Beam Test Measurements on Planar Pixel Sensors for CMS Phase 2

Universität Hamburg
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GEFÖRDERT VOM
Bundesministerium
für Bildung
und Forschung

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University of Hamburg, *DESY

January 18, 2019

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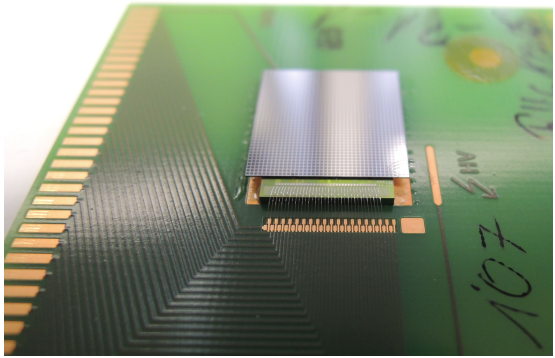


Introduction – CMS Phase-2 Upgrade

High-Luminosity LHC

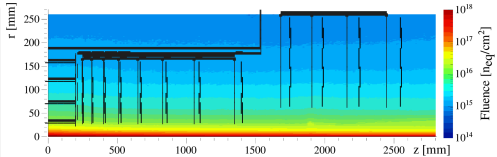
- Luminosity of up to $7.5 \times 10^{34}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$
- Up to an average of 200 events per 25 ns bunch crossing

To keep occupancy low and improve spatial resolution $\Rightarrow$ reduce pixel size

- 25x100 $\mu\mathrm{m}^2$ or
- 50x50 $\mu\mathrm{m}^2$ compared to 150x100 $\mu\mathrm{m}^2$

To face radiation damage up to a dose of 12 MGy and $\Phi_{eq} \approx 2.3 \times 10^{16}\,\mathrm{n_{eq}/cm^2}$

- 100 - 150 µm planar sensors compared to 285 µm
- Or 3D sensors (layer 1)



1 MeV neutron equivalent in silicon, $3000\,\mathrm{fb}^{-1}$

Layer	Φ_{eq} [$10^{16}\,\mathrm{n_{eq}/cm^2}$]
1	2.3
2	0.5
3	0.2
4	0.15

Expected CMS barrel fluence per layer

Introduction – Investigated Samples

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CMS Phase-2 Prototype Design Variations

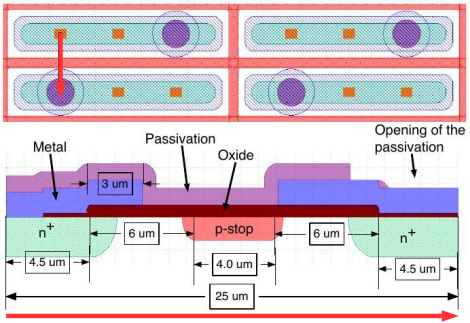
- n^+p-pixel sensors with p^+ backside
- Different thicknesses
- Geometry, 100x25 µm^2 and 50x50 µm^2
- Pixel isolation schemes
- With and without biasing scheme

Readout Chip – PSI ROC4SENS

- All samples are bump bonded to a PSI ROC4SENS analogue readout chip
- No zero suppression but low rate (120 Hz)
- Region of interest based data taking

Irradiation with neutrons in Ljubljana (TRIGA)

Top view 100x25 µm^2 default design



Cut image along red arrow

Introduction – Investigated Samples

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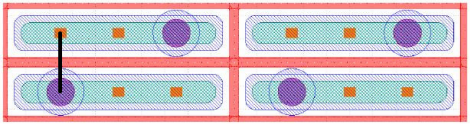
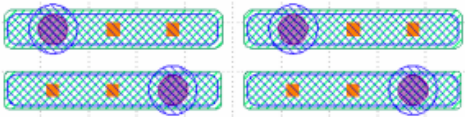
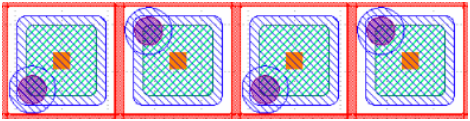


100x25 µm^2 p-stop default

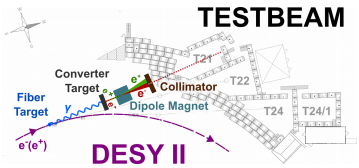


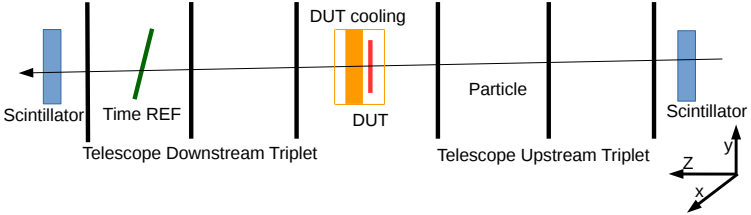
100x25 µm^2 p-spray maximum implant



50x50 µm^2 p-stop default design

Setup – Description





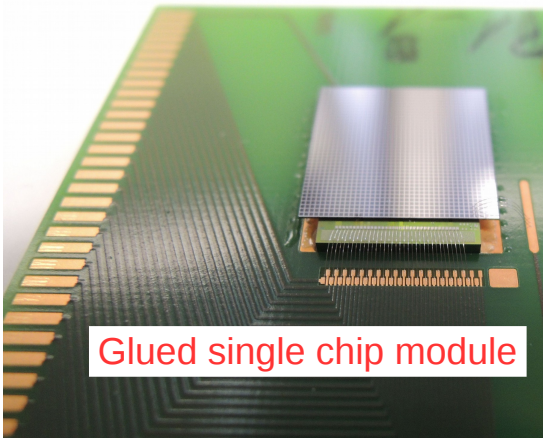
DESY II Beam Test Facility

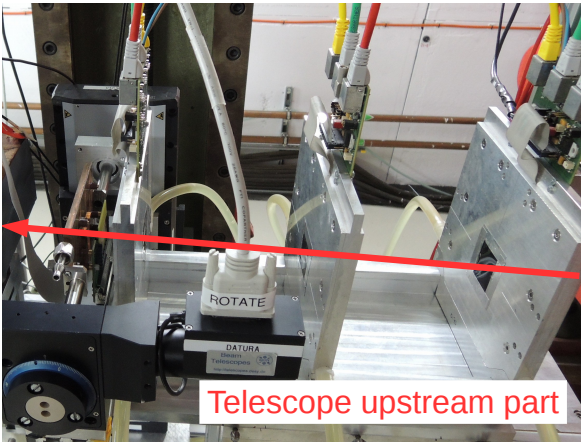
- Radius r = 46.6 m
- Electron/ positron synchrotron beam
- Conversion $e^-(e^+) \rightarrow \gamma \rightarrow e^-(e^+)$
- Energies from 1 to 6 GeV
- Peak rates around 10 kHz

Beam Telescope

- EUDET DATURA Telescope for tracking
- Scintillators for triggering
- 6 MIMOSA 26 planes (t_{int} = 115 µs)
- Time **REF**erence module
- **D**evice **U**nder **T**est

Setup – In Pictures





Telescope Resolution – Upstream Triplet Resolution

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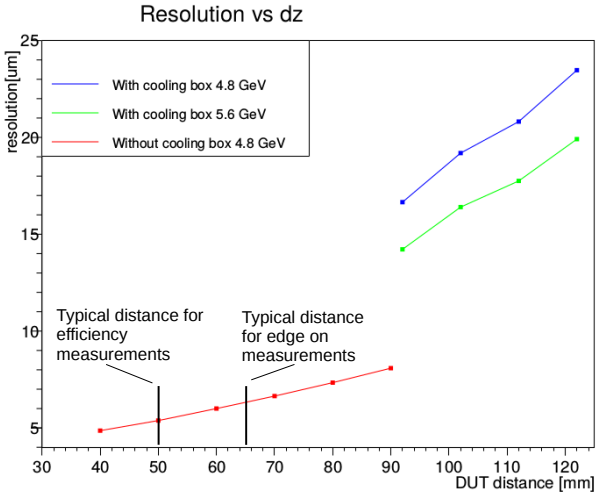
Telescope-only study to measure triplet track resolution at different DUT positions

Technique

- Extrapolate upstream triplet to 4th telescope plane
- Fit residual distribution with Student't
- Subtract 3.3 µm intrinsic plane resolution

$$\sigma_{track} = \sqrt{\sigma^2_{meas} - \sigma^2_{intr}}$$

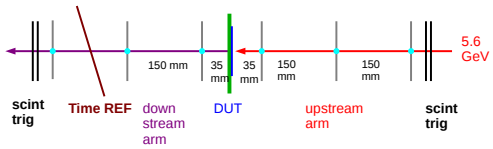
Using only the upstream triplet mitigates the effect of multiple scattering in copper cooling block



Efficiency – Efficiency Definition

Hit Efficiency

- Efficiency $= \frac{N(hit\ on\ track)}{N(track)}$
- Track definition:
  - Get upstream and downstream triplets
  - Match triplets using 0.1 mm cut
  - Demand REF-link; 0.15 mm cut
  - Demand 0.6 mm isolation at time REF
- Hit on track definition:
  - Extrapolate upstream-track to DUT
  - Demand DUT-link (pixel); 0.2 mm cut
  - Pixel ΔPH cut
    - Significance cut of 4 (RMS $\approx$ 7 ADC)
- Fiducial region 0.2 mm to sensor edges



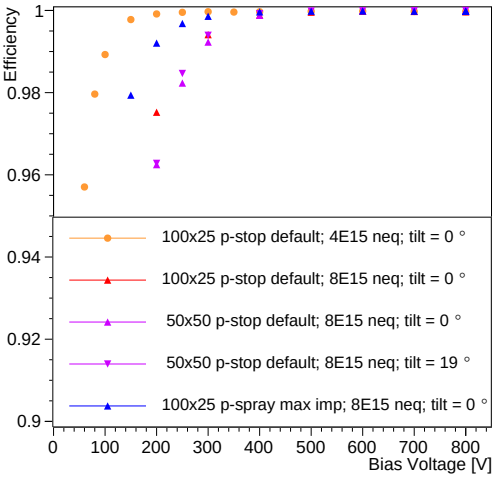
Efficiency – Results on Neutron Irradiated Samples

Comments

- Final selection $\approx$ 60 k for 160 k triggers
- $4 \times 10^{15}\,\mathrm{n/cm^2}$ noise RMS $\approx$ 4 ADC
- $8 \times 10^{15}\,\mathrm{n/cm^2}$ noise RMS $\approx$ 7 ADC
- At $\approx -24\,^{\circ}\mathrm{C}$; no additional annealing
- Error calculation: Efficiency $= \epsilon = k/N$
  $\sigma_\epsilon = (1/\sqrt{N}) \cdot \sqrt{\epsilon(1-\epsilon)}$

Observations

- Efficiency above 99 % for all samples above 300 V
- Max imp - highest efficiency at 8E15
- Effect of 19° tilt is smaller then 0.5 %



Efficiency – In Pixel x-Dependence

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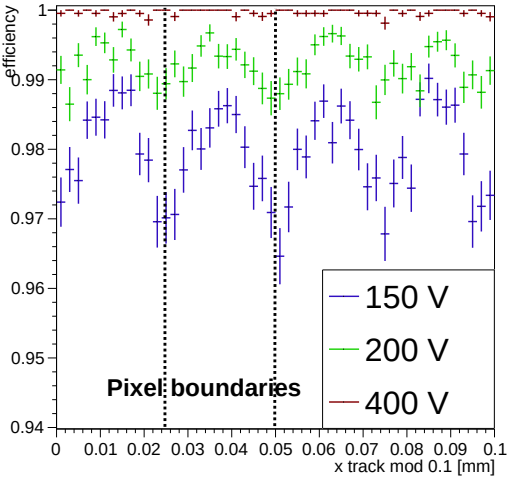
Where do we lose efficiency?

Sample and Conditions

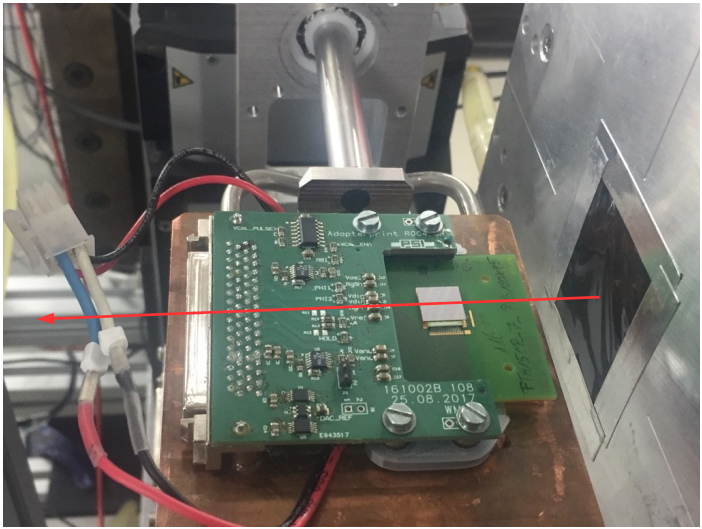
- P-spray max imp
- Irradiated with $8 \times 10^{15}\,\mathrm{n/cm^2}$
- At $\approx -24\,^{\circ}\mathrm{C}$; no additional annealing

Observations

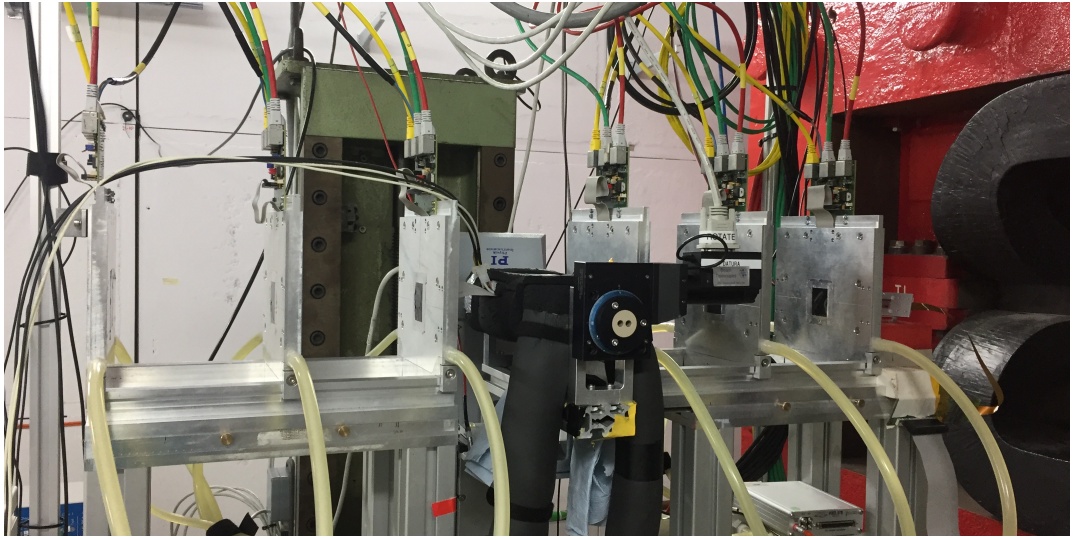
- Lower voltages: Efficiency drop 1 - 2 % on the pixel edges
- In pixel features can be resolved even in direction of the small pitch (25 µm)



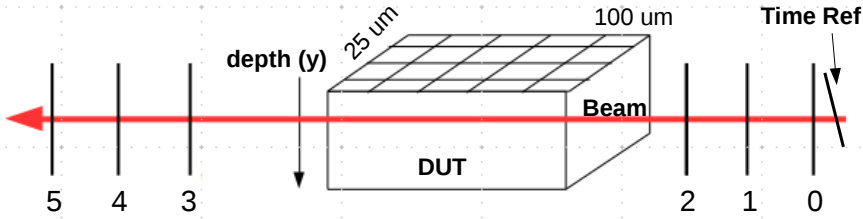
Edge-On – Picture I



Edge-On – Picture II



Edge-On – Setup



Setup

- Beam in 100 µm direction
- Track reconstruction using upstream triplet
- Time REF module upstream

The Idea

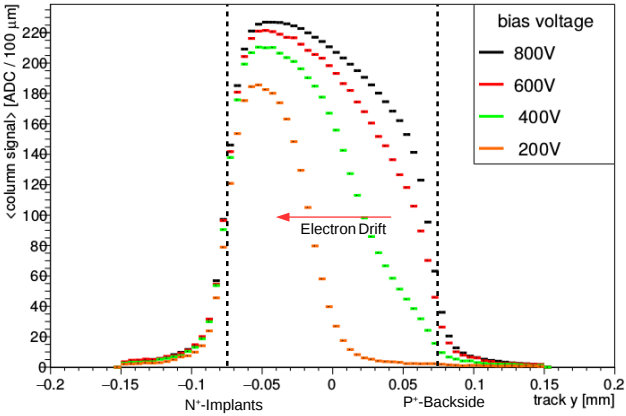
- Measure charge collection as a function of depth
- Allows detailed studies of trapping effects

Edge-On – Charge Collection Profile

Sample and Conditions

- 100x25 p-stop default
- Irradiated with $4 \times 10^{15}\,\mathrm{n/cm^2}$
- At $\approx -24\,^{\circ}\mathrm{C}$
- No additional annealing

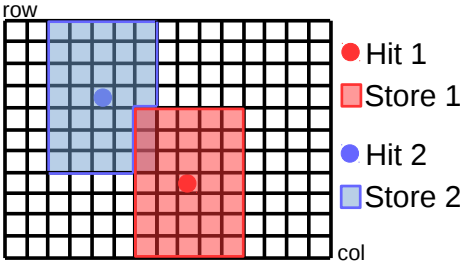
- Very sensitive measurements for model tuning
- But we can do even better...



Edge-On – Data Storage

- Take pixel above significance cut of 4 – hit
- Define Region Of Interest (ROI)
  - E.g. field of 7×7 (column $\times$ row) pixels
  - Centered around each hit
- Store hit **position** (column, row) and **trigger number**
- Store **position** (column, row) and **PH**
  - Of all pixel in ROI
  - IF not stored in any previous hit of the same trigger number (no double counting)
- Thereby store $\leq n \times 3 \times 49$ instead of 24800 numbers per event
- But we maintain quasi threshold less readout

Example storage pattern



Edge-On – Charge Collection Tomography

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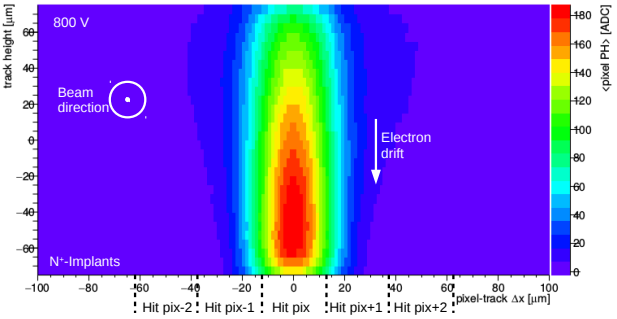
Sample and Conditions

- 100x25 p-stop default
- Irradiated with $4 \times 10^{15}\,\mathrm{n/cm^2}$
- At $\approx -24\,^{\circ}\mathrm{C}$; 150 V, 800 V
- No additional annealing

Observation

- Direct charge collection and charge sharing information
- Negative signal induced in neighboring pixels for low voltages
- Only possible with this chip



- Reconstruct height (y) and x with the telescope
- Plot pulse height vs y and pixel-track distance

Edge-On – Charge Collection Tomography

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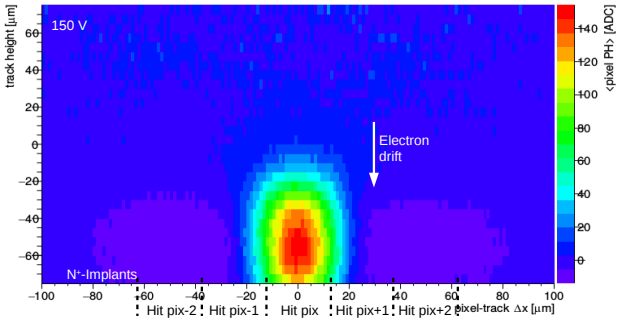

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Conclusion and Outlook

Conclusion

- Results on neutron irradiated ROC4SENS sensor assemblies (up to $8 \times 10^{15}\,\mathrm{n/cm^2}$)
  - Efficiency above 99 % for all samples and above 300 V
  - Highest efficiency for sensors with p-spray isolation and enlarged implants
    – next test beam: Sensors with biasing scheme
- Despite the low energy of DESY II we are able to resolve in-pixel features for vertical incidence and edge-on measurements to study details of charge collection

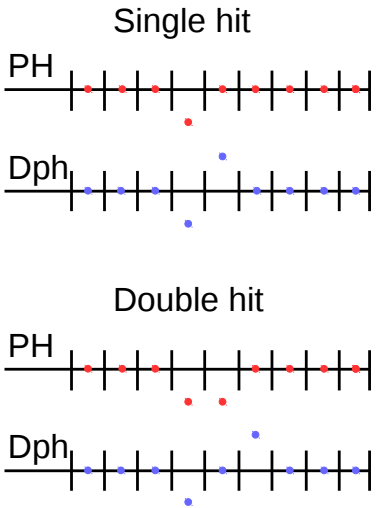
Outlook

- Due to the high efficiency at $8 \times 10^{15}\,\mathrm{n/cm^2}$ we will measure new irradiated samples with fluences up to $1.6 \times 10^{16}\,\mathrm{n/cm^2}$
- Use charge collection tomography for model tuning, simulations and template generation

Backup – Hit Finding Method

Method

- $Dph_j = PH_j - PH_{j-1}$
- $Sph_j = Dph_j/\sigma(Dph_j)$ (significance)
- Set a threshold of 4
- Pixel j marked as hit if $Sph_j < 4$
- Pixel $j-1$ marked as hit if $Sph_j > -4$



Backup – Clustering Algorithm

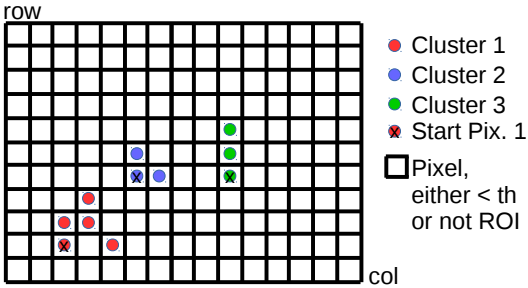
Before Clustering – DUT

- Common mode correction is applied
- Gain equalization is applied
- ROC coordinates ⇒ sensor coordinates

Center of Gravity Clustering – All Planes

- Take any not yet clustered pixel over threshold
- Add all neighbors to cluster
- Charge weighted average position of all pixels in the cluster ⇒ Cluster position
- Start next cluster

Clustering



- DUT: Threshold ≈ 4 signi. cut on ΔPH
- Telescope: Binary, skip hot pixels

Backup – Common Mode Correction

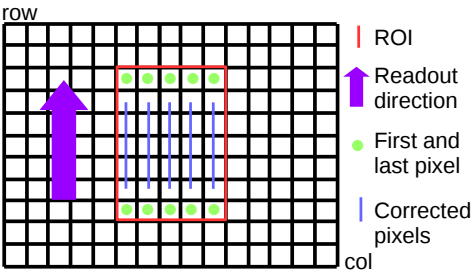
Online

- Perform pedestal correction
- Take difference of neighboring pixels Dph_j
- Calculate significance Sph_j
- Use threshold of $\pm$ 4
- Store region of interest (ROI)
- Not suitable in offline analysis

Offline

- ROI-based data
- Perform column wise correction
- Find first and last pixel of the column
  Subtract average PH from those in between

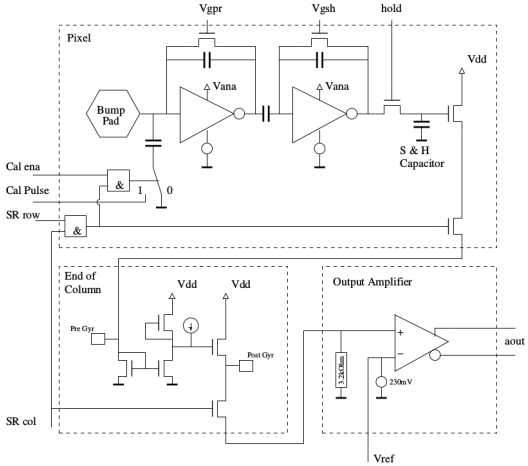
Correction Scheme



*If the first and the last pixel have the same distance we correct by the last.

Backup – ROC4SENS

- Geometry: 50 x 50 µm pitch
- 155 x 160 pixels
- Analogue readout chain:
  - **Preamplifier**
  - **Shaper**
  - Sample and hold
  - Output Amplifier
- No discriminator, no zero suppressio, no ADC: 50 kB/event
- $\approx$ 0.7 ms for a readout cycle (at 40 MHz)
- Operated with Pixel **D**igital **T**est **B**oard

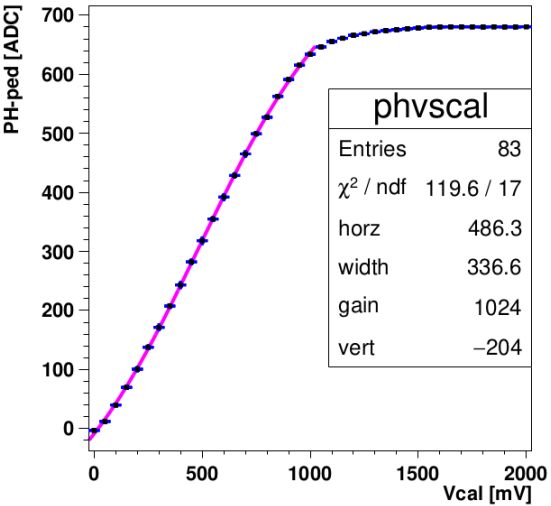


Schematic of the analogue readout chain

Backup – Gain Equalization

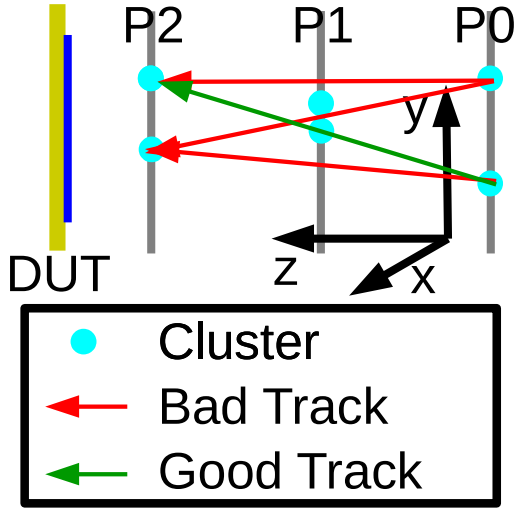
Take Gain Calibration

- Use internal calibrations pulses (V_{cal}) of the ROC4SENS
- Draw $PH - ped$ vs V_{cal}
- Fit by Fermi function for every pixel
  $PH - ped = p_3 + \frac{p_2}{1 + \exp(-u)}$; $u = \frac{V_{cal} - p_0}{p_1}$
- Use inverse function to get the charge
  $Q(PH - ped) = V_{cal}$
- Correction for **relative gain variations** of the pixels!
- Source calibration missing
  $\Rightarrow$ Abs. calibration to expected charge



Backup – Telescope Reconstruction

The clusters in each plane are combined to get tracks

Building Telescope Triplets Tracks

- Build all combinations of P0 and P2
- Cut angle 0.005 rad
- Interpolate to P1
- Calculate $dx = x_{int} - x_{cl}$
- Reject tracks with $\|dx\| > 0.05$ mm
- Same procedure in y
- And for the downstream triplet (cut 0.10 mm)