Performance of irradiated CMS forward pixel detector

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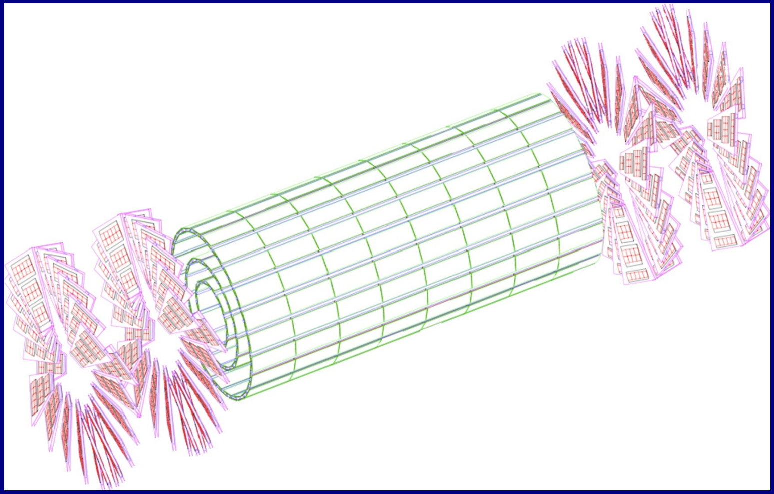
on the behalf of the CMS collaboration

Outline

- CMS forward pixel detector
- Test-beam setup
- Performance of irradiated detector
  - Charge collection
  - Detection efficiency
  - Charge sharing characteristic
  - Charge – track impact point correlation
  - Cluster size

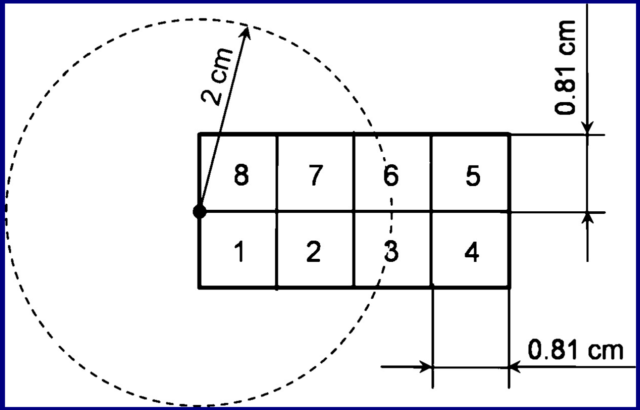
CMS Forward Pixel detector

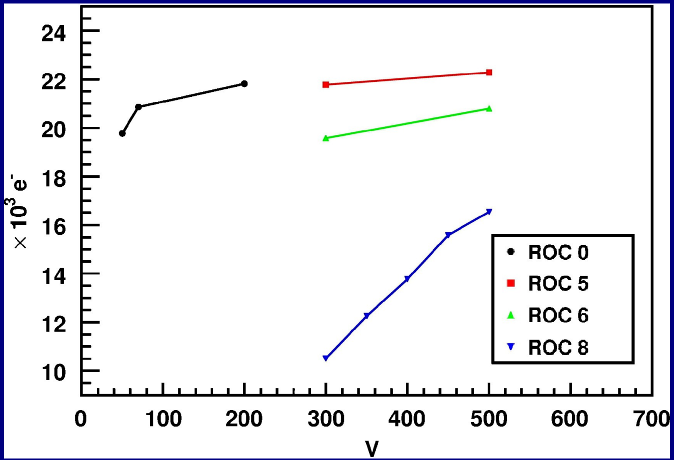


- 4 disks:
  - Z = ±34.5, 46.5 cm
  - Inner radius: 6.1 cm
  - Outer radius: 15.0 cm
- Si sensor produced by SINTEF:
  - Type: n+/n
  - Pixel cell: 100x150 μm^2
  - Thickness: 270 μm
  - Open p-stop ring isolation technology
- Maximum dose: 7Mrad/year at the inner disk at LHC design luminosity
  - Dose decreasing $\sim r^{-1.8}$

Test – beam

- A plaquette of 2x4 ROCs was exposed to a peak dose of 45Mrad at the Indiana University Cyclotron Facility using a 200 MeV proton beam.
  The beam was centered on one edge and it was roughly Gaussian in shape with σ~2cm
- Results are compared with a non – irradiated single chip plaquette
- Test with 120 GeV proton beam at Fermilab:
  - 6 plane pixel telescope
    - 50x400 μm^2 cells
    - Extrapolated track resolutions on the CMS pixel plane: σ_x=4.9 µm, σ_y=6.2 µm
- Bias voltages:
  - 200 V reference detector (ROC 0)
  - 500 V irradiated plaquette.
    - It is below the depletion voltage for the most irradiated region (ROC 8)
    - 500 V maximum allowed by power supply





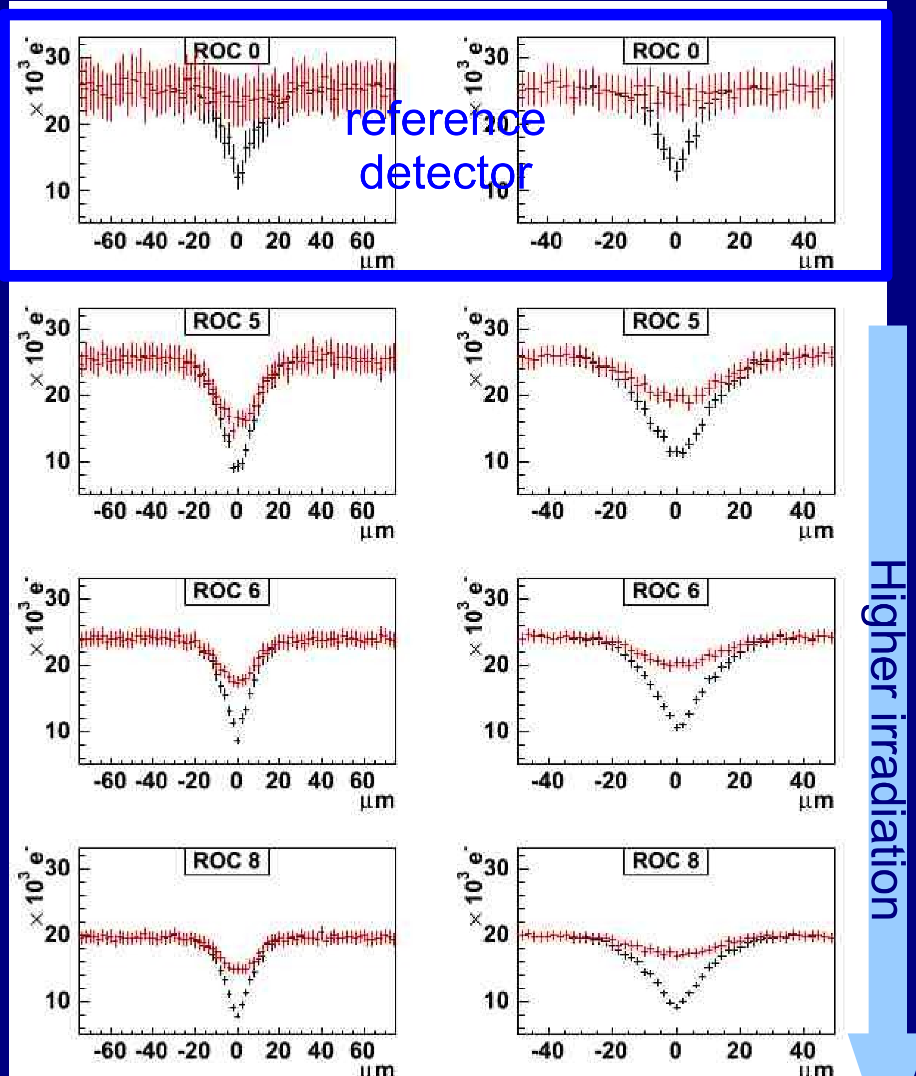
- Thresholds: 3800e⁻ for reference detector and 3300e⁻ for irradiated plaquette

Charge Collection

- Collected charge as a function of the track impact point distance from the two adjacent pixel divide.
    - Fiducial cuts are applied to exclude sharing with other pixels but those under study
- RED points: total charge collected by the two adjacent pixels.
- BLACK points: charge collected by the sole pixel pointed by the track.

Asymptotic points, far away from the divide, correspond to single hit.

- Left column plots are for adjacent pixels on the same row, right column for the adjacent pixels on the same column
- Reference/non-irradiated detector shows a very good charge collection efficiency even in presence of sharing.

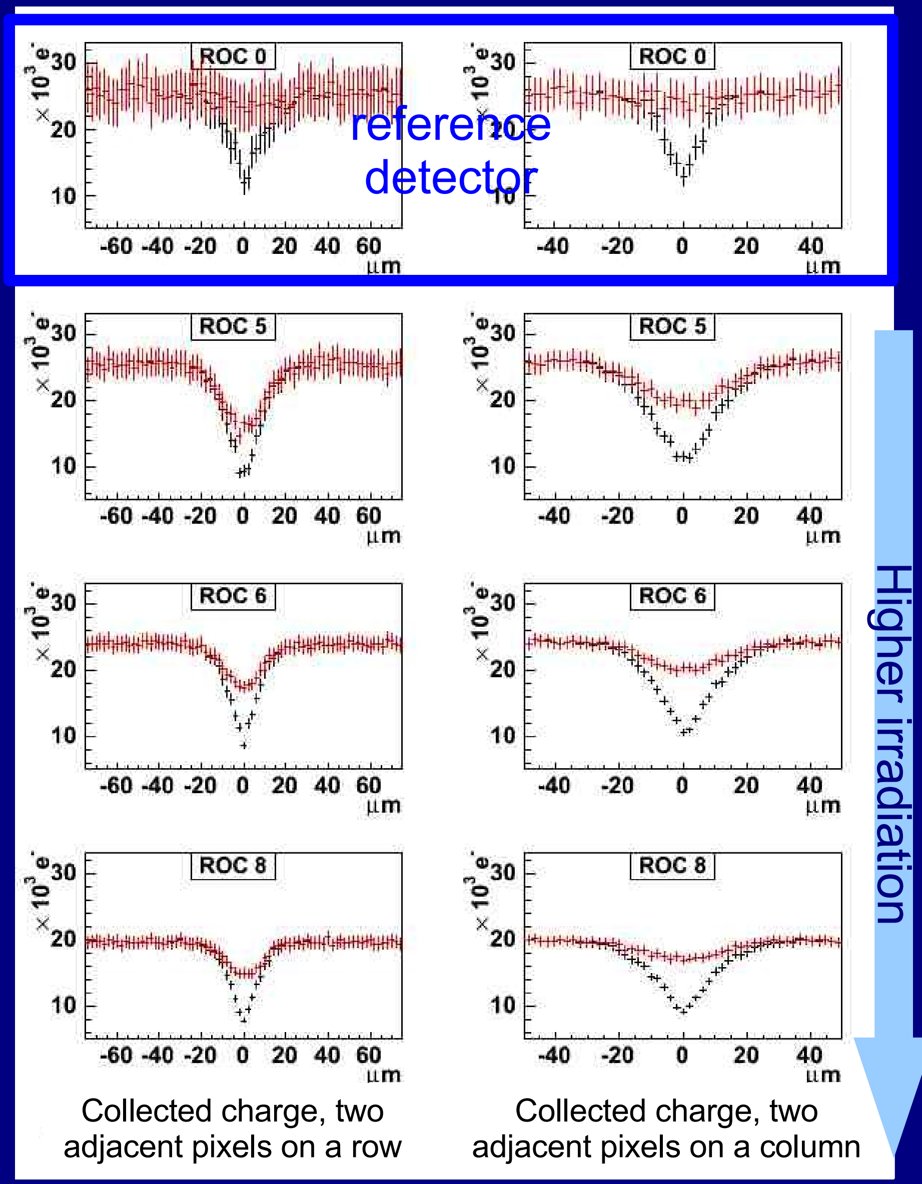


Collected charge, two adjacent pixels on a row

Collected charge, two adjacent pixels on a column

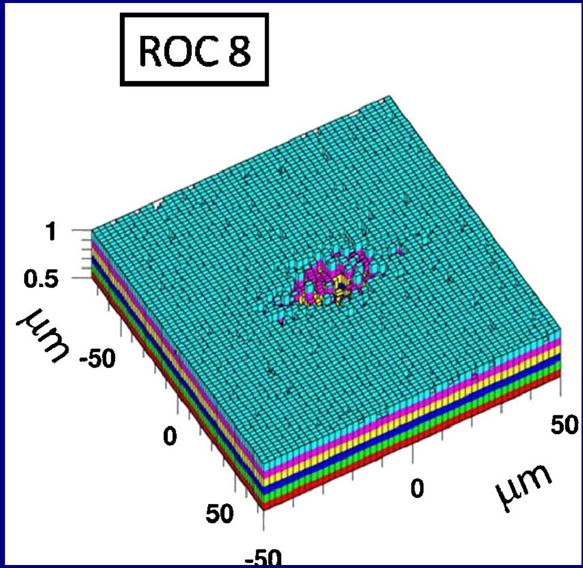
Charge Collection

- First of all
  - Single hit charge collection efficiency degrades moving toward higher irradiated regions
    - ~100 % in ROC5, ~95 % in ROC6, ~75 % in ROC8.
  - A clear drop in collected charge is present whenever charge is shared between the two adjacent pixels.
  - The drop is relatively larger for sharing between two pixels along a row, e.g. 31% vs 28% for ROC6
    - This is due to the presence of the break on the p-stop ring between pixels on the same column.
- It is interesting to notice that in case of sharing, the percentage of lost charge wrt the single hit value becomes smaller moving toward the most irradiated region, 40% in ROC5 (row) vs 19% in ROC8
  - This apparently anomalous behavior can be explained by the drastic change of the electric field at high radiation doses.
  - The formation of a new junction on the n+ side, as a result of the type-inversion, radically changes the field configuration between adjacent pixel-implants.



Detection efficiency

ROC	ε %
0	98.61±0.15
5	97.69±0.10
6	98.78±0.05
8	97.46±0.06



- Inefficiency is confined near the pixel corners: this is due to two main reasons
  - Signal in each pixel could be small and below the threshold
  - Signal could be outside the synchronization time window because of the time walk
- Anyway, the maximum achievable efficiency is limited to ~99%, because of ~1% systematic inefficiency of the readout system

η distribution – I

- Charge sharing between two pixels is investigated using the variable:

$$\eta = \frac{Q_r}{Q_r + Q_l}$$

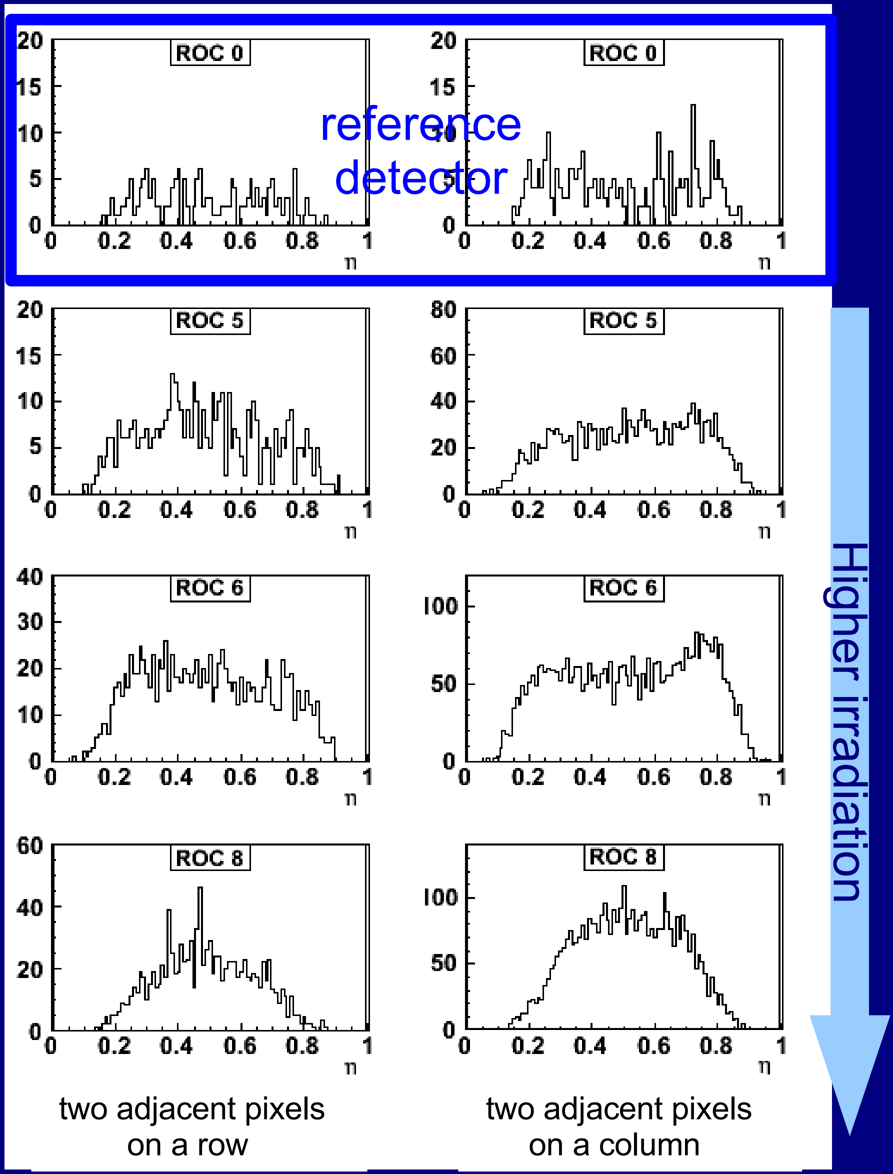
Q_l: charge collected by the pixel at the left side

Q_r: charge collected by the pixel at the right side

- Moving toward the most irradiated regions, the continuous effective increase of the threshold shrinks the central part of the η distribution

- ROC6 (left): slope due to the non perfect orthogonality of the detector to the beam tracks

- ROC6 (right): effect of the non orthogonality superimpose to those from the p–stop break which unbalances the charge sharing

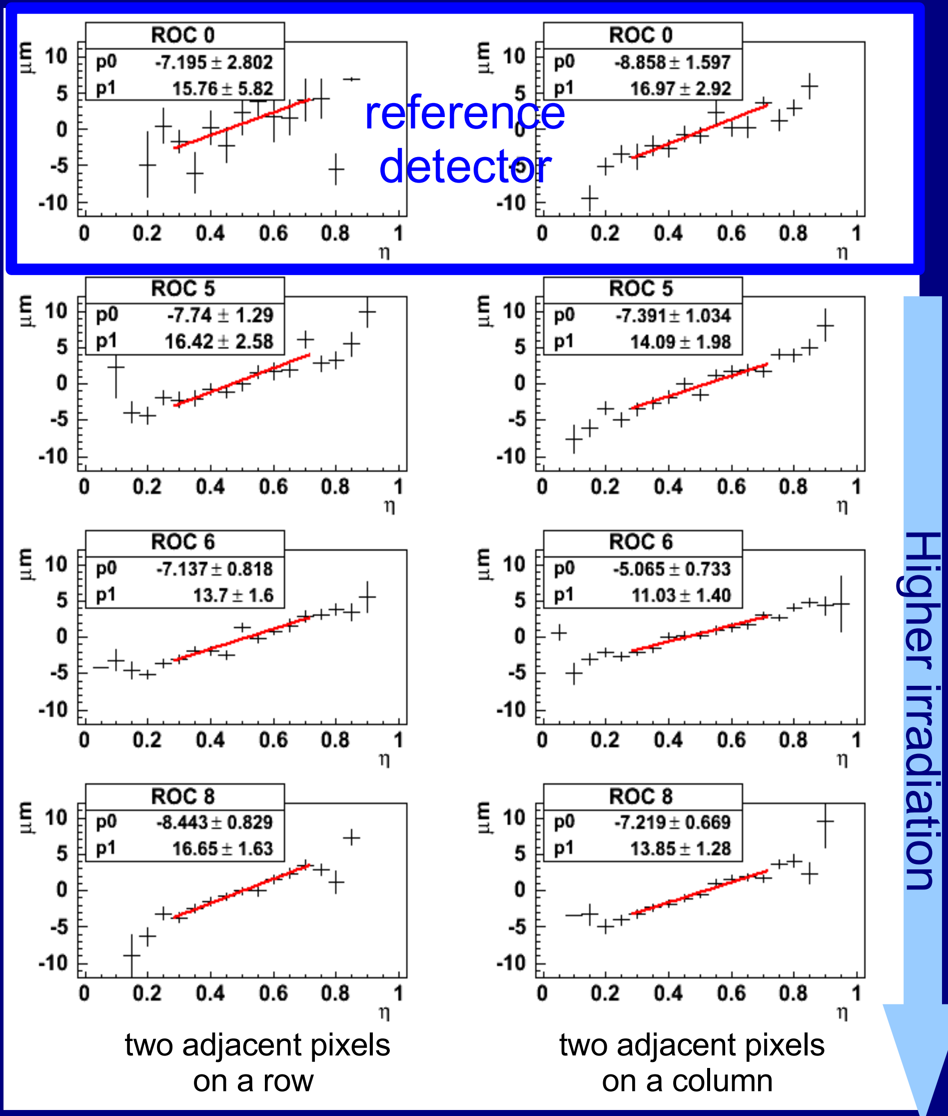


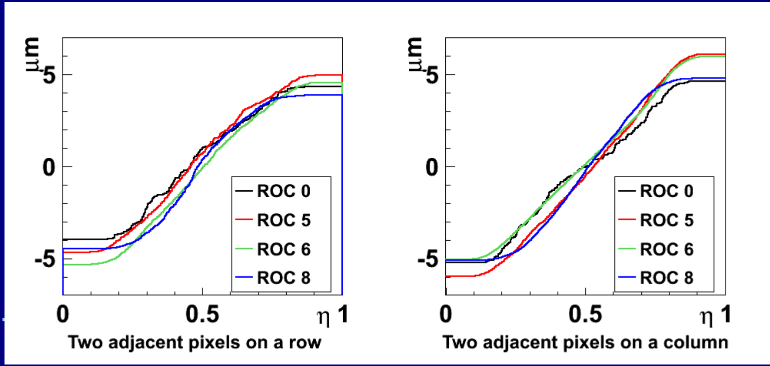
η – distribution – II

- Correlation between the track impact point and measured η value is investigated using two methods:
  - Mean value of signed distance vs η bin (plots on the right)
  - Indirect method: for a certain value of η, the signed distance x(η) is given by

$$\int_{-p}^{x(\eta)} \frac{dN_x}{dx}\, dx = \int_{0}^{\eta} \frac{dN_\eta}{d\eta}\, d\eta$$

  - The two results match each other





Cluster size

- Lower charge collection efficiency induced by radiation damage corresponds to a higher effective threshold
  - The number of sharing events in ROC 8 is close to that of ROC 0 which has a higher threshold (3800 e^- wrt 3300 e^-)

Cluster size	ROC0 (%)	ROC5 (%)	ROC6 (%)	ROC8 (%)
1	85.42 ± 0.70	81.78 ± 0.43	82.03 ± 0.28	85.57 ± 0.27
2	12.75 ± 0.66	16.00 ± 0.40	15.17 ± 0.26	12.73 ± 0.26
3	**0.75 ± 0.17**	1.15 ± 0.12	1.29 ± 0.08	**0.84 ± 0.07**
4	0.83 ± 0.18	0.72 ± 0.09	1.05 ± 0.07	0.55 ± 0.06
5	0.08 ± 0.06	0.12 ± 0.03	0.21 ± 0.03	0.14 ± 0.03

Summary and Conclusions

- CMS FPix performance tested up to a maximum dose of 45Mrad
  - Loss of ~25% of the signal relesed by a MIP
  - High efficiency: ~99%
    - Only marginal drop near the pixel corners
  - η distribution symmetry altered by the p–stop breaks

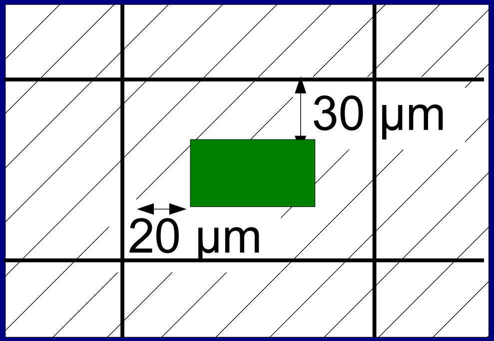
- Despite the observed damages, the detector remains fully operational and suitable to accomplish the CMS physics goal for years inside the LHC

Backup slides

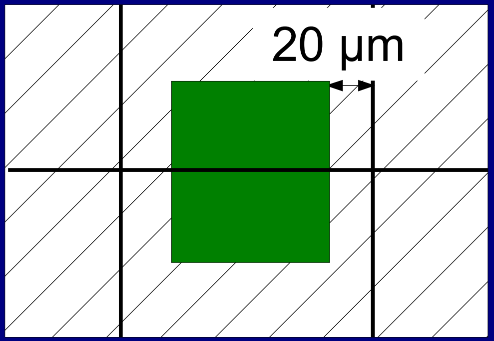
Fiducial cuts

- Fiducial cuts are applied to exclude sharing with other pixels but those under study

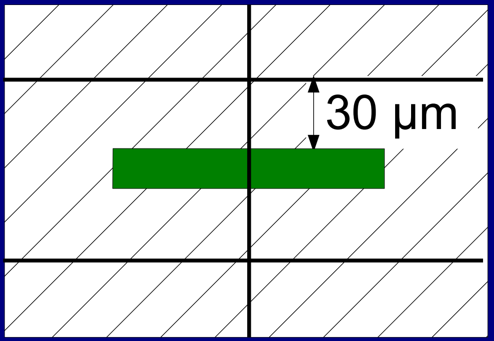
Single pixel: fiducial cuts at 30 microns in Y and 20 microns in X from the pixel boundaries



Two adjacent pixels on the same column: fiducial cut at 20 microns from the adjacent pixel in the row (X direction)

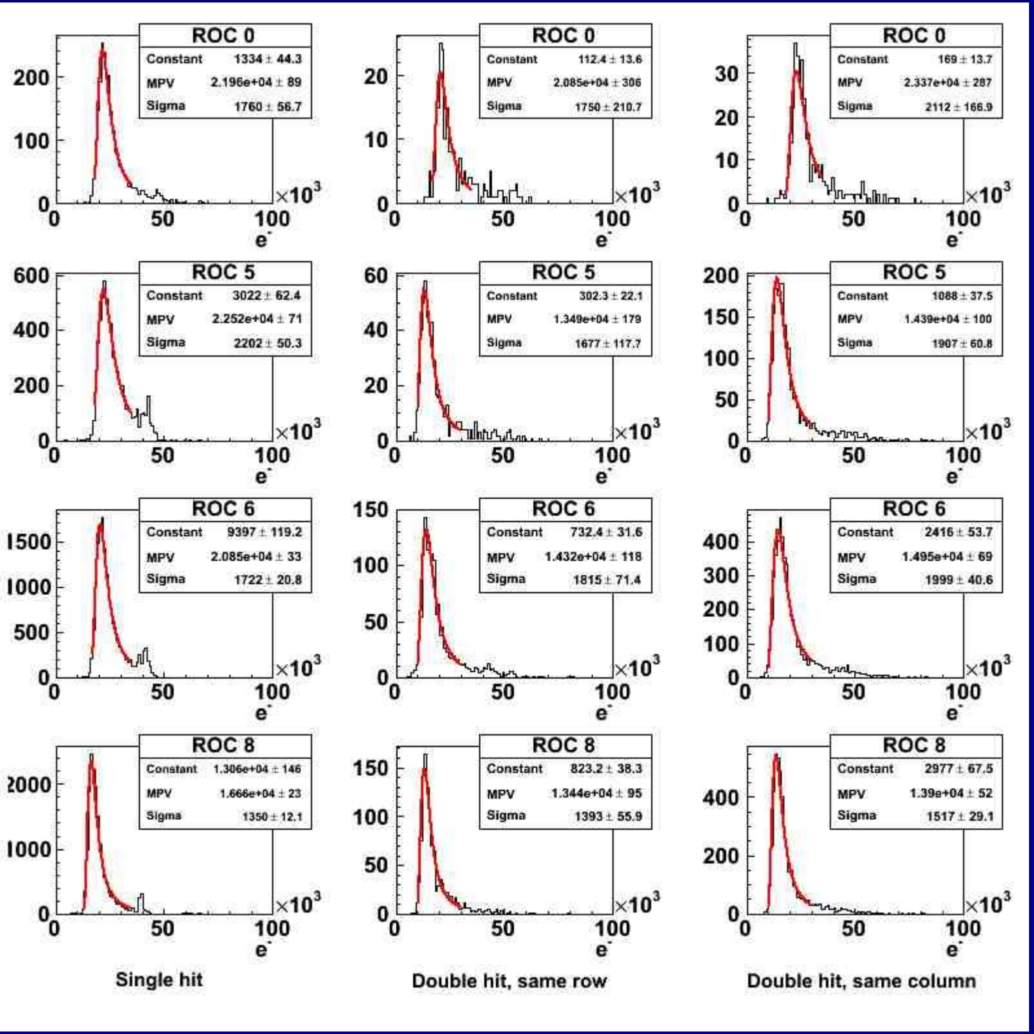


Two adjacent pixels on the same row: fiducial cut at 30 microns from the adjacent pixel in the column (Y direction)



Charge collection I

- Single hit and double hit spectra are investigated separately
- Less irradiated region (ROC5): the sensor can still collected all the charge if it is released in one pixel only
- In the most irradiated region (ROC8) the collection efficiency is limited: Landau peak ~75% of the expected value (one pixel)
- Intermediate region (ROC6): Landau peak ~95% of the expected value (one pixel)



ROC	MPV (e^-) Single hit	MPV (e^-) same row	MPV (e^-) same col
0	21956 ± 89	20853 ± 305	23374 ± 287
5	22521 ± 71	13490 ± 179	14388 ± 100
6	20854 ± 33	14317 ± 118	14945 ± 69
8	16663 ± 23	13436 ± 95	13898 ± 52

Charge Collection II

- The percentage of lost charge wrt single hit value decreases moving forward ROC8.
  - The charge collection efficiency degrades with a lower rate in the inter–pixel region, indication of drastic change in the expected electric field at high radiation dose

ROC	Charge loss (%) Same row cluster	Charge loss (%) Same col cluster
5	40.10 ± 4.42	36.11 ± 4.51
6	31.35 ± 3.34	28.34 ± 3.38
8	19.36 ± 3.38	16.59 ± 3.41

Charge sharing

- The charge sharing correlation between two adjacent pixels deteriorates moving toward the most irradiated region
  - Corner regions are excluded in the study
  - Correlations between two adjacent pixels on the same column are reported as example