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Edge-on technique using a high energy electron beam for characterization of irradiated pad diodes

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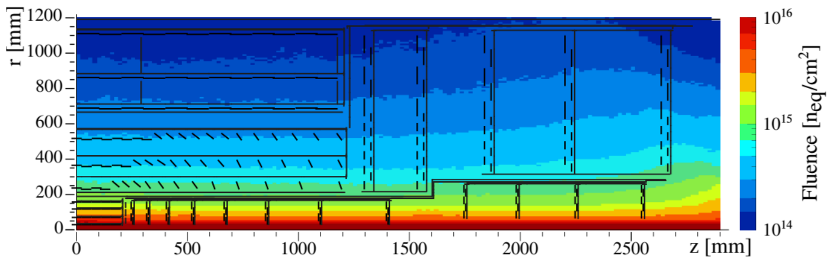
Introduction

- 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.



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 4.0 GeV

The performed measurements

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

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

Introduction

Issues of top TCT measurements with short absorption length radiation:

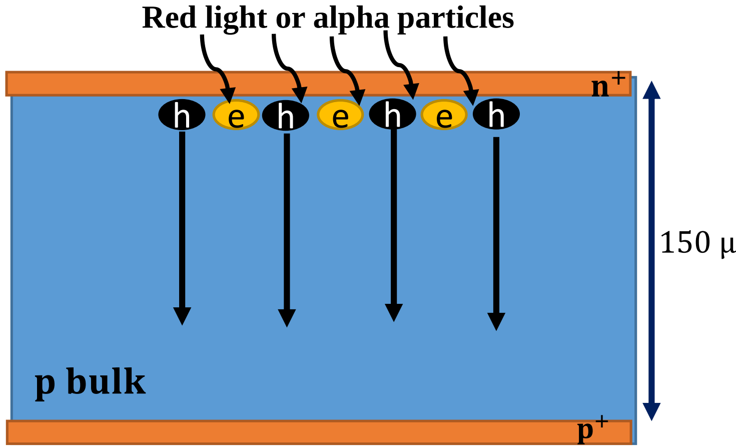
- Difficult to obtain information about charge collection as a function of depth in the sensor
- Very sensitive to any inactive layers at sensor implants

Issues of edge TCT measurement with laser light:

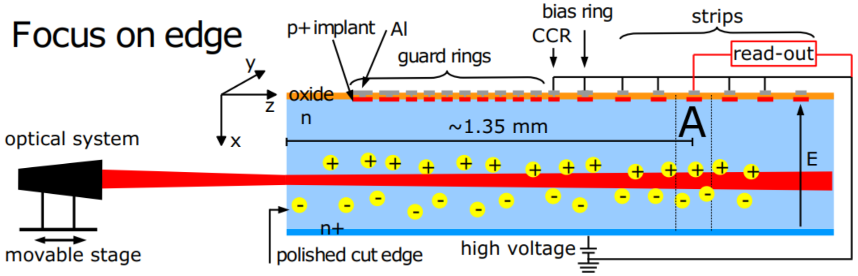
- Changing of the beam radius as it travels into the sensor
- Sensitive to quality of the polished edge
- Commonly used for segmented sensors (complicated weighting filed)
- **The measurements cannot be normalized to an absolute value**

Proposal:

- Using electron beam for characterizing pad diodes with edge-on measurements



Top TCT

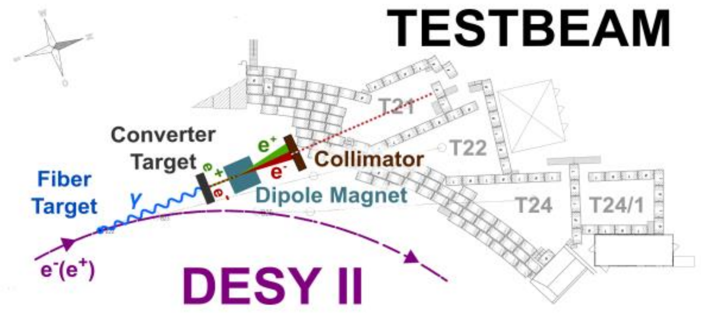


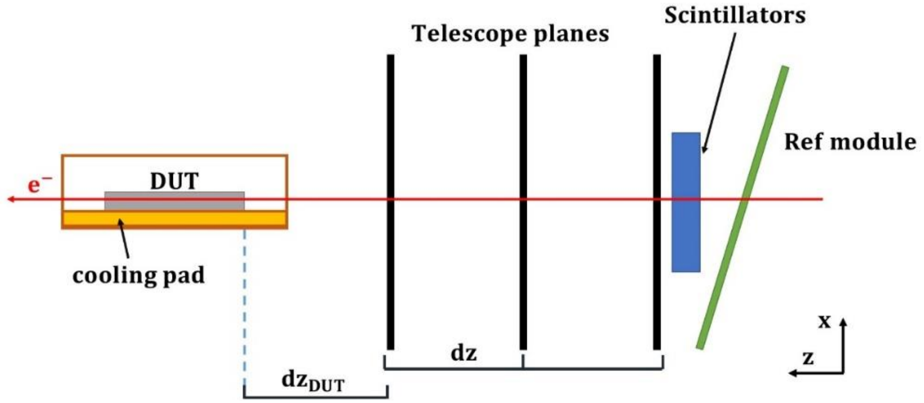
Edge TCT

Measurement setup

DESY II beam test facility:

- Electron/positron beam with energy of 1-6 GeV
- Beam energy of 4.0 GeV was chosen for the measurements
- Three telescope planes for the track reconstruction
- Intrinsic resolution of telescope $\approx 5\ \mu m$
- Timing reference module for reducing in-time pile up
- Scintillator for providing the readout trigger ($8 \times 3\ mm^2$ triggering area)
- Rotation stage for the DUT with a precision of $0.25°$(4 mrad)





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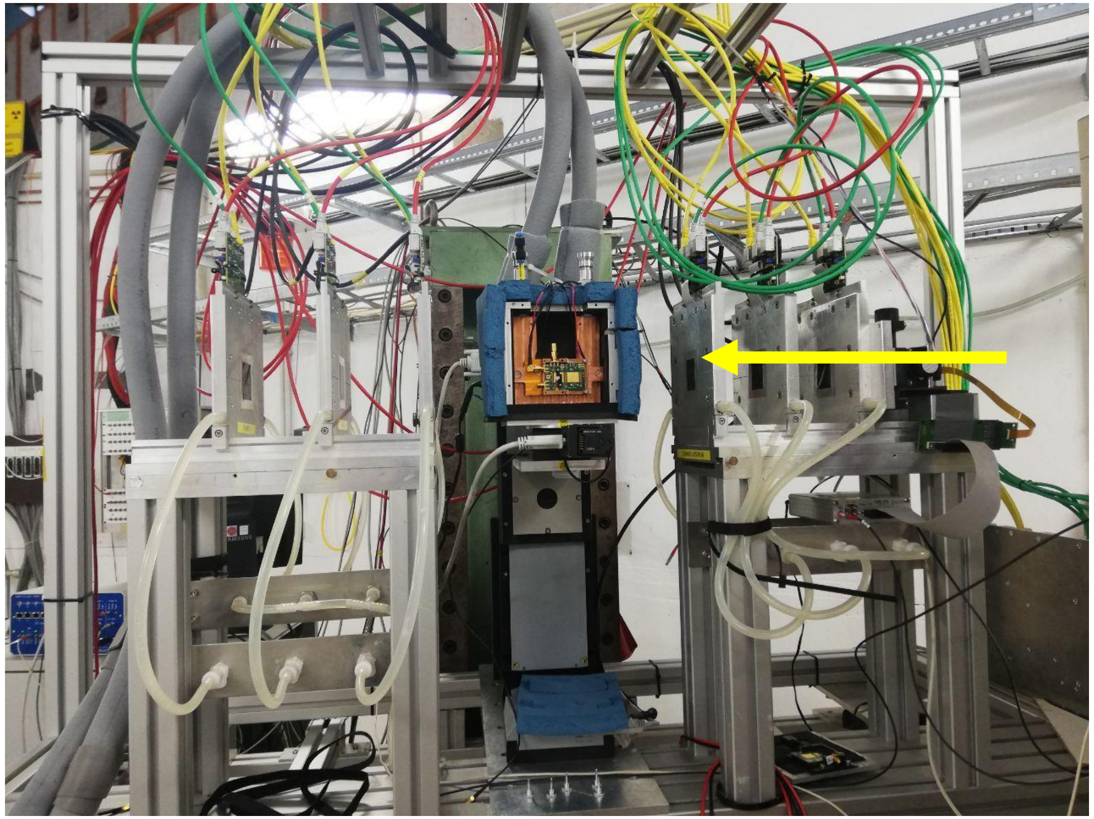
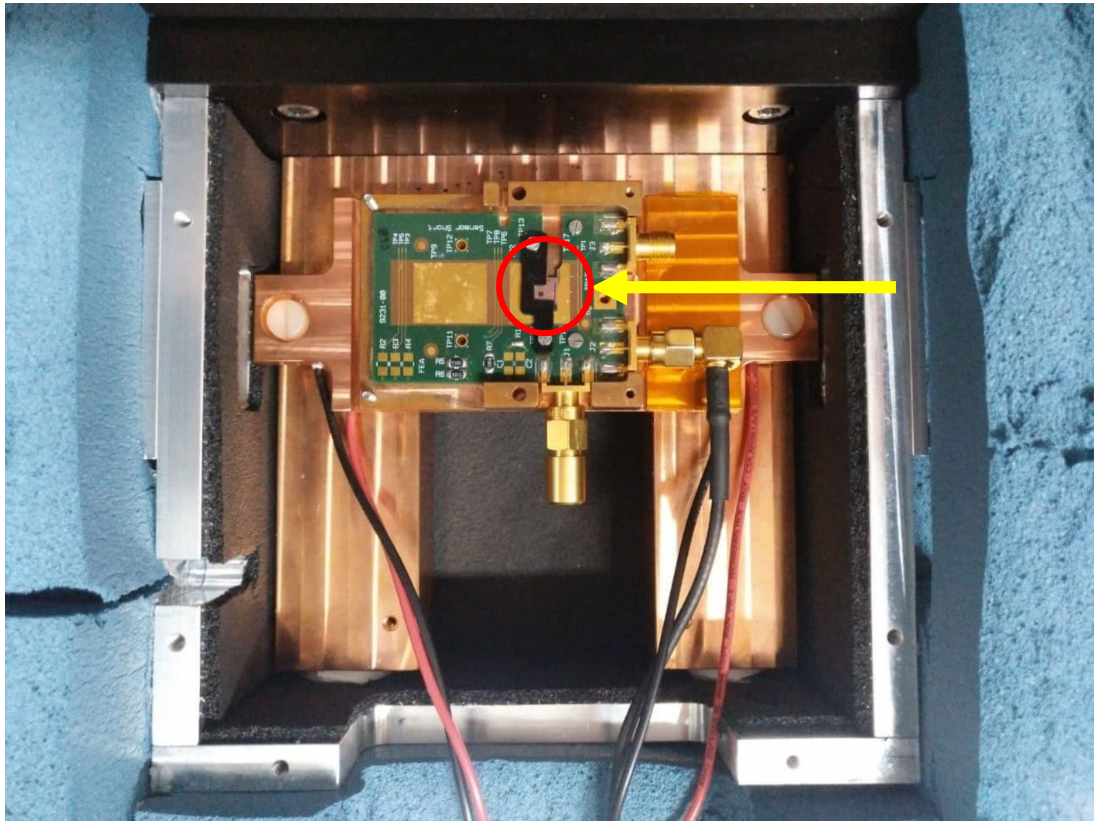
Measurement setup

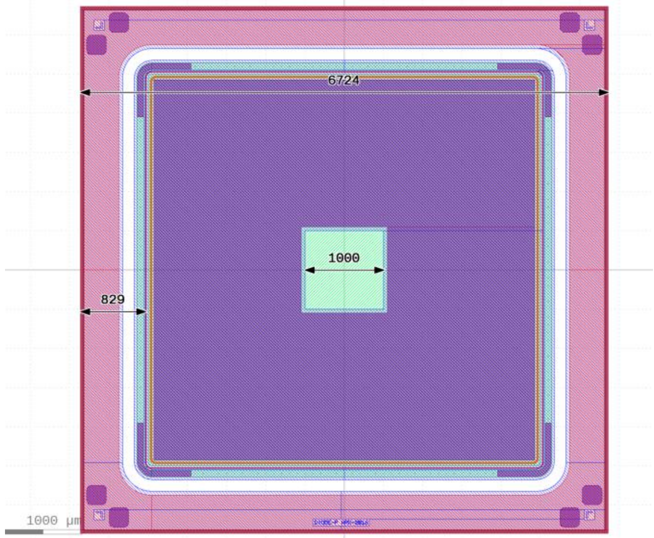




Specifications of the studied diodes

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

Top view (dimensions are in micrometer)



For irradiation study

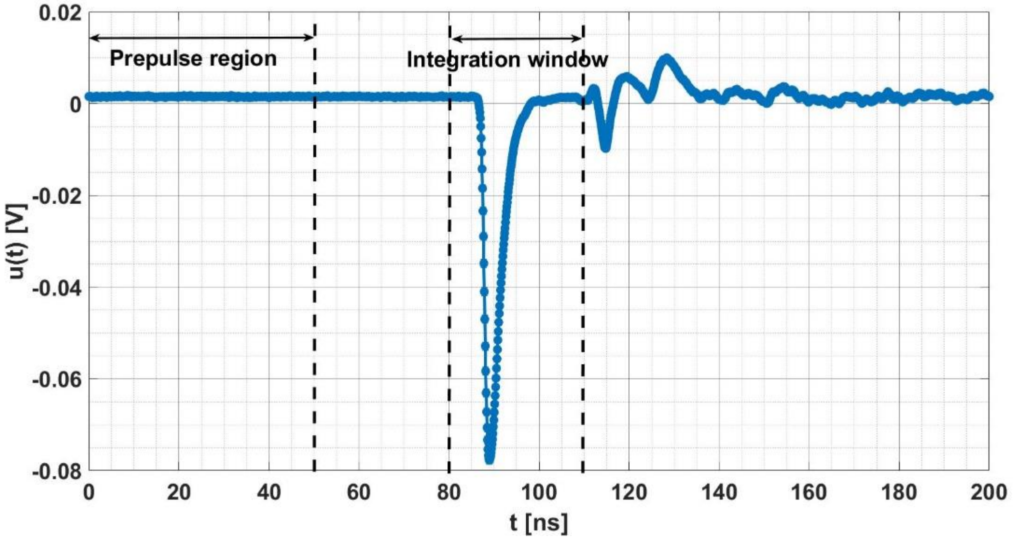
- Irradiation with 23 MeV protons at Karlsruhe Institute of Technology (KIT)
- Irradiation to equivalent fluence $\Phi_{eq} = 2$ and 4×10^{15} cm^{-2} (hardness factor of $\kappa = 2.2$)

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 (baseline correction)
- Collected charge for the diode is given as

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

Average transient



In-situ alignment procedure

Purpose of in-situ alignment:

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

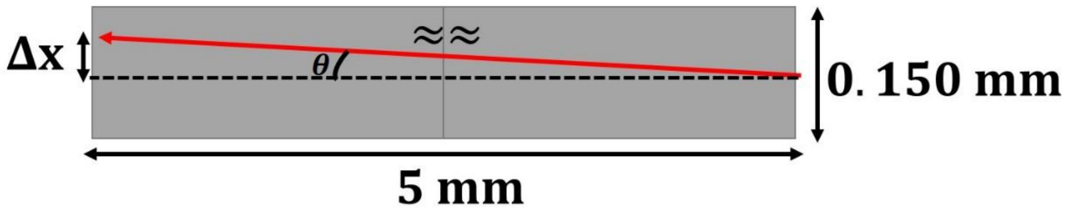
Procedure of in-situ alignment:

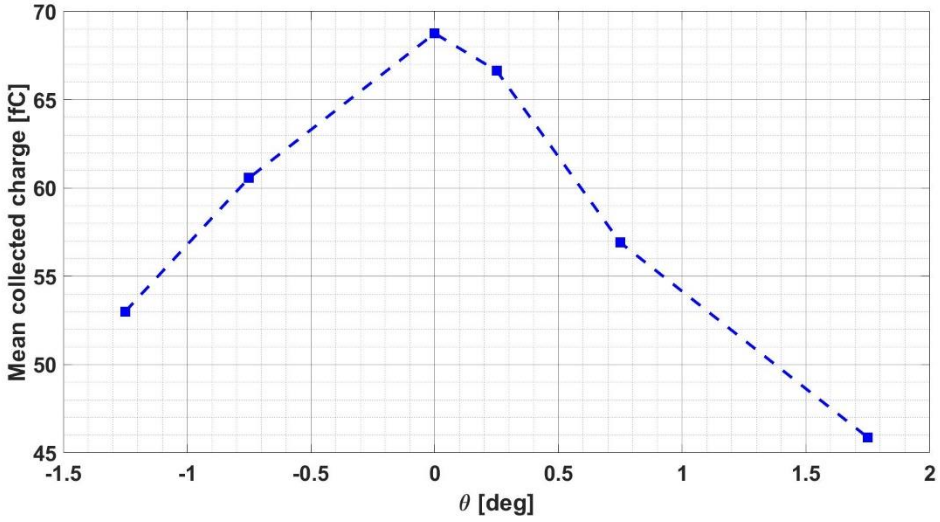
- Rotation of the DUT with small steps (0.25°)
- Calculate the mean collected charge of the diode
- Find the angle in which collected charge is maximum

Advantage of using this procedure:

- No track reconstruction is required
- Independent of the telescope resolution

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





On-line alignment procedure

Measurement conditions:

- Room temperature
- $V_{bias} = 100$ V
- θ: −1.25°, 0°, +0.75°

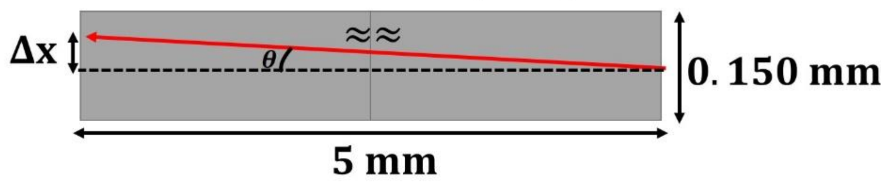
DUT:

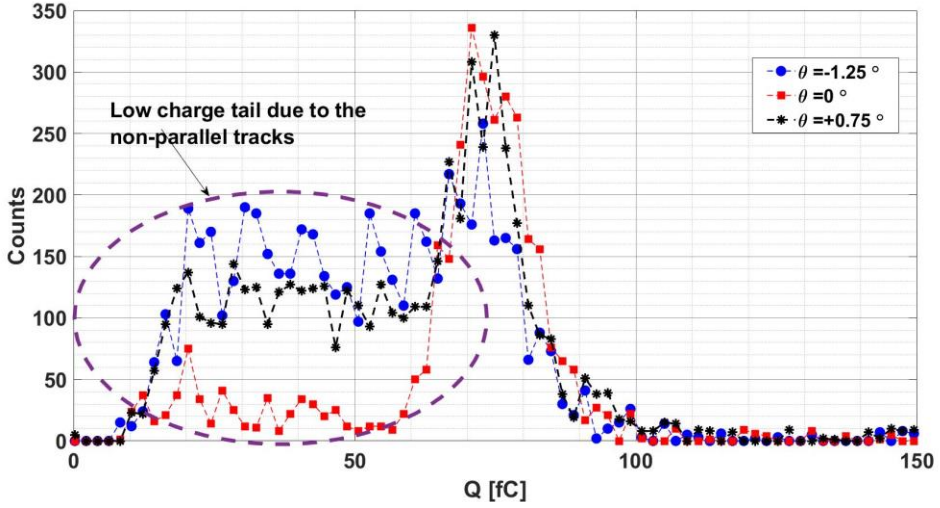
- Non-irradiated

Observations:

- At non-zero θ, tracks close to the surface leave the diode, therefore charge distribution has a low charge tail.
- By rotating the DUT with fine steps, the best angle of incident could be achieved.
- This procedure has to be repeated for each diode.

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





Charge profile, non-irradiated diode

Measurement conditions:

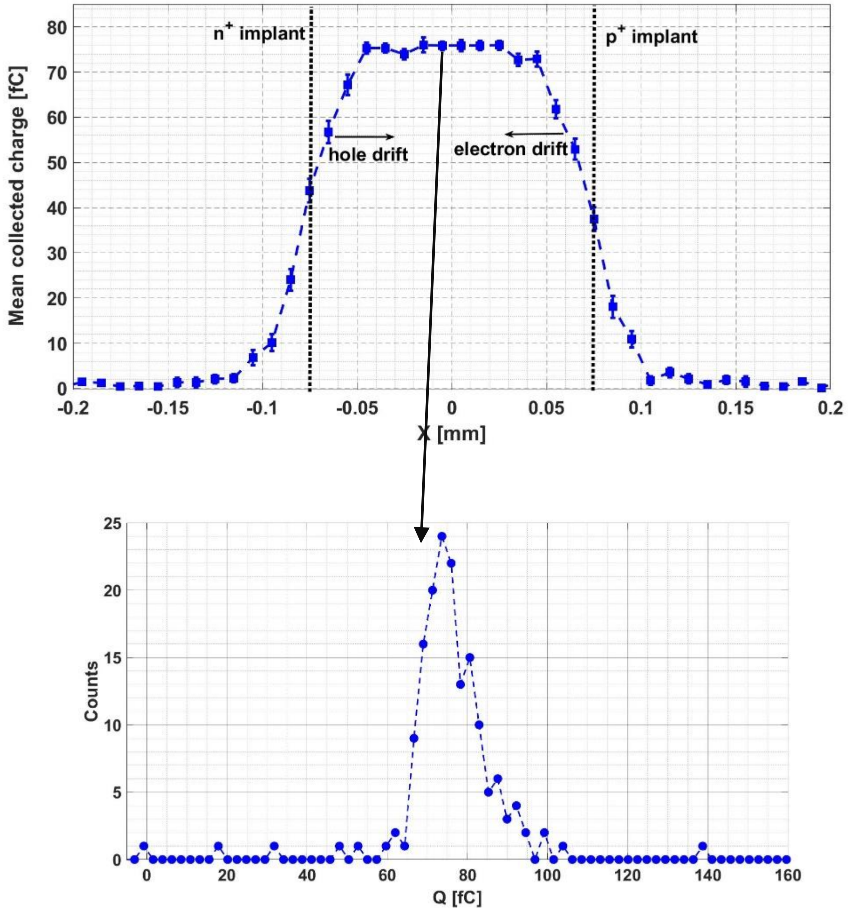
- Room temperature
- $V_{bias} = 100$ V
- θ : 0°
- Beam divergence: ±1 mrad

DUT:

- Non-irradiated diode

Observations:

- Charge distribution is uniform as a function of beam position with 10 μm bin width.



Charge profile, non-irradiated diode

Estimation of the diode thickness:

- Fit an error function to the rising edge of profile:

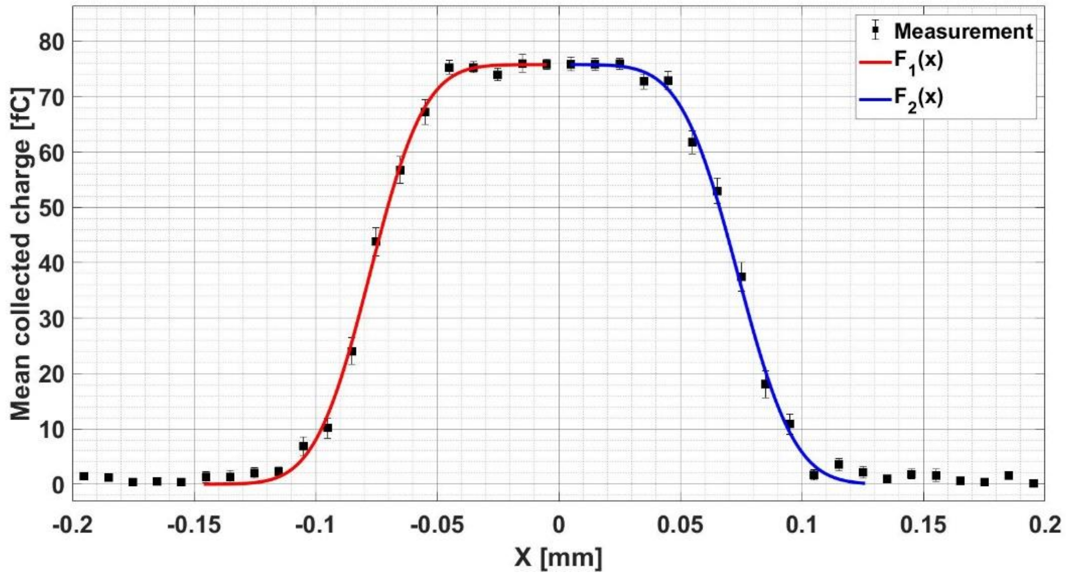
$$F_1(x) = A_1\left(0.5 + 0.5 \cdot \mathrm{erf}\left(\frac{x-\mu_1}{\sqrt{2}\sigma_1}\right)\right)$$

- Fit an error function to the falling edge of profile:

$$F_2(x) = A_2\left(0.5 - 0.5 \cdot \mathrm{erf}\left(\frac{x-\mu_2}{\sqrt{2}\sigma_2}\right)\right)$$

- Thickness of the diode is estimated as:

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



The result of the estimation:

$$t_{\mathrm{diode}} = 151.4 \pm 1.15\ \mu\mathrm{m}$$

$$\sigma_1 \approx \sigma_2 \approx 18\ \mu\mathrm{m}$$

Charge profile, irradiated diode

Measurement conditions:

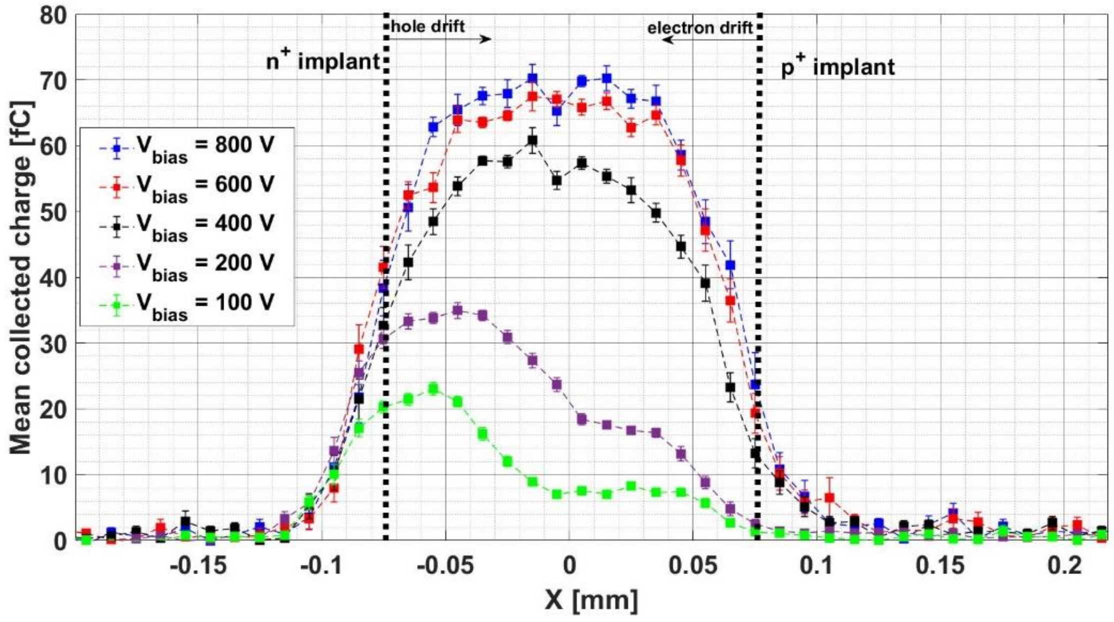
- Temperature: -20 C
- $V_{bias} = 800, 600, 400, 200, 100$ V
- Angle of incident: 0°

DUT:

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

Observations:

- Charge profile is not uniform as a function of beam position.
- Holes have a higher charge collection than electrons



Charge profile, irradiated diode

Measurement conditions:

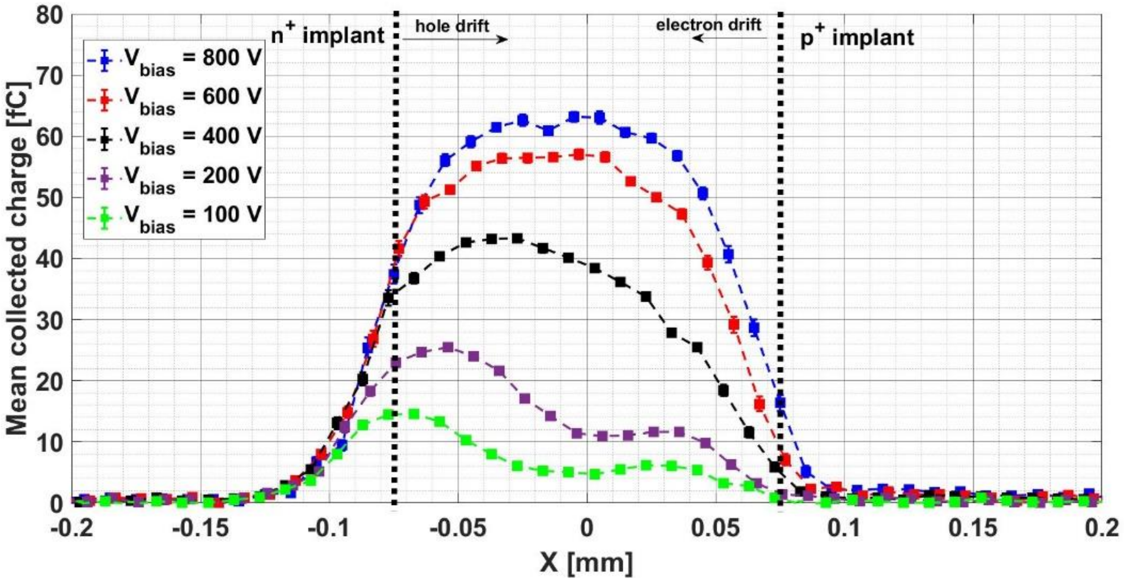
- Temperature: -20 C
- $V_{bias} = 800, 600, 400, 200, 100$ V
- Angle of incident: 0°

DUT:

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

Observations:

- Charge profile is not uniform as a function of beam position.
- Holes have a higher charge collection than electrons



CCE as a function of bias voltage

Measurement conditions:

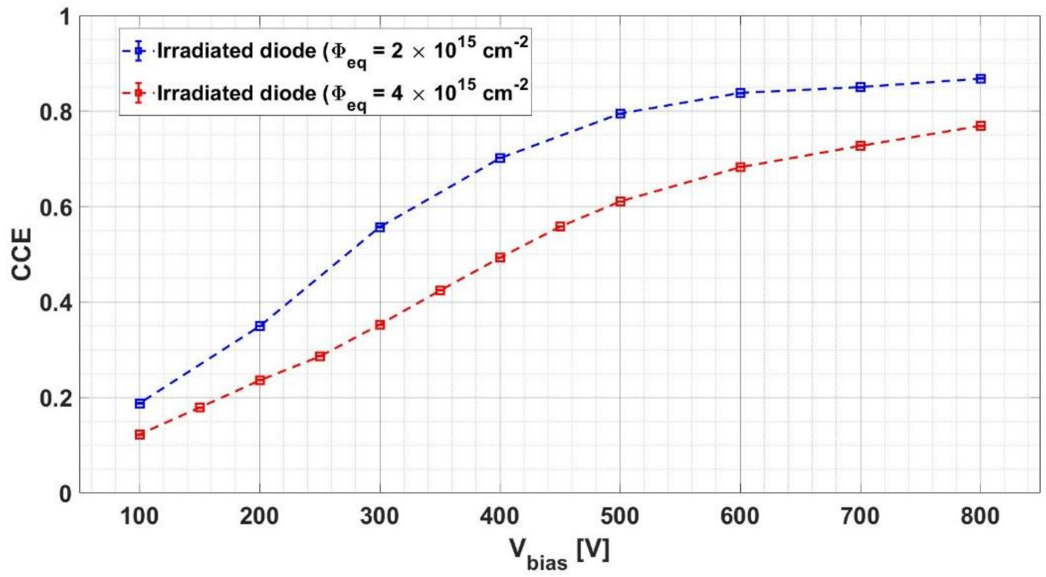
- Temperature: -20 C
- $V_{bias} = 100 - 800$ V
- Angle of incident: 0°

DUT:

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

CCE is calculated as:

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



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Summary and outlook

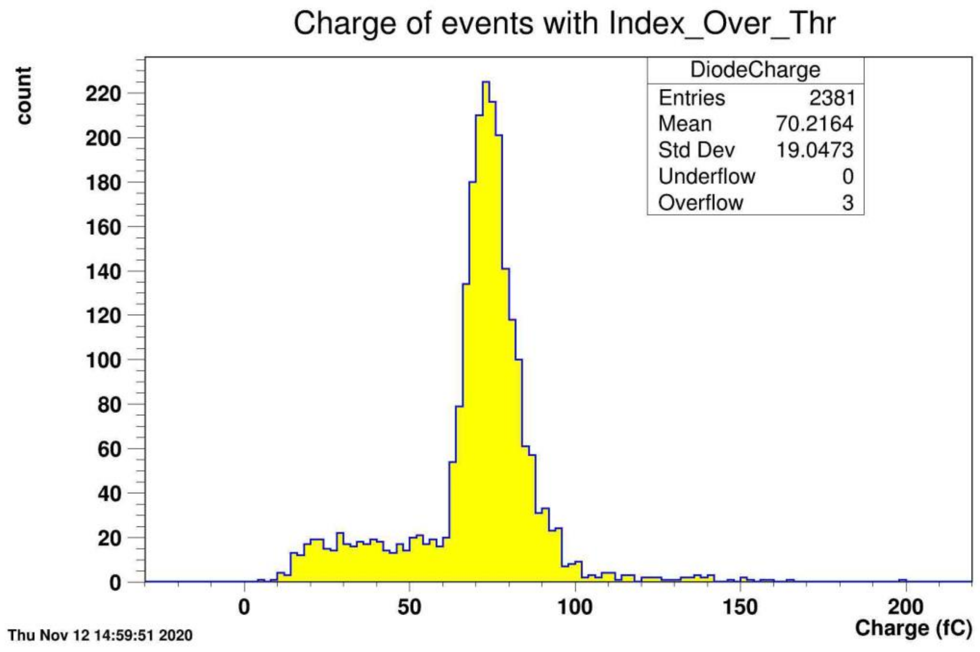
Summary

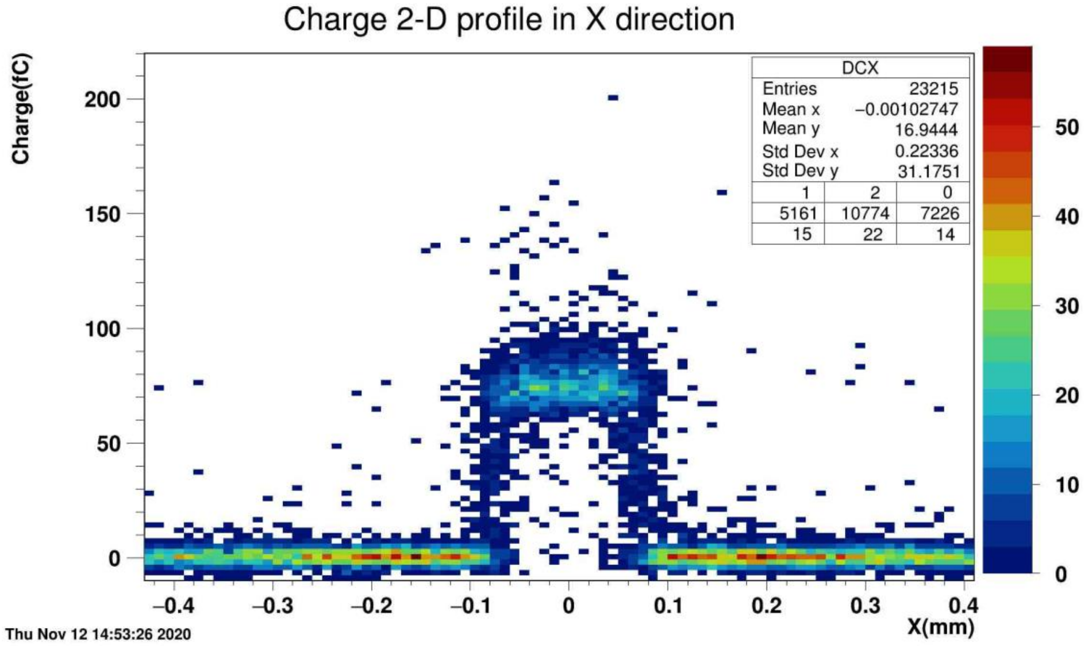
- Edge-on measurement can be used to obtain charge collection as a function of depth in irradiated pad diodes.
- In this work, the method was implemented using the high energy electron beam.
- The advantages of using the electron beam are:
  - It can be used for pad diodes
  - The chare profiles can be normalized to an absolute value
- This work introduces a procedure for in-situ alignment of the beam direction with respect to the DUT surface.
- Charge profiles were obtained for one non-irradiated and two irradiated diodes
- By using the charge profiles, CCE of irradiated diodes were estimated

Outlook

- Compare the measured charge profiles with results of the simulations (from TCAD model)
- Trying to calibrate the results of pixel measurements using the edge-on diode results
- Repeat the method for higher irradiation fluence

Back up, charge profile and charge distribution





Charge distributions , irradiated and non-irradiated diodes

Measurement conditions:

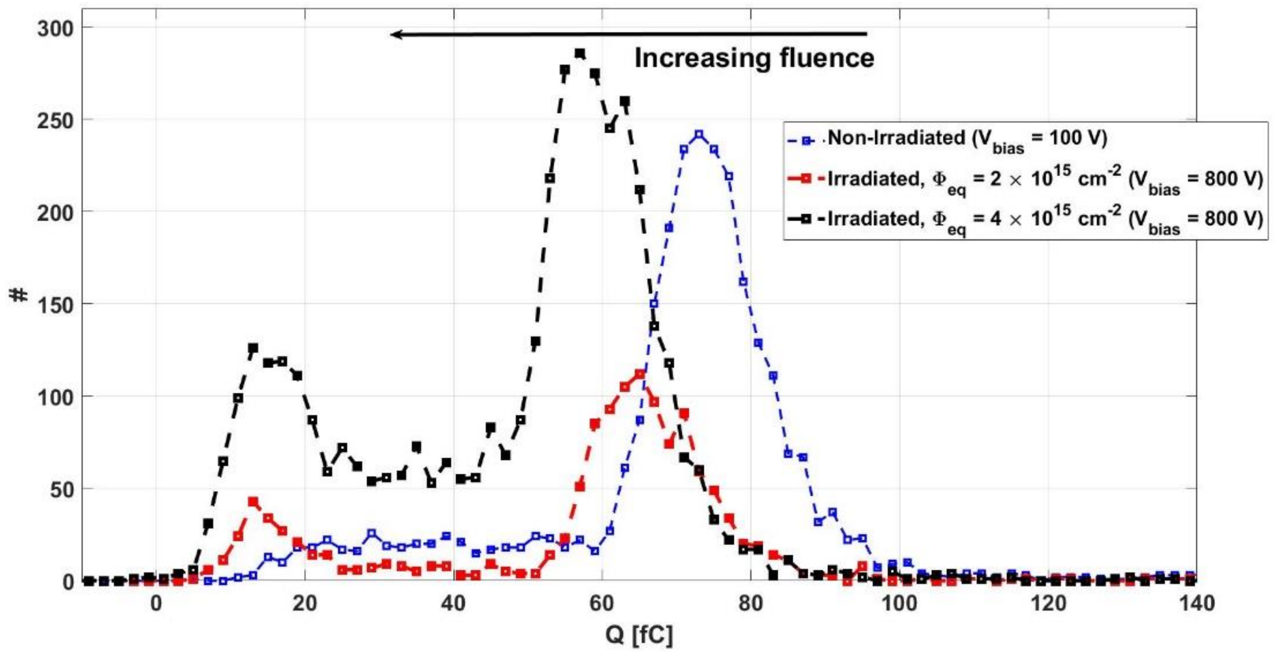
- Temperature: -20 C
- $V_{bias} = 800{,}100$ V
- Angle of incident: 0°

DUTs:

- Proton irradiated at $\Phi_{eq} = 0, 2$ and 4×10^{15} cm^{-2}

Observations:

- The total charge distribution is shifted to the lower charge as the irradiation fluence increases.



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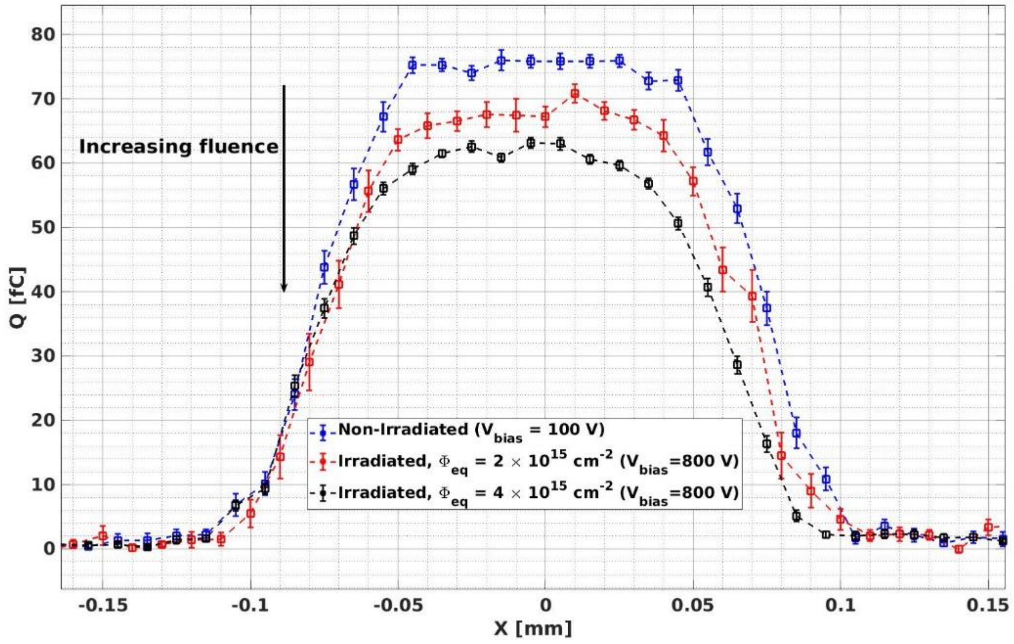
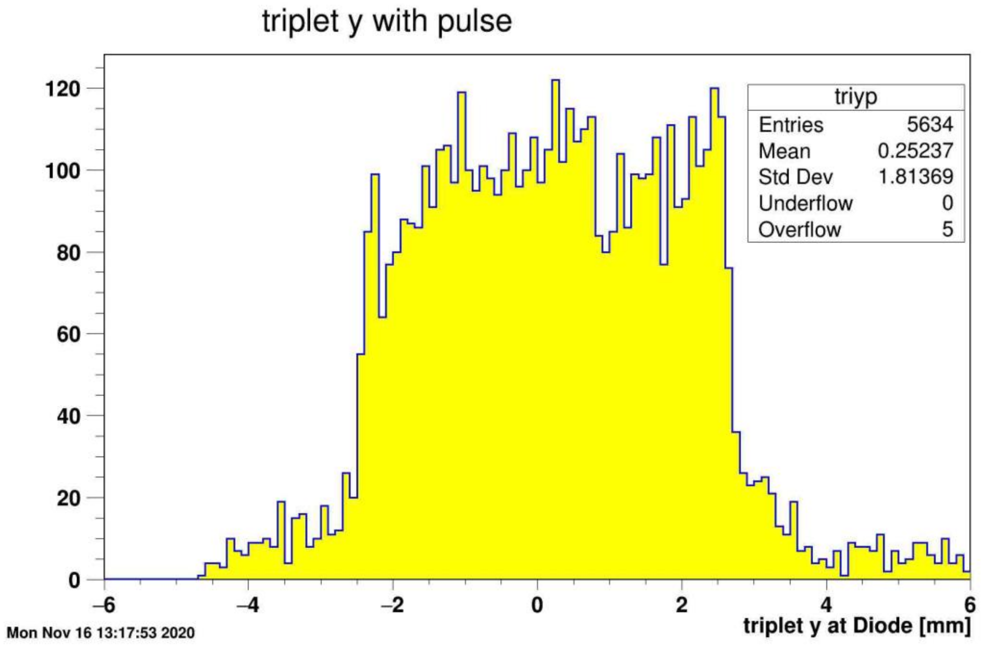
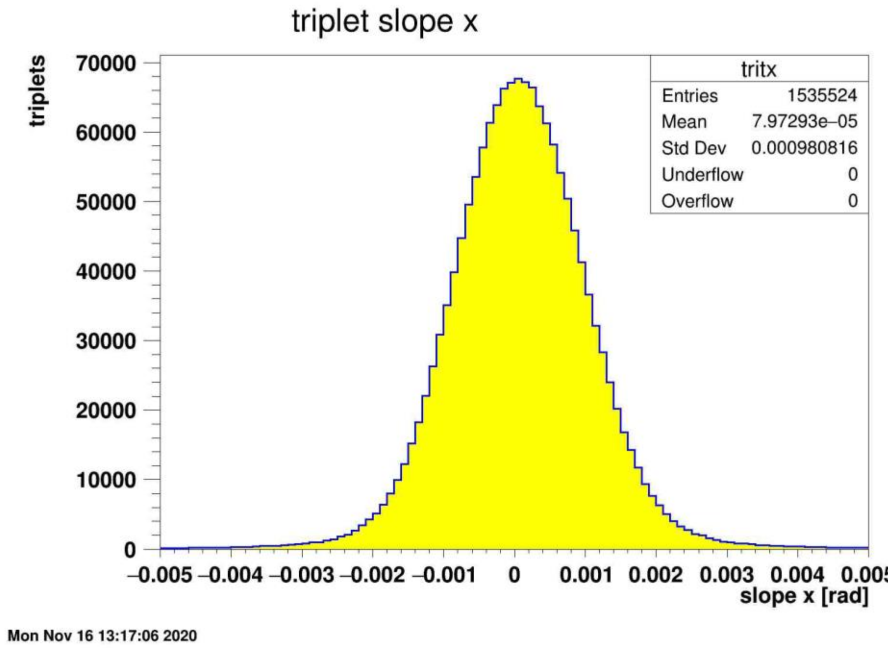


Back up, Geometrical cuts

$|y_{dut}| < 2.5$ mm

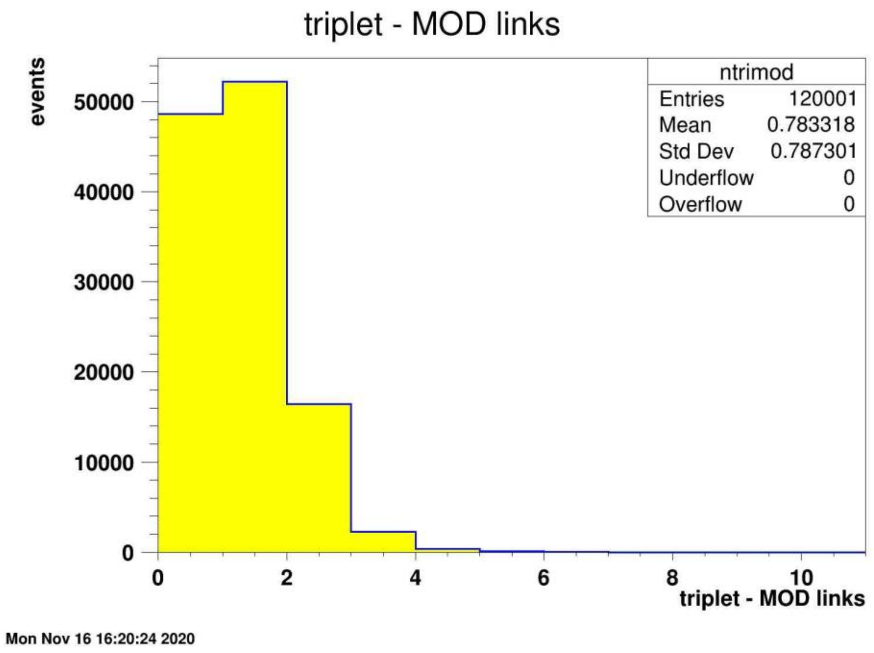


$|\theta_x| < 1$ mrad



Back up, Cuts on number of tracks per event

$|N_{tracks}| < 2$



Hit map of the DUT

Measurement conditions:

- Room temperature
- $V_{bias} = 100$ V

DUT:

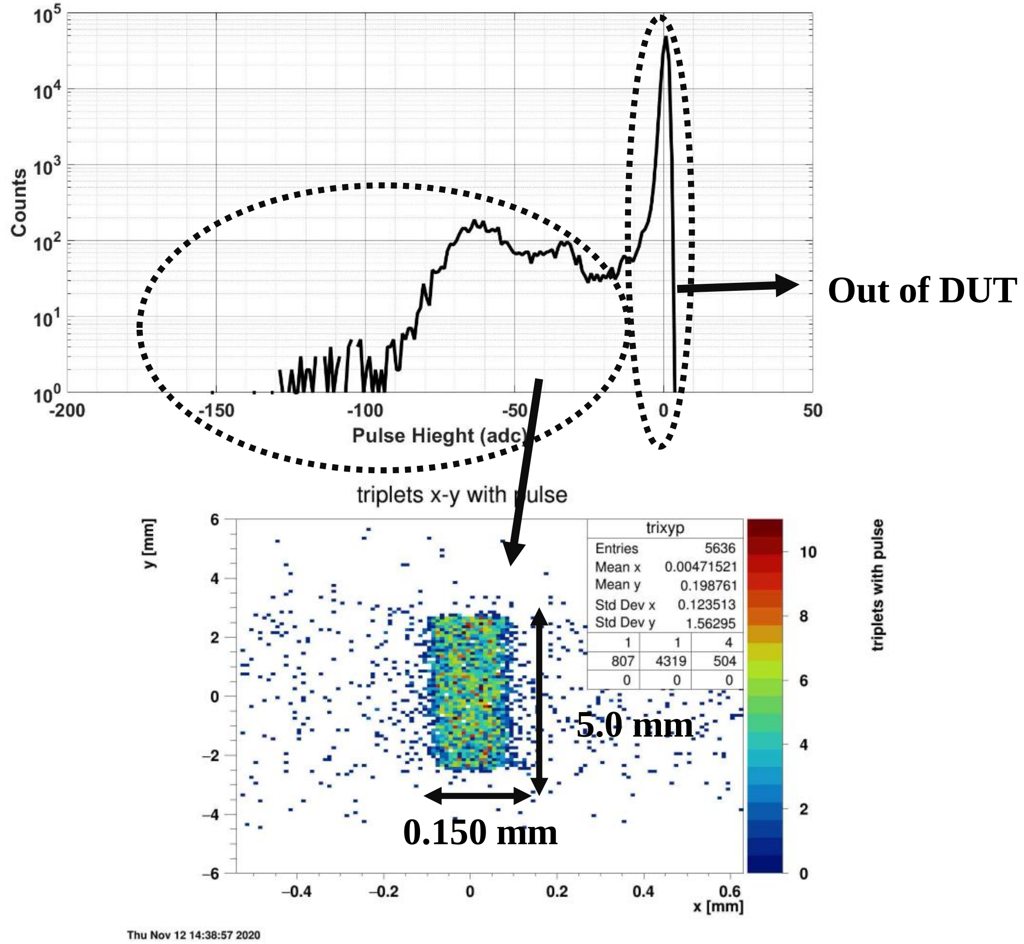
- Non-irradiated

Observations:

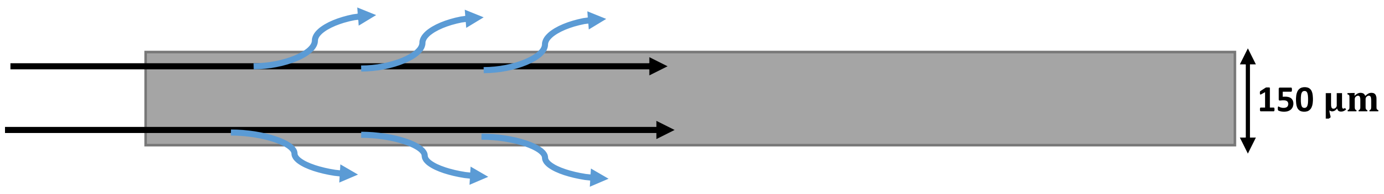
- Pulse height distribution of the DUT for all events
- Reconstructed tracks with amplitude over offline threshold

Conclusions:

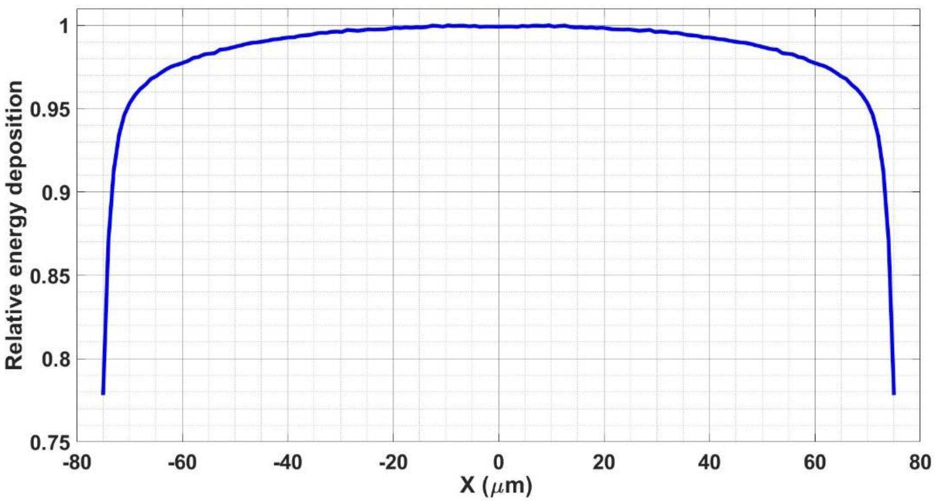
- Most of tracks are out of the DUT plane
- 1~2 % of tracks produce pulse in the diode



Back up, GEANT4 simulation result



Less energy deposition at edges than center



Charge profile, non-irradiated diode

Measurement conditions:

- Temperature: -20 C
- $V_{bias} = 20, 100, 200, 300$ V
- θ : 0°

DUT:

- Non-irradiated

Observations:

- At bias voltage of 20 V, the diode is only partially depleted from the front side. No charge collection in the rear side.
- For bias voltages above 100 V, the charge profile remains unchanged.