New results of edge-on measurements with electron beam on pad diodes

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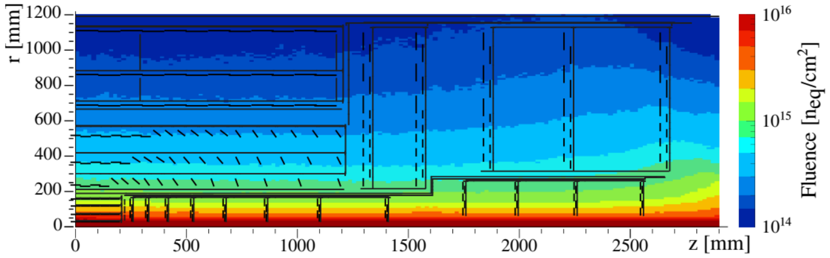
38th RD50 Workshop

Introduction

- Luminosity in the CMS Phase-2 is up to $7.5 \times 10^{34}\ \mathrm{cm^{-2}s^{-1}}$.
- This causes a neutron equivalent fluence of $2.3 \times 10^{16}\mathrm{cm^{-2}}$ (after 3000 $\mathrm{fb^{-1}}$) in the first layer.
- The radiation damage changes the electric field and trapping times of the sensors used in the inner tracker.



After 3000 $\mathrm{fb^{-1}}$

Layer	$\Phi_{eq}[10^{16}\ \mathrm{cm^{-2}}]$
1	2.3
2	0.5
3	0.2
4	0.15

The motivation of this talk

- Understanding the charge collection in highly irradiated silicon diodes

The tool of study

- Edge-on measurement using electron beam with an energy of 5.2 GeV

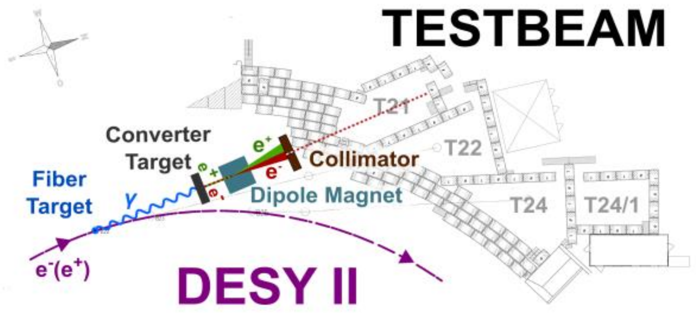
The performed measurements

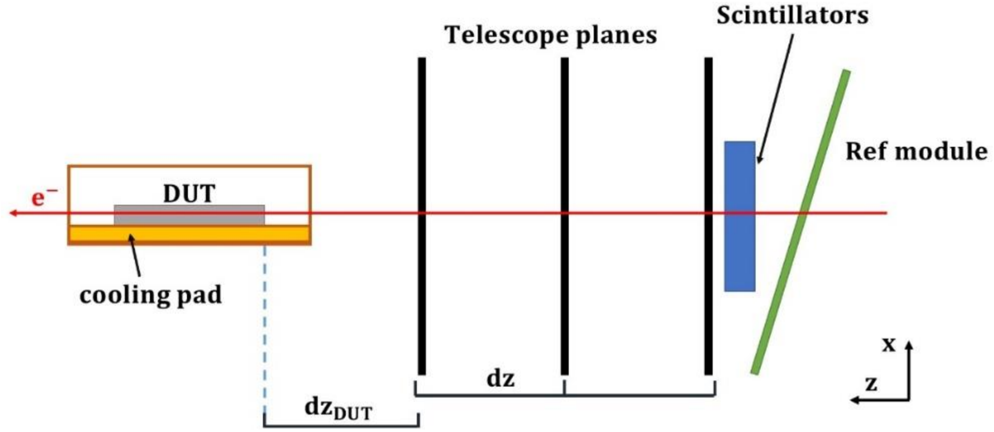
- Charge profiles of non-irradiated and irradiated diodes at different bias voltages

Measurement setup

DESY II beam test facility:

- Electron/positron beam with energy of 1-6 GeV
- Beam energy of 5.2 GeV was chosen for the measurements
- Intrinsic resolution of each plane of telescope ≈ 3.2 μm
- Timing reference module for reducing in-time pile up
- Scintillator for providing the readout trigger
- Rotation stage for the DUT with a precision of 0.10°(1.7 mrad)





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Measurement setup

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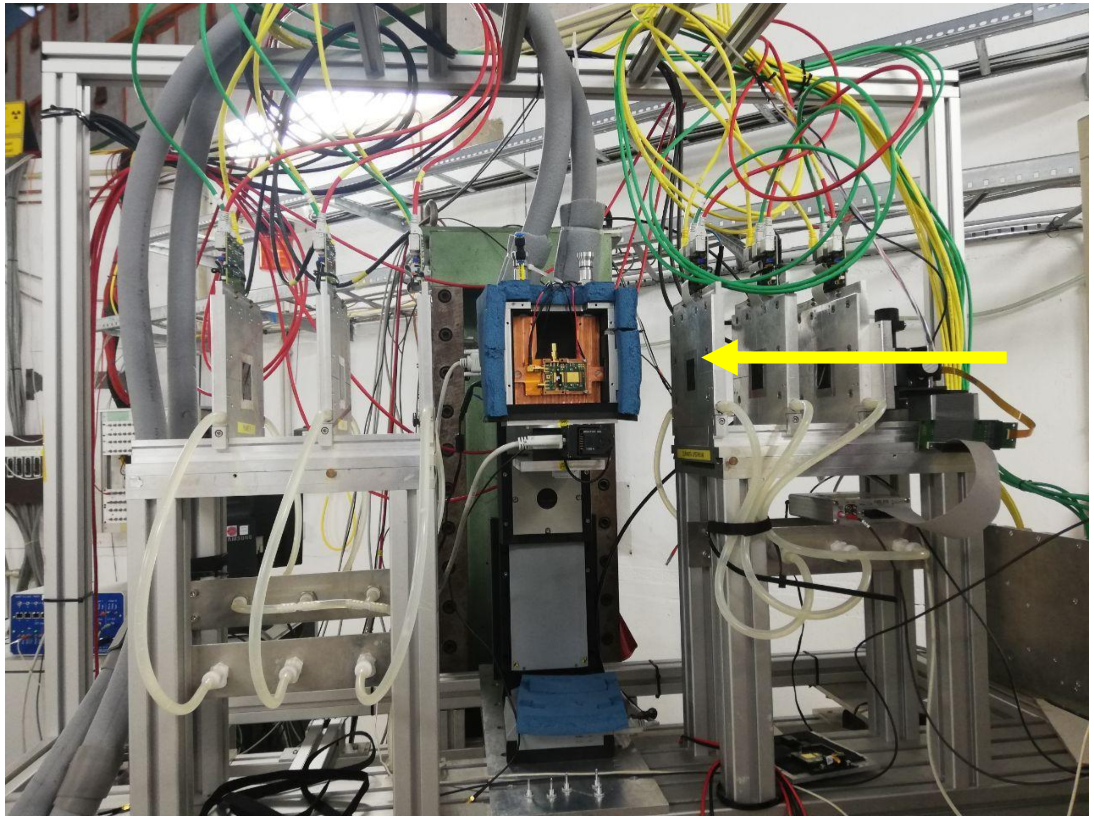
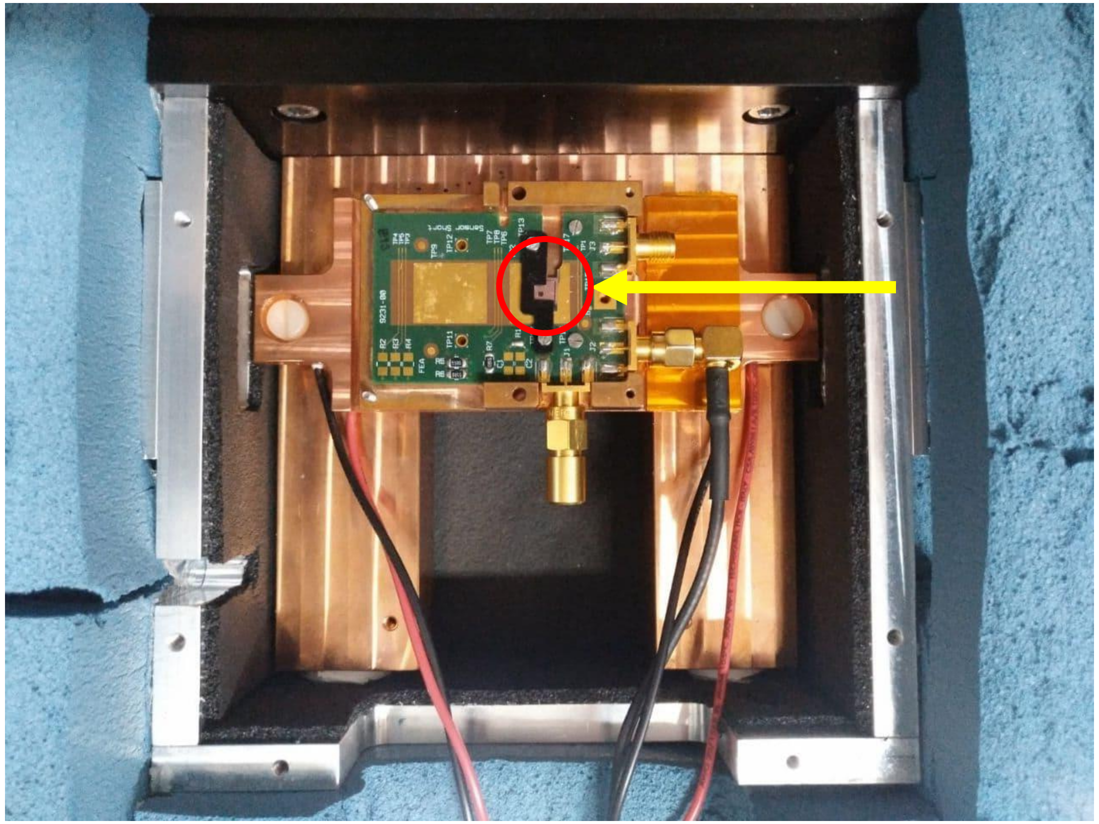
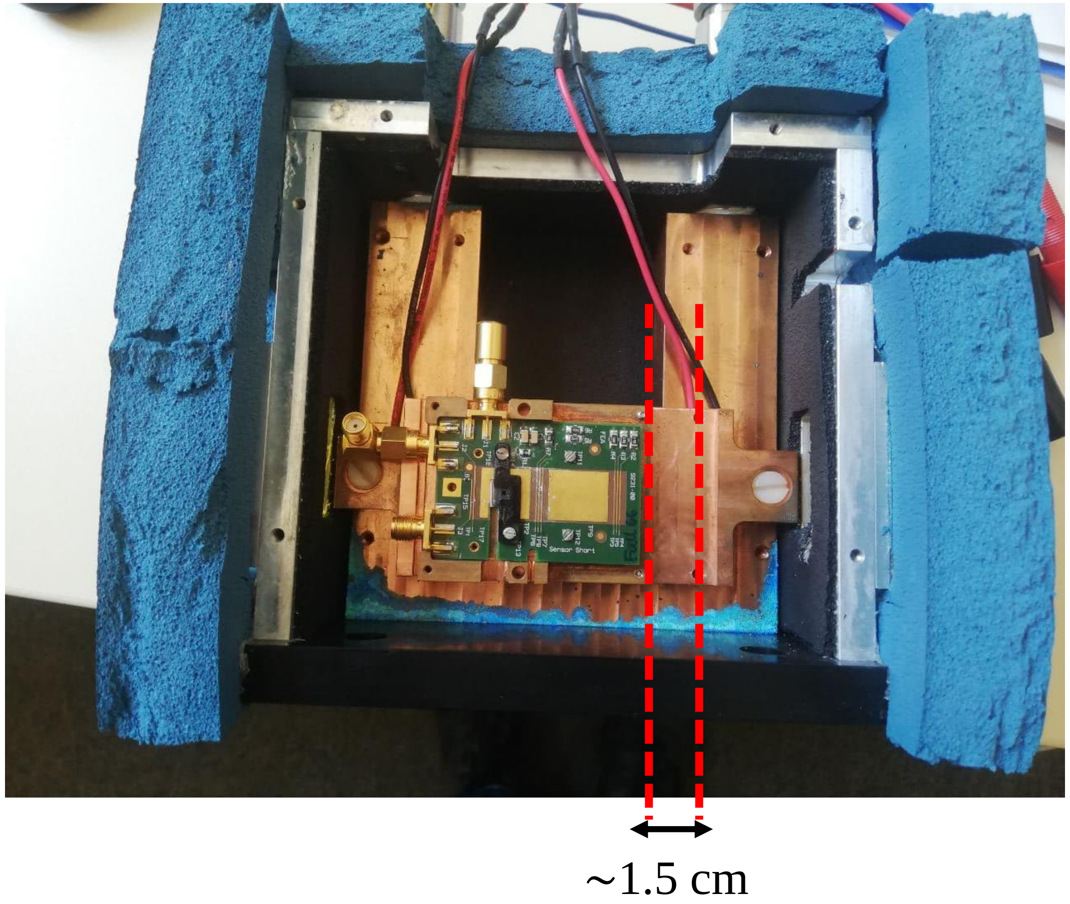
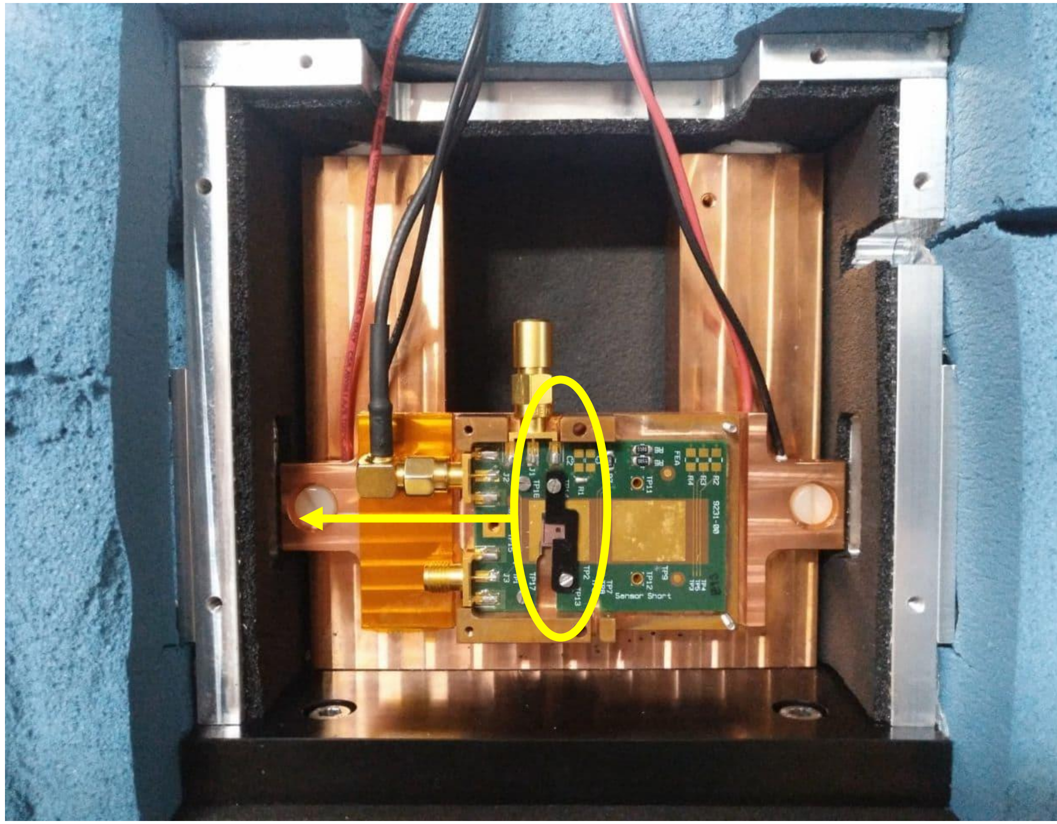




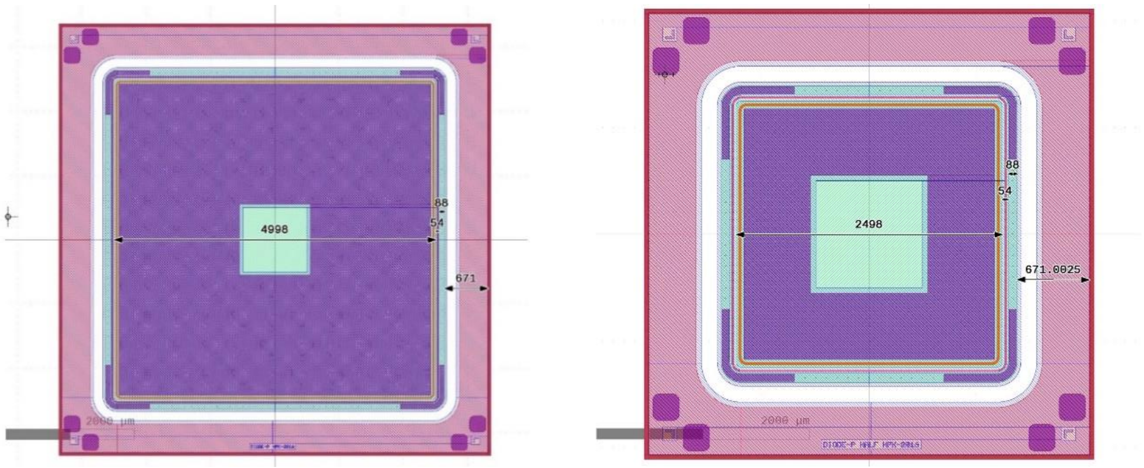
Closer DUT-to-telescope distance





Specifications of the diodes

Top view (dimensions are in micrometer)



- Active thickness 150 µm
- Area ≈ 25 and 12.5 mm^2
- p-type (n^+pp^+ configuration)
- Doping concentration $\approx 4.5 \times 10^{12}$ cm^{-3}
- Depletion voltage 75 V
- Manufactured by Hamamatsu Photonic K.K (HPK)
- Guard-ring is floating

For irradiation study

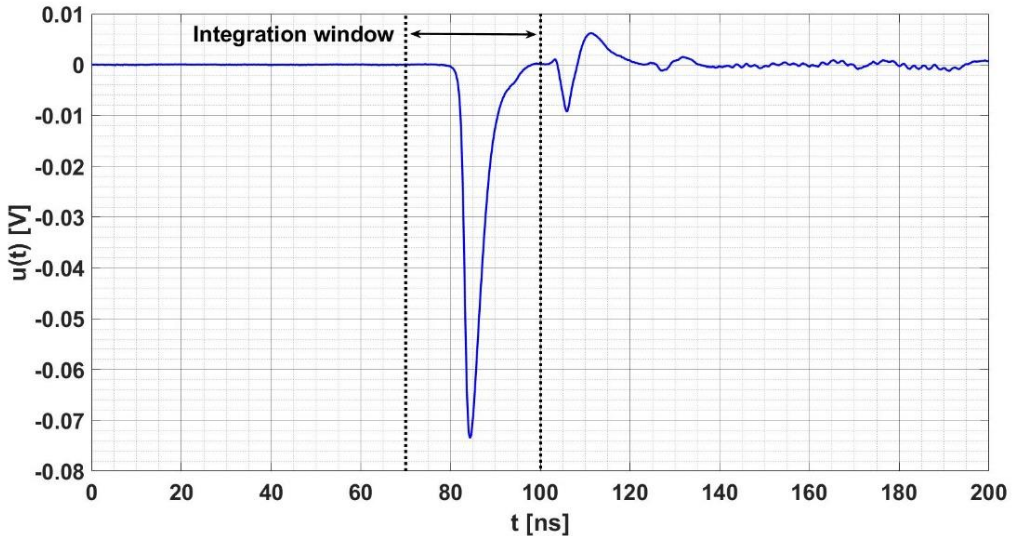
- Irradiation with 23 MeV protons at Karlsruhe Institute of Technology (KIT)
- Irradiation to equivalent fluence $\Phi_{eq} = 2, 4, 8$ and 12×10^{15} cm^{-2} (hardness factor of $\kappa = 2.2$)

Collected charge measurement

- Transients of the diode ($u_0(t)$) are recorded
- The average of transients in the prepulse region is subtracted from the whole transient (baseline correction)
- Collected charge for the diode is calculated by

$$Q_0 = \int_{t_0}^{t_1} \frac{u_0(t)}{G \cdot R_L} dt \ , \qquad R_L = 50\ \Omega\ , G = 100, t_1 - t_0 = 30\ \text{ns}$$

Average transient



$$BW_{Oscilloscope} = 2.5\ \text{GHz}$$

$$\text{Sampling rate} = 20\ \frac{\text{GS}}{\text{s}}$$

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In-situ alignment

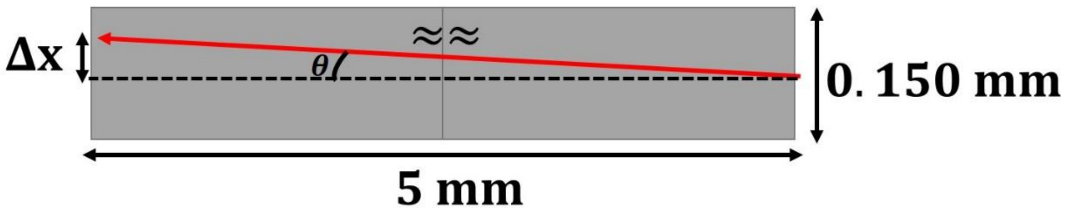
Purpose of in-situ alignment:

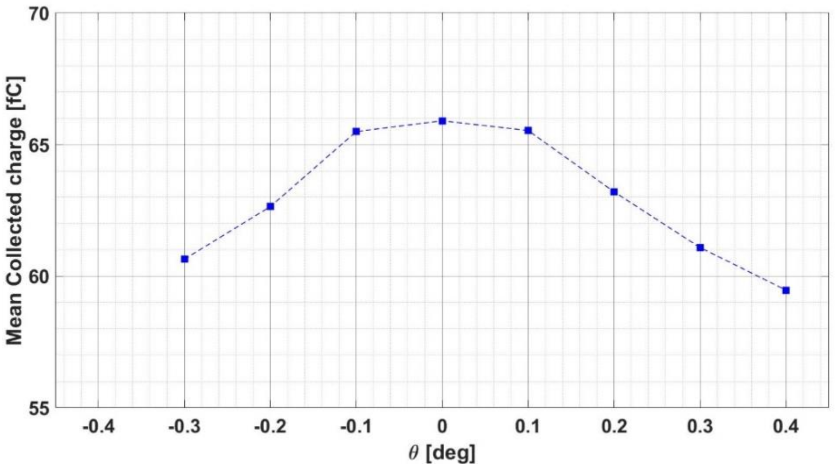
- Find the angle for which tracks are parallel with the diode surface, i.e. $\theta = 0$

Measurement conditions:

- Room temperature
- $V_{bias} = 120$ V
- $E_{beam} = 4$ GeV (higher beam rate, faster data taking)
- Offline threshold: -20 mV
- Step of angle scan: 0.1° (1.7 mrad)

$$\Delta x = 5 \times \tan(\theta)\ [mm]$$

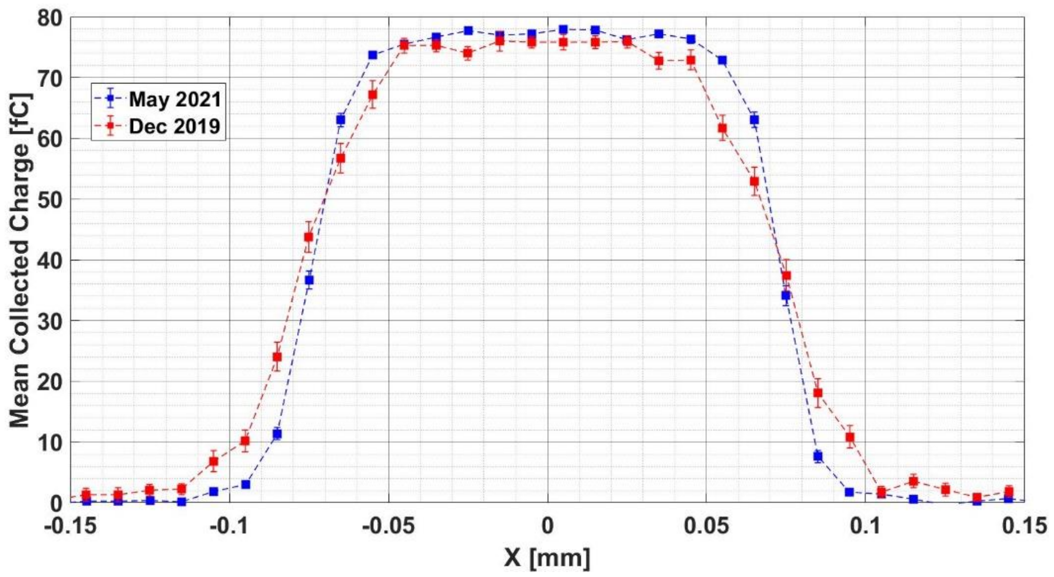




Charge profile, non-irradiated diode

Measurement conditions:

- Room temperature
- $V_{bias} = 100\ V, 120V$
- Diode size: $25\ mm^2$
- $E_{beam} = 4.0\ GeV, 5.2\ GeV$
- Beam divergence: ± 1 mrad
- $dz_{dut} \approx 110\ mm, 95\ mm$



Observations:

- A sharper profile is observed for the new measurements
- The spatial resolution has improved considerably

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Charge profile, non-irradiated diode

Estimation of the diode thickness:

- Fit two error functions with the same width to the profile:

$$F(x) = A\int_{x}^{x+dx}\left(\operatorname{erf}\left(\frac{x'-\mu_1}{\sqrt{2}\sigma}\right)-\operatorname{erf}\left(\frac{x'-\mu_2}{\sqrt{2}\sigma}\right)\right)dx'$$

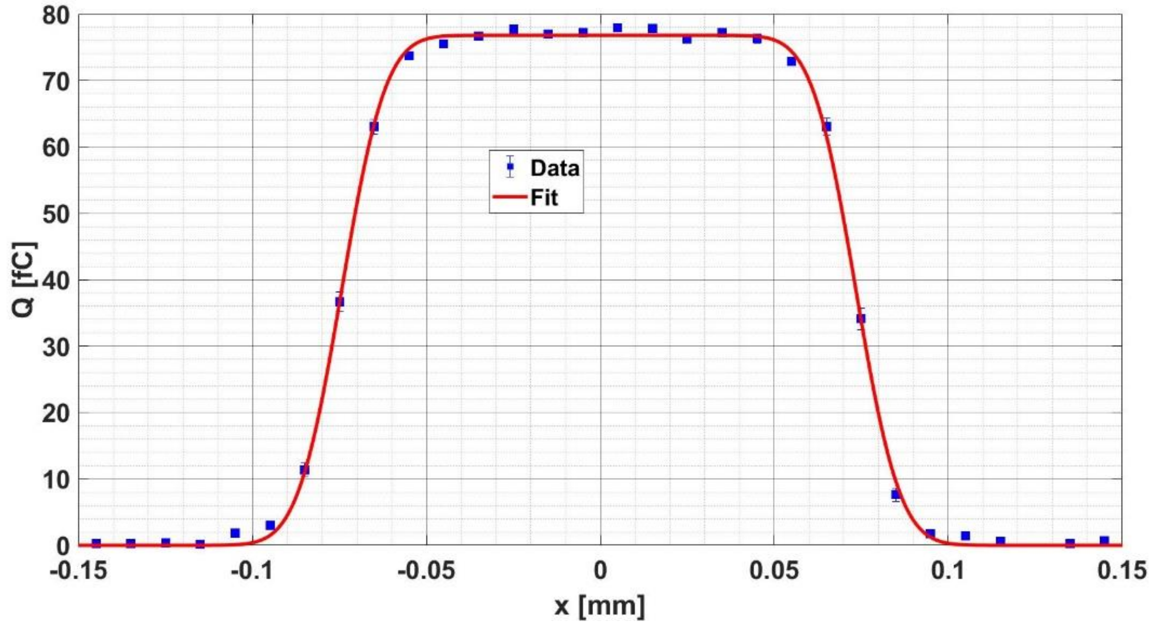
- Thickness of the diode is estimated as:

$$t_{diode} = \mu_2 - \mu_1$$

The result of the estimation:

$$\mathbf{t_{diode} = 147.9 \pm 0.3\ \mu m}$$

$$\boldsymbol{\sigma = 9.6 \pm 0.2\ \mu m}$$



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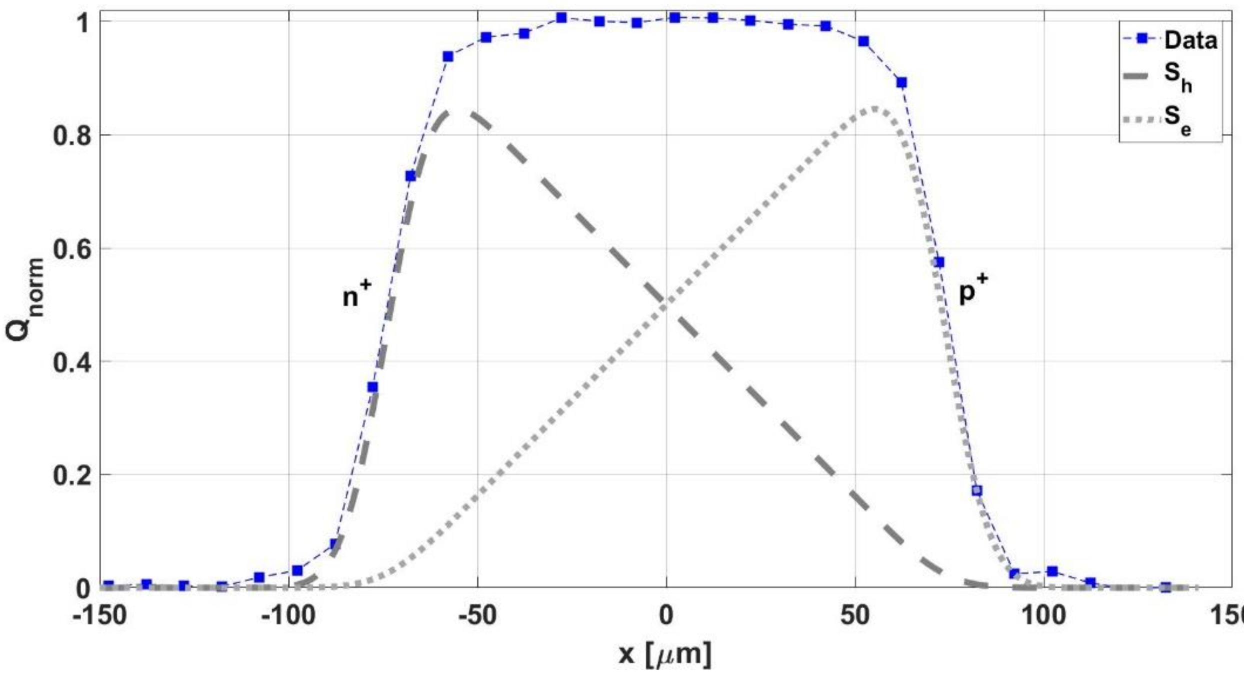
Charge profile, non-irradiated diode

Measurement conditions:

- Temperature: Room temperature
- $V_{bias} = 120$ V
- Beam divergence: ± 1 mrad

The induced signal by electrons and holes

$$\begin{cases} Q_e(x) = \int_{-\frac{d}{2}}^{x} E_w(y) \cdot \exp\left(\int_x^y \frac{d\acute{y}}{\lambda_e(\acute{y})}\right) dy \\ Q_h(x) = \int_x^{\frac{d}{2}} E_w(y) \cdot \exp\left(-\int_x^y \frac{d\acute{y}}{\lambda_h(\acute{y})}\right) dy \end{cases}$$



λ_e, λ_h: charge collection length of electrons and holes

$E_w(y) = \frac{1}{d}$, weighting field of a pad diode

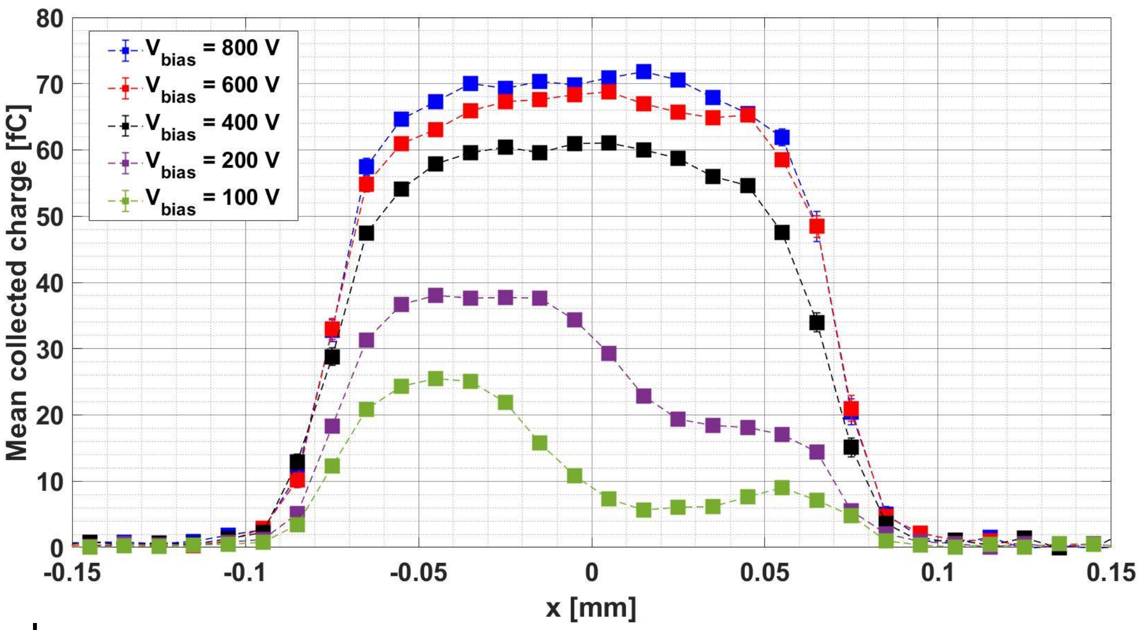
Charge profile, irradiated diode

Measurement conditions:

- Temperature: -20 C
- $V_{bias} = 800, 600, 400, 200, 100$ V
- Diode size: 25 mm^2
- Beam divergence: ± 1 mrad

DUT:

- Proton irradiated at $\Phi_{eq} = 2 \times 10^{15}$ cm^{-2}



Observations:

- For high bias voltages (>=600V) a box shape profile is observed
- At low bias voltages, charge collection near n^+ implant is systematically higher than p^+.

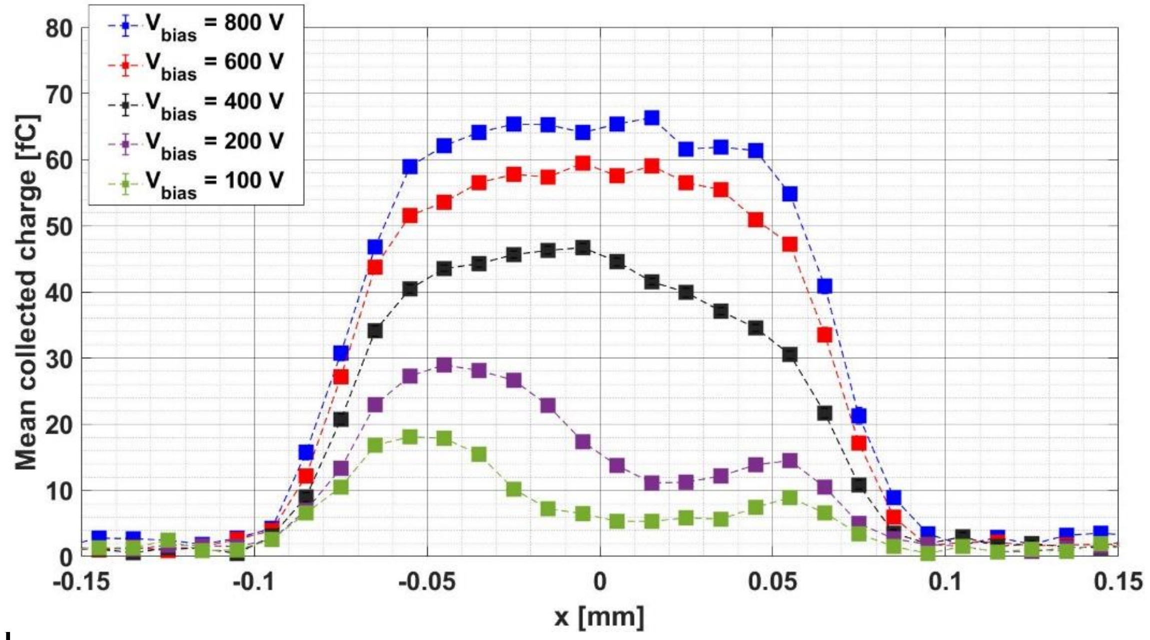
Charge profile, irradiated diode

Measurement conditions:

- Temperature: -20 C
- $V_{bias} = 800, 600, 400, 200, 100$ V
- Diode size: 25 mm^2
- Beam divergence: ± 1 mrad

DUT:

- Proton irradiated at $\Phi_{eq} = 4 \times 10^{15}$ cm^{-2}



Observations:

- For the highest bias voltages, a box shape profile is observed
- At low bias voltages, charge collection near n^+ implant is systematically higher than p^+.

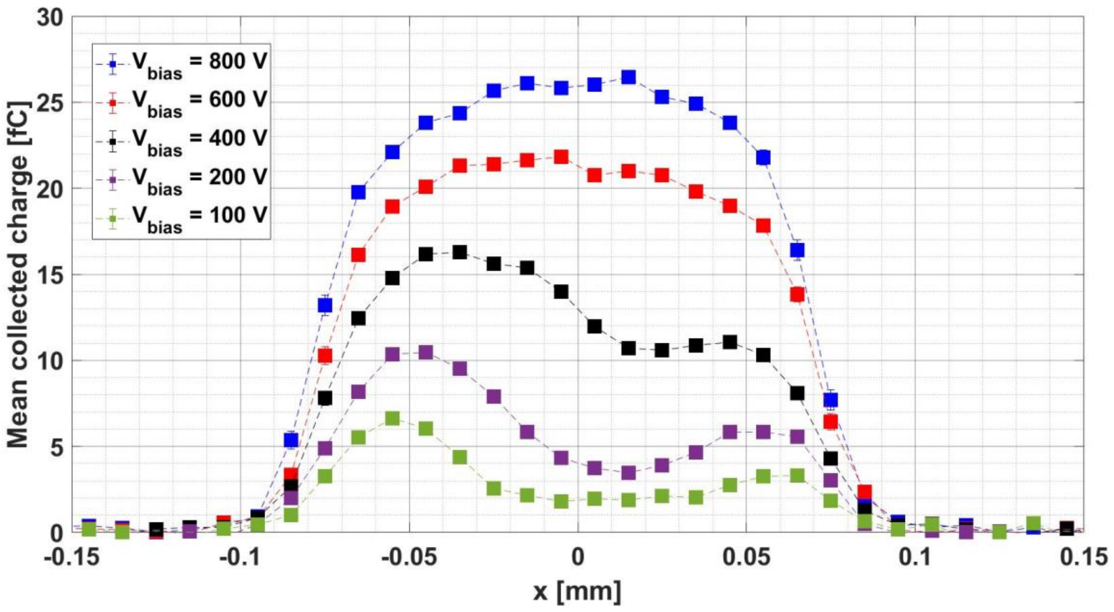
Charge profile, irradiated diode

Measurement conditions:

- Temperature: -20 C
- $V_{bias} = 800, 600, 400, 200\ , 100$ V
- Diode size: 12.5 mm^2
- Beam divergence: ± 1 mrad

DUT:

- Proton irradiated at $\Phi_{eq} = 8 \times 10^{15}\ cm^{-2}$



Observations:

- For the highest bias voltages, a box shape profile is observed
- At low bias voltages, charge collection near n^+ implant is systematically higher than p^+.

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Charge profile, irradiated diode

Measurement conditions:

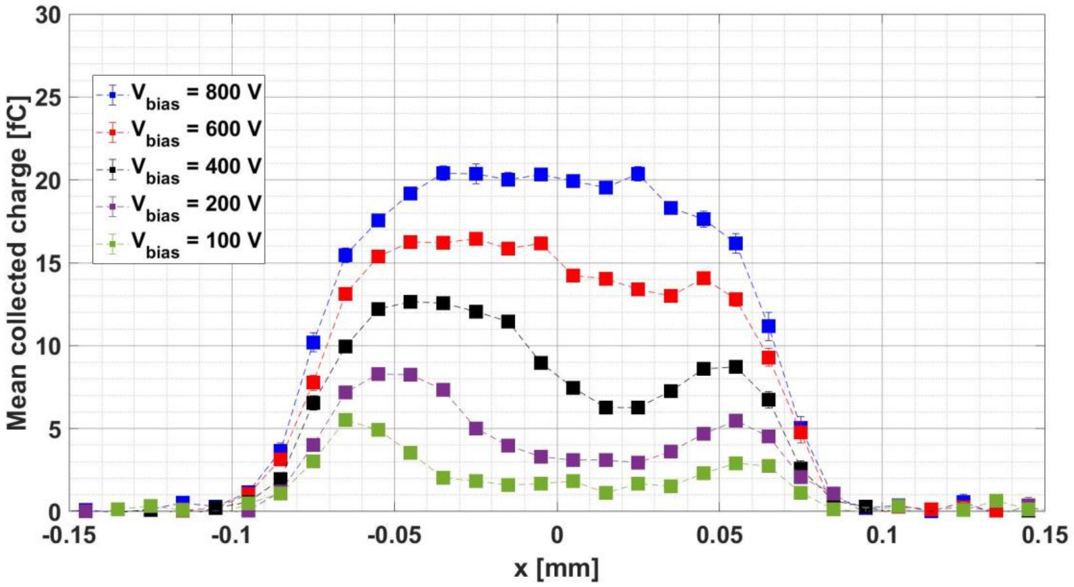
- Temperature: -20 C
- $V_{bias} = 800, 600, 400, 200, 100$ V
- Diode size: $12.5\ mm^2$
- Beam divergence: ± 1 mrad

DUT:

- Proton irradiated at $\Phi_{eq} = 12 \times 10^{15}\ cm^{-2}$

Observations:

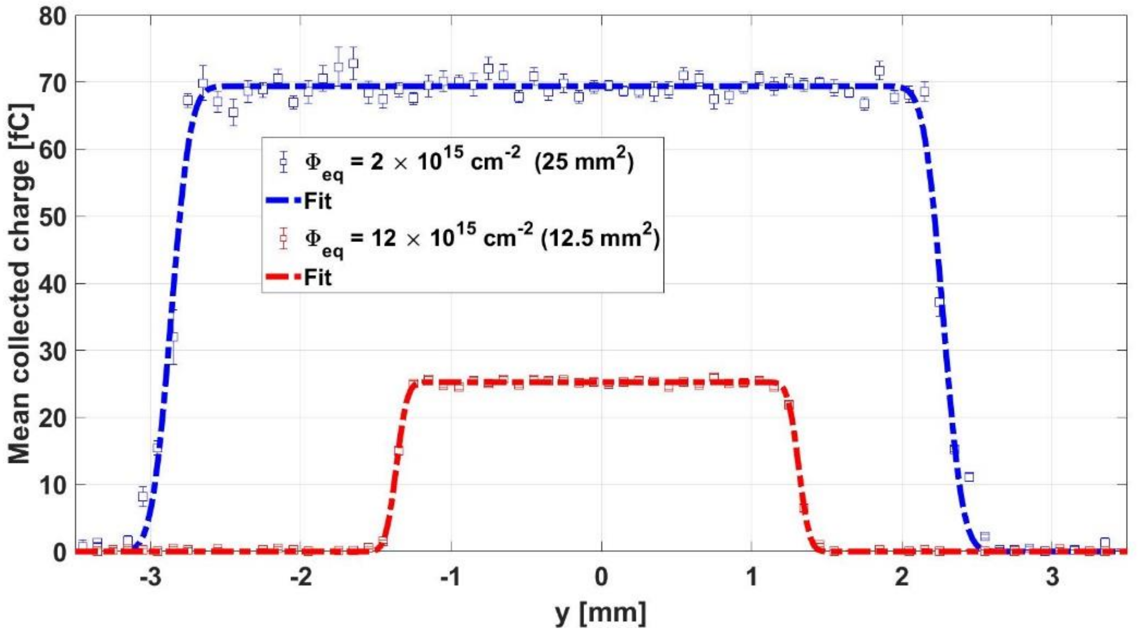
- For the highest bias voltages, a box shape profile is observed
- At low bias voltages, charge collection near n^+ implant is systematically higher than p^+.



Estimation of path length for half size diode

Fit two error functions to the profile:

$$F(y) = A\left(\mathrm{erf}\left(\frac{y-\mu_1}{\sqrt{2}\sigma}\right) - \mathrm{erf}\left(\frac{y-\mu_2}{\sqrt{2}\sigma}\right)\right)$$



Width of the diode is estimated as:

$$w_{diode} = \mu_2 - \mu_1$$

$$W_1 = 5.1 \pm 0.1 \text{ mm}$$

$$W_2 = 2.6 \pm 0.1 \text{ mm}$$

The charge profile of half size diodes is scaled with the following factor:

$$R = \frac{W_1}{W_2} = 1.96$$

Charge profile, irradiated diode

Measurement conditions:

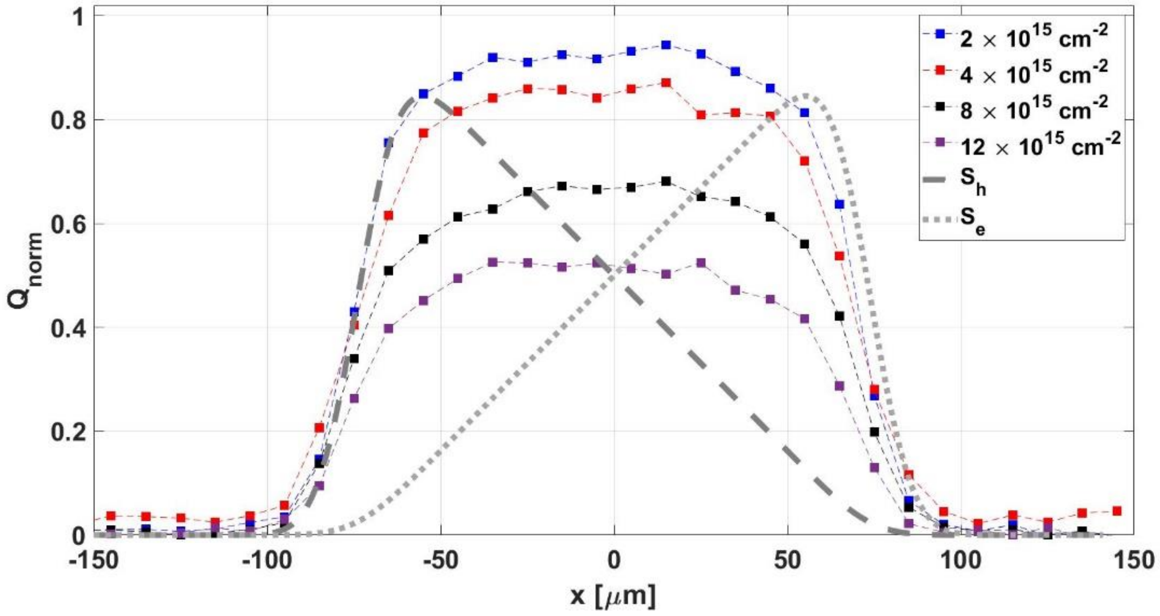
- Temperature: -20 C
- $V_{bias} = 800$ V
- Diode size: 25 and 12.5 mm^2
- Beam divergence: ± 1 mrad

DUT:

- Proton irradiated at $\Phi_{eq} = 2, 4, 8, 12 \times 10^{15}$ cm^{-2}

Observations:

- Similar charge collection lengths for electrons and holes
- At higher fluences, contribution of holes in the signal increases



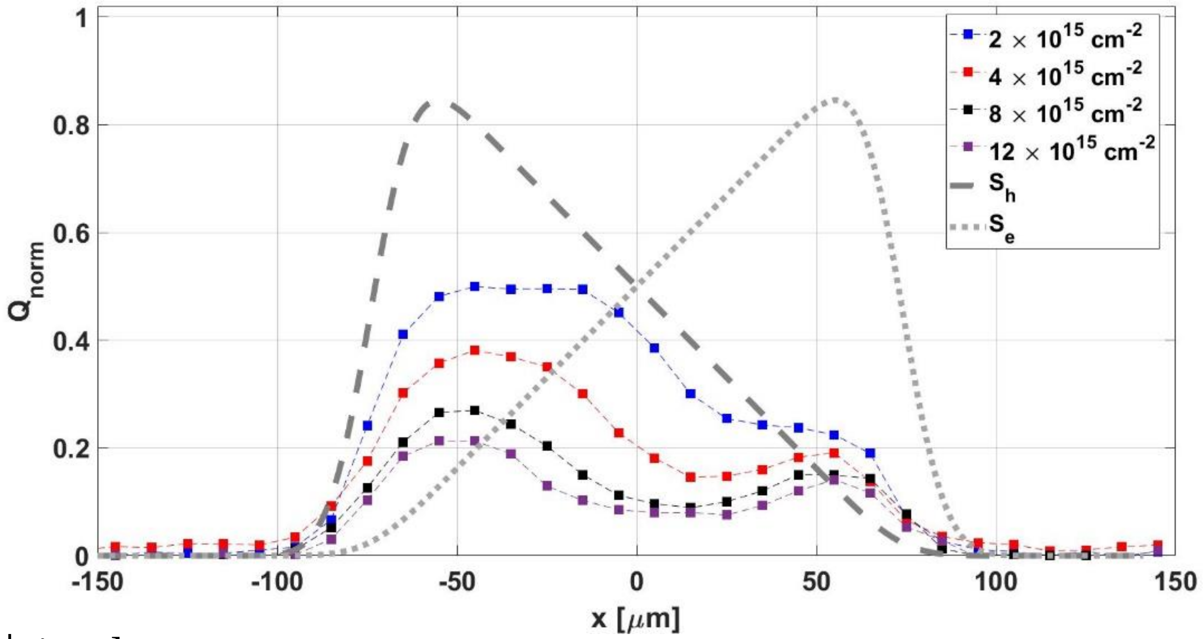
Charge profile, irradiated diode

Measurement conditions:

- Temperature: -20 C
- $V_{bias} = 200$ V
- Diode size: 25 and 12.5 mm^2
- Beam divergence: ± 1 mrad

DUT:

- Proton irradiated at $\Phi_{eq} = 2, 4, 8, 12 \times 10^{15}$ cm^{-2}



Observations:

- Evidence of a double junction in the region close to the p^+ implant
- Holes have a higher charge collection length than electrons, main losses come from electrons
- The effect becomes pronounced with increasing irradiation fluence

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Summary and outlook

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Summary

- Edge-on measurement can be used to obtain charge collection as a function of depth in irradiated pad diodes.
- The quality of measurements has improved in several aspects:
  - Finer steps for the angular scan
  - Better spatial resolution
  - Higher statistics
- Results for irradiated results reveals:
  - Holes have a higher contribution in the induced signal than electrons as irradiation fluence increases and bias voltage decreases
  - Evidence of double junction at lower bias voltages
  - Low electric field in the center of the diode
  - Position dependency of charge collection length

Outlook

- Extract the charge collection lengths of electrons and holes
- Comparison of the results with existing models and measurements

Back up
Charge distribution, non-irradiated diode

Measurement conditions:

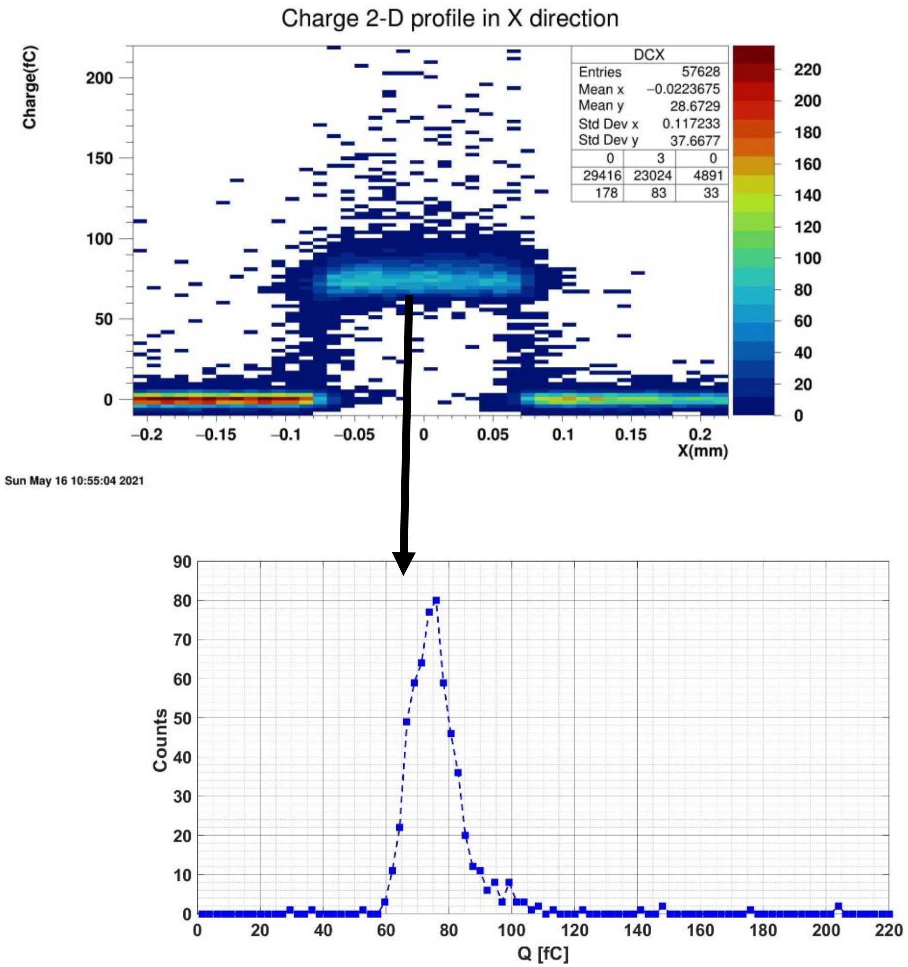
- Room temperature
- $V_{bias} = 120\ V$
- $\theta : 0°$
- $E_{beam} = 5.2\ GeV$
- Beam divergence: ± 1 mrad

Observations:

- In the central region of the diode (i.e. $0.07\ mm < X < 0.07\ mm$)

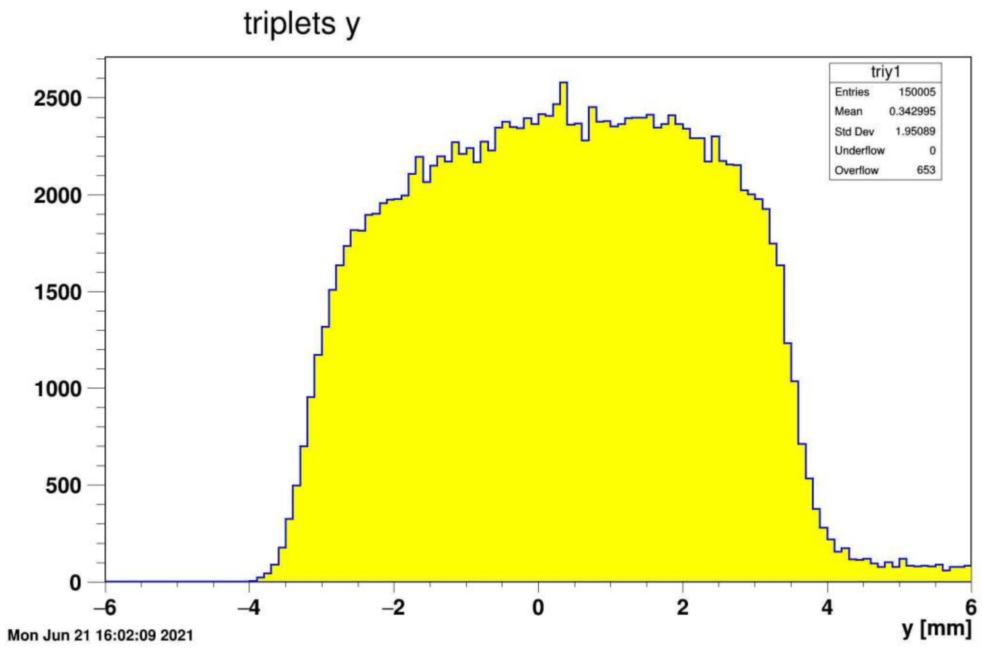
the collected charge is well above the noise level

- Data taking without zero suppression enables us measuring very low charges (relevant for irradiated diodes)

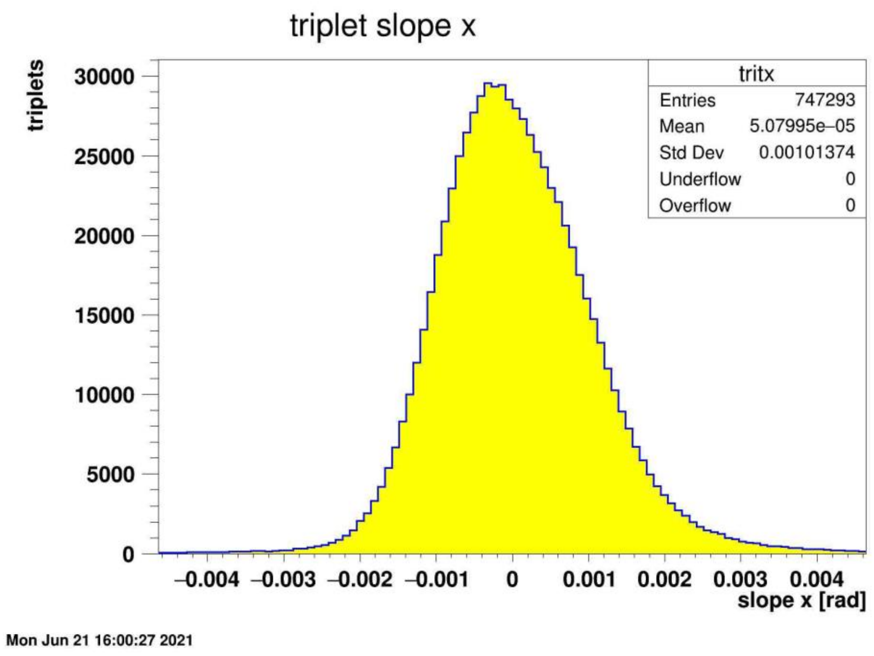


Back up
Geometrical cuts

$|y_{dut}| < 2.0$ mm



$|\theta_x| < 1$ mrad



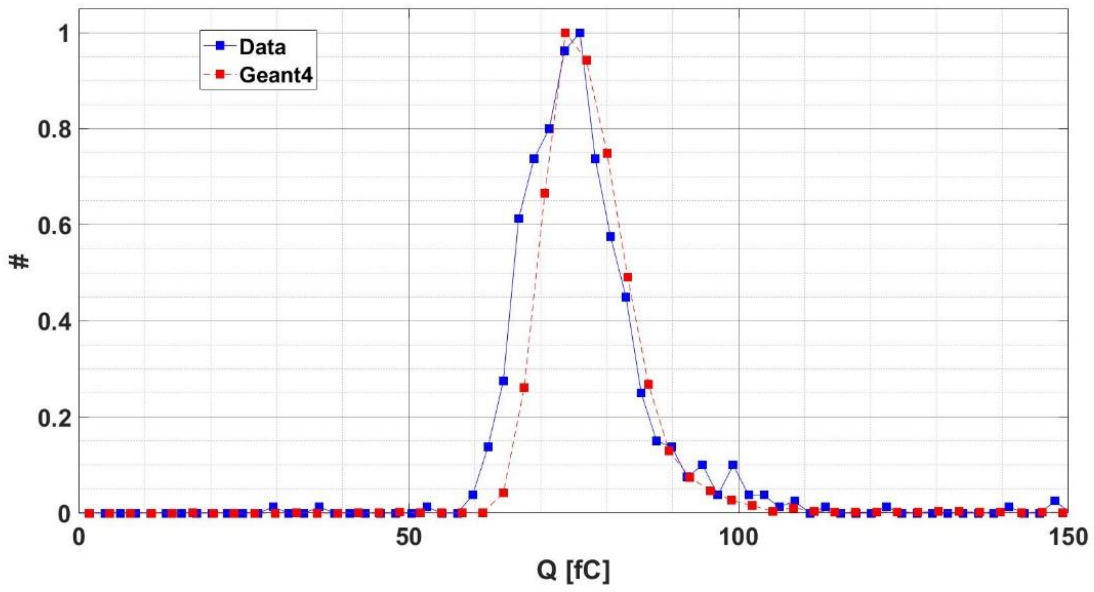
Back up
Charge distribution, non-irradiated diode

Measurement conditions:

- Room temperature
- $V_{bias} = 120$ V
- $\theta : 0°$
- $E_{beam} = 5.2$ GeV
- Beam divergence: ± 1 mrad
- Depth of tracks: $0.00 \text{ mm} < X < 0.01 \text{ mm}$

Simulation conditions:

- Energy deposition distribution for 7 mm silicon $\frac{dN}{dE}$
- Charge deposition distribution for 5 mm silicon: $\frac{dN}{dQ} = \frac{dN}{dE} \times \frac{q_0}{\epsilon} \times \frac{5 \text{ mm}}{7 \text{ mm}}$
- Depth of tracks: $X = 0.00$ mm



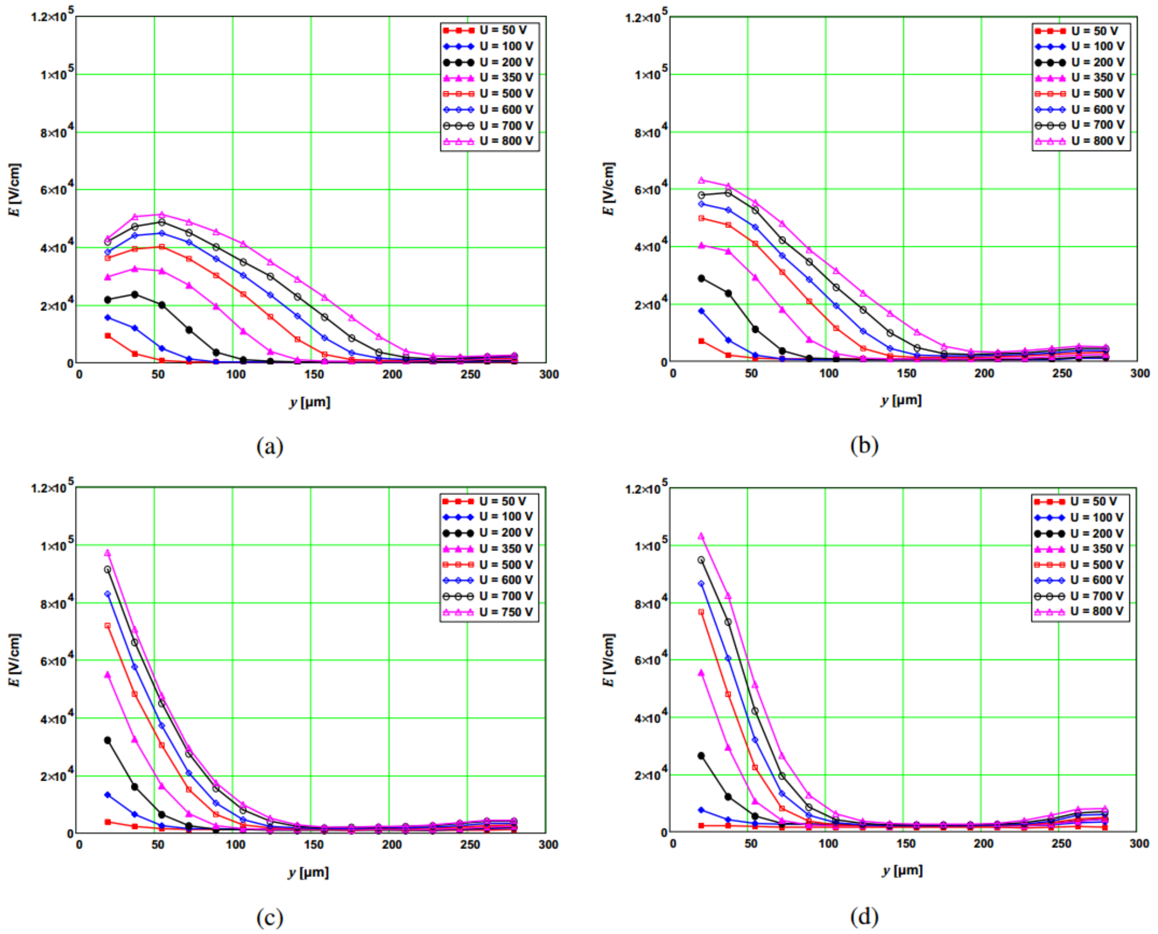
Back up
Electric field profile of irradiated strip sensors

$\Phi_{eq} = 10^{15}\mathrm{cm}^{-2}$(a)

$\Phi_{eq} = 2 \times 10^{15}\mathrm{cm}^{-2}$(b)

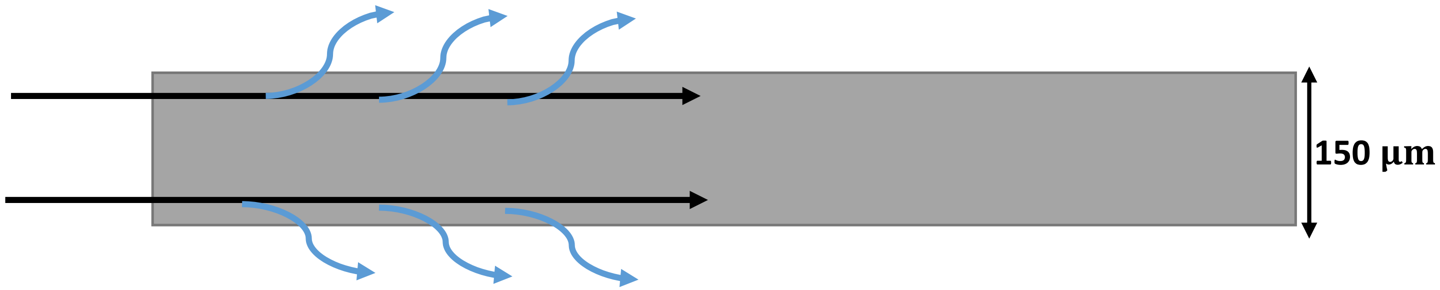
$\Phi_{eq} = 5 \times 10^{15}\mathrm{cm}^{-2}$(c)

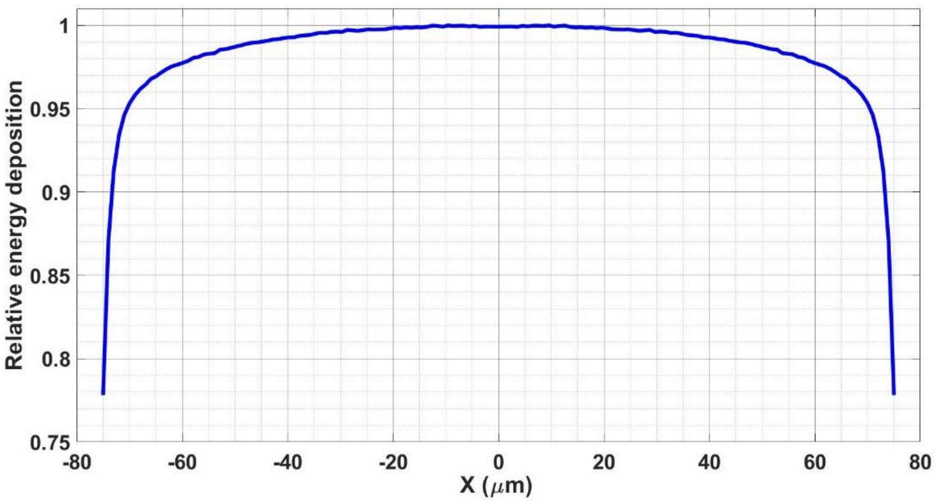
$\Phi_{eq} = 10^{16}\mathrm{cm}^{-2}$(d)



Back up
GEANT4 simulation result

Less energy deposition at edges than center





Back up
CCE as a function of bias voltage

Measurement conditions:

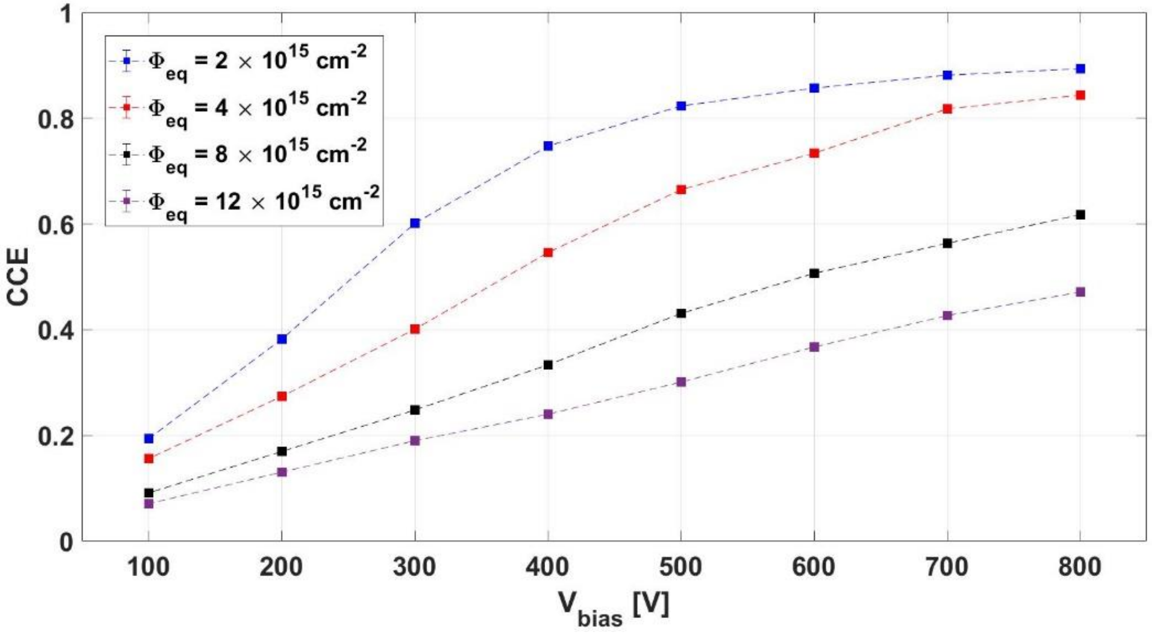
- Temperature: -20 C
- $V_{bias} = 100 - 800$ V

DUTs:

- Proton irradiated at $\Phi_{eq} = 2, 4, 8, 12 \times 10^{15}$ cm^{-2}

CCE is calculated as:

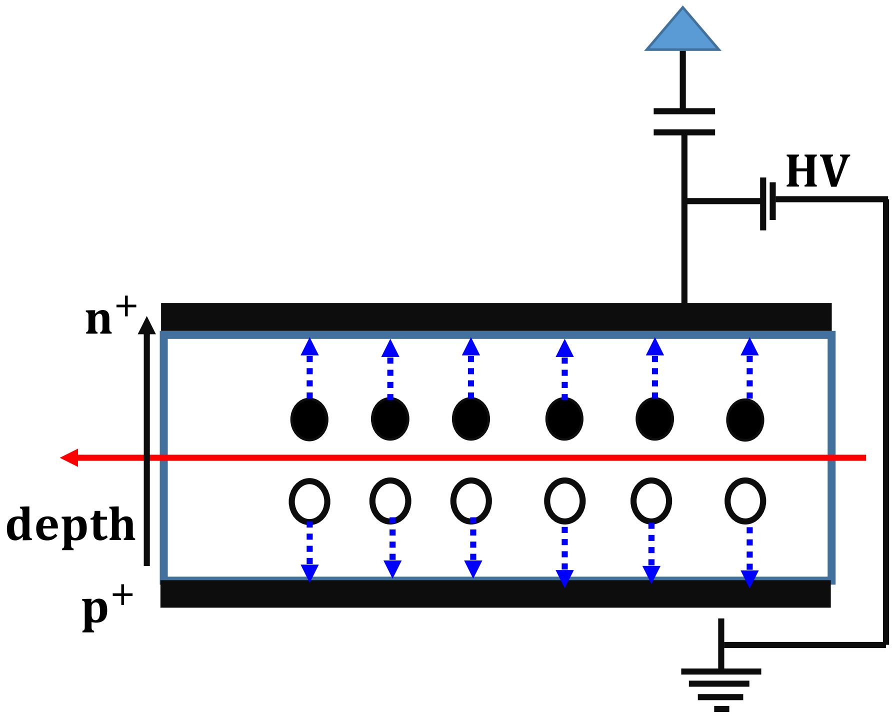
$$\mathrm{CCE}(V_{bias}) = \frac{\sum_{x=-150\ \mu m}^{+150\ \mu m} Q_{x,irradaited}\,(V_{bias})}{\sum_{x=-150\ \mu m}^{+150\ \mu m} Q_{x,non-irradaited}}$$



Backup
Measurement concept

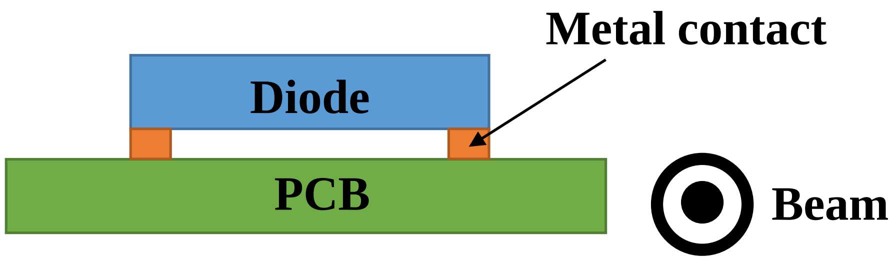
Advantages of using this method:

- The beam direction does not change significantly inside the diode
- The number of e-h pairs produced by beam can be estimated
- The energy deposition of beam is independent of irradiation fluence
- The readout electronic is independent of the Device Under Test (DUT)
- It can be used for pad diodes (simple geometry and weighting field)



Back up
Separation of the diode from PCB

- The electron beam produces showers inside the PCB
- These showers ionizes inside the diode
- Two metal contacts were inserted between PCB and diode to neutralize the effects of showers
- The thickness of these contacts is around 0.5 mm



Back up
Charge profile, non-irradiated diode

Estimation of the diode width:

- Fit two error functions to the profile:

$$F(y) = A\left(\mathrm{erf}\left(\frac{y-\mu_1}{\sqrt{2}\sigma}\right) - \mathrm{erf}\left(\frac{y-\mu_2}{\sqrt{2}\sigma}\right)\right)$$

- Width of the diode is estimated as:

$$w_{diode} = \mu_2 - \mu_1$$

The result of the estimation:

$$\mathbf{w_{diode} = 5.11 \pm 0.1\ mm}$$

No charge collection from the guard-ring is observed