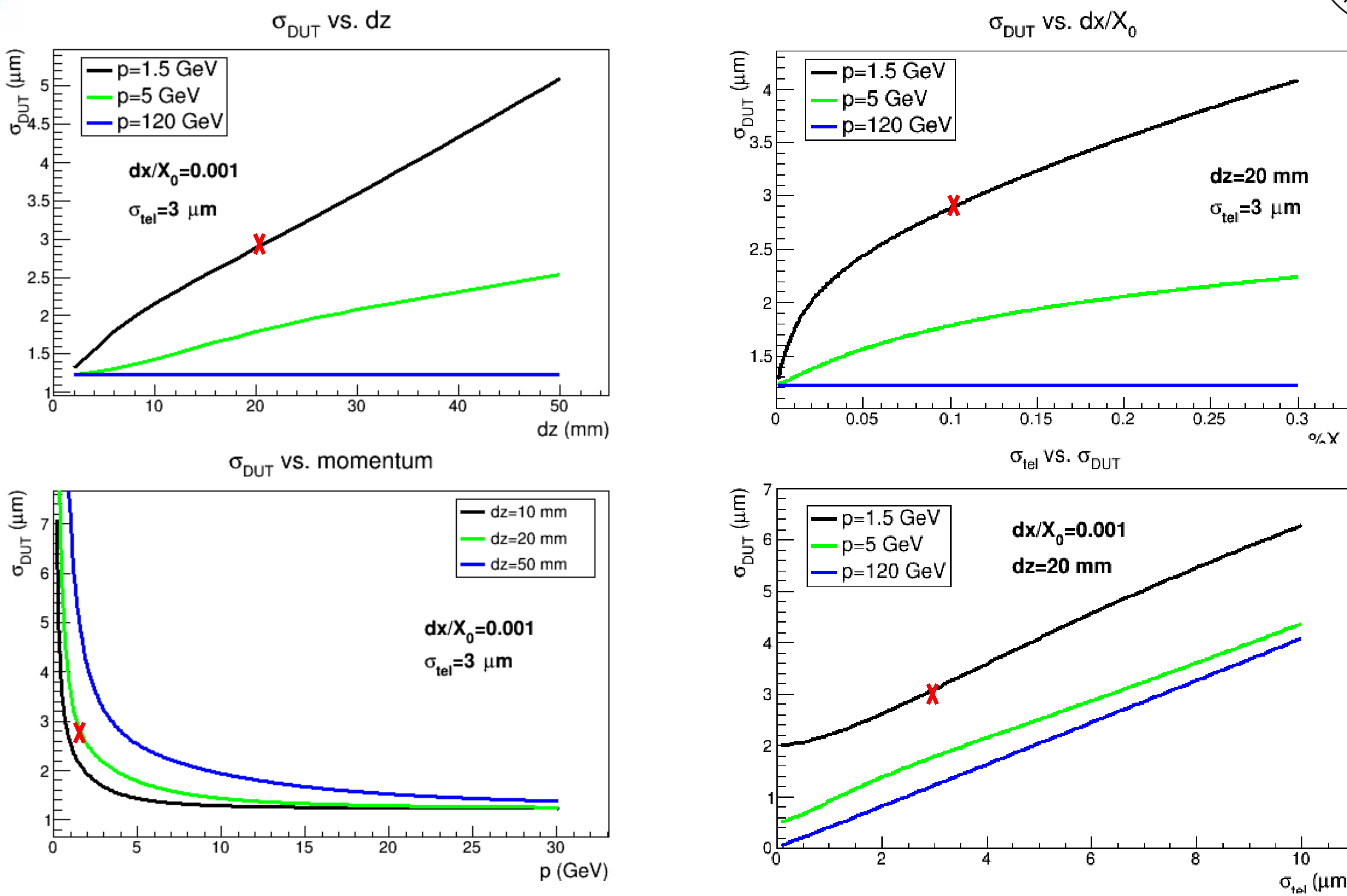
The matrix is:

```
[   c+b,  -2*b,     b,     0,     0,     0,     0]
[  -2*b, c+5*b,  -4*b,     b,     0,     0,     0]
[     b,  -4*b, c+6*b,  -4*b,     b,     0,     0]
[     0,     b,  -4*b,   6*b,  -4*b,     b,     0]
[     0,     0,     b,  -4*b, c+6*b,  -4*b,     b]
[     0,     0,     0,     b,  -4*b, c+5*b,  -2*b]
[     0,     0,     0,     0,     b,  -2*b,   c+b]
```

The error at the DUT position is:

$$\tilde{\sigma}_{DUT} = \sqrt{S_{44}} = \left[\frac{2b^3 + 26b^2c + 13bc^2 + c^3}{c(12b^3 + 44b^2c + 6bc^2)}\right]^{\frac{1}{2}}$$

Analytical verification (4/4)



p = 1.5 GeV, dz = 20 mm, dx/X_0 = 0.001, $sigma_{tel}$ = 3 μm → $sigma_{dut}$ = 2.88 μm

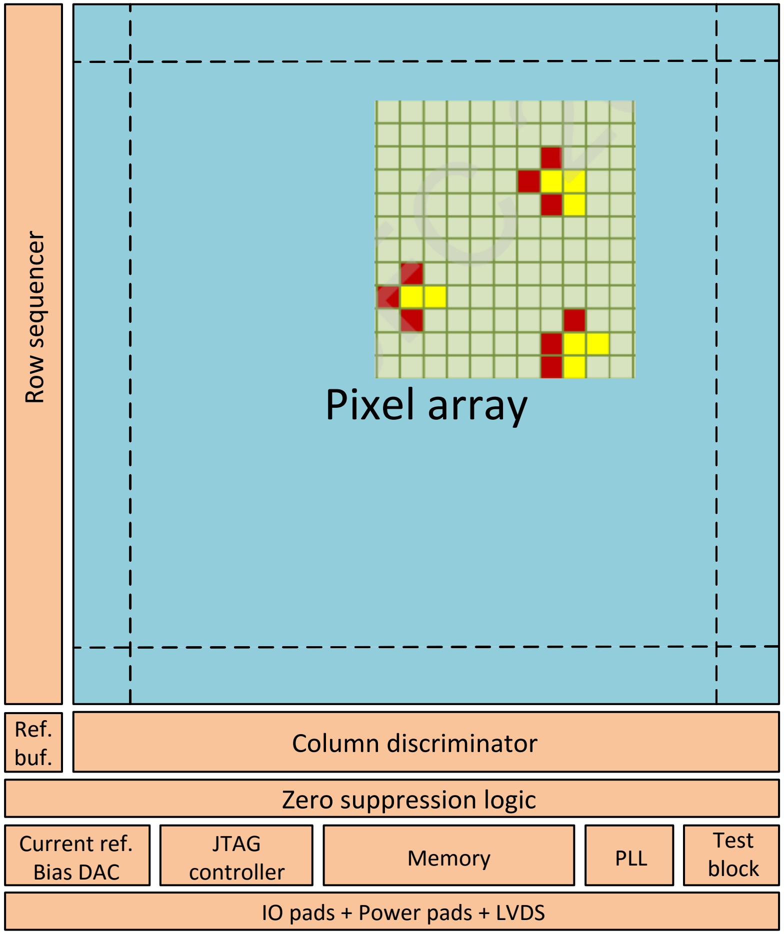
p = 120 GeV, dz = 20 mm, dx/X_0 = 0.001, $sigma_{tel}$ = 3 μm → $sigma_{dut}$ = 1.23 μm

Pixel sensor

Sensor specification:

- Pixel pitch 16 μm by 16 μm → ~ 3 μm spatial resolution
- ~2 cm x 2 cm
- Rolling-shutter readout mode with zero-suppression
- Thinned to ~ 50 μm → lower MS effect

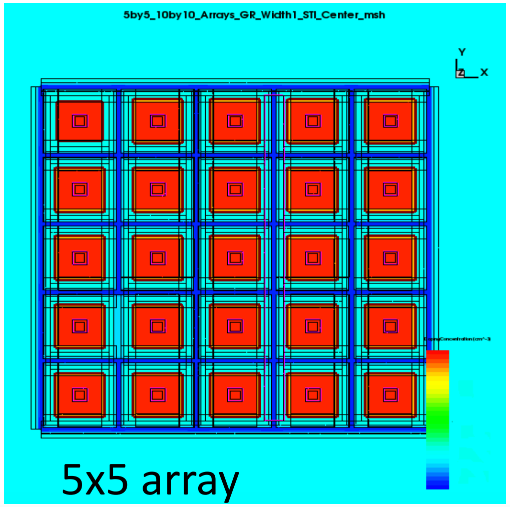
Smaller pixel pitch would cause more significant charge sharing → lower single pixel amplitude → optimized charge sensing geometries and low noise in-pixel circuits are needed!!

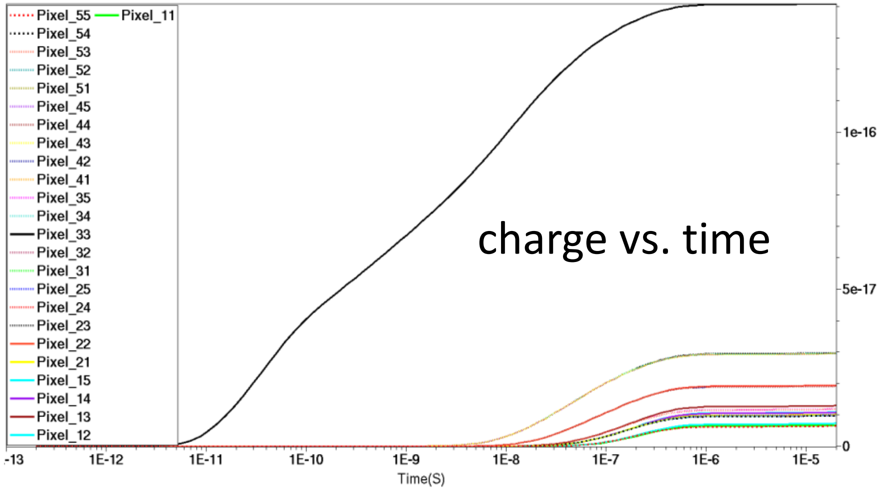


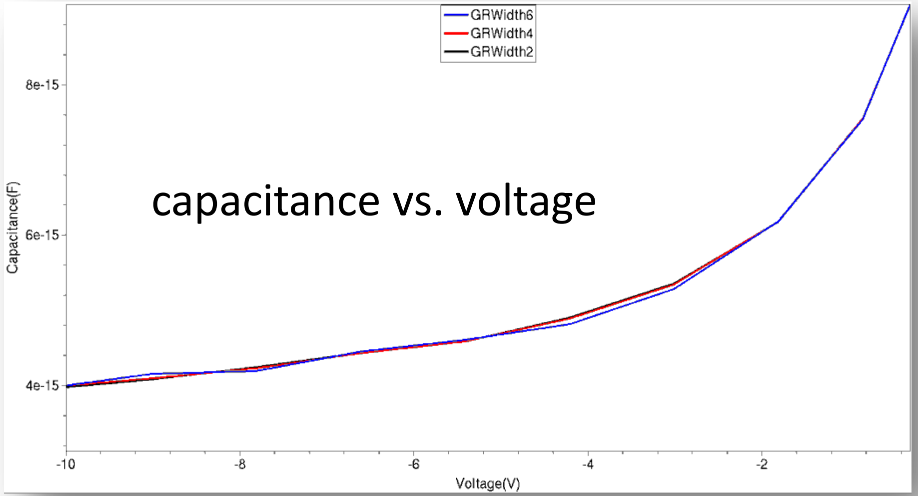
Sensor simulation

The DC, AC and Transient simulations have been performed by using the Sentaurus TCAD in order to optimize the charge collection efficiency and the diode capacitance.

For a typical 16 µm x 16 µm pixel, approximately 2000 e- could be collected and the diode capacitance is roughly 6 fF.





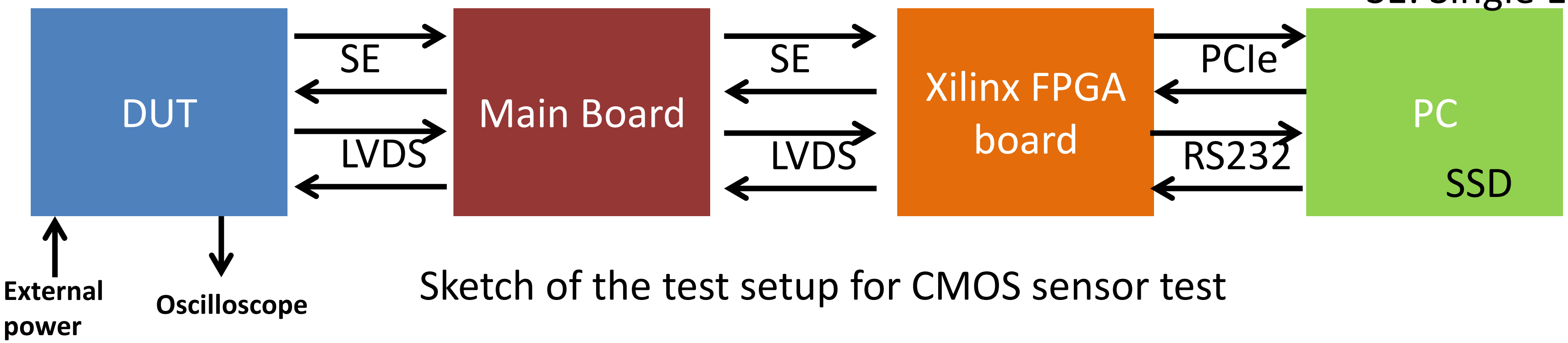


Long Li et al. ***TCAD Simulation based on a 0.18µm technology for a Beam Telescope***

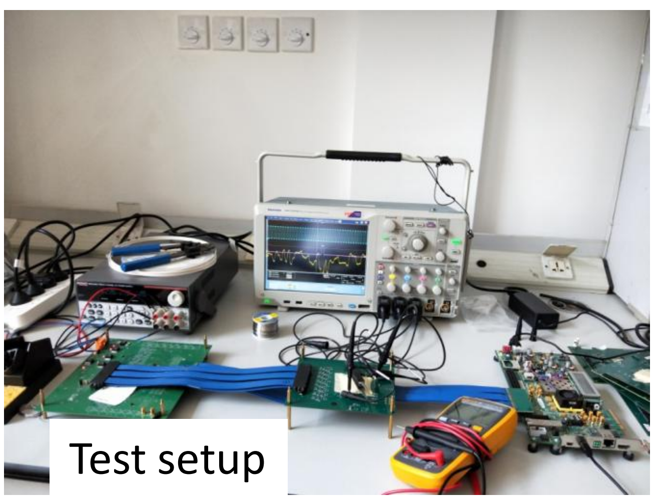
Sensor characterization

A flexible test setup has been constructed for a precursor prototype. The setup is based on a Xilinx Kintex FPGA board and could be adapted to the telescope sensor characterization.

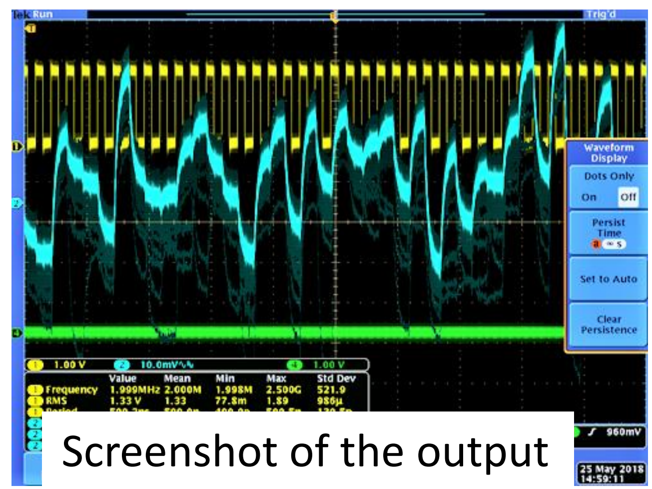
SE: Single Ended



Sketch of the test setup for CMOS sensor test



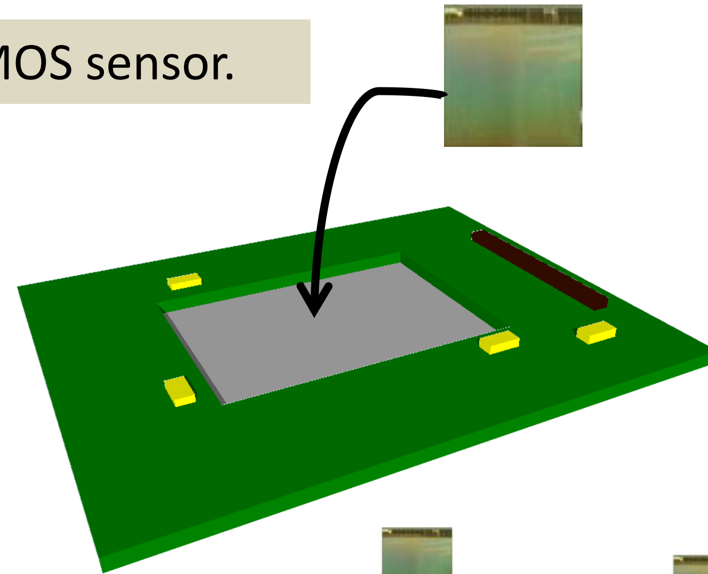
Test setup



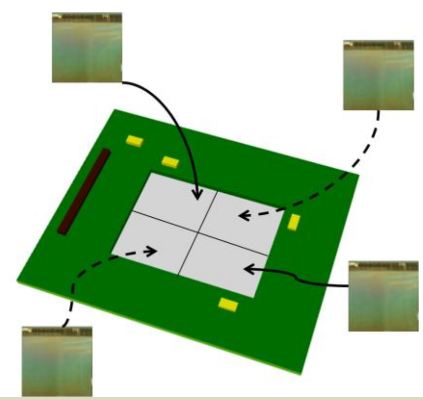
Screenshot of the output

Telescope module

For a baseline design, each module carries one CMOS sensor.



- The sensor is mounted via wire-bonding on a PCB featuring a beam hole to reduce the material budget.
- Kapton foils to protect sensor surface
- The PCB is fixed by a thin metal jig, which is placed on a aluminium movable arm.
- Cooling interface.
- Temperature and humidity monitor.



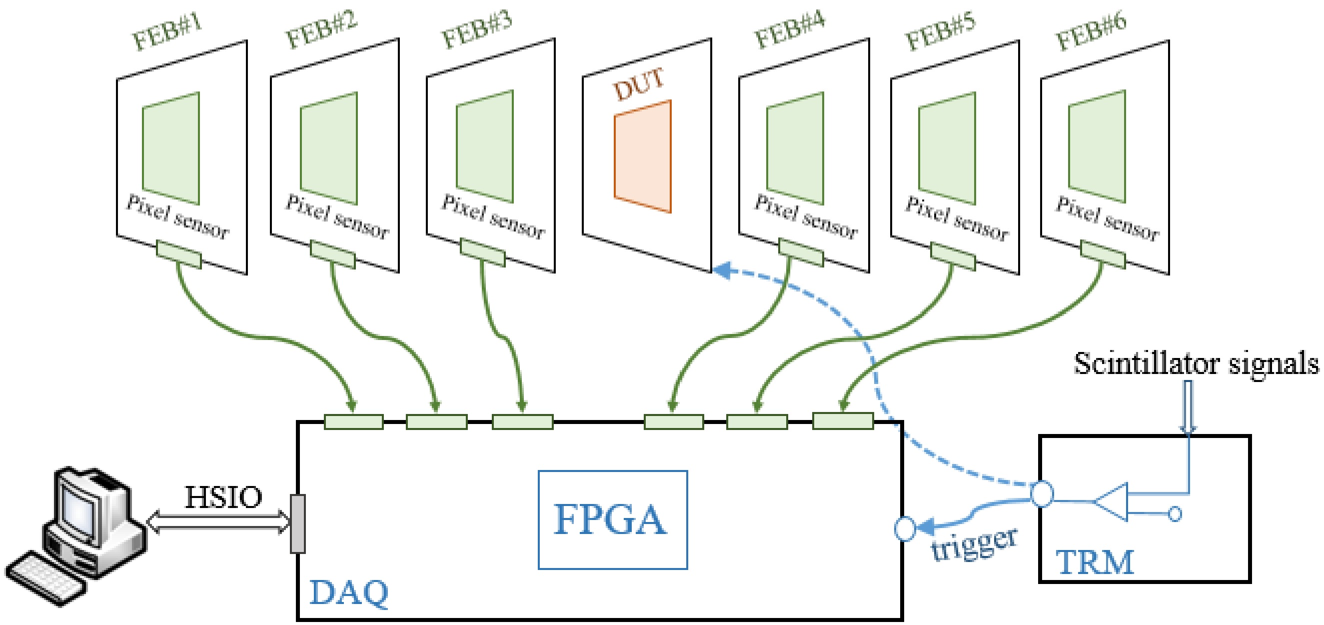
- Total thickness less than 10 mm. (Default module interval is 20 mm.)
- Active region ~2 cm x 2 cm.
- Material budget < 0.1 $\%X_0$ in active region.

Attempt at an aggressive layout:
- 2x2 sensor array
- sensitive region ~ 4 cm x 4 cm !!

Readout

The DAQ system mainly consists of:

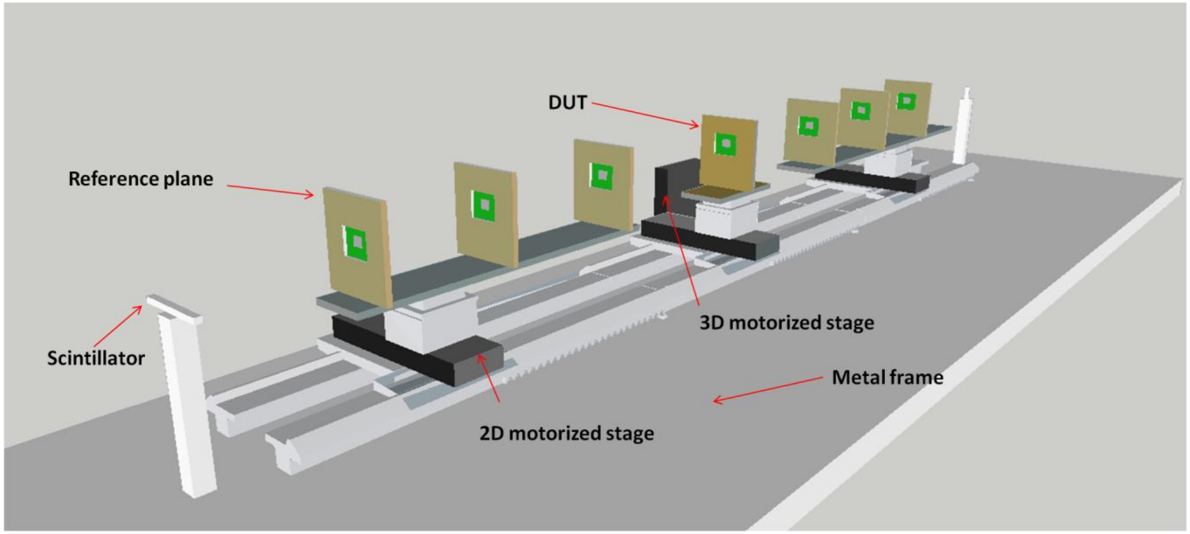
- 6 Front-end PCBs (carrying the sensor, level shifting…)
- DAQ board (sensor configuration, data RX, data buffer…)
- Trigger module (TRM)



Jianing Dong et al. ***Conceptual Design of the readout electronics for high spatial resolution beam telescope based on CMOS pixel sensors***

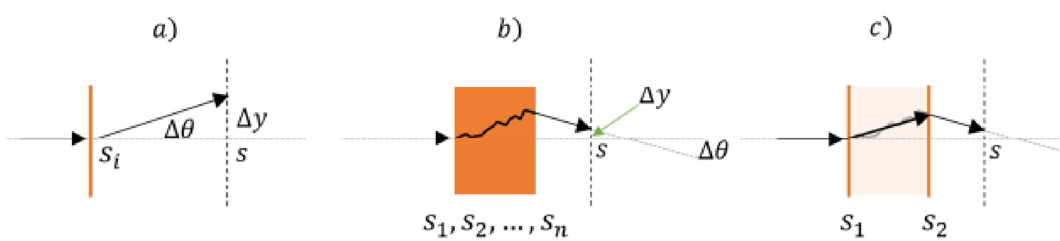
Mechanics and services

- The telescope is mounted on a rotatable metal frame → orientation adjustment & cosmic ray test
- Two arms are mounted on two 2D motorized stages with the resolution of 3 μm
- DUT is placed on a 3D motorized stage with the resolution of 3 μm
- DAQ PCBs are fixed on the frame
- Power supplies
- Cooling system
- Temperature and humidity monitoring

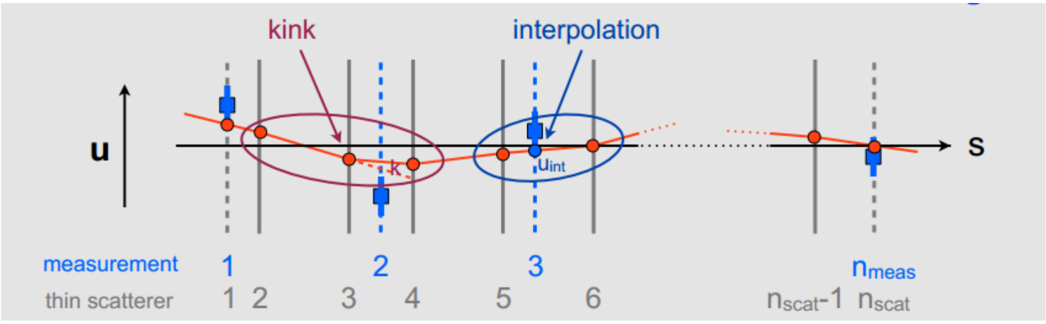


Reconstruction and alignment (1/2)

- General Broken Line (GBL): a track model with proper description of multiple scattering.
  - a) an ideal scatterer at s_i results only angular deflection leading to track displacement at s.
  - b) a realistic material causes both the angular deflection and displacement.
  - c) two thin scatterers to describe the realistic material.



- Triplets are built from hits in the three upstream and three downstream planes separately with proper constrains.
- Matching triplets from the up- and downstream planes → GBL tracks are formed.



Reconstruction and alignment (2/2)

Alignment:

- A few microns misalignments during the telescope assembling could increase the track fit residuals significantly → alignment is needed to push the precision well below the intrinsic resolution.

Millepede-II:

- Track-based alignment algorithm. Used for CMS and EUDET. Minimization of the Chi^2 expression w.r.t. all alignment and track parameters.

$$\chi^2(\mathbf{p},\mathbf{q}) = \sum_j^{tracks} \sum_i^{measurements} \left(\frac{m_{ij} - \mathrm{f}_{ij}(\mathbf{p},\mathbf{q_j})}{\sigma_{ij}}\right)^2$$

- * $m_{ij} \pm \sigma_{ij}$: measurement and its error
- * f_{ij} : track fit prediction
- * $\mathbf{q_j}$: parameters of track
- * $\mathbf{p}$: alignment parameters

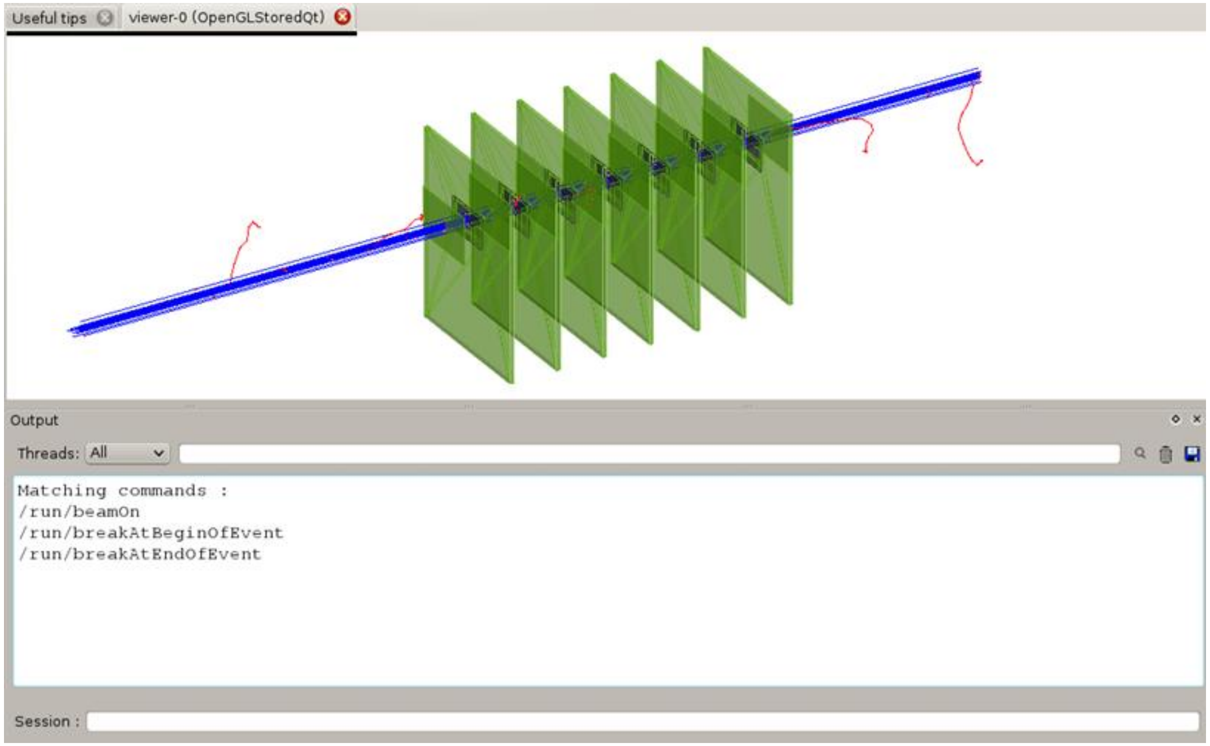
Simulation (1/2)

AllPix^2:

- A generic simulation framework for silicon tracker and vertex detectors.
- Built on Geant4 (the deposition of charge carriers in the sensor) and ROOT (producing histograms).
- LCIO format convertor.

Simulations in process:

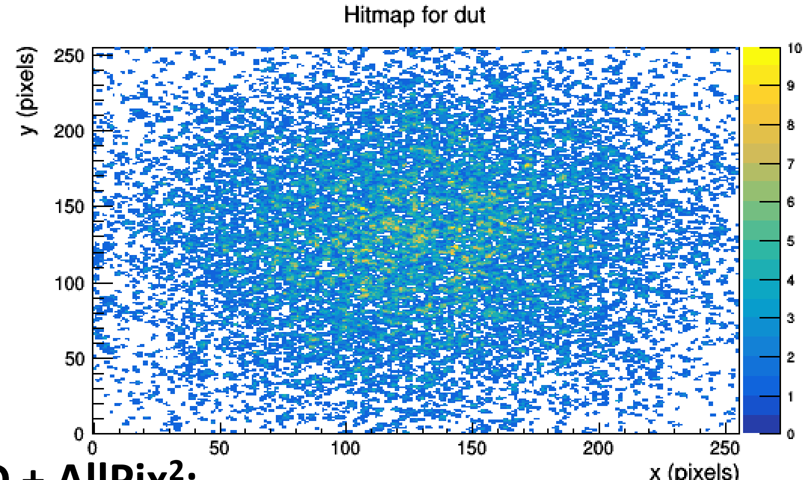
- 7 planes: 6 reference + 1 DUT
- Sensor size 5 mm x5 mm
- Sensor thickness 50 µm
- Linear e-field
- 2 Kapton foils 25 µm + 25 µm
- beam: 1.5 GeV e-

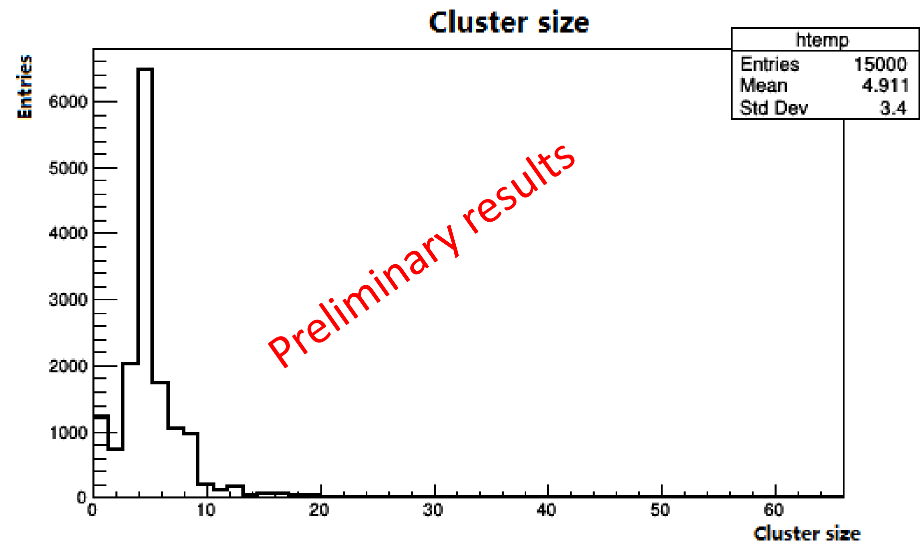


Simulation (2/2)

Hits at DUT:

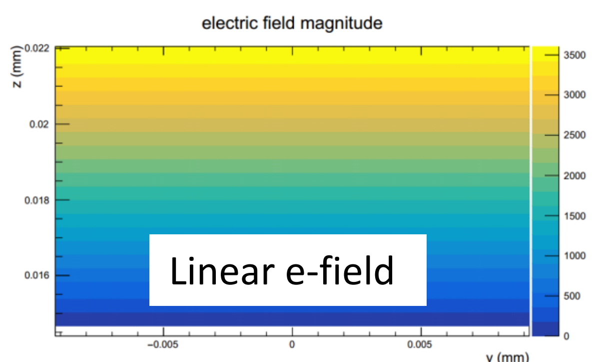
- Hits observed from the DUT.
- 15000 hits with the mean cluster size of 4.7.

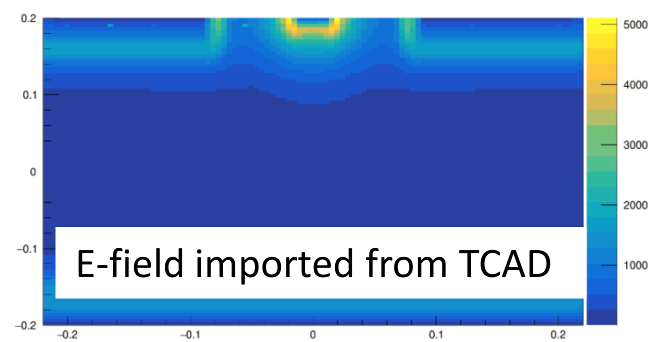




TCAD + AllPix^2:

- Default e-field is a linear distribution in z-axis.
- INIT format e-field derived from the 3D TCAD simulations could be introduced into the AllPix2 to improve the charge collection simulation.





Summary

- A high spatial resolution (~3 μm @ 1.5 GeV e-) beam telescope is under study at SDU.
- The pixel sensor size will be 2 cm x 2 cm, and the intrinsic resolution will reach ~3 μm.
- The active area will be 2 cm x 2 cm. The possibility of 4 cm x 4 cm will also will explored.
- GBL/Millepede-II based track reconstruction, pattern recognition and alignment is under investigate.
- Sensor design and TCAD + Allpix^2 simulations are in process.

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Thanks for your attention!!